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PRODUCTION DYNAMICS AND HIGH p_T SPIN EFFECTS*

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ABSTRACT

We will emphasize the importance of spin for our understanding of production dynamics at high p_T. Within the framework of perturbative QCD several predictions for interesting spin observables are presented for various reactions. They are crucial tests accessible to existing or future experimental programs.

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ABSTRACT

We will emphasize the importance of spin for our understanding of production dynamics at high p_T. Within the framework of perturbative QCD several predictions for interesting spin observables are presented for various reactions. They are crucial tests accessible to existing or future experimental programs.

1. Introduction

Hadrons are made of fundamental constituents carrying several quantum numbers and among them spin which is the most intriguing one. Valence quarks and sea quarks (antiquarks) are spin-1/2 objects, gluons are spin-1 objects and in the same way we begin to learn how, in a high energy collision, the *proton momentum* is distributed among its constituents, we would like to know how the *proton spin* is shared among them. Clearly the answer to this question requires measurements of cross sections in pure spin states with the determination of the polarization of either the beam, the target, or the final state and suitable combinations of these three. Hadronic collisions at high momentum transfers are expected to provide the most valuable information on short distance dynamics, so we are very much interested to know what are the sizeable spin effects and what sign to expect for them in this particular kinematic region. This is the purpose of this report and, as we will see, there are already some striking experimental results for the single transverse spin asymmetry in inclusive pion production whose theoretical interpretation is far from being obvious. We will evaluate double helicity asymmetries for a set of reactions which are uniquely accessible in the experimental program of the Fermilab polarized proton beam[1] and transmitted helicity asymmetries which can be also measured at CERN with the future installation of a polarized gas target by the UA6 Collaboration.[2] The outline of the paper is as follows. In the next section we recall the definition of some spin observables and we briefly describe the theoretical framework we will use to calculate them. In section 3 we discuss the problem of transverse polarization and single transverse spin asymmetries. Section 4 is devoted to lepton pair production and in section 5 we consider double helicity asymmetries for direct photon production, hyperon production, pion production and jet production.

2. Observables and Basis of the Theoretical Framework

Let us consider the hard scattering hadronic reaction

$$a + b \rightarrow c\,(\text{or jet}) + X \tag{1}$$

which is described in terms of two to two parton subprocesses in the QCD parton model as shown in fig. 1. The corresponding inclusive cross section, provided factorization holds, is given by

$$d\sigma\,(a+b\rightarrow c+X) = \sum_{ij} \frac{1}{1+\delta_{ij}} \int dx_a dx_b \left[f_i^{(a)}\left(x_a, Q^2\right) f_j^{(b)}\left(x_b, Q^2\right) + (i \leftrightarrow j) \right] d\hat{\sigma}_{ij}. \tag{2}$$

The summation runs over all contributing parton configurations; the parton distribution $f_i^{(a)}\left(x_a, Q^2\right)$ is the probability that hadron "a" contains a parton "i" carrying a fraction x_a of the hadron's momentum. It represents the parton flux available in the colliding hadron which is universal, that is process independent. Clearly the parton distributions play a crucial role because they allow the connection between hadron-hadron collisions and elementary subprocesses. $d\hat{\sigma}_{ij}$ is the cross section for the interaction of two partons i and j which can be calculated perturbatively. The total energy of the partons in the subprocess center of mass frame is $\sqrt{\hat{s}} = \sqrt{x_a x_b\, s}$ where $\sqrt{s}$ denotes the total center of mass energy of the initial hadrons. Finally Q^2 which is defined in terms of the invariants of the subprocess, characterizes the physical momentum scale. The distributions $f_i\left(x, Q^2\right)$ are extracted from deep inelastic data at low Q^2 and their Q^2 dependence, which is logarithmic, is predicted in perturbative QCD. If the initial particles are polarized, one can define correspondingly polarized parton distributions. For a given parton (quark, antiquark or gluon) we denote $f_\pm\left(x,Q^2\right)$ the parton distributions in a polarized nucleon either with helicity parallel (+) or antiparallel (−) to the parent nucleon helicity. As usual, we define the ***unpolarized distribution*** $f = f_+ + f_-$ and the ***parton helicity asymmetry*** $\Delta f = f_+ - f_-$. Similarly for transverse spin we denote $f_\uparrow\left(x,Q^2\right)$ and $f_\downarrow\left(x,Q^2\right)$ the parton distributions with transversity parallel (↑) or antiparallel (↓) to the parent transversity and the ***parton transversity asymmetry*** is $\Delta f^T = f_\uparrow - f_\downarrow$.

The simplest measurable quantity if, for example, hadron "a" is transversally polarized is the up-down asymmetry or single transverse spin asymmetry

$$A = \frac{d\sigma_{a(\uparrow)} - d\sigma_{a(\downarrow)}}{d\sigma_{a(\uparrow)} + d\sigma_{a(\downarrow)}} \tag{3}$$

which is given by

$$A\,d\sigma = \sum_{ij} \frac{1}{1+\delta_{ij}} \int dx_a dx_b \left[\Delta f_i^{T(a)}\left(x_a,Q^2\right) f_j^{(b)}\left(x_b,Q^2\right) + (i \leftrightarrow j)\right] \hat{a}^{ij} d\hat{\sigma}_{ij} \tag{4}$$

assuming the factorization property, where $d\sigma$ is given by Eq. (2) and $\hat{a}^{ij}$ denotes the subprocess up-down asymmetry for initial partons i and j. We will come back to this in the next section. When both initial hadrons are longitudinally polarized, one can also measure the double helicity hadron asymmmetry A_{LL} defined as

$$A_{LL} = \frac{d\sigma_{a(+)b(+)} - d\sigma_{a(+)b(-)}}{d\sigma_{a(+)b(+)} + d\sigma_{a(+)b(-)}} \tag{5}$$

which is given by

$$A_{LL}\,d\sigma = \sum_{ij} \frac{1}{1+\delta_{ij}} \int dx_a dx_b \left[\Delta f_i^{(a)}\left(x_a,Q^2\right) \Delta f_j^{(b)}\left(x_b,Q^2\right) + (i \leftrightarrow j)\right] \hat{a}_{LL}^{ij} d\hat{\sigma}_{ij} \tag{6}$$

where $\hat{a}_{LL}^{ij}$ denotes the subprocess double helicity asymmetry. The explicit expressions of these quantities for various subprocesses are given in Ref. 3. To get a rough estimate of A_{LL} one can use the following approximation

$$A_{LL} \sim \sum_{ij} \left\langle \frac{\Delta f_i}{f_i} \right\rangle \left\langle \frac{\Delta f_j}{f_j} \right\rangle \hat{a}_{LL}^{ij} \tag{7}$$

in terms of the average of the *parton polarizations* defined as $\frac{\Delta f_i}{f_i}$. It shows that, even if at the parton level $\hat{a}^{ij}_{LL}$ is as large as $\pm\,100\%$, it is expected to be diluted *twice* at the hadron level since the parton polarizations are less than one in the relevant kinematic region.

Finally, if only one initial hadron is longitudinally polarized and one observes the longitudinal polarization of the final state c, one can consider the transmitted helicity asymmetry D_{LL} defined as

$$D_{LL} = \frac{d\sigma_{a(+)c(+)} - d\sigma_{a(+)c(-)}}{d\sigma_{a(+)c(+)} + d\sigma_{a(+)c(-)}} \tag{8}$$

whose expression is similar to Eqs. (4) and (6). A rough estimate of D_{LL} reads

$$D_{LL} \sim \sum_i \left\langle \frac{\Delta f_i}{f_i} \right\rangle \hat{d}^{ic}_{LL} \tag{9}$$

where $\hat{d}^{ic}_{LL}$ is the subprocess transmitted asymmetry and we have ignored the complications from the fragmentation function of c, assuming it is a photon or a jet. In this case if $\hat{d}^{ic}_{LL}$ is large it will be diluted only *once* and we expect a fairly large D_{LL}.

