Review of SSA results on deuteron at COMPASS

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bmb+f - Förderschwerpunkt
COMPASS
Großgeräte der physikalischen Grundlagenforschung

Transversity 08, Ferrara, Italia

Transverse Spin Physics

Three distribution functions are necessary to describe the spin structure of the nucleon in LO:

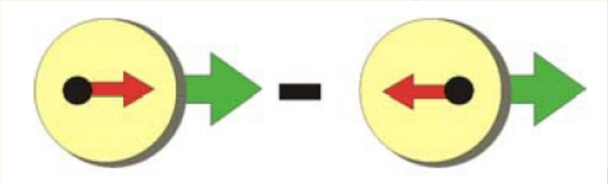
$q(x)$ (= $f_1(x)$) momentum distribution

describes the probability of finding a quark with a fraction x of the nucleon momentum,

well known

$\Delta q(x)$ (= $g_1(x)$) helicity distribution

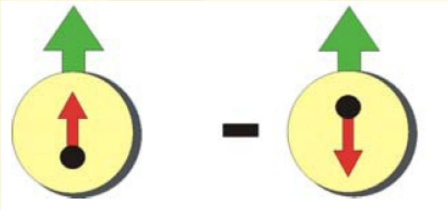
describes the probability in a longitudinally polarized nucleon (w.r.t. the direction of motion) of finding a quark with spin parallel to the nucleon spin,



known

$\Delta_T q(x)$ (= $h_1(x)$) transversity distribution

describes the probability in a transversely polarized nucleon (w.r.t. the direction of motion) of finding a quark with spin parallel to the nucleon spin.



Largely unknown

Transverse Spin Physics in SIDIS

For measuring Transversity:
quark spin must flip
→ $\Delta_T q(x)$ decouples from inclusive DIS

product of $\Delta_T q(x)$ and another chiral-odd function needed
→ $\Delta_T q(x)$ can be measured by SIDIS on a transversely polarized target.

Channels measured by COMPASS:

$l\,N \rightarrow l'\,h\,X$ Collins asymmetry,
Sivers asymmetry (measured, but no channel f. $\Delta_T q(x)$)

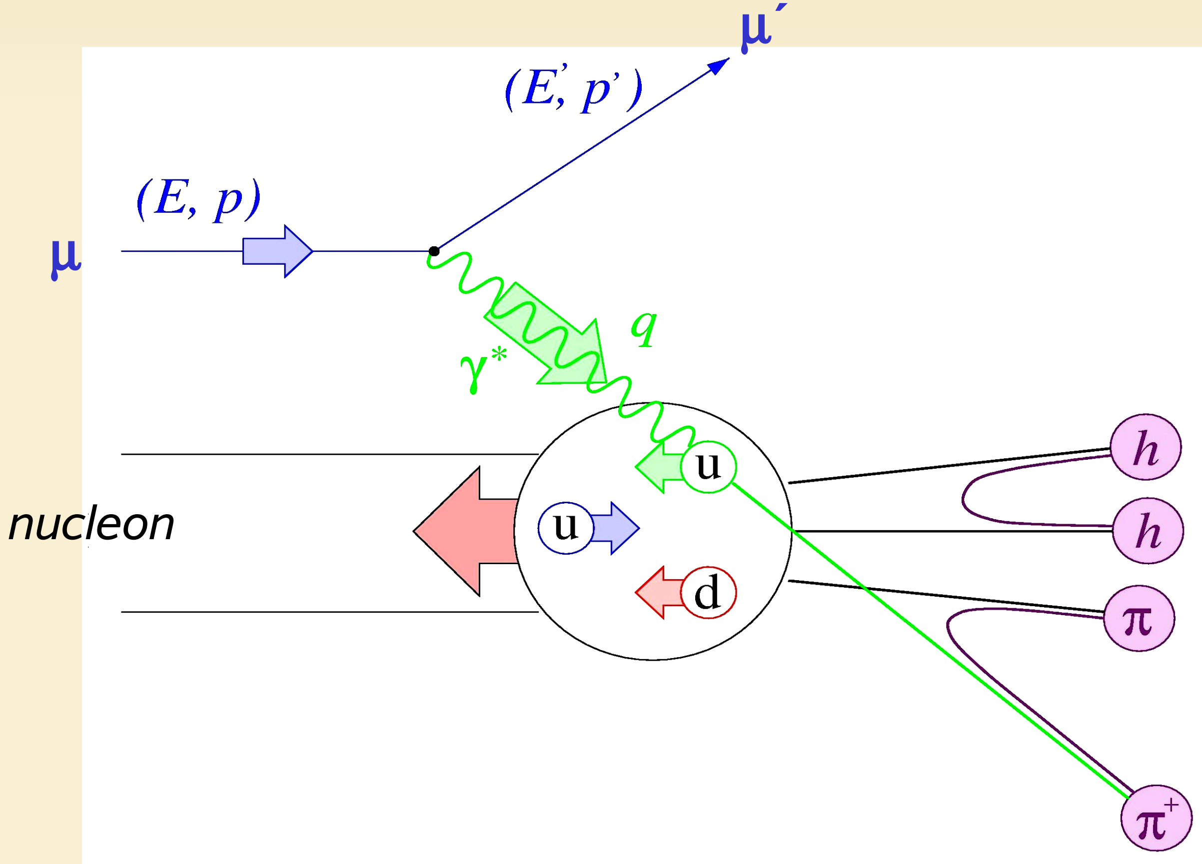
$l\,N \rightarrow l'\,h\,h\,X$ hadron pair asymmetry

$l\,N \rightarrow l'\,\Lambda\,X$ Λ polarisation (→ See talk by Teresa Negrini)

Transverse Spin Physics in SIDIS

<u>Two steps:</u>

- Scattering of the lepton on the quark **(distribution function)**
- Production of hadrons from the struck quark **(fragmentation function)**

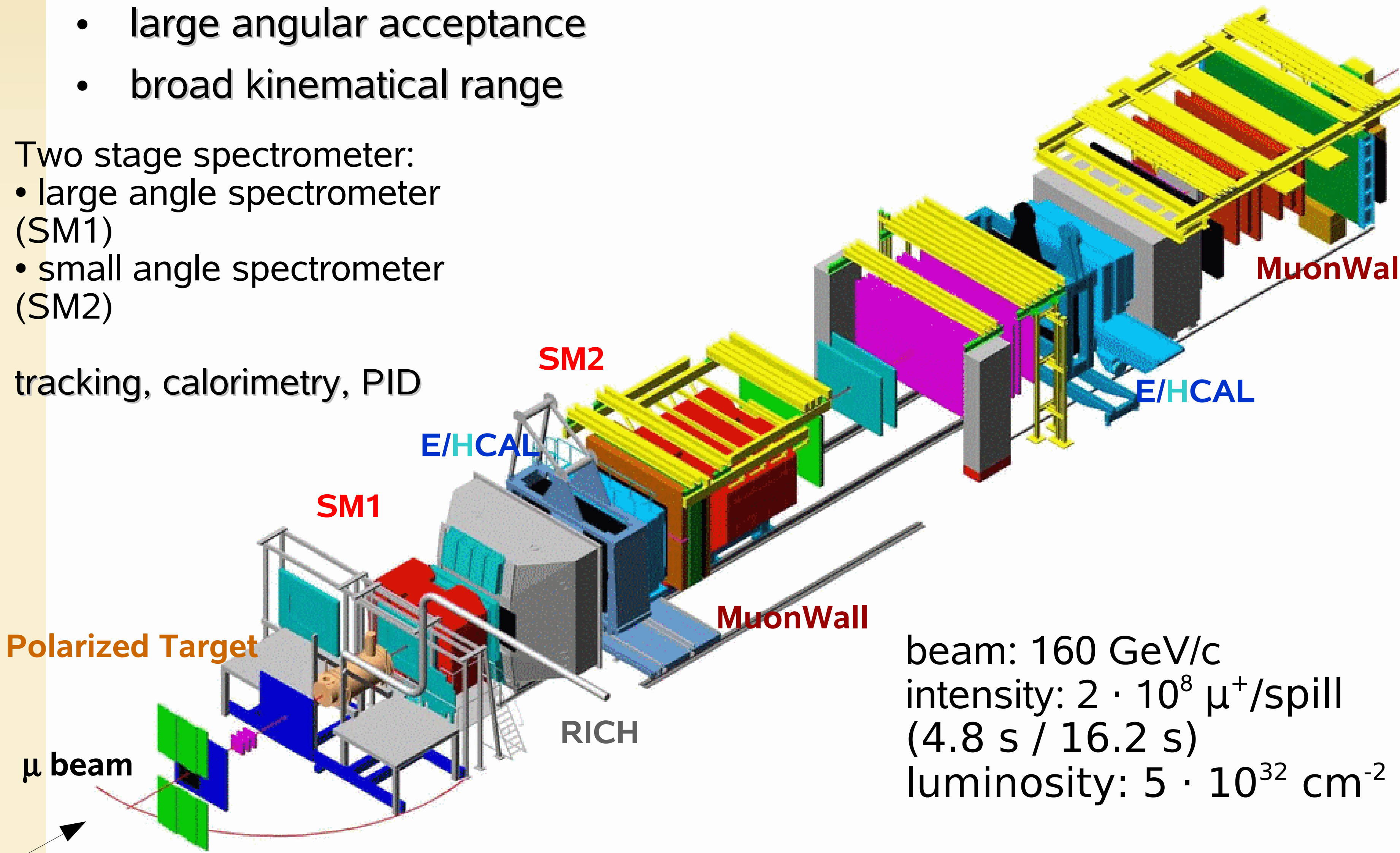


Compass Spectrometer at CERN

- high energy beam
- large angular acceptance
- broad kinematical range

Two stage spectrometer:
• large angle spectrometer (SM1)
• small angle spectrometer (SM2)

tracking, calorimetry, PID

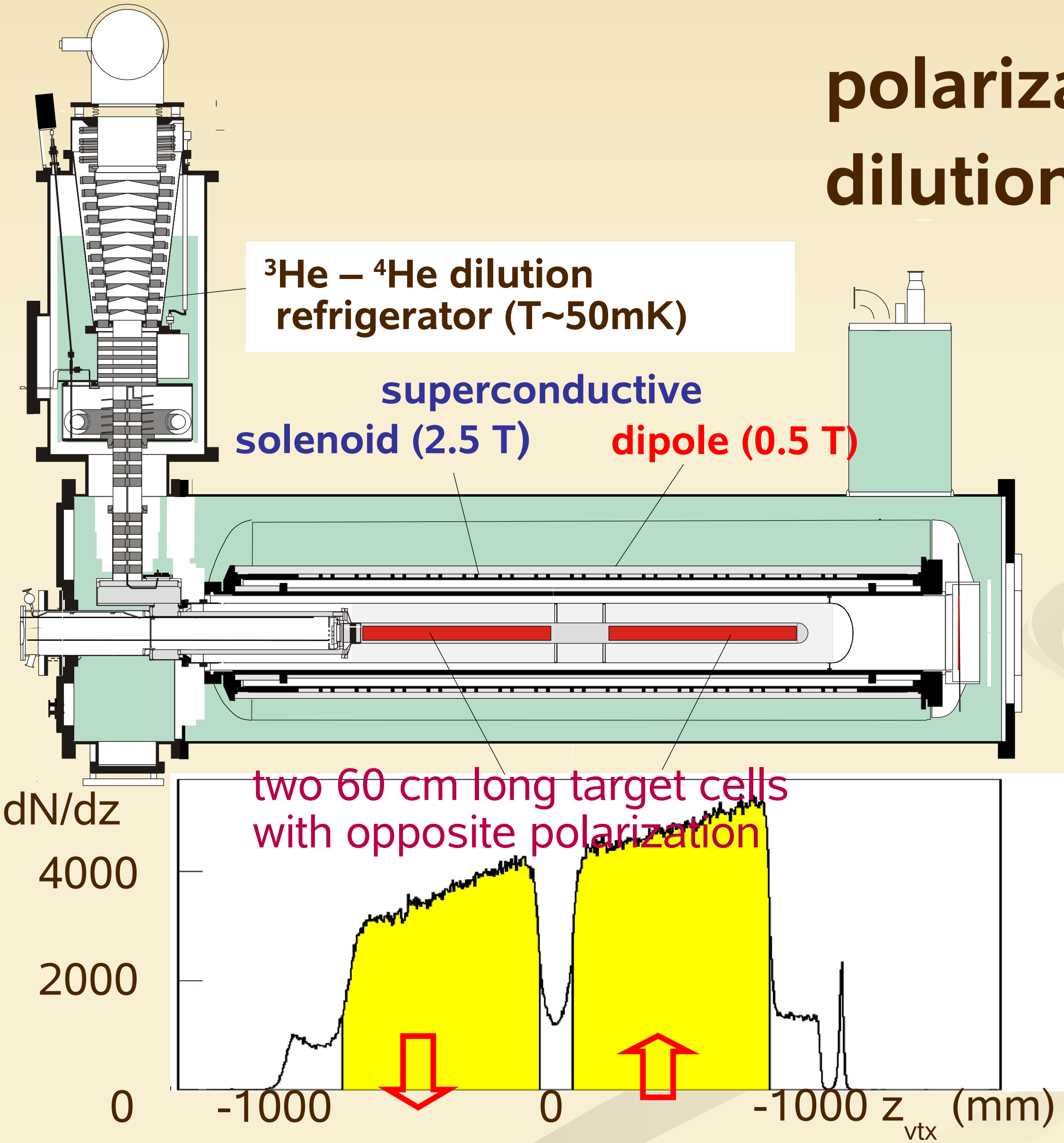


beam: 160 GeV/c
intensity: $2 \cdot 10^8$ μ^+/spill
(4.8 s / 16.2 s)
luminosity: $5 \cdot 10^{32}$ cm^{-2} s^{-1}

