Probing Spin-Dependent Parton Distributions Trough Polarization Measurements In $P + \vec{P} \to \bar{\Lambda}^0(\Lambda^0) + X$

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Abstract

It is shown that the inclusive polarization of $\bar{\Lambda}^0$ (Λ^0) produced in hard pp scattering is sensitive to $\Delta\bar{s}(x)$ ($\Delta s(x)$) and $\Delta G(x)$. Monte Carlo simulations predict a value of the polarization $\sim 2\%$ with statistical errors $\sim 0.1\%$ at $2\,GeV/c \leq P_T \leq 5\,GeV/c$ and $z_\Lambda \geq 0.5$ for existing HERA proton beam , target parameters and HERMES acceptance. abstract of your contribution.

1 Introduction

It was found in the SLAC and EMC experiments [1,2] that the contributions of quark spins to the proton spin is surprisingly small (so called 'spin crisis'). This experimental result points presumably to a large negative polarization of sea quarks or large positive gluon polarization (see for example reviews [3,4]). It is known that both the valence and sea quark polarization can be studied through the spin asymmetry measurements in semi-inclusive deep inelastic scattering of polarized leptons on polarized protons and nuclei [5,6]. But the main problem of such experiments is a low statistics of useful events. We are going to discuss in the present work a possibility of studying the polarized sea quark and gluon distributions via polarization measurements in inclusive $\bar{\Lambda}^0$ and Λ^0 production in hard pp collisions at HERA. It will be shown below that the longitudinal polarization of Λ^0 and $\bar{\Lambda}^0$ produced in hard scattering of an unpolarized proton beam from a longitudinally polarized proton target is sensitive both to sea quark and gluon helicity distributions. But it is practically insensitive to the valence quark spin-dependent distributions. We conclude that hard pp collisions provide an additional information compared to lepton-nucleon deep inelastic scattering (DIS) data.

The idea of the proposed experiment is the following. The longitudinal polarization of s or $\bar{s}$ quarks knocked out in hard pp scattering from the polarized target contains information about the spin-dependent parton distributions in the longitudinally polarized proton (or nucleus). We suppose that the polarized outgoing $\bar{s}$- and s-quarks transmit its polarization with a significant probability to $\bar{\Lambda}^0$ and Λ^0, respectively. The Λ-hyperon polarization can be easily measured in the weak self-analyzing decay

$$\Lambda^0 \to p + \pi^- \quad . \tag{1}$$

The spin-dependent fragmentation functions for the processes $q \to \Lambda^0$ $(q = u,\ d,\ s)$ are to be taken from other processes, for example from deep inelastic lepton-nucleon scattering or from e^+e^--annihilation off, near, and on the Z^0 peak [7]. The importance of studying spin-dependent fragmentation functions for better understanding of the confinement mechanism has been recently discussed in [8].

2 Properties of Λ^0-Hyperon

Here we remind properties of Λ^0-hyperon which are important for the proposed measurement. In the quark parton model (QPM) Λ^0 consists of the ud-diquark with a total spin S and isospin I equal to 0, and the s-quark carrying the hyperon spin. In terms of spin-dependent distributions we have in QPM

$$\Delta s^{\Lambda^0} = 1, \quad \Delta u^{\Lambda^0} = \Delta d^{\Lambda^0} = 0, \quad \Delta \bar{s}^{\Lambda^0} = \Delta \bar{d}^{\Lambda^0} = \Delta \bar{u}^{\Lambda^0} = 0 \ , \tag{2}$$

where

$$\Delta q = \int_0^1 \Delta q(x) dx \ \ , \quad \Delta q(x) = q_+(x) - q_-(x) \ \ , \tag{3}$$

$q = u,\ d,\ s,\ \bar{u},\ \bar{d},\ \bar{s}$. In (3) $q_+(x)$ ($q_-(x)$) denotes a distribution of a quark of flavour q with its spin parallel (antiparallel) to the nucleon spin and x is the hadron momentum fraction carried by the quark.

As in QPM u- and d-quarks are coupled to the scalar diquark then processes $u \to \Lambda^0$ and $d \to \Lambda^0$ produce unpolarized Λ^0-hyperons and hence their spin-dependent fragmentation functions are equal to zero

$$\Delta D_u^{\Lambda^0}(z) = \Delta D_d^{\Lambda^0}(z) = 0, \tag{4}$$

where z is the ratio of hyperon to quark energy. In QPM a Λ^0-hyperon can acquire polarization only during the fragmentation of the polarized s-quark into Λ^0. In our estimates we put

$$\Delta D_s^{\Lambda^0}(z) = C\ D_s^{\Lambda^0}(z) \ , \tag{5}$$

with the spin transfer coefficient C equal to 1. $D_q^{\Lambda^0}(z)$ describing the fragmentation
$q \to \Lambda^0$ for unpolarized particles and the spin-dependent fragmentation function $\Delta D_q^{\Lambda^0}(z)$ are defined by

$$D_q^{\Lambda^0}(z) = D_{q+}^{\Lambda^0 +}(z) + D_{q+}^{\Lambda^0 -}(z) \ , \tag{6}$$

$$\Delta D_q^{\Lambda^0}(z) = D_{q+}^{\Lambda^0 +}(z) - D_{q+}^{\Lambda^0 -}(z) \ . \tag{7}$$

Here $q+$ and $q-$ (Λ^0+, Λ^0-) denote a quark (hyperon) with a positive and negative helicity, respectively.

More realistic estimates of the first momenta for Λ^0 have been obtained in [7] using the SU(3)-flavour symmetry, the EMC results for $g_1^p(x)$, and well known values of invariant matrix elements in β-decays of baryons F and D

$$\Delta u^{\Lambda^0} = \Delta d^{\Lambda^0} = -0.23 \pm 0.06 \ , \quad \Delta s^{\Lambda^0} = 0.58 \pm 0.07 \ . \tag{8}$$

It follows from (8) that

$$\Delta\Sigma^{\Lambda^0} = \Delta u^{\Lambda^0} + \Delta d^{\Lambda^0} + \Delta s^{\Lambda^0} = 0.12 \ . \tag{9}$$

A model proposed in [9] which explains the proton spin crisis predicts

$$\Delta s^{\Lambda^0} = 0.64 \ , \quad \Delta u^{\Lambda^0} = \Delta d^{\Lambda^0} = -0.115 \ , \tag{10}$$

which agree reasonably with (8). Relation (9) says that the spin of Λ^0 is not constructed from quark spins but related to an orbital angular momentum or the gluon spin. In the latter case we should expect a large contribution of the process

$$g \to \Lambda^0 \tag{11}$$

to the polarization of Λ^0. One might conclude from (8) or (10) that the contributions to the polarization in hard pp scattering of the fragmentation $u \to \Lambda^0$ and $d \to \Lambda^0$ cancel considerably the contribution of $s \to \Lambda^0$. But u- and d-quarks have opposite polarizations in the proton [3,4] and $\Delta D_u^{\Lambda^0}(z) = \Delta D_d^{\Lambda^0}(z)$ since Λ^0 is the isospin singlet. Hence contributions of u- and d-quarks into the polarization of Λ^0 cancel each other to a certain extent. As Λ^0 does not contain a valence gluon then by choosing large z we suppress the relative contribution of process (11) to the polarization. It follows from the above discussion that the contribution of the s-quark fragmentation to the polarization of Λ^0 dominates at large z. But in distinction from QPM the coefficient C in (5) of the polarization transfer from s to Λ^0 is smaller than 1 , say 0.6 (see (8), (10)).

In the quark-parton model $\bar{\Lambda}^0$ consists of $\bar{u}$, $\bar{d}$, $\bar{s}$ which are sea quarks in the proton, hence for a study of the sea quark polarization $\bar{\Lambda}^0$ is a more suitable object. In the case if all sea quarks in the proton have negative polarization, then in accordance with relations (8) and (10) for antiquarks the positive contributions to the $\bar{\Lambda}^0$ polarization of processes $\bar{u} \to \bar{\Lambda}^0$ and $\bar{d} \to \bar{\Lambda}^0$ cancel partially the negative contribution to the $\bar{\Lambda}^0$ polarization of the fragmentation $\bar{s} \to \bar{\Lambda}^0$. When $\bar{s}$ fragments to $\bar{\Lambda}^0$ it has to pick up light

$\bar{u}$- and $\bar{d}$-quarks from the vacuum. The fragmenting light antiquark has to pick up $\bar{s}$ from the vacuum. The latter process is suppressed compared to the former one when $z \to 1$. Hence by selecting events with large z we can suppress the relative contribution of the $\bar{u}$ and $\bar{d}$ fragmentation to $\bar{\Lambda}^0$ (and $g \to \bar{\Lambda}^0$ too) compared with the fragmentation $\bar{s} \to \bar{\Lambda}^0$.

