transverse momentum and spin distributions at COMPASS

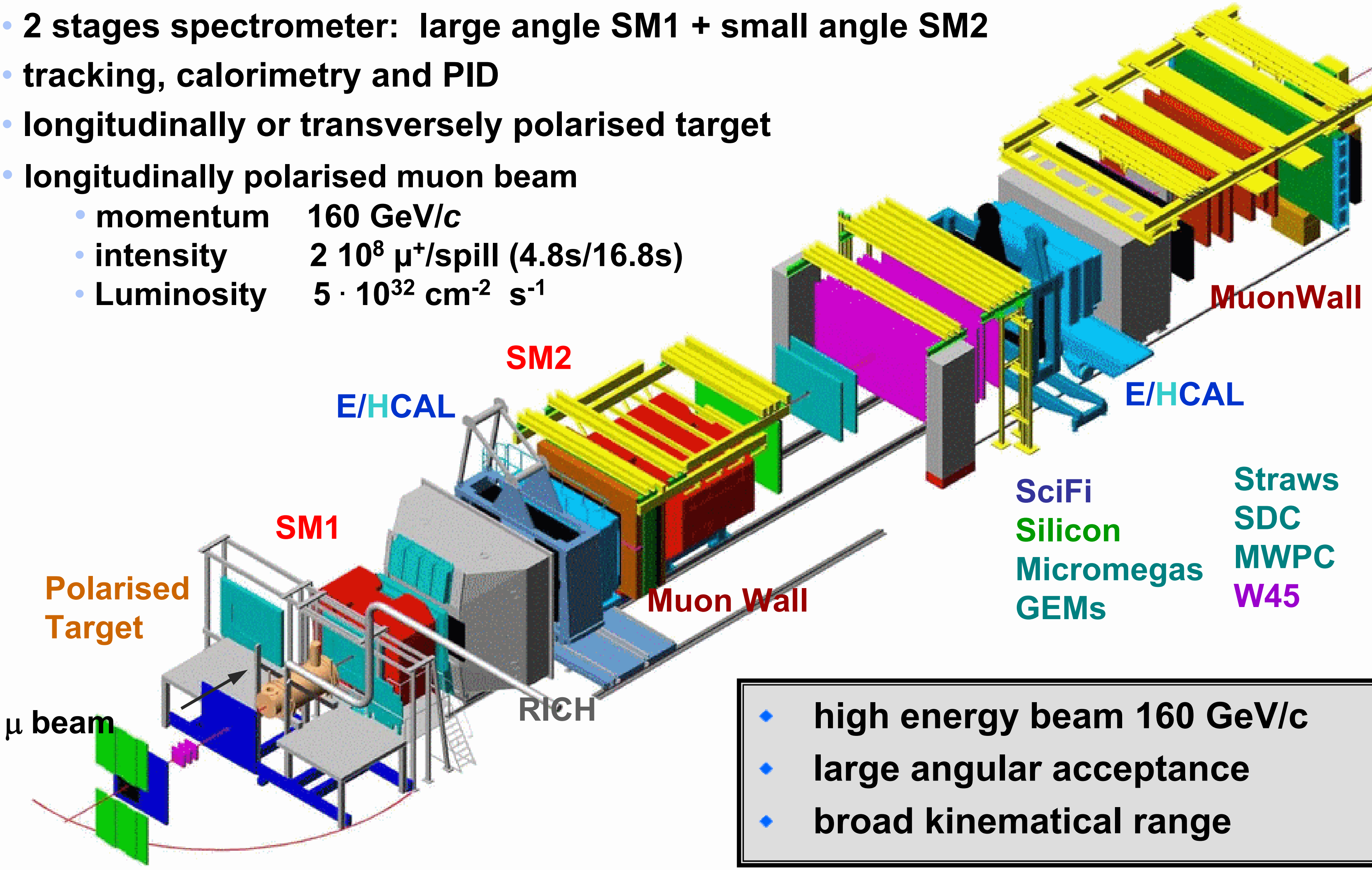
Andrea Bressan, Trieste INFN, INFN Trieste and CERN
Nicole d'Hose, Saclay CEA/DAPNIA
JLab, 24 May 2007
on behalf of the COMPASS Collaboration

Outline

- The COMPASS experiment
- Results on:
  - Collins/Sivers asymmetries
    - positive and negative hadrons
    - $\pi^{\pm}$, $K^{\pm}$
  - two identified hadron asymmetries
    - $\pi\pi$, πK, KK
  - other Transv. Mom. Dependent (TMD) asymmetries

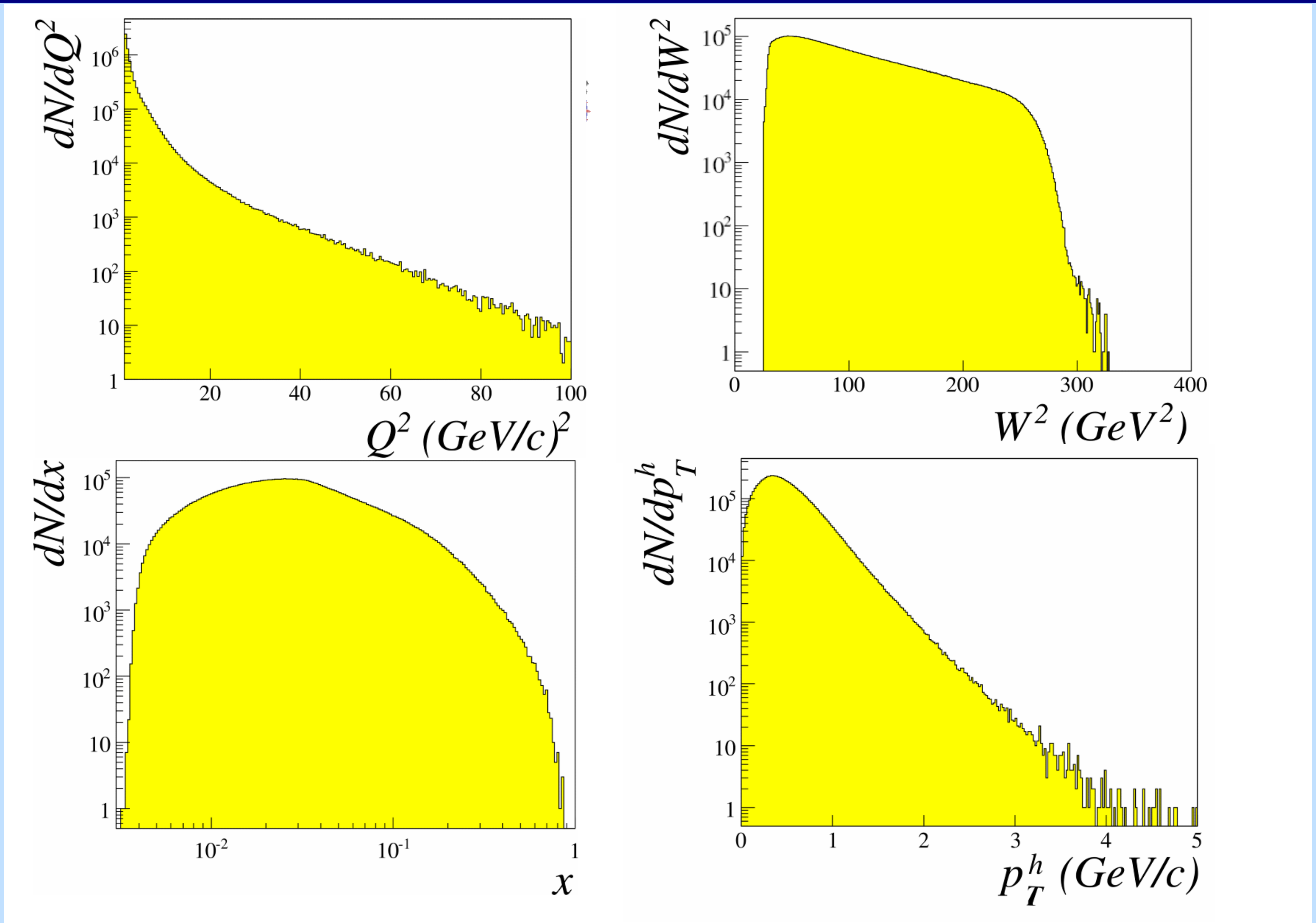
COMPASS spectrometer

- 2 stages spectrometer: large angle SM1 + small angle SM2
- tracking, calorimetry and PID
- longitudinally or transversely polarised target
- longitudinally polarised muon beam
  - momentum 160 GeV/*c*
  - intensity $2\ 10^8\ \mu^+$/spill (4.8s/16.8s)
  - Luminosity $5 \cdot 10^{32}\ cm^{-2}\ s^{-1}$



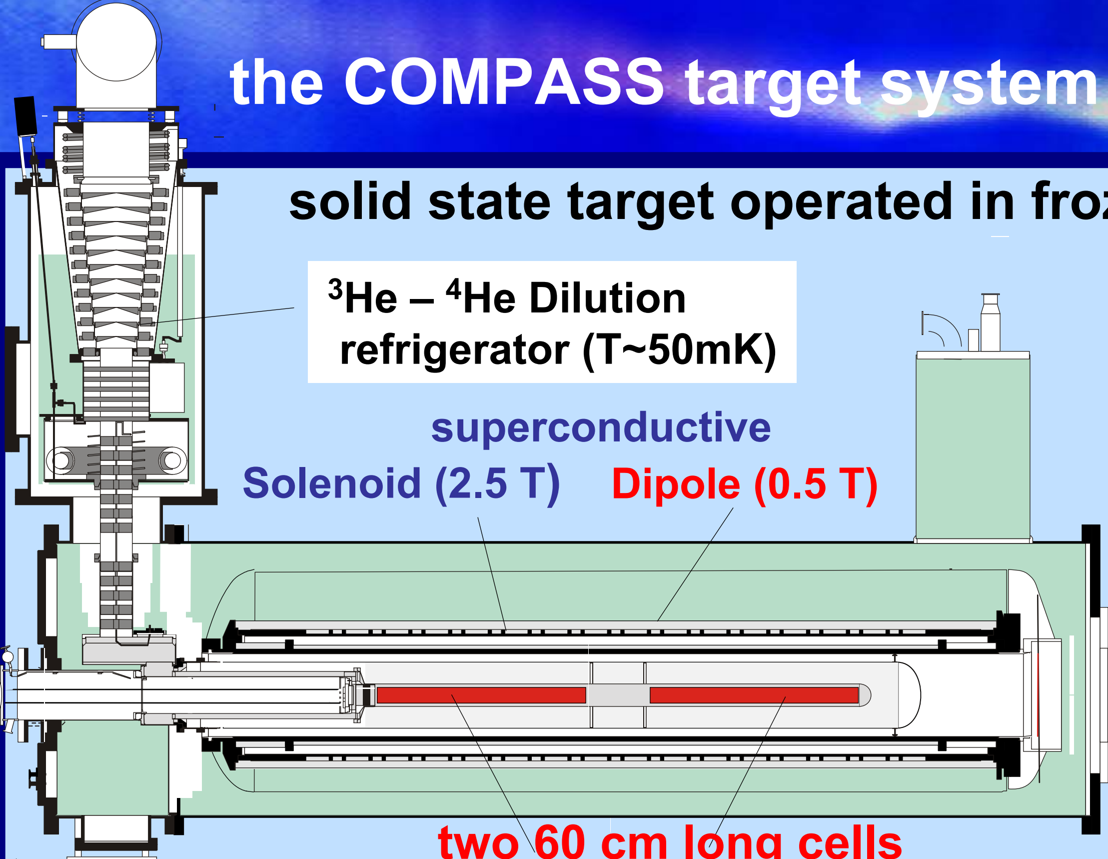
- high energy beam 160 GeV/c
- large angular acceptance
- broad kinematical range

SIDIS kinematics

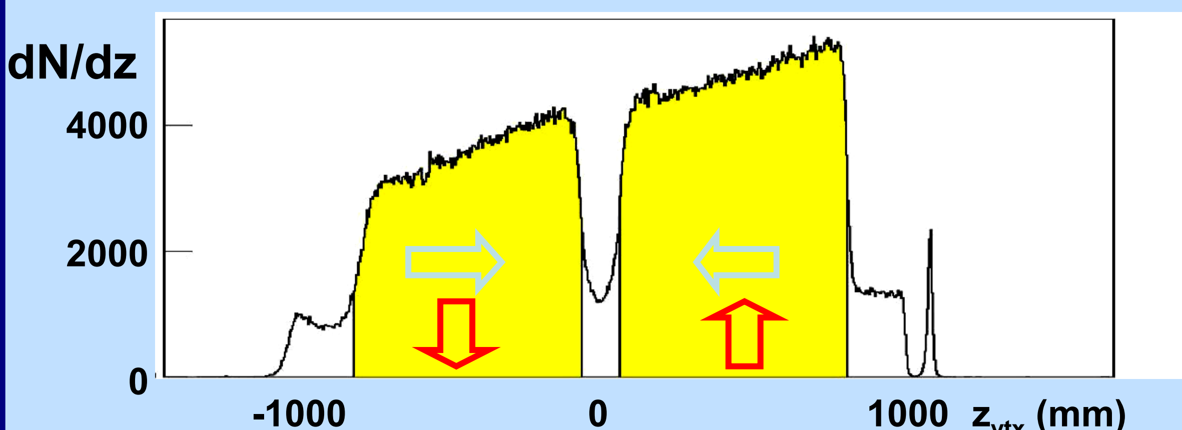


the COMPASS target system

solid state target operated in frozen spin mode



two 60 cm long cells
with *opposite polarisation* (systematics)



2002-2004: ^{6}LiD
- dilution factor f = 0.38
- polarization P_T = 50%
- ~20% of the time transversely polarised

during data taking with transverse polarization
- dipole field always ↑
- polarization reversal in the 2 cells after ~ 5 days

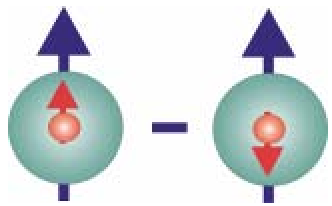
transversity DF

$\Delta_T q(x) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)$

$h_1^q(x)$,

$\delta q(x)$,

$\delta_T q(x)$



$q = u_v, d_v, q_{sea}$

quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

Properties:

- probes the relativistic nature of quark dynamics
- no contribution from the gluons → simple Q^2 evolution
- Positivity: Soffer bound................. $2|\Delta_T q| \leq q + \Delta q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge.......... $\Delta_T q \equiv \int dx\, \Delta_T q(x)$
- sum rule for transverse spin in Parton Model framework............ $\frac{1}{2} = \frac{1}{2}\sum \Delta_T q + L_q + L_g$ *Bakker, Leader, Trueman, PRD 70 (04)*
- it is related to GPD's
- is chiral-odd: decouples from inclusive DIS

how to measure it in SIDIS

the Transversity DF is chiral-odd:

→ survives only by the product with another chiral-odd function

can be measured in SIDIS on a transversely polarised target via "quark polarimetry"

$\ell N^{\uparrow} \rightarrow \ell' h X$	Collins Asymmetry (Collins FF)
$\ell N^{\uparrow} \rightarrow \ell' hh X$	Two hadrons asymmetry (Interference FF)
$\ell N^{\uparrow} \rightarrow \ell' \Lambda X$	Λ polarization (FF of $q^{\uparrow} \rightarrow \Lambda$)

