Measurement of transverse spin effects at COMPASS

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on behalf of the COMPASS Collaboration

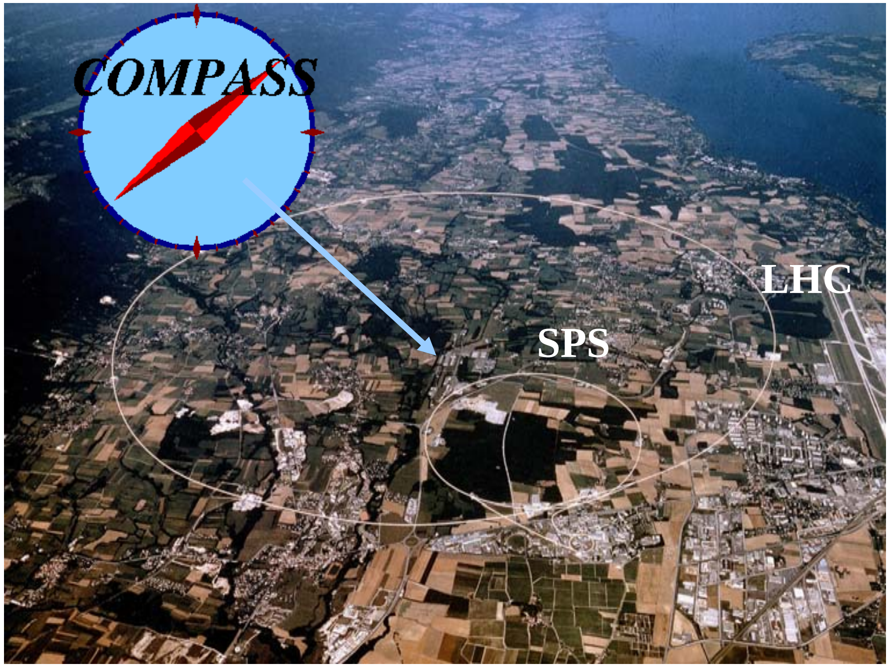
Outline

- the COMPASS experiment
- transverse spin physics
- results on:
  - Collins/Sivers asymmetries for $\pi^{\pm}$, $\mathbf{K^{\pm}}$
  - beyond Collins/Sivers
  - two hadron asymmetries
- conclusions

The COMPASS experiment

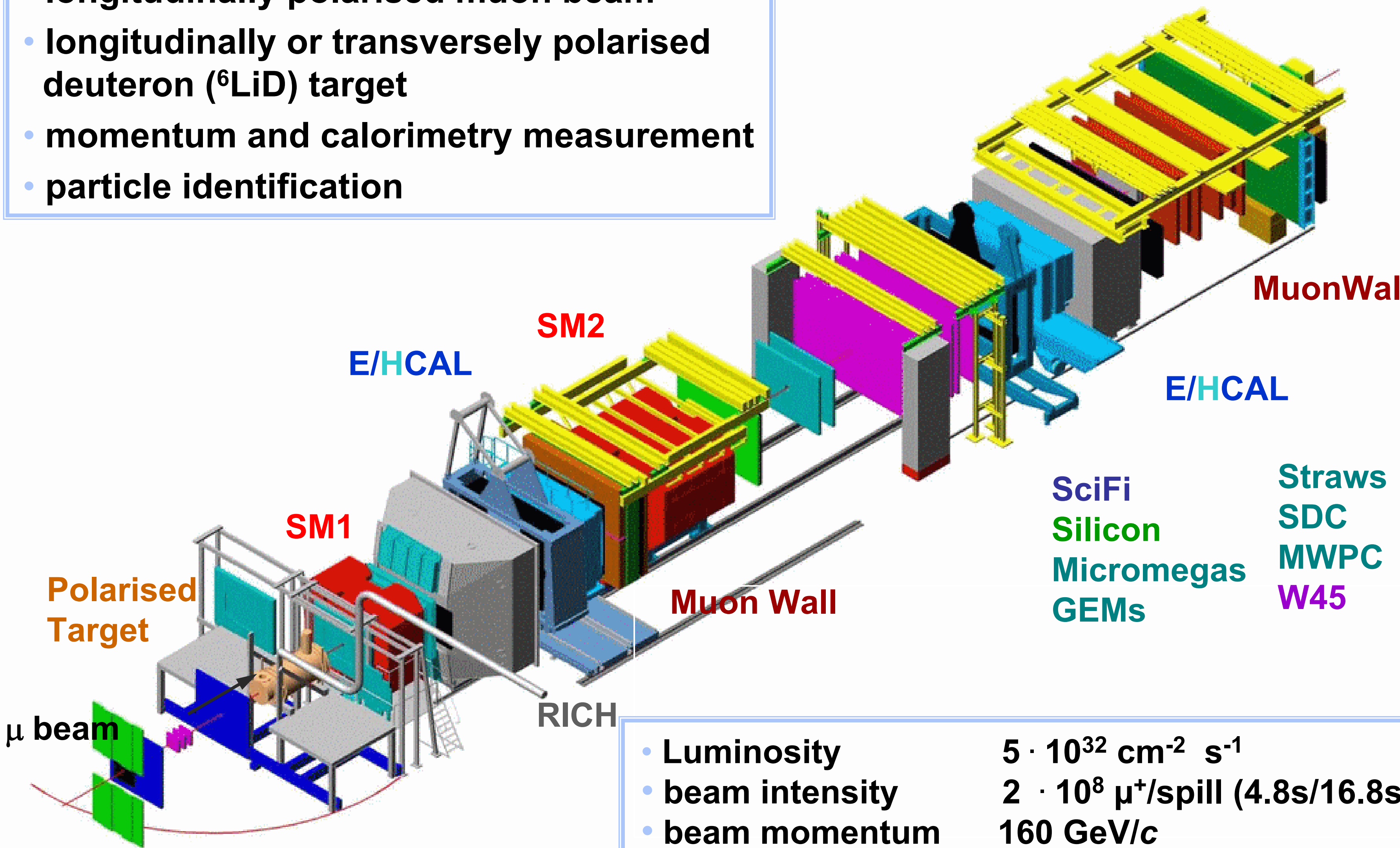
Fixed target experiment at the CERN SPS:
240 physicists from 28 institutes, 11 Countries.

Very broad physics program focused on **nucleon spin structure** and on **hadron spectroscopy.**



COMPASS spectrometer

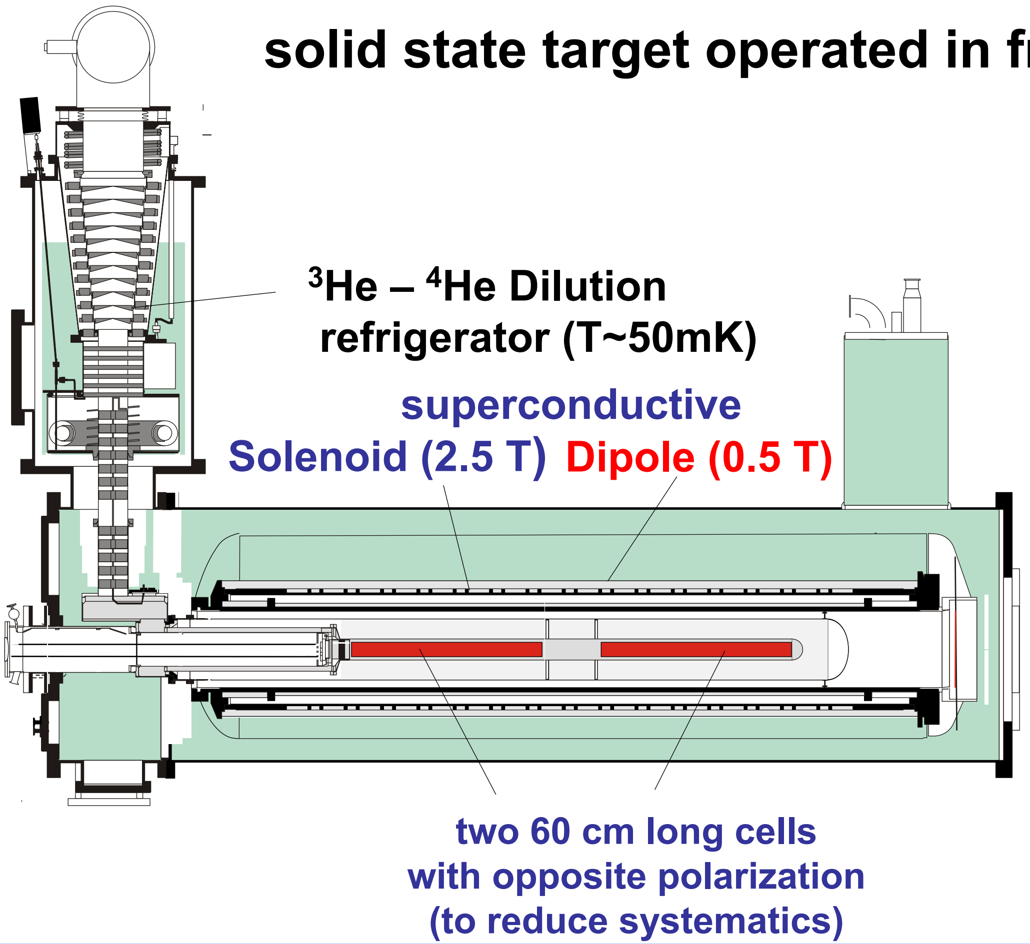
- longitudinally polarised muon beam
- longitudinally or transversely polarised deuteron (^{6}LiD) target
- momentum and calorimetry measurement
- particle identification



- Luminosity $5 \cdot 10^{32}$ cm^{-2} s^{-1}
- beam intensity $2 \cdot 10^8$ μ^+/spill (4.8s/16.8s)
- beam momentum 160 GeV/*c*

The COMPASS polarized target

solid state target operated in frozen spin mode



<u>2002-2004 data taking:</u>

target material: ^{6}LiD

- **polarization ~ 50%**
- **dilution factor ~ 0.38**

Data taking with a transversely polarised proton target (NH_3) is going on.

