CERN/SPSC/88-9
SPSC/I168

16th April 1988

Letter of Intent

Study of Spin Effects in $p\bar{p}$ and pp Interactions at the SPS Using a Polarized Atomic Hydrogen Beam Target

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GENEVA

1988

1. INTRODUCTION.

The original proposal [1] for a gas jet target in the SPS tunnel was based on a polarized atomic hydrogen jet. It was designed to study the spin dependence of elastic scattering and of the inclusive production of π^0's and Λ^0's in pp interactions by using the jet during fixed target operation of the SPS. When the $p\bar{p}$ collider was approved it became possible to study, with high statistics, differences between pp and $p\bar{p}$ collisions in the production of π^0's, η's, direct photons, electron pairs and photon pairs as well as in elastic scattering. In all the above reactions the largest differences are expected at the highest transverse momenta, p_T, and at the highest invariant masses. Since this is also where cross sections are smallest, it was of interest to use as dense a jet as possible. It was therefore decided to use a high density molecular jet instead of the polarized atomic hydrogen jet. A proposal to study the above high transverse momentum reactions using a molecular jet was submitted [2] to the SPSC in 1980 and approved as experiment UA6.

After an initial short run in 1984, UA6 collected data in the $p\bar{p}$ mode in 1985 and in the pp mode in 1986. Results have been published on π^0 cross sections [3] (Fig.1), on the η/π ratio [3] (Fig.2), on direct photon cross sections [4] (Fig.3) and on small t elastic scattering [5] (Fig.4). Analysis continues on electron pairs(J/Ψ) and on direct photons in pp interactions among other things.

The approval of ACOL, which is expected to yield a tenfold increase in the $\bar{p}$ intensity led to the approval of a UA6 upgrade [6]. The present schedule of UA6 is to collect pp data in 1988 and $p\bar{p}$ data in 1989, thus completing the high transverse momentum phase.

Although polarization had been measured in hadronic reactions at low energies, it was expected not so long ago that at high energies spin effects in hadronic collisions would disappear. This behaviour was indeed evident in elastic scattering where polarization effects were found to diminish with increased energy. The dogma was that at high energies and modest p_T hadron collisions were so complicated and involved so many inelastic channels that no coherent interference of amplitudes and hence no spin effects could result. However the physics of spin in high energy hadronic reactions has continued to produce unexpected results. A few examples are :

a) at large t asymmetries continued to be observed in elastic scattering [7].

b) the discovery that inclusively produced Λ's are polarized, that their polarization increases with transverse momentum [8] and that it is present even at the highest energies at which it was measured [9] ($\sqrt{s}$ of 53 GeV).

c) the observation of single spin asymmetries in the inclusive production of protons and pions using polarized targets or beams (see section 2.2),

d) the recent and unexpected EMC result shows our lack of understanding of the spin structure of the proton.

A convincing theoretical explanation of these large spin effects has yet to come. Various phenomenological models have been proposed. None are general enough to successfully explain more than a few results at best. Unfortunately, at low transverse momentum ($\leq$ 3 GeV/c), where most of the data lie, QCD can say little or nothing as perturbative methods do not apply. It is therefore of fundamental importance to measure these effects at the highest transverse momenta and highest energies where perturbative QCD calculations can be performed.

The UA6 collaboration, joined by some new groups, is therefore proposing to develop a polarized jet and install it in place of its molecular jet in the SPS tunnel **in 1990**. The physics aim is to make a comprehensive study of the single spin asymmetries in elastic scattering and in inclusive high p_T single particle production in both $p\bar{p}$ and pp interactions at 315 GeV/c incident momentum.

2. PHYSICS GOALS.

In an elastic or inelastic interaction the production plane is defined as the plane containing the incident and the outgoing particles. In a measurement of an asymmetry in single particle production, the target or the beam is polarized with the spin of the proton normal to the production plane (Fig.5). Furthermore the spin can be either up (+) or down (-). The measurement consists in counting the number of particles scattered in a given detector located, say, to the right of the beam direction for spin up (N_+) and for spin down (N_-). An asymmetry A is then defined as

$$A = \frac{N_+ - N_-}{N_+ + N_-}$$

The error in the asymmetry is given by

$$dA = \frac{1 - AP}{P} \times \frac{1}{\sqrt{(L\sigma T)}} \times \sqrt{(1 + 2\alpha)}$$

where L = luminosity,

σ = spin averaged cross section per nucleon,
T = running time,
α = background/signal ratio averaged over the two spin orientations
P = target (or beam) polarization

It is conventional to quote a figure of merit for a single spin asymmetry measurement facility as

$$F = P^2 L$$

2.1 ELASTIC SCATTERING IN THE COULOMB INTERFERENCE REGION.

Recent experimental results in elastic scattering of hadrons show that the dynamics of hadronic interactions are not yet well understood. For example, the difference between the differential cross sections for $p\bar{p}$ and pp observed at the ISR [10] has not found a definite explanation and the recent result [11] of the UA4 collaboration for the ratio, ρ , of the real to the imaginary parts of the $p\bar{p}$ amplitude at collider energies raises questions which cannot presently be answered unambiguously.

With a polarized gas jet target very interesting effects can be detected in pp elastic scattering. For small momentum transfer, |t| , the polarization parameter, P, obtained by measuring the single spin asymmetry, can be expanded [12] :

$$P\frac{d\sigma}{dt} = \frac{P_1}{\sqrt{-t}} + P_2\sqrt{-t}$$

where at high energies:

$$P_1 = -\frac{8\pi\alpha}{\sqrt{s}} \, \mathrm{Im}\frac{\Phi_5^N}{\sqrt{-t}}\Big|_{t=0} + \frac{\alpha(\mu-1)}{2m}\left[\sigma_{tot} + 2\Delta\sigma_T\right] + O(\alpha^2 \ln|t|)$$

and

$$P_2 = \frac{1}{\sqrt{-t}}\left(P\frac{d\sigma}{dt}\right) \quad + O(\alpha)$$

P_2 has a finite limit at t=0 and is expected to be independent of t in the interference region. The leading interference contribution comes from P_1 which apart from the term of order $a^2 \ln|t| \sim 3 \cdot 10^{-4}$ is constant in |t|. Measurements of the polarization in the Coulomb interference region will provide a relationship between the single spin flip nuclear helicity amplitude Φ_5 and $\Delta\sigma_T$ which depends on the double spin flip amplitude Φ_2. Given $\Delta\sigma_T$ the measurement will give Φ_5, or vice versa, if Φ_5 is given or inferred by extrapolation from low energy data, it will yield $\Delta\sigma_T$. A similar development can be made for $p\bar{p}$ elastic scattering data.