Polarized Deuteron Target (^{6}LiD)

polarization: $P_T \approx 50$ %

dilution factor f = 0.38



<u>transverse target polarization:</u>
dipole field

<u>changed by microwave reversal:</u>
once a week

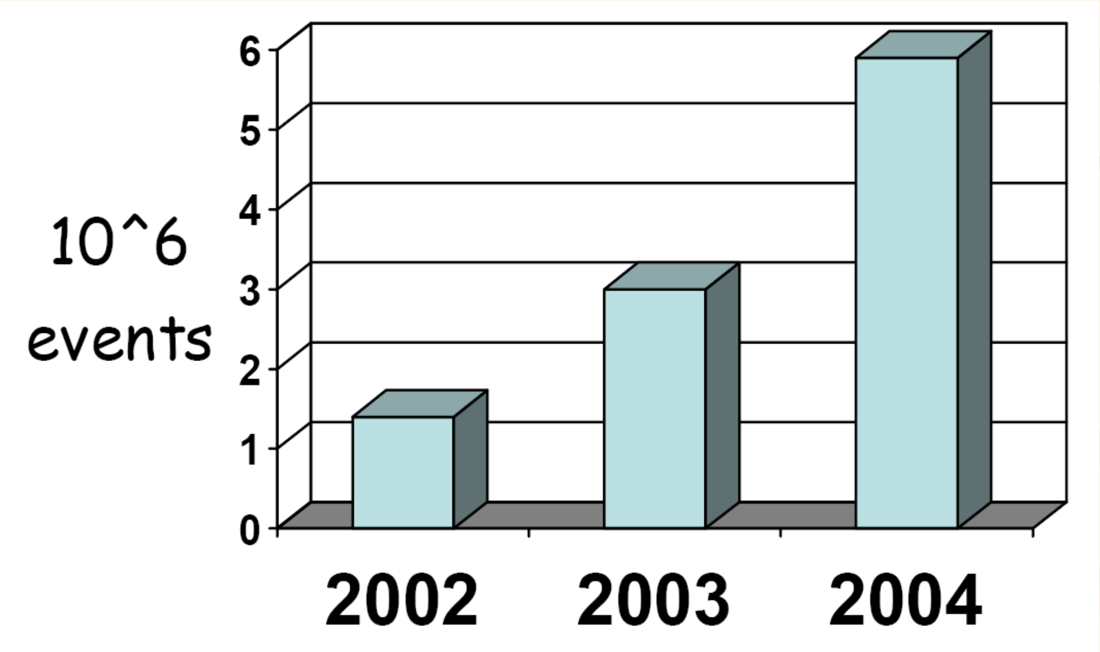
Data Taking 2002-04

Transversely polarized deuteron target:
ca. 20 % of the running time

2002: 19 days of data taking: 2 periods

2003: 14 days of data taking: 1 period → trigger upgrade (large Q^2, large x_{bj}) PID (ECAL, RICH)

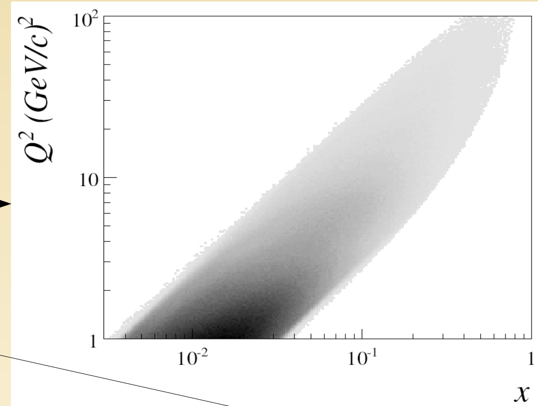
2004: 14 days of data taking: 2 periods → DAQ improved, online filter added

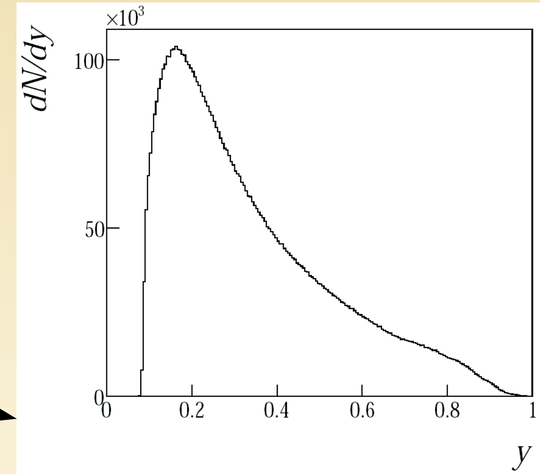


2002-04 together:
$\approx 10^6$ DIS events
(transverse data)

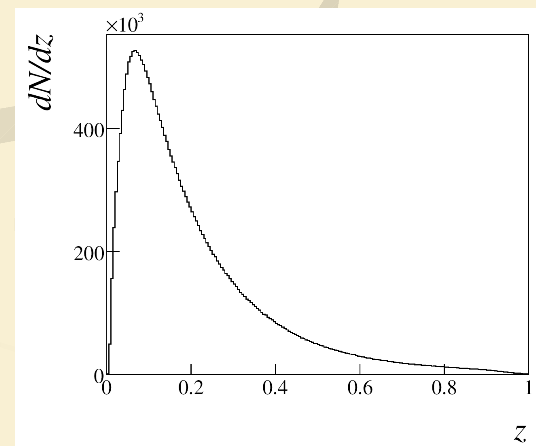
Event Selection I

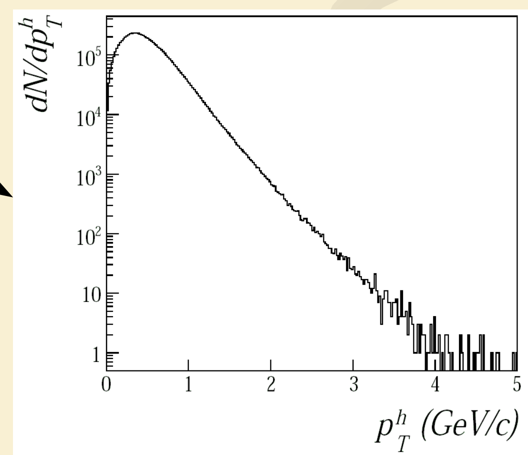
DIS cuts:
- $Q^2 > 1\ (GeV/c)^2$
- $0.1 < y < 0.9$
- $W > 5\ GeV/c^2$

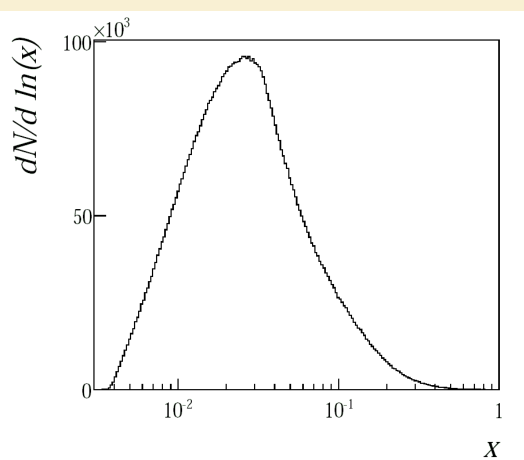




Hadron cuts:
- Two samples:
  - all hadrons: $z > 0.2$
  - leading (most energetic) hadron: $z > 0.25$
- $p_t > 0.1\ GeV/c$







distribution of x_{bj}

Single Hadron Asymmetries

Two important possible azimuthal asymmetries in the distribution of single hadrons in SIDIS on a transversely polarized target:

a) Fragmentation of a transversely polarized quark with finite transverse momentum into a Spin 0 ("unpolarized") hadron.

→ **Collins effect**

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

Collins fragmentation function: being measured at Belle

→ **possibility to measure transversity!**

f: dilution factor

P_T: target polarization

D_{nn}: depolarization factor

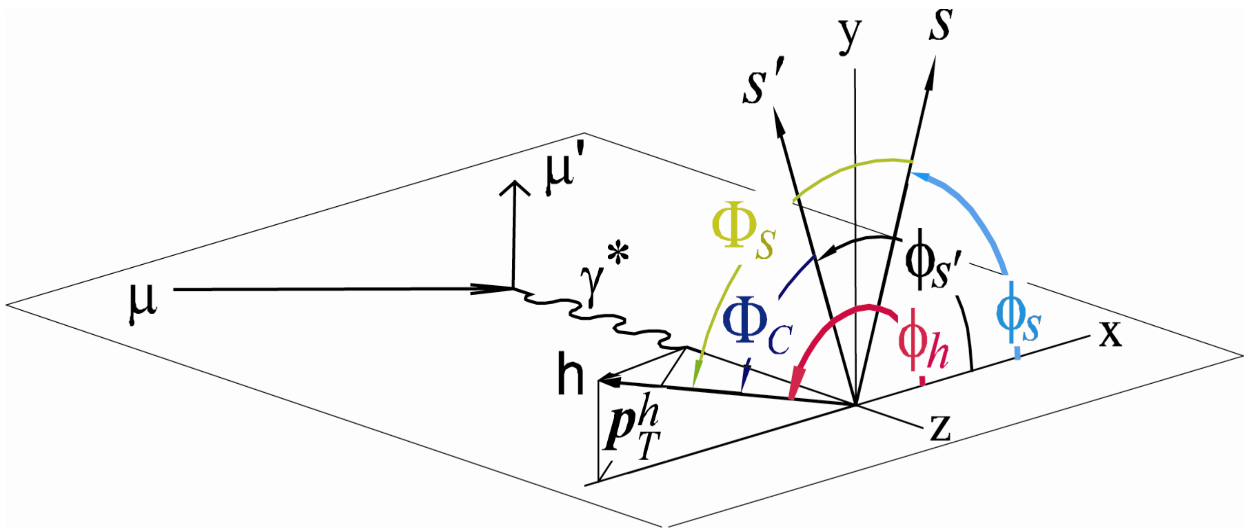
b) Fragmentation of an unpolarized quark inside a transversely polarized nucleon.

→ **Sivers effect**

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

The Coordinate System

Collins and Sivers terms depend on different combination of angles:



Collins:

$A_{Coll} \sim \sin \Phi_C$

$\Phi_C = \phi_h - \phi_{S'} =$

$\phi_h + \phi_S - \pi$

Sivers:

$A_{Siv} \sim \sin \Phi_S$

$\Phi_S = \phi_h - \phi_S$

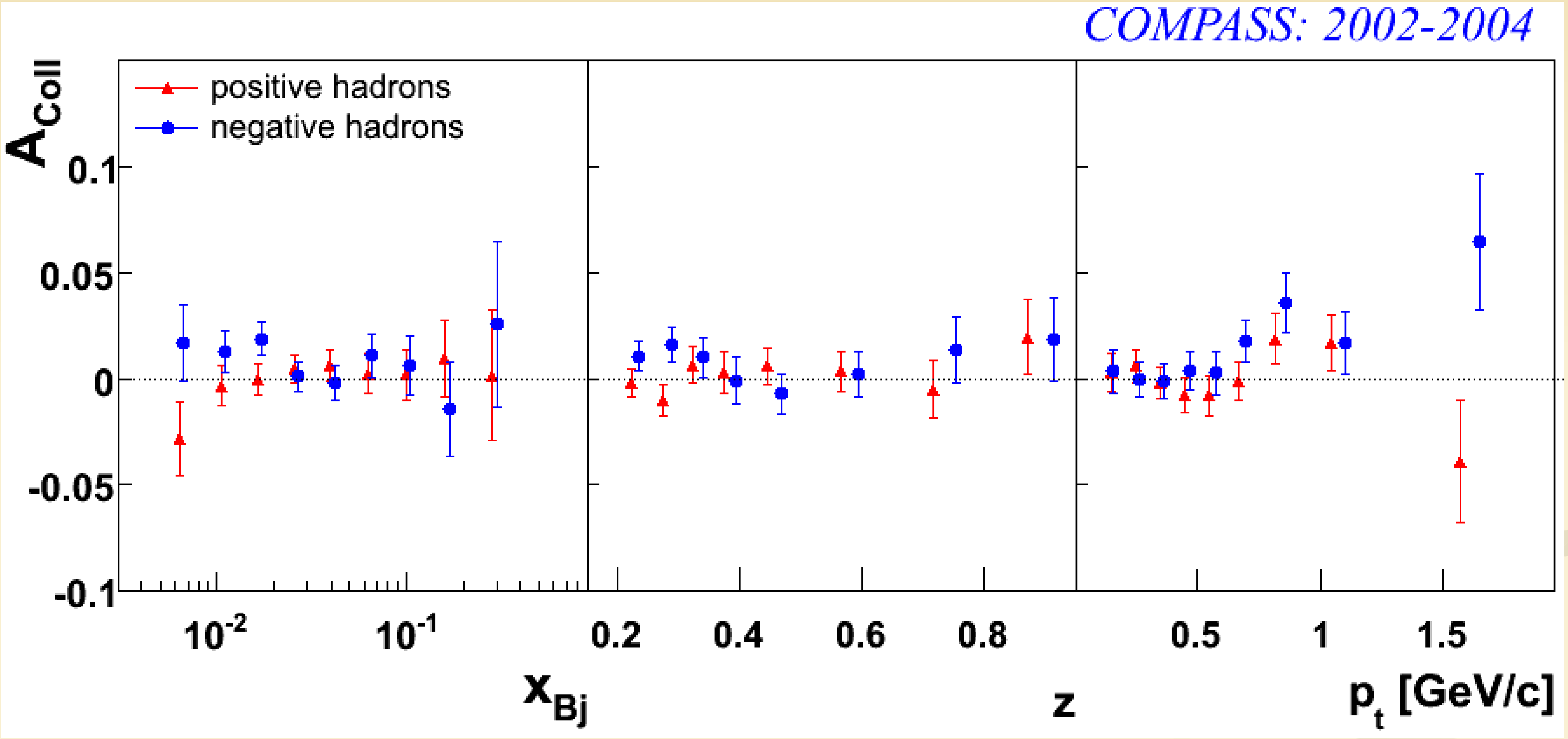
ϕ_h: azimuthal angle of the hadron

ϕ_S: azimuthal angle of the spin of the initial quark

$\phi_{S'}$: azimuthal angle of the spin of the fragmenting quark

with $\phi_{S'} = \pi - \phi_S$ (spin flip)

Collins Asymmetries 2002-04 Data



- only statistical errors shown, systematic errors considerably smaller
- small asymmetries, compatible with 0 (leading hadron: similar)

<u>Final results, all deuteron data:</u> **NP B765 (2007) 31-70**

Hadron Identification: Charged Hadrons

$\pi^{\pm}$ $K^{\pm}$

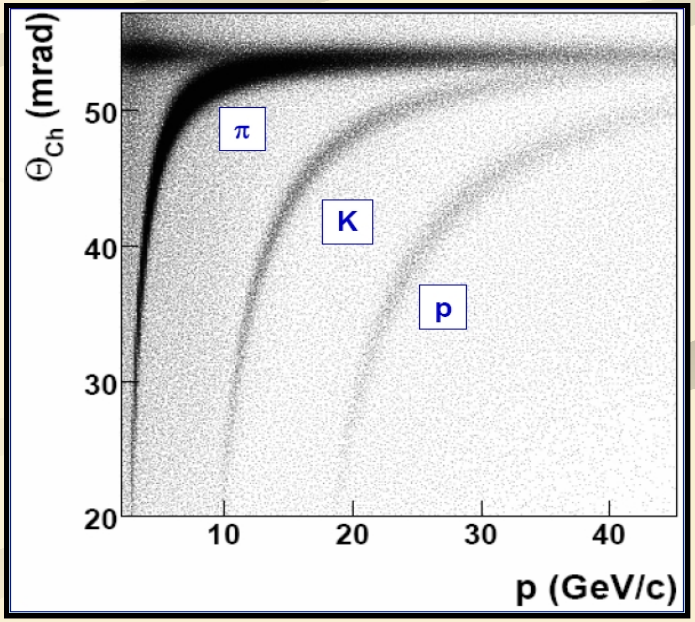
Based on RICH response.
Likelihood algorithm.
Used for analysis of transverse data from 2003 and 04.

