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Strangeness
In
Collisions

February 16-17, 2006

Organizers:
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Preface to the Series

The RIKEN BNL Research Center (RBRC) was established in April 1997 at Brookhaven National Laboratory. It is funded by the "Rikagaku Kenkyusho" (RIKEN, The Institute of Physical and Chemical Research) of Japan. The Center is dedicated to the study of strong interactions, including spin physics, lattice QCD, and RHIC physics through the nurturing of a new generation of young physicists.

The RBRC has both a theory and experimental component. The RBRC Theory Group currently consists of about twenty researchers, and the RBRC Experimental Group, of about fifteen researchers. Positions include the following: full time RBRC Fellow, half-time RHIC Physics Fellow, and full-time, post-doctoral Research Associate. The RHIC Physics Fellows hold joint appointments with RBRC and other institutions and have tenure track positions at their respective universities or BNL. To date, RBRC has ~40 graduates of which 14 theorists and 6 experimenters have attained tenure positions at major institutions worldwide.

Beginning in 2001 a new RIKEN Spin Program (RSP) category was implemented at RBRC. These appointments are joint positions of RBRC and RIKEN and include the following positions in theory and experiment: RSP Researchers, RSP Research Associates, and Young Researchers, who are mentored by senior RBRC Scientists. A number of RIKEN Jr. Research Associates and Visiting Scientists also contribute to the physics program at the Center.

RBRC has an active workshop program on strong interaction physics with each workshop focused on a specific physics problem. Each workshop speaker is encouraged to select a few of the most important transparencies from his or her presentation, accompanied by a page of explanation. This material is collected at the end of the workshop by the organizer to form proceedings, which can therefore be available within a short time. To date there are seventy-seven proceeding volumes available.

A 10 teraflops RBRC QCDOC computer funded by RIKEN, Japan, was unveiled at a dedication ceremony at BNL on May 26, 2005. This supercomputer was designed and built by individuals from Columbia University, IBM, BNL, RBRC, and the University of Edinburgh, with the U.S. D.O.E. Office of Science providing infrastructure support at BNL. Physics results were reported at the RBRC QCDOC Symposium following the dedication. A 0.6 teraflops parallel processor, dedicated to lattice QCD, begun at the Center on February 19, 1998, was completed on August 28, 1998 and is still operational.

N. P. Samios, Director
October 2005

*Work performed under the auspices of U.S.D.O.E. Contract No. DE-AC02-98CH10886.

CONTENTS

Strangeness in Collisions

Since the earliest days of ultra-relativistic heavy ion physics, there has been interest in strange particle production. Originally, an anomalously large strangeness production was believed to be a signature of the Quark Gluon Plasma. Now the flavor composition of the plasma as reflected in the ratios of abundances of strange and non-strange particles is believed by advocates to tell us the temperature and baryon number density of the Quark Gluon Plasma at decoupling. In addition, there are arguments that suggest that the abundances of strange particles might at intermediate energy or at non-central rapidity, signal the existence of a critical end point of phase transitions in the baryon number chemical potential temperature plane.

The purpose of this workshop is to assess the current theoretical and experimental understanding of strangeness production for ultra-relativistic heavy ion collisions.

H. Caines, L. McLerran, M. Lamont, K. Redlich, R. Witt

Strangeness Production and Partonic EoS at RHIC

Nu Xu

Lawrence Berkeley National Laboratory

Many thanks to organizers
and

S. Blyth, *X. Dong, H. Huang, M. Kaneta, Y. Lu, M. Oldenburg, A. Poskanzer*
H. Ritter, K. Schweda, P. Sorensen, Z. Xu

P. Huovinen, R. Rapp, K. Redlich, ...

Outline

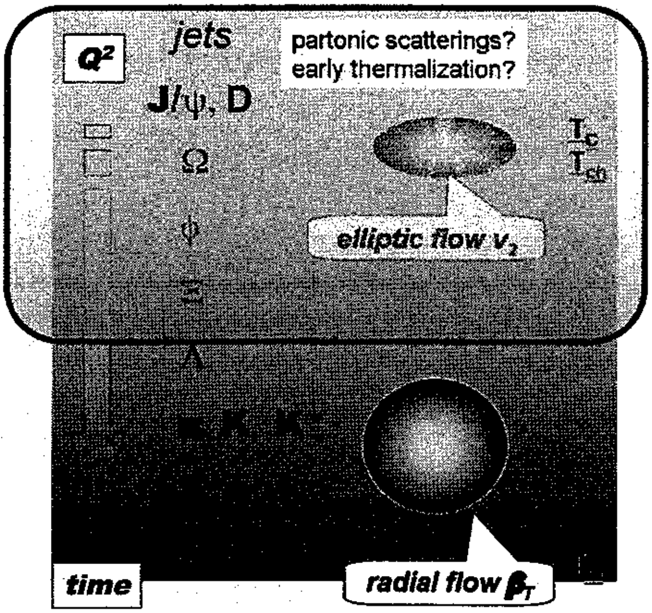
- Motivation
- Strangeness production
- Partonic EOS in high-energy nuclear collisions
- Questions

High-Energy Nuclear Collisions

Initial Condition
- initial scatterings
- baryon transfer
- E_T production
- parton dof

System Evolves
- parton interaction
- parton/hadron expansion

Bulk Freeze-out
- hadron dof
- interactions stop



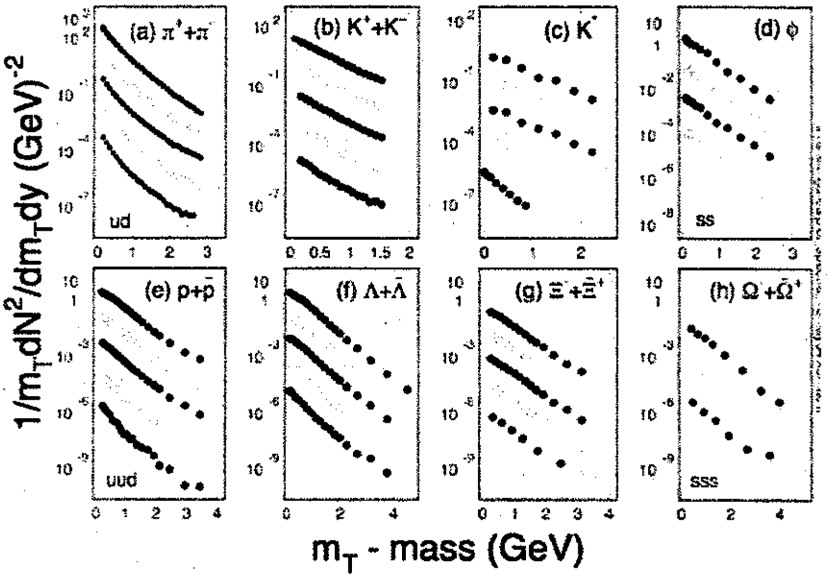
partonic scatterings?
early thermalization?

elliptic flow v_2

radial flow β_T

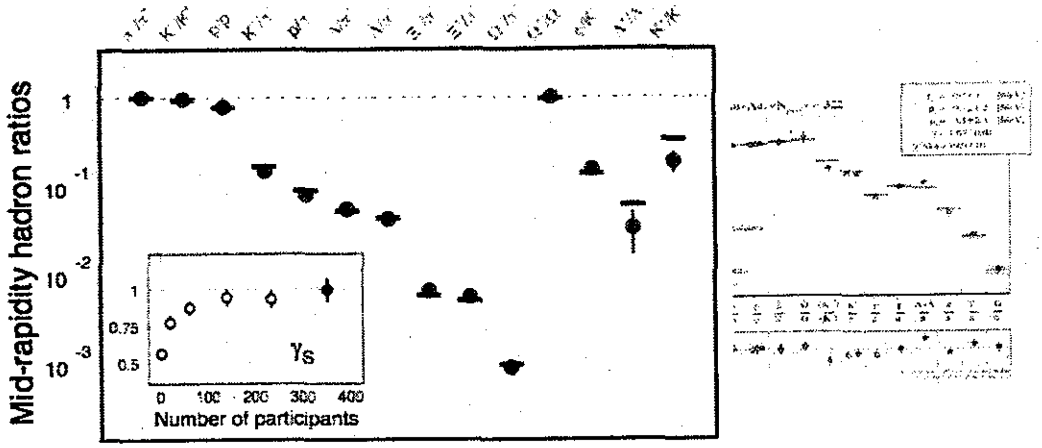
Hadron spectra from RHIC

p+p and Au+Au collisions at 200 GeV



White papers - STAR: Nucl. Phys. A757, p102;

Ratio analysis



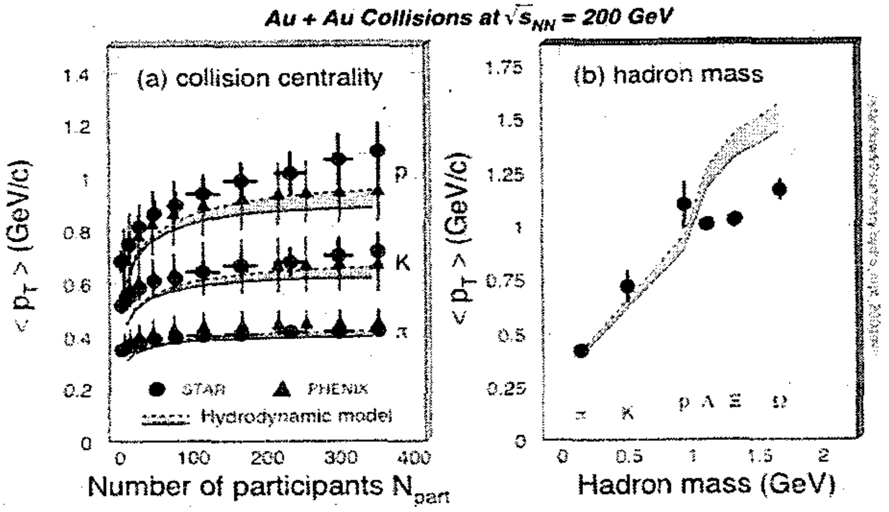
200 GeV ^{197}Au + ^{197}Au central collision

In central collisions, thermal model fit well, $\gamma_S = 1$. ***The system is thermalized.***

Short lived resonances show deviation - ***There is life after chemical freeze-out!***

White papers - STAR: Nucl. Phys. A757, p102; PHENIX: p184(2005)

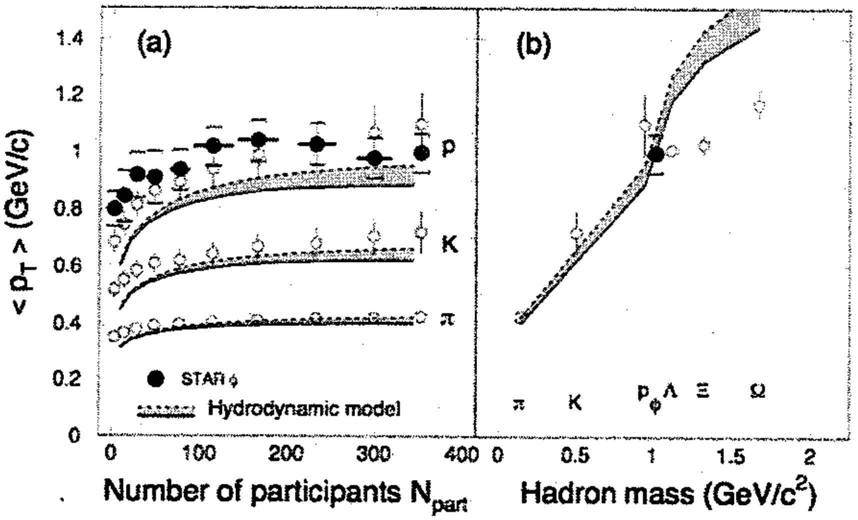
Compare with hydro-model results



This model results fit to pion, Kaon, and proton spectra well, but over predicted the values of <p_T> for multi-strange hadrons

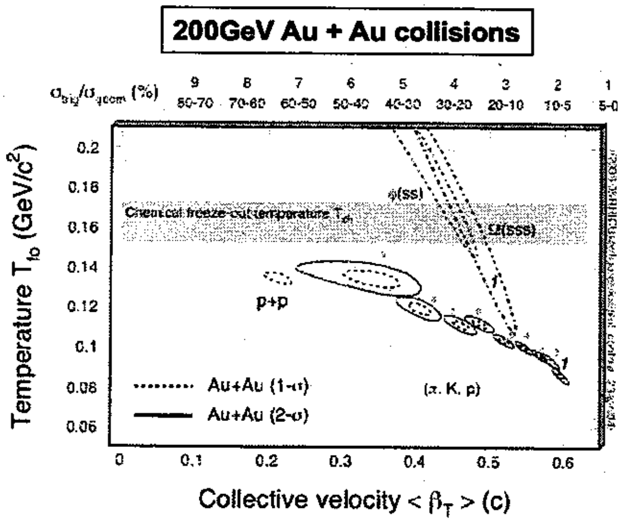
(T_C=165 MeV, T_{fo}=100 MeV +...) *P. Kolb et al., Phys. Rev. C62, 054909 (2000).*

ϕ results



ϕ mean p_T almost flat versus collision centrality
The mechanism for ϕ-meson production still a puzzle

Blast wave fits: T_{fo} vs. $< \beta_T >$



1) π, K, and p change smoothly from peripheral to central collisions.

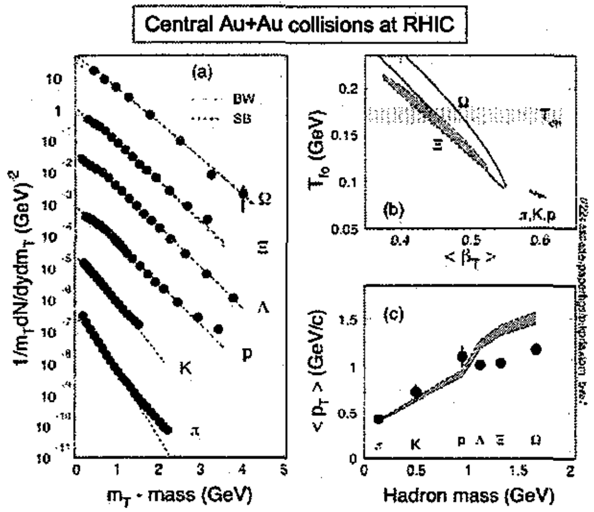
2) At the most central collisions, $<\beta_T>$ reaches 0.6c.

3) Multi-strange particles ϕ, Ω are found at higher T and lower $<\beta_T>$

⇨ Sensitive to early partonic stage!
⇨ How about v_2?

STAR: NP**A715**, 458c(03); *PRL* **92**, *112301(04)*; **92**, *182301(04)*.

Early freeze-out



1) Multi-strange hadrons seem to freeze out earlier than others ⇨ sensitive probe for early dynamics

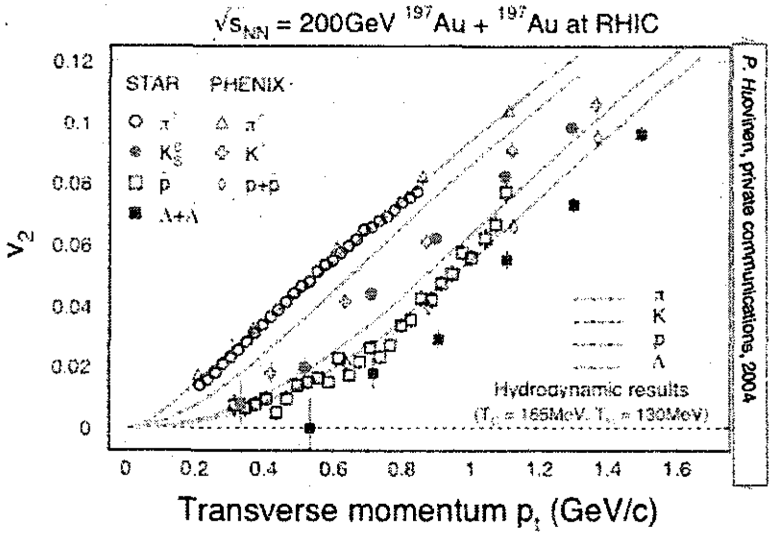
2) Charm-hadrons should be better. A possible complication is the pQCD hard spectrum.

3) J/ψ coalescence/melting: a tool for early dynamics CGC, deconfinement, and thermal equilibrium

PHENIX: Phys. Rev. C69 034909 (04).
STAR: Phys. Rev. Lett. 92, 112301(04);
Phys. Rev. Lett. 92, 182301(04).
A. Andronic et al., NPA715, 529(03).
P. Kolb et al., Phys. Rev. C67 044903(03)

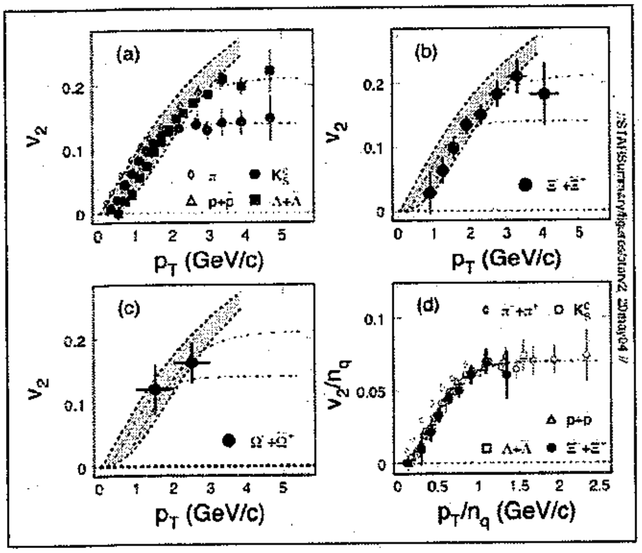
Chemical Freeze-out: inelastic interactions stop
Kinetic Freeze-out: elastic interactions stop

v_2 at low p_T region



- Minimum bias data! At low p_T, model result fits mass hierarchy well!
- Details does not work, need more flow in the model!

Collectivity, Deconfinement at RHIC



- v_2, spectra of light hadrons and multi-strange hadrons
- scaling of the number of constituent quarks

At RHIC, I believe we have achieved:

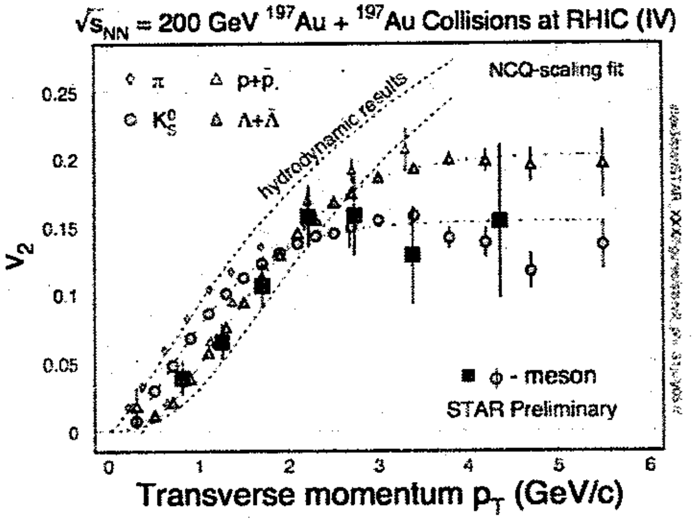
⇨ **Partonic Collectivity**

⇨ **Deconfinement**

*PHENIX: PRL**91**, 182301(03)*
*STAR: PRL**92**, 052302(04), **95**, 122301(05)*
nucl-ex/0405022

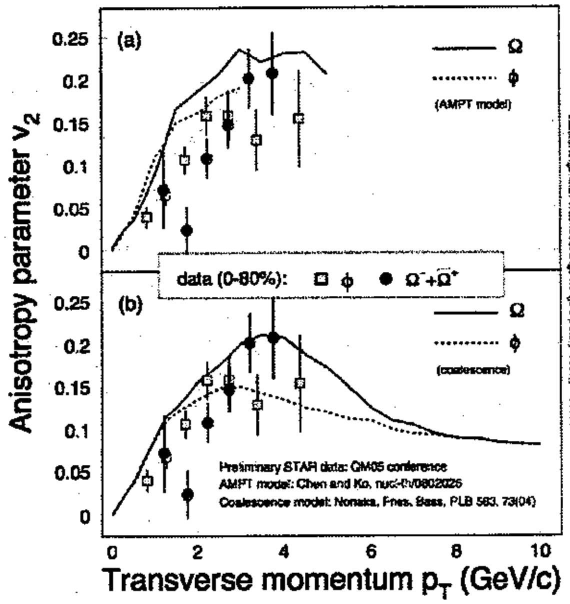
S. Voloshin, NPA715, 379(03)
*Models: Greco et al, PRC**68**, 034904(03)*
*X. Dong, et al., Phys. Lett. **B597**, 328(04).*
....

ϕ-meson flows



STAR Preliminary, QM05 conference

Dynamic model results



Models seem to work in $2.5 < p_T < 5$ GeV/c

In those models, almost no interactions at the late hadronic stage. Flow has developed prior to hadronization:

⇒ **partonic collectivity**

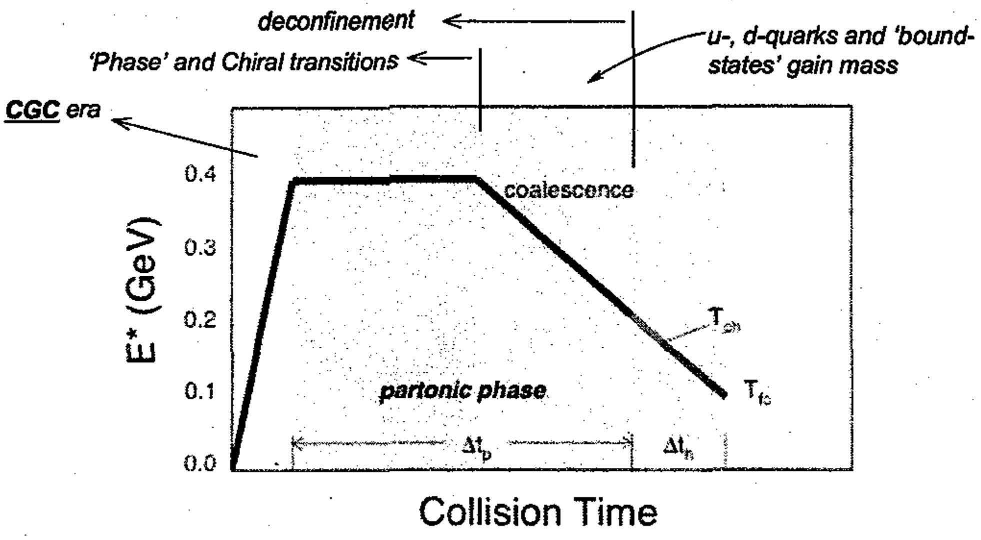
⇒ **indication of de-confinement**

Summary and outlook

- Strangeness production and dynamics play important role for understanding the hot/dense medium at RHIC

- The experimental results on spectra and v_2 measurements, **especially with the multi-strange hadrons**, have clearly demonstrated the development of partonic collectivity at RHIC. An important step towards the fixing EOS at RHIC!

Collision Time - a picture for RHIC



1) *Coalescence processes occur during phase transition and hadronization;*
2) *The u-,d-quarks and 'bound-states' gain mass accompanied by expansion;*
3) ***Early partonic thermalization and its duration need to be checked.***

Open issues

- Measure the partonic velocity to infer pressure parameter - important for mapping the EoS at RHIC
- Understand the meson and baryon difference in p+p collisions - more non-biased p+p data should be collected at RHIC
- Resonance v_2 measurements are needed to understand the number of constituent quark scaling AND the activities in the later hadronic period
- In order to demonstrate the possible early partonic thermalization, we are pushing for the heavy flavor collectivity measurement - RHIC heavy flavor program
- In order to demonstrate the possible phase transition, we should push for the energy scan program at RHIC!

System-size dependence of Strangeness Production at the SPS

(... and RHIC, AGS and SIS)

Claudia Höhne, GSI Darmstadt

- **data**

The system-size dependence of relative strangeness production from NA49 at 158 AGeV beam energy [PRL 94, 052301 (2005)] shows a fast increase for small systems and a saturation for $N_{part} \geq 60$ on. Qualitatively , in statistical models this can be understood by the release of canonical strangeness suppression due to the increasing system size, quantitatively, however, a large discrepancy remains if assuming the volume to be proportional to N_{part}.

- **model** [hep-ph/0507276]

The (macroscopic) hadronization volume used by the statistical model is redefined starting from a microscopic view of the collision process. The collision process is separated into two independent steps. First, overlapping collisions/ strings form clusters of highly excited and strongly interacting matter (percolation calculation). Second, these clusters are hadronized independently as a coherent entity (statistical model). According to this model, several clusters exist in smaller collision systems, while in central Pb+Pb basically one large cluster is created comprising all participating nucleons. The model gives an excellent quantitative description of the data and is applicable in the energy regime $\sqrt{s} \geq 17$ GeV.

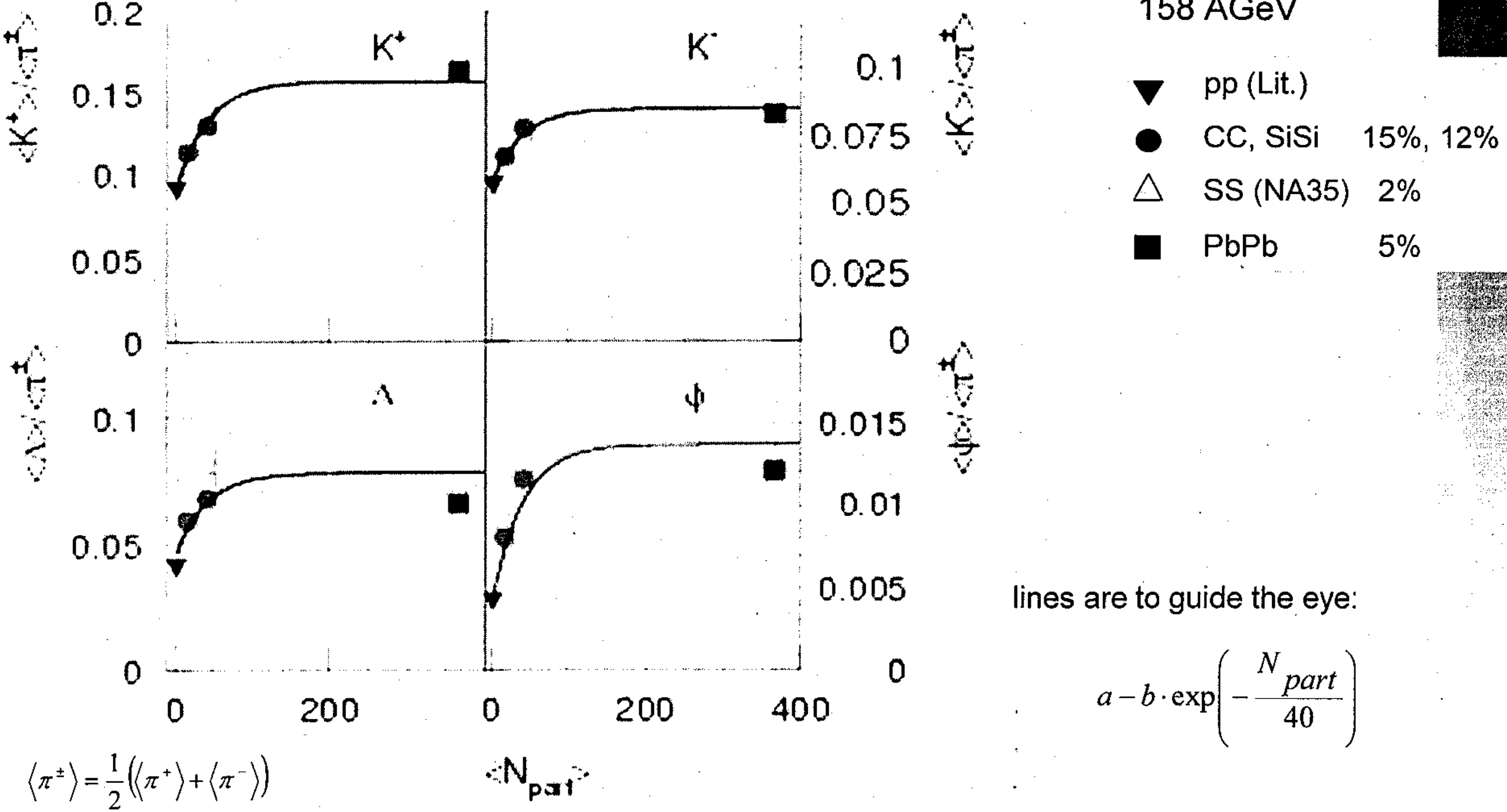
- **energy dependence of system-size dependence**

Data on relative strangeness production (K^+, K^-) in dependence on centrality for AuAu or PbPb collisions are available for SIS, AGS, SPS, and RHIC energies. Depending on the normalization (N_{part}, π) either a strong change of the shape between AGS and SPS or a smooth evolution of the shape is observed for all energies. Also, the K/π ratio seems to be not saturated or just saturated, respectively, which has important input on the interpretation.

s-production vs system-size

- fast increase for small systems, saturation from $N_{part} > 60$ on!

[NA49, PRL 94, 052301 (2005)]



$\langle \pi^{\pm} \rangle = \frac{1}{2}\left(\langle \pi^{+} \rangle + \langle \pi^{-} \rangle\right)$

lines are to guide the eye:

$$a - b \cdot \exp\left(-\frac{N_{part}}{40}\right)$$

Redefine hadronization volume V

- microscopic model of A+A collisions → high density of collisions/strings
- assign a transverse extension to the individual NN collisions ("string-radius"), assume that due to the overlap of these strings clusters of highly excited and strongly interacting matter are formed; strings/collisions no longer independent

percolation model: cluster formation

- assume independent hadronization of these clusters
- particle compositions (here: relative strangeness production) calculated from the statistical model (as it is so succesful for central AuAu/ PbPb)

statistical model: cluster hadronization

- main purpose: calculate system-size dependence of relative strangeness production in A+A collisions (at 158 AGeV)

Comparison with experiment

- experimentally, total relative s-production is not accessible:

approximate with
$$E_s = \frac{\langle \Lambda \rangle + 2\left(\langle K^+ \rangle + \langle K^- \rangle\right)}{\langle \pi \rangle}$$

- assume

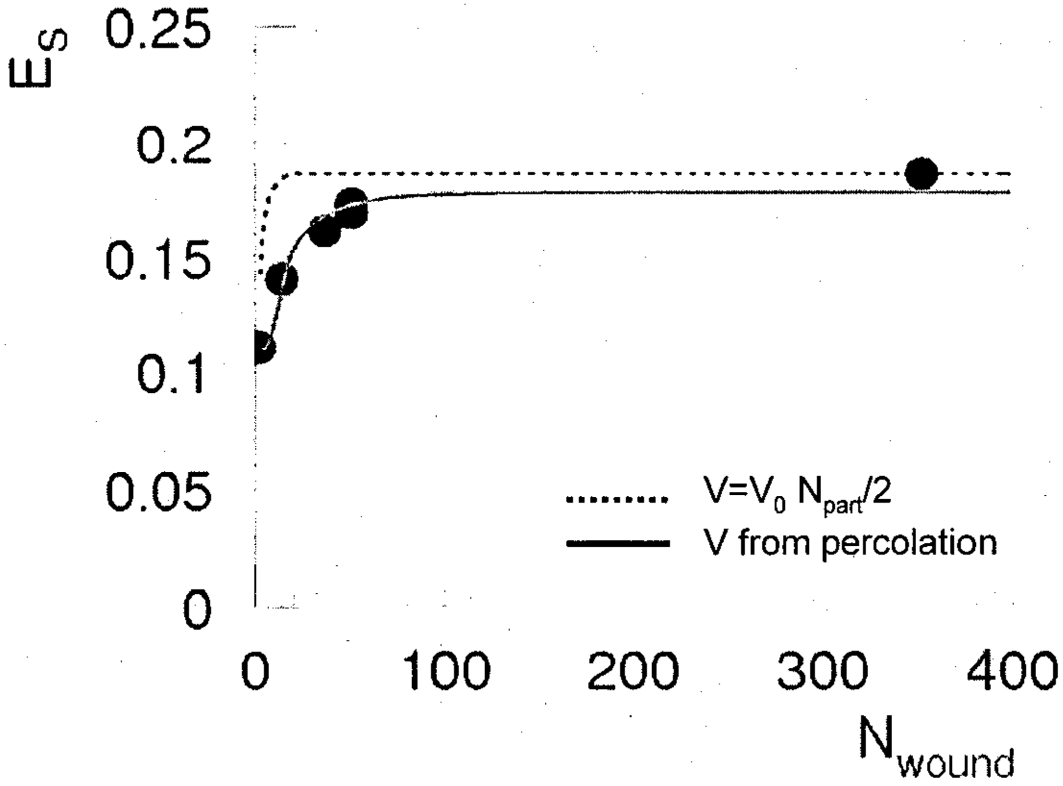
$$E_S(N_{wound}) \cong a\langle \eta(V_h) \rangle$$

parameters:

r_s = 0.3fm V_0=4.2fm^3

m_s=280 MeV T=160MeV

a=0.18

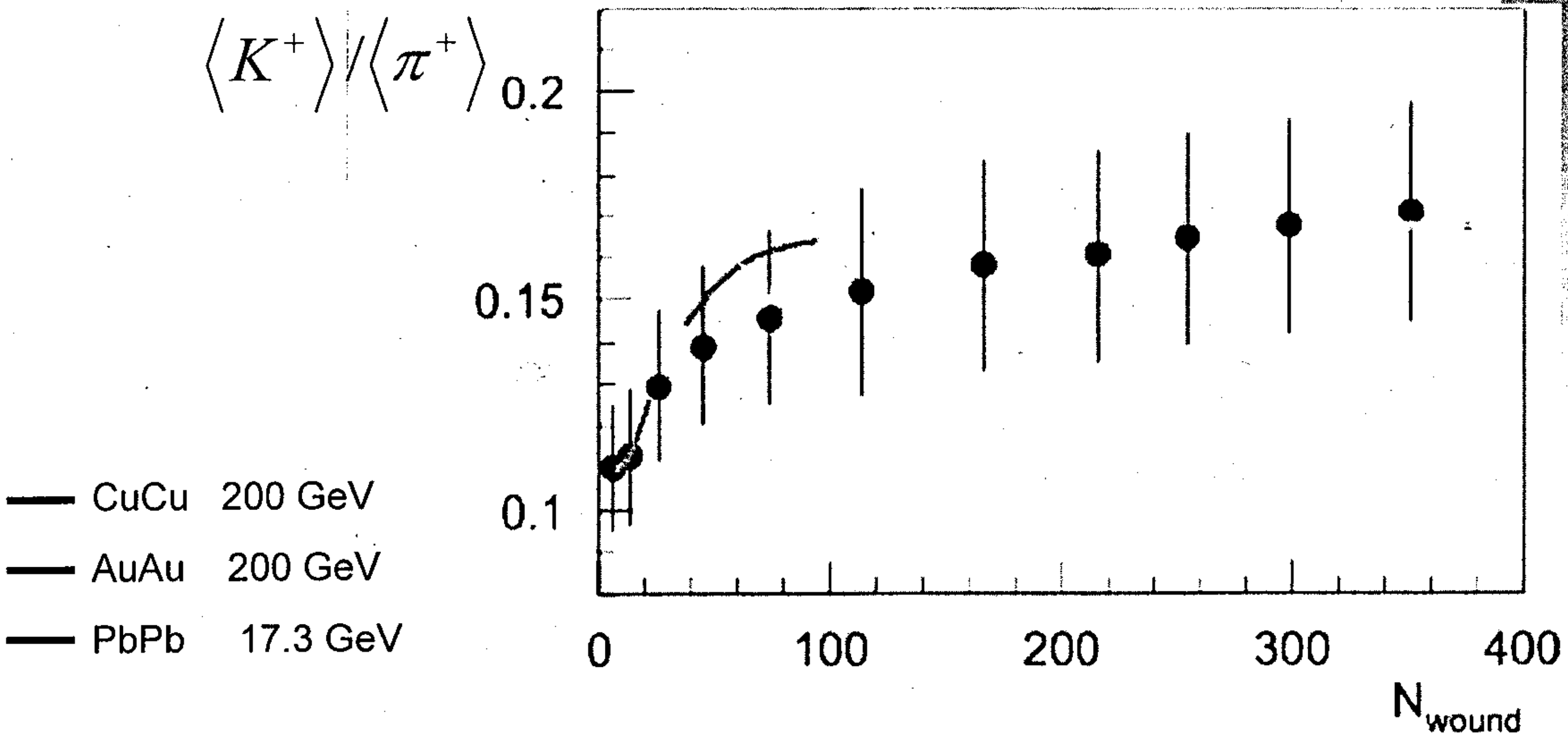


[hep-ph/0507276]

Comparison to RHIC

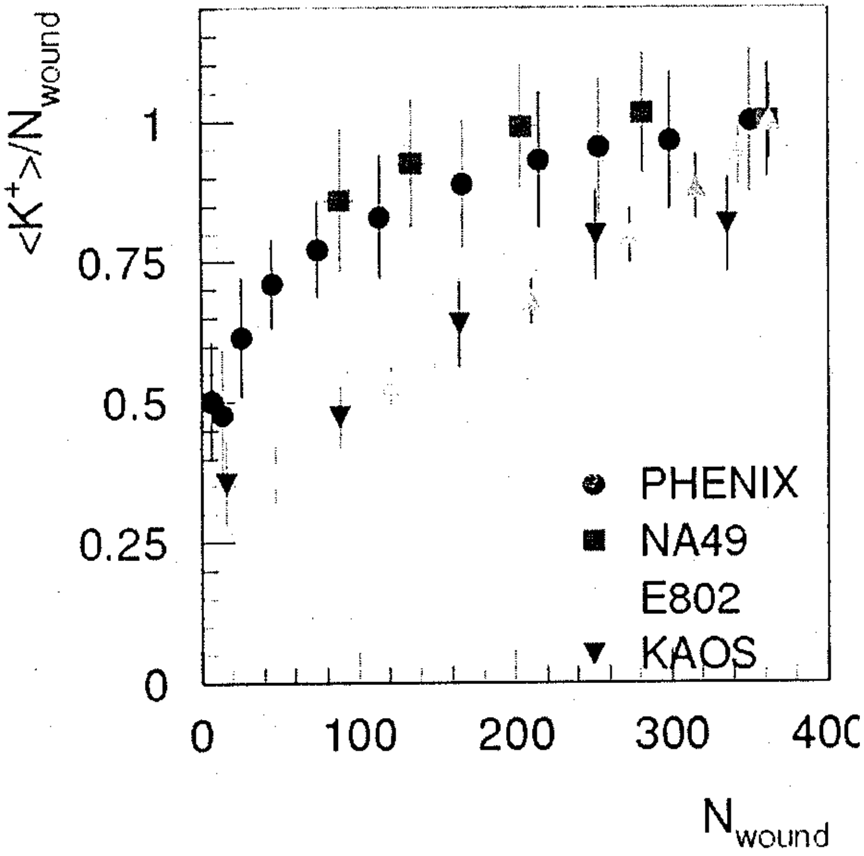
- PHENIX: K^+/π^+ ratio at midrapidity [PRC 69 (2004) 034909]
- T=164 MeV to adjust for lower total s-enhancement
- assume K^+/π^+ ratio at midrapidity to be representative for the total relative s-production

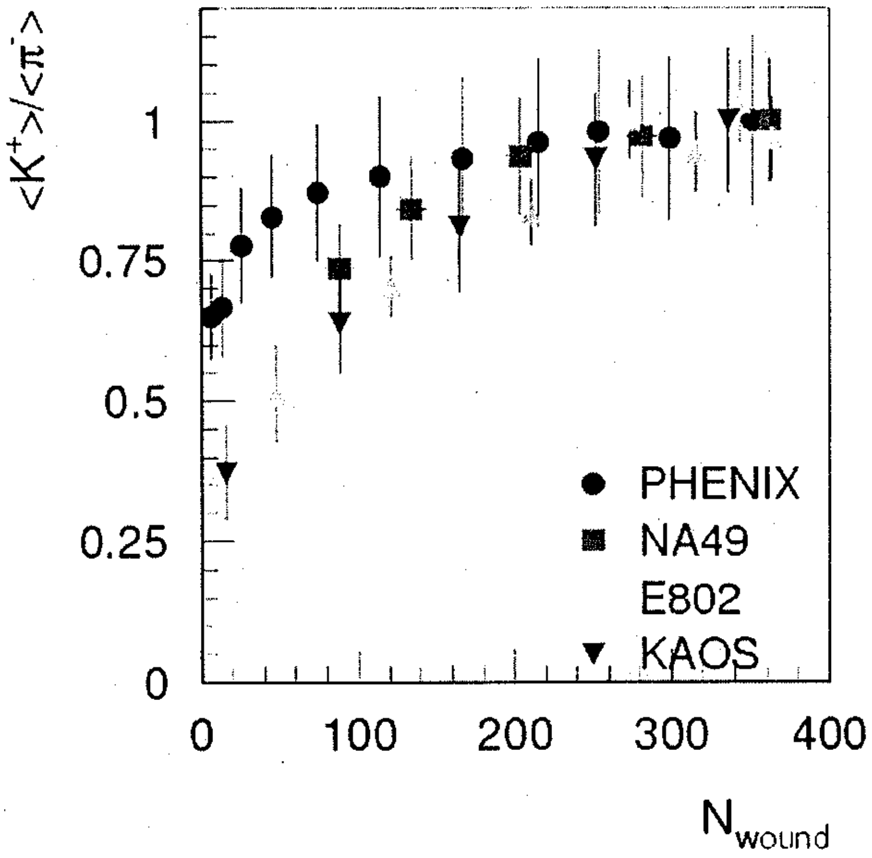
  BRAHMS: ratio nearly independent on rapidity [JPG 30 (2004) S1129]



Discussion

- **saturation of relative strangeness production for all energies – or only for higher??**
- role of pions in PbPb/ AuAu?: usage of small systems instead better defined?
- calculation of N_{wound}?

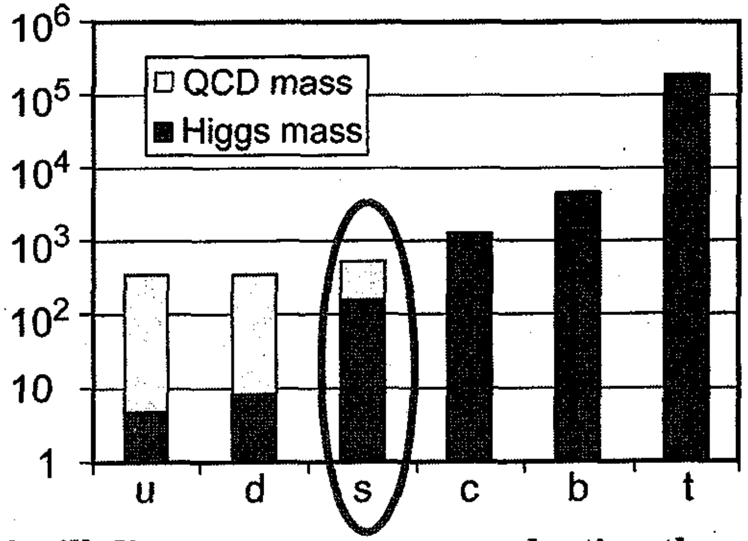




Claudia Höhne Strangeness in Collisions workshop, BNL, February 16-17, 2006

RHIC Strangeness Physics at high pt

R. Bellwied (Wayne State University)

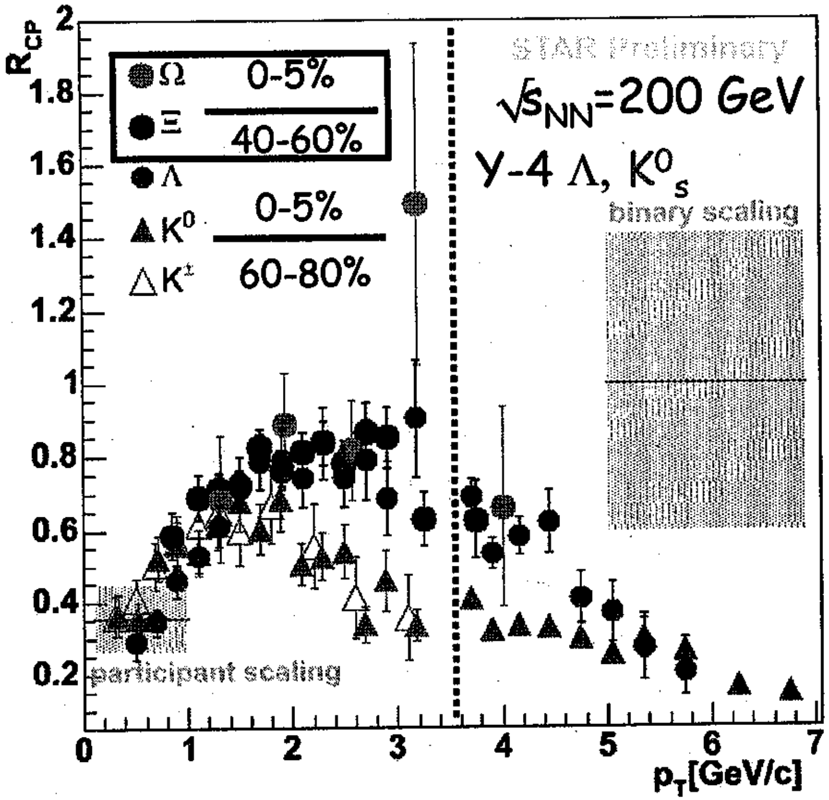


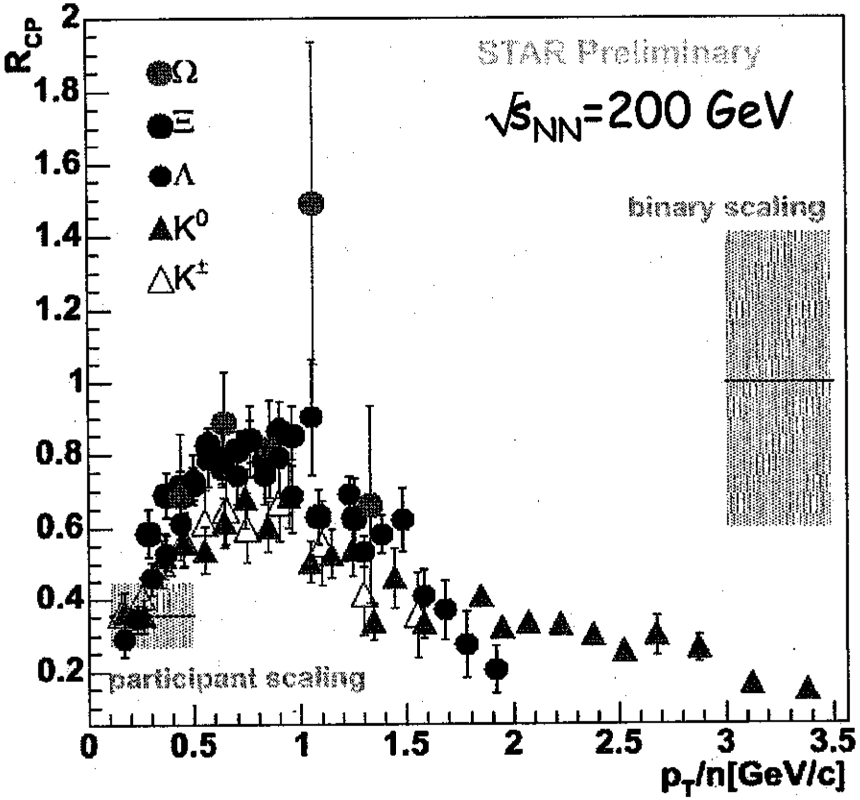
Is strangeness production in medium different than production in vacuum ?

I will discuss strangeness production through fragmentation in pp and compare the production of strange particles at high p_T from pp to central AuAu collisions. I show that recombination of partonic degrees of freedom can explain the suppression differences between strange baryons and mesons in AA collisions, but that the effect of canonical suppression of strangeness in pp is needed to understand the difference between pp and AA strange particle production. Canonical suppression will be investigated and its dependence on p_T and the correlation volume will be shown. Finally I study medium modification of fragmentation in AA by measuring particle identified two-particle correlations at high p_T.

Strangeness Workshop, BNL, Feb.16-17,2006

Nuclear Modification Factor R_{cp}



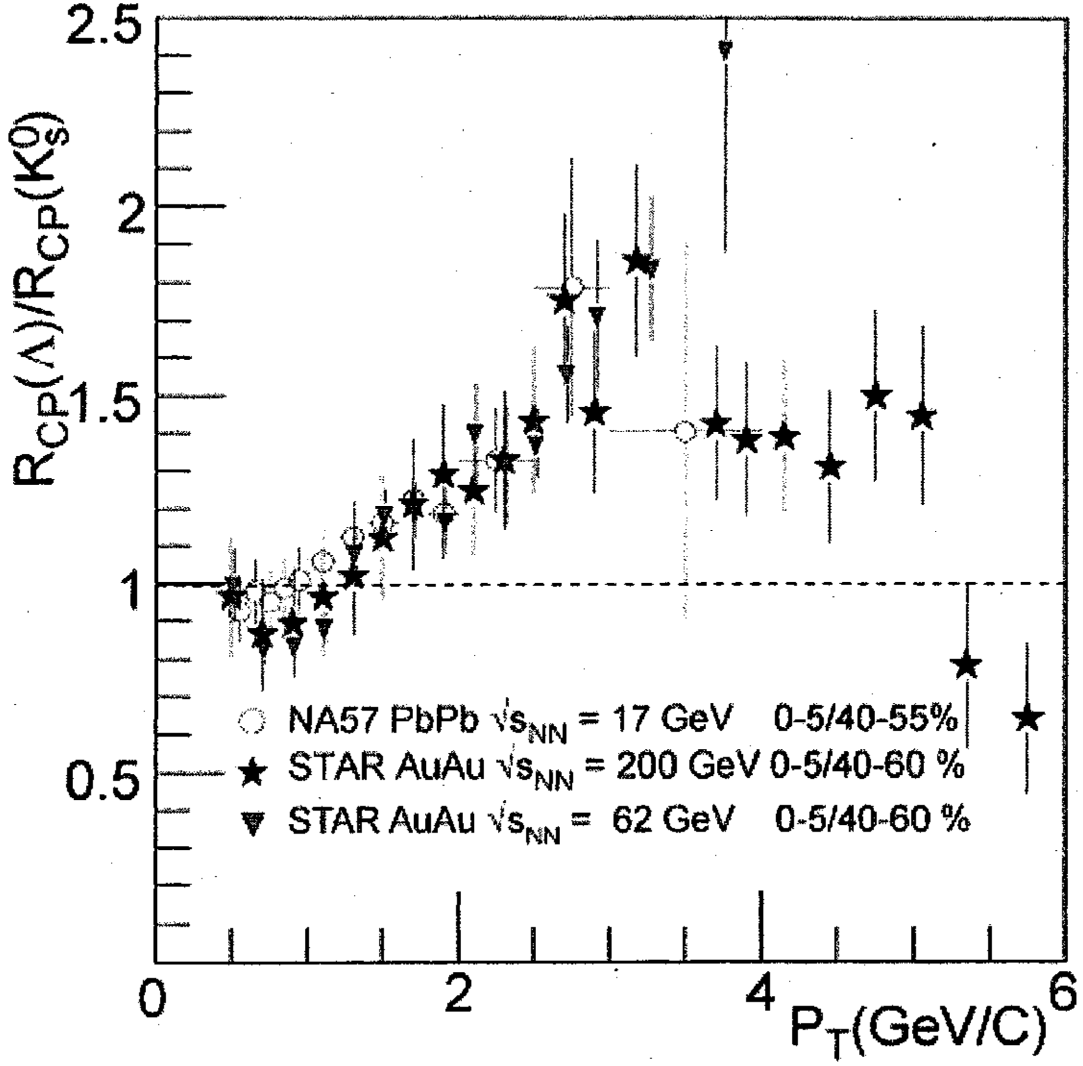


Strange R_{CP} signals range of recombination model relevance

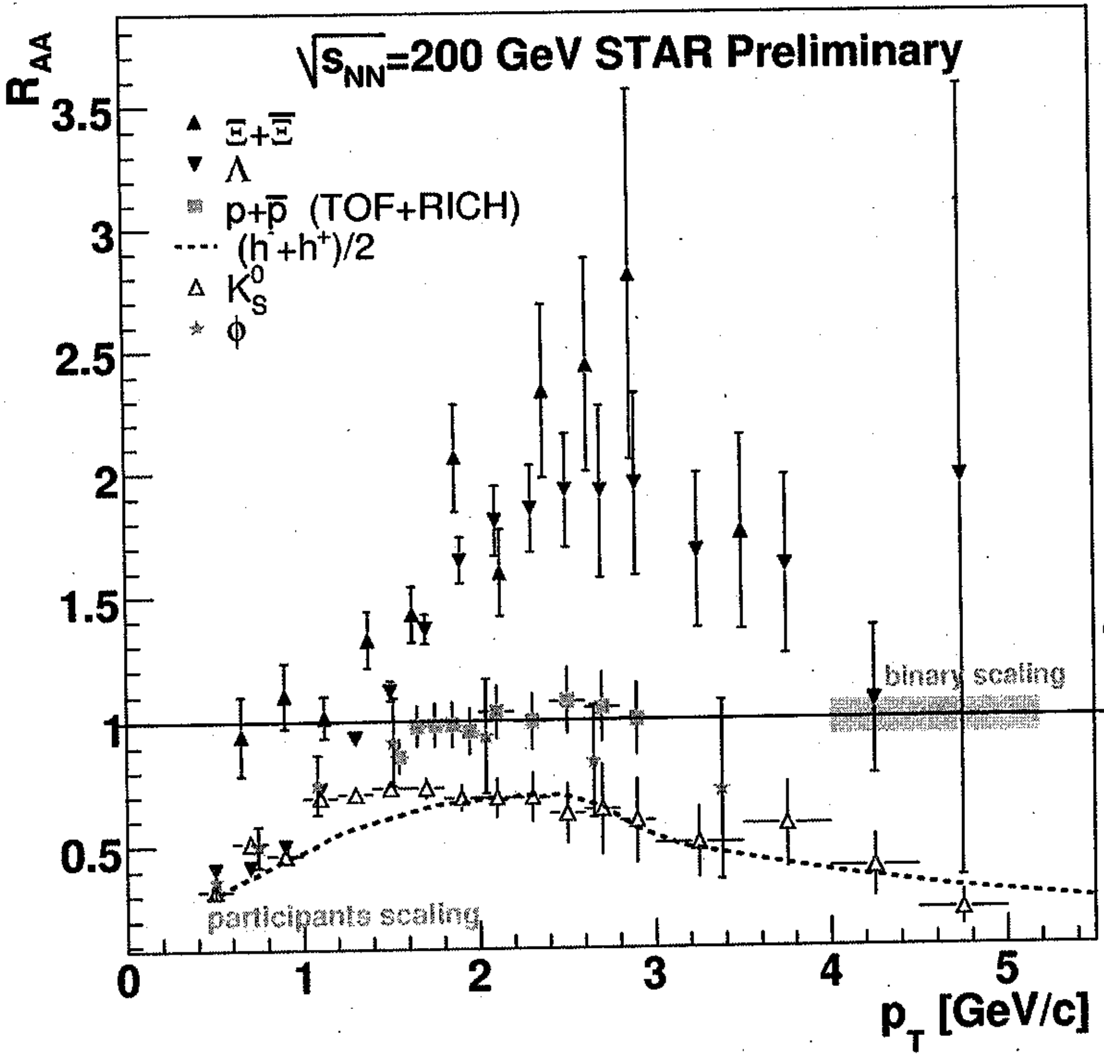
Recombination scaling can be applied to R_{CP} as well as v2

Baryon and meson suppression sets in at the same quark p_T .

R_{CP} double ratios independent of collision energy ! Recombination at SPS ?



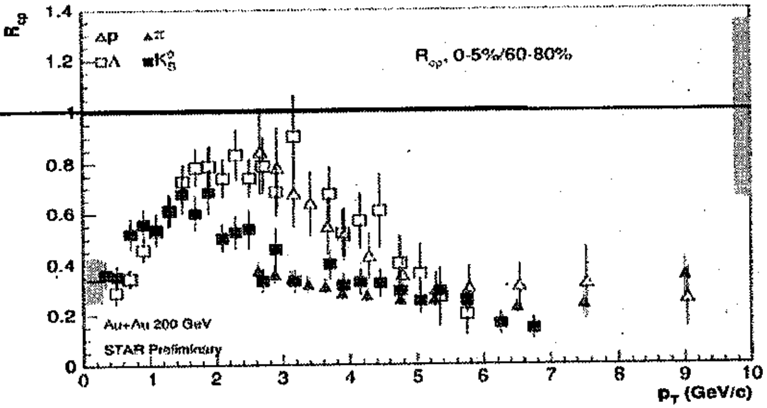
R_{AA} of strange baryons



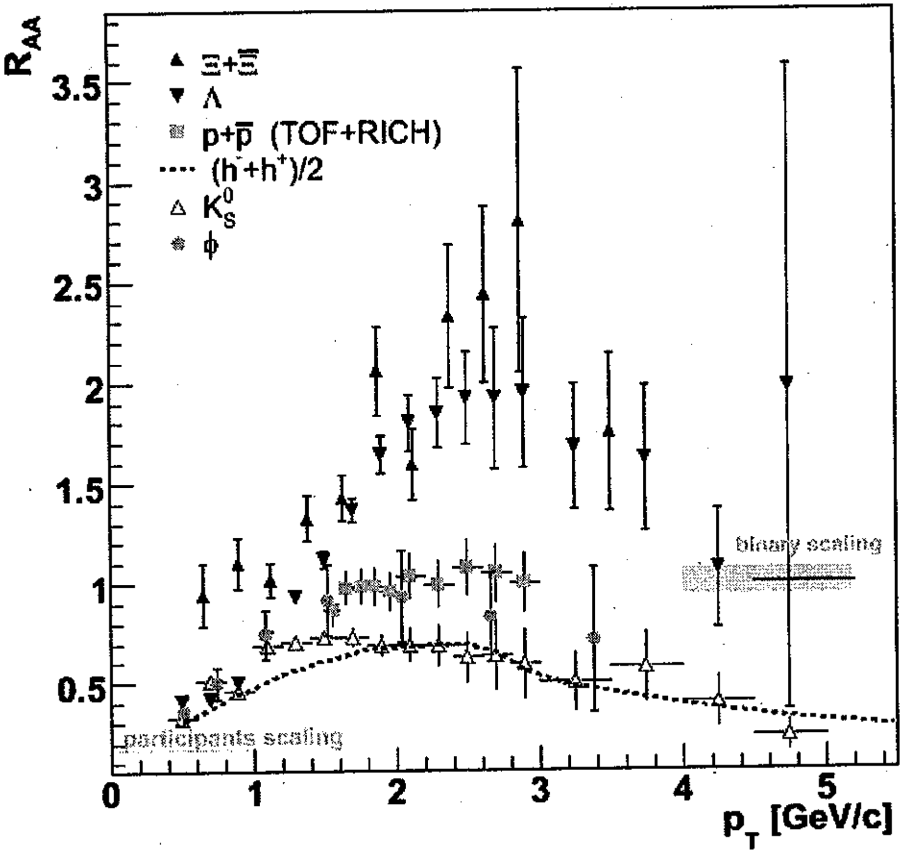
A remarkable difference between R_{AA} and R_{CP} that seems unique to strange baryons. Ordering with strangeness content.

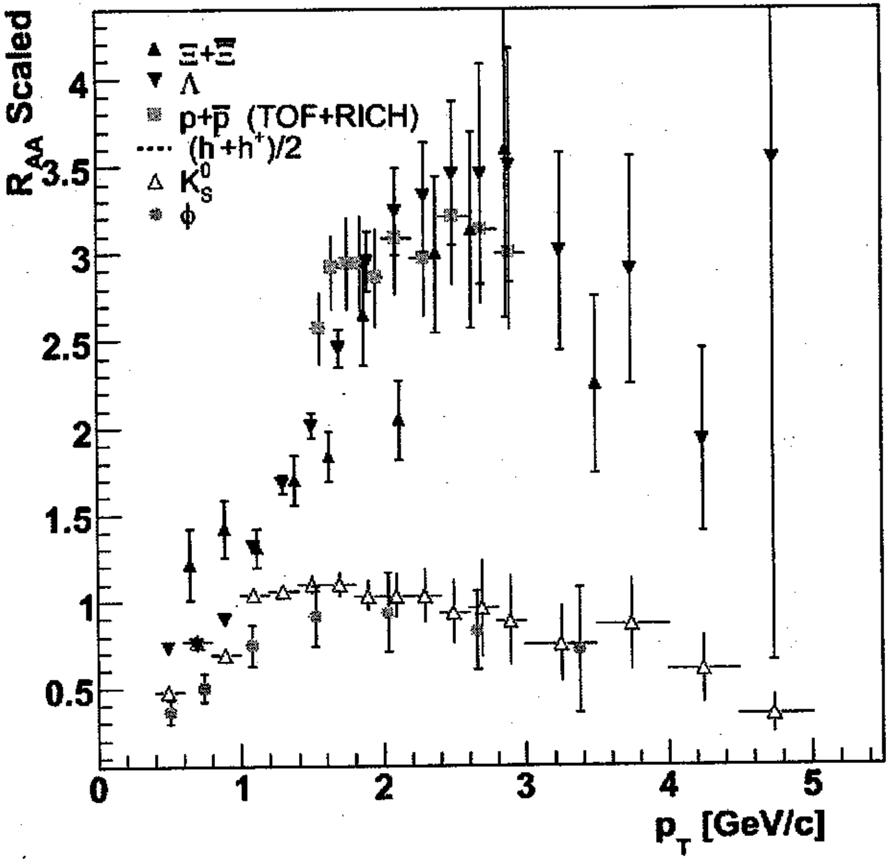
This effect must occur 'between' pp and peripheral AA collisions (canonical suppression in pp). Is it unique to strange hadrons ? Charmed mesons in AA are suppressed like pions and kaons. (STAR, QM 2005).

we need a charmed baryon measurement



Quark Scaled R_{AA} of Strange Particles



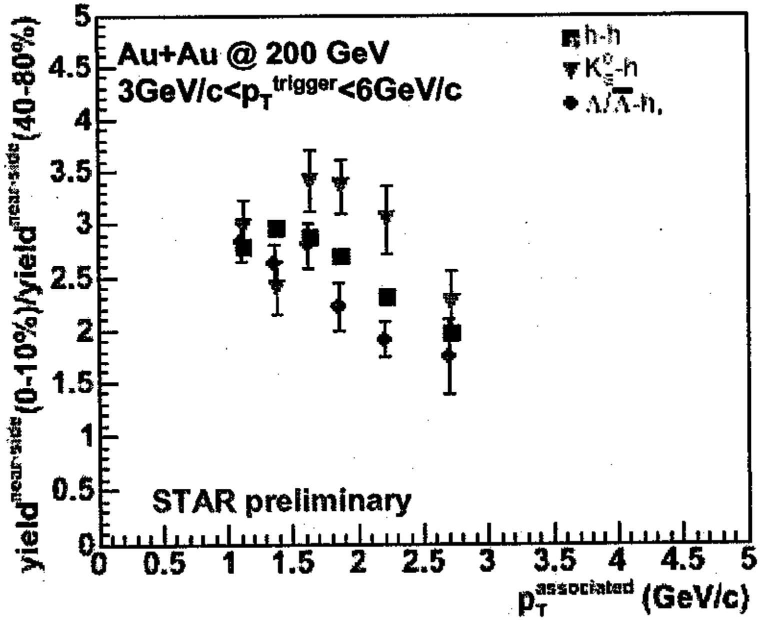


s-quarks scaled with N_{Bin}

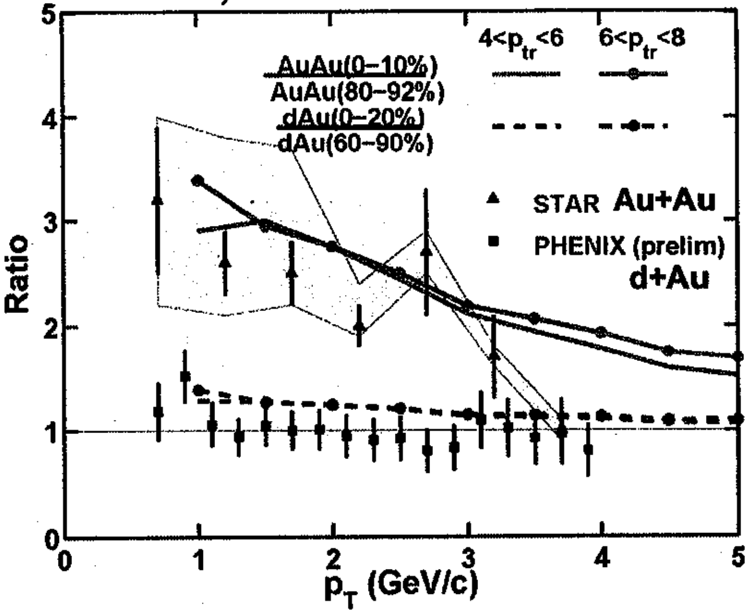
u&d-quarks scaled with N_{part}

ϕ scaled with N_{part}

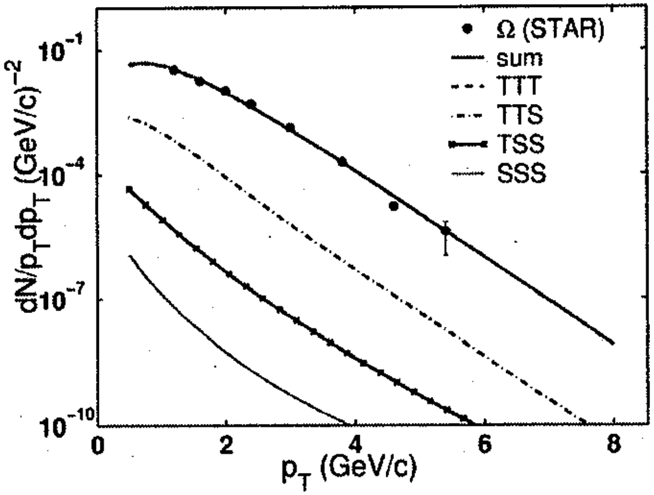
What does a parton recombination model predict?



