Review of COMPASS results on transverse spin effects in SIDIS and fragmentation functions

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SIDIS cross section

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

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

18 structure functions

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

$$+\,S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h}+\varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right]+S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL}+\sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right]$$

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

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

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

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

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

COMPASS measures all of them

8 transverse target spin dependent asymmetries

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = {}& \\
\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{ & F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
& + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} \\
& + S_\parallel\left[\sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_h\,F_{UL}^{\sin\phi_h} + \varepsilon\sin(2\phi_h)\,F_{UL}^{\sin 2\phi_h}\right] + S_\parallel\lambda_e\left[\sqrt{1-\varepsilon^2}\,F_{LL} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos\phi_h\,F_{LL}^{\cos\phi_h}\right] \\
& + |\boldsymbol{S}_\perp|\Big[\sin(\phi_h-\phi_S)\left(F_{UT,T}^{\sin(\phi_h-\phi_S)} + \varepsilon\,F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
& \quad + \varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)} + \varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)} \\
& \quad + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin\phi_S\,F_{UT}^{\sin\phi_S} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\sin(2\phi_h-\phi_S)\,F_{UT}^{\sin(2\phi_h-\phi_S)}\Big] \\
& + |\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)} + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\mathrm{c}\ldots \\
& \quad + \sqrt{2\,\varepsilon(1-\varepsilon)}\,\cos(2\phi_h-\phi_S)\,F_{LT}^{\cos(2\phi_h-\phi_S)}\Big]\Bigg\},
\end{aligned}
$$

Sivers

Correlation between the **transverse spin of the nucleon** and the **transverse momentum of the quark**

→ **access Sivers PDF**

Collins

Correlation between the **transverse spin of the nucleon** and the **transverse polarisation of the quark**

→ **access transversity PDF (h_1^q)**

The COMPASS spectrometer

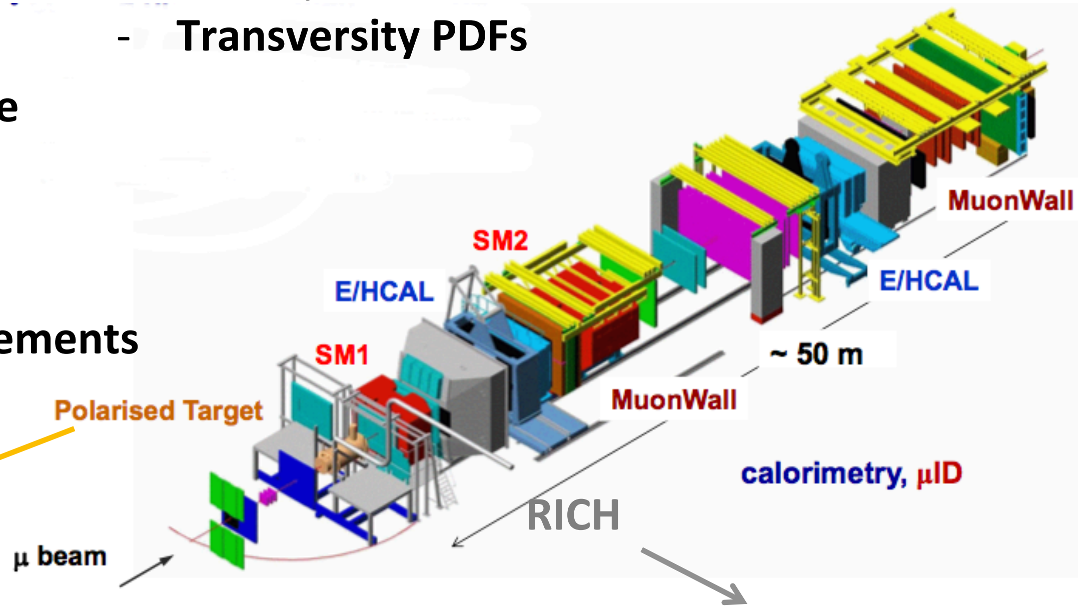
Fixed target experiment @ CERN
High energy beam: 160 GeV/c
Beam intensity 2.10^{8} μ^{+}/spill (4.8s)

Two stages spectrometer (with SM1/2 magnets), 180 mrad angular acceptance

Muon identification
Variety of tracking detectors
Hadron identification for SIDIS measurements

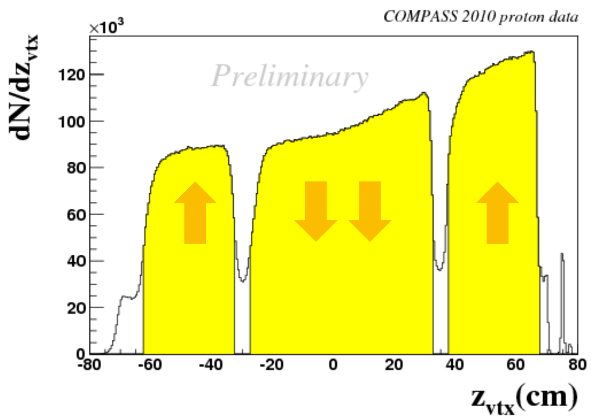
Nucleon spin structure Study with longitudinally and transversely polarized targets:

- Gluon polarisation
- Helicity PDFs
- **Transversity PDFs**



3 target cells: 30-60-30 cm
Oppositely polarised

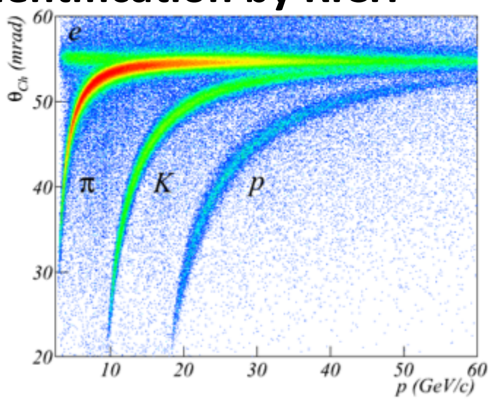
	$d(^{6}LiD)$	$p(NH_3)$
p_T	50%	90%
F	40%	16%



Hadron identification by RICH

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

Thresholds:
π: 3 GeV/c
K: 9 GeV/c
P: 18 GeV/c



Results

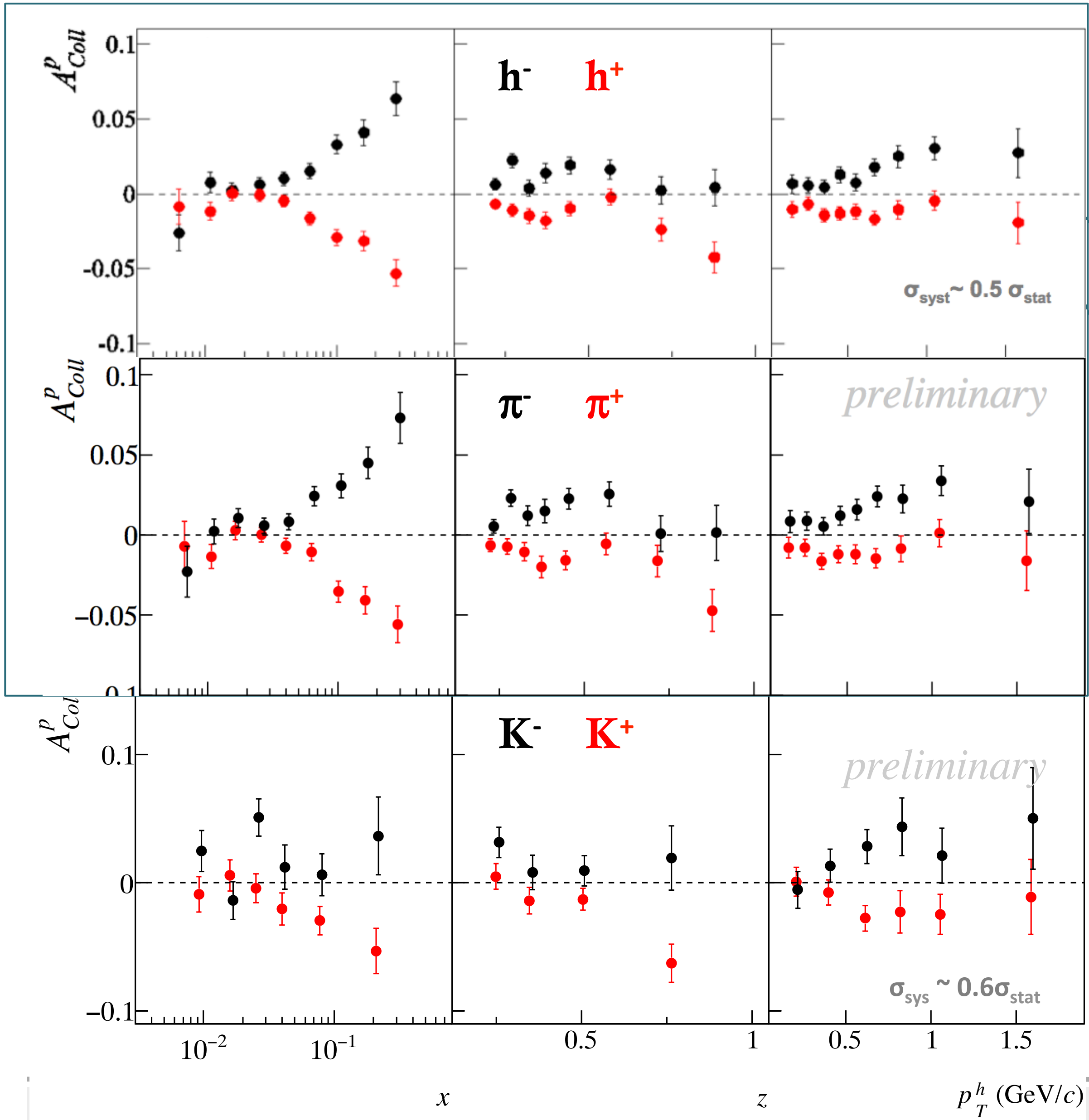
Collins & Sivers asymmetry

proton (NH_3) target, 160 GeV muon-beam
2007, 2010 runs

deuteron (^6LiD) target, 160 GeV muon-beam
2002, 2003, 2004 runs

Collins asymmetries on proton

Combined 2007 & 2010 results: Very good agreement between the 2 independent data sets