Cherenkov thresholds: $p_{\pi} \approx 3$ GeV/c

$p_K \approx 9$ GeV/c

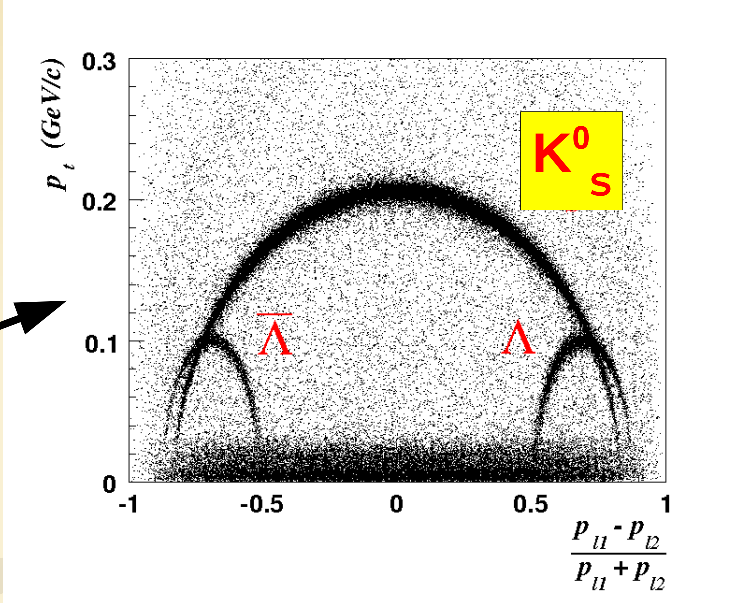
$p_p \approx 17$ GeV/c

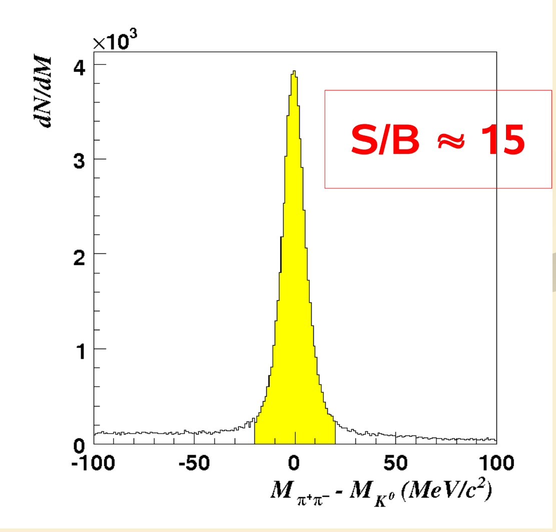
Statistics 2003-04	positive	negative
$\pi^{\pm}$	$5.2 \cdot 10^6$	$4.5 \cdot 10^6$
$K^{\pm}$	$0.9 \cdot 10^6$	$0.6 \cdot 10^6$



Hadron Identification: Neutral K^0_S

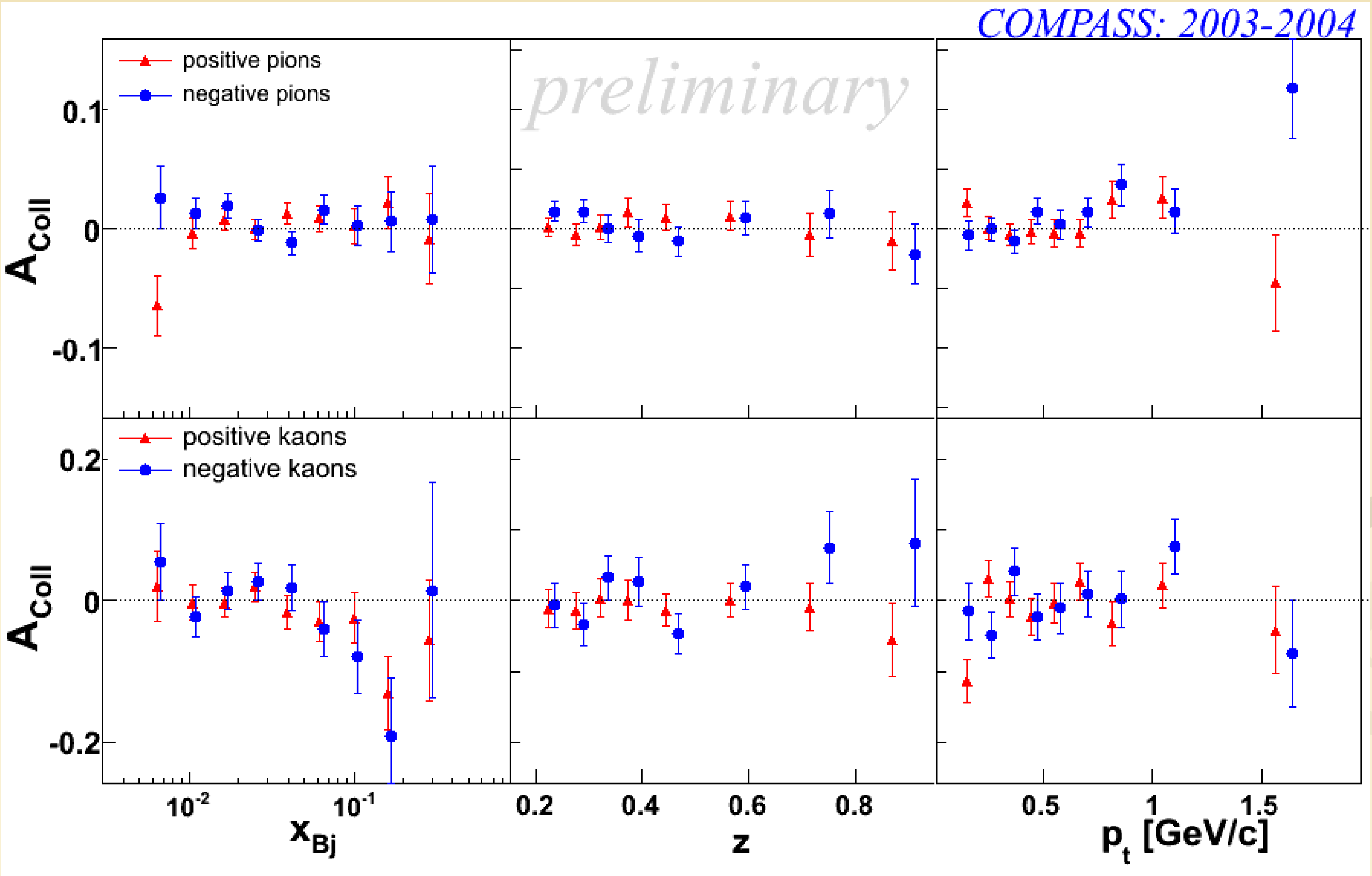
- V^0 vertex with oppositely charged tracks
- **target pointing:** angle < 0.01 rad
- **distance cut:** $Z(V^0)$ - Z(prim. vert.) > 10 cm
- **Armenteros cut:** $p_{t,\,Arm} > 0.025$ GeV/c
- $-0.2\ \text{GeV}/c^2 < M_{\pi+\pi-} - M_{K0(lit)} < 0.2\ \text{GeV}/c^2$





Statistics 2002-04	
K^0_S	$2.6 \cdot 10^6$

Collins Asymmetries $\pi^{\pm}$ $K^{\pm}$



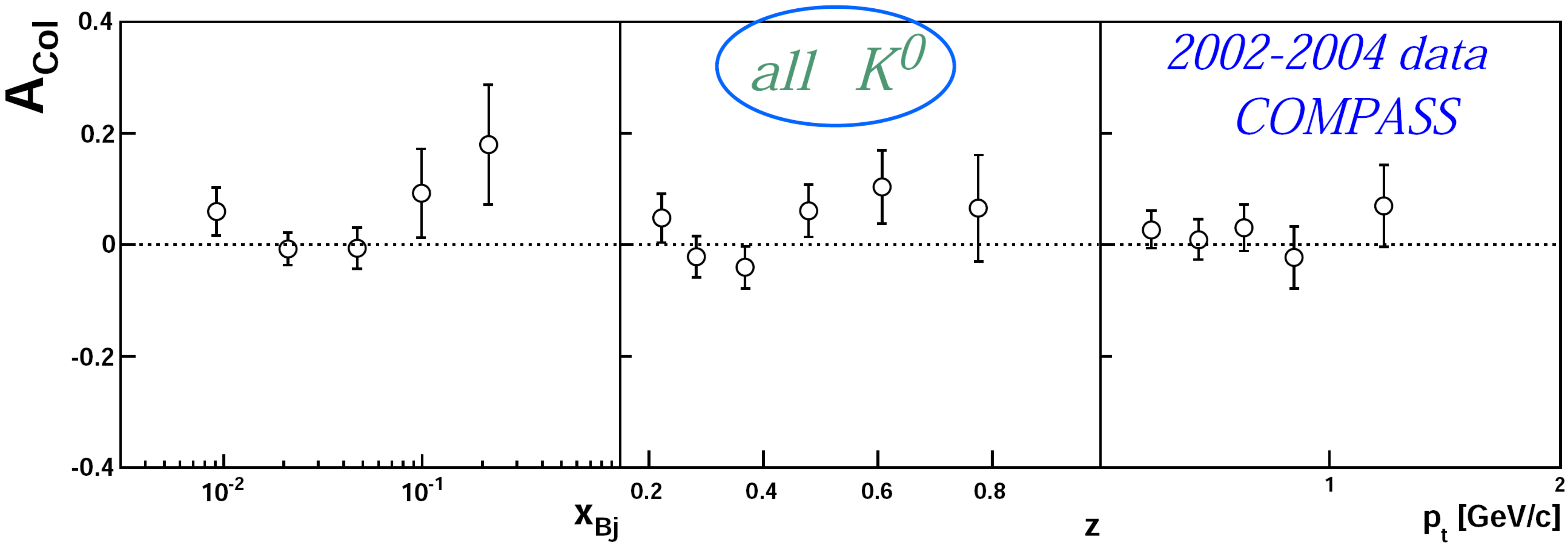
Final results,
all deuteron data

hep-ex/0802.2160
(subm. PLB)

- only statistical errors shown, systematic errors considerably smaller
- small asymmetries, compatible with 0

(leading hadron: similar)

Collins Asymmetries K^0_S



<u>Final results,</u>
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(leading hadron: similar)

Interpretation: Collins

Naïve interpretation of the data (parton model, valence region):

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

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

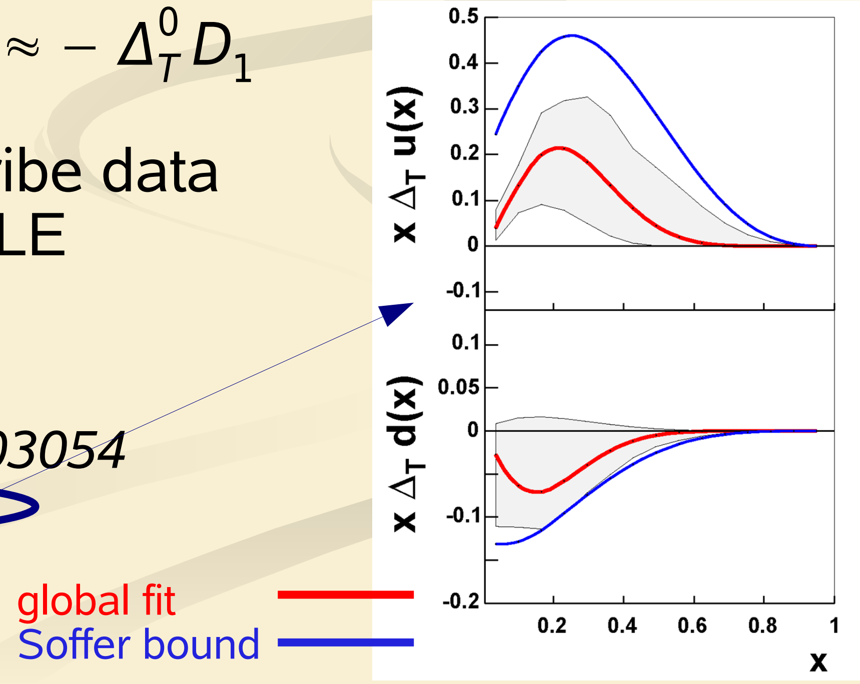
Small asymmetries → cancellation between $\Delta_T u(x)$ and $\Delta_T d(x)$

