Transversity Measurements at COMPASS

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On behalf of the COMPASS Collaboration

- Transverse spin physics
- COMPASS results on asymmetries
  - Transversity distribution function
  - Sivers distribution function
- Conclusions and outlook – GPDs

new COMPASS result for leading hadron-pairs

new COMPASS result for exclusive ρ production

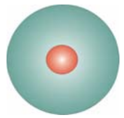
Photon 2007, Paris, July 11

bmb+f - Förderschwerpunkt COMPASS
Großgeräte der physikalischen Grundlagenforschung

Transverse Spin Physics

3 distribution functions are necessary to describe the spin structure of the nucleon at LO:

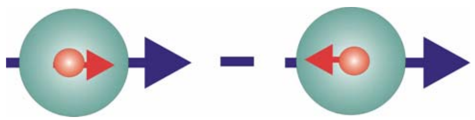
$q(x)$



momentum distribution

well known - unpolarized DIS

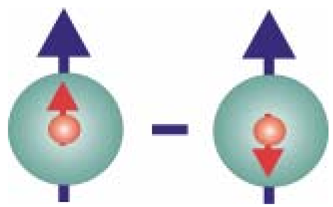
$\Delta q(x)$



helicity distribution

known - polarized DIS

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



transversity distribution

still unknown

$\Delta_T q(x)$ decouples from inclusive DIS: helicity flip of quark
➔ SIDIS experiment

Transversity: How to measure it in SIDIS?

Transversity $\Delta_T q$ (x) chiral odd: observable effect only in combination with chiral odd **fragmentation function**

Suggested quark polarimeters in SIDIS:

- Azimuthal distribution of single hadrons
  Collins fragmentation function

- Azimuthal dependence of the plane containing a hadron pair
  2-hadron interference fragmentation function

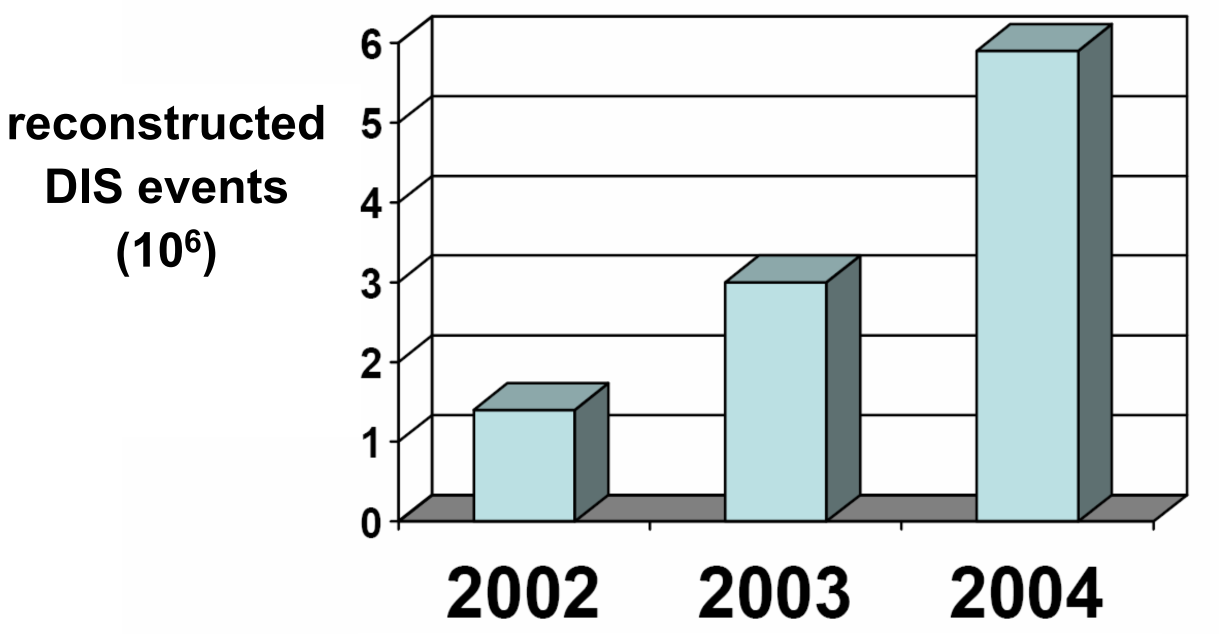
- Measure transverse polarization of Λ
  fragmentation function q→ Λ

Transversity Data Sample

transversely polarized deuteron target
~ 20% of the running time

2002	**11 days of data taking**
2003	**9 days of data taking**
2004	**14 days of data taking**

trigger (large x, Q^2)
+ PID (ECAL, RICH)

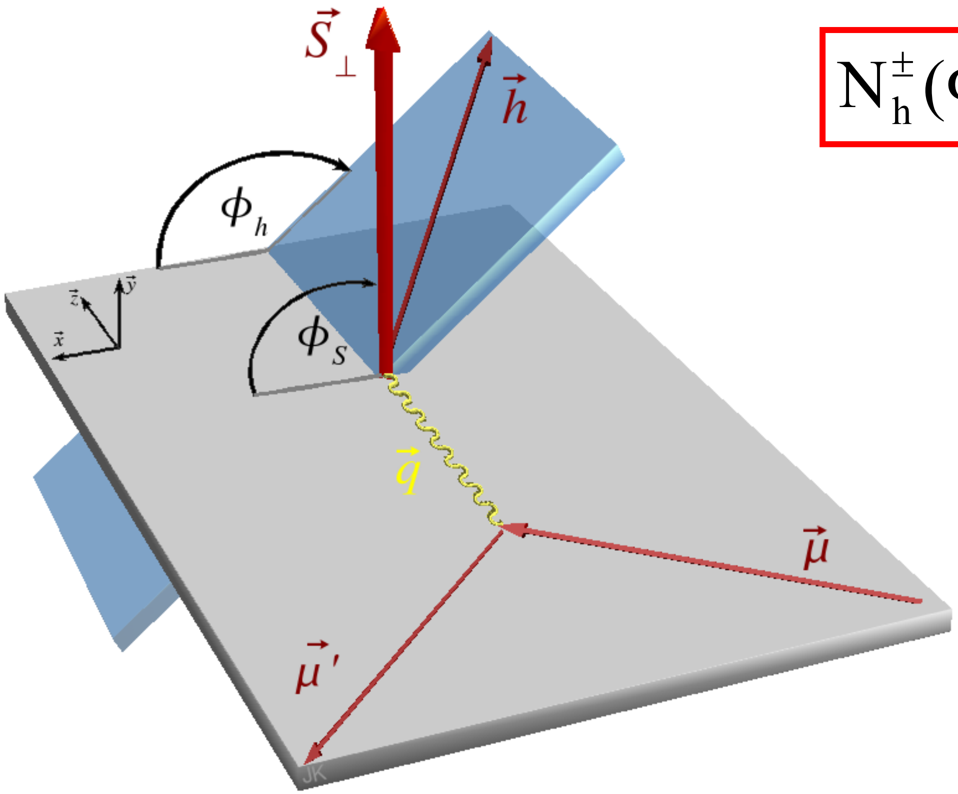


10 Mill. DIS events

Collins Asymmetry

SIDIS on a transversely polarized target: l N$^{\uparrow}$ → l´h X

Fragmentation of a transversely polarized quarks into hadrons
→ azimuthal asymmetry:



$$N_h^{\pm}(\Phi_{Coll}) = N_h^0 \{1 \pm A_C^h \cdot \sin \Phi_{Coll}\}$$

In SIDIS, the Collins angle Φ_{Coll} is defined as:

$$\Phi_{Coll} = \phi_h + \phi_S - \pi$$

Collins Asymmetry

The measured asymmetry A_{Coll} gives access to the transversity distribution times the Collins fragmentation function:

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

f: Dilution factor ≈ 0.38

D_{nn}: Depolarization factor

$D_{nn}=2(1-y)/(1+(1-y)^2)$

P_T: Target polarization ≈ 0.5

$\Delta_T q(x)$: Transversity distribution

$\Delta_T^0 D_q^h$: Collins fragmentation function (measured in e^+e^- at BELLE)

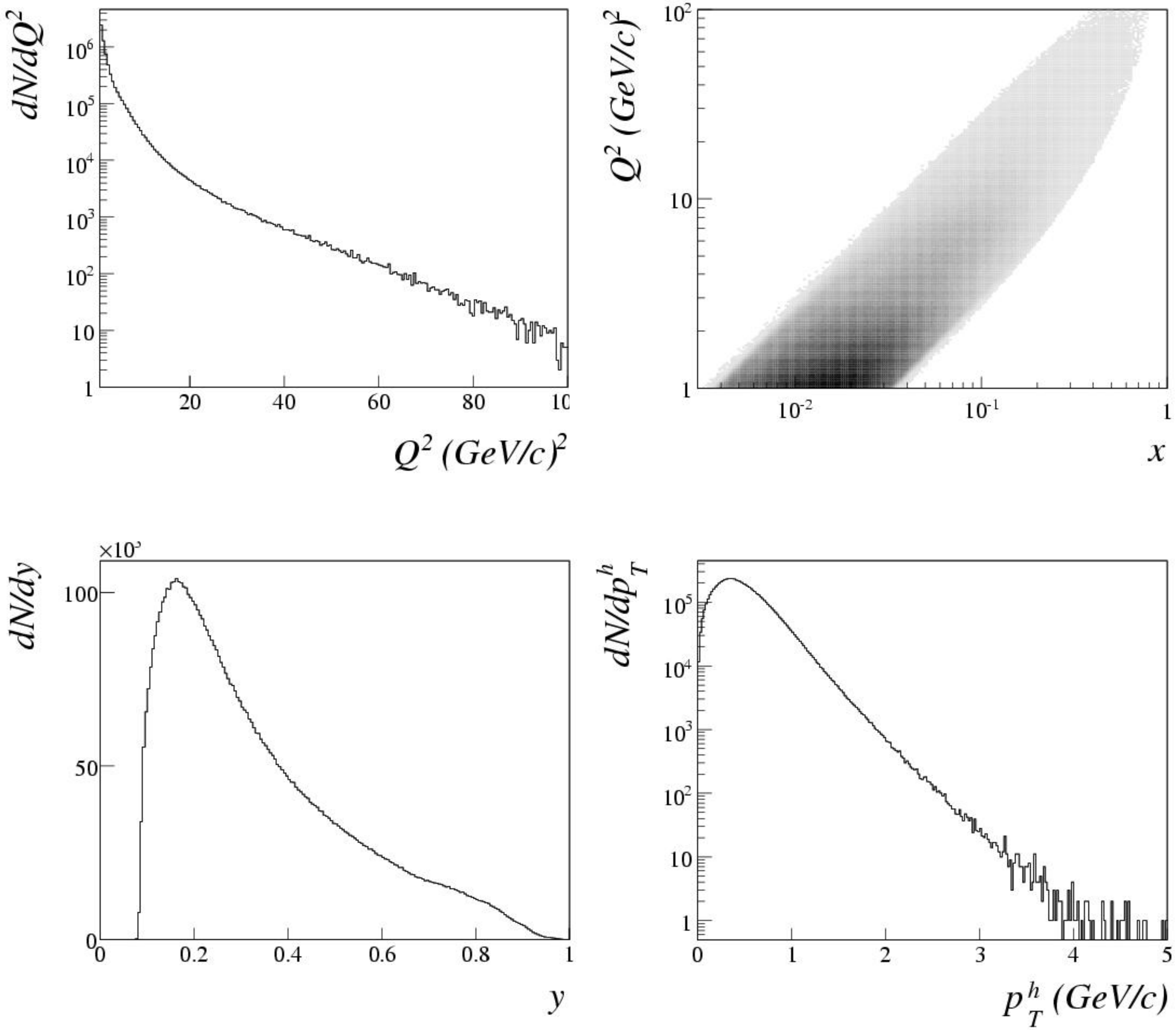
Selection of SIDIS Events

DIS cuts:

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

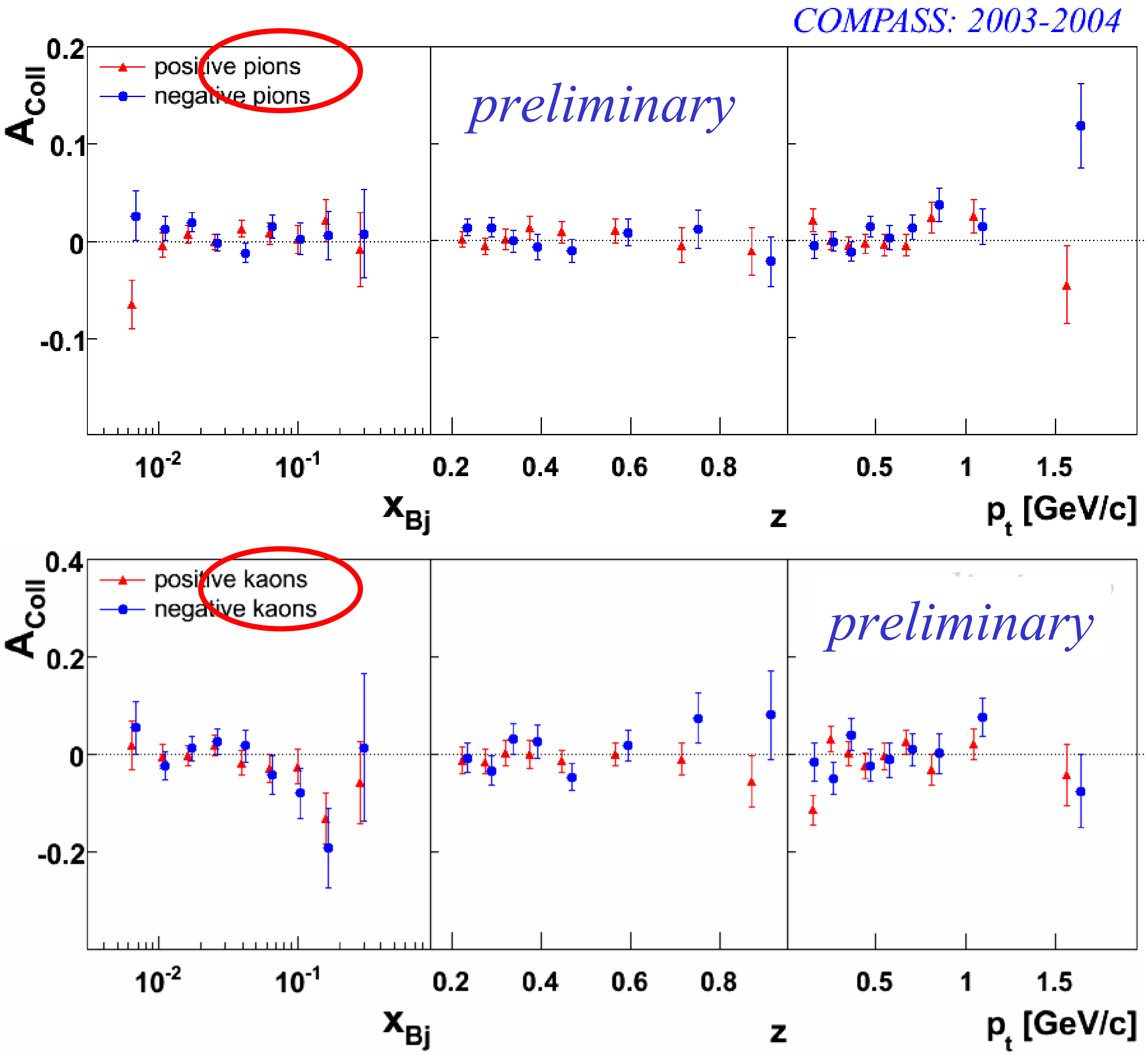
hadron selection:

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



COMPASS Results: Collins Effect

Deuteron target



only statistical errors shown (systematical errors considerably smaller)

Interpretation

- naive interpretation: parton model, valence region:

$$A_{Coll}^{d,\pi^+}(x) \cong \frac{\Delta_T u_v(x) + \Delta_T d_v(x)}{u_v(x) + d_v(x)} \cdot \frac{4\Delta_T^0 D_1 + \Delta_T^0 D_2}{4D_1 + D_2}$$