2007 *PLB 692 (2010) 240*
2010 *PLB 717 (2012) 376*

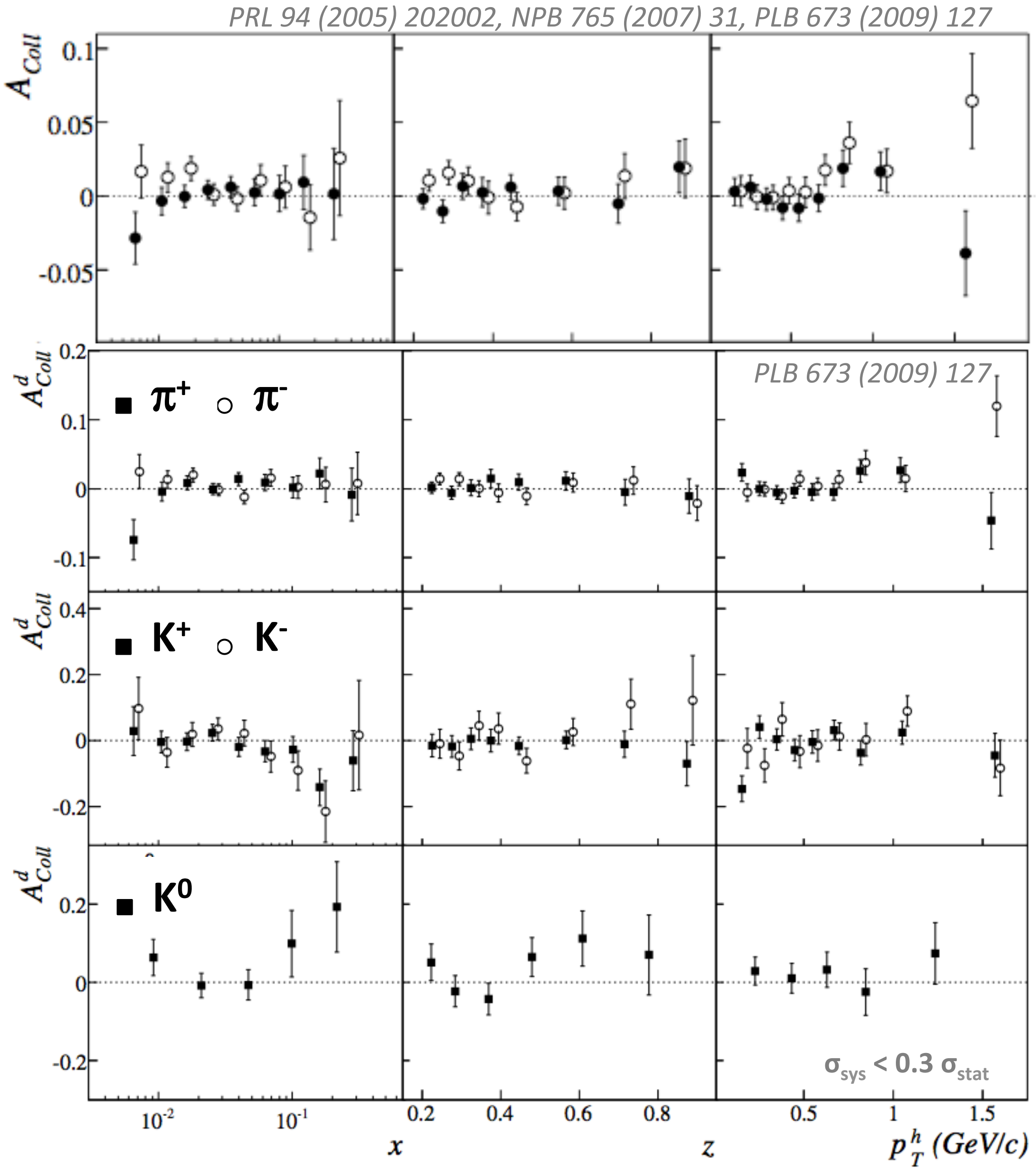
- **Precise measurement**
- **Asymmetries compatible with zero at small x**

- **Significant signal in the valence region**
- **opposite signs for h⁺ & h⁻, for π⁺ & π⁻**

K⁺ negative trend in the valence region (as for π⁺)
K⁻ positive in average

Collins asymmetries on deuterium

PRL 94 (2005) 202002, NPB 765 (2007) 31, PLB 673 (2009) 127



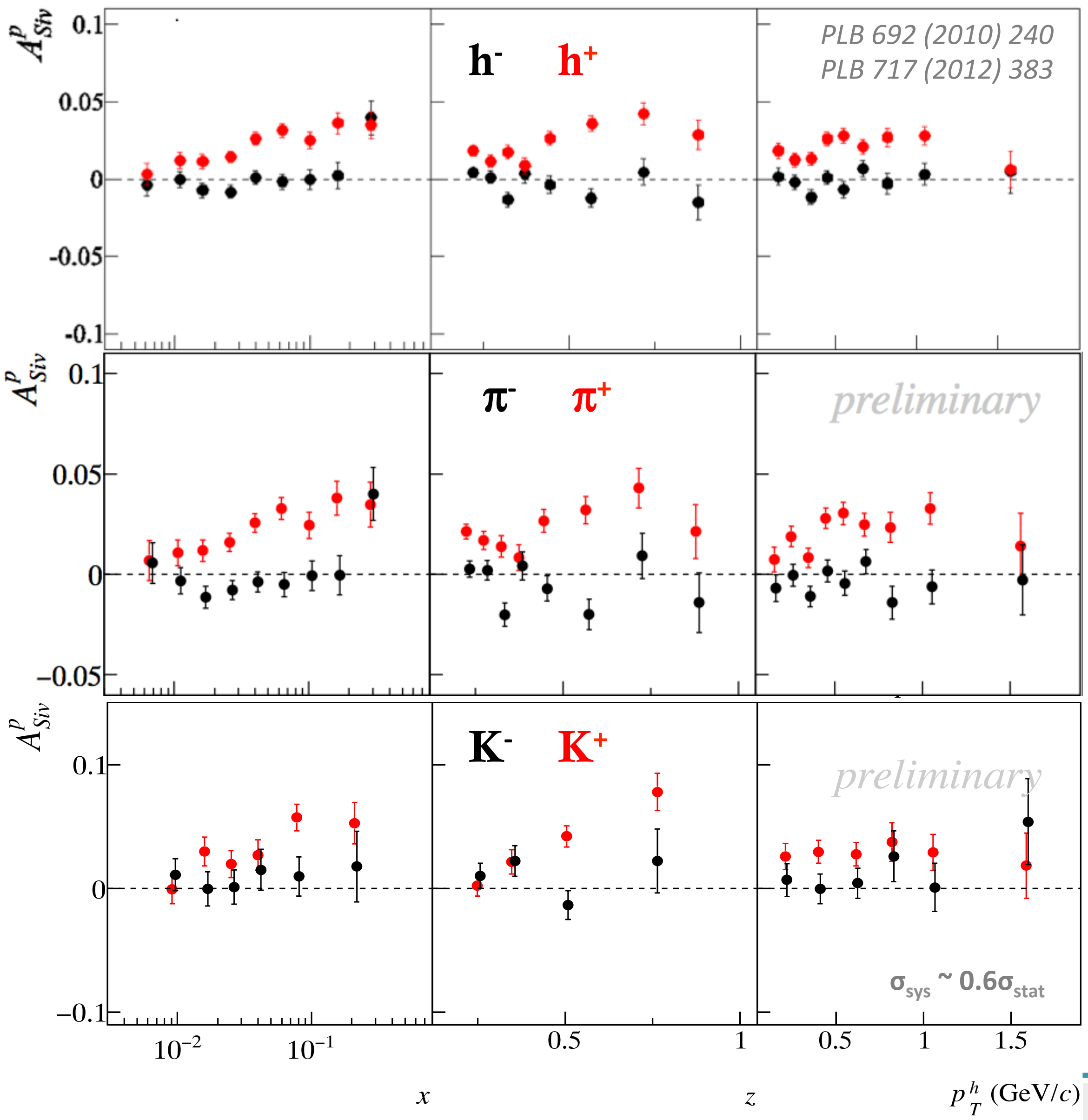
Charged hadrons
2002-04 data

Charged π, K and K^0
2003-04 data

Asymmetries compatible with zero
→ Cancellation between
$\Delta_T u(x)$ and $\Delta_T d(x)$

Sivers asymmetries on proton

Combined 2007 & 2010 results: Very good agreement between the 2 independent data sets



- ***vs* x: Large signal for positive hadrons over all the measured range**
- ***vs* z: Increasing signal**
- **Linear p_T^h dependence at small p_T^h, constant for large p_T^h**

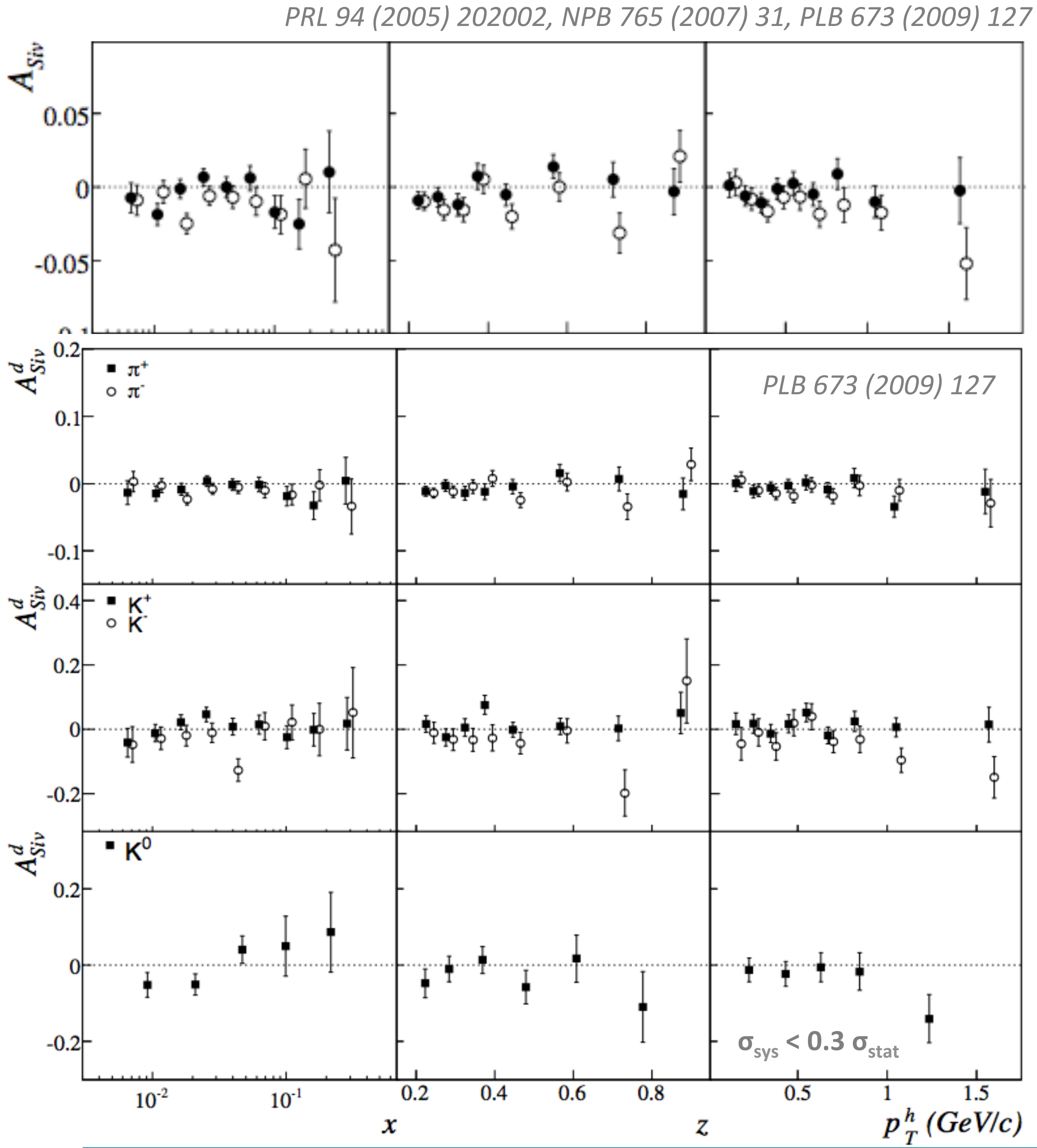
K^+ positive in average

signal larger than π^+

Important role of sea quark ?

