Transverse SPIN Effects measured in COMPASS

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International Workshop on Hadron Structure
and Spectroscopy IWHSS10
March 14 - 17, 2010

OUTLOOK

- the COMPASS experiment
- results on
  - transversity : Collins asymmetries
    2 hadron asymmetries
    Λ polarization
  - Sivers asymmetries
  - other TMD asymmetries
  - unpolarised azimuthal asymmetries
  - exclusive ρ asymmetries
- future plans for SIDIS and DY

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COMPASS

fixed target experiment at the CERN SPS

broad physics programme

data taking since 2002:

muon beam	**deuteron (^{6}LiD) polarised target**	**2002 2003 2004**	**L/T target polarisation 4:1**
		2006	**L target polarisation only**
	proton (NH_3) polarised target	**2007**	**L /T target polarisation 1:1**
hadron beam	**LH target**	**2008 2009**	

muon beam: 160 GeV/c longitudinal polarisation -80%

intensity $2\cdot10^8$ μ^+/spill (4.8s/16.2s)

COMPASS

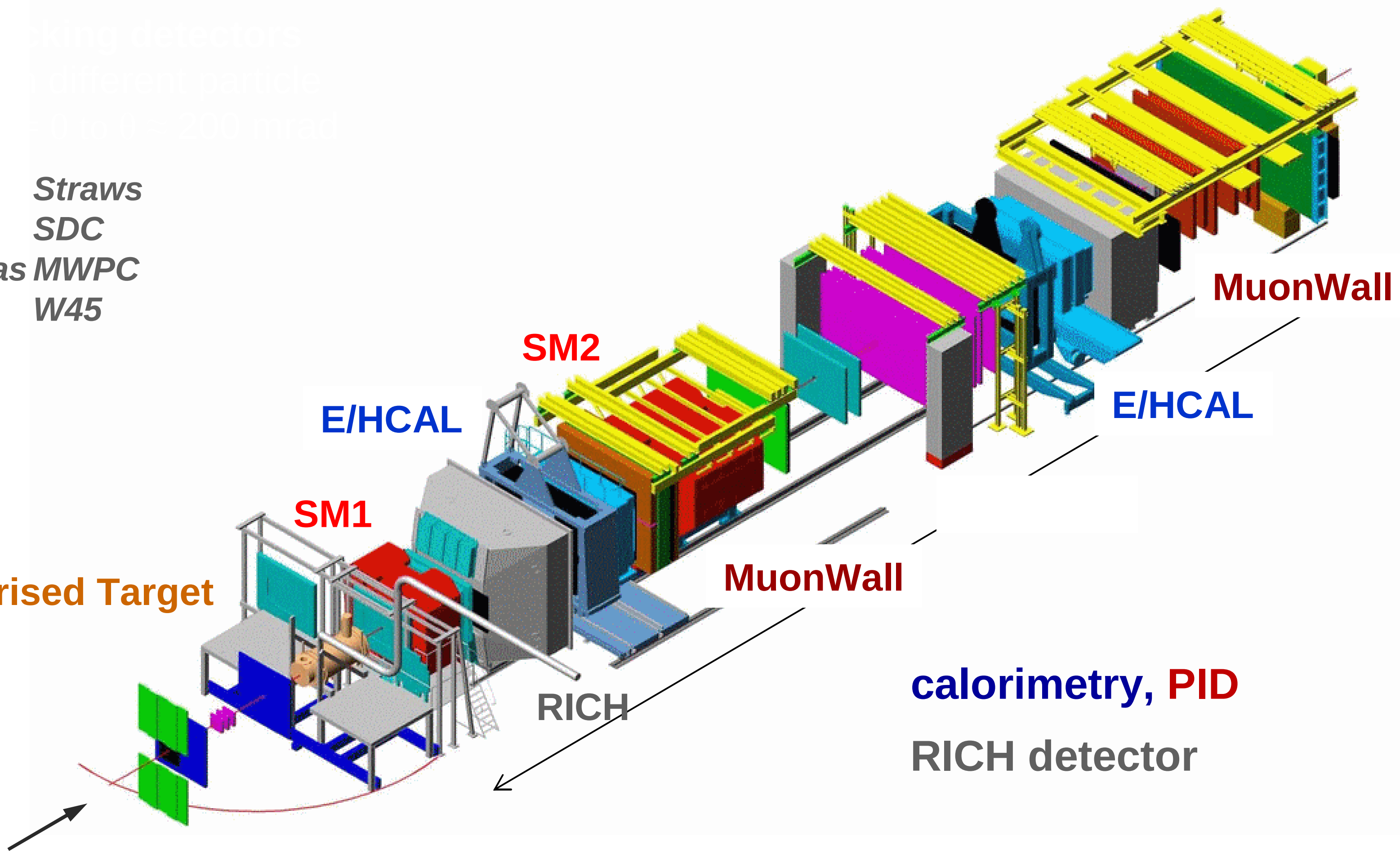
- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

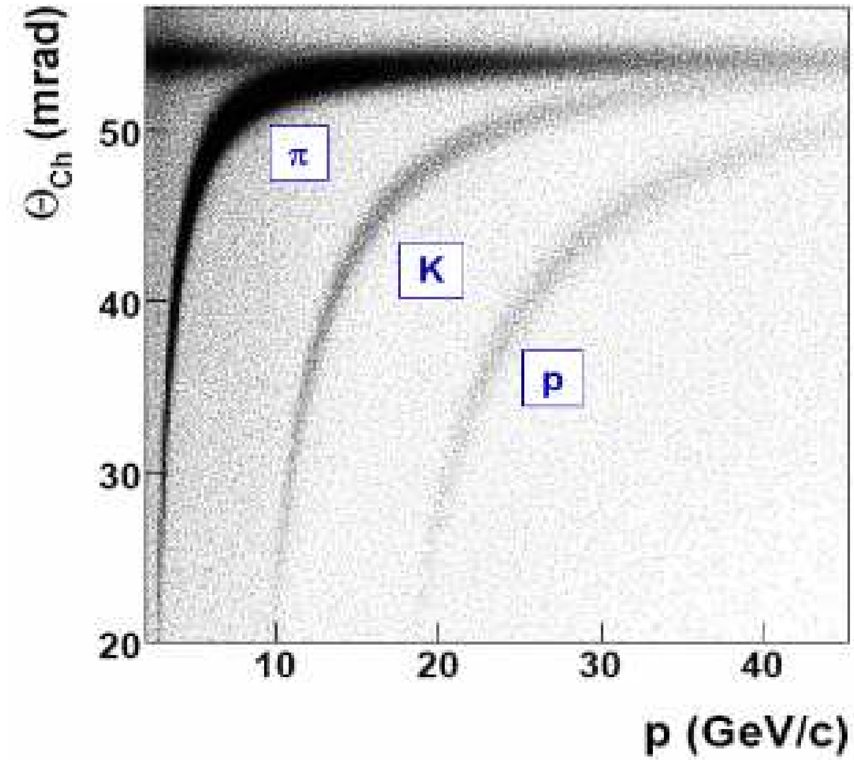
SciFi *Straws*
Silicon *SDC*
Micromegas *MWPC*
GEMs *W45*



calorimetry, PID

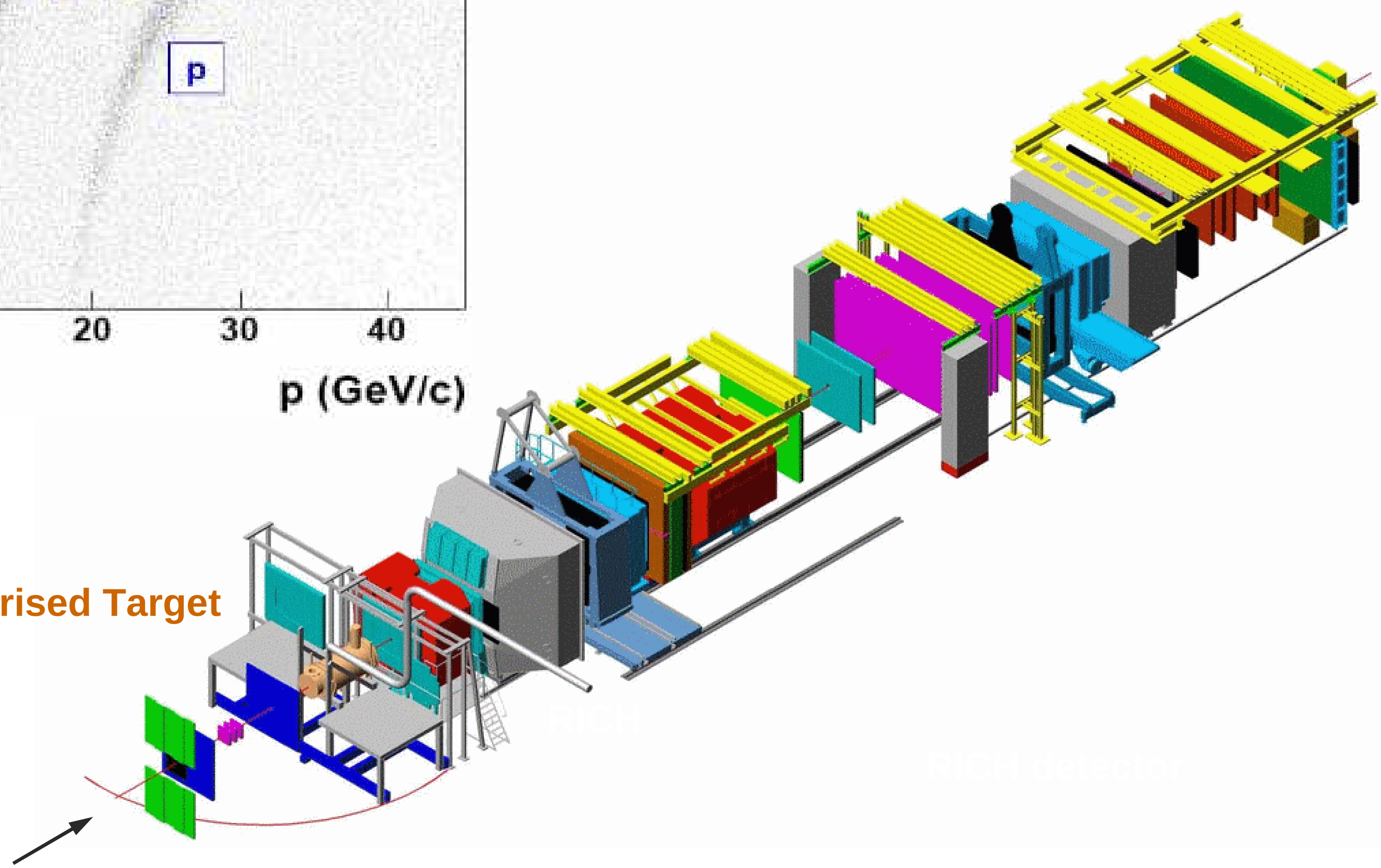
RICH detector

COMPASS



radiator C_4F_{10}

threshold: π ~2 GeV/c
K ~ 10 GeV/c

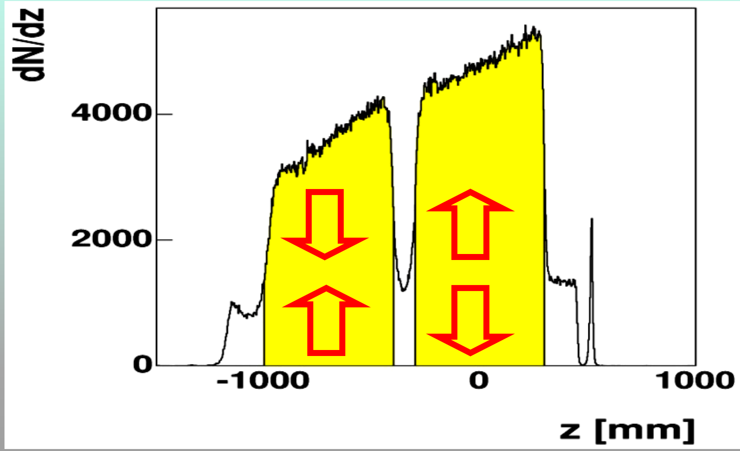


The Target System

solid state target operated in frozen spin mode

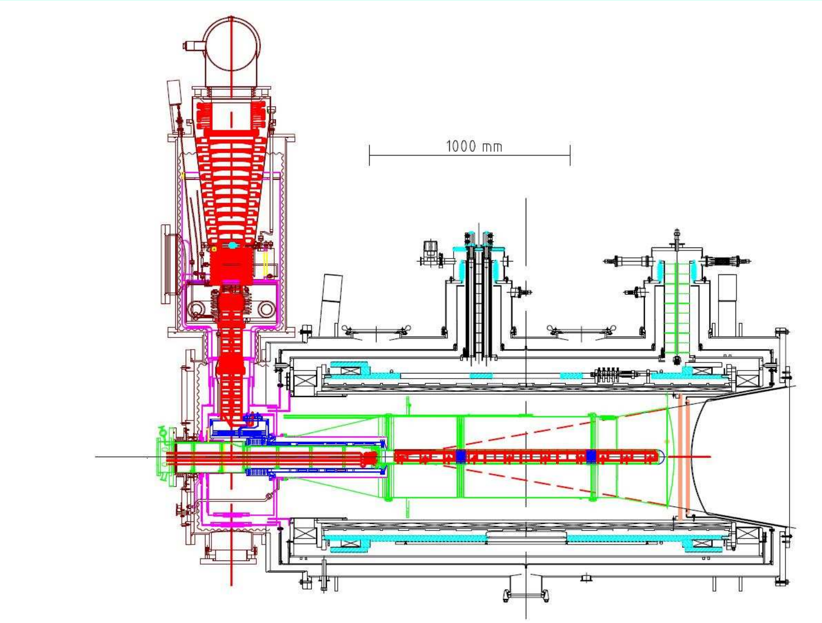
2002-2004: ^{6}LiD (polarised deuteron)
dilution factor f = 0.38
polarization P_T = 50%

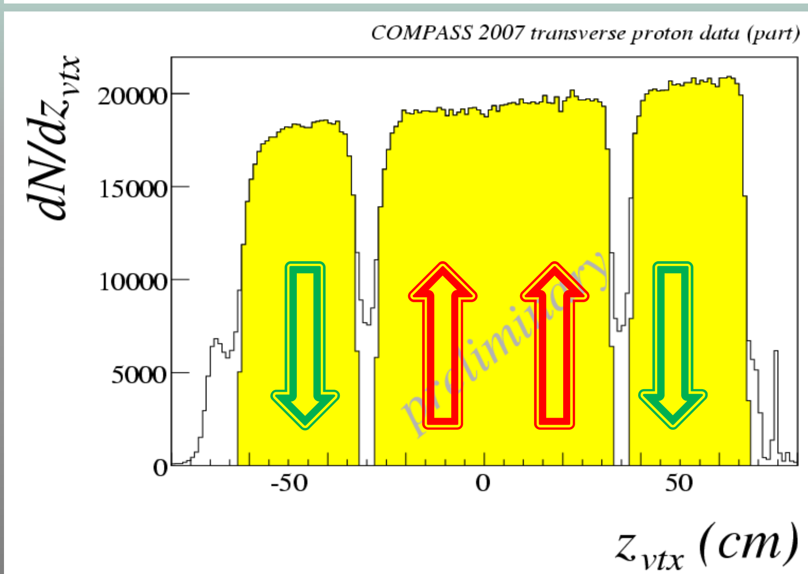
two 60 cm long cells with opposite polarization



during data taking with transverse polarization,
polarization reversal after ~ 4-5 days

Polarized Target





New COMPASS target magnet:

→180 mrad geometrical acceptance

→excellent field homogeneity

To match larger acceptance:

→new microwave cavity

→3 target cells: reduction of false asymmetries

Target material:

→NH_3

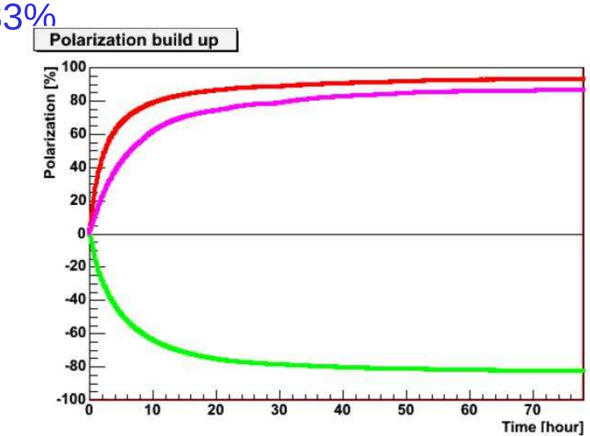
→high polarisation

→very long relaxation time (~ 4000 h)

→magnetic field rotation without polarisation loss

→ Polarisation of NH_3 in 2007:

