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Event Generator Overview

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Due to their ability to provide detailed and quantitative predictions, the event generators have become an important part of studying relativistic heavy ion physics and of designing future experiments. In this talk, I will briefly summarize recent progress in developing event generators for the relativistic heavy ion collisions.

1. BRIEF HISTORY OF EVENT GENERATORS

Almost all event generators for relativistic heavy ion collisions contain parts borrowed from event generators in particle physics. So it is instructive to first take a look at their evolution in particle physics (Table 1).

Table 1

The main focus of particle physics event generators in the past five decades. The development can be summarized by the saying: "yesterday's signal is today's background."

Decade	Physics Focus	Models & Parameters
50's	Uniform Phase Space	multiplicity, masses and widths
60's	Longitudinal Phase Space	leading particles and limited p_t
70's	Hadronic Strings	string tension, fragmentation, ...
80's	Jets	parton evolution, backward scattering, ...
90's	Supersymmetry	squarks, sleptons, charginos, neutralinos, ...

The need for event generators was apparent in the early days of particle physics when the final state multiplicity became greater than two. In order to locate and identify various hadronic resonances, a Monte-Carlo code was usually used to generate the appropriate background corresponding to a uniform phase space distribution,

$$d(\text{PS}) = \prod_{n=0}^N \frac{d\vec{p}_n}{(2\pi)^3 2E_n} \delta^3(\sum \vec{p}_n) \delta(\sum E_n - E_{cm}).$$

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This is perhaps the only stage when the event generators can be considered as free of parameters. As the colliding energy increases, the spectra gradually deviate from that of a uniform distribution; so extra parameters were required to simulate the leading particle behavior and to limit transverse momenta. In the early seventies, an alternative to parameterizing the phase-space, hadronic string phenomenology, was developed. By the early eighties, instead of distribution of individual particles, the focus was shifted to jet production. It is interesting to note that the content of particle physics event generators can be classified into two parts: the parameterization of the known physics from past experimental results, and the parameterization of new physics from various theoretical models. So, in principle, the signal versus background is clearly defined within each event generator. This is one of the key differences (see Table 2) between event generators for particle physics and those for heavy ion physics.

Table 2

Key differences in event generators between particle physics and relativistic heavy ion physics.

	Particle Physics	Heavy Ion Physics
System energy	fixed	changed by rescattering
Hadronization environment	clean	messy
Hadronic final state interaction	negligible	very important
Signal vs. background	clearly defined	not easily definable

In particle physics the collisions occur at some fixed beam energies, while in heavy ion collisions rescatterings lead to lower and lower energies. One must be able to handle all center of mass energies at and below the beam energy. Although several hadronization recipes were created [1–3], the details of hadronization are still an open question. Since the hadronization environment in heavy ion physics is far more complicated than that in particle physics, it is most likely that the recipes developed for particle physics are insufficient. In fact, the nature of hadronization is one of the very problems we hope to solve through heavy ion collisions.

The signal and the background in particle physics are both given in terms of some production rate, so we could obtain the signal by subtracting the background from the observed rate. In heavy ion physics, however, often what we are searching for can not be simply converted to a production rate. Defining signals and backgrounds is not as straightforward as in particle physics. Because of these differences it is necessary to develop new types of event generators for relativistic heavy ion physics. A number of event generators were developed in the late eighties. Table 3 is a partial list of both the past and the current efforts. Event generators which were used mainly at lower energy heavy ion collisions are not listed. A summary of these event generators can be found in a review by Cugnon for Quark Matter'82[4].

In Quark Matter'88, Awe and Sorensen gave a report on their workshop held shortly before the conference. They stated that of the ten event generators, "at the time of the

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Table 3

The event generators for relativistic heavy ion collisions. The top part lists, alphabetically, event generators developed in the eighties and early nineties; and the lower part lists new models from the last two years.