K^- compatible with zero

Sivers asymmetries on deuterium



Charged hadrons
2002-04 data

Charged π, K and K^0
2003-04 data

All asymmetries on deuterium target compatible with zero

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

Results

hadron pair asymmetry

an alternative way to access poorly known transversity

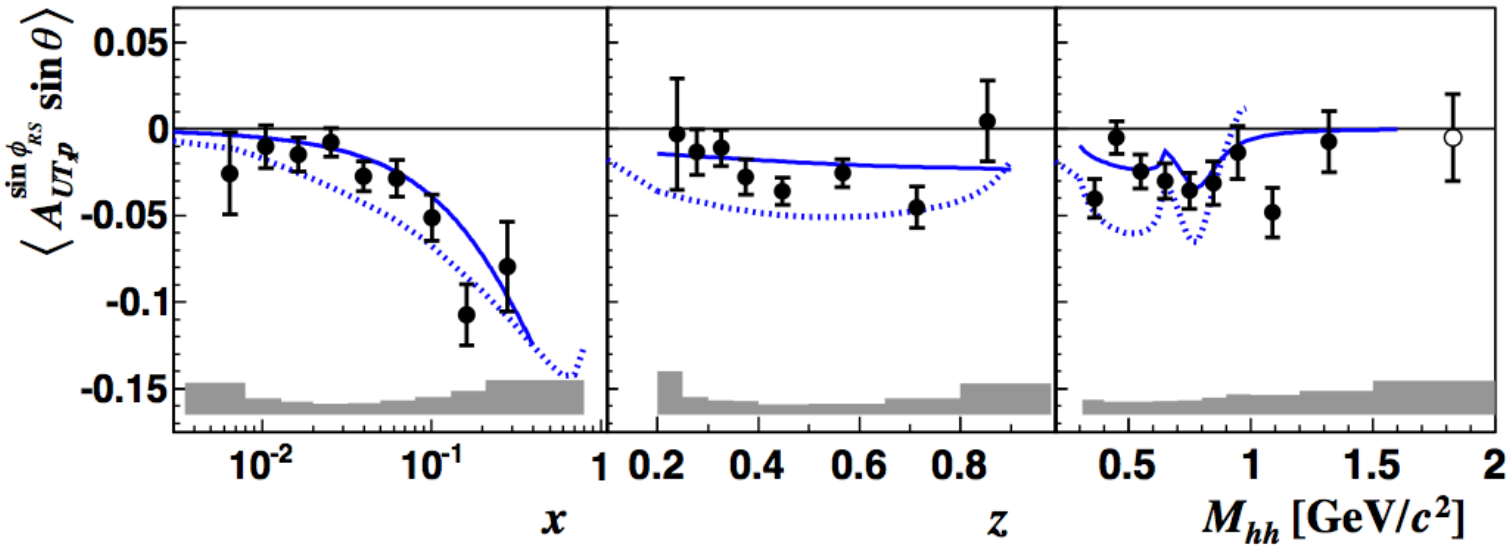
deuteron (^{6}LiD) target, 160 GeV muon-beam
2002, 2003, 2004 runs

proton (NH_3) target, 160 GeV muon-beam
2007, 2010 runs

Hadron pair asymmetries on proton – h^+h^-

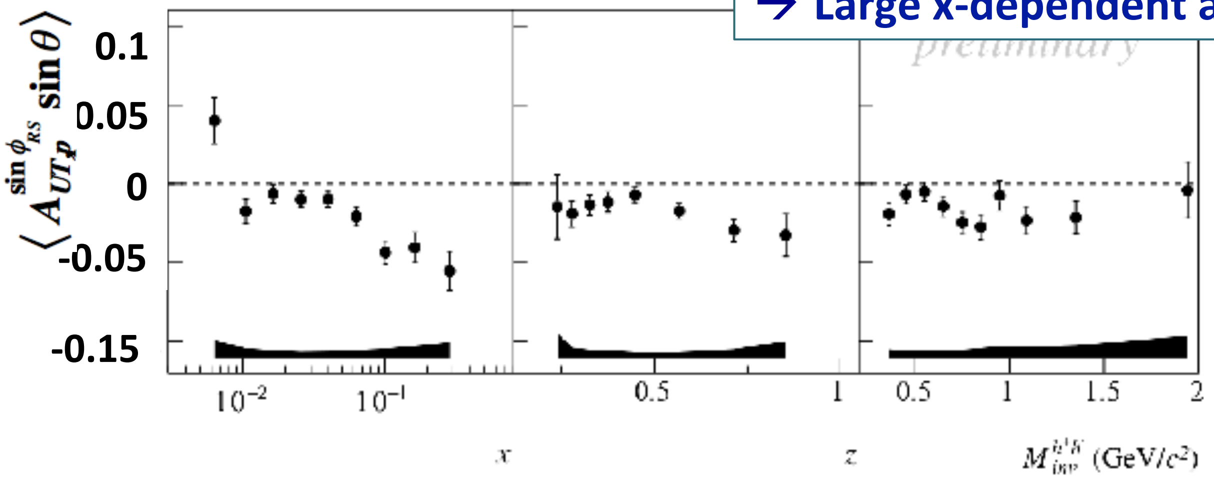
2007

COMPASS *PLB 713 (2012) 10*,
Bachetta ***et al.*** *PRD 74 (2006) 114007*, **Ma B.-Q.** ***et al.*** *PRD 77 (2008) 014035*

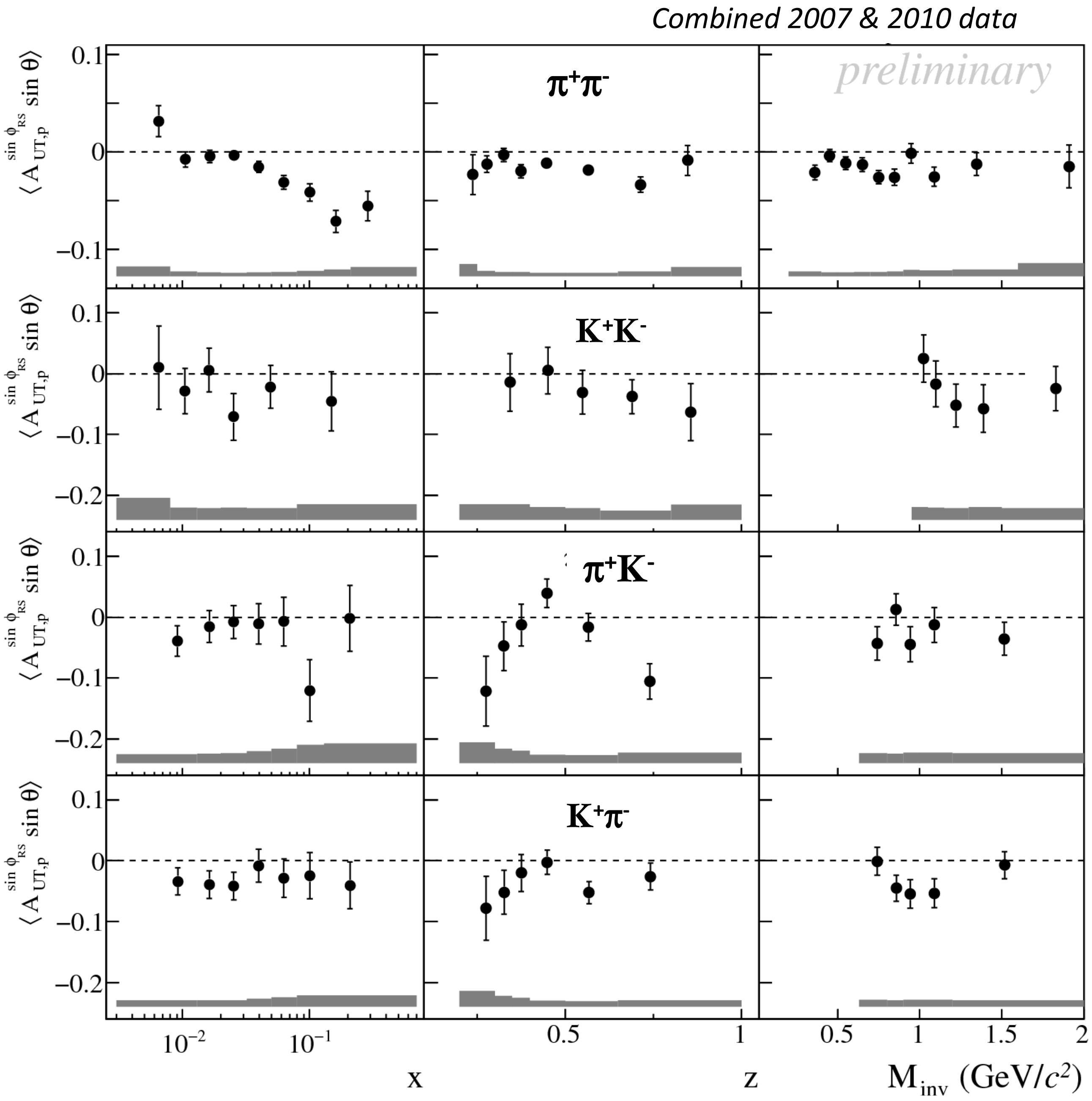


2010

→ Large x-dependent asymmetry, up to 10%



Hadron pair asymmetries on proton



Recent results from all data on proton target (2007 & 2010) for all pairs

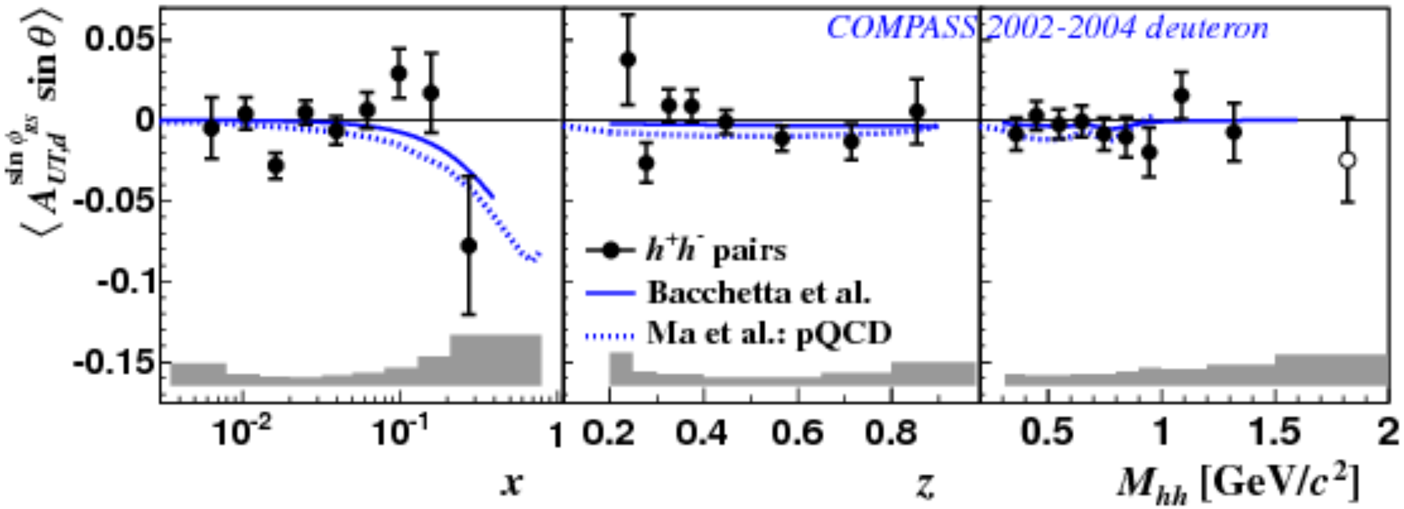
$\pi^+\pi^-$ pairs: trend very similar to the Collins asymmetries

- compatible with zero asymmetries at small x,
- large signal in the valence region
- clear dip around ρ^0 mass

Other π,K pair combinations
K^+K^-, π^+K^-, $K^+\pi^-$

No significant signal/clear trend observed

2002-04 **COMPASS** *PLB 713 (2012) 10,*
Bachetta ***et al.*** *PRD 74 (2006) 114007,* **Ma B.-Q.** ***et al.*** *PRD 77 (2008) 014035*



Asymmetries compatible with zero
→ cancellation of the u and d quark transversity

For identified pairs $\pi^+\pi^-$, K^+K^-, π^+K^-, $K^+\pi^-$

all measured asymmetries compatible with zero

Results on unpolarised data

deuteron (^{6}LiD) target, 160 GeV muon-beam

Single-hadron multiplicities (2006)

hadron-pair multiplicities (2004)

and unpolarized azimuthal asymmetries (from 2004
(will not be shown here)

Hadron pair (h^+h^-) multiplicities

motivation:

transversity h_1^q from hadron pair transverse spin asymmetry

$$A_{UT}^{\sin(\Phi_R+\Phi_S)\sin\theta}(x,z,M_h;Q^2) = -C_y \frac{|R|}{M_h} \frac{\sum_q e_q^2 h_1^q(x;Q^2) H_{1,sp}^q(z,M_h;Q^2)}{\sum_q e_q^2 f_1^q(x;Q^2) D_1^q(z,M_h;Q^2)}$$