For transversity:

1) ↑ ↓

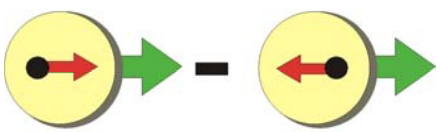
2) ↓ ↑

Reversed once a week
(relaxation time > 2000h)

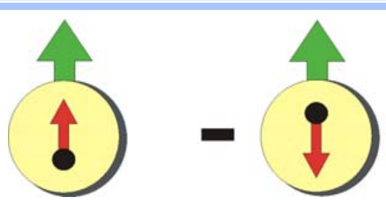
Transverse spin physics

At leading order, the inner structure of the nucleon can be described with three **Parton Distribution Function** (PDF):

$q(x)$ momentum distribution: decribes the probability of finding a quark with a fraction x of the nucleon momentum;



$\Delta q(x)$ helicity distribution : describes the probability, in a longitudinal polarized nucleon (w.r.t. the beam direction), of finding a quark with spin parallel to the nucleon spin;



$\Delta_T q(x)$ transversity distribution : describes the probability, in a transversely polarized nucleon (w.r.t. the beam direction), of finding a quark with spin parallel to the nucleon spin;

Collins asymmetry

The transversity DF is chiral-odd:

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

One way to measure it: SIDIS reactions on a transversely polarised target

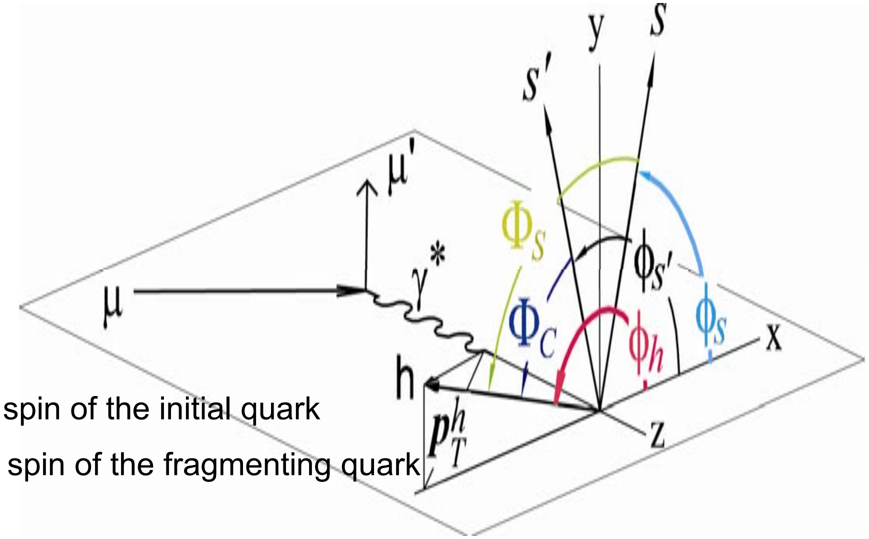
$l\,N^{\uparrow} \rightarrow l'\,h\,X$ Collins Asymmetry (Collins FF)

Collins effect

- In the hadronization process from transversely polarized quarks, the produced hadrons show an azimuthal asymmetry

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

$\Phi_C = \phi_h - \phi_{s'}$ is the "Collins angle"



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)***

Collins asymmetry

The measured Collins asymmetry gives assess to the transversity distribution function convoluted with the Collins fragmentation function:

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

Collins fragmentation function ($\Delta_T^0 D_q^h$)

Different from zero (*Belle 2005*)

Transversity distribution function ($\Delta_T q$)

$\sum_q$: sum on quarks

D_q^h: fragmentation function

q : unpolarized PDF

F dilution factor

P_T target polarization

D_{nn} depolarization factor

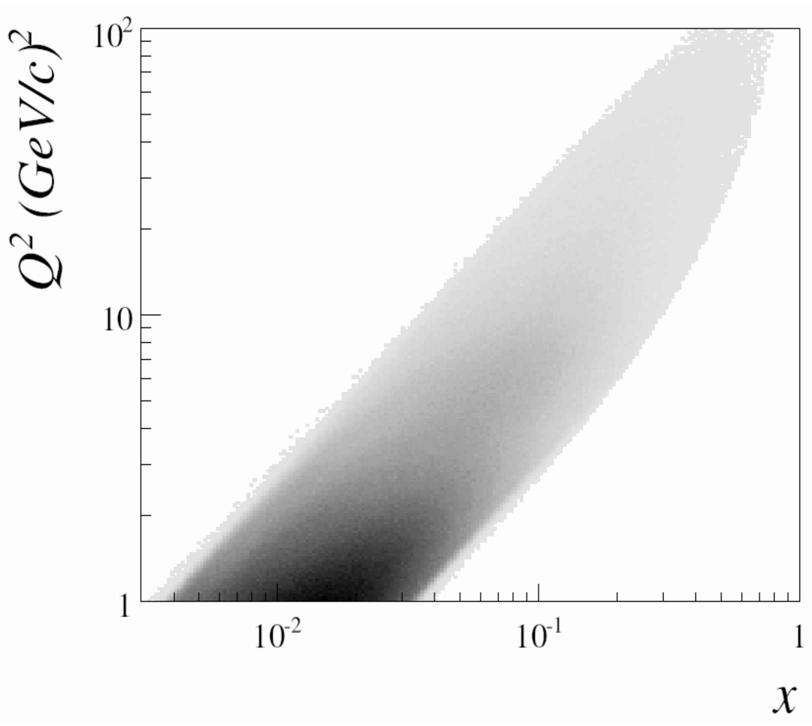
selection of SIDIS events

DIS cuts:

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

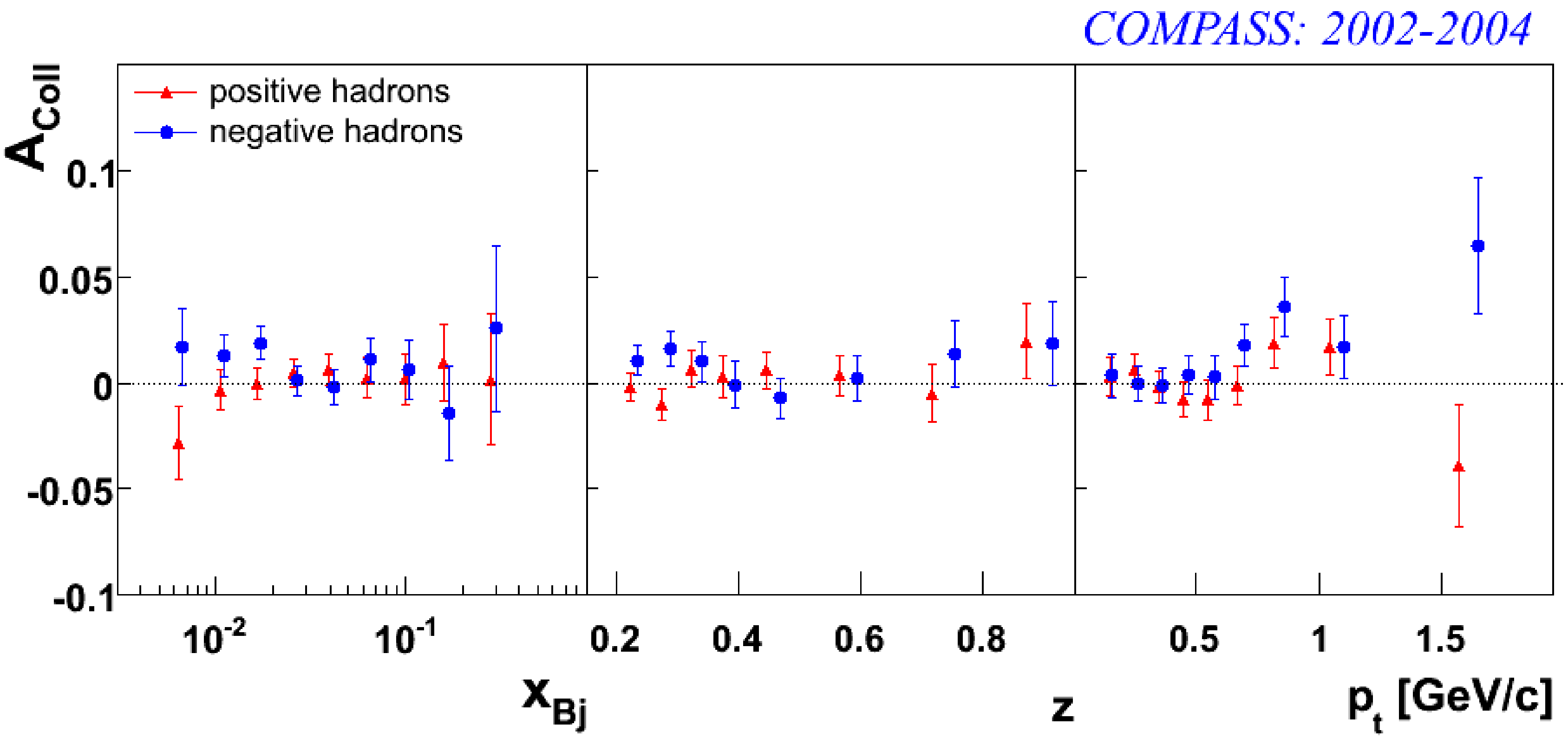
hadron selection:

- $z > 0.2$
- $p_t > 0.1$GeV/c



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

Collins asymmetries 2002-2004 data



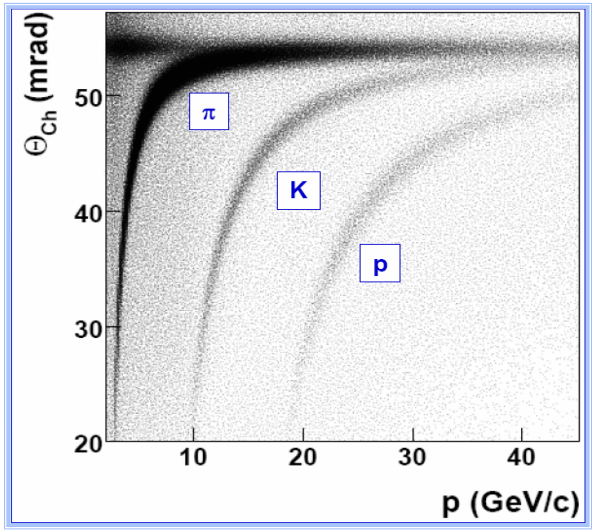
- only statistical errors shown (systematic errors considerably smaller)
- Small asymmetries

(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.

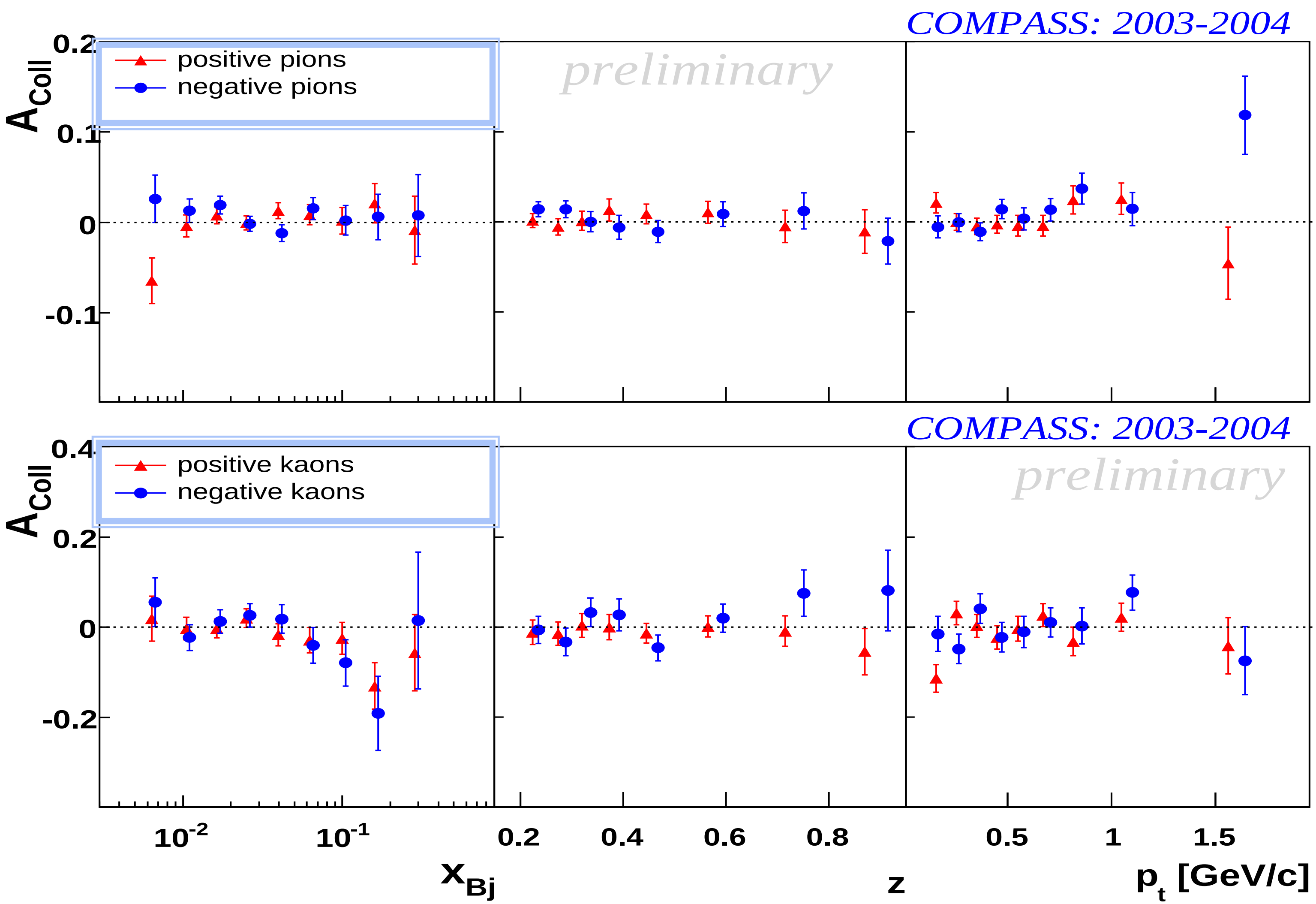
Cherenkov thresholds: π ~ 3 GeV/c
K ~ 9 GeV/c
p ~ 17 GeV/c



2 σ π /K separation at 43 GeV/c

Statistics 2003-2004:	positive	negative
π	5.2M	4.5M
K	0.9M	0.6M

Collins asymmetries 2003-2004 data



- only statistical errors shown (systematic errors considerably smaller)
- Small asymmetries

Interpretation

- **naïve interpretation of the data (parton model, valence region)**

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

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

Small asymmetries→cancellation between $\Delta_T u(x)$ and $\Delta_T d(x)$

expected even if $\Delta_T^0 D_2 \approx -\Delta_T^0 D_1$

(suggested by data on proton target – HERMES experiment)

- Phenomenological works by different groups on the interpretation of the data by COMPASS, HERMES and BELLE experiments:
  - Vogelsang – Yuan ***(Phys.Rev.D72:054028,2005; hep-ph/0507266)***
  - Efremov, Goeke and Schweitzer ***(Phys.Rev.D73:094025,2006; hep-ph/0603054)***
  - Anselmino et al ***(Phys.Rev.D75:054032,2007; hep-ph/0701006)***

Sivers effect

The intrinsic transverse momentum of unpolarized quarks in a transversely polarized nucleon can introduce a different azimuthal asymmetry, not connected with the transversity distribution.

