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OVERVIEW OF HIGH ENERGY PHYSICS WITH
POLARIZED PARTICLES

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ABSTRACT

The purpose of this talk is to review spin effects in various areas of particle physics at high energy and by selecting the most interesting topics, to show the relevance of dealing with polarized particles. We will see that it provides crucial tests for the Standard Model and can give us clear signatures to uncover new interactions. We will also discuss some striking experimental facts recently observed in hadronic collisions and their implications for current theoretical ideas.

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OVERVIEW OF HIGH ENERGY PHYSICS WITH POLARIZED PARTICLES

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Résumé – Le but de cet exposé est de présenter une revue des effets de spin dans divers domaines de la physique des particules à haute énergie et en sélectionnant les sujets les plus intéressants, de montrer l'importance qu'il faut accorder aux particules polarisées. Nous verrons que cela produit des tests cruciaux pour le Modèle Standard et peut nous fournir de bonnes signatures pour la mise en évidence de nouvelles interactions. Nous discuterons aussi divers faits expérimentaux marquants observés récemment dans les collisions hadroniques et leurs implications pour les idées théoriques actuelles.

Abstract – The purpose of this talk is to review spin effects in various areas of particle physics at high energy and by selecting the most interesting topics, to show the relevance of dealing with polarized particles. We will see that it provides crucial tests for the Standard Model and can give us clear signatures to uncover new interactions. We will also discuss some striking experimental facts recently observed in hadronic collisions and their implications for current theoretical ideas.

1 – INTRODUCTION

High energy spin physics has been very active over the last twenty years or so. New experimental results together with relevant progress in understanding the dynamical mechanisms are periodically reported in topical conferences devoted to this exciting field of research /1/. Here, my task will be to provide a survey, far from being exhaustive, of the most significant spin effects, expected or already observed, in various areas of high energy physics, together with their consequences. Some of these effects are actual experimental data which have or do not have a clear interpretation, as we will see. We will also make some speculations for new effects which remain to be discovered either within the framework of the Standard Model or beyond, using polarized initial beams or final state polarization measurements. Spin dependent observables contain a unique type of information which is buried in unpolarized cross sections. Spin has been shown to be very useful in the limited energy range it has been explored so far, and we anticipate that polarization phenomena is likely to play a significant role for future high energy programs. As we will stress, this should motivate new theoretical efforts, in order to generate further experimental challenges.

The outline of the paper is as follows. Section 2 contains a discussion of spin effects in high energy electron-positron annihilation which allows, in particular, establishing the spin-1/2 nature of the quarks, and measuring their electroweak couplings. Section 3 covers polarized deep-inelastic ep scattering dealing with weak interaction issues, compositeness and very briefly with the question of the proton spin and polarized structure functions. In section 4 we consider spin effects in hadronic collisions mainly for exclusive reactions at large angles and for some typical inclusive reactions.

In electron-positron collisions, the incident beams annihilate into a virtual intermediate state which is either a photon or a Z^0 according to the Standard Model. The amplitude is fully determined by the coupling constants of these gauge bosons to the produced final state and we expect characteristic effects depending on the initial and final spins. Clearly, this is one of the most interesting areas for testing the structure of the electroweak gauge theory. As an illustration, we will only consider two different cases with either effects related to polarized initial beams or with unpolarized beams and the observation of the polarization of particles produced in the final state.

Figure 1: Observed hadron yield for all particles with $x > 0.3$ per 15° of azimuthal angle (a) at $\sqrt{s} = 7.4$ GeV, and (b) at the spin-depolarization resonance at $\sqrt{s} = 6.2$ GeV. The angle $\phi = 0$ is in the horizontal plane (taken from Ref. 2).

i) Spin of the quarks

In e^+e^- storage rings, radiative effects generate a natural beam *transverse* polarization $P_T(e^+) = -P_T(e^-) = P$ with a maximum value of 92%. The existence of this beam polarization has been observed both at SPEAR/2/ and PETRA/3/ up to $\sqrt{s} = 30$ GeV. It leads to a specific azimuthal distribution which has been used to determine the degree of the beam polarization and also to check directly that quarks are spin-1/2 objects. Let us consider the inclusive process $e^+e^- \rightarrow hX$ where the hadron h is a fragmentation product of a quark q (or antiquark $\bar{q}$) in $e^+e^- \rightarrow \gamma^* \rightarrow q\bar{q}$. The angular distribution of h has the simple expression