But di-hadron fragmentation functions unknown

→ **Extract them via hadron pair multiplicities**

Hadron pair (h^+h^-) multiplicities

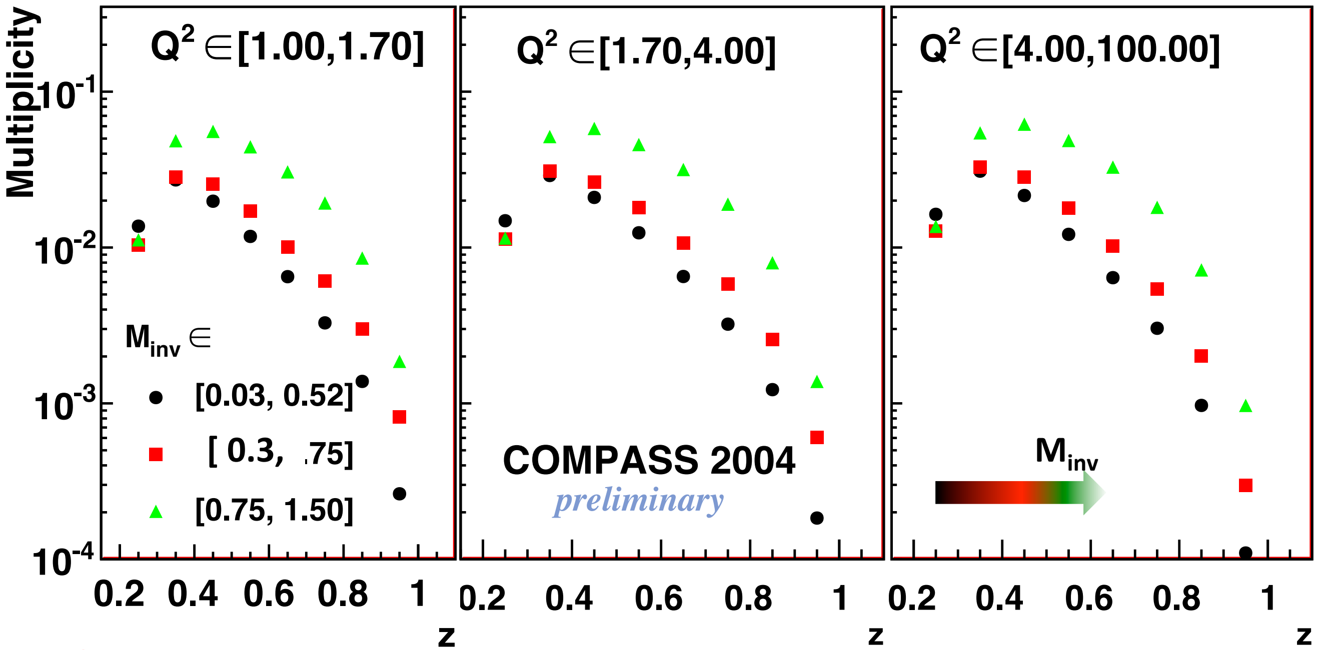
motivation:

transversity from hadron pair transverse spin asymmetry

$$A_{UT}^{\sin(\Phi_R+\Phi_S)\sin\theta}(x,z,M_h;Q^2) = -C_y \frac{|R|}{M_h} \frac{\sum_q e_q^2 h_1^q(x;Q^2) H_{1,sp}^q(z,M_h;Q^2)}{\sum_q e_q^2 f_1^q(x;Q^2) D_1^q(z,M_h;Q^2)}$$

Hadron pair multiplicities to extract di-hadron fragmentation functions

First measurement in M_{inv}, $z=z_1+z_2$, Q^2 bins



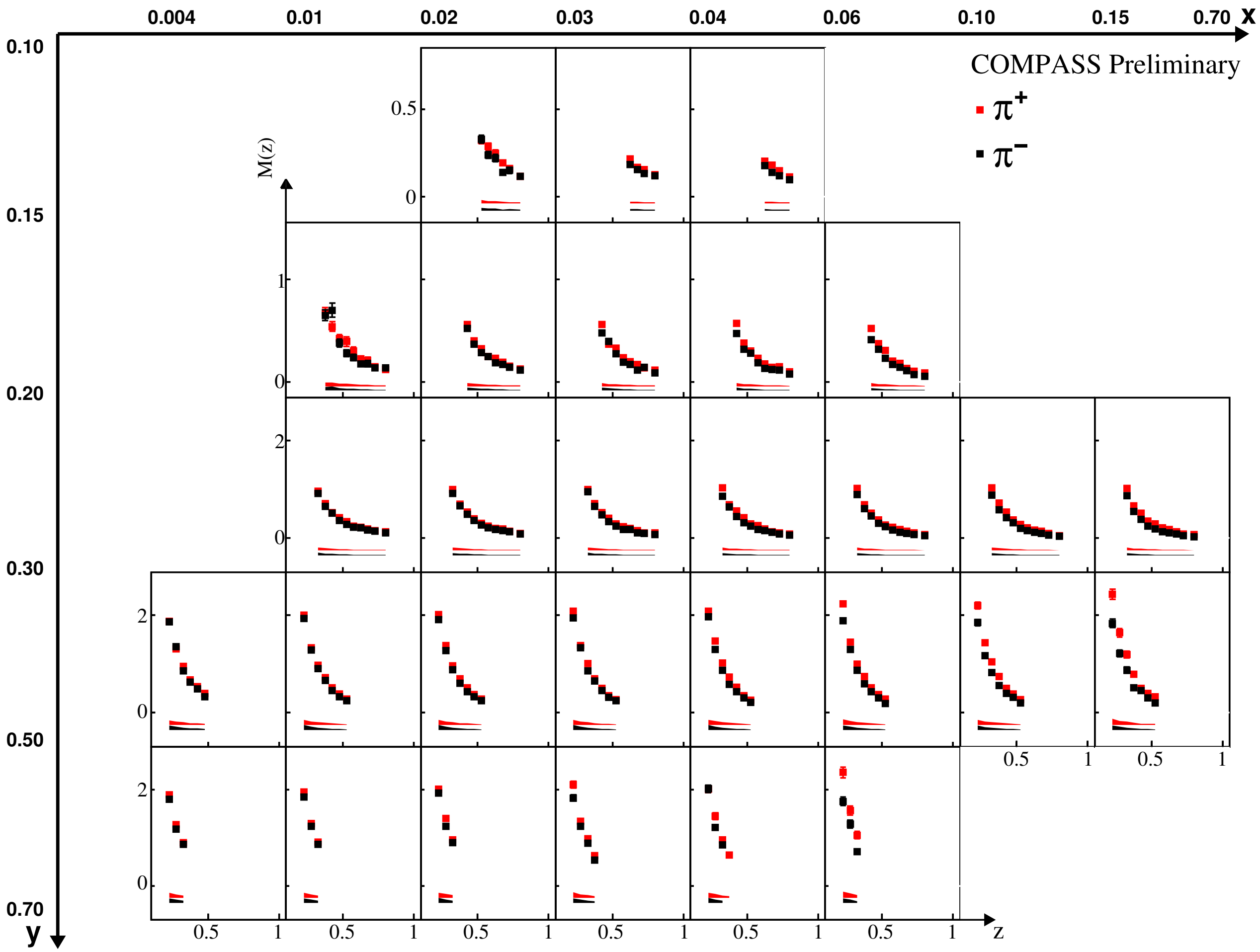
Significant z,M_{inv} dependence
in agreement witgh Lepto

Charged pion multiplicities vs (x,y,z)

main motivation:

fragmentation functions via single hadron multiplicities (at LO)

$$M^h = \frac{\sum_q e_q^2 (q(x,Q^2) D_q^h(z) + \bar{q}(x,Q^2) D_{\bar{q}}^h(z))}{\sum_q e_q^2 (q(x,Q^2) + \bar{q}(x,Q^2))}$$



Kinematic domain

$Q^2 > 1$ (GeV/c)^2

$0.1 < y < 0.7$

$W > 5$ GeV/c

$0.004 < x_B < 0.7$

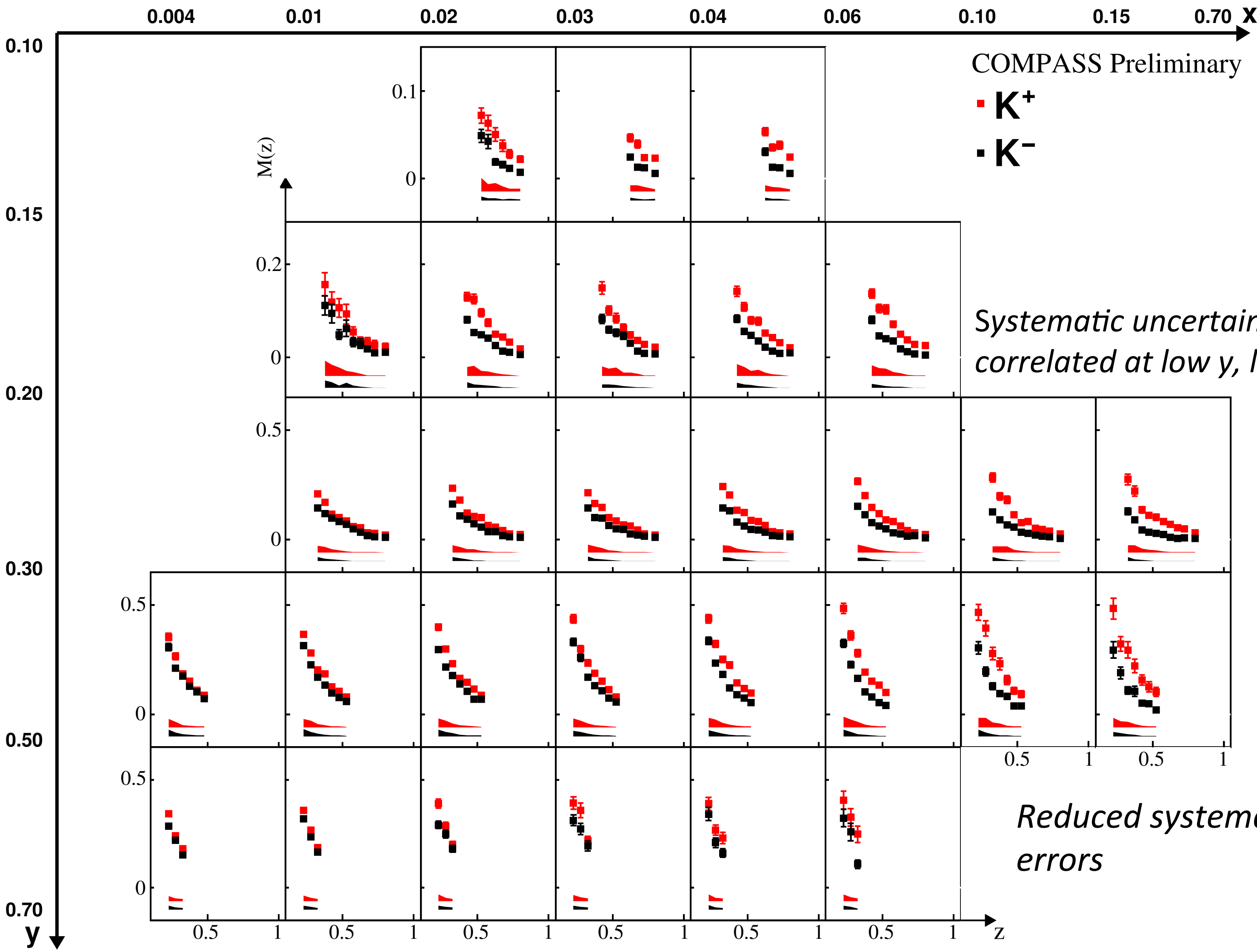
$0.2 < z_h < 0.85$

2006 data on deuterium (^{6}LiD) target

- **Precise measurement**
- **Wide kinematic coverage**
- **Input for global QCD fit**