Due to their large life range ($c\tau = 7.89\ cm$) the Λ^0-hyperons produced in hard pp scattering at $E_{beam} = 820\ GeV$ and having typical energies of 20 to 40 GeV decay far from the target ($l = c\tau\gamma \sim 1.5 - 3\ m$, where $\gamma^{-1} = \sqrt{1 - V^2}$). The decay $\Lambda^0 \to p\ \pi^-$ has the branching ratio $(63.9 \pm 0.5)\%$ [10]. Hence candidates for $\bar{\Lambda}^0$ and Λ^0 production events can be easily selected from all jet events. The pion momentum k_π^{cm} in process (1) in the Λ^0 rest frame system is small ($0.1\ GeV/c$). As a result the ratio of the nucleon momentum K_N in the laboratory system to the pion one K_π is approximately equal to the ratio of their masses

$$K_N/K_\pi \approx M_N/M_\pi \gg 1\ . \tag{12}$$

Therefore we have a candidate for a Λ^0 decay event if the momentum of a particle with positive electrical charge is much larger than the momentum of the negatively charged one. Then by utilizing the measured particle momenta and attributing the nucleon mass M_N to the positive particle and M_π to the negative one we are to calculate the invariant mass of the two particles and compare it with the Λ^0-hyperon mass. If the momentum of the negative particle is larger than that of the positive one we have a candidate for the decay of $\bar{\Lambda}^0$. It follows from all the above mentioned properties of Λ^0 and $\bar{\Lambda}^0$ that we do not need a particle identification system for detecting Λ^0 and $\bar{\Lambda}^0$ in hard pp scattering.

The angular distribution for the decay (1) in the Λ^0 rest frame system looks like

$$W = \frac{1}{4\pi}(1 + B\xi_\Lambda cos\theta_0)\ , \tag{13}$$

where $B = 0.642 \pm 0.013$ [10]. Here ξ_Λ denotes the Λ^0-polarization and θ_0 is the angle between the proton momentum and the hyperon spin. Due to the large value of B in (13) it is easy to measure the hyperon polarization. Measuring angle distribution (13) we find ξ_Λ but we can have a false asymmetry due to an angle dependence of a detector efficiency. But changing a sign of the target polarization and therefore a sign of ξ_Λ we reduce systematical errors in the Λ^0 polarization measurements.

3 Polarization of Outgoing s-Quark

First we are going to discuss if hard pp scattering data can give information about spin-dependent parton distributions which cannot be obtained from deep inelastic lepton-nucleon scattering. It is well known that it is difficult to fix the gluon distribution from DIS data only because gluons do not carry electrical charges. Therefore it is not surprising that the spin-dependent gluon distributions shown in Fig. 1 are quite different. In this respect more surprising is the difference shown in Fig. 2 between the sea quark helicity distributions obtained in [11,12,13]. We see that the differences are significant although all the different sets of distributions are well describing SLAC and EMC data [1,2]. On the one hand, the differences between the different sets might be reduced when high statistics DIS data appear. But on the other hand, the differences under discussion cannot be removed completely since there exists the principal possibility to vary parton distributions without affecting the lepton-nucleon cross sections (see [3,4,14] and references therein). However hard pp scattering data are in principle able to reduce this freedom which exists in lepton-nucleon scattering. The results of our calculations of the polarization (ξ_s) of the s-quark knocked out in hard proton-proton scattering as a function of θ_{cm} are presented in Fig. 3. One can see that the polarizations for the sets of the distributions [11,12,13] are quite different. The unpolarized parton distributions [15] have been used in the calculations. Here θ_{cm} denotes an angle between s-quark and beam momentum in the pp center-of-mass system.

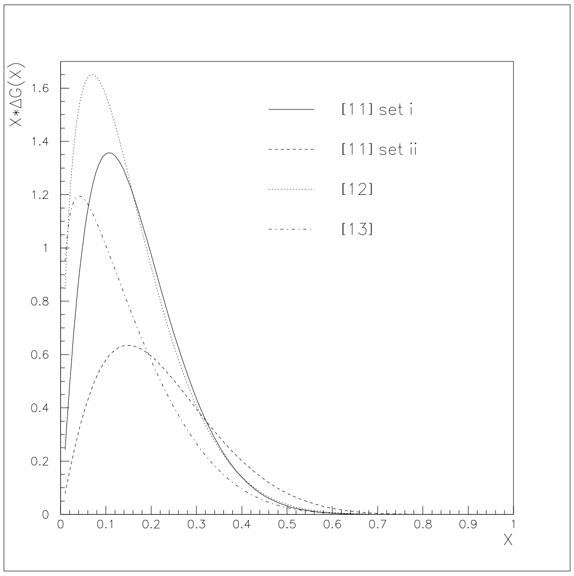

Figure 1: Gluon helicity distributions. Shown parton distributions have been taken from [11,12,13].

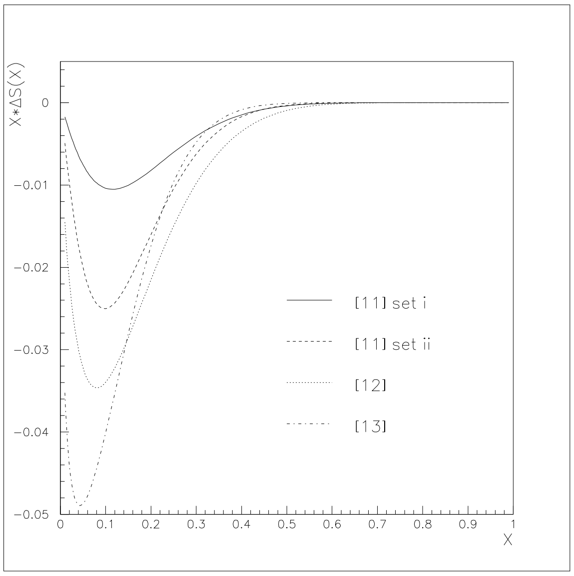

Figure 2: s-quark spin-dependent distributions. Notations of the curves as in Fig. 1.

The s-quark polarization depends linearly on the parton helicity distributions. Fig. 4 shows that the most important contributions to the s-quark polarization are given by the spin-dependent s-quark distribution $\Delta s(x)$ and the polarized gluon distribution $\Delta G(x)$. The contributions of the spin-dependent valence u- and d-quark distributions are very small. The influence of the gluon polarization on the outgoing s-quark polarization is due to the polarization transfer in the parton subprocess $q + \vec{g} \to \vec{q} + \vec{g}$ where $\vec{g}$ and $\vec{q}$ denote a polarized gluon and quark, respectively. Formulae for parton-parton cross sections for unpolarized and polarized cases have been taken from [16,17]. The unpolarized parton distributions by Owens [15] and the spin-dependent ones by Keller and Owens [12] have been applied in the calculations of the curves presented in Fig. 4.

Fig. 5 illustrates the dependence of the s-quark polarization on θ_{cm} and the transverse momentum P_T transferred to the quark. It seems as if $\Delta s(x)$ and $\Delta G(x)$ could be extracted separately as their relative contributions to the s-quark polarization are

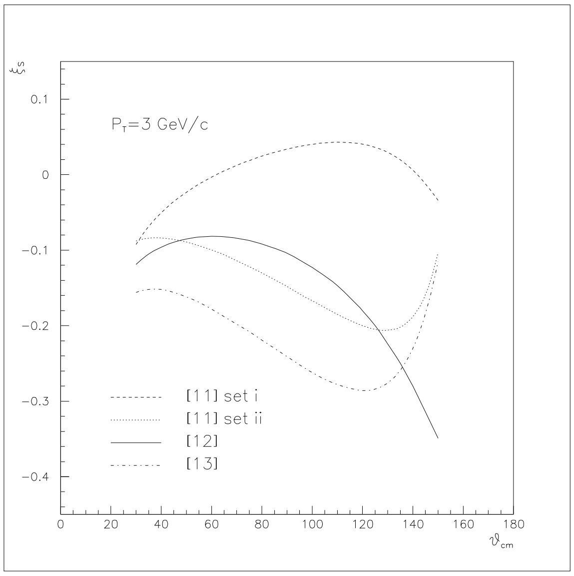

Figure 3: Polarization of outgoing s-quarks. Polarized [11,12,13] and unpolarized [15] parton distributions have been applied in the calculations. Here θ_{cm} denotes angle between s-quark and beam momentum in pp center-of-mass system.