2.2 INCLUSIVE SINGLE PARTICLE PRODUCTION.

Non-zero asymmetries have been observed in the inclusive production of :

a) protons using a polarized incident proton beam of11.75 GeV/c [13] and of 13.5 and 18.5 GeV/c [14].
b) negative and positive pions using a polarized incident proton beam of 11.75 GeV/c [13] and of 13.5 and 18.5 GeV/c [14] (Fig.6).
c) π^0 mesons using an incident proton beam of 24 GeV/c on a polarized target [15] (Fig.7).
d) π^0 mesons using an incident π^- beam of 40 GeV/c on a polarized target [16] (Fig.8).
e) π^0 mesons using an antiproton beam of 40 GeV/c on a polarized target [17] (Fig.9).

Large asymmetries are observed in several of the above reactions. Their origin is as yet unclear. Since all the above experiments have been limited to incident beam momenta lower than 40 GeV/c and to transverse momenta of the observed particle smaller than 3 GeV/c, it is uncertain whether one is in the domain of hard scattering where perturbative QCD can be applied. It is the intention of UA6 to extend these measurements to the production of π^0's, η's and direct photons up to p_T of 6 GeV/c using both protons and antiprotons of 315 GeV/c incident momentum.

3. THE TARGET:

The target will be similar to the atomic beam part of a polarized ion source. Hydrogen is dissociated in an electrodeless discharge and passes through a cooled nozzle. In the strongly inhomogeneous field of a sextupole, the atoms in two of the four hyperfine states are focussed while atoms in the other two states are defocussed and therefore lost in the sides of the sextupoles. After the beam passes through an RF-transition, a second sextupole again removes half of the atoms. About 90% of the atoms in the resulting beam are in a given state of nuclear polarization.

Atomic beams for ion sources, using now "conventional" technology (dissociator nozzle cooled to 35 K, room temperature magnets with apertures up to about 30mm and poletip field of 1 T) produce densities up to about 10^{12} atoms/cm^3 within a diameter of about 10 mm, adapted in emittance to the acceptance of the ionizer.

In order to increase this value to at least 2 x 10^{12}atoms/cm^3 and if possible to 10^{13}atoms/cm^3, we plan to make improvements in two areas :

- increase substantially the acceptance of the magnet system by using superconducting magnets with 60mm aperture and 4 T poletip field. This is reasonable since the "acceptance" of the target region is much larger than the acceptance of an ionizer.

- improve the beam formation region near the nozzle,to allow a higher gas input.

The more powerful magnet system increases the acceptance both in angular and radial directions. If we run a nozzle similar to classical beams (diameter 4 to 6 mm) we would make use of the angular acceptance increase only, resulting in a density of a few x 10^{12} atoms/cm^3. Making use of the enlarged radial acceptance by a larger nozzle, nozzle array or even several dissociators could give a density around 10^{13} atoms/cm^3. Only practical experience can show to what extent the higher gas throughput can be tolerated.

Particular care will be taken to keep the background gas pressure in the target region low, since it is one of the factors determining the effective polarization of the target. A magnetic field in the target region defines the spin direction and can be switched at a rate of a few hertz to reduce systematic errors. Its magnitude must be sufficiently high compared to the local stray field from magnets and beam effects, but low enough not to affect the detection of very low energy recoil particles for the elastic scattering measurement.

4. RATES.

In order to calculate the luminosity we shall assume the following:

a) a polarized jet density of 2×10^{12} atoms/cm^3. This is a conservative factor of 200 lower than the present molecular jet.

b) a jet length of 2 cm along the beams.

c) 1×10^{12} protons and 5×10^{11} antiprotons circulating in the SPS.

With this, and the SPS revolution frequency of 43.4 kHz, we obtain an instantaneous $p\bar{p}$ luminosity of at least:

$$(2 \times 10^{12} \text{ atoms/cm}^3) \times (2 \text{ cm}) \times (5 \times 10^{11}\ \bar{p}) \times (4.34 \times 10^4 \text{ Hz})$$

$$= \mathbf{L_{\bar{p}} = 8.7 \times 10^{28}\ cm^{-2}.\ s^{-1}}.$$

and a pp luminosity of

$$\mathbf{L_p = 1.9 \times 10^{29}\ cm^{-2}.\ s^{-1}}.$$

The basic parameters of the polarized atomic beam target, compared to our existing molecular hydrogen jet target, are listed below.

	Polarized atomic beam	**Molecular jet**
Target density	2×10^{12} _ 1×10^{13}	4×10^{14} atoms/cm^3
Target dimension along the beam	2 cm	0.8 cm
Background gas pressure	$< 10^{-7}$ mbar	$< 10^{-6}$ mbar
Polarization	> 0.9	_
Magnetic field in target region	0.005 - 0.010 T	_
Luminosity ($p\bar{p}$)	$(0.9\text{-}4.4) \times 10^{29}$	7.0×10^{30} cm^{-2}.s^{-1}

The figures of merit are $\mathbf{F_p \geq 1.7 \times 10^{29}}$ and $\mathbf{F_{\bar{p}} \geq 7.2 \times 10^{28}}$ for pp and $p\bar{p}$ operation respectively.

The integrated luminosity for a 100 day $p\bar{p}$ run at 50% running efficiency can be computed as:

$$(8.7 \times 10^{28}\ cm^{-2}.s^{-1}) \times (100 \times 8.64 \times 10^{4}\ s) \times (0.5)$$

$$= \mathbf{3.8 \times 10^{35}\ cm^{-2} = 380\ nb^{-1}}.$$

The expected pp luminosity is twice as high.

4.1 Elastic Scattering.

The polarization parameter, P, for low |t| elastic scattering can be measured with the position sensitive silicon detector already used in the measurement of the elastic cross-section [5]. This measurement has shown that in the range of interest, $0.002 < |t| < 0.03\ GeV^2$, the background is smaller than 10%. Therefore for an integrated luminosity of $380\ nb^{-1}$ a statistical accuracy of $\Delta P = + 0.1$ % can be reached for the expected polarization of approximately 4 % (Fig. 10).