Charged kaon multiplicities vs (x,y,z)

Play a key role in the strange quark polarization puzzle



Systematic uncertainty fully correlated at low y, low z

Reduced systematic errors

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$
$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h\,\boxed{F_{UU}^{\cos\phi_h}}$$
$$+\varepsilon\cos(2\phi_h)\,\boxed{F_{UU}^{\cos 2\phi_h}}+\lambda_e\sqrt{2\varepsilon(1-\varepsilon)}\sin\phi_h\,F_{LU}^{\sin\phi_h}$$

$$A^{UU}_{\cos\phi_h} = \frac{1}{Q}Cahn + \frac{1}{Q}BM$$

Cahn effect + Boer-Mulders DF

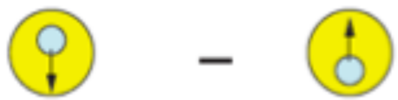
$$A^{UU}_{\cos 2\phi_h} = BM + \frac{1}{Q^2}Cahn$$

Boer- Mulders x Collins FF + Cahn effect

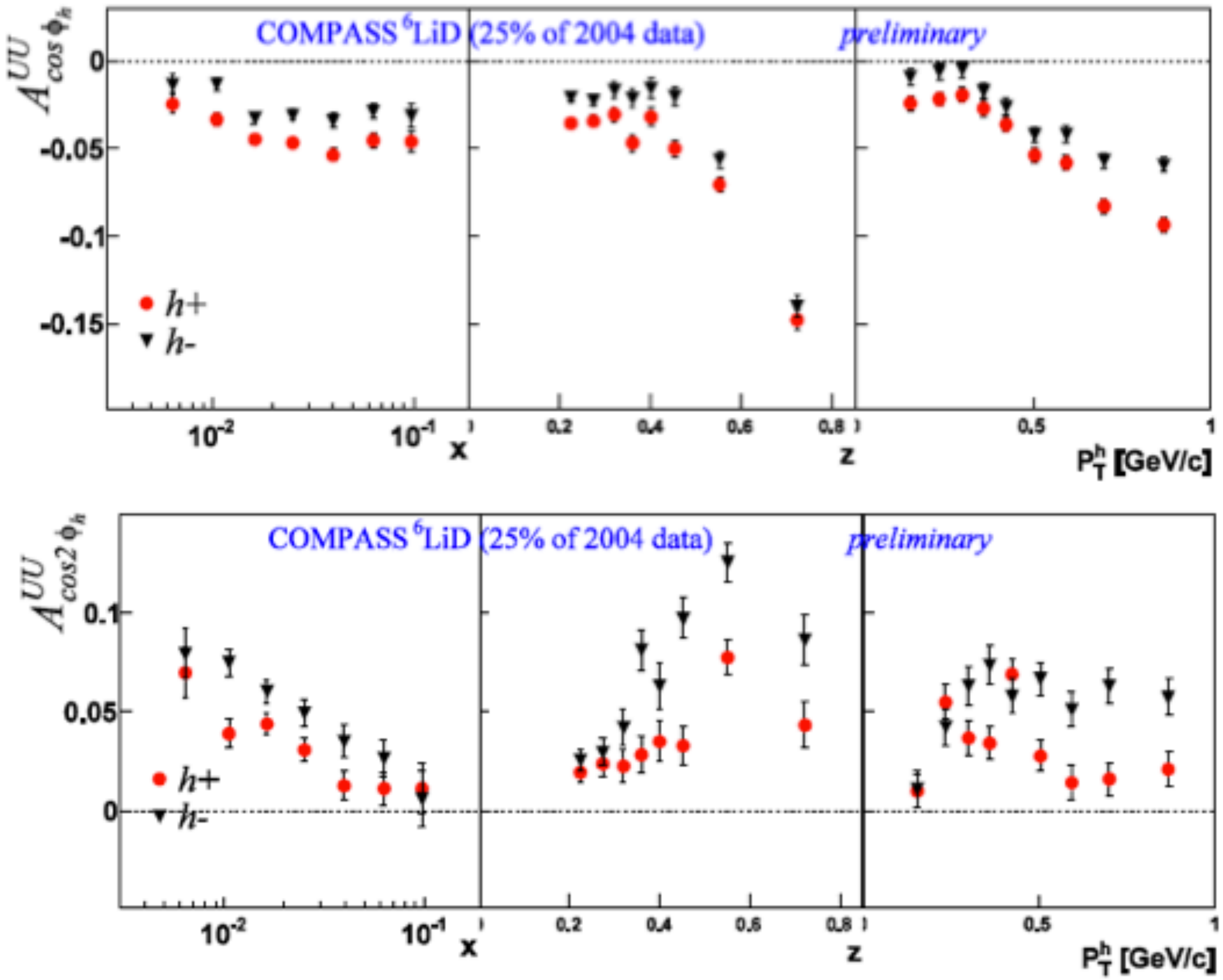
Cahn effect
kinematical effect due to quark transverse momentum

$$\frac{d\sigma}{d\phi_h} \propto 1 - 4\frac{\langle k_t^2\rangle z P_t}{Q\langle P_t^2\rangle}D_{\cos\phi_h}(y)\cos\phi_h + \ldots$$

Boer-Mulders PDF
Correlation between the **quark transverse momentum** and the **quark spin** in an **unpolarized nucleon** quark



SIDIS cross section: azimuthal asymmetries



cos Φ

- Large signal in the whole x range
- Strong z dependence

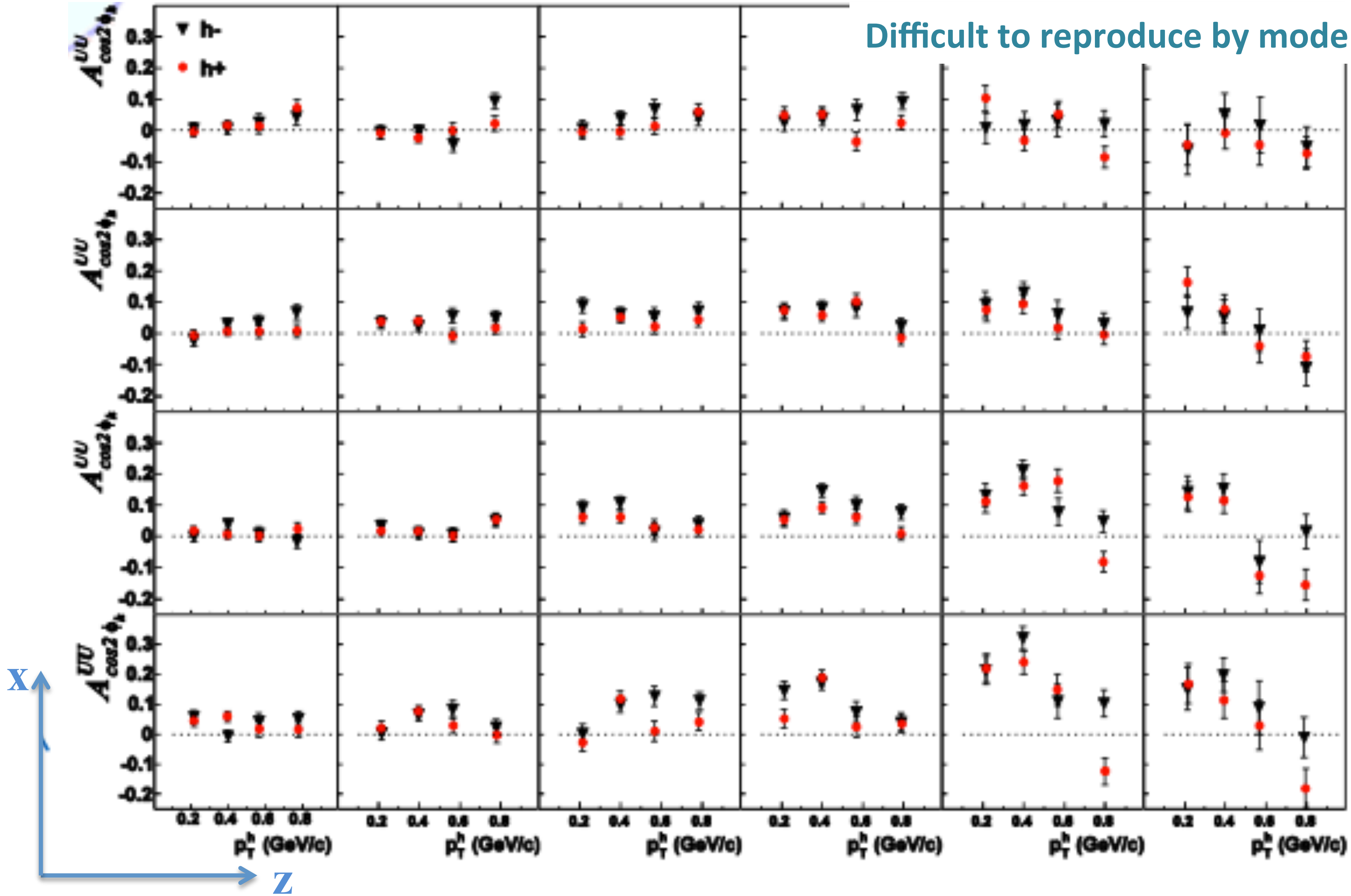
cos 2Φ

- different for h^+ & h^-
- Significant signal at small x
- Strong dependence upon x,z, p_T

Investigate unexpected kinematic dependences observed via a multi-dimensional analysis

SIDIS cross section: azimuthal asymmetries

COMPASS ^{6}LiD (25% of 2004 data) preliminary



Difficult to reproduce by models

Conclusions

COMPASS has investigated transverse spin effect via SIDIS off deuterium and proton targets

Results on Collins and Sivers asymmetries for charged and identified hadrons
Clear signals on p to be deeply investigated via multidimensional analysis (x, Q^2, z, p_T) of the p data

Possible measurements on p and d with different beam energies on a longer time scale

Results on hadron pair transverse spin asymmetries off p and d
very similar trend for $\pi^+\pi^-$ than for the Collins asymmetries