The number of produced hadrons depend on the "Sivers angle":

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

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

Independent from Collins angle;
possible to measure both effects in the same data

The Sivers asymmetry:

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

Sivers function

$\sum_q$: sum on quarks

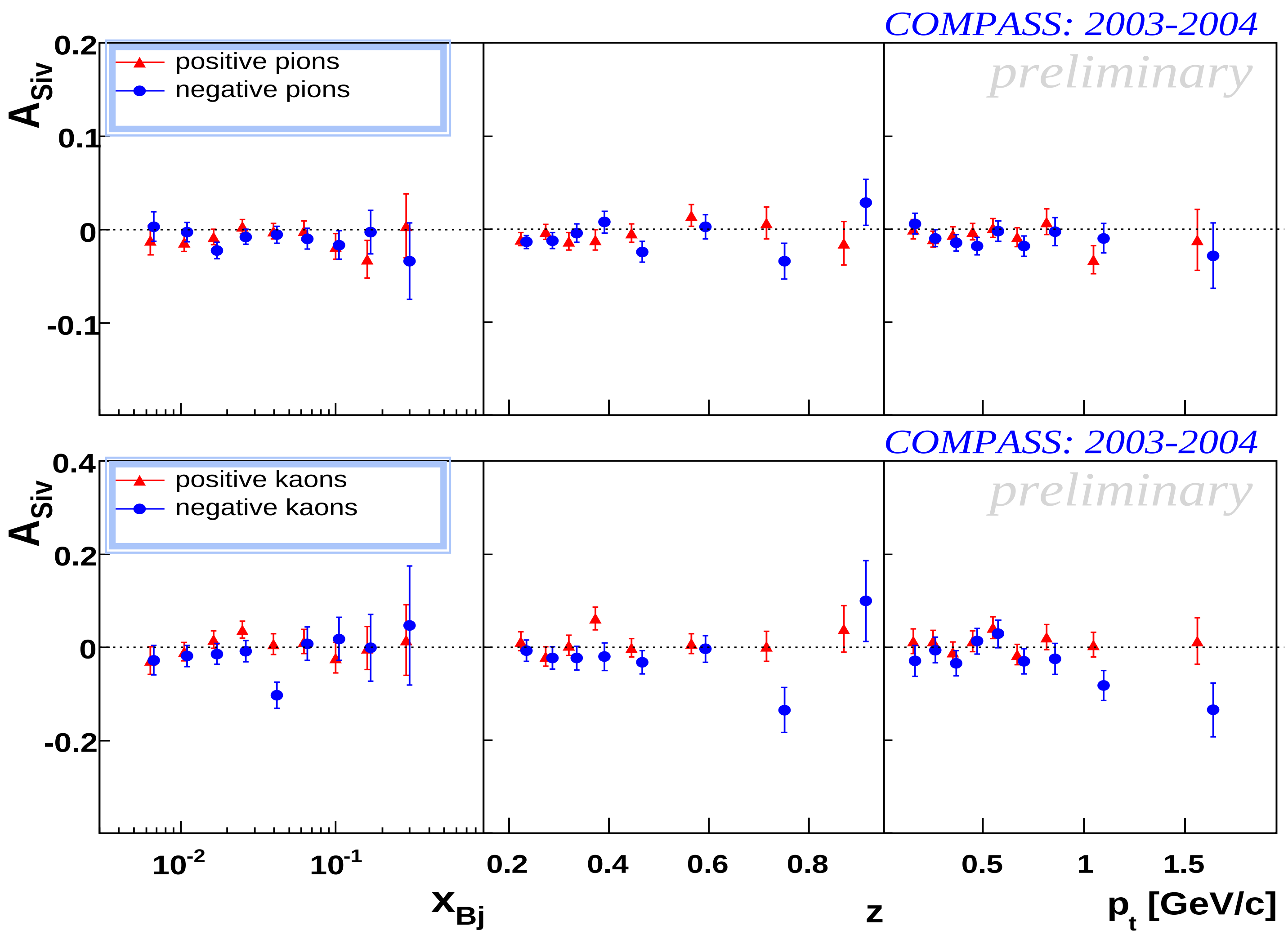
D_q^h : fragmentation function

q : unpolarized PDF

F dilution factor

P_T target polarization

Sivers asymmetries 2003-2004 data



- **only statistical errors shown (systematic errors considerably smaller)**
- **Small asymmetries**

Interpretation

- naïve interpretation of COMPASS data (parton model, valence region)

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

Small asymmetries suggest $\Delta_0^T d_v \simeq -\Delta_0^T u_v$

- Data on proton target (HERMES experiment) different from zero:
  phenomenological works by different groups describing COMPASS and HERMES data are summarized in **hep-ph/0511017**
  *"**Comparing extractions of Sivers functions**" by Anselmino et al.*

- **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.

Beyond Collins and Sivers mechanism

In the complete SIDIS cross section more terms are present:

18 structure functions, 8 transverse target dependent spin asymmetries with different azimuthal dependences:

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

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\cdots\cdots$$

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

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

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

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$

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

$f_{1T}^{\perp q}\otimes D_{1q}^h$ **Sivers**

$h_1^q\otimes H_{1q}^{\perp h}$ **Collins**

Beyond Collins and Sivers mechanism

$$F_{LT}^{\cos(\phi_h-\phi_s)} \propto g_{1T}^q \otimes D_{1q}^h$$

$$F_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

Two twist-2 asymmetries can be interpreted in QCD parton model and will allow to extract unexplored DFs

$$F_{LT}^{\cos(\phi_s)} \propto \frac{M}{Q} g_{1T}^q \otimes D_{1q}^h$$

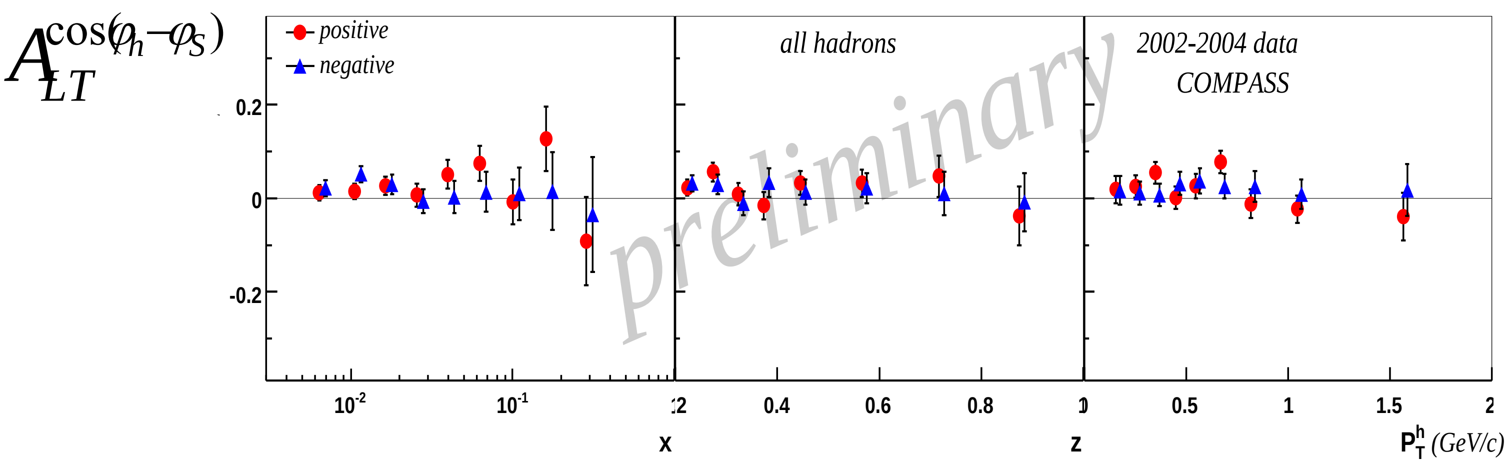
$$F_{LT}^{\cos(2\phi_h-\phi_s)} \propto \frac{M}{Q} g_{1T}^q \otimes D_{1q}^h$$

$$F_{UT}^{\sin(\phi_s)} \propto \frac{M}{Q} \left(h_1^q \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h \right)$$

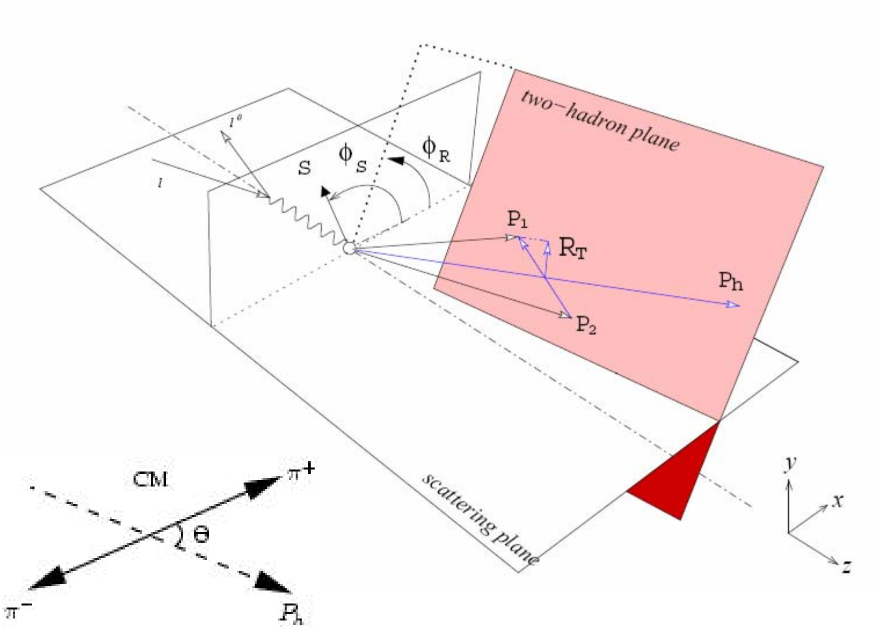
$$F_{UT}^{\sin(2\phi_h-\phi_s)} \propto \frac{M}{Q} \left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h \right)$$

Remaining four can be interpreted as twist-3 contributions

All asymmetries measured for the first time, found compatible with zero:
again cancellation between proton and neutron?