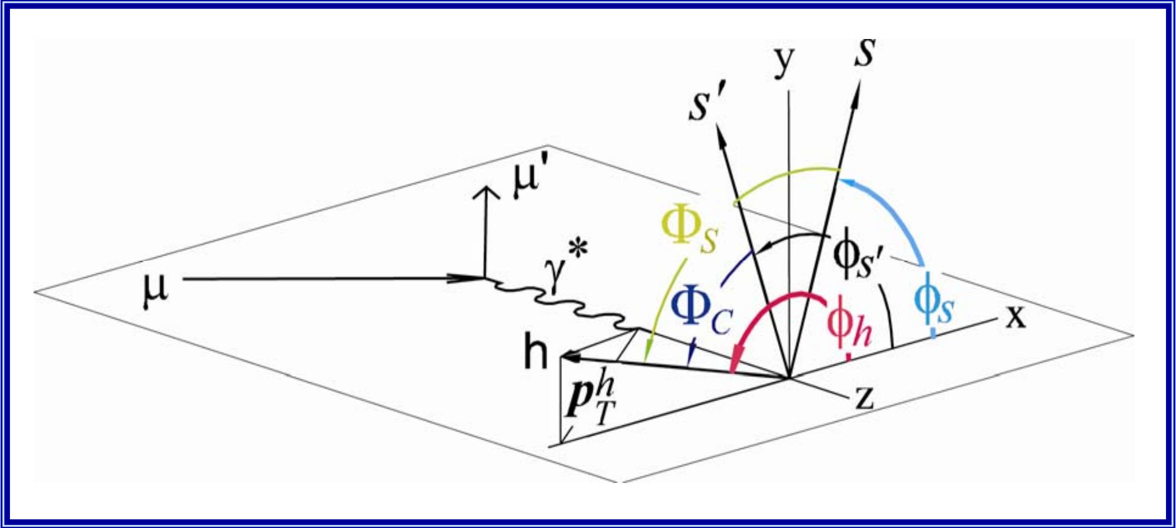
Collins and Sivers terms in SIDIS cross sections depend on different combination of angles:

Collins angle

$$\Phi_C = \phi_h - \phi_{s'}$$
$$= \phi_h + \phi_s - \pi$$

Sivers angle

$$\Phi_S = \phi_h - \phi_s$$



ϕ_h azimuthal angle of the hadron

ϕ_s azimuthal angle of the transverse spin of the initial quark

$\phi_{s'}$ azimuthal angle of the transverse spin of the fragmenting quark

$\phi_{s'} = \pi - \phi_s$ ***(spin flip)***

Φ_C and Φ_S are independent angles → independent extraction of the asymmetries

COLLINS asymmetry

Collins effect:

a quark moving horizontally and polarized upward (downward) prefers to emit the leading meson to the left (right) side of the jet (quark direction).

i.e.

the fragmentation function of a transversely polarized quark has a spin dependent part

$$D_q^h(z,\vec{p}_T^{\,h}) = D_q^h(z,p_T^h) + \Delta_T^0 D_q^h(z,p_T^h) \times \sin(\varphi_h - \varphi_{s'})$$

And the resulting measured asymmetry:

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot \left\{ 1 \pm A_C^h \cdot \sin\Phi_C \right\} \qquad \Phi_C = \phi_h + \phi_s - \pi$$

$$A_{Coll} = \frac{A_C^h}{f \cdot P_T \cdot D} = \frac{\sum_q e_q^2 \cdot \Delta_T q \, \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

event selection

DIS cuts:

- $Q^2 > 1$
- $0.1 < y < 0.9$
- W > 5 GeV/c

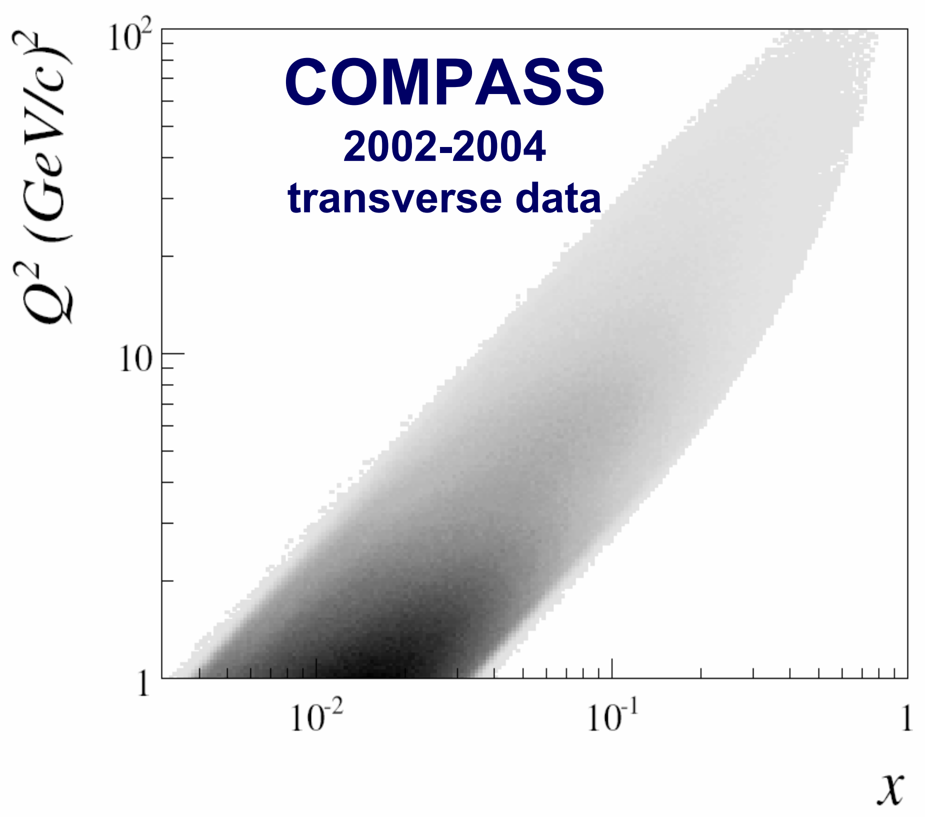
All hadron selection:

- $z > 0.20$
- $p_t > 0.1$

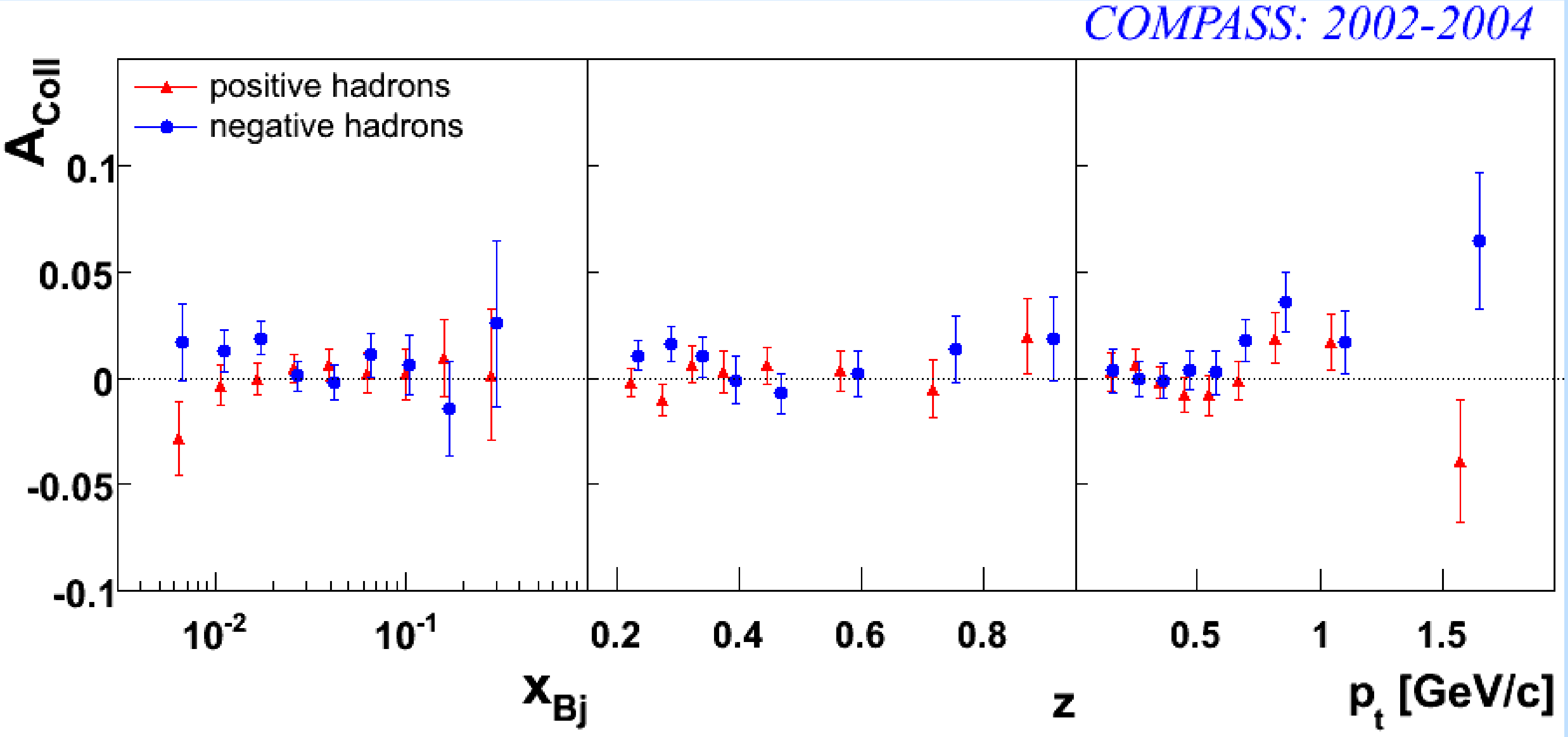
Plus for leading hadron:

- $z_l > 0.25$
- No signals in the CALOs from neutral particles with $z > z_l$

Statistics 2002 - 2004:
$8.5 * 10^6$ positive hadrons
$7.0 * 10^6$ negative hadrons



COLLINS asymmetries 2002-2004 data



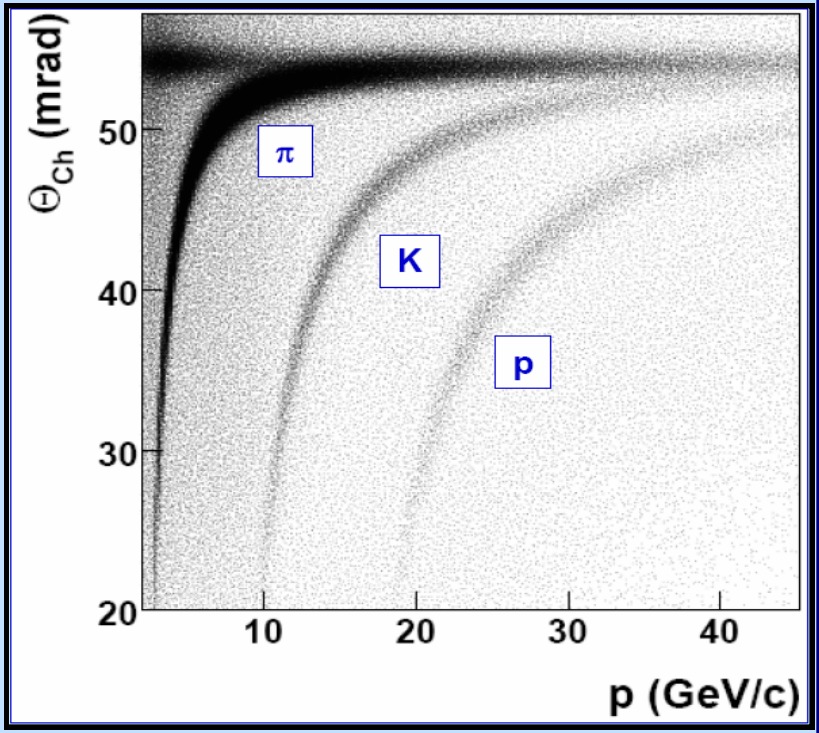
- only statistical errors shown (~1%),
- systematic errors considerably smaller
- small asymmetries compatible with 0 for both + and – hadrons

[NP B765 (2007) 31-70]

hadron identification

- Hadron identification is based on RICH response: several studies performed on the stability in time of the detector.
- Cherenkov thresholds: π ~ 3 GeV/c
  K ~ 9 GeV/c
  p ~ 17 GeV/c
- 2 σ π/K separation at 43 GeV/c
- In the leading hadron sample:
  ~76% pions
  ~12% kaons

	positive	negative
leading π	3.4M	2.8M
leading K	0.7M	0.4M



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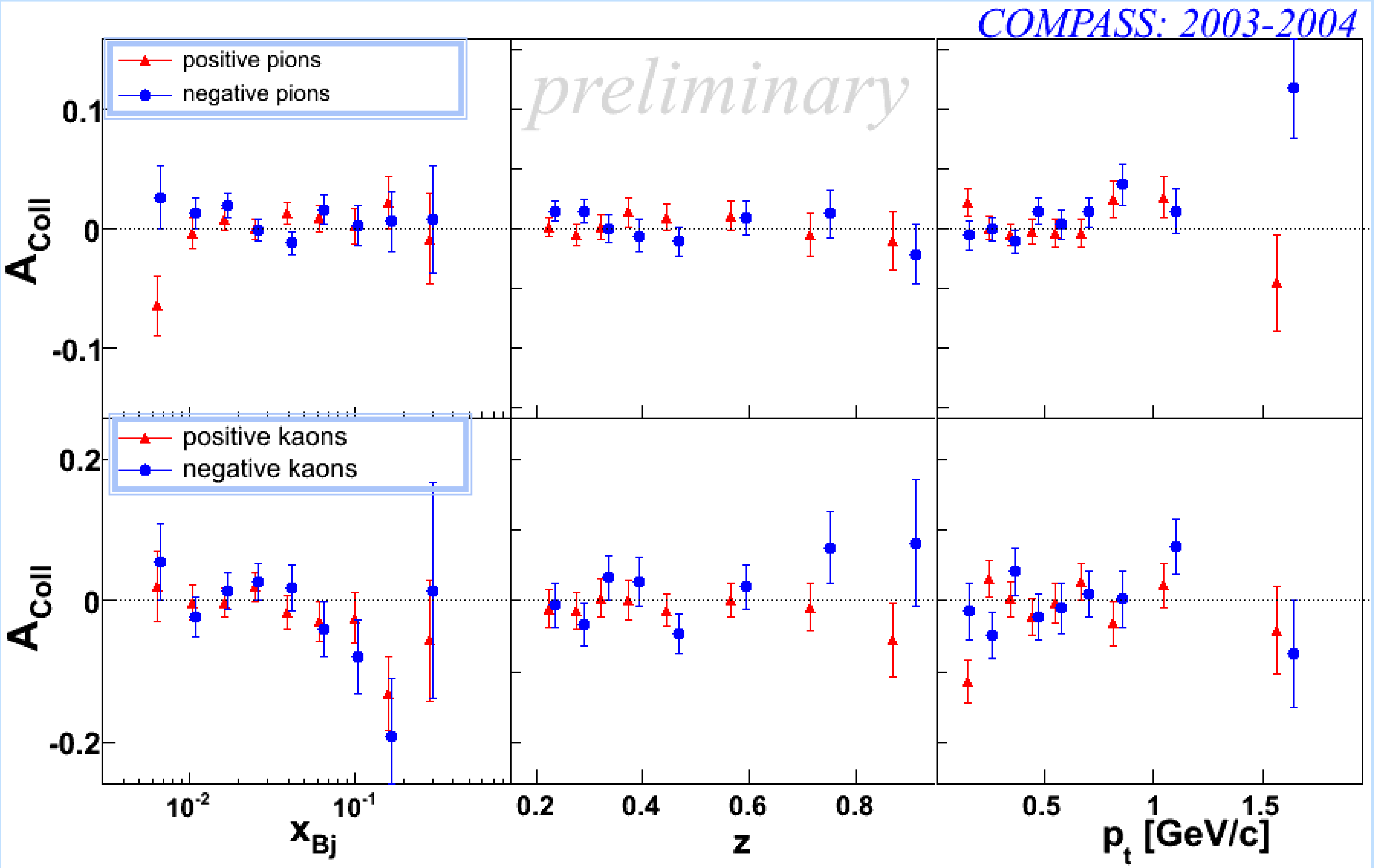


naïve interpretation (parton model, valence region)