COMPASS has produced interesting results on SIDIS off unpolarised deuterium

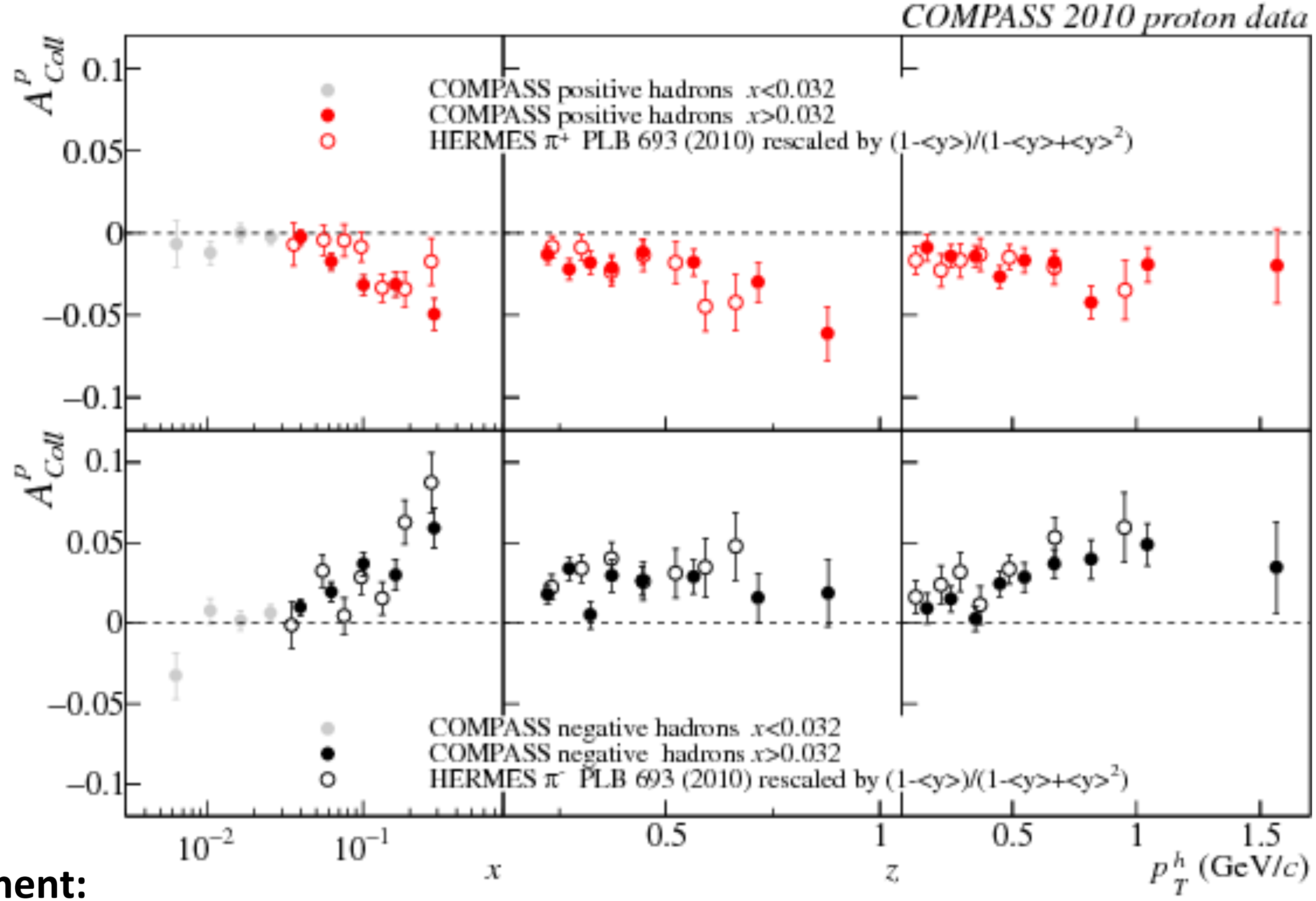
- **Single hadron multiplicities vs (x,y,z) and p_T^2**
- **Hadron pair multiplicities for the first time in (z,Q^2,M_{inv})**

Unpolarized azimuthal asymmetries & multiplicities on p from the SIDIS data which will be collected in parallel with DVCS after 2015

backup

Collins asymmetries on protons: COMPASS vs HERMES

COMPASS x range limited to x>0.032 region (overlap with HERMES)



Good agreement:

Non trivial result, COMPASS Q^2 larger by a factor 2-3 than HERMES's Q^2 in the last 3 x bins → Weak Q^2 dependence of the Collins effect

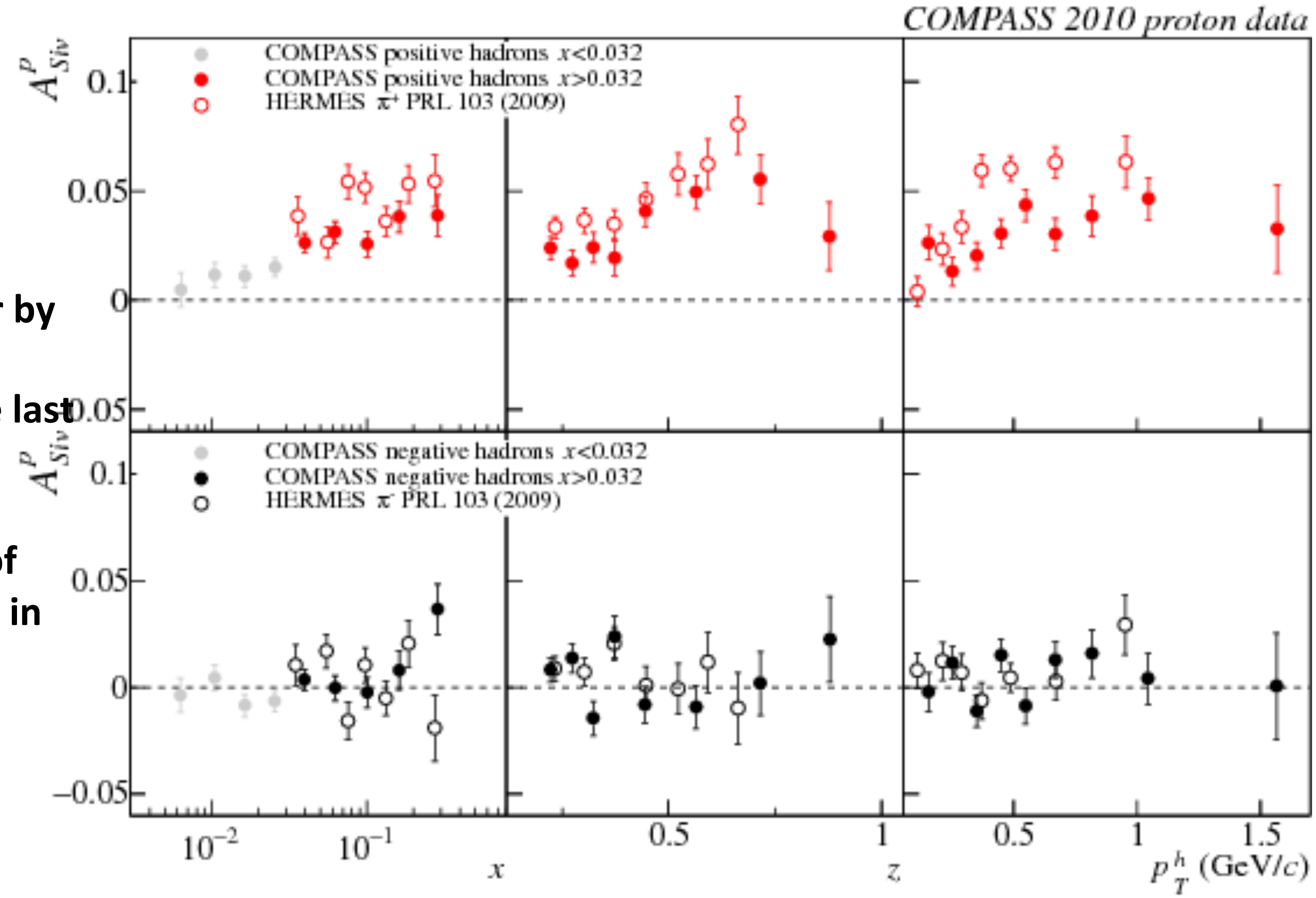
Sivers asymmetries on protons: COMPASS vs HERMES

COMPASS x range limited to x>0.032 region (overlap with HERMES)

HERMES π^+ and K^+ asymmetries larger than COMPASS

COMPASS Q^2 larger by a factor 2-3 than HERMES's Q^2 in the last 3 x bins

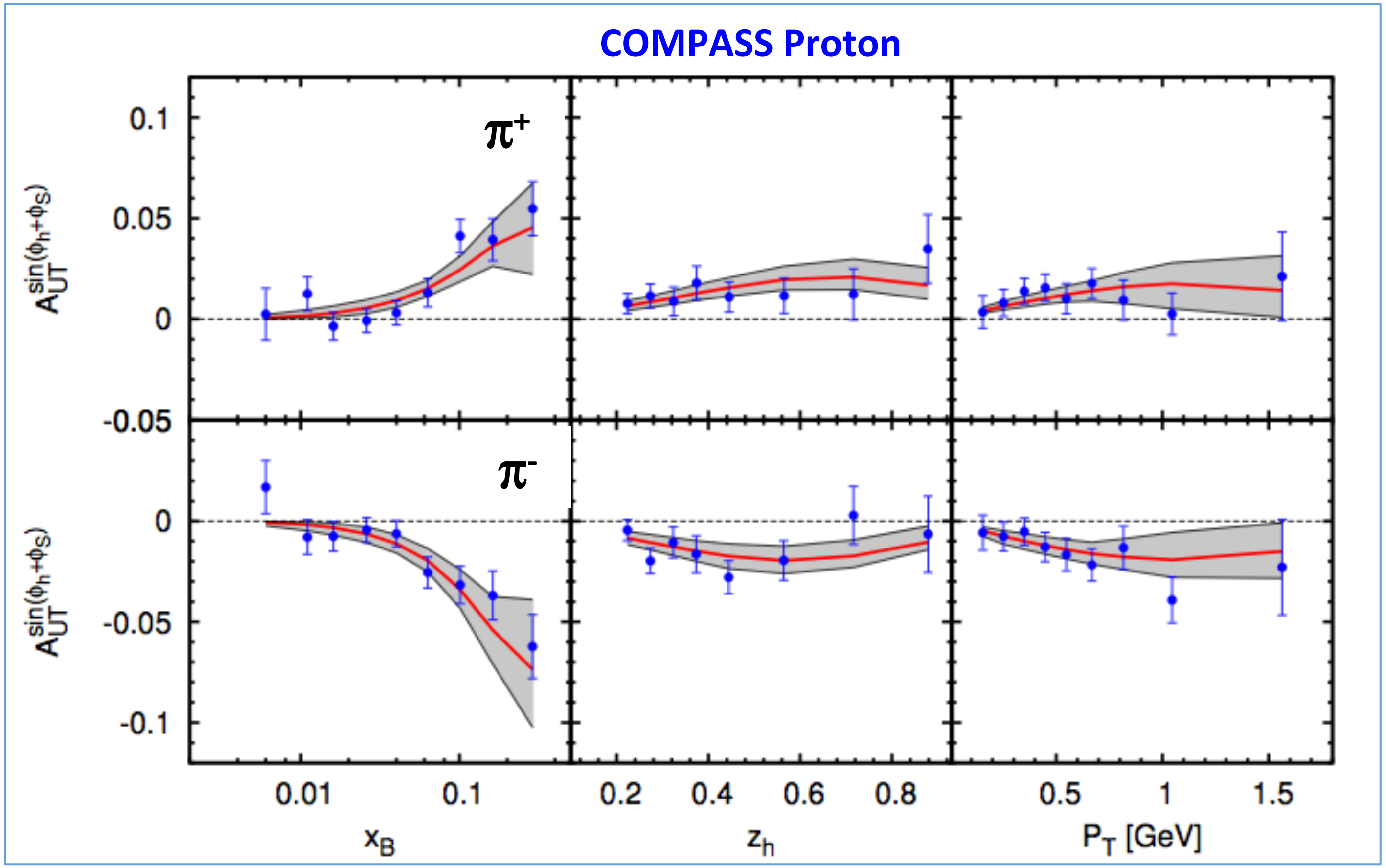
→ Important role of the Q^2 dependence in Sivers case