-92%, +88%, -83%



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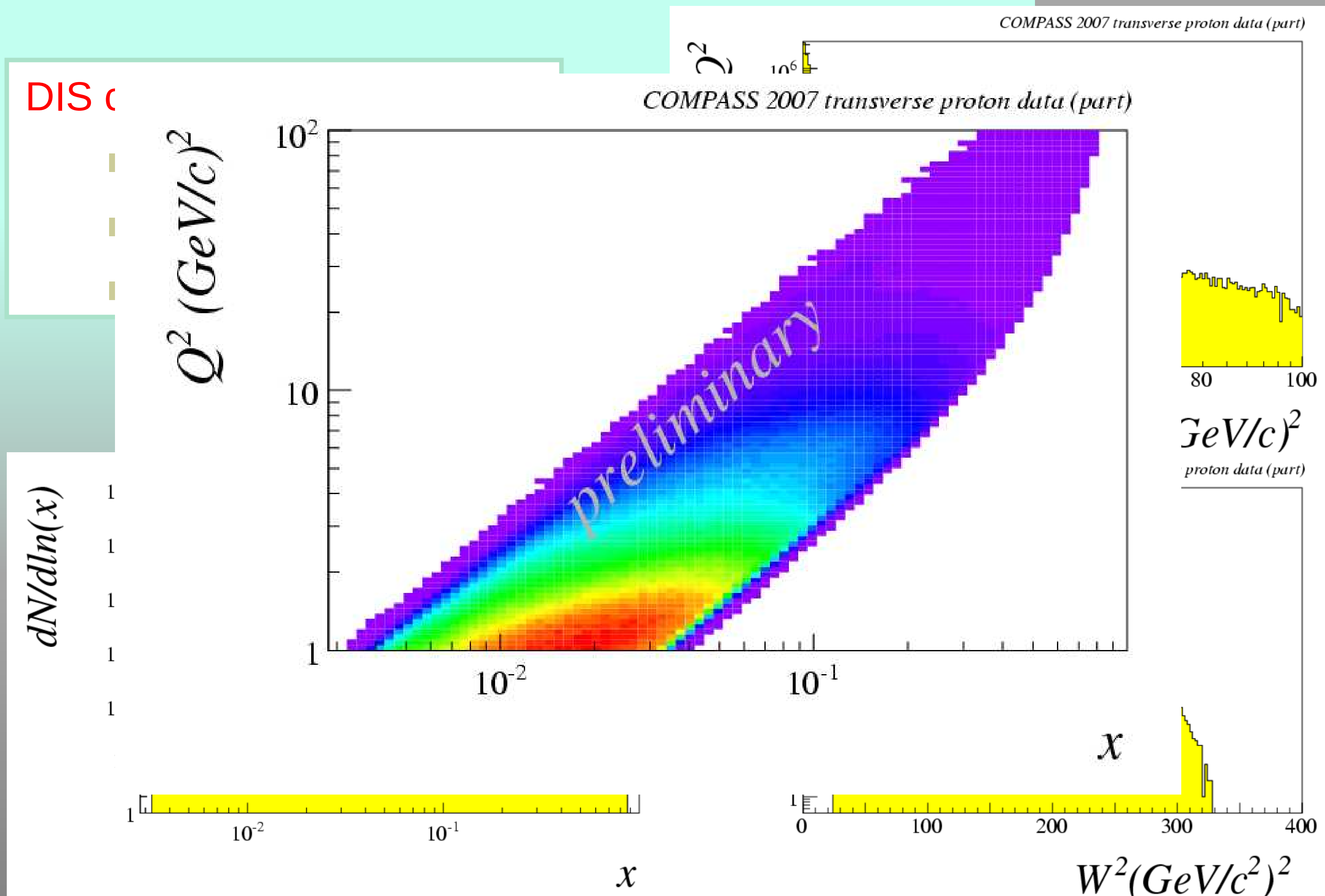
DIS Event Selection

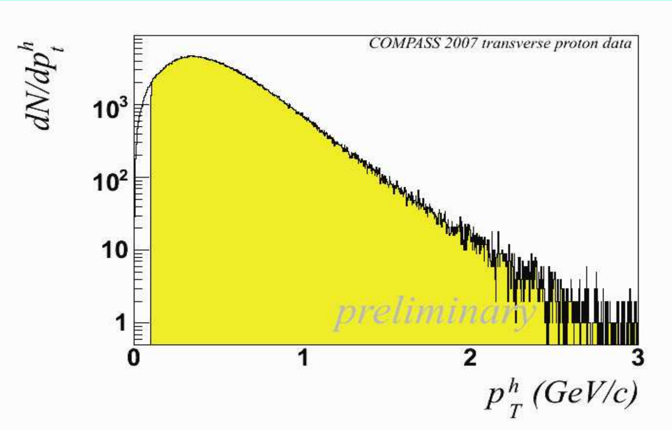
DIS c

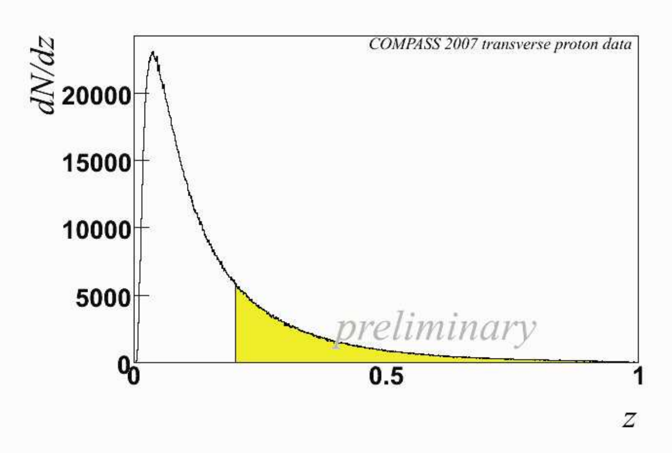


Hadron Selection

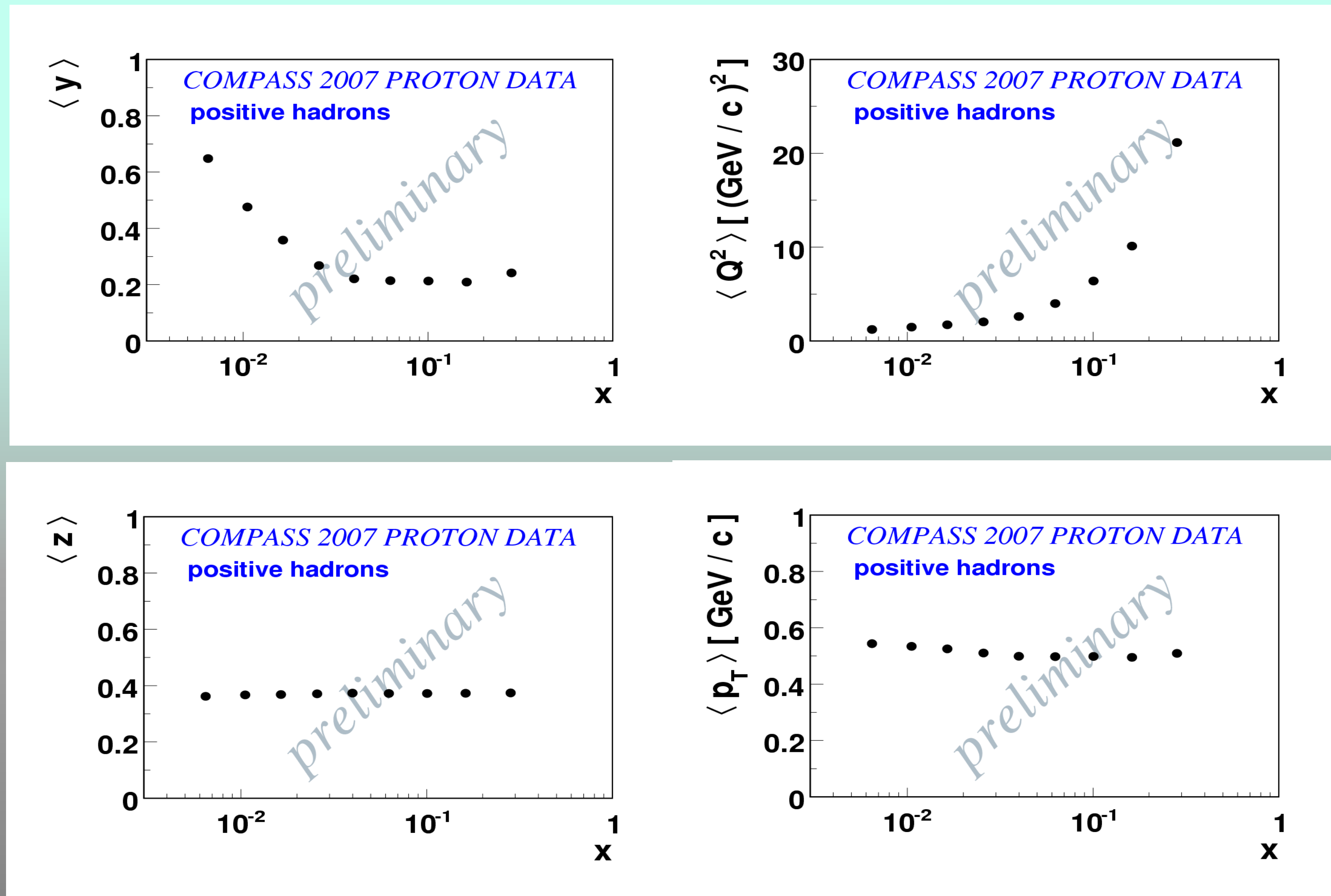
All hadrons

- Energy Deposit in HCALs>Thr. (4 GeV HCal1 and 5 GeV Hcal2)
- Only 1 HCAL fired
- p_T>0.1 GeV/c
- z>0.2





Mean of kinematical quantities



SIDIS azimuthal asymmetries

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

All possible 8 azimuthal asymmetries extracted at once.

From **A. Bacchetta** et al., **JHEP 0702:093,2007**.
e-Print: **hep-ph/0611265**

Sivers

Collins

6 further modulations

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

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

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

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

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

Nucleon Structure

eight leading order PDFs shows up,
when taking into account the quark intrinsic transverse momentum k_T

		nucleon polarization		
		U	L	T
quark polarization	U	f_1 *number density*		$f_{1T}^{\perp}$ -
	L		g_1 - *helicity*	g_{1T} -
	T	$h_1^{\perp}$ -	$h_{1L}^{\perp}$ -	h_1 - *transversity* $h_{1T}^{\perp}$ -

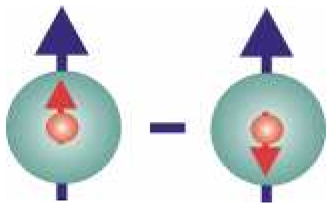
Transversity DF

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

$h_1^q(x)$,

$\delta q(x)$,

$\delta_T q(x)$



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

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

Transversity Distribution Function

is chiral-odd:

observable effects are given only by the product of $\Delta_T q\,(x)$ and an other chiral-odd function

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

$l\,N^{\uparrow} \rightarrow l'\,h\,X$	**"Collins" asymmetry** **"Collins" Fragmentation Function**
$l\,N^{\uparrow} \rightarrow l'\,h\,h\,X$	**"two-hadron" asymmetry** **"Interference" Fragmentation Function**
$l\,N^{\uparrow} \rightarrow l'\,\Lambda\,X$	**Λ polarisation** **Fragmentation Function of $q\uparrow \rightarrow \Lambda$**

all explored in COMPASS

Collins Asymmetry

→ **azimuthal distribution of the hadrons produced in** $l\,N^{\uparrow} \rightarrow l'\,h^{\pm}\,X$

$$N_h^{\pm}(\Phi_C) = N_h^0 \cdot \left[1 \pm P_T \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_C\right]$$

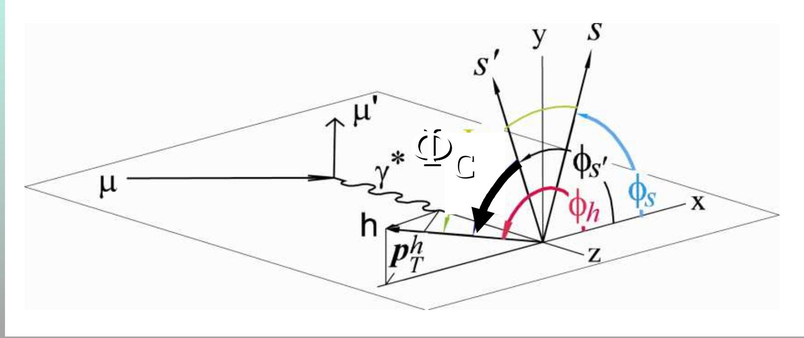
± refer to the opposite orientation of the transverse spin of the nucleon

P_T is the target polarisation; D_{NN} is the transverse spin transfer coefficient initial → struck quark

"Collins angle"

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

$\phi_{h,s',S}$ azimuthal angles of hadron momentum, of the spin of the fragmenting quark and of the nucleon in the GNS

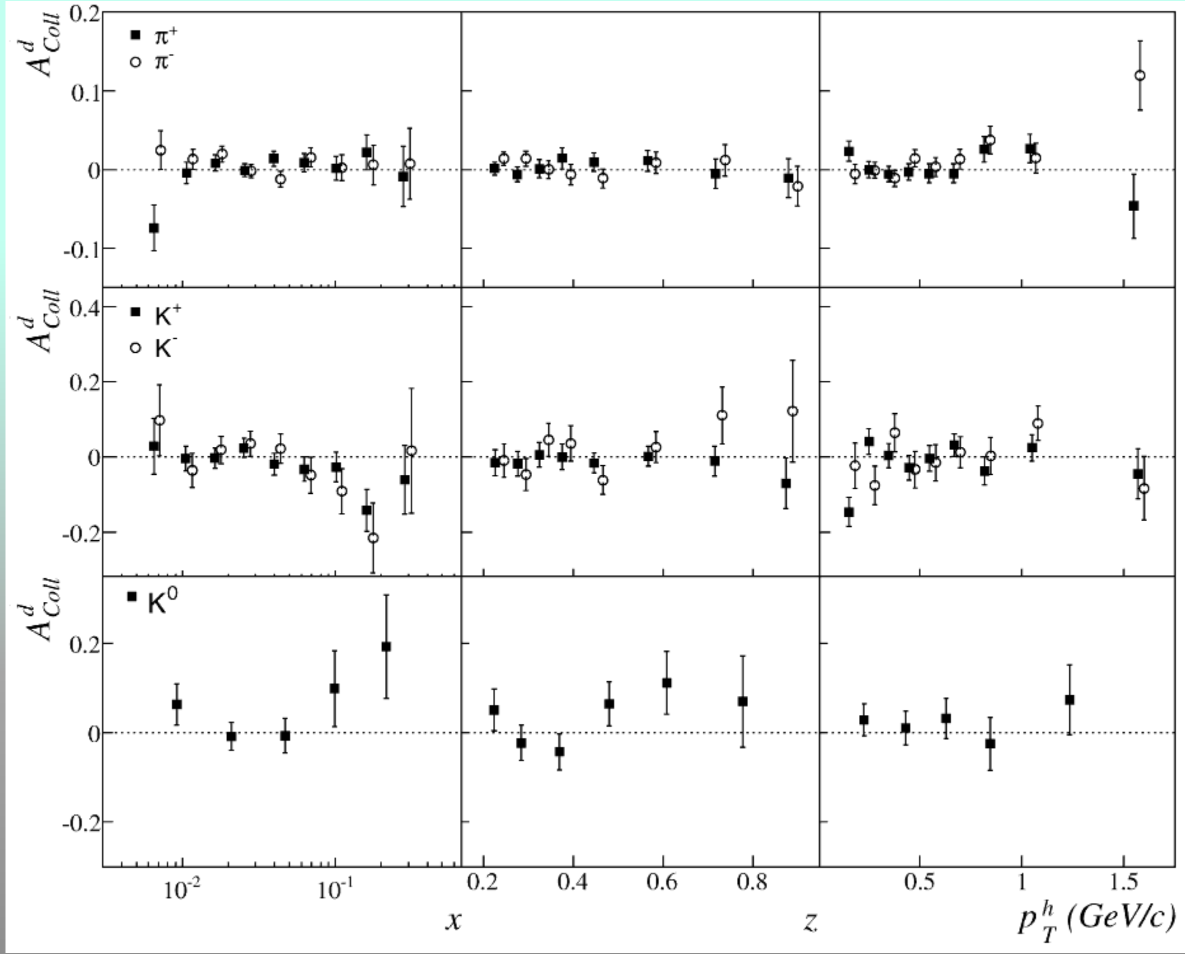


from the azimuthal distribution of the hadrons one measures the "Collins Asymmetry"