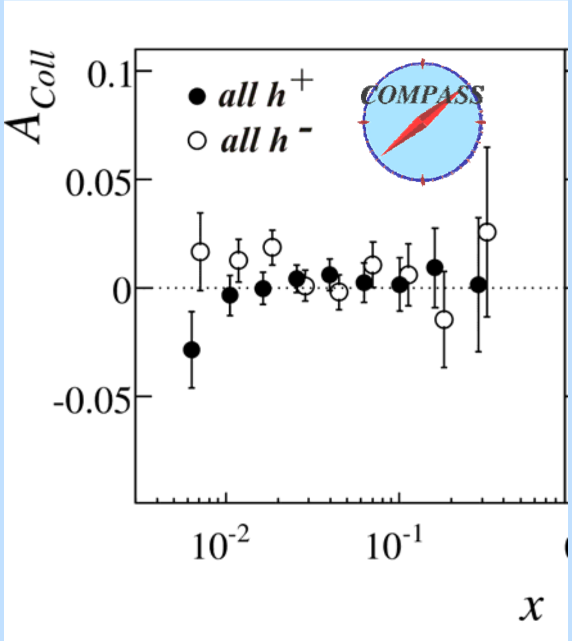
- **from proton data (HERMES)** non zero Collins asymmetry

  → unfavored Collins FF ≈ – favored Collins FF

$$\Delta_T^0 D_2 \approx -\Delta_T^0 D_1$$ *at variance with unpol case*

from proton: u quark dominance (d quark DF ~ unconstrained)

- **deuteron data (COMPASS)** small asymmetries compatible with 0



$$A_{Coll}^{d,\pi^+} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{4\Delta_T^0 D_1 + \Delta_T^0 D_2}{4D_1 + D_2}$$

$$A_{Coll}^{d,\pi^-} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{\Delta_T^0 D_1 + 4\Delta_T^0 D_2}{D_1 + 4D_2}$$

→ Cancellation between $\Delta_T u\ (x)$ and $\Delta_T d\ (x)$

→ Deuteron data give access to $\Delta_T d\ (x)$

for a global analysis of Hermes, Belle and Compass data
see the works of Vogelsang and Yuan, Efremov et al., Anselmino et al.

SIVERS mechanism

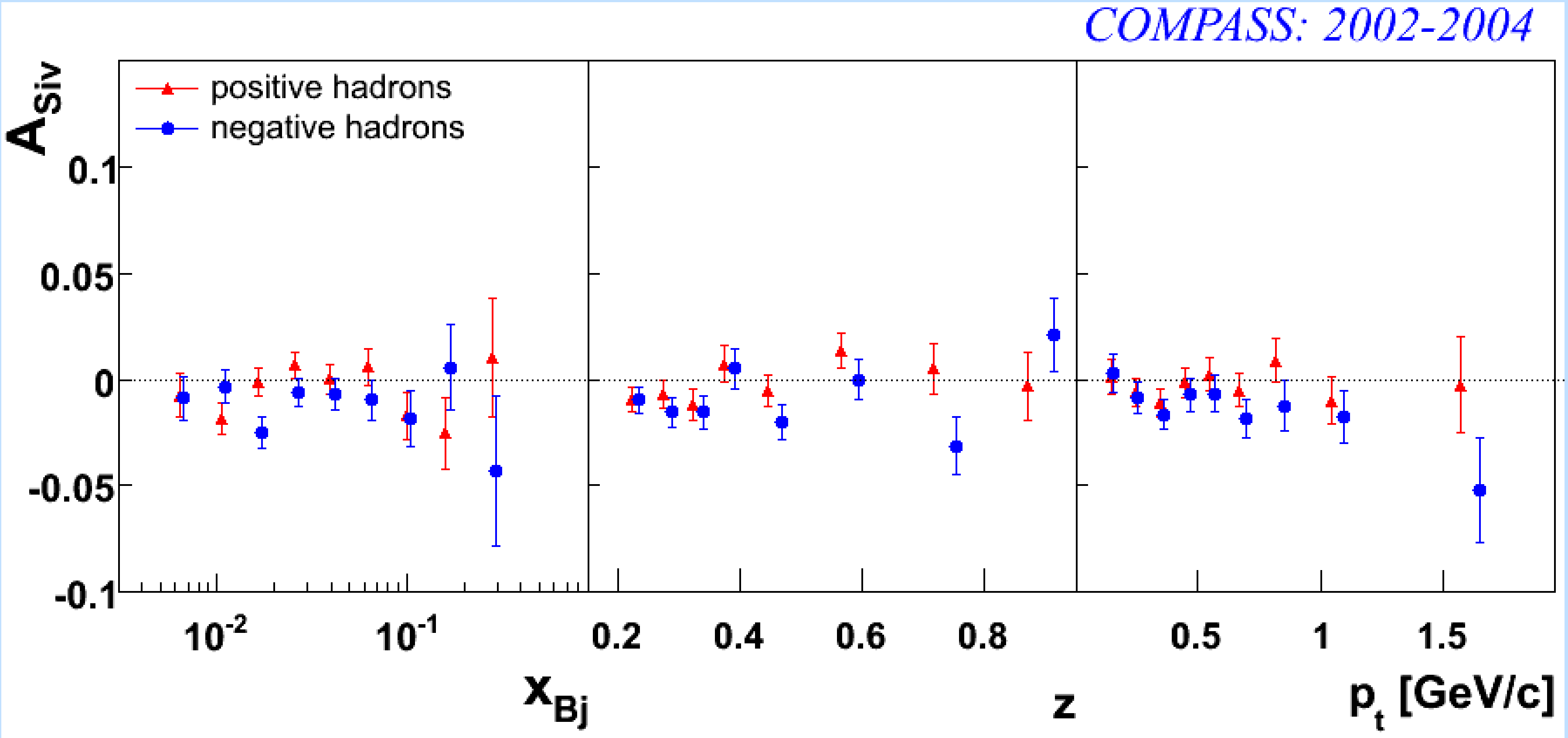
- The Sivers DF $\Delta_0^T q$ is probably the most famous between TMDs…
- gives a measure of the correlation between
  the transverse momentum and the transverse spin
- requires final/initial state interactions
  quark rescattering via soft gluon exchange
- it is related to the parton orbital angular momentum
  in a transverely polarized nucleon
- should change sign from SIDIS to DY $\Delta_0^T q\,(x,k_T^2)_{SIDIS} = -\Delta_0^T q\,(x,k_T^2)_{DY}$

In SIDIS:

$$N_h^{\pm}(\Phi_S) = N_h^0 \cdot \left\{ 1 \pm A_S^h \cdot \sin\Phi_S \right\}$$

$$A_{Siv} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

SIVERS asymmetries 2002-2004 data



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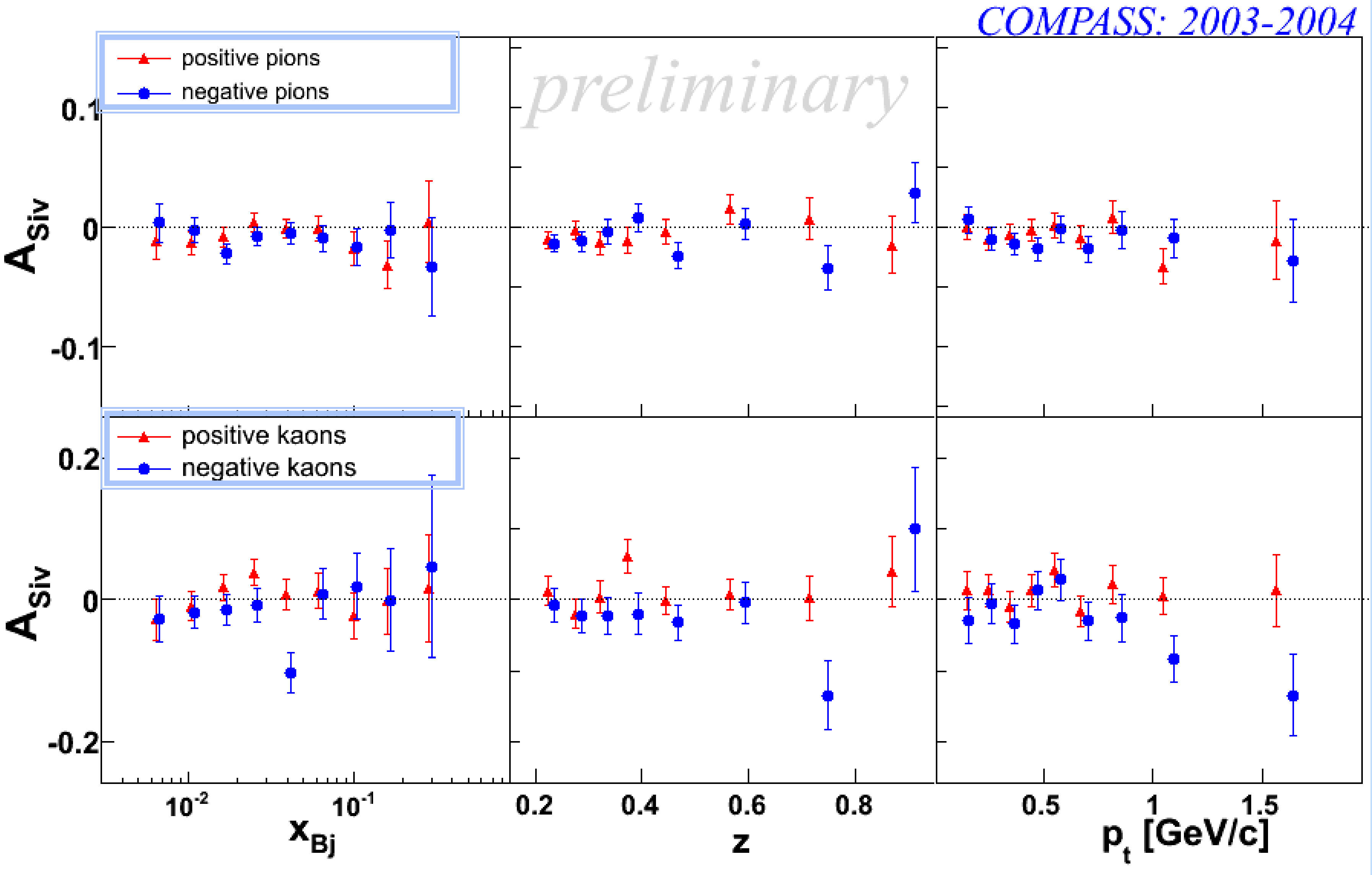
SIVERS asymmetries 2003-2004 data



naïve interpretation (parton model, valence region)

- **proton data (HERMES)**

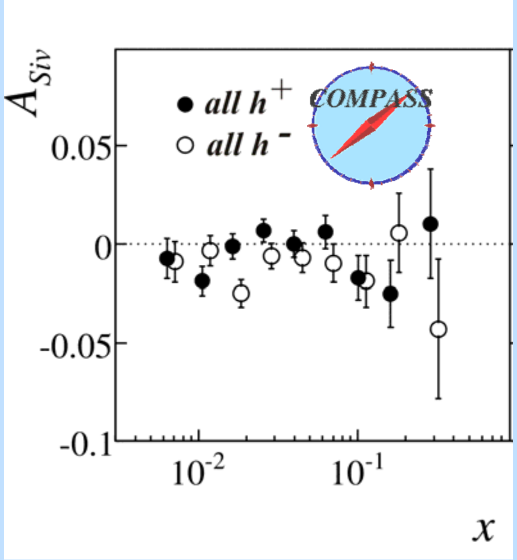
asymmetry for $\pi^+ > 0$, asymmetry for $\pi^- \approx 0$

$$A_{Siv}^{p,\pi^+} \simeq \frac{4\Delta_0^T u_v D_1 + \Delta_0^T d_v D_2}{4u_v D_1 + d_v D_2} \qquad A_{Siv}^{p,\pi^-} \simeq \frac{4\Delta_0^T u_v D_2 + \Delta_0^T d_v D_1}{4u_v D_2 + d_v D_1}$$

→ **Sivers DF for d-quark ≈ - 2 Sivers DF for u-quark**

$$\Delta_0^T d_v \simeq -2\ \Delta_0^T u_v$$

- **deuteron data (COMPASS)**



$$A_{Siv}^{d,\pi^+} \simeq A_{Siv}^{d,\pi^-} \simeq \frac{\Delta_0^T u_v + \Delta_0^T d_v}{u_v + d_v}$$

the measured asymmetries **compatible with zero** suggest

$$\Delta_0^T d_v \simeq -\Delta_0^T u_v$$

SIVERS on deuteron: hint for small L_g

the measured asymmetry on deuteron compatible with zero has been interpreted as

Evidence for the Absence of Gluon Orbital Angular Momentum in the Nucleon

S.J. Brodsky and S. Gardner, PLB643 (2006) 22

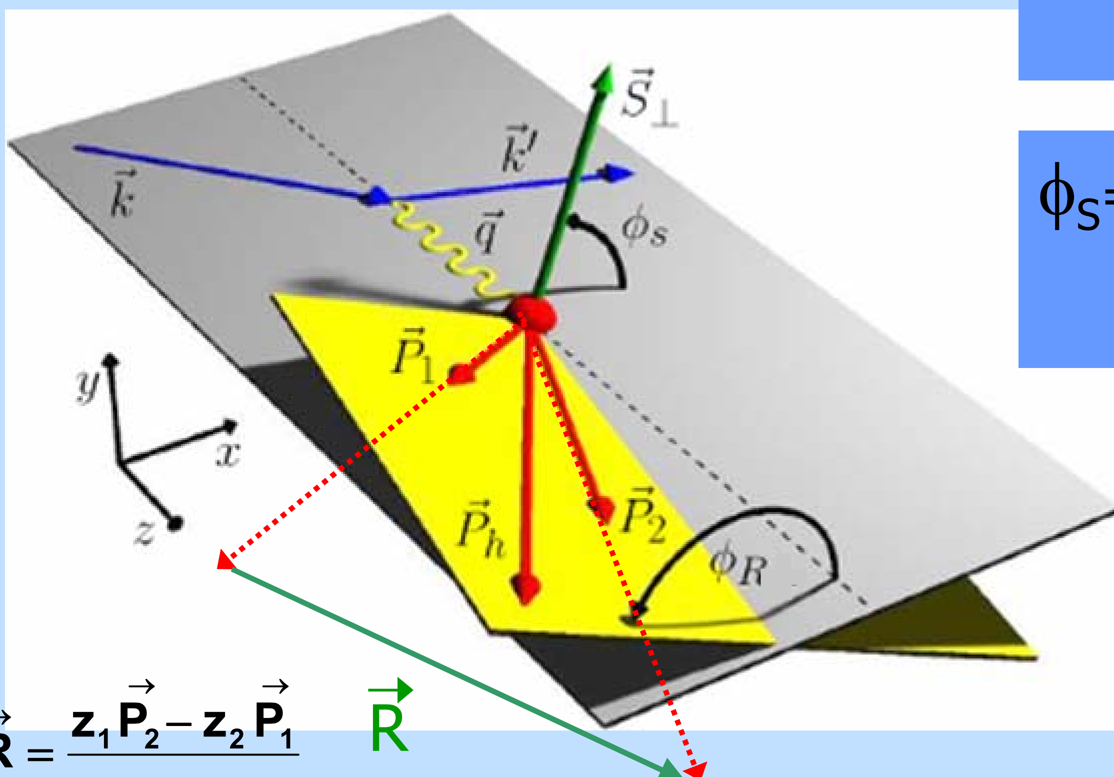
The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentums carried by gluons in the nucleon, is small.