Collins asymmetries *vs* model predictions

Comparison with fit to HERMES p, COMPASS p & d, BELLE e+e- data by

M. Anselmino et al., arXiv:1303.3822



➔ **Good agreement for x, z, p_T^h within the uncertainties**

Collins asymmetries *vs* model predictions

Comparison with fit to HERMES p, COMPASS p & d, BELLE e+e- data by

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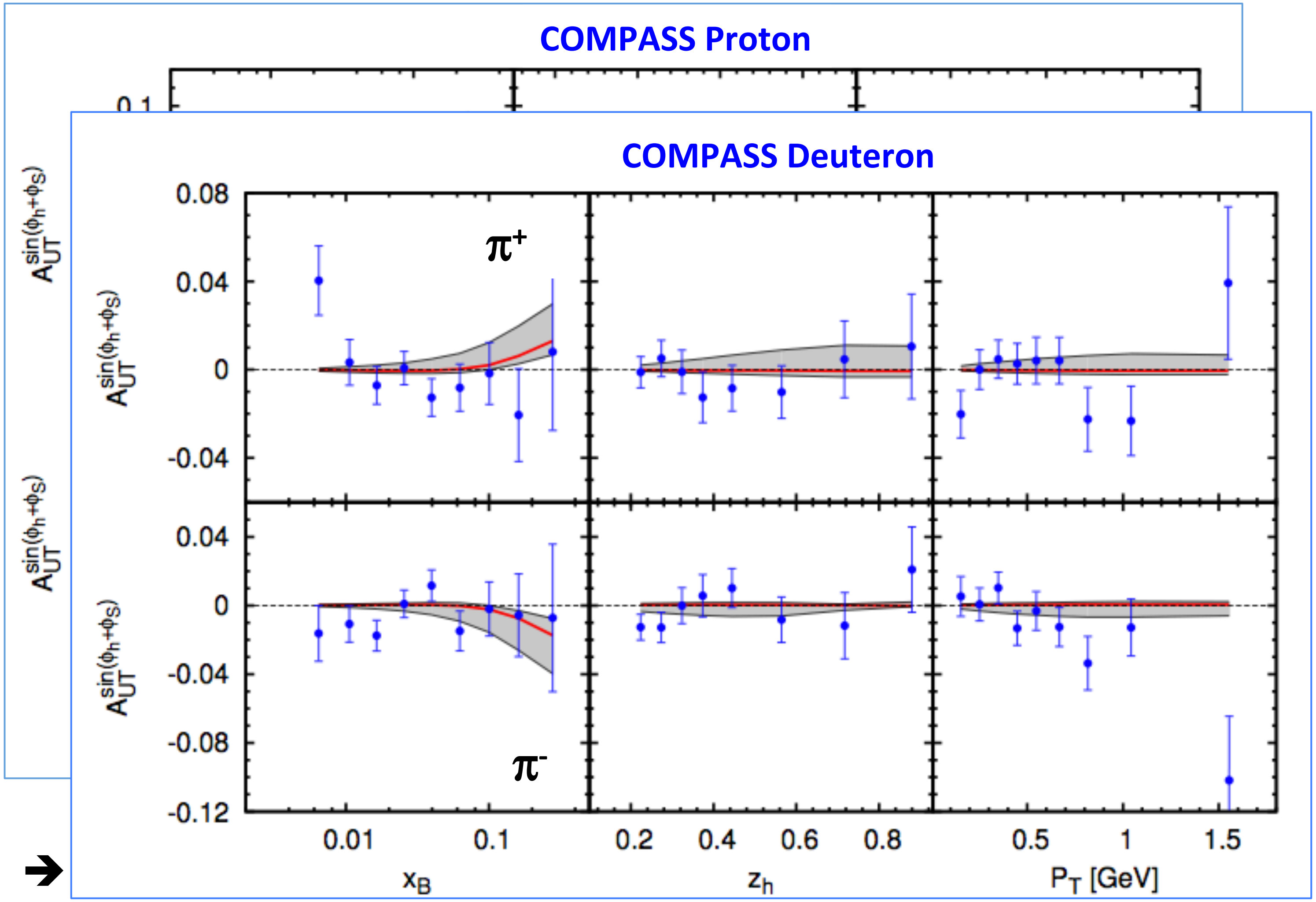
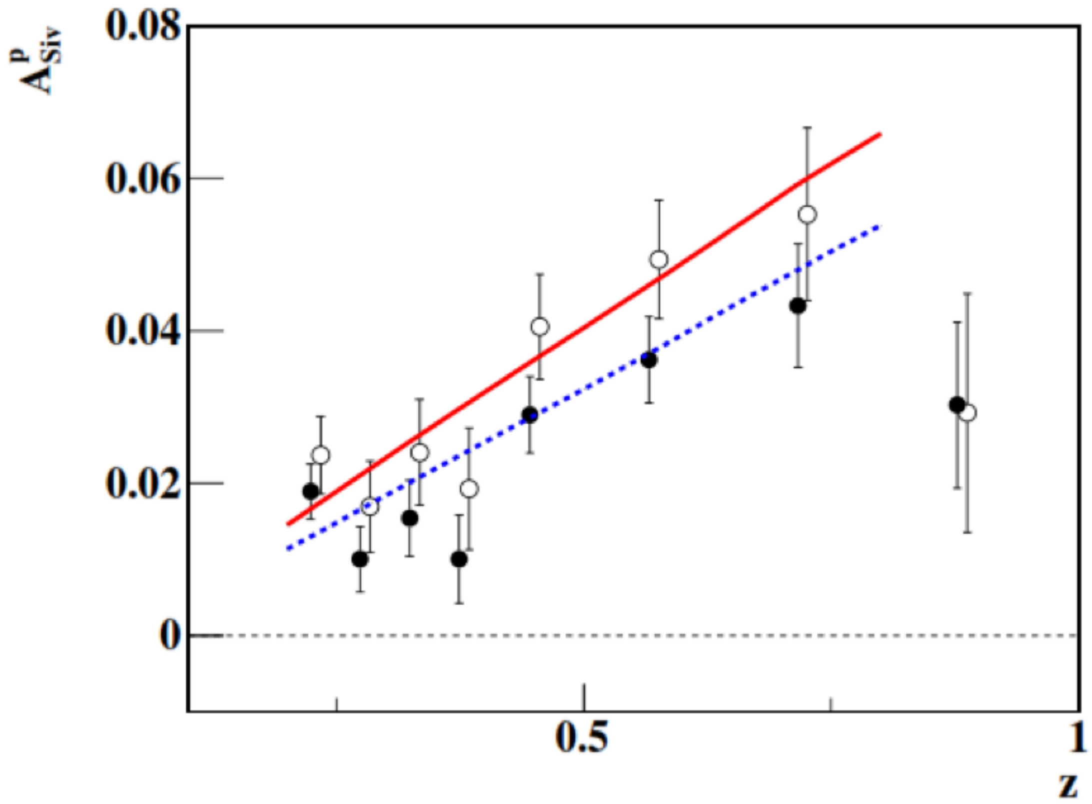


Charged hadrons , 2010 data compared with model calculation by
S.M.Aybat, A. Prokudin and T. C. Rogers, PRL 108 (2012) 242003



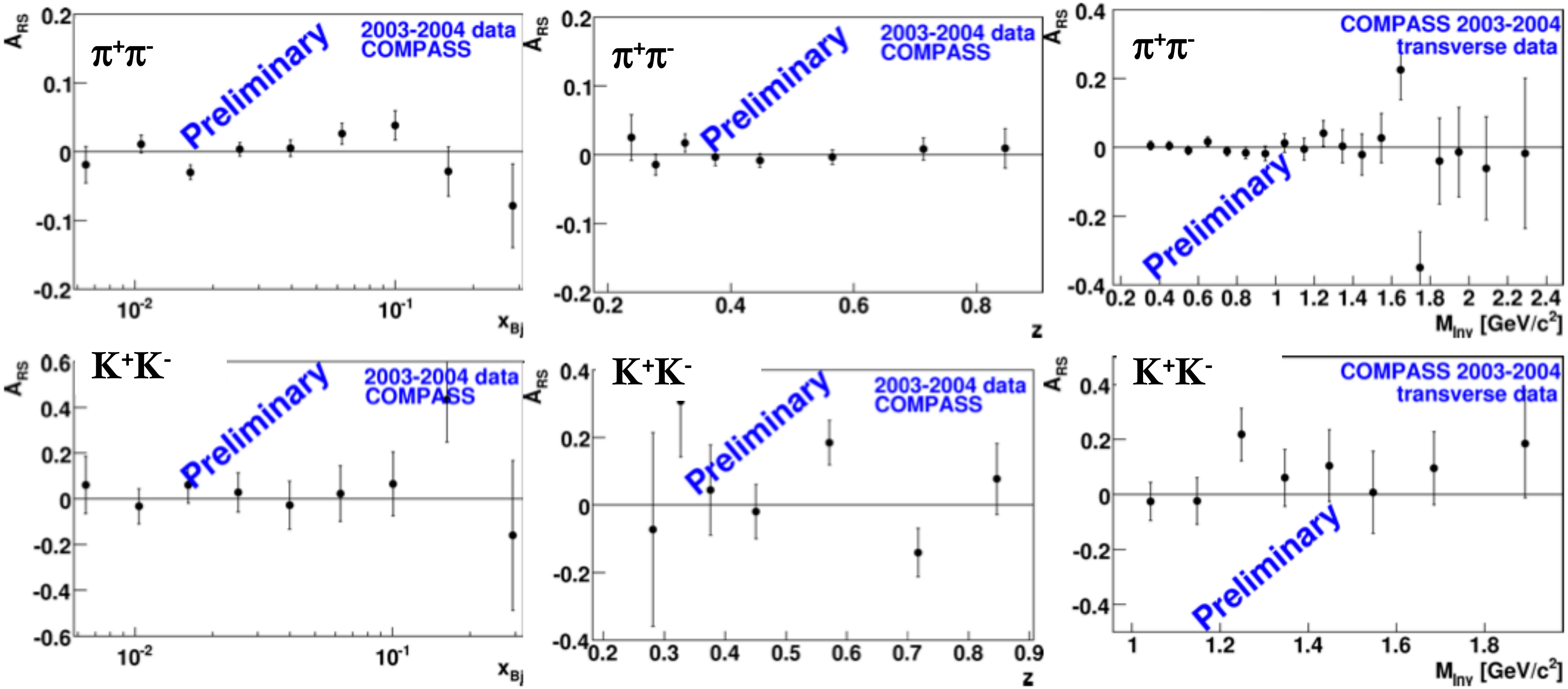
x > 0.032
$\langle Q^2 \rangle$ = 8.7 $(GeV/c)^2$