3. Single Transverse Spin Asymmetry

As we will explain now it is not at all straightforward to calculate the single transverse spin asymmetry A for a given inclusive reaction, say Eq. (1). We have seen (Eq. (4)) that in addition to the ingredients needed to compute the unpolarized cross section, namely f_i and $d\hat{\sigma}^{ij}$, we have to know Δf^T_i *and* $\hat{a}^{ij}$. Δf^T_i could be measured directly in polarized deep inelastic scattering (DIS) with a transversally polarized proton target but it has never been done. However it is possible to get some information[4] from positivity which implies that

$$|\Delta f^T_i| < \sqrt{2R} f_i \tag{10}$$

where R is the ratio of the longitudinal to transverse virtual photon cross sections which is expected to vanish in the scaling limit. Since positivity also requires $|\hat{a}^{ij}| < 1$, we get the simple *nontrivial* bound

$$|A| < \sqrt{2R}. \tag{11}$$

Given the fact that R is of the order of 0.10 to 0.15 (see Ref. 5), one has the safe result

$$|A| < .50 \tag{12}$$

which should be satisfied by any data. On the other hand we know that in the original simple parton model

$$\Delta f^T(x) = \sum_i e_i^2 \Delta f_i^T(x) = g_1(x) + g_2(x) \tag{13}$$

where g_1 and g_2 are the scaling limits of the two spin-dependent structure functions G_1 and G_2 occurring in polarized DIS. Using Wilson's operator expansion, one can derive various sum rules[6] for g_1 and g_2 and in particular one has, to some approximation, the following result

$$g_1(x) + g_2(x) = \int_x^1 \frac{dy}{y} g_1(y) \tag{14}$$

which allows one to calculate $\Delta f^T(x)$ from the knowledge of $g_1(x)$. The new EMC data[7] on $g_1(x)$ leads to the interpolation displayed in fig. 2. From this it is possible to calculate $g_2(x)$ using Eq. (14) and the result is also shown in fig. 2. This guess leads to a fairly large $\Delta f^T(x)$ at small x values and it almost vanishes for x about 0.5. It would be nice to have direct confirmation of this result from experiment.

Let us now turn to $\hat{a}^{ij}$, the subprocess up-down asymmetries. There exists no perturbative calculation for these quantities but still we can guess that

$$\hat{a}^{ij} \sim m_{q_i} \alpha_s \tag{15}$$

since they should involve an imaginary part which requires higher order in the strong coupling constant α_s and a flip amplitude which is proportional to the quark mass m_{q_i} as a consequence of helicity conservation in perturbative QCD. Although, according to recent work, the relevant mass scale for A is the hadron mass, the resulting asymmetries are very small[8]. This is in contradiction with experimental data on π^0 inclusive production near 90° where a large effect has been observed, first at $p_{\rm lab} = 24$ GeV/c in pp collisions at CERN[9], and later at $p_{\rm lab} = 40$ GeV/c in πp collisions at Serpukhov,[10] as shown in figs. 3a and b. In both cases A is negative and grows with p_T. An important positive effect in π^+ production has recently been reported from a BNL experiment[11] at lower energy.

4. Lepton Pair Production

One should realize that the cross section for lepton pair production at high p_T is fairly small, e.g., of the order of 1 pb at $p_T = 3$ GeV/c. Since it is not easily accessible to experiment, we will stay with $p_T = 0$. (For positivity bounds on A versus p_T, see Ref. 12.) At $p_T = 0$ the situation is simpler and provides a good illustration of what we can learn from polarization measurements. The basic subprocess in the Drell Yan mechanism is

$$q_i\,(h_a)\,\bar{q}_i\,(h_b) \rightarrow \mu^+\,(h_+)\,\mu^-\,(h_-) \tag{16}$$

where we have specified the helicities of all particles. The differential cross section reads

$$\frac{d\hat{\sigma}_i}{d\hat{t}} = \frac{2\pi\alpha^2}{\hat{s}^2}\frac{e_i^2}{4}\left[(1-h_a h_b)\,(1-h_+h_-)\,\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2} - (h_a h_b)\,(h_+ - h_-)\,\frac{\hat{t}^2-\hat{u}^2}{\hat{s}^2}\right] \tag{17}$$

so the transmitted asymmetry is $\hat{d}_{LL} = \pm\left(\hat{t}^2 - \hat{u}^2\right)/\left(\hat{t}^2 + \hat{u}^2\right)$. The transmitted helicity asymmetry D_{LL} between one initial hadron A and the negative outgoing muon in $\vec{A}B \rightarrow \vec{\mu}^-\mu^+X$ is, after integrating out the muon distribution

$$D_{LL} = \left(\frac{x_a^2 - x_b^2}{x_a^2 + x_b^2}\right)\frac{\sum_i e_i^2\left[\Delta q_i\,(x_a)\,\bar{q}_i\,(x_b) - \Delta\bar{q}_i\,(x_a)\,q_i\,(x_b)\right]}{\sum_i e_i^2\left[q_i\,(x_a)\,\bar{q}_i\,(x_b) + \bar{q}_i\,(x_a)\,q_i\,(x_b)\right]} \tag{18}$$

where $x_a = \frac{1}{2}\left[x_F + \sqrt{x_F^2 + 4\hat{s}/s}\right]$ and $x_b = \frac{1}{2}\left[x_F - \sqrt{x_F^2 + 4\hat{s}/s}\right]$. Note that for the positive outgoing muon D_{LL} changes sign. From the x-behavior of the quark distributions we see that for $x_a > x_b$ i.e., $x_F > 0$, the lepton pair is produced in the forward direction and D_{LL} is dominated by $\Delta q/q$ i.e., the valence quark polarization which is known from Ref. 7. For $x_a < x_b$, i.e., $x_F < 0$ the lepton pair is produced in the backward direction and D_{LL} is dominated by $\Delta\bar{q}/\bar{q}$, i.e., the sea quark polarization. The result of the calculation is shown in fig. 4 where a small positive sea quark polarization was assumed.

Let us now consider the double helicity asymmetry A_{LL} in $\vec{A}\vec{B} \rightarrow \mu^-\mu^+X$. From Eq. (17) we find $\hat{a}_{LL} = -1$ so

$$A_{LL} = -\frac{\sum_i e_i^2\left[\Delta q_i\,(x_a)\,\Delta\bar{q}_i\,(x_b) + (x_a \leftrightarrow x_b)\right]}{\sum_i e_i^2\left[q_i\,(x_a)\,\bar{q}_i\,(x_b) + (x_a \leftrightarrow x_b)\right]}. \tag{19}$$

Clearly in pp collisions $A_{LL} = 0$ unless the sea quarks are polarized and its sign is opposite to that of the sea quark polarization. We show in fig. 5 the result at $x_F = 0$ versus $M_{\mu\mu}$ together with the effect for $\bar{p}p$ collisions which is larger in magnitude because in this case $\Delta\bar{q}$ is a valence quark helicity asymmetry.

Finally, let us mention an interesting high p_T effect in muon pair production which has recently been observed at CERN by the NA10 Collaboration with π^- beams[13]. The angular distribution in the Collins-Soper frame can be written as

$$\frac{dN}{d\Omega} \propto 1 + \lambda\cos^2\theta + \mu\sin 2\theta\,\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi. \tag{20}$$

In the parton model $\lambda = 1$, $\mu = \nu = 0$ so there is no ϕ dependence. This contrasts with the data as shown in fig. 6. In QCD one should have, for both annihilation and Compton scattering, the Callan-Gross type relation $\lambda = 1 - 2\nu$ which reflects the transversality of the virtual timelike photon producing the muon pair. This property is not seen in the data, mainly at high p_T, which might mean that there is a large longitudinal component. However in $\pi^- p$ collisions annihilation dominates and in this case another relation should hold in lowest order, namely $\lambda = \nu$. This also is not very well supported by the data. Maybe one has to take into account higher order effects or QCD has failed this important test.

5. Single Inclusive Reactions

In this section we will consider a few examples of single inclusive reactions which will be easier to measure at high p_T because they have larger cross sections, typically at $p_T = 3$ GeV/c direct photon production has a cross section of the order of 1 nb, while for jet production its value is 50 nb.