$$\frac{d\sigma}{d\Omega} = \sigma_0 (1 + \alpha \cos^2 \theta + P^2 \alpha \sin^2 \theta \cos 2\phi) \quad (1)$$

where θ and ϕ are the polar angles in the frame where Oz is the electron beam direction and Oy is that of the magnetic guide field. If σ_L and σ_T are the cross sections where the virtual photon γ^* is purely longitudinal, respectively purely transverse, we have $\alpha = (\sigma_T - \sigma_L)/(\sigma_T + \sigma_L)$ so for spin-1/2 quarks $\sigma_L = 0$, i.e., $\alpha = +1$, whereas for spin-0 quarks $\sigma_T = 0$, i.e., $\alpha = -1$. The ϕ distribution observed at SPEAR, as shown in fig. 1a, has minima for $\phi = \pi/2, 3\pi/2$, whereas fig. 1b, which corresponds to unpolarized beams,

Figure 2: The energy dependence of the polarization P_u of u (or c) quarks and of the polarization P_s of s (or b) quarks at $\cos \theta = 0$ for unpolarized (—), right-handed $\alpha = +$ (---) and left-handed $\alpha = -$ (— · —) initial e^+e^- in the reaction $e^+e^- \rightarrow q\bar{q}$ (from ref. 4).

shows a flat distribution. A similar pattern has been measured at PETRA up to $\sqrt{s} = 30$ GeV. Therefore, one concludes that quarks are indeed spin-1/2 particles.

ii) Electroweak quark couplings

Among the various fundamental tests of the Standard Model, one should measure the electroweak quark couplings which are predicted unambiguously, i.e., for the Z^0 interaction $-e\gamma^\mu(a_q - b_q\gamma^5)$ one has

$$\begin{aligned} a_q &= 1 - 8/3 \sin^2 \theta_w, & b_q &= 1 & \text{for } q = u, c, t \\ a_q &= -1 + 4/3 \sin^2 \theta_w, & b_q &= -1 & \text{for } q = d, s, b. \end{aligned} \quad (2)$$

A possible method for doing that is to consider unpolarized (or polarized) e^+e^- annihilation into $q\bar{q}$ in lowest order in the energy range $30 < \sqrt{s} < 150$ GeV. Due to the axial couplings of the Z^0 , the quark (or antiquark) has a non-zero *longitudinal* polarization $P_q = (\sigma_+ - \sigma_-)/(\sigma_+ + \sigma_-)$ where $\sigma_+(\sigma_-)$ is the cross section with the quark helicity $+(-)$. An obvious calculation leads to the results displayed in fig. 2 and we see that even in the case of unpolarized beams the effects are large. Note that at the Z^0 peak one finds

$$P_q = 2a_q b_q / (a_q^2 + b_q^2) \quad (3)$$

which reaches a value close to 100% for the down-type quarks (see fig. 2). Of course since the quarks are confined this effect cannot be observed directly and it has to be transmitted to the outgoing hadrons produced by the quark (antiquark) fragmentation. Among them, certainly the hyperon Λ is favoured because first, in the $SU(6)$ limit, the Λ polarization P_Λ is that of the s quark it contains, and second, the Λ polarization is relatively easy to measure due to its characteristic decay angular distribution. As an illustration we show in fig. 3 some predictions for P_Λ versus $\sqrt{s}$ and for different values of $z = E_\Lambda/(\sqrt{s}/2)$.

Figure 3: P_{Λ} versus $\sqrt{s}$ at $\cos \theta = 0.8$ for different values of z with unpolarized beams (from ref. 4).

As expected the Λ 's observed with a large z , have an s quark directly coupled to the Z^0 and therefore have a maximum P_{Λ} which depends very weakly on the fragmentation model. From the measured cross section at PEP/5/ it seems that at LEP energy, the event rate for Λ production at high z is sizeable enough to make this test practical.

Apart from these, if one goes beyond the Standard Model, polarization effects can be used to search, in a deeper way, anomalous effects in $e^+e^- \rightarrow \gamma\gamma$, γZ , ZZ for heavy lepton pair production and to provide a clear signature for the production of supersymmetric particles. For example,/6/ as a consequence of eq. (1), the ϕ dependence in the reaction $e^+e^- \rightarrow \tilde{e}^+\tilde{e}^-$ is predicted to have minima shifted to $\phi = 0, \pi$.