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

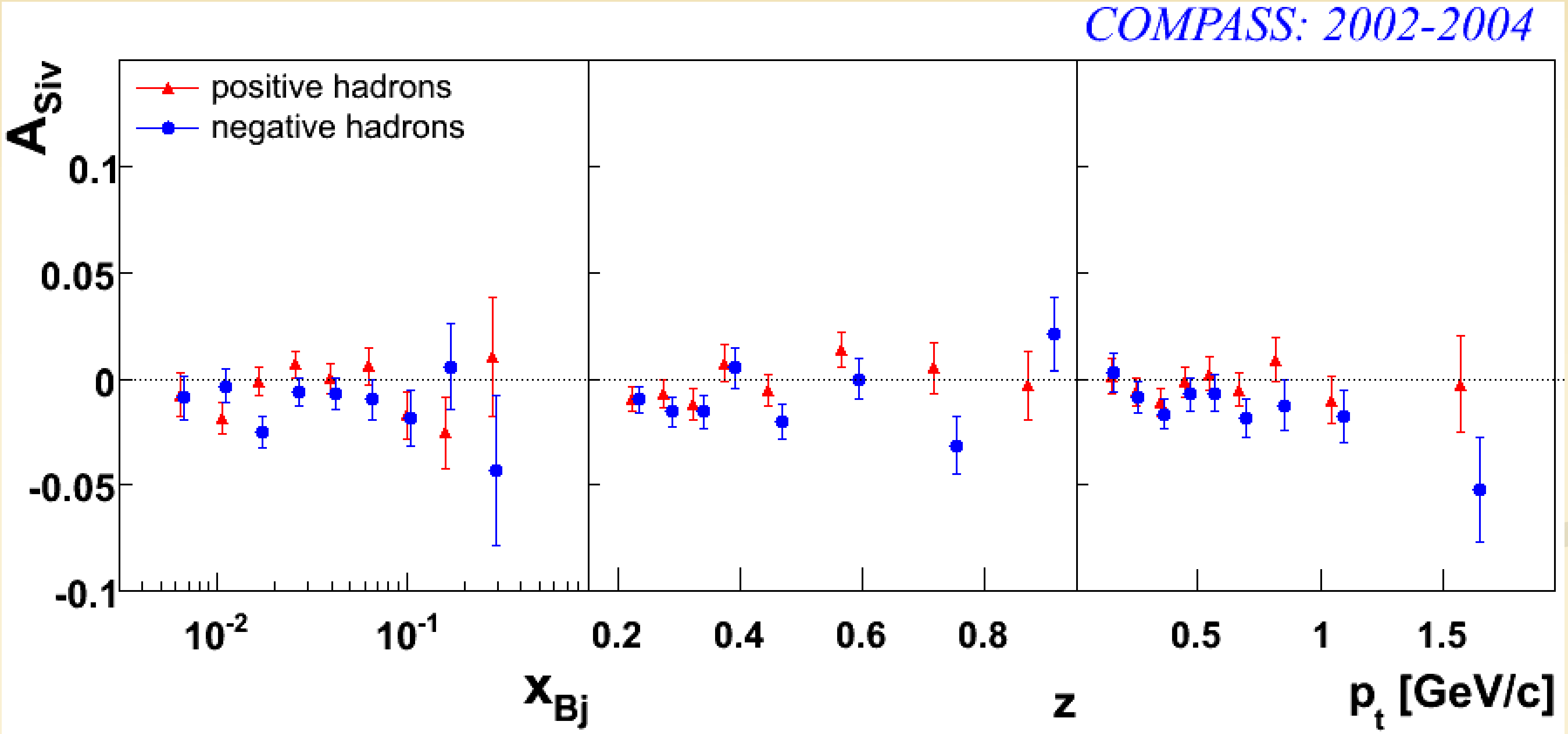
From proton data of Hermes: $\Delta_T^0 D_2 \approx -\Delta_T^0 D_1$

<u>Phenomenological models</u> can describe data from COMPASS, HERMES and BELLE at the same time:

- *Vogelsang, Yuan: hep-ph/0507266*
- *Efremov, Goeke, Schweitzer: hep-ph/0603054*
- *Anselmino et al.: hep-ph/0701006*



Sivers Asymmetries 2002-04 Data



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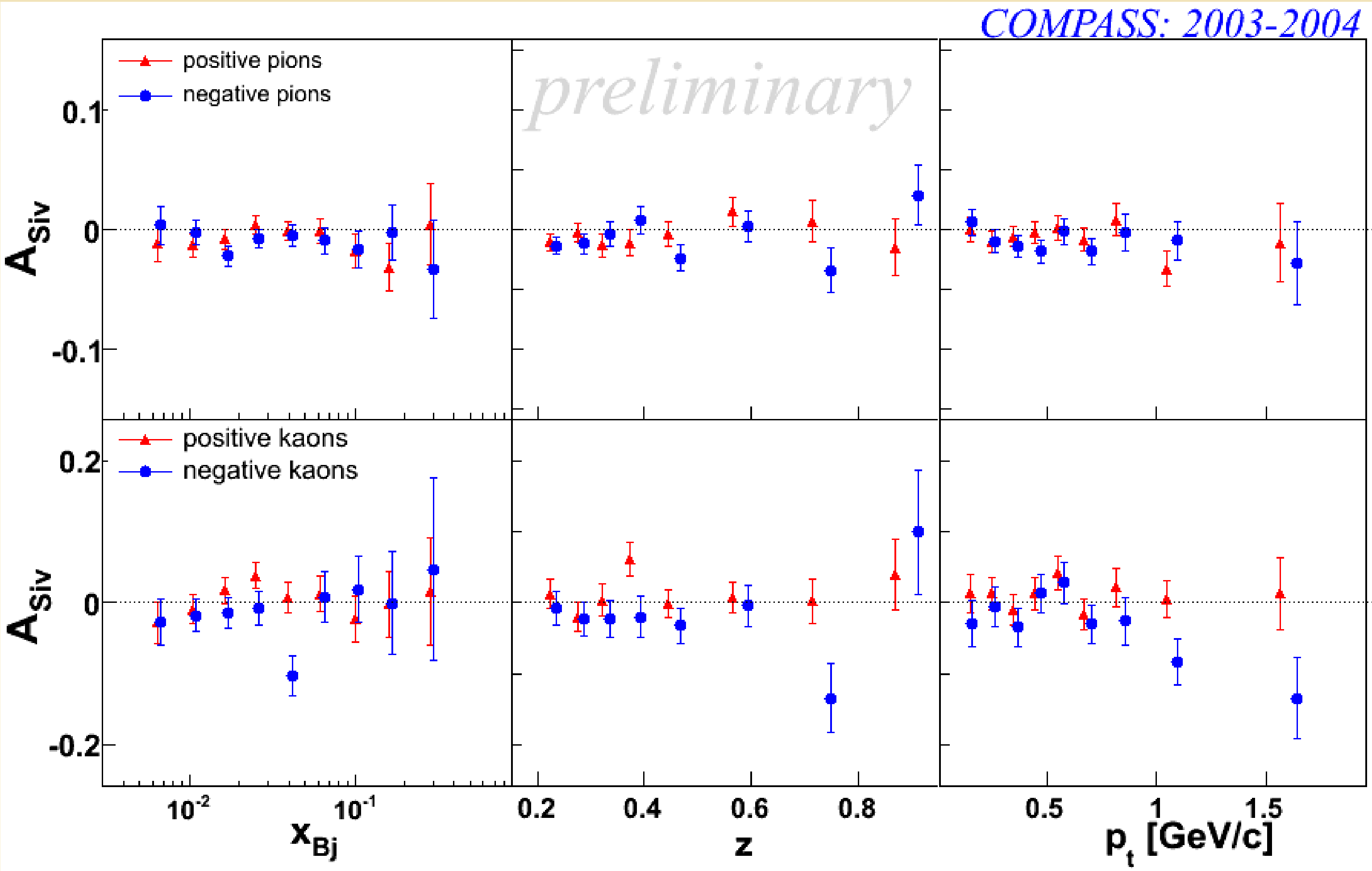
Sivers Asymmetries $\pi^{\pm}$ $K^{\pm}$



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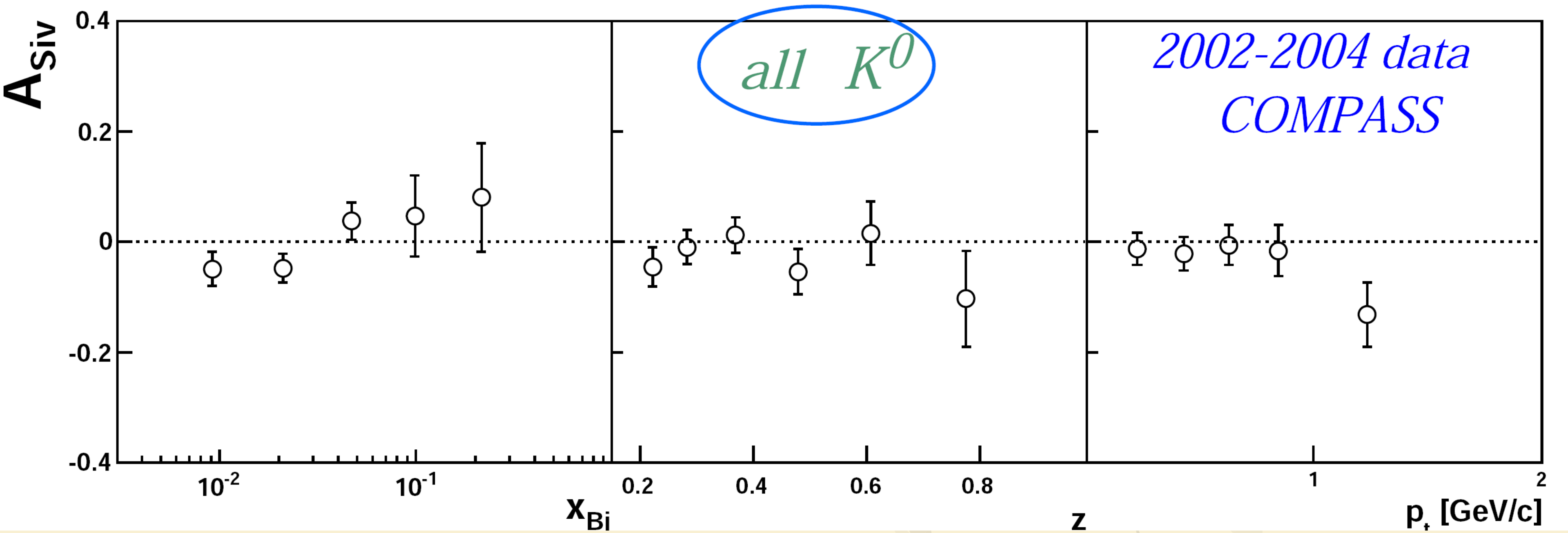
Sivers Asymmetries K^0_s



<u>Final results,</u>
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(subm. PLB)

- only statistical errors shown, systematic errors considerably smaller
- small asymmetries, compatible with 0

(leading hadron: similar)

Interpretation: Sivers

- Naïve interpretation of the COMPASS deuteron 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 → $\Delta_0^T d_v \simeq -\Delta_0^T u_v$

- **Data on proton target (HERMES) are different from 0.**
  → Phenomenological works by different groups
  Simultaneous description of **COMPASS and HERMES data**
  Summary: **Anselmino et al.: hep-ph/0511017**

- **Interpretation of the measured asymmetry on deuteron compatible with 0 by:**

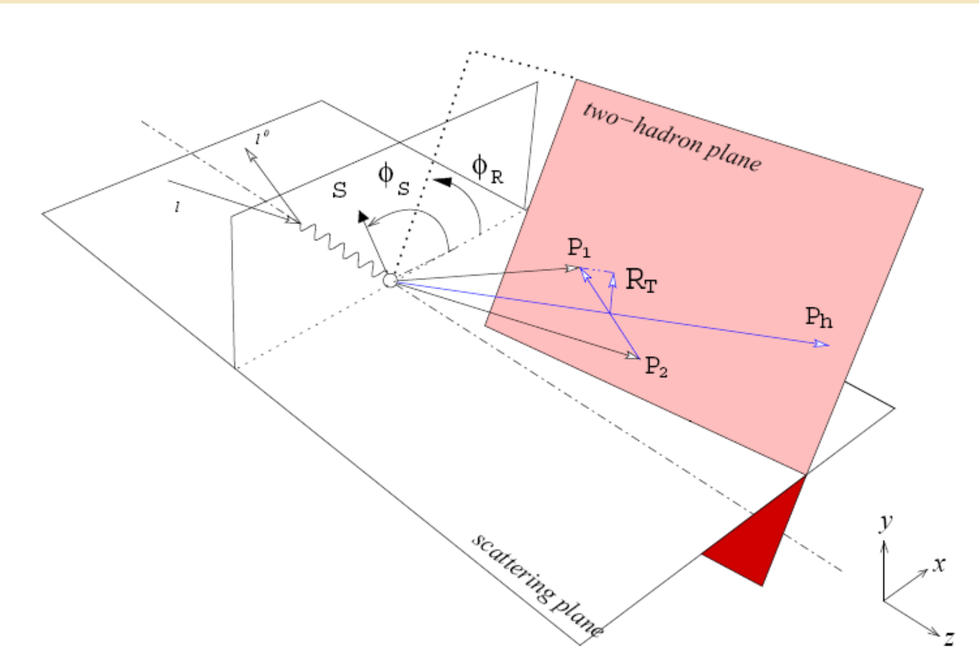
S.J. Brodsky, S. Gardner: PLB643 2006 (22)

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

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 Hadron Asymmetries

In the production of hadron pairs one can define the angle ϕ_R and measure an azimuthal asymmetry from the modulation of the numbers of events in $\phi_{RS} = \phi_R - \phi_{S'}$