$$A_{Coll} \propto \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

the convolution of TRANSVERSITY and COLLINS FF

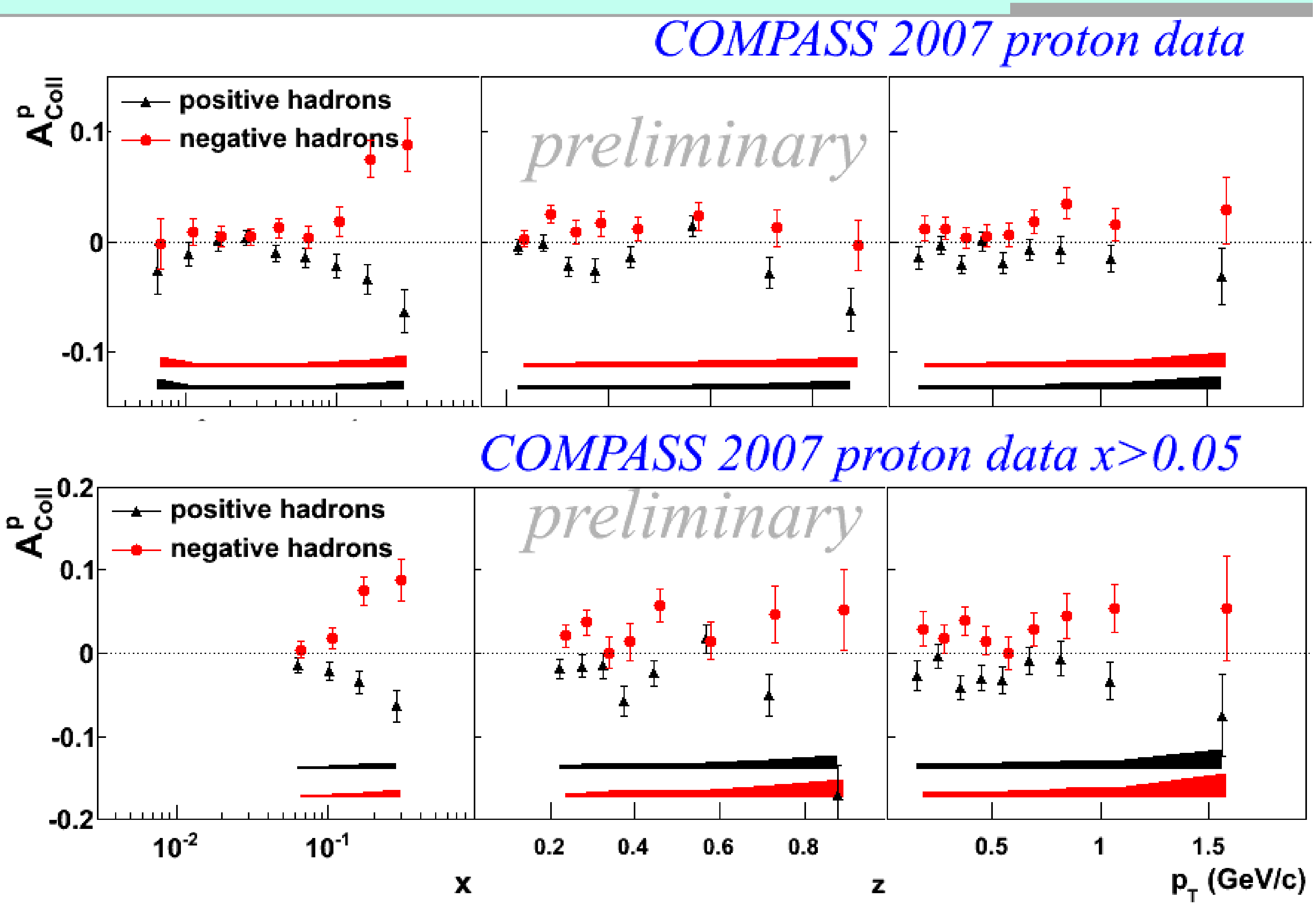
Collins Final on Deuteron



COMPASS Collaboration Physics Letters B 673 (2009) 127–135

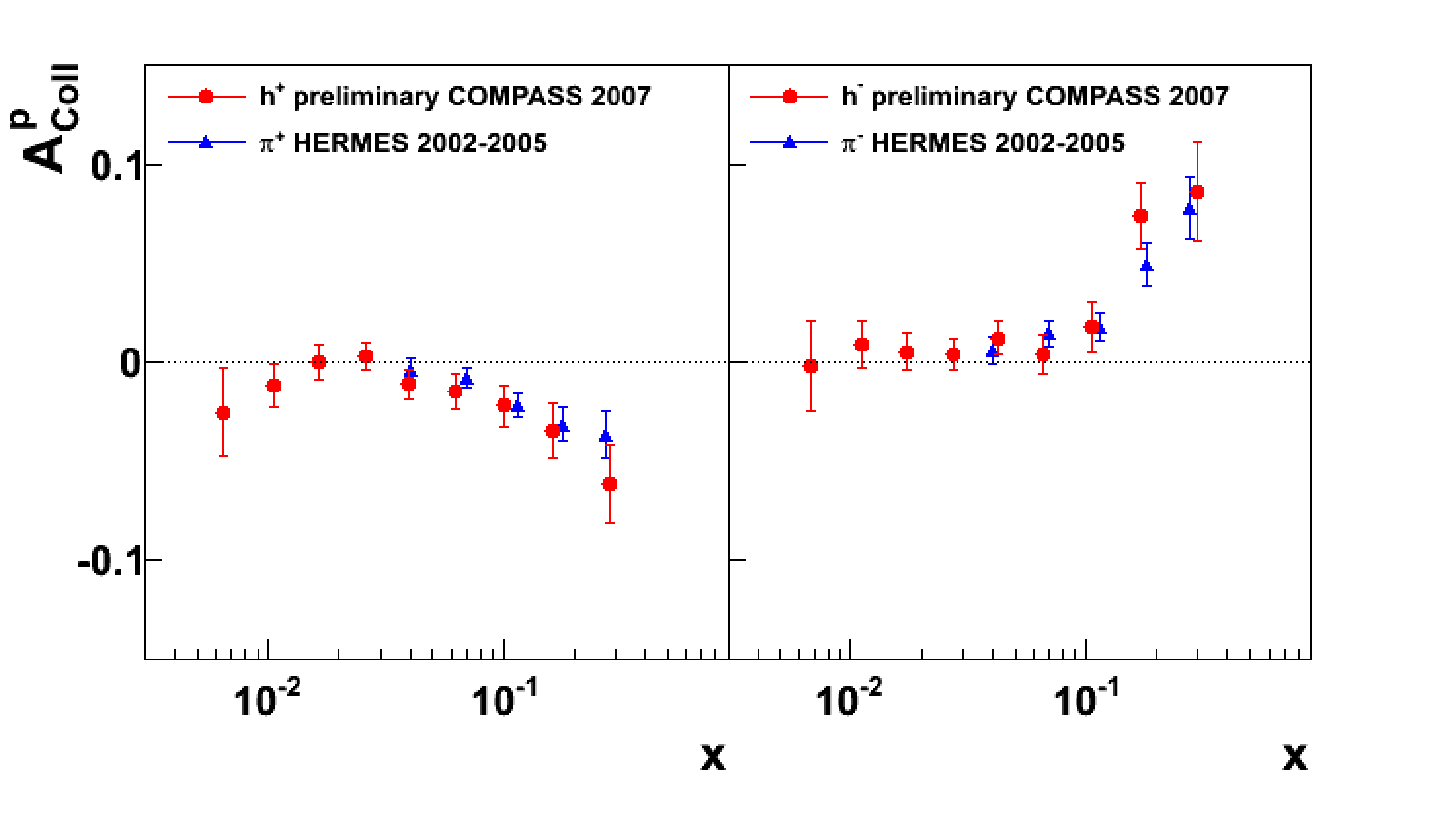
Systematic error well below 30% of the statistical one

Collins asymmetry



Compass proton data

comparison with HERMES



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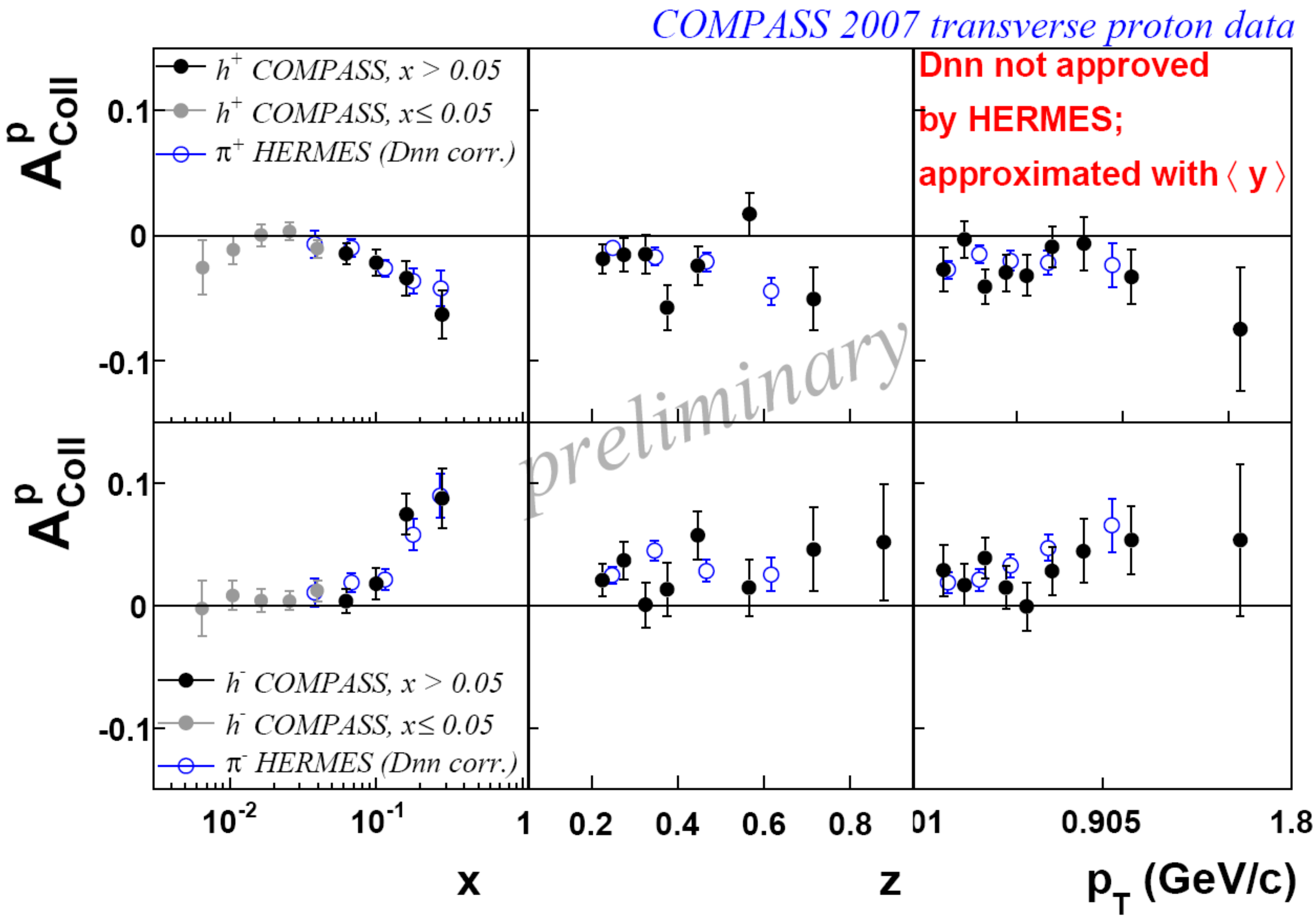
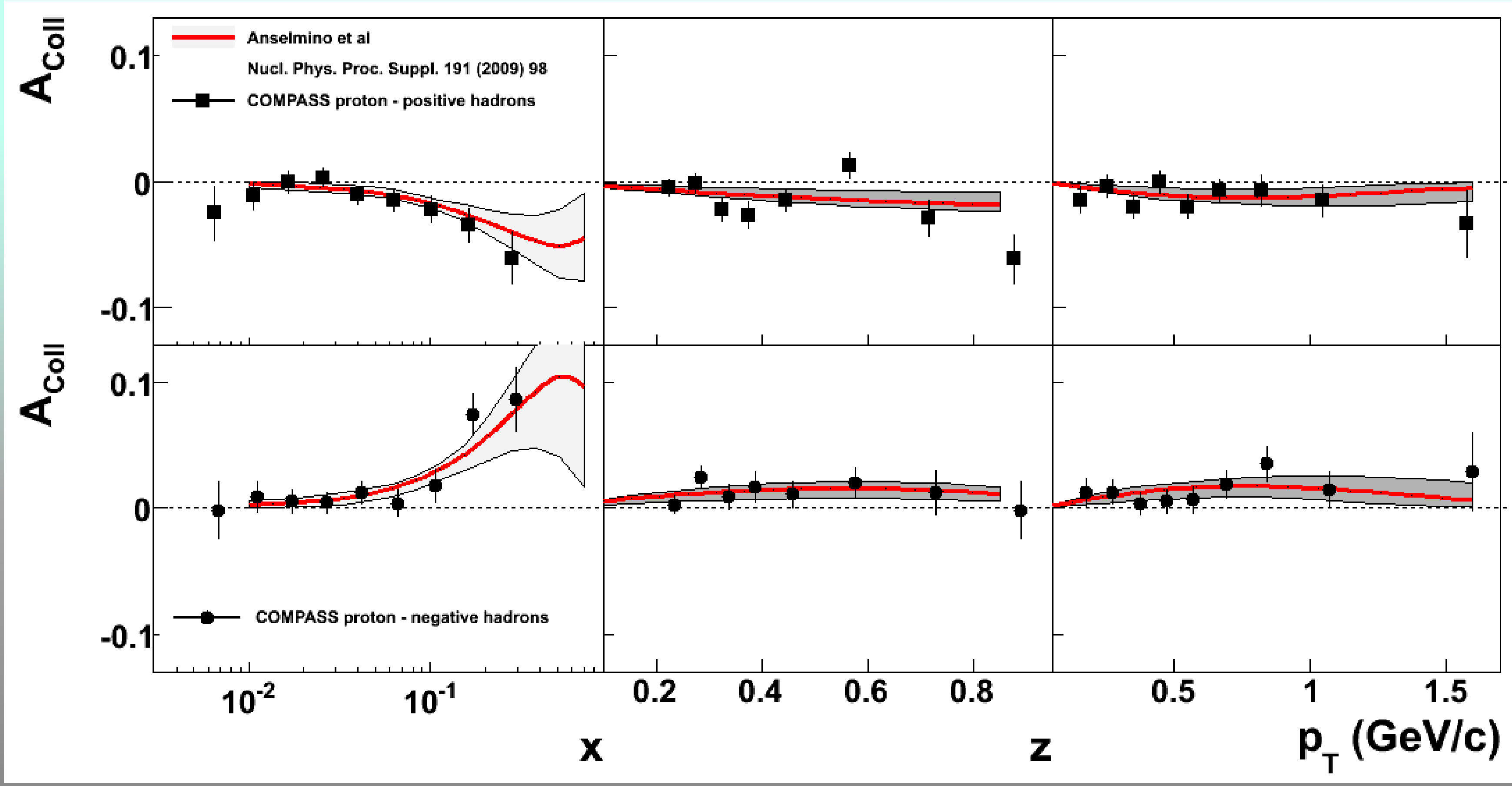


Compass proton data

comparison with M. Anselmino et al. predictions



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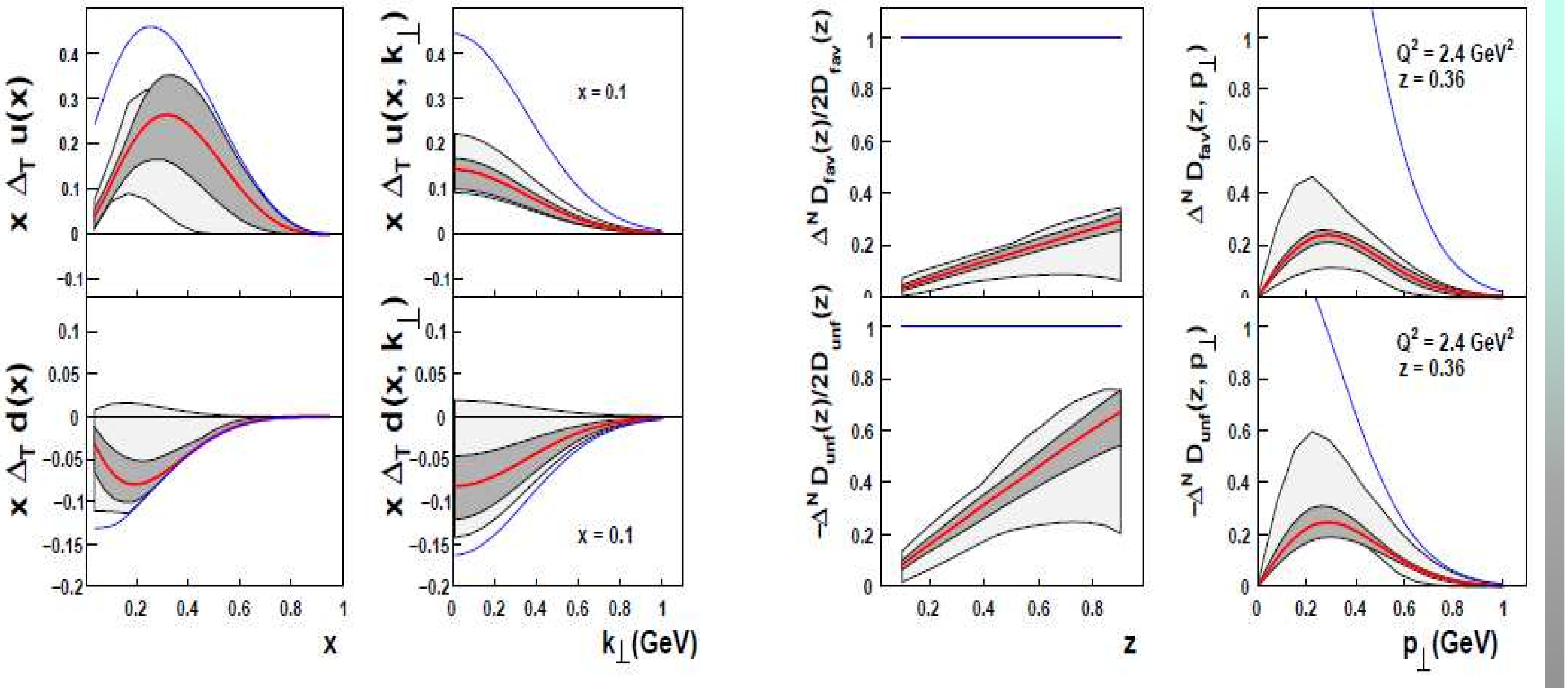
Transversity & Collins