Full x range
$\langle Q^2 \rangle$ = 3.8 $(GeV/c)^2$

Good agreement between data and model calculations

Dihadron asymmetry on deuteron – $\pi^+\pi^-$ and K^+K^-

2002-04

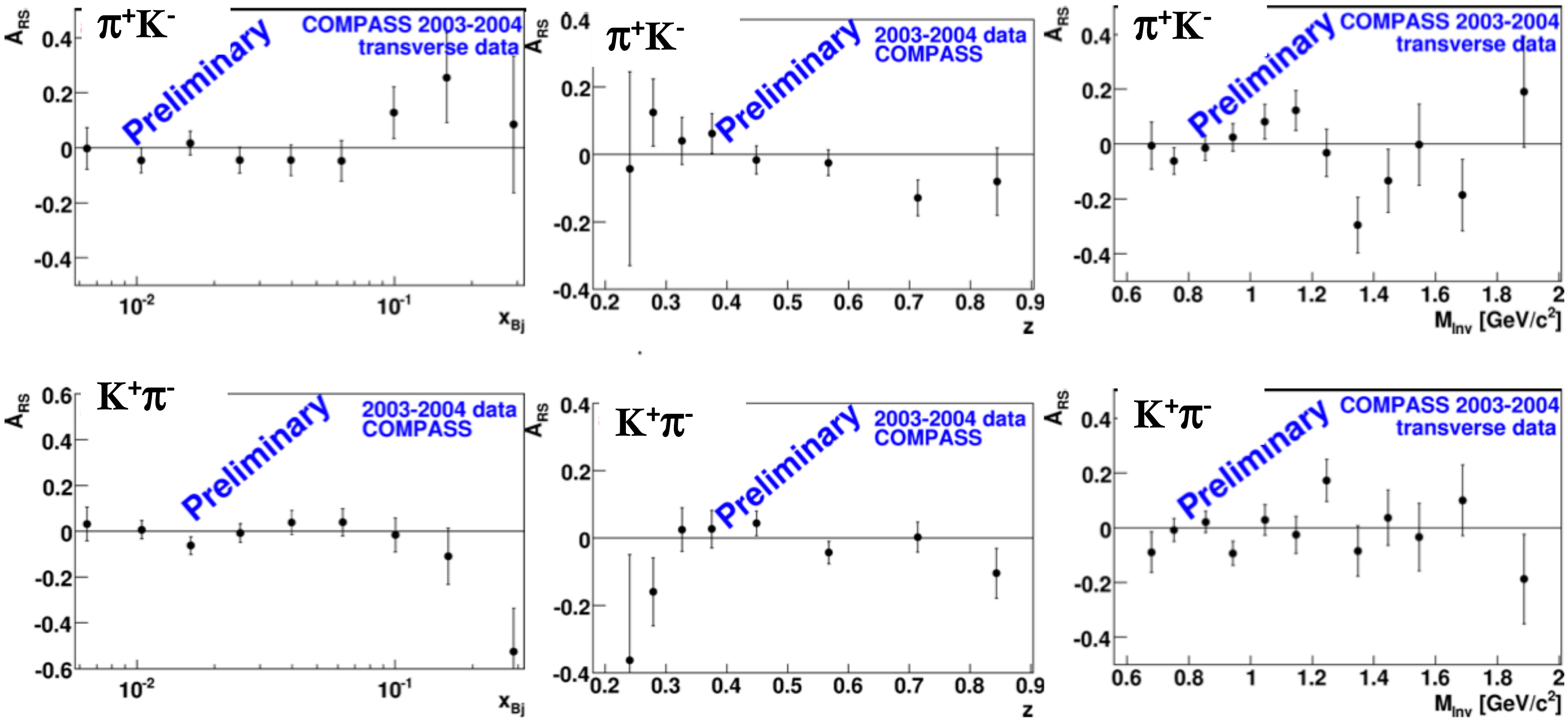


$\pi^+\pi^-$: Compatible with zero asymmetries

K^+K^- : Low statistics

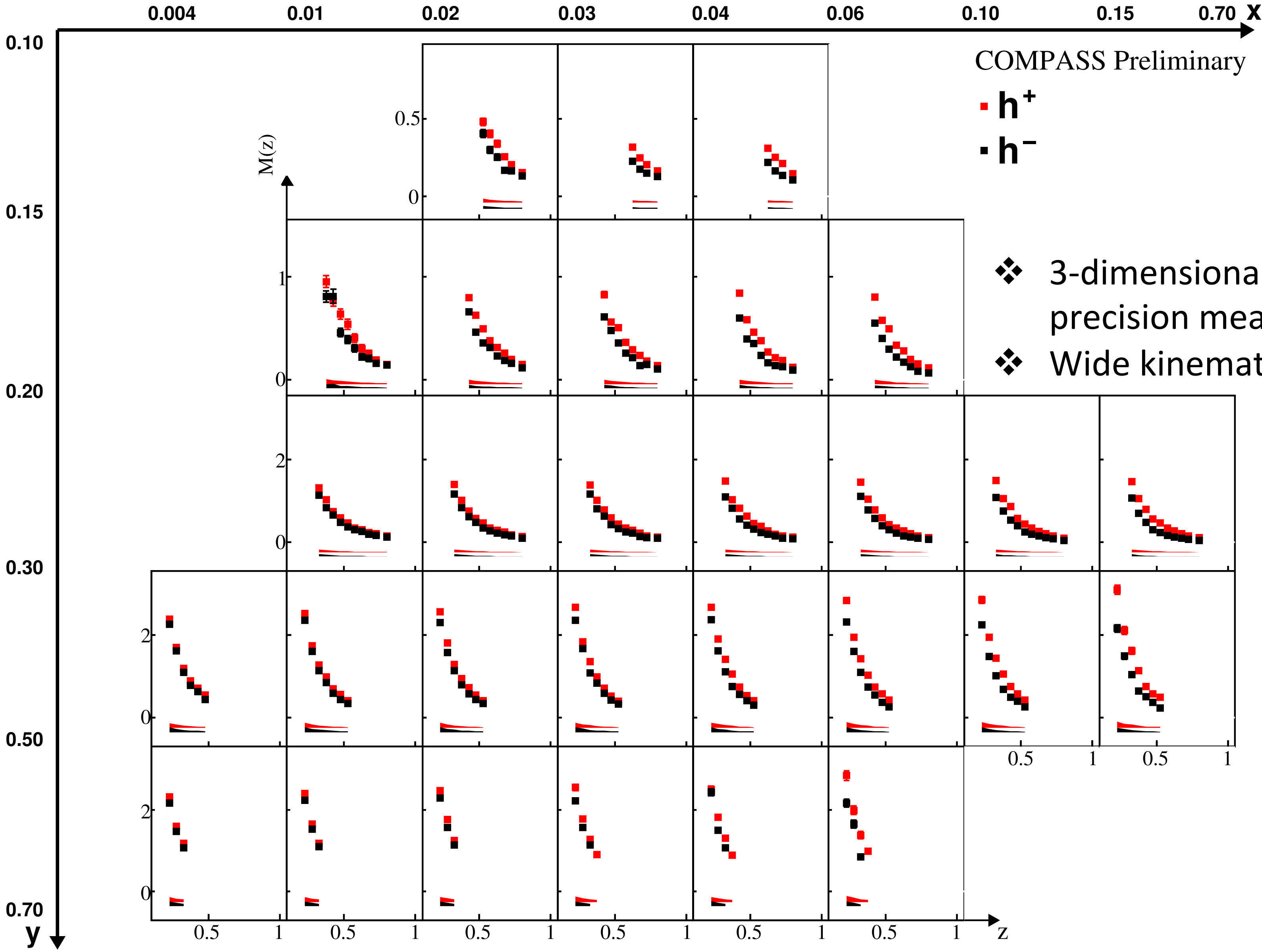
Dihadron asymmetry on deuteron – π^+K^- & $K^+\pi^-$

2002-04



No clear signal

Unidentified hadron multiplicities vs (x,y,z)

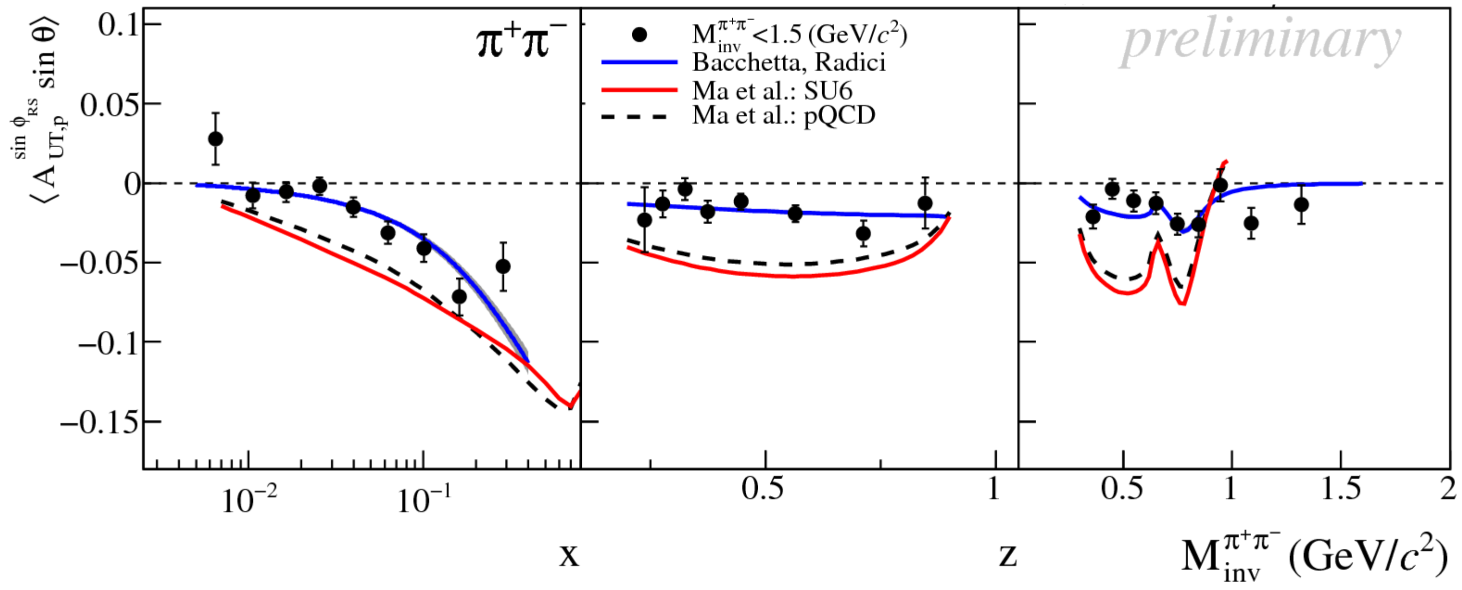


- 3-dimensional High precision measurement
- Wide kinematic domain

Dihadron asymmetry on proton: $\pi^+\pi^-$ vs model

Combined 2007 & 2010 data

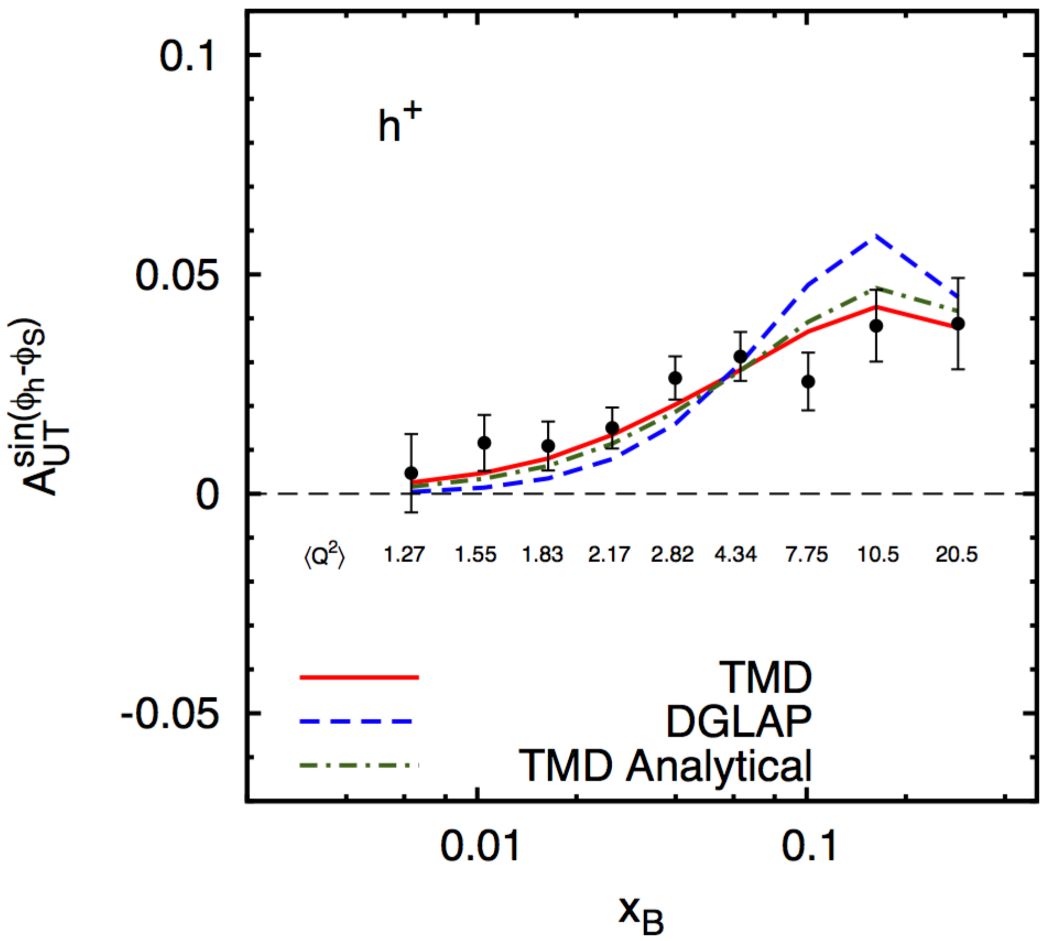
Bachetta ***et al.*** *PRD 74 (2006) 114007*, **Ma B.-Q.** ***et al.*** *PRD 77 (2008) 014035*



good agreement with Bachetta's calculation

Sivers asymmetry on proton – Q^2 evolution

Charged hadrons , 2010 data compared with model calculation by
M. Anselmino, M. Boglione, S. Melis arXiv:1204.1239



Good agreement between data and model calculations