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

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

ϕ_R: azimuthal angle of R_T

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

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

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

Transversity distribution function

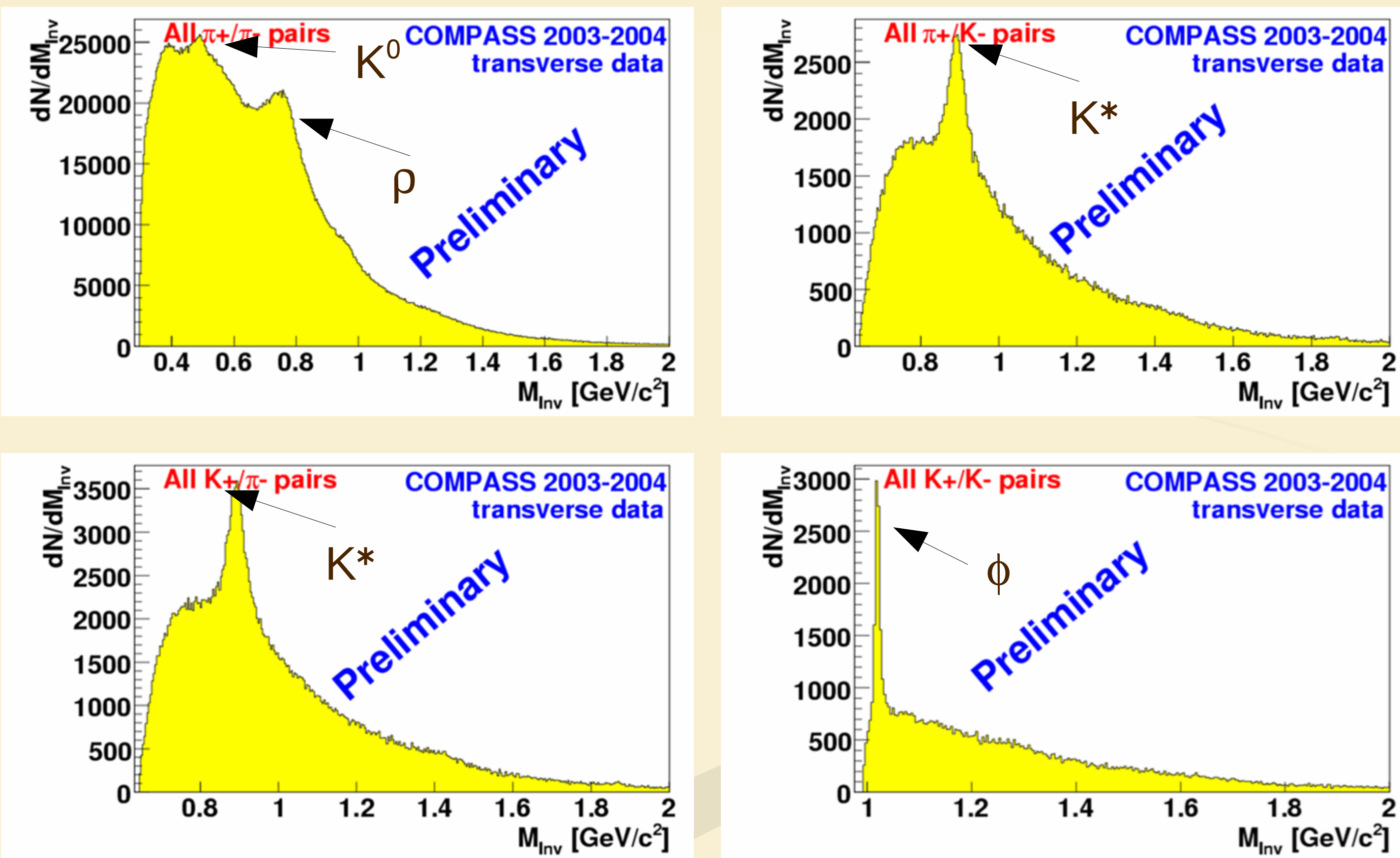
Interference fragmentation function,
being measured at BELLE

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

Two Hadron Asymmetries

2 different analysis:
1) All hadron pairs (ordered by type)

	without PID	$\pi_+ \pi_-$	π_+ K-	K+ π_-	K+ K-
total	$5.3 \cdot 10^6$	$3.7 \cdot 10^6$	$0.24 \cdot 10^6$	$0.3 \cdot 10^6$	$0.087 \cdot 10^6$



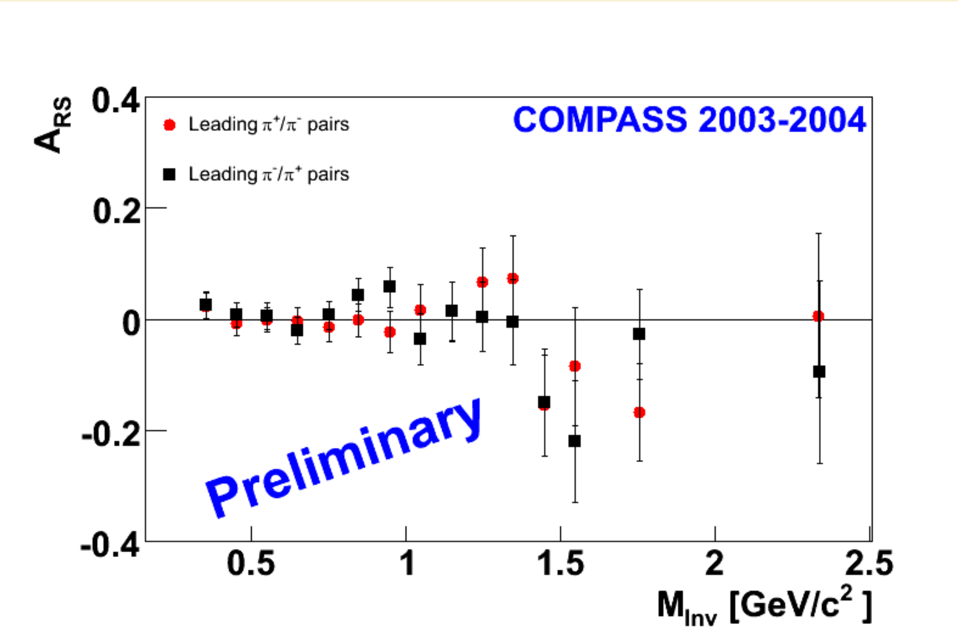
Invariant mass spectra

Two Hadron Asymmetries

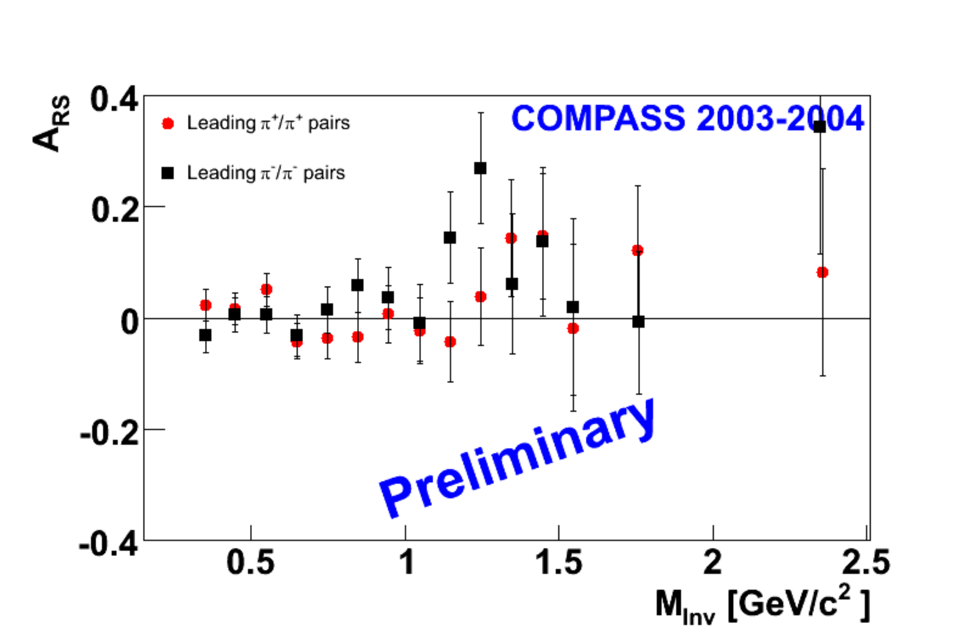
2) z ordered pairs:
select in the event the two hadrons with the highest relative energy z.

Reason: For leading hadron pairs an enhancement of the signal is predicted. Hadrons with higher energy may carry more information about the polarization of the fragmenting quark.

π with opposite charge

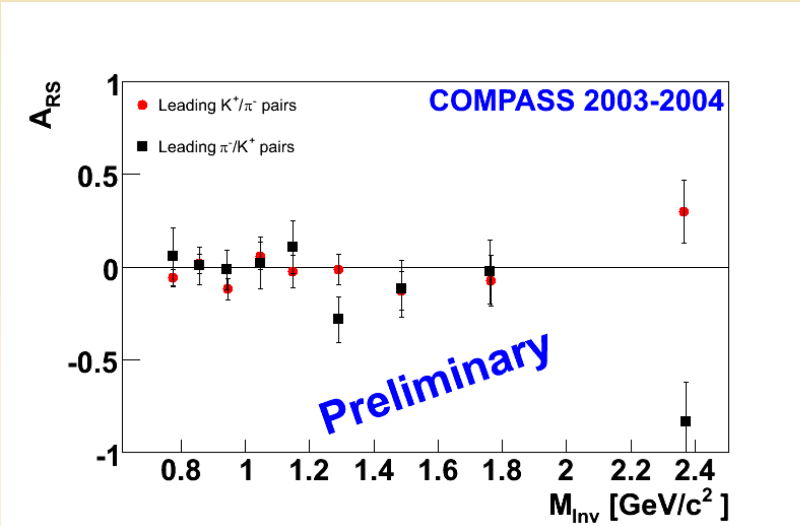


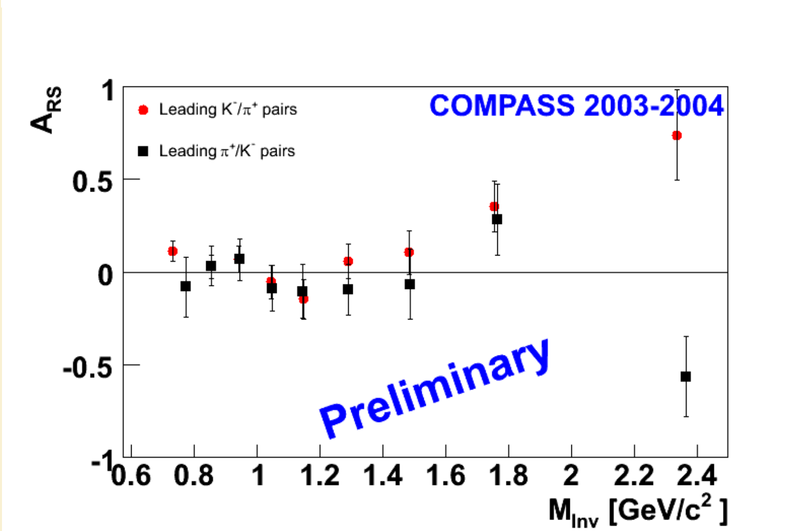
π with same charge



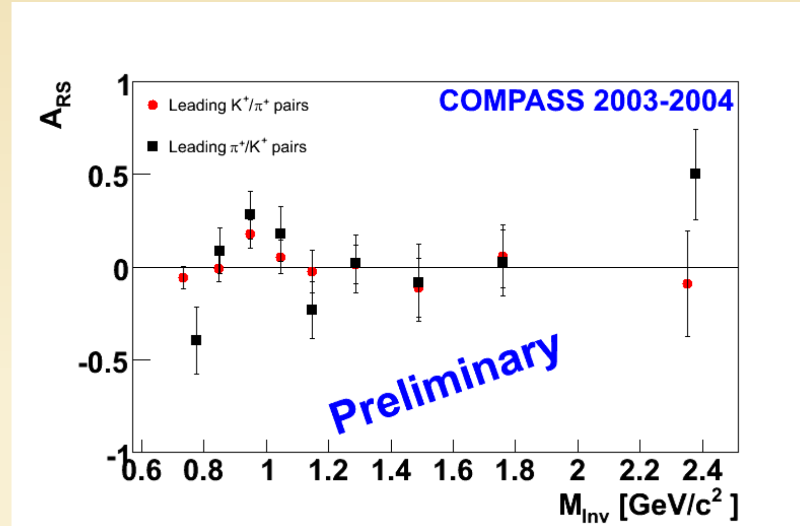
Two Hadron Asymmetries

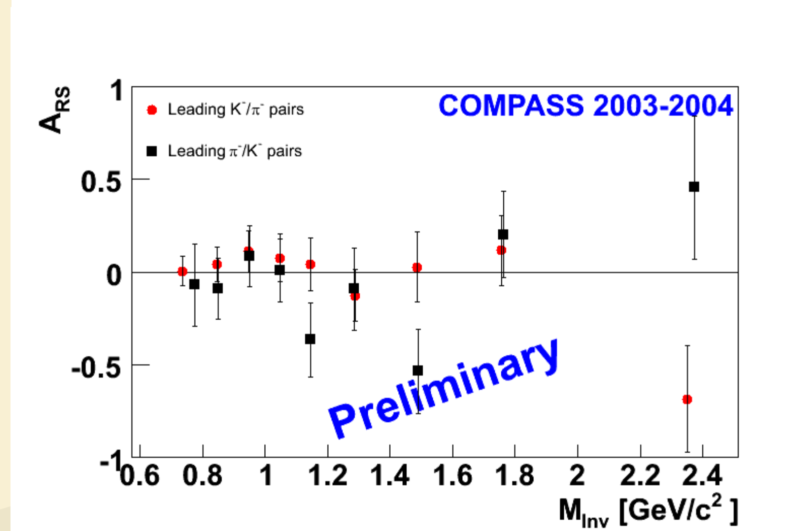
K/π and π/K with opposite charge





K/π and π/K with same charge





Only statistical errors shown, systematic errors considerably smaller.