two hadrons - the coordinate system

z-axis = virtual photon direction
x-z plane = lepton scattering plane

ϕ_R = angle between lepton scattering plane and two-hadron plane

ϕ_S = azimuthal angle of initial quark versus lepton scattering plane



$$\vec{R} = \frac{z_1 \vec{P}_2 - z_2 \vec{P}_1}{z_1 + z_2}$$

$\phi_{S'} = \pi - \phi_S$
(fragmenting quark)

$\phi_{RS} = \phi_R - \phi_{S'}$
$= \phi_R + \phi_S - \pi$

(A. Bacchetta, M. Radici, hep-ph/0407345)
(X. Artru, hep-ph/0207309)

azimuthal asymmetry for two-hadron production

Target single spin asymmetry $A_{RS}(x,z,M_h^2)$:

$z=z_1+z_2$

$$N^{\pm}\left(\Phi_{RS}\right) = N_0 \left\{1 \pm A_{UT}^{\sin\phi_{RS}} \sin\Phi_{RS}\right\}$$

and

$$A_{RS} = \frac{1}{f\,P_T\,D} A_{UT}^{\sin\phi_{RS}}$$

$N^{\pm}(\phi_{RS})$: Number of events for target spin up (+) and down (-)

f: Dilution factor ≈ 0.38

D: Depolarisation factor $D=(1-y)/(1-y+y^2/2)$

P_T: Target polarisation ≈ 0.5

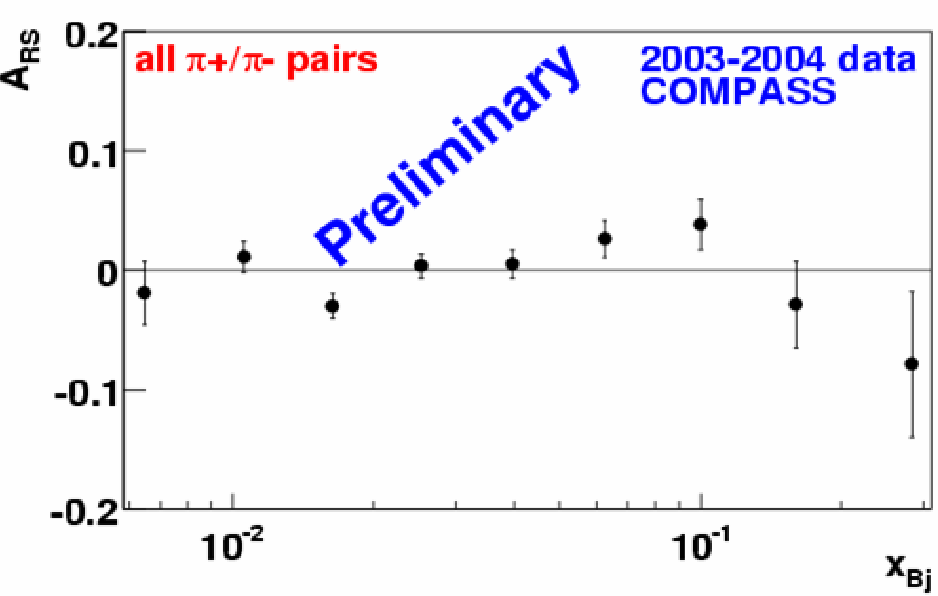
$$A_{RS}(x,z,M_h^2) = \frac{\sum_q e_q^2\, \Delta_T q(x)\, H_q^{\perp\angle h}(z,M_h^2)}{\sum_q e_q^2\, q(x)\, D_q^h(z,M_h^2)}$$

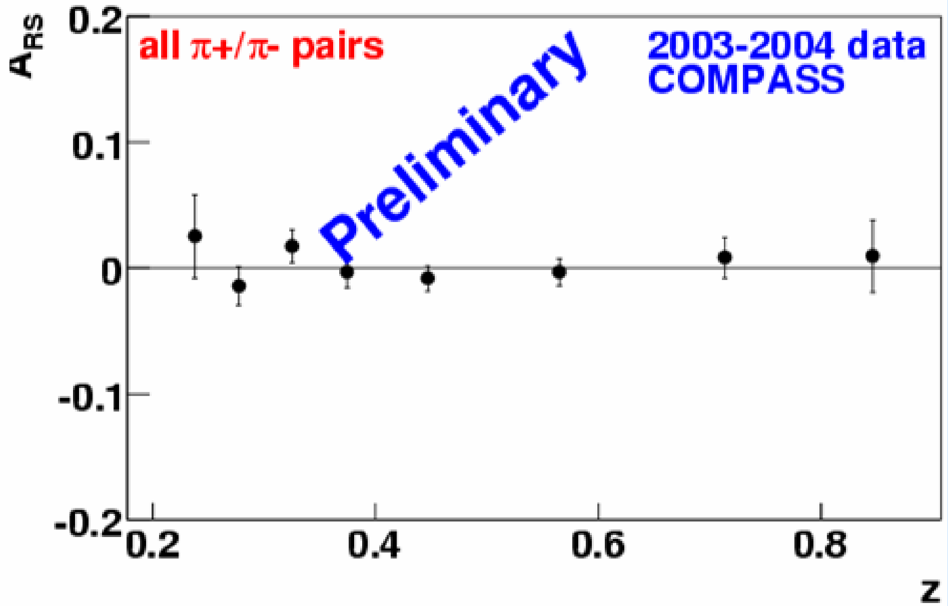
D_q^h, $H_q^{\perp\angle h}$ presently unknown can be measured in e^+e^- (BELLE)

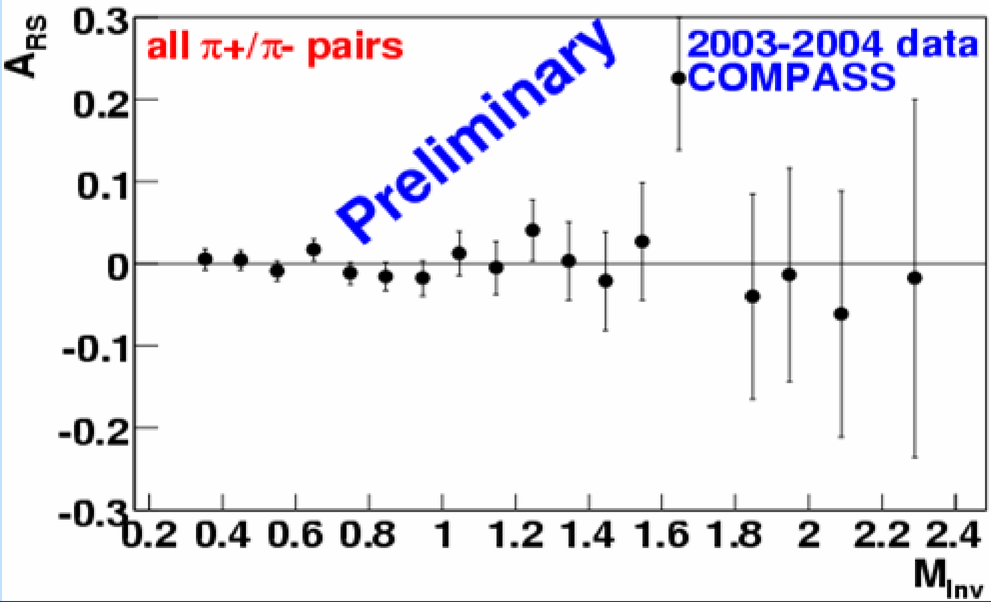
expected to depend on the hadron pair invariant mass

(X. Artru, hep-ph/0207309)

results for $\pi^+ \pi^-$ pairs (RICH identification)

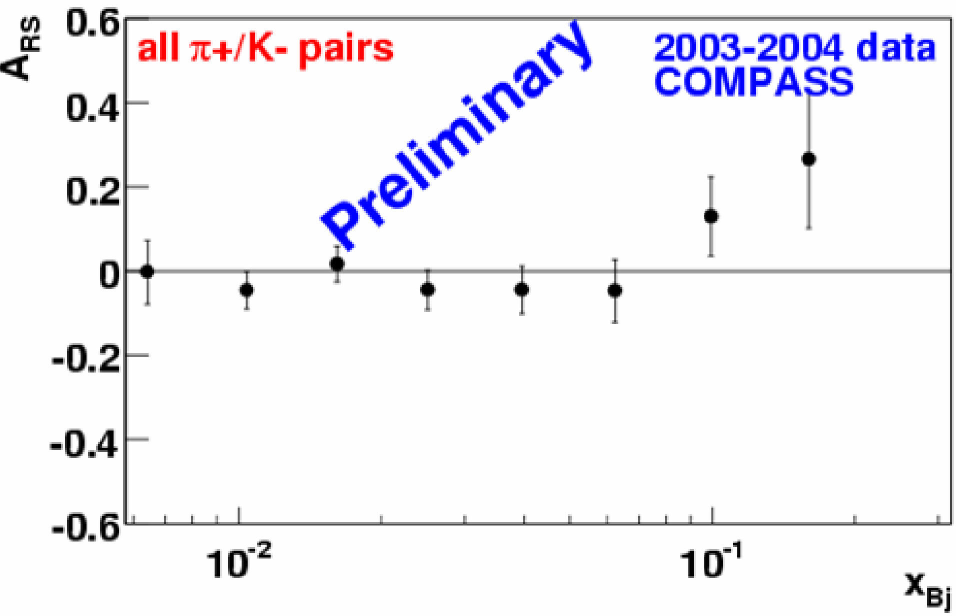


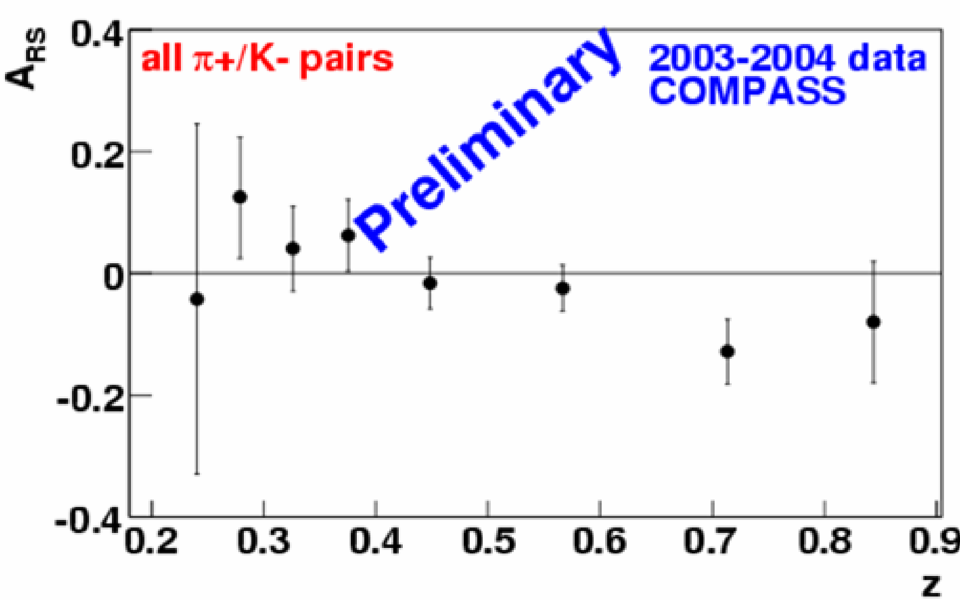


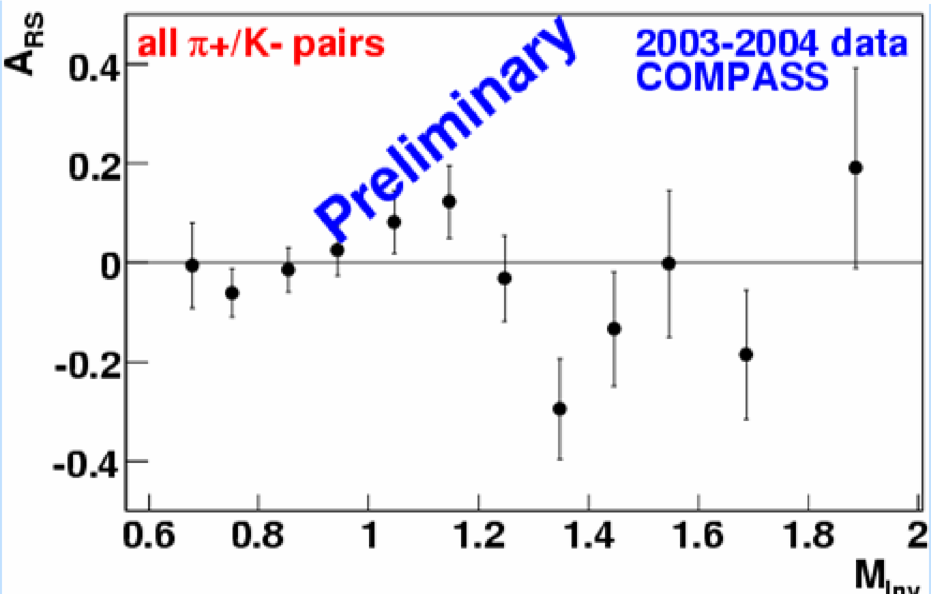


$z = z_1 + z_2$

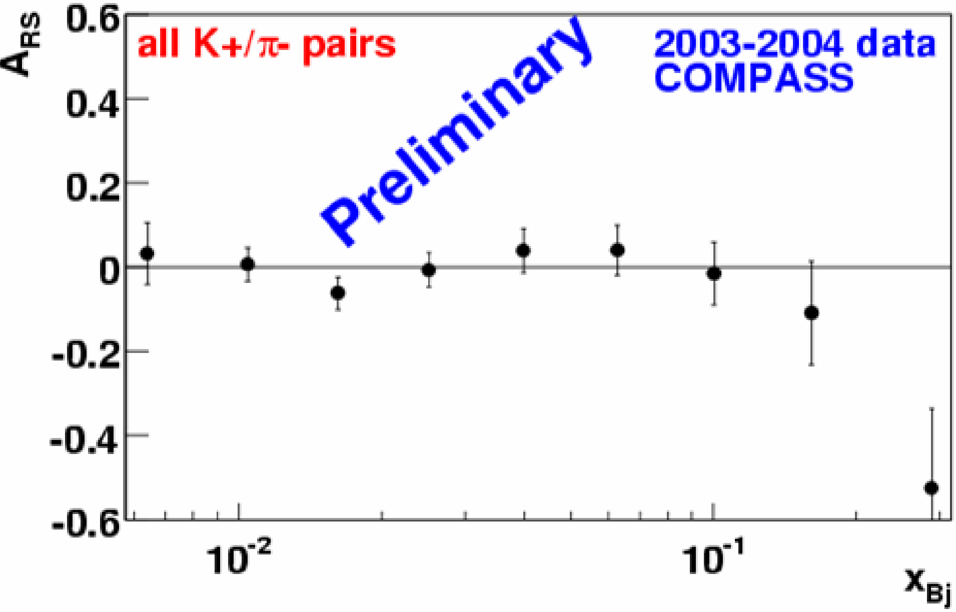
results for $\pi^+ K^-$ pairs (RICH identification)