R. Hwa, Z.Tan: nucl-th/0503060



- the ratio of near-side associated yield in central/peripheral Au+Au collisions decreases slowly with $p_T^{associated}$
- data are in a good agreement with predictions from recombination model: in Au+Au the thermal-shower recombination dominates.
- The relevance of recombination can be tested with Ω triggered correlations (R.Hwa, nucl-th/0602024)



Production of Strange Particles at Intermediate p_T at RHIC

Rudolph C. Hwa

University of Oregon

Strangeness in Collisions

BNL/RIKEN Workshop

February 2006

Outline

What's interesting about the problem

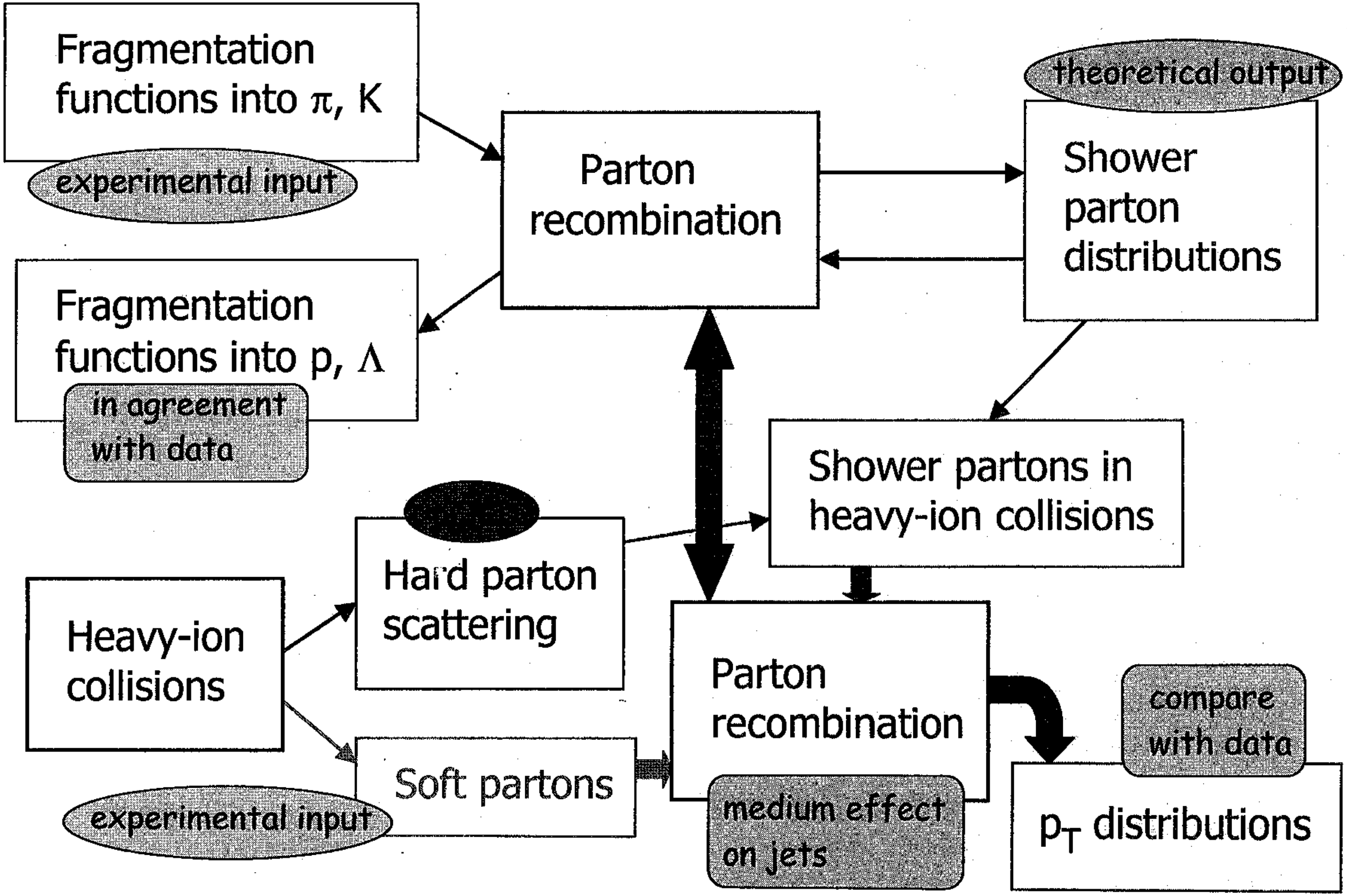
Quick review of recombination

New results on shower partons

Production of K, Λ, ϕ, Ω by recombination

Implications of the results

Logical connections and experimental relevance



Fragmentation functions into π, K

experimental input

Parton recombination

theoretical output

Shower parton distributions

Fragmentation functions into p, Λ

in agreement with data

Shower partons in heavy-ion collisions

Hard parton scattering

Heavy-ion collisions

Soft partons

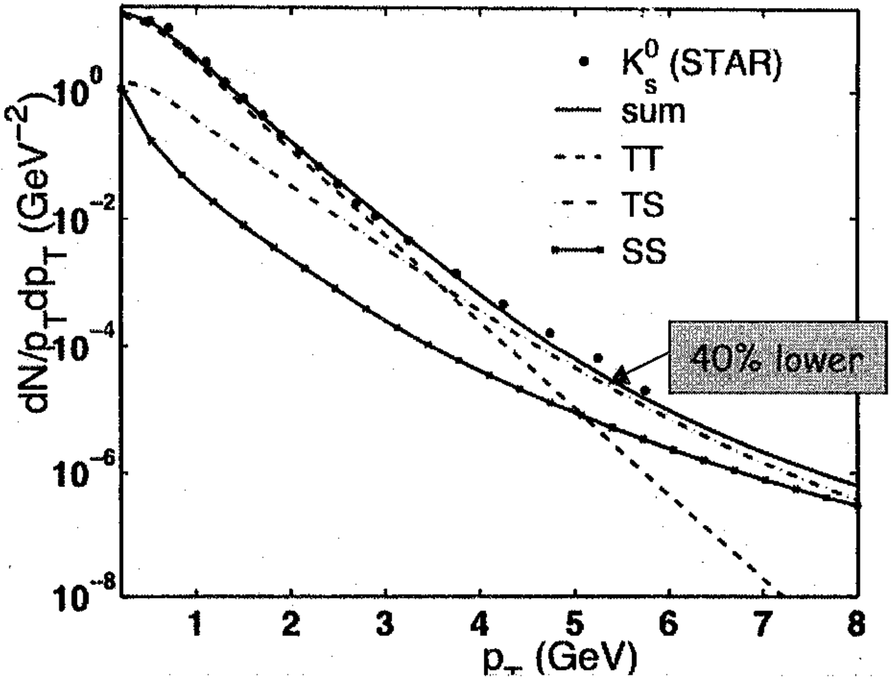
experimental input

Parton recombination

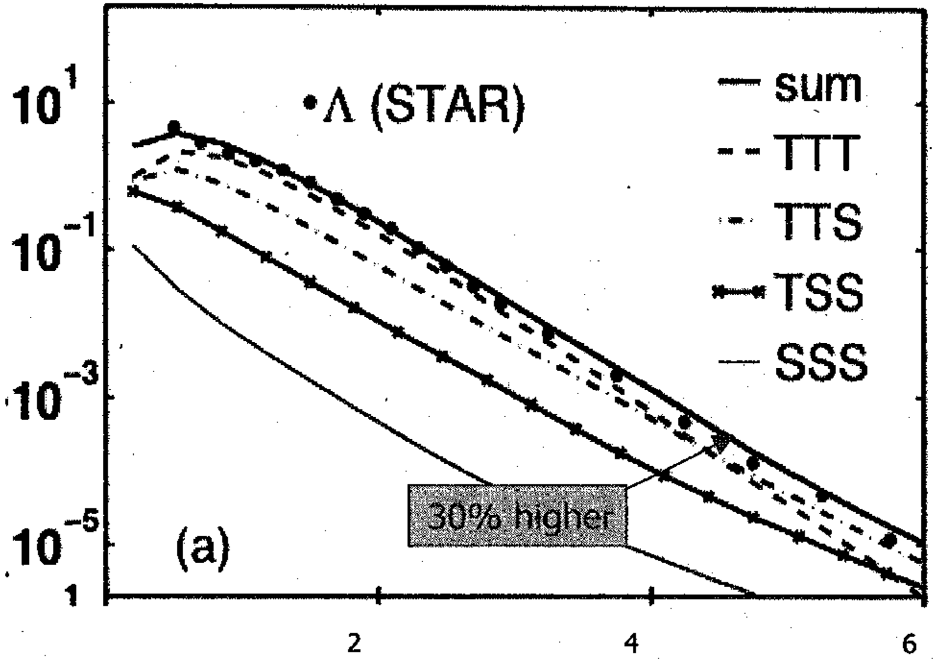
medium effect on jets

compare with data

p_T distributions



40% lower

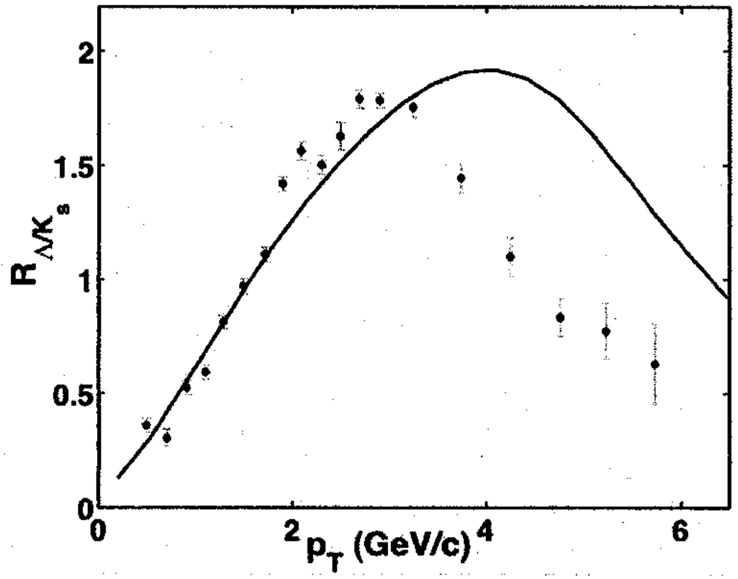


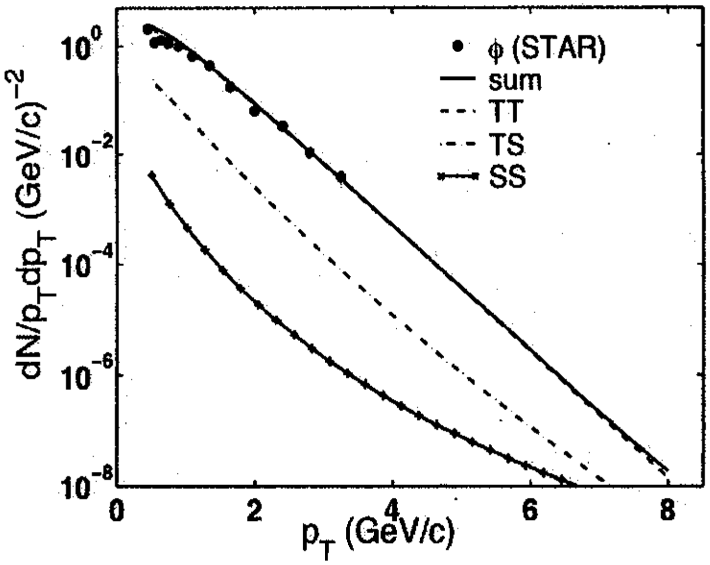
30% higher

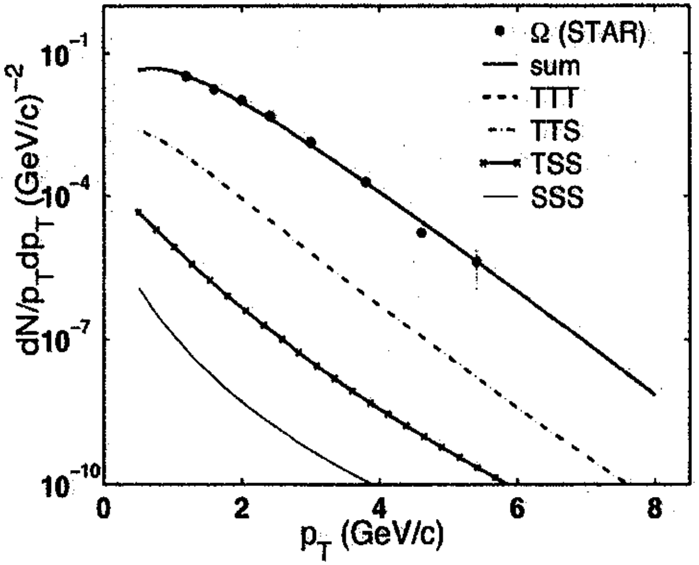
Data from STAR
nucl-ex/0601042

TS and TTS recombination is important.

Hwa & CB Yang, nucl-th/0602024







$$\boxed{R_{\Omega/\phi} \propto p}$$

We expect $R_{\Omega/\phi}$ not to bend for $p_T < 8$ GeV/c.

No jets are involved.

Select events with ϕ or Ω in the $3<p_T<6$ region, and treat them as trigger particles.

Predict: no associated particles giving rise to peaks in $\Delta\phi$, near-side or away-side.

Conclusion

- K, Λ well described by thermal-thermal, and thermal-shower recombination.

  But $R_{\Lambda/K}$ is not well reproduced. Need some fine-tuning.

- ϕ, Ω are due mainly to T_sT_s, $T_sT_sT_s$ recombination.

  Rate of recombination is suppressed due to light quark environment. Inverse slope is higher.

- s quark shower partons have no effect in the production of ϕ, Ω for pT<8 GeV/c. Jets are not involved.

  No peaks in associated particle distribution.

Baryon-Strangeness Correlations

VOLKER KOCH

In collaboration with A. Majumder & J. Randrup

Baryon-Strangeness Correlations

- Introduction
- BS and other correlations
- Some speculations

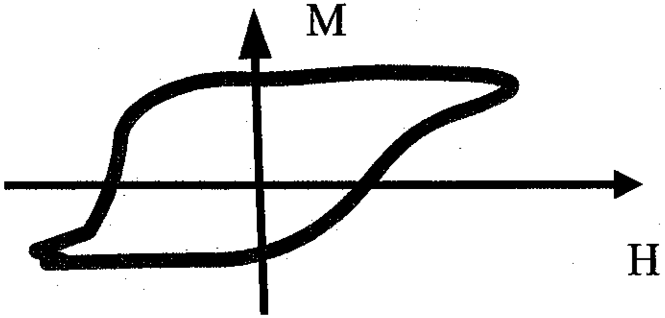
Work in collaboration with: A. Majumder and J. Randrup

Susceptibilities

$$E = E_0 + mH + \mu Q$$

$$\langle m \rangle = \frac{dF}{dH}$$

$$\langle Q \rangle = \frac{dF}{d\mu}$$



Susceptibilities

$$\chi_m = \frac{d^2 F}{dH^2}$$

$$\chi_Q = \frac{d^2 F}{d\mu^2}$$

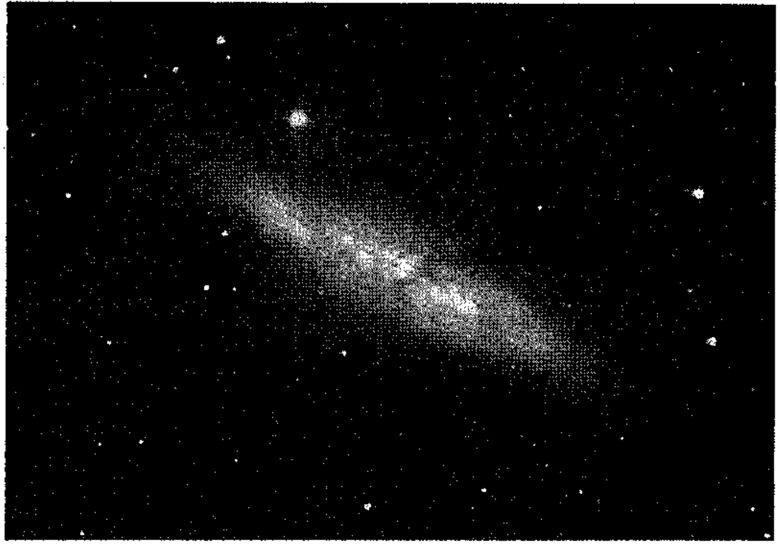
$$\langle \delta m \rangle = \chi_m \delta H$$
$$\langle \delta Q \rangle = \chi_Q \delta \mu$$

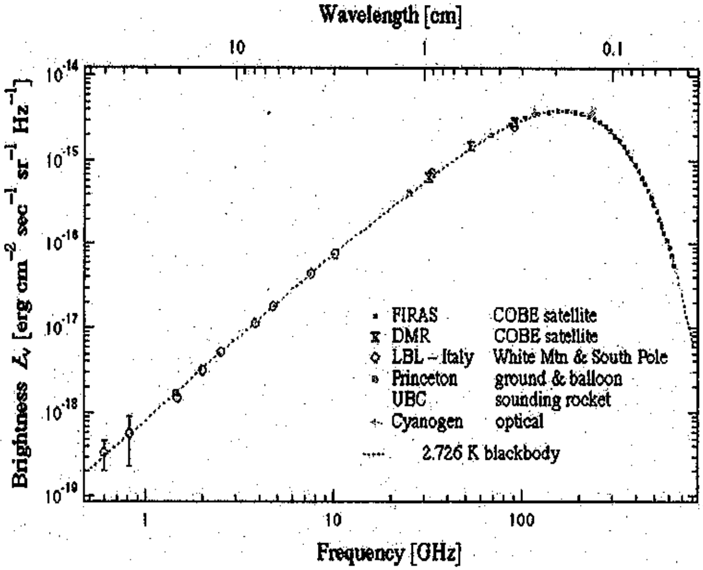
Linear response

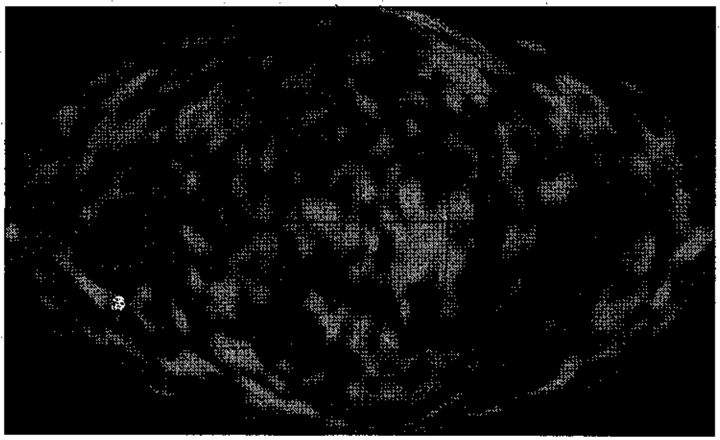
$$\langle (\delta m)^2 \rangle = \chi_m$$
$$\langle (\delta Q)^2 \rangle = \chi_Q$$

Fluctuations

The mother of all thermal spectra and fluctuations

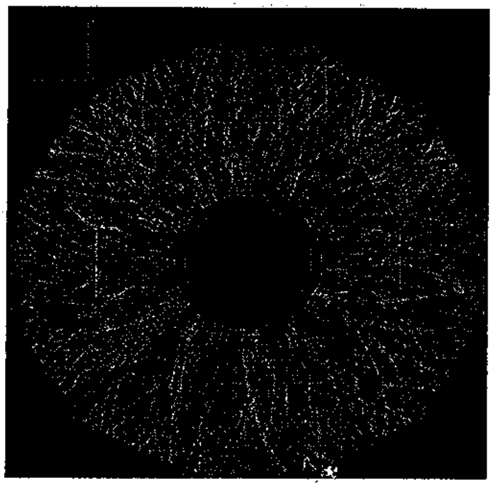


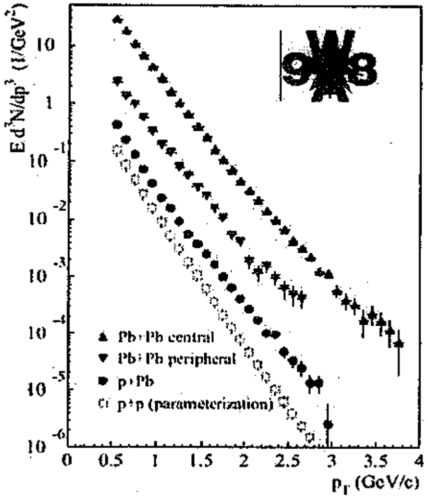




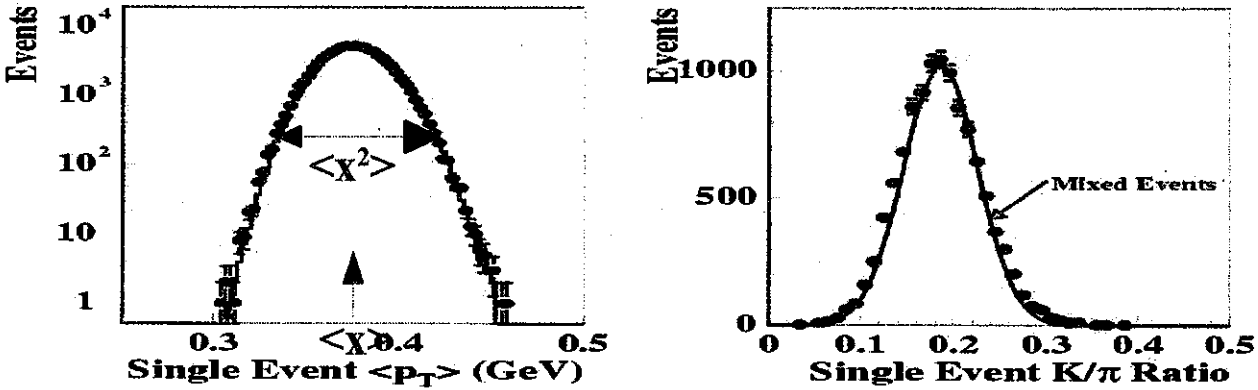
Fluctuations at the level of 10^{-5} !!!

Heavy Ions: Event-by-Event





NA49 Pb+Pb Event-by-Event Fluctuations



The physics is in the width

E-by-E measures
2-particle correlations

Fluctuations in thermal system

e.g. Lattice QCD

$$Z = Tr\left[\exp\left(-\beta\left(H - \mu_Q Q - \mu_B B - \mu_S S\right)\right)\right]$$

Mean : $\langle X \rangle = T \frac{\partial}{\partial \mu_X} \log(Z) = -\frac{\partial}{\partial \mu_X} F$ $\qquad X = Q, B, S$

Variance: $\langle (\delta X)^2 \rangle = T^2 \frac{\partial^2}{\partial \mu_X^2} \log(Z) = -T \frac{\partial^2}{\partial \mu_X^2} F$

Co-Variance: $\langle (\delta X)(\delta Y) \rangle = T^2 \frac{\partial^2}{\partial \mu_X \partial \mu_Y} \log(Z) = -T \frac{\partial^2}{\partial \mu_X \partial \mu_Y} F$

Susceptibility: $\chi_{XY} = -\frac{1}{V} \frac{\partial^2}{\partial \mu_X \partial \mu_Y} F = -\frac{1}{V} \frac{\partial}{\partial \mu_X} \langle Y \rangle$

Simple Observation

Or how can we test the sQGP

<u>Simple</u> QGP: strangeness is carried by strange quarks

→ Baryon Number and Strangeness are correlated

Hadron Gas: strangeness is carried mostly by mesons

→ Baryon Number and Strangeness are uncorrelated

<u>Bound state</u> QGP: strangeness is carried by partonic bound states

→ Baryon Number and Strangeness should be uncorrelated

<BS> and the Bound State QGP

Define: $$C_{BS} \equiv -3\,\frac{\langle(\delta B)(\delta S)\rangle}{\langle(\delta S)^2\rangle} = -3\,\frac{\langle|B-\langle B\rangle||S-\langle S\rangle|\rangle}{\langle|S-\langle S\rangle|^2\rangle} = -3\,\frac{\langle BS\rangle}{\langle S^2\rangle} = -3\,\frac{X_{BS}}{X_{SS}}$$

(-3) compensates baryon-number and strangenes of quarks

In Experiment $$C_{BS} = -3\,\frac{\frac{1}{N_{eve.}}\sum_i B_i S_i - \frac{1}{N_{eve.}^2}\sum_i B_i \sum_j S_j}{\frac{1}{N_{eve.}}\sum_i S_i^2 - \frac{1}{N_{eve.}^2}\sum_i S_i \sum_j S_j}$$

Uncorrelated particles: $$C_{BS} = -3\,\frac{\sum_i \langle N_i\rangle S_i B_i}{\sum_i \langle N_i\rangle S_i^2}$$

Simple estimates

$$C_{BS}=\frac{-3\langle BS\rangle}{\langle S^2\rangle}$$

In a QGP phase

$$-3\langle BS\rangle=\langle n_s\rangle+\langle n_{\bar{s}}\rangle$$

$$\langle S^2\rangle=\langle n_s\rangle+\langle n_{\bar{s}}\rangle$$

At *all* T and μ

CBS = 1

In hadron gas phase

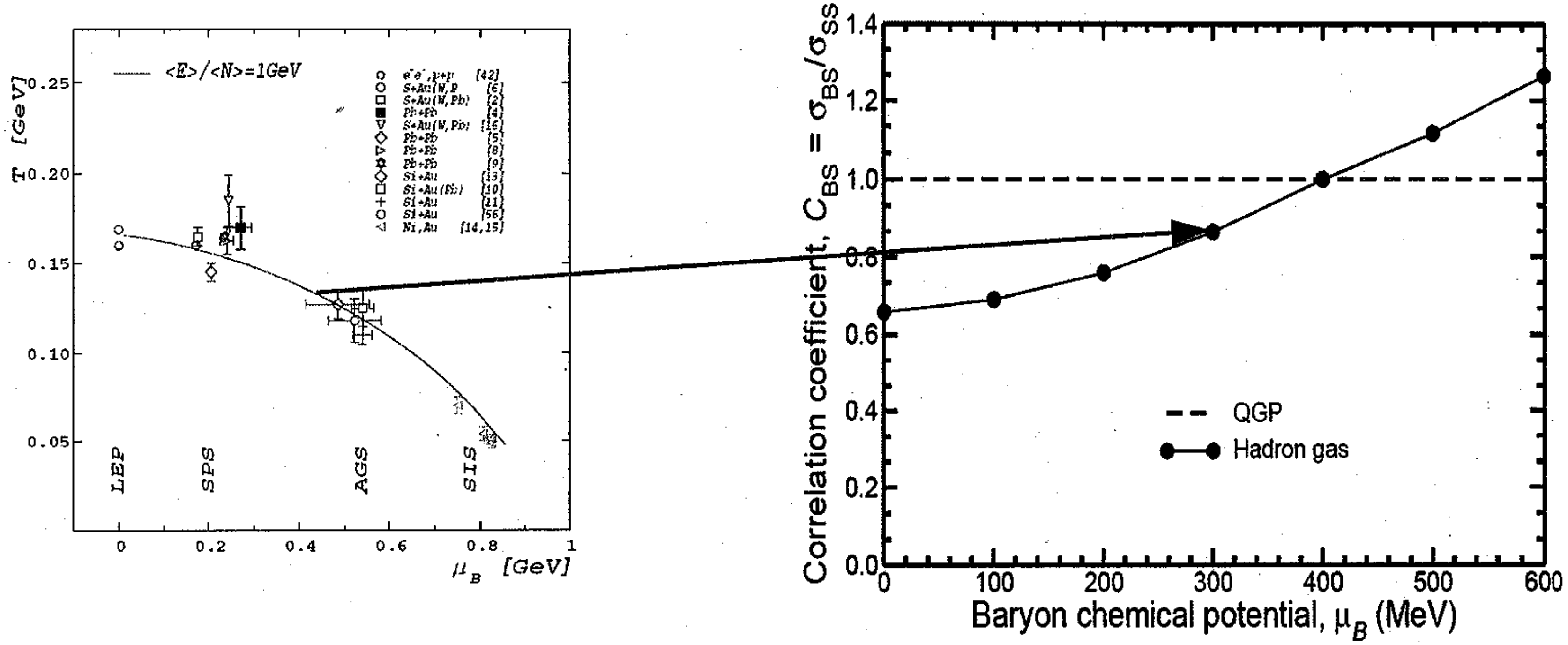
$$-3\langle BS\rangle=3[\Lambda+\bar{\Lambda}+\Sigma+\bar{\Sigma}+\ldots]$$
$$+6[\Xi+\bar{\Xi}+\ldots]+9[\Omega+\ldots]$$

$$\langle S^2\rangle=K^{+}+K^{-}+K^{0}+\Lambda+\bar{\Lambda}+\ldots$$

At T=170MeV, μ=0

CBS = 0.66

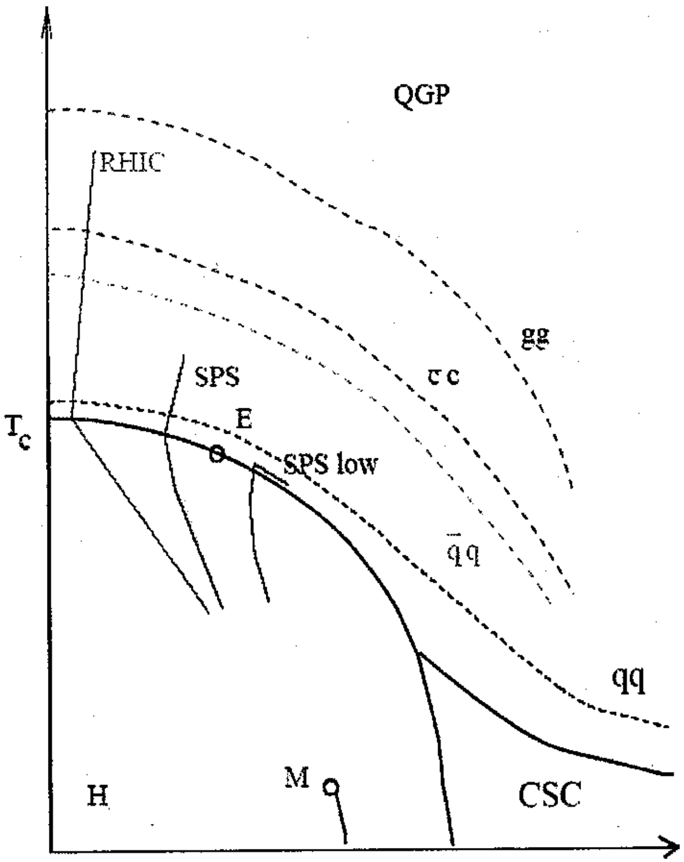
Hadron gas



At large μ: N(K⁺) = N(Λ+ Σ)

$$C_{BS} = 3\frac{\Lambda+\Sigma}{K^+ + \Lambda + \Sigma} = \frac{3}{2} \qquad \text{at large } \mu$$

The Bound State QGP



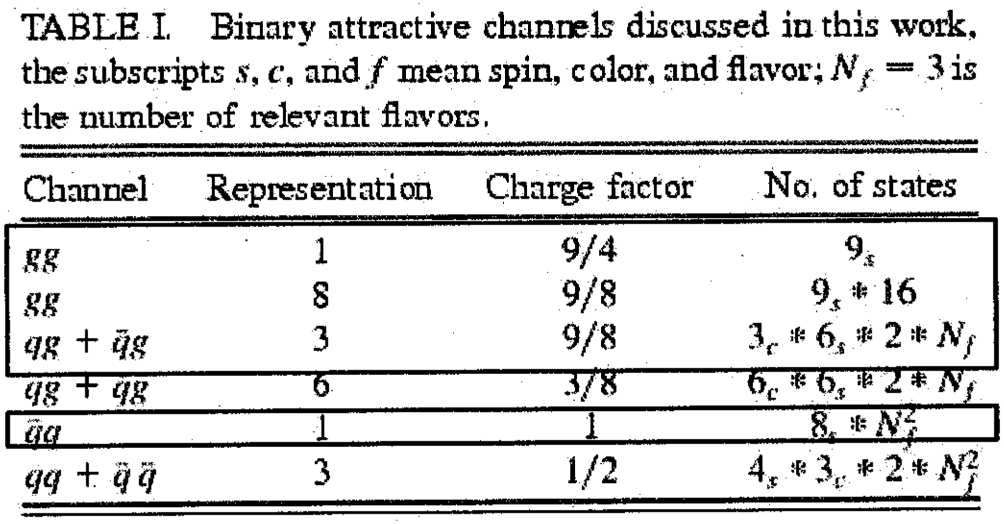


TABLE I. Binary attractive channels discussed in this work, the subscripts s, c, and f mean spin, color, and flavor; $N_f = 3$ is the number of relevant flavors.

Channel	Representation	Charge factor	No. of states
gg	1	9/4	9_s
gg	8	9/8	$9_s * 16$
$qg + \bar{q}g$	3	9/8	$3_c * 6_s * 2 * N_f$
$qg + qg$	6	3/8	$6_c * 6_s * 2 * N_f$
$\bar{q}q$	1	1	$8_s * N_f^2$
$qq + \bar{q}\bar{q}$	3	1/2	$4_s * 3_c * 2 * N_f^2$

Gluon-Gluon states do not contribute!

C_{BS} in bound state QGP

- Heavy quark, antiquark quasiparticles: $C_{BS} = 1$
- Quark gluon states (color triplet, 36 states): $C_{BS} = 1$
- Quark-antiquark states: 8 π like, 24 ρ like: $\mathbf{C_{BS} = 0}$

T=1.5Tc, $C_{BS} = 0.61$

Similar to Hadron gas estimate…

Estimates from the Lattice

$$\langle BS\rangle = \frac{T}{V}\frac{\partial}{\partial\mu_B}\frac{\partial}{\partial\mu_S}\log(Z)_{\mu_B=0} = X_{BS}$$

$$C_{BS} = -3\frac{\langle BS\rangle}{\langle S^2\rangle} = -3\frac{\left\langle \frac{1}{3}(u+d+s)(-s)\right\rangle}{\langle S^2\rangle} = \frac{X_{ss}+X_{us}+X_{ds}}{X_{ss}} = 1+\frac{X_{us}+X_{ds}}{X_{ss}}$$

Calculated by (quenched): R.V. Gavai, S. Gupta, Phys.Rev.D66:094510,2002

At T = 1.5 Tc $X_{us}\approx X_{ds}\ll X_{ss}$

$$\boxed{C_{BS} = 1+ 0.00(3)/0.53(1)}$$

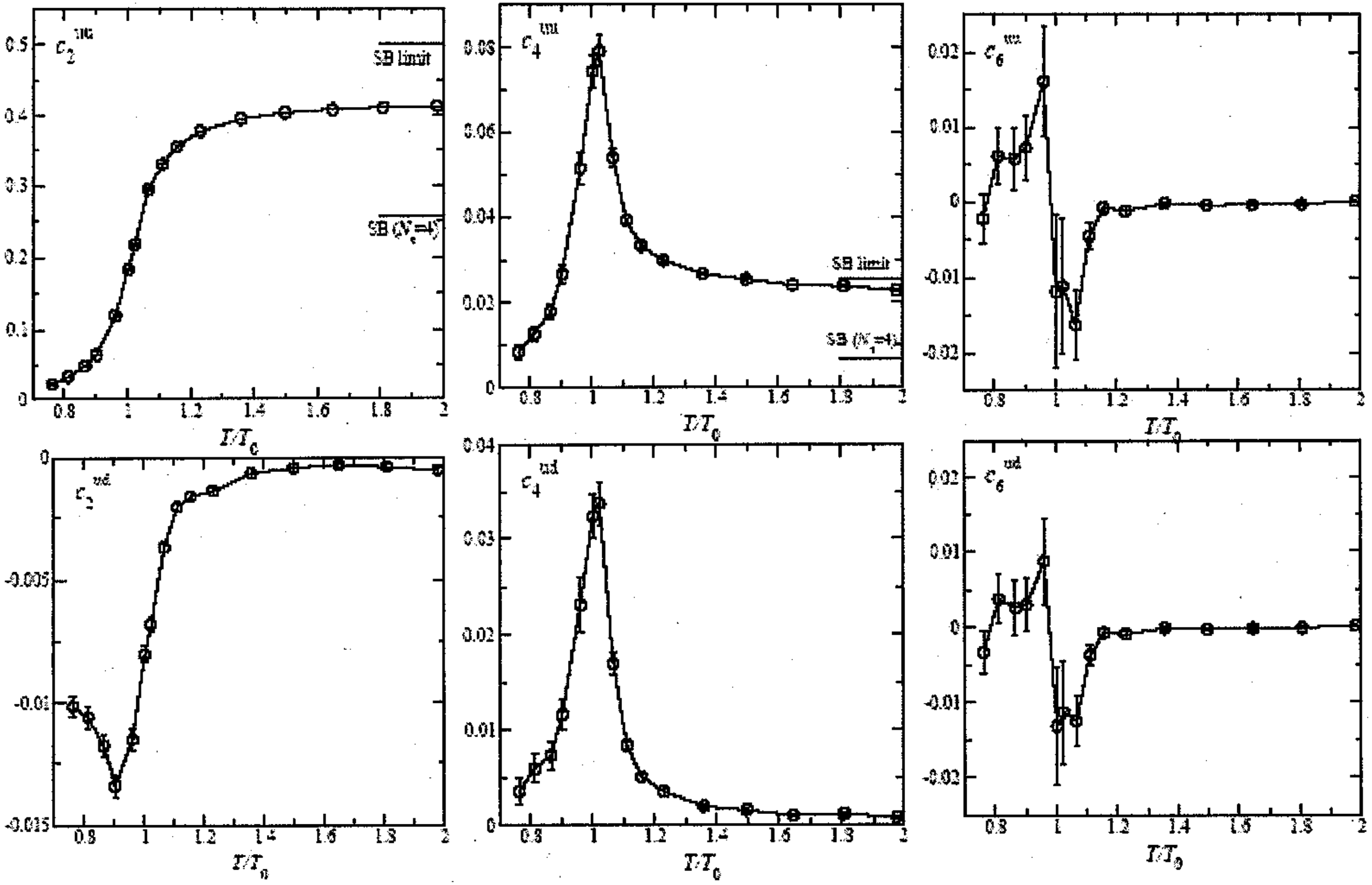
Essential result: off-diagonal susceptibilities << diagonal susceptibilities

Results

- Hadron Gas $\mathbf{C_{BS} = 0.66}$
- Bound State QGP $\mathbf{C_{BS} = 0.62}$
- Independent quarks $\mathbf{C_{BS} = 1}$
- Lattice QCD $\mathbf{C_{BS} = 1}$

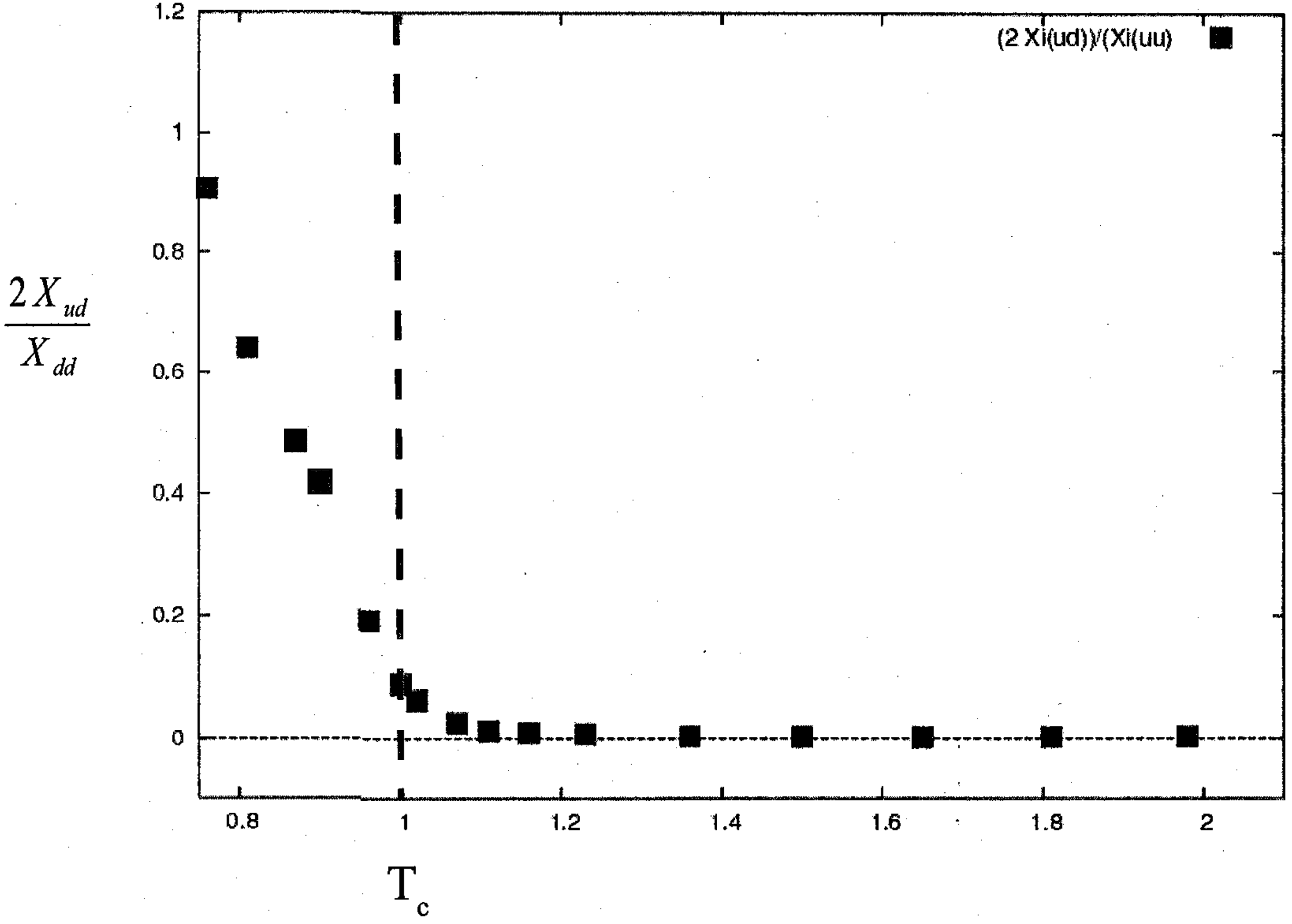
Full QCD, but with 2 flavors, gives similar insight!

$$\frac{X\left(T,\mu_q\right)}{T^2} = 2c_2+12c_4\left(\frac{\mu_q}{T}\right)^2+30c_6\left(\frac{\mu_q}{T}\right)^4+\ldots$$



From C.R. Alton et. al. Phys.Rev.D71:054508,2005

Ratio of Susceptibilities



Correlations and Lattice

(quenched) Lattice QCD:

$$X_{ud} = X_{us} = X_{ds} \approx 0$$

NO cross correlations among quark flavors!

quark – anti-quark bound states ? ☹

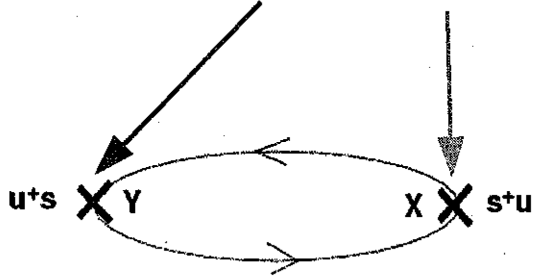
Strongly interacting QGP??? Why are there no correlations? 😕

Quarks appear to be independent Quasi-Particles

Bound states and off-diagonal Susceptibilities

Correlator:

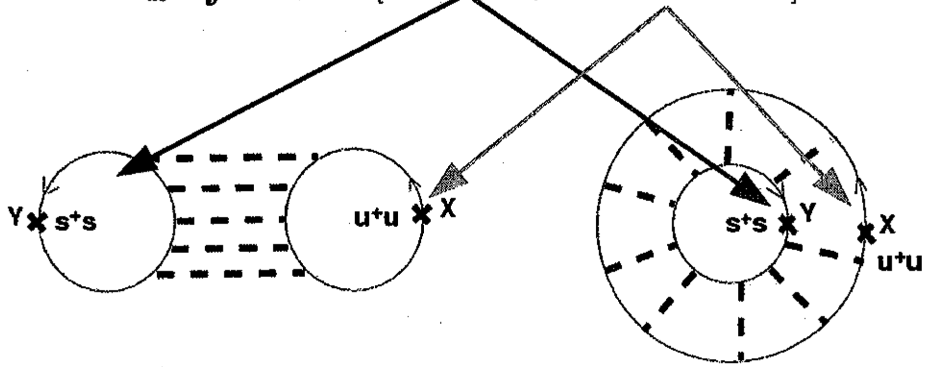
$$C(x,y)=tr\left[\rho(u^{+}(y)s(y))\,(s^{+}(x)u(x))\right]$$



Measure for mass, correlation length of bound state

Susceptibility (χ_{us})

$$\chi_{us}=\int dx\,dy'\,tr\left[(s^{+}(y)s(y))(u^{+}(x)u(x))\right]$$



"Simply" counts number of bound states

Some issues

- No statement about gluon bound states
- No statement about quark gluon bound states
- No statement about the heavy states (> 1.5 GeV) seen in correlation functions (Hatsuda et al, Karsch et al.)
  - Susceptibilities only measure the bulk!
  - Possibly collective modes ????? (G. Brown, QM 04)

Ways out...

- As many quark-quark states as quark-antiquark states
    - Not consistent with Shuryak model
    - Problem with higher order susceptibilities (Ejiri et al. hep-ph/0509051

- Large width of bound states
    - ~1 % correction is allowed by lattice
    - What is a bound state with large width?

Measuring C_{BS}

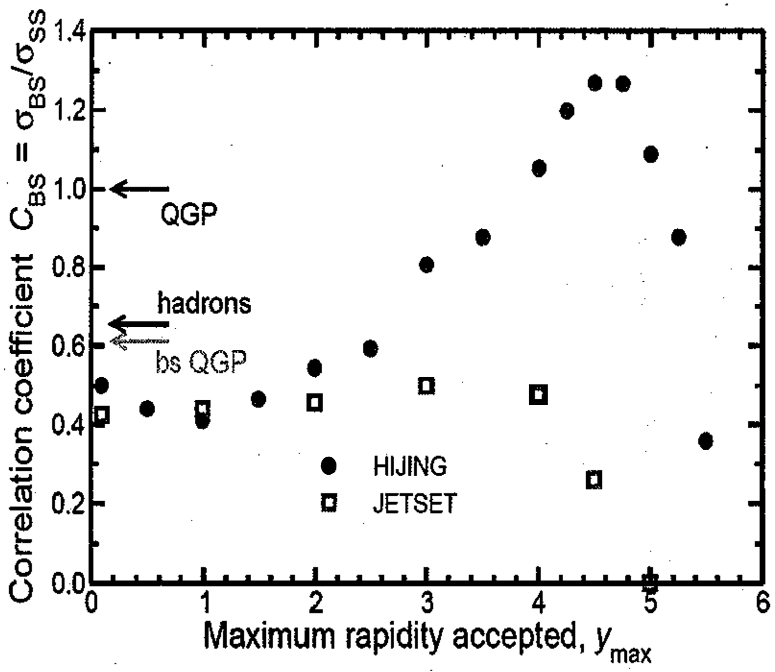
C_{BS} can be measured in principle

Advantages:

- Conserved quantities
- "Heavy" particles
  - Less uncertainty due to hadronization

Issues:

- Baryon number (neutrons)
- Weak decay corrections for strangeness



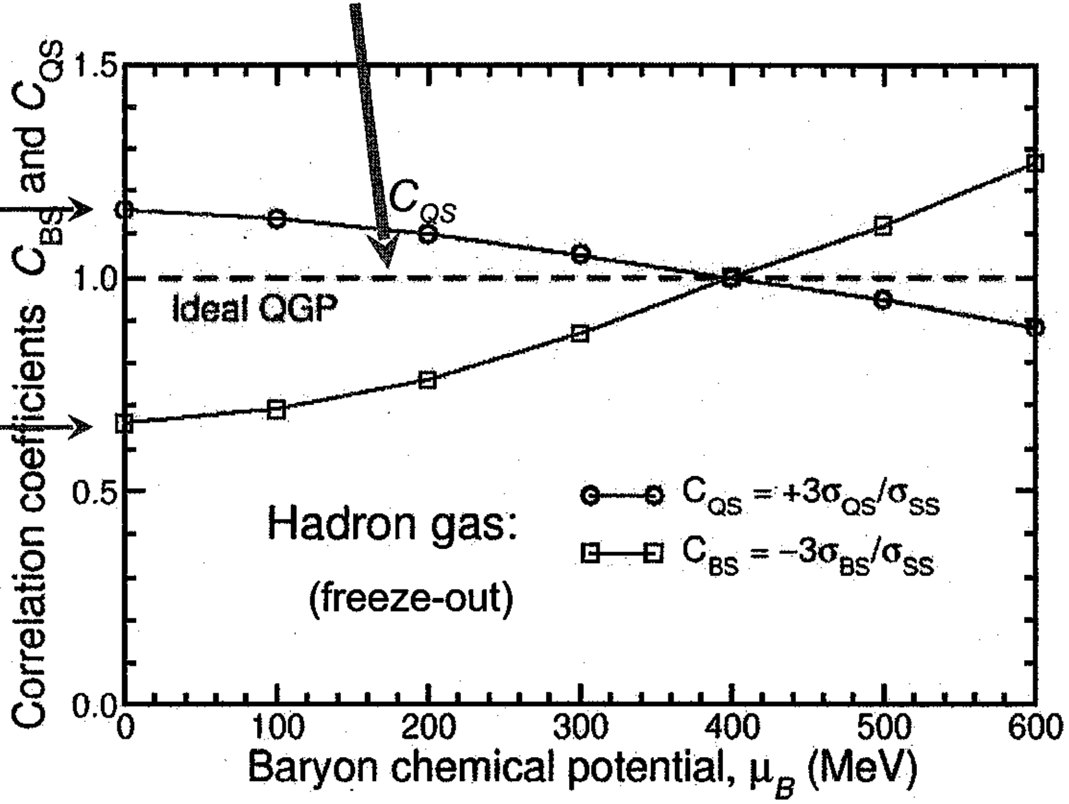
Alternative: C_{QS}

Ideal QGP: $C_{BS} = C_{QS} = 1$

$$C_{QS} = 3\frac{\langle QS \rangle}{\langle S^2 \rangle}$$

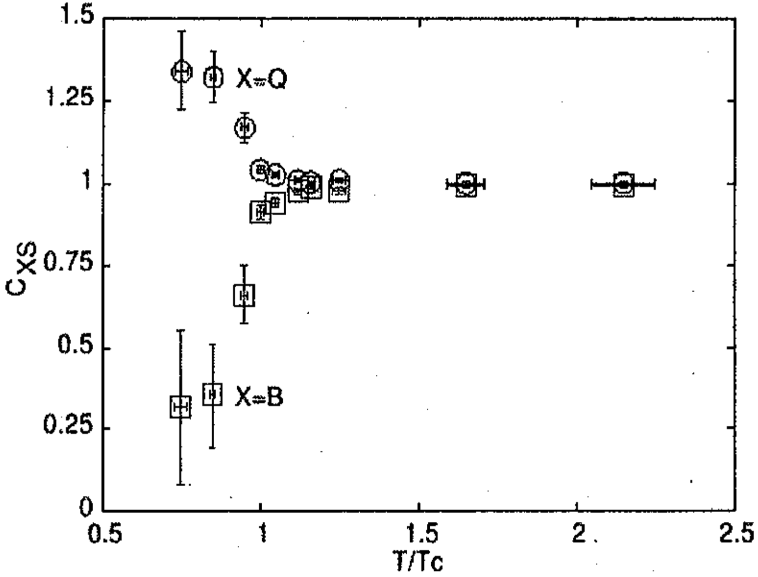
$C_{QS}(\mu=0) = 1.15$

$C_{BS}(\mu=0) = 0.66$



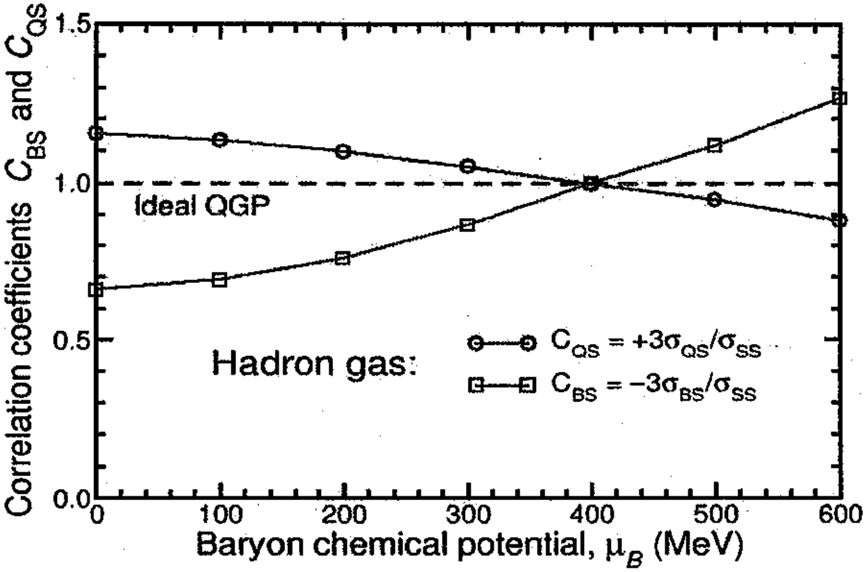
J. Randrup
Panic '05

C_{QS} continued



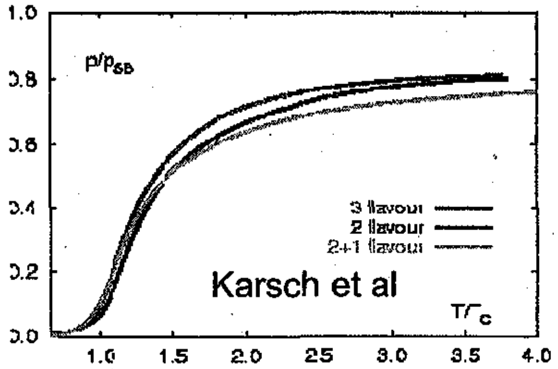
Gavai,Gupta, hep-lat/0510044

Hadron Gas



Speculations!

- Pressure in LQCD < ideal gas
- Lattice suggests a quasi-particle picture for QGP
- Lattice EOS requires **massive** quasi-particle
- This suggests a **repulsive** mean field (~500 MeV!!!)
- A repulsive mean field generates **flow**!
- RHIC data possibly consistent with **large** viscosity



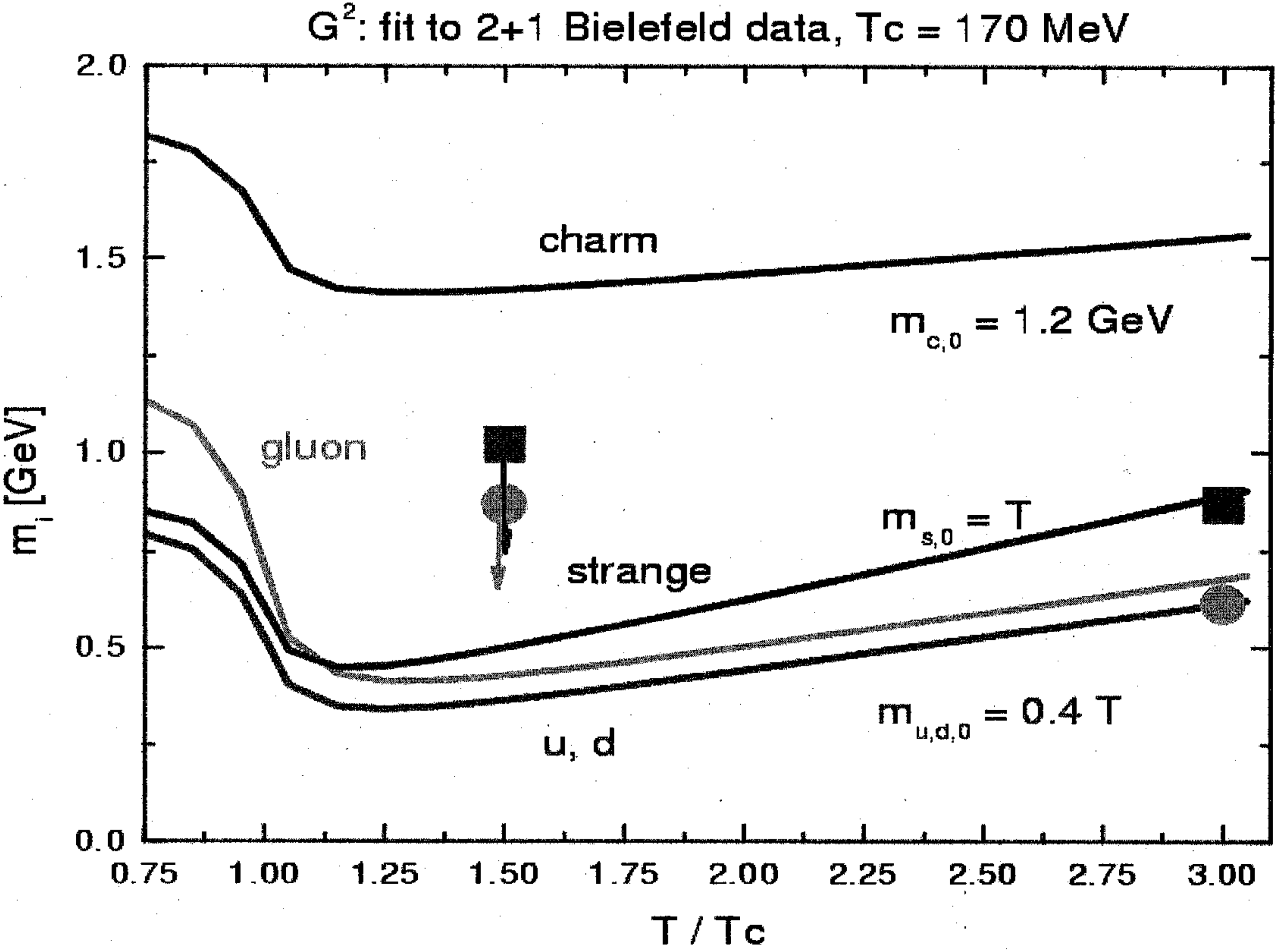
- Alternative:
  - Glue has low viscosity and quarks tag along

A. Peshier, B. Kampfer and G. Soff, Phys.Rev. D66:094003,2002.

J. P. Blaizot, E. Iancu and A. Rebhan, Phys.Rev. D63:065003,2001.

Summary

- BS correlation valuable diagnostic for structure of matter
- BS correlations impose strong limit on existence of bound states in the QCP
- Lattice QCD consistent with quasi-particle quarks
- Higher order "susceptibilities" need to be analyzed as well
- Mean field? Flow? High Viscosity? ?????

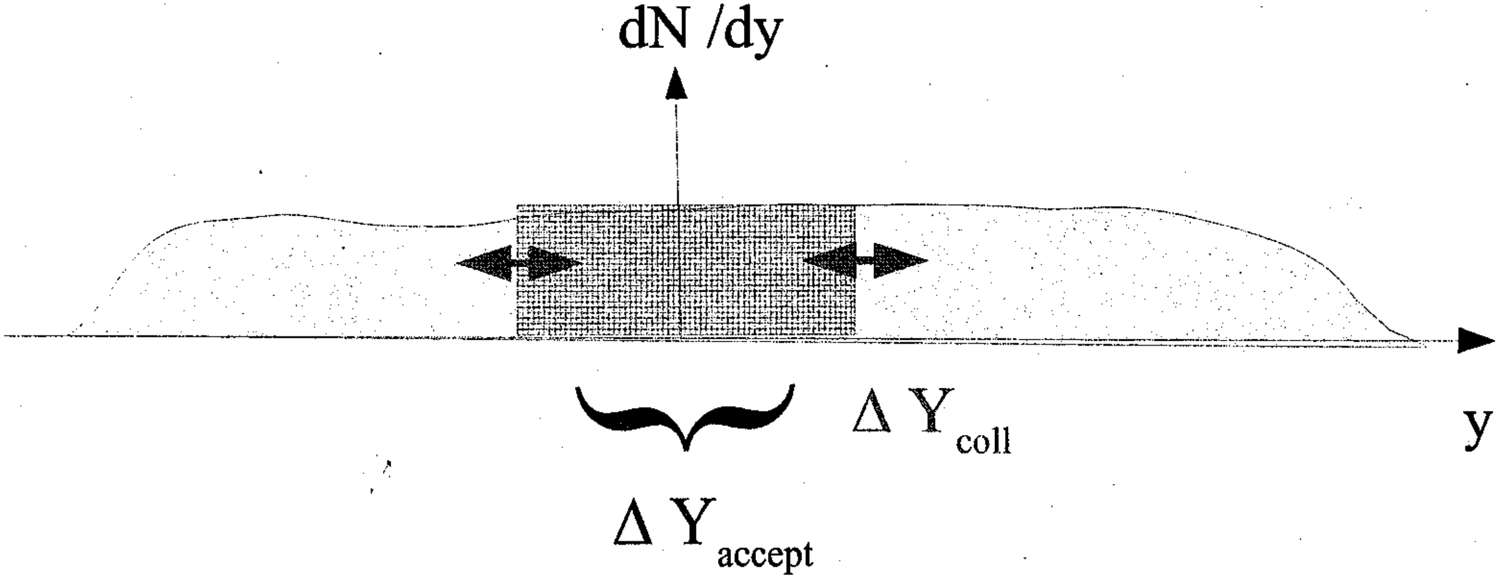


B. Kaempfer, SQM 2004

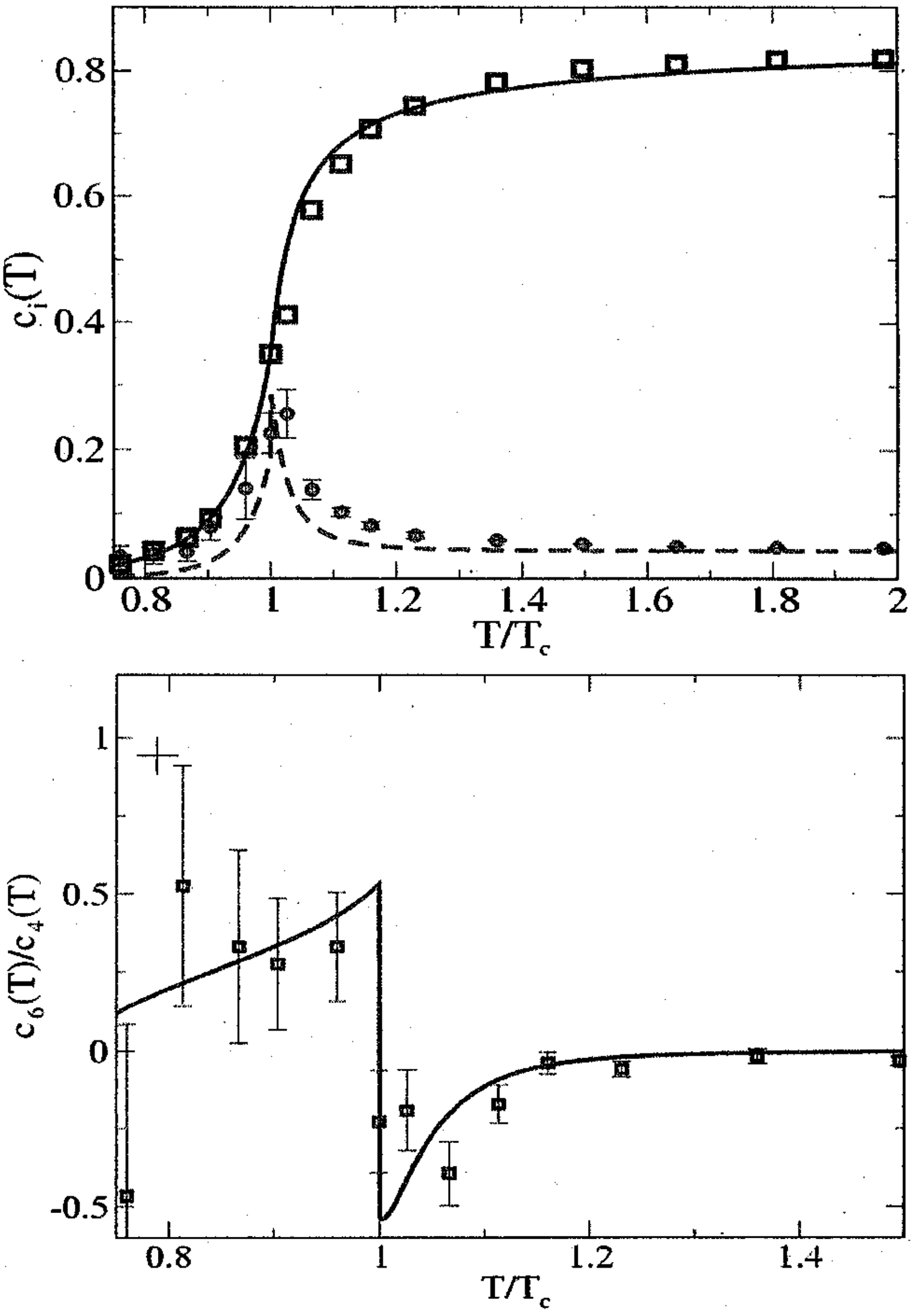
Fluctuations of conserved quantities

Quantum numbers conserved in Heavy ion collisions:

- Baryon number B (exactly)
- Charge Q (exactly)
- Strangeness S (almost!)
- Combinations are also conserved : BS, QS, BQ etc.