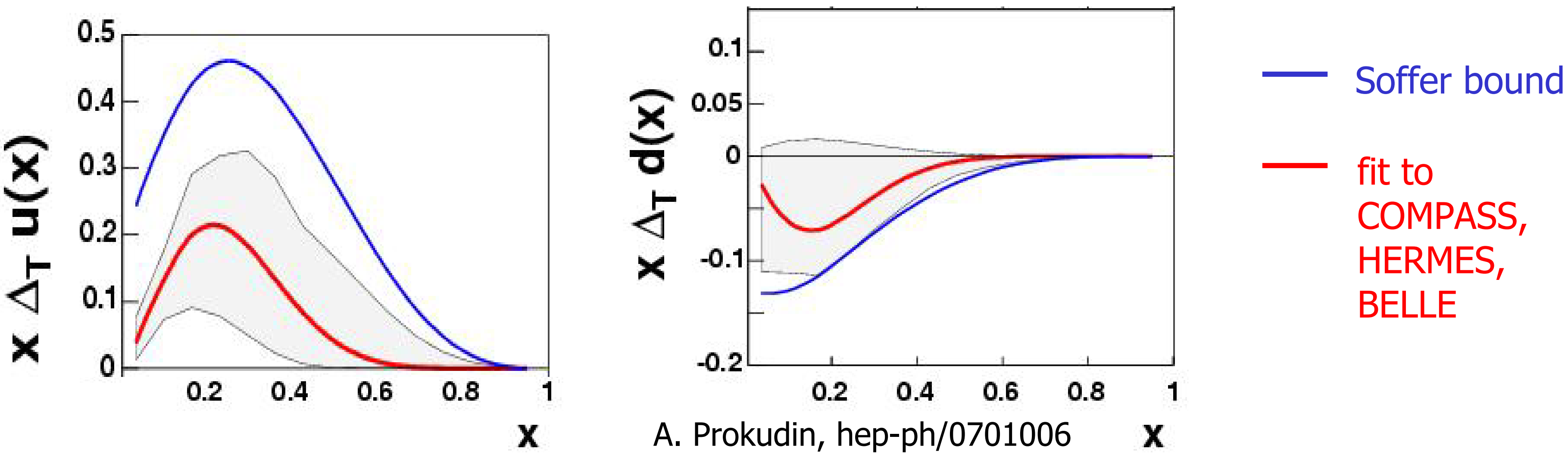
$$A_{Coll}^{d,\pi^-}(x) \cong \frac{\Delta_T u_v(x) + \Delta_T d_v(x)}{u_v(x) + d_v(x)} \cdot \frac{\Delta_T^0 D_1 + 4\Delta_T^0 D_2}{D_1 + 4D_2}$$

isospin-symmetric deuteron target

D_1: favored FF
D_2: disfavored FF

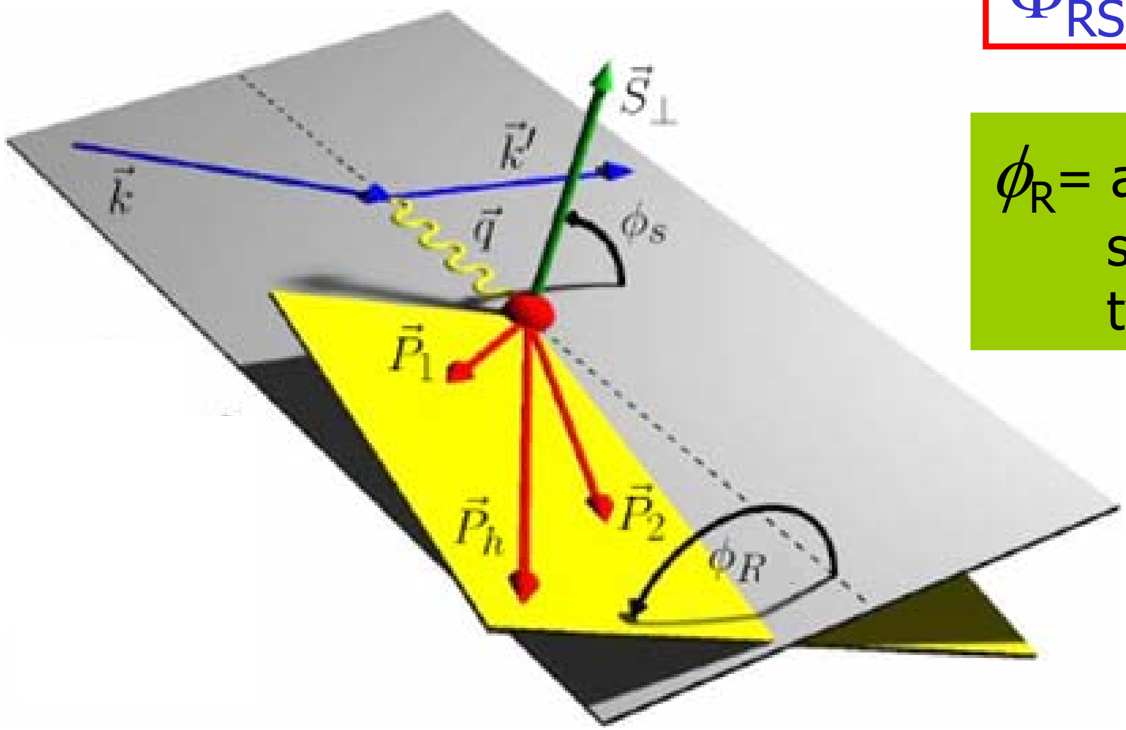
Small asymmetries → cancellation between $\Delta_T u(x)$ and $\Delta_T d(x)$

- Extraction of transversity distribution from COMPASS (deuteron), HERMES (proton) and BELLE (Collins FF) data:



A. Prokudin, hep-ph/0701006

Transversity in Hadron-Pair Production



Collins-Angle replaced by:

$$\Phi_{RS} = \phi_R + \phi_S - \pi$$

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

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

(X. Artru, hep-ph/0207309)

Azimuthal Asymmetry for Hadron-Pair Production

Target single spin asymmetry $A_{RS}(x,z,M_h^2)$: $z=z_1+z_2$

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

(X. Artru, hep-ph/0207309)

$H_q^{\angle h}(z, M_h^2)$: Two-hadron interference fragmentation function

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

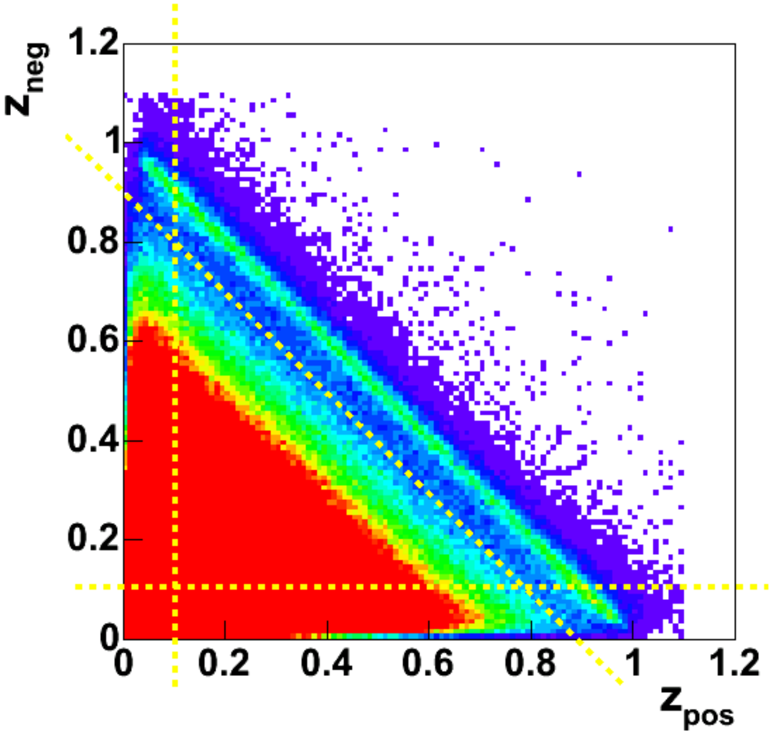
↓

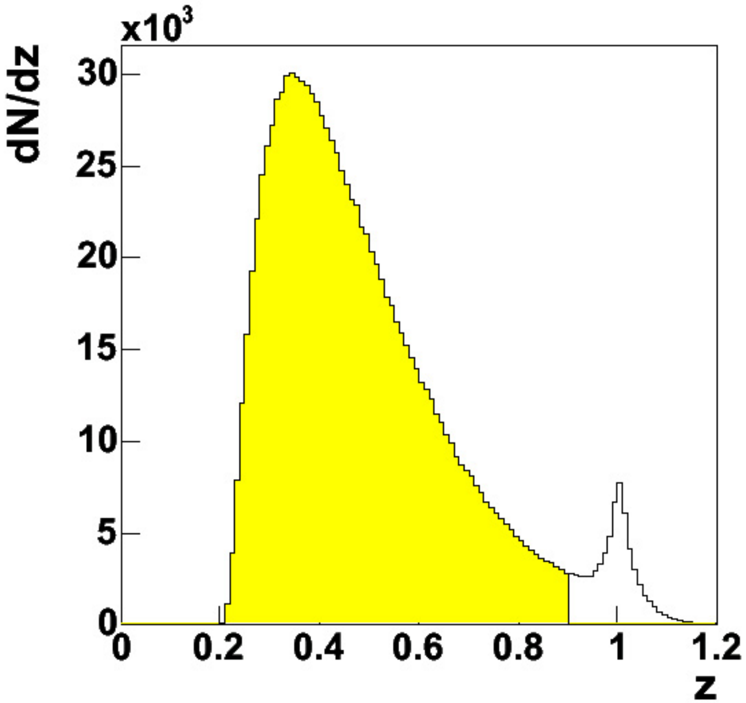
expected to depend on the hadron pair invariant mass

Event Selection

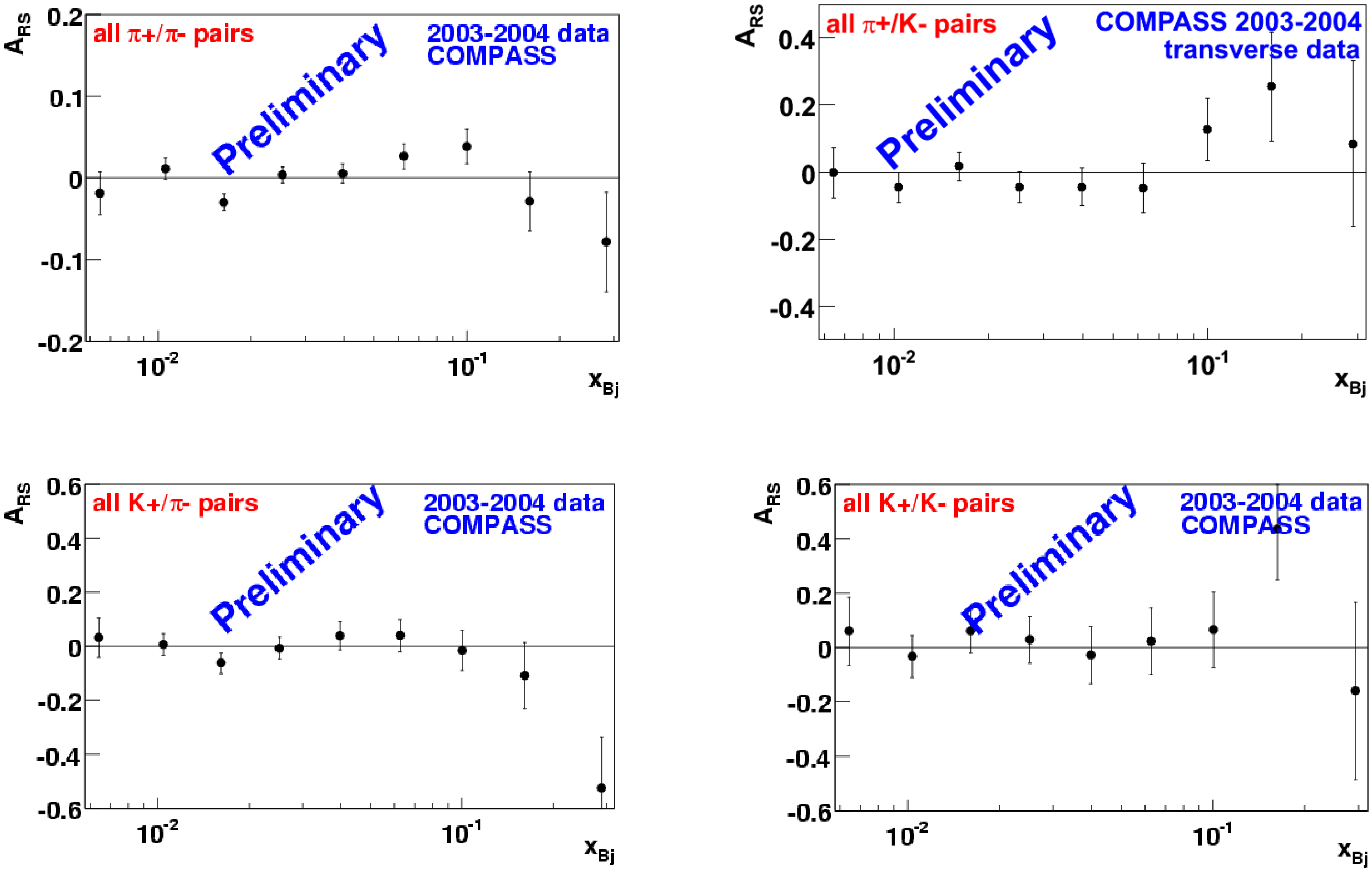
Hadron pair selection:

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

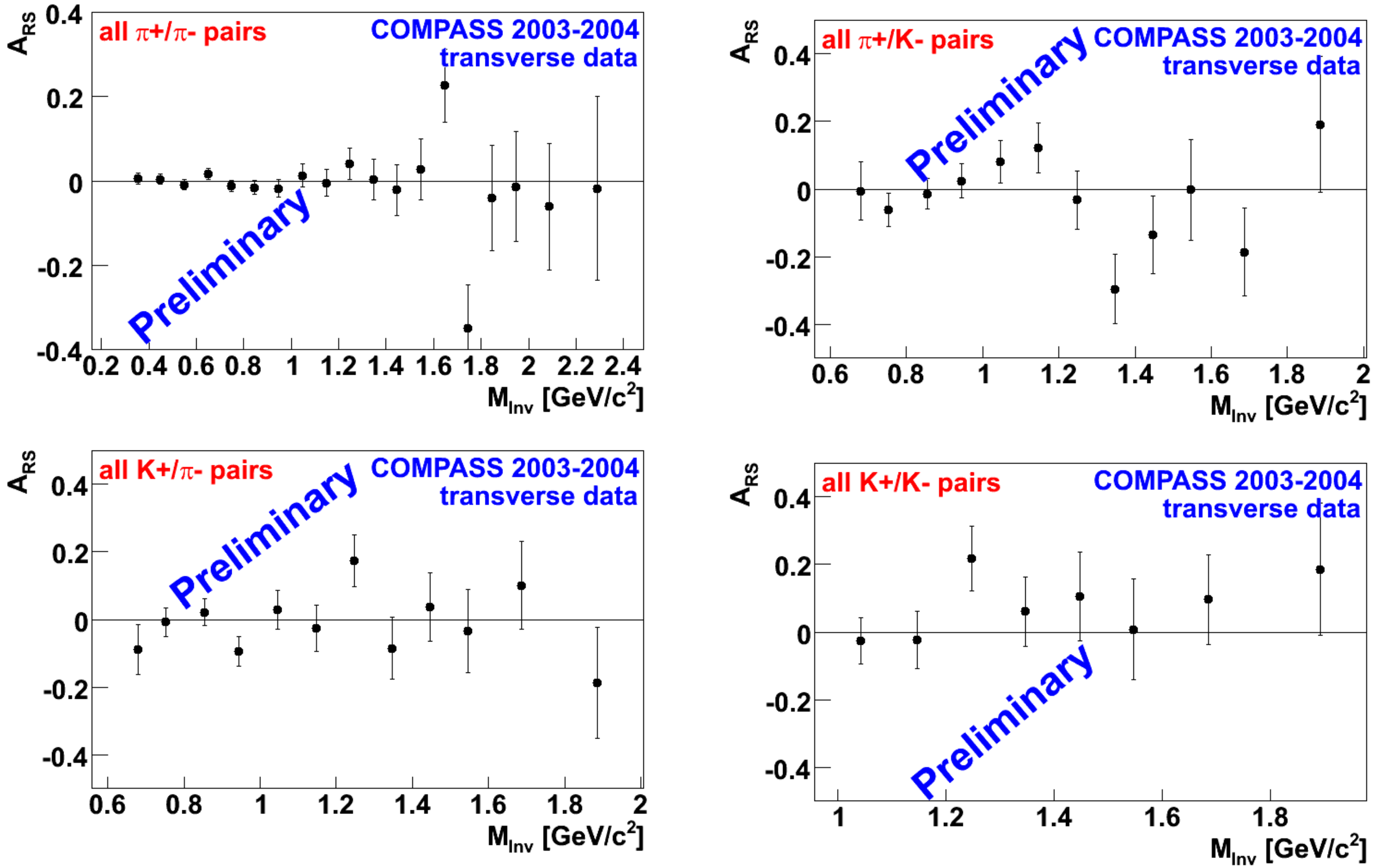




COMPASS Results for Hadron Pairs



COMPASS Results for Hadron Pairs



Model calculations suggest (A. Bacchetta, M. Radici, hep-ph/0608037):

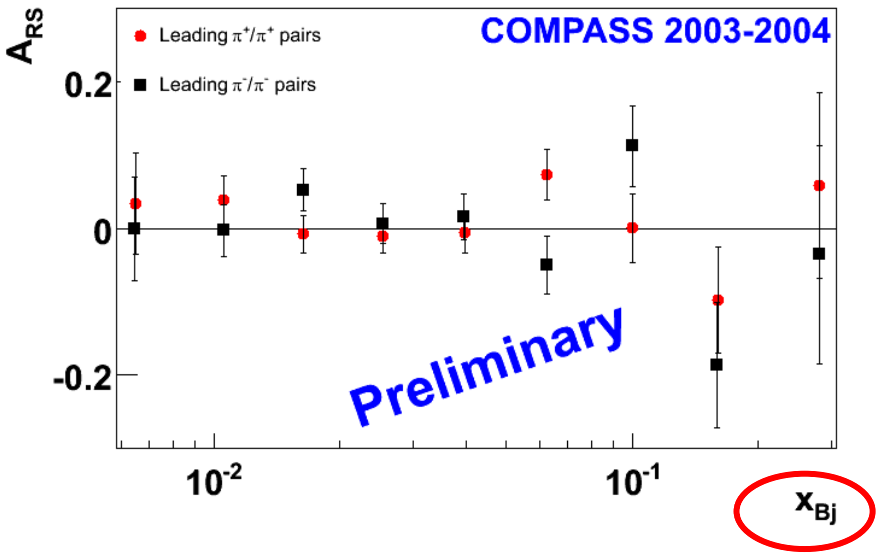
cancellation between $\Delta_T u_v(x)$ and $\Delta_T d_v(x)$