4.2 ASYMMETRY IN π^0 PRODUCTION.

Our first publication on π^0 and η production was based on $43\ nb^{-1}$. Assuming an unmodified detector and given the $380\ nb^{-1}$ derived above, we can expect approximately 9 times more events than in our publication (see Table I). The published π^0 cross-section extends to $p_T = 5$ GeV/c (fig. 1). One can therefore expect to measure asymmetries in π^0 and η production up to about 6 Gev/c. The expected statistical errors based on the calculated numbers of events are listed in columns 4 and 6 of Table I for π^0's and η's respectively.

4.3 ASYMMETRY IN DIRECT PHOTON PRODUCTION.

The attraction of direct photon physics is that, at leading order, only two subprocesses dominate direct photon production. The gluon Compton scattering diagram ($gq \rightarrow \gamma q$) dominates in pp interactions and the annihilation diagram ($q\bar{q} \rightarrow \gamma g$) dominates at high x_T in $p\bar{p}$ interactions. Full next-to-leading order calculations [18] of the cross-sections allow a detailed comparison with experiments [19]. The SPS direct photon data obtained with incident pions and protons constrain the QCD scale parameter $\Lambda_{\overline{MS}}$ to a value [20] consistent with, and as accurate as the value obtained recently from an analysis [21] of scaling violations in DIS. The applicability of QCD to this channel at SPS energies is thus firmly established by the cross-section analysis. Single spin asymmetries are expected to be zero at lowest order [22,23]. The observation of any non-zero asymmetry would thererefore help to identify any higher order mechanism.

The expected number of events in a 100 day run, based on the numbers of events in our recent publication [4], is given in Table II as a function of p_T, together with the error in the asymmetry including the background subtraction.

5. COMPARISON WITH EXISTING FACILITIES:

5.1 Solid polarized targets.

The advantages of a polarized jet over existing polarized targets are many:

a) A high degree of polarization (90%). Thus any "physics" asymmetry is not diluted by interactions occuring in bound unpolarized nucleons. For example in [15] a propanediol ($C_3H_8O_2$) target was used and the physics asymmetry was reduced by a dilution factor of about 10. Conversely when going from a raw to a final asymmetry systematic errors are multiplied by the same factor of 10. Moreover this dilution factor varies with rapidity and transverse momentum.

b) The spin of the protons in the jet is aligned using a weak magnetic field over the interaction region. It can therefore be reversed by merely changing the direction of current flow in a coil. The frequency of spin reversal can therefore be several Hz. In contrast in a propanediol target the polarization is reversed every two hours. Using a polarized jet will again reduce systematic errors.

c) The low density of the jet allows very low energy recoil protons (about 1 MeV) to be observed in solid state detectors placed inside the vacuum. This makes feasible the study of elastic scattering in the Coulomb-nuclear interference region [5].

d) The small longitudinal dimension of the target (approximately point-like) allows easy computation of transverse momenta in real-time, straight forward clustering algorithms and discrimination against particles not originating in the jet.

e) Radiation damage which is a problem for most solid polarized targets is of course irrelevant for the jet target.

5.2 Polarized beams.

The only existing high energy polarized beam is the 200 GeV proton and anti-proton beam at the Fermilab Tevatron (the Brookhaven polarized beam is limited to about 20 GeV). This new facility will be taking data in 1989 and is characterized by the following main features:

- a beam of 200 GeV/c protons or antiprotons,

- an intensity of 3×10^7 protons/spill or 1×10^6 antiprotons/spill, where a spill occurs once every 60 seconds,

- a tagged polarization of 40 % . The position of the incident particle must be known accurately as the polarization reverses across the profile of the beam. The polarization distribution at the target is reversed every 10 minutes using a Siberian Snake.

- an achievable luminosity with a 1m long liquid hydrogen target of :

$$L_p = (3 \times 10^7 / 60) \times (4 \times 10^{24}\ \mathrm{cm}^{-2}) = \mathbf{2 \times 10^{30}\ cm^{-2}.\ s^{-1}}.$$

$$L_{\bar{p}} = (1 \times 10^6 / 60) \times (4 \times 10^{24}\ \mathrm{cm}^{-2}) = \mathbf{7 \times 10^{28}\ cm^{-2}.\ s^{-1}}.$$

The respective figures of merit are $\mathbf{F_p = P^2L = 3 \times 10^{29}\ cm^{-2}.s^{-1}}$ for protons and $\mathbf{F_{\bar{p}} = 1 \times 10^{28}\ cm^{-2}.s^{-1}}$ for antiprotons.

It appears that the UA6 polarized jet figures of merit will be comparable for protons and appreciably better for antiprotons. It is to be noted however that UA6 will be better off on energy (315 instead of 200 GeV) which is very important at high p_T, and also better off as far as beam purity, degree of polarization and target size.

The Fermilab experiment would of course be unique for double-spin measurements (polarized beam- polarized target) which for a jet target would require acceleration of polarized protons.

6. THE APPARATUS.

We are currently investigating two possibilities. The first one would be to leave the apparatus as it stands today and replace the jet only. This implies obtaining the pp and $p\bar{p}$ data in two consecutive collider periods with a rotation of the experiment between the two. The second possibility would be to place the jet in the middle of the medium straight section and install two spectrometers one on either side of the jet, thus allowing simultaneous collection of pp and $p\bar{p}$ data. The advantage of the latter would be an increase in the number of events collected for two reasons

-doubling of the running time available in each of the two modes (pp and $p\bar{p}$) since the data would be collected simultaneously,

-increase of the solid angle of the detector since the calorimeters would be closer to the jet in order to fit within the medium straight section.

The second option would entail building more calorimeter modules. Because of the smaller calorimeter-jet distance it would also entail improving the spatial resolution of at least the first module of the calorimeters in order to retain our good γ/π^0 discrimination.

7. BUDGET.

The budget can be divided essentially in two parts: the atomic beam and improvements to the detector.