Anselmino et al., Nucl. Phys., Proc. Suppl. 191 (2009) 93

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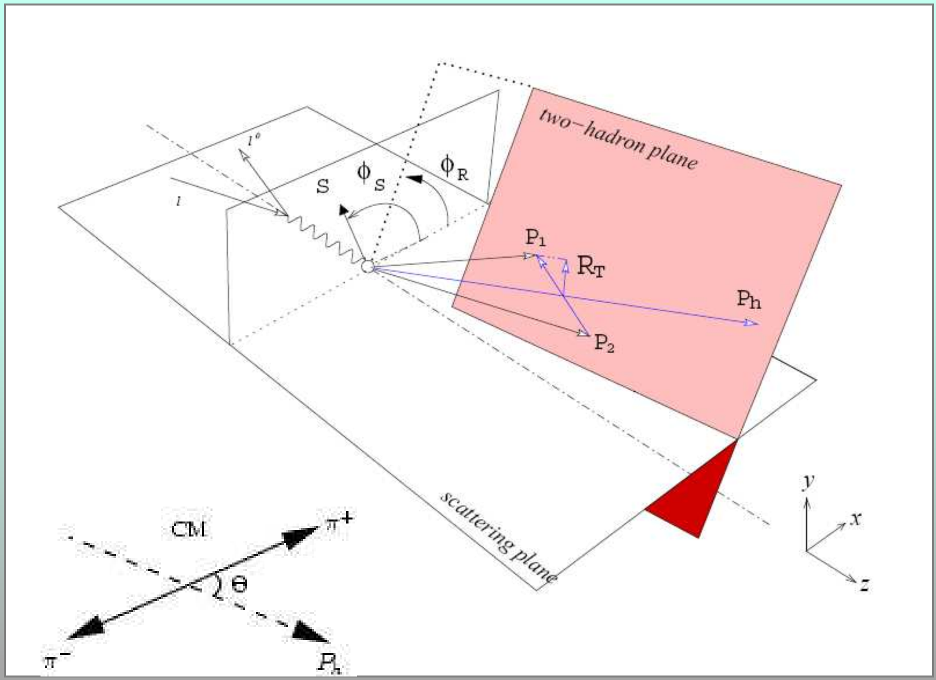
Two Hadron Asymmetries



azimuthal asymmetry in

$$\phi_{RS} = \phi_{R\perp} - \phi_S,$$

$\phi_{R\perp}$ **is the azimuthal angle of the plane defined by the two hadrons**

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

Interference Fragmentation Function

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

ϕ_{RS} defined by:

$$R = (z_1 p_2 - z_2 p_1)/(z_1 + z_2)$$

(X. Artru, hep-ph/0207309)

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

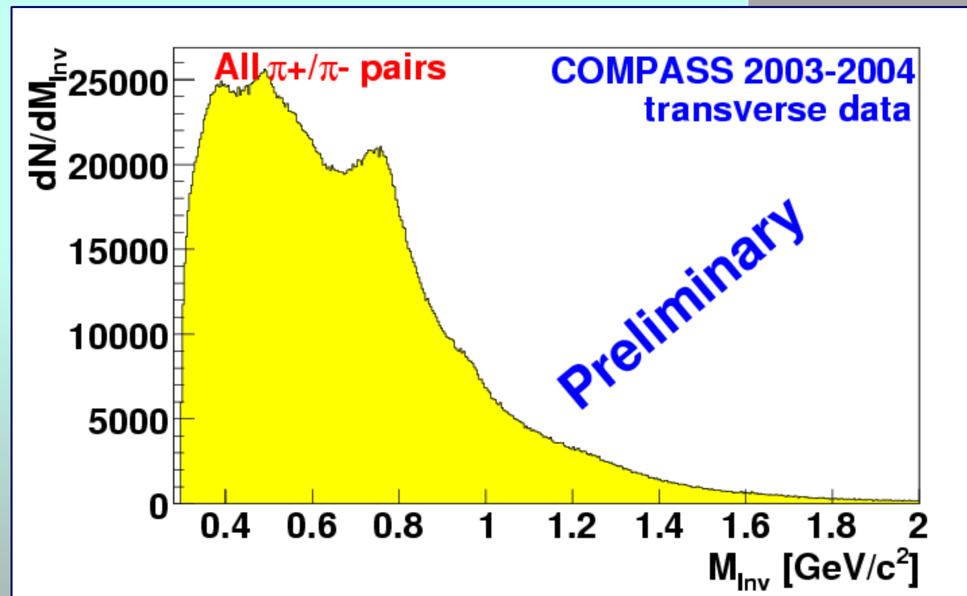
2H Asymmetries – Deuteron

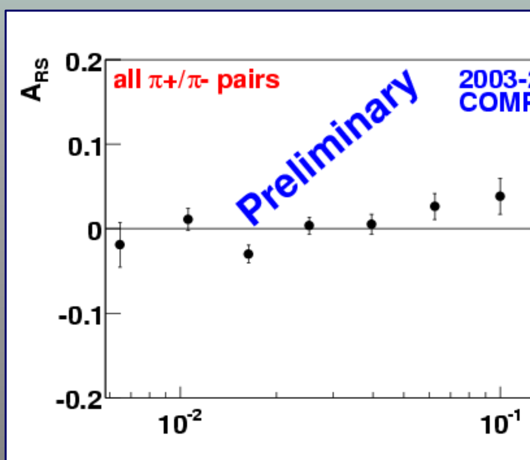
$x_F > 0.1$

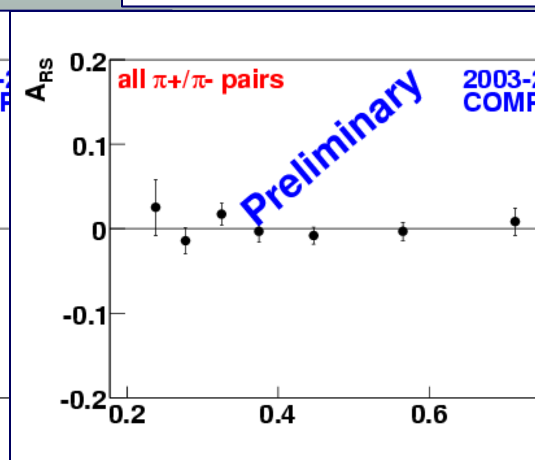
$z_{1,2} > 0.1$

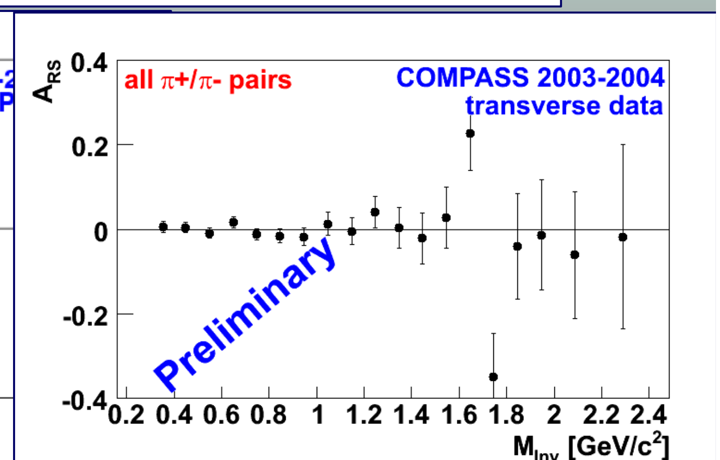
$Z = z_1 + z_2 < 0.9$

$R_T > 0.05$ GeV/c









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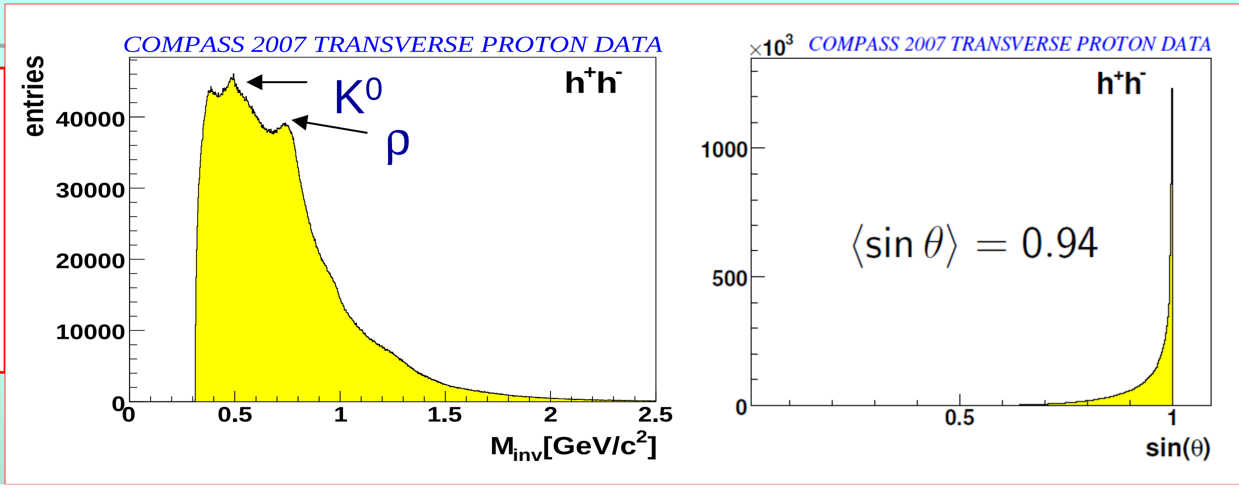
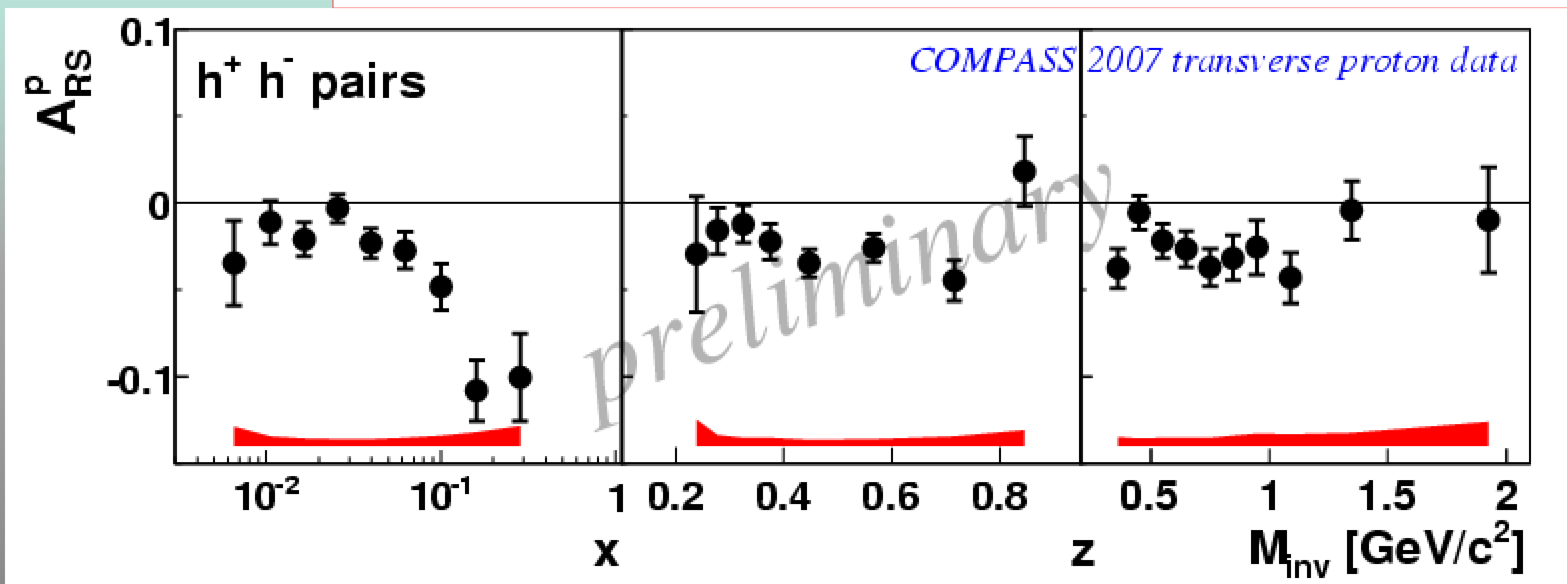
2H Asymmetries – Proton

- $x_F > 0.1$
- $z_{1,2} > 0.1$
- $Z = z_1 + z_2 < 0.9$
- $R_T > 0.07$ GeV/c





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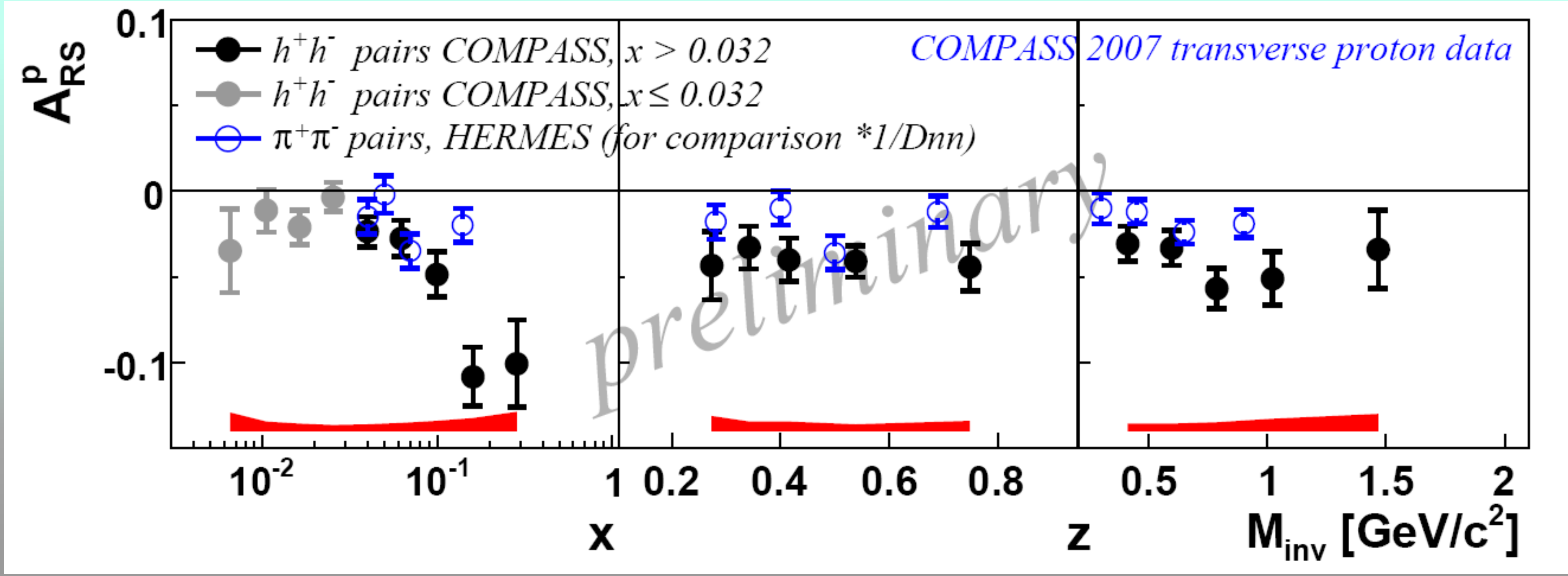
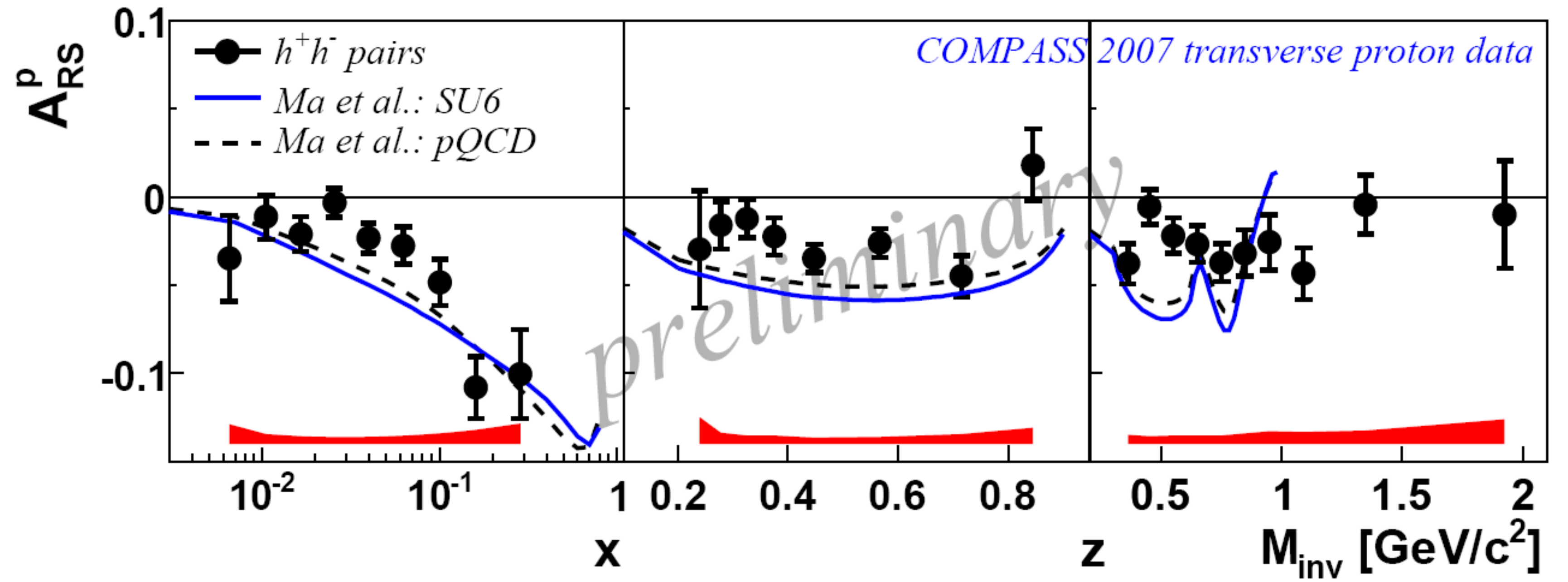