Two Hadrons Asymmetries



in inclusive production of hadron pairs, one can define the angle $\phi_{R\perp}$ and measure an azimuthal asymmetry from the modulation of the number of events in $\phi_{RS} = \phi_{R\perp} - \phi_S$,

$$N^{\pm}(\Phi_{RS}) = N^0 \cdot \{1 \pm A \cdot \sin\Phi_{RS}\}$$

Transversity distribution function

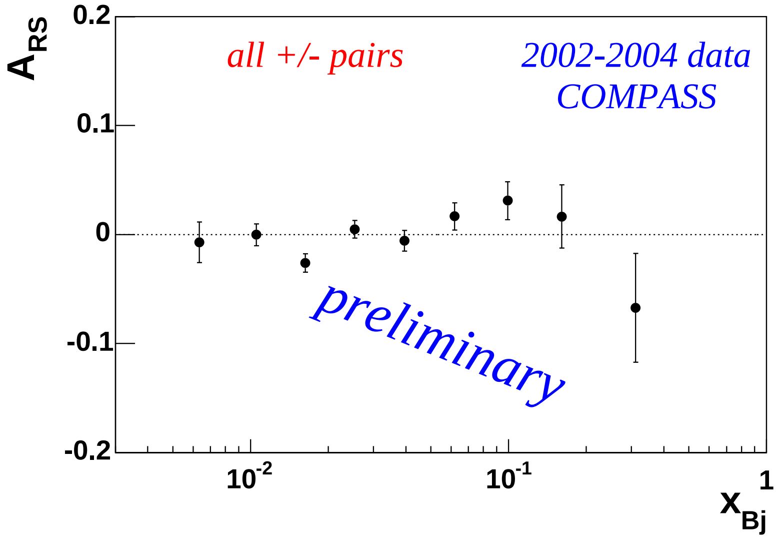
$$A_{RS} = \frac{1}{f \cdot P_T \cdot D} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{\angle}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, M_h^2)}$$

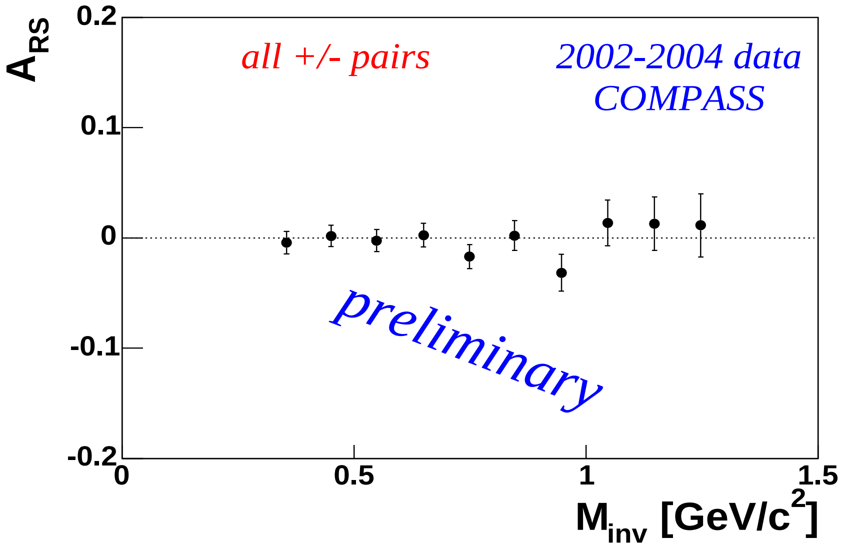
Interference fragmentation function presently unknown, being measured at BELLE

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

Two Hadrons Asymmetries

Selection of all combinations of positive and negative hadrons in DIS events





- **only statistical errors shown (systematic errors considerably smaller)**
- **small asymmetries**
- **also studies on z-ordered pairs were done**

In agreement with predictions for a deuterium target (M. Radici, QCDN 06, hep-ph/0608037)

RICH identification: different combination of hadrons $\pi\pi$, KK, πK, Kπ .

Conclusions

- In all the channels investigated up to now:
  - Collins/Sivers asymmetries on positive and negative h, $\pi^\pm$, $K^\pm$
  - beyond Collins and Sivers mechanism: other “new” 6 observables
  - two hadron asymmetries (identified h, z-ordered)
  - transverse Λ polarization (not described in this talk)

  the **measured asymmetries on a ^{6}LiD polarized target are very small and compatible with zero** within the statistical errors;
  (systematic errors considerably smaller)

- Collins and Sivers effects:
  a lot of theoretical work aimed at a first extraction of the transversity and Sivers parton distribution function is ongoing by different groups:
  a consistent picture of all present data is being worked out

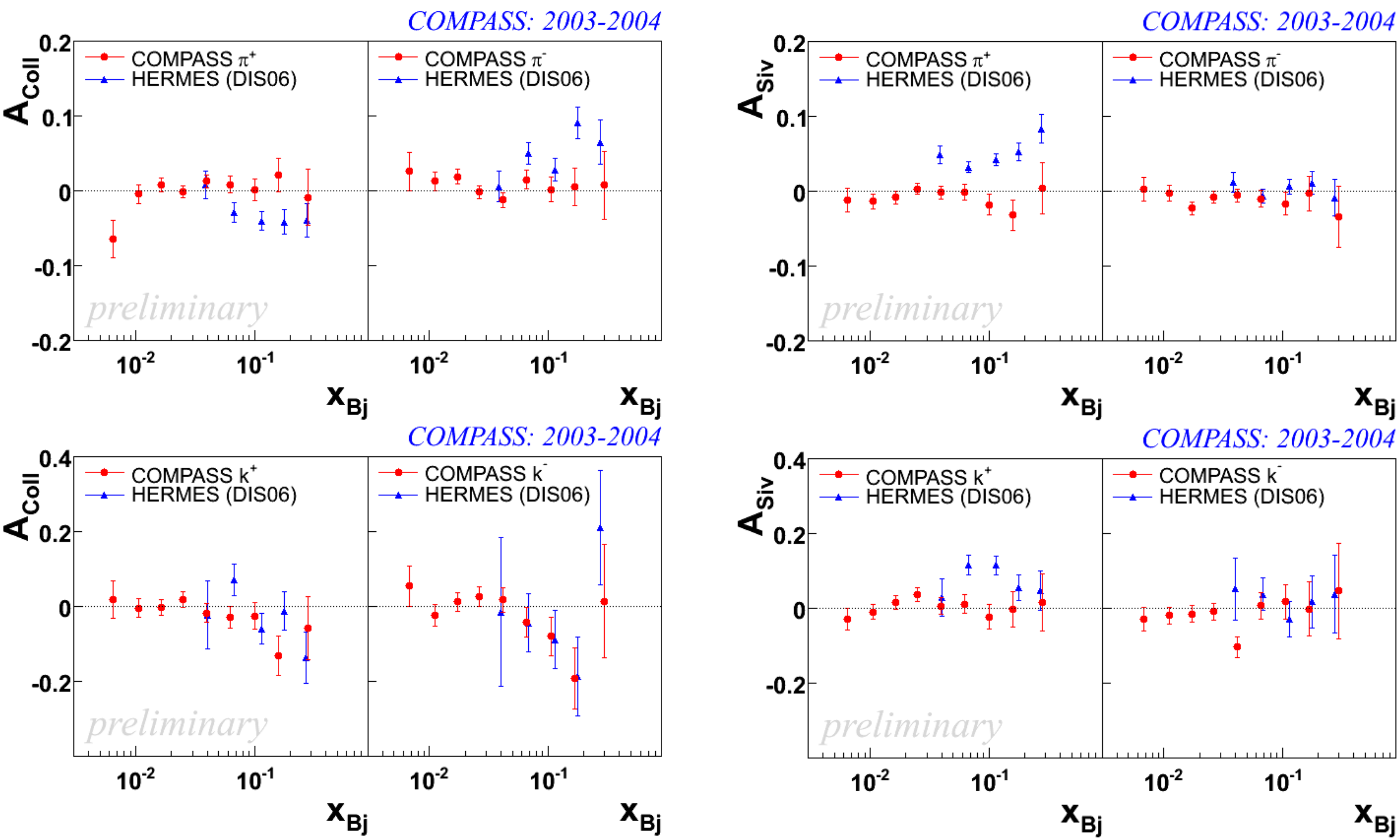
<u>Outlook:</u>
Analysis continuing on collected deuterium data

- K^0 asymmetries
- Exclusive ρ production on transversely polarised target

Data of comparable statistics are being collected on a transversely polarized proton target (NH_3)

Just in case...