We estimate the cost for the atomic beam at **1060ksF**. Vacuum and other components with a value of about **360 kSF** have already been bought by the collaboration as spares for the existing cluster target or in preparation for the polarized target development. Therefore the total cost for the atomic beam will be only **700 kSF.**

If it were decided to double the calorimeters as outlined earlier the cost of the new modules would be about **900 kSF.**

8. CONCLUSION.

The introduction of a polarized jet in the UA6 set-up, **in 1990**, would allow us to study single-spin asymmetries in π^0, η and direct photon production in both pp and $p\bar{p}$ interactions up to p_T of 6 GeV/c at a $\sqrt{s}$ of 24.3 GeV. This is clearly in a domain where hard scattering ideas can be applied. In particular the results could be confronted with perturbative QCD predictions. In addition the asymmetry in elastic scattering could be measured in the momentum transfer region $0.002 < |t| < 0.03$ GeV^2.

A strong case can be made why CERN should continue the development of the polarized atomic beam target. The existing molecular cluster jet has operated successfully and reliably for several years. An experienced development team exists at CERN and an existing experiment would put the target to immediate use. The applicability to LEP in the near future is a distinct possibility. A program to build a polarized jet for use at UNK has also been proposed recently by several of our collaborators and the development work would of course be performed jointly.

It should also be noted that many members of our group have done polarization experiments, and indeed, participated in the various pioneering experiments at high energies at the CERN PS, the CERN SPS, the Fermilab Hyperon Beam, the Fermilab Polarized Beam, at Brookhaven and at SLAC. We are also in contact with groups at Frascati and in the USSR who are interested in the physics goals of the experiment and could decide to join us.

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Table I

π^0 and η Asymmetry

P_T range	π^0's in Ref. 3	Expected π	Error on π asym. %	Expected η	Error on η asym. %
2.7-2.9	3923	34668	0.59	4376	2.6
2.9-3.3	3136	27713	0.66	3980	2.7
3.3-3.7	839	7414	1.27	1260	4.9
3.7-4.1	203	1794	2.59	296	10.1
4.1-5.1	78	689	4.20	128	15.3

Table II

Direct Photon Asymmetry

P_T range	Expected γ's	Error on Asymmetry %
3.3-3.5	795	6.4
3.5-3.7	598	6.9
3.7-3.9	354	8.6
3.9-4.1	220	10.4
4.1-5.1	300	8.6

FIGURE CAPTIONS

1) The invariant differential cross section for inclusive π^0 production in $p\bar{p}$ at $\sqrt{s} = 24.3$ GeV.

2) The η/π ratio as a function of p_T for pp and $p\bar{p}$ interactions.

3) The invariant differential cross section for direct photon production in $p\bar{p}$ interactions at $\sqrt{s} = 24.3$ GeV. The dashed and solid lines are various theoretical predictions.

4) a) The differential cross sections as a function of $|t|$ for pp and $p\bar{p}$ interactions at $\sqrt{s} = 24.3$ GeV.
b) Comparison of the UA6 results (open circles) to measurements of $\rho(pp)$ and $\rho(p\bar{p})$ at other energies.

5) A schematic representation of single particle production with a polarized target.

6) The single spin asymmetry in π^+ and π^- production [14].

7) The single spin asymmetry in π^0 production measured with protons of 24 GeV/c incident momentum [15].

8) The single spin asymmetry in π^0 production measured with a negative pion beam of 40 GeV/c momentum [16].

9) The single spin asymmetry as a function of x in π^0 production measured with an antiproton beam of 40 GeV/c.

10) The expected accuracy in a measurement of the polarization parameter P in elastic scattering at the Coulomb interference region for a run of 380 nb^{-1}.

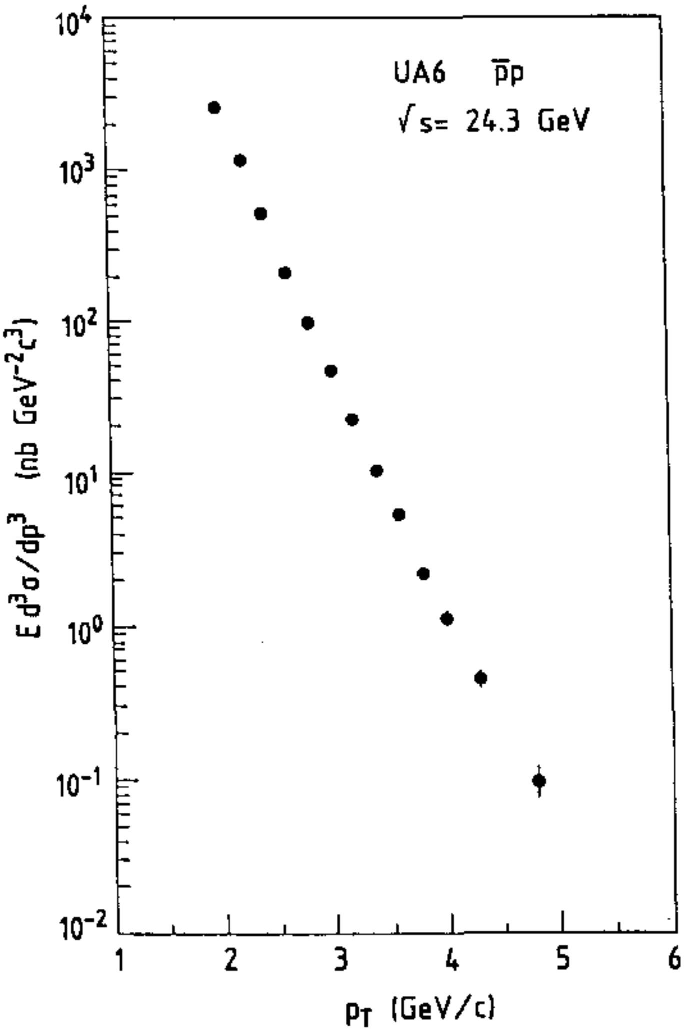
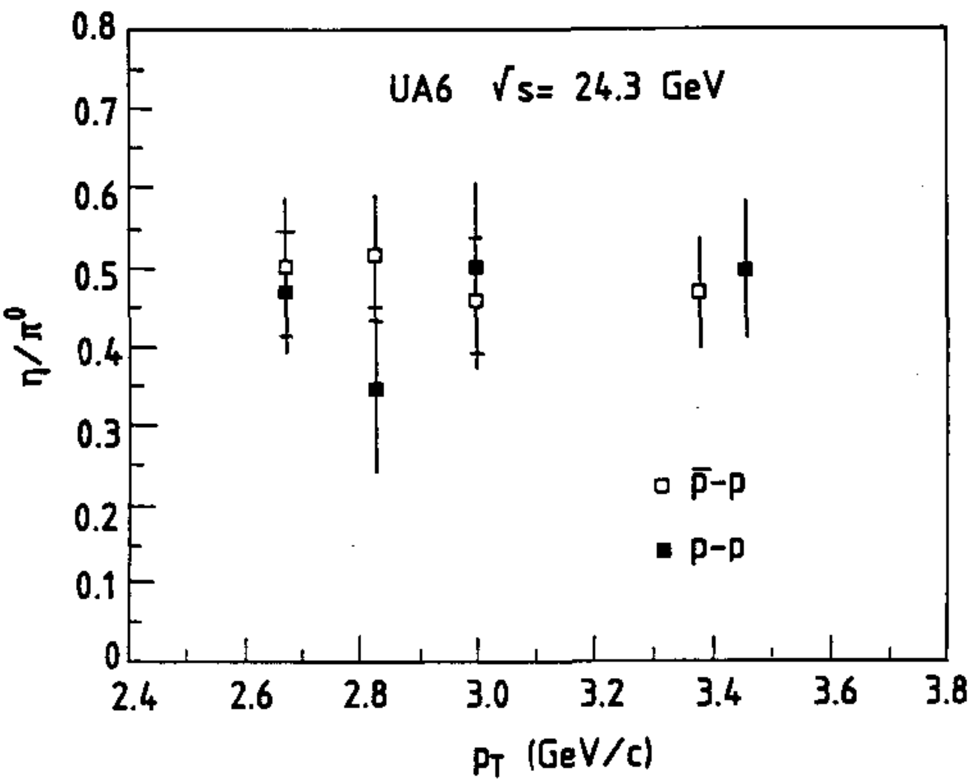