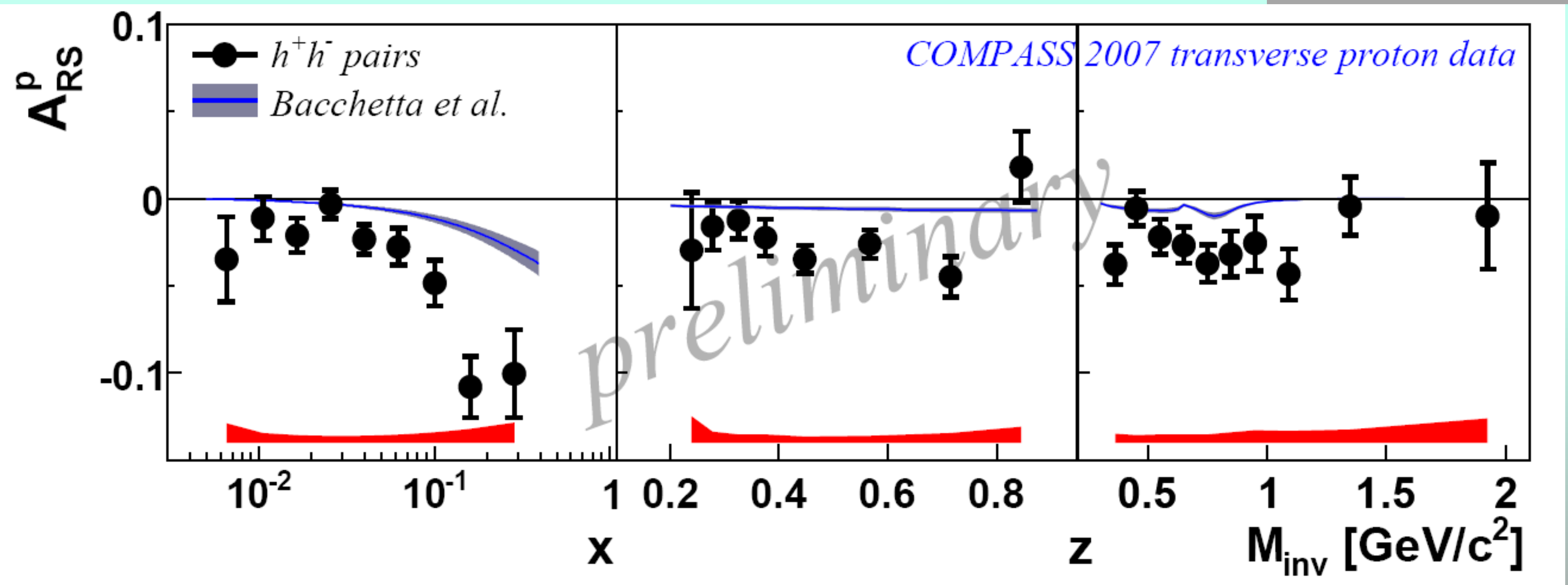
COMPARISON WITH HERMES

2H Asymmetries – Proton



Calculation by Ma et al. , TPSH09, Armenia, June 2009.

2H Asymmetries – Proton

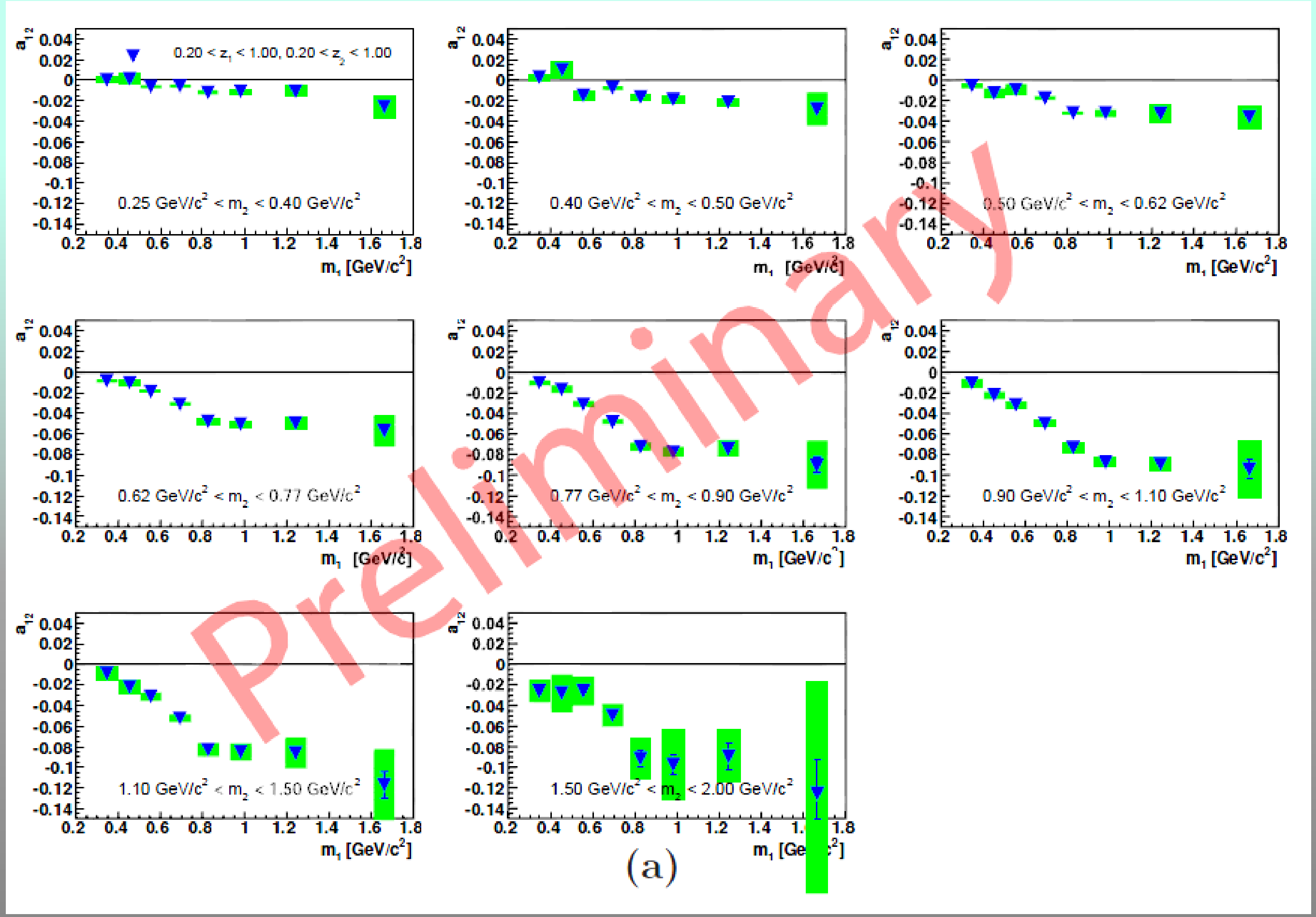


Prediction by Bacchetta, Radici, hep-ph/0608037
(Interference Fragmentation function scaled down to fit HERMES data)

Recent BELLE measurement of the IFF

Belle results on IFF

$$a_{12}(y, z_1, z_2, m_1, m_2) \sim B(y) \cdot \frac{\sum_q e_q^2 H_1^{\sphericalangle}(z_1, m_1) \bar{H}_1^{\sphericalangle}(z_2, m_2)}{\sum_q e_q^2 D_1(z_1, m_1) \bar{D}_1(z_2, m_2)}$$



A. Vossen et al. arXiv:0912.0353v2 [hep-ex]

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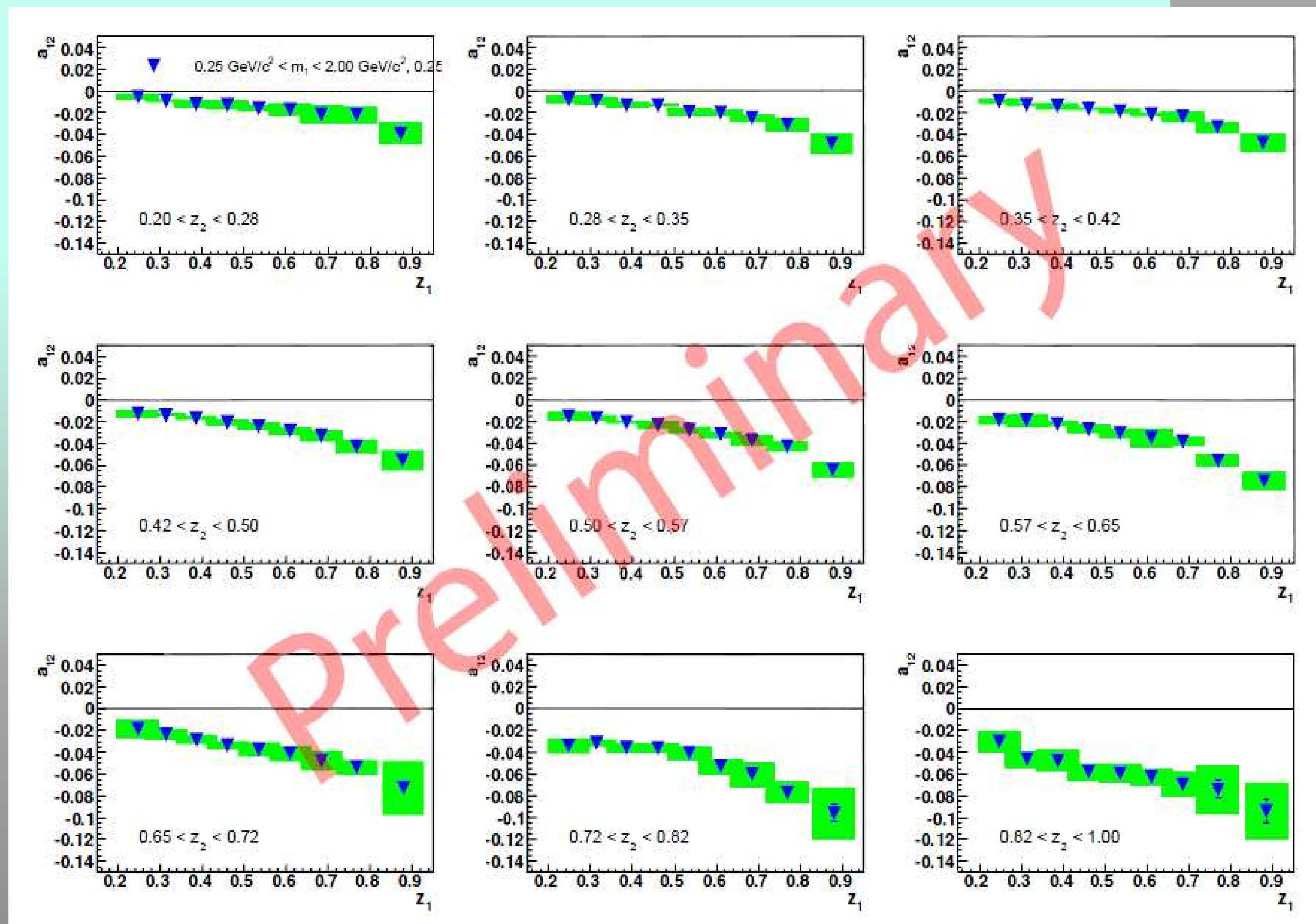
Belle results on IFF



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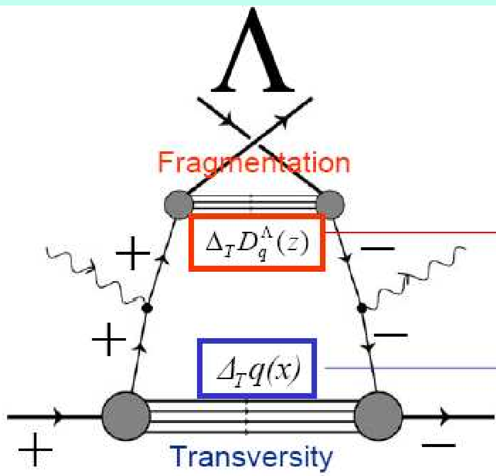
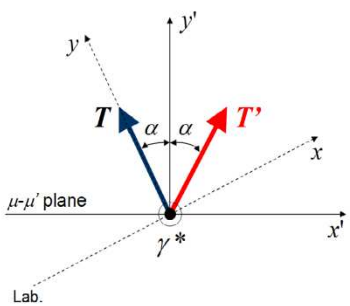
Transverse Λ polarization



$\mu N^{\Uparrow} \rightarrow \mu' \Lambda^{\Uparrow} X$ @ SIDIS ($Q^2 > 1$ (GeV/c)^2)

Differentiate between terms $\Delta_T D(z)$ and $\Delta_T q(x)$ due to factorization in x and z?



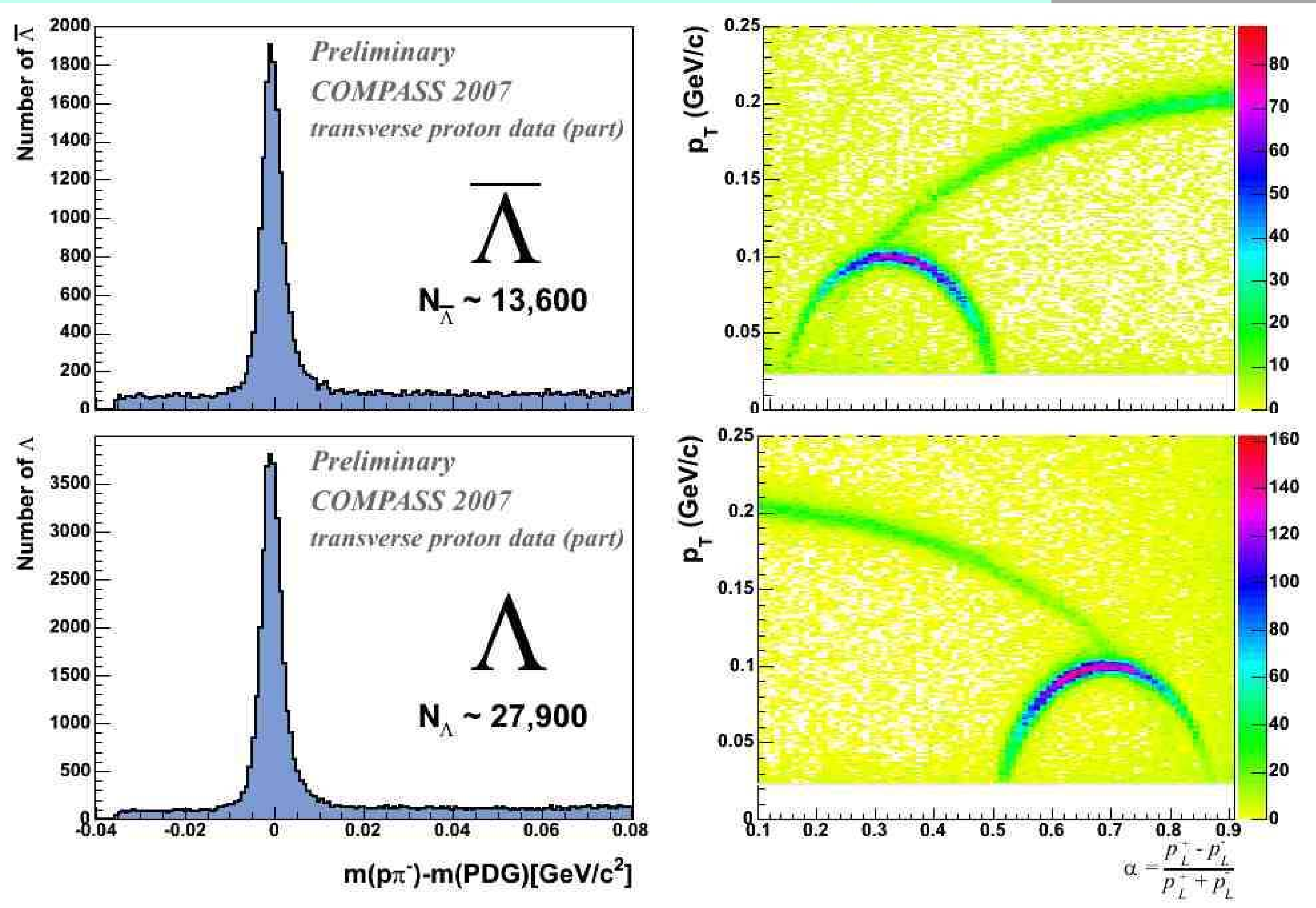
Transverse Λ polarization in a transversely polarized target

$$P^\Lambda \propto \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_q^\Lambda(z)}{\sum_q e_q^2 q(x) D_q^\Lambda(z)}$$