comparison with HERMES



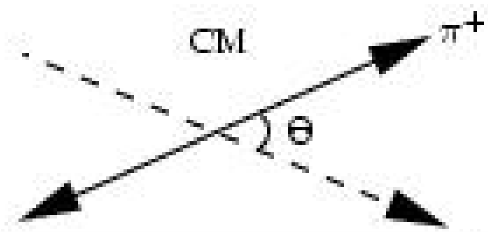
HERMES data from `Transversity results from HERMES', L.Pappalardo et al., to appear in the proceedings of the XIV International Workshop on Deep Inelastic Scattering, Tsukuba city, Japan, April 20-24, 2006., courtesy of the HERMES Collaboration

sinθ dependance

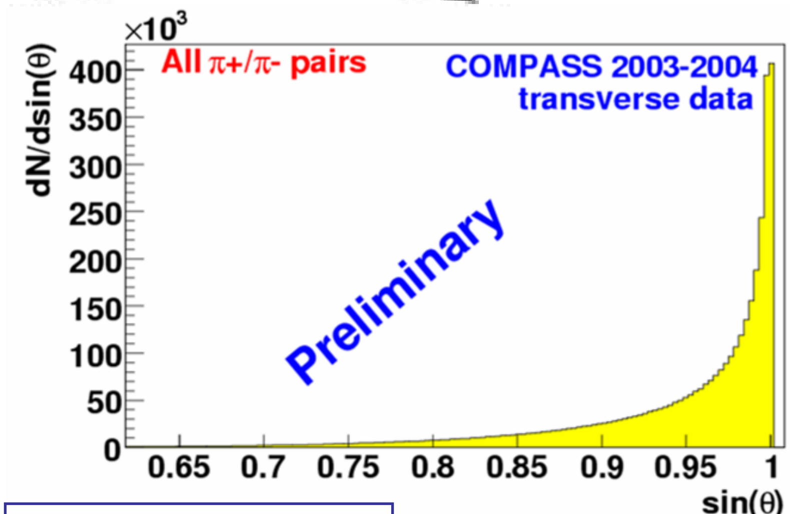
Cross section σ_{UT} for two-π fragmentation depends on sinθ:
(Interference of s- and p-wave of the 2π-state)

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

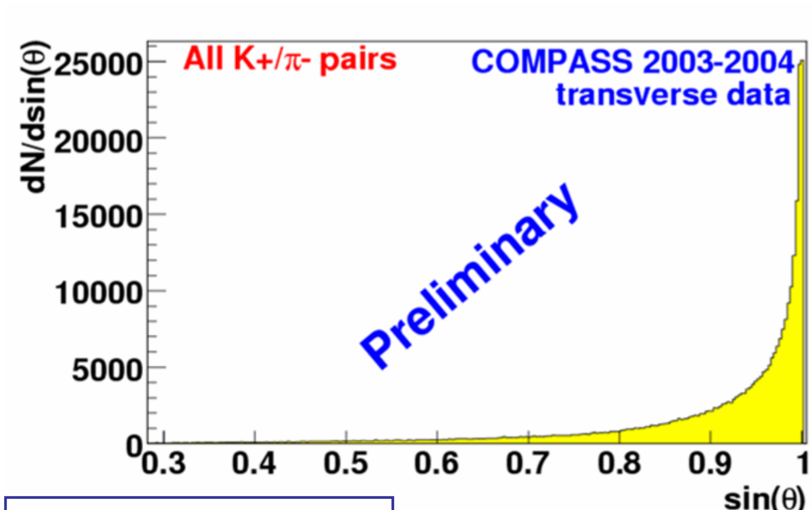
(A. Bacchetta and M. Radici, hep-ph/0212300)



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



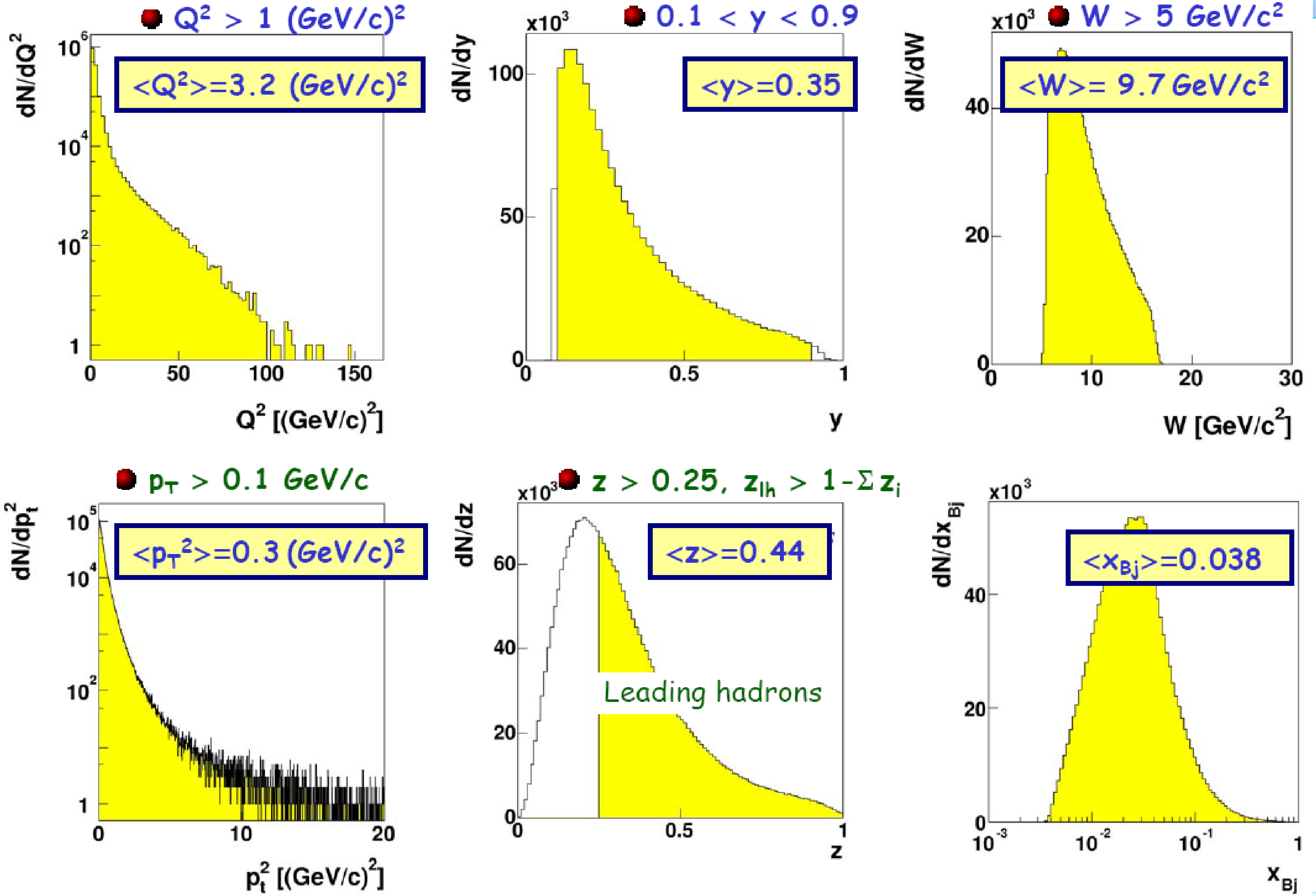
$\langle\sin\theta\rangle = 0.95$



$\langle\sin\theta\rangle = 0.90$

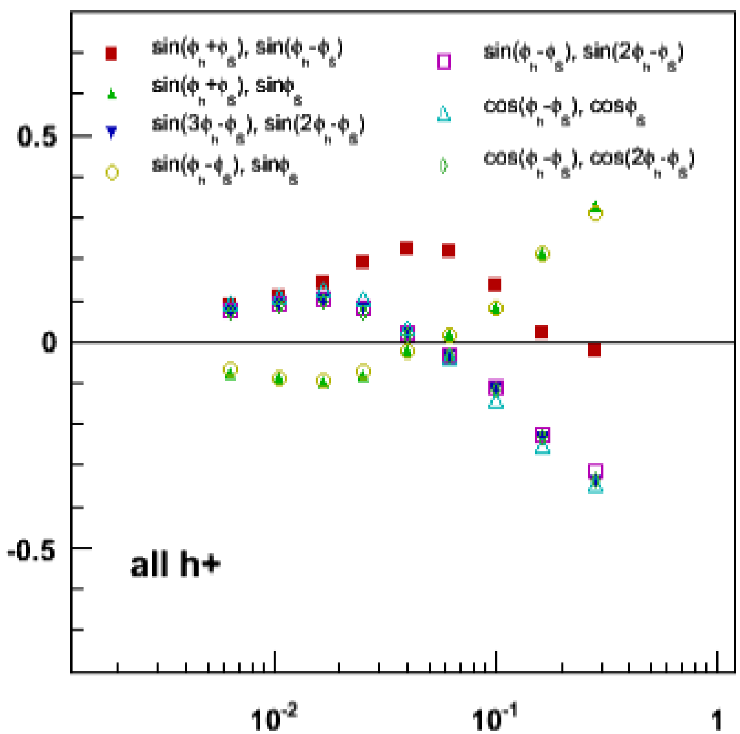
➔ small contribution in the kinematic region of COMPASS