Condition for charge fluctuations: $\Delta Y_{total} >> \Delta Y_{accept} >> \Delta Y_{coll}$

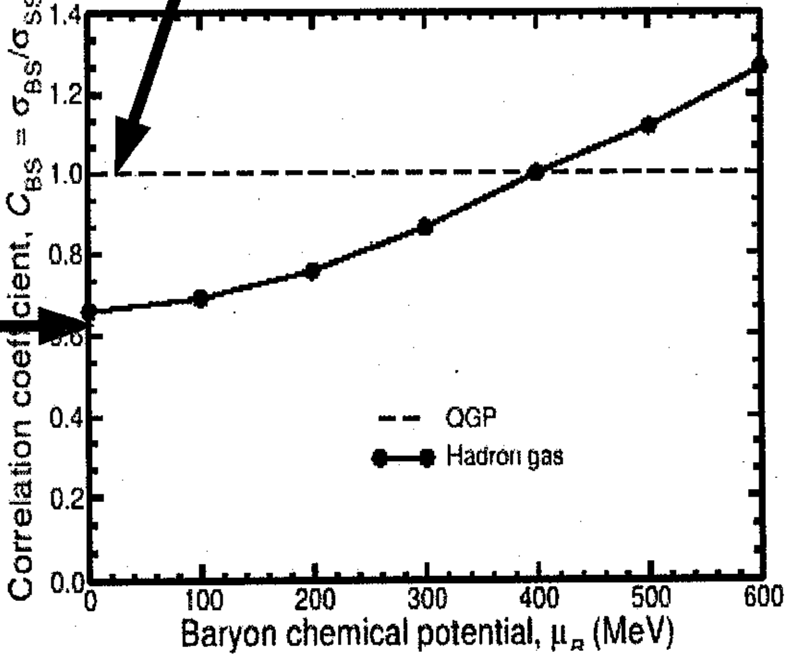


Quasi-particle model by
Bluhm et al, hep-ph/0411106

<BS> continued

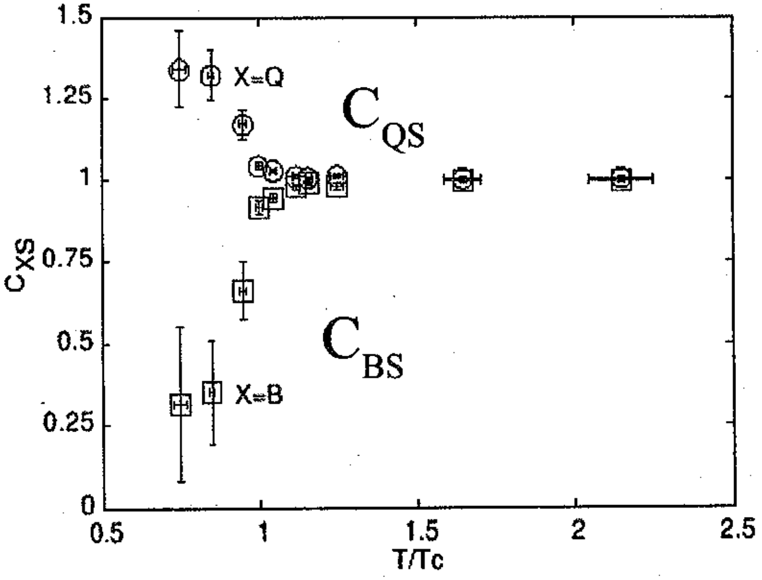
Independent quarks and LATTICE QCD for T>1.1T_c

Bound state QGP



V.K, Majumder, Randrup PRL95:182301,2005

$$C_{QS} = -3\frac{\langle QS\rangle}{\langle S^2\rangle}$$

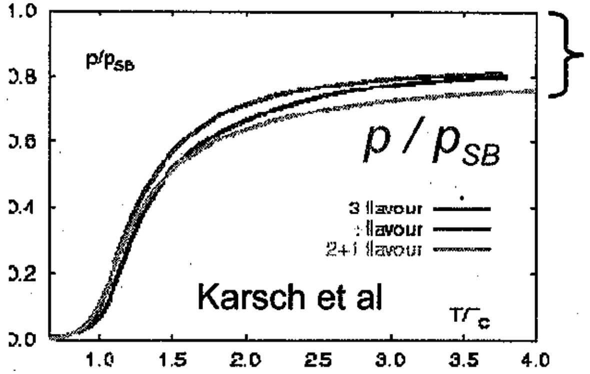


Gavai,Gupta, hep-lat/0510044

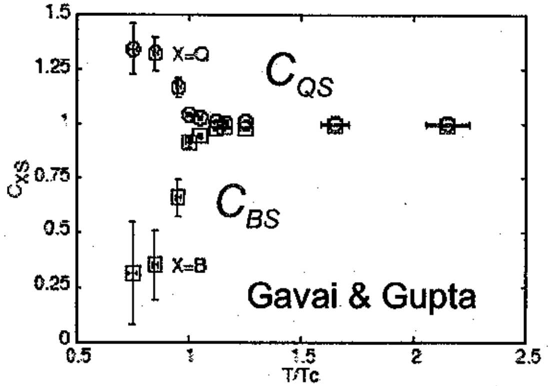
Speculation / conjecture

Lattice gauge calculations show that ..

.. the QGP is *not* an ideal quark-gluon gas:



.. the quarks and antiquarks in QGP behave as *independent* particles:



$$p < p_{SB} \quad \overset{?}{\Longleftrightarrow} \quad \frac{C_{XS}\ \text{(lattice QCD)}}{C_{XS}\ (q\text{-}qbar\ \text{gas})} = 1 \qquad (X = B, Q)$$

This apparent inconsistency might be resolved in a ***mean-field*** picture:

The quark acquires an *effective mass* by the medium: $m\uparrow \Rightarrow p\downarrow$

The associated repulsive interaction may contribute to the *flow*

Strangeness in Collisions

RIKEN-BNL Workshop, February 16-17, 2006 BNL

Applicability of (Ideal) Hydrodynamics to (Strangeness) RHIC Data

(from an Experimentalist's View)

- Ideal Hydrodynamics
- Comparison with data
  - Spectra
  - Elliptic flow
- Beyond Ideal Hydro
- Summary, Conclusion and Open Questions

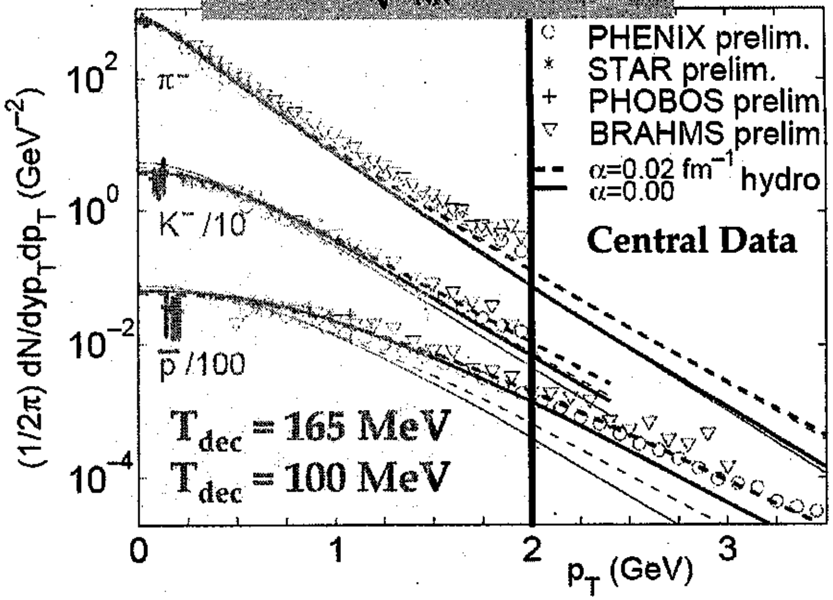
Jeff Speltz

Institut de Recherches Subatomiques, Strasbourg

Central Spectra

π^-, K^-, $\bar{p}$

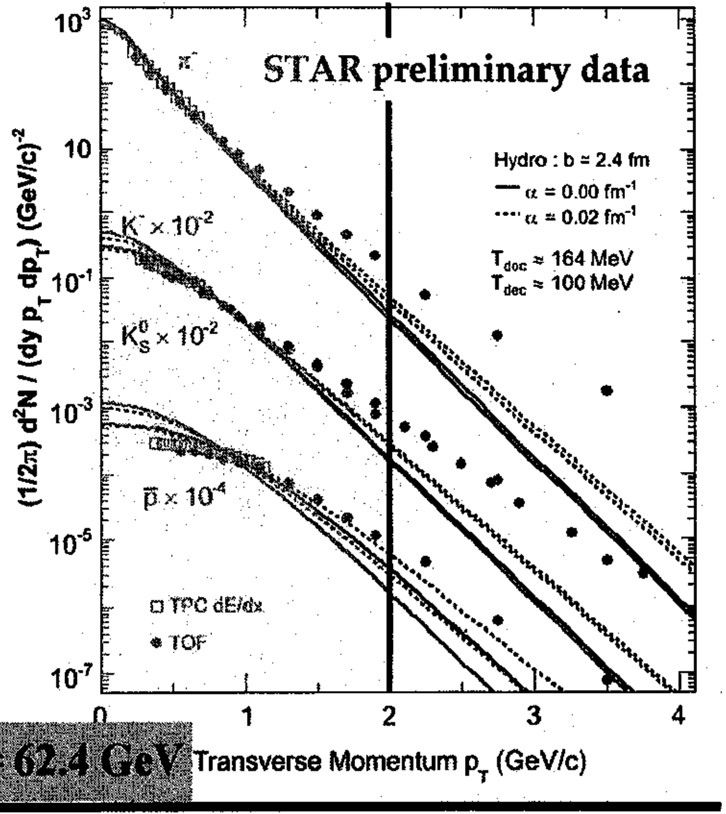
Au+Au, $\sqrt{s_{NN}} = 200$ GeV



P.F. Kolb and R. Rapp, Phys. Rev. **C 67** (2003) 044903

α : initial (at τ_0) transverse velocity : $v_T(r)=\tanh(\alpha r)$

- Best agreement for :
  T_{dec}= 100 MeV ; $\alpha = 0.02$ fm^{-1}
- $\alpha \neq 0$: importance of initial conditions
- Only at low p_T ($p_T < 1.5 - 2$ GeV/c)
- Failing at higher p_T (> 2 GeV/c) expected:
  - Less rescattering $\Longrightarrow$ Thermalization validity limit



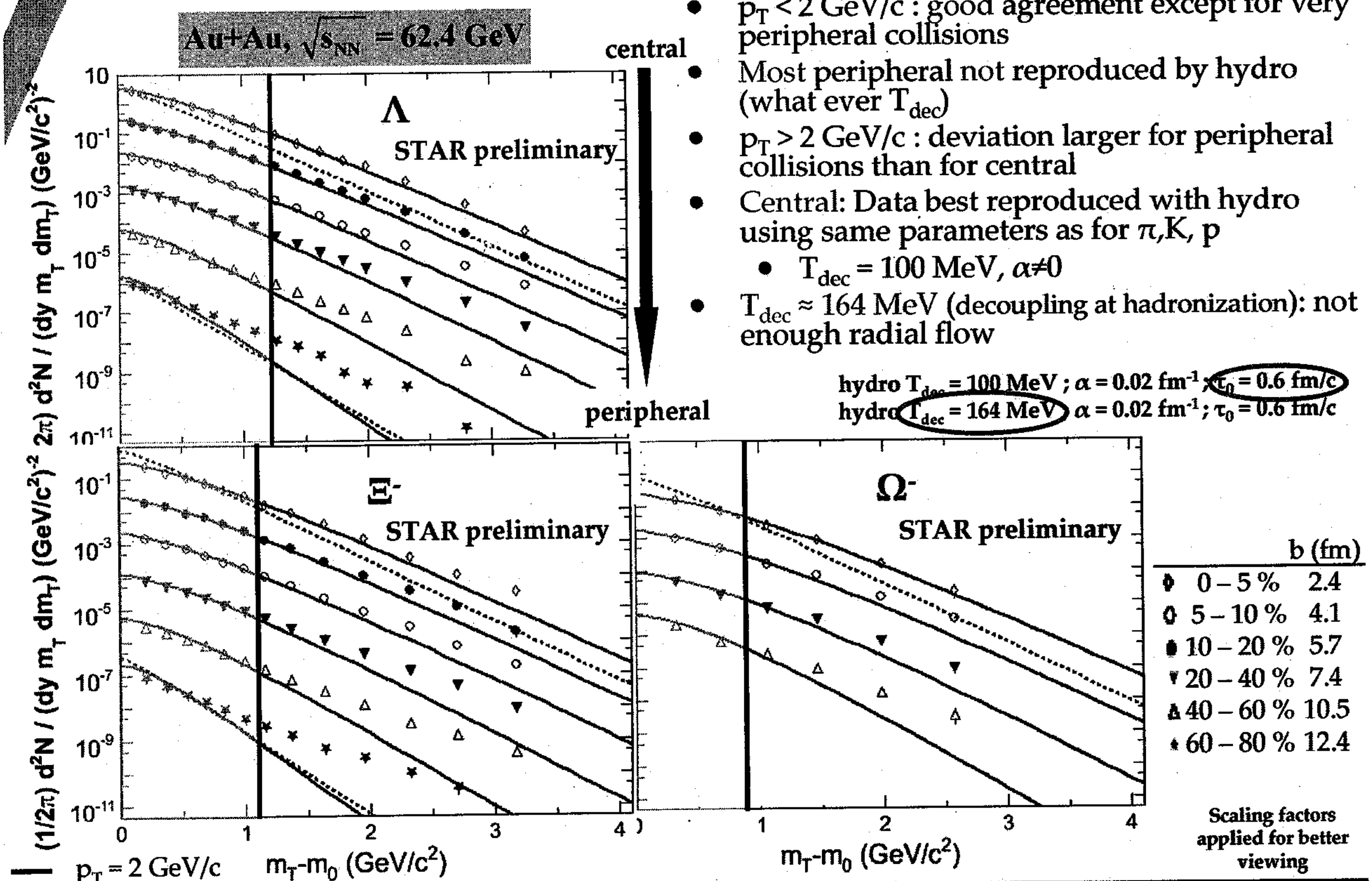
Au+Au, $\sqrt{s_{NN}} = 62.4$ GeV

- Caveat: Predictions normalized to data
- Limited range of agreement
- Hydro starts failing at 62 GeV?
- different feed-down treatment in data and hydro?
- Different initial / final conditions as at 200 GeV ?
  - Lower T_{dec} at 62 GeV ?
  - Larger τ_0 at 62 GeV ?

Spectra, centrality dependence : 62.4 GeV

Strange Baryons

- $p_T < 2$ GeV/c : good agreement except for very peripheral collisions
- Most peripheral not reproduced by hydro (what ever T_{dec})
- $p_T > 2$ GeV/c : deviation larger for peripheral collisions than for central
- Central: Data best reproduced with hydro using same parameters as for π,K, p
  - $T_{dec} = 100$ MeV, $\alpha \neq 0$
- $T_{dec} \approx 164$ MeV (decoupling at hadronization): not enough radial flow

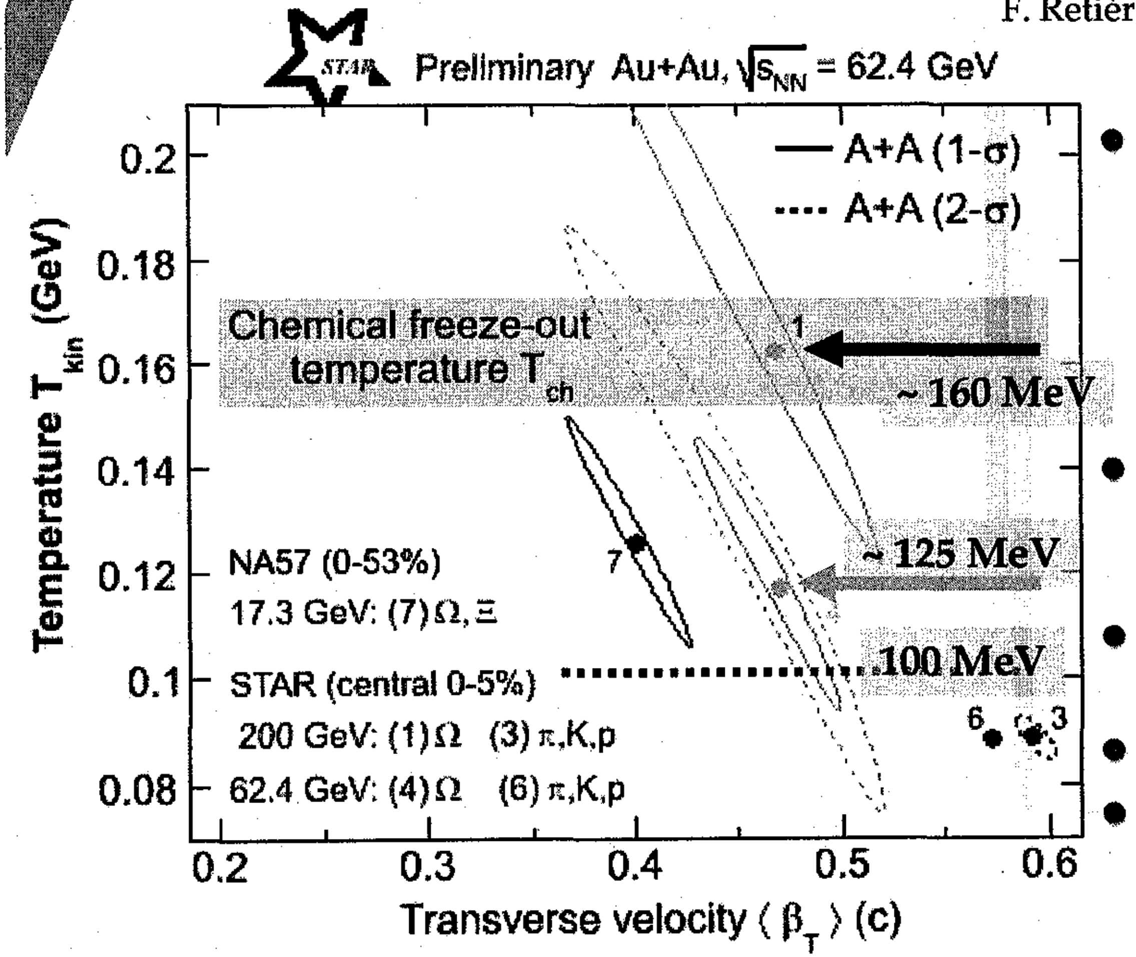


Scaling factors applied for better viewing

Central Spectra

Blast-Wave

E. Schnedermann *et al.*, Phys. Rev. **C 48** (1993) 2462
F. Retière and M. Lisa, Phys. Rev. **C 70** (2004) 044907



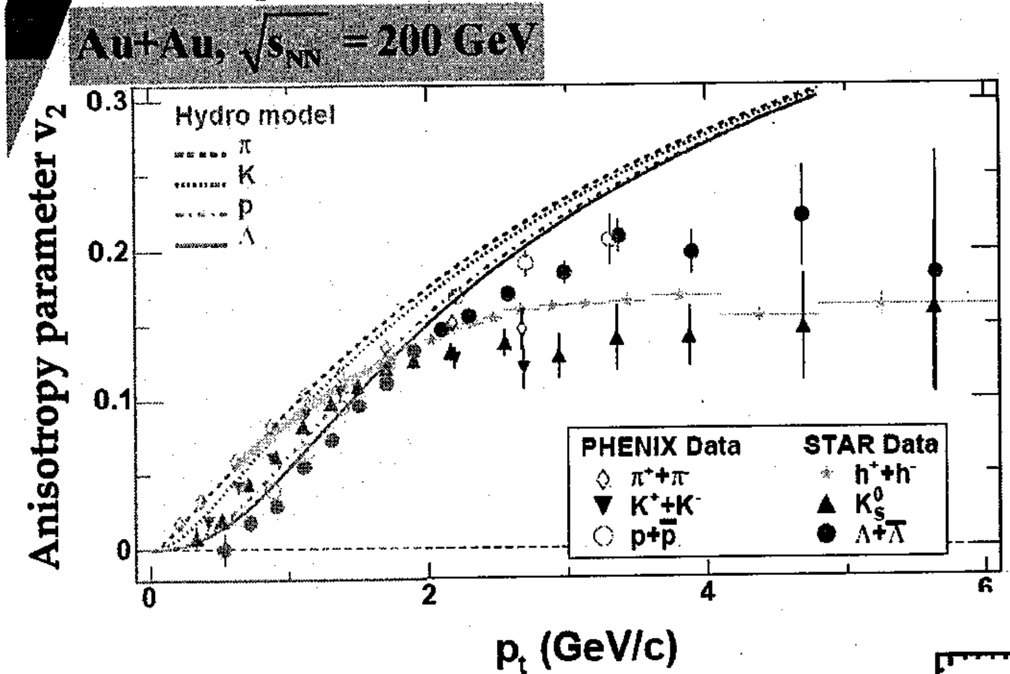
J. Speltz (for the STAR Collaboration), nucl-ex/0512037

- Blast-Wave: hydro inspired parameterization:
  - Parameter T_{kin}
  - Parameter $\langle\beta_T\rangle$
  - Direct fit (X^2) on the data
- Blast-Wave gives slightly different results than hydro :
  - $T_{kin} \sim T_{ch} > 100$ MeV
- sensitivity on fit range and on the velocity profile?
- Large errors
- B-W fit on hydro : $T_{kin} \neq T_{dec}$ (up to 30 MeV difference)
- Are T_{dec} and T_{kin} the same physical quantity?

Elliptic flow : 200 GeV

Hydro features

- Self-quenching : Sensitive to early stage of the evolution

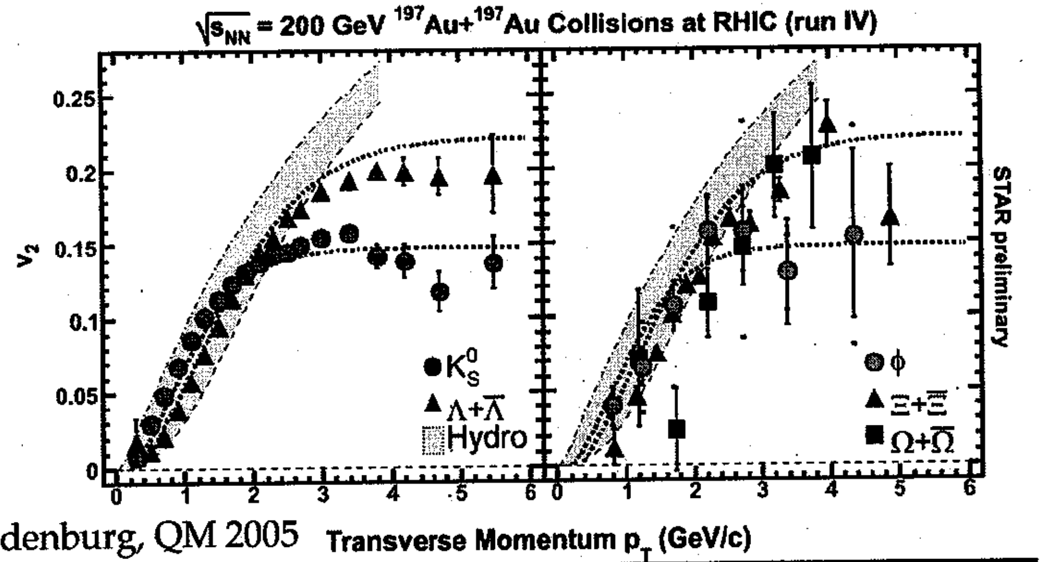


J. Adams *et al.*, Phys. Rev. **C 72** (2005) 014904

- Mass hierachy at low p_T from hydro in data
- Agreement until p_T ~ 2 GeV/c
  - Same as for spectra
- p_T > 2 GeV/c data deviates from hydro
  - Describtion possible with dissipative effects

D. Molnar and M. Gyulassy,
Nucl. Phys. A **697** (2002) 495

- Early thermalization : account for large v_2
- s quark flow : further indication of thermalization and partonic dof (Ω small cross-section, φ flow, baryon/meson difference)



M. Oldenburg, QM 2005

Conclusion/Summary and open questions

- Ideal hydro gives good agreement with (strangeness) data:
  - Spectra and Elliptic flow at all RHIC energies (62 GeV to 200 GeV)
  - EoS including phase transition gives nice accord
  - Indication for (early) thermalization
  - Kinetic Freeze-out (T_{dec}) similar for all particles
  - clarify on Blast-Wave (more precise measurement, Alice…)
  - Ω : Mass evolution and test full equilibrium of all light flavors
  - Interplay of τ_0, α and T_{dec}: is it really understood?
  - Importance of 62.4 GeV! Possible insight to hydro breakdown

- Nothing is really perfect (ideal):
  - but closest to perfect we have ever seen
  - Breakdown (peripheral, finite η): hybrid models, viscosity
  - Test these tools on strangeness

Hydrodynamics at RHIC – Successes, Failures, and Perspectives

Ulrich Heinz
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Collective flow measurements provide access to the Equation of State (EOS) of the expanding fireball matter. This connection is most direct and clear if the matter behaves like an ideal fluid. Predictions of collective flow features, especially of anisotropic elliptic flow at midrapidity, based on ideal relativistic fluid dynamics have been very successful at RHIC. Roughly speaking, ideal fluid dynamics describes the bulk (> 99%) of hadron production, up to transverse momenta of about 1.5–2 GeV/c. This includes the successful hydrodynamic prediction of the mass splitting of $v_2(p_T)$ for identified hadrons, and the preference of this observed splitting for an EOS with a quark-hadron phase transition over equations of state without such a transition.

However, the ideal fluid dynamical description of RHIC data also has its limitations. If one assumes chemical equilibrium all the way down to kinetic freeze-out, one reproduces the shapes of spectra and $v_2(p_T)$ for identified hadrons, but not the relative hadronic yields. If one corrects the hadronic EOS to take into account chemical freeze-out directly at hadronization ($T_{\text{chem}} \simeq 170\,\text{MeV}$), one reproduces the hadronic yields and the shapes of their p_T spectra, but overpredicts the p_T-slope of $v_2^\pi(p_T)$. This shows that, even though in the hydrodynamic simulation the total momentum anisotropy saturates before hadronization, final hadronic kinetics redistributes it among the different hadronic species in a way that depends on the chemical composition of the hadronic phase, and if one assumes that the latter behaves as an ideal fluid one cannot describe all aspects of the hadron spectra simultaneously. The discrepancies at midrapidity in minimum bias Au+Au collisions at RHIC disappear if one replaces for the late hadronic stage the ideal fluid dynamic model by a (highly viscous) hadron resonance cascade model.

The hydrodynamic picture also breaks down for $v_2(p_T)$ at $p_T > 1.5\,\text{GeV}/c$ for mesons and $p_T > 2.5$ GeV/c for baryons. This can be attributed to viscous effects, but the limits for the shear viscosity that one extracts from these deviations from ideal behaviour are very small, making the quark-gluon plasma the most perfect fluid so far created in the laboratory.

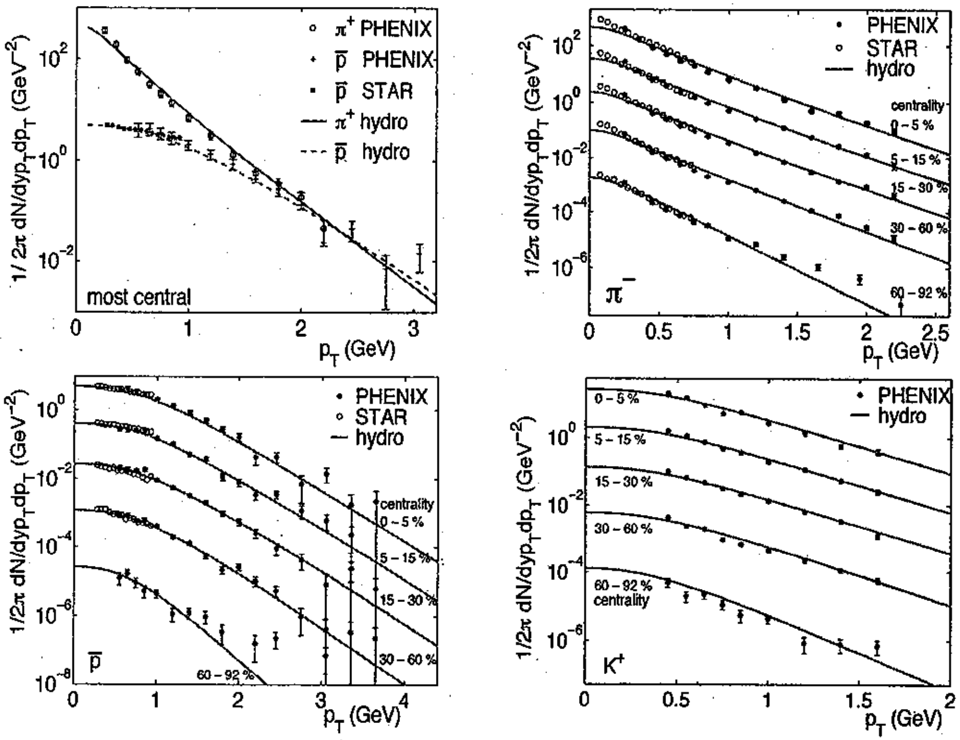
Further and more significant deviations from ideal fluid dynamical behaviour are seen in the elliptic flow in peripheral Au+Au collisions at RHIC, at forward rapidities in minimum bias collisions at RHIC, and in collisions of all centralities at lower collision energies. All these deviations seem to scale with the ratio of charged multiplicity density dN_{ch}/dy over transverse overlap area which can be directly related to the initial entropy density produced in the collision which again controls the time until the point of hadronization is reached. Recent work has shown that all these deviations from ideal fluid dynamics can be eliminated if the late hadronic stage is described by a realistic (and highly viscous) hadron rescattering model instead of ideal fluid dynamics. With Glauber model initial conditions, *hadronic* dissipation can account for *all* observed deviations from ideal fluid predictions at $p_T < 1.5\,\text{GeV}/c$. If one instead uses the more eccentric initial entropy density profiles calculated from the Color Glass Model, the predicted elliptic flow is still too large and must be further reduced by shear viscosity *in the QGP phase.*

An extraction of the value of the QGP shear viscosity requires a viscous relativistic hydrodynamic code for comparison with the data. Work along this direction is in progress, and some first results are shown.

References to relevant work are given on the attached transparencies.

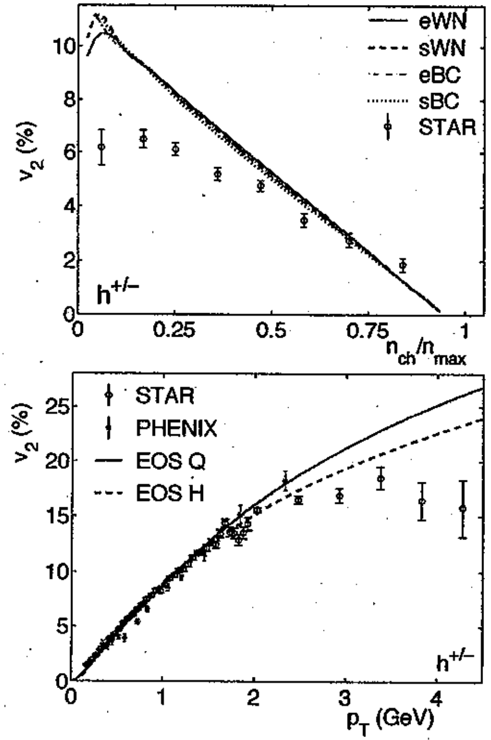
Successes of hydrodynamics at RHIC:

Single particle spectra from central and peripheral Au+Au @ 130 A GeV (STAR, PHENIX):



Model parameters fixed with π, $\bar{p}$ spectra at $b = 0$; all other spectra predicted (UH & P.Kolb, hep-ph/0204061).

Centrality and momentum dependence of elliptic flow v_2 (STAR, PHENIX, PHOBOS):

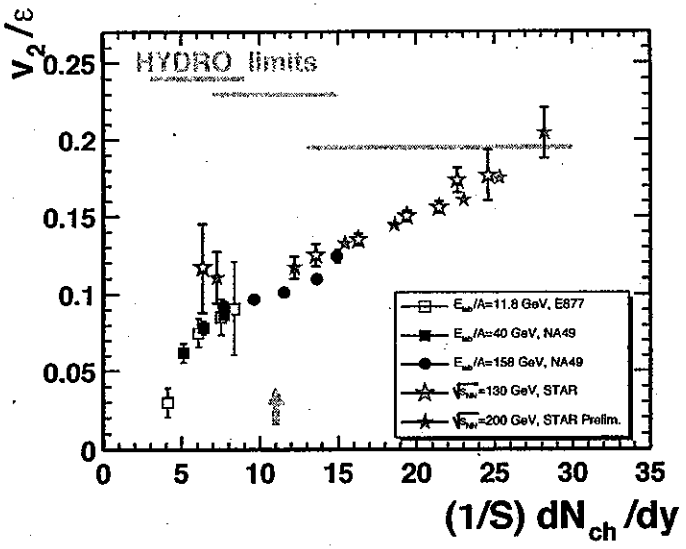


$$v_2 = \langle \cos(2\phi) \rangle$$

Final radial flow $\langle v_\perp \rangle > 0.5\,c \Longrightarrow$ bang!

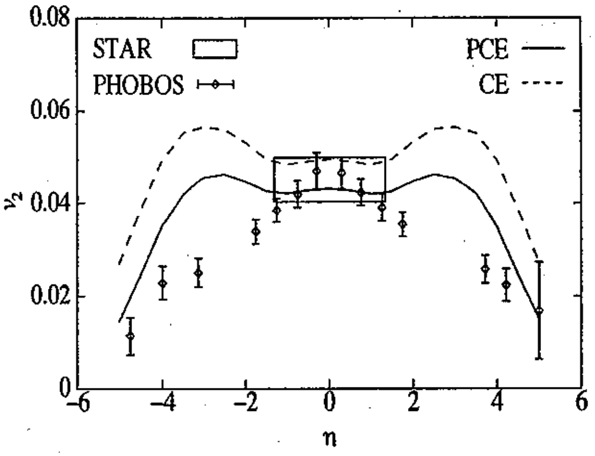
Limits of ideal fluid dynamics: smaller, less dense systems

STAR, PRC 66 ('02) 034904; NA49, PRC 68 ('03) 034903



3d hydro:

T. Hirano, PRC 65 ('02) 011901; 66 ('02) 054905



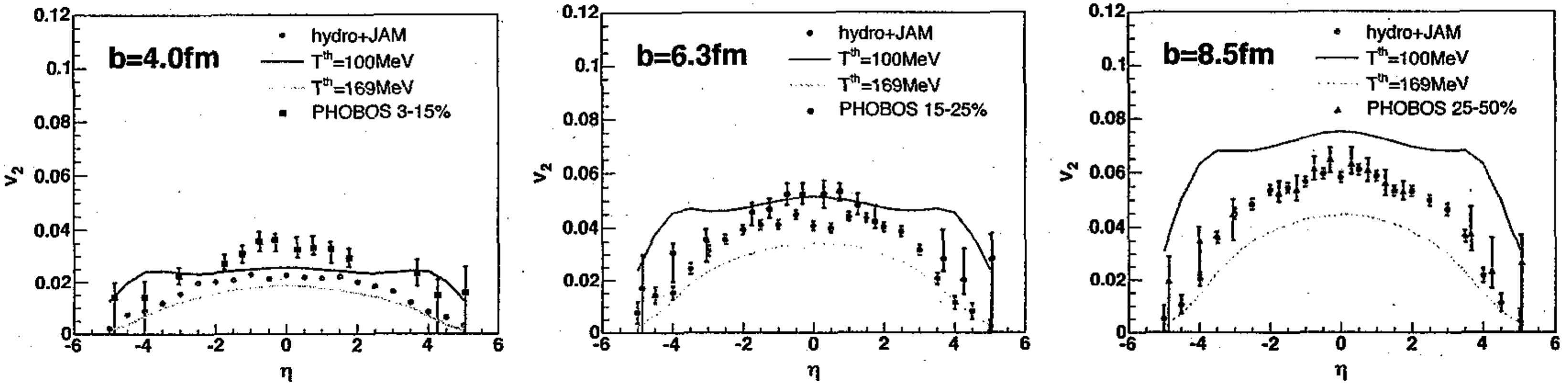
- $\frac{v_2^{\text{measured}}}{v_2^{\text{hydro}}}$ scales with $\frac{1}{S}\frac{dN_{\text{ch}}}{dy} \propto s_{\text{init}}$
- $e_{\text{init}} > 10\,\text{GeV/fm}^3$ needed for v_2 to saturate before hadronization and exhaust ideal hydro limit!
- hydrodynamics predicts non-monotonic v_2/ϵ: between AGS and RHIC it decreases, due to softening of EOS by quark-hadron transition (Kolb, Sollfrank, UH, PRC 62 (2000) 054909)
- data show instead monotonous increase of v_2/ϵ with $\sqrt{s}$!?

What's going on??

Is hadronic dissipation enough to explain deviations from perfect fluidity?

(T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, nucl-th/0511046)

3D Hydro+Cascade Model: Ideal fluid dynamics for QGP above T_c, hadronic cascade with realistic cross sections (JAM) below T_c (similar to Bass & Dumitru (1D), Teaney & Shuryak (2D))

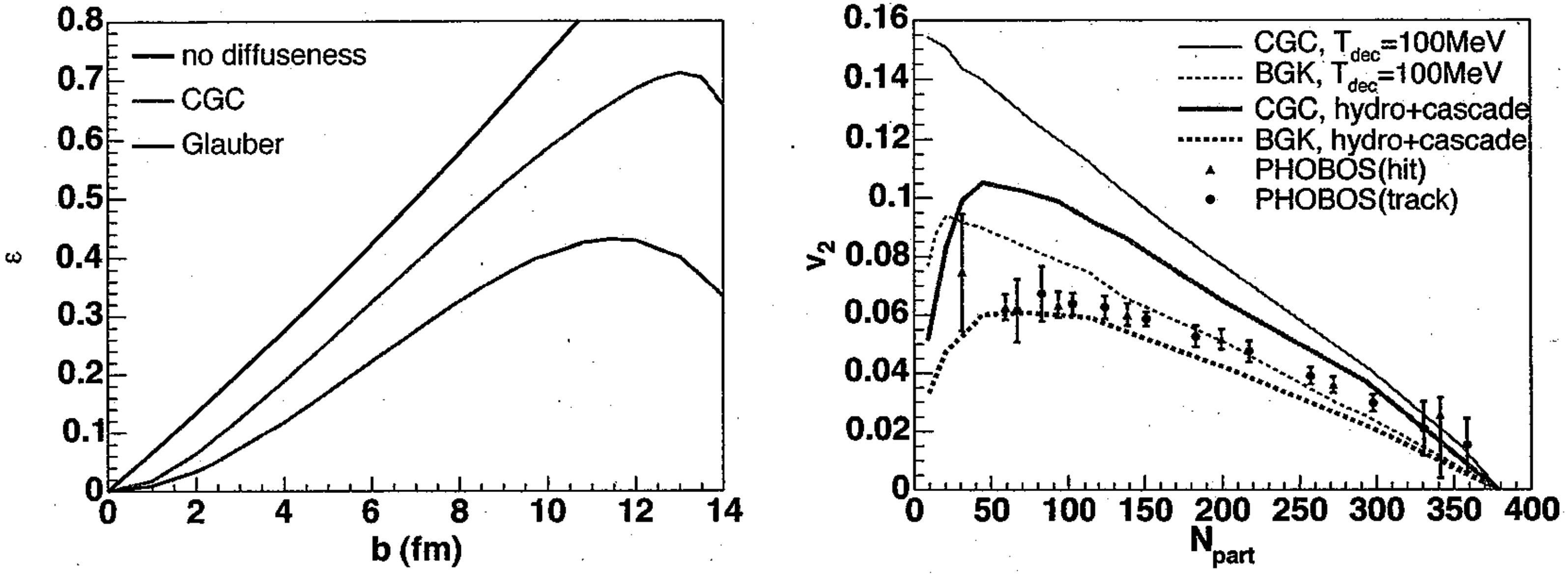


[Glauber model initial conditions (85% soft/15% hard)]

- Not enough elliptic flow from perfect QGP fluid – hadronic contribution to v_2 is required
- Treating hadronic stage as ideal fluid overpredicts v_2 in peripheral collisions and at forward rapidities
- Dissipation in hadronic cascade brings theory in line with data (except for small b – excess in data due to event-by-event geometry fluctuations? (Miller & Snellings))

CGC initial conditions give larger elliptic flow – is the QGP 'imperfect' after all?

(T. Hirano, U. Heinz, D. Kharzeev, R. Lacey, Y. Nara, nucl-th/0511046)



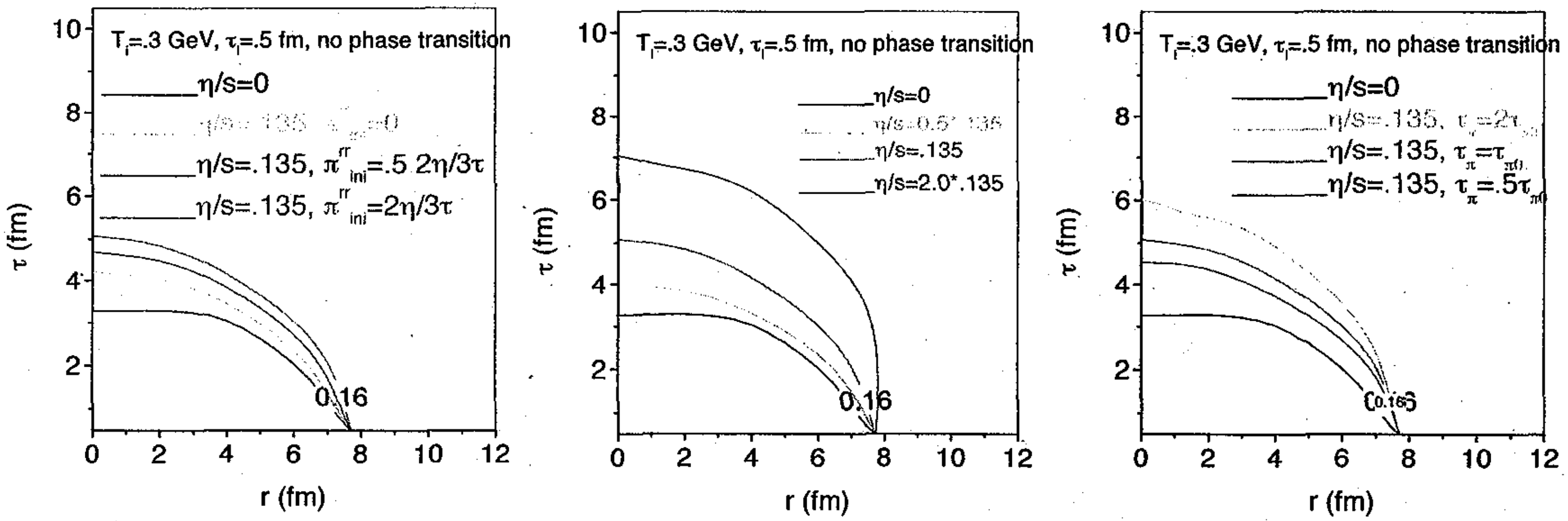
- Color Glass Condensate (CGC) model (McLerran & Venugopalan 1994; Kharzeev, Levin, Nardi 2001) produces steeper edge of initial distribution, resulting in larger eccentricities ϵ than in Glauber model
- Ideal hydrodynamics turns larger spatial eccentricity ϵ into larger elliptic flow v_2
- Hadronic dissipation insufficient to reduce the calculated v_2 enough to agree with data $\Longrightarrow$ additional QGP viscosity needed!?

$\Longrightarrow$ Need better control over initial conditions!

(1+1)-d viscous hydrodynamics: first results (II)

(Chaudhuri & Heinz, nucl-th/0504022)

Sensitivity to initial π^{rr}, $\frac{\eta}{s}$, and relaxation time τ_π ($T_{\rm f} = 160\,\text{MeV}$):



$\tau_\pi = \frac{3\eta}{2p}$, $\frac{\eta}{s} = 0.135$

$\tau_\pi = \frac{3\eta}{2p}$, $\pi^{rr}_{\rm ini} = \frac{2\eta}{3\tau_i}$

$\eta/s = 0.135$, $\pi^{rr}_{\rm ini} = \frac{2\eta}{3\tau_i}$

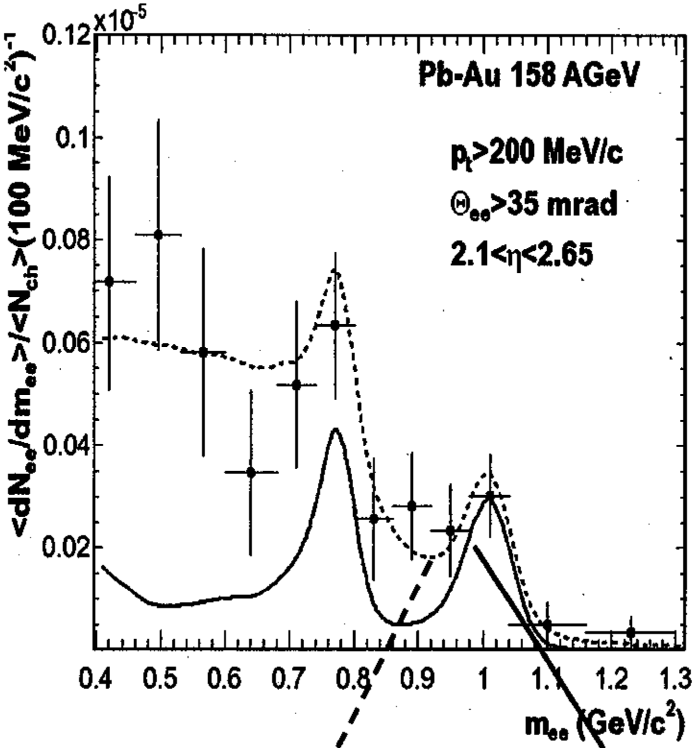
- Larger initial viscous pressures create larger overall viscous effects ("memory effect")
- Significant viscous effects for $\frac{\eta}{s} > \frac{\hbar}{4\pi}$
- At fixed $\frac{\eta}{s}$, viscous effects increase with increasing relaxation time τ_π

Leptonic and Charged Kaon Decay Modes of the ϕ meson Measured in Heavy-Ion Collisions at CERN-SPS

A. Marín (GSI) for the Ceres Collaboration

We report a measurement of ϕ meson production in central Pb+Au collisions at $E_{lab}/A=158$ GeV. For the first time in heavy-ion collisions, ϕ mesons were reconstructed in the same experiment both in the K^+K^- and the dilepton decay channel. Near mid-rapidity, this yields rapidity densities, corrected for production at the same rapidity value, of $2.05 \pm 0.14(stat) \pm 0.25(syst)$ and $2.04 \pm 0.49(stat) \pm 0.32(syst)$, respectively. The shape of the measured transverse momentum spectra is also in close agreement in both decay channels. The data rule out a possible enhancement of the ϕ yield in the leptonic over the hadronic channel by a factor larger than 1.6 at 95% CL.

Invariant mass $\phi \rightarrow e^+e^-$



Decay cocktail

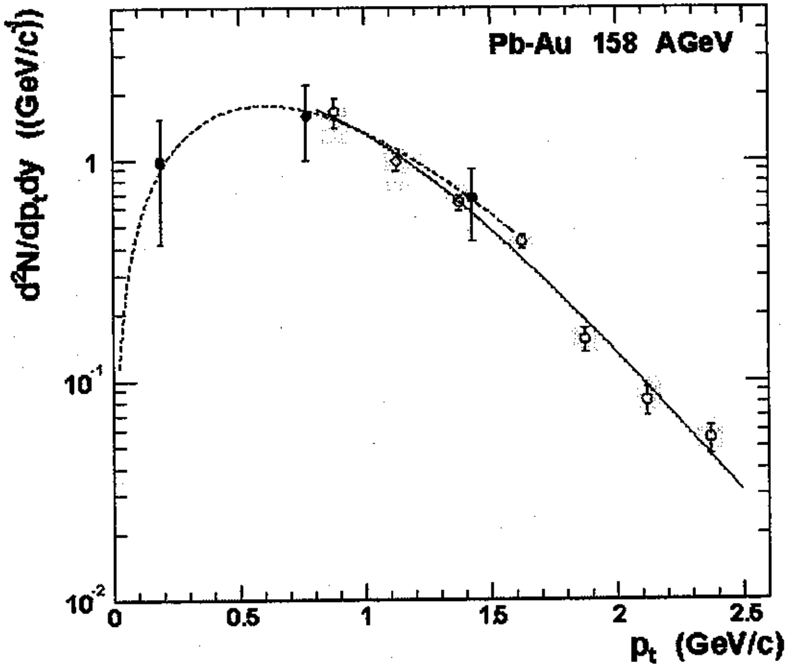
Decay cocktail+rho+QGP

ϕ : mass 0.9-1.1 GeV/c2
229 ± 53 Counts
S/B=1/12

Physics Background:

in-medium modified rho
dilepton yield from QGP
35% contribution in ϕ peak
(R. Rapp)

Comparison between two decay channels



Different rapidity

$dN_\phi/dy^{\,2-2.4} = 0.93.(dN_\phi/dy)^{2.1-2.65}$
(from NA49, PLB 491(2000) 59)

K^+K^-:
dN/dy=2.05±0.14(stat)±0.25(syst)
T = 273± 9(stat)±10(sys) MeV

e^+e^- :
dN/dy=2.04±0.49(stat)±0.32(syst)
T = 306 ± 82(stat) MeV

Results in both channels in close agreement → **$dN/dy\ (\phi \rightarrow e^+e^-)/dN/dy(\phi \rightarrow K^+K^-) < 1.6$ at 95% CL**

Ceres Collaboration: nucl-ex/0512007

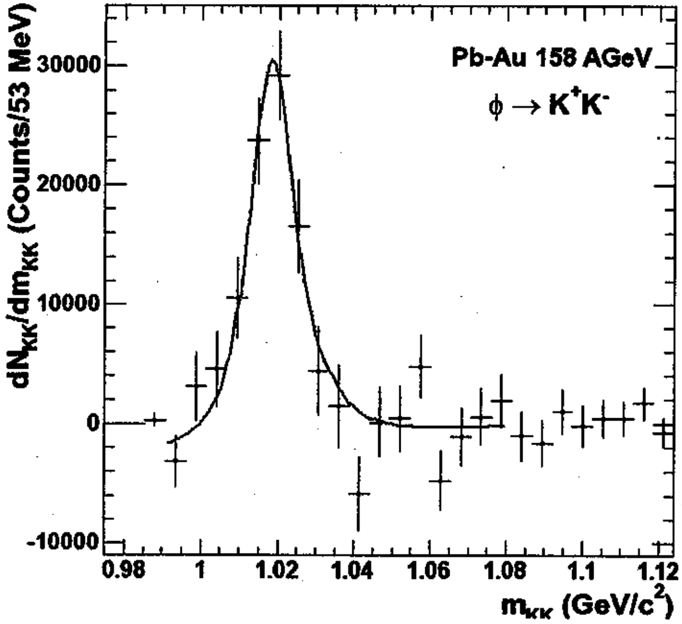
Invariant mass $\phi \to K^+K^-$

All charged particles asigned the Kaon mass (no PID)

Selection of target tracks with matched SDD-TPC tracks

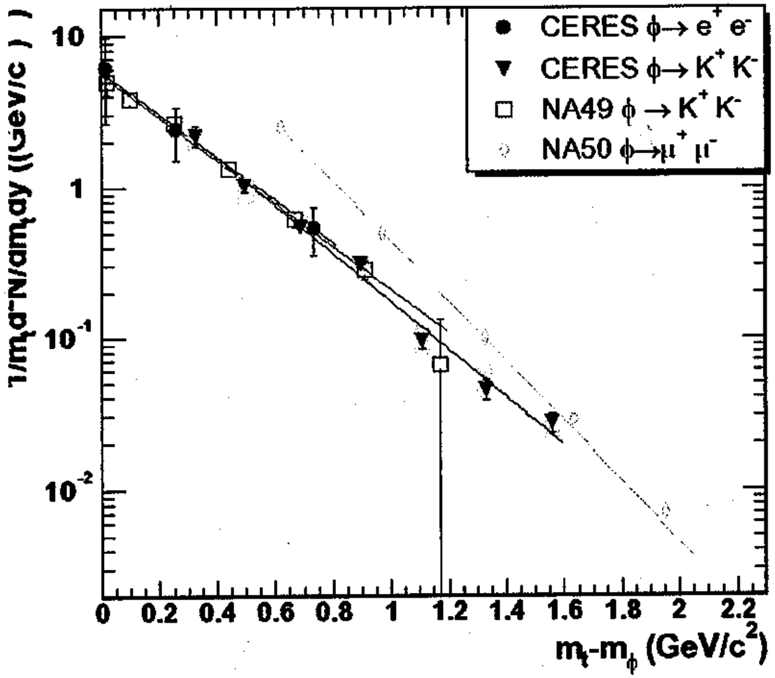
Single track cuts: $0.13<\theta<0.24$ rad, $p_t>0.250$ GeV/c

Opening angle vs pt cut following the ϕ, Armenteros cut



1.5 GeV/c < p_t < 1.75 GeV/c
2.2<y<2.4

Comparison to NA49/NA50 results



NA49 and NA50: D.Röhrich, J.Phys.G.27(2001)355
CERES: nucl-ex/0512007

Different measurement conditions:

	NA49	CERES	Correction
centrality:	4%	7%	$h^-_{4\%}/h^-_{7\%}$ CERES
rapidity:	3.4	2.2	dN/dy NA49

Scaling factor: F =1.15 ± 0.12

CERES results in K^+K^- and e^+e^- decay channels agree with NA49 results

Conclusions

- For the first time in heavy-ion collisions the leptonic and charged kaon decay channels of the ϕ meson are measured in the same experiment
- The measured rapidity densities and transverse momentum spectra are in agreement in both decay channels
- The data rule out a possible enhancement of the ϕ yield in the leptonic over hadronic channel by a factor larger than 1.6 at 95% CL.
- CERES results are in agreement with NA49 results
- Possible differences of maximum 40-50% as expected by models like UrQMD or up to 70% at lowest pt as expected by AMPT model cannot be ruled out by CERES results.

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Strangeness Signature of QGP

BNL, February 16, 2006

ABSTRACT: nucl-th/0602047, with Jean Letessier

We study the process of chemical equilibration of strangeness in dynamically evolving QGP fireball formed in relativistic heavy ion collisions at RHIC and LHC. We account for the contribution of direct and explore the thermal-QCD strangeness production mechanisms. The specific yield of strangeness per entropy is the primary target variable. We explore the effect of collision impact parameter, *i.e.*, fireball size, on strangeness chemical equilibration in QGP. Insights gained in study the RHIC data are applied to the study strangeness production at the LHC. We further consider how characteristic hadronic observables are influenced by the differences in the chemical equilibration, given a specific per entropy strangeness yield.OBJECTIVES:

1. Introduction: nonequilibrium + statistical hadronization
2. Analysis and parameters for strangeness RHIC results (2xPRC, nucl-th/0412072,0506044)
3. Strangeness equilibration with fireball expansion
4. Centrality dependence of s/S at RHIC-200 and LHC
5. Soft strange hadrons at RHIC and LHC

With Jean Letessier, Inga Kuznetsova, and Giorgio Torrieri, now Montreal

Supported by a grant from the U.S. Department of Energy, DE-FG02-04ER41318

Johann Rafelski, Department of Physics, University of Arizona, TUCSON, AZ 85718, USA

Smooth across the phase boundary are the yields strangeness, charm, entropy = multiplicity and hence ratios, we will focus in this presentation on the observables:

$$\frac{s \text{ or } c}{S}=\frac{\text{number of valance strange, charm quark pairs}}{\text{multiplicity} = \text{entropy content in final state}}$$

And across any phase boundary when V does not adjust (and even in that case)

$$\gamma_s^{\rm QGP}\neq\gamma_s^{\rm h} \qquad \gamma_q^{\rm QGP}\neq\gamma_q^{\rm h}$$

Examples of what non-equilibrium parameters do

- $\tilde\gamma_s\equiv\gamma_s/\gamma_q$ **shifts the yield of strange vs non-strange hadrons:**

$$\text{the horn}: \frac{\mathrm{K}^+}{\pi^+}\propto\frac{\gamma_s^{\rm h}}{\gamma_q^{\rm h}}, \qquad \phi \text{ enhancement } \frac{\phi}{h}\propto\frac{\gamma_s^{\rm h\,2}}{\gamma_q^{\rm h\,2}},$$

$$\text{enhancement rise with strangeness number}: \frac{\Omega}{\Lambda}\propto\frac{\gamma_s^{\rm h\,2}}{\gamma_q^{\rm h\,2}},$$

- **For fixed $\tilde\gamma_s\equiv\gamma_s/\gamma_q$ and fixed other statistical parameters $(T,\lambda_i,\ldots)$:**

$$\frac{\text{baryons}\propto\gamma_q^{\rm h\,3}}{\text{mesons}\propto\gamma_q^{\rm h\,2}}\propto\gamma_q^{\rm h}.$$

Counting particles

The counting of hadrons is conveniently done by counting the valence quark content $(u,d,s,\ldots\lambda_q^2=\lambda_u\lambda_d,\ \lambda_{I3}=\lambda_u/\lambda_d)$:

$$\Upsilon_i\equiv\Pi_i\gamma_i^{n_i}\lambda_i^{k_i}=e^{\sigma_i/T};\qquad \lambda_q\equiv e^{\frac{\mu_q}{T}}=e^{\frac{\mu_b}{3T}},\qquad \lambda_s\equiv e^{\frac{\mu_s}{T}}=e^{\frac{[\mu_b/3-\mu_S]}{T}}$$

Example of NUCLEONS $\gamma_N=\gamma_q^3$:

$$\Upsilon_N=\gamma_N e^{\frac{\mu_b}{T}},\qquad \Upsilon_{\overline{N}}=\gamma_N e^{\frac{-\mu_b}{T}};$$

$$\sigma_N\equiv\mu_b+T\ln\gamma_N,\qquad \sigma_{\overline{N}}\equiv-\mu_b+T\ln\gamma_N$$

Meaning of parameters from e.g. the first law of thermodynamics:

$$\begin{aligned} dE+P\,dV-T\,dS &= \sigma_N\,dN+\sigma_{\overline{N}}\,d\overline{N}\\ &= \mu_b(dN-d\overline{N})+T\ln\gamma_N(dN+d\overline{N}). \end{aligned}$$

NOTE: For $\gamma_N\to1$ the pair terms vanishes, the μ_b term remains, it costs $dE=\mu_B$ to add to baryon number.

Strangeness / Entropy in QGP

Relative s/S yield measures the number of active degrees of freedom and degree of relaxation when strangeness production freezes-out. Perturbative expression in chemical equilibrium:

$$\frac{s}{S} = \frac{\frac{g_s}{2\pi^2}T^3(m_s/T)^2K_2(m_s/T)}{(g2\pi^2/45)T^3+(g_s n_{\rm f}/6)\mu_q^2 T} \simeq 0.028$$

much of $\mathcal{O}(\alpha_s)$ interaction effect cancels out

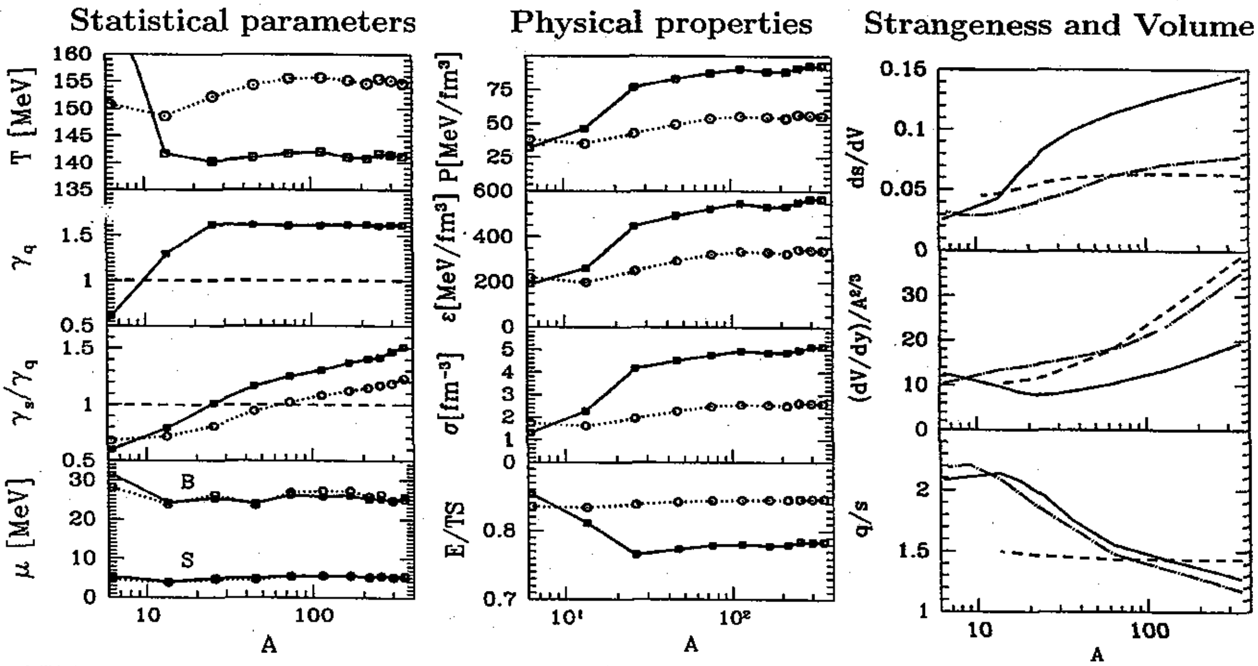
Allow for chemical non-equilibrium of strangeness $\gamma_s^{\rm QGP}$, and possible quark-gluon pre-equilibrium – gradual increase to the limit expected:

$$\frac{s}{S}=\frac{0.03\gamma_s^{\rm QGP}}{0.4\gamma_{\rm G}+0.1\gamma_s^{\rm QGP}+0.5\gamma_q^{\rm QGP}+0.05\gamma_q^{\rm QGP}(\ln\lambda_q)^2}\to 0.028.$$

We expect the yield of gluons and light quarks to approach chemical equilibrium fast and first: $\gamma_{\rm G}\to 1$ and $\gamma_q^{\rm QGP}\to 1$, thus $s/S\simeq 0.028\gamma_s^{\rm QGP}$.

CHECK: FIT YIELDS OF PARTICLES, EVALUATE STRANGENESS AND ENTROPY CONTENT AND COMPARE WITH EXPECTED RATIO,

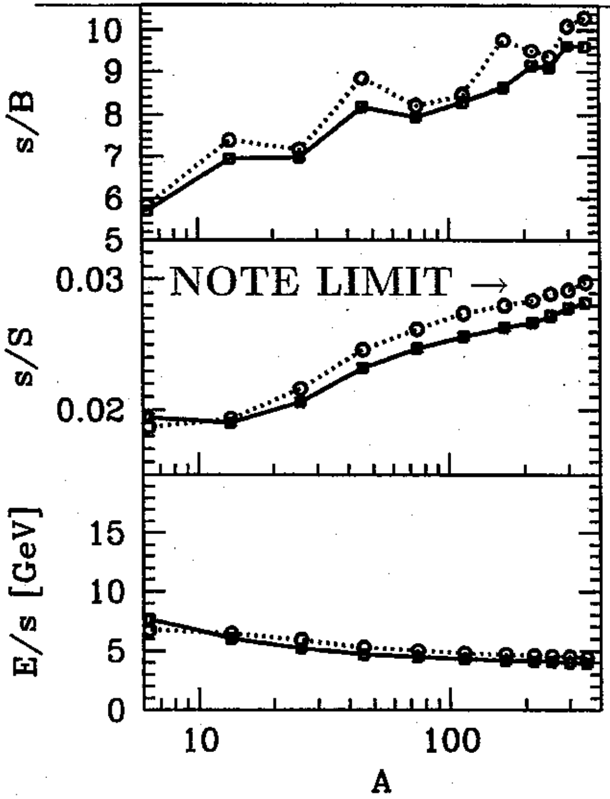
RHIC200 results: dependence on centrality



LINES: blue: nonequilibrium $\gamma_s, \gamma_q \neq 1$ and green semi-equilibrium $\gamma_s \neq 1, \gamma_q = 1$, $\gamma_s = \gamma_q = 1$

Highlights: γ_q changes with $A \propto V$ from under-saturated to over-saturated value,
$\gamma_s^{\rm HG}$ increases steadily to 2.4, implying near saturation in QGP.
P, σ, ϵ increase by factor 2–3, at $A > 20$ (onset of new physics?),
E/TS decreases with A - test of EoS.
Geometric transverse size scaling

s/b and s/S rise with increasing centrality $A \propto V$; E/s falls



Showing results for both $\gamma_q, \gamma_s \neq 1$, for $\gamma_s \neq 1, \gamma_q = 1$. Note little difference in the result, even though the value of T will differ significantly.

1) $s/S \to 0.027$, as function of V;
2) most central value near QGP chemical equilibrium;
3) no saturation for largest volumes available;

Behavior is consistent with QGP prediction of steady increase of strangeness yield with increase of the volume, which implies longer lifespan and hence greater strangeness yield, both specific yield and larger $\gamma_s^{\rm QGP}$.

NOW ON TO THE THEORY: DO WE UNDERSTAND s/S?

STRANGENESS IN ENTROPY CONSERVING EXPANSION

QGP expansion is adiabatic i.e. ($g_G = 2_s 8_c = 16, g_q = 2_s 3_c n_{\rm f}$)

$$S = \frac{4\pi^2}{90} g(T) V T^3 = \text{Const.} \quad g = g_G \left(1 - \frac{15\alpha_s(T)}{4\pi} + \dots\right) + \frac{7}{4} g_q \left(1 - \frac{50\alpha_s(T)}{21\pi} + \dots\right) .$$

The volume, temperature change such that $\delta(gT^3V) = 0$. Strangeness phase space occupancy, $g_s = 2_s 3_c \left(1 - \frac{k\alpha_s(T)}{\pi} + \dots\right)$, $k = 2$ for $m_s/T \to 0$:

$$\gamma_s(\tau) \equiv \frac{n_s(\tau)}{n_s^\infty(T(\tau))}, \quad n_s(\tau) = \gamma_s(\tau) T(\tau)^3 \frac{g_s(T)}{2\pi^2} z^2 K_2(z), \quad z = \frac{m_s}{T(t)}, \quad K_i : \text{Bessel f.}$$

evolves due to production and dilution, keeping entropy fixed:

$$\frac{d}{d\tau}\frac{s}{S} = \frac{A_G}{S/V}\left[\gamma_{\rm G}^2 - {\gamma_s}^2\right] + \frac{A_q}{S/V}\left[\gamma_{\rm q}^2 - {\gamma_s}^2\right]$$

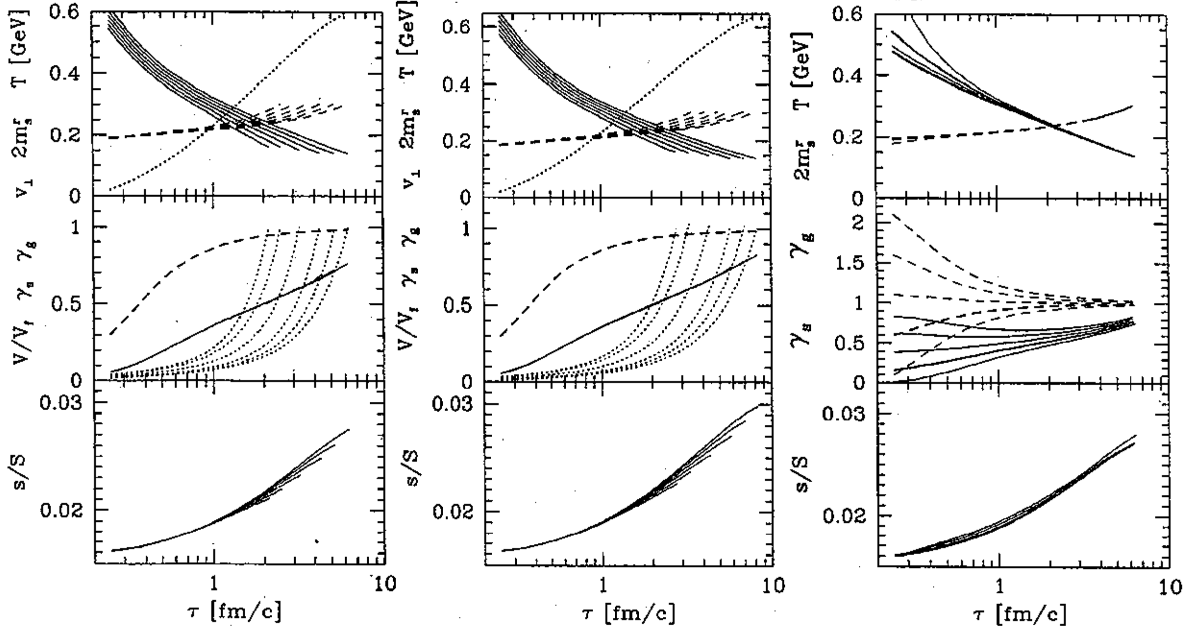
Which for γ_s assumes the form that makes dilution explicit:

$$\frac{d\gamma_s}{d\tau} + \gamma_s \frac{d\ln[g_s z^2 K_2(z)/g]}{d\tau} = \frac{A_G}{n_s^\infty}\left[\gamma_{\rm G}^2 - {\gamma_s}^2\right] + \frac{A_q}{n_s^\infty}\left[\gamma_{\rm q}^2 - {\gamma_s}^2\right]$$

For $m_s \to 0$ dilution effect decreases, disappears, and $\gamma_s \leq \gamma_{G,q}$, importance grows with mass of the quark, $z = m_s(T)/T$, which grows near phase transition boundary.