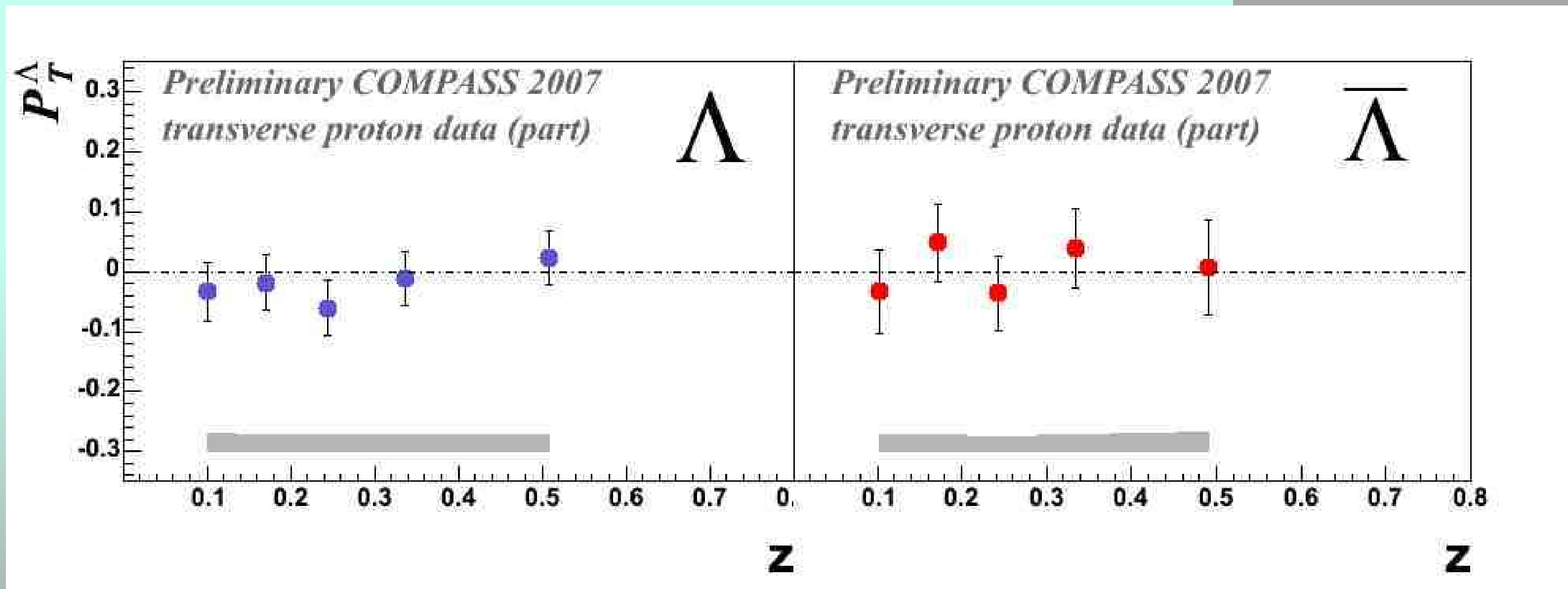
$\Delta_T q(x)$ = transversely polarized quark distribution
$q(x)$ = unpolarized quark distribution function

$\Delta_T D_q(z)$ = transversely polarized fragmentation
$D_q(z)$ = unpolarized fragmentation function

Data Selection



Results with proton target



- ~60% higher statistics with respect deuteron data
- Systematic errors have been estimated to be smaller than statistical errors from false polarization.
- No dependence on *x.*

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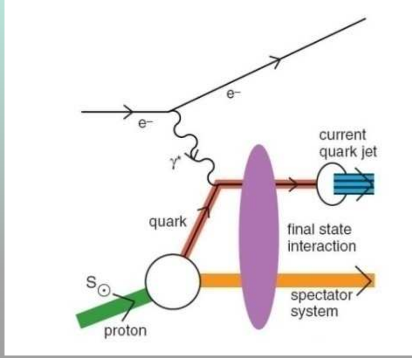
SIVERS Mechanism

- 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

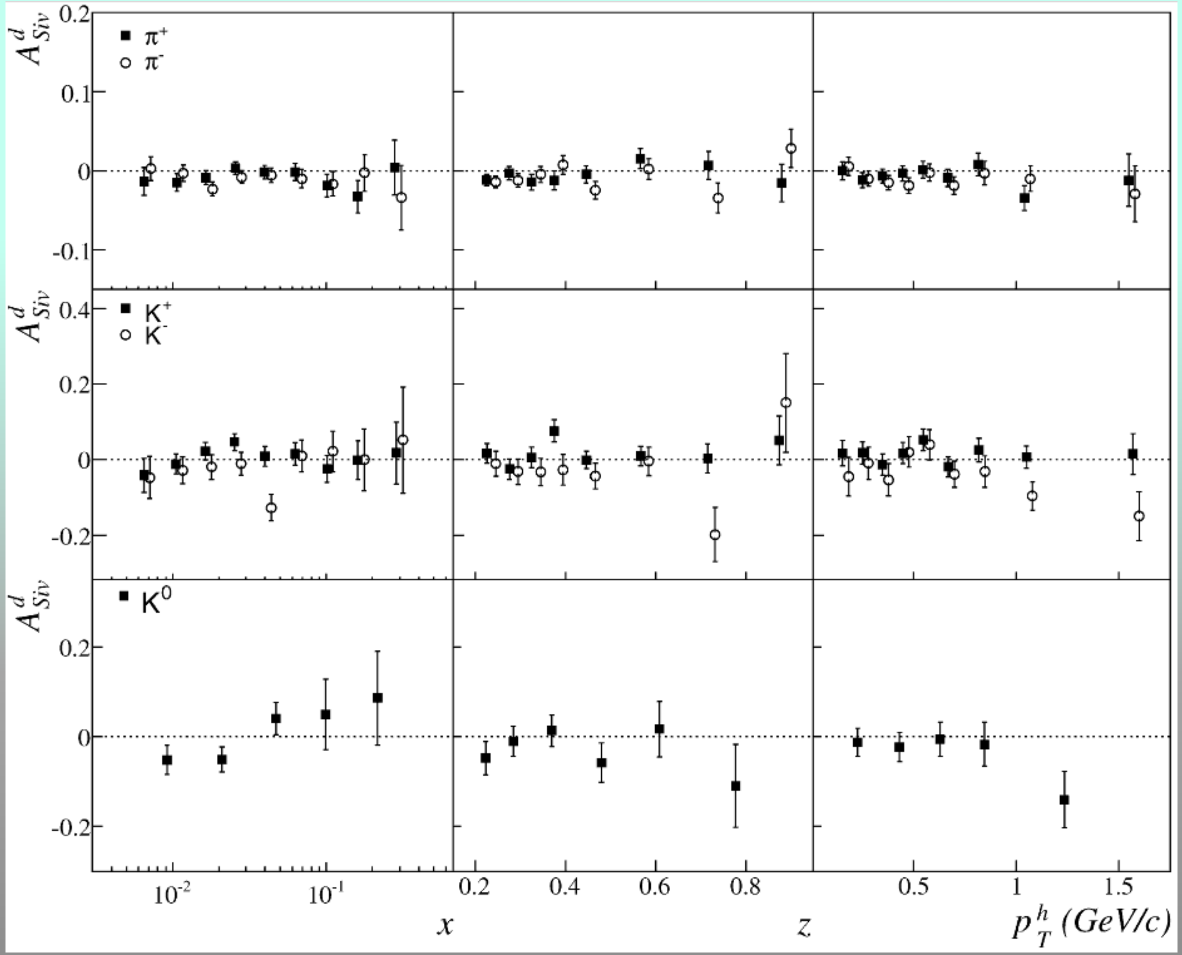


- In SIDIS:

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

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

Sivers Final on Deuteron



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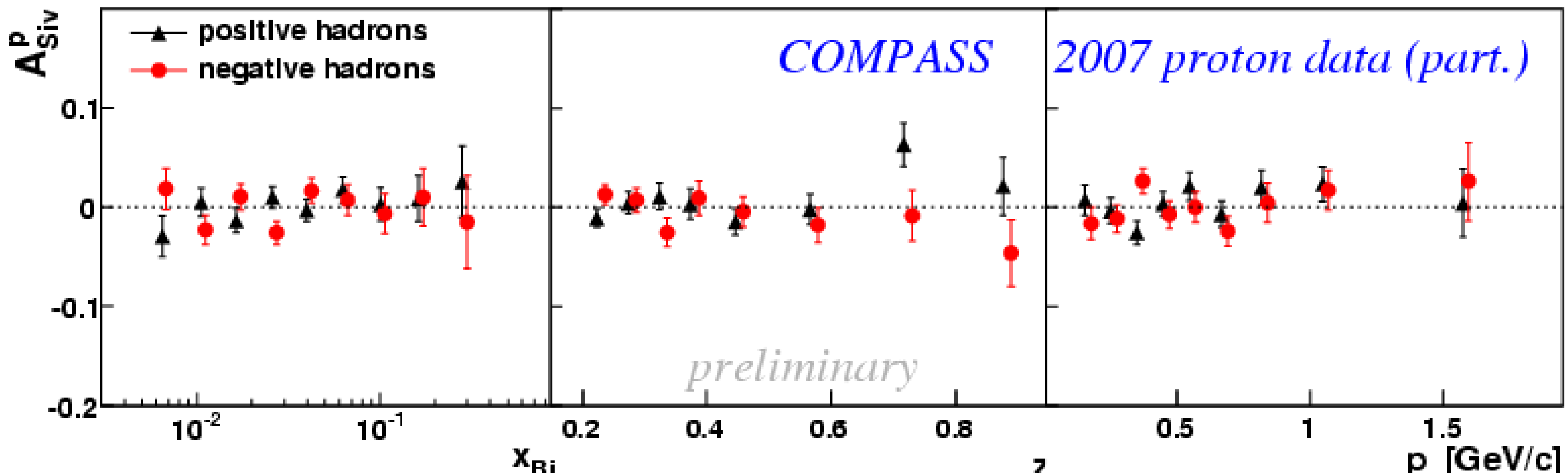
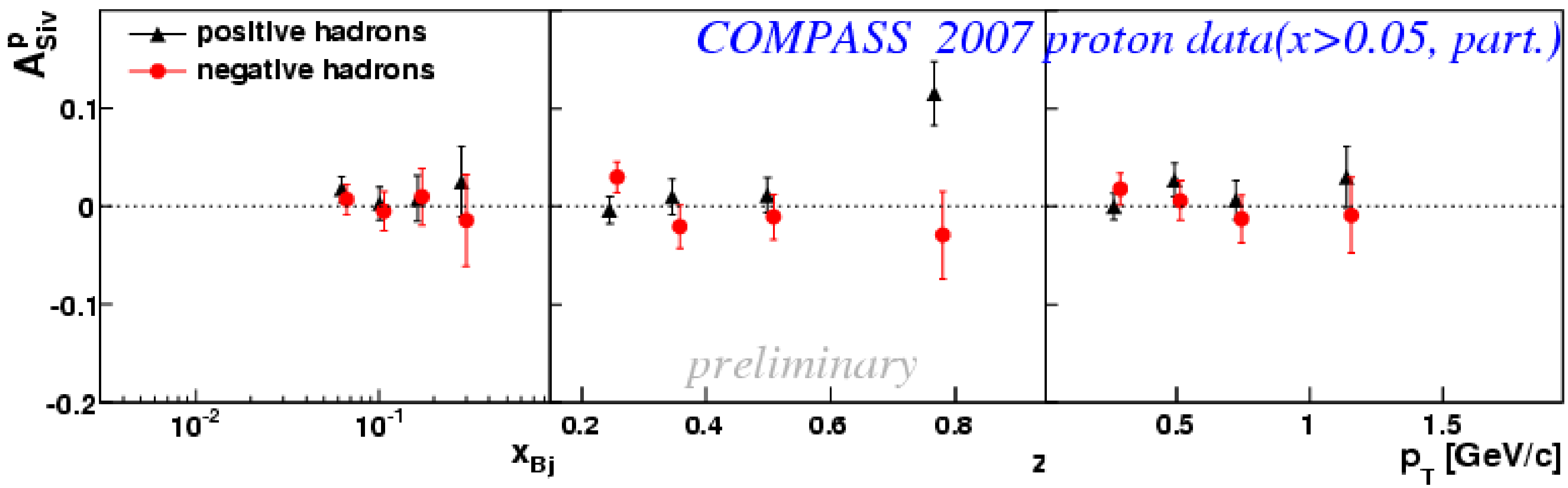
Systematic error well below 30% of the statistical one

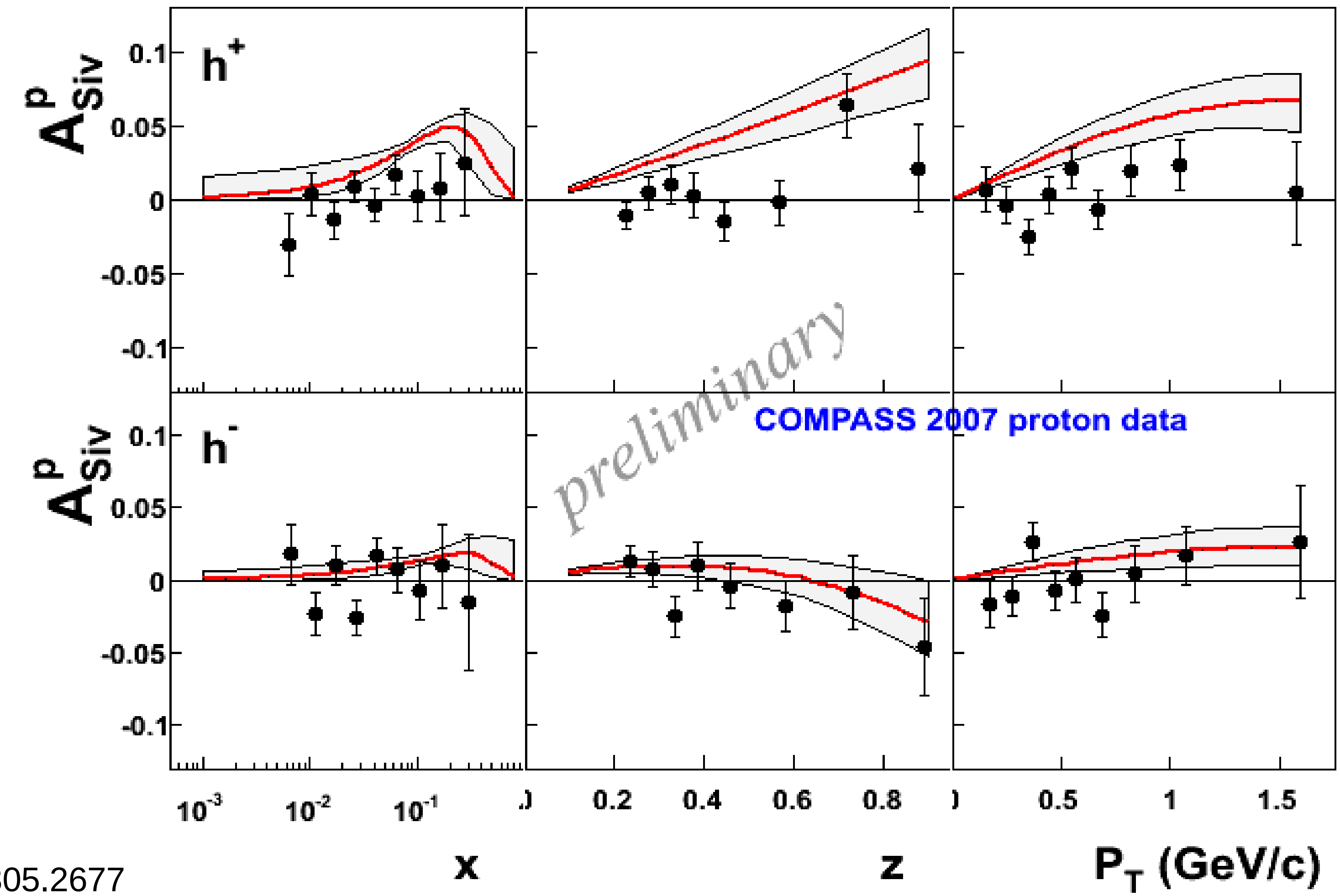
Sivers – proton data





Sivers asymmetry– proton data

comparison with the most recent predictions from M. Anselmino et al.

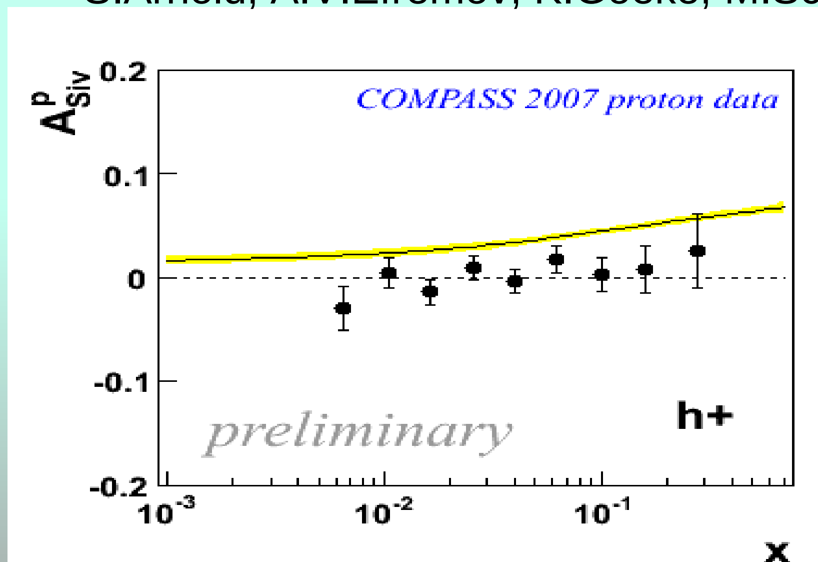


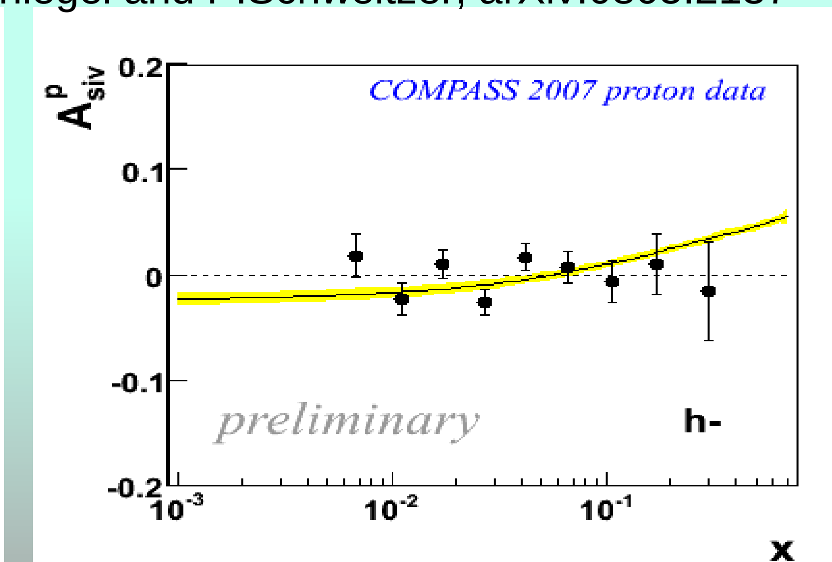
arXiv:0805.2677

Results: Sivers asymmetry

comparison with predictions from

S.Arnold, A.V.Efremov, K.Goeke, M.Schlegel and P.Schweitzer, arXiv:0805.2137





$$A_{UT\,\mathrm{measured}}^{\sin(\phi-\phi_S)} = \left\{ \text{'twist-2 Sivers effect' in Eqs. (11, 15)} \right\} + C(Q)\,\frac{M_N^2}{Q^2}$$

Maybe such corrections are irrelevant for $Q^2 > 1\,\mathrm{GeV}^2$ which is typically used as DIS-cut. In any case, a careful comparison of all (present and future) data from COMPASS, HERMES and JLab will shed light on the possible size of power corrections.