UA6 $\bar{p}p$
$\sqrt{s}$= 24.3 GeV
$E\,d^3\sigma/dp^3$ (nb GeV^{-2}c^3)
p_T (GeV/c)

Fig. 1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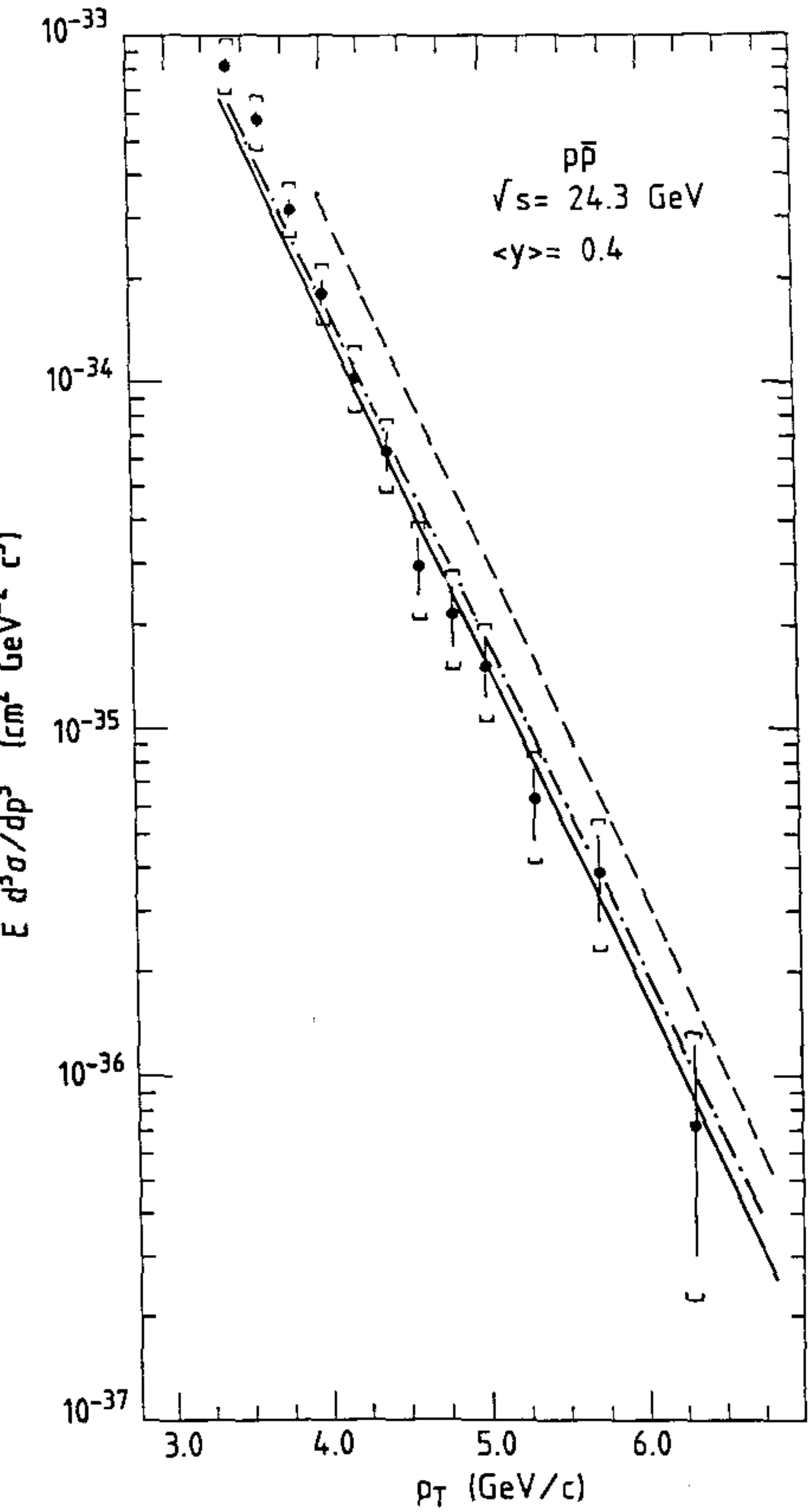
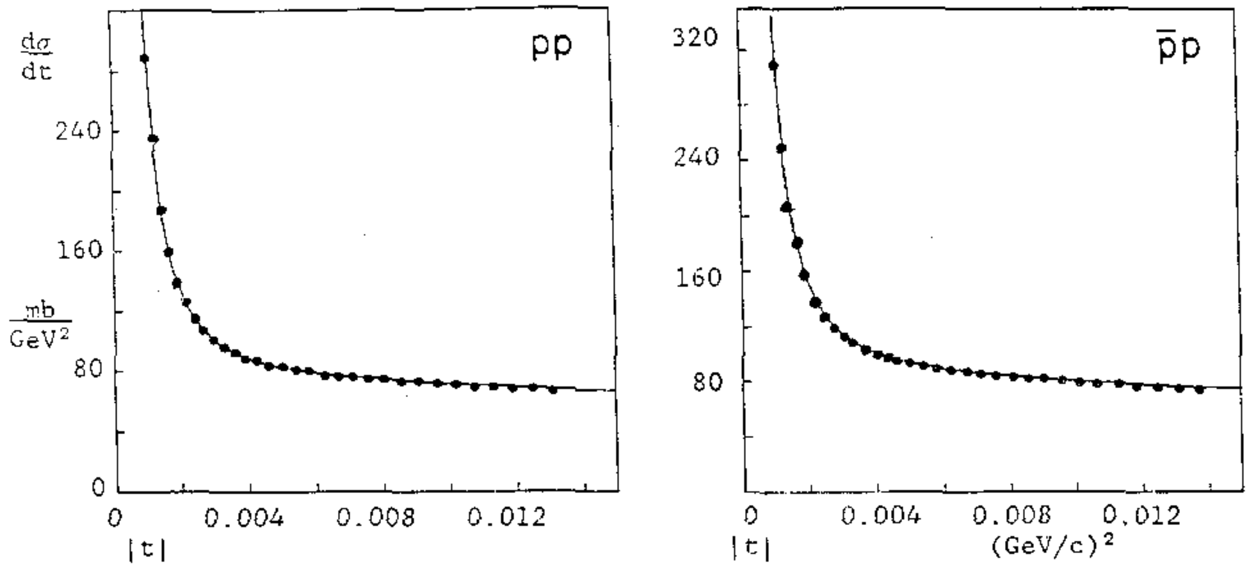
η/π^0
$\bar{p}$–p
p–p
p_T (GeV/c)