Event Generator	Model Content	Since	References
ATTILA	Strings	1987	[5]
ARC	Hadrons	1991	[6,7]
DPM	Dual Parton Model	1981	[8,9]
DTUJET/NUC	Strings + Jets	1982	[10]
FRITIOF	Lund	1986	[11,12]
HIJET	ISAJET	1989	[13]
HIJING	Strings + Minijets	1991	[14,15]
IRIS	Dual Parton Model	1988	[16]
QGSM	Strings + Jets	1989	[17]
PCM	Partons	1990	[18]
RQMD	Hadrons + Strings	1989	[19,20]
VENUS	Strings	1987	[21]
ART	Hadrons + Meanfield	1996	[22]
BEM	Hadrons + Meanfield	1996	[24]
BNC	Hadrons	1996	[23]
GCP	General Cascade	1996	[25]
LUCIAE	Strings + Hadrons	1996	[26]
UrQMD	Hadrons + Strings	1996	[27]
VNI	Partons	1996	[28]
ZPC	Partons	1996	[29]

workshop, only FRITIOF, HIJET, and VENUS were found to produce results which were not obviously incorrect and which conserve energy to a high degree.” We have certainly come a long way since that humble beginning. The problem of energy non-conservation can mostly be traced to the original high energy event generators.

The surprisingly large strangeness enhancement observed by the E802 experiment at the AGS[31], and the subsequent hadronic mechanism for explaining this enhancement by RQMD[32] demonstrate the importance of computing detailed reaction rates in non-equilibrium systems with different reaction thresholds. This also illustrates the difficulty of defining signals versus backgrounds in relativistic heavy ion collisions, and the need for event generators.

In subsequent years, other event generators were also able to reproduce the observed strangeness enhancement, but the details of the model often differ from the original RQMD. Since none of the models start from the first principle of QCD, the lack of uniqueness means we do not yet have the complete and satisfactory answer to the observed strangeness enhancement. I think it is fair to say that this situation applies to

essentially all potential signatures currently being studied.

2. OPEN STANDARD CODES AND ROUTINES (OSCAR)

To make further progress, one must be able to systematically compare and verify all possible recipes. Since the complete physics content of any event generator is only defined by the source code, one has the identity:

code $\equiv$ model.

From the very beginning, event generators such as FRITIOF, HIJING and VENUS, were available in source codes, so people outside of the collaboration could reproduce and verify the published results. Unfortunately, this has not been true for all event generators.

The need for accessibility of the source codes and documentation, systematic version controls, standardized tests, and common interfaces is now recognized by most developers of the new event generators. In a workshop sponsored by the recently formed RIKEN BNL Research Center, Open Standard Codes and Routines (OSCAR) [33] for event generators were developed.

A set of minimum requirements, Table 4, defines accessibility of the source codes and documentation, and the reproducibility of the published results. Of course, compliance with these requirements alone does not ensure the quality of the codes, but it should guarantee that all mistakes are reproducible.

Table 4

OSCAR mandatory requirements address the issues of accessibility of event generator source codes and documentation, and the reproducibility of published results. All OSCAR compliant event generators must pass all of these requirements.

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- Minimum accessibility of the source code: Author(s) should make available to the public a package containing source codes, parameter files, and sufficient documentation to enable others to verify and reproduce published results. (This package is called the Source Code Package.) The author(s) may restrict the use of the package beyond the purpose of verifying and reproducing published results.
 - The Source Code Package must be made accessible, either through anonymous ftp or WWW, by the time a publication is submitted.
 - Each OSCAR code must carry a unique version number; and different source codes must have different version numbers.
 - Each OSCAR code must have the option to write in the OSCAR Output File Format.
 - Each OSCAR code should provide a list of platforms on which it was tested.
 - Sample input files, some output files, and necessary instruction should be provided with each source code.
 - For each new version of the code, a list of key differences from the previous version must be provided, and the sample input, output files, and instructions should be updated.
 - The OSCAR code should provide a reference on its physics content.
 - The OSCAR code should have a complete list of adjustable parameters, with explanations.
-

To improve the technical quality of the codes, OSCAR recommends, Table 5, that each event generator adheres to better programming practices such as modularity and the ability to perform simple, and also some not so simple, tests.

Table 5

OSCAR recommendations encourage better programming practice, and suggest a series of standardized tests for event generators.

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- Each source code should have a modular structure which permits individual modules to be checked independently.
 - Each source code should contain some comments on each subtle aspect.
 - Each code should produce clear warning messages or error messages.
 - Each code should be able to run on more than one platform.
 - Each code should have an option to use portable random number generators.
 - Each code should be able to run some tests as proof of its correctness under special conditions.
 - Each code should be able to run a standard set of tests.
 - Each cascade code should be able to run a free streaming test.
 - Each cascade code should be able to run the hydro initial condition.
 - Each cascade code should be able to run the box boundary condition.
 - Each cascade code model should be able to calculate the equation of state for simple interactions.
-

Considering the enormous technical complexities and many conceptual difficulties involved in developing high quality event generators, the current OSCAR is just a small, but necessary, step towards establishing the right physics-model for relativistic heavy ion collisions. The OSCAR initiative also signals a new beginning in forging collaborative efforts among different groups. It now seems likely that large scale, objective comparisons of event generators will be carried out in the near future within the OSCAR framework.