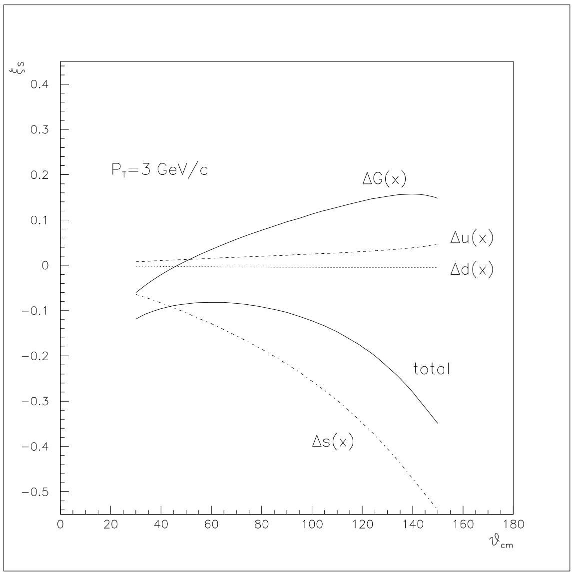

Figure 4: Dependence of outgoing s-quark polarization on parton helicity distributions. Parton distributions have been taken from [12,15].

different for the different curves presented in Fig. 5. But, as a matter of fact, ξ_S depends practically only on one variable x_{2min}

$$x_{2min} = x_T \tan(\theta_{cm}/2)/[2 - x_T \cot(\theta_{cm}/2)] \ , \quad x_T = 2p_T/\sqrt{S} \ , \qquad (14)$$

which is the minimum momentum fraction carried by the incident target parton. Here S denotes the Mandelstam variable for pp scattering. As it is seen from Fig. 6, ξ_s depends almost on x_{2min} only and is not very sensitive to a value of P_T. Hence studying the polarization of Λ^0 we might distinguish between different sets of parton distributions but it is practically impossible extracting $\Delta s(x)$ and $\Delta G(x)$ separately . On the other hand, the polarization property under discussion means that to decrease statistical errors we can combine pp scattering events with different P_T and the same value of x_{2min}. For the calculations presented in Fig. 6 we have applied the helicity distributions taken from [13] and the unpolarized ones proposed in [18], but the discussed property exists for other distributions too.

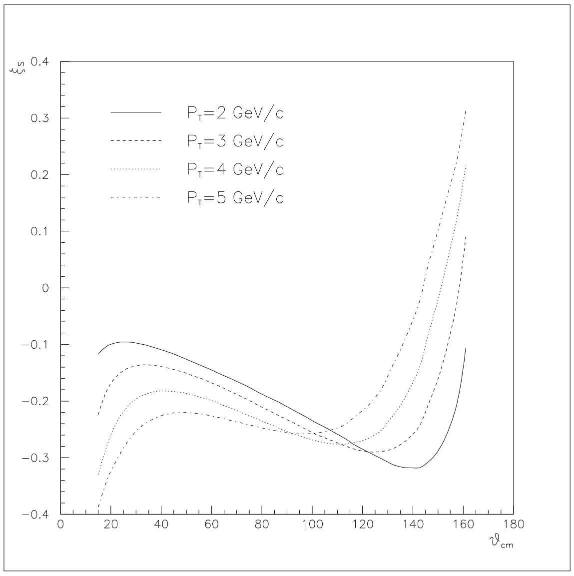

Figure 5: Dependence of s-quark polarization on θ_{cm} and P_T. Helicity distributions of [13] and unpolarized ones from [18] have been applied in the calculations.

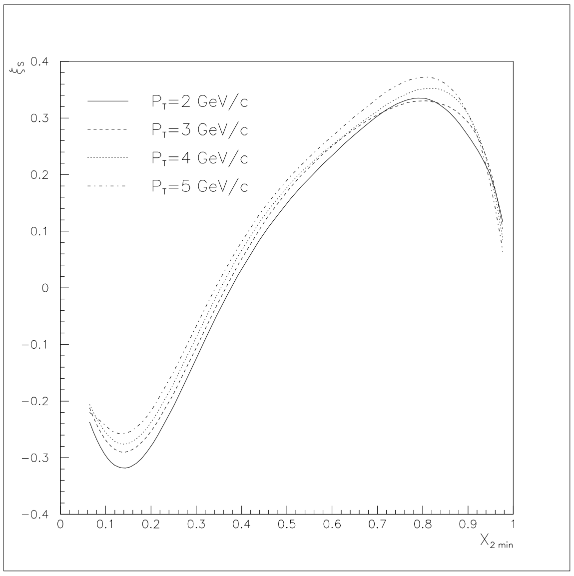

Figure 6: Dependence of s-quark polarization on P_T and x_{2min}. Description as in Fig. 5, except x_{2min} defined in (14).

4 Model for Estimate of Hyperon Polarization

Instead of applying $D_q^{\Lambda^0}(z)$ to describe the fragmentation processes for unpolarized particles we make use of the MC programs PYTHIA 5.7 and JETSET 7.4 which give reasonable agreement with experimental data (see for instance

[19,20]). To describe the polarization transfer from partons to Λ^0 we apply a procedure proposed in [21]. The MC simulation allows to follow all chains of parton transformations to Λ^0. If Λ^0 contains the initial s-quark then its polarization ξ_{Λ^0} has been set equal to ξ_s. In other words, the transfer coefficient C in the relation

$$\xi_{\Lambda^0} = C\ \xi_s \qquad (15)$$

is equal to 1. If Λ^0 contains an s-quark which has been picked up from the vacuum in the process $q \to \Lambda^0$ then $C = 0$ in (15). This means a validity of (4) and the relation

$$\Delta D_g^{\Lambda^0} = 0\ . \qquad (16)$$

If the s-quark fragments to some hyperon H which produces Λ^0 after some electroweak decay then for such MC events, in accordance with the results of work [21], we put C equal to the values given in Table 1.

Table 1

H	Λ^0	Σ^0	$\Sigma(1385)$	Ξ	$\Xi(1530)$
C	1	1/9	5/9	3/5	1/2

5 Results of MC Simulations

To get a realistic estimate of the $\bar{\Lambda}^0$-hyperon polarization in hard pp scattering we have to take into account an experimental acceptance. The reduction of useful events due to the acceptance of the HERMES detector for different center-of-mass system (CMS) $\bar{\Lambda}^0$ production angles is illustrated in Fig. 7. In calculating the histograms we have taken into consideration the branching ratio of reaction (1) and demanded that both $\bar{p}$ and π^+ from the decay of $\bar{\Lambda}^0$ are in the HERMES acceptance. The total number of accumulated jet events in the interval $2\ GeV/c \leq P_T \leq 5\ GeV/c$ is $8 \cdot 10^7$. The number of events with $\bar{\Lambda}^0$ having $z \geq 0.5$ is equal to 37000 and the number of $\bar{p}\pi^+$ pairs which are in

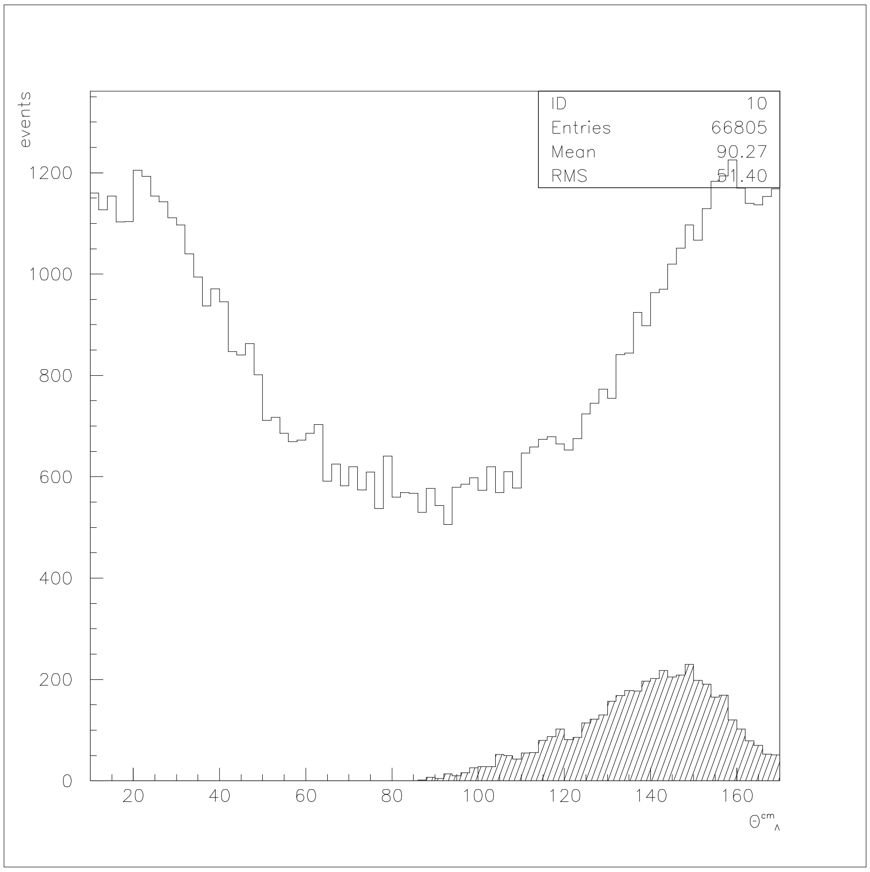

Figure 7: Number of events of reaction $\bar{\Lambda}^0 \to \bar{p} + \pi^+$ versus CMS $\bar{\Lambda}^0$ production angle $\theta^{cm}_{\bar{\Lambda}^0}$. Full histogram shows all generated events, the shaded one shows events after HERMES acceptance cut.

the HERMES acceptance is equal to 2339. We have put in our estimates the target polarization ξ_T and the integrated luminosity equal to the following values [22]

$$\xi_T = 0.8, \quad \int L dt = 240 \; pb^{-1} \; . \tag{17}$$

Calculated error bars correspond to the values (17). The dependence of the $\bar{\Lambda}^0$ polarization on θ_{lab} at different regions of P_T is presented in Fig. 8. The negative sign of the $\bar{\Lambda}^0$ polarizations is explained with dominating the negative $\Delta\bar{s}(x)$ contribution in the kinematical region under consideration. To avoid some misunderstanding we