Direct photon production at high p_T is dominated by Compton scattering in pp collisions and by annihilation scattering in $\bar{p}p$ collisions. The double helicity asymmetries A_{LL} read in these approximations for pp collisions

$$A_{LL} = \frac{\sum_i \int \left[\Delta q_i (x_a) \Delta G (x_b) \hat{a}^c_{LL} d\hat{\sigma}^c_i / d\hat{t} + (x_a \leftrightarrow x_b)\right]}{\sum_i \int \left[q_i (x_a) G (x_b) d\hat{\sigma}^c_i / d\hat{t} + (x_a \leftrightarrow x_b)\right]} \tag{21}$$

where $\hat{a}^c_{LL} = \frac{\hat{s}^2 - \hat{t}^2}{\hat{s}^2 + \hat{t}^2}$ and $d\hat{\sigma}^c_i / d\hat{t} = -e_i^2 \frac{\pi \alpha \alpha_s}{3 \hat{s}^2} \left(\frac{\hat{s}^2 + \hat{t}^2}{\hat{s}\hat{t}}\right)$ and for $\bar{p}p$ collisions

$$A_{LL} = \frac{\sum_i \int \Delta q_i (x_a) \Delta \bar{q}_i (x_b) \hat{a}^A_{LL} d\hat{\sigma}^A_i / d\hat{t}}{\sum_i \int q_i (x_a) \bar{q}_i (x_b) d\hat{\sigma}^A_i / d\hat{t}} \tag{22}$$

where $\hat{a}^A_{LL} = -1$ and $d\hat{\sigma}^A_i / d\hat{t} = e_i^2 \frac{\pi \alpha \alpha_s}{\hat{s}^2} \frac{8}{9} \left(\frac{\hat{t}^2 + \hat{u}^2}{\hat{t}\hat{u}}\right)$. In these expressions the integration has to be done over the appropriate parton phase space. Let us first discuss pp collisions. The gluon helicity asymmetry ΔG which occurs in Eq. (21b) is not directly known from experiment, so we will assume it is positive and such that gluons carry about 20% of the proton spin. This can be debated[14] on the light of the data from Ref. 7, but the measurement of A_{LL} is another way of getting $\Delta G(x)$.[15] The results are shown in fig. 7 for two different values of the c.m. production angle $\theta_{c.m.} = 45°$ and 90° and A_{LL} would vanish if $\Delta G = 0$ and if annihilation could be fully neglected. For $\bar{p}p$ collisions from Eq. (21b) we see that A_{LL} is expected to be larger because $\Delta\bar{q}$ is a valence quark asymmetry and it is negative following the sign of $\hat{a}^{A}_{LL}$ whose magnitude will also enhance the effect. We show the results in fig. 7 which are all increasing with p_T.

The transmitted helicity asymmetry D_{LL} in pp collisions[16] between one initial polarized proton and the final state photon is expressed in terms of two subprocess transmitted asymmetries, quark to photon $\hat{d}^{c}_{LL}(\vec{q}g \to \vec{\gamma}q) = (\hat{s}^2 - \hat{t}^2)/(\hat{s}^2 + \hat{t}^2)$ and gluon to photon $\hat{d}^{c}_{LL}(\vec{g}q \to \vec{\gamma}q) = 1$ and we have

$$D_{LL} = \frac{\sum_i \int \left[\Delta q_i(x_a)\, G(x_b) \left(\frac{\hat{s}^2-\hat{t}^2}{\hat{s}^2+\hat{t}^2}\right) d\hat{\sigma}^c_i/d\hat{t} + q_i(x_a)\, \Delta G(x_b)\, d\hat{\sigma}^c_i/d\hat{u}\right]}{\sum_i \int \left[q_i(x_a)\, G(x_b)\, d\hat{\sigma}^c_i/d\hat{t} + (x_a \leftrightarrow x_b)\right]} \tag{23}$$

In this case also for $x_F > 0$, i.e., the photon is produced in the forward direction with respect to the polarized proton, D_{LL} is driven by $\Delta q/q$ whereas for $x_F < 0$ it is driven by $\Delta G/G$. The results are shown in fig. 8 and we see that the magnitude of the effect which grows with p_T is very sensitive to the value of x_F. Clearly this is an important measurement to be made.

One can also consider the transmitted asymmetry in hyperon production e.g., $\vec{p}p \to \vec{\Lambda}X$ which is easy to measure because the Λ polarization is directly obtained from its decay distribution. For illustration, if we assume that the production mechanism to leading order is dominated by the double gluon process $\vec{g}g \to \vec{s}\bar{s}$ whose transmitted asymmetry is $\hat{d}_{LL} = -(\hat{t}^2 - \hat{u}^2)/(\hat{t}^2 + \hat{u}^2)$ shown in fig. 9a, it is clear that D_{LL} will increase for smaller c.m. production angle and this is the trend observed in fig. 9b. The question of next-to-leading corrections was not discussed because one would expect them to be small in asymmetries which are ratios of cross sections. However this is a case where this conjecture is not valid, and according to Ref. 17 higher order corrections lead to a D_{LL} opposite in sign and significantly larger in magnitude as shown in fig. 9b.

Finally, let us consider the double helicity asymmetries in pion and jet production. Cross sections for these reactions are large and many subprocesses contribute to them, i.e., $uu \to uu$, $ud \to ud$, $qg \to qg$, etc. .... For most of them $\hat{a}^{ij}_{LL}$ is positive[3], so we expect A_{LL} to be positive provided Δq_i and ΔG are positive. This is in agreement with the results shown in fig. 10, except for the π^- production where the down quark asymmetry

Δd, which is negative according to several models[3], dominates. In all cases the magnitude of A_{LL} is growing with x_T.

In conclusion we would like to stress that a large single transverse spin asymmetry has been observed at high p_T near 90° in π^0 production and it should be checked and also measured in other reactions like direct photon or jet production. We also badly need data on the A_{LL} and D_{LL} parameters at high p_T to test the general framework behind the theoretical predictions presented here for various well defined processes.

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Figure Captions

Fig. 1: Parton model representation of a hadron-hadron collision at short distances.

Fig. 2: Interpolation of $g_1(x)$ versus x from Ref. 7 (solid curve) and resulting $g_2(x)$ using Eq. (14) (dashed curve).

Fig. 3: Results on single transverse spin asymmetry for $x_F \sim 0$, versus p_T. (a) data from Ref. 9, (b) data from Ref. 10.

Fig. 4: The transmitted helicity asymmetry for lepton pair production versus x_F for $M_{\mu\mu} = 5\mathrm{GeV/c}^2$.

Fig. 5: The double helicity asymmetry for lepton pair production at $x_F = 0$ versus $M_{\mu\mu}$ for pp and $\bar{p}p$ collisions.

Fig. 6: Data on the parameters, λ, μ and ν as a function of p_T in the Collins-Soper frame from Ref. 13.

Fig. 7: The double helicity asymmetry versus p_T for direct photon production at $\sqrt{s} = 25$ GeV and the different values of the c.m. production angle $\theta_{c.m.} = 45°$ and $90°$.

Fig. 8: The transmitted helicity asymmetry versus p_T for $pp \to \gamma X$ at $\sqrt{s} = 25$ GeV and different x_F values.

Fig. 9a: Born transmitted asymmetry for $gg \to s\bar{s}$ versus the subprocess c.m. scattering angle.

Fig. 9b: The transmitted asymmetry values $x_T = 2p_T/\sqrt{s}$ for $\vec{p}p \to \vec{\Lambda}X$ at two different c.m. production angles. Leading order (solid curves). Higher order corrections (dashed curves) from Ref. 17.

Fig. 10: The double helicity asymmetry at $x_F = 0$ versus x_T for pion and jet production.