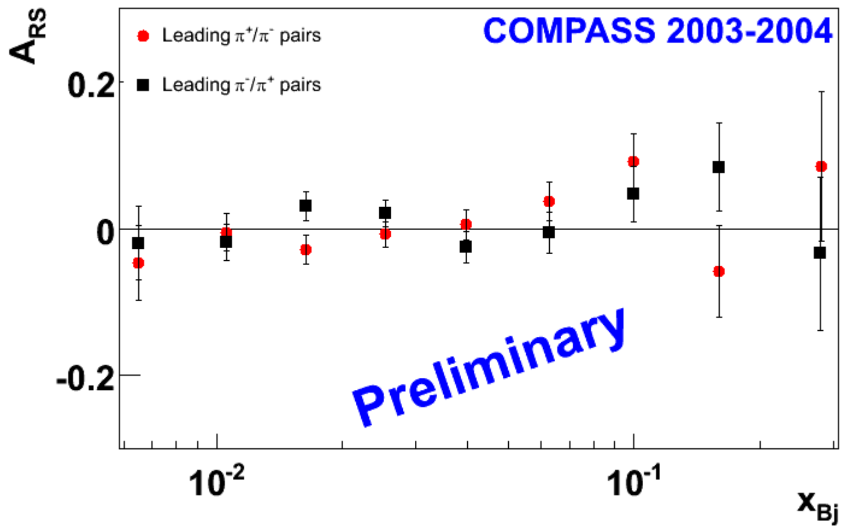
New Results: Leading Hadron Pairs z-ordered

Leading hadrons may carry more information about the fragmenting quark

- z-ordered hadron pairs: $z_1 > z_2$
- $z = z_1 + z_2 > 0.25$

h_1: leading hadron
h_2: sub-leading hadron





$\pi^+\pi^+$
$\pi^-\pi^-$

$\pi^+\pi^-$
$\pi^-\pi^+$

New Results: Leading Hadron Pairs z-ordered

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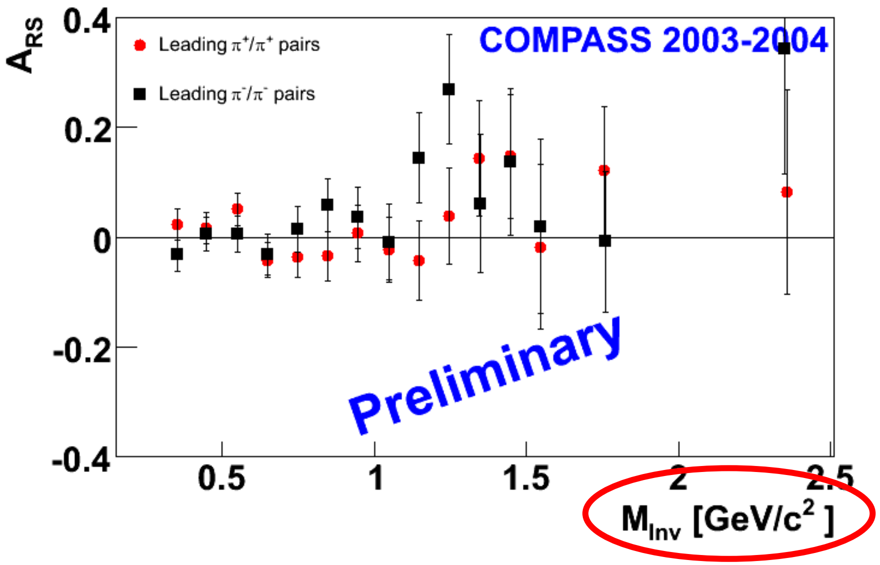
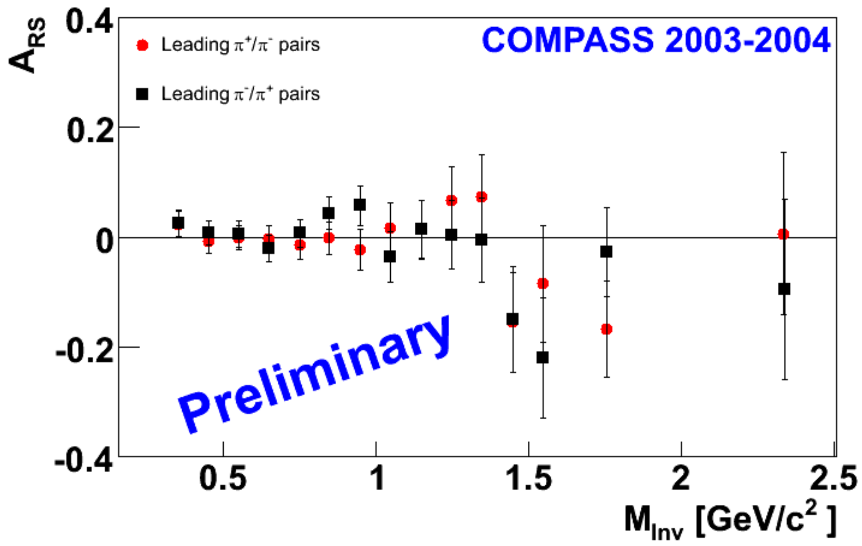


$\pi^+\pi^+$
$\pi^- \pi^-$



$\pi^+\pi^-$
$\pi^- \pi^+$

Sivers Effect

- Intrinsic transverse momentum of unpolarized quarks in a transversely polarized nucleon → azimuthal asymmetry

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

$\Phi_{Siv} = \phi_h - \phi_S$

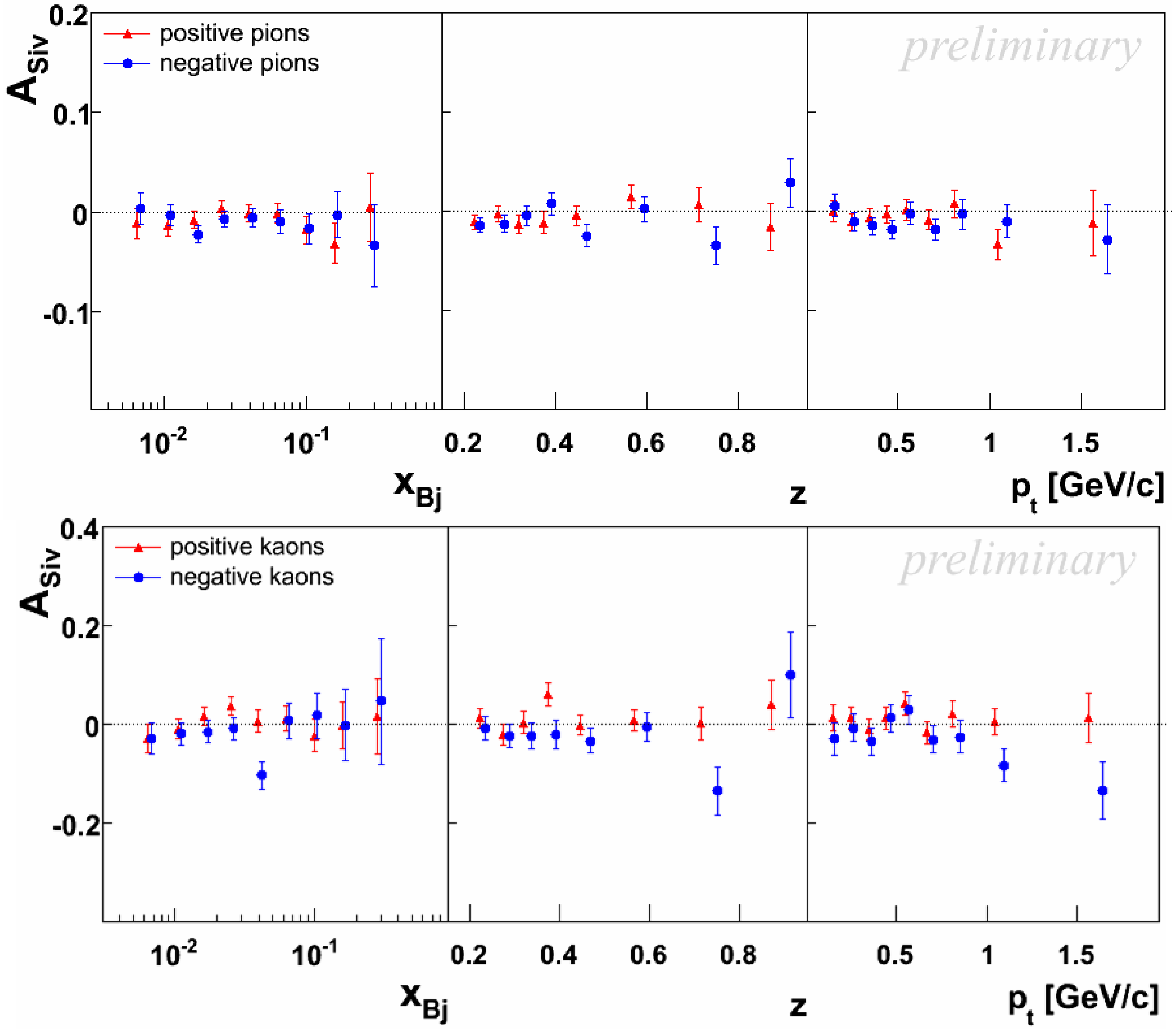
Sivers angle independent of Collins angle: measure both in the same data

The Sivers asymmetry:

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

$\Delta_0^T q(x)$: Sivers function

COMPASS Results: Sivers effect



only statistical errors shown (systematical errors considerably smaller)

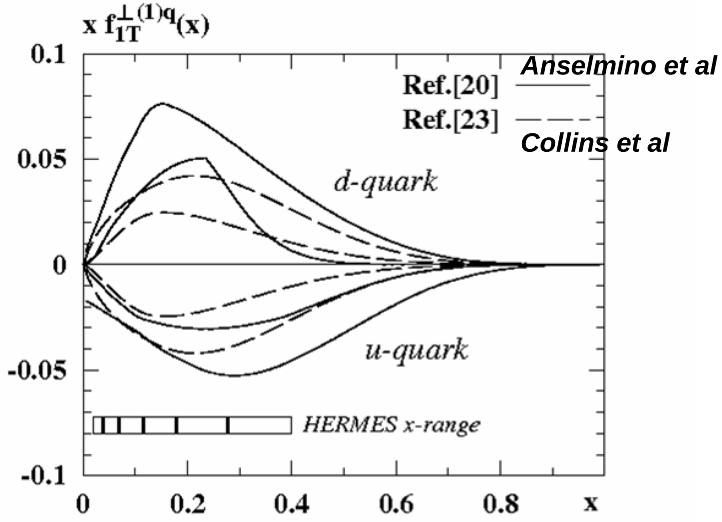
Interpretation

- naive interpretation: parton model, valence region:

$$A_{Siv}^{d,\pi^+}(x) \approx A_{Siv}^{d,\pi^-}(x) \approx \frac{\Delta_0^T u_v(x) + \Delta_0^T d_v(x)}{u_v(x) + d_v(x)}$$

Small asymmetries suggest $\Delta_0^T d_v(x) \cong -\Delta_0^T u_v(x)$

- Data on the proton (HERMES experiment) different from zero, extraction of the Sivers function from COMPASS & HERMES:



Anselmino et al. hep-ph/0511017

Beyond Collins and Sivers Mechanism

SIDIS cross-section in one-photon exchange approximation:
8 transverse target spin dependent azimuthal modulations

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

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

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

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

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

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

Sivers

Collins

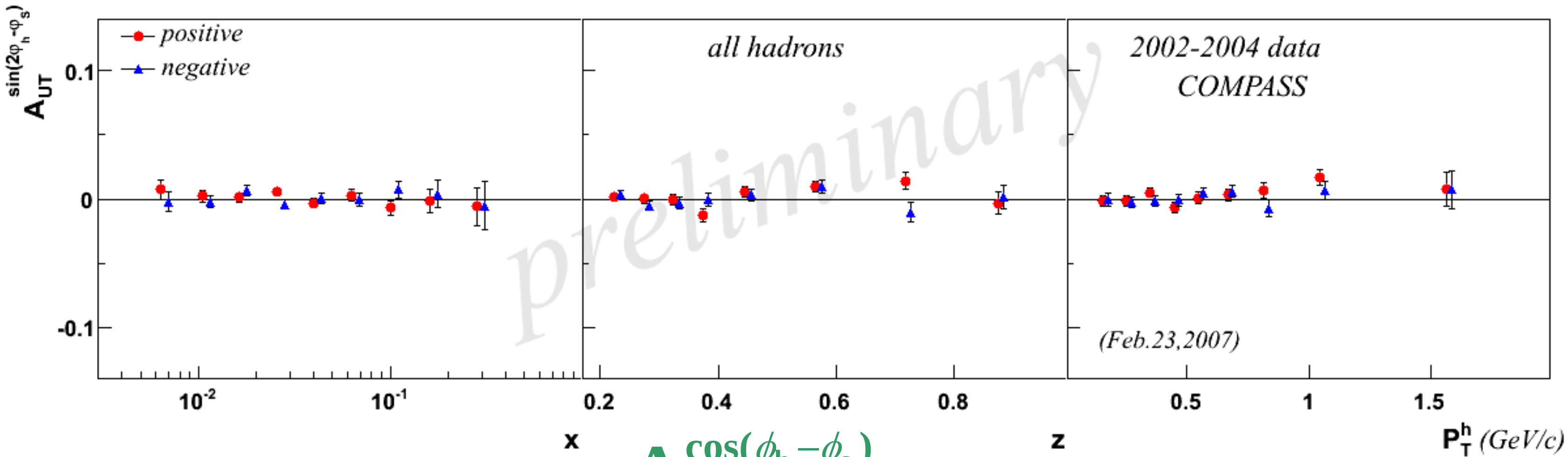
6 further modulations

ε-photon flux

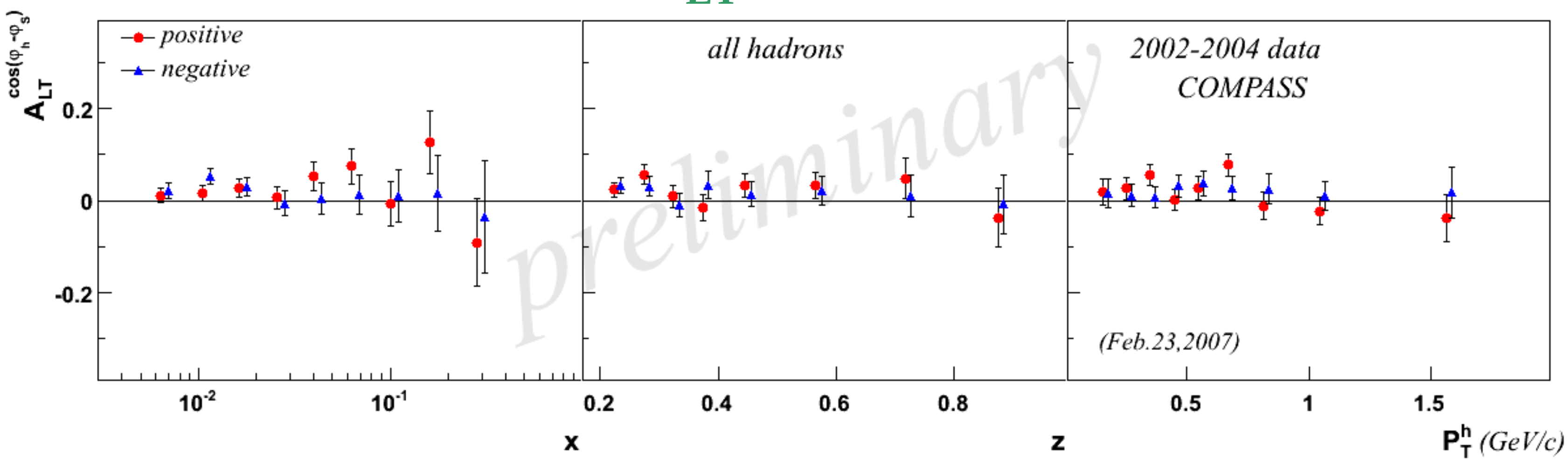
M. Diehl, S. Sapeta,
Eur.Phys.J **C41** (2005) 515-533
hep-ph/0503023

Beyond Collins and Sivers Mechanism

$$A_{UT}^{\sin(2\phi_h - \phi_s)}$$



$$A_{LT}^{\cos(\phi_h - \phi_s)}$$



all new asymmetries small and compatible with zero

Conclusions and Outlook

- Precise COMPASS data for transverse spin asymmetries on the deuteron

- Channels investigated so far:
  - Collins asymmetries on positive and negative hadrons, $\pi^{\pm}$, $K^{\pm}$
  - Hadron pair asymmetries
  - Sivers asymmetries
  - 6 new observables beyond Collins and Sivers