Other Single Spin Asymmetries

More terms are present in the complete SIDIS cross section:
8 transverse target spin dependent asymmetries
with different azimuthal dependencies

All 8 asymmetries measured at COMPASS

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{ \ldots$$

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

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

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

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

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

Sivers: $F_{UT,T}^{\sin(\phi_h-\phi_S)}$

Collins: $F_{UT}^{\sin(\phi_h+\phi_S)}$

6 further asymmetries

Other Single Spin Asymmetries

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

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

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

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

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

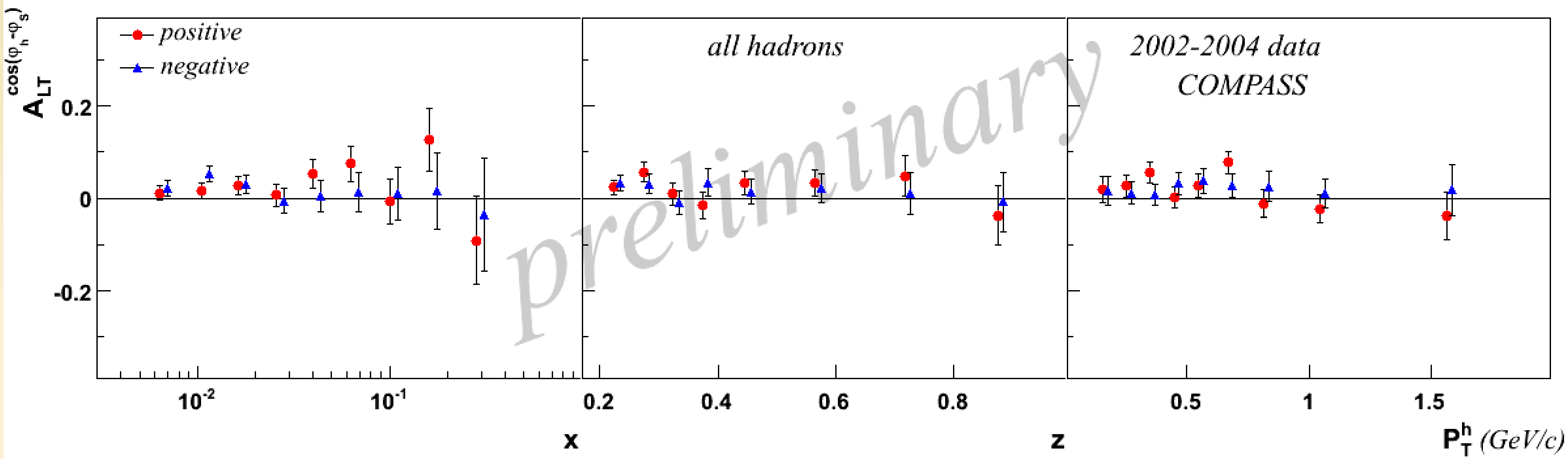
$$F_{UT}^{\sin(2\phi_h-\phi_s)} \propto \frac{M}{Q} \left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h \right)$$

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

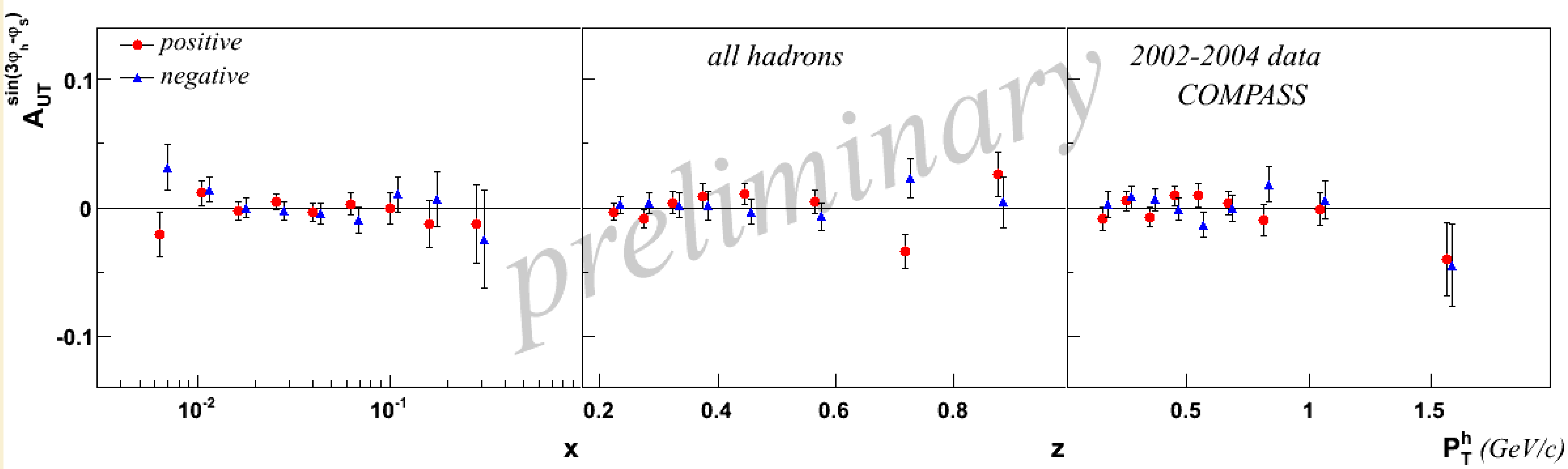
The four remaining ones can be interpreted as twist-3 contributions.

Other SSA: Twist-2

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

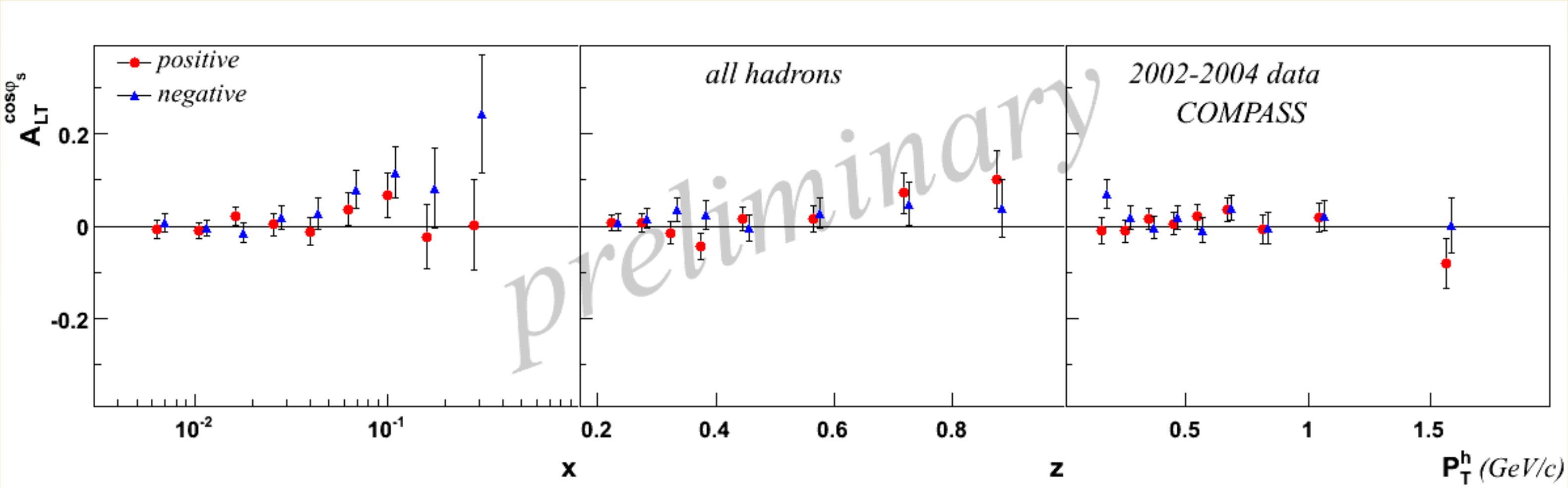


$$F_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

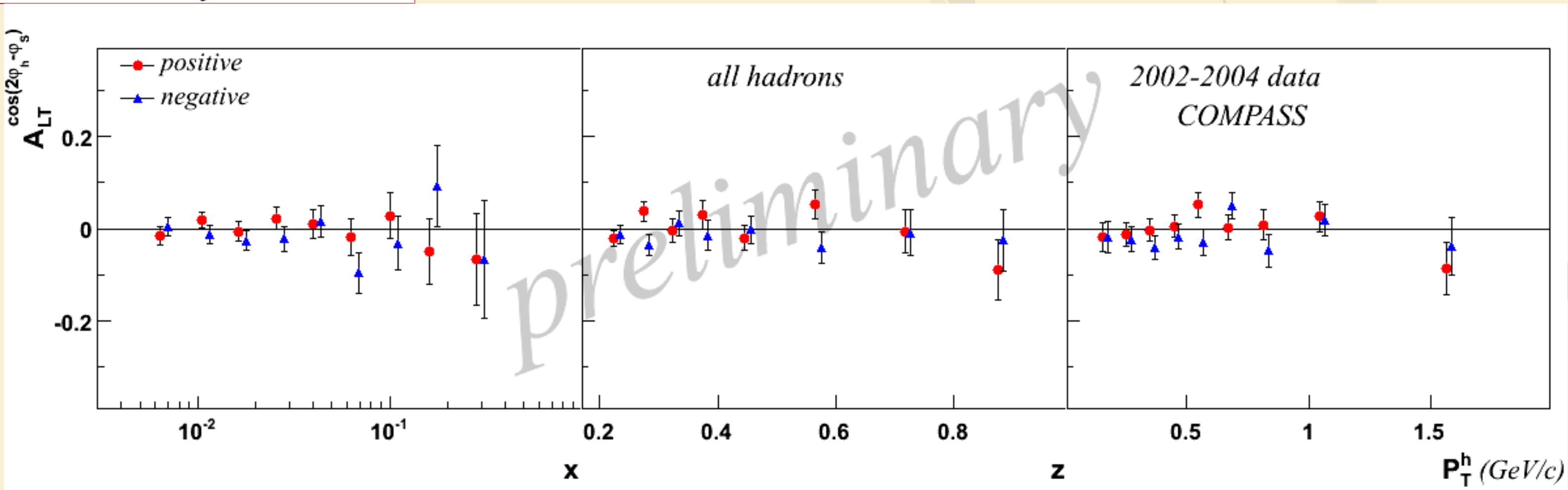


Other SSA: Twist-3

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

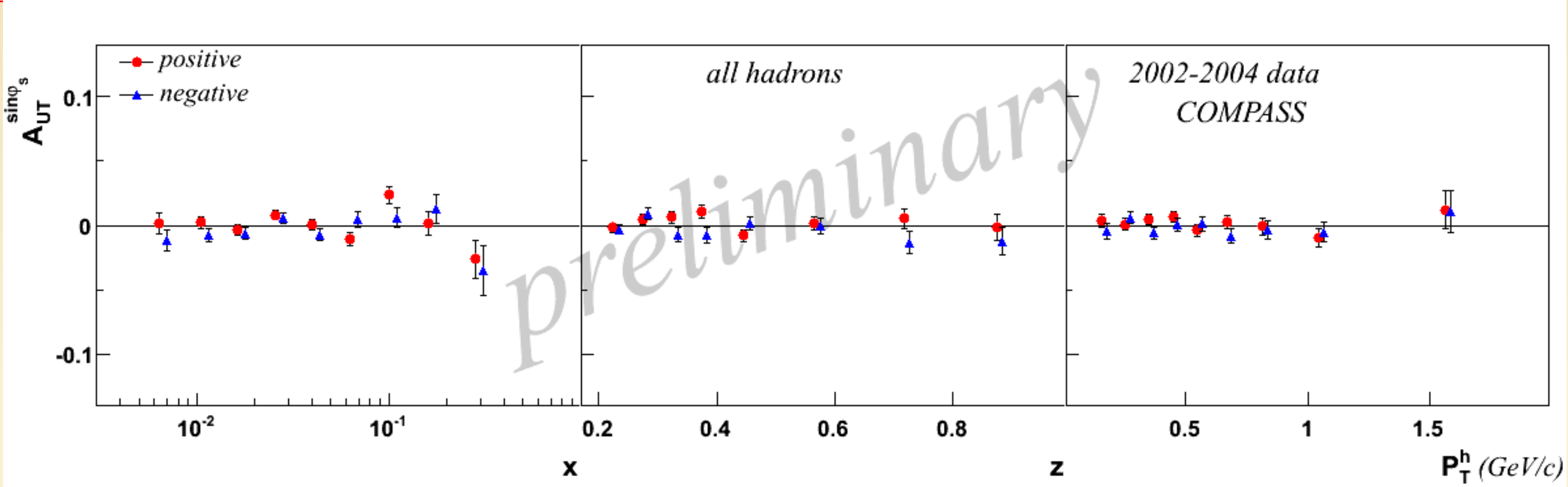


$$F_{LT}^{\cos(2\phi_h-\phi_s)} \propto \frac{M}{Q} g_{1T}^{q} \otimes D_{1q}^{h}$$

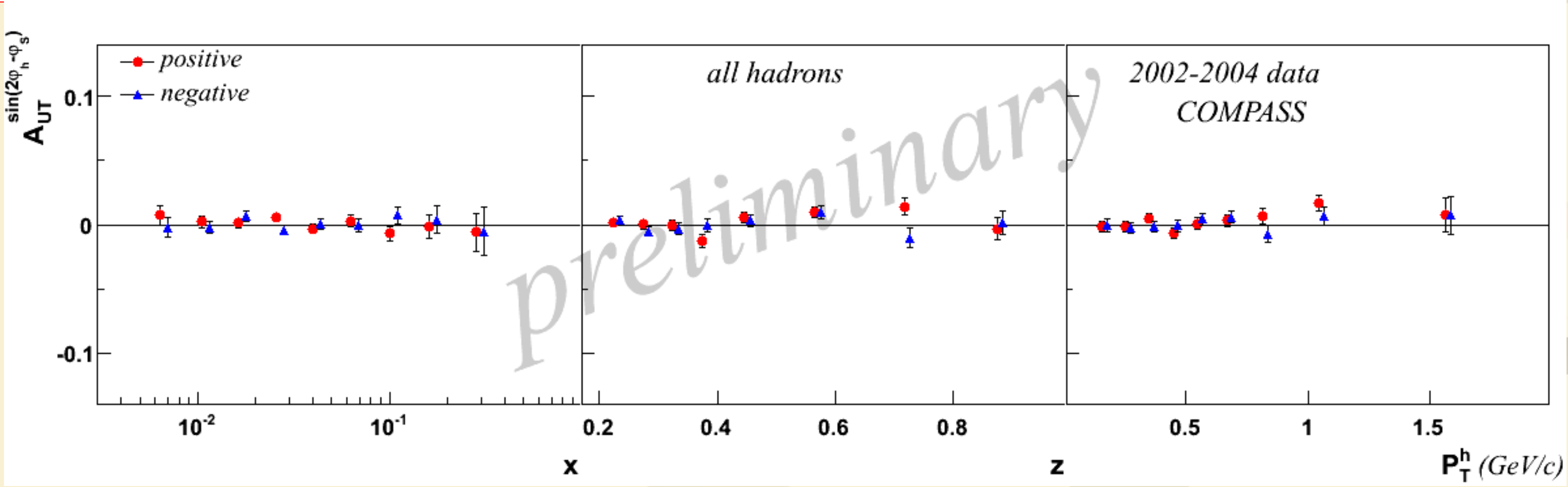


Other SSA: Twist-3

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



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



→ **All those asymmetries are compatible with 0.**

Summary and Outlook

- Full set of SSA from the data collected on a deuterium target analysed. Analysis finished.