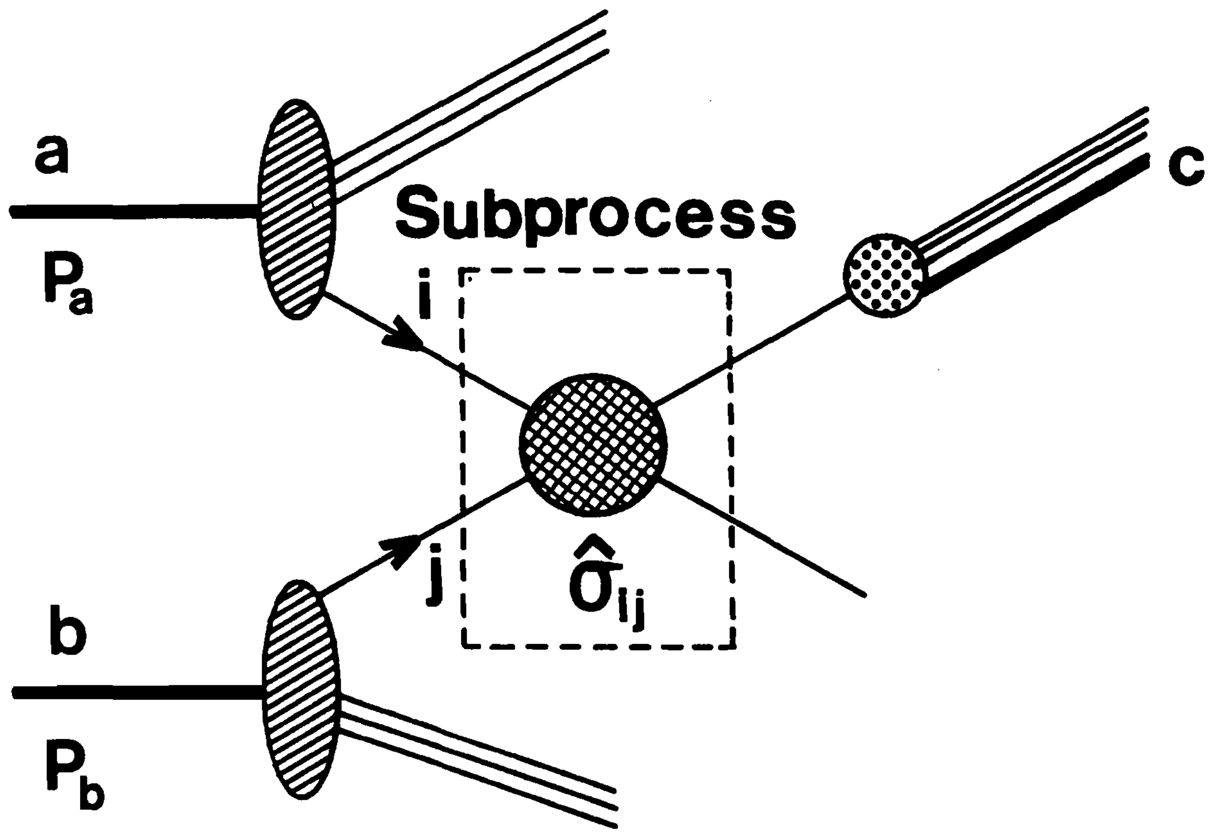


Fig. 1

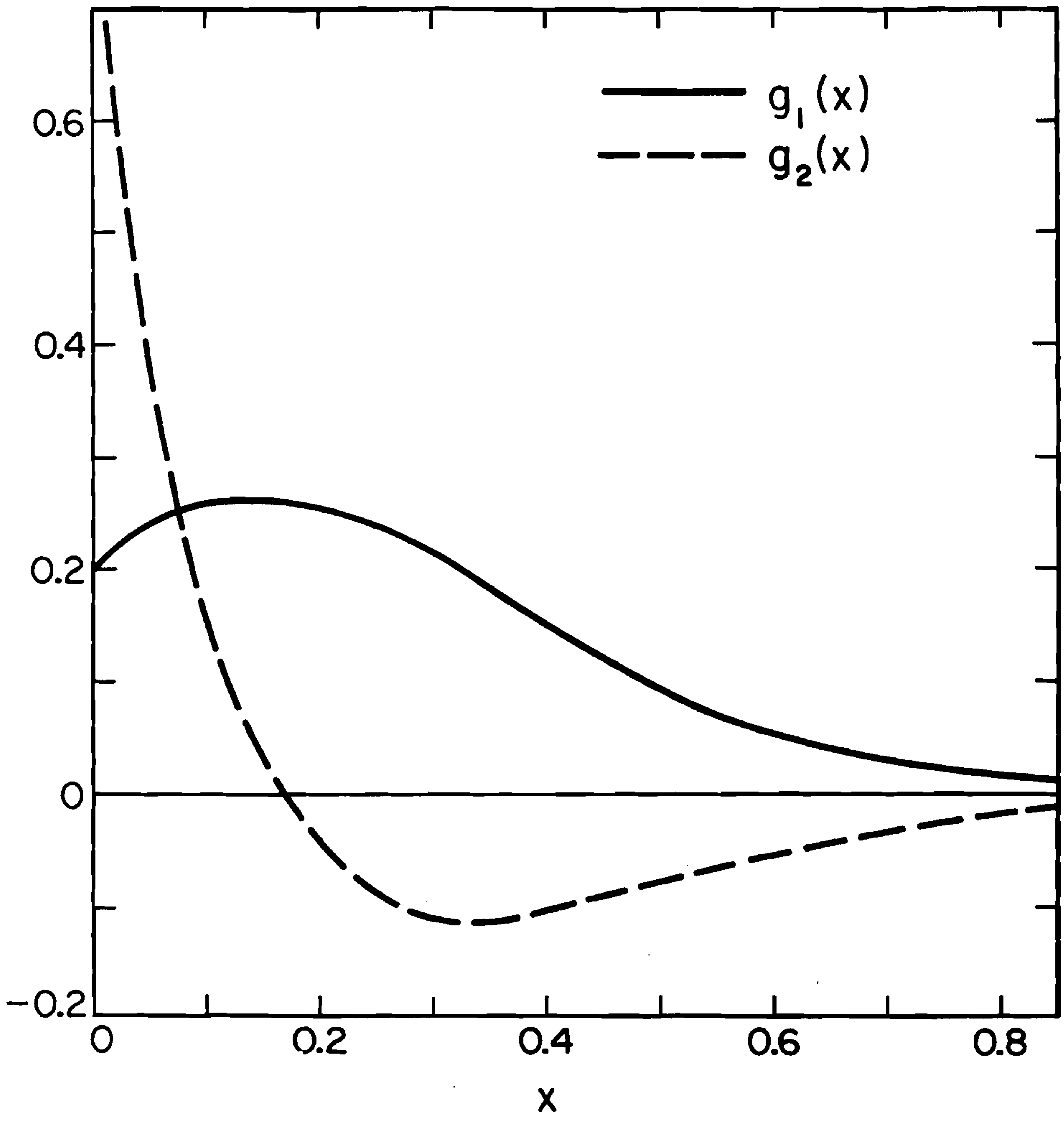
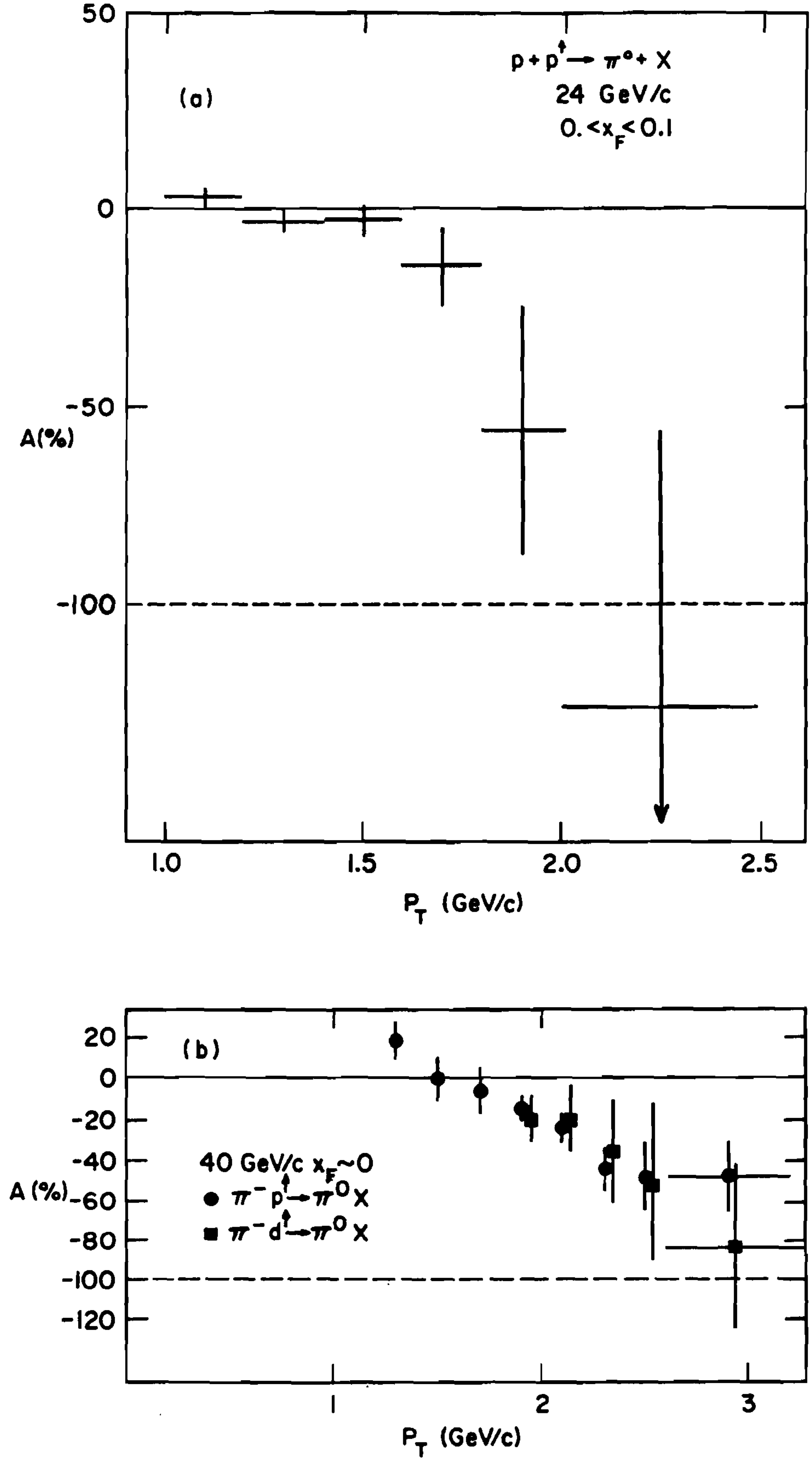