VOLUME EXPANSION, THROUGH ENTROPY CONTENT THIS FIXES $T(\tau)$

s/S and γ_s at RHIC: centrality dependence

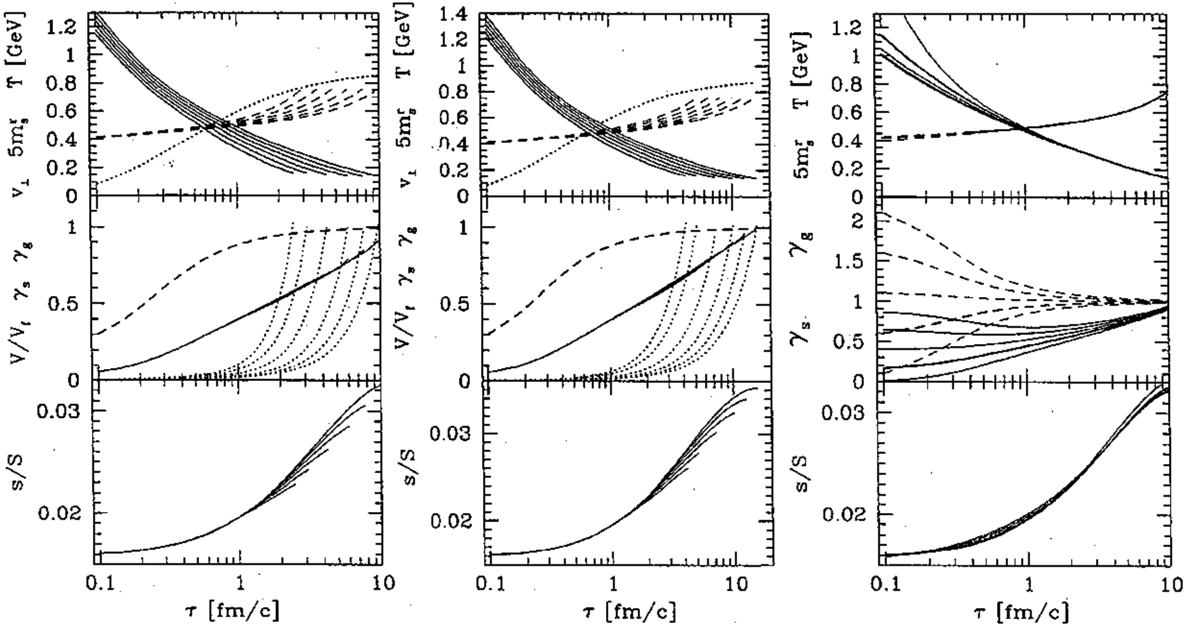


The two left panels: Comparison of the two transverse expansion models, bulk expansion (left), and wedge expansion. Different lines correspond to different centralities. On right: study of the influence of the initial density of partons.

Top: T, middle γ_s and bottom s/S

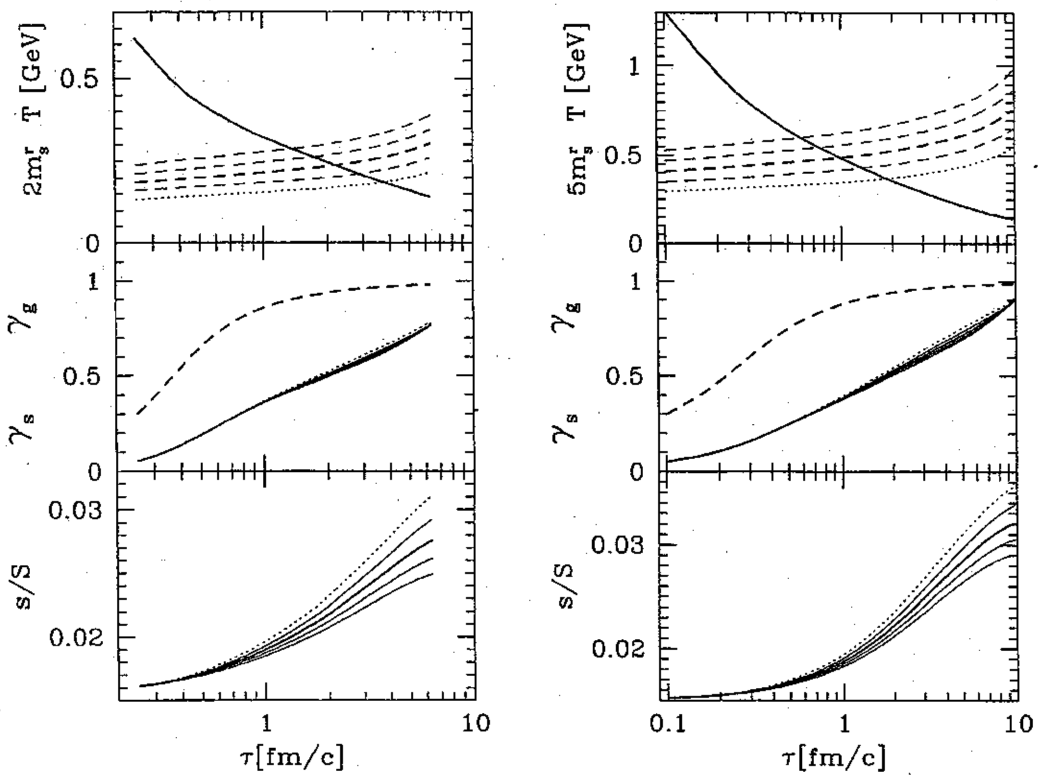
Assumptions:
dotted top panel: profile of $v_\perp(\tau)$, the transverse expansion velocity; middle panel: dashed $\gamma_g(\tau)$,(which determines slower equilibrating γ_q dotted: normalized $dV/dy(\tau)$ normalized by the freeze-out value.

What this means for LHC



Comments (same LHC and RHIC:
Top Panel: Initial temperatures accommodate $dS/dy|_f$ beyond participant scaling.
Middle Panel: Solid line(s): resulting γ_s for different centralities overlay;
Bottom panel: resulting s/S for different centralities, with R_0 stepped down for each line by factor 1.4.

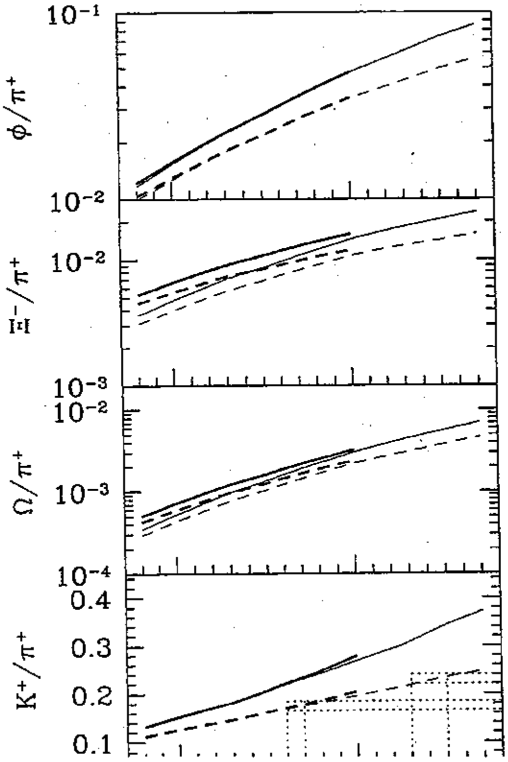
Strange quark mass matters



Left RHIC, right LHC, bulk volume expansion. m_s varies by factor 2.

γ_s overlays: Accidentally two effects cancel: for smaller mass more strangeness production, but by definition γ_s smaller. s/S of course bigger for smaller mass.

Multi strange hadrons are more sensitive to s/S



Top three panels: Φ/π^+, Ξ^-/π^+, Ω^-/π^+ (log scale) relative yields of multistrange hadrons, as function of s/S Φ/π^+, Ξ^-/π^+, Ω^-/π^+ (log scale).

Solid lines primary relative yields, dashed lines after all weak decays. Thick line with $s/S < 0.3$ are for RHIC and thin lines are for LHC physics environment.

Bottom panel: K^+/π^+.

Hadron production at chemical equilibrium

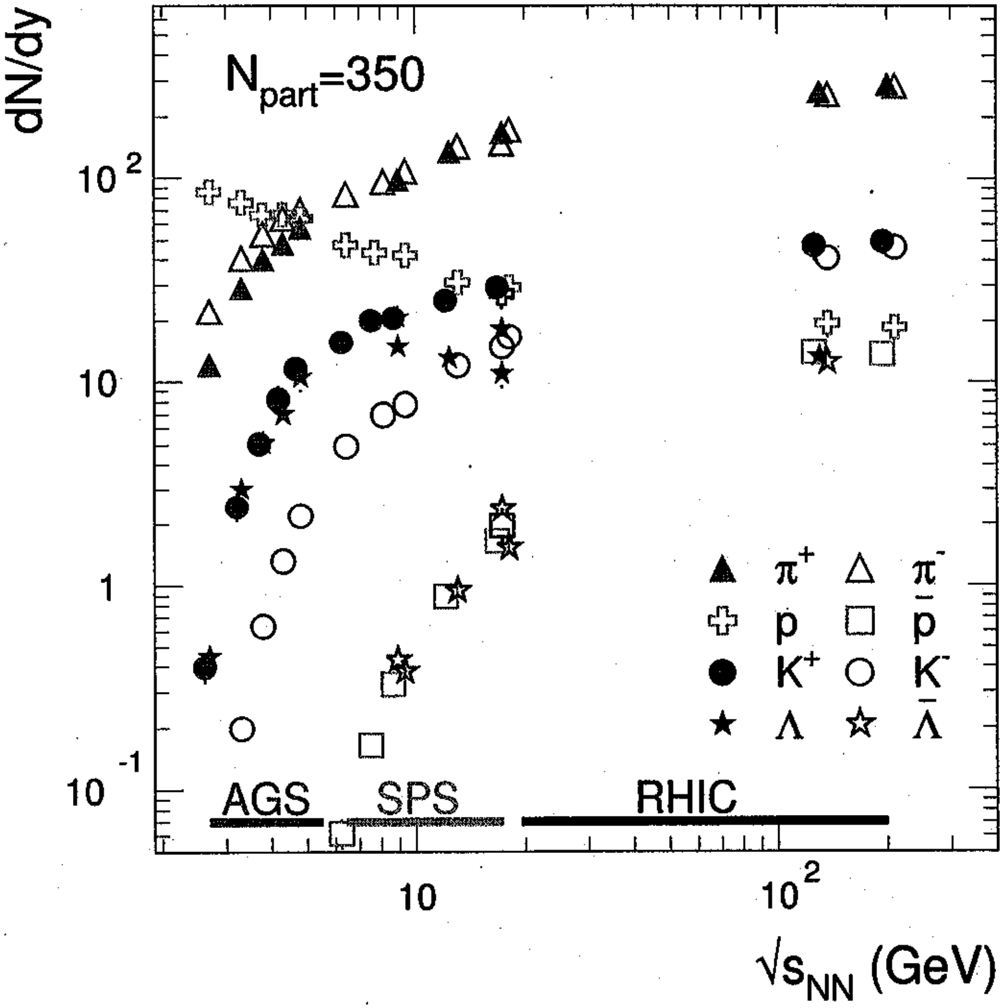
from E_{beam}/A=2 GeV to $\sqrt{s_{NN}}$=200 GeV (central collisions)

A.Andronic, P.Braun-Munzinger, J.Stachel, nucl-th/0511071

- Thermal fits
- Energy dependence of T, μ_b - comparison to other results
- Excitation function of particle ratios
- QCD phase diagram

A. Andronic – "Strangeness in collisions", BNL, February 2006

Measured yields at mid-rapidity



Thermal fits

- conservation (on average) of the quantum numbers:
  i) baryon number: $V \sum_i n_i B_i = N_B$
  ii) isospin: $V \sum_i n_i I_{3i} = I_3^{tot}$
  iii) strangeness: $V \sum_i n_i S_i = 0$
  iv) charm: $V \sum_i n_i C_i = 0$.
- interactions: excluded volume correction
- widths of resonances taken into account
- minimize: $\chi^2 = \sum_i \frac{(R_i^{exp} - R_i^{therm})^2}{\sigma_i^2}, \quad \delta^2 = \sum_i \frac{(R_i^{exp} - R_i^{therm})^2}{(R_i^{therm})^2}$

▷ R_i: ratio of *hadron* yields ($\Rightarrow T$, μ_b) or yield (extra param., V)

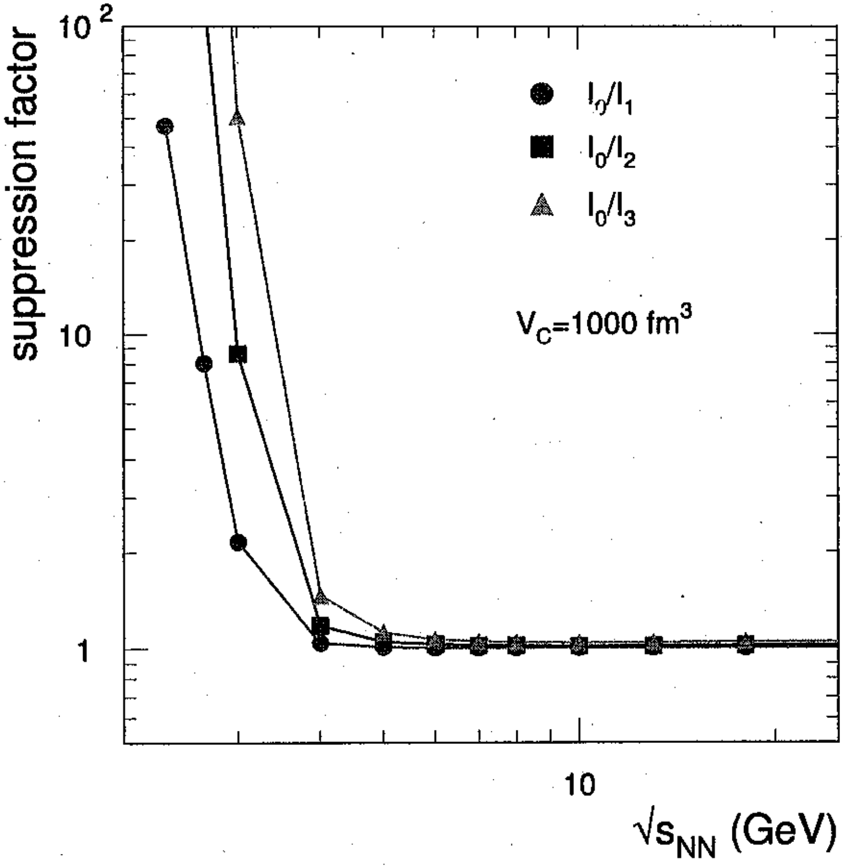
▷ Data: 4π or $\mathrm{d}N/\mathrm{d}y$ data (our choice, unless stated 4π)

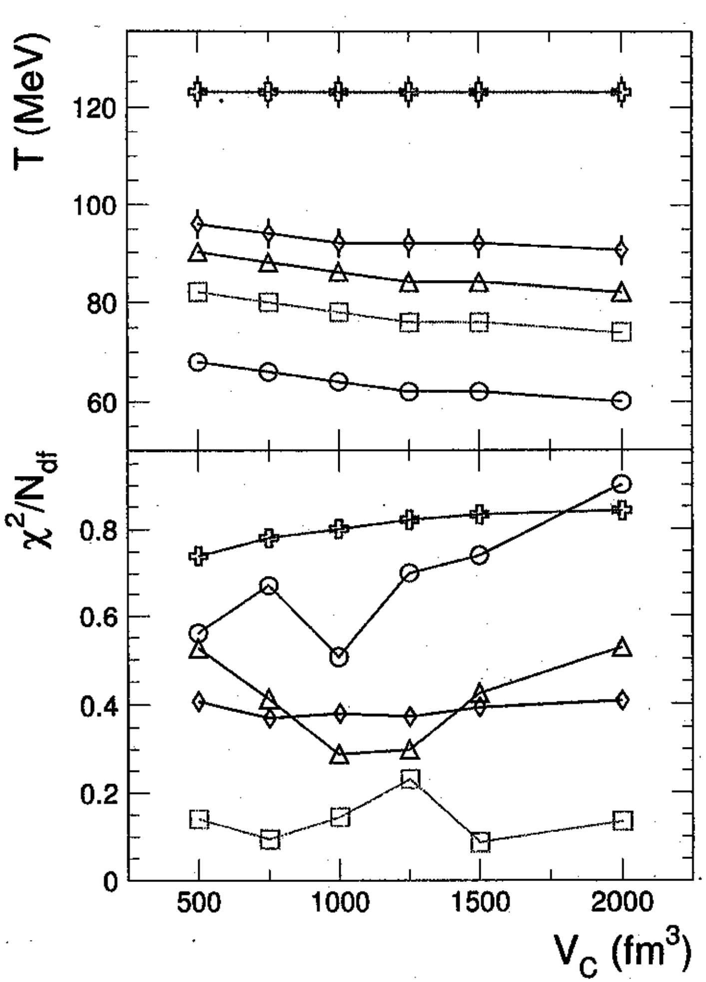
? extra parameters: γ_S, λ's (physical meaning?) (NOT, in our case)

One more ingredient: the canonical volume

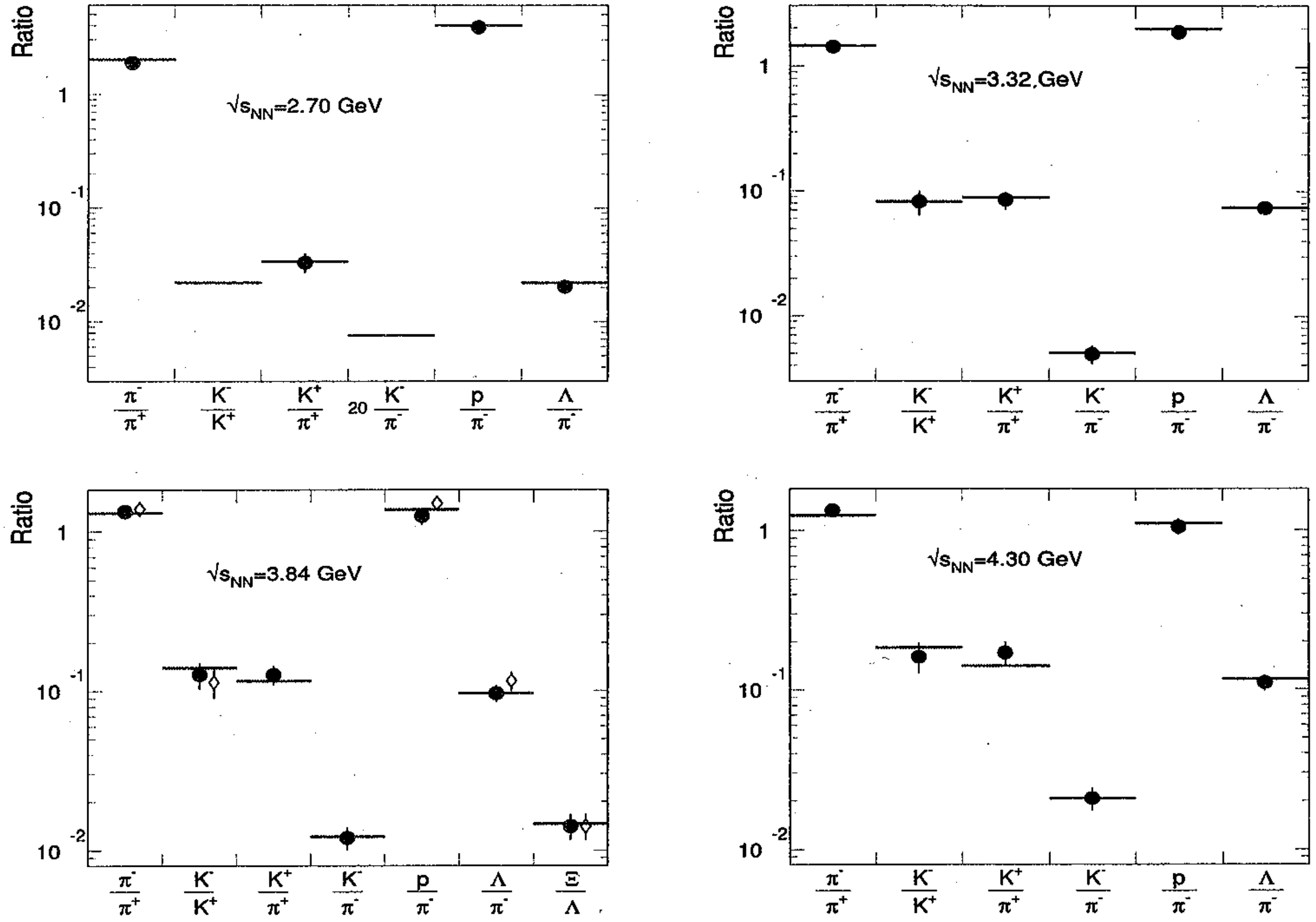
Canonical suppression ...whenever the yields are very small (low energies)

$$n_{i,s}^{C} = n_{i,s}^{GC}/F_s, \quad F_s = I_0(N_s)/I_s(N_s)$$





AGS, 2-8 AGeV



$(T,\ \mu_b)$

(64,760)

(78,670)

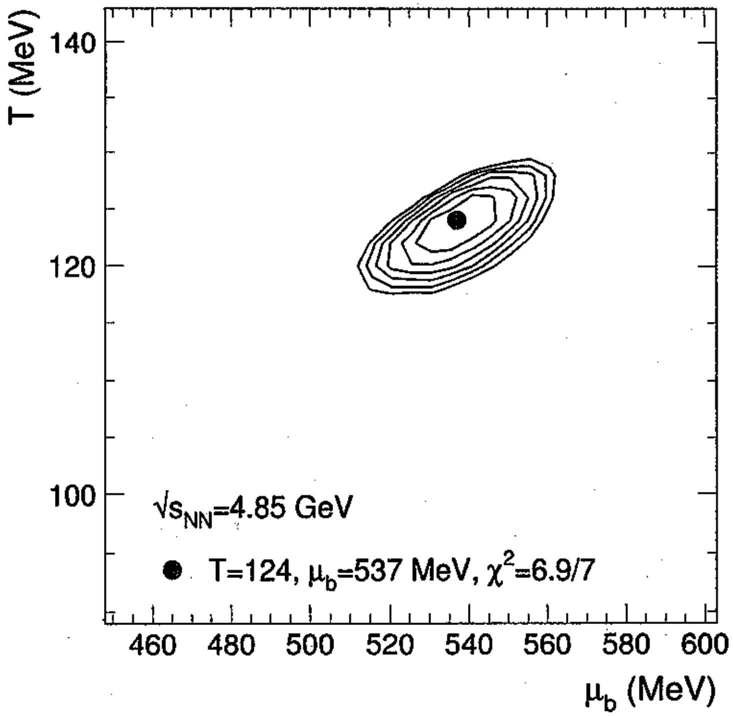
(86,615)

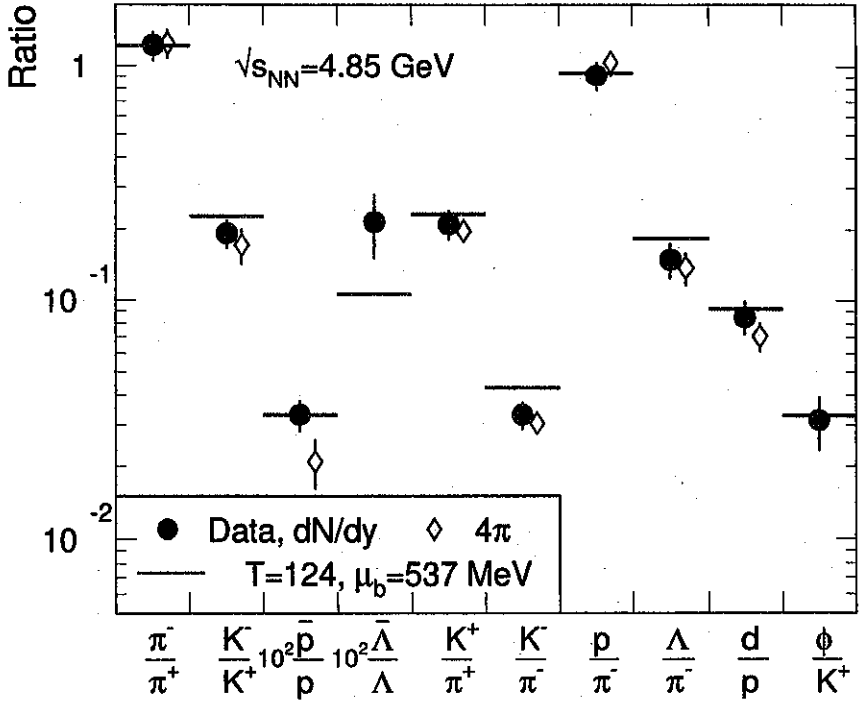
(93,580)

Λ: from 4π

(width = p)

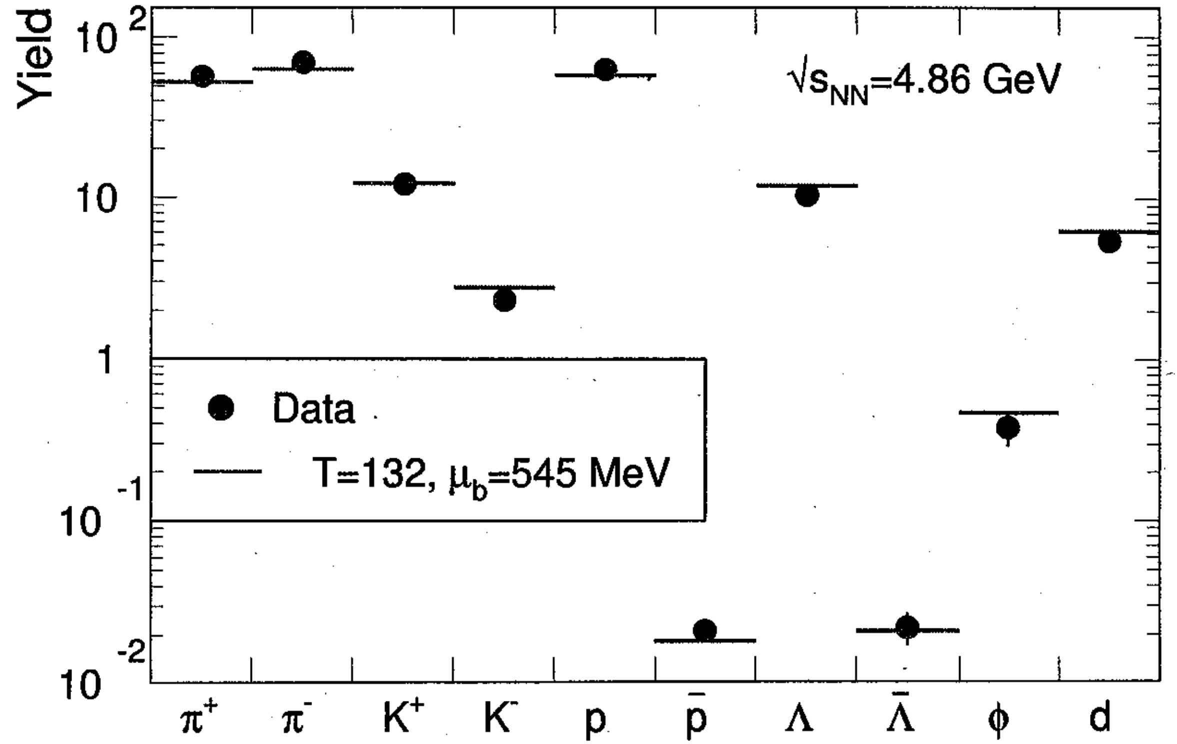
AGS, 10.7 AGeV





- $T = 124 \pm 3$, $\mu_b = 537 \pm 10$ MeV, χ^2/N_{df}=6.9/7 (no K^-/π^-)
- no d/p, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$ and ϕ/K^+ (to check bias at lower energies):
  $T = 108 \pm 9$, $\mu_b = 555 \pm 18$ MeV, χ^2/N_{df}=1.3/3.

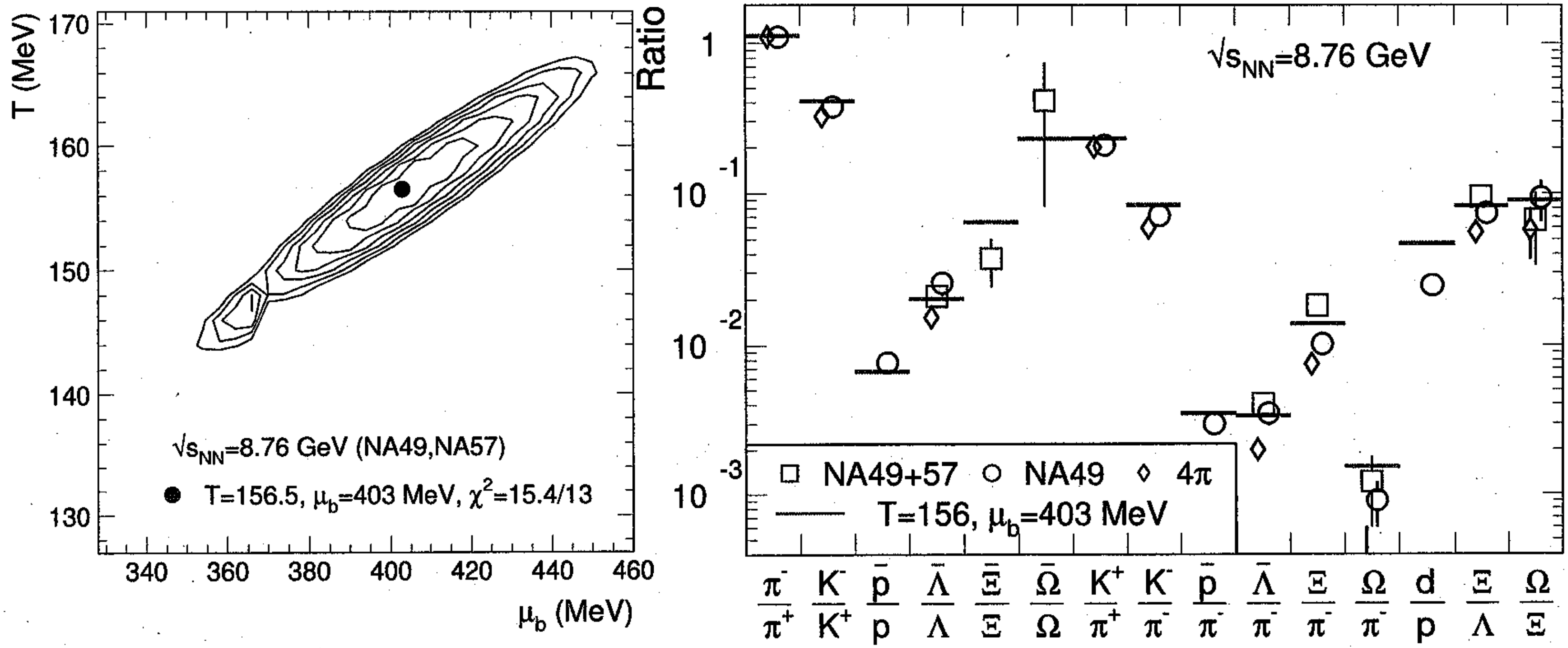
AGS: fits of yields



χ^2/N_{df}=8.3/7, V=950 fm^3; even $\bar{\Lambda}$ works (higher T)

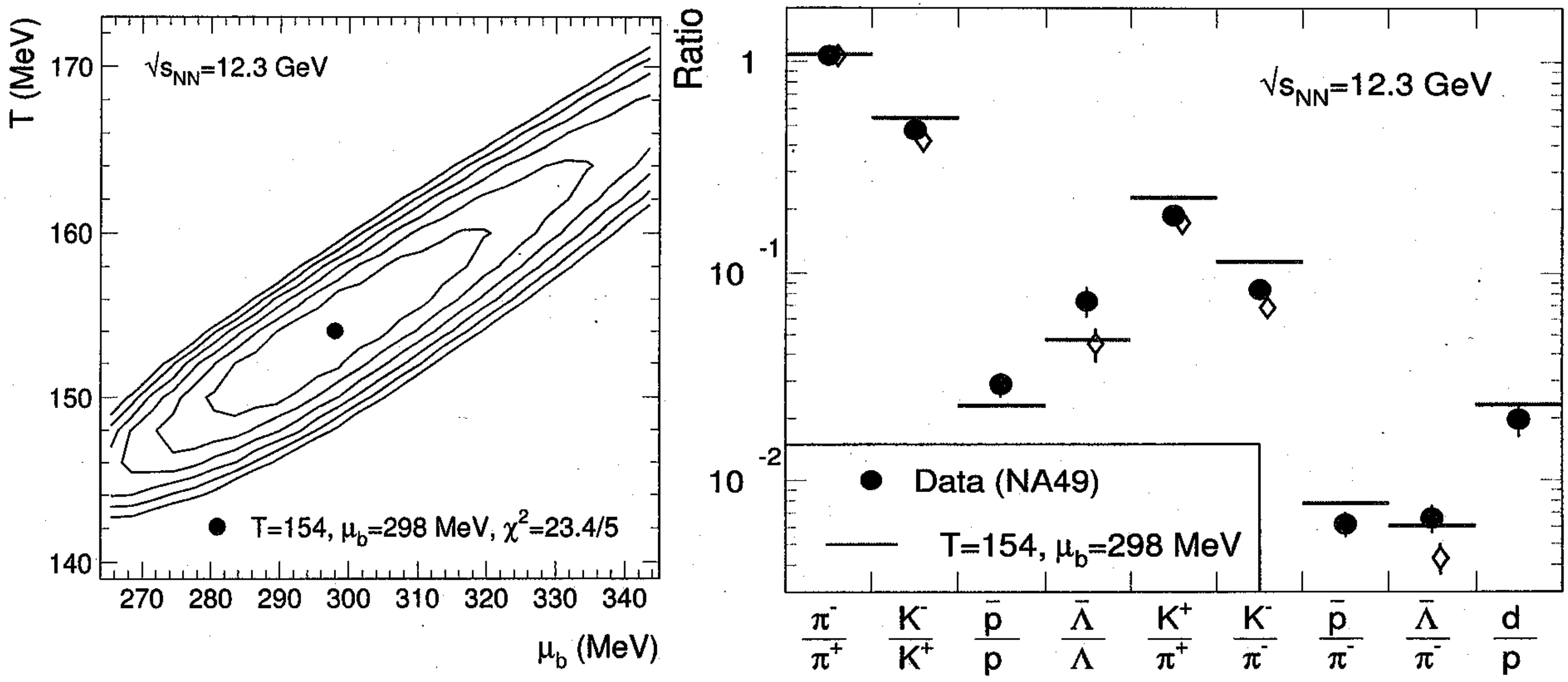
excluding $\bar{p}$, $\bar{\Lambda}$, ϕ, d: T=110, μ_b=550 MeV, χ^2/N_{df}=1.2/3, V=2620 fm^3

SPS, 40 AGeV



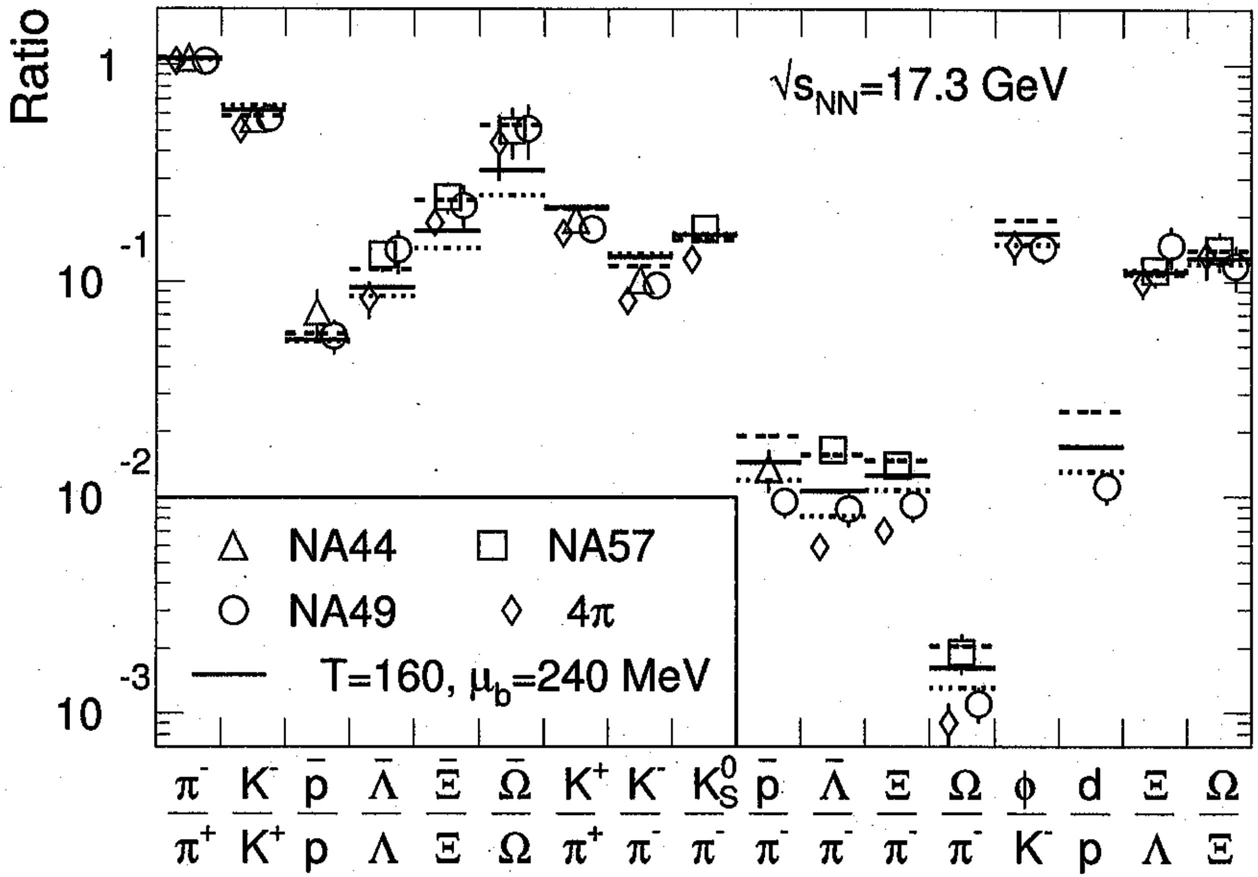
not included in the fit: K^-/π^-, Ξ/π^-, Ω/π^-, d/p

SPS, 80 AGeV



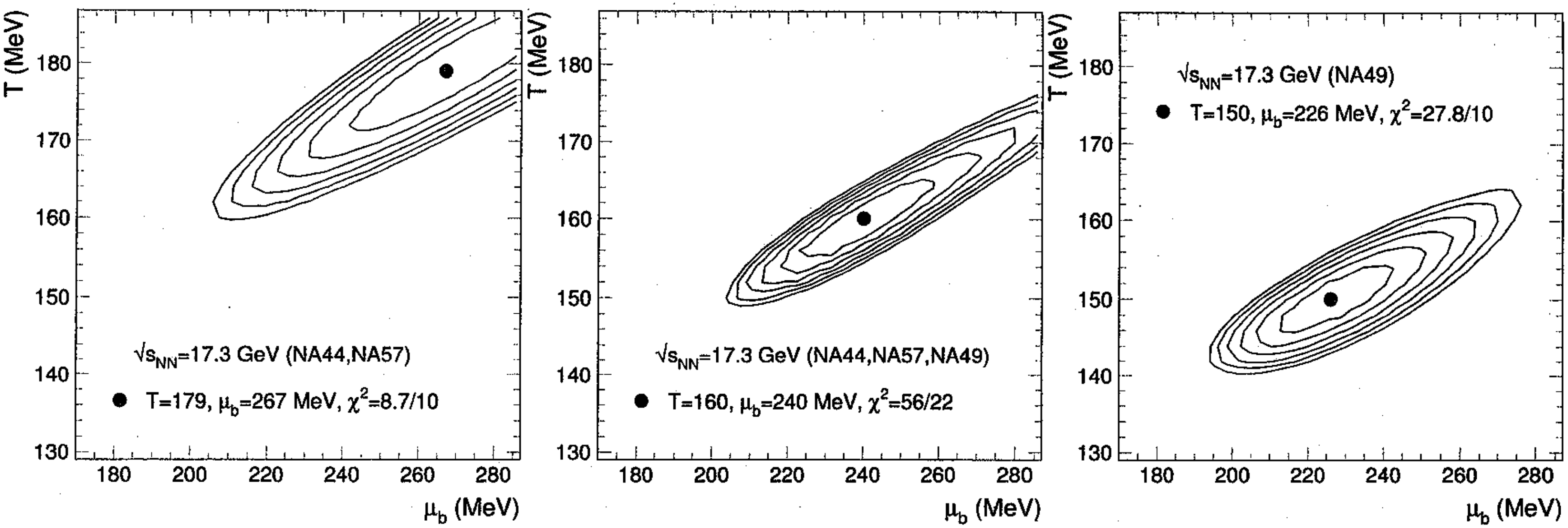
not included in the fit: K^-/π^-, d/p

SPS, 158 AGeV



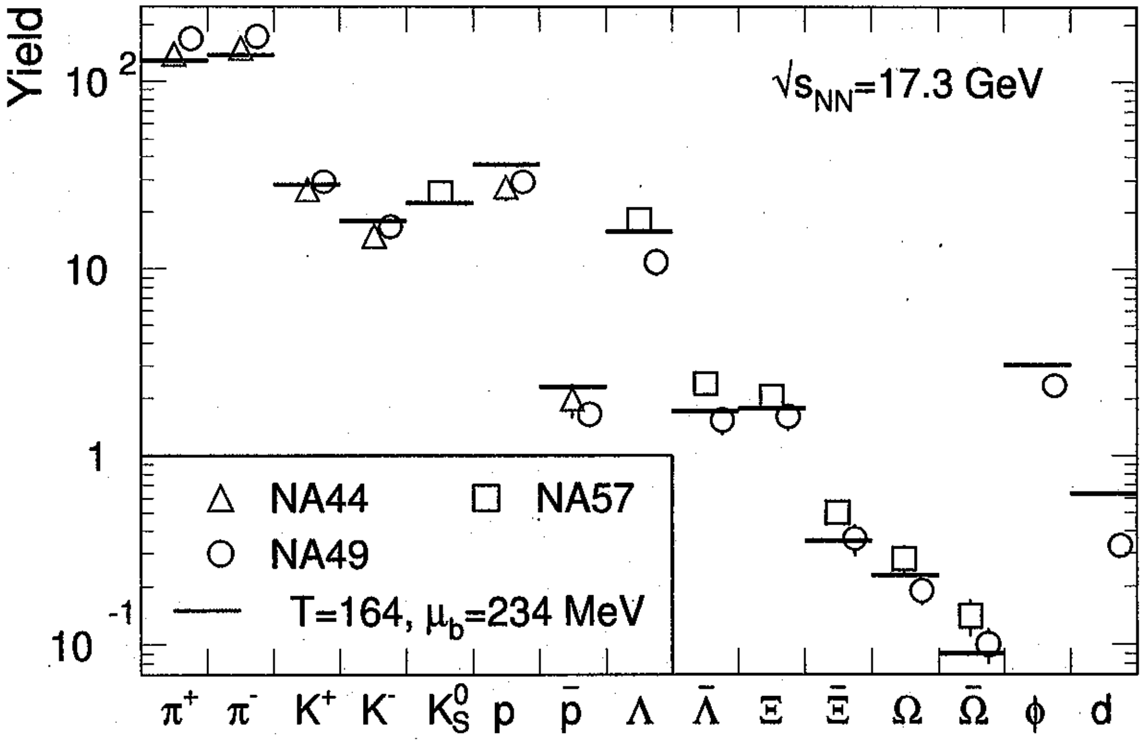
not included in the fit: K^-/π^-, Ξ/π^-, Ω/π^-, d/p

SPS, 158 AGeV



data set	T (MeV)	μ_b (MeV)	χ^2/N_{df}	T (MeV)	μ_b (MeV)	δ^2
NA44+NA57	179±7.5	267±26	8.7/10	174	243	0.15
NA49	150±4.5	226±15	27.8/10	168	240	0.66
combined	160±5	240±18	56/22	172	243	0.86

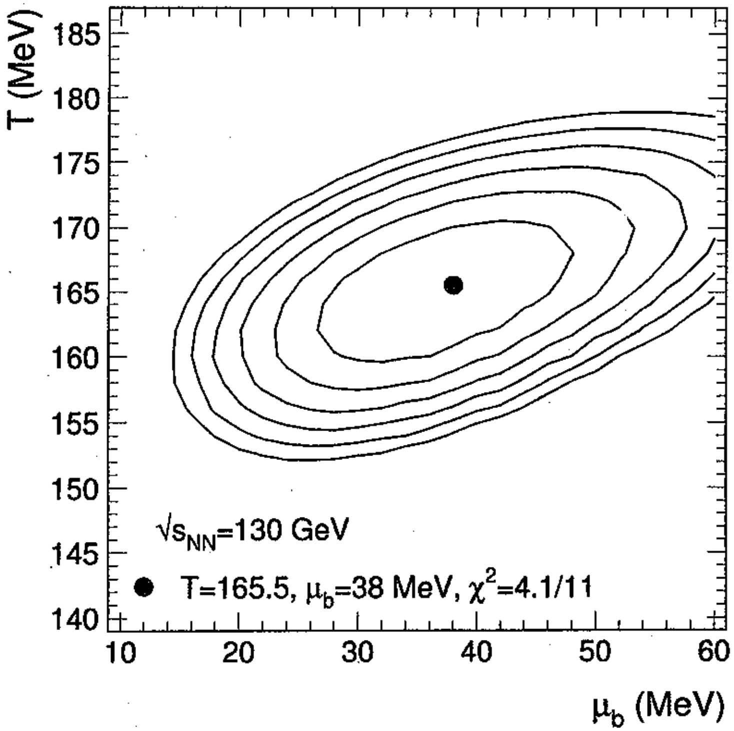
SPS: fits of yields

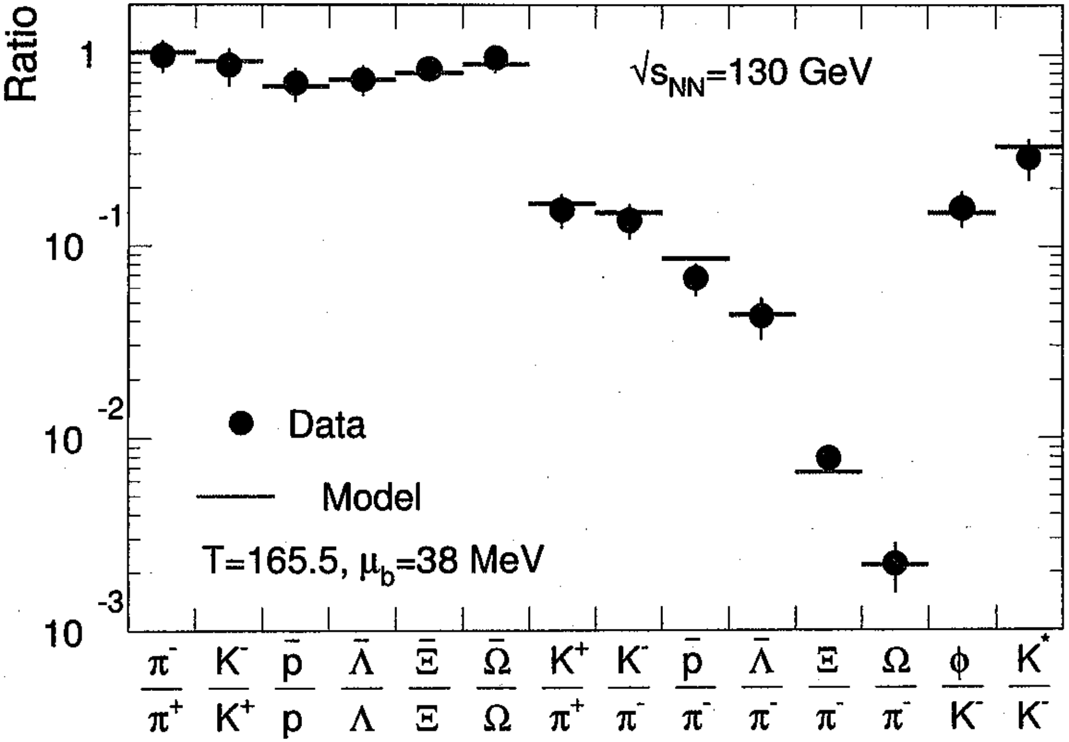


χ^2/N_{df}=105/23, V=1000 fm^3 (no d)

NA44+NA57: T=174, μ_b=240 MeV, V=750 fm^3, χ^2/N_{df}=24.2/10
NA49: T=158, μ_b=231 MeV, V=1250 fm^3, χ^2/N_{df}=56.2/10

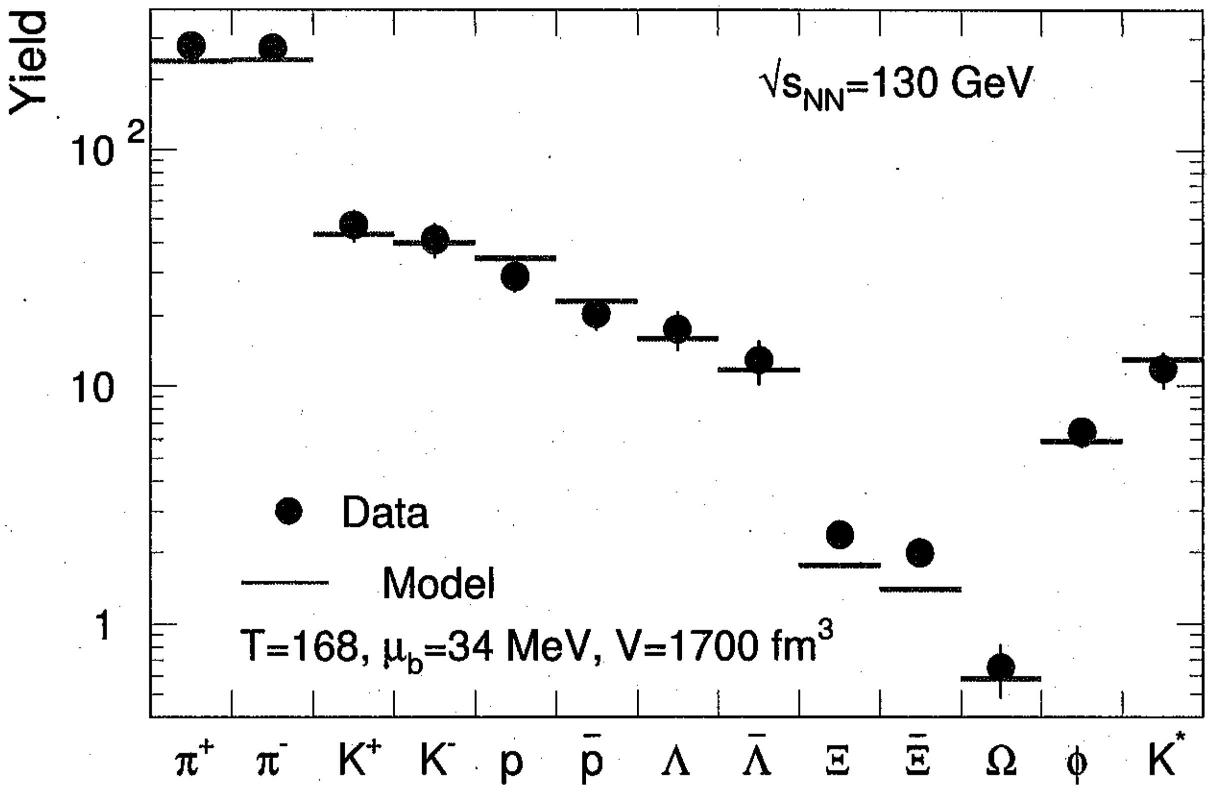
RHIC, 130 GeV





experimental pion yields not corrected for feed-down!
we assumed 30% contribution

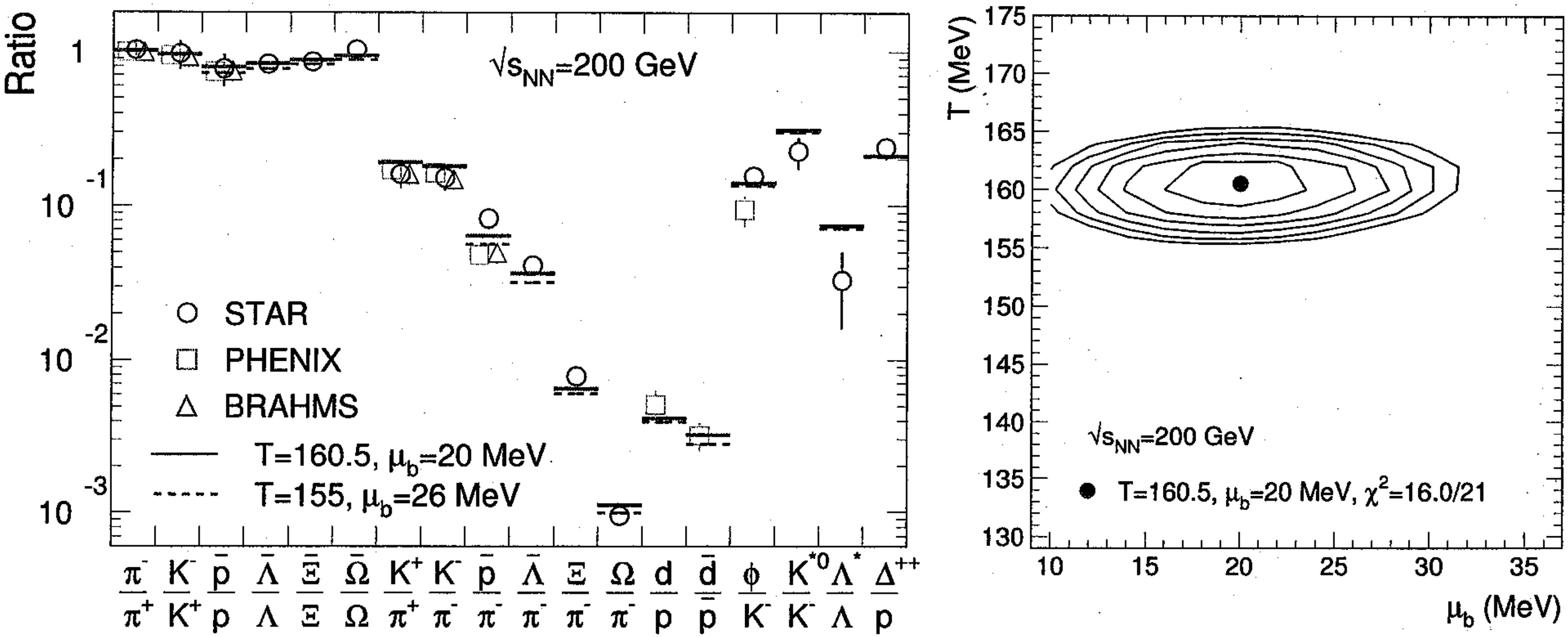
RHIC 130: fits of yields



$$\chi^2/N_{df}=15.3/10$$

<u>No Ξ's:</u> T=160, μ_b=32 MeV, V=2200 fm^3, χ^2=4.3/8 (less bias in ratios)

RHIC, 200 GeV

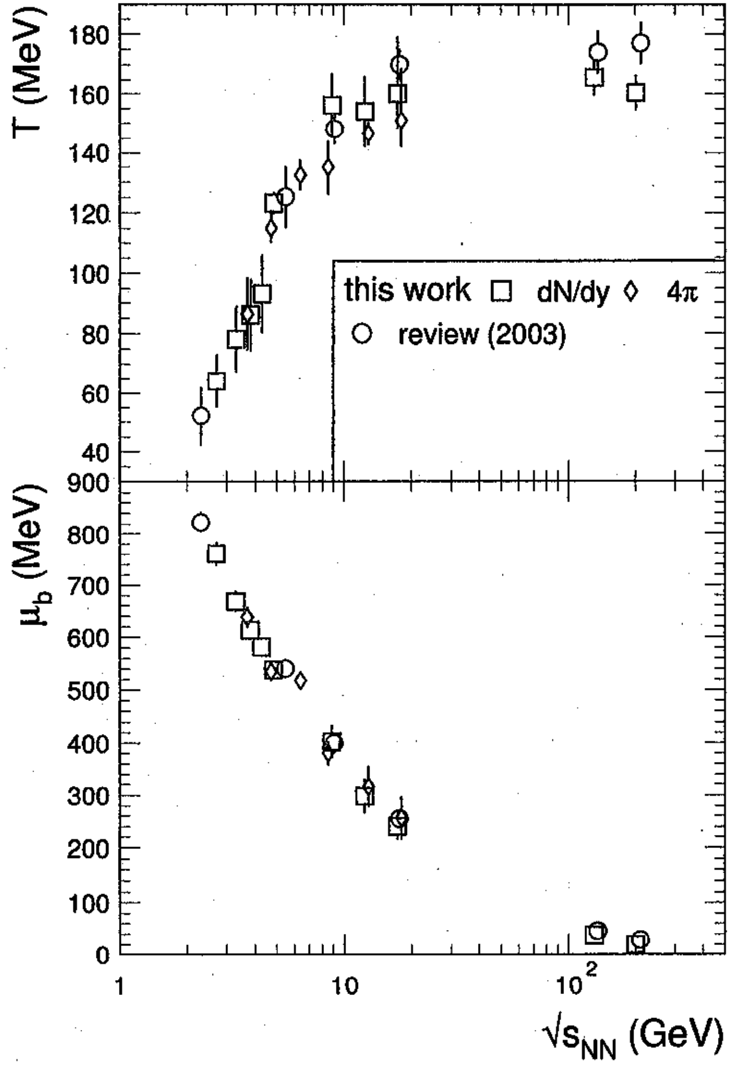


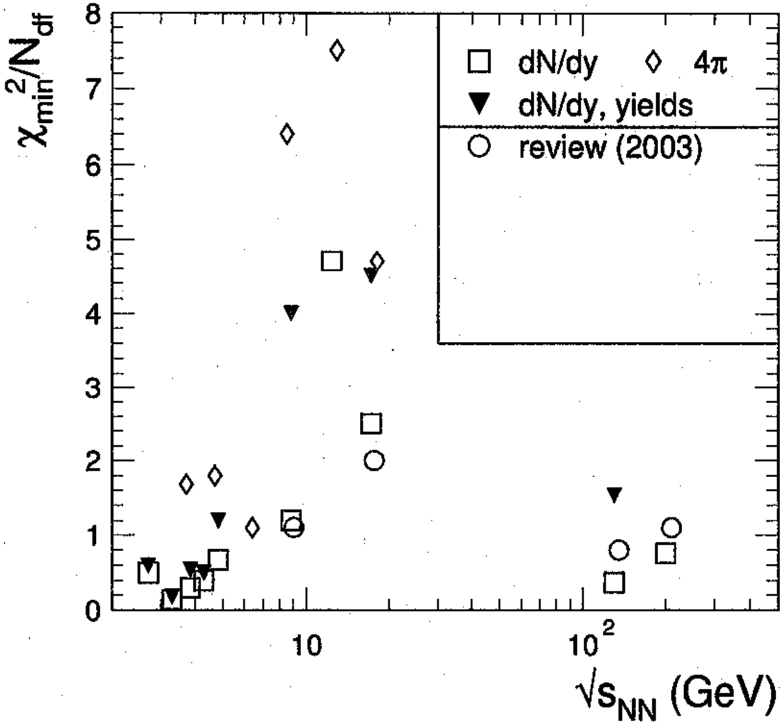
i) all data (no K^*/K^-, Λ^*/Λ, and Δ^{++}/p): $T = 155 \pm 2$ MeV, $\mu_b = 26 \pm 5$ MeV, $\chi^2/N_{df} = 34.1/23$

(with resonances: $T = 155 \pm 2$ MeV, $\mu_b = 25 \pm 5$ MeV, $\chi^2/N_{df} = 41.8/26$)

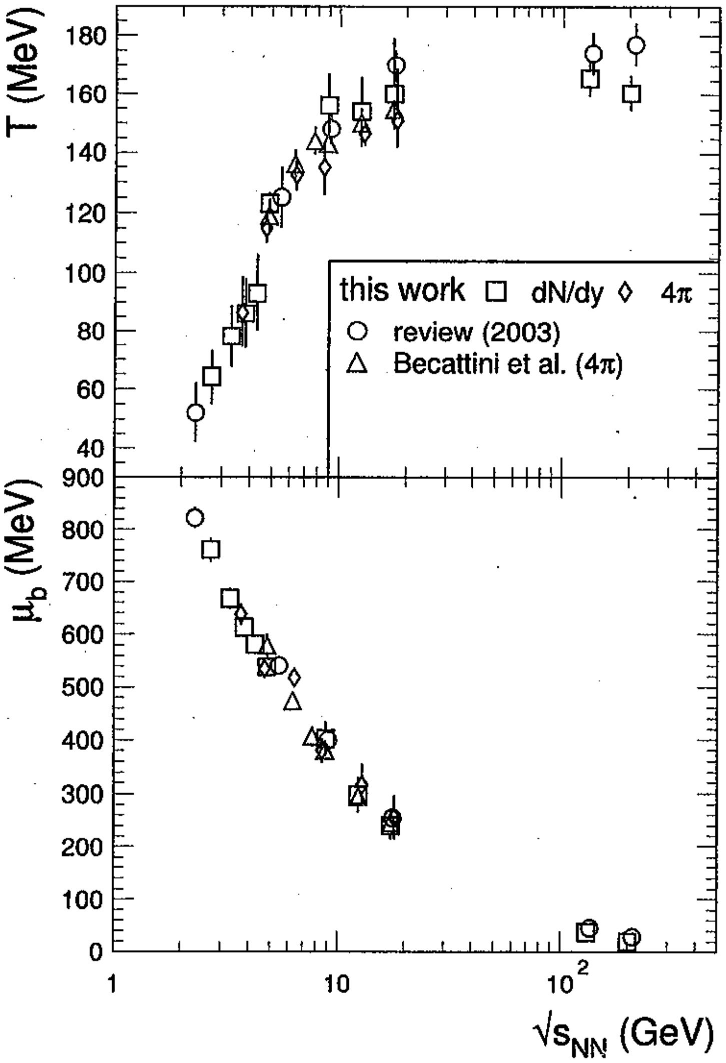
ii) excluding $\bar{p}/\pi^-$ and ϕ/K^- from PHENIX: $T = 160.5 \pm 2$ MeV, $\mu_b = 20 \pm 4$ MeV, χ^2/N_{df}=16.0/21

Energy dependence of the thermal parameters

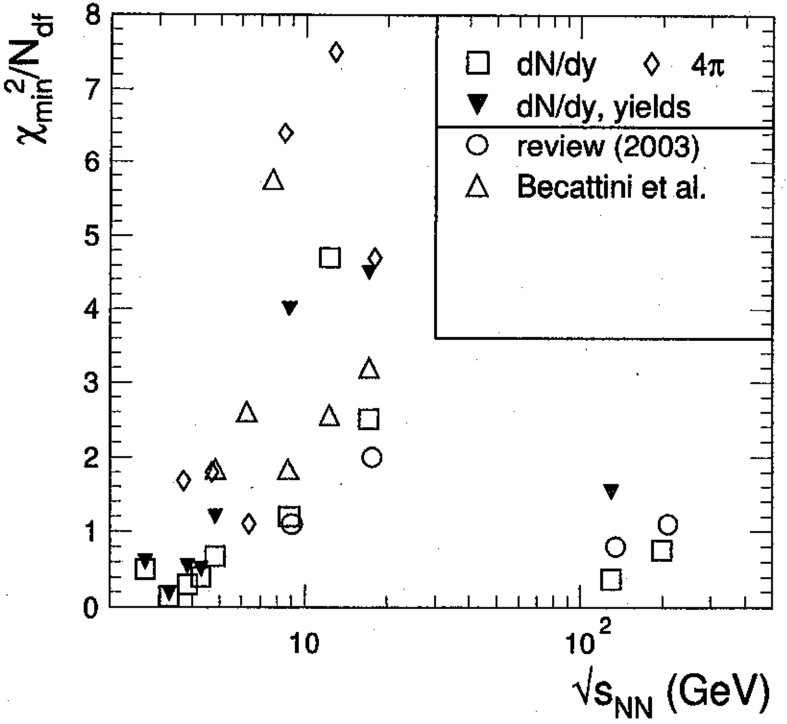




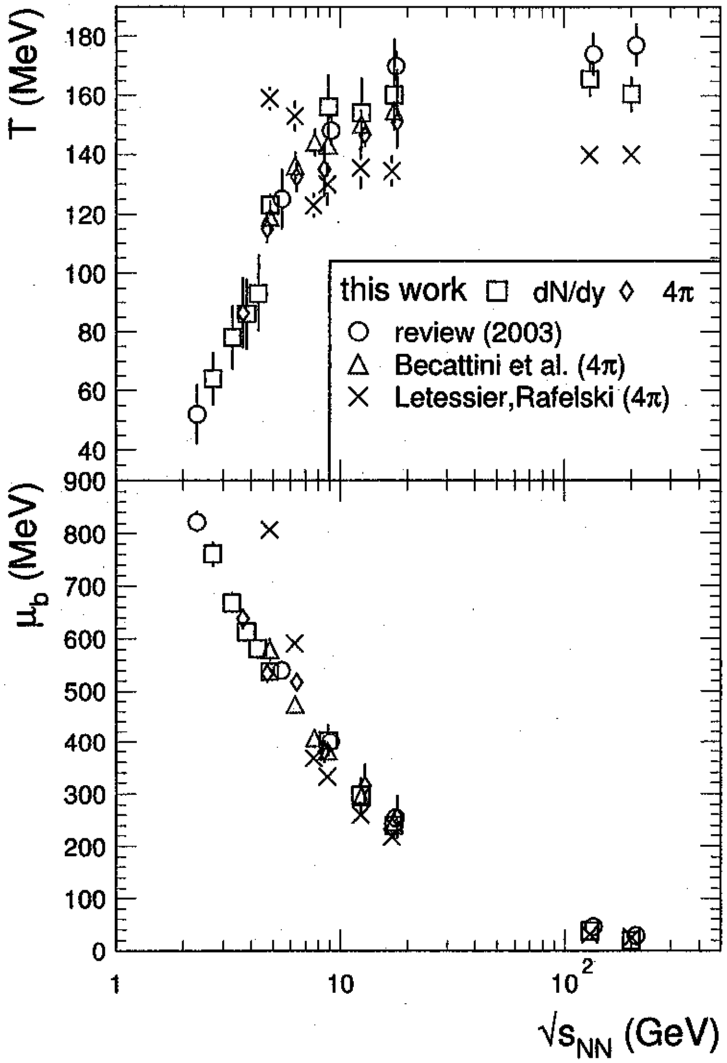
Energy dependence of the thermal parameters



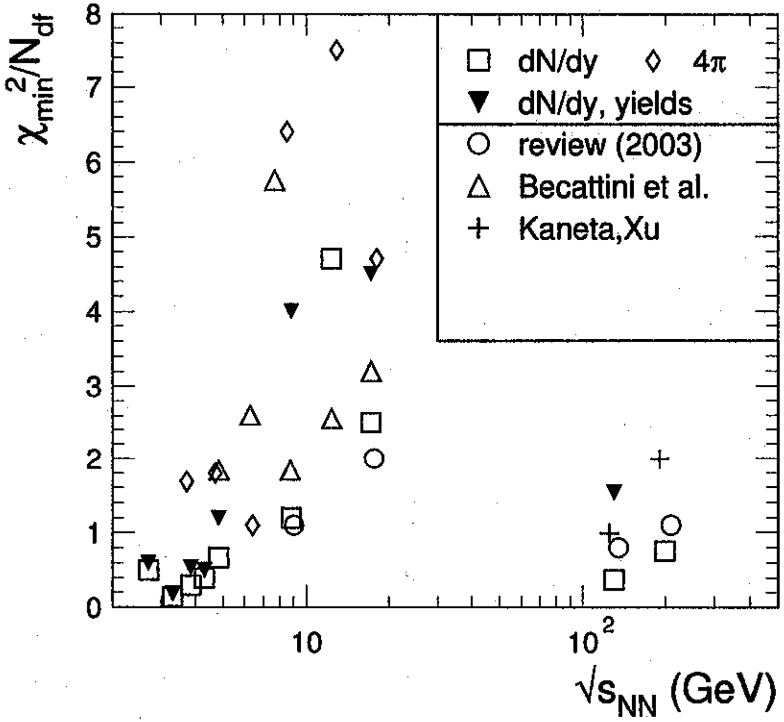
- Becattini et al.: $+\gamma_S$ (V) - hep-ph/0511092



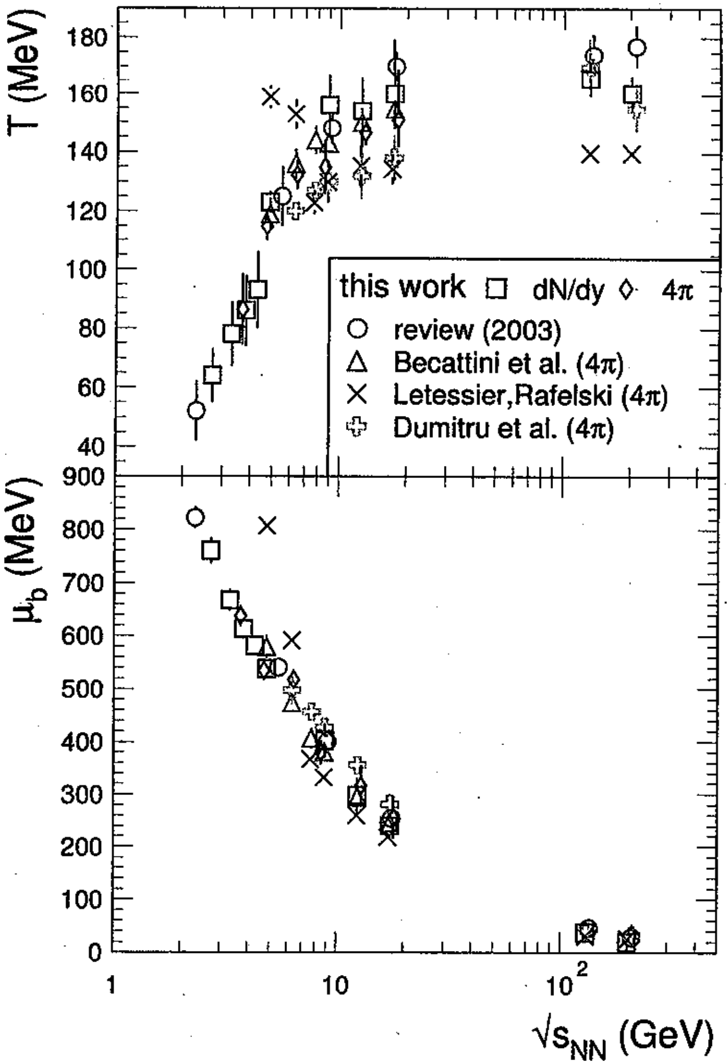
Energy dependence of the thermal parameters



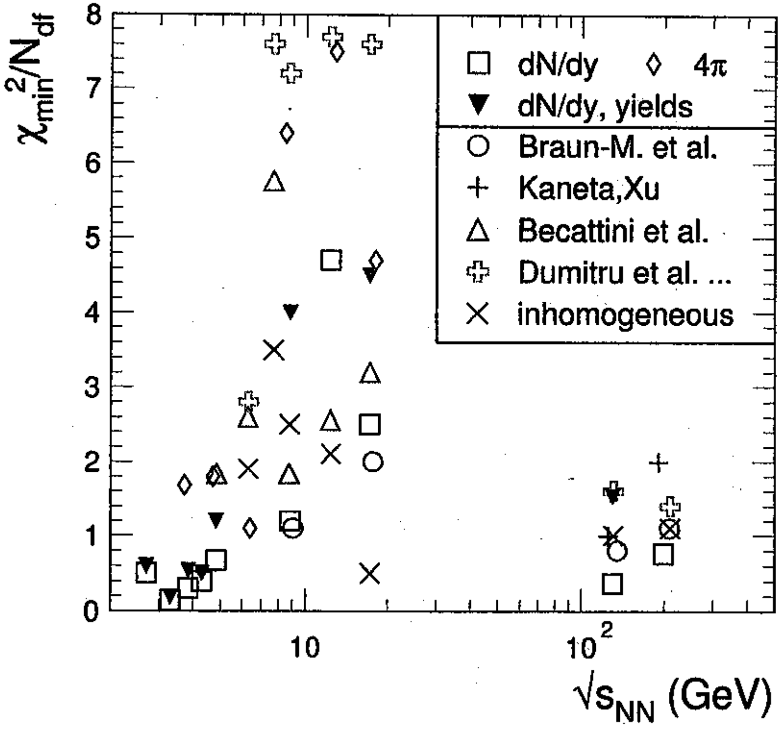
- Becattini et al.: $+\gamma_S$ (V) - hep-ph/0511092
- Rafelski et al.: T, V, $\gamma_{S,q}$, λ_{q,S,I_3} - nucl-th/0504028
  γ_S=0.18,0.36,1.72,1.64,...
  γ_q=0.33,0.48,1.74,1.49,1.39,1.47...