Fig. 2



10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
$p\bar{p}$
$\sqrt{s}$= 24.3 GeV
<y>= 0.4
E $d^3\sigma/dp^3$ (cm^2 GeV^{-2} c^3)
3.0
4.0
5.0
6.0
p_T (GeV/c)

Fig. 3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160
80
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0
0.004
0.008
0.012
|t|
pp
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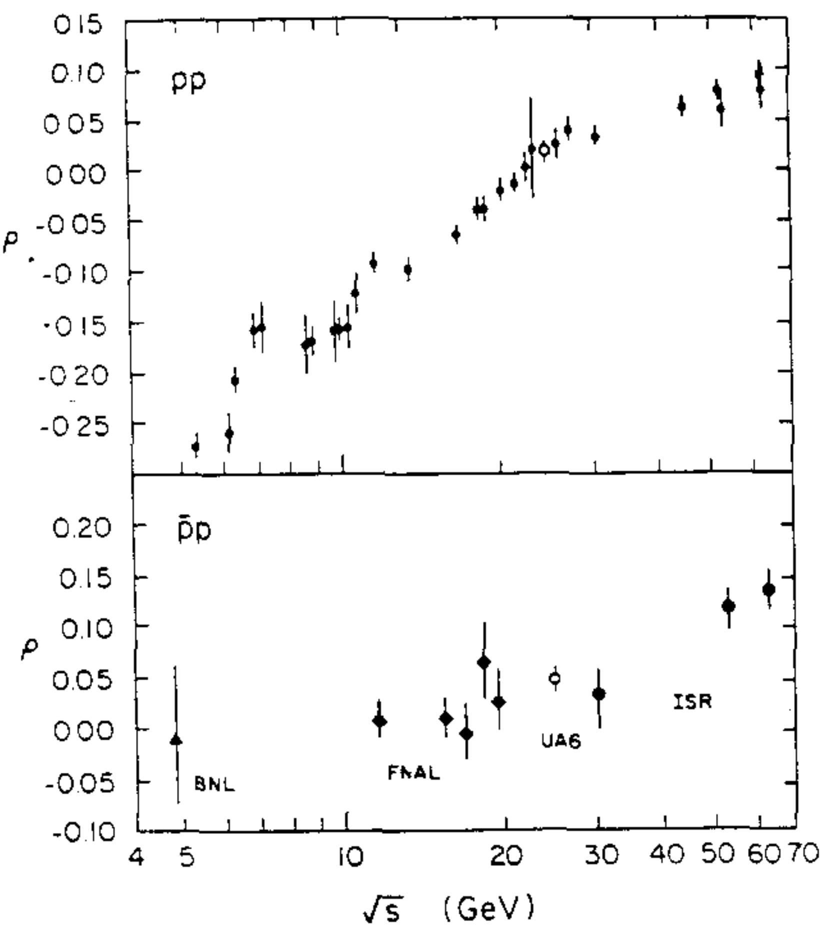
80
0
0.004
0.008
0.012
|t|
(GeV/c)²
p̄p

Fig.4a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0.05
0.00
-0.05
-0.10
-0.15
-0.20
-0.25
ρ
p̄p
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
ρ
BNL
FNAL
UA6
ISR
4
5
10
20
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60
70
√s (GeV)