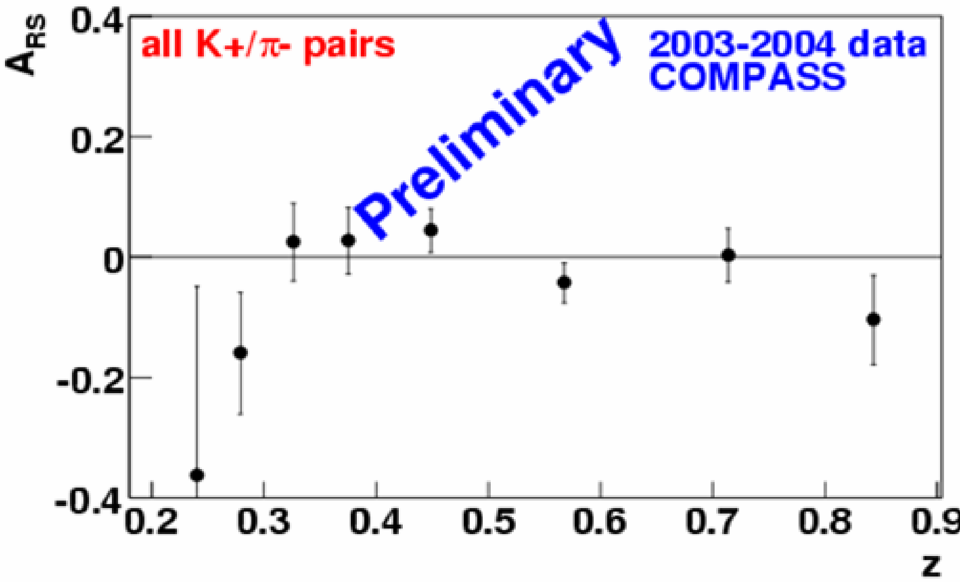


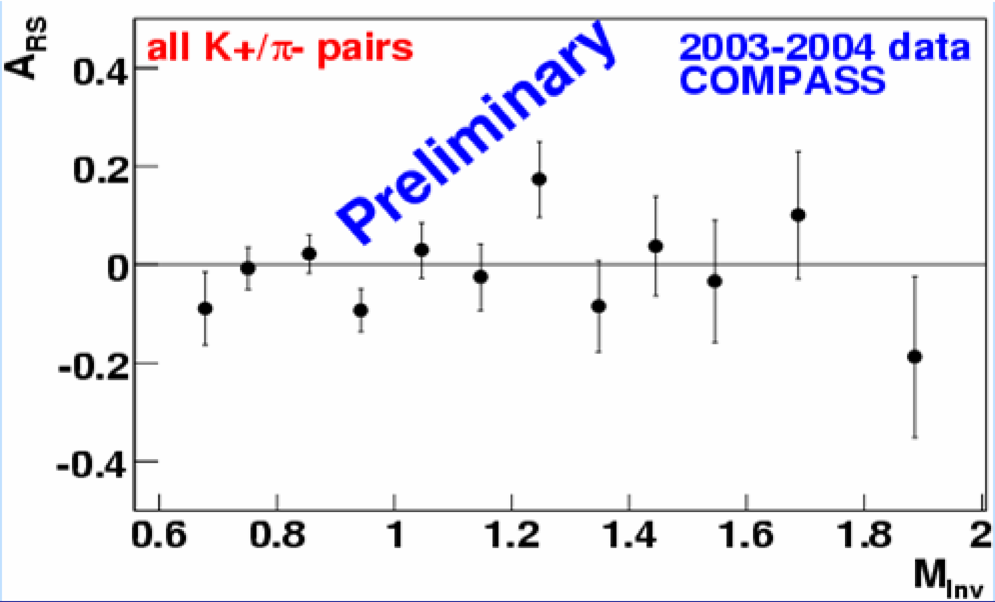




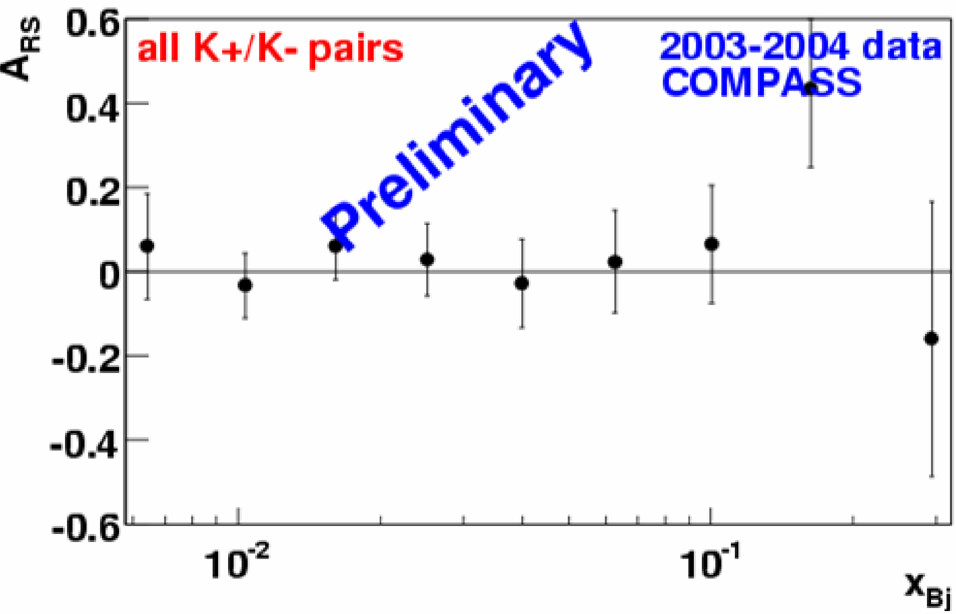
results for $K^+ \pi^-$ pairs (RICH identification)

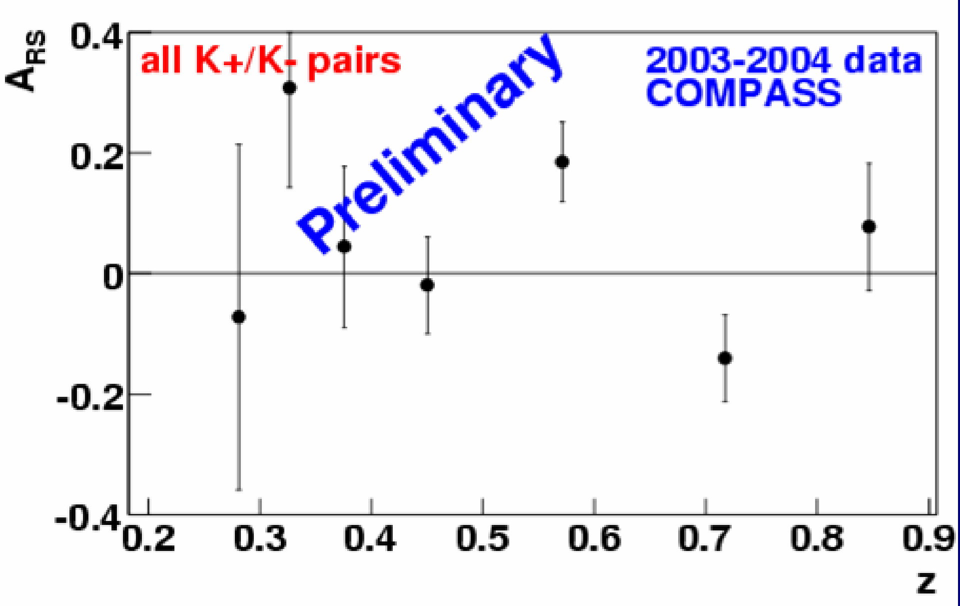


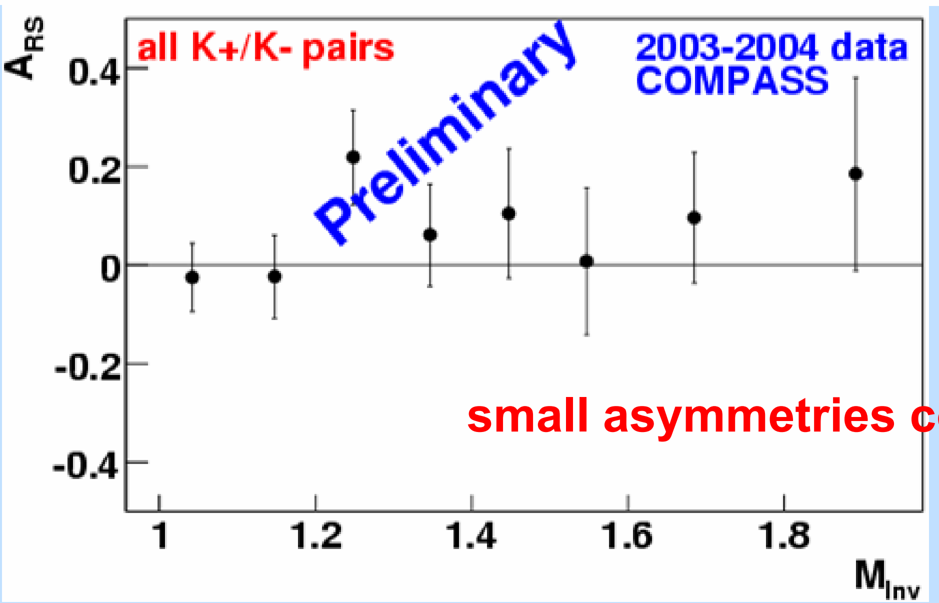




results for $K^+ K^-$ pairs (RICH identification)







small asymmetries compatible with 0

other TMDs: general expression of polarized SIDIS xSections

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,F_{UU}^{\cos\phi_h}$$

$$+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h}+P_{beam}\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$+P_L\left[\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]$$

$$+P_LP_{beam}\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

$$+|\boldsymbol{P}_T|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)}+\varepsilon F_{UT,L}^{\sin(\phi_h-\phi_S)}\right)$$

Sivers

$$+\varepsilon\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$

'Collins'

$$+\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_S\,F_{UT}^{\sin\phi_S}+\sqrt{2\varepsilon(1+\varepsilon)}\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big]$$

$$+|\boldsymbol{P}_T|P_{beam}\Big[\sqrt{1-\varepsilon^2}\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

$$+\sqrt{2\varepsilon(1-\varepsilon)}\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Big\},$$

Azimuthal modulations:

2 polarization independent

1 single beam polarization dependent

2 single target longitudinal polarization dependent

1 double beam + target longitudinal polarization dependent

+

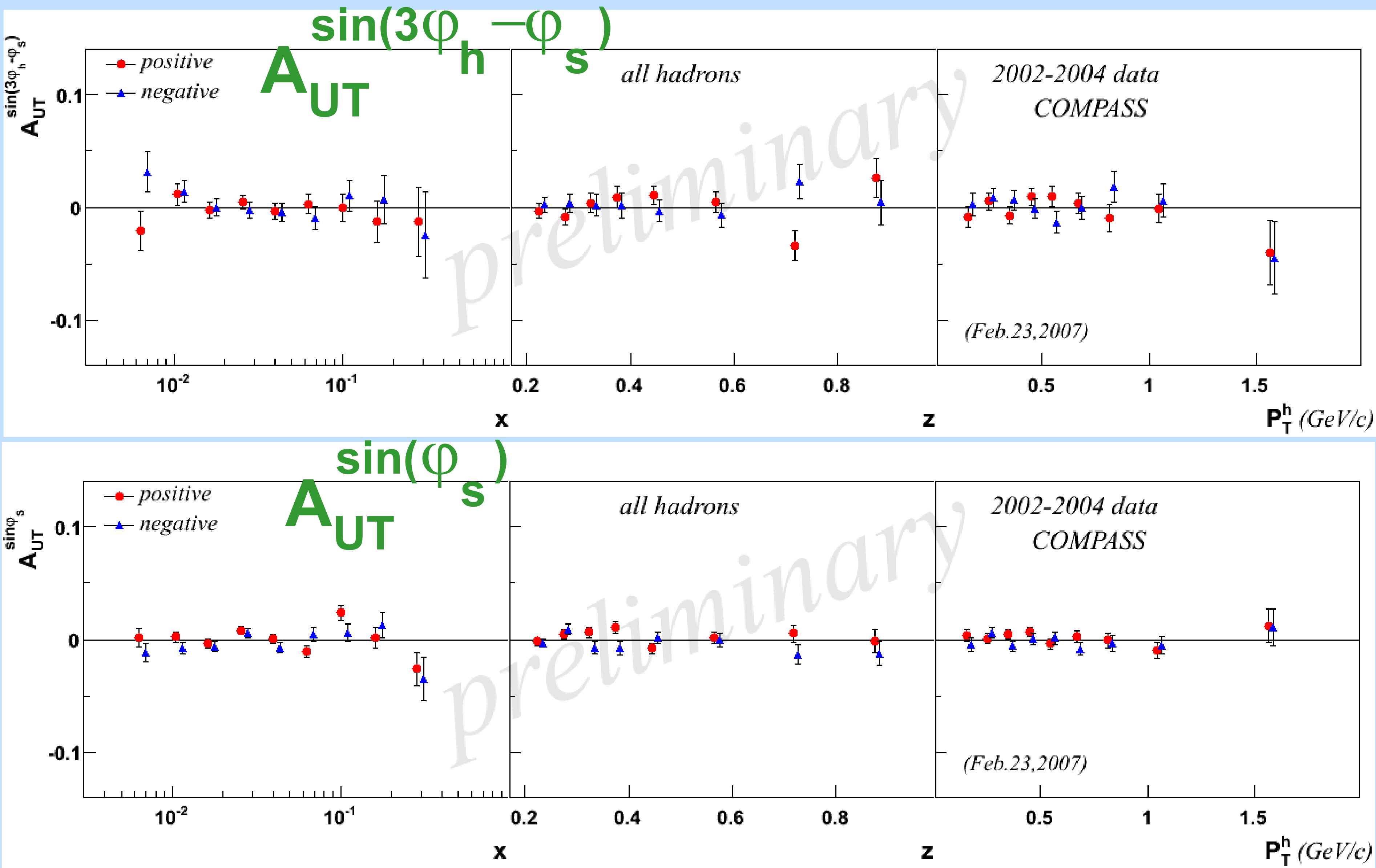
5 single target transverse polarization dependent