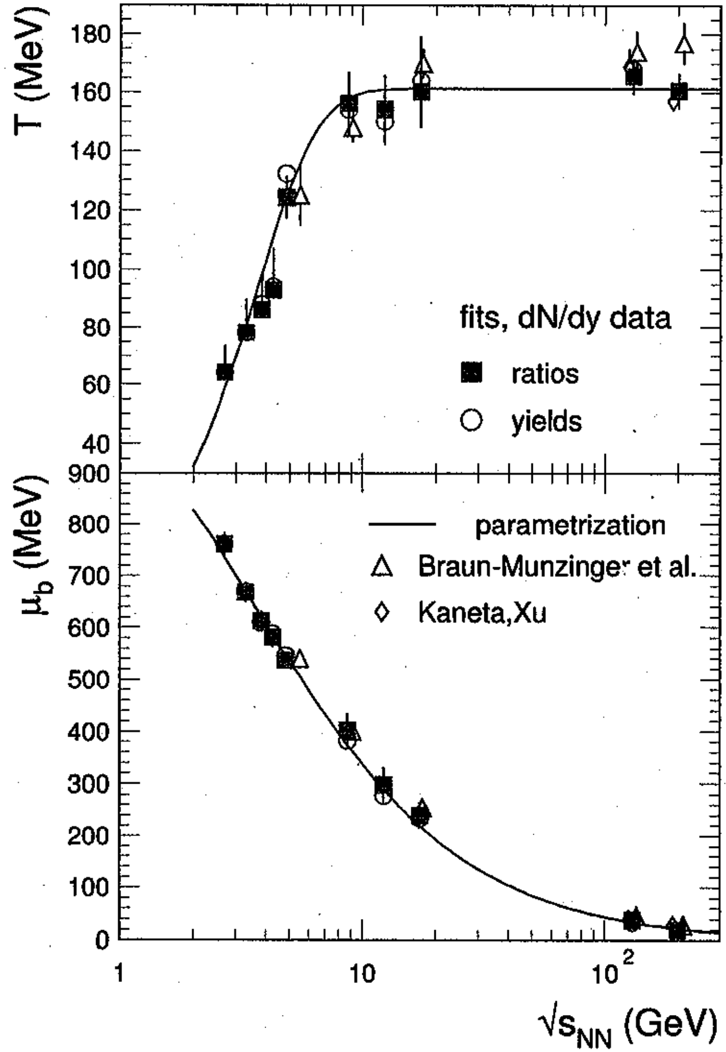
Energy dependence of the thermal parameters



- Becattini et al.: $+\gamma_S$ (V) - hep-ph/0511092
- Rafelski et al.: T, V, $\gamma_{S,q}$, λ_{q,S,I_3} - nucl-th/0504028
  γ_S=0.18,0.36,1.72,1.64,...
  γ_q=0.33,0.48,1.74,1.49,1.39,1.47...
- Dumitru et al.: inhom. (δT, $\delta \mu_B$) - nucl-th/0511084



Energy dependence of (T, μ_b)+ parametrizations



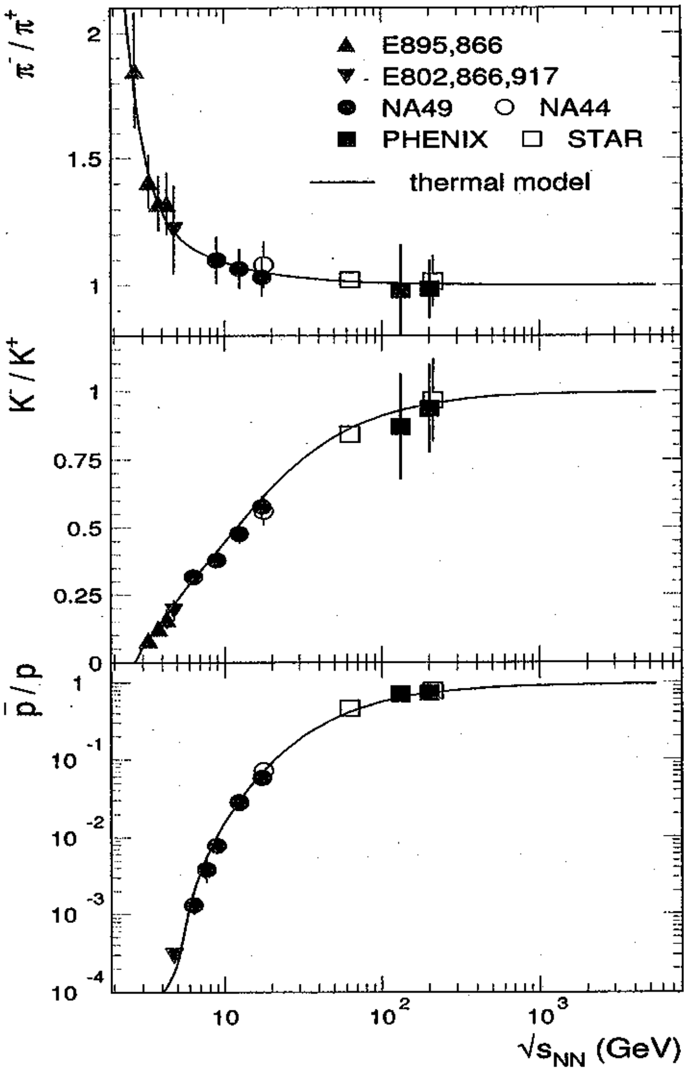
$$T[\mathrm{MeV}] = T_{lim}\left(1 - \frac{1}{0.7 + (\exp(\sqrt{s_{NN}}(\mathrm{GeV})) - 2.9)/1.5}\right)$$

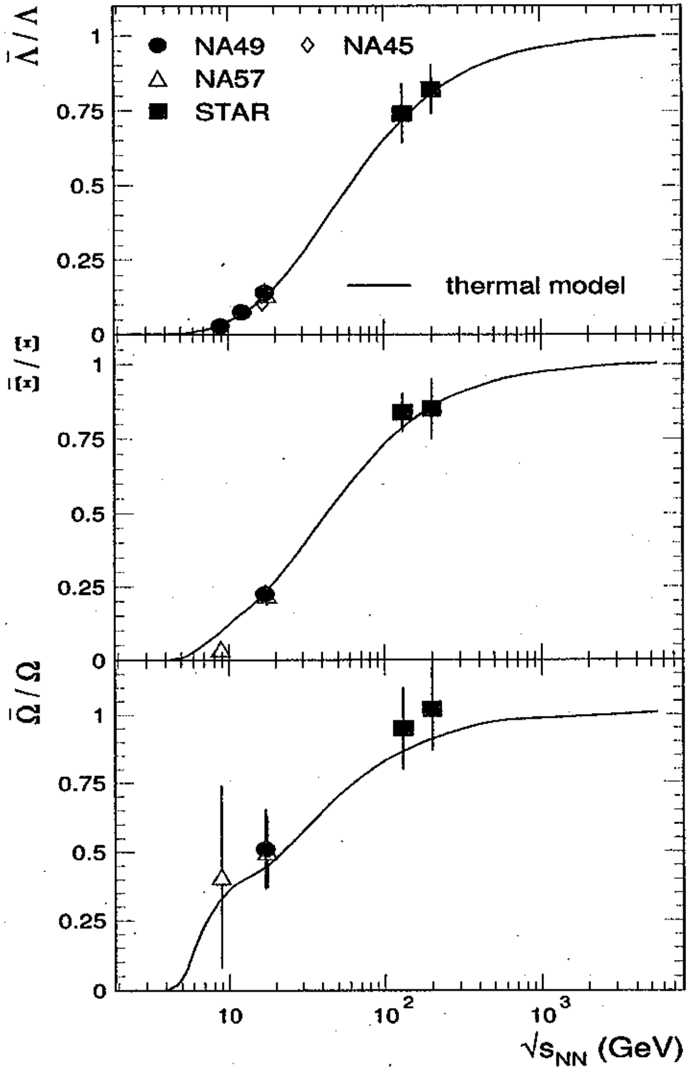
$T_{lim} = 161 \pm 4$ MeV (χ^2/N_{df}=0.3/3)

$$\mu_b[\mathrm{MeV}] = \frac{a}{1 + b\sqrt{s_{NN}}(\mathrm{GeV})}$$

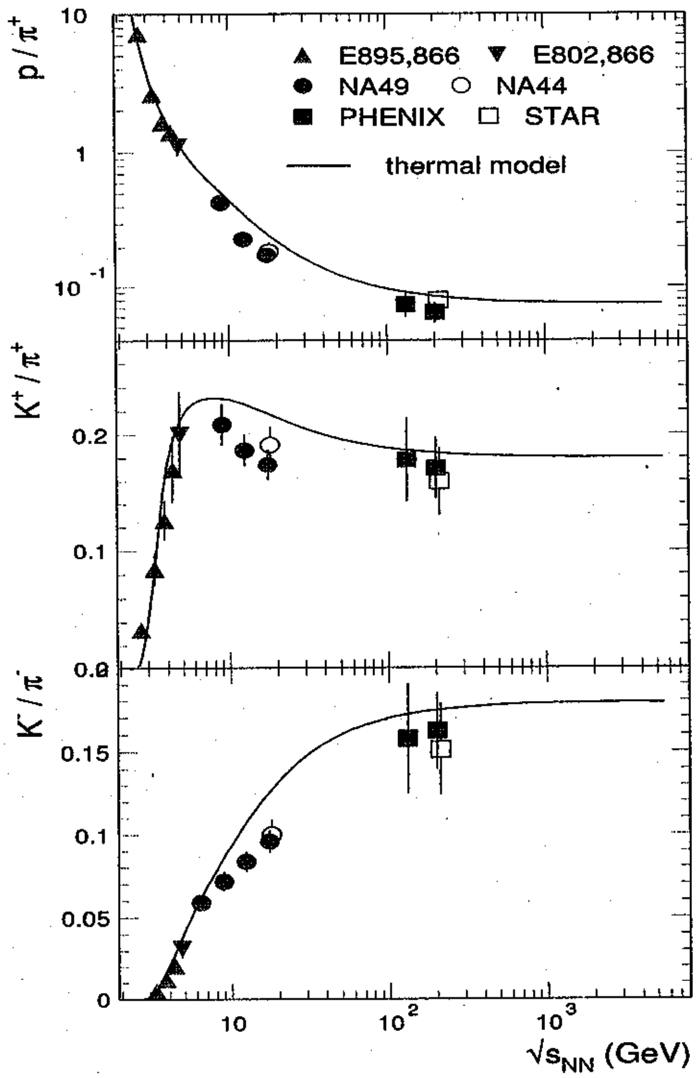
$a = 1303 \pm 120$ MeV, $b = 0.286 \pm 0.049$ GeV^{-1} (χ^2/N_{df}=0.5/8)

Antiparticle/particle ratios



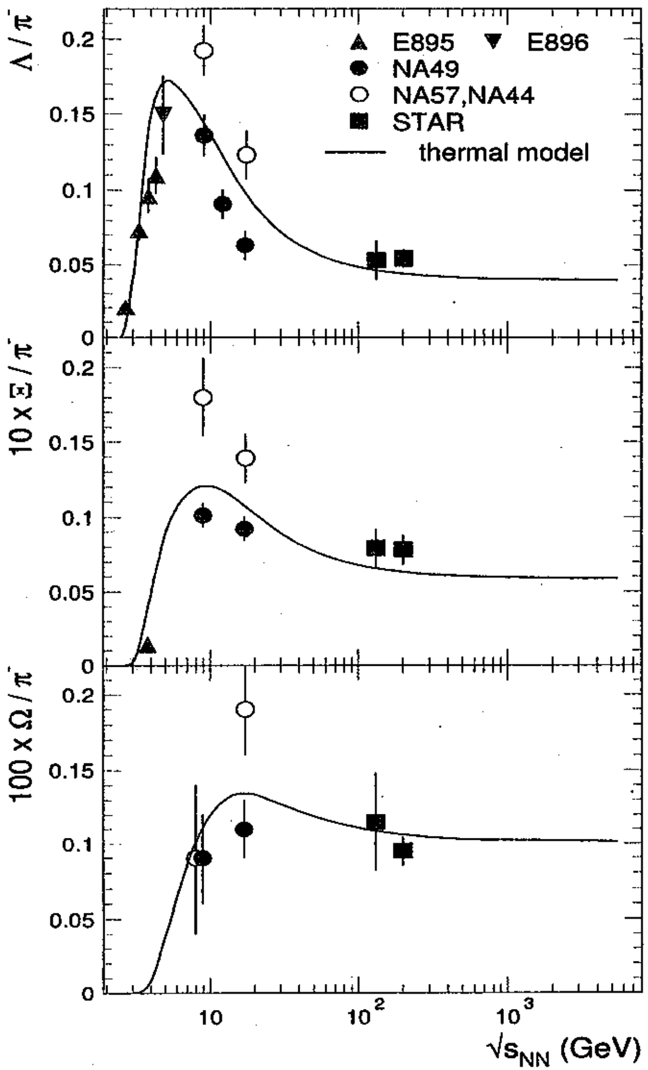


Ratios to pions



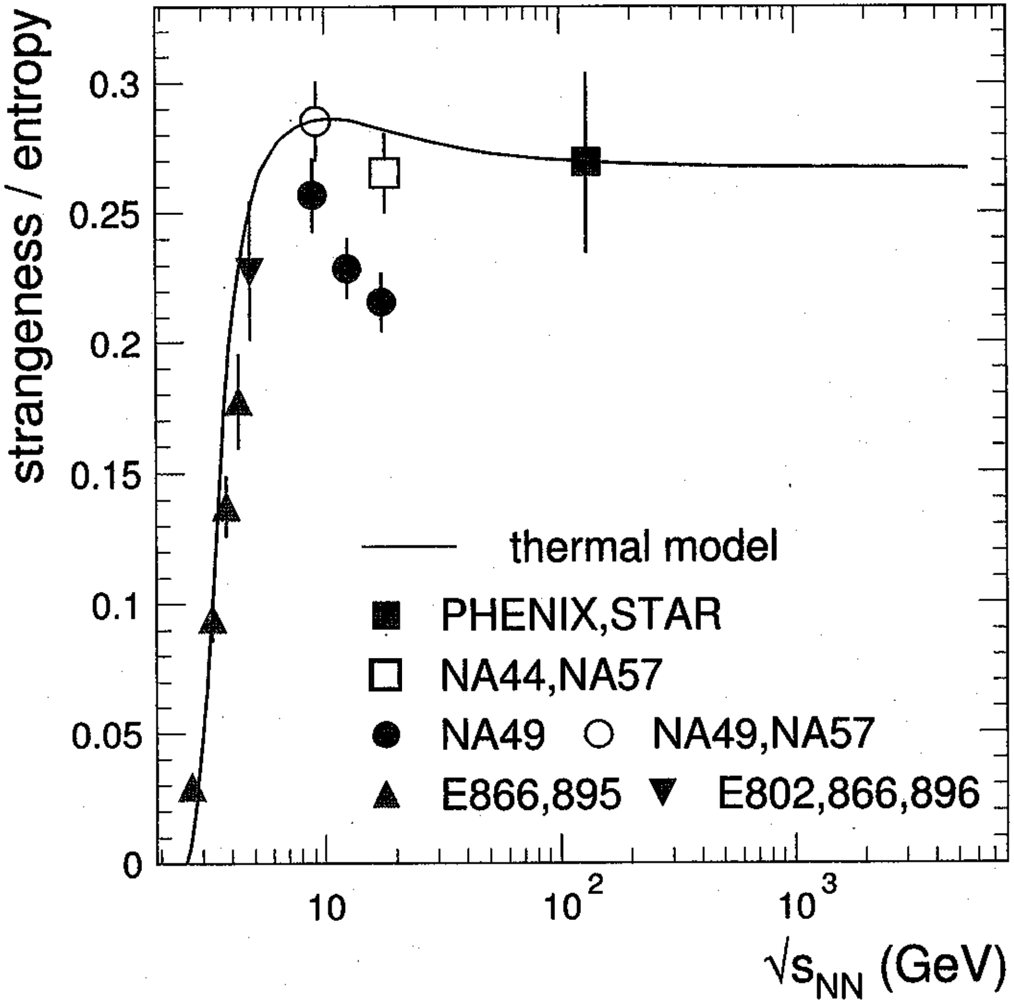
- main features reproduced
- ... including the "horn" (broader in the model)
- disagreement at higher SPS en. (both K^+/π^+ and K^+/π^+)

Hyperon ratios to pions



- main features reproduced
- discrepancies in the data
- ...model is in between
  (”by construction”, fits of all data)
- ”hierarchy” of maxima
  (determined by T and μ_b)

A global ratio: strangeness/entropy



"strangeness":

$2 \times (K^+ + K^-) + 1.54 \times (\Lambda + \bar{\Lambda})$

"entropy":

$1.5 \times (\pi^+ + \pi^-) + 2 \times \bar{p}$

anything beyond thermal?

hard to argue...

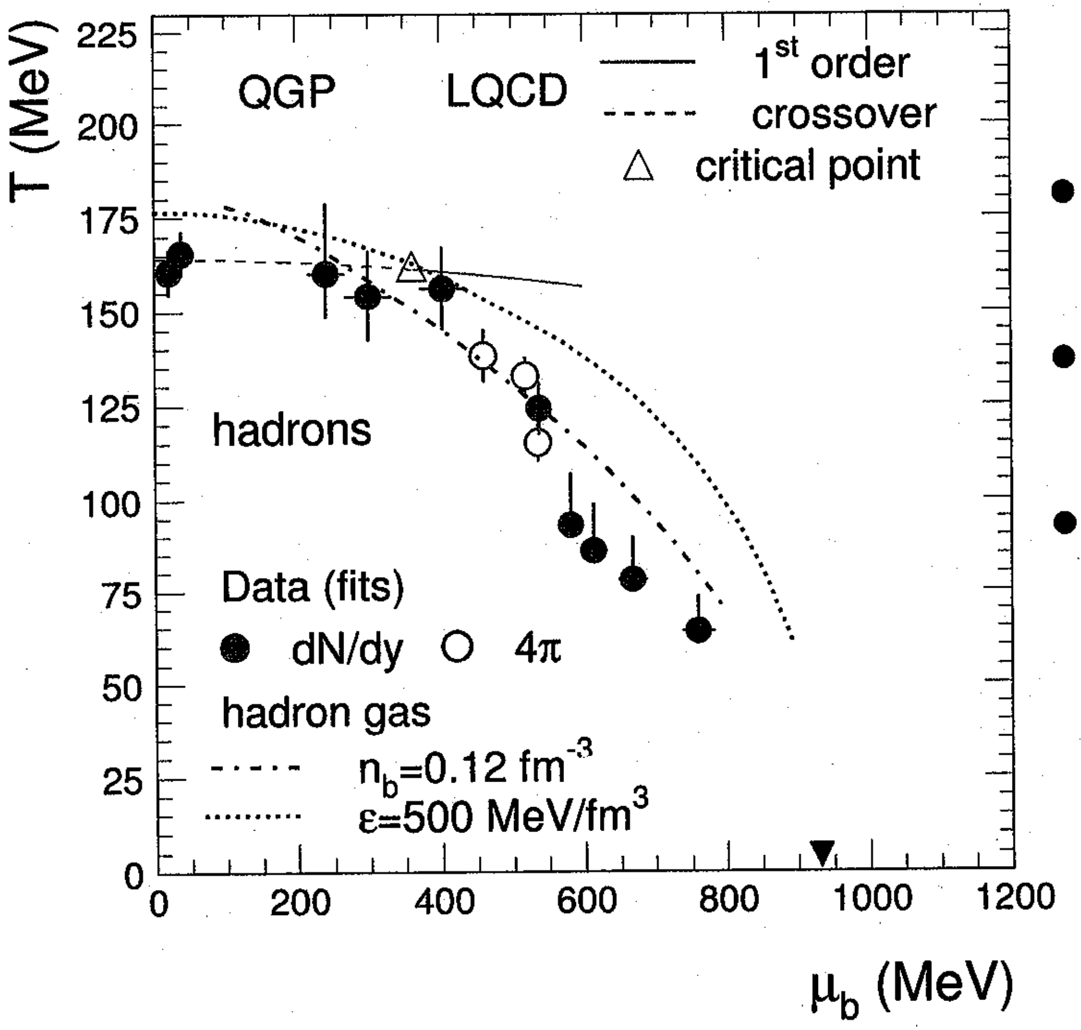
Predictions for LHC

... based on the extrapolation of parametrized T, μ_b

π^-/π^+	K^-/K^+	$\bar{p}/p$	$\bar{\Lambda}/\Lambda$	$\bar{\Xi}/\Xi$	$\bar{\Omega}/\Omega$
1.00	0.99	0.95	1.00	1.00	1.00

p/π^+	K^+/π^+	K^-/π^-	Λ/π^-	Ξ^-/π^-	Ω^-/π^-
0.074	0.180	0.179	0.039	0.0058	0.0010

The phase diagram of QCD



- the only way to put points on the diagram
- phase boundary reached at low SPS energies
- ...in the vicinity of the CP Fodor,Katz,hep-lat/0402006 *(not the final word on it)*

→ effect on thermal fits?

Summary

- limiting temperature ⇒ phase boundary (LQCD)
  → there are skeptics though... *LHC case will be decisive*
- indications (bad fits) for the critical point?
  → case weakened by discrepancies in the data

indications for strangeness non-equilibrium (γ_S) in central collisions?
our results: clearly not (others: not at SIS, RHIC, some yes at AGS-SPS)

are resonances (K^*, Λ^*) different? case rather weak (only Λ^* at 200)

Strangeness: where to go?

...besides "little" clarifications (Ξ's at 130, ϕ at 200...) and final data at 200...

SPS energies - not only resolve discrepancies, but strengthen case for CP (?)

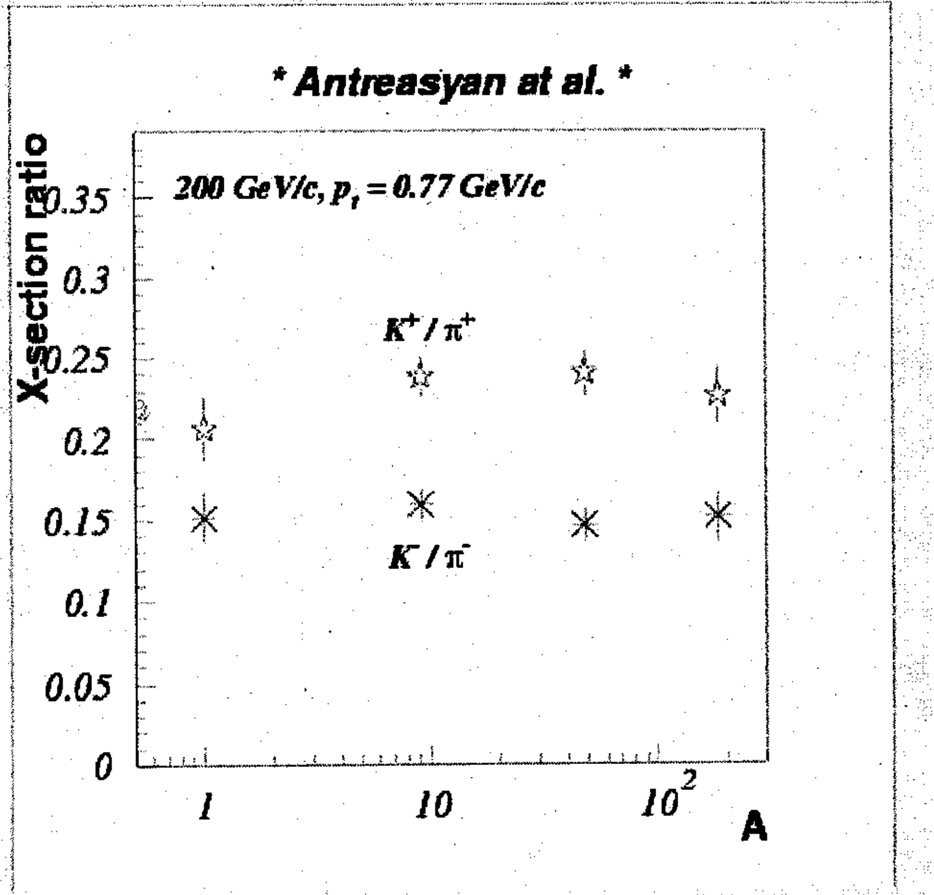
From pp to pA (and to heavy ions)

Karel Šafařík, CERN, Geneva, Switzerland
Karel.Safarik@cern.ch

In this talk, the importance to study both pp and pA collisions is addressed. On few examples it is shown how in the past the reference data from pp and pA interactions allowed for discovering new effects in AA collisions. pA collisions were studied in details in 80s. When the particle yields are parameterized as A^{α}, the fits are always slightly above the pp experimental results. This effect may be attributed to neglecting the neutron content of nuclear targets or to rescattering inside nuclei. Also the K/π ratio is slightly higher in pA than in pp, however, independent on A. Recent reports about steady increase of strangeness enhancement in pA and AA are based on different definition of enhancement factor. This new definition calculates the enhancement under assumption that the increase in production happens only in beam fragmentation hemisphere and put this factor only for that part of the event. This way the enhancement factor for pA became numerically larger and A-dependent. Further we discussed the pp and dA data from RHIC, showing examples where they were useful standalone, not only as a reference. At the end the possibility to collide pA at LHC is discussed, and the necessity to study pp interactions in ALICE detector both, for comparison with AA, and for genuine pp physics, is argued. Example of study of baryon-number transfer in large rapidity gap is given.

A-dependence (3/3)

- **K/π ratio in central region in pp and pA**

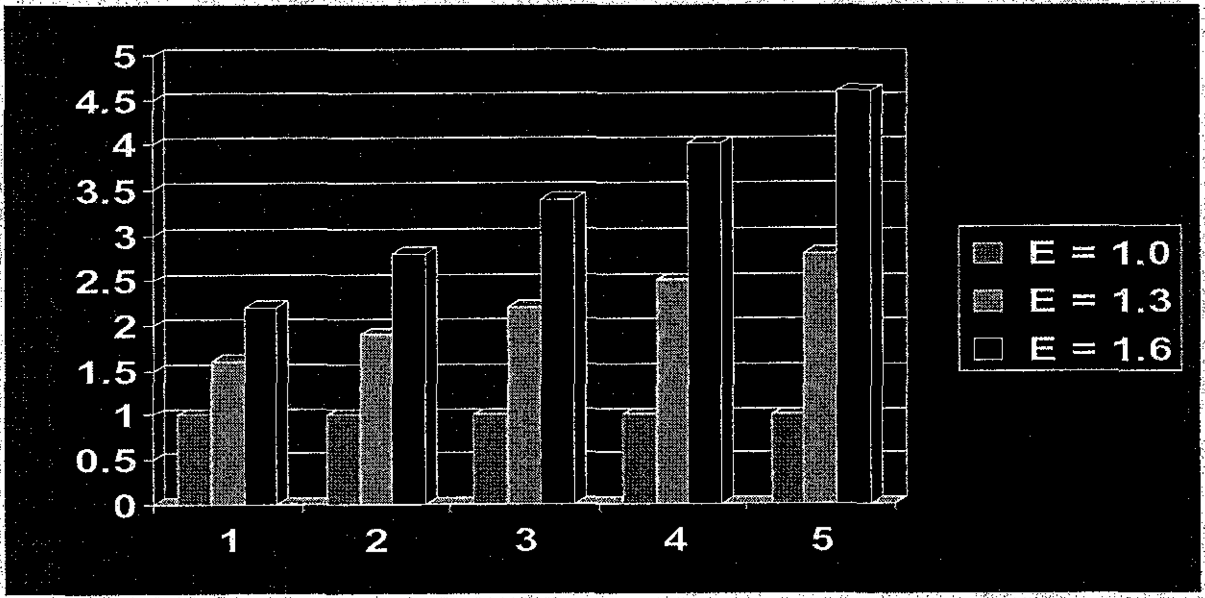


Strangeness Enhancement pp → pA

- If we blame strangeness enhancement on some part of the pA event, the enhancement factor (F) has to be larger than if we assume enhancement for all event (E)

$$F = E + (E - 1) \times \nu$$

- and increases with ν



Comparison: ATLAS and CMS

- p_t cut-off
  - Magnetic field (but this could be lowered)

	Magnetic field (T)
ALICE	0.2 – 0.4
ATLAS	2.0
CMS	4.0

  - Material thickness (hard to change)

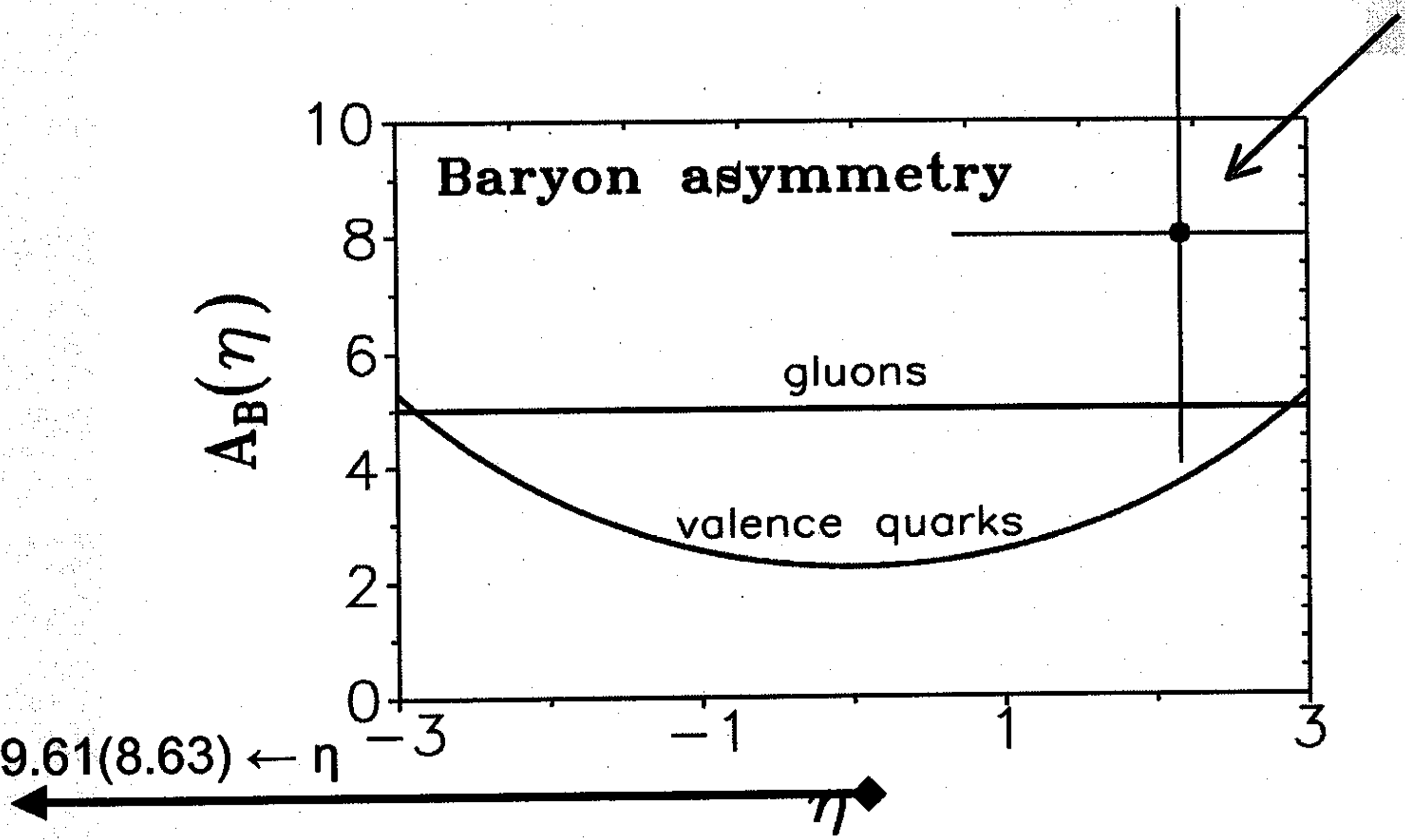
	Material thickness X/X_0 (%)	Minimal pion ($\pi^{\pm}$) momentum (MeV)	Minimal kaon ($K^{\pm}$) momentum (MeV)
ALICE	7	80	200
ATLAS	30	130	305
CMS	20	115	280

- Particle identification (TOF and HMPID)
- ATLAS and CMS have better η coverage

Central region at LHC

Asymmetry $A_B = 2 * (B - \text{anti-}B) / (B + \text{anti-}B)$

H1 (HERA)
Δη ~ 7



$-9.61(8.63) \leftarrow \eta$

(B. Kopeliovich)

Conclusions

- ALICE detector has large potential to study minimum bias pp physics which will dominate at the initial LHC stage
- Minimum bias pp physics is important for both
  - its intrinsic interest
  - reference for comparison with p-A and A-A collisions
- Complete ALICE detector has considerable advantages compared to other LHC detectors at low luminosity stage
  - low momentum threshold
  - good momentum and angle resolution
  - unique particle identification capability
- ALICE should not miss this opportunity and should be ready right at LHC start-up

Strangeness in Collisions Workshop

"Strangeness in p+p: Data vs Models"

Mark T. Heinz, Yale University

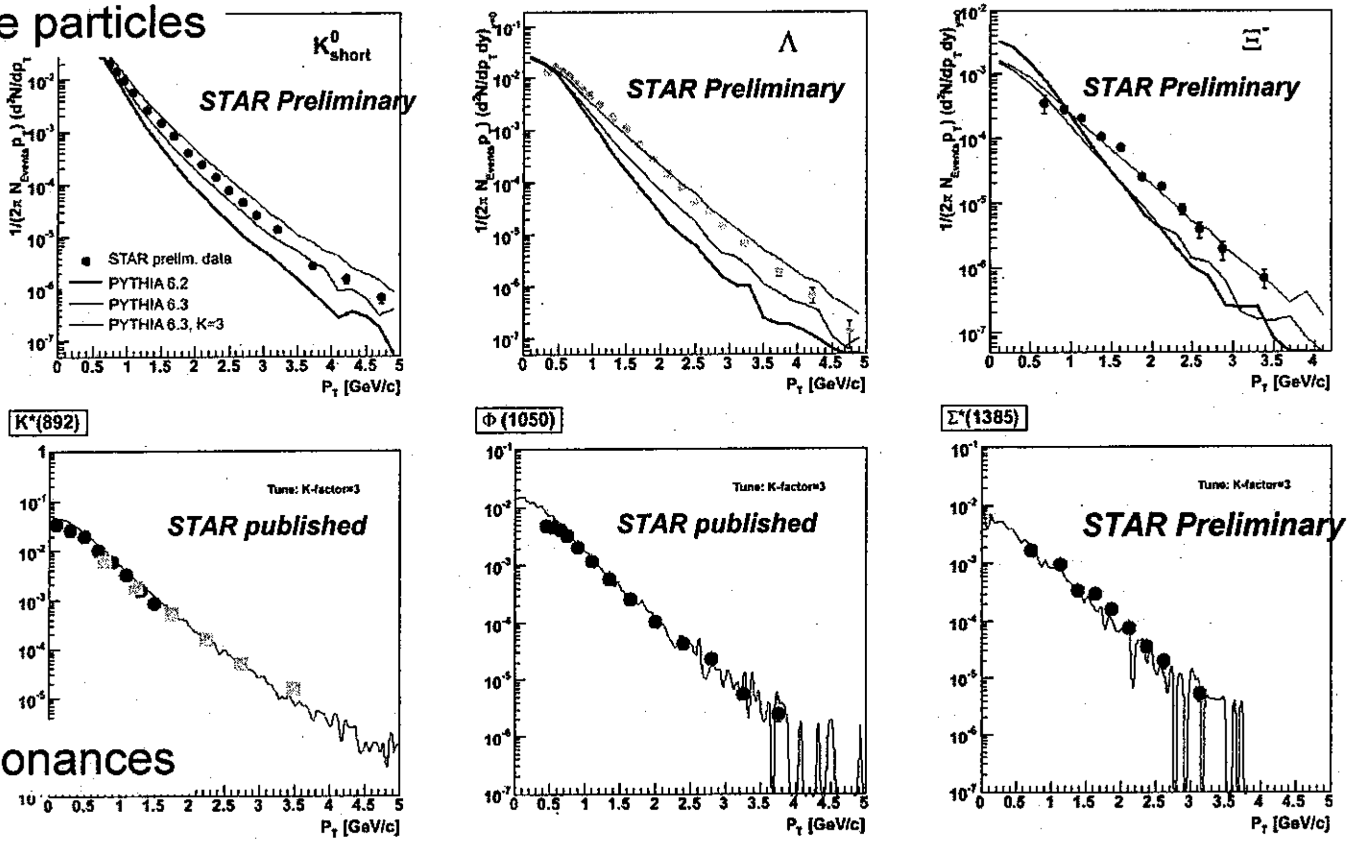
Summary

- New version of the PYTHIA model (6.3) describes strange particle and resonance data well when a K-factor of 3 is used. For mesons no K-factor is required.
- Increase in $<p_T>$ with N_{ch} due to mini-jets & multiple scattering is succesfully modeled in PYTHIA 6.3 with K-factor 3.
- Further statistics needed to see drop of anti-baryon/baryon ratio vs p_T as predicted from quark vs gluon jet phenomenology
  - Baryon/meson "anomalie" is not reproduced in pQCD models
- m_T scaling also shows interesting baryon vs meson differences at intermediate p_T
- AKK (Albino,Kniehl,Kramer) NLO calculations using constrained fragmentation functions reproduce STAR and UA1 strangeness data nicely
- EPOS does a good job compared to our p+p d+Au data.
- Statistical models (THERMUS) can describe our particle yields in p+p collisions with T~177 MeV

p_T-spectra comparison

- First comparisons with PYTHIA version 6.2 (2004)
- Version 6.3 (January 2005): New multiple scattering algorithm
- Tune K-Factor: accounts for NLO processes in hard cross-section

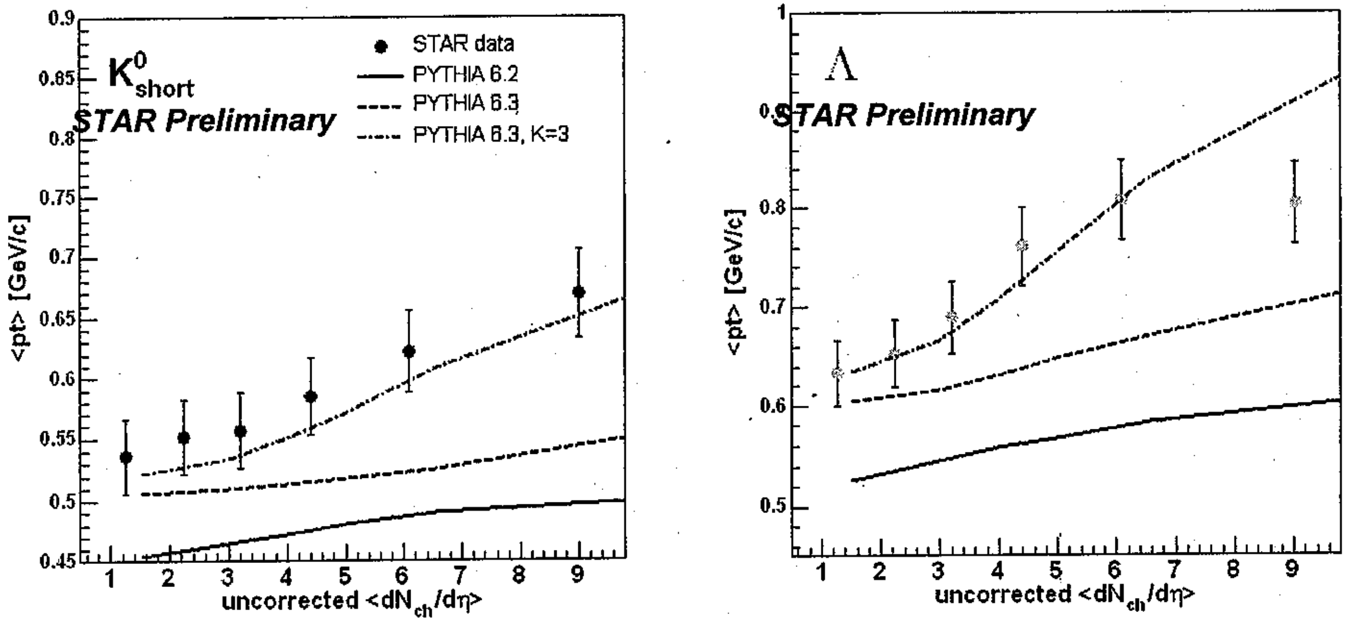
Stable particles



Resonances

PYTHIA $<p_T>$ vs N_{ch}

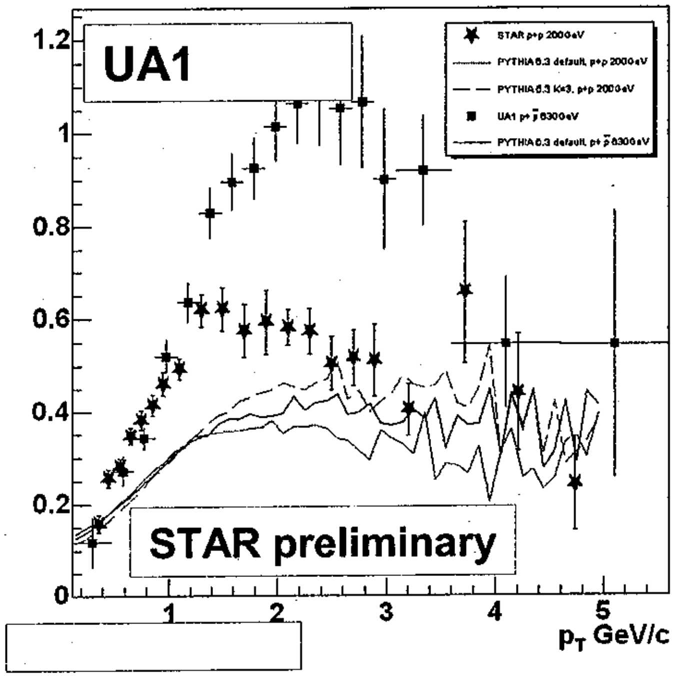
- More sensitive observable to implementation of multiple scattering algorithm -> mini-jets.
- K-factor is required to account for increase of $<p_T>$ with charged multiplicity



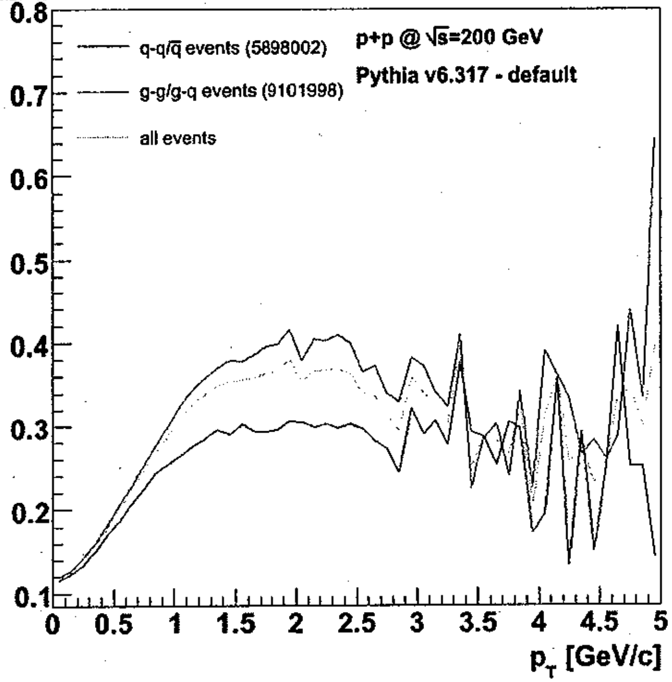
Baryon-meson "anomalies"

- Baryon production is interesting at intermediate p_T
- Strange baryon/meson ratio is under-predicted by PYTHIA at 200 and 630 GeV

$\Lambda+\bar{\Lambda}/2*K^0_{short}$ (no feeddown corrections)

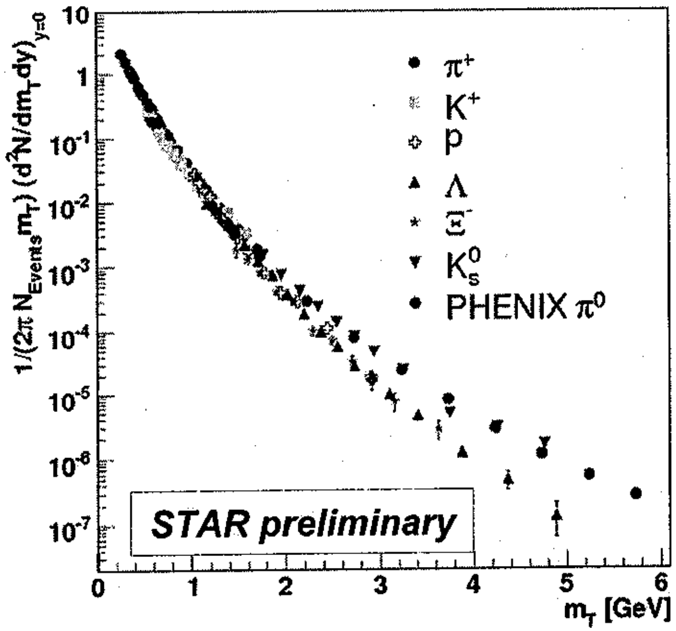


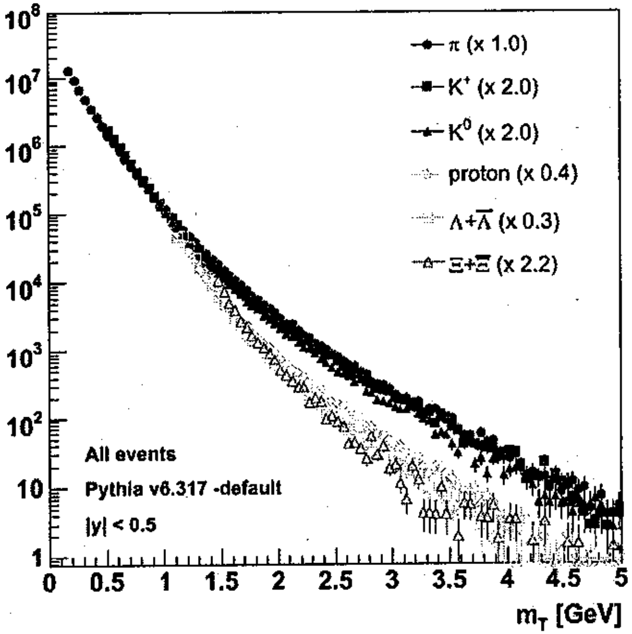
PYTHIA 6.3



m_T - scaling

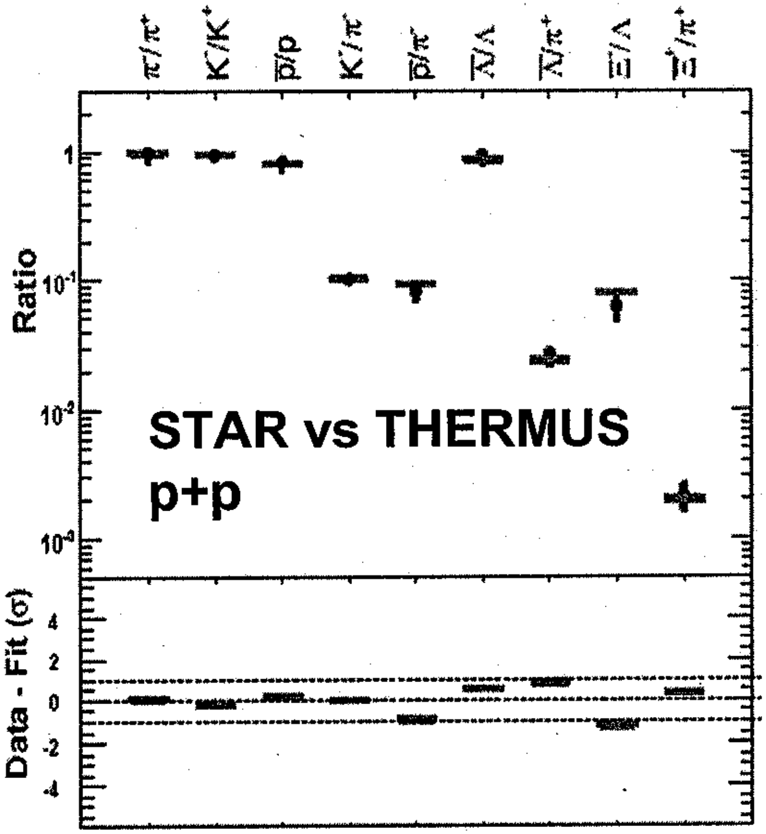
- m_T-scaling first studied with ISR data.
- In the Color Glass Condensate (CGC) picture m_T-scaling would be indicative of evidence of gluon saturation.
- No absolute scaling. Species are scaled with prefactors
- STAR data reveals an interesting feature of baryon vs meson splitting above 2 GeV in m_T
- PYTHIA reproduces shape difference between mesons and baryons





Statistical models in p+p

- Statistical models have been proposed by Becattini et al for small systems (e+e-, p+p)
- Canonical calculation
- How do we interpret the model parameter T ?
- Codes are now available publicly: SHARE, THERMUS



	Becattini UA5 p+p	STAR p+p
T (MeV)	175±15	177±9
γs	0.54±0.07	0.5 ±0.04

The Glasma

Larry Mc Lerran

Glasma

Definition:

The matter which is intermediate between the Color Glass Condensate and the Quark Gluon Plasma

It is not a glass, evolving on a natural time scale

It has components which are highly coherent,

$$A^\mu \sim 1/g$$

Components which are particle like

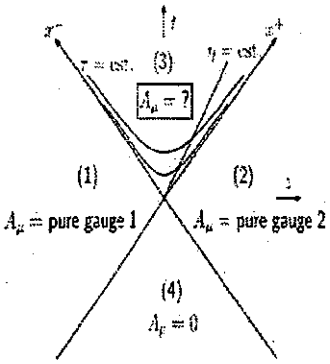
$$A^\mu \sim 1$$

Components of strength in between

$$1 \leq A^\mu \leq 1/g$$

Initially it has large longitudinal color electric and color magnetic fields, and maximal topological charge density

Bo was right!



Choose A = 0 in backward light cone.

In left and right halves, pure gauge.

Discontinuity across light cone to match color charge sources on light cone

Field is not pure gauge in forward lightcone

Physical motivation: Renormalization group description.

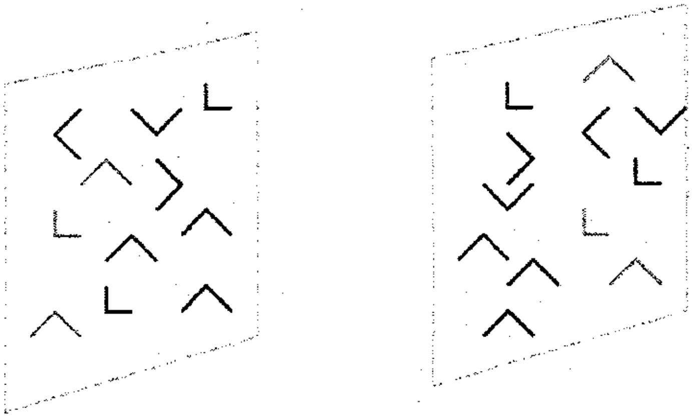
In center of mass frame, degrees of freedom with

$$y << 1/\alpha_S$$

are coherent fields.

Larger y are sources

$$\alpha_S(Q_S) << 1$$



Before the collision, two sheets of mutually transverse color electric and color magnetic fields.

Boosted Coulomb fields

Random in color

Thickness of sheets is

$$\Delta z \sim \frac{1}{Q_S} e^{-\kappa/\alpha_S}$$

Initial fields:

$$\alpha^i_{(1,2)} = \frac{1}{ig} U_{(1,2)}(x_T) \nabla^i U^\dagger_{(1,2)}(x_T)$$

In radial gauge,

$$x^+ A^- + x^- A^+ = 0$$

the fields in the forward light cone are:

$$A^\pm = \pm x^\pm \alpha(\tau, x_T)$$
$$A^i = \alpha^i_3(\tau, x_T)$$

Assume boost invariant solution

Boundary conditions are determined by solving equations across the light cone:

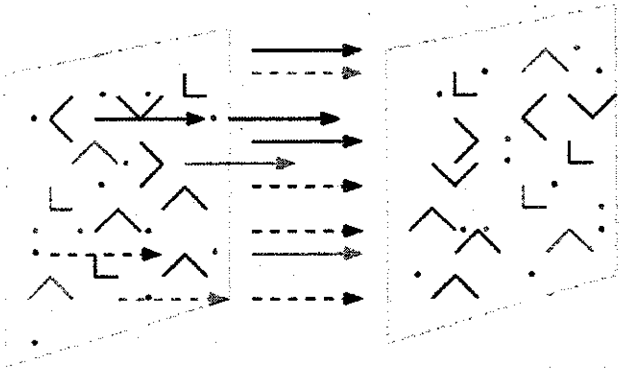
Infinitesmally after the collision there are

No transverse fields

Longitudinal magnetic and electric fields

$$E^z = ig[\alpha_1^i, \alpha_2^i]$$

$$B^z = ig\epsilon_{ij}[\alpha_1^i, \alpha_2^j]$$



These fields have a local topological charge density

Chern-Simons charge

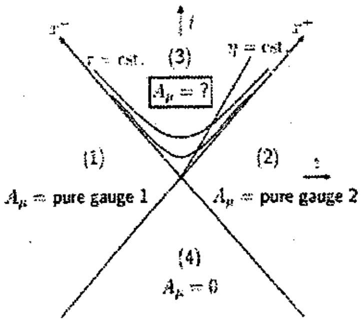
$$FF^d \sim \partial_\mu K^\mu$$

The Chern-Simons charge density is maximal!

$$FF^d \sim 1/g^2$$

and has a transverse correlation length

$$\Delta x_T \sim 1/Q_S$$



How do the sources of color magnetic and color electric field arise?

$$D \cdot E = 0$$

$$\nabla \cdot E = -g[A, E]$$

$$D \cdot B = 0$$

$$\nabla \cdot B = -g[A, B]$$

In forward light cone, the vector potential from one nucleus can multiply the CGC field from the other.

Equal and opposite densities of charge

The Lund model made the daring proposal that there were longitudinal electric fields which decay by pair production

There is also a longitudinal magnetic field

It can also decay by rearrangement of the charge in the classical field (classical screening) whch is naively dominant

Kharzeev and Tuchin and Janik, Shuryak and Zahed made the daring proposal that particles are made by decay of Chern-Simons charge.

Both are correct!

They are included in the color glass initial conditions!

Everyone is HAPPY!

The matter which is this melting glass, or hadronizing strings or sphaleron decays is the Glasma

The Glasma has three components:

Coherent classical fields:

Hard particles:

Degrees of freedom which can be described as either hard particles or coherent fields

$$A \sim 1/g \qquad p_T << 1/\tau$$

$$A << 1/g \qquad p_T >> 1/(\alpha_S \tau)$$

$$1 << A << 1/g \qquad 1/\tau << p_T << 1/(\alpha_S \tau)$$

The Glasma has mostly evaporated by a time $\tau \sim 1/(\alpha_S Q_S)$

During this time, scattering among the hard modes (parton cascade) is not important

Interactions in the coherent fields takes place on a scale of order 1/Qs

Because of coherence, interactions of hard particles with the classical fields,

$g \times 1/g \sim 1$

Also take place on a time scale 1/Qs

Very rapid strongly interacting system

But boost invariance is a problem, as this does not allow longitudinal momentum to become thermalized

Important for two reasons:

Almost certainly instabilities of the hard-soft coupled system under boost non-invariant perturbations

The local topological charge wants to decay, and this is easiest with a boost non-invariant distribution

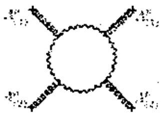
Technical problem: Probably not classical chaos since expect

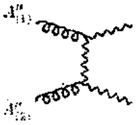
$$\Delta S >> 1$$

$$e^{i\Delta S}$$

Oscillates wildly for configurations initially very close together in phase space

rt from quantum fluctuations:





Summary:

The Glasma may be responsible for rapid thermalization seen at RHIC

It has longitudinal color electric and magnetic fields formed immediately after the collision

There fields carry maximal Chern-Simons charge

Instabilities may be important for rapid thermalization, and for the decay of Chern-Simons charge

Non-zero total Chern-Simons charge may arise from such instabilities

Chern-Simons charge change may be responsible for:

Large CP violation on an event by even basis

(Kharzeev, Pisarski and Tytgat)

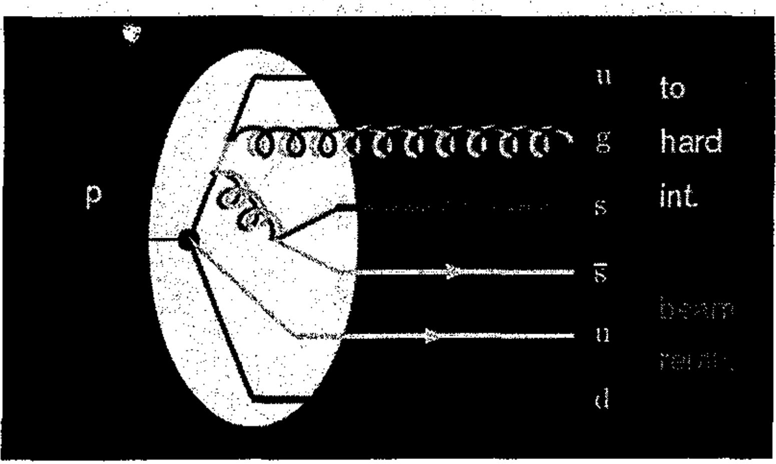
The generation of mass

Peter Z. Skands

Power Showers, the Underlying Event, and other news in PYTHIA

More detailed models for pp collisions are emerging, involving more sophisticated descriptions of collective phenomena such as the underlying event, baryon number flow, and colour (re)connections in hadronisation. These developments will undoubtedly have implications for heavy ion physics as well. Recent theoretical progress on a new parton shower and on the underlying event, implemented in the Pythia generator, is described. Some points of contact between Tevatron/LHC physics and RHIC physics which I believe to be important are emphasized. Interesting questions raised by the new models are briefly touched on.

A complete model should address...



How are the initiators and remnant partons correllated?

- in impact parameter?
- in flavour?
- in x (longitudinal momentum)?
- in k_T (transverse momentum)?
- in colour (→ string topologies!)
- What does the beam remnant look like?
- (How) are the showers correlated / intertwined?

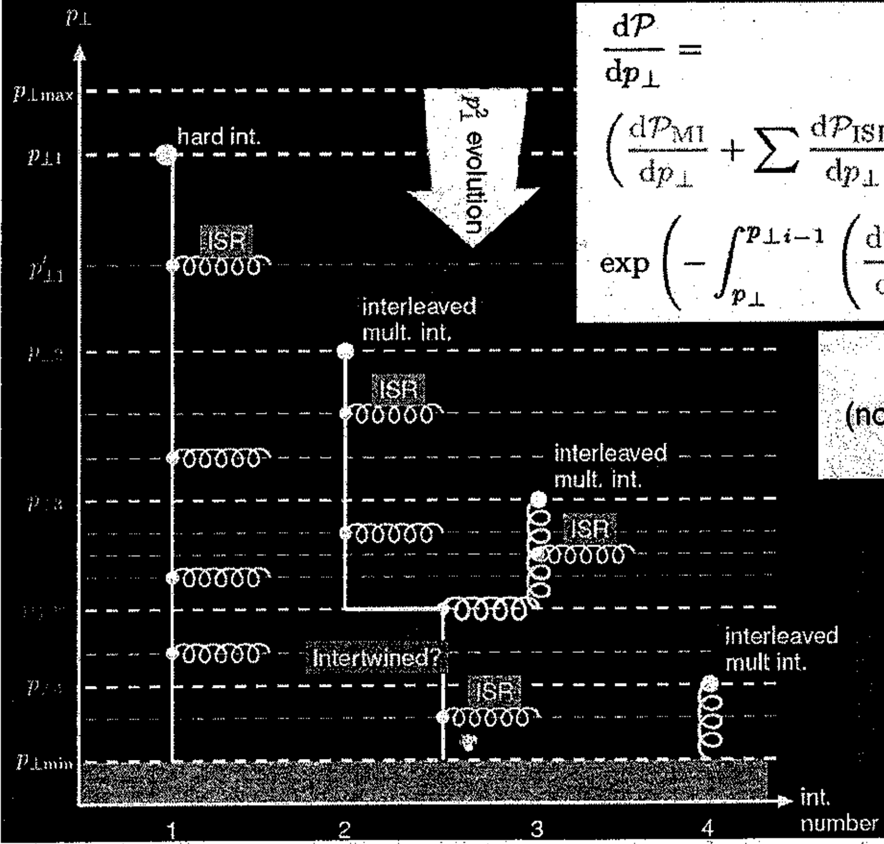
If a model is simple, it is wrong!