Fig. 4b

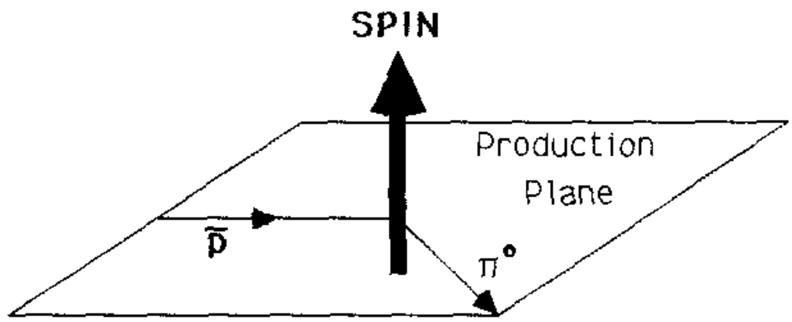

Fig. 5

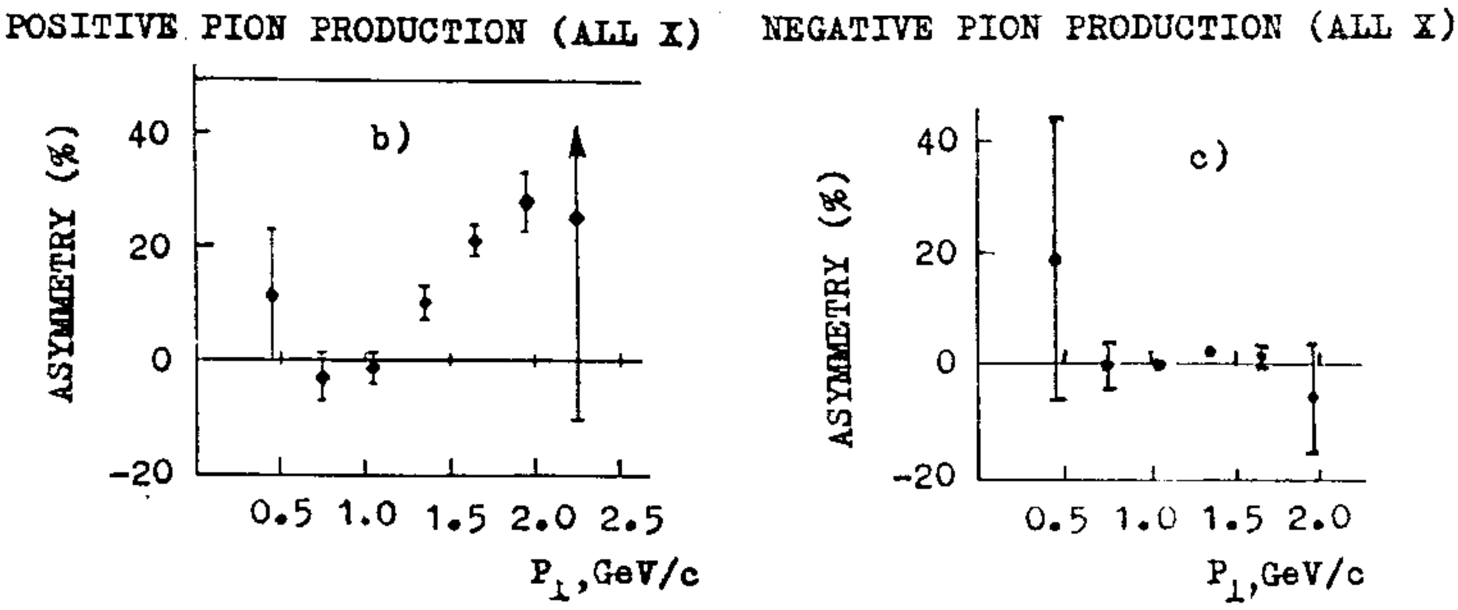
POSITIVE PION PRODUCTION (ALL X)
NEGATIVE PION PRODUCTION (ALL X)
b)
c)
ASYMMETRY (%)
40
20
0
-20
0.5 1.0 1.5 2.0 2.5
0.5 1.0 1.5 2.0
P⊥,GeV/c

Fig. 6

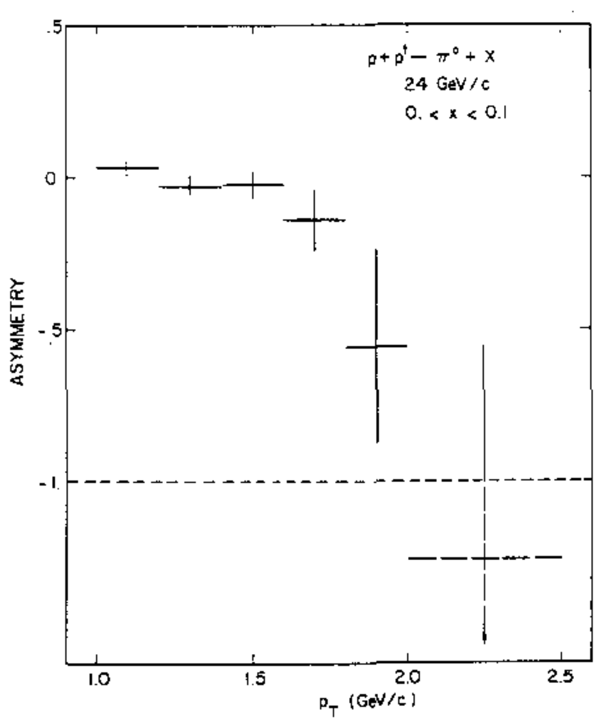
p+p↑ → π° + X
24 GeV/c
0. < x < 0.1
ASYMMETRY
.5
0
-.5
-1.
1.0
1.5
2.0
2.5
pT (GeV/c)

Fig. 7

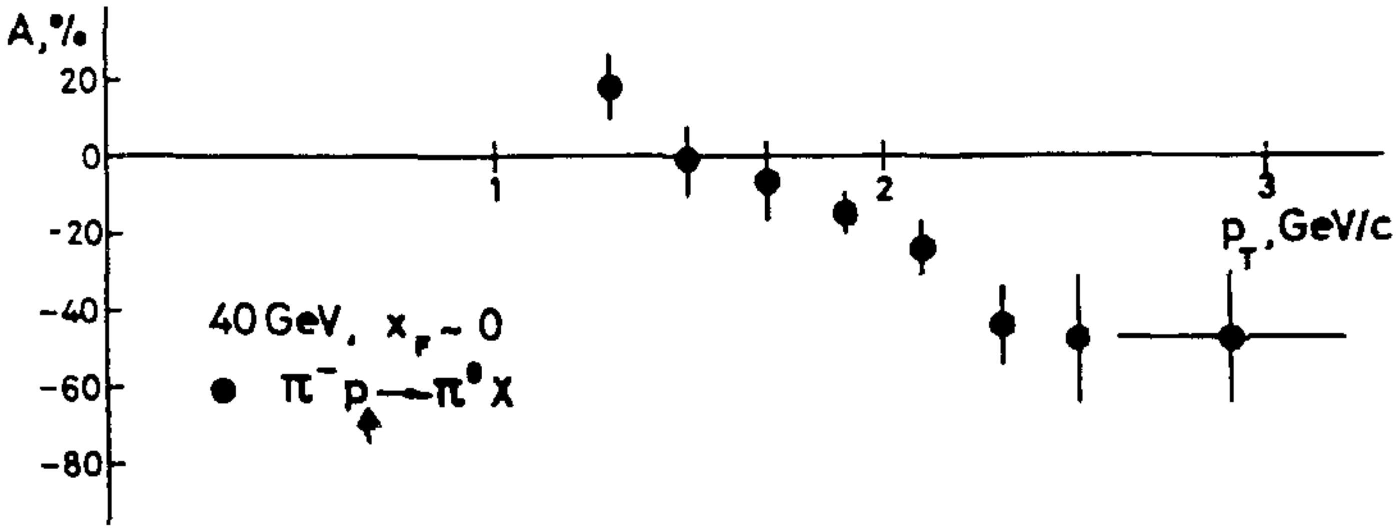
A,%
20
0
-20
-40
-60
-80
1
2
3
p_T, GeV/c
40 GeV, $x_F \sim 0$
$\pi^- p_\uparrow \to \pi^0 X$