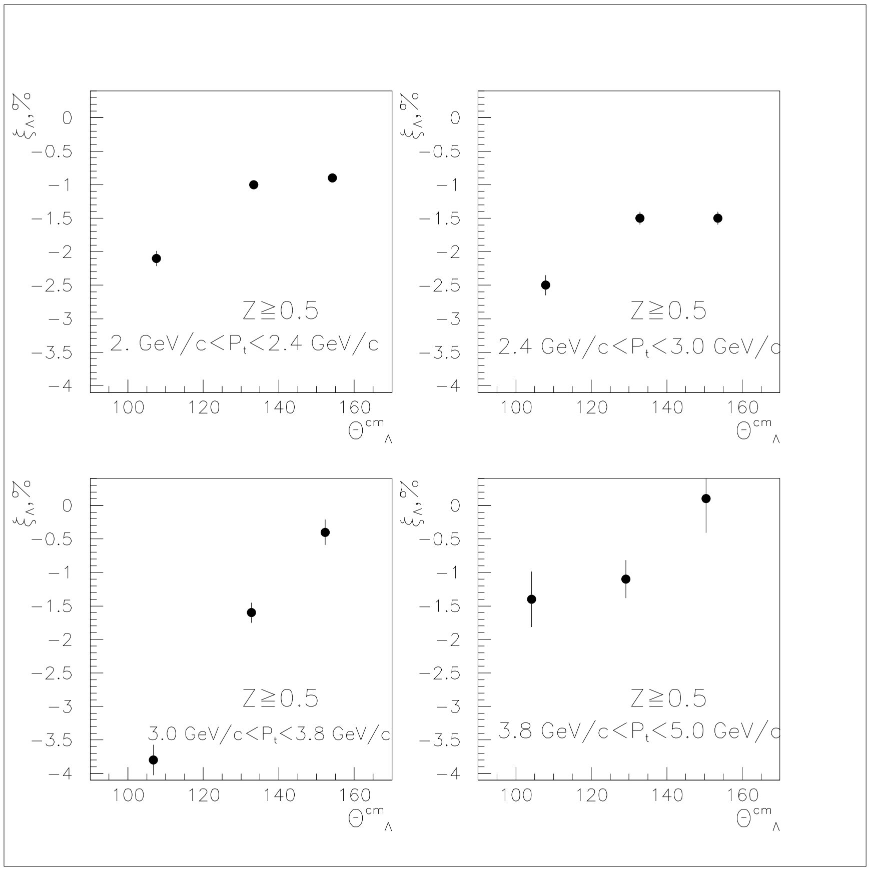

Figure 8: Dependence of $\bar{\Lambda}^0$ polarization on P_T and CMS $\bar{\Lambda}^0$ production angle $\theta^{cm}_{\bar{\Lambda}^0}$. Integrated luminosity and target polarization are the same as in (17). Parton distribution have been taken from [12,15].

should remark as follows. The points presented in Fig. 8 and Fig. 9 have their own Monte Carlo statistical errors corresponding to a number of the accumulating $\bar{p}+\pi^+$ events equal to 2339. We reduce the errors considerably in accordance with (17). As a result of this procedure one can observe some irregular behavior of the polarization etc. One can see from Fig. 8 that relative errors of the $\bar{\Lambda}^0$ polarization for $P_T \geq 5\ GeV/c$ became large ($\sim$ 30%) and we have to measure the polarization at $P_T \leq 5\ GeV/c$ only. The same MC data is presented in Fig. 9 which shows the dependence of the antihyperon polarization on x_{2min} defined by (14). Parton distributions for the calculations shown in Fig. 8 and Fig. 9 have been taken from [12,15]. It is easy to see from Fig. 9 that the relative statistical errors are reasonably small ($\sim$ 5%) therefore we can reliably find a value of the polarization of $\bar{\Lambda}^0$ from experimental data. As one can see from Fig. 3

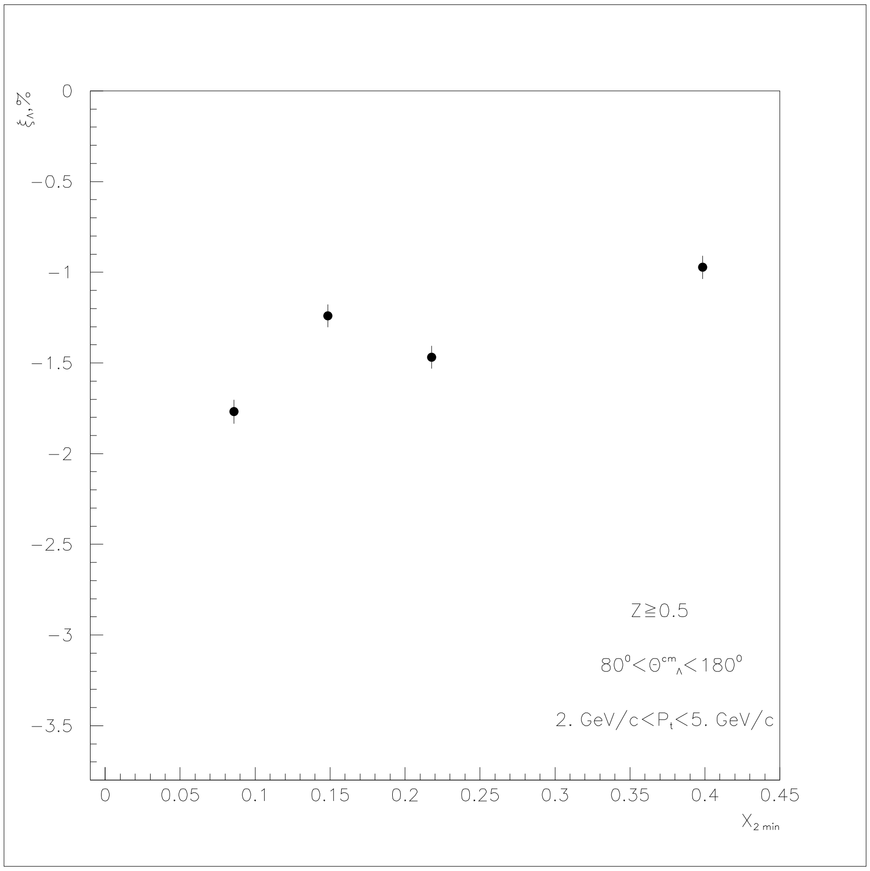

Figure 9: Dependence of $\bar{\Lambda}^0$ polarization on x_{2min}. Description as in Fig. 8, except x_{2min} defined in (14).

the relative differences between the s-quark polarizations predicted with different sets of parton distributions are as large as 30% or even 100%. Therefore we believe in the possibility to distinguish between these sets by measuring the $\bar{\Lambda}^0$ (or Λ^0) polarization. We conclude that the proposed measurement can be fulfilled at HERA with reasonable statistical accuracy and provide a valuable information about the spin-dependent distributions $\Delta s(x)$, $\Delta\bar{s}(x)$ and $\Delta G(x)$ in the polarized proton.