- **All measured asymmetries on deuterium are very small and compatible with 0.**

- In 2007 COMPASS has measured with a transversely polarized proton target.
  → see next talk by Stefano Levorato

Just in case…

Event Selection 2 Hadron Asymmetries

DIS cuts:

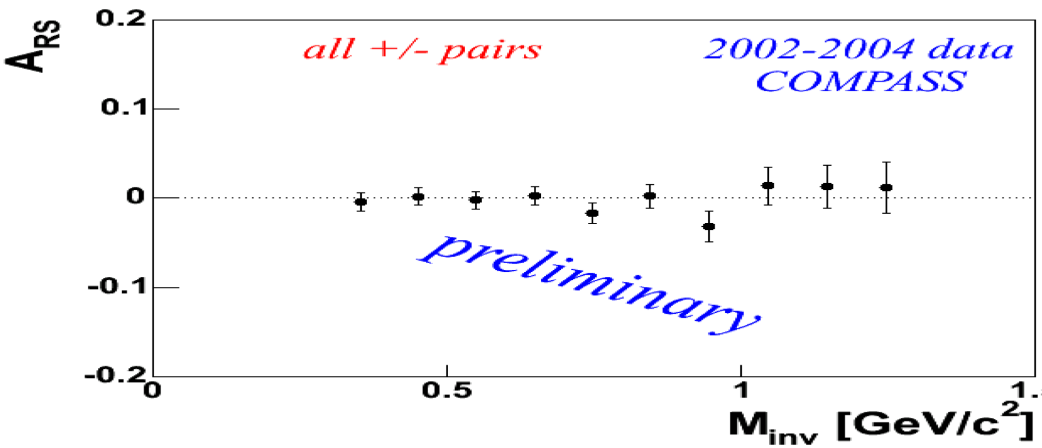
- $Q^2 > 1\ (GeV/c)^2$
- $0.1 < y < 0.9$
- $W > 5\ GeV/c^2$

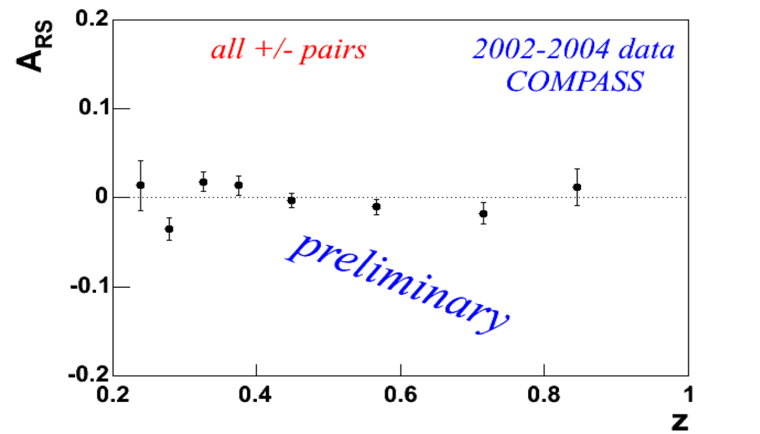
Hadron cuts:

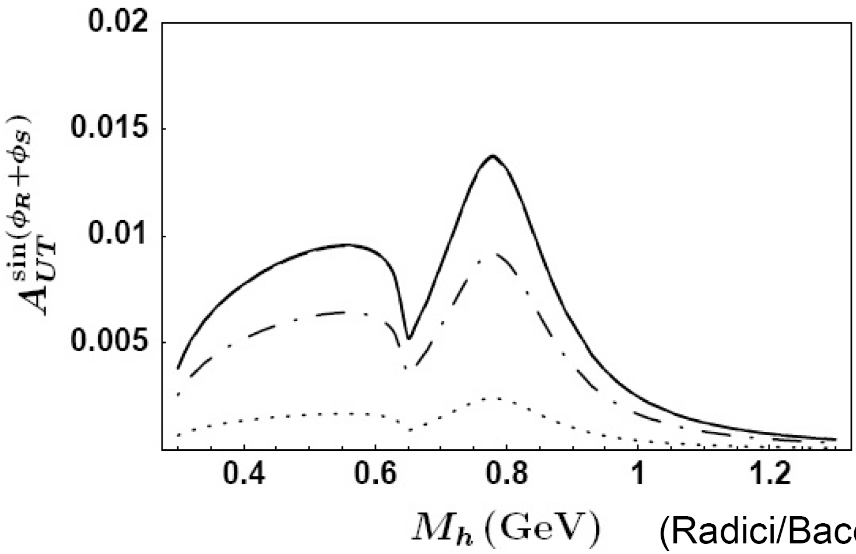
- $z_{1,2} > 0.1$
- $x_{F1,2} > 0.1$
- $z_1 + z_2 < 0.9$ (exclusive ρ)
- RICH identification of K/π

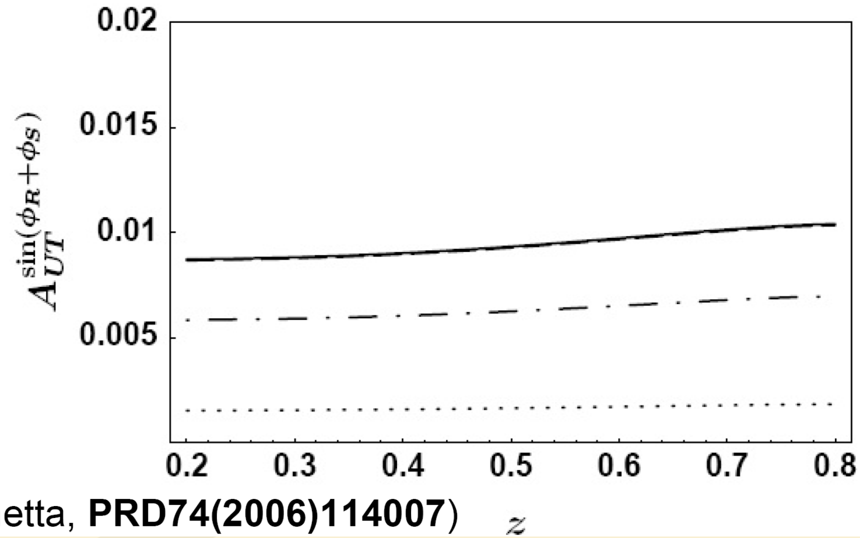
Two Hadron Asymmetries

Small asymmetries are expected:





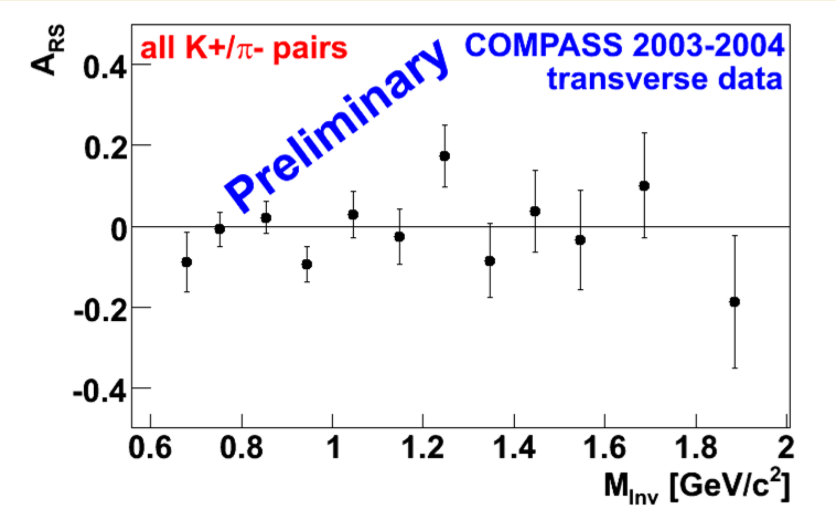


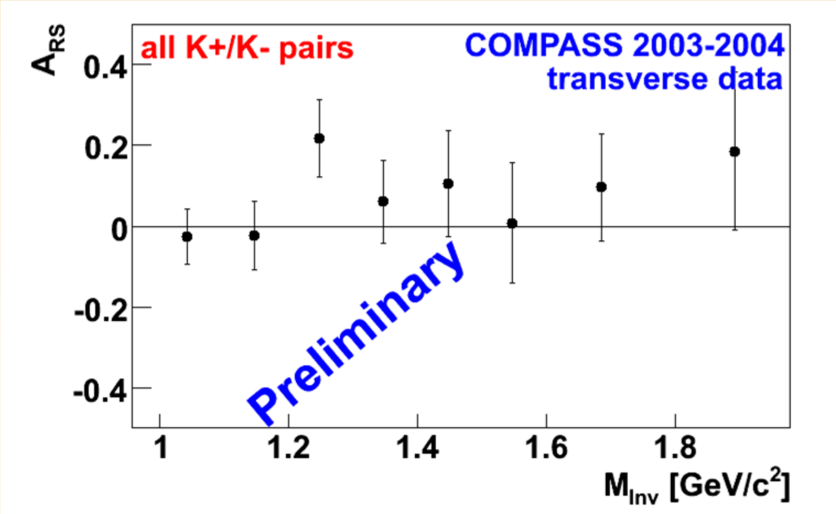


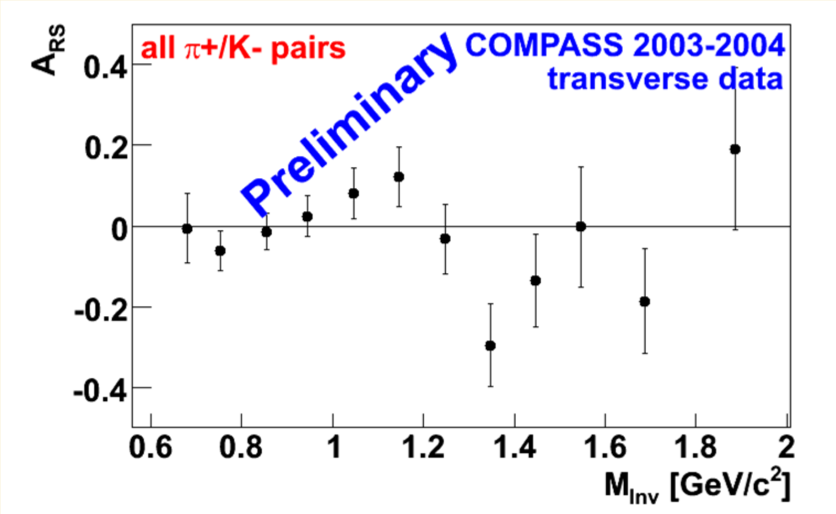
(Radici/Bacchetta, **PRD74(2006)114007**)

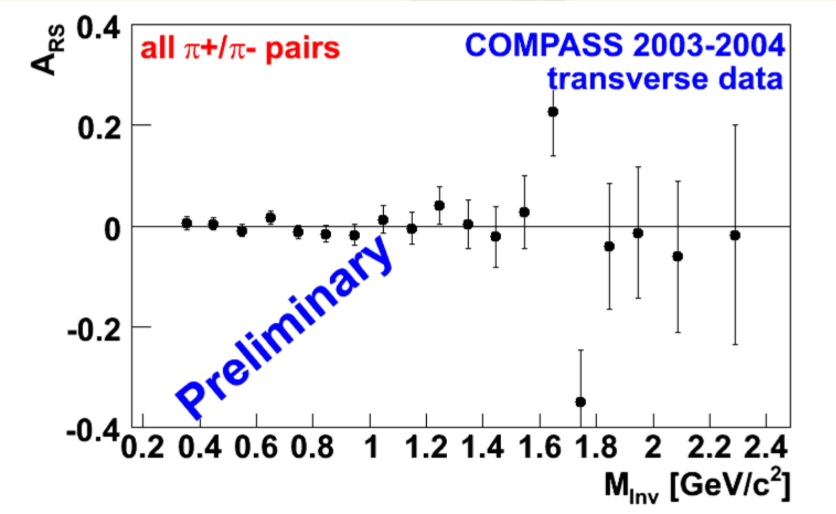
Two Hadron Asymmetries

All hadron pairs:





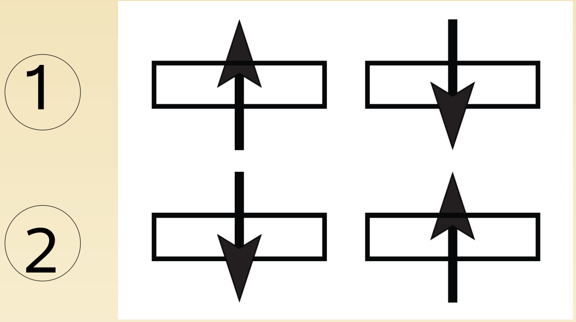




Asymmetry Extraction

Example: Collins/Sivers

target polarization in the two subperiods:



Counting rates:

$N_h^{\pm}(\Phi_{C/S}) = N_h^0 \cdot (1 \pm A_{C/S}^h \sin \Phi_{C/S})$; $A_{C/S}^h$: Collins/Sivers raw asym.