3 - POLARIZED DEEP INELASTIC LEPTON SCATTERING

There are various theoretical ideas about the physics which is expected to be tested by present and future $e^\pm p$ colliders with polarized beams. We will first briefly recall some weak interactions issues and search for new physics accessible in a very high Q^2 range. Next we will make some short comments on the exciting problem of the structure of the proton spin which will be extensively discussed by the next speaker/7/.

i) Weak interactions and new physics issues

Some fundamental questions remain to be answered by the future HERA ep collider at the energy $\sqrt{s} = 314$ GeV, in particular from the study of electron-quark scattering induced by neutral and charged currents.

Parity is violated in deep inelastic lepton scattering because of the $\gamma^* - Z^0$ interference and in the reaction $\tilde{e}p \rightarrow eX$, with an unpolarized proton and a longitudinally polarized electron beam, the single helicity asymmetry defined as

$$A_L = \frac{d\sigma_- - d\sigma_+}{d\sigma_- + d\sigma_+} \quad (4)$$

behaves like

$$A_L \sim \frac{G_F}{\alpha} Q^2 \quad (5)$$

where G_F is the Fermi constant and α the fine structure constant. Note that A_L is growing with Q^2 and some years ago, an heroic SLAC experiment/8/ has found at small Q^2 values

$$A_L/Q^2 = (9.5 \pm 1.6) \times 10^{-5} (\text{GeV})^{-2} \quad (6)$$

Figure 4: The asymmetry A_L versus Q^2 at the value $x = 0.5$ of the scaling variable and $\sqrt{s} = 314$ GeV. Dotted curve is the Standard Model prediction. Solid curves are deviations due to compositeness effects (taken from ref. 9).

in excellent agreement with the Standard Model expectation. Now with a machine such as HERA one can reach much larger Q^2 values, so this asymmetry will be of the order of 20-30% and therefore very easily accessible. The x and Q^2 dependence of A_L is well predicted by the Standard Model as shown in fig. 4.

If quarks and leptons have a substructure compositeness effects in eq interactions can be treated by considering models based on contact interactions with the effective Lagrangian

$$\mathcal{L}_{eff} = \eta_{ab} \frac{4\pi}{\Lambda_H} (\bar{e}_a \gamma^\mu e_a) (\bar{q}_b \gamma_\mu q_b) \quad (7)$$

where $\eta_{ab} = \pm 1$, $a, b = L$ or R (Left or Right) and Λ_H is the compositeness energy scale. The Standard Model prediction shown in fig. 4 is then greatly modified and this is illustrated for two choices of interaction $+(LL)$ and $+(RR)$ and different values of Λ_H . Deviations in the measurement of the Standard Model asymmetry could also reveal the existence of a new heavy gauge boson Z' predicted in some theories/10/ and the size of the effect is detectable (see for example ref. 11). Finally polarized $e^\pm$ beams can be used in the reactions $ep \rightarrow \nu_e X$ to check that the ratio $\sigma(e_L^- p)/\sigma(e_R^+ p)$ is large, due to the lefthandedness of the standard charged currents. One can also try to detect right-handed currents in the "wrong" helicity reaction $e_R^- p \rightarrow \nu_e X$.

ii) Polarized structure functions and the proton spin

The parity violating spin symmetry discussed above, which does not involve polarized protons, is indeed insensitive to the proton spin and to polarized structure functions. This information can be obtained from deep inelastic lepton scattering with both electron and proton polarized.

Two years ago the European Muon Collaboration (EMC) has reported the results of an accurate experiment/12/ in polarized leptonproduction which has created a great deal of interest in the dynamical

origin of the proton spin. The measured quantity is the double helicity asymmetry

$$A = \frac{d\sigma_{++} - d\sigma_{+-}}{d\sigma_{++} + d\sigma_{+-}} \quad (8)$$

in polarized muon-proton deep inelastic scattering. Here $d\sigma_{++}$ and $d\sigma_{+-}$ denote the cross sections where the muon beam polarization is along the beam axis and the target polarization is either parallel (+) or antiparallel (-) to it. This measurement allows, in the scaling limit, the determination of the quantity

$$A_1(x) = \frac{\sum_i e_i^2 [\Delta q_i(x) + \Delta \bar{q}_i(x)]}{\sum_i e_i^2 [q_i(x) + \bar{q}_i(x)]} \quad (9)$$