Fig. 2



(a)
p + p↑ → π° + X
24 GeV/c
0. < x_F < 0.1
A(%)
50
0
-50
-100
1.0
1.5
2.0
2.5
P_T (GeV/c)
(b)
40 GeV/c x_F~0
$\pi^- p^\uparrow \to \pi^0 X$
$\pi^- d^\uparrow \to \pi^0 X$
A (%)
20
0
-20
-40
-60
-80
-100
-120
1
2
3
P_T (GeV/c)

Fig. 3

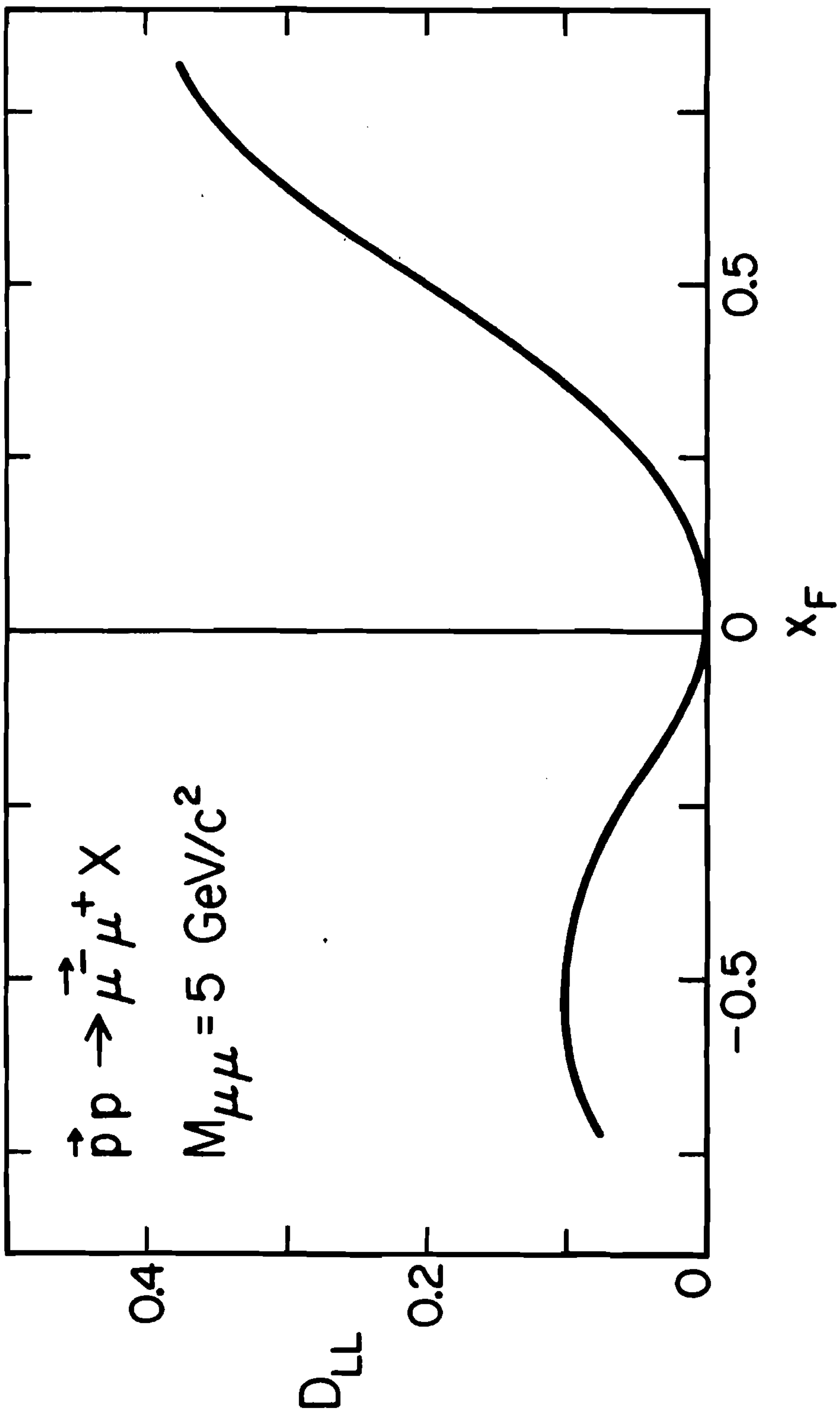


Fig. 4

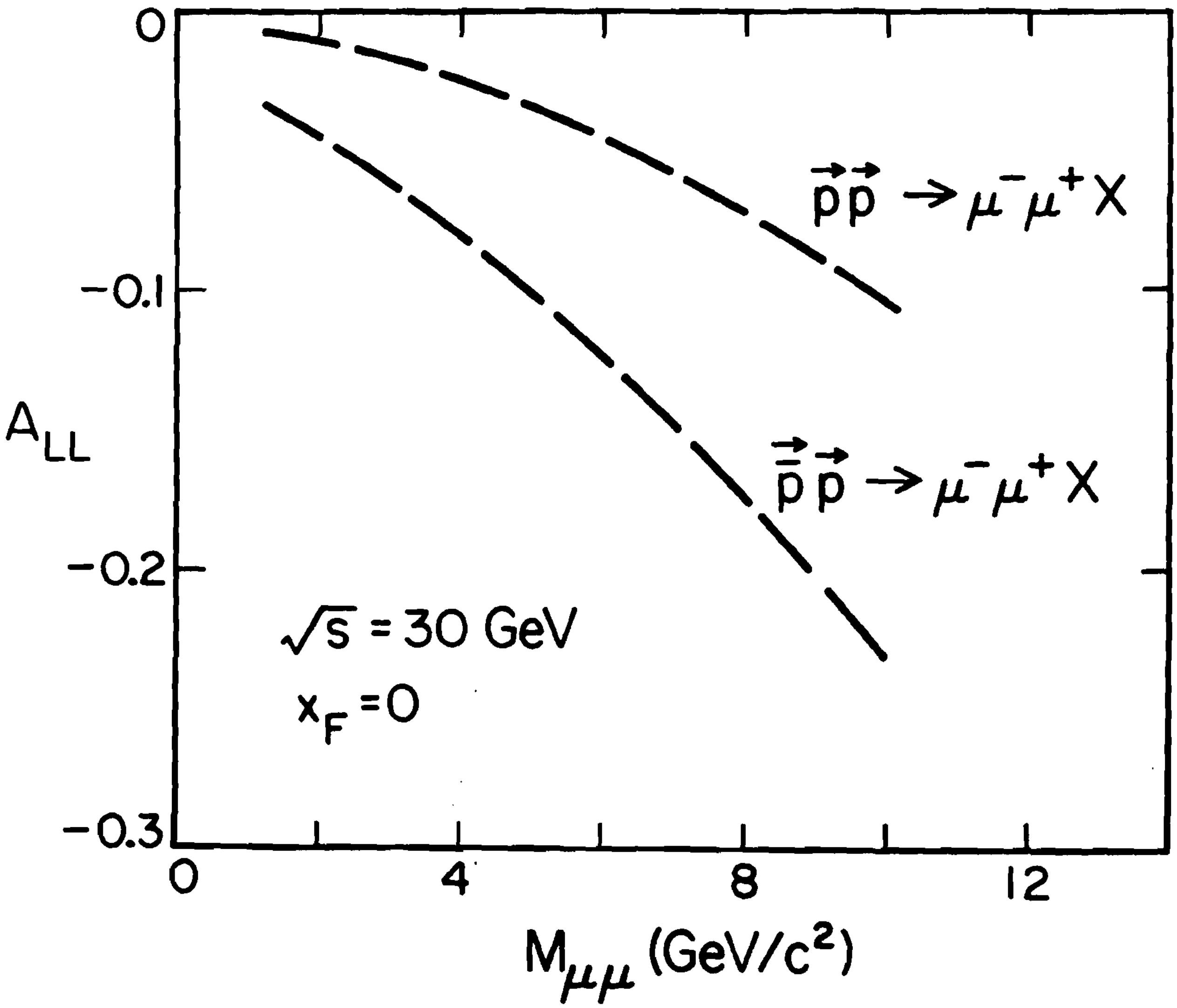

0
-0.1
-0.2
-0.3
A_{LL}
$\vec{p}\vec{p} \to \mu^- \mu^+ X$
$\vec{\bar{p}}\vec{p} \to \mu^- \mu^+ X$
$\sqrt{s} = 30$ GeV
$x_F = 0$
0
4
8
12
$M_{\mu\mu}$ (GeV/c^2)