Acknowledgements

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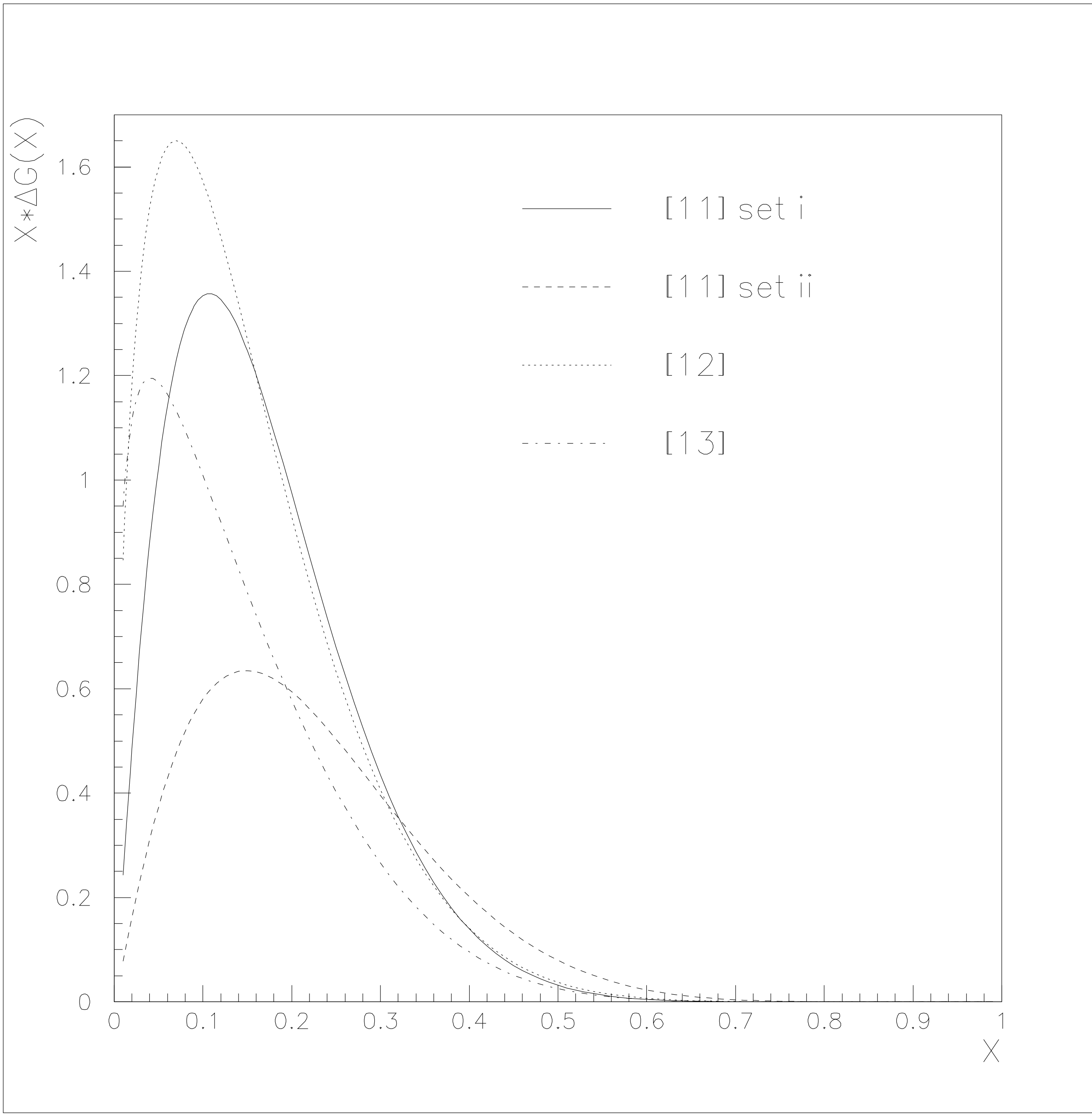

X∗ΔG(X)
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
X
[11] set i
[11] set ii
[12]
[13]

Figure 1: Gluon helicity distributions. Shown parton distributions have been taken from [11,12,13].

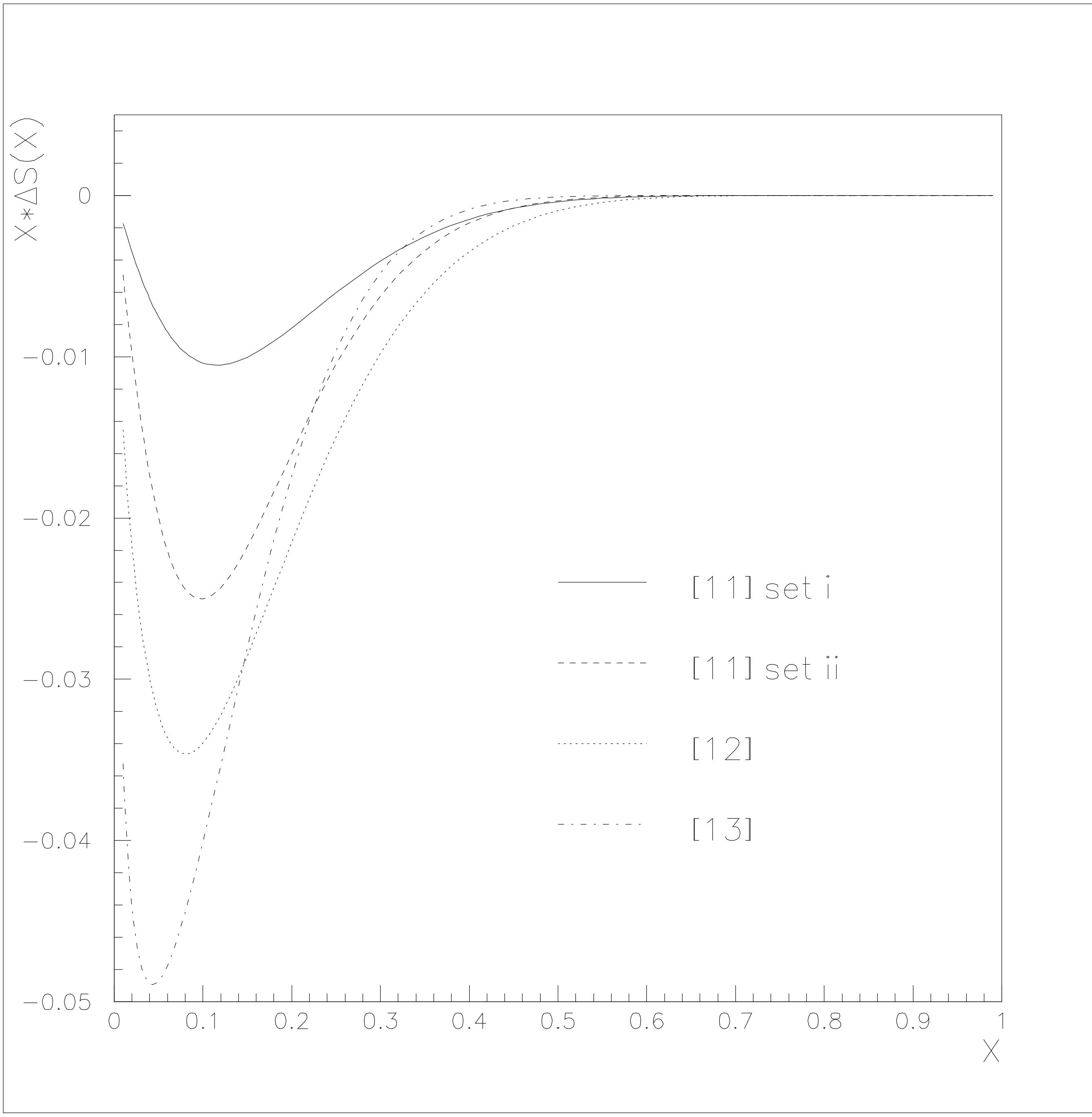
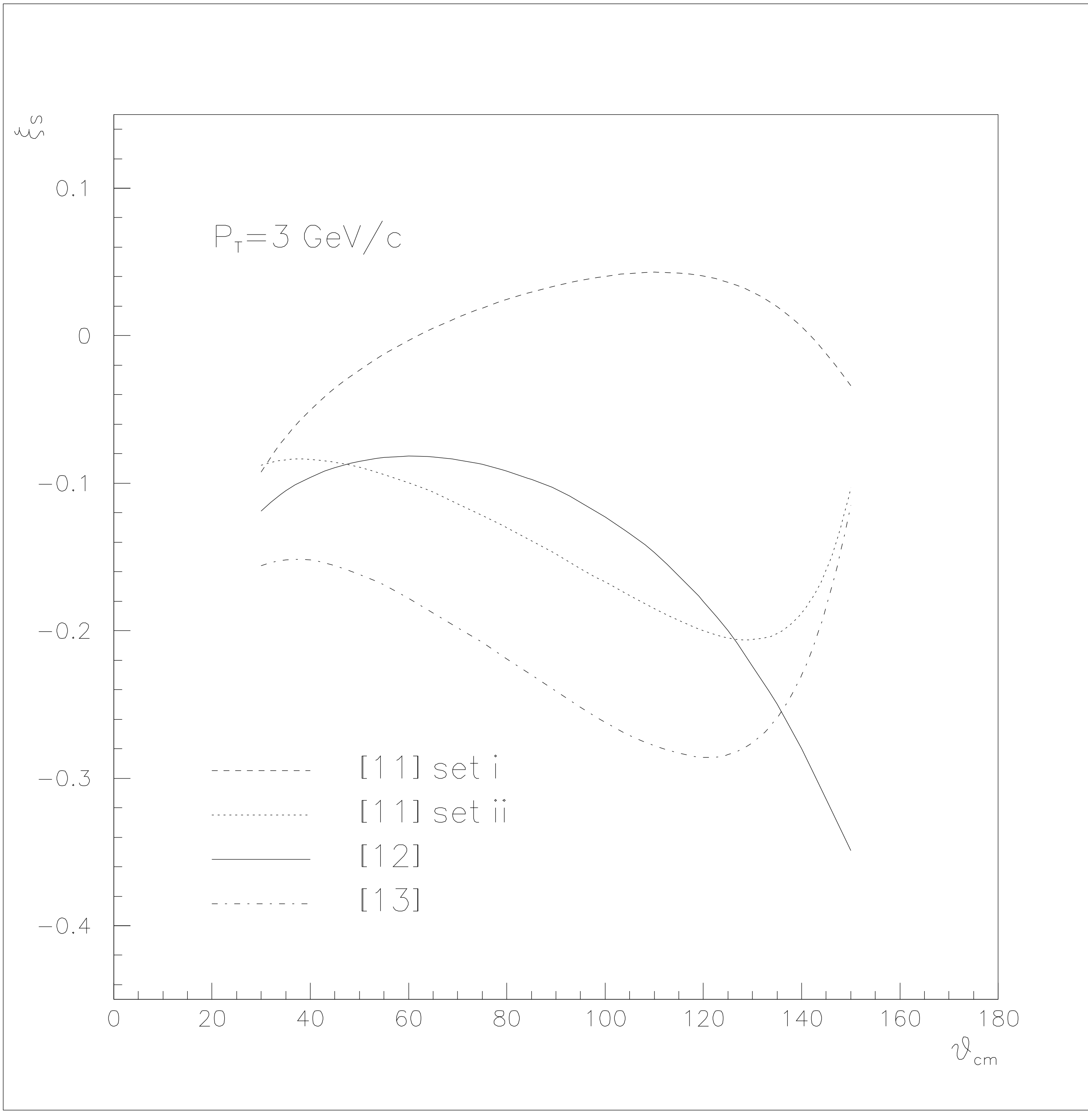
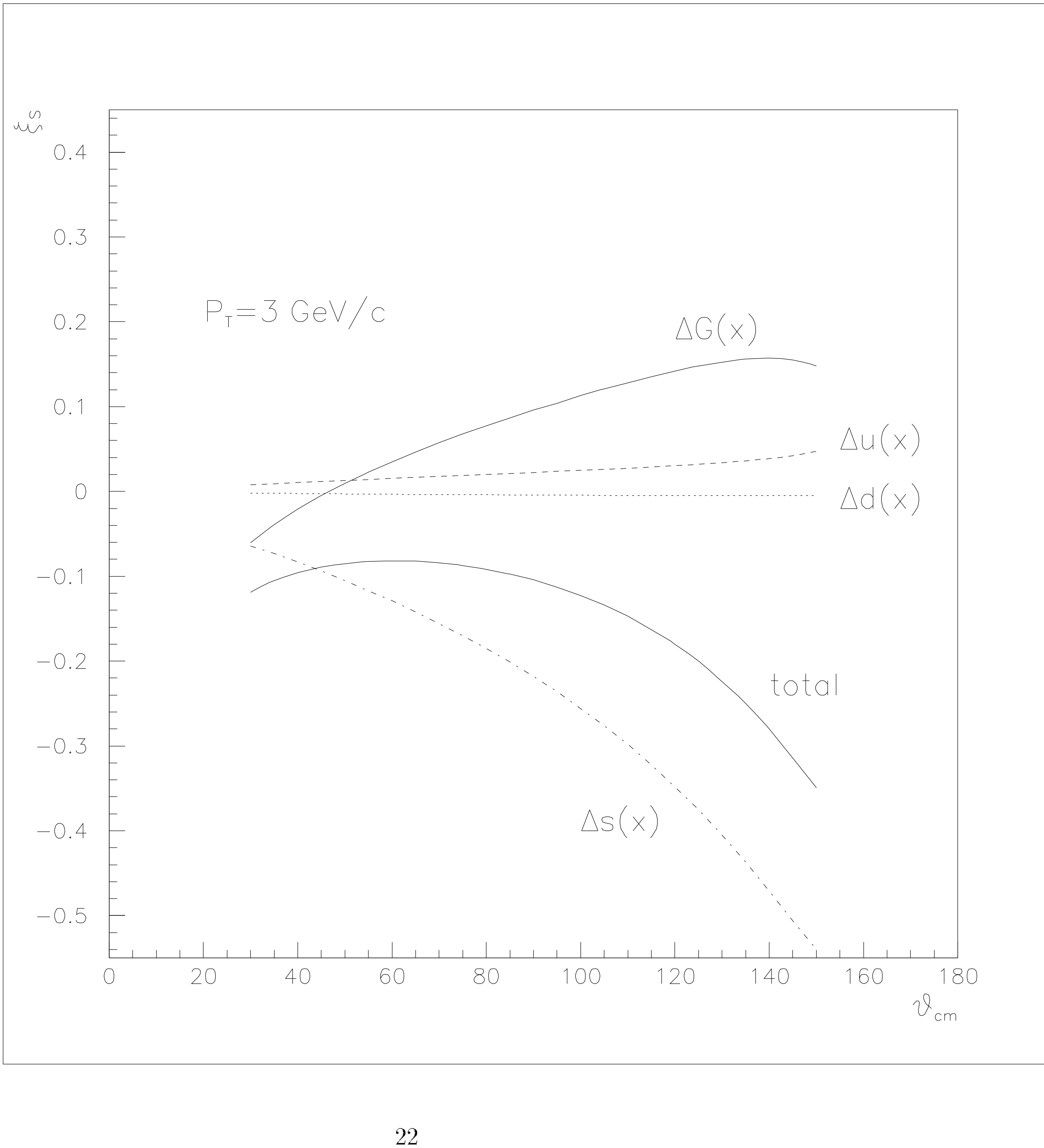