where, as usual in the parton model, we define for a given parton the *unpolarized distribution* $f = f_+ + f_-$ and the *parton helicity asymmetry* $\Delta f = f_+ - f_-$, $f_{\pm}$ being the distributions of this parton in a polarized nucleon with helicity either parallel (+) or antiparallel (-) to that of the parent nucleon. Here x denotes the Bjorken variable. Clearly gluons do not contribute to the sum in eq. (9) because they don't couple to photons. We show in fig. 5 the result for the asymmetry A_1 on polarized protons from an earlier SLAC-Yale experiment/13/ and from the recent EMC experiment over the kinematic range $0.015 \leq x \leq 0.7$ and $1.5 \leq Q^2 \leq 70 \text{ GeV}^2$. The two sets of data are fairly consistent for $x > 0.1$, but the very small x range has been uniquely explored by the EMC.

Figure 5: Data on the asymmetry A_1 versus x from ref. 12 compared with two theoretical predictions. Solid curve is a quark-parton calculation/14/ and dashed curve is resulting from the MQM/QGD approach/15/.

We recall that the total amount of the proton spin carried by quarks and antiquarks is

$$\Delta\Sigma = \Delta u + \Delta d + \Delta s \quad (10)$$

where

$$\Delta q_i \equiv \int_0^1 [\Delta q_i(x) + \Delta \bar{q}_i(x)] dx \quad (11)$$

In addition the proton spin can also get contributions from gluon helicity asymmetry and parton orbital angular momentum provided one satisfies the obvious first constraint

$$\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \langle L_z \rangle \quad (12)$$

where similarly to eq. (11), ΔG is defined as the integral over x of $\Delta G(x)$ and $\langle L_z \rangle$ is the average orbital angular momentum. Second, there is the well known Bjorken sum rule/16/ which reads

$$\int_0^1 [g_1^p(x) - g_1^n(x)] dx = \frac{1}{6} (-G_A/G_V) \quad (13)$$

where g_1^p and g_1^n are the proton and neutron polarized structure functions, defined as

$$g_1(x) = \frac{1}{2} \sum_i e_i^2 [\Delta q_i(x) + \Delta \bar{q}_i(x)] \quad (14)$$

which can be extracted from the measurement of A_1 on proton and neutron target and where G_A and G_V denote the vector and axial vector β -decay couplings. From the EMC result shown in fig. 5, providing a good determination of the small x region, one can obtain a very accurate value for the integral of $g_1^p(x, Q^2)$, which is in principle a function of both x and Q^2 , if there are scaling violations, that is

$$\int_0^1 dx g_1^p(x, Q^2) = 0.116 \pm 0.009(\text{stat}) \pm 0.019(\text{syst}) \quad (15)$$

One way to interpret this result/12/, because Δs is found to be large and negative/17/, is to conclude that the proton spin is not carried by the quarks, i.e., $\Delta \Sigma \simeq 0$, in clear contradiction with the naive quark model expectations,/18/ i.e., $\Delta \Sigma = 1$. Another possible interpretation related to the consideration of the anomaly of the flavor singlet axial-vector current/7/, leads to invoke a large and positive ΔG . This gluon polarization should generate spectacular spin effects at short distances in hadronic collisions, i.e. direct photon or jet production, which remain to be discovered.

4 - HADRONIC COLLISIONS

Perturbative QCD is a dynamical approach going beyond the parton model which is meant to describe accurately what one observes in hadronic collisions at high energy. As we will see, definite expectations from perturbative QCD based on helicity conservation are not satisfied by experimental polarization data. Another crucial problem, which is a real challenge for perturbative QCD, is to know how to treat transverse polarization? We will first consider exclusive reactions at large angles, which are far from being fully understood, and then inclusive reactions where large transverse spin effects have been extensively observed in hyperon production and also in meson production and which remain to be explained.

i) Exclusive reactions at large angles

These processes are described in terms of hard scattering models and are expected to provide important tests on hadronic wavefunctions at short distances and on the nature of parton-parton interactions. One possible theoretical framework is perturbative QCD/19/ which is predicting for the cross section of any exclusive process $a + b \rightarrow c + d$, the asymptotic scaling law

$$\frac{d\sigma}{dt} = s^{-n} F(\theta_{c.m.}) \quad (16)$$

where s is the center of mass energy square and $\theta_{c.m.}$ is the center of mass scattering angle. For baryon-baryon and baryon-antibaryon scattering one expects $n = 10$, but this behaviour does not seem to agree with recent data reported in fig. 6.