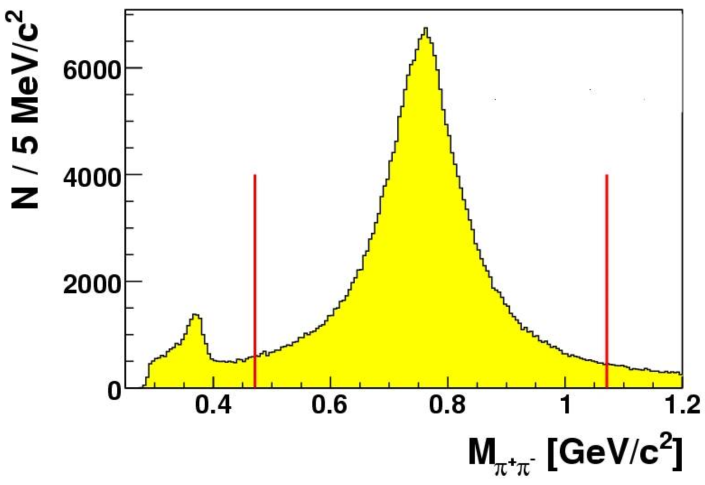
- All measured asymmetries very small and compatible with zero

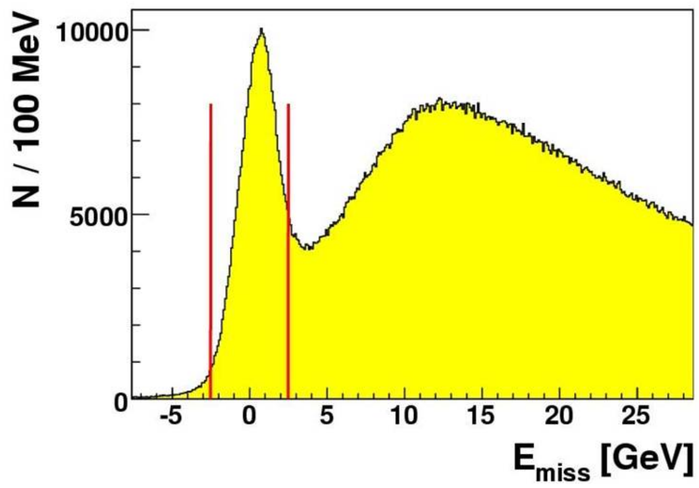
- Combined analysis of deuteron (COMPASS) and proton (COMPASS/HERMES) data allows extraction of transversity $\Delta_T q(x)$

Outlook:

- COMPASS data taking on a transversely polarized proton target started in June 2007
- Analysis of single spin asymmetries in exclusive reactions to get access to GPDs

Outlook: SSA for Exclusive Rho Production





$\mu + d \rightarrow \mu' + d + \rho$

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

Exclusive Rho:

$-2.5\ \text{GeV} < E_{miss} < 2.5\ \text{GeV}$

$0.01\ (\text{GeV}/c)^2 < p_T^2 < 0.5\ (\text{GeV}/c)^2$

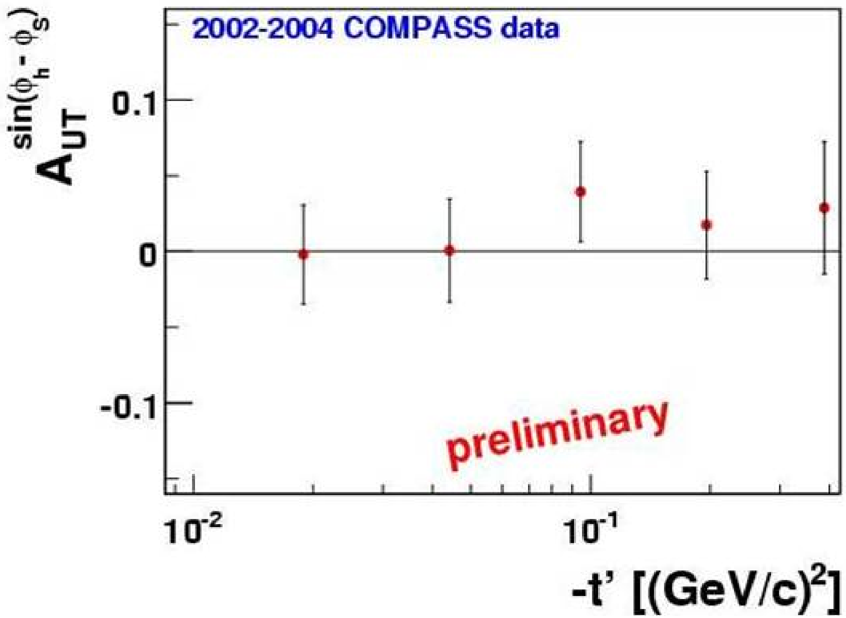
$-0.3\ (\text{GeV}/c)^2 < M_{\pi\pi} - M_\rho < 0.3\ (\text{GeV}/c)^2$

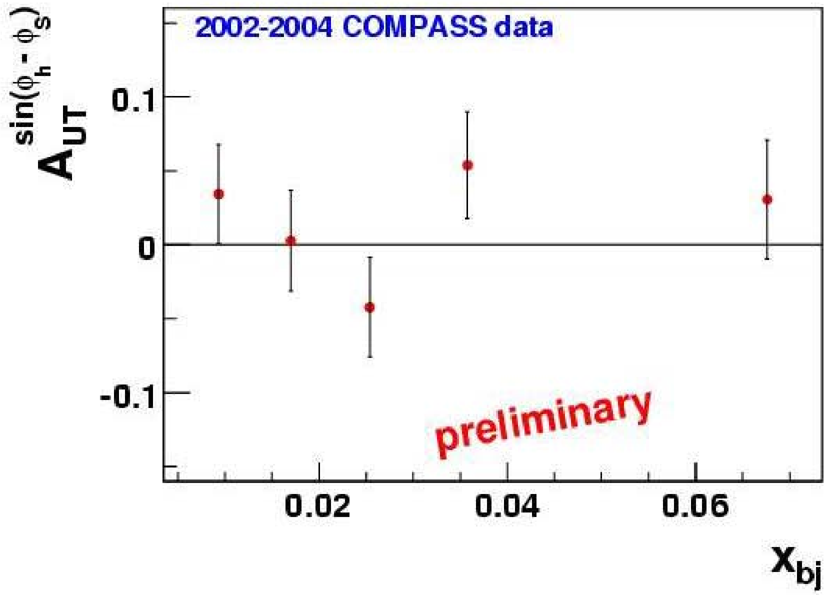
- Exclusive vector meson production on the deuteron sensitive to the GPDs H, E

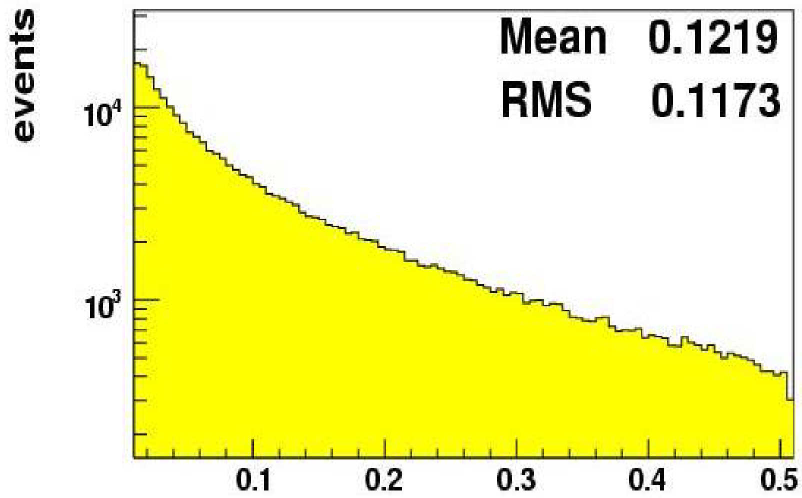
Berger, Cano, Diehl et al.
hep-ph/0106192

- GPDs may give access to total angular momentum of quarks in the nucleon

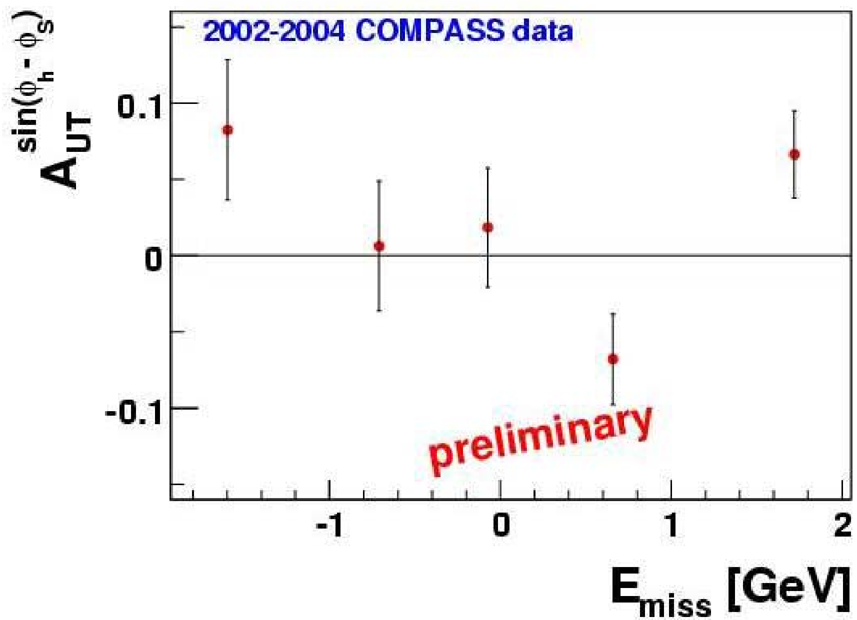
New Results: SSA for Exclusive Rho Production





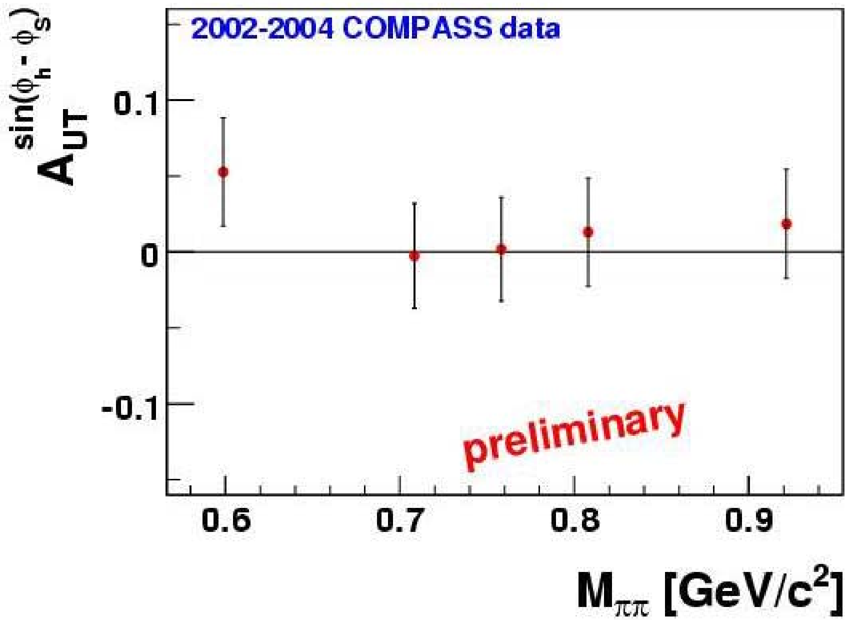


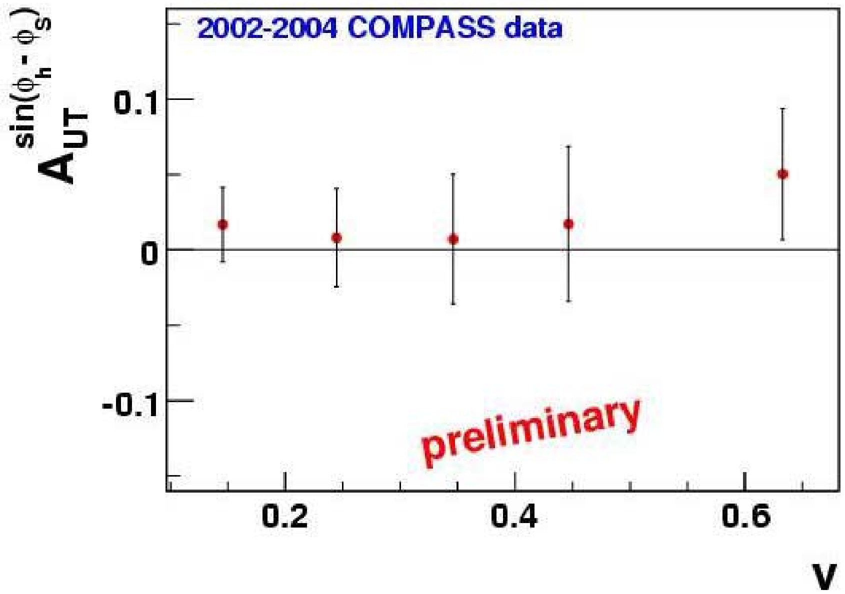
Reduced 4-momentum transfer -t' [(GeV/c)^2]

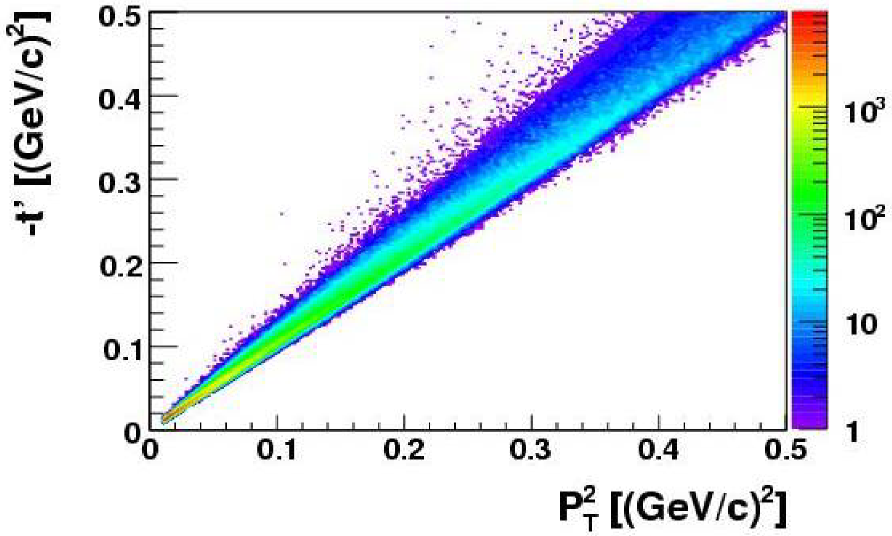


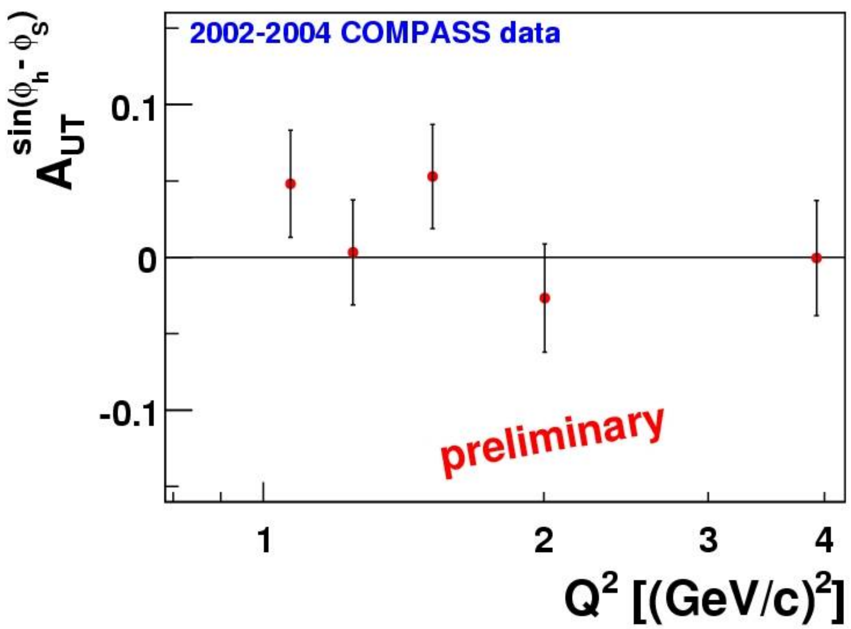
Thank you!