X*ΔS(X)
0
−0.01
−0.02
−0.03
−0.04
−0.05
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1
X
[11] set i
[11] set ii
[12]
[13]

Figure 2: s-quark spin-dependent distributions. Notations of the curves as in Fig. 1.



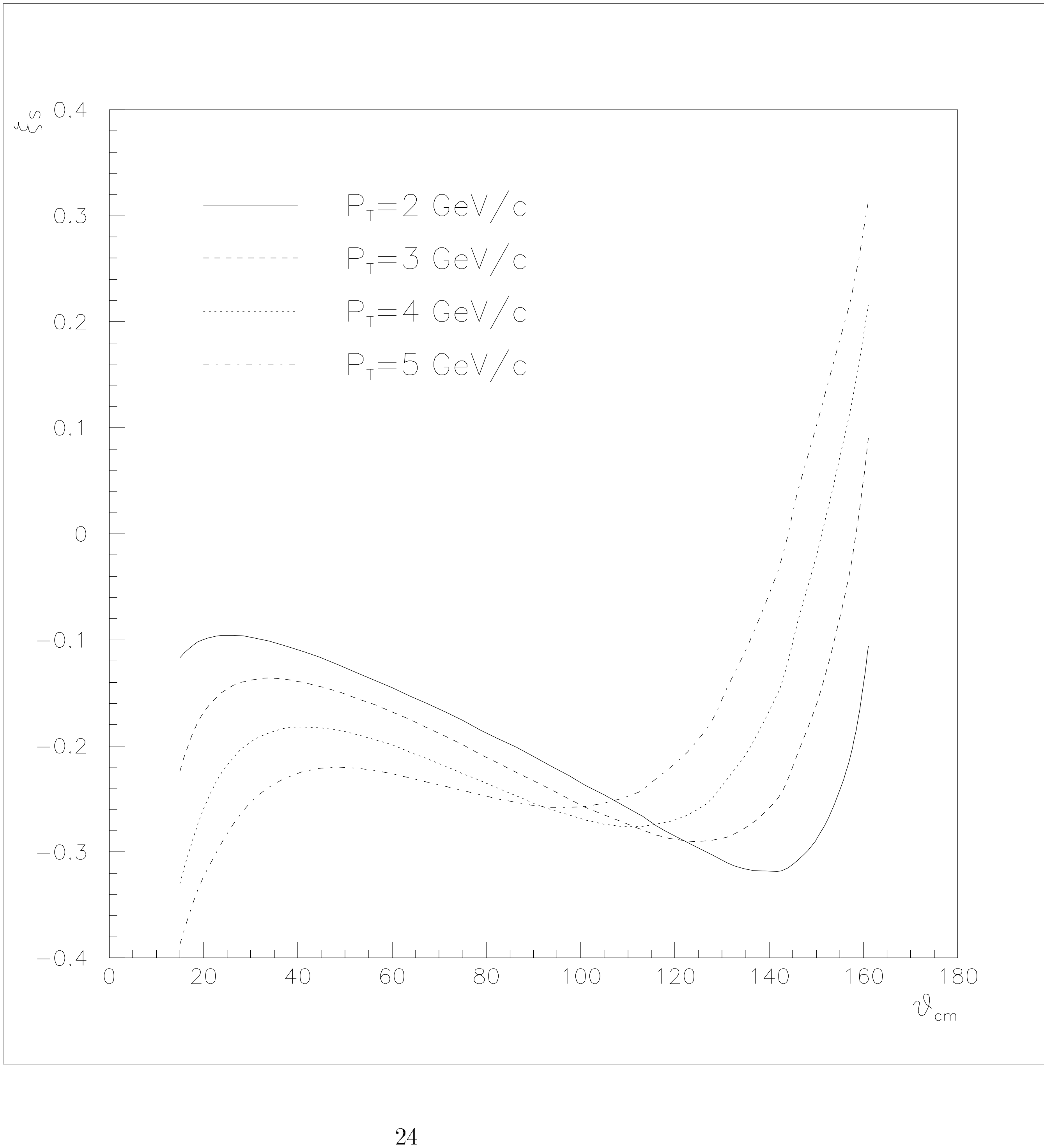
ξs
0.1
0
−0.1
−0.2
−0.3
−0.4
P_T=3 GeV/c
[11] set i
[11] set ii
[12]
[13]
0
20
40
60
80
100
120
140
160
180
ϑcm

Figure 3: Polarization of outgoing s-quarks. Polarized [11,12,13] and unpolarized [15] parton distributions have been applied in the calculations. Here θ_{cm} denotes angle between s-quark and beam momentum in pp center-of-mass system.