3 double beam + target transverse polarization dependent

5 independent angles

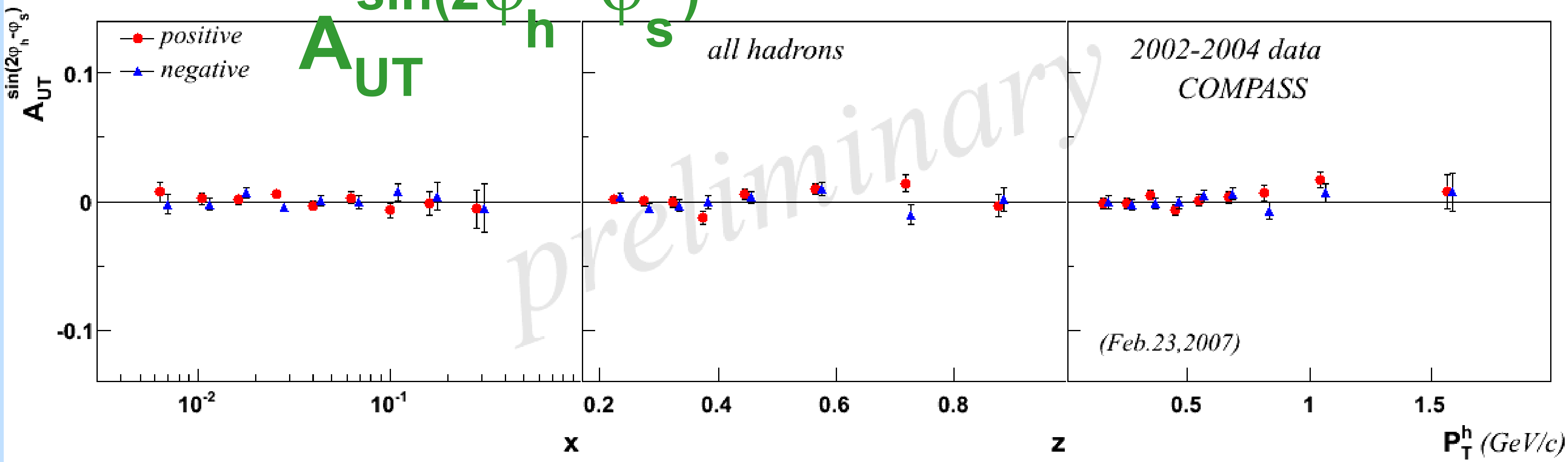
$$\Phi_1=\phi_h-\phi_s$$
$$\Phi_2=\phi_h+\phi_s$$
$$\Phi_3=3\phi_h-\phi_s$$
$$\Phi_4=\phi_s$$
$$\Phi_5=2\phi_h-\phi_s$$

asymmetry extraction - I

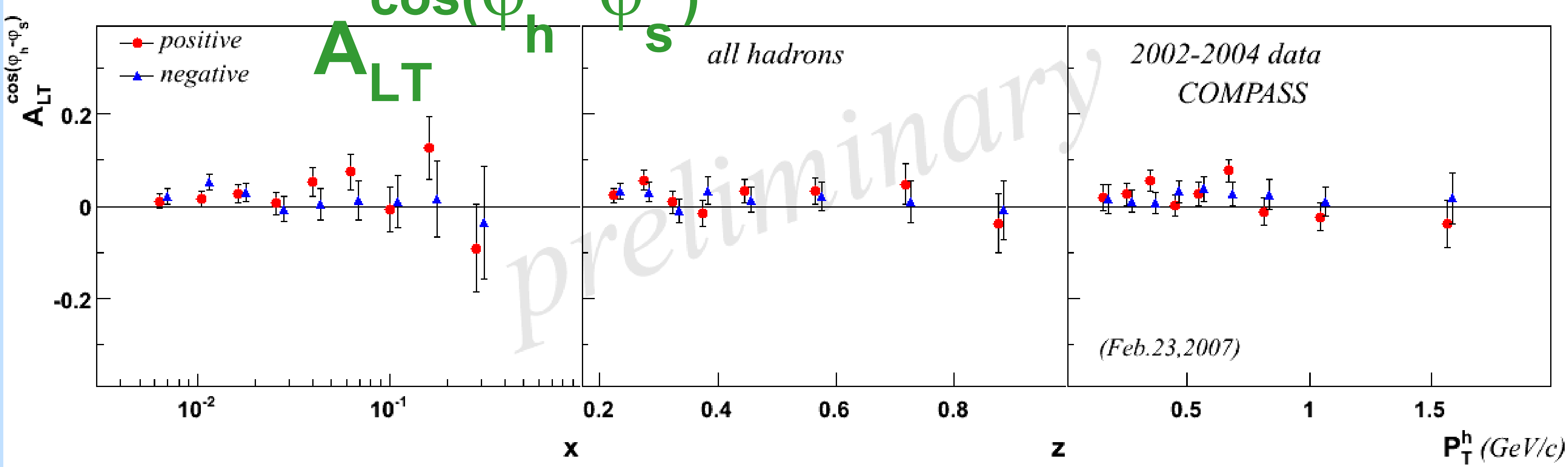


asymmetry extraction - II

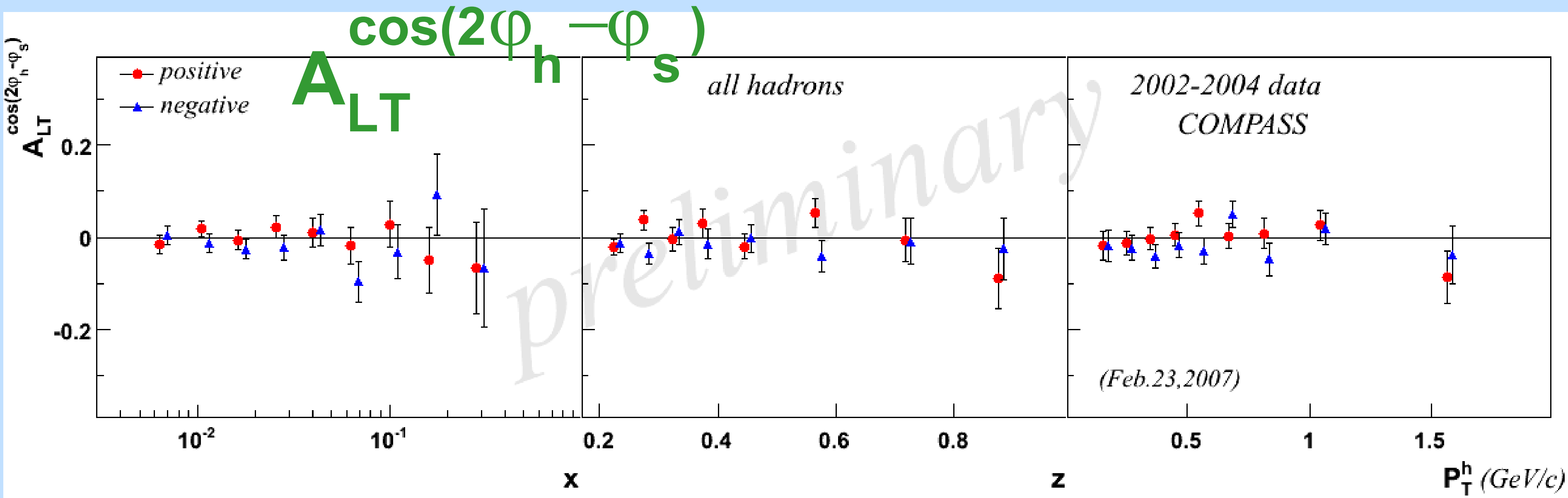
$A_{UT}^{\sin(2\varphi_h - \varphi_s)}$

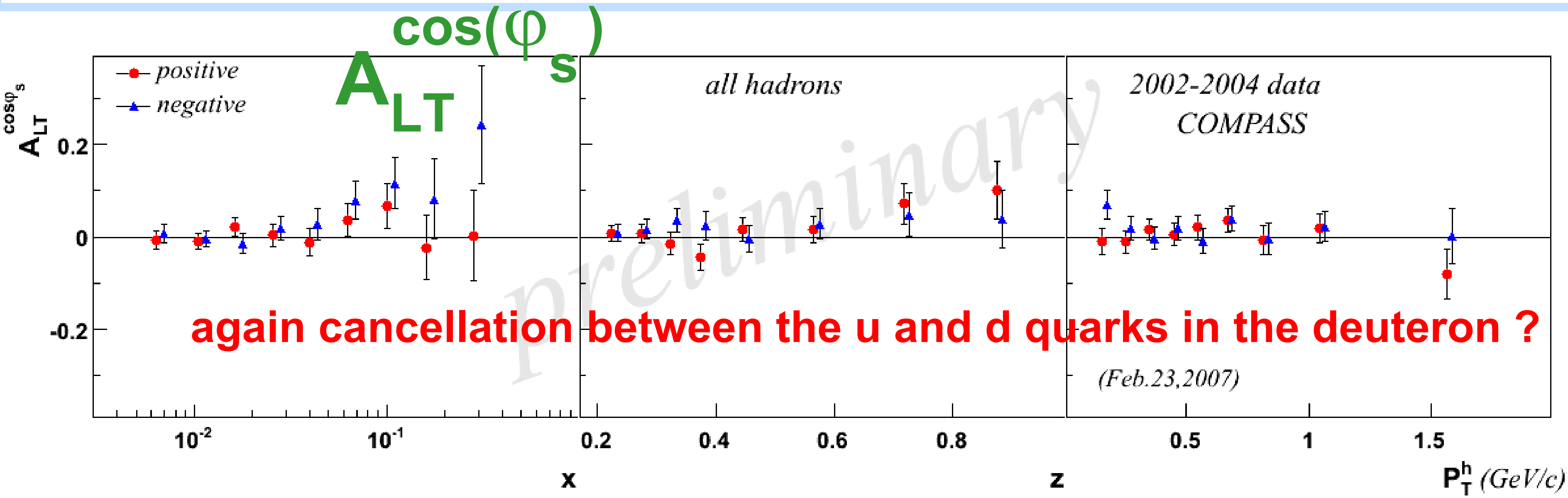


$A_{LT}^{\cos(\varphi_h - \varphi_s)}$



asymmetry extraction - III





again cancellation between the u and d quarks in the deuteron ?

summary and outlook

now: precise deuteron data from COMPASS are available

Collins and Sivers asymmetries $h^{\pm}$, $\pi^{\pm}$, $K^{\pm}$

Two hadron asymmetries

all other TMD SSA azimuthal asymmetries

→ deuteron asymmetries very small, compatible with zero

→ first extractions of the u and d quark DFs

near future: COMPASS will complete the analysis of the recorded deuteron data

- ***K^0 asymmetries***
- ***exclusive ρ asymmetries on transversely polarised target → GPD E***
- ***transverse effects from longitudinal data***
- ***Cahn and Boer-Mulders effect***

2007: COMPASS data will be with a transversely polarised proton target (NH_3)

with 50 days, same precision at small x as for deuterium, better at “large” x for the new PT magnet

on a longer time scale: good perspective for a measurement of Drell-Yan pairs in COMPASS