New Results: SSA for Exclusive Rho Production

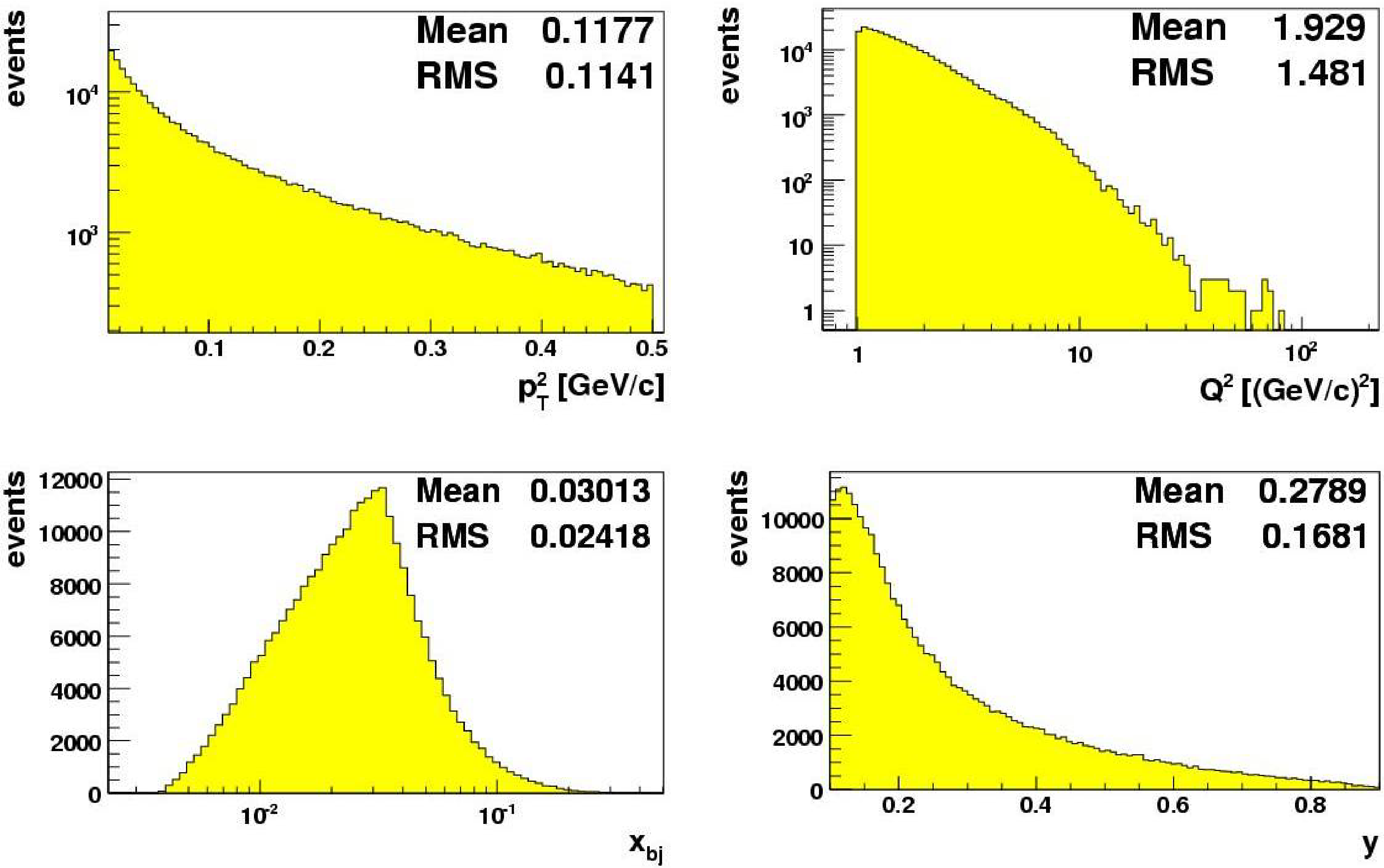




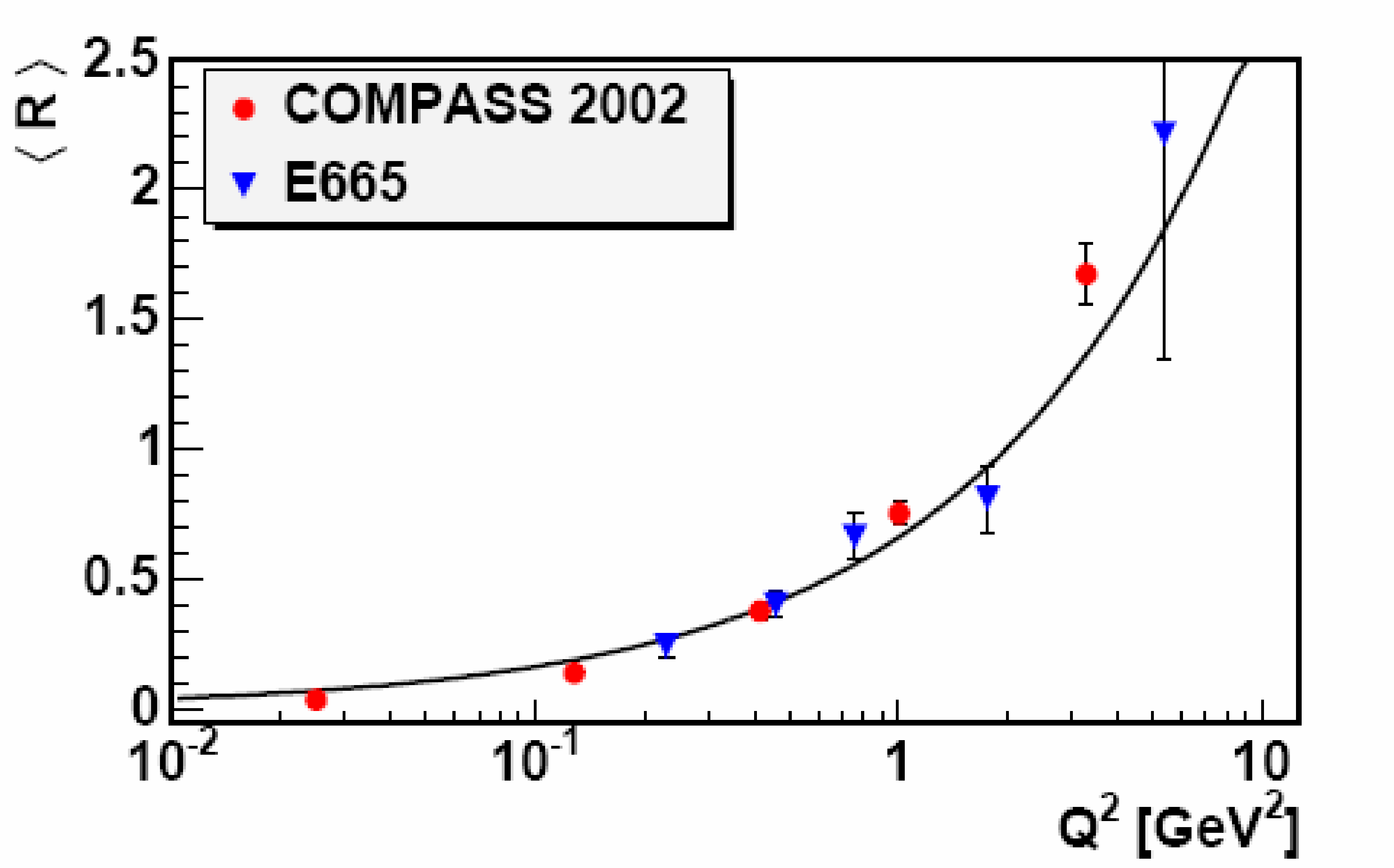




New Results: SSA for Exclusive Rho Production

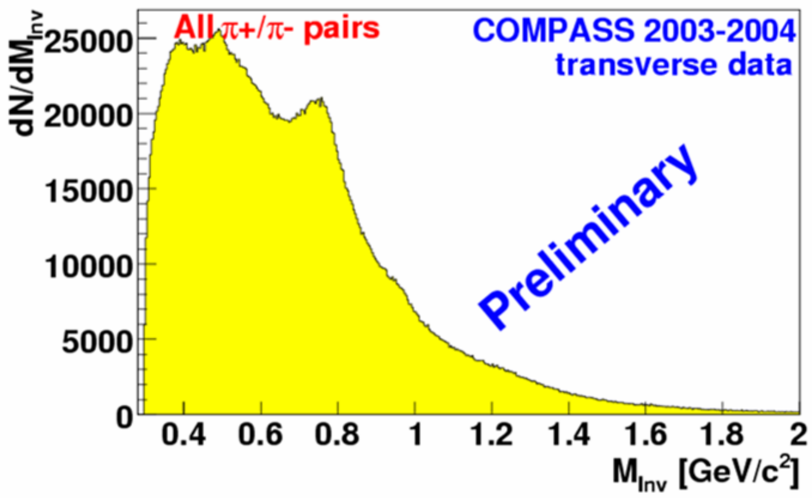


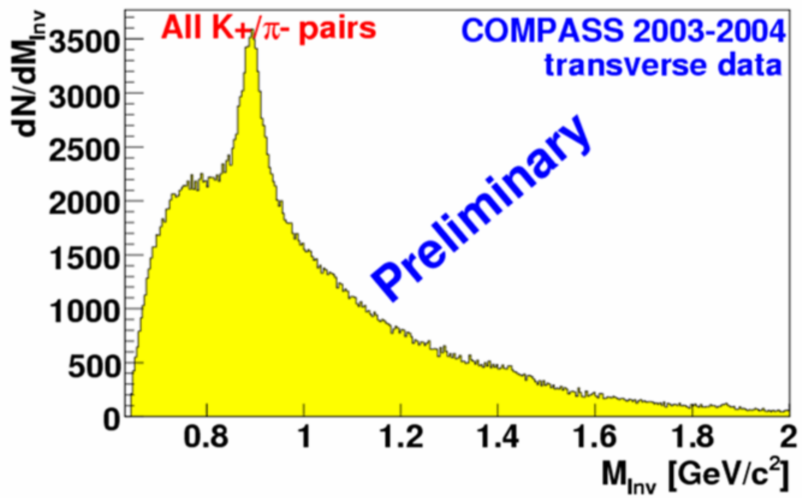
$R=\sigma_L/\sigma_T$ for Exclusive ρ Production

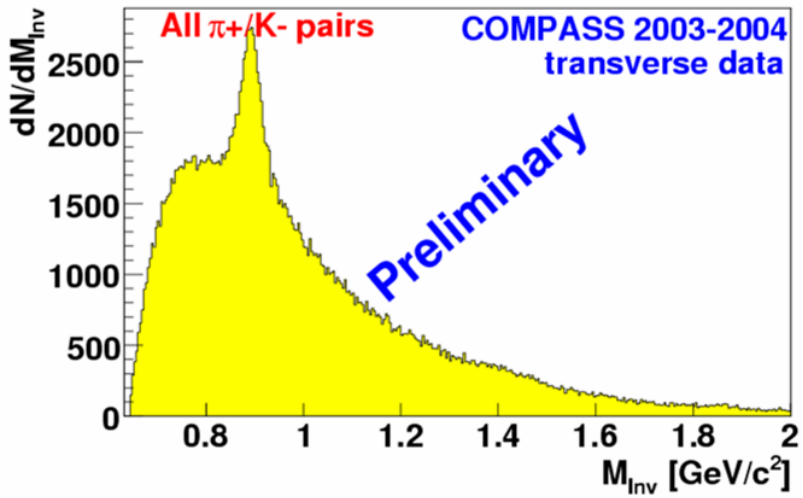


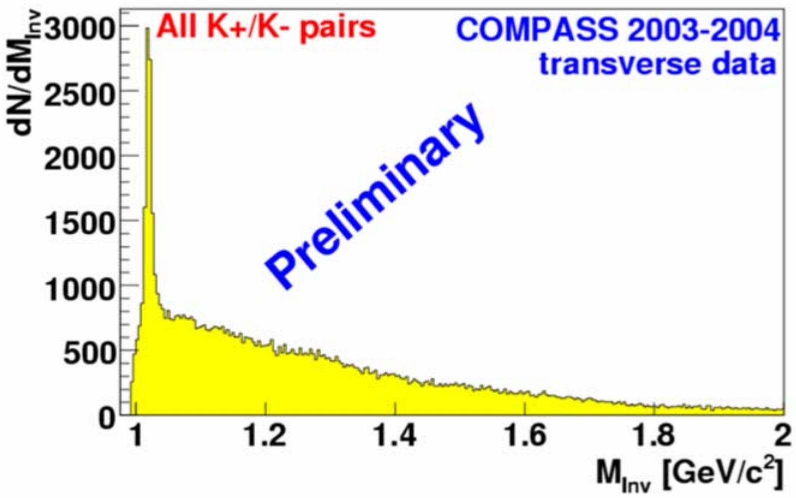
Hadron Pairs Invariant Mass Spectra

all hadron pairs: 5.3 M

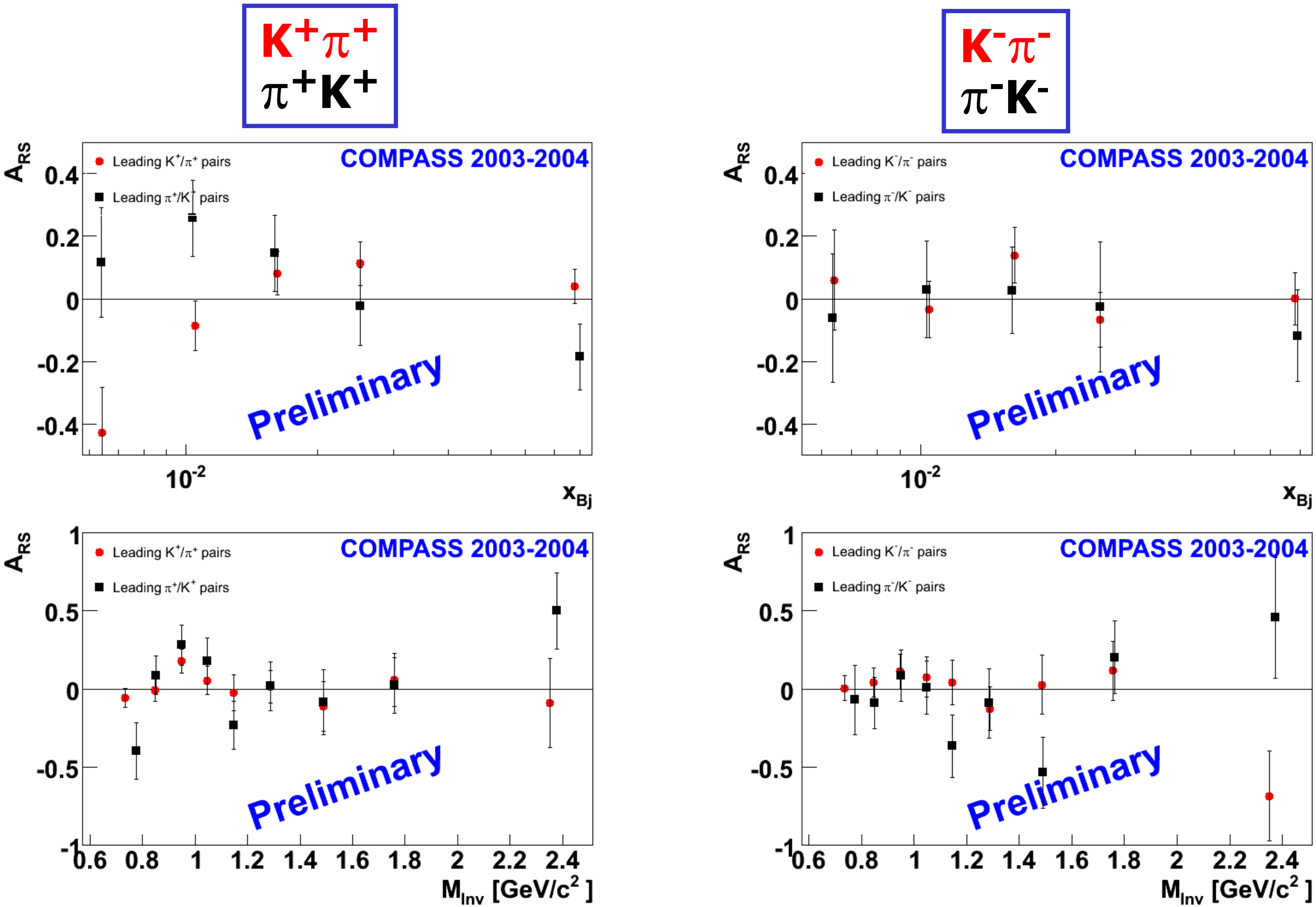








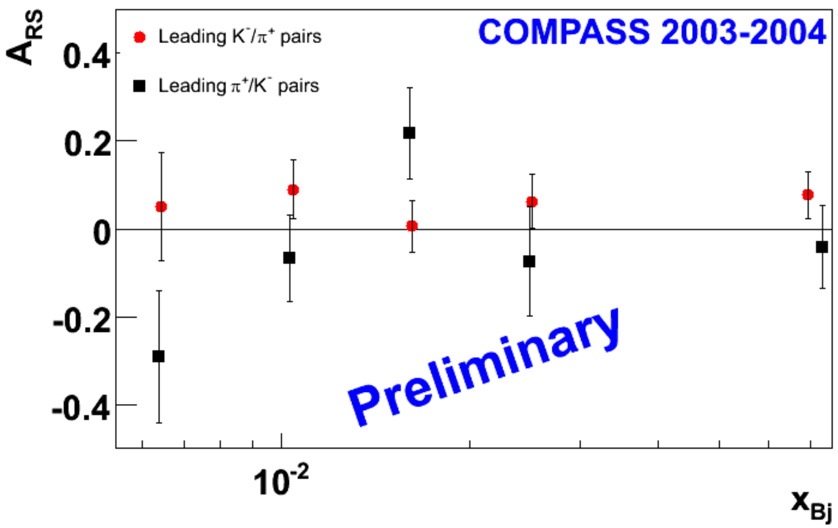
New Results: Leading π/K Pairs z-ordered