Fig. 5

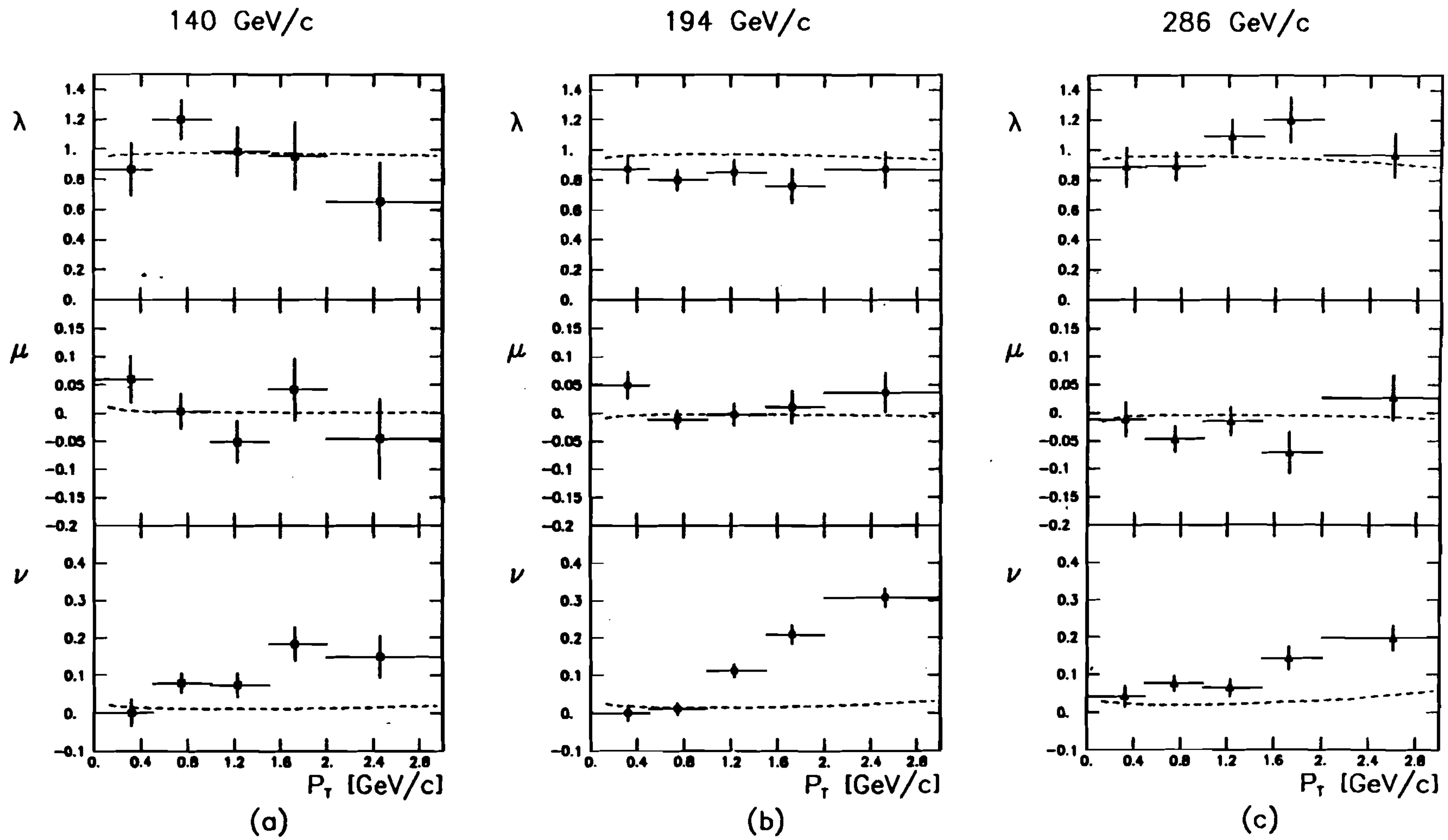
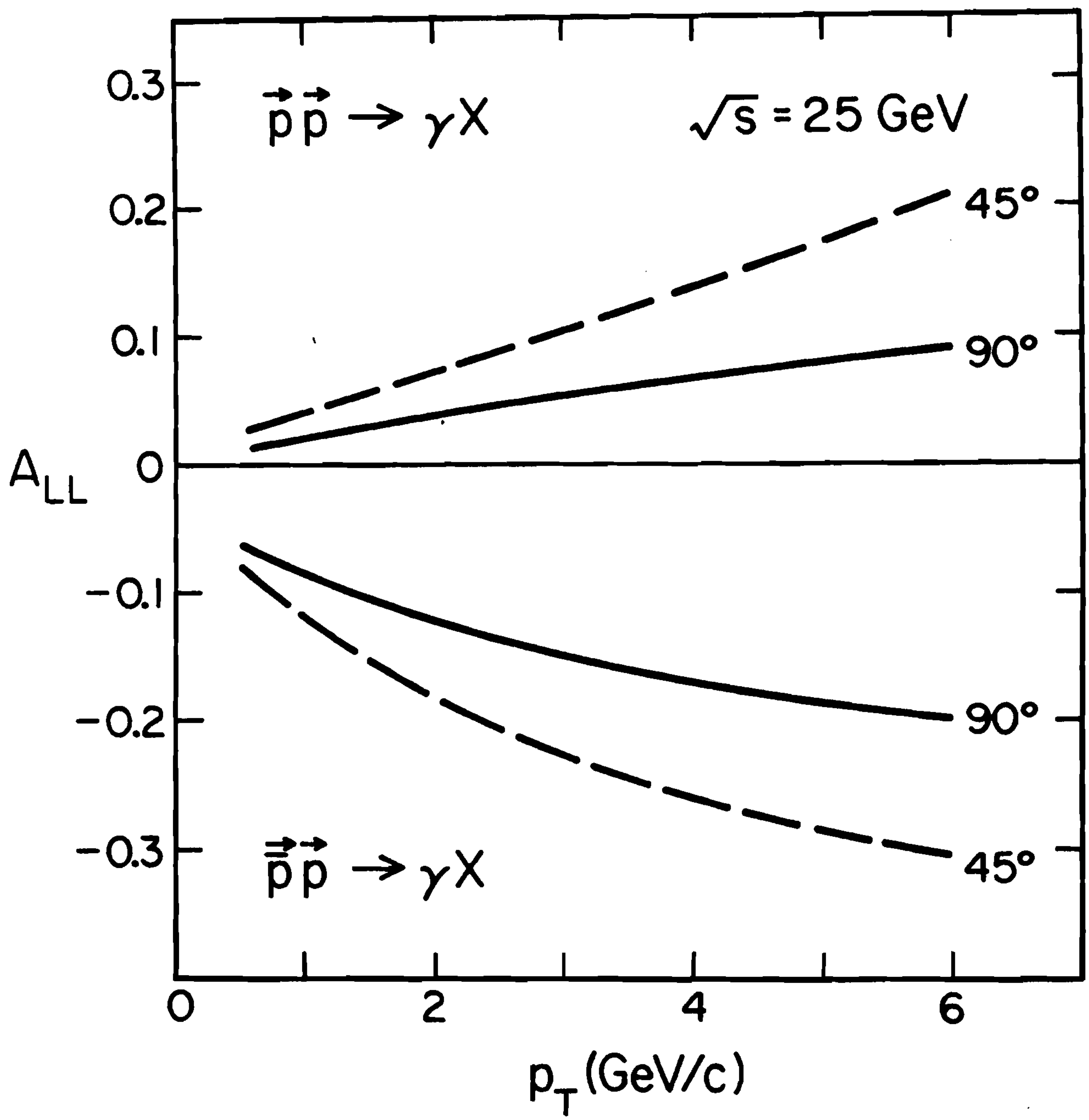
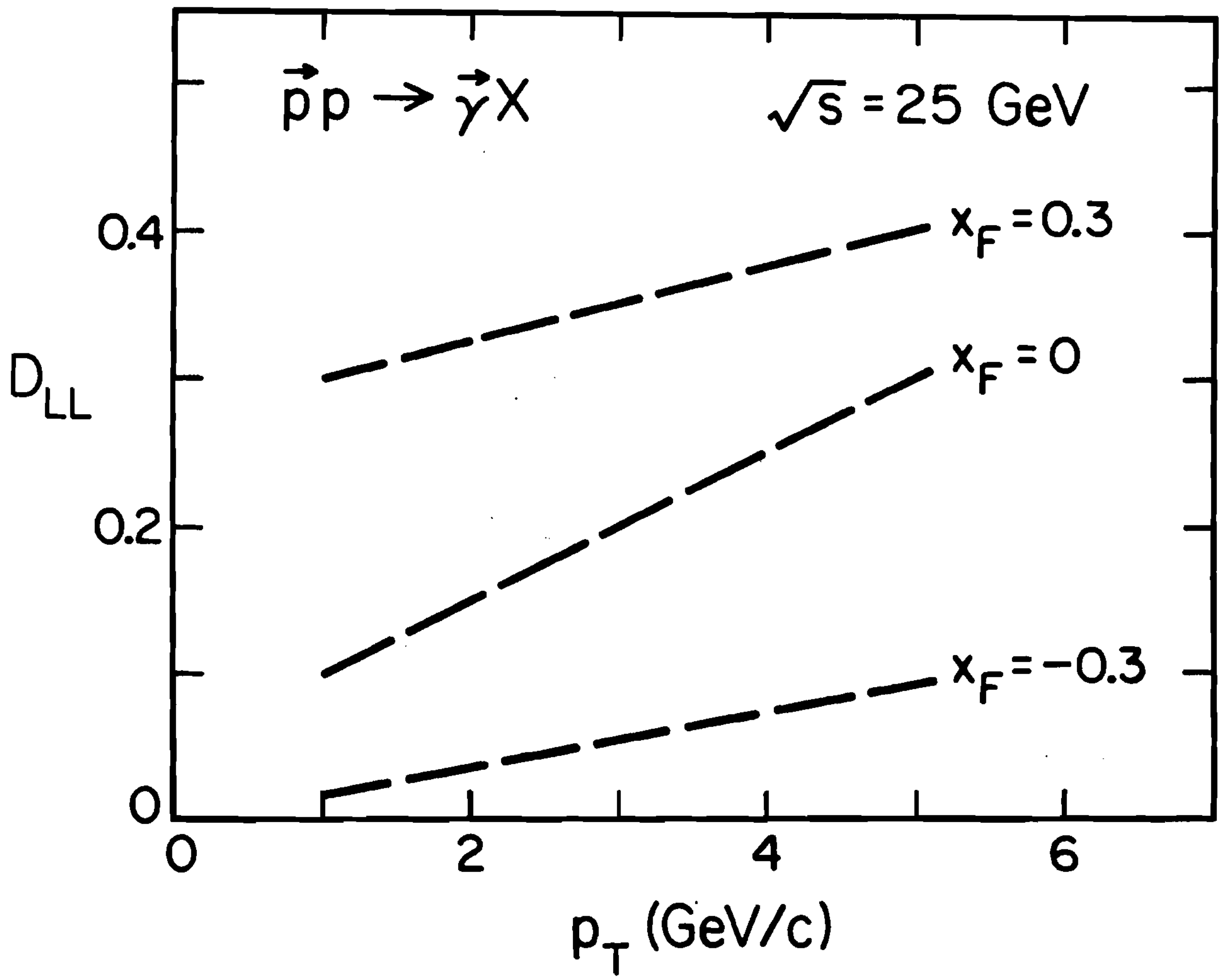


Fig. 6



0.3
0.2
0.1
0
-0.1
-0.2
-0.3
A_{LL}
$\vec{p}\,\vec{p} \rightarrow \gamma X$
$\sqrt{s} = 25$ GeV
45°
90°
90°
45°
$\vec{\vec{p}}\,\vec{p} \rightarrow \gamma X$
0
2
4
6
p_T (GeV/c)

Fig. 7



$\vec{p}p \rightarrow \vec{\gamma}X$
$\sqrt{s} = 25$ GeV
$x_F = 0.3$
$x_F = 0$
$x_F = -0.3$
D_{LL}
0.4
0.2
0
0
2
4
6
p_T (GeV/c)