OUTLOOK

- the COMPASS experiment
- results on
  - transversity : Collins asymmetries
    2 hadron asymmetries
    Λ polarization
  - Sivers asymmetries
  - other TMD asymmetries
  - unpolarised azimuthal asymmetries
  - exclusive ρ asymmetries
- future plans for SIDIS and DY

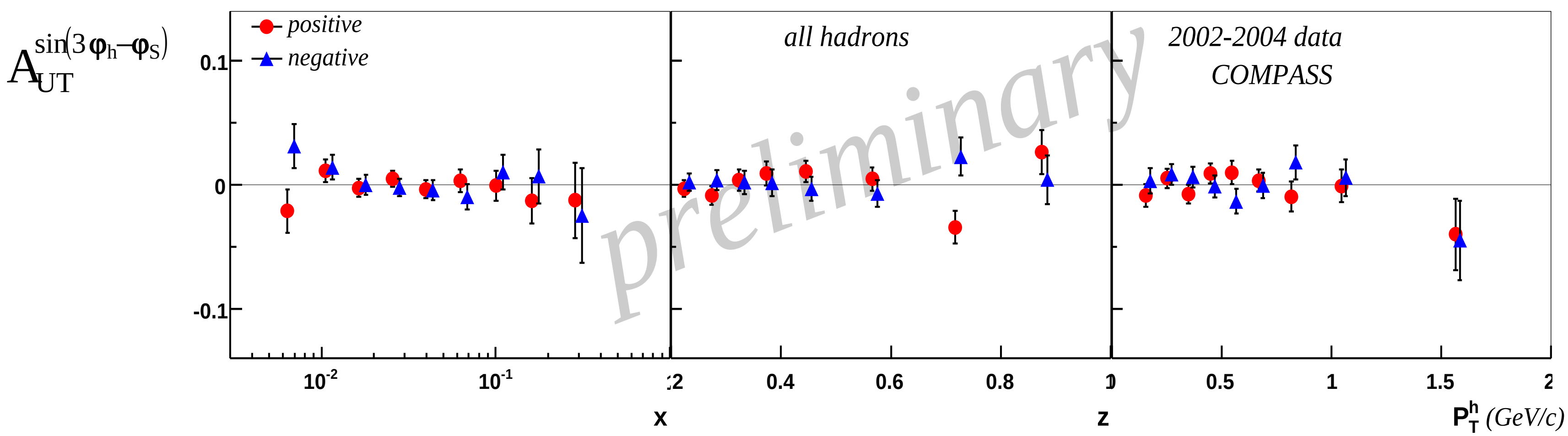
Other SSAs - Deuteron data

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

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

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

"pretzelosity" ⊗ Collins FF



on deuteron asymmetries compatible with zero: again cancellation between proton and neutron?

OUTLOOK

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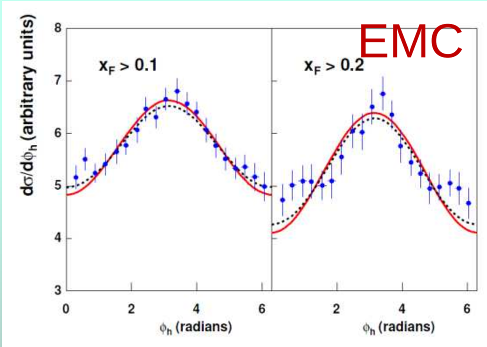
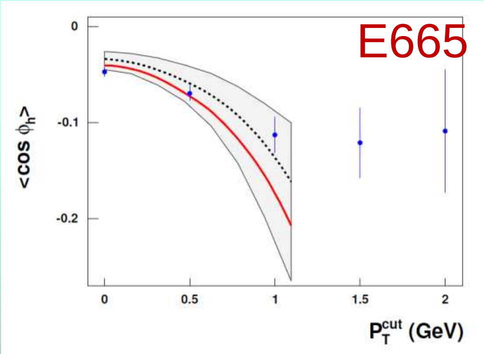
Experimental status

- Azimuthal modulations in lp→l'hX measured by
  - EMC
  - E665





Fits from M. Anselmino, V. Barone, E. Boglione,U. D'Alesio, F. Murgia, A. Prokudin, A. Kotzinian, and C. Turk

- Large modulations up to 40% for cosϕ, while cos2ϕ ~ 5%

  (with ϕ or ϕ_h the the hadron azimuthal angle in GNS)

  - More recently ZEUS in the high-pT (pQCD region)

Since last year, new data from COMPASS and HERMES

Cahn effect – a reminder

The unpolarized SIDIS cross section is:

$$d\sigma^{lp\to l'hX} = \sum_q f_q\left(x,Q^2\right)\otimes d\sigma^{lp\to l'q}\otimes D_q^h\left(z,Q^2\right)$$

with f the PDF and D the FF
In collinear PM than the elementary xSection is

$$d\sigma^{lp\to l'q} \propto \hat{s}^2+\hat{u}^2 \propto x\left(1+(1-y)^2\right)$$

i.e. no dependence on ϕ_h. Taking into account the parton transverse momentum in the kinematics leads to:

$$\hat{s} = sx\left[1-\frac{2k_T}{Q}\sqrt{1-y}\cdot\cos\phi\right]+O\left(\frac{k_T^2}{Q}\right) \qquad \hat{u} = sx(1-y)\left[1-\frac{2k_T}{Q\sqrt{1-y}}\cdot\cos\phi\right]+O\left(\frac{k_T^2}{Q}\right)$$

Resulting in the cos ϕ_h and cos $2\phi_h$ modulations observed in the azimuthal distributions

Unpolarised target SIDIS cross-section

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

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

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

$$F_{LU}^{\sin\phi_h}=\frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xe\,H_1^\perp+\frac{M_h}{M}f_1\frac{\tilde{G}^\perp}{z}\right)+\frac{\hat{h}\cdot p_T}{M}\left(xg^\perp D_1+\frac{M_h}{M}h_1^\perp\frac{\tilde{E}}{z}\right)\right]$$

Cahn effect

Cahn effect + Boer-Mulders DF

Boer-Mulders DF

$$F_{UU}^{\cos\phi_h}=\frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{h}\cdot k_T}{M_h}\left(xh\,H_1^\perp+\frac{M_h}{M}f_1\frac{\tilde{D}^\perp}{z}\right)-\frac{\hat{h}\cdot p_T}{M}\left(xf^\perp D_1+\frac{M_h}{M}h_1^\perp\frac{\tilde{H}}{z}\right)\right]$$

he

nucleon spin in an unpolarised

cleon

$$F_{UU}^{\cos 2\phi_h}=\mathcal{C}\left[-\frac{2\left(\hat{h}\cdot k_T\right)\left(\hat{h}\cdot p_T\right)-k_T\cdot p_T}{M M_h}h_1^\perp H_1^\perp\right]$$

Boer- Mulders x Collins FF
+ Cahn effect

and R. Sassot. PR D71

Data used for this analysis

- part of the 2004 (^{6}LiD target) data collected with longitudinal (L) and transverse (T) polarization
- with both target orientation configurations to cancel possible polarization effects

Event selection:

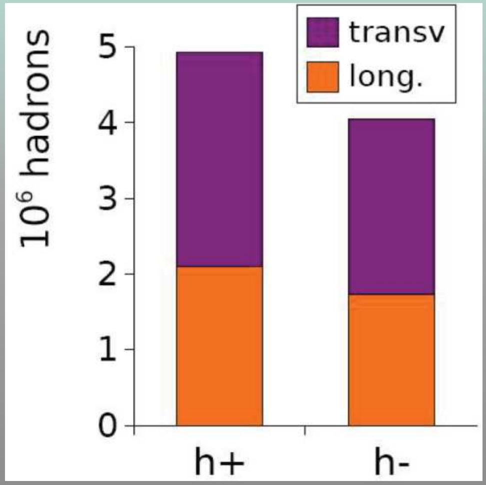
DIS events…

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

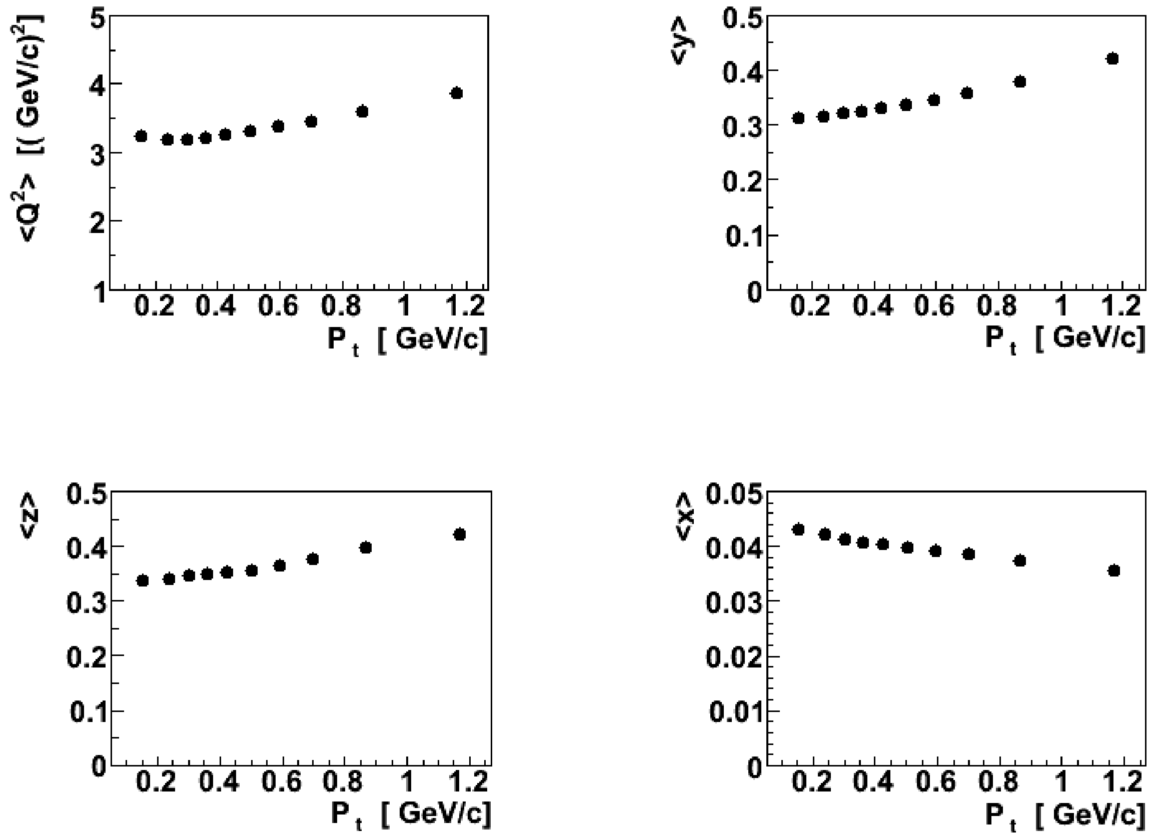
Hadrons

- $0.2< z < 0.85$
- $0.1<p_T<1.5$ (GeV/c)

Statistics of this analysis:



Mean kinematical values



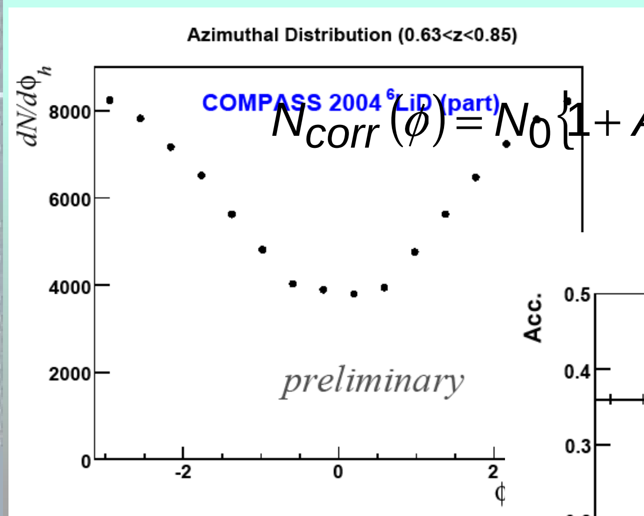
unpolarised target SIDIS cross-section

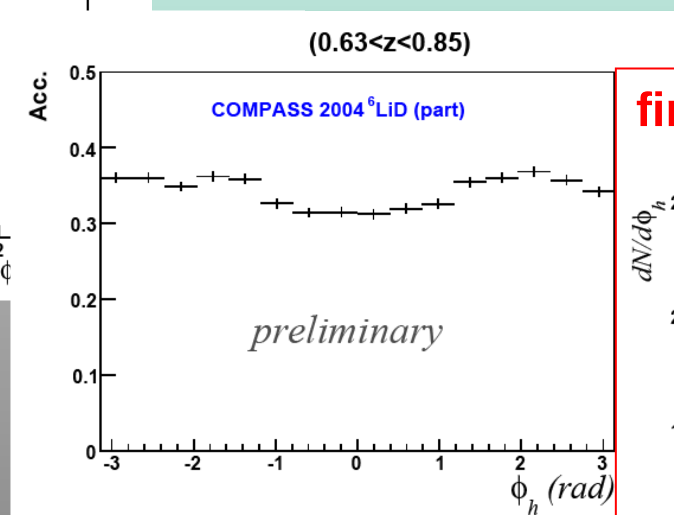
to extract the asymmetries the azimuthal distributions have to be corrected by the apparatus acceptance

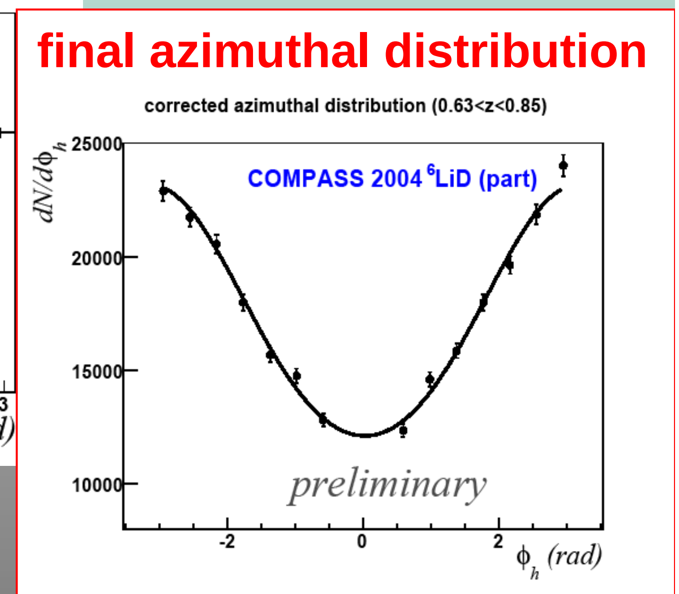
⇒ Final distributions fitted with the following function:

⇒ dedicated MC simulations for L and T target polarisation data

$$N_{corr}(\phi) = N_0\{1 + A_{\cos\phi}\cdot\cos\phi + A_{\cos 2\phi}\cdot\cos 2\phi + A_{\sin\phi}\cdot\sin\phi\}$$