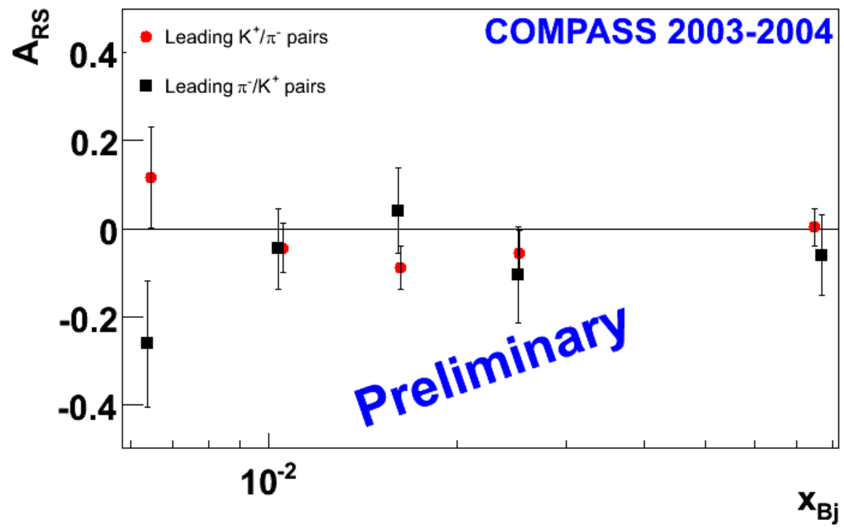


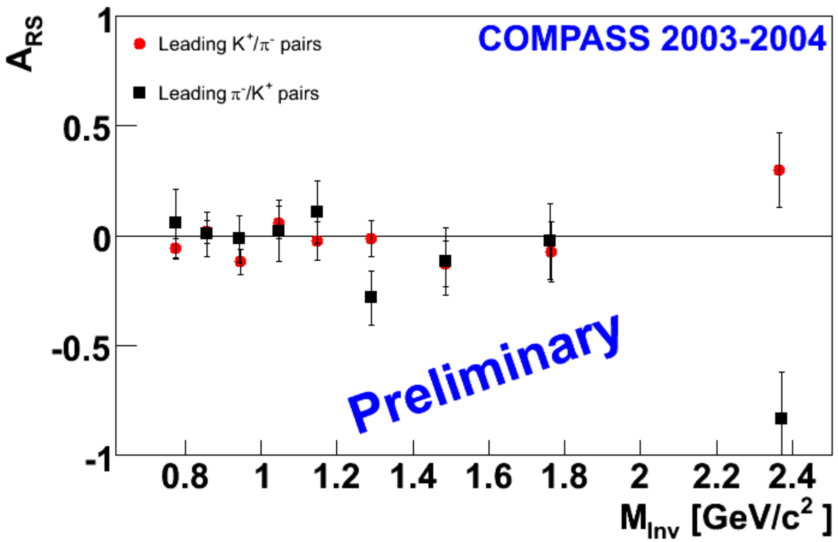
New Results: Leading π/K Pairs z-ordered

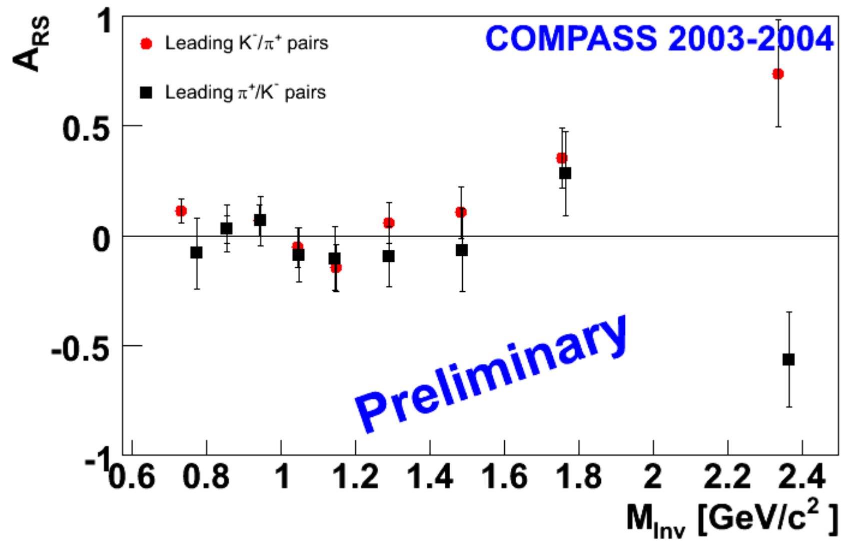
$K^-\pi^+$
π^+K^-

$K^+\pi^-$
π^-K^+

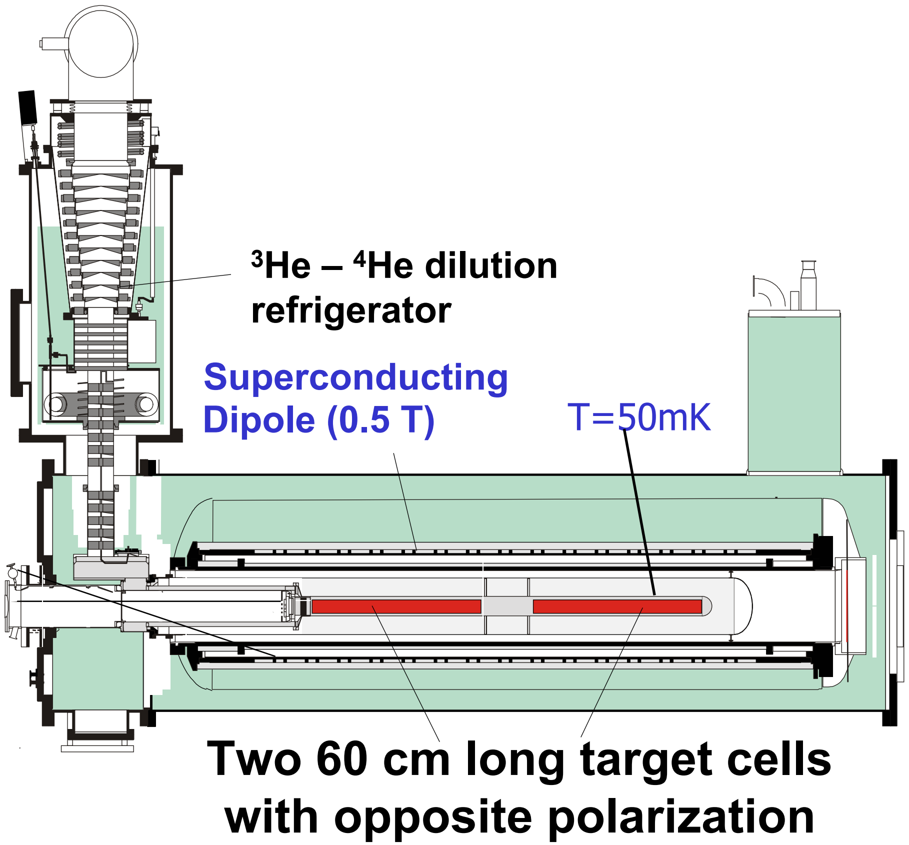




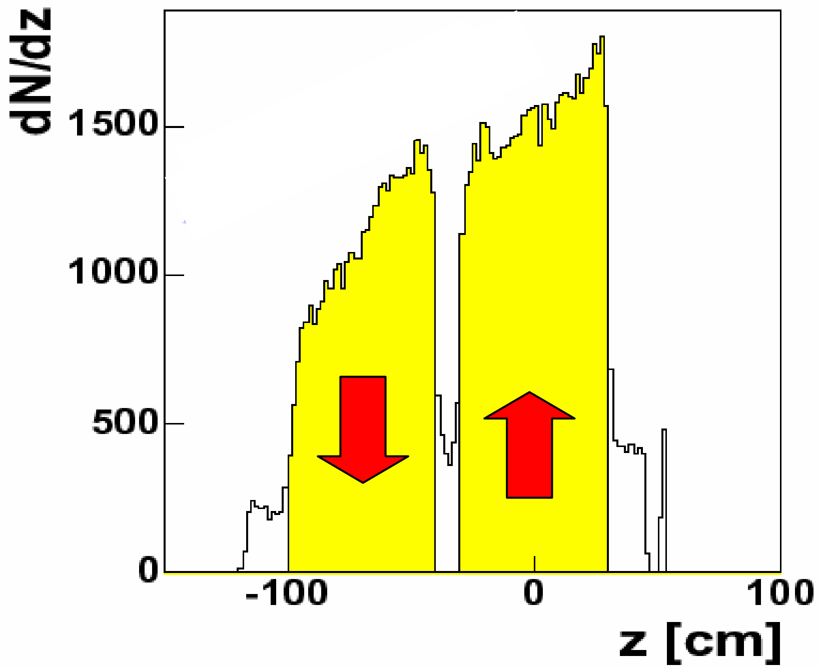




The polarised ^{6}LiD-Target



Vertex distribution:



Transverse target polarization:
Reversed one a week

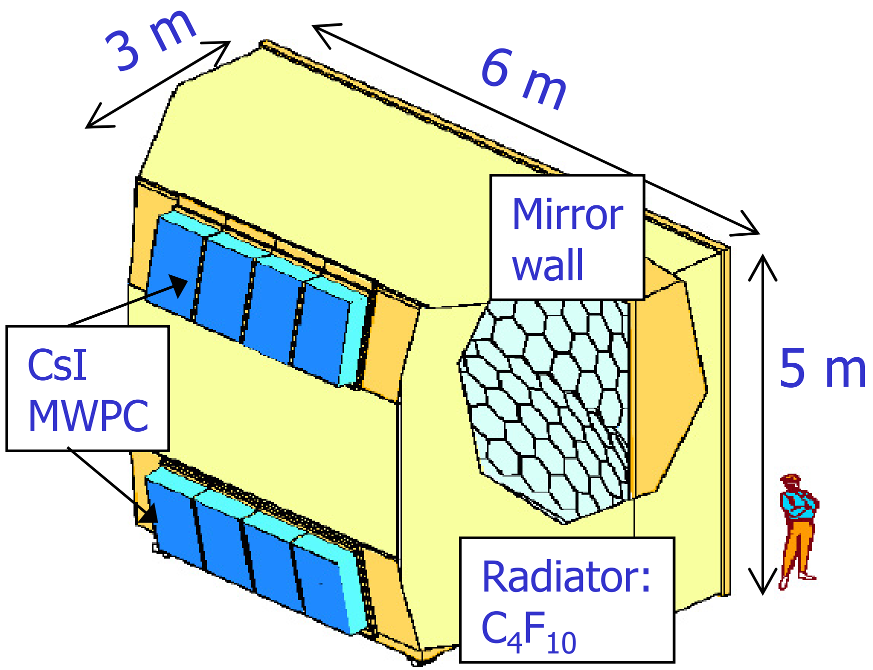
Polarization: 50 %
Dilution factor: 0.38

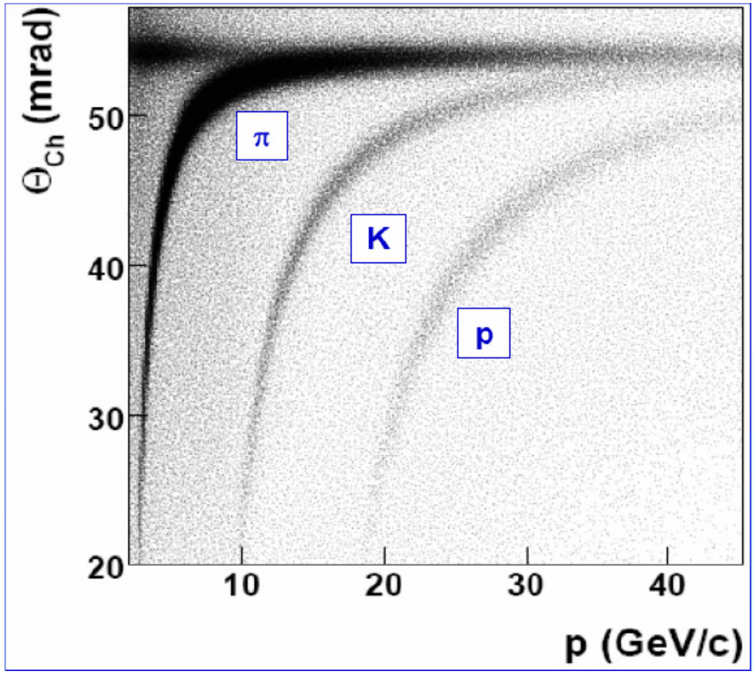
Ring Imaging Cherenkov Detector

Identification of π, K and protons

Cherenkov thresholds: $\pi \approx 3$ GeV/c
$K \approx 9$ GeV/c
$p \approx 17$ GeV/c