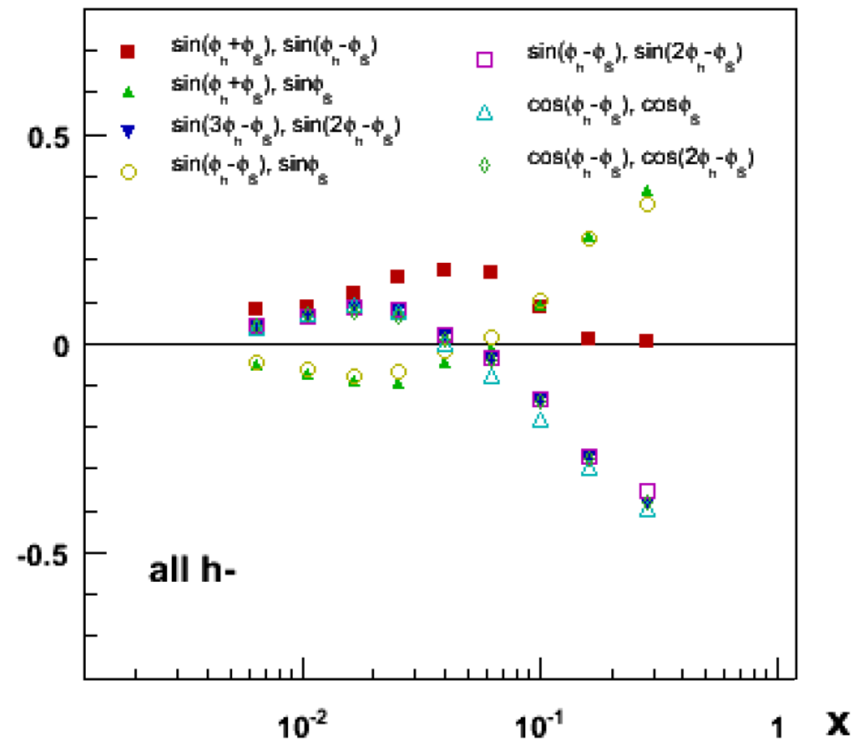
Event selection

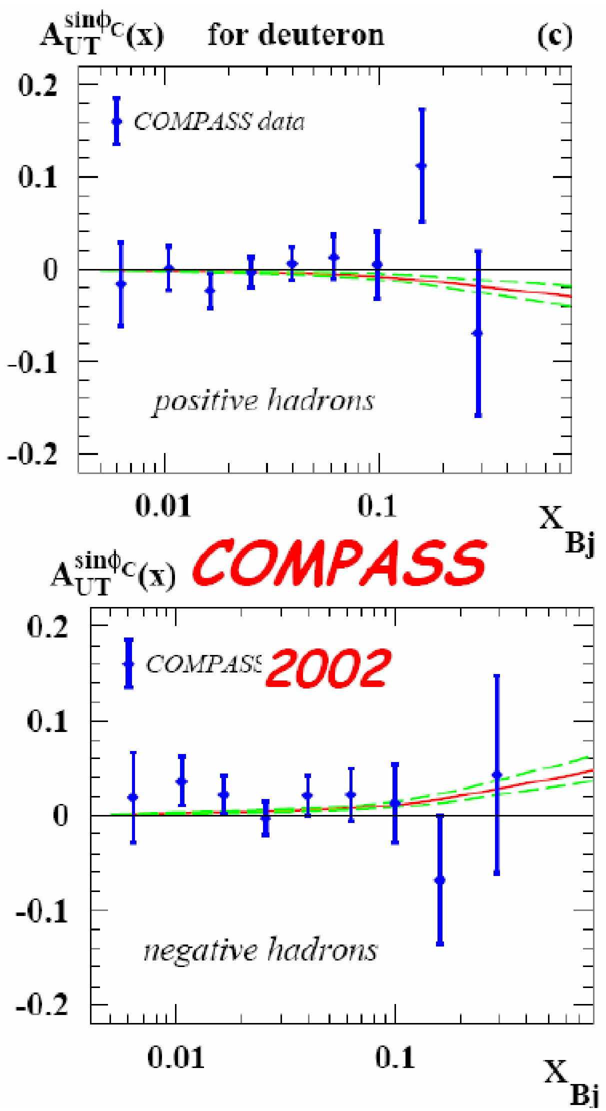


2D fit

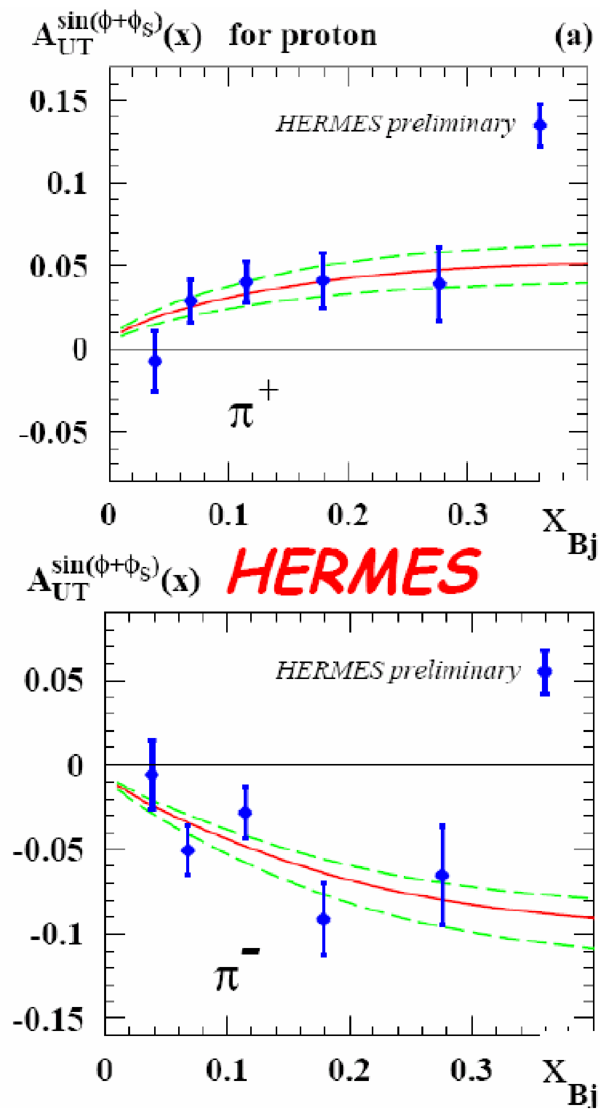
correlations by different modulations are small