Fig. 8

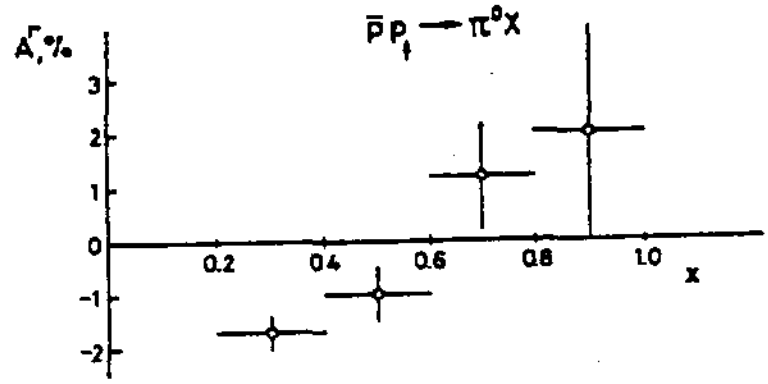
A,%
$\bar{p} p_\uparrow \to \pi^0 X$
3
2
1
0
-1
-2
0.2
0.4
0.6
0.8
1.0
x

Fig. 9

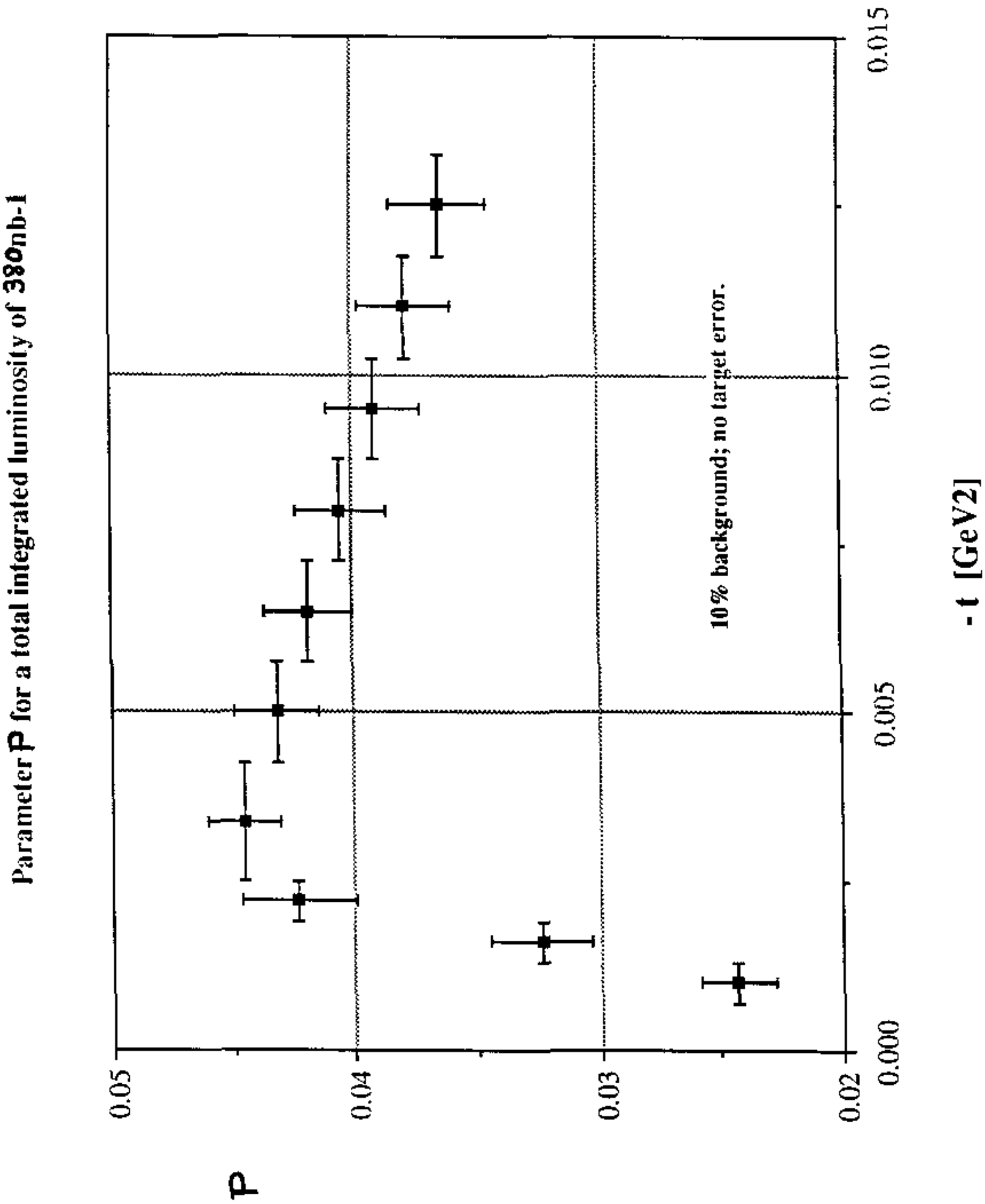
Parameter P for a total integrated luminosity of 380nb-1
10% background; no target error.
0.05
0.04
0.03
0.02
P
0.000
0.005
0.010
0.015
-t [GeV2]

Fig. 10