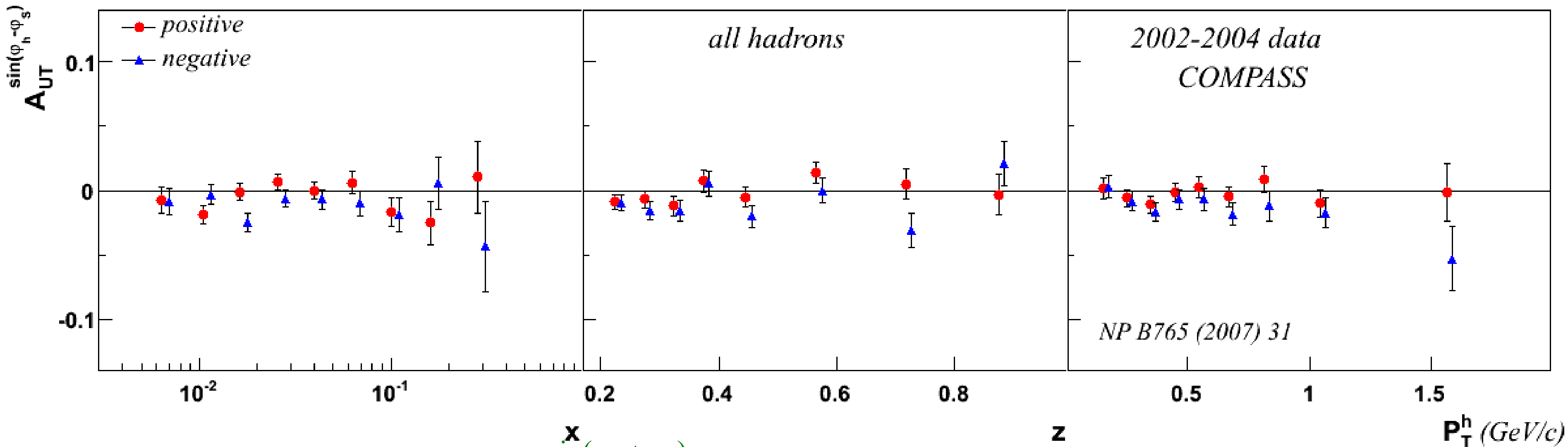
2σ π/K separation at 43 GeV/c



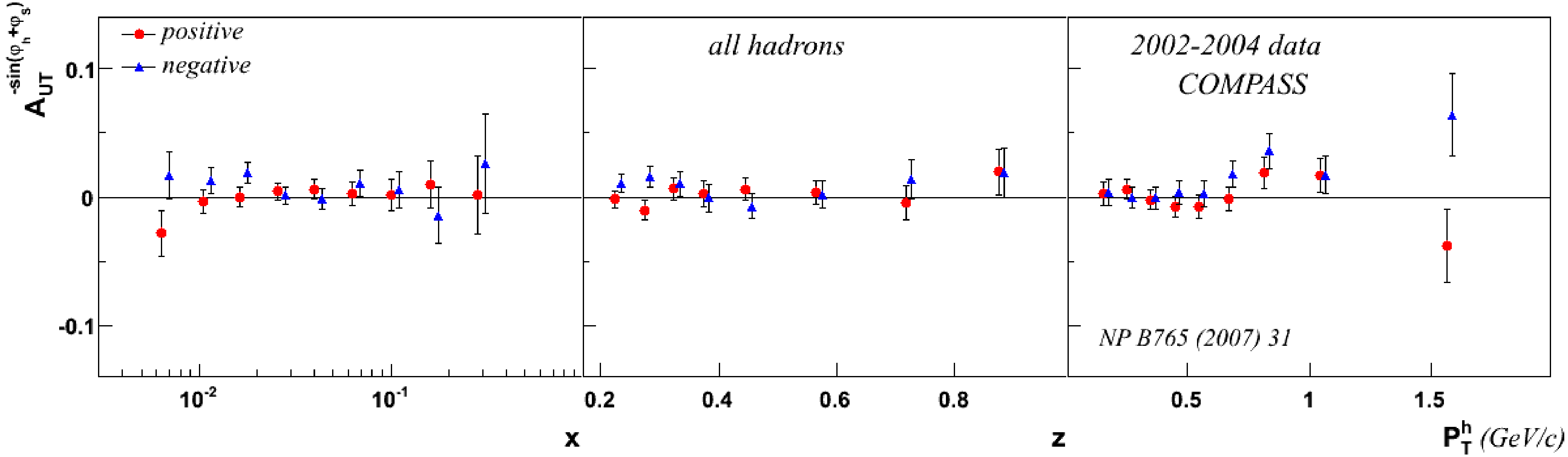


Results for all hadrons

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

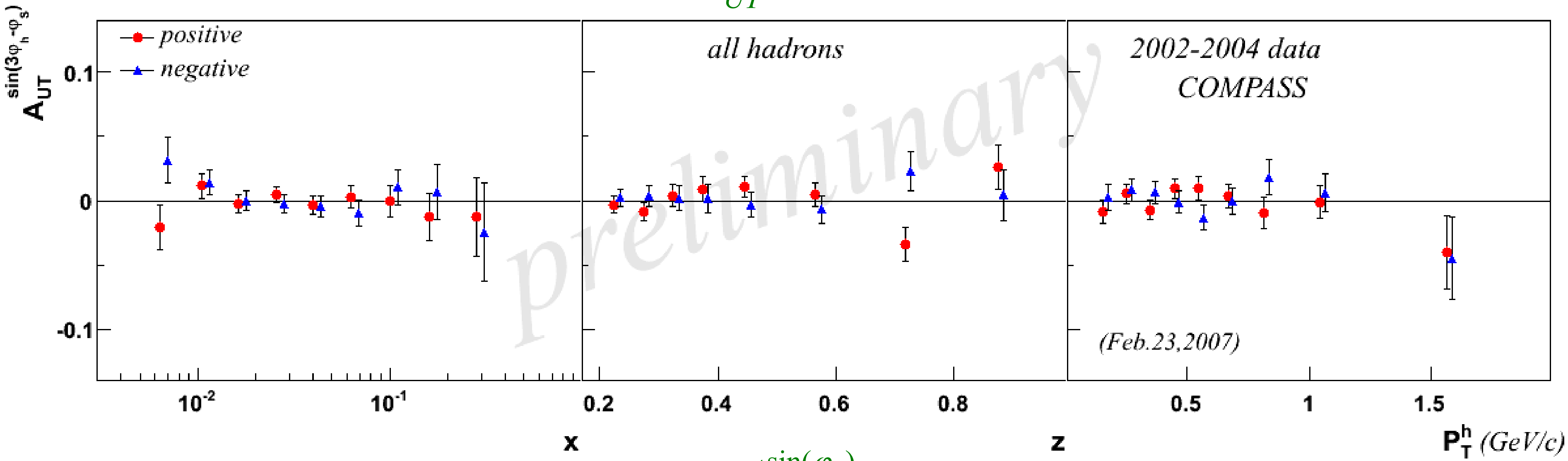


$-A_{UT}^{\sin(\varphi_h + \varphi_s)}$ - Collins asymmetry

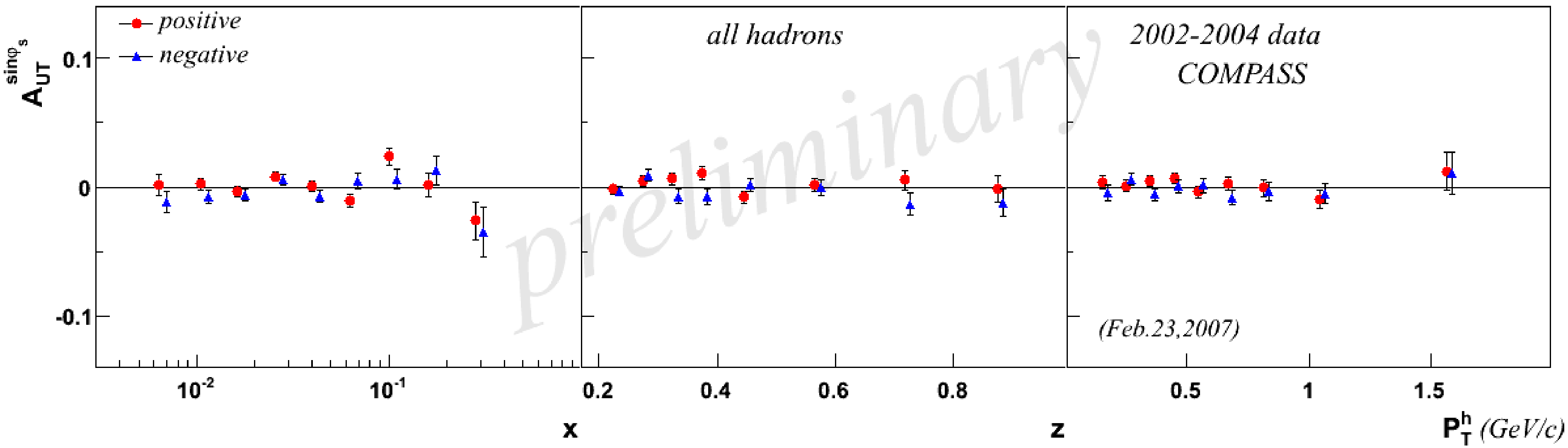


Results beyond Collins and Sivers

$A_{UT}^{\sin(3\varphi_h - \varphi_s)}$

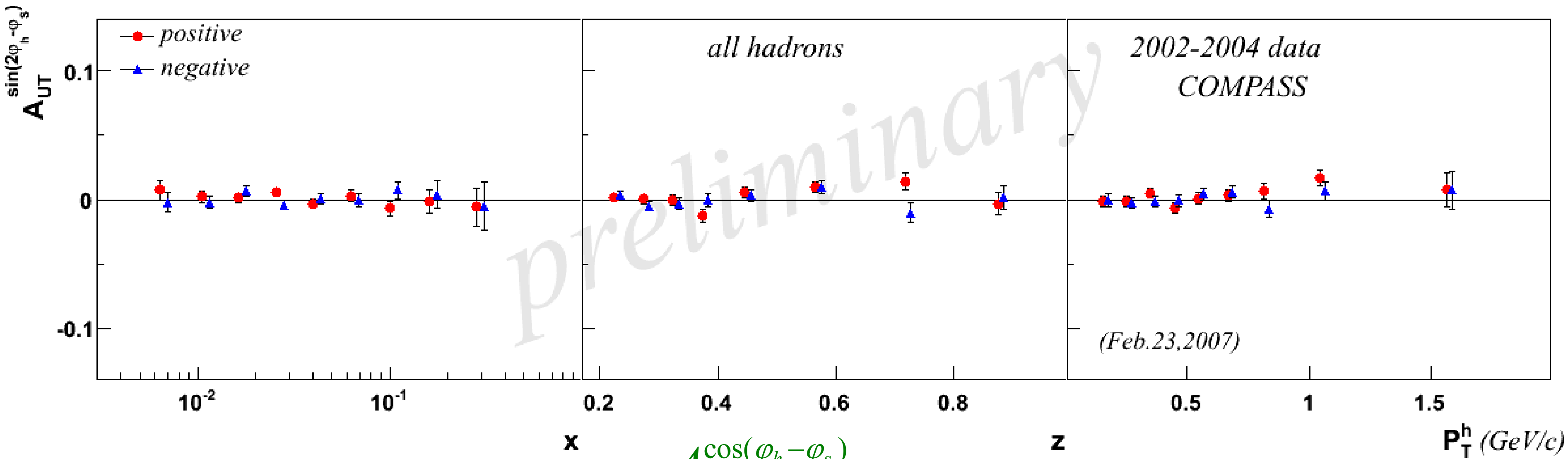


$A_{UT}^{\sin(\varphi_s)}$

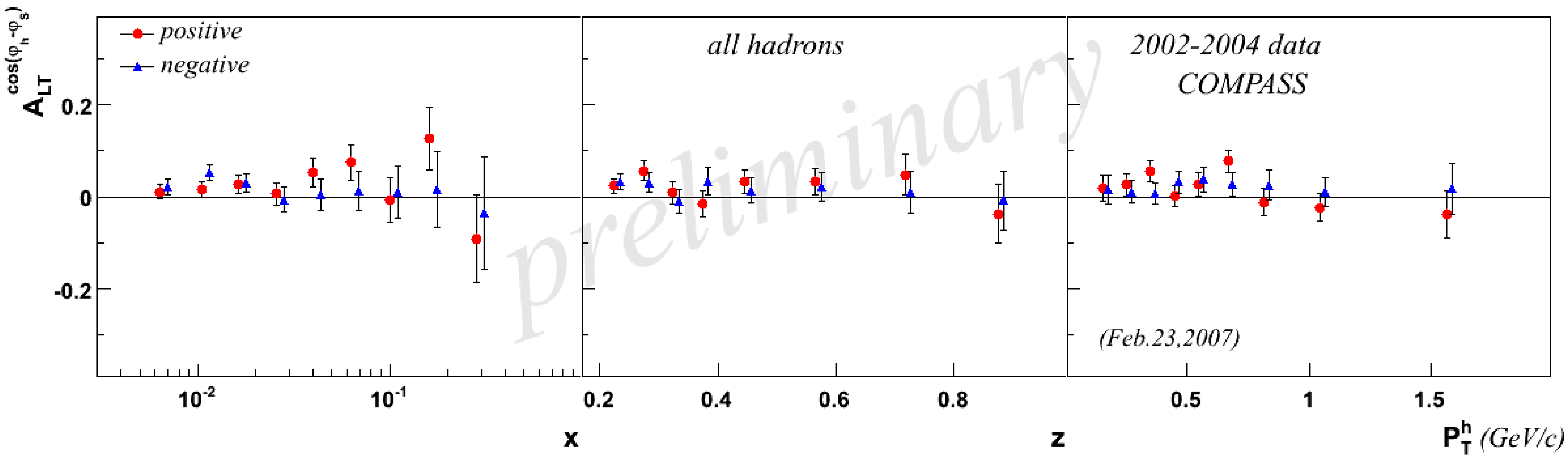


Results beyond Collins and Sivers

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

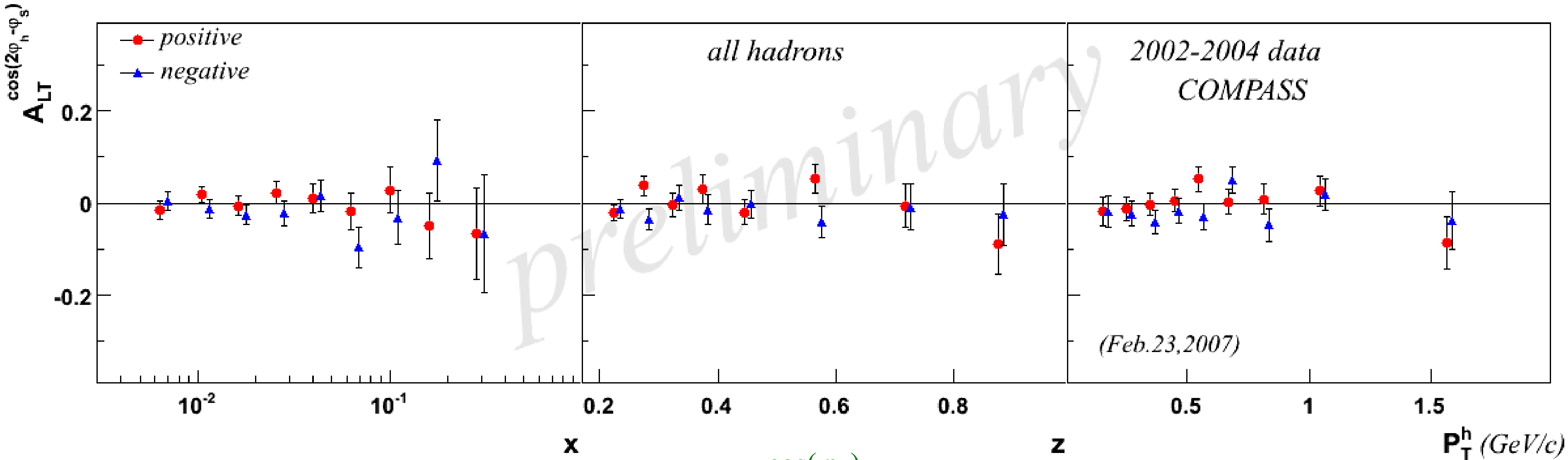


$A_{LT}^{\cos(\varphi_h-\varphi_s)}$

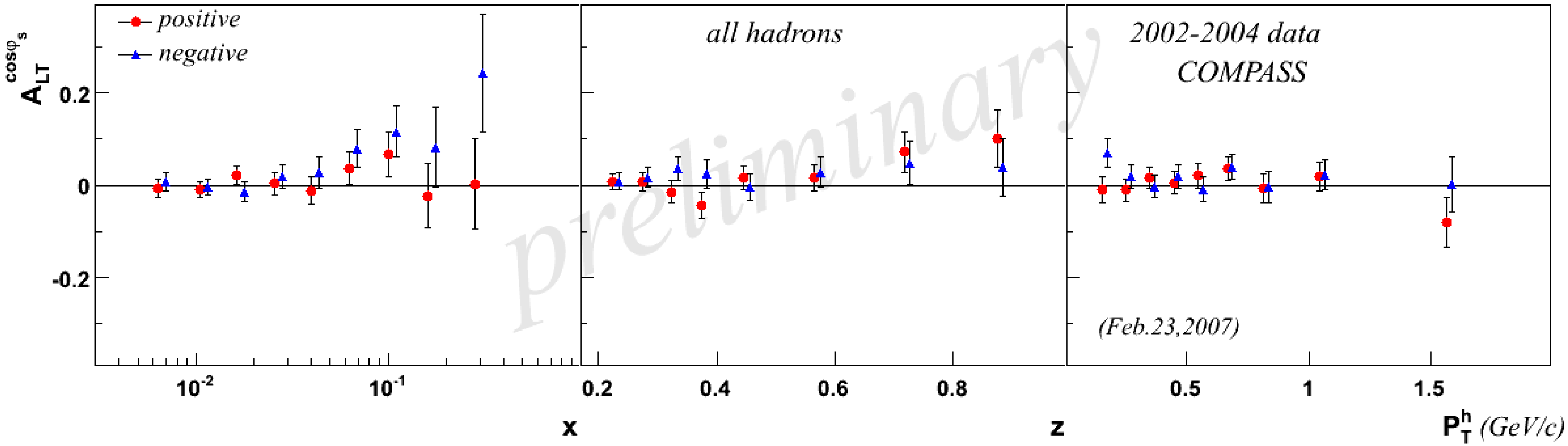


Results beyond Collins and Sivers

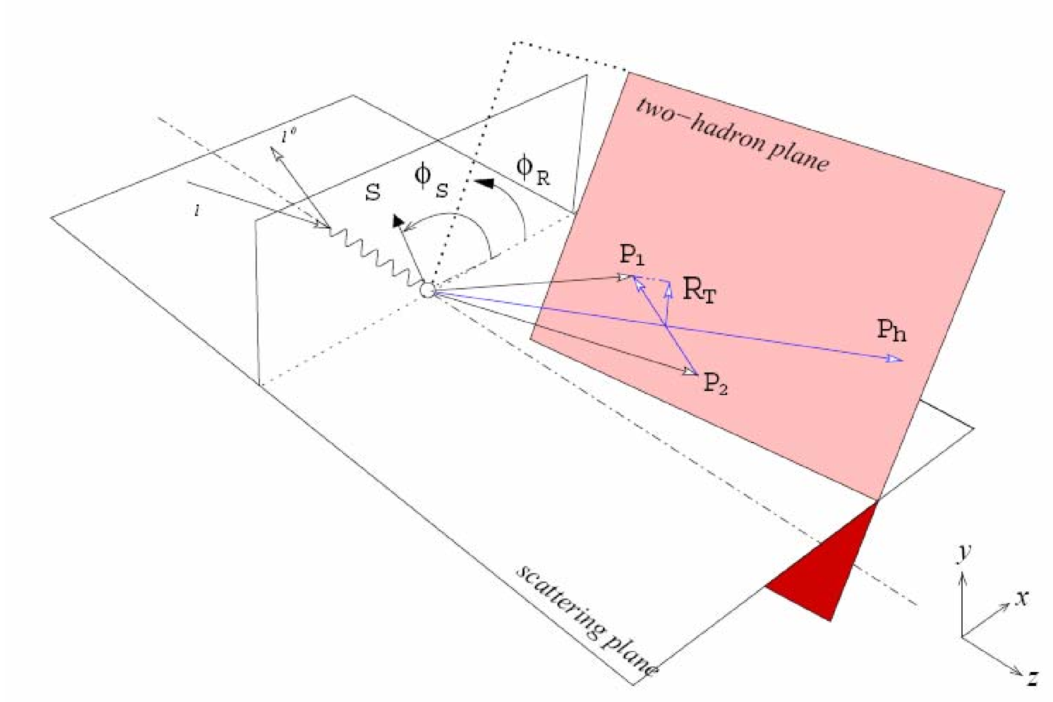
$A_{UT}^{\sin(2\varphi_h-\varphi_s)}$



$A_{UT}^{\cos(\varphi_s)}$



Frame independent definition of φ_R



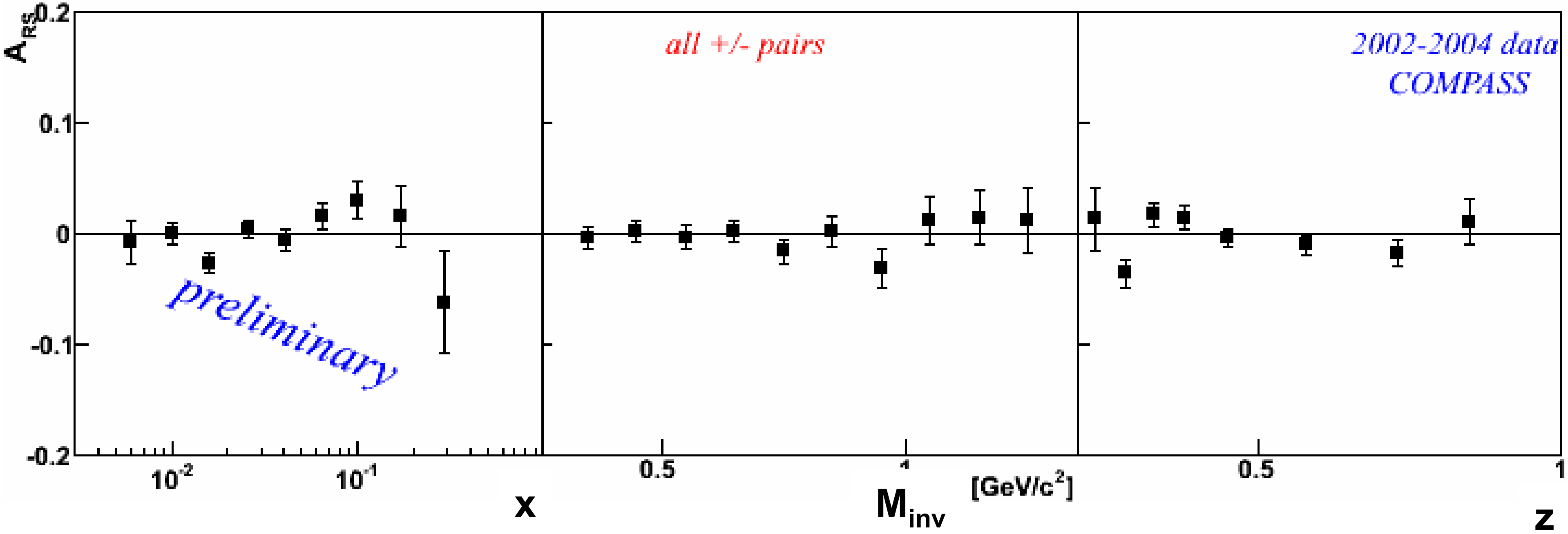
A. Baccetta, hep-ph/0608037

with: $$R_T = \frac{z_2 P_{1T} - z_1 P_{2T}}{z_1 + z_2}$$ where P_{1T} and P_{2T} are the transverse components of the hadron momenta