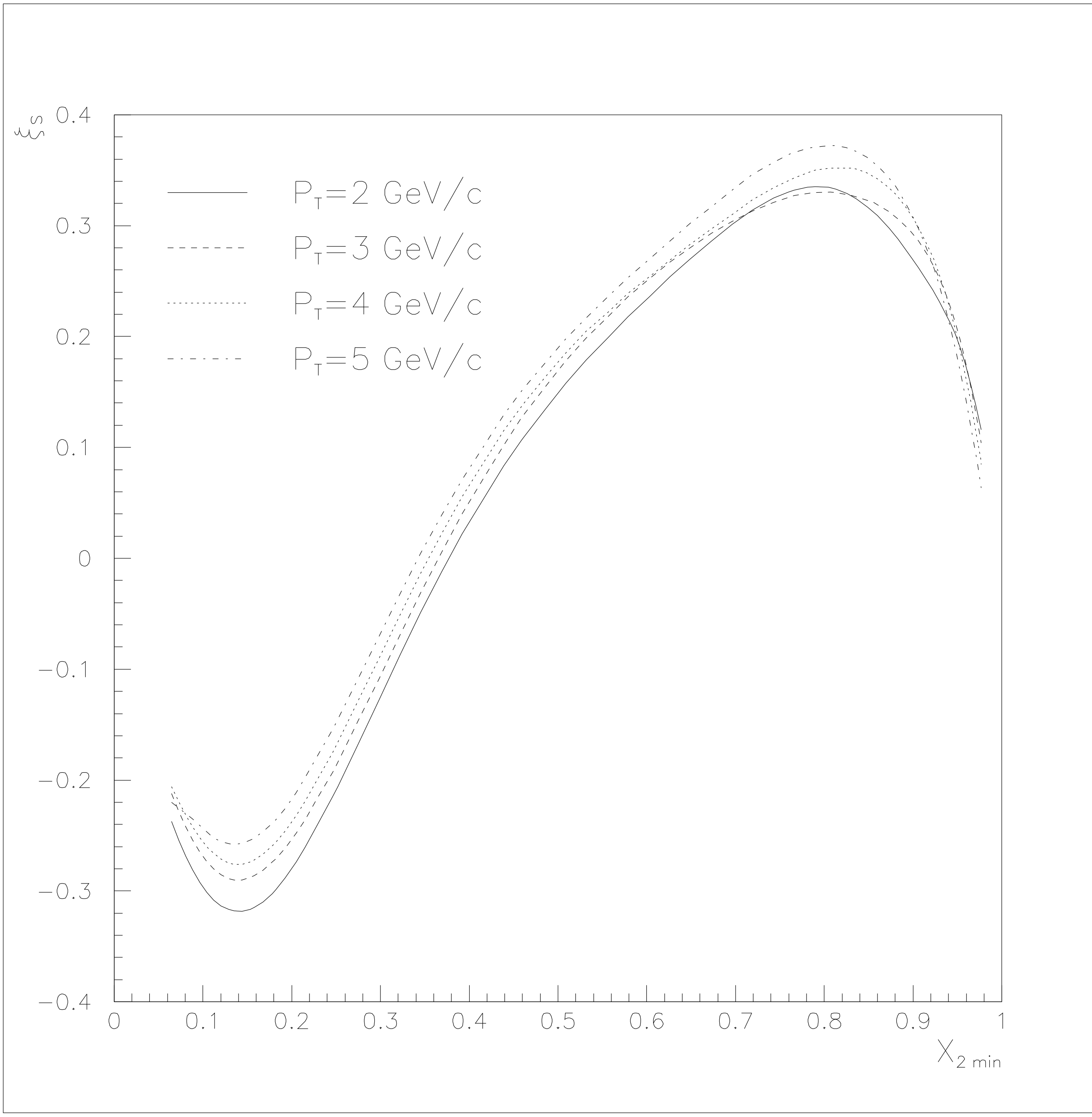
ξ_S
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
−0.5
0
20
40
60
80
100
120
140
160
180
ϑ_{cm}
P_T=3 GeV/c
ΔG(x)
Δu(x)
Δd(x)
total
Δs(x)

Figure 4: Dependence of outgoing s-quark polarization on parton helicity distributions. Parton distributions have been taken from [12,15].



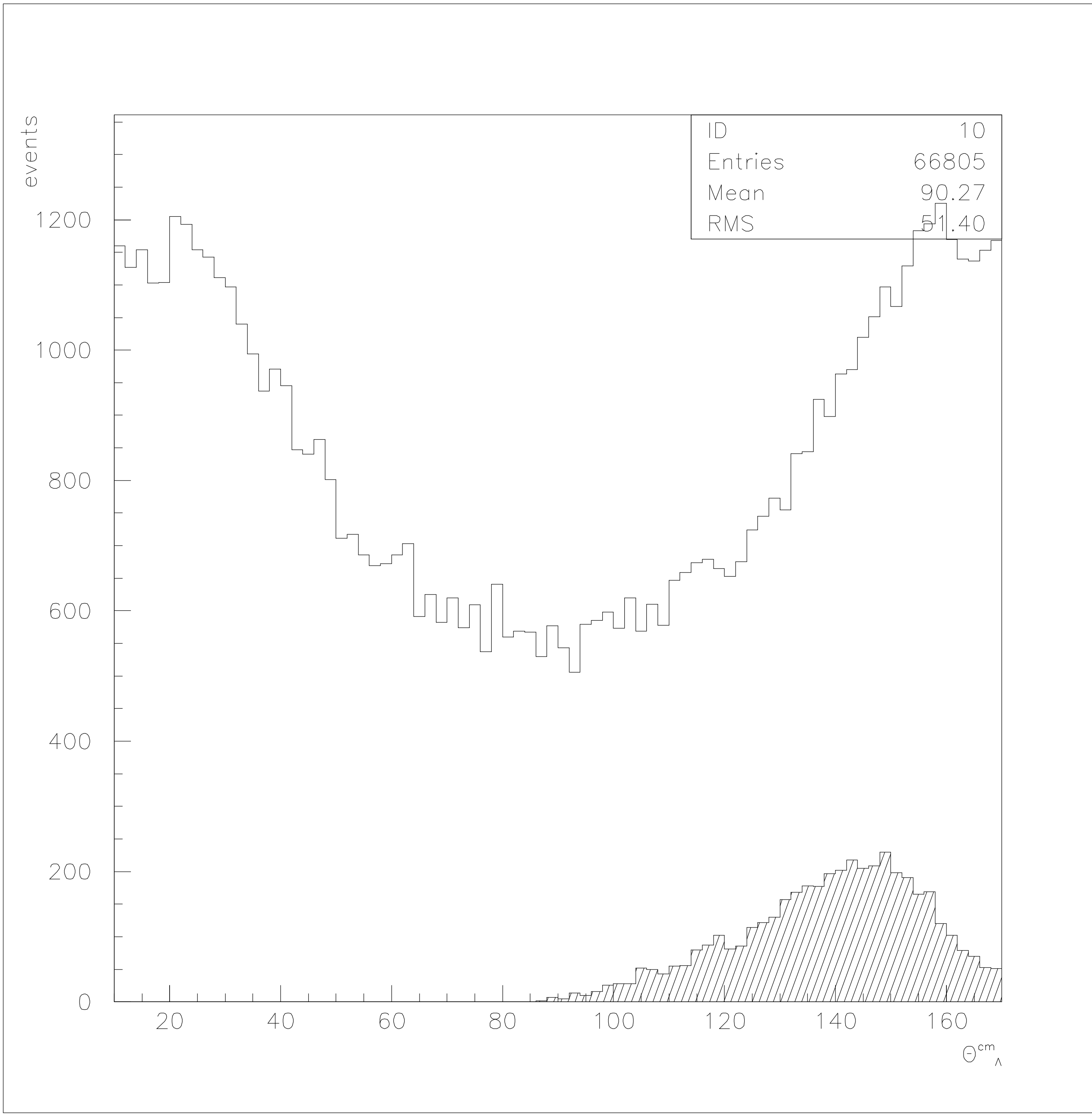
ξ_S
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
P_T=2 GeV/c
P_T=3 GeV/c
P_T=4 GeV/c
P_T=5 GeV/c
0
20
40
60
80
100
120
140
160
180
ϑ_{cm}

Figure 5: Dependence of s-quark polarization on θ_{cm} and P_T. Helicity distributions of [13] and unpolarized ones from [18] have been applied in the calculations.