+ this is one pp scattering. Additional complications/questions in AA

‘Interleaved evolution’ with Multiple Parton Interactions

The new picture: start at the most inclusive level, $2 \to 2$.

Add exclusivity progressively by evolving *everything* downwards.



Pythia 6.3

$$\frac{d\mathcal{P}}{dp_\perp} = \left(\frac{d\mathcal{P}_{\rm MI}}{dp_\perp} + \sum \frac{d\mathcal{P}_{\rm ISR}}{dp_\perp} + \sum \frac{d\mathcal{P}_{\rm JI}}{dp_\perp}\right) \times \exp\left(-\int_{p_\perp}^{p_{\perp i-1}} \left(\frac{d\mathcal{P}_{\rm MI}}{dp'_\perp} + \sum \frac{d\mathcal{P}_{\rm ISR}}{dp'_\perp} + \sum \frac{d\mathcal{P}_{\rm JI}}{dp'_\perp}\right) dp'_\perp\right)$$

→ Underlying Event

(note: interactions correllated in colour: hadronization not independent)

~ “Finegraining”

→ correlations between all perturbative activity at successively smaller scales

Sjostrand & PS : Eur.Phys.J.C39(2005)129 + JHEP03(2004)053

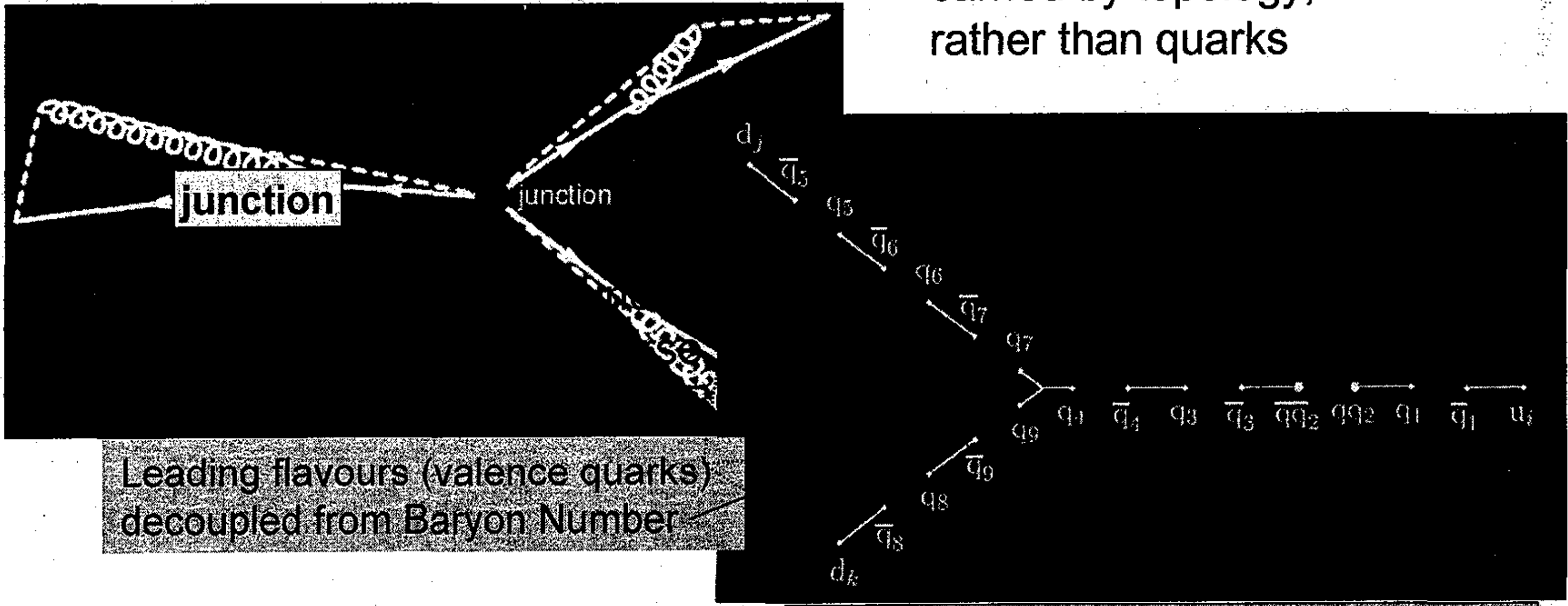
Multiple Parton Interactions: Junction Hadronisation

- Several valence quarks kicked out → string topology with explicit baryon number → 'Junction hadronisation'

$$B_{i_1 i_2 i_3} = \epsilon^{\alpha_1 \alpha_2 \alpha_3} \prod_{n=1}^{3} P\left[e^{ig \int_{\mathcal{P}(x,x_n)} A_\mu \mathrm{d}x^\mu} q_{i_n}(x_n)\right]_{\alpha_n}$$

Montanet, Rossi, Veneziano : Phys.Rep.63(1980)149

Assume Y-shaped topology. Baryon number carried by topology, rather than quarks



Leading flavours (valence quarks) decoupled from Baryon Number

Sjöstrand & PS : Nucl.Phys.B659(2003)243

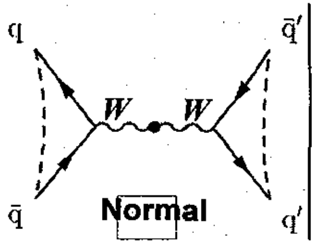
Underlying Event and Colour

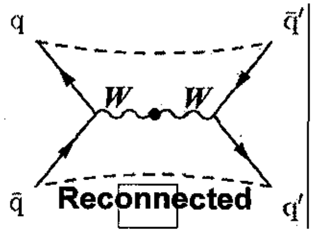
- Fragmentation strongly depends on colour connections.
  - Multiplicity in string fragmentation ~ log(m_{string})
    - More strings → more hadrons, but <u>average</u> p_T stays same
    - Flat $<p_T>(N_{ch})$ spectrum ~ ‘soft’ underlying event
  - But if MPI interactions correlated in colour
    - Sjostrand & v.Zijl : Phys Rev D36 2019 1987 → ‘Old’ Pythia model
    - each scattering does not produce an independent string,
    - average p_T → not flat.
  - Central point: multiplicity vs pT correllation probes colour correllations! (applicable in AA as well?)

Sjostrand, Khoze, Phys Rev Lett 72(1994)28 & Z. Phys C62(1994)281 + more

Colour Reconnections?

- Searched for at LEP (major source of W mass uncertainty) Most aggressive scenarios excluded, but effect still largely uncertain.
  OPAL, Phys Lett B453(1999)153 & **OPAL**, hep-ex0508062





- Prompted by CDF data and Rick Field's 'Tune A' to reconsider. What do we know?

- More prominent in hadron-hadron collisions? Top mass? QCD? AA?

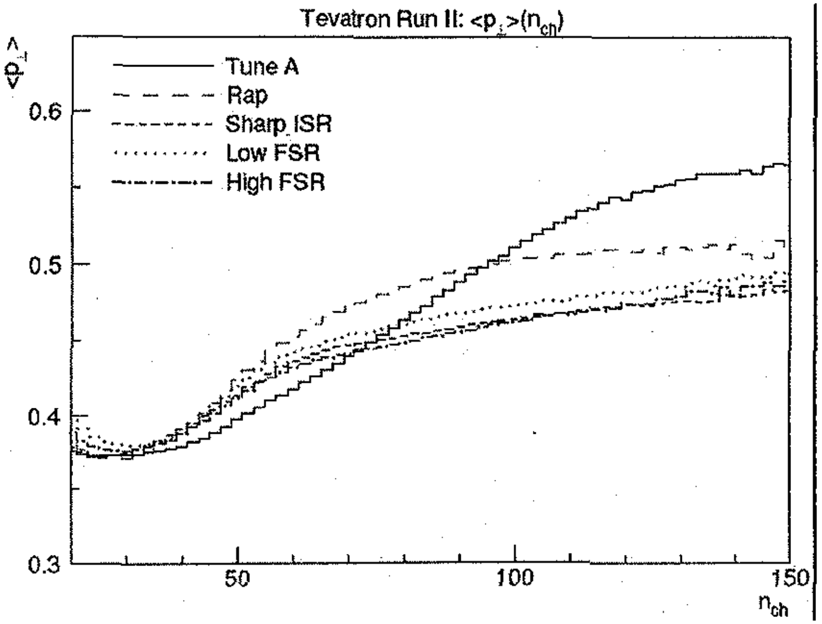
A possible complete picture?

MPI: perturbative 2→2 interactions

+ interleaved with perturbative bremsstrahlung (parton showers)

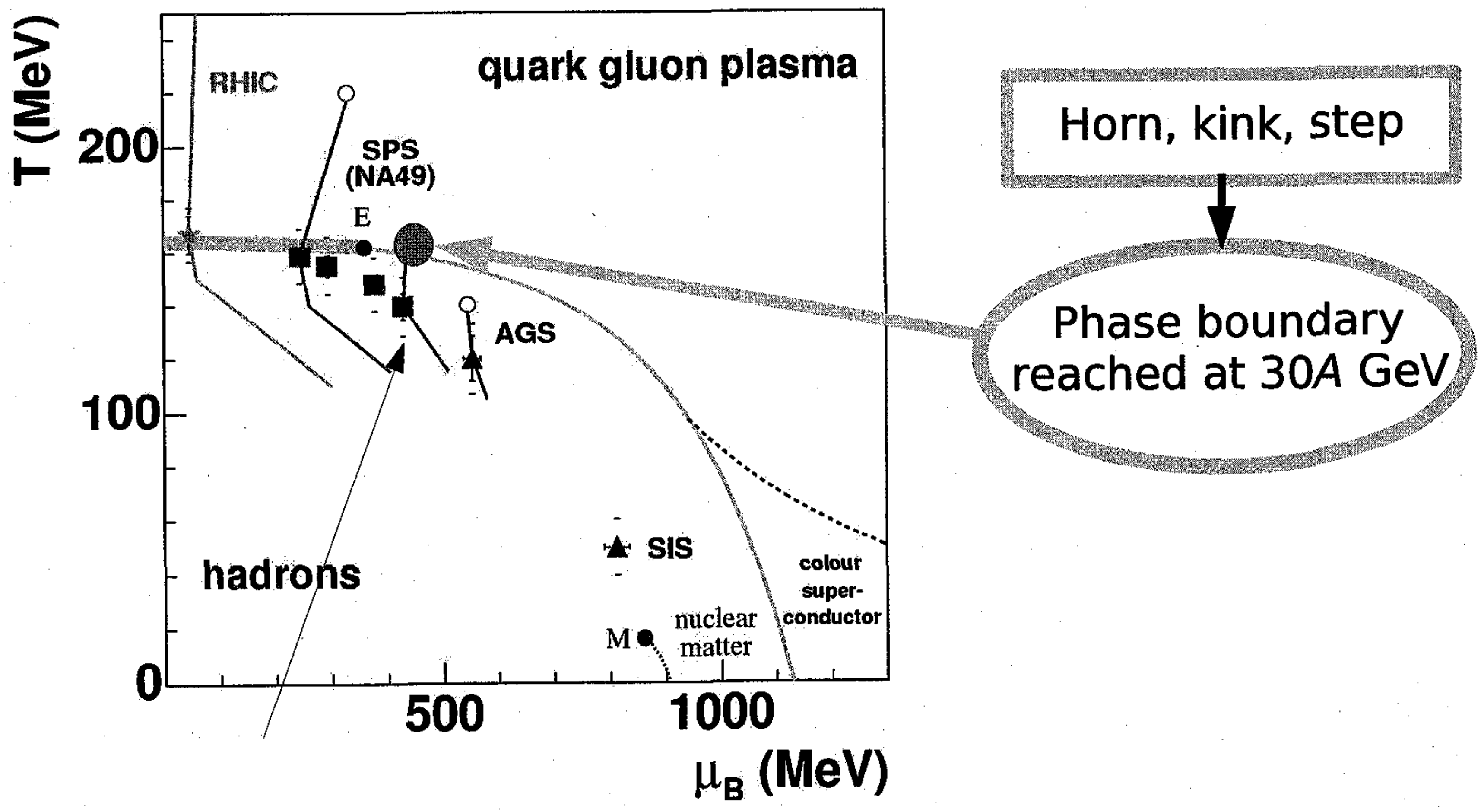
plus non-perturbative interconnection effects? From hadronic vacuum? More in AA? What is $<p_T>(N_{ch})$ telling us?

(string) hadronization (Nielsen-Olesen vortex lines w/ linear V~kr) still universal?



Energy dependence of strangeness production and Onset of deconfinement

M. Gazdzicki, University of Frankfurt and Swietokrzyska Academy, Kielce

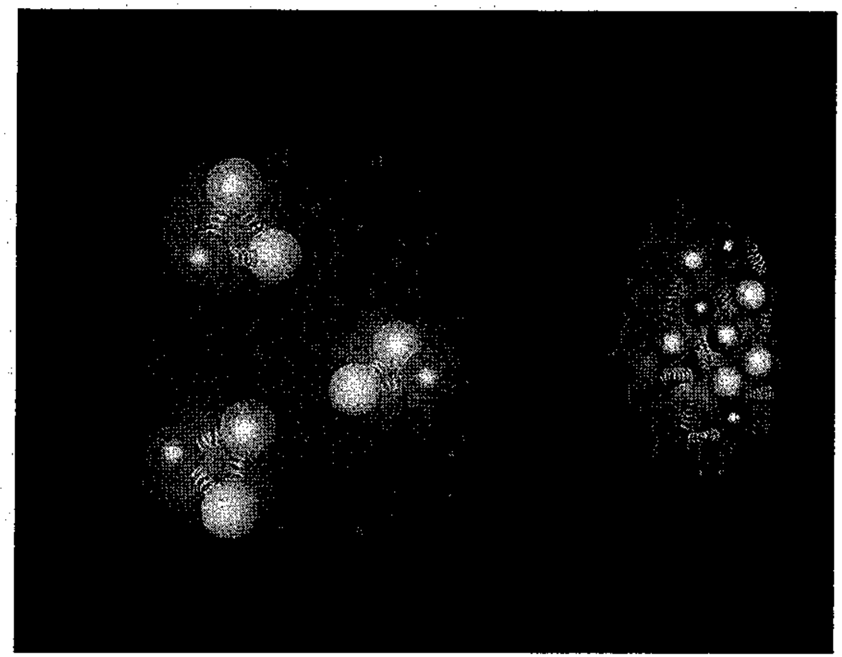


Horn, kink, step

Phase boundary reached at 30*A* GeV

Heating curves of strongly interacting matter

hadrons **mixed** **QGP**

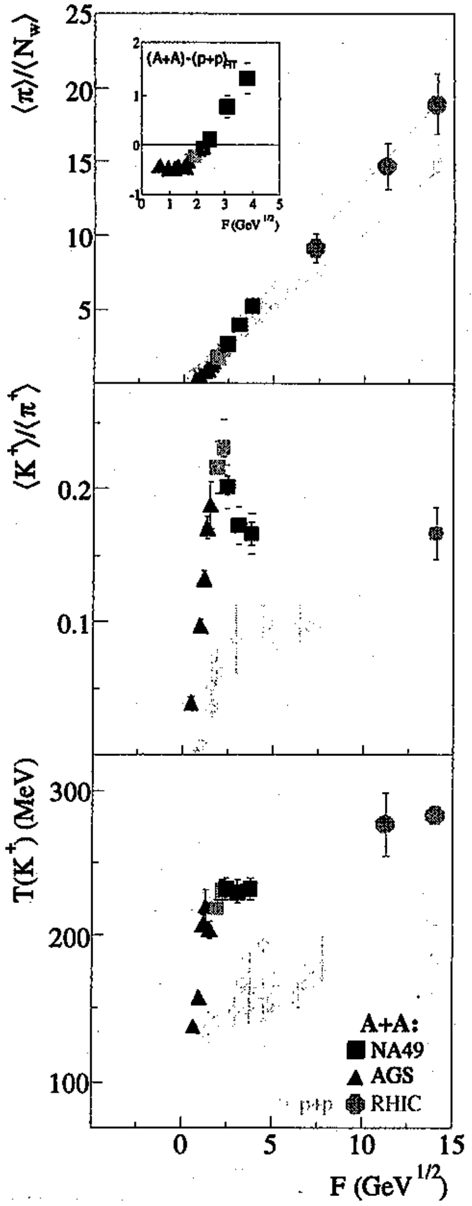


AGS **SPS** **RHIC**

collision energy

AGS SPS RHIC

hadronic observables



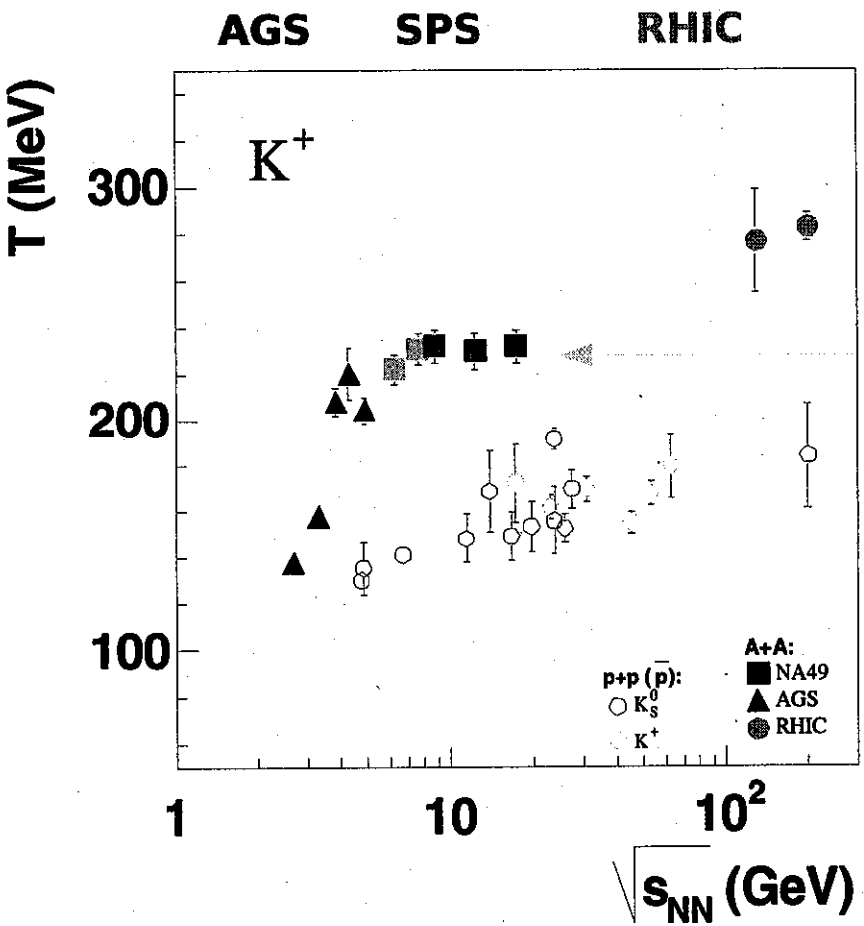
Kink

Horn

Step

collision energy

The step in m_T slopes



Deconfinement

↓

Constant temperature and pressure in the mixed phase region

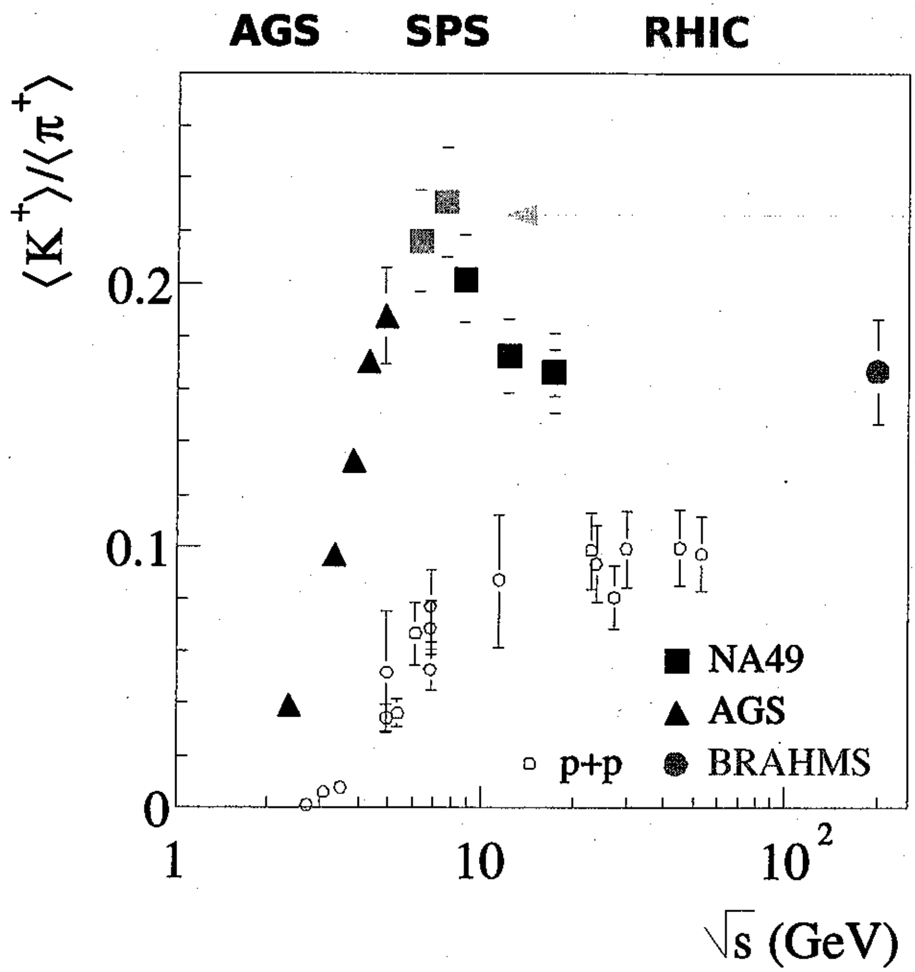
↓

Weaker energy dependence of the shape of transverse mass spectra

T – inverse slope parameter of transverse mass spectra

Gorenstein, M.G., Bugaev

The horn in strangeness yield



Deconfinement

↓

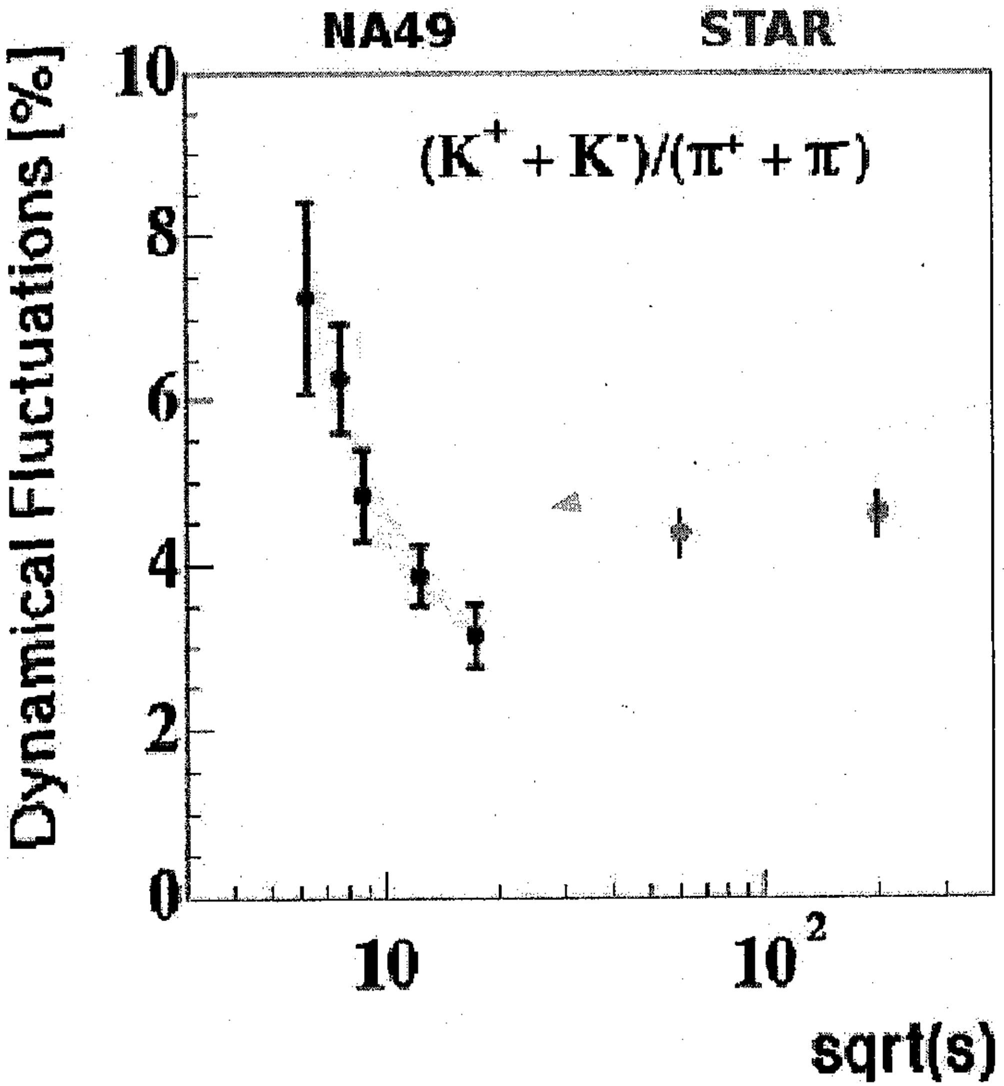
Decrease of masses of strangeness carriers and the number ratio of strange to non-strange degrees of freedom

↓

A sharp maximum in the strangeness to pion ratio

M.G., Gorenstein

The kaon/pion fluctuations

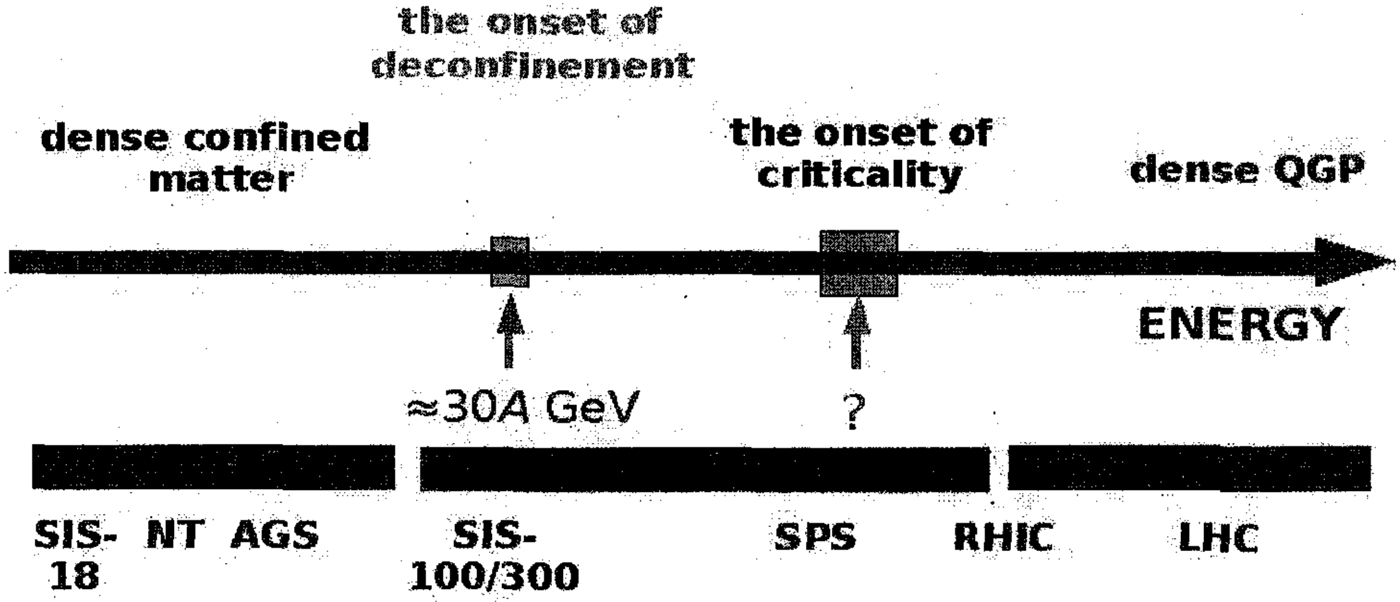


Is the observed change in energy dependence related to deconfinement?

To do list : strangeness and deconfinement

Finish analysis of already taken data, in particular:
- centrality dependence at 20A and 30A GeV,
- particle fluctuations

Confirm and extend the NA49 results by new measurements:
- in the near future: at RHIC and at SPS
- in the far future: at FAIR



the onset of deconfinement

dense confined matter

the onset of criticality

dense QGP

ENERGY

≈30*A* GeV

?

SIS-18 NT AGS

SIS-100/300

SPS

RHIC

LHC

A hadronic non-equilibrium interpretation of the K/π horn

Boris Tomášik[†] and Evgeni Kolomeitsev[*]
[†] Univerzita Mateja Bela, Banská Bystrica, Slovakia
[*] University of Minnesota, Minneapolis, Minnesota

We ask whether the "horn" in the excitation function of the ratio of multiplicities $\langle K^+ \rangle / \langle \pi^+ \rangle$ is indeed a signature for the onset of deconfined phase. We test a hadronic non-equilibrium scenario, where strange species production is accounted for by kinetic equations. In contrast to other approaches presently or previously on the market we make an *ansatz* for the expansion pattern of the fireball. This ansatz is motivated by the measured femtoscopic data and hadronic single particle distributions. We find that a hadronic non-equilibrium scenario cannot be safely ruled out just by comparison to the multiplicity data (the horn). Cross checks with other sorts of data will be necessary if hadronic scenario should be ruled out safely.

The model

- want to calculate ratios of yields → look at densities of species
- study evolution of the (kaon, pion, B, ...) densities

$$\frac{dn_K}{d\tau} = \frac{d}{d\tau}\frac{N_K}{V} = -\frac{N_K}{V}\frac{1}{V}\frac{dV}{d\tau} + \frac{1}{V}\frac{dN_K}{d\tau}$$

$$\frac{dn_K}{d\tau} = \qquad n_K\left(-\frac{1}{V}\frac{dV}{d\tau}\right) + \qquad \mathcal{R}^+ \qquad - \qquad \mathcal{R}^-$$

expansion rate   production rate   annihilation rate

ansatz for this   calculate from known cross-sections and evolved densities

Ansatz for the expansion

$$\varepsilon(\tau) = \begin{cases} \varepsilon_0(1 - a\tau - b\tau^2) & \tau < \tau_s \quad \text{acceleration} \\ \frac{\beta}{(\tau-\tau_0)^\alpha} & \tau > \tau_s \quad \text{power-law expansion} \end{cases}$$

$$n_{B,I}(\tau) = \begin{cases} n_{0;B,I}(1 - a\tau - b\tau^2)^\delta & \tau < \tau_s \quad \text{acceleration} \\ \frac{\gamma}{(\tau-\tau_0)^{\alpha\delta}} & \tau > \tau_s \quad \text{power-law expansion} \end{cases}$$

- explore a range of values for the model parameters
- at the end power-law scaling suggested by HBT
- this is a parametrisation "between Landau and Bjorken"

Production and annihilation

Calculation of densities:

- explicit kinetic calculation: K^+, K^0, K^{*+}, K^{*0} (vacuum properties)
- kaons in kinetic equilibrium (until decoupling)
- chemical equilibrium: non-strange species
- relative chemical equilibrium: $S < 0$ sector ($\bar{K}$, Λ, Σ, Ξ, Ω)
- no antibaryons assumed at these energies

Implemented K-production (and annihilation) rates:

$$\pi N \leftrightarrow KY, \qquad \pi N \to NK\bar{K}, \qquad \pi\Delta \leftrightarrow KY, \qquad \pi\Delta \to NK\bar{K}$$

$$NN \to KNY, \qquad NN \to NNK\bar{K}, \qquad NN \to \Delta KY$$

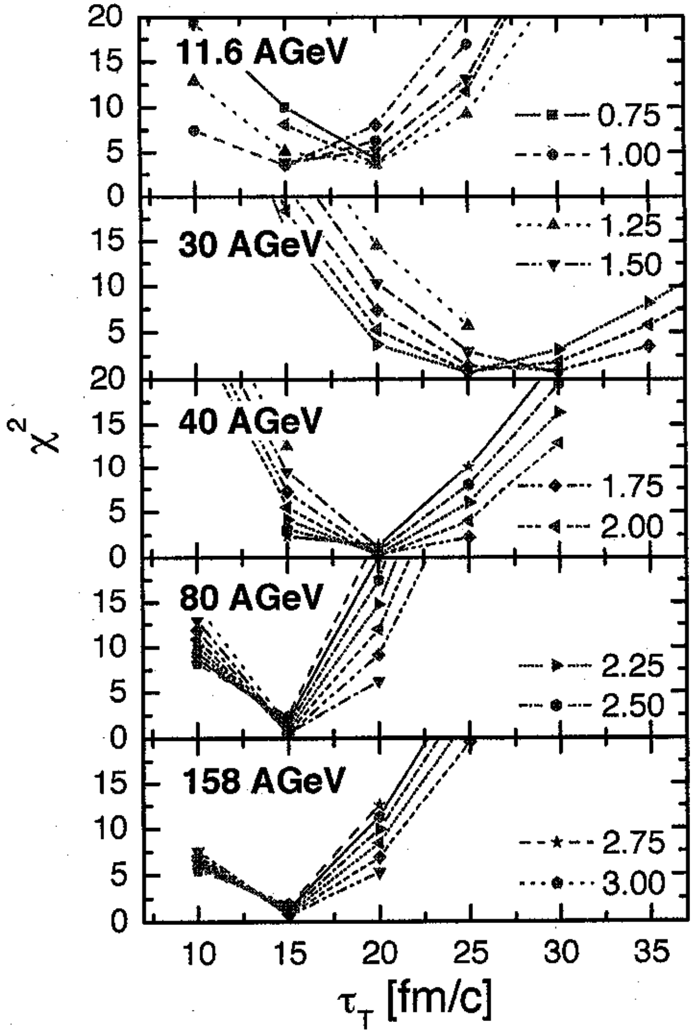
$$N\Delta \to NYK, \qquad N\Delta \to NNK\bar{K}, \qquad N\Delta \to \Delta KY$$

$$\Delta\Delta \to \Delta YK, \qquad \Delta\Delta \to NNK\bar{K}$$

$$\pi\pi \leftrightarrow K\bar{K}, \qquad \pi\rho \leftrightarrow K\bar{K}, \qquad \rho\rho \leftrightarrow K\bar{K}, \qquad \pi\rho \leftrightarrow K\bar{K}^*$$

$$K^* \leftrightarrow K\pi, \qquad \pi Y \leftrightarrow K\Xi,$$

Summary of allowed lifetimes and initial energy densities



Plotted:

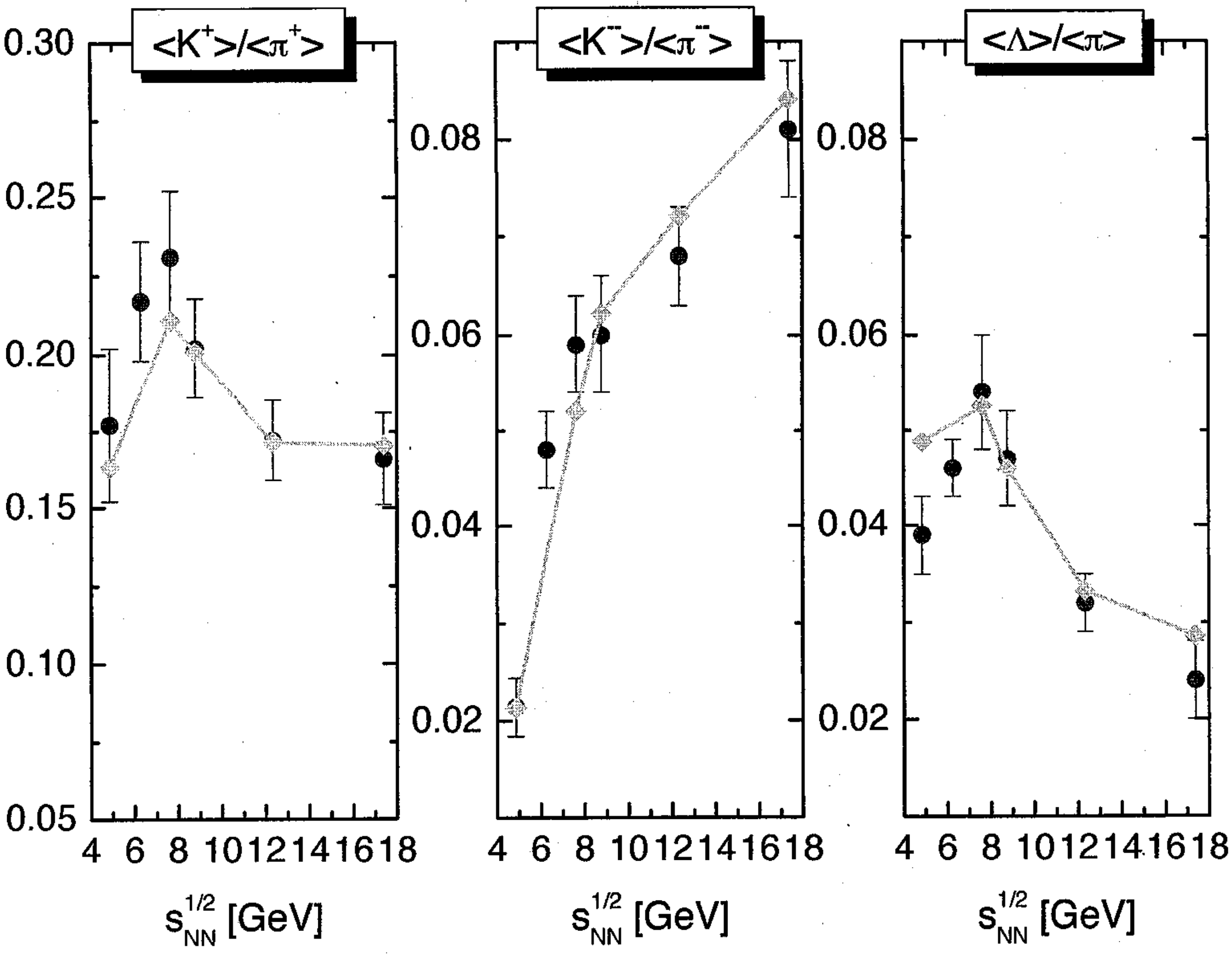
$$\chi^2 = \sum_{i=1}^{3} \frac{(t_i - d_i)^2}{e_i^2}$$

t_i calculated value

d_i data value

e_i error

Comparison to data



Centrality Dependence of Strange Particle Yields from SIS up to RHIC

Helmut Oeschler
Darmstadt University of Technology

Brookhaven Nat. Lab., February 17th, 2006

K$^-$ and K$^+$ are linked

Au+Au and Ni+Ni 1.5 AGeV

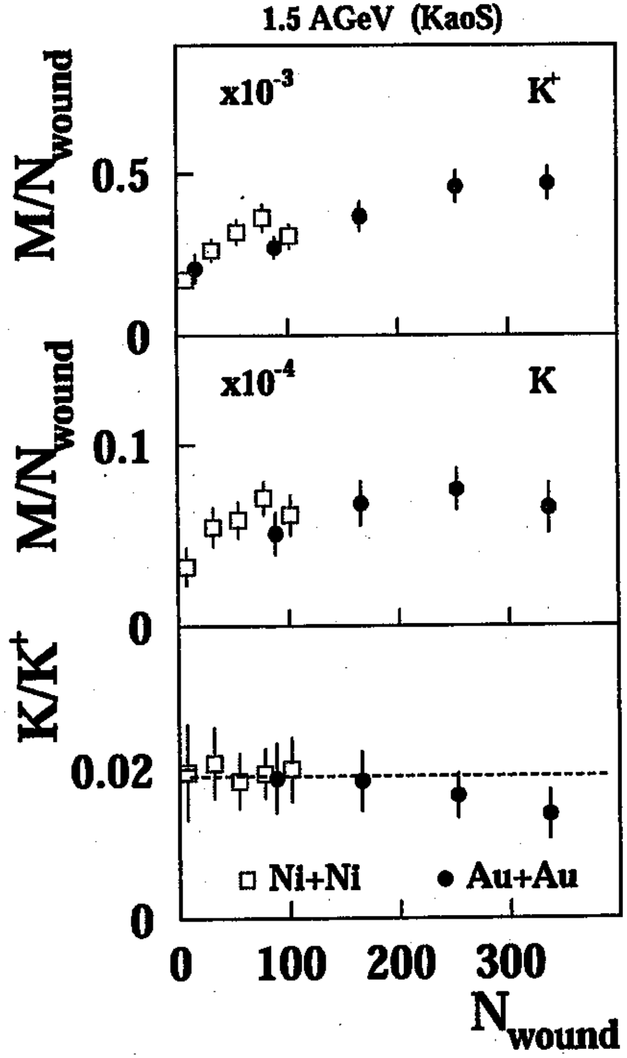
A. Förster, F. Uhlig et al.,
KaoS PRL 91 (2003) 152301

dashed line: stat. Model
Step 1 NN -> Λ K$^+$ N
Step 2 Λ π -> K$^-$ N

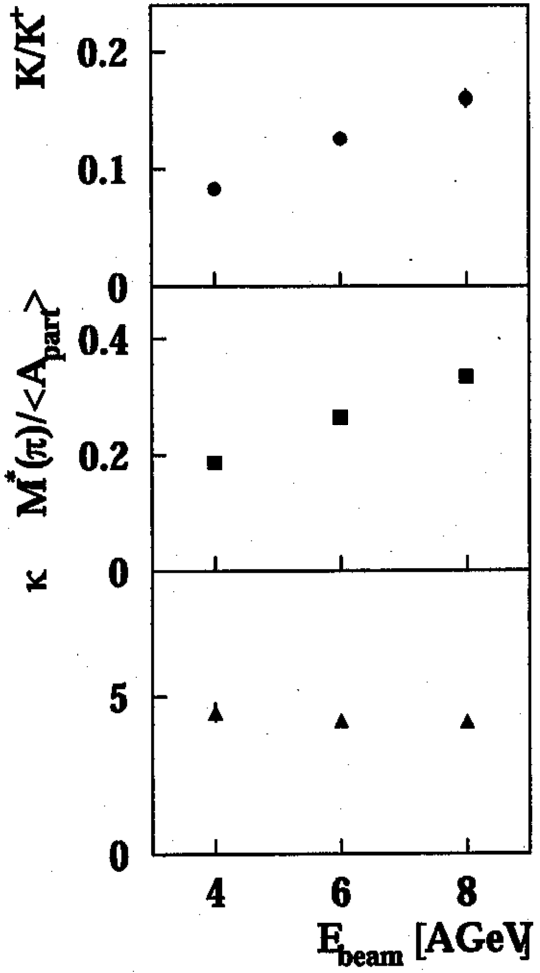
K$^-$ and K$^+$ are linked via strangeness exchange

„Law of mass action“

J. Cleymans, et al. PLB603(2004)

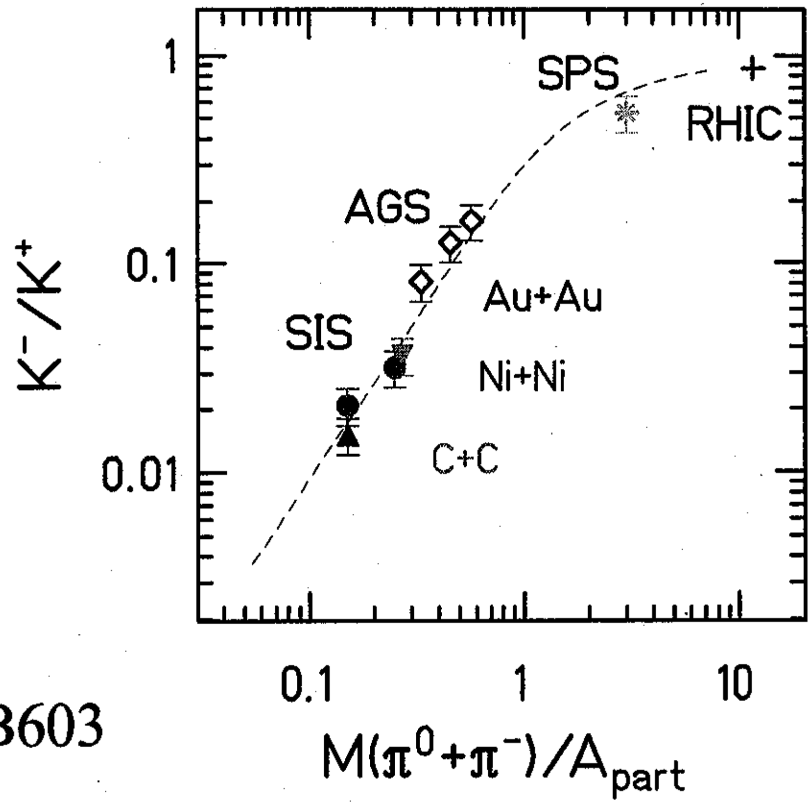


Strangeness Exchange at AGS?



PLB603

AGS:
L. Ahle et al., PLB 490
J. Klay et al., PRC68



Expected Centrality Dependence (SM)

Pion density

$n(\pi) = exp(-E_\pi/T)$

Strangeness is conserved!

Kaon density

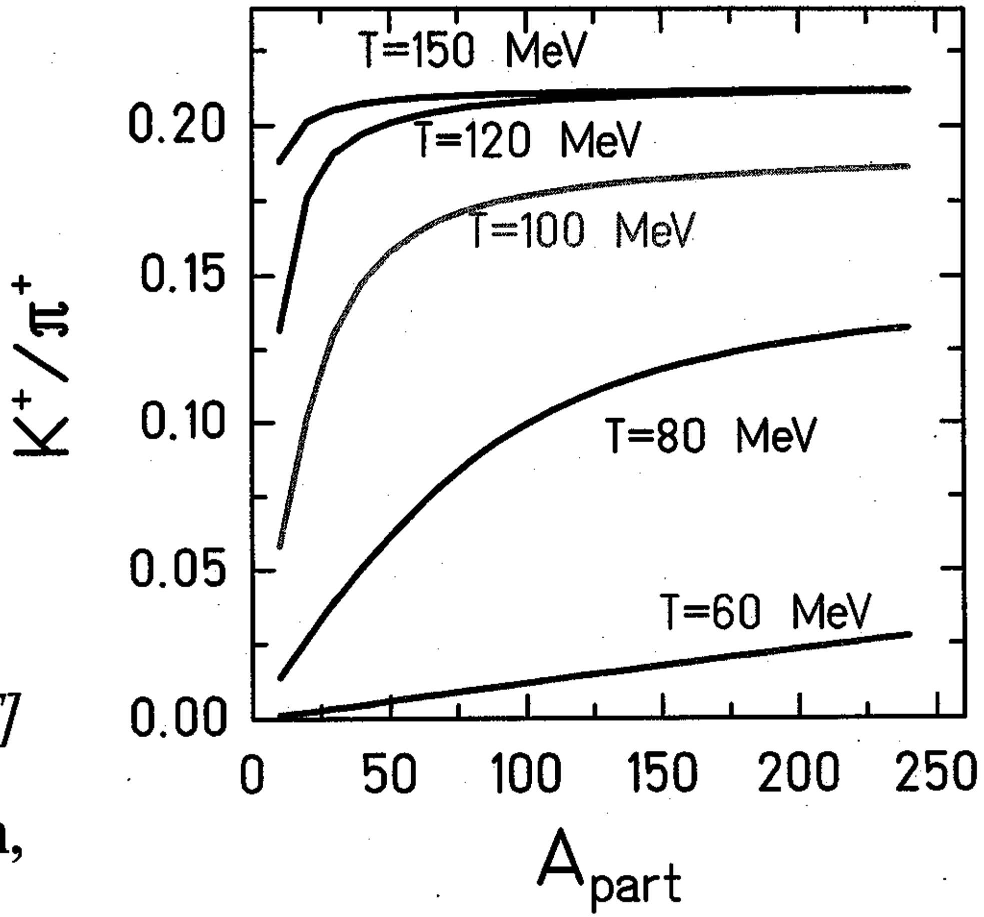
$NN \rightarrow N\,\Lambda\,K^+$

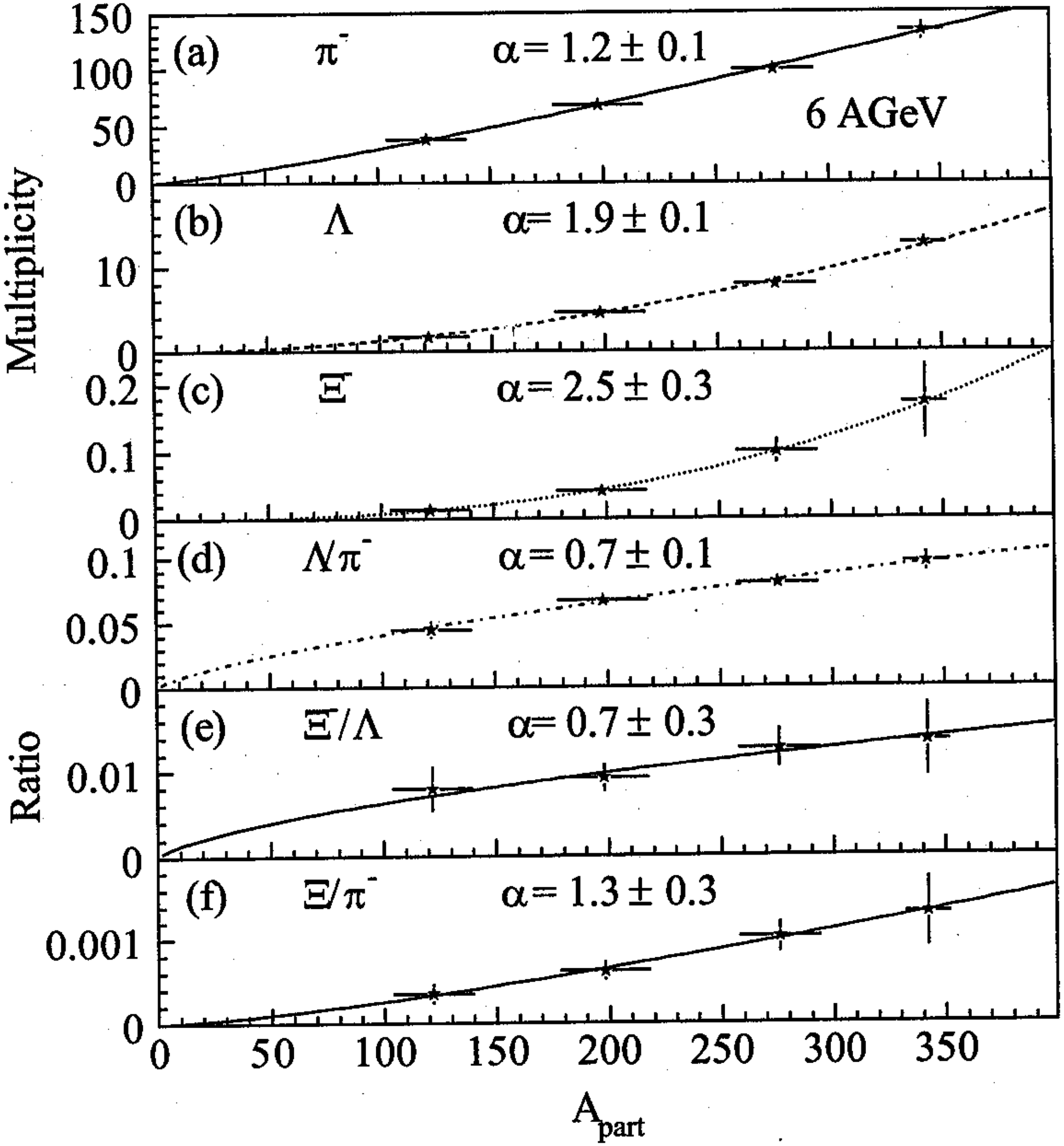
$n(K) = exp(-E_K/T)$

$[g\,V\ \int \ldots\ exp[-(E_\Lambda-\mu_B)/T]$

J. Cleymans, HO, K. Redlich,

PRC 60 (1999)





AGS

Au+Au 6 A GeV

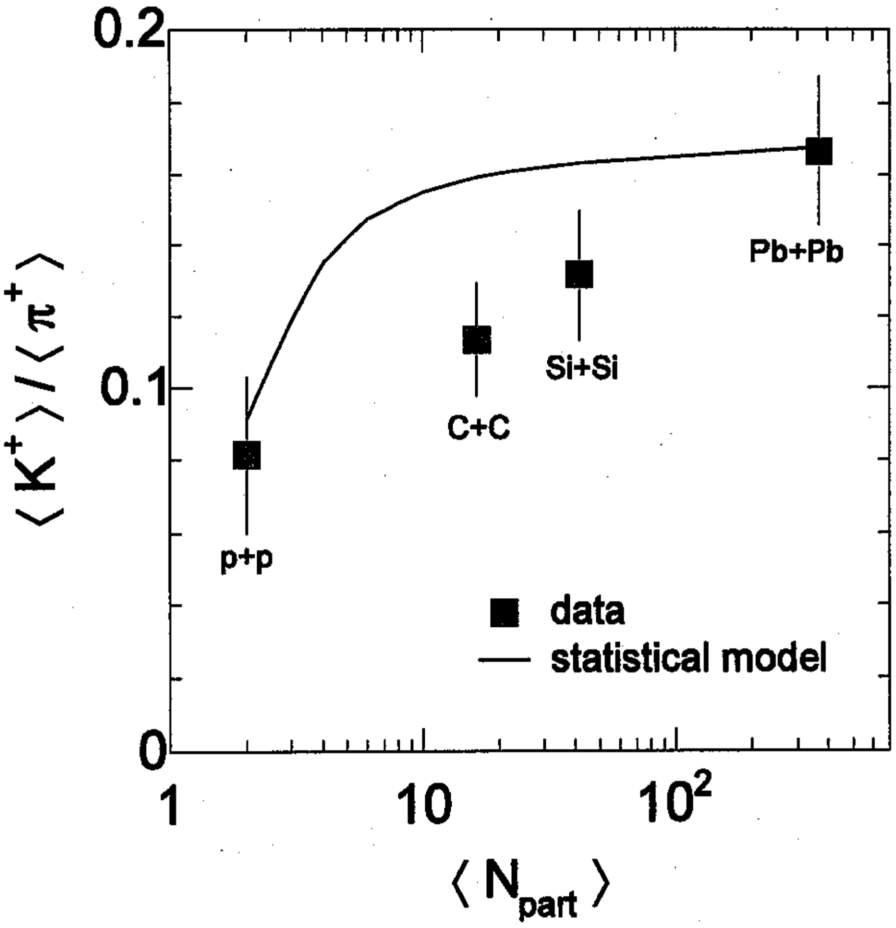
P. Chung et al.,

E895 Coll.

PRL 91(2003)

updated

NA49 Data - 158 AGeV PRL …



Ingrid Kraus et al.,
to be published

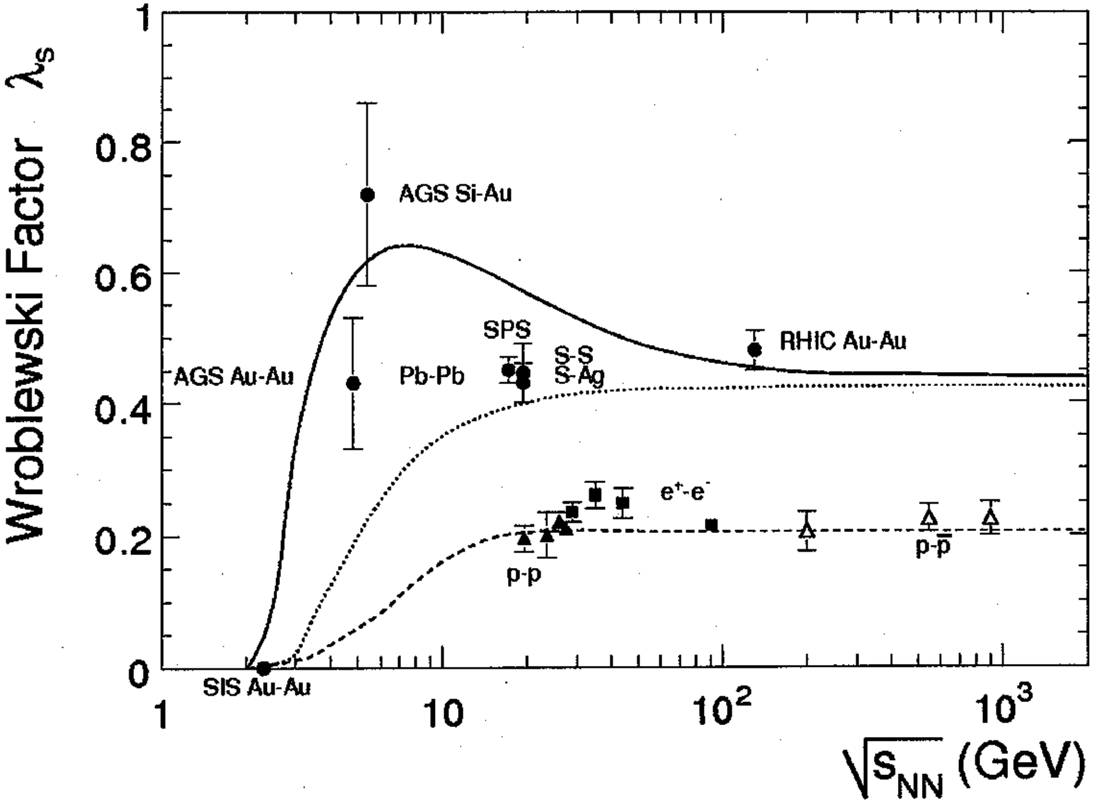
Corr. vol. NOT prop to A_{part}

Strangeness opportunities at the LHC

1. **Strangeness at LHC energies**	Extrapolations / Motivations
2. **Strange probes with ALICE**	Detector and Simulations
3. **First p+p Collisions and beyond**	First measures to target

Boris HIPPOLYTE, STRASBOURG

Wroblewski factor extrapolation to LHC energies



Wroblewski factor:

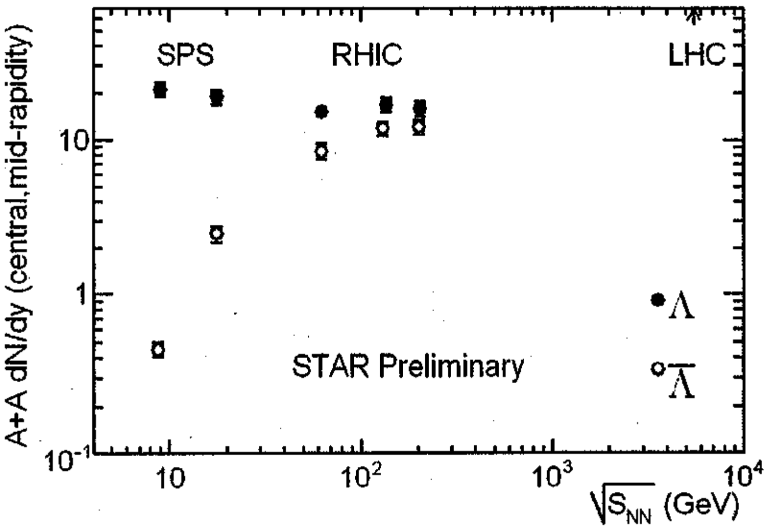
$$\lambda_s \equiv 2\frac{\langle s\bar{s}\rangle}{\langle u\bar{u}\rangle + \langle d\bar{d}\rangle}$$

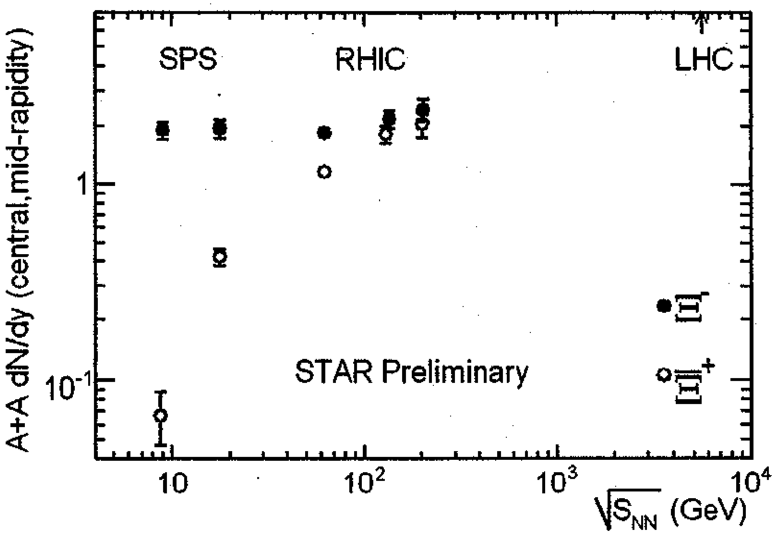
Extrapolation at the LHC
A+A ~0.45
p+p ~0.25

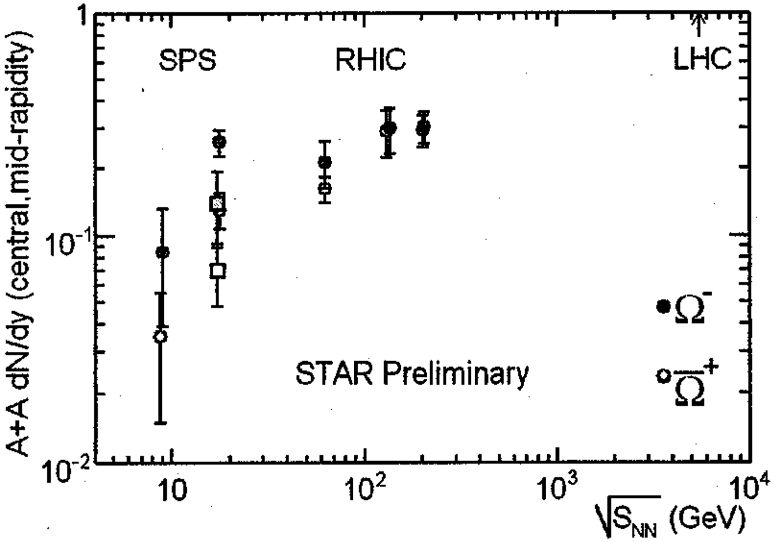
Data compilation using **Becattini et al.**, PR C64 (2001) 024901, hep-ph/0002267 and references therein

Using thermal model description with corresponding system formalism (canonical or grand-canonical), extrapolation is straightforward.

Excitation functions of hyperons yields in A+A







dN/dy extrapolations at the LHC

for Λ : 10~30
for Ξ : 3~6
for Ω : 0.4~0.7

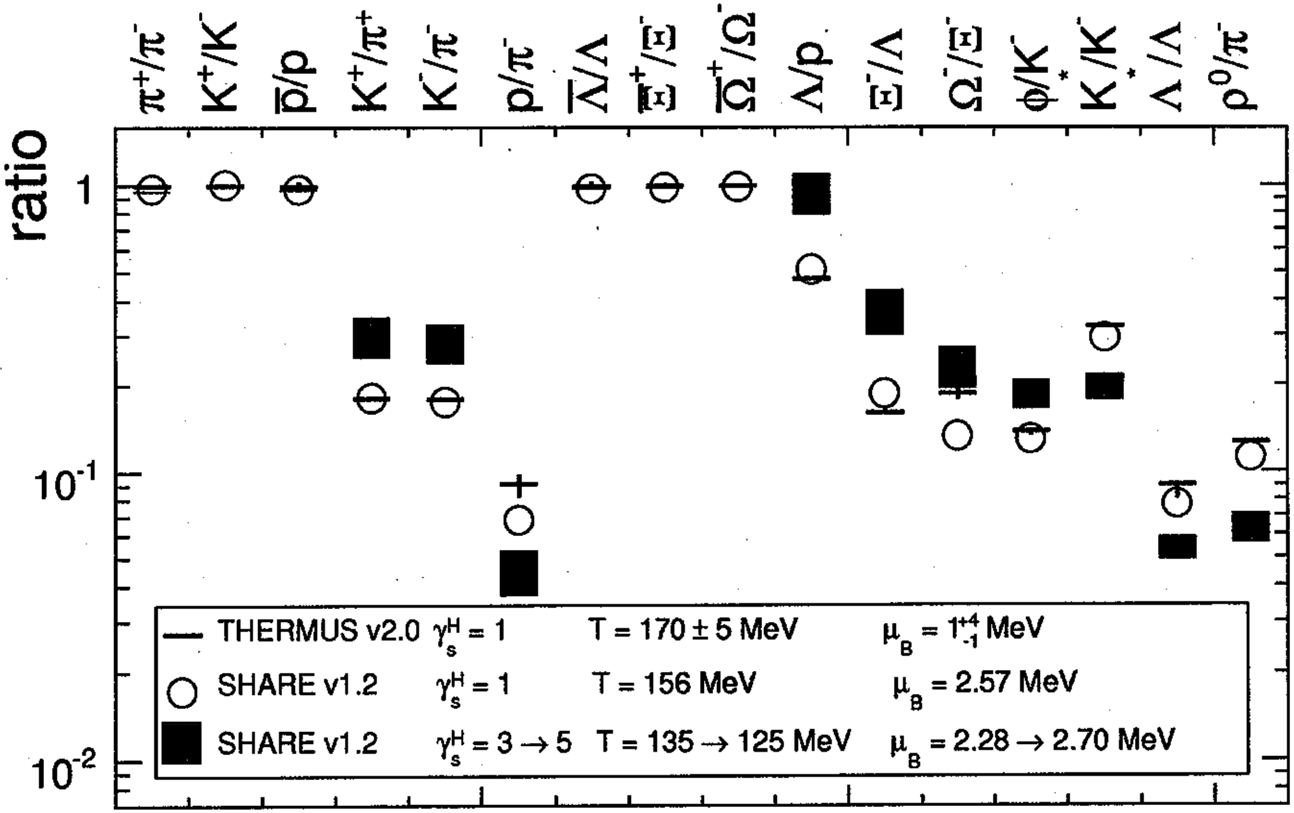
Expected modifications

total multiplicity scaling
non-equilibrium scenario

Equilibrium vs non–equilibrium scenarii in A+A

Eq. [Oeschler et al., to be published]
[Andronic et al., nucl-th/0511071]
Non Eq. [Rafelski et al., Eur. J. Phys. C45 (2006) 61]

ALICE Estimates : Equilibrium vs Non Eq. particle ratios

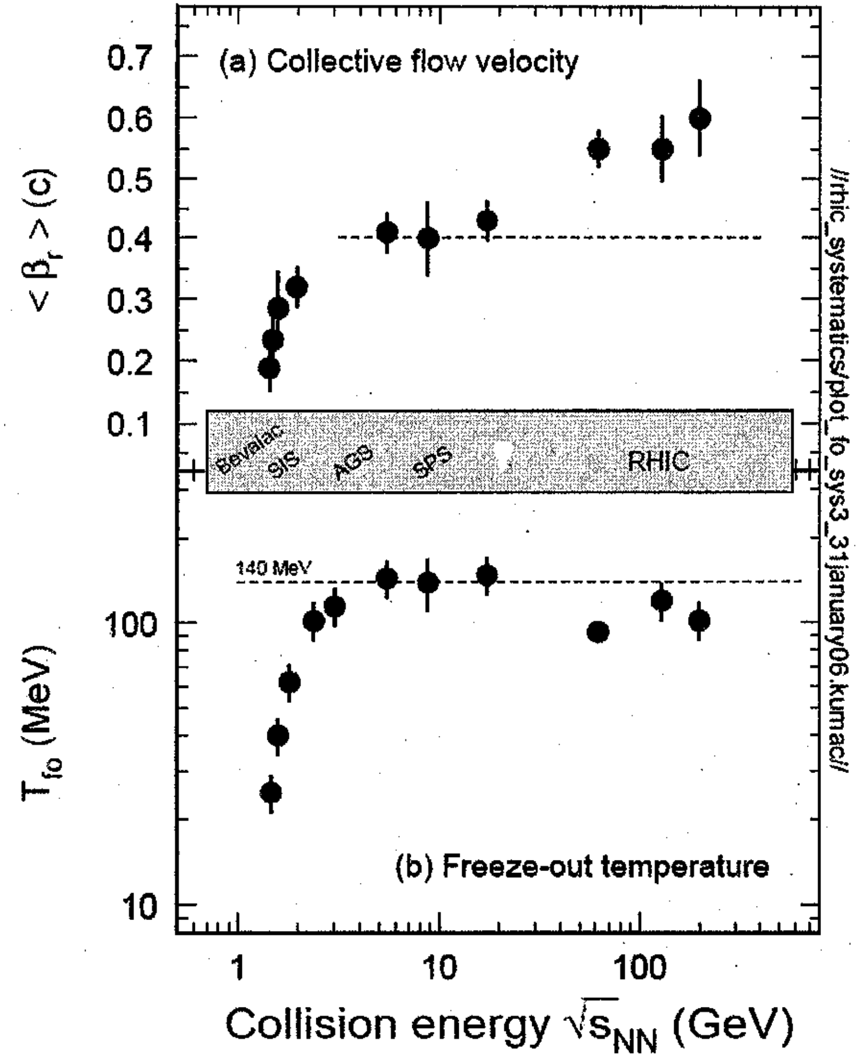


Calculations from
Kraus et al., (Eq.)
Rafelski et al., (Non Eq.)