Although, unlike in particle physics, we do not yet have a clear division between known physics and new physics in most of our event generators. Nevertheless some of the rules are certain, such as energy-momentum conservation, relativistic invariance, and detailed balance; there are also bounds on hadronic cross-sections from experiments, and cross-section for hard parton scatterings from pQCD. Furthermore, any event generator should be first checked with existing pp and pA data. Developing a set of systematic tests, and applying it uniformly to all event generators will be the top priority for OSCAR. Some of the newer event generators already have these tests in mind, as shown in Figures 1 and 2.

The geometric cross-section used in the cascade algorithm breaks Lorentz invariance explicitly. As a result, there can be ambiguities in the collision ordering. Figure 1 (a) shows the ratio between causal collisions (ordering independent of the frame) and non-causal collisions (ordering depends on the frame) in a parton cascade as a function of the ratio of the interaction length to the mean free path, χ . This curve is a generic feature of both partonic and hadronic cascades. Figure 1(b) compares the equation of state computed from ZPC (dots) with the exact result (line).

As particle multiplicity increases, it is difficult to maintain detailed balance in transport models. In the UrQMD example, Figure 2, detailed balance is achieved by allowing only

Figure 1. Ratio of causal to noncausal collisions versus ratio of interaction length to mean free path (a), and a calculation of equation of state (b), in ZPC [34,35].

Figure 2. Detailed balance can be satisfied for hadronic final state interaction in UrQMD, as shown here for simulations done with particles in a box.

two body decays. There is a strong indication of approach to chemical equilibrium in central nucleus-nucleus collisions [36]. To quantify the degree of equilibration in the event generator simulations, it is perhaps better to sacrifice certain rates in favor of maintaining detailed balance.

Most of the existing pp and pA data comes from spectrometers with a very small phase space coverage for any given event. For the purpose of constraining model parameters, high statistics data from 4π detectors are desperately needed. It is very encouraging that, experiment E910 [37] has already completed such detailed measurements at the AGS, and NA49 [38] at SPS also has a large number of high quality pA events on tape. Through systematic comparisons with measurements like these we will learn the details of particle production, the mechanism of stopping in nucleus-nucleus collisions, and the effect of final state interactions. Only then, can we have confidence in our event generator predictions.

3. BUILDING AND TESTING OF EVENT GENERATORS

The basic ingredients for event generators are summarized in Table 6 [39]. These reflect our current understanding of what is involved in a typical heavy ion collision at ultra-relativistic energies. At this moment, no single event generator manages to incorporate all of these physics components; nor would I recommend anyone to try this. Undoubtedly the lists will change over time, so building robust modules, each containing only one or a few well defined physics, would be much more efficient than devoting one's efforts to a big toe (theory of everything).

When comparing different event generators, or when comparing an event generator with existing data, two features stand out: stopping, and hadronic final state interaction. For the current event generators most of the differences in particle spectra could be attributed to these two aspects. The stopping is more important of the two, since it determines the initial condition for final state interactions. Table 7 lists the diverse mechanisms for stopping in models applied to SPS energies. Interestingly, despite the major differences in physics it is found that in all of these models, the "right" amount of stopping could be achieved.

To understand the reason behind this versatility of the event generators in reproducing stopping, one needs to first locate the most sensitive parameter which governs the amount of stopping in each model. In UrQMD, Figure 3, stopping can be controlled by the rescattering recipe for the leading particles. The default is a reduced cross-section within a formation time τ . This is a very sensitive parameter because full cross-section or zero cross-section within the same time τ produces drastically different results, even in S on S collisions.

One might question the validity of the totally hadronic description of stopping in UrQMD. However, two other studies [40,41], also suggest that, at least for stopping at AGS and SPS energies, it is possible to describe both pA and AA by a one parameter fit to hadronic based models. Figure 4 shows the result from the Multi-Chain Model [40].

Since baryons carry major part of the energy and momentum in collisions at AGS and SPS energies, baryon stopping and energy deposition are essentially the same thing. At RHIC, although the total cross-section for pp maybe still be dominated by soft QCD interactions, the energy density at mid-rapidity will be dominated by non-baryonic matter,

Figure 3. In hadronic based models, such as UrQMD [27], the amount of stopping is very sensitive to the rescattering of leading baryons.