The pp data fit to s^{-9} and this line extrapolates reasonably well to the data at $p_{lab} = 10$ GeV/c obtained at BNL/21/, i.e., (48 ± 5) nb/(GeV/c)². The $\bar{p}p$ data fall more rapidly than the lower curve which is s^{-12}

Cross-sections at 90 degrees

Figure 6: The pp and $p\bar{p}$ elastic differential cross-sections at $\theta_{c.m.} = 90^\circ$ as a function of s (taken from ref. 20).

and this is consistent with some upper limits obtained at higher energies. So the quark counting rule attached to eq. (16) is not obeyed and it is not clear either whether the absolute normalization of the cross section given by $F(\theta_{c.m.})$, which is in principle calculable from an impressive number of lowest order diagrams, is correct/22/. Even more serious are the failures associated to the helicity conservation rule predicted by perturbative QCD implying that

$$\lambda_a + \lambda_b = \lambda_c + \lambda_d \quad (17)$$

as a consequence of the vectorial nature of the gluon and of the chiral limit for light quarks. For pp elastic scattering this rule implies, in particular, that the single flip amplitude ϕ_5 must be zero at large angles, so the analyzing power A must vanish because it is linear in ϕ_5 . This is obviously not verified by the data presented in fig. 7 and the sizeable effect observed in the large angle region was shown to be simply predicted/24/ by means of an interference mechanism, with no free parameter, involving a set of hard scattering amplitudes which violates eq. 17.

The same mechanism anticipates for the transverse spin-spin correlation parameter A_{NN} at $\theta_{c.m.} = 90^\circ$ a value of 90% or so for $p_{lab} = 20 \text{ GeV}/c$ which will remain large as energy increases. This is very different from an earlier prediction of the quark-interchange model/25/ using also eq. (17) which leads to $A_{NN}(90^\circ) = 1/3$. The available data on this parameter shown in fig. 8 has a clear excursion up to 60% at $p_{lab} = 12 \text{ GeV}/c$. However, there are other theoretical possibilities trying to describe the energy dependence of $A_{NN}(90^\circ)$ by considering either dibaryon resonances/27/ or Sudakov effects/28/ which lead to an oscillatory pattern. Clearly more data are needed for $p_{lab} > 12 \text{ GeV}/c$ to clarify this important issue.

In meson-baryon scattering there is also interesting data at large angles and in particular one finds a strong ρ alignment/29/ in $\pi p \rightarrow \rho^- p$ which was well predicted by a hard scattering model/30/ which obviously does not obey eq. (17).

Figure 7: The analyzing power A for pp elastic scattering versus $p_{\perp}^2$. The black squares are from ref. 23 and the black circles from a recent BNL experiment at $p_{\text{lab}} = 24 \text{ GeV}/c$.

Figure 8: The A_{NN} parameter for pp elastic scattering at $\theta_{\text{c.m.}} = 90^\circ$ versus p_{lab} from Ref. 26. The curve is hand-drawn to guide the eye.

Figure 9: Values and upper limits for several two-body cross sections at 90° taken from ref. 31.

We now turn to a very interesting set of data on various elastic and inelastic meson-baryon cross sections at 90° and 10 GeV/c /31/. The results are reported in fig. 9 and clearly it is striking to observe that the smallest cross sections are those for the reactions which do not allow a quark interchange. For example K^+p elastic scattering has a cross section of a few nanobarns whereas K^-p has a much smaller cross section. It corresponds to the fact that K^+ which is a $u\bar{s}$ state can interchange its u quark with one of the proton whereas K^- which is a $\bar{u}s$ state cannot. Notice also the huge difference between pp and $\bar{p}p$ (see also fig. 6), the first one allowing a maximum quark interchange and the second one none. One can also remark from fig. 9 that d quark interchange in reactions 2 and 6 leads to smaller cross sections than u quark interchange in reactions 1, 3, 5 and 7. In this respect, let us recall that at 12 GeV/c np elastic scattering is about one half of pp elastic scattering/32/.