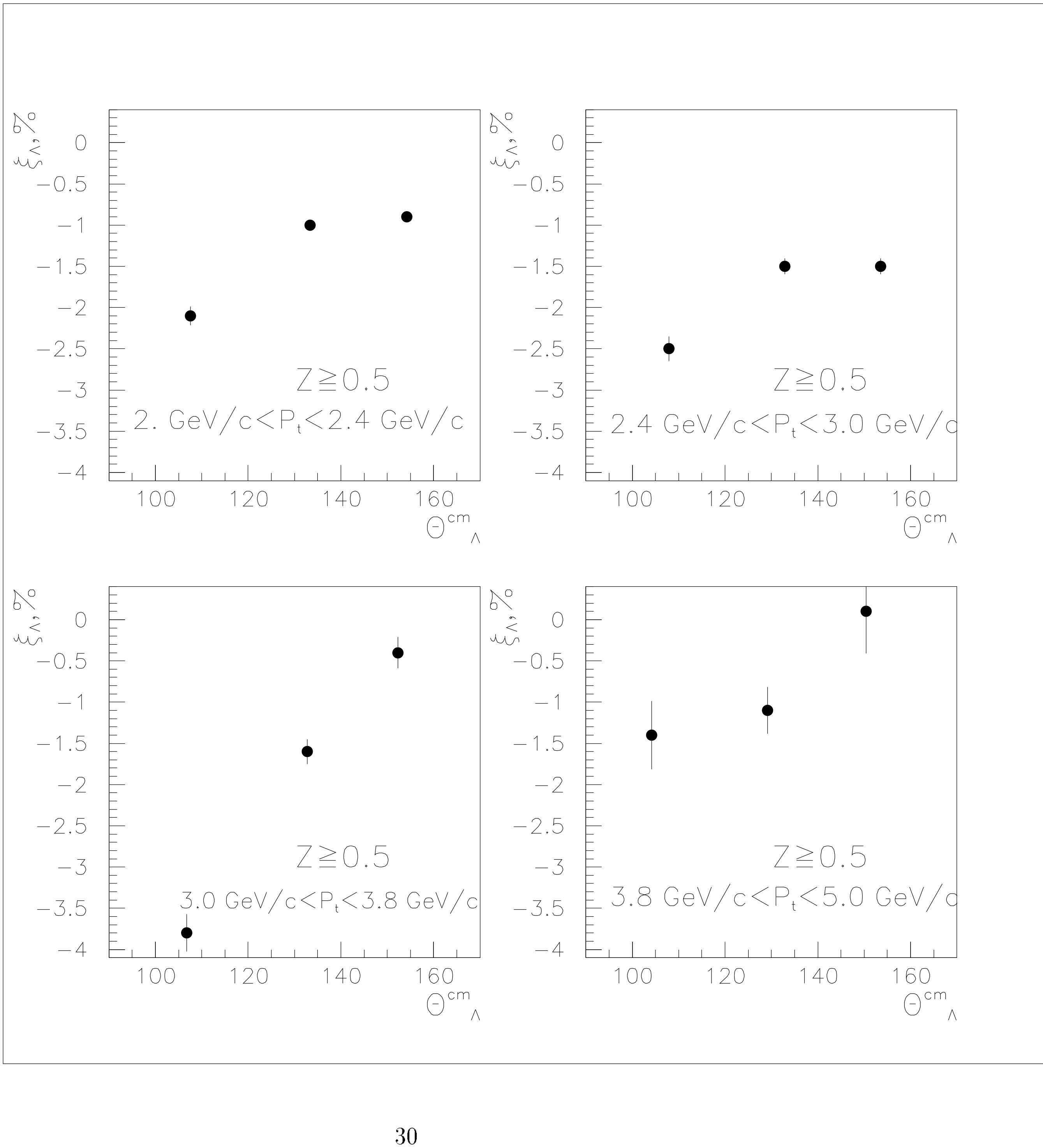
ξ_S
0.4
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
−0.4
P_T=2 GeV/c
P_T=3 GeV/c
P_T=4 GeV/c
P_T=5 GeV/c
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$X_{2\ min}$

Figure 6: Dependence of s-quark polarization on P_T and x_{2min}. Description as in Fig. 5, except x_{2min} defined in (14).



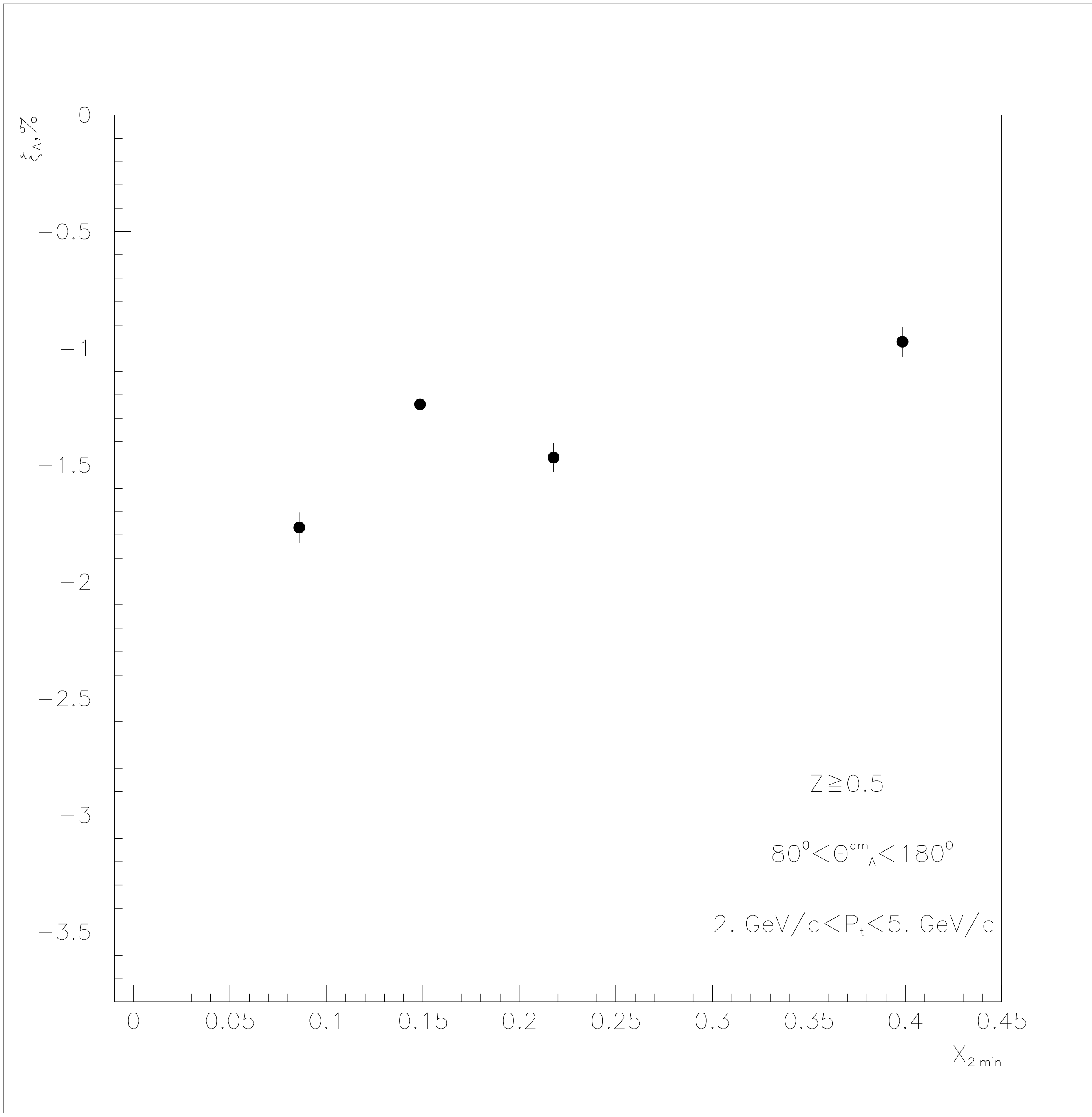
events
ID 10
Entries 66805
Mean 90.27
RMS 51.40
0
200
400
600
800
1000
1200
20
40
60
80
100
120
140
160
Θ^{cm}_{Λ}

Figure 7: Number of events of reaction $\bar{\Lambda}^0 \to \bar{p} + \pi^+$ versus CMS $\bar{\Lambda}^0$ production angle $\theta^{cm}_{\bar{\Lambda}^0}$. Full histogram shows all generated events, the shaded one shows events after HERMES acceptance cut.



ξΛ, %
Z≧0.5
2. GeV/c<Pt<2.4 GeV/c
2.4 GeV/c<Pt<3.0 GeV/c
3.0 GeV/c<Pt<3.8 GeV/c
3.8 GeV/c<Pt<5.0 GeV/c
Θcm Λ

Figure 8: Dependence of $\bar{\Lambda}^0$ polarization on P_T and CMS $\bar{\Lambda}^0$ production angle $\theta^{cm}_{\bar{\Lambda}^0}$. Integrated luminosity and target polarization are the same as in (17). Parton distributions have been taken from [12,15].



ξ_{Λ},%
0
−0.5
−1
−1.5
−2
−2.5
−3
−3.5
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
$X_{2\,min}$
Z≧0.5
$80^0 < \Theta^{cm}_{\Lambda} < 180^0$
2. GeV/c$<P_t<$5. GeV/c

Figure 9: Dependence of $\bar{\Lambda}^0$ polarization on x_{2min}. Description as in Fig. 8, except x_{2min} defined in (14).