and further measurements of transverse spin effects in SIDIS

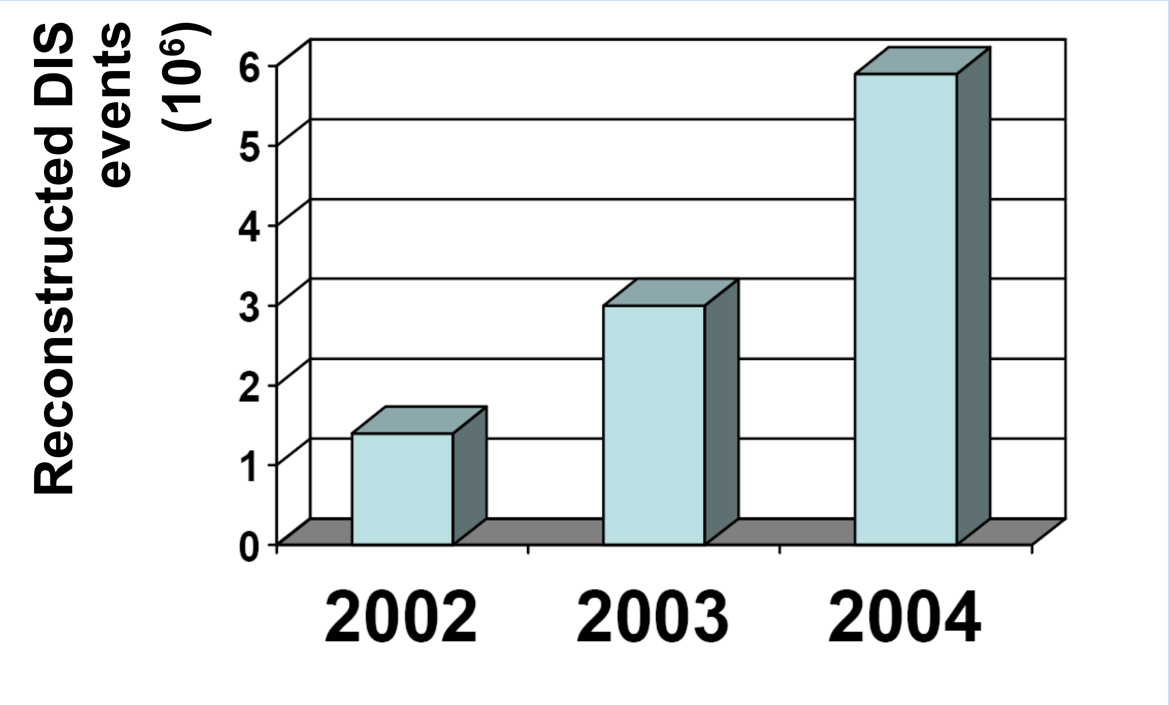
data taking 2002-2004

transversely polarised deuteron target (^6LiD)
~ 20% of the running time

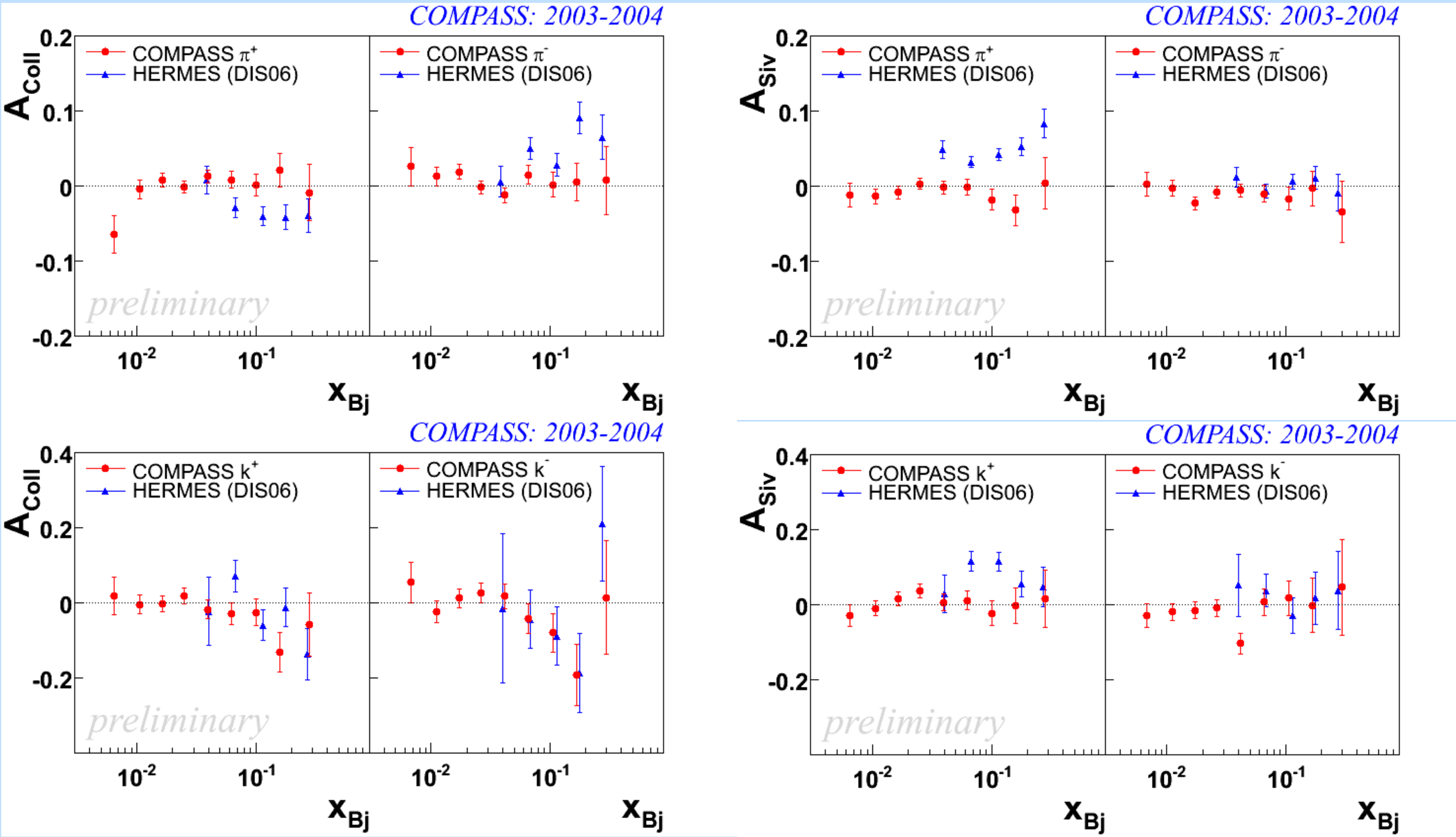
2002	11 days of data taking,	2 periods
2003	9 days of data taking,	1 period
2004	14 days of data taking,	2 periods

trigger (large x, Q^2)

DAQ, on line filter



comparison with HERMES for Collins and Sivers asym



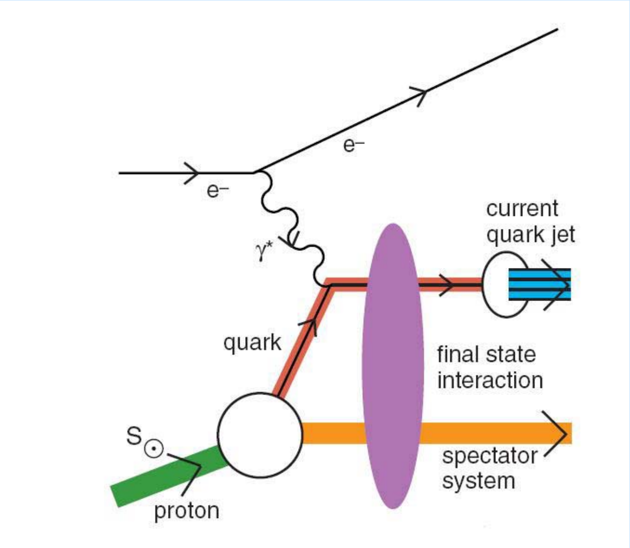
HERMES data from `Transversity results from HERMES', L.Pappalardo et al., to appear in the proceedings of the XIV International Workshop on Deep Inelastic Scattering, Tsukuba city, Japan, April 20-24, 2006., courtesy of the HERMES Collaboration

SIVERS mechanism

- The Sivers DF $\Delta_0^T q$ is probably the most famous between TMDs…
- gives a measure of the correlation between the transverse momentum and the transverse spin
- requires final/initial state interactions of the struck quark with the spectator system and the interference between different helicity Fock states to survive time-reversal invariance
- Time-reversal invariance implies:

$$\Delta_0^T q(x,k_T^2)_{SIDIS} = -\Delta_0^T q(x,k_T^2)_{DY}$$

…to be checked



- In SIDIS:

$$\mathbf{N_h^{\pm}(\Phi_S) = N_h^0 \cdot \{1 \pm A_S^h \cdot \sin\Phi_S\}}$$

$$\mathbf{A_{Siv} = \frac{A_S^h}{f \cdot P_T} = \frac{\sum_q e_q^2\, \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}}$$

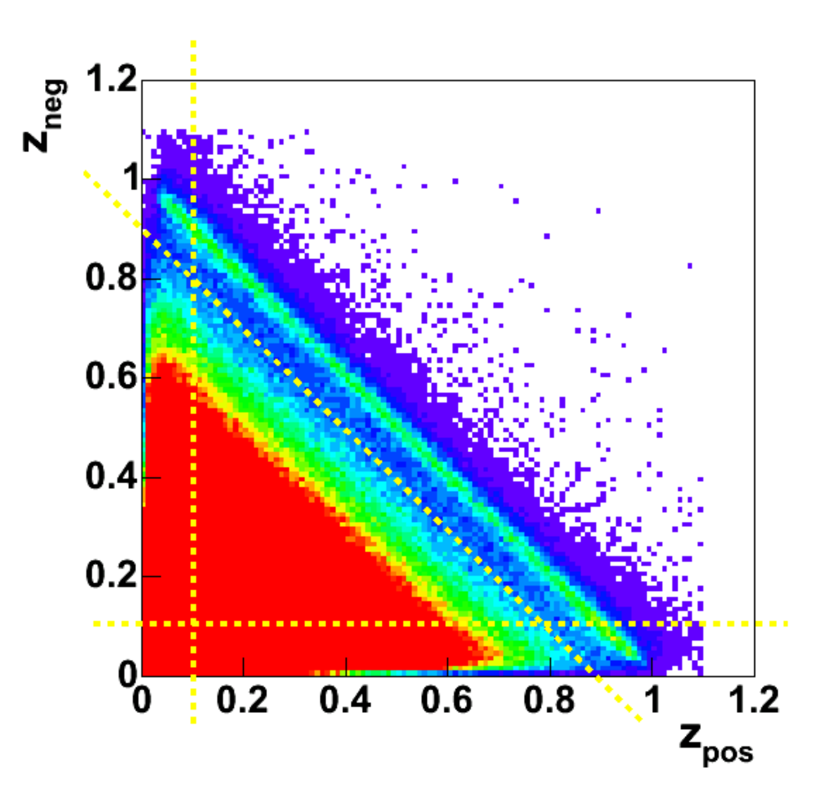
event selection for 2 hadrons

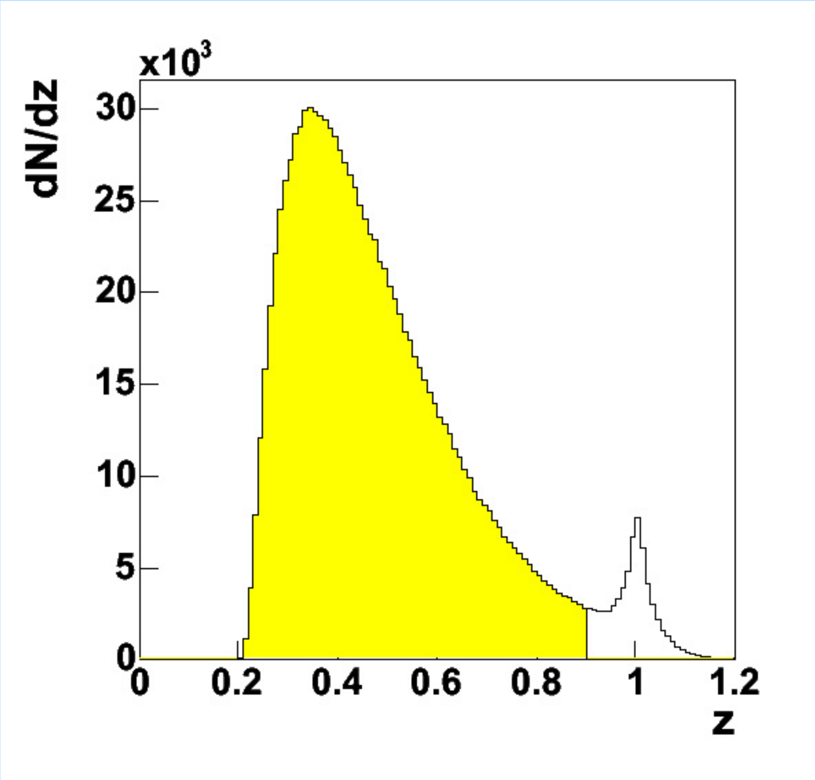
DIS cuts:

- $Q^2 > 1\ GeV^2/c^2$
- $0.1 < y < 0.9$
- $W > 5\ GeV/c^2$

Hadron selection:

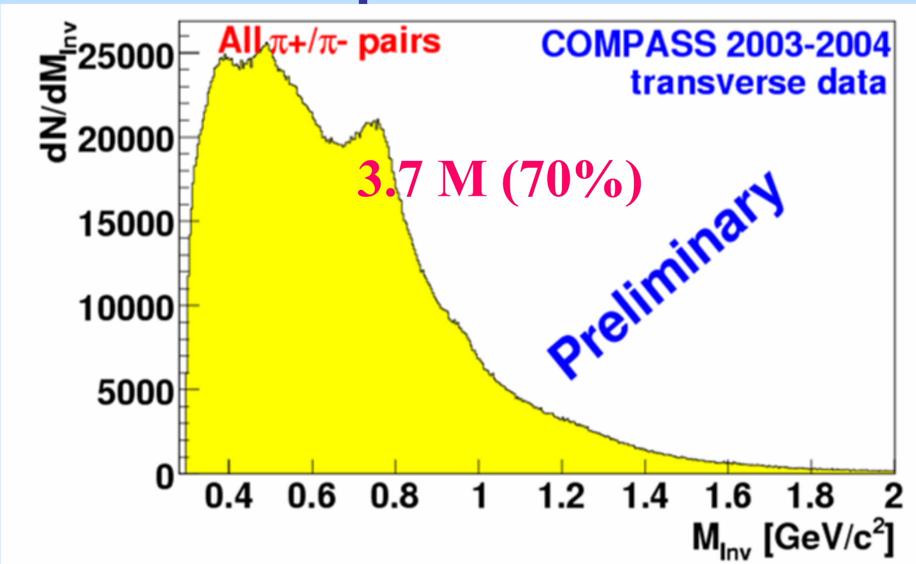
- $z_{1,2} > 0.1$ (current fragmentation)
- $x_{F1,2} > 0.1$
- $z = z_1 + z_2 < 0.9$ (exclusive rho)
- RICH identification of π, K