There are several other inelastic reactions where one could check the dominance of quark interchange over pure gluon exchange, for example $K^-p \rightarrow \pi^0 \Lambda$ and $\pi^- p \rightarrow \pi^0 n$. From the values of the cross section known around 5 GeV/c by using eq. (16), assuming it holds for meson-baryon scattering, one can extrapolate to get their magnitudes at 10 GeV/c. We find that they turn out to be of the order of one nanobarn, which is large, but a direct confirmation from experiment is needed. We conjecture that quark interchange is also related to sizeable transverse baryon polarization effects in the large angle region and there is already some evidence for that in $K^-p \rightarrow \pi^0 \Lambda$ /33/, $pn \rightarrow np$ /34/ and $\bar{p}p \rightarrow \pi^+\pi^-$ /35/.

ii) Transverse spin in inclusive hadronic reactions

Let us consider the inclusive hadronic reaction

$$a + b \rightarrow c + X \quad (18)$$

where one observes the transverse polarization state of one of the hadrons (initial or final). The simplest measurable quantity is the single transverse spin asymmetry (or up-down asymmetry) defined as, for example if c is polarized,

$$A = \frac{d\sigma_c(\uparrow) - d\sigma_c(\downarrow)}{d\sigma_c(\uparrow) + d\sigma_c(\downarrow)} \quad (19)$$

By using the generalized optical theorem one can write

$$A d\sigma = \text{Im} (f_+^* f_-) \quad (20)$$

where $d\sigma = \sigma_c(\uparrow) + d\sigma_c(\downarrow)$ is the corresponding unpolarized inclusive cross section described by means of f_+ , the forward non-flip $3 \rightarrow 3$ helicity amplitude $ab\bar{c}\lambda \rightarrow ab\bar{c}\lambda$, while f_- is the forward flip amplitude $ab\bar{c}\lambda \rightarrow ab\bar{c}-\lambda$. In order to get a non-zero A , one needs both f_+ and f_- ; moreover these two amplitudes should have a phase difference. This point is important and should be taken seriously if we want to have a real understanding of the available experimental data. These asymmetries for inclusive hyperon production in proton induced reactions were discovered to be large, more than ten years ago/36/ and since then, they have been the subject of a systematic study for several hyperons and antihyperons, leading to typical patterns/37/ for the measured $A(x_F, p_T)$ as a function of x_F and p_T . One important observation is that the asymmetries are essentially independent of the incident beam energy. This is also true for the meson induced reactions which have also yielded some very interesting information, for example, the Λ asymmetry is large and positive in the K^- fragmentation region./38/ These large spin effects occur mainly in the fragmentation region of either the beam or the target, i.e. $|x_F| \sim 0.5$ and they should help to identify the underlying dynamical mechanism. Some semiclassical fragmentation models/39/ provide simple arguments for a qualitative understanding of the data, but since they ignore the question of the phase, they fail to make serious quantitative predictions.

Figure 10: A results for K_S^0 produced with a 18.50 GeV/c beam as a function of x_T and for different bins of x_F (from Ref. 41).

Meson inclusive production in the central region ($x_F \sim 0$) is another class of hadronic reactions where striking single transverse spin asymmetries have been observed. Very accurate data have been obtained by means of the polarized proton beam at BNL/40,41/ at $p_{lab} = 13.30$ and 18.50 GeV/c and one finds that A is always positive and growing with p_T for π^+ , whereas it vanishes for π^- . The asymmetry for K_S^0 has no p_T dependence in the central region as shown in fig. 10 with an average value of -10%. Going up in energy, let us recall a result from Serpukhov/42/ at $p_{lab} = 40$ GeV/c with a polarized target in $\pi^- p \rightarrow \pi^0 X$ where a large effect has been observed which is, in sign and magnitude, consistent with the BNL π^+ data. A satisfactory interpretation of these data is not yet available and although $x_F \sim 0$ is a kinematic region where perturbative methods and hard scattering models may apply, the incident energy is most probably too low and it could very well be that these mesons which populate the central region are decaying products of resonances produced in the fragmentation regions. The behaviour of the unpolarized cross section can

certainly help to decide. Finally, let us mention that with the 200 GeV/c FNAL polarized proton beam, a large asymmetry in $pp \rightarrow \pi^0 X$ has been found/43/ for p_T above 3 GeV/c but opposite in sign to those at lower energies. This is totally unexpected and makes the present situation even more puzzling.

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