extraction of asymmetries with ratio product for 8 bins in $\Phi_{C/S}$:

$$F(\Phi_{C/S}) = \frac{N_u^+(\Phi_{C/S}) \cdot N_d^+(\Phi_{C/S})}{N_u^-(\Phi_{C/S}) \cdot N_d^-(\Phi_{C/S})}$$

u: upstream cell, d: downstream cell,

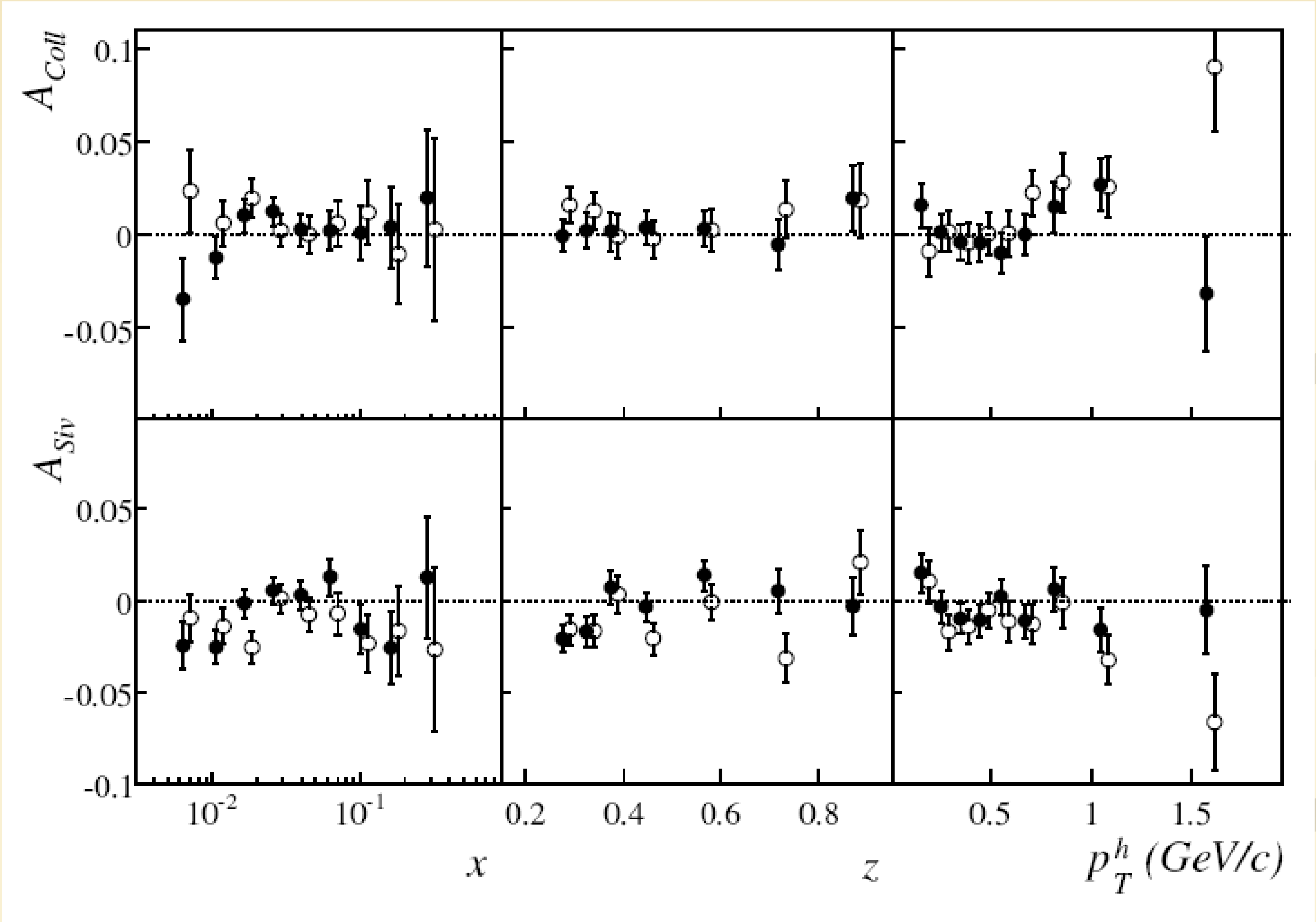
+/-: target polarization

$F(\Phi_{C/S}) = const \cdot (1 \pm 4\, A_{C/S}^h \sin \Phi_{C/S})$

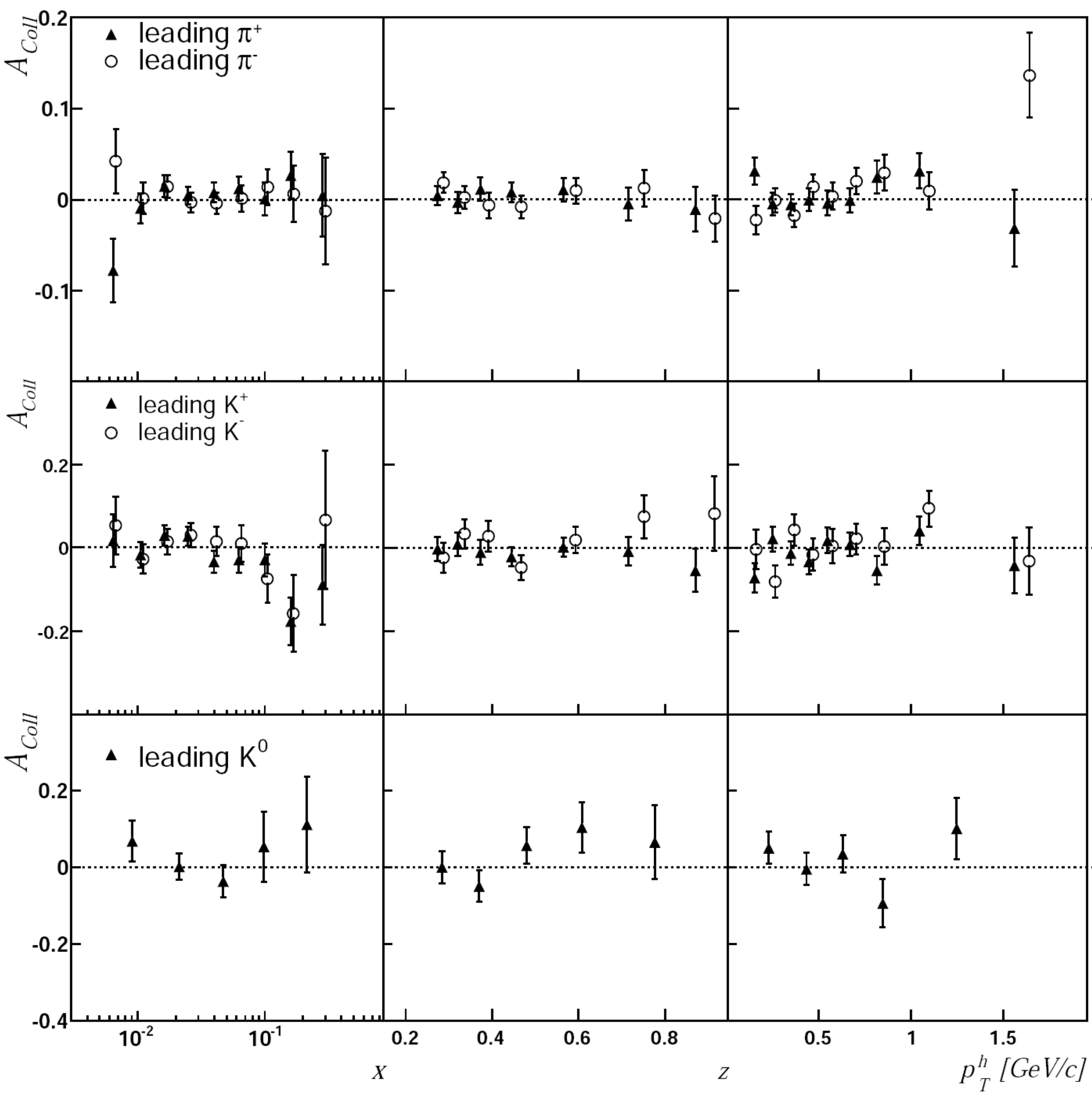
From raw asymmetries:

$A_{Coll} = 1/(f\, P_T\, D_{NN})\, A_c^h$; $A_{Siv} = 1/(f\, P_T)\, A_S^h$

Collins and Sivers Asymmetries for Leading Hadrons (Unidentified) in 2002-04



Collins Asymmetries for Leading Identified Hadrons in 2002-04

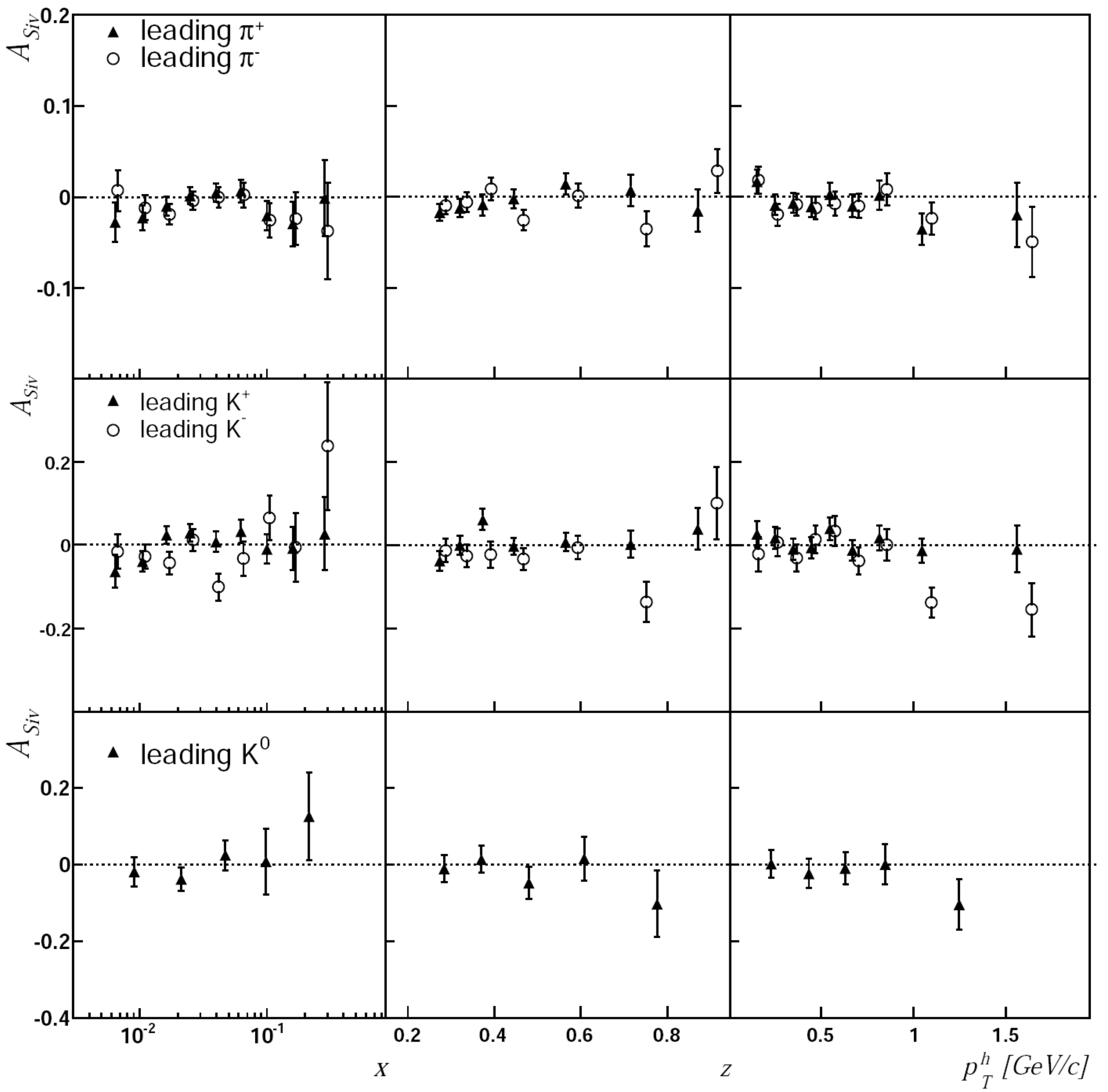


Final sample (03-04):
leading π^+: $3.38 \cdot 10^6$
leading π^-: $2.84 \cdot 10^6$

Final sample (03-04):
leading K^+: $0.72 \cdot 10^6$
leading K^-: $0.44 \cdot 10^6$

Final sample (02-04):
leading K^0_S: $0.175 \cdot 10^6$

Sivers Asymmetries for Leading Identified Hadrons in 2002-04

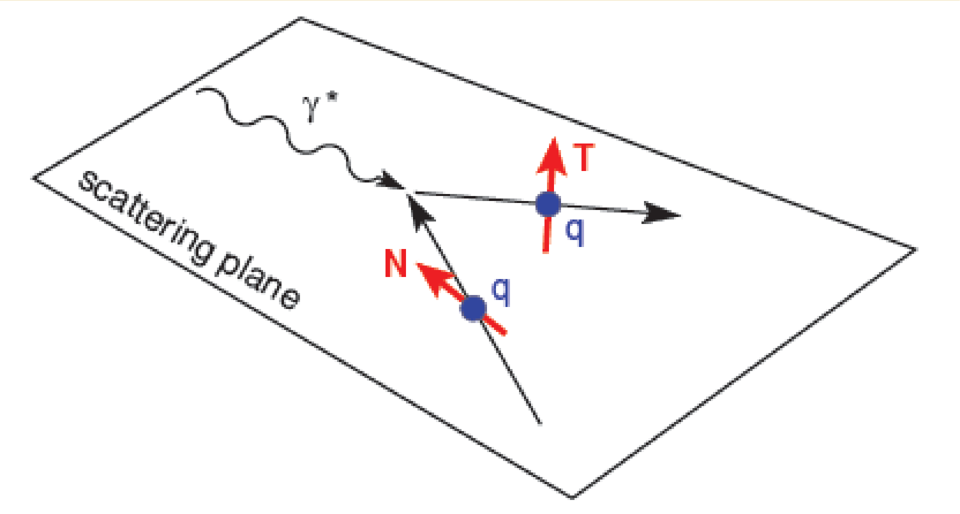


Λ Polarimetry

Information on $\Delta_T q(x)$ can be accessed in the process:

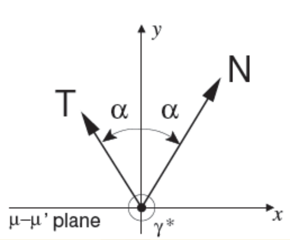
$$\mu \; N^{\uparrow} \;\rightarrow\; \mu' \Lambda^{\uparrow} X$$

(analog for $\bar{\Lambda}$)



N: component of target spin perpendicular to p_{γ^*}

T: symmetric of N wrt. the normal to the scattering plane



$$P_{T,exp}^{\Lambda} = \frac{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} - d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}}{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} + d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}} = f P_N D(y) \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)}$$

f = target dilution factor, P_N = target polarization,

$D(y)$ = virtual photon depolarization factor

$$\Delta_T D_{\Lambda/q}(z) = D_{\Lambda^{\uparrow}/q^{\uparrow}}(z) - D_{\Lambda^{\downarrow}/q^{\uparrow}}(z)$$

more on Λ polarimetry:
→ See talk by Teresa Negrini

Λ Polarimetry