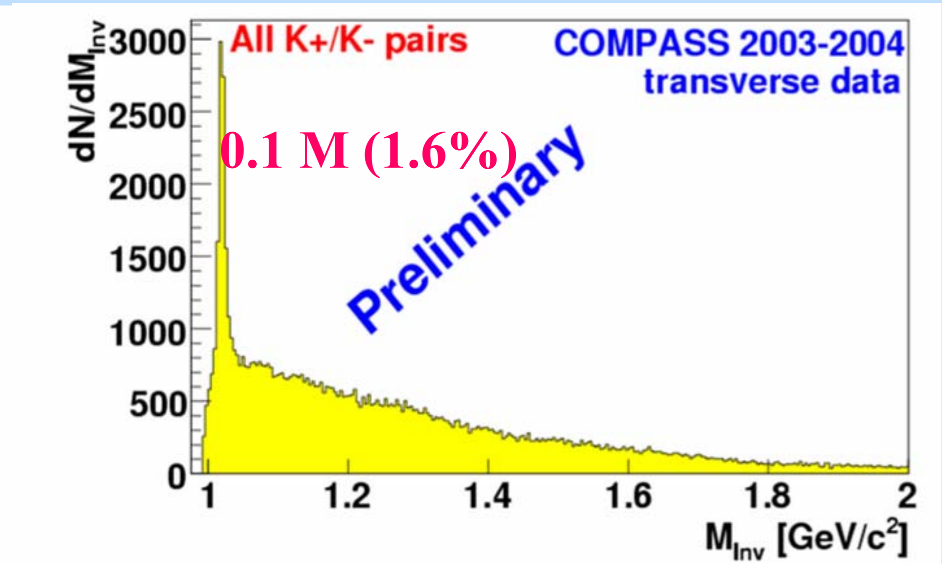


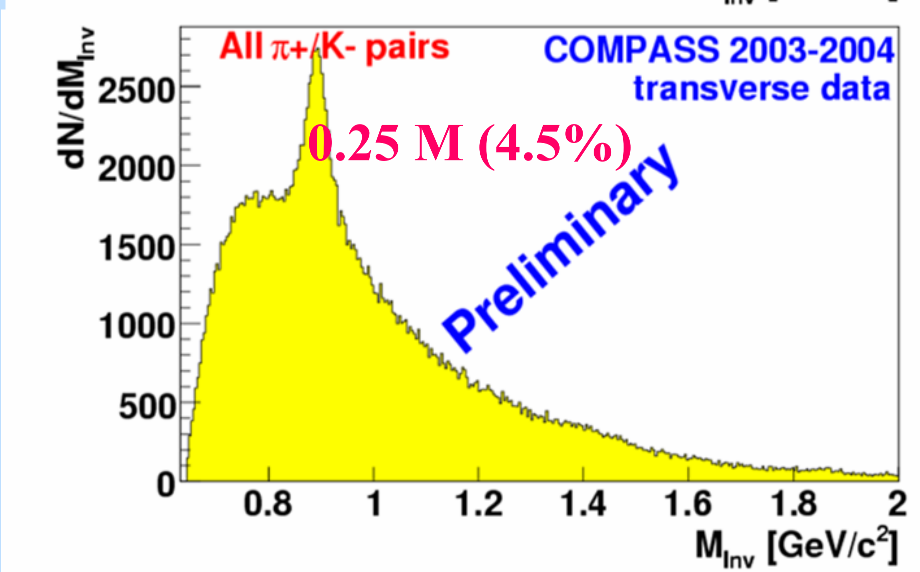


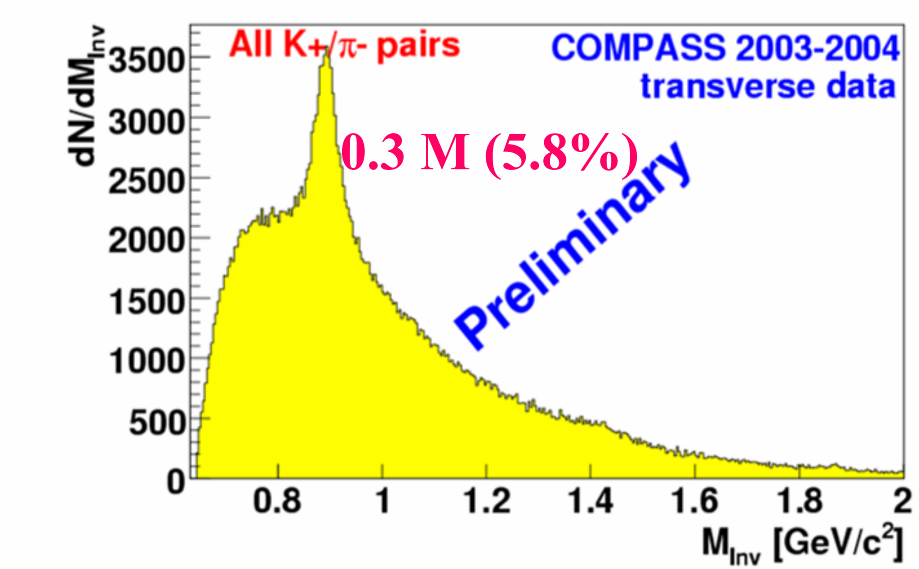
RICH hadron identification

all hadron pairs: 5.3 M







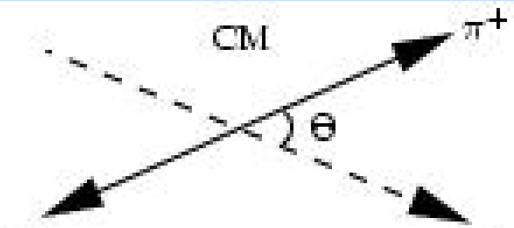


sinθ dependance

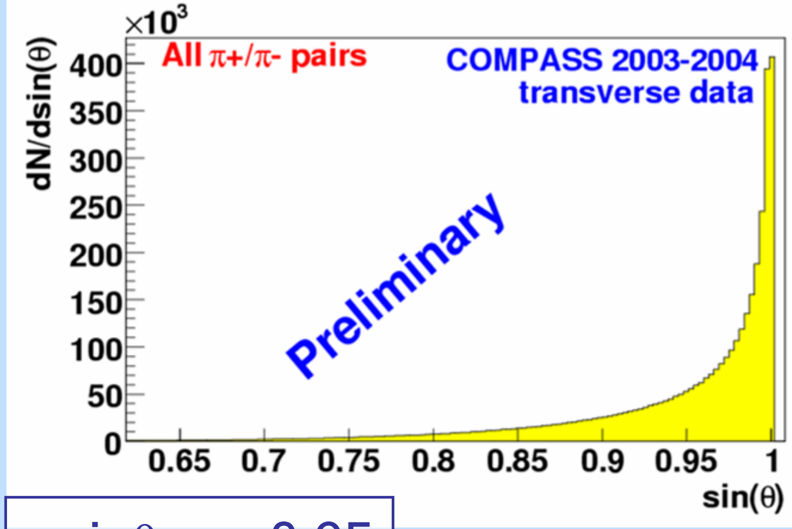
Cross section σ_{UT} for two-π fragmentation depends on sinθ:
(Interference of s- and p-wave of the 2π-state)

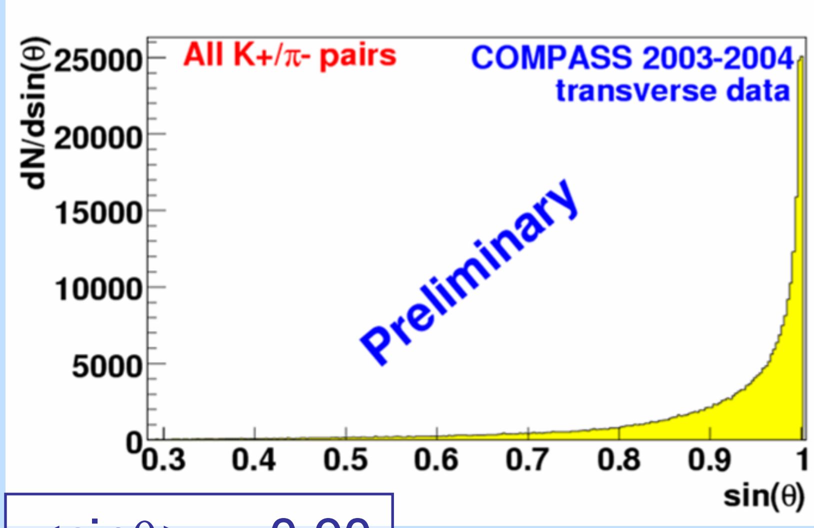
$$\sigma_{UT} \propto \sum_q e_q^2 \left|S_T\right| \sin\theta \sin\phi_{RS} \Delta_T q(x) H_q^{\perp\angle h}(z, M_h^2)$$

(A. Bacchetta and M. Radici, hep-ph/0212300)



θ : Angle of h_1 in the two-hadron CMS to the direction of $P_h = P_{h1} + P_{h2}$





<sinθ> = 0.95

<sinθ> = 0.90

➔ small contribution in the kinematic region of COMPASS

asymmetry extraction

The number-of-events asymmetries

$$A_{UT,\,raw}^{w_i(\phi_h,\phi_s)} = D^{w_i(\phi_h,\phi_s)}(y)\, f\, |S_T|\, A_{UT}^{w(\phi_h,\phi_s)}, \quad (i=1,5),$$
$$A_{LT,\,raw}^{w(\phi_h,\phi_s)} = D^{w(\phi_h,\phi_s)}(y)\, f\, P_{beam}|S_T|\, A_{LT}^{w(\phi_h,\phi_s)}, \quad (i=6,8)$$

Independent angles

$$\Phi_1 = \phi_h - \phi_s$$
$$\Phi_2 = \phi_h + \phi_s$$
$$\Phi_3 = 3\phi_h - \phi_s$$
$$\Phi_4 = \phi_s$$
$$\Phi_5 = 2\phi_h - \phi_s$$

Azimuthal modulations

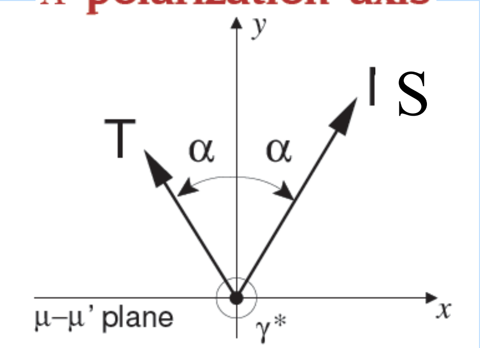
$$W_1(\Phi_1) = A_{raw}^{w1(\phi_h,\phi_s)} \sin(\Phi_1) + A_{raw}^{w6(\phi_h,\phi_s)} \cos(\Phi_1)$$
$$W_2(\Phi_2) = A_{raw}^{w2(\phi_h,\phi_s)} \sin(\Phi_2)$$
$$W_3(\Phi_3) = A_{raw}^{w3(\phi_h,\phi_s)} \sin(\Phi_3)$$
$$W_4(\Phi_4) = A_{raw}^{w4(\phi_h,\phi_s)} \sin(\Phi_4) + A_{raw}^{w7(\phi_h,\phi_s)} \cos(\Phi_4)$$
$$W_5(\Phi_5) = A_{raw}^{w5(\phi_h,\phi_s)} \sin(\Phi_5) + A_{raw}^{w8(\phi_h,\phi_s)} \cos(\Phi_5)$$

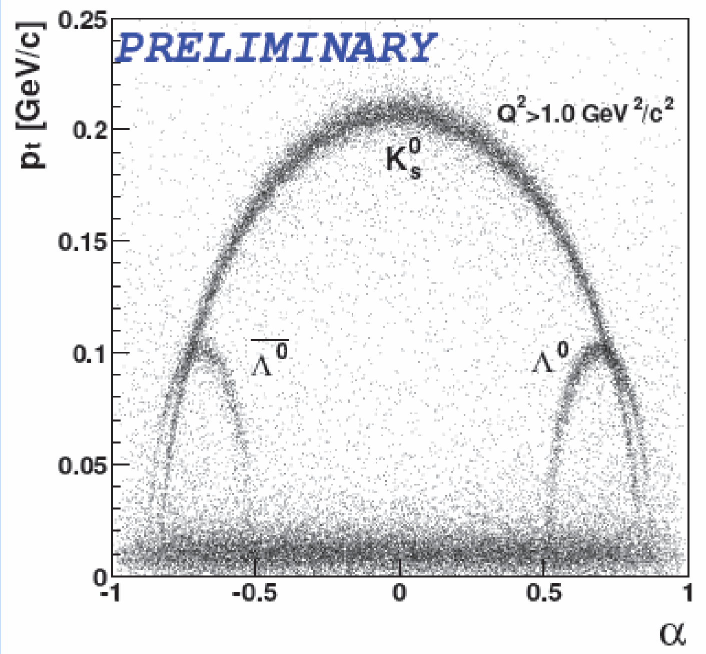
transversity from Λ polarimetry

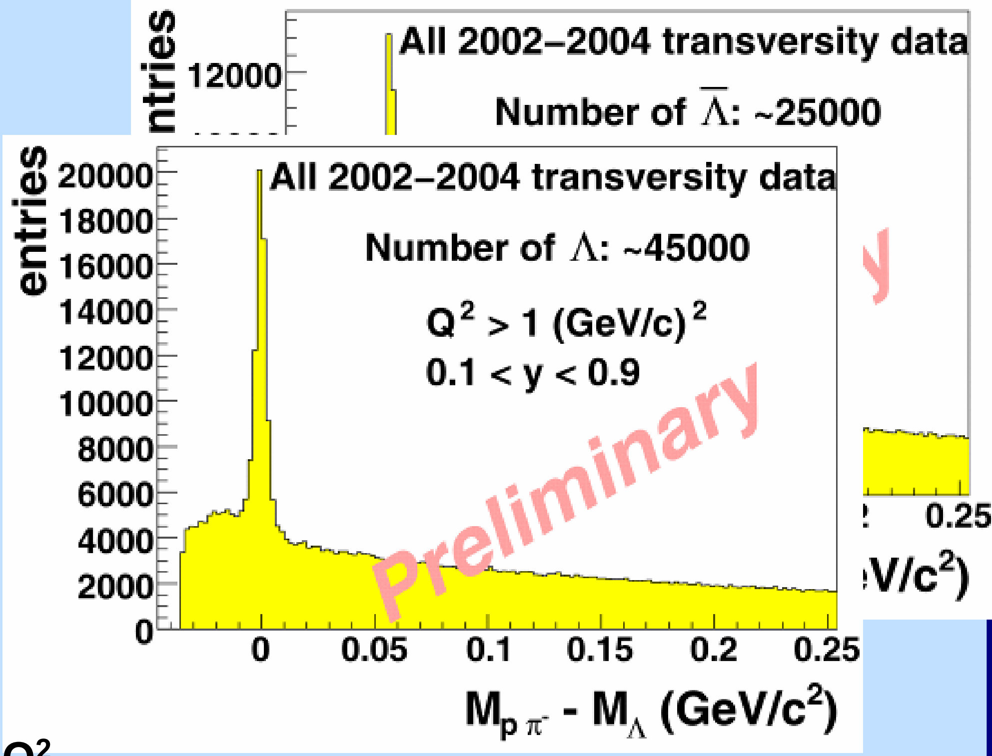
$$P_{T,exp}^{\Lambda} = \frac{d\sigma^{\mu N^{\uparrow}\to\mu'\Lambda^{\uparrow}X} - d\sigma^{\mu N^{\downarrow}\to\mu'\Lambda^{\uparrow}X}}{d\sigma^{\mu N^{\uparrow}\to\mu'\Lambda^{\uparrow}X} + d\sigma^{\mu N^{\downarrow}\to\mu'\Lambda^{\uparrow}X}}$$

$$= f P_N D(y) \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)}$$

Λ polarization axis

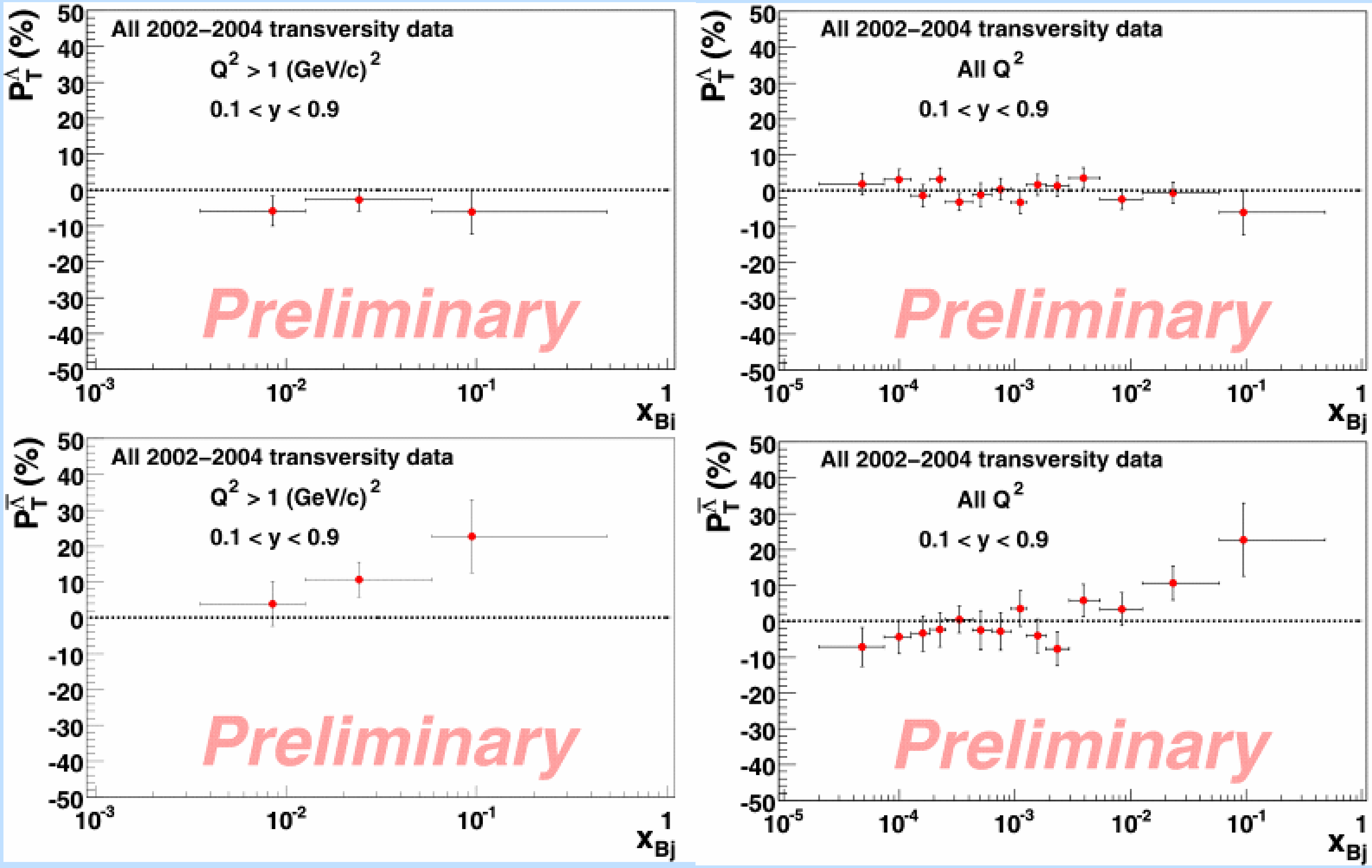






x 10 all Q^2

Λ polarimetry



systematic errors not larger than statistical errors