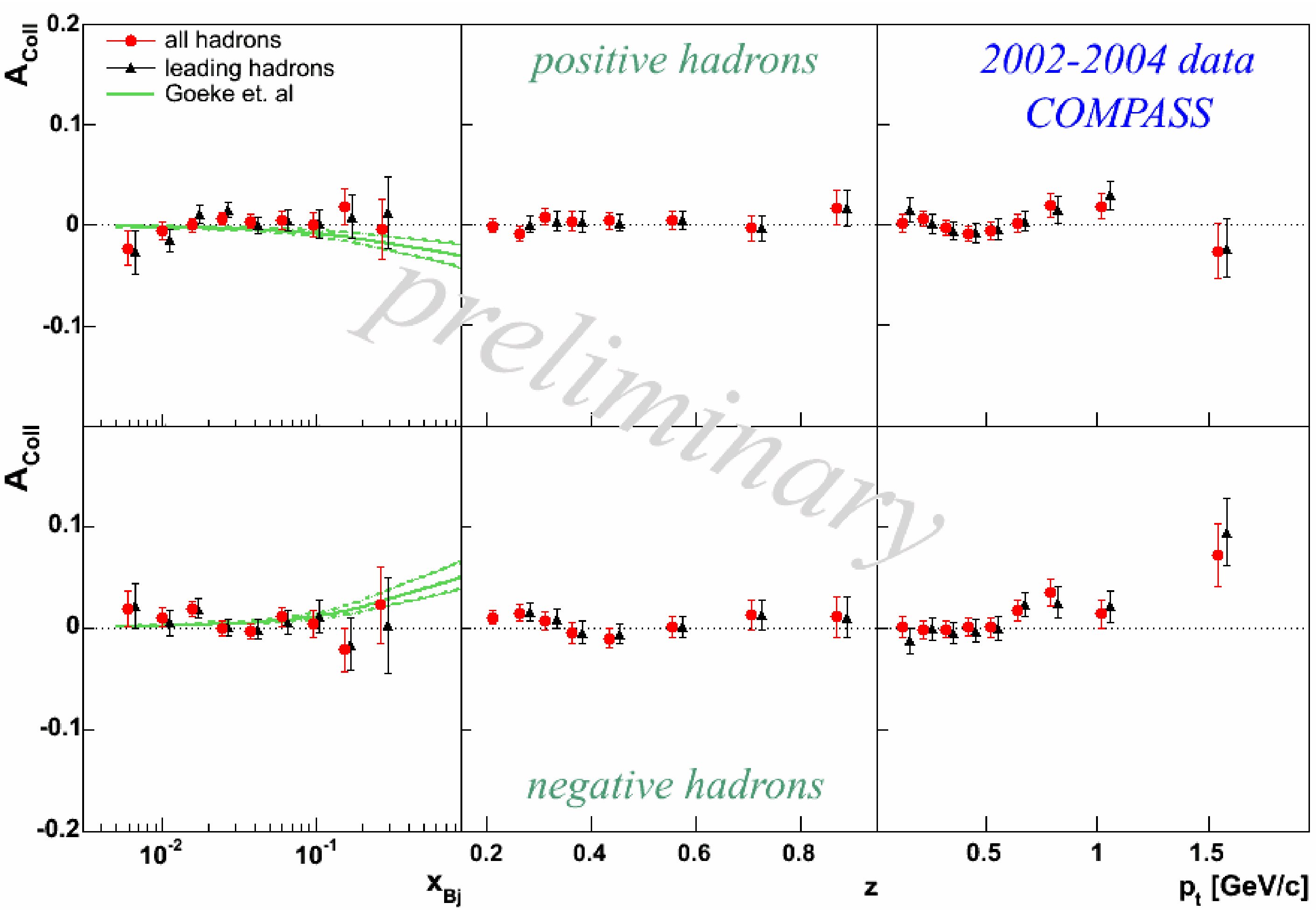




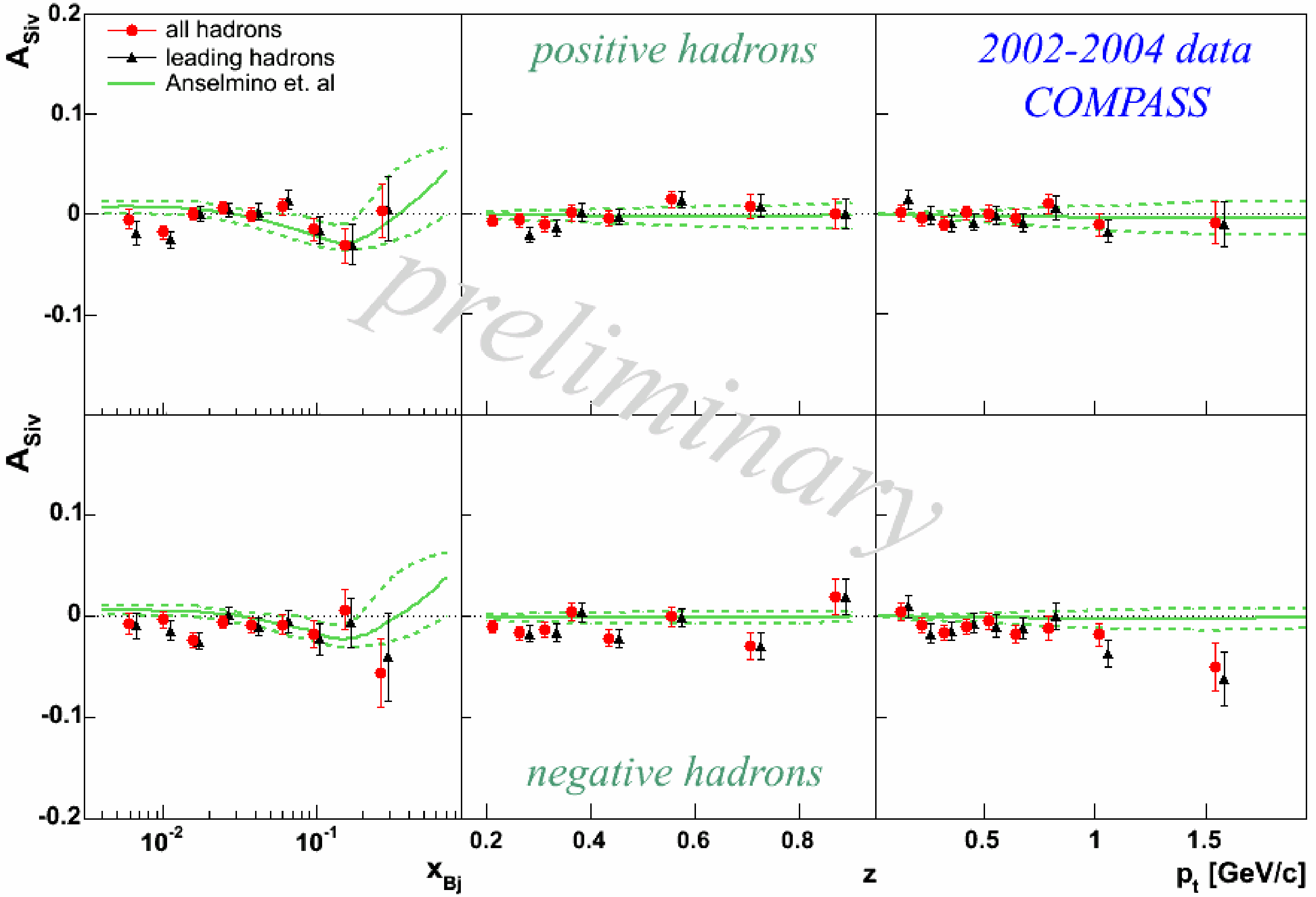
Collins



A. V. Efremov, K. Goeke and P. Schweitzer
Collins on Proton and Deuterium
(hep-ph/0603054)



A. V. Efremov, K. Goeke and P. Schweitzer, Collins on Proton and Deuterium (hep-ph/0603054)



M. Anselmino et al.

Sivers on Deuterium (hep-ph/0507181)

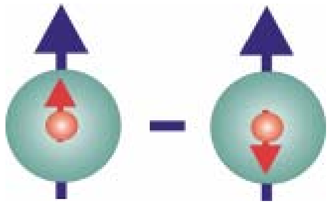
transversity DF

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

$h_1^q(x)$,

$\delta q(x)$,

$\delta_T q(x)$

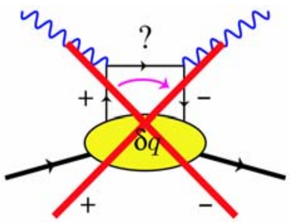


$q = u_v, d_v, q_{sea}$

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

$h_1(x)$ decouples from leading twist DIS because helicity of quark must flip

NO MIXTURE WITH GLUON

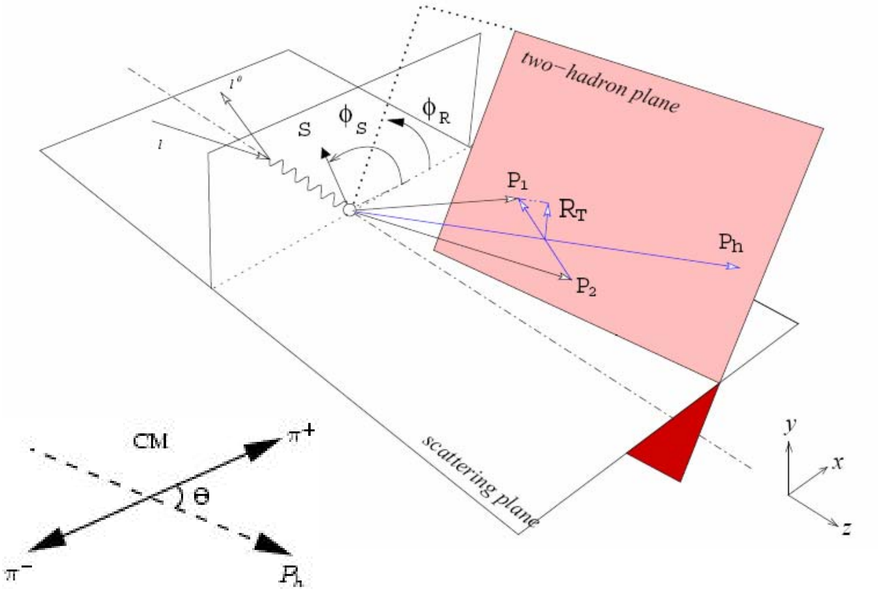


Properties:

- 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

Two Hadrons Asymmetries

looking at two hadron production, a different asymmetry can be measured



$$\vec{P}_h = \vec{P}_1 + \vec{P}_2$$

$$\vec{R}_T = \frac{z_2\vec{P}_{1T} - z_1\vec{P}_{2T}}{z_1 + z_2}$$

$$\Phi_{RS} = \phi_R - \phi_{s'}$$

ϕ_R azimuthal angle of $\vec{R}_T$

$\phi_{s'} = \pi - \phi_s$ azimuthal angle of the spin of the fragmenting quark

$$N^{\pm}(\Phi_{RS}) = N^0 \cdot \{1 \pm A \cdot \sin\Phi_{RS}\}$$

Transversity distribution function

$$A_{RS} = \frac{1}{f \cdot P_T \cdot D} \cdot A = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_q^{\angle}(z, M_h^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, M_h^2)}$$

Interference fragmentation function presently unknown, being measured at BELLE

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Transverse Λ Polarization