<u>we define:</u> $$\cos\phi_R = \frac{(q\times l)}{|q\times l|}\cdot\frac{(q\times R_T)}{|q\times R_T|} \qquad \sin\phi_R = \frac{(l\times R_T)\cdot q}{|q\times l||q\times R_T|}$$

Results for two unidentified hadrons

all combinations of + (h1) and – (h2) hadrons



2002-2004 COMPASS data

Double Ratio Method

double ratio: $$F(\Phi_{Coll}) = \frac{N_{up}^{\uparrow}(\Phi_{Coll}) \cdot N_{down}^{\uparrow}(\Phi_{Coll})}{N_{up}^{\downarrow}(\Phi_{Coll}) \cdot N_{down}^{\downarrow}(\Phi_{Coll})}$$

$N_{up/down}$: upstream / downstream target cell

$N^{\uparrow\downarrow}$: target polarization vector pointing up / down

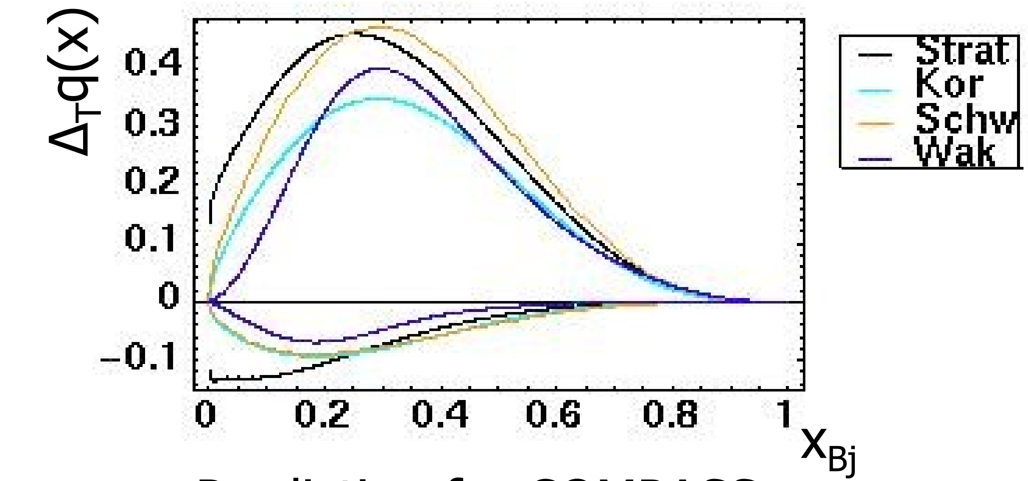
fit function: $$F(\Phi_{Coll}) = c \cdot (1 + 4 \cdot A_C^h \sin \Phi_{Coll})$$

final asymmetry: $$A_{Coll} = \frac{1}{f\, P_T\, D} A_C^h$$

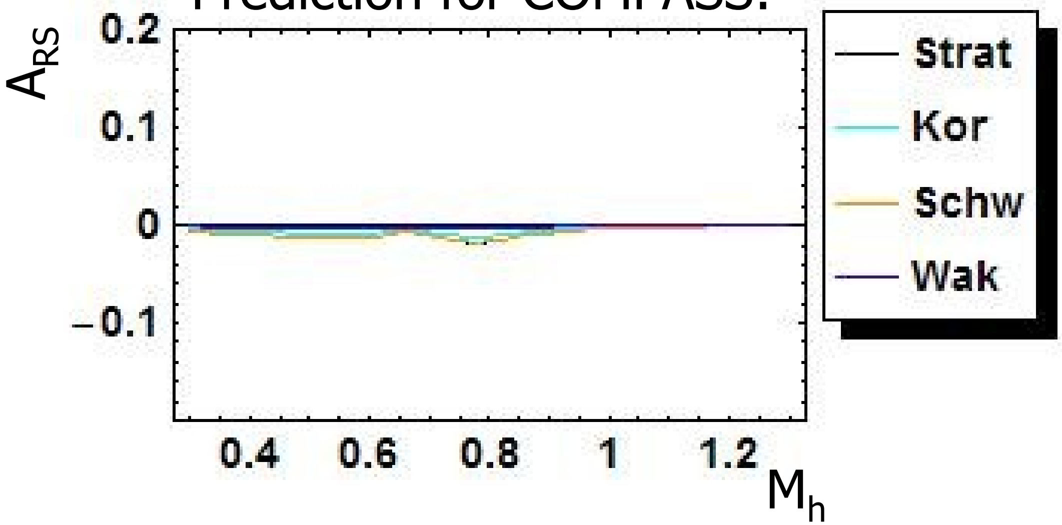
Comparison with Theory

Model calculations for COMPASS kinematics (M. Radici, QCDN 06, hep-ph/0608037):

Model for transversity:



Prediction for COMPASS:

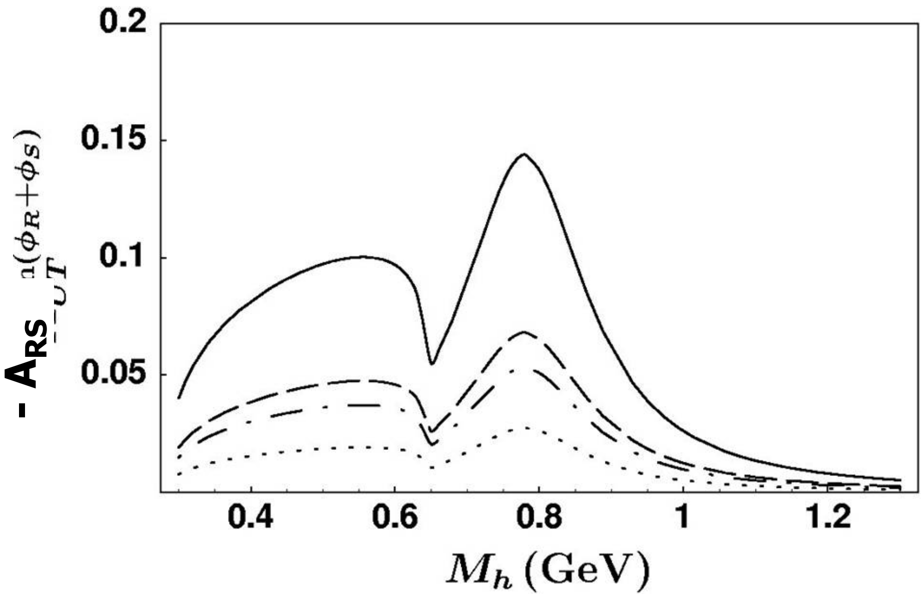


- Soffer, Stratmann, Vogelsang, P.R. D65 (02) 114024
- Korotkov, Nowak, Oganessian, E.P.J. C18 (01) 639
- Schweitzer et al., P.R. D64 (01) 034013
- Wakamatsu P.L. B509 (01) 59

➔ small asymmetries on the deuteron

Predictions for Asymmetries on the Proton

Predictions for two-hadrons asymmetries on the proton at COMPASS:



(M. Radici, hep-ex/0608037)

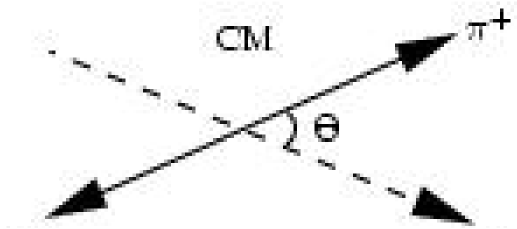
- Soffer, Stratmann, Vogelsang, P.R. D65 (02) 114024
- Korotkov, Nowak, Oganessian, E.P.J. C18 (01) 639
- Wakamatsu P.L. B509 (01) 59

sinθ Dependence

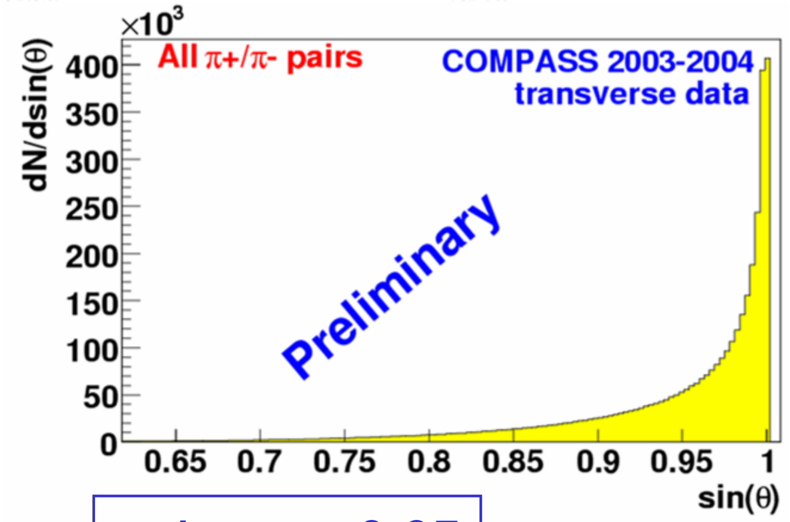
Cross section σ_{UT} for two-π fragmentation depends on $\sin\theta$:
(Interference of s- and p-wave of the 2π-state)

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

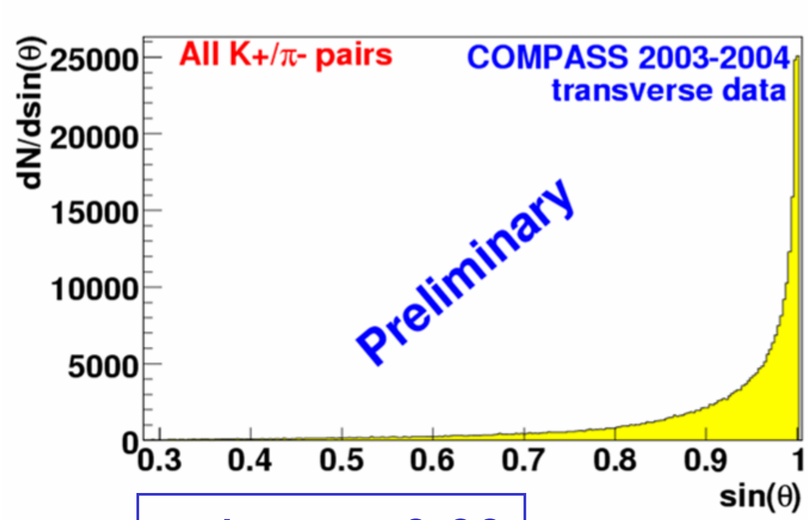
(A. Bacchetta and M. Radici, hep-ph/0212300)



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



<sinθ> = 0.95

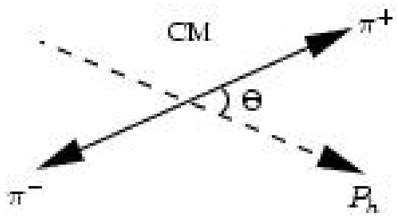


<sinθ> = 0.90

➔ small contribution in the kinematical region of COMPASS

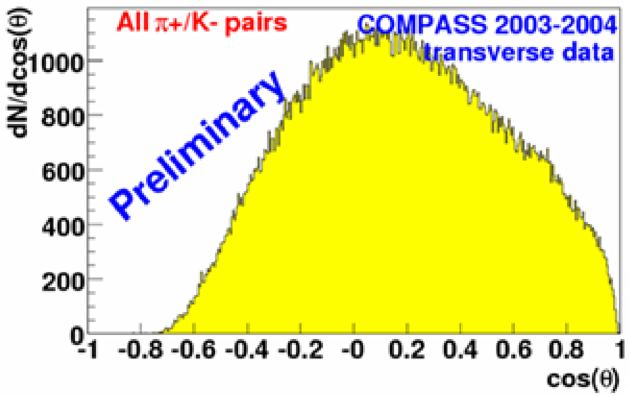
Partial wave expansion of $H_q^{\angle h}(z)$

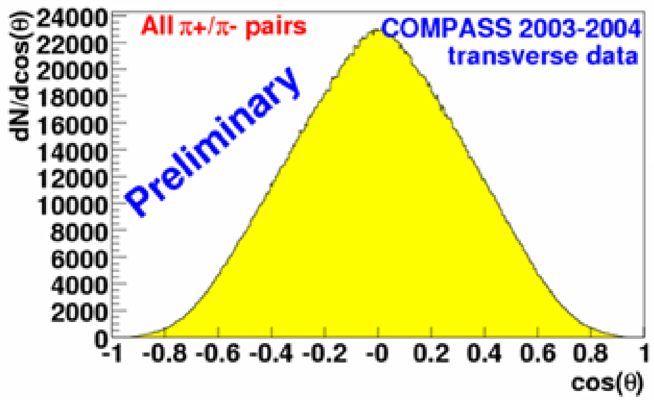
$$H_q^{\angle h}(z, \cos\theta, M_h^2) = H_{q,0t}^{\angle h}(z, M_h^2) + H_{q,lt}^{\angle h}(z, M_h^2)\cos\theta$$

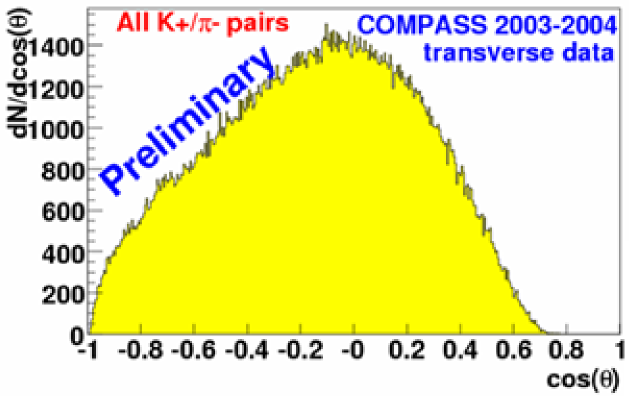


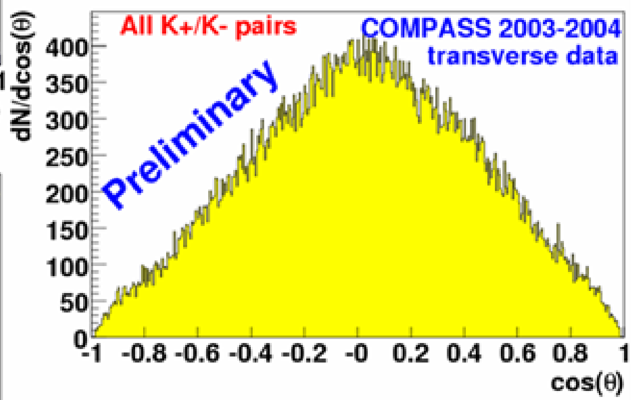
A. Baccetta, hep-ph/0708037

cosθ-Distributions of our data:



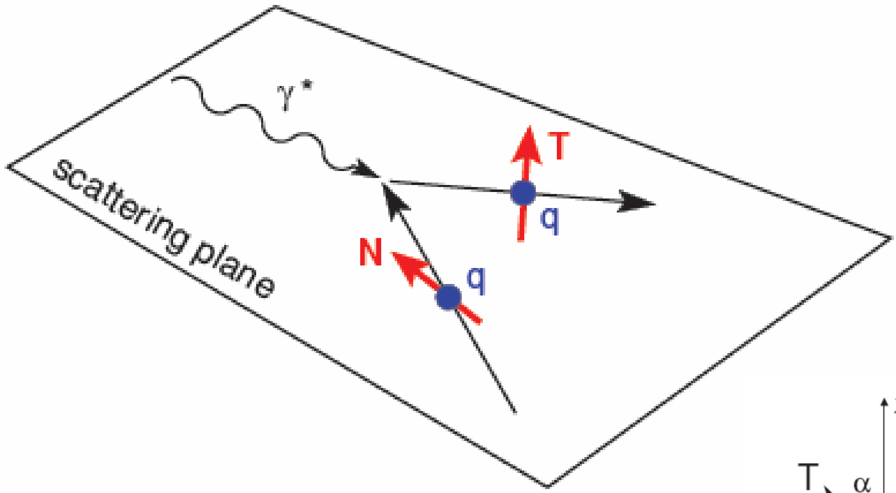


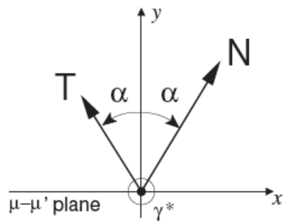




Transverse Λ Polarization

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





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

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

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

f = target dilution factor, P_N = target polarization,

$D(y)$ = virtual photon depolarization factor

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

Transverse Λ Polarization