Fig. 8

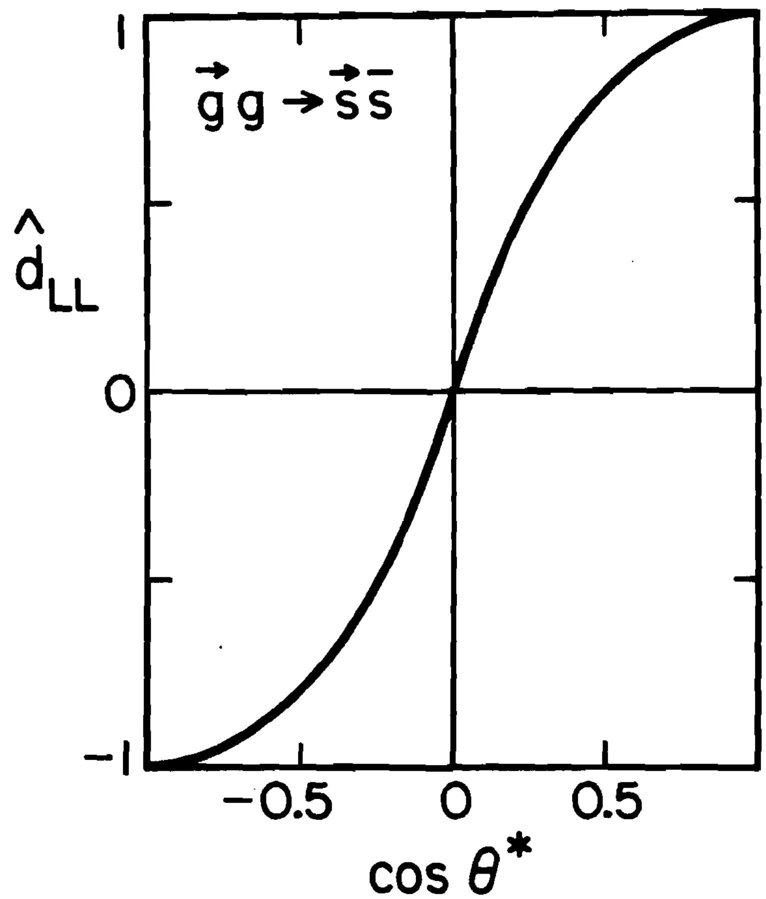


Fig. 9a

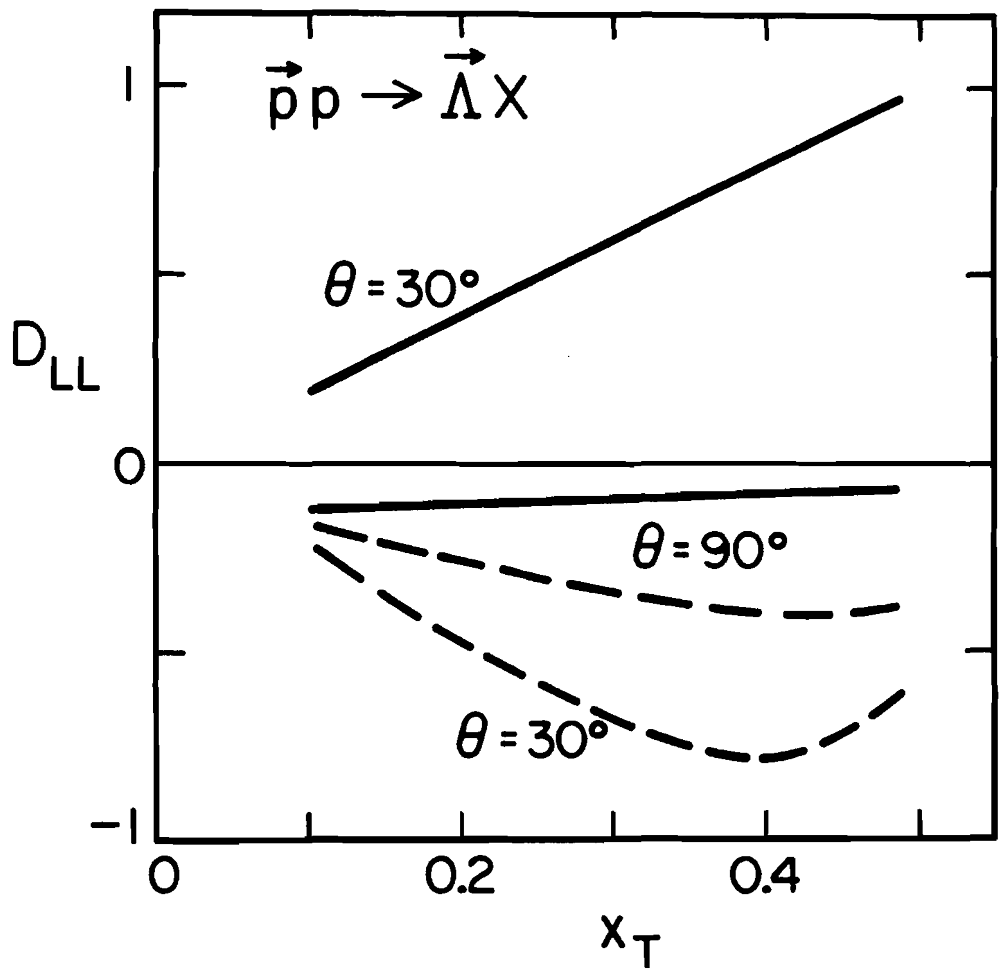


Fig. 9b

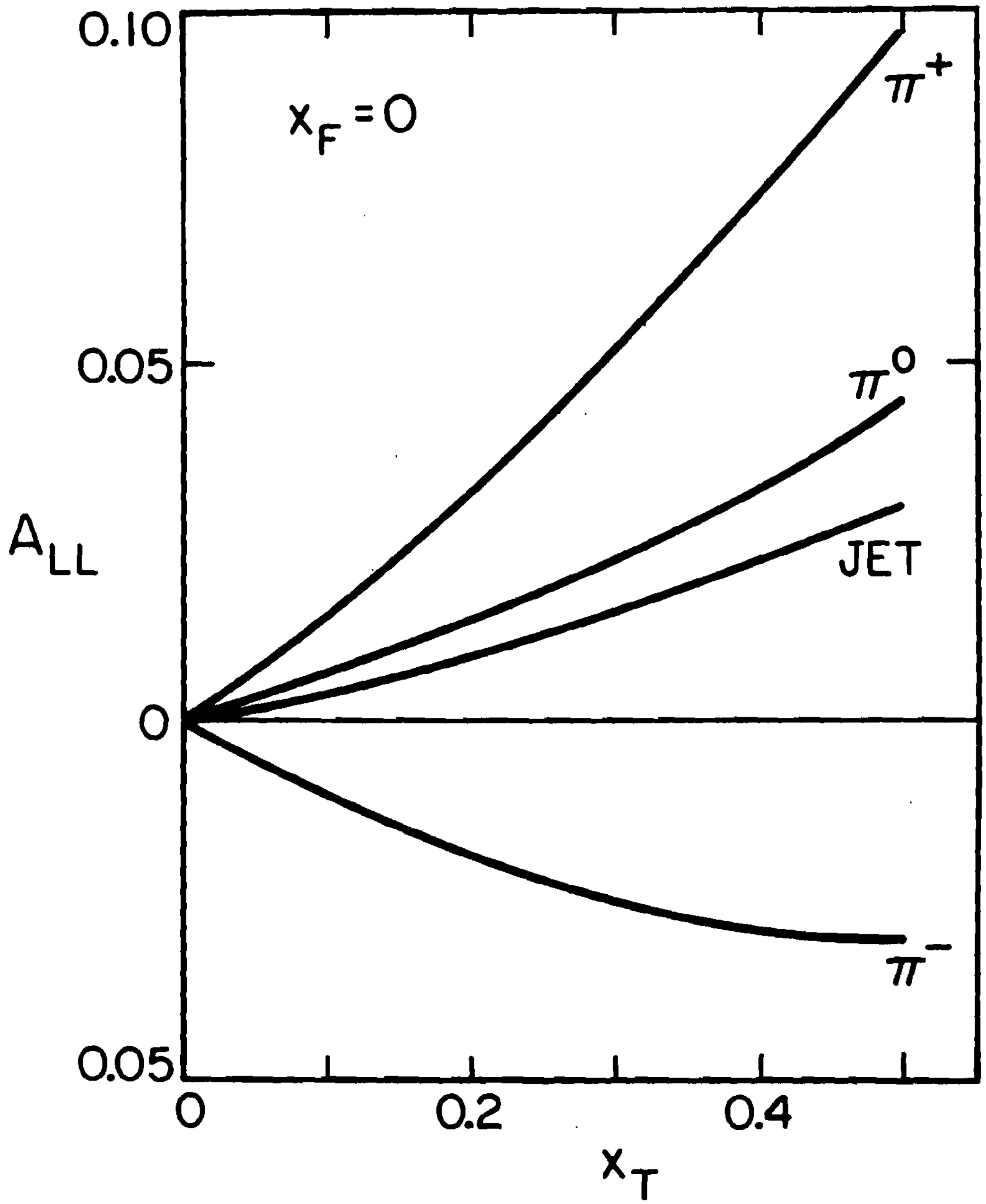


Fig. 10