Expectations at the LHC energies (eq.):
T_{ch} ~170 MeV
μ_B ~1 MeV

Scenarii for γ_s

Blast-Wave parameters $\langle\beta_T\rangle$ and T_{fo} extrapolation



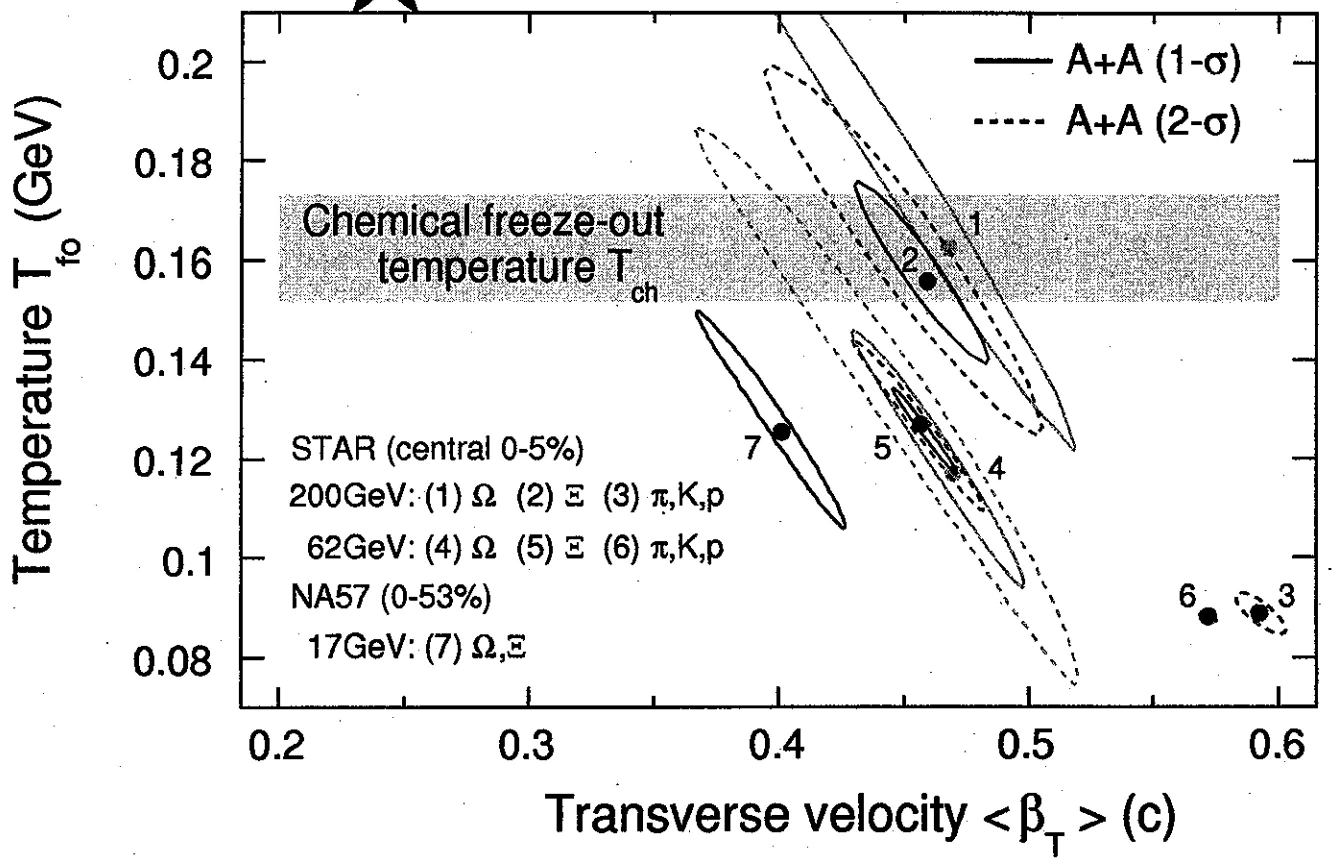
Compilation from **N. Xu**

Excitation functions of the radial flow velocity and the kinetic freeze-out temperature parameters for central Au+Au or Pb+Pb collisions.

Global **trend** for Blast-Wave parameters ($\langle\beta_T\rangle$ and T_{fo}) is clear

Blast-Wave for Multi-Strange Baryons vs $\sqrt{s_{NN}}$

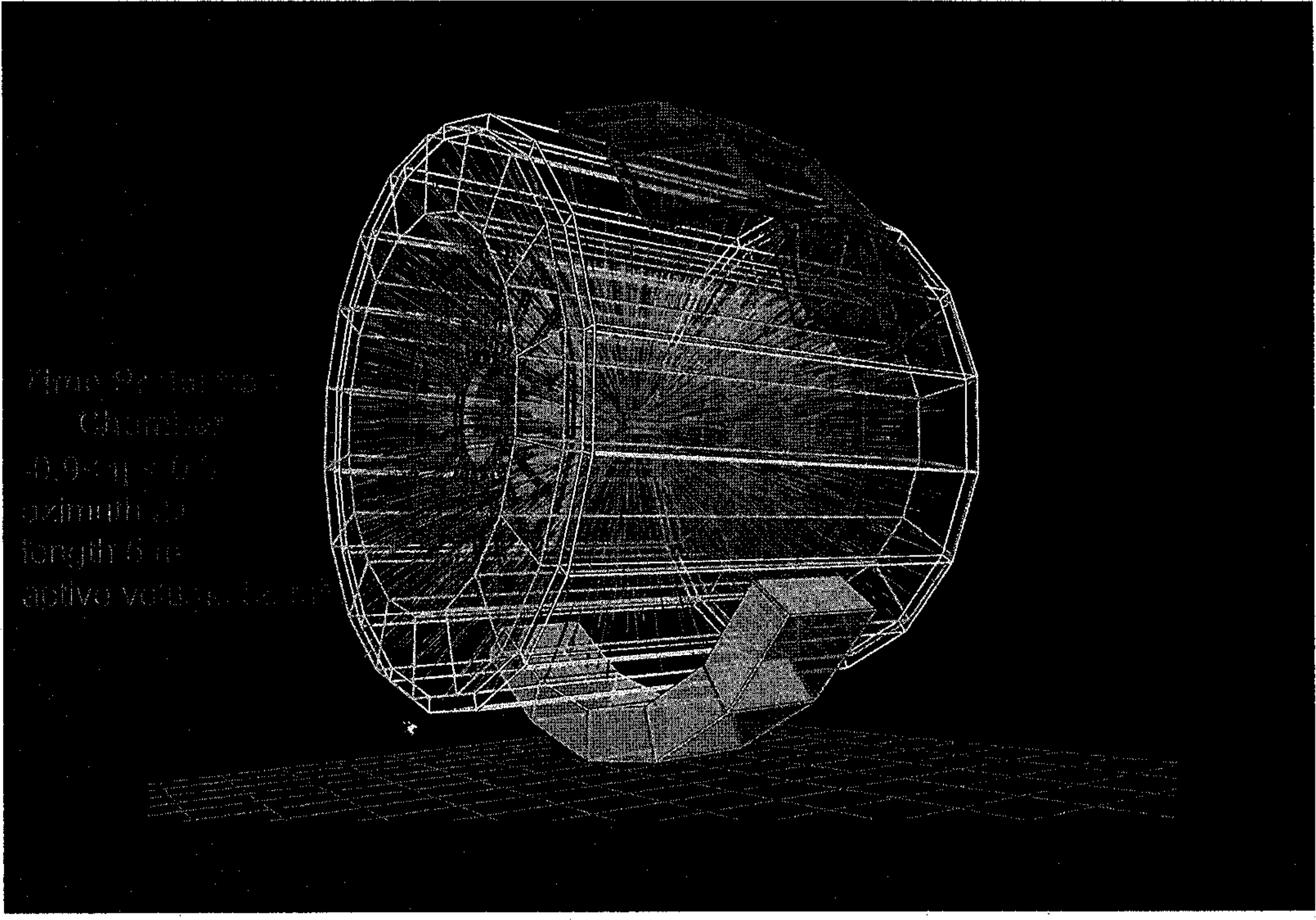
Preliminary Au+Au 62 GeV



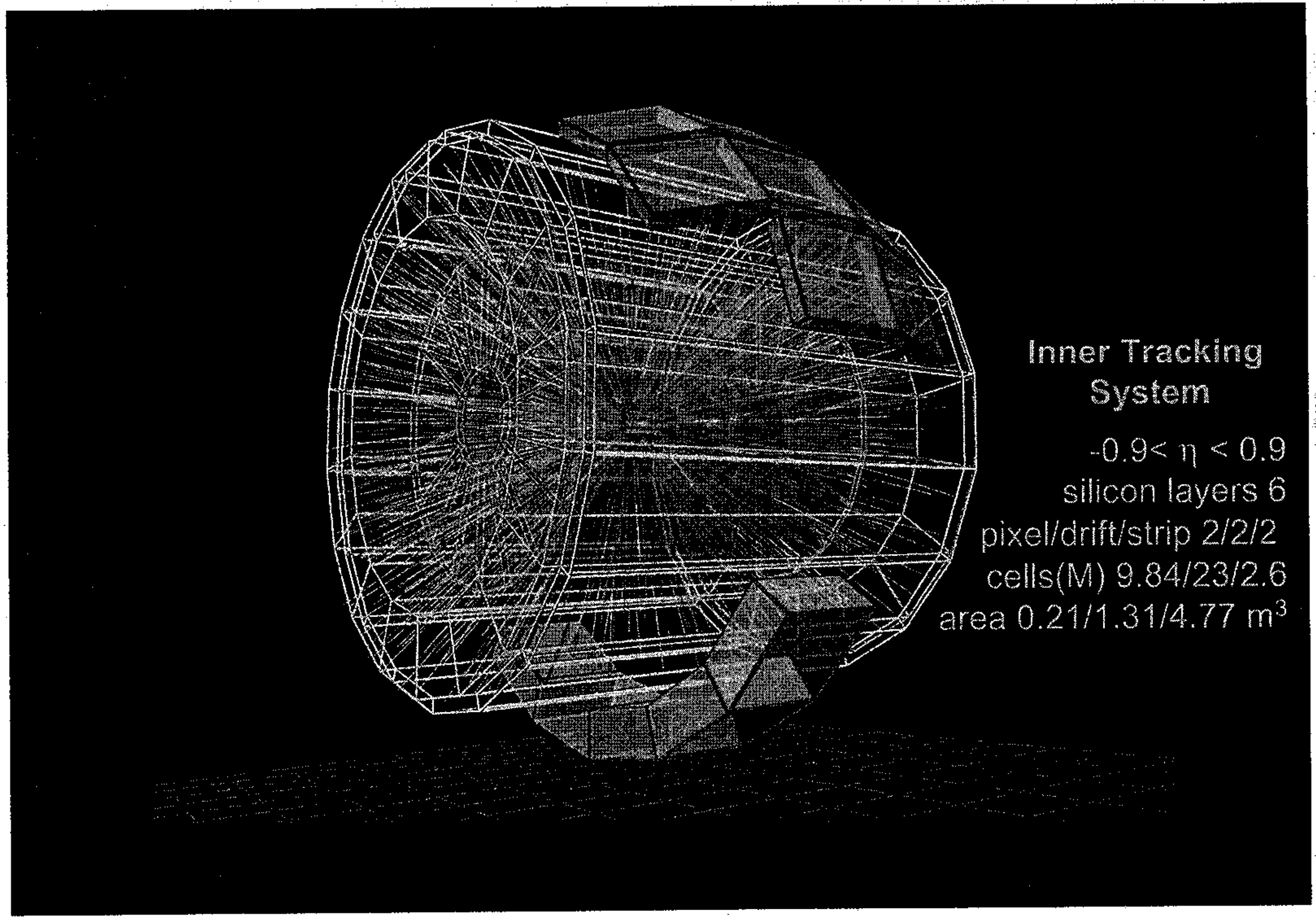
G.E. Bruno J.Phys. G 31 (2005) s127
J. Speltz nucl-ex/0512037
S. Salur nucl-ex/0509036

Evolution of parameters up to LHC energies and systematics study for T_{fo}

The central detectors of the ALICE experiment



The central detectors of the ALICE experiment



Inner Tracking System

-0.9< η < 0.9
silicon layers 6
pixel/drift/strip 2/2/2
cells(M) 9.84/23/2.6
area 0.21/1.31/4.77 m^3

The central detectors of the ALICE experiment

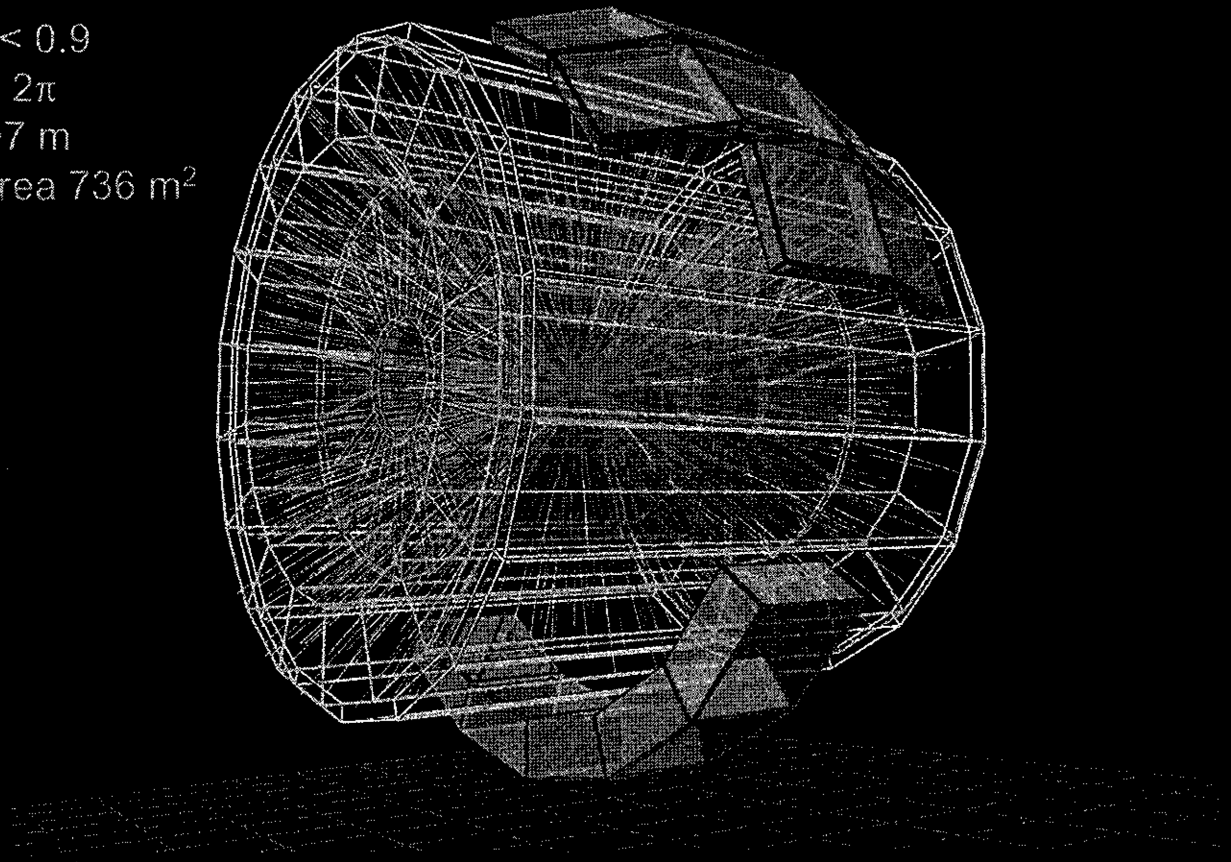
Transition-Radiation Detector

$-0.9 < \eta < 0.9$

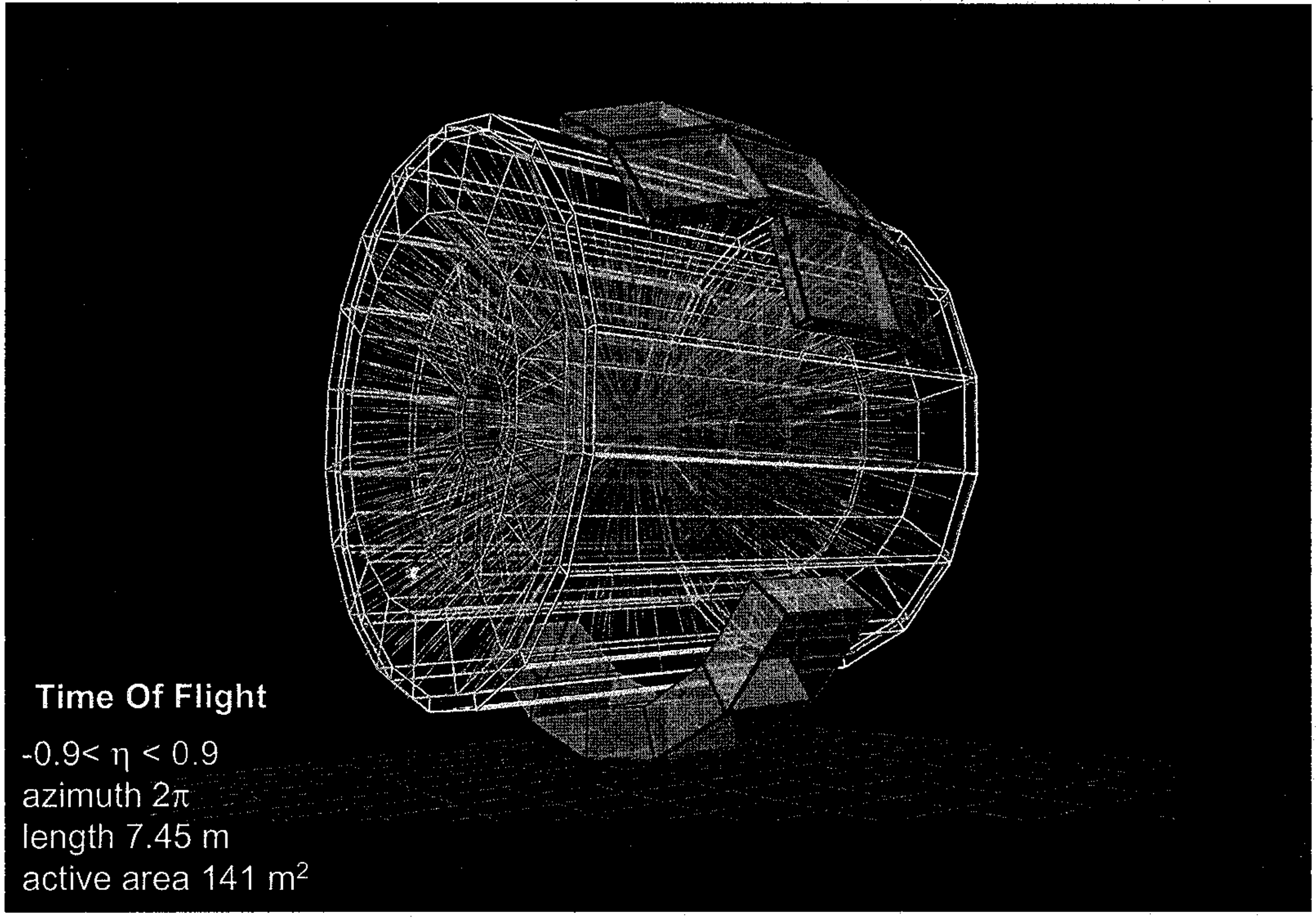
azimuth 2π

length ~7 m

active area 736 m^2



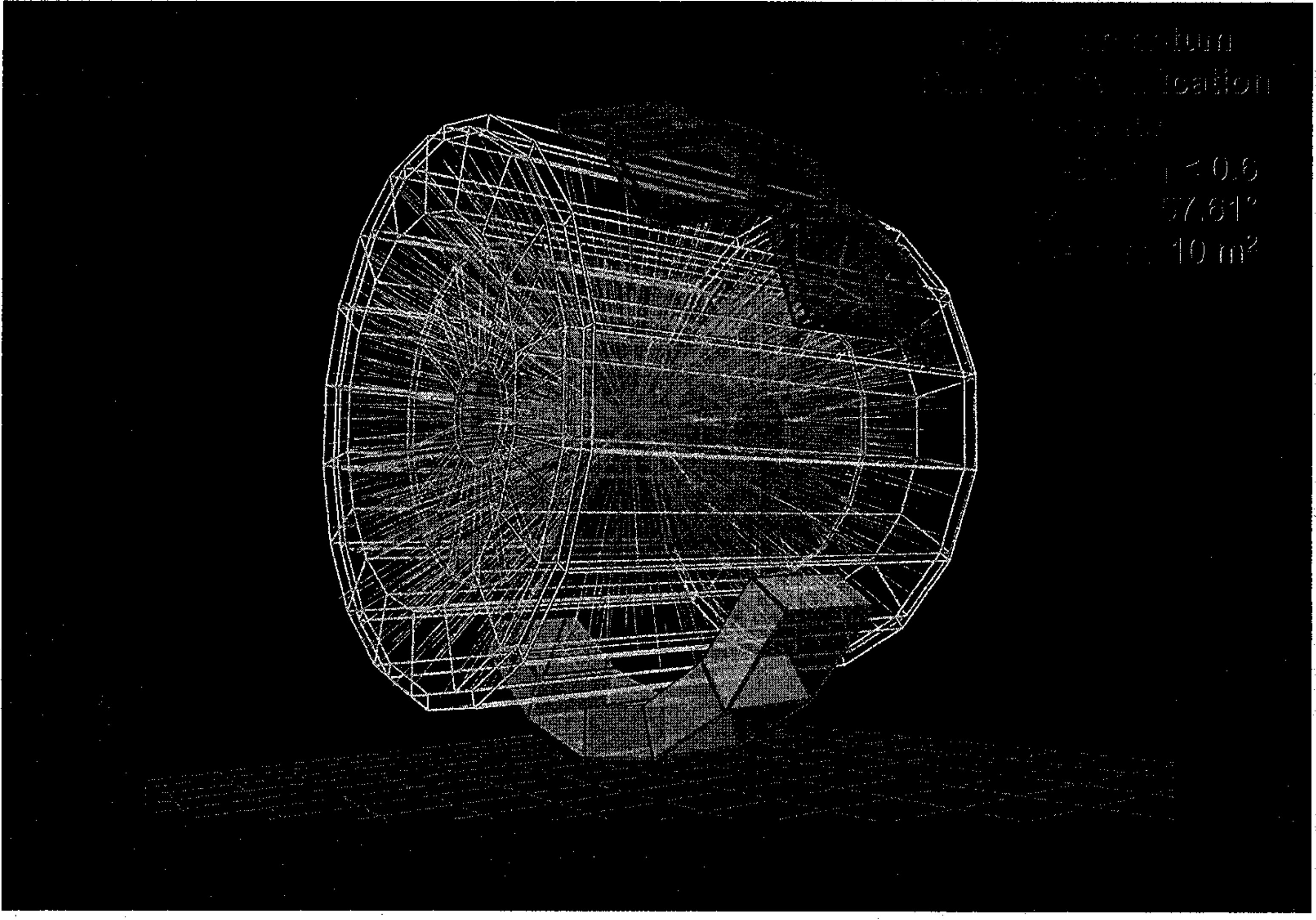
The central detectors of the ALICE experiment



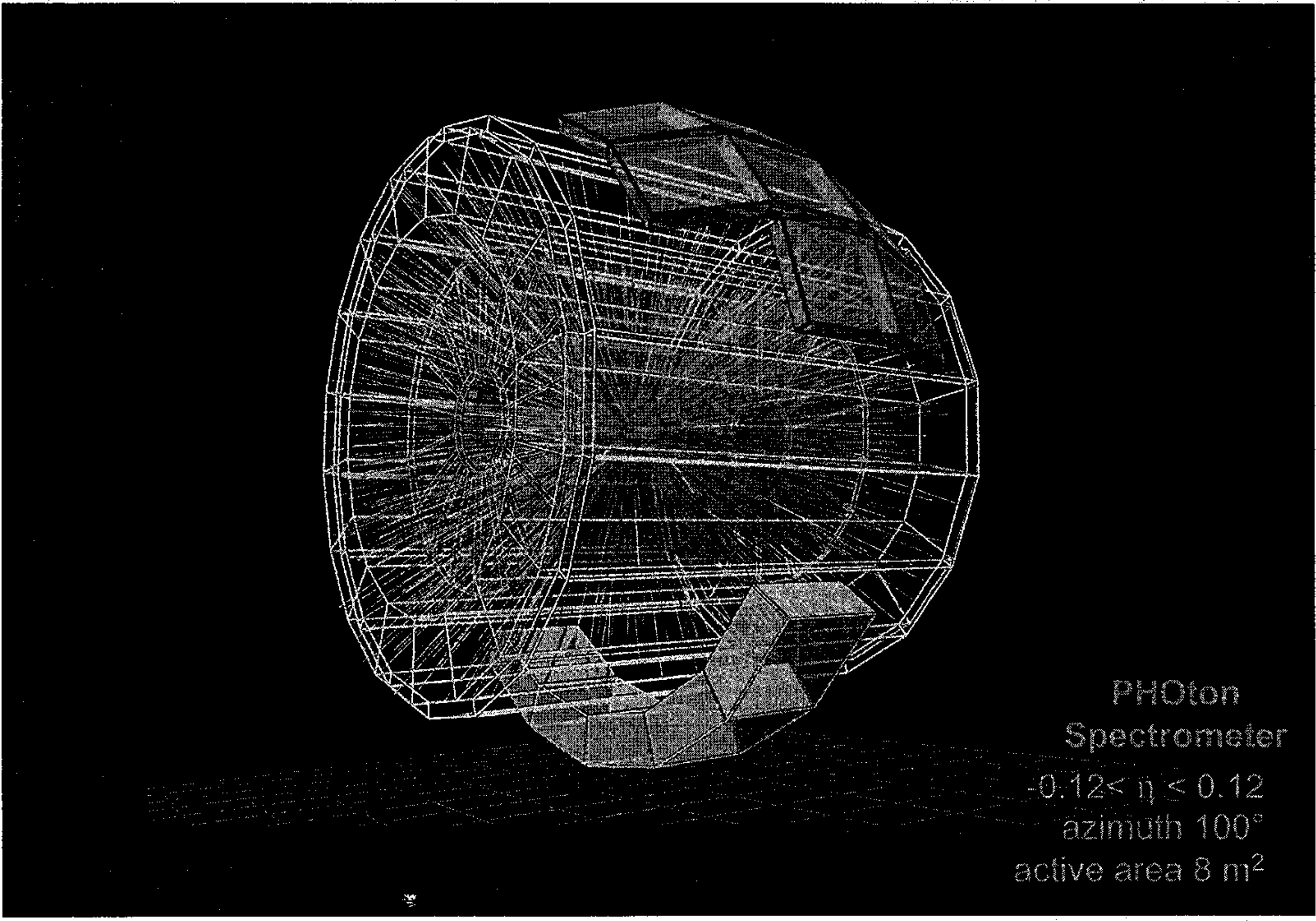
Time Of Flight

$-0.9 < \eta < 0.9$
azimuth 2π
length 7.45 m
active area 141 m^2

The central detectors of the ALICE experiment



The central detectors of the ALICE experiment



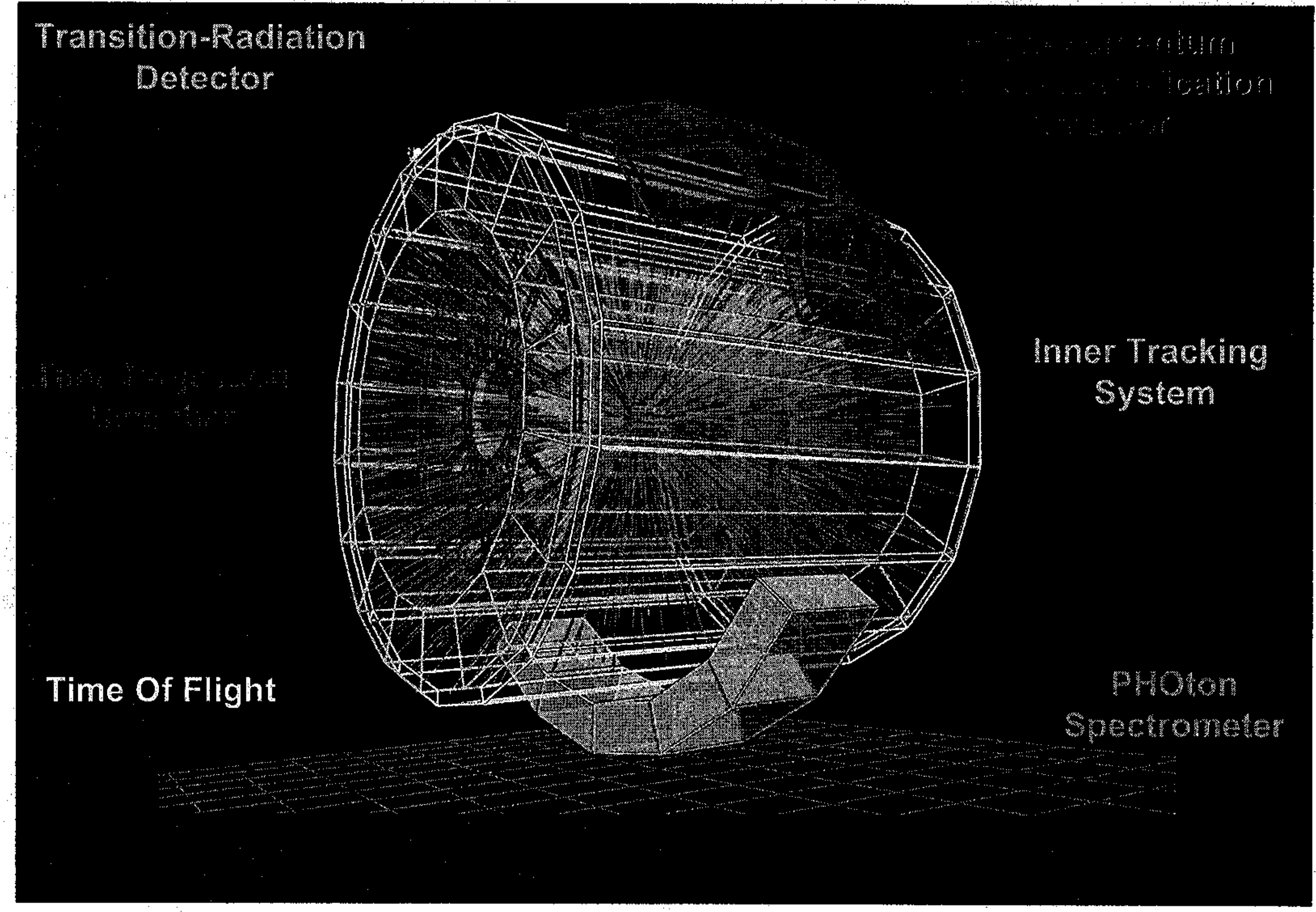
PHOton Spectrometer

$-0.12 < \eta < 0.12$

azimuth 100°

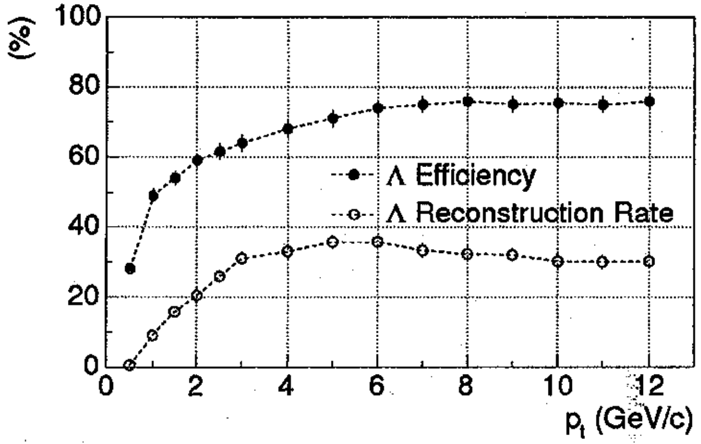
active area 8 m^2

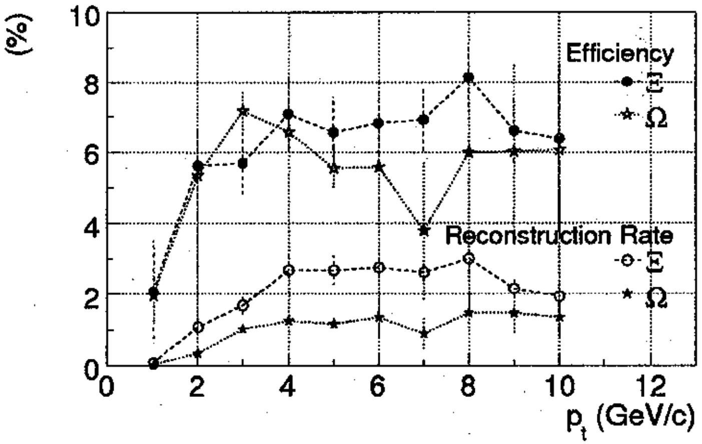
The central detectors of the ALICE experiment



Fiducial volume and reconstruction strategies

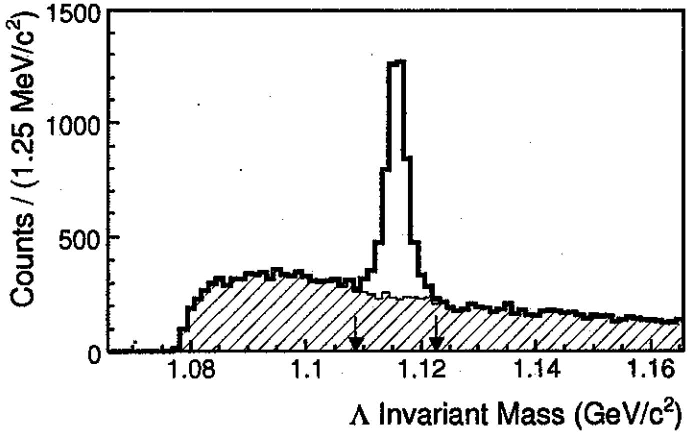
Standard / extended fiducial volume leading to high purity / efficiency for strange particle reconstruction





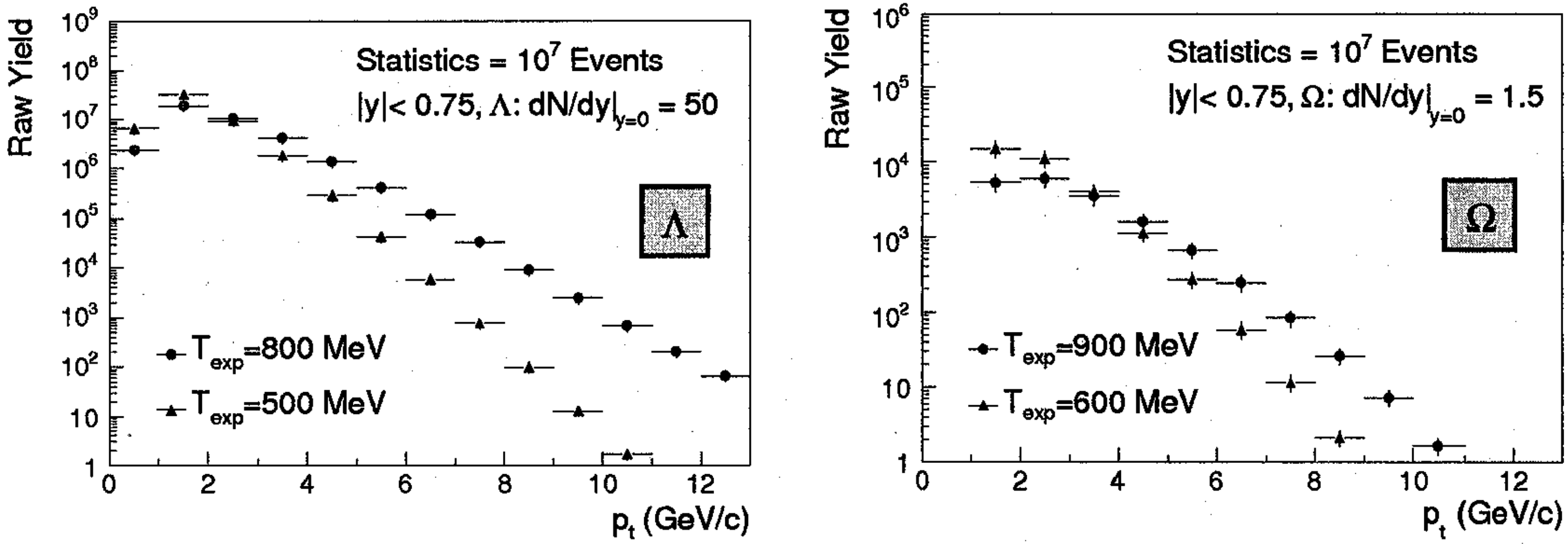
Simulation of hyperons in Pb+Pb

R. Vernet et al. ALICE Internal Note 2005 - 042



⇦ Expected Λ invariant mass distribution for 300 central HIJING simulated events.

Expected raw spectra extrapolated to 10^7 central events (first year Pb+Pb data).



PID Range of ALICE at mid-rapidity

Estimates as in the Physics Performance Report Vol.II
for one year of Pb+Pb data-taking (central events)

10^7 central Pb+Pb events

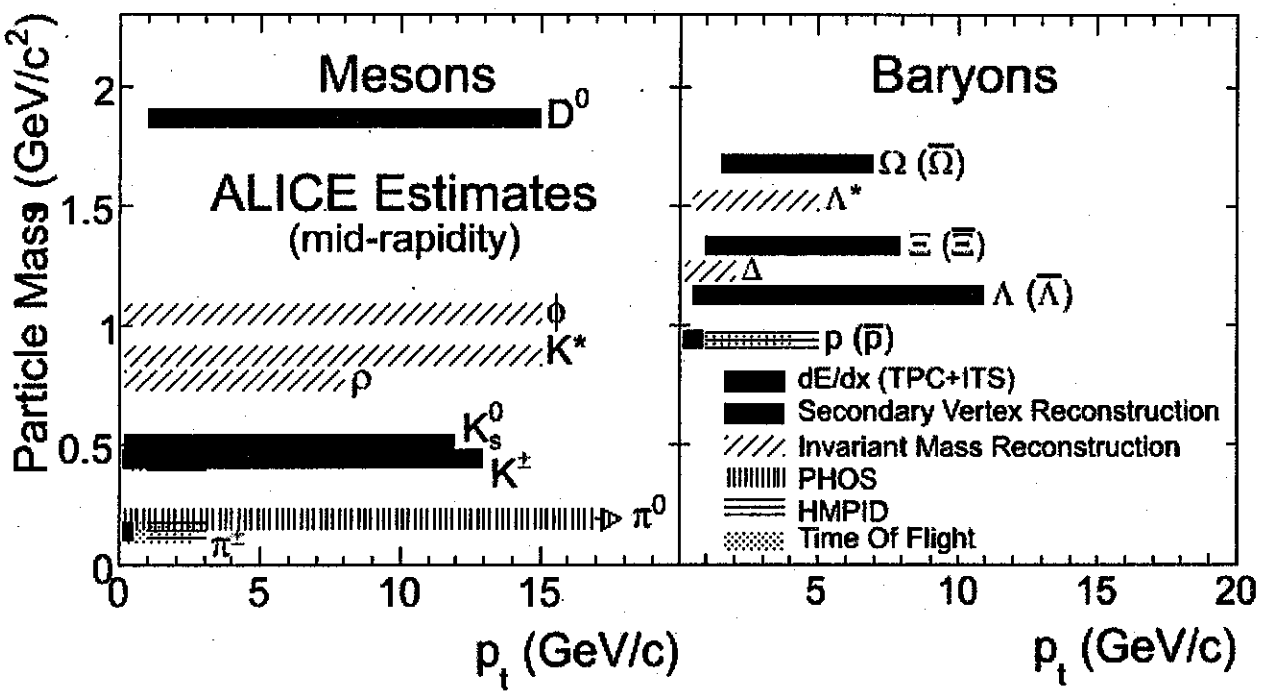
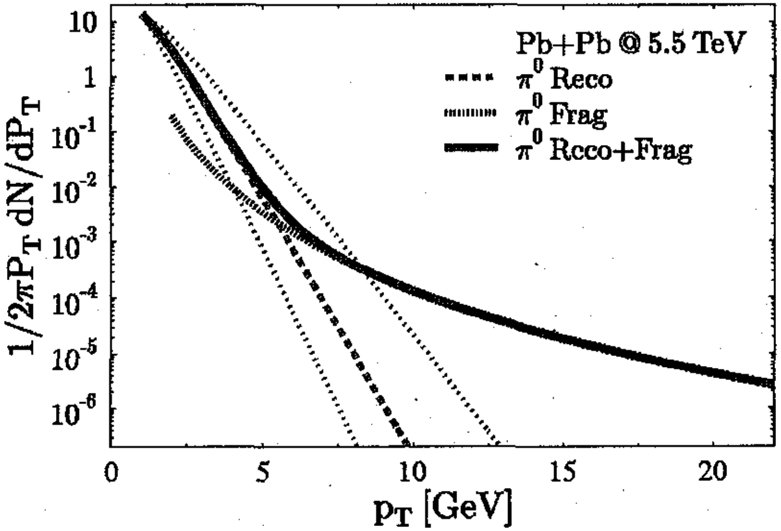


Figure 6.87: Tranverse momentum ranges for particle identification at mid-rapidity using the main sub-detectors of the ALICE experiment. Each range is an estimate for 10 M most central events. Mesons and baryons p_t ranges are shown in the left panel and right panel respectively. Arrows are specified when the PID range exceeds that of the figure i.e. 20 GeV/*c*.

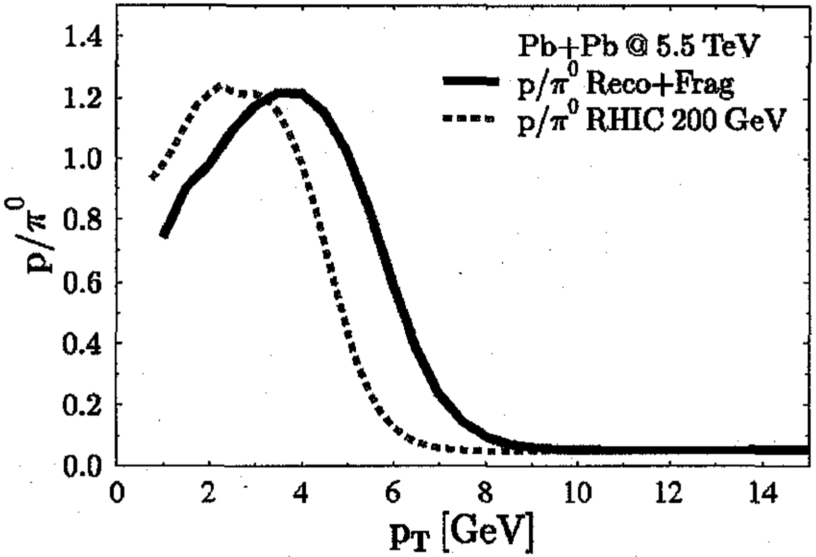
Hadronization via coalescence at LHC energies

Fries and Müller, EJP C34, S279 (2004)

Calculation implies assumption on transverse radial flow extrapolation



Amplitude for mixed ratio is the same at LHC than for RHIC but the limit is pushed to higher p_T



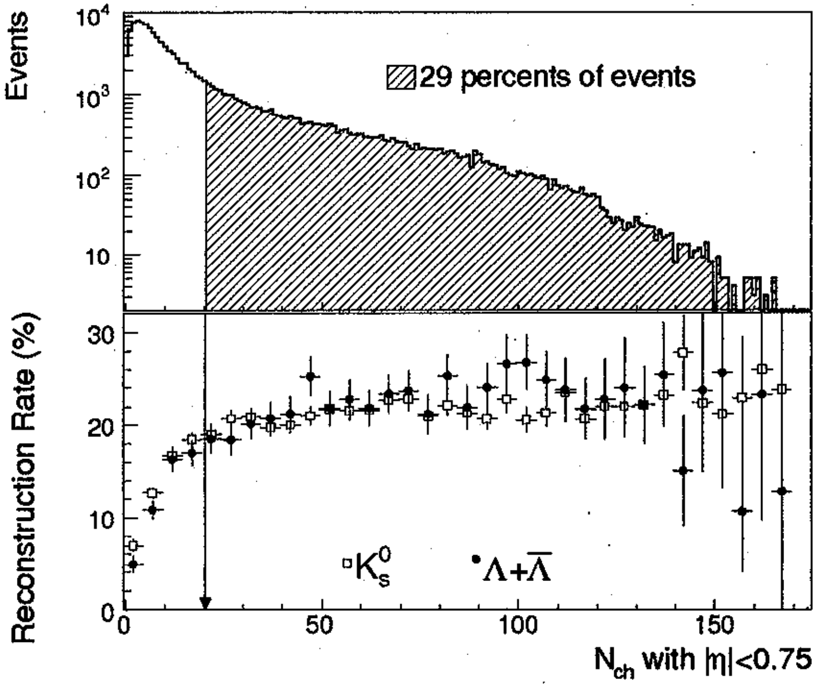
Probing baryon/meson differences at LHC energies implies PID over a large p_T range and ALICE is perfectly designed for this.

But first ALICE data will be elementary collisions ⇨ check magnitude of this behaviour then assume coalescence mechanisms if needed.

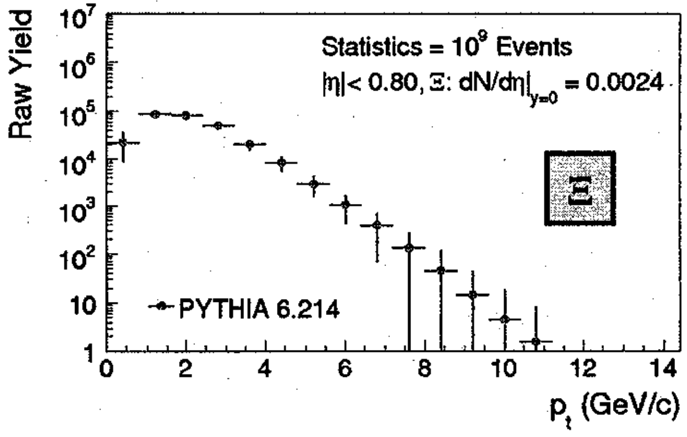
Simulation of hyperons in p+p

L. Gaudichet et al. ALICE Internal Note 2005 - 041

Reconstruction rates for different multiplicity regimes (soft / hard)

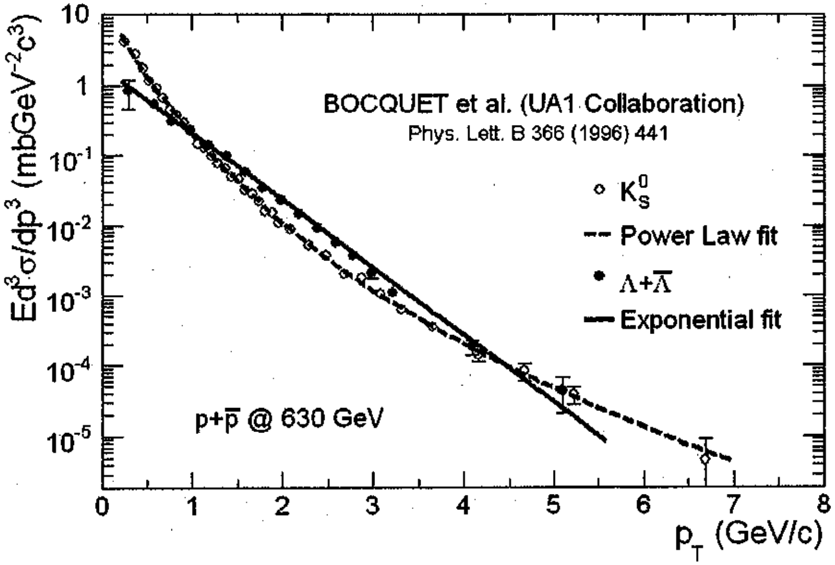


Expected raw spectra extrapolated to 10^9 events (first year p+p data).



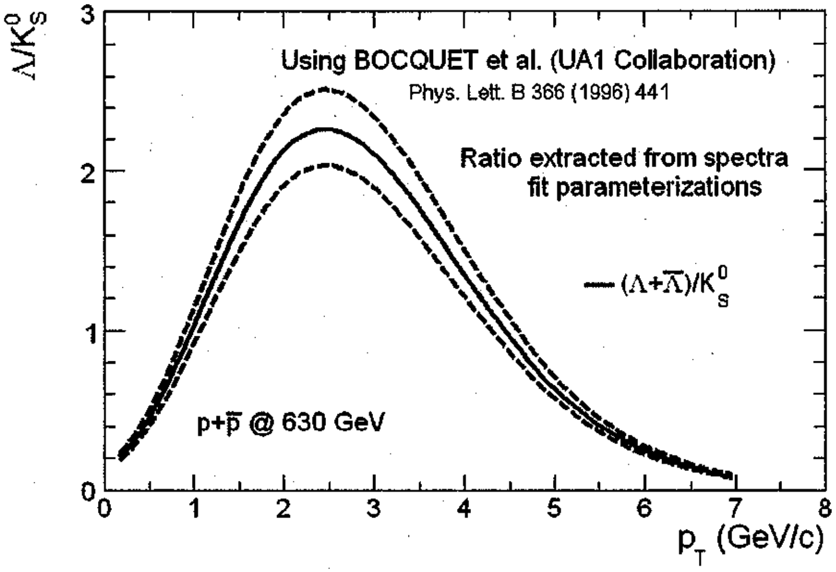
Baryon over meson ratio in p+p collisions (gluonic baryon junction).

Mixed ratio @ UA1: p+$\bar{p}$ @ 630 GeV



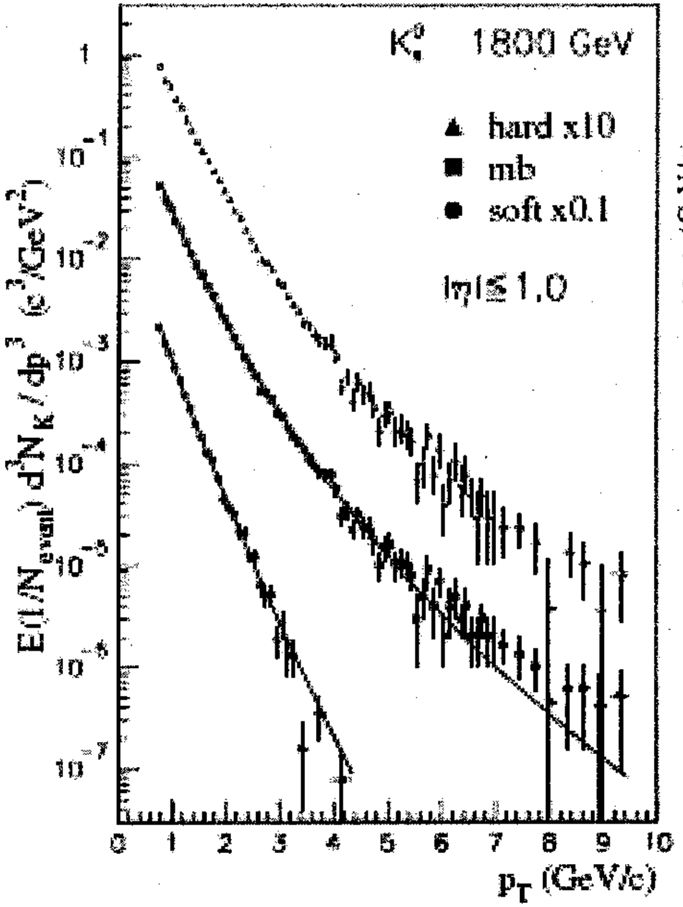
Extracting mixed ratio from 1996 UA1 strange particle data

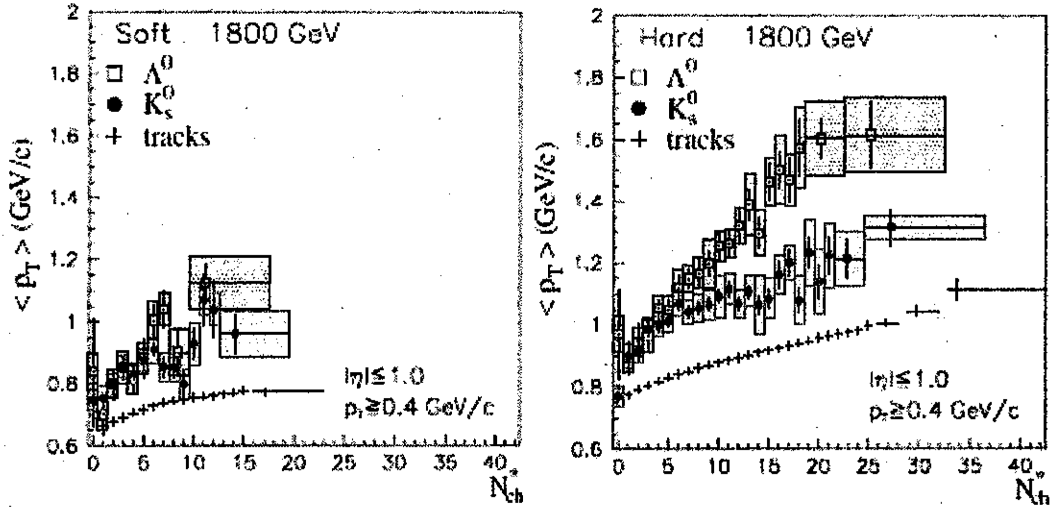
Ratio vs p_T already surprisingly high in p+p data at high energies



Hard/soft/min.bias spectra @ CDF: p+$\bar{p}$ @ 1800 GeV

Extrapolation using CDF strange particle publication: PR **D72** (2005) 052001

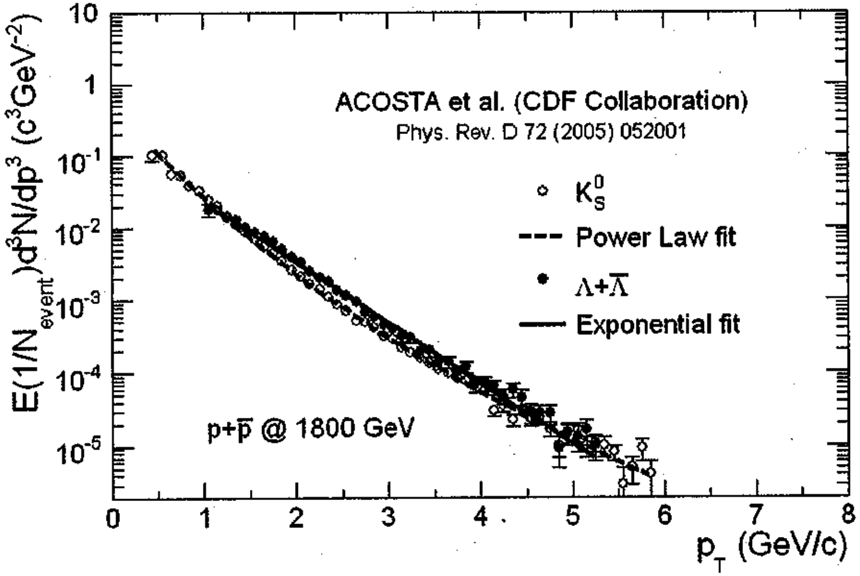




☺ Main difference between preprint and final publication is a comparison with PYTHIA 6.216

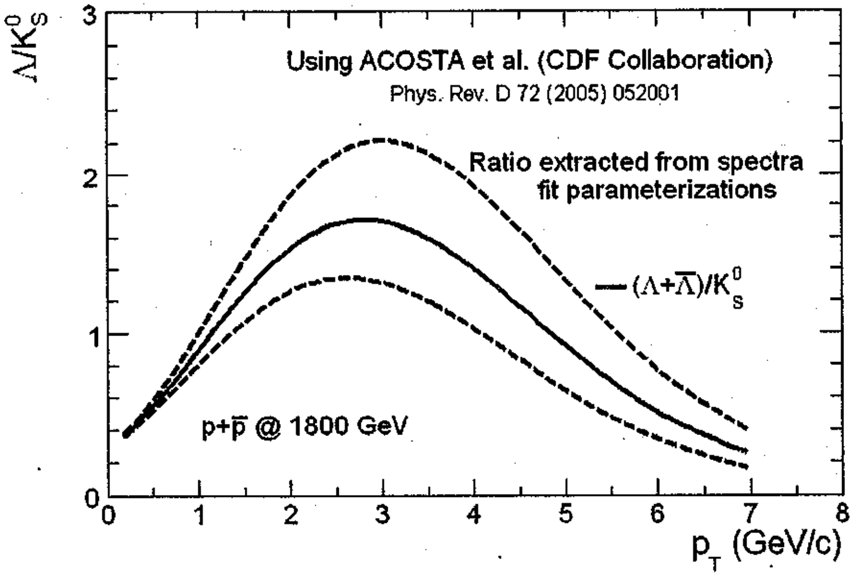
After PYTHIA tuning with pions, the bottom line is min. bias Λ spectra is close but K0s is slightly overestimated

Mixed ratio @ CDF: p+p̄ @ 1800 GeV

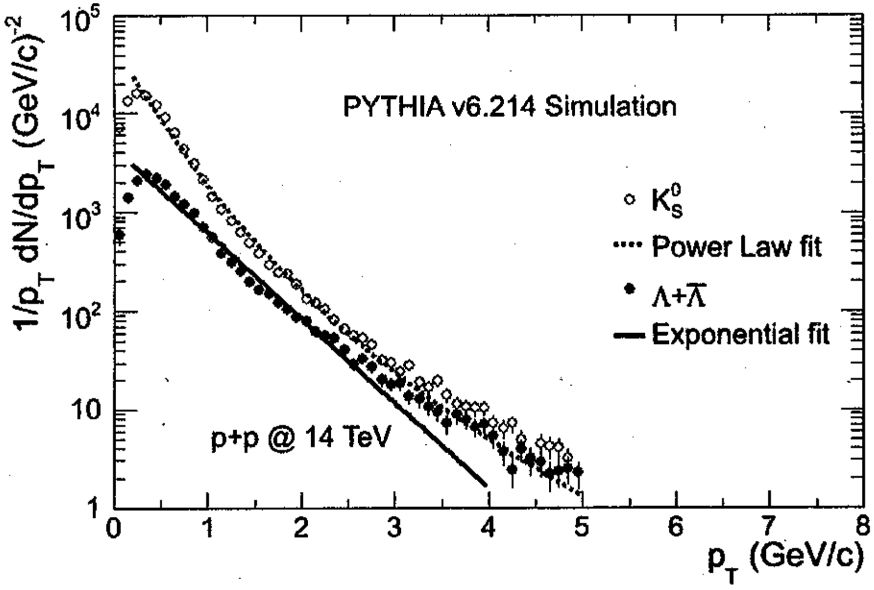


Extracting mixed ratio from 2005 CDF strange particle data

Ratio vs p_T slightly lower but compatible within errors



Mixed ratio using PYTHIA: p+p @ 14 TeV



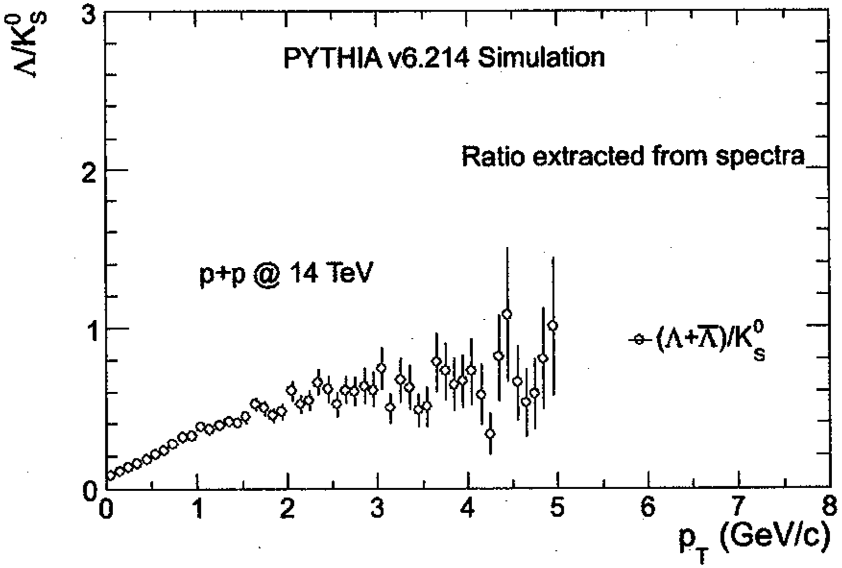
Simulation used for PPR analysis by **L. Gaudichet**

Extrapolation of the main behaviours from RHIC, UA1 and CDF data is currently being investigated.

This feature is **not** observed in default **PYTHIA** at 14 TeV:

1) Going from **LO to NLO** may help getting the **magnitude**;

2) Other **ingredients** may be needed to get the **shape.**



Conclusion

<u>Using strangeness as a powerfull probe at LHC energies with the PID capabilities of the ALICE experiment</u>

a) equilibrium vs non-equilibrium scenario
b) kinetic freeze-out of multi-strange particles
c) hadronization and coalescence validity at LHC

⇨ **strange particles (specific probes and PID) !**

<u>First measurements of strange particles in p+p to extract:</u>

1) interesting for baryon creation mechanisms
2) references for Pb+Pb mandatory

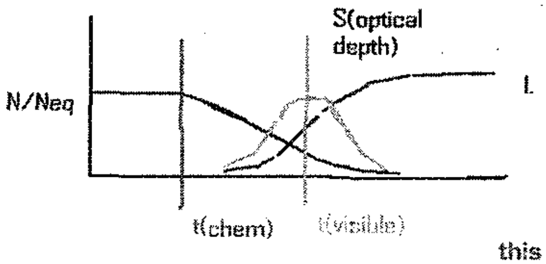
WARNING: minimum bias trigger for p+p !

Testing freezeout by resonances

E.Shuryak, Stony Brook

- **Time when `visible resonances' are produced**
- Absorbtion and optical depth
- [illegible]
- [illegible]
- [illegible]

A time picture



Optical depth = probablity for all Decay product to escape without rescattering

Before t(chem) the decay and production processes are in chemical equilibrium,
After it the production does not keep up with decays

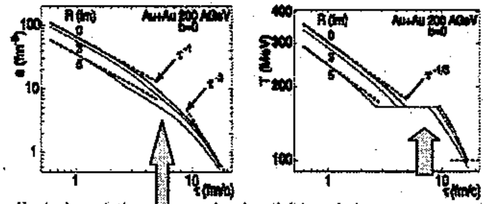
this time, t(visible)
Is the maximum of the production of resonances **visible to the detector**
It is maximal when absobtion of products and their production in the decay have **the same rate!**

Popular (but very naïve) myths

- All hadrons including resonances are produced at the same chemical freezeout time, at "T=Tc"
- after it one can ignore reproduction but include decays only. Also there is no rescattering.

•But, T=Tc is not a time moment but actually a rather long period of time – the mixed phase, about 4 fm/c - in which densities change by a large factor
•At t(chem) both rates are in fact equal, while at very late time reproduction must dominate since it decays as a power of time, not exponent.
•There are no thousends of Maxwell demons which would prevent collisions: trust your (n sigma v) formula!

Universal expansion for RHIC (but different for SPS)



From P.Kolb, nucl-th/0304036

Fig. 1. Evolution of the e[illegible]opy density (left) and the temperature (right) for central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV. Shown are the densities and temperatures at distances $R = 0$, [illegible] and 5 fm from the center of the system.