Figure 4. Baryon transport in minimum bias p on Au (a) and central Pb on Pb (b) at SPS. Solid and dashed histograms correspond to HIJING[14] and VENUS[21] models, and continuous curves are predictions of the Multi-Chain Model[42]

Table 6

Components of event generators based on our current knowledge of relativistic heavy ion collisions [39]. Almost all event generators contain one or more of these components, however, the creation of a robust event generator which contains all of these elements remains a major challenge.

	Model Components	Model Parameters
Initial condition	Strings and things	$\kappa = 1 \sim 4 \text{ GeV/fm}^3$
	Minijets	$p_0 = 1 \sim 2 \text{ GeV}$
	Yang-Mills Fields	$Q_{YM} = 0.5 \sim 2 \text{ GeV}$
Parton Transport	Elastic	Screening μ, α_s
	Inelastic $n < - > m$	$\Sigma(x, p)$
	Condensates	$\sigma(x, t), F_a^{\mu\nu}$
Hadronization	Fragmentation	Independent/Coherent
	Cluster Models	Coalescence
	Effective Fields	DCC
Hadron Transport	Resonances	m_{eff}, Γ_{eff}
	Hadrochemistry	cross-sections
	Symmetrization	HBT
Experimental Filters	PHENIX	
	STAR	Data $dN/dy, \dots$
	...	

so baryon stopping and energy deposition may become uncorrelated. It will be very interesting to see if the above models could be extrapolated to RHIC energies.

Before one concludes that stopping at SPS energies can be explained by hadronic mechanism, one must also explore other possibilities. In the parton cascade, VNI [28], stopping is the result of hard parton-parton scattering. In this model, the hadronic physics comes only at the very end, and plays essentially no role in stopping. The model, in principle, derives from e^+e^- collisions, so it is not clear if there is one or more parameters which are extra sensitive to stopping. In addition, one also needs to systematically compare this model to all available pp and pA data, since these data are not used as input.

Another creative mechanism for stopping was proposed by Kharzeev [43], and implemented in HIJING by Vance [15]. In this model, the baryon junction is responsible for transporting a net baryon number to the mid-rapidity. The authors also found that the strange antibaryons are more sensitive in differentiating the stopping mechanisms.

While there are many different mechanisms for stopping, there are fewer varieties in the hadronic final state interaction. The reason might be the lack of hadronic final state interaction in many event generators. Most people seem to agree on what should be included in the hadronic final state interaction, *i.e.* all stable hadrons plus the low energy resonances. It is a very tedious task to parameterize all possible combination of reactions. A robust module for hadronic interactions would be a great service to the community. Whether strange antibaryons are good signals might depend on their final state interactions.

Table 7

Mechanism for stopping in event generators is very different.

Model	Mechanism
DPM	Multiple string-excitation
FRITIOF, LUCIAE	Multiple string-excitation
HIJING/B	Baryon Junction
RQMD, UrQMD	Leading quark/diquark rescattering
VENUS 4.12	Multiple string-excitation
VNI 3.1	Hard scattering of partons

Figure 5. In parton based models, such as VNI [28], the stopping is the result of *hard* scatterings of on-shell and off-shell partons.

There are attempts to break the equality between the code and the model. One way is to create a universal code for many different models, such as GCP [25] which is a general transport equation solver with a flexible user interface for defining particle species and interactions. It is also possible to break the equality if a large collection of events with intermediate states is available. One could in principle verify the recipe by analyzing the intermediate states, without reading the entire source code. To make this practical on a large scale, and for more than one event generators, a common interface for intermediate states is required.

4. CONCLUDING REMARKS

Through relativistic heavy ion collisions we hope to observe the change in QCD vacuum, and subsequently determine its properties. This requires very different types of event

generators than those for particle physics.

In the past ten years, there has been significant effort in developing event generators for relativistic heavy ion collisions. Although, using event generators we have gained much insight in the global features of these collisions, there still lacks a systematic parameterization within the event generator for the possible phase transitions.

The main difficulty in analyzing relativistic heavy ion data is identifying the signals among thousands of final state particles from each central collision. At present, the event generators are the only link we have between the particles we observe and the phenomena we want to study.

Further development in event generators requires both discipline and collaborative efforts among the model builders. The OSCAR is the very first step in this direction.

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