•Transition from 1d to 3d expansion happens in the mixed phase
•T remains constant till the onset of hadronic phase
• but density changes all the time
• little dependence on r – position of the fluid cell
•But scales with R – the size of the system (centrality)
– because hydro is scale independent

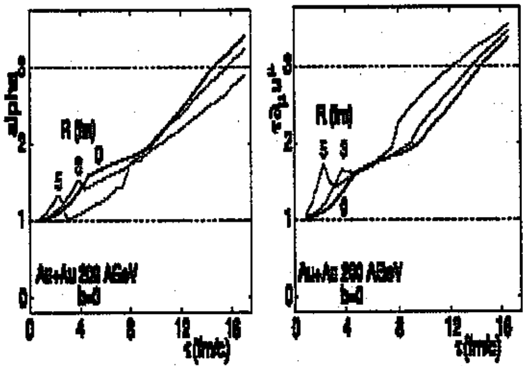


Fig. 3. Evolution of the local expansion parameter α and the product of expansion rate and time. $\tau \partial_\mu u^\mu$ at distances $R = 0, 3$ and 5 fm from the center.

Let me propose very simple parameterization of the volume(t)

$$\alpha = -\frac{\tau}{s}\frac{\partial s}{\partial \tau} = -\frac{\partial \log s}{\partial \log \tau}$$

$$V(\tau) = V(0)\exp\left(\int \alpha(t)dt\right)$$

⇒1+2(tau/tau_fs) till free streaming

⇒3 after that

For those who are not interested in rescattering/absoption

- Select resonances with similar width and decay products, but different internal structure
- PiPi resonaces rho, f0(980) and f2(1200): they all produced at about the same time. Are their ratio thermal (with T at that time)?
- At T=Tc or in QGP s-wave ones (rho,K*) are expected to survive while p-wave (f0,f2) melt down. Does it matter for yields? (if reproduction is very robust, it should not be...)

Two more extreme pipi resonances

- **f0(500) or old sigma meson.** Expected to get shifted toward zero mass at Tc and gets very narrow (suppressed 2pi decays).
- It is the lowest resonance ever, good for cool late stages
- There were STAR indications for it, never published (to my knowledge...)
- Another is **f0(1700) the glueball candidate:**
- Would there be anything special for its production from glue-rich QGP?

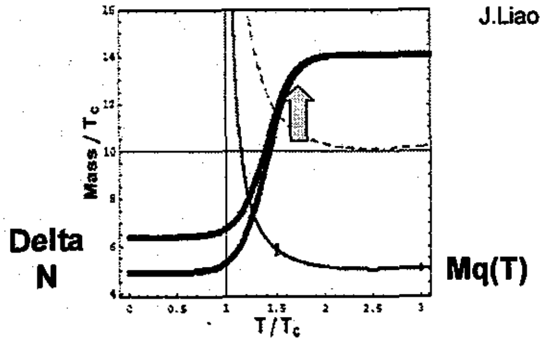
What happens with resonances in QGP/mixed phase?

- S-wave hadrons seem to survive,

Including mesons (rho,K*,phi) and baryons (N,Delta,Y...) up to 1.6Tc or so, getting heavier (!)

- P-wave ones do not (e.g. f_0(980),f_2, Lambda(1520) or N*(1440))
- The **formers show yield larger** than expectation (from chem fr.at Tc), the latter ones more suppressed

Baryons go from light to heavy!



J.Liao, ES hep-ph/

Unlike colored objects, Such as q, qg, qq etc, Baryons (N...) should Evolve through the QCD phase transition Continuously Their mass grows Into the sQGP side because Quasiparticle quarks are heavy

This will generate T and mu Derivatives!

FIG. 5. Masses of various states studied in this work. The thin solid line is for quark and the dashed line is twice quark mass which is roughly for quark-gluon and diquark. The lower thick solid line is for nucleon states and the upper one for Δ states. These masses are used for calculation of Fig.7.

Baryons dominate d4 and d6

$\partial^2\mu I$/$\partial^2\mu$=((2I_3)/B)^2

Derivatives work like this:
- **For quarks d_In/d_n=1**
- **For N and Delta+, Delta0=1/9**
- **For Delta ++ and Delta -=1**

- **For 4 N and 16 Delta = .466**

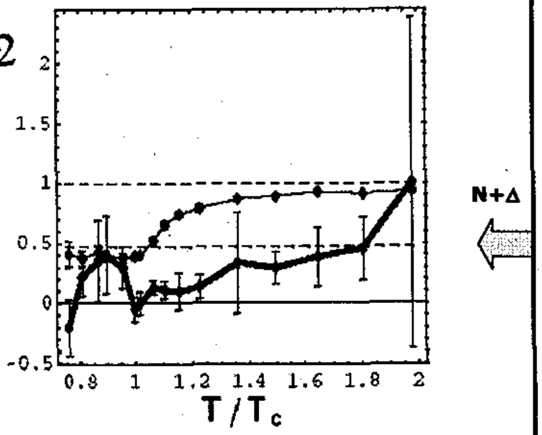


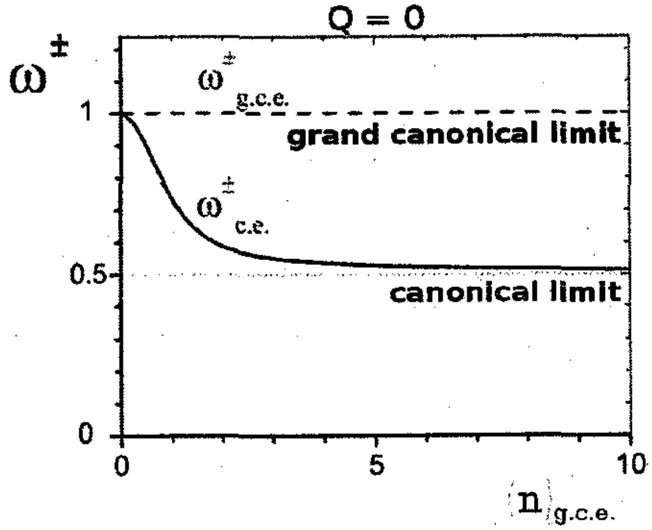
FIG. 6. The susceptibilities ratios d_4^I/d_4 (the thin solid) and d_6^I/d_6 (the thick solid). The dashed lines correspond to ideal quark gas (upper) and ideal baryonic gas (lower).

Statistical Hadronization phenomenology...

G. Torrieri, Physics Department, McGill University
Based on: nucl-th/0510024,0509077,0509067,0503026
(Review coming shortly) In collaboration with
S. Jeon, J. Rafelski, J. Letessier

- The usefulness of fluctuations: They can provide an experimental answer to each of the questions below:
  - Is statistical hadronization really there?
  - What is the strangeness enhancement mechanism?
  - How significant are post freeze-out reinteractions?
  - Is there quark chemical non-equilibrium?
  - What is the chemical freeze-out temperature?
- The pitfalls of using fluctuations,and how to deal with them
  - Volume fluctuations
  - Global conservation laws
  - Detector acceptance corrections for primary particles
  - Detector acceptance corrections for resonances
- Conclusions and use SHARE!

The dependance of fluctuations on yields is Ensemble-specific (Begun,Gorenstein,Gazdzicki,Zozulya)



It is very unlikely for the incorrect ensemble to describe both yields and fluctuations with the same parameters

If canonical ensemble is a good description of strangeness in p-p collisions, than it has to describe strangeness fluctuations in p-p collisions with same T,V as yields

Third question: How much re-interaction between chemical and thermal freeze-out?

Consider $Y^* \to Y\pi(\text{eg } K^* \to K\pi, \Delta \to p\pi)$

$\sigma_{Y/\pi}$ probes correlation of Y and π from Y^* at chemical freeze-out.

$$\sigma_{Y/\pi} = \frac{\langle(\Delta Y)^2\rangle}{\langle Y\rangle^2} + \frac{\langle(\Delta\pi)^2\rangle}{\langle\pi\rangle^2} - \frac{2}{\langle Y\rangle\langle\pi\rangle} \underbrace{\langle \Delta Y \Delta\pi\rangle}_{Y^* \to Y\pi}$$

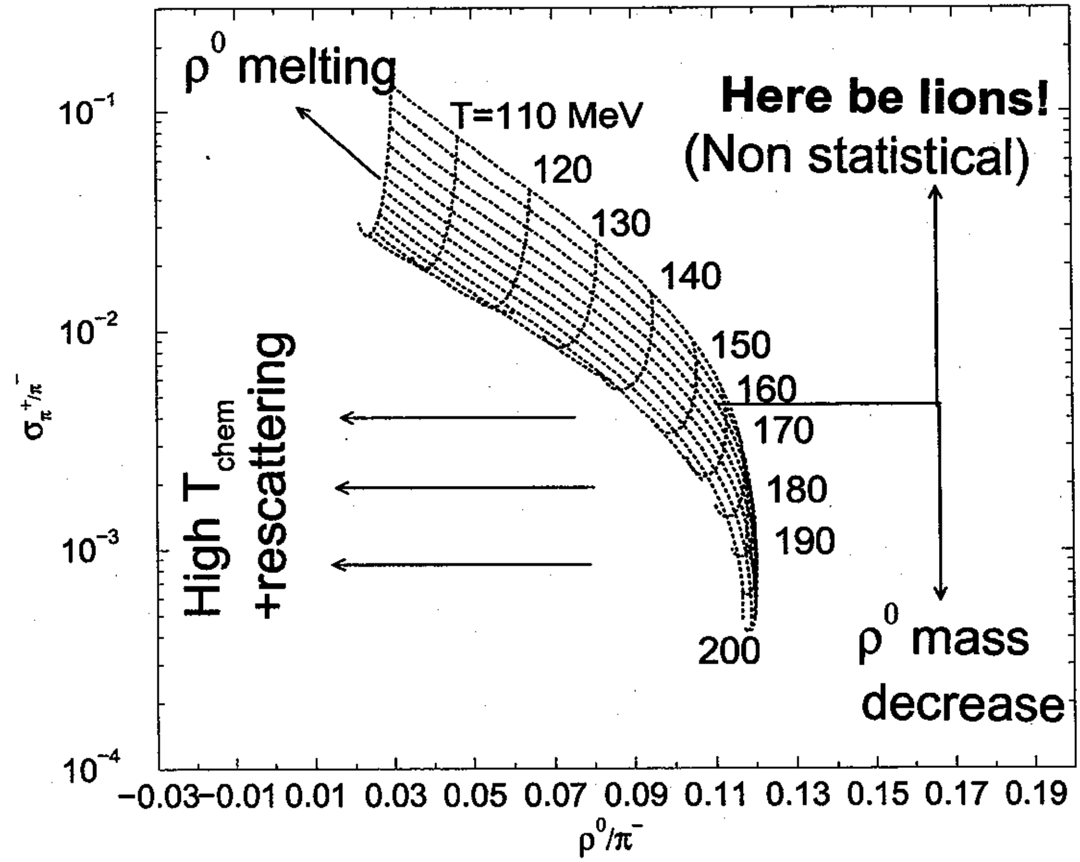
(further rescattering/regeneration does not change the correlation.)

Y^*/Y **yield** probes Y^*at thermal freeze-out (after all rescattering.

So...

- If can fit stable particles and resonances and fluctuations in same fit → no reinteraction
- If Stable particles+ Fluctuations fit gives wrong value for resonances → magnitude of reinteraction

σ_{π^+/π^-}vs ρ^0/π^-
Probes (lack of?) reinteraction and mass modification separately



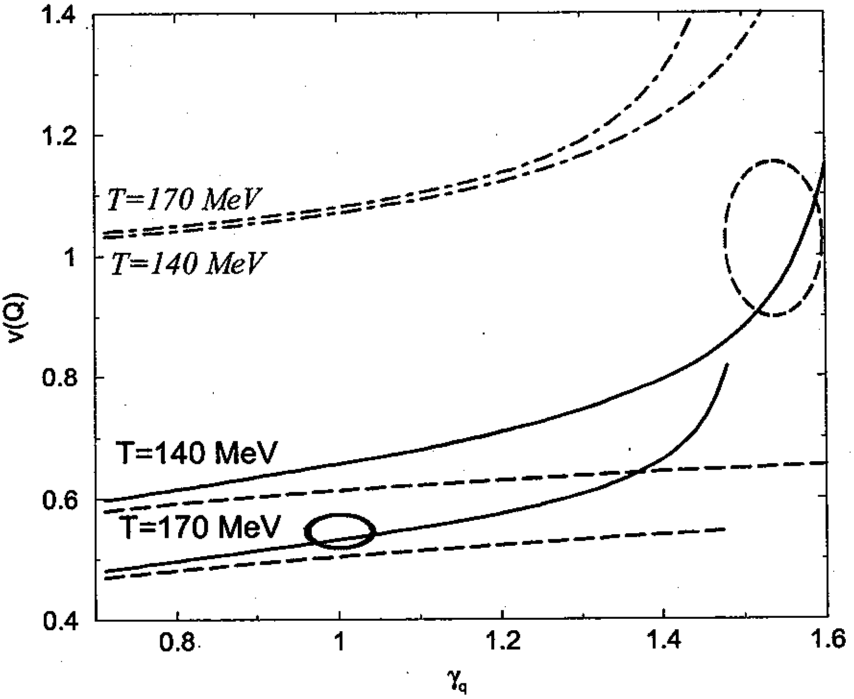
(I am cheating a bit here since σ_{π^+/π^-} contains a volume dependance... but as we will see, this is easy to get around!

Third and fourth questions

We heard about 2 statistical models!

Equilibrium statistical model	Non-equilibrium
oven-like	Explosion-like
High T (~ 165 MeV)	Supercooled (~ 140MeV)
Equilibrium ($\gamma_{q,s} = 1$)	Over-saturation ($\gamma_{q,s} > 1$)
Staged freeze-out	Sudden freeze-out
Resonances don't freeze-out at same T	Resonances freeze-out at same T
Strangeness systematics due to approach to thermodynamic limit (Canonical → GC)	Strangeness systematics due to phase transition γ_s/γ_q grows since more s/Q in QGP
No info on phase transition	First order or sharp cross-over
No info on early phase	Early phase probed

Fluctuations: Non-equilibrium



T increase ⇒ π Fluctuations decrease because of enhanced resonance production
Resonances affect correlations

over-saturation $(\gamma_q > 1)$ ⇒ π Fluctuations increase faster than yields because of BE corrections

$$\gamma_q^2 e^{m_\pi/T} = 1-\epsilon \Rightarrow \frac{\langle N_\pi \rangle}{V} \sim \epsilon \qquad \frac{\left\langle (\Delta N_\pi)^2 \right\rangle}{V} \sim \epsilon^2$$

$\gamma_q > 1$ affects primordial fluctuations so can's compensate for T

Strangeness and multi-strangeness in pp, dAu and AuAu at RHIC, within HIJING/$B\bar{B}$ v2.0 model.

Workshop Strangeness in Collisions,
BNL-Rieken, February 16-17, 2006

V. Topor Pop

McGill University, Montreal, Canada

Collab.
J. Barrette, C. Gale, McGill Univ.
M. Gyulassy, Columbia University, NY
R. Bellwied, Wayne State University

Acknowledgements
N. Xu, X. N. Wang, S. Jeon

Phys .Rev. C72, 054901 (2005)

Phys .Rev. C70, 064906 (2004)

Phys .Rev. C69, 054906 (2004)

Phys .Rev. C68, 054902 (2003)

and Work in progress

HIJING/B$\bar{\text{B}}$ v2.0 +(SCF) 04

- In microscopic string models the heavier flavors are suppressed according to Schwinger formula:

$$\gamma_Q = \frac{P(Q\bar{Q})}{P(q\bar{q})} = exp\left(-\frac{\pi(m_Q^2 - m_q^2)}{\kappa}\right)$$

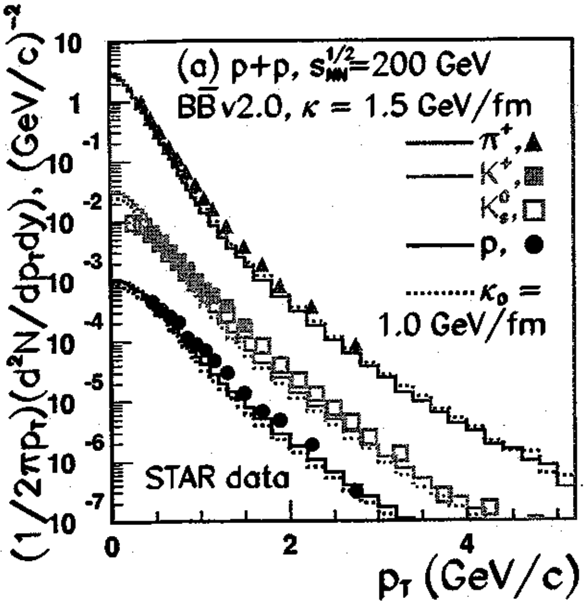
  $\kappa = |eE|$ is the *string tension*; m_Q is a quark mass; (Q=s for strange quark; Q=qq for a di-quark), and q=u,d are the light nonstrange quarks.

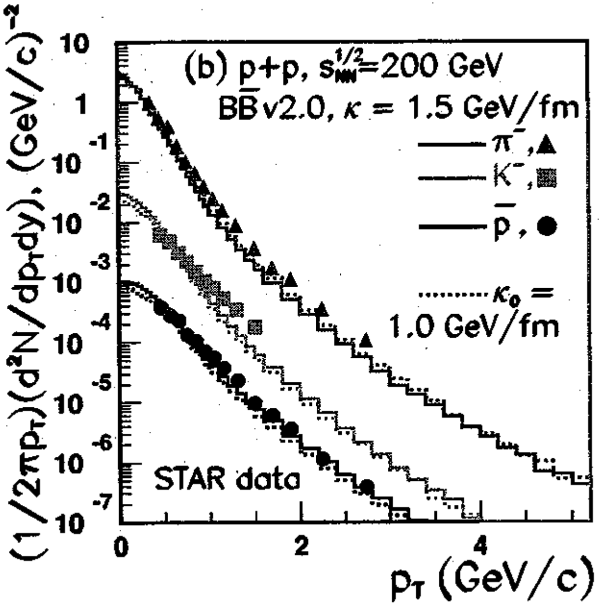
- Two possible processes leading to an increase of (multi) strangeness production. i) increasing the field strength by a modified string tension κ = (1-3) κ_0; $\kappa_0 \approx 1$ GeV/fm. or ii) dropping the quark masses due to chiral symmetry restoration (Brown, Rho PRL66(91)).

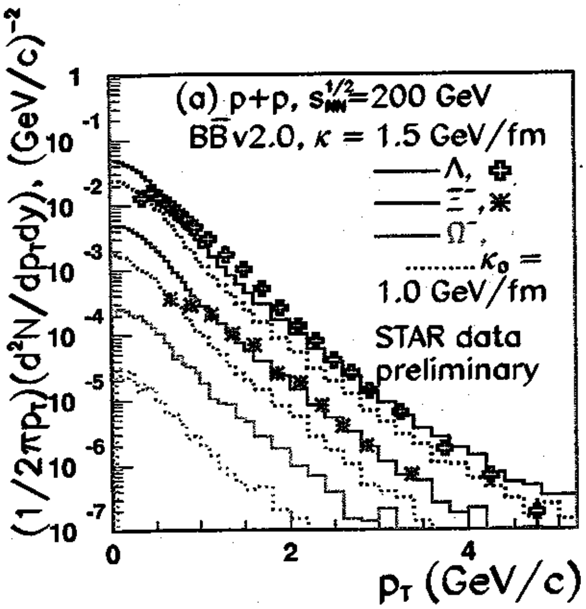
- The *current quark masses* (PDB-PLB592(04)): m_u =1.5-5 MeV; m_d=3-9 MeV, m_s=80-190 MeV; di-quark m_{qq}=450 MeV (Ripka, PRD71(05)). *The Constituent quark masses* $M_{u,d}$= 230 MeV, M_s=350 MeV, M_{qq}=550 ± 50 MeV.

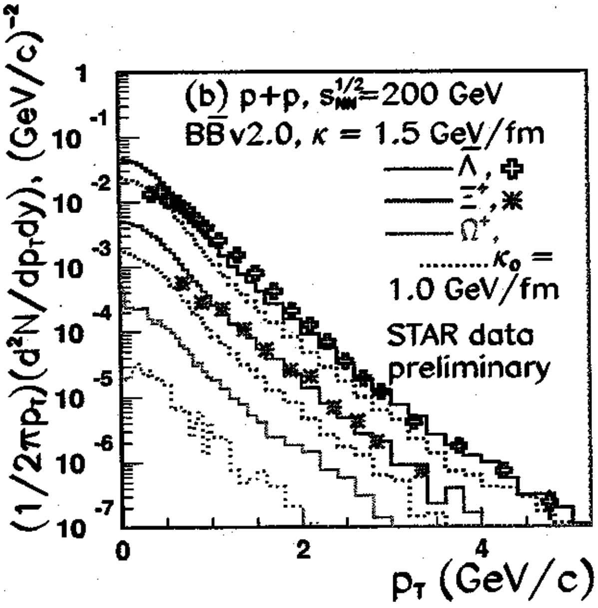
- Schwinger tunneling: could explain the thermal caracter of spectra; if κ fluctuates we can define an apparent temperature $T = \sqrt{<\kappa>/2\pi}$ (Florkowski, AP Polonica(04).); ($T \approx$ 250 MeV, for $<\kappa> = 2$ GeV/fm); ($T \approx$ 310 MeV, for $<\kappa> = 3$ GeV/fm)

Upper: p,π^+,K^+ (left); $\bar{\text{p}}$,π^-, K^- (right).
Lower: Λ,Ξ^-,Ω^- (left); $\bar{\Lambda}$,$\bar{\Xi}^-$, $\bar{\Omega}^-$ (right).

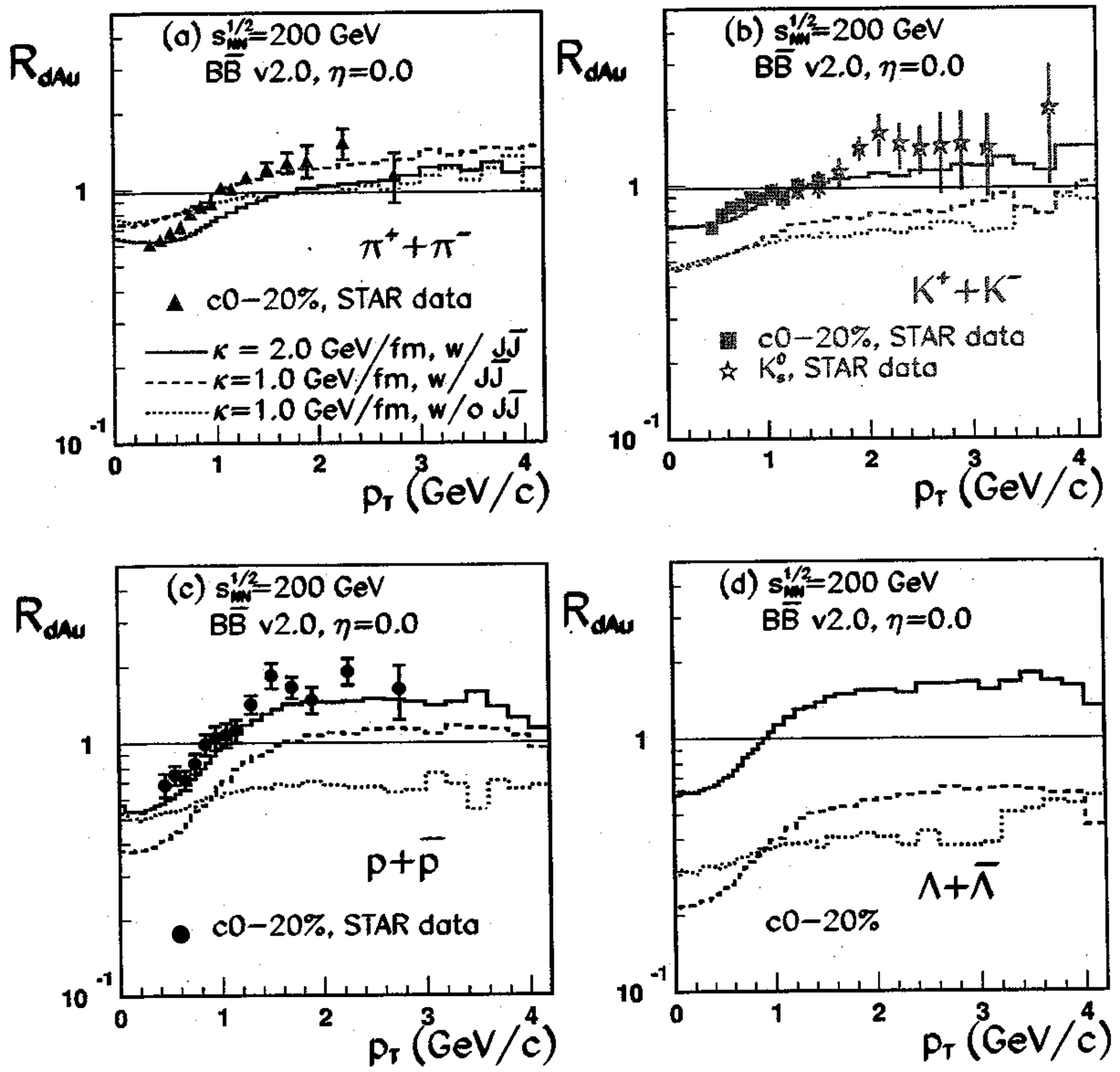




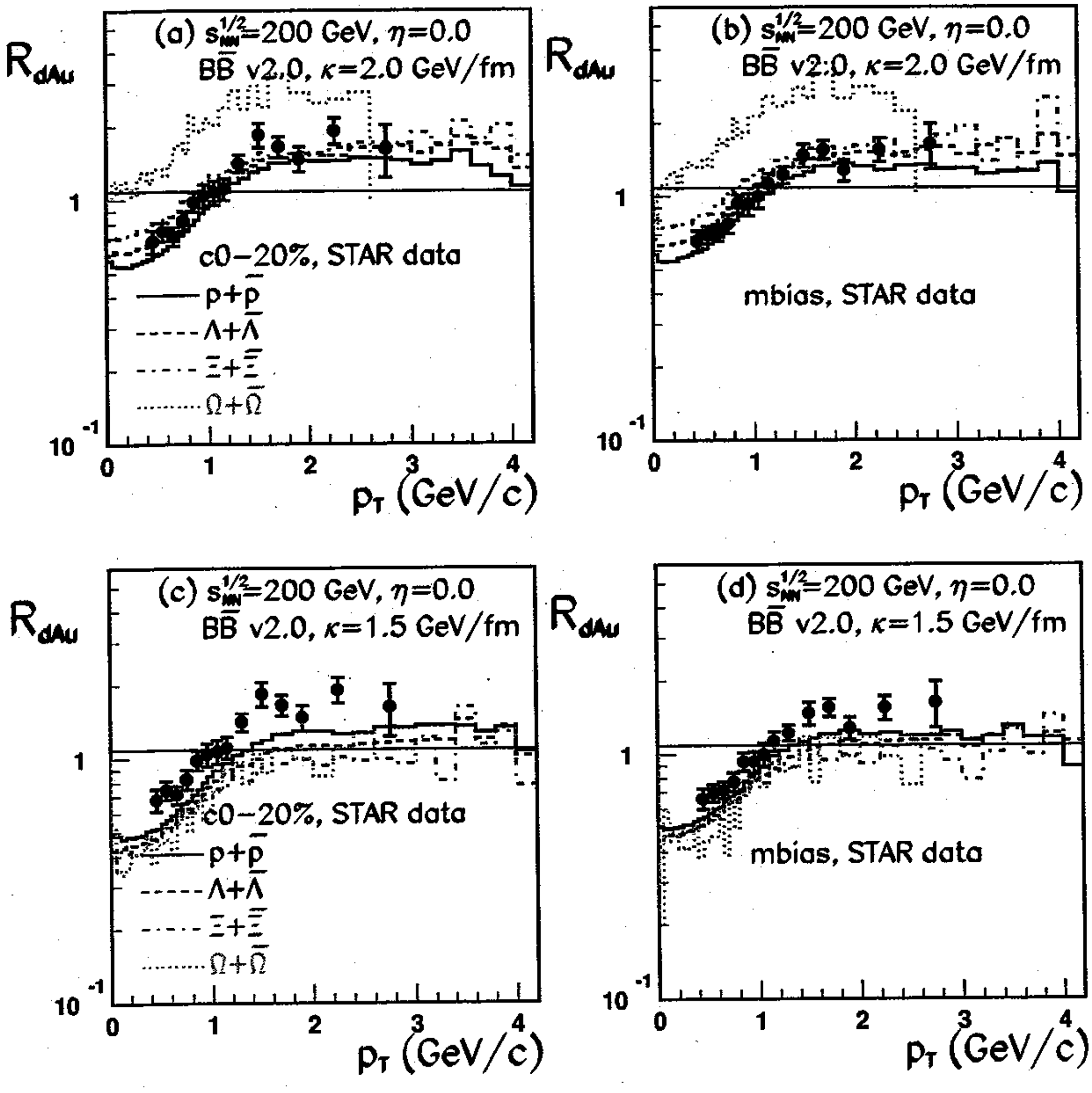




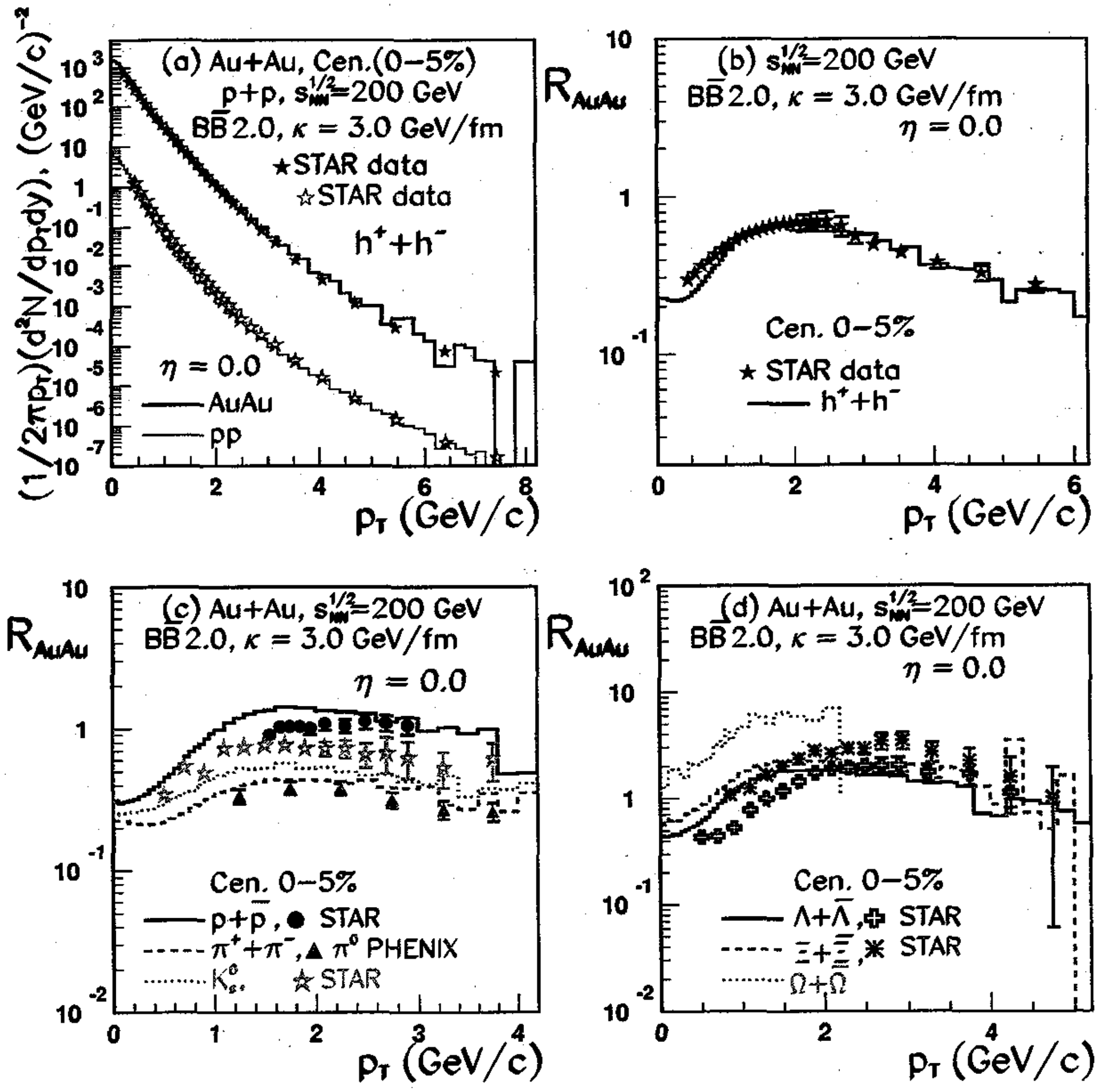
R_{dAu}; ID particles.
Centrality 0-20% (N_{part}=14.7)



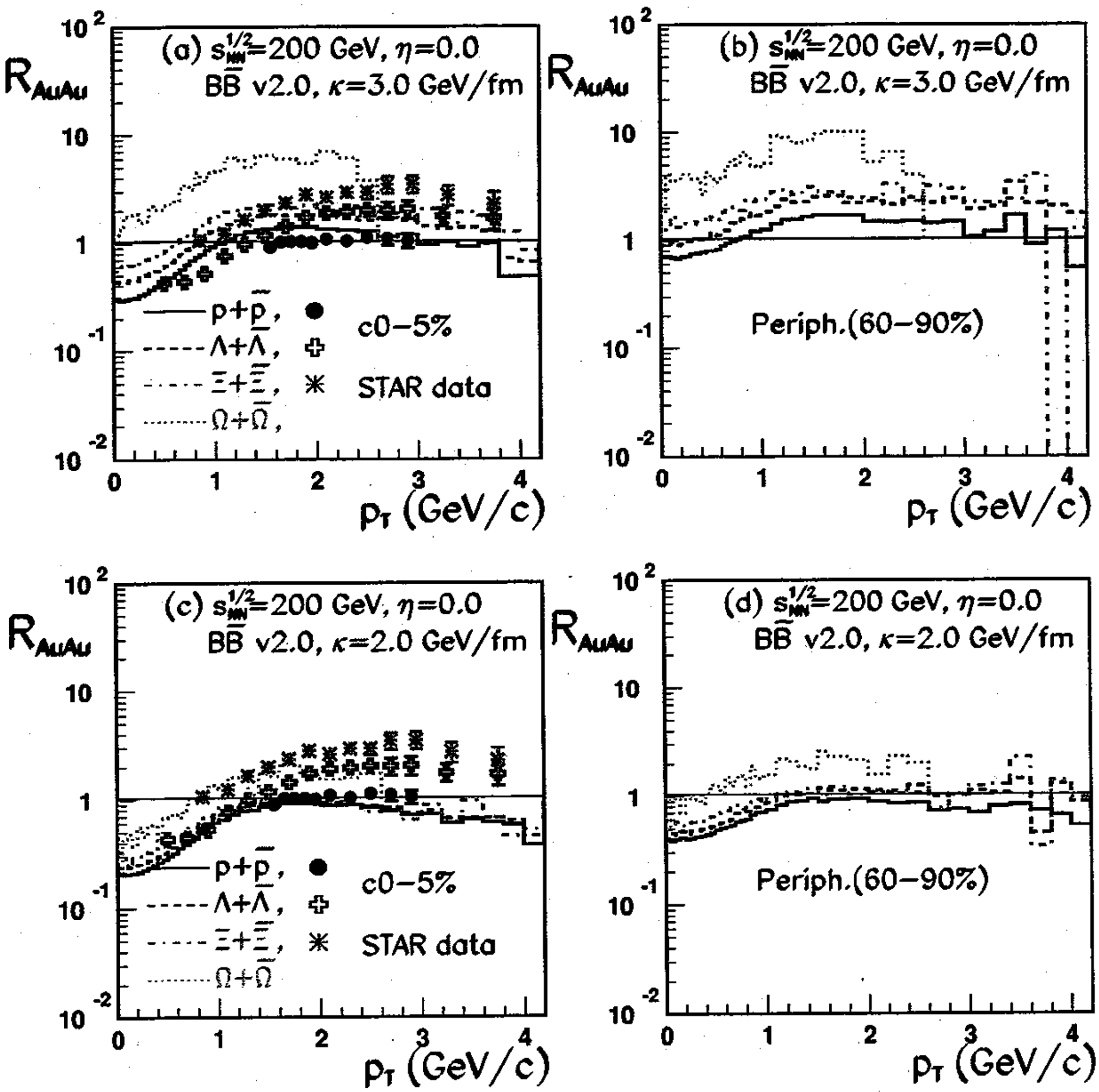
Sensitivity to string tension κ.
R_{dAu}; ID particles.
Centrality 0-20% (left); Minbias (right).



$h^+ + h^-$, p_T spectra. (left); R_{AuAu} (right). Lower: Centrality 0-5%; ID particles.



Sensitivity to string tension κ. R_{AuAu}; ID particles. Cen.0-5% (left); Periph.60-90% (right).



Summary and Conclusions 01

- Multi-gluon dynamics, "gluon junctions" play an important role in particle production at mid-rapidity at RHIC.
- Introducing a corrected junction loop algorithm leads to a significant improvement in the description of the recent RHIC data.
- The strange and multistrange particles could only be described in the framework of string models, if we consider strong color field effects SCF.
- A greater sensitivity to SCF effects was predicted for the nuclear modification factors of (multi)strange hyperons. The measurement of Ω and $\bar{\Omega}$ yields would provide an important test of the consistency of SCF and baryon junction mechanisms at RHIC.
- The full understanding of the production of (multi)strange particles in relativistic heavy-ion collisions remain an exciting open question.

Parton Ladder Splitting and Fusion: How to Understand Particle Production at RHIC and LHC

Klaus Werner[1] [2], **Nantes**

Claim: All pp, dAu, AuAu data at RHIC, pp, CC, SiSi, PbPb data at SPS can be understood within a single picture!

1 Basic ideas

☐ Take a sophisicated parton model (EPOS), which works at pp, and which is formulated such that it can be generalized towards AA (unlike Pythia).

☐ Add an effective treatment of parton ladder splitting to account for nuclear effects in pA or dA (EPOS+).

☐ Add another feature, important for AA (EPOS++): consider the possibility that pieces of parton ladders (mainly in the middle) interact -> fuse to form clusters, when corresponding densities are high.
Let the clusters decay according to phase space (covariant microcanical procedure), allowing for radial flow (two parameters), at some given energy density (parameter). Very few parameters !!

☐ Works excellently for small pt's! Enormous predictive power! There are essentially three parameters, very little freedom, centrality dependence, system size dependence, is really predicted, nothing to tune.

☐ Works even for intermediate pt's, with the exception of pions in central AuAu collisions...

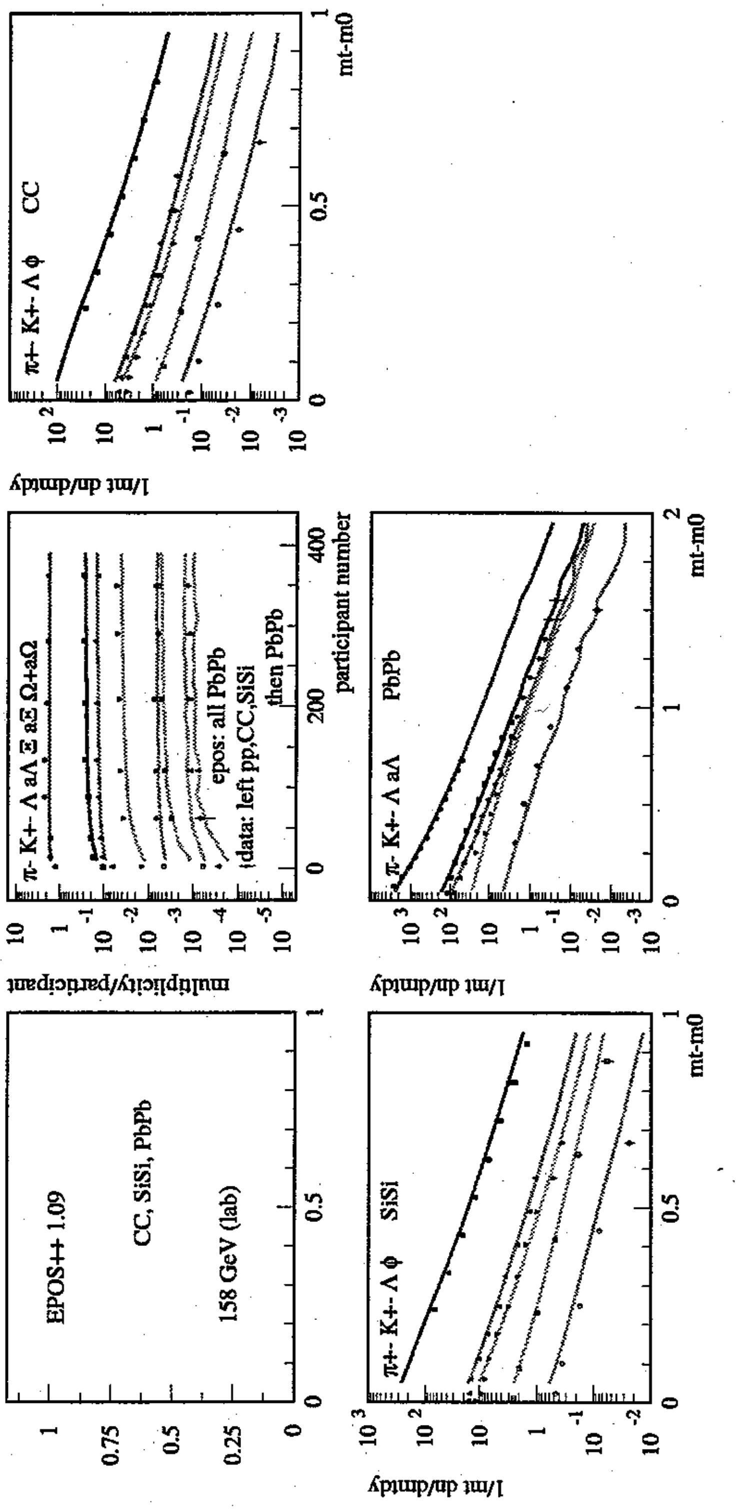
but this should be so
(see discussion at the end)

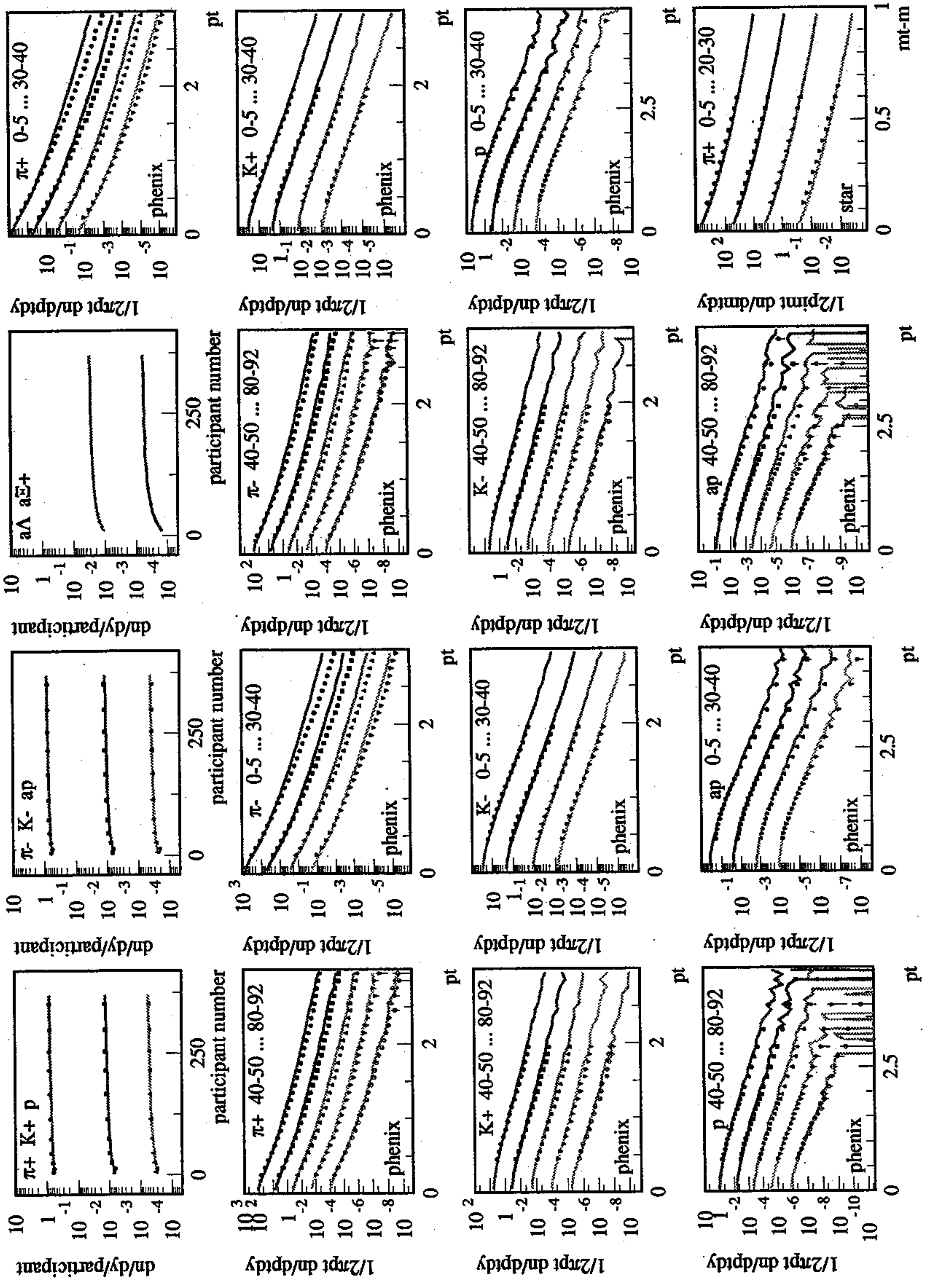
☐ There are some small deviations, but the RHIC simulation curves are ususally between the PHENIX and STAR data points[3].

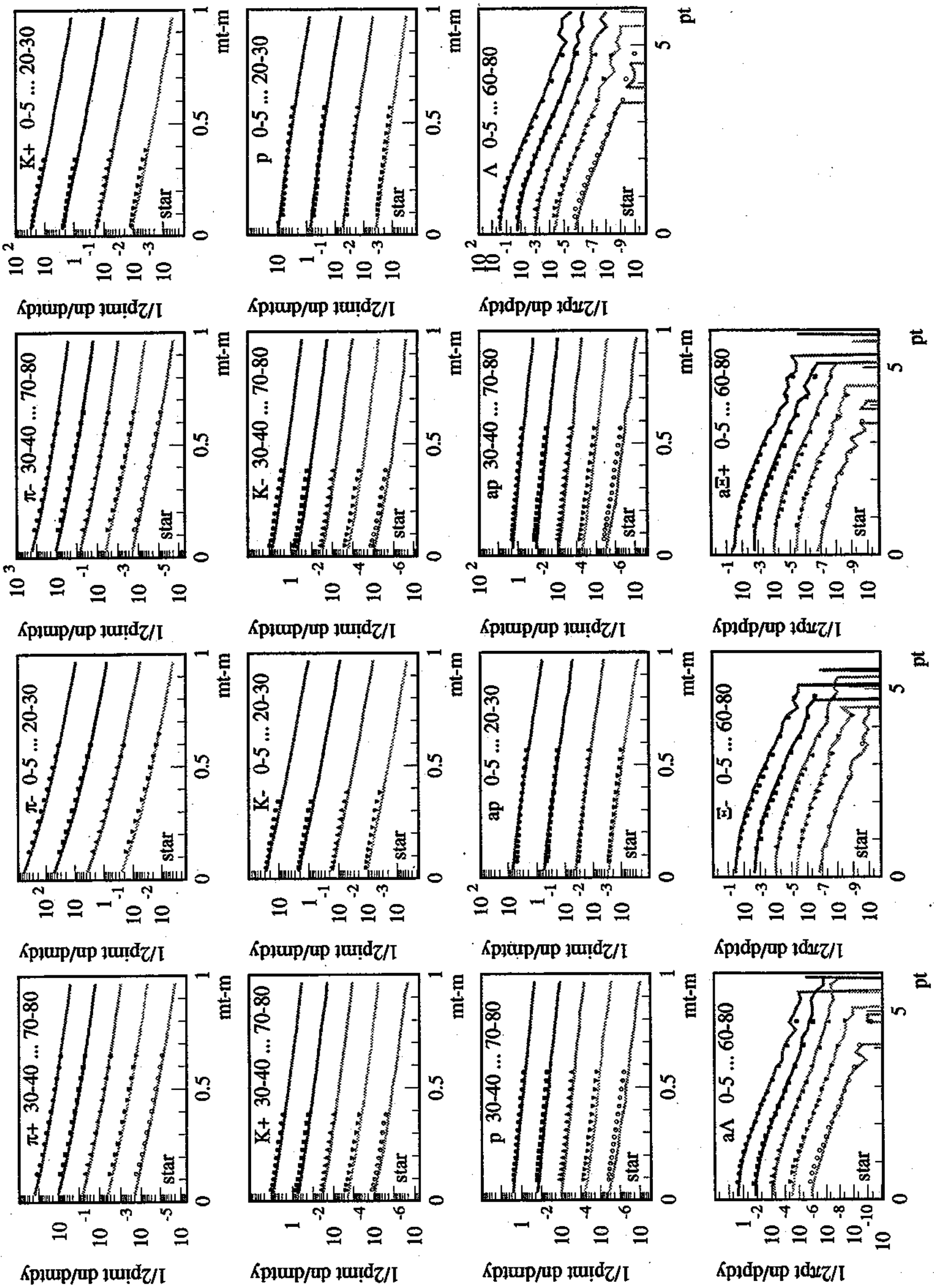
---

[1] werner@subatech.in2p3.fr
[2] in collaboration with F.M. Liu, T. Pierog
[3] presented differently, so I cannot plot them together

2 Spectra

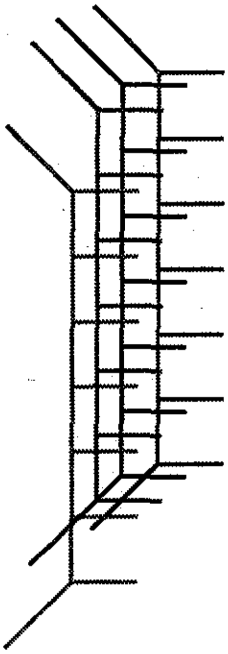

EPOS++ 1.09
CC, SiSi, PbPb
158 GeV (lab)
π- K+- Λ aΛ Ξ aΞ Ω+aΩ
epos: all PbPb
data: left pp,CC,SiSi
then PbPb
multiplicity/participant
participant number
π+- K+- Λ φ CC
π+- K+- Λ φ SiSi
π- K+- Λ aΛ PbPb
1/mt dn/dmtdy
mt-m0


π+ K+ p
π- K- ap
aΛ aΞ+
dn/dy/participant
participant number
0
250
π+ 0-5 ... 30-40
π- 0-5 ... 30-40
π+ 40-50 ... 80-92
π- 40-50 ... 80-92
K+ 0-5 ... 30-40
K- 0-5 ... 30-40
K+ 40-50 ... 80-92
K- 40-50 ... 80-92
p 0-5 ... 30-40
ap 0-5 ... 30-40
p 40-50 ... 80-92
ap 40-50 ... 80-92
π+ 0-5 ... 20-30
phenix
star
1/2πpt dn/dptdy
1/2πmt dn/dmtdy
pt
mt-m
0.5
1
2
2.5


π+ 30-40 ... 70-80
π- 0-5 ... 20-30
π- 30-40 ... 70-80
K+ 0-5 ... 20-30
K+ 30-40 ... 70-80
K- 0-5 ... 20-30
K- 30-40 ... 70-80
p 0-5 ... 20-30
p 30-40 ... 70-80
ap 0-5 ... 20-30
ap 30-40 ... 70-80
Λ 0-5 ... 60-80
aΛ 0-5 ... 60-80
Ξ- 0-5 ... 60-80
aΞ+ 0-5 ... 60-80
star
1/2pimt dn/dmtdy
1/2πpt dn/dptdy
mt-m
pt
0
0.5
1
5

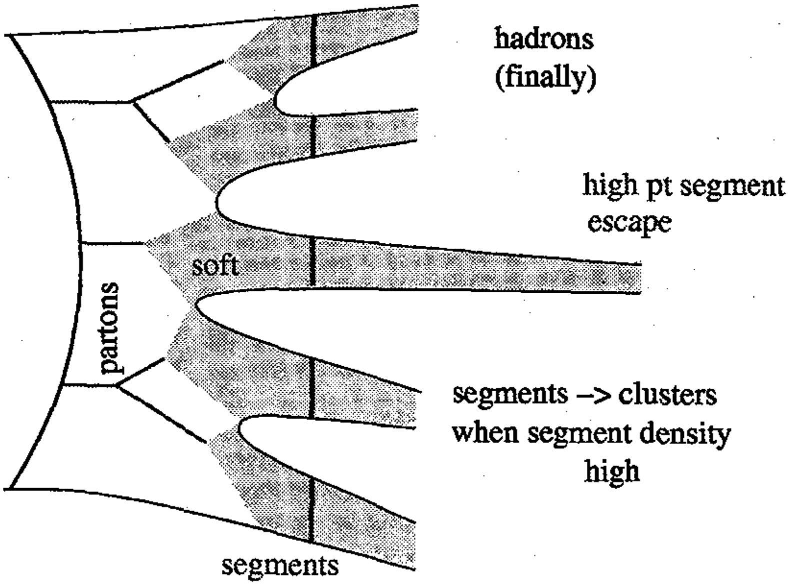
4

3 EPOS++



In (central) AA there are many parton ladders in parallel, impossible to hadronize independently

→collective hadronization



In practice:

☐ We define a grid in $x - y - \eta - \tau$ coordinates. The corresponding volume element $\Delta\tilde{V}$ is considered to be the “proper volume” of the local matter.

☐ We consider the segments at some τ_0. If the density of segments per “proper volume” is bigger than some ρ_{clu}, the the corresponding segments are considered to be part of the cluster,

☐ unless a segment has a p_t bigger than some p_{clu}.

☐ Connected cluster cells build global clusters, which are expected to expand and acquire flow.

☐ The cluster decays at some energy density ϵ_{clu}, which is taken to be the same for all energies and centralities.

☐ We assume a linear transverse flow profile (in tranverse rapidity), with some maximum transverse rapidity increasing logarithmically with energy: $y_{\mathrm{rad}}^{\mathrm{max}} = a_{\mathrm{rad}} + b_{\mathrm{rad}} \log \sqrt{s/s_{\mathrm{SPS}}}$.

☐ The cluster decays according to the covariant microcanonical phase space :

$$\prod_{\text{species }\alpha} \frac{1}{n_\alpha!} \prod_{i=1}^{n} \frac{d^3p_i}{(2\pi\hbar)^3 2E} g_i |M|^2 \delta(E - \Sigma\varepsilon_i)\, \delta(\Sigma\vec{p}_i)\, \delta_{Q,\Sigma q_i},$$

where we assume that $|M^2|$ is proportional to the total proper volume. In addition, there is a factor $1 \pm \epsilon$ for each strange particle (sign plus inside a baryon, sign minus inside a meson). (maybe not necessary?)

☐ In the whole procedure, we perfectly conserve energy, momentum and flavor.

☐ The cluster formation parameters are not too much affecting the results, the "real" parameters are the decay density ϵ_{clu} and the flow parameters a_{rad},b_{rad}.

☐ Our procedure has nothing in common with thermal fitting, there is no freedom whatsoever concerning the energy of the initial state, it is a straight extrapolation of pp and dAu.

4 Can we understand the data?

☐ The model works very well (considering the available parameters, the predictive power is enormous!)

☐ Why ?

☐ To understand the data , we first have to understand that we have always two contributions : cluster decay and "normal stuff" (as in pp). In central collisions this "normal" contribution is very small, but it grows with decreasing centrality

☐ ...and it is exactly this interplay between these two contributions which explains everything !

☐ How to understand the centrality dependence? Why does the Omega or Xi yield increase so much?

☐ This is because Ω's or Ξ's are much less supressed in phase space decay compared to string decay, so the cluster makes relatively much more Ω's and Ξ's than we observe in the "normal" contribution.

☐ And the change of the relative weight of these two contributions with centrality explains this strong centrality dependence.

☐ Why do baryon nuclear modification functions behave so differently compared to mesons?

☐ Look at the pt spectra of of Ξ's. They are totally dominated by cluster contributions, well beyond 3 GeV (flow!!!), not the pions.

☐ Even for central collisions, the normal contribution exceeds the cluster particles already at 1.5 GeV. So what we observe is flow!

STRANGENESS IN COLLISIONS

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STRANGENESS IN COLLISIONS
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Nu Xu	Lawrence Berkeley National Laboratory	nxu@lbl.gov

STRANGENESS IN COLLISIONS WORKSHOP

February 16 – 17, 2006

Physics Department Large Seminar Room

AGENDA

Thursday Morning, February 16 **(Chair: Matthew Lamont)**

8:30 - 9:00	**REGISTRATION**
9:00 - 9:10	**WELCOME**
9:10 - 9:50	**Nu Xu** .... Strangeness Production and Partonic Equation of State at RHIC
9:50 - 10:20	**Claudia Hoehne**....System-size Dependence of Strangeness Production at the SPS
10:20 - 11:00	**COFFEE BREAK**
11:00 - 11:40	**Rene Bellwied**...... High pt Phenomena in Strangeness
11:40 - 12:20	**Rudy Hwa** .... Production of Strange Particles at Intermediate pT at RHIC
12:20 - 2:00	**LUNCH** (served at the Berkner Hall Cafeteria until 1:30)

Thursday Afternoon, February 16 **(Chair: Krzysztof Redlich)**

2:00- 2:40	**Volker Koch**.......... Baryon Strange Correlations
2:40 - 3:10	**Jeff Speltz** .... Applicability of Hydrodynamic Models to Strange RHIC Spectra
3:10 - 3:50	**Ulrich Heinz**.........Hydrodynamics at RHIC– Successes, Limitations & Perspectives
3:50 - 4:20	**COFFEE BREAK**
4:20 - 4:50	**Ana Marin**...........The Leptonic and Charged Kaon Decay Modes of ϕ Meson Measured In Heavy-Ion Collisions at the CERN SPS
4:50 - 5:30	**Johan Rafelski**.......Strangeness Signature of QGP
5:30 - 6:00	**Anton Andronic** ....Energy Dependence on Hadron Production in Central Heavy Ion Collisions Within the Statistical Model
6:30 - 7:30	**RECEPTION AT BERKNER HALL** (Main Lobby)
7:30 - 9:00	**BUFFET DINNER – BERKNER HALL** (Meeting Room 'A')

STRANGENESS IN COLLISIONS WORKSHOP

February 16 – 17, 2006
Physics Department Large Seminar Room

AGENDA

Friday Morning, February 17 (Chair: Richard Witt)

9:00 - 9:40	**Karel Safarik........**	Strangeness Production in p-p and p-A
9:40..- 10:20	**Mark Heinz...........**	Strangeness in p+p: Data vs Models
10:20 – 11:20	**Larry McLerran...**	The glasma
11:20.- 11:40	**Peter Skands.........**	Power Showers, Underlying Events and Other News in PYTHIA
11:40 - 12:00	COFFEE BREAK	
12:00 - 12:30	**Marek Gazdzicki..**	Energy Dependence of Strangeness Production and Onset of Deconfinement
12:30 – 13:10	**Boris Tomasik......**	The K/pi Horn and the Lifetime of the Fireball
13:10 - 2:00	LUNCH	(served at the Berkner Hall Cafeteria until 1:30)

Friday Afternoon, February 17 (Chair: Helen Caines)

2:00 - 2:30	**Helmut Oeschler ..**	Centrality Dependence of Strange Particle Yields from SIS up to RHIC
2:30 - 3:00	**Boris Hippolyte ....**	Strangeness Opportunities at the LHC
3:00 - 3:30	**Edward Shuryak..**	The Role of Resonances in Understanding the Medium Produced in Collisions at RHIC and SPS
3:30 - 4:00	COFFEE BREAK	
4:00 - 4:40	**Giorgio Torrieri ...**	Phenomenology of Fluctuations in Heavy Ion Collision
4:40 - 5:20	**Vasile Topor-pop**	Strangeness and Multi-Strangeness in pp, dAu and AuAu
5:20 - 5:50	**Klaus Werner.......**	The Effect of Parton Ladder Splitting on Strange Particle Production in dAu and pp at RHIC

Additional RIKEN BNL Research Center Proceedings:

Volume 78 – Heavy Flavor Productions and Hot/Dense Quark Matter, December 12-14, 2005 – BNL-
Volume 77 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 76 – Odderon Searches at RHIC, September 27-29, 2005 – BNL-75092-2005
Volume 75 – Single Spin Asymmetries, June 1-3, 2005 – BNL-74717-2005
Volume 74 – RBRC QCDOC Computer Dedication and Symposium on RBRC QCDOC, May 26, 2005 – BNL-74813-2005
Volume 73 – Jet Correlations at RHIC, March 10-11, 2005 – BNL-73910-2005
Volume 72 – RHIC Spin Collaboration Meetings XXXI(January 14, 2005), XXXII (February 10, 2005), XXXIII (March 11, 2005) – BNL-73866-2005
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Volume 69 – Review Committee – BNL-73546-2004
Volume 68 – Workshop on the Physics Programme of the RBRC and UKQCD QCDOC Machines – BNL-73604-2004
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Volume 66 – RHIC Spin Collaboration Meeting XXIX, October 8-9, 2004, Torino Italy – BNL-73534-2004
Volume 65 – RHIC Spin Collaboration Meetings XXVII (July 22, 2004), XXVIII (September 2, 2004), XXX (December 6, 2004) - BNL-73506-2004
Volume 64 – Theory Summer Program on RHIC Physics – BNL-73263-2004
Volume 63 – RHIC Spin Collaboration Meetings XXIV (May 21, 2004), XXV (May 27, 2004), XXVI (June 1, 2004) – BNL-72397-2004
Volume 62 – New Discoveries at RHIC, May 14-15, 2004 – BNL- 72391-2004
Volume 61 – RIKEN-TODAI Mini Workshop on "Topics in Hadron Physics at RHIC", March 23-24, 2004 – BNL-72336-2004
Volume 60 – *Lattice QCD at Finite Temperature and Density* – BNL–72083-2004
Volume 59 – RHIC Spin Collaboration Meeting XXI (January 22, 2004), XXII (February 27, 2004), XXIII (March 19, 2004)– BNL-72382-2004
Volume 58 – RHIC Spin Collaboration Meeting XX – BNL-71900-2004
Volume 57 – High pt Physics at RHIC, December 2-6, 2003 – BNL-72069-2004
Volume 56 – RBRC Scientific Review Committee Meeting – BNL-71899-2003
Volume 55 – Collective Flow and QGP Properties – BNL-71898-2003
Volume 54 – RHIC Spin Collaboration Meetings XVII, XVIII, XIX – BNL-71751-2003
Volume 53 – Theory Studies for Polarized *pp* Scattering – BNL-71747-2003
Volume 52 – RIKEN School on QCD "Topics on the Proton" – BNL-71694-2003
Volume 51 – RHIC Spin Collaboration Meetings XV, XVI – BNL-71539-2003
Volume 50 – High Performance Computing with QCDOC and BlueGene – BNL-71147-2003
Volume 49 – RBRC Scientific Review Committee Meeting – BNL-52679
Volume 48 – RHIC Spin Collaboration Meeting XIV – BNL-71300-2003
Volume 47 – RHIC Spin Collaboration Meetings XII, XIII – BNL-71118-2003

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Volume 42 – Baryon Dynamics at RHIC – BNL-52669
Volume 41 – Hadron Structure from Lattice QCD – BNL-52674
Volume 40 – Theory Studies for RHIC-Spin – BNL-52662
Volume 39 – RHIC Spin Collaboration Meeting VII – BNL-52659
Volume 38 – RBRC Scientific Review Committee Meeting – BNL-52649
Volume 37 – RHIC Spin Collaboration Meeting VI (Part 2) – BNL-52660
Volume 36 – RHIC Spin Collaboration Meeting VI – BNL-52642
Volume 35 – RIKEN Winter School – Quarks, Hadrons and Nuclei – QCD Hard Processes and the Nucleon Spin – BNL-52643
Volume 34 – High Energy QCD: Beyond the Pomeron – BNL-52641
Volume 33 – Spin Physics at RHIC in Year-1 and Beyond – BNL-52635
Volume 32 – RHIC Spin Physics V – BNL-52628
Volume 31 – RHIC Spin Physics III & IV Polarized Partons at High Q^2 Region – BNL-52617
Volume 30 – RBRC Scientific Review Committee Meeting – BNL-52603
Volume 29 – Future Transversity Measurements – BNL-52612
Volume 28 – Equilibrium & Non-Equilibrium Aspects of Hot, Dense QCD – BNL-52613
Volume 27 – Predictions and Uncertainties for RHIC Spin Physics & Event Generator for RHIC Spin Physics III – Towards Precision Spin Physics at RHIC – BNL-52596
Volume 26 – Circum-Pan-Pacific RIKEN Symposium on High Energy Spin Physics – BNL-52588
Volume 25 – RHIC Spin – BNL-52581
Volume 24 – Physics Society of Japan Biannual Meeting Symposium on QCD Physics at RIKEN BNL Research Center – BNL-52578
Volume 23 – Coulomb and Pion-Asymmetry Polarimetry and Hadronic Spin Dependence at RHIC Energies – BNL-52589
Volume 22 – OSCAR II: Predictions for RHIC – BNL-52591
Volume 21 – RBRC Scientific Review Committee Meeting – BNL-52568
Volume 20 – Gauge-Invariant Variables in Gauge Theories – BNL-52590
Volume 19 – Numerical Algorithms at Non-Zero Chemical Potential – BNL-52573
Volume 18 – Event Generator for RHIC Spin Physics – BNL-52571
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Volume 16 – RIKEN Winter School - Structure of Hadrons - Introduction to QCD Hard Processes – BNL-52569
Volume 15 – QCD Phase Transitions – BNL-52561
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Volume 4 – Inauguration Ceremony, September 22 and Non -Equilibrium Many Body Dynamics –BNL-64912
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Volume 1 – Open Standards for Cascade Models for RHIC – BNL-64722

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RIKEN BNL RESEARCH CENTER

Strangeness In Collisions

February 16 – 17, 2006

Li Keran

Nuclei as heavy as bulls
Through collision
Generate new states of matter.
T.D. Lee

Speakers:

Anton Andronic
Rene Bellwied
Marek Gazdzicki
Mark Heinz
Ulrich Heinz
Boris Hippolyte
Claudia Hoehne
Rudy Hwa
Volker Koch
Ana Marin
Helmut Oeschler
Johan Rafelski
Karel Safarik
Peter Skands
Edward Shuryak
Boris Tomasik
Jeff Speltz
Vasile Topor-pop
Giorgio Torrieri
Klaus Werner
Nu Xu
Larry Mc Lerran

Organizers: Helen Caines. Larry McLerran, Matthew Lamont, Krzysztof Redlich and Richard Witt