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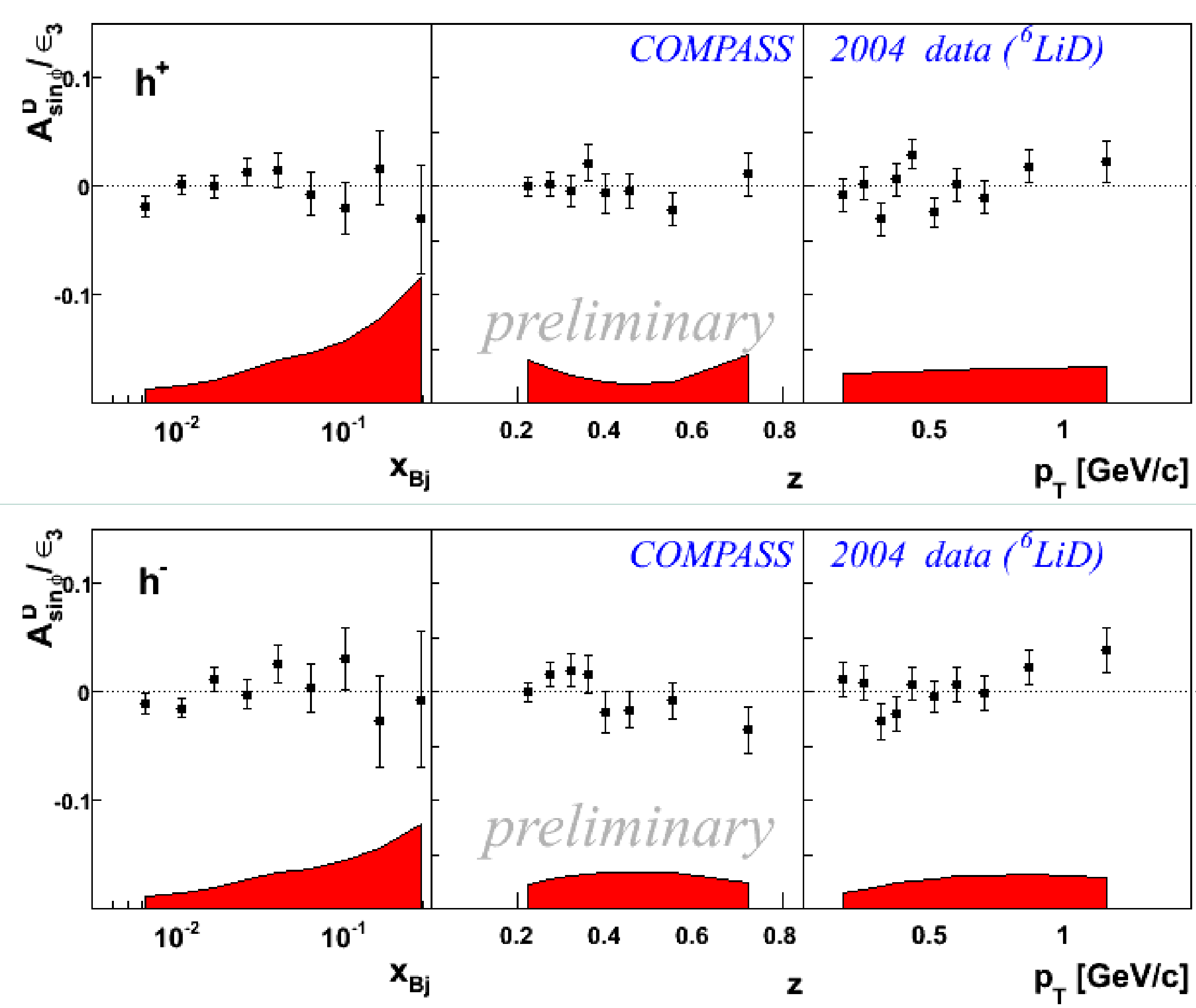
Systematic Error

- The systematic error is evaluated from:
  - compatibility of results with L and T target polarization (different experimental conditions, different MCs)
  - comparison of results obtained using two different MCs with different settings for each data set (LEPTO default, standard COMPASS high pt; ~extreme cases)
  - compatibility of results from subsamples corresponding to:
    - different periods
    - different geometrical regions for the scattered muon

Results: sinϕ modulation

$A_{\sin\phi} / \varepsilon_s$

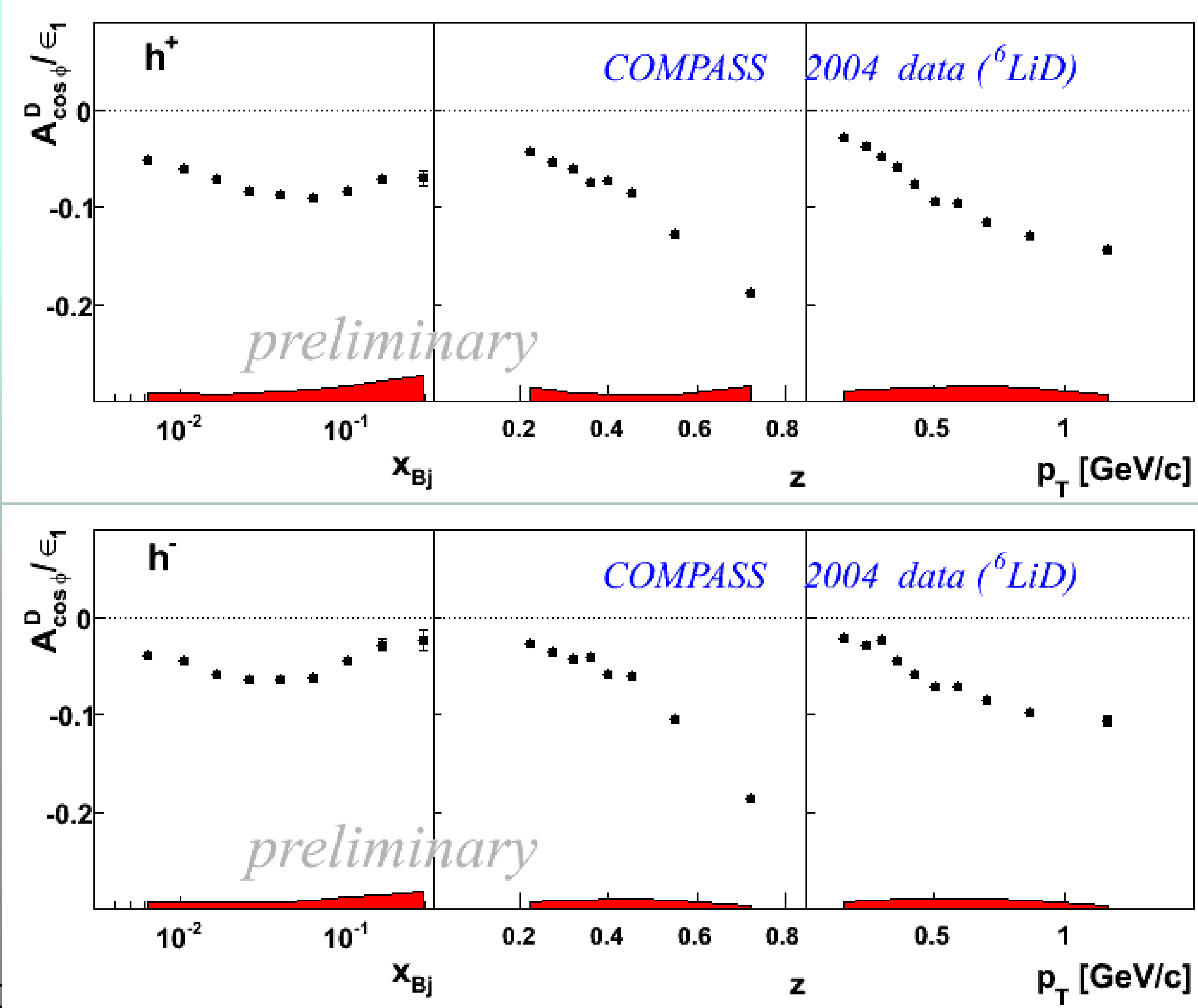
$$\varepsilon_s = \frac{2y\sqrt{1-y}}{1+(1-y)^2}$$



error bars:
statistical errors

bands:
systematical errors

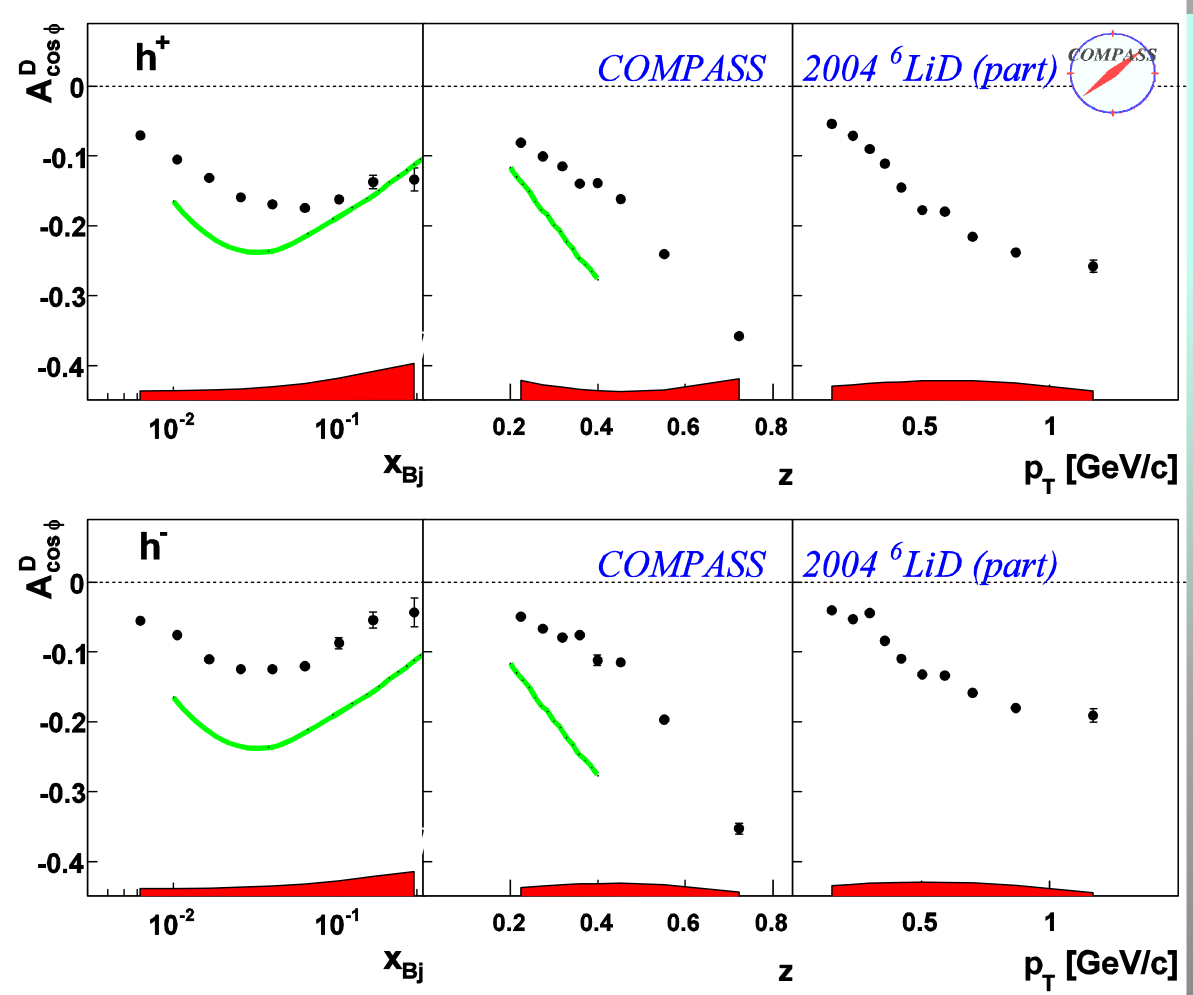
Results: cosϕ modulation



$A_{\cos\phi} / \varepsilon_c$

$$\varepsilon_c = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

What was expected

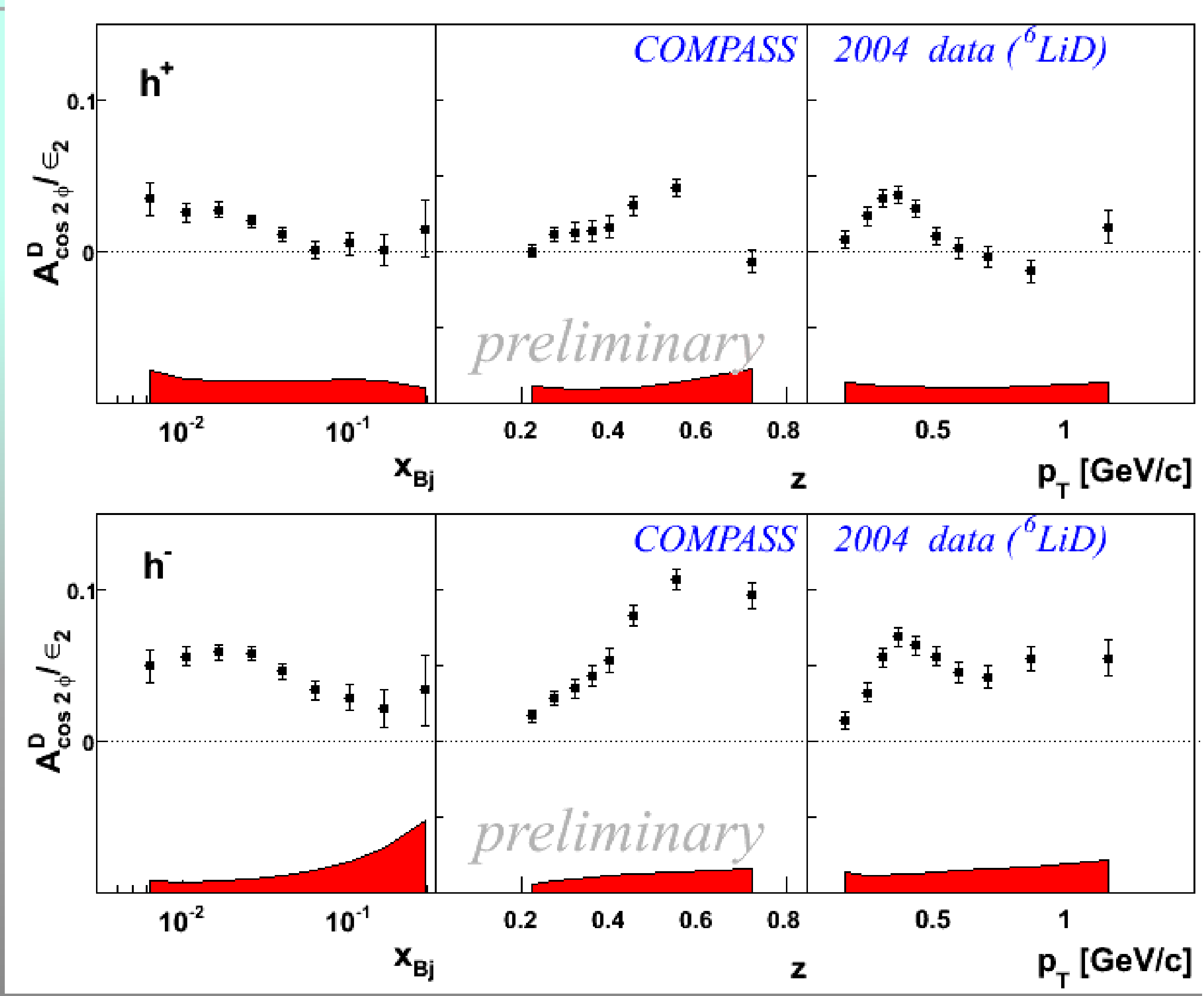


M. Anselmino, M. Boglione, A. Prokudin, C. Türk
Eur. Phys. J. A 31, 373-381 (2007)
does not include Boer – Mulders contribution

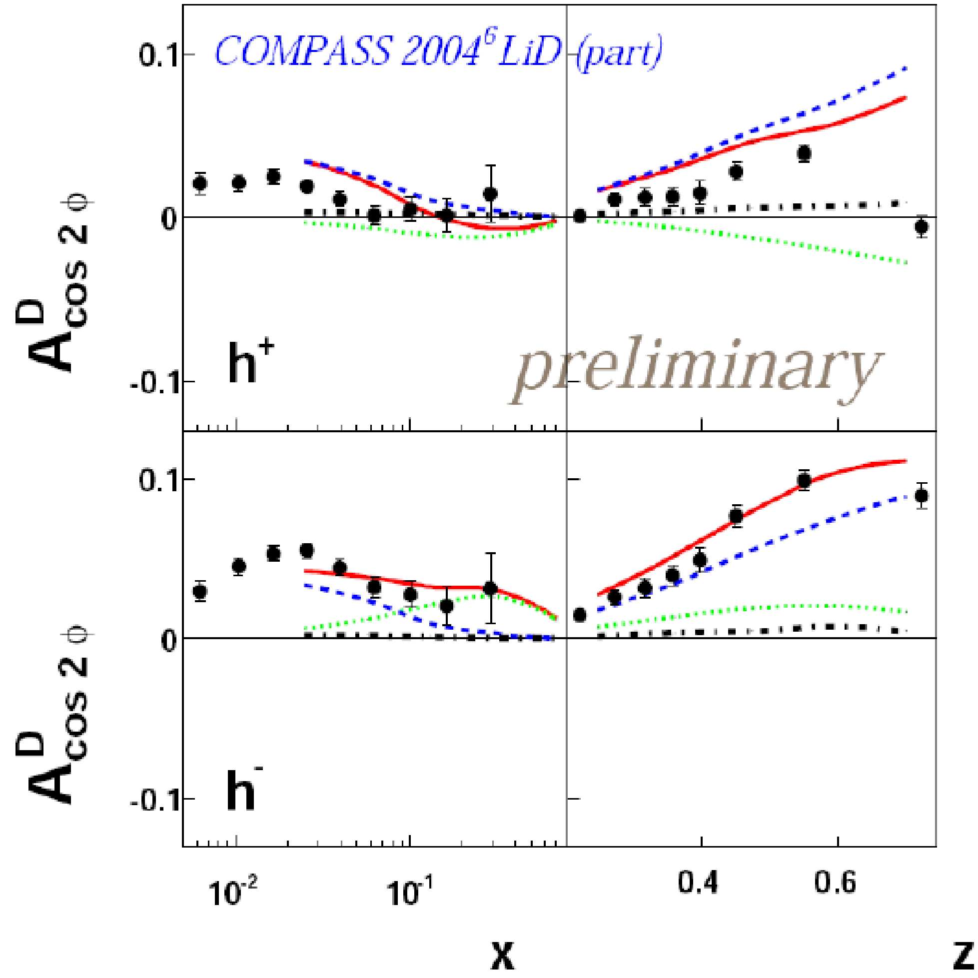
results: cos 2ϕ modulation

$A_{\cos 2\phi} / \varepsilon_2$

$$\varepsilon_2 = \frac{2(2-y)}{1+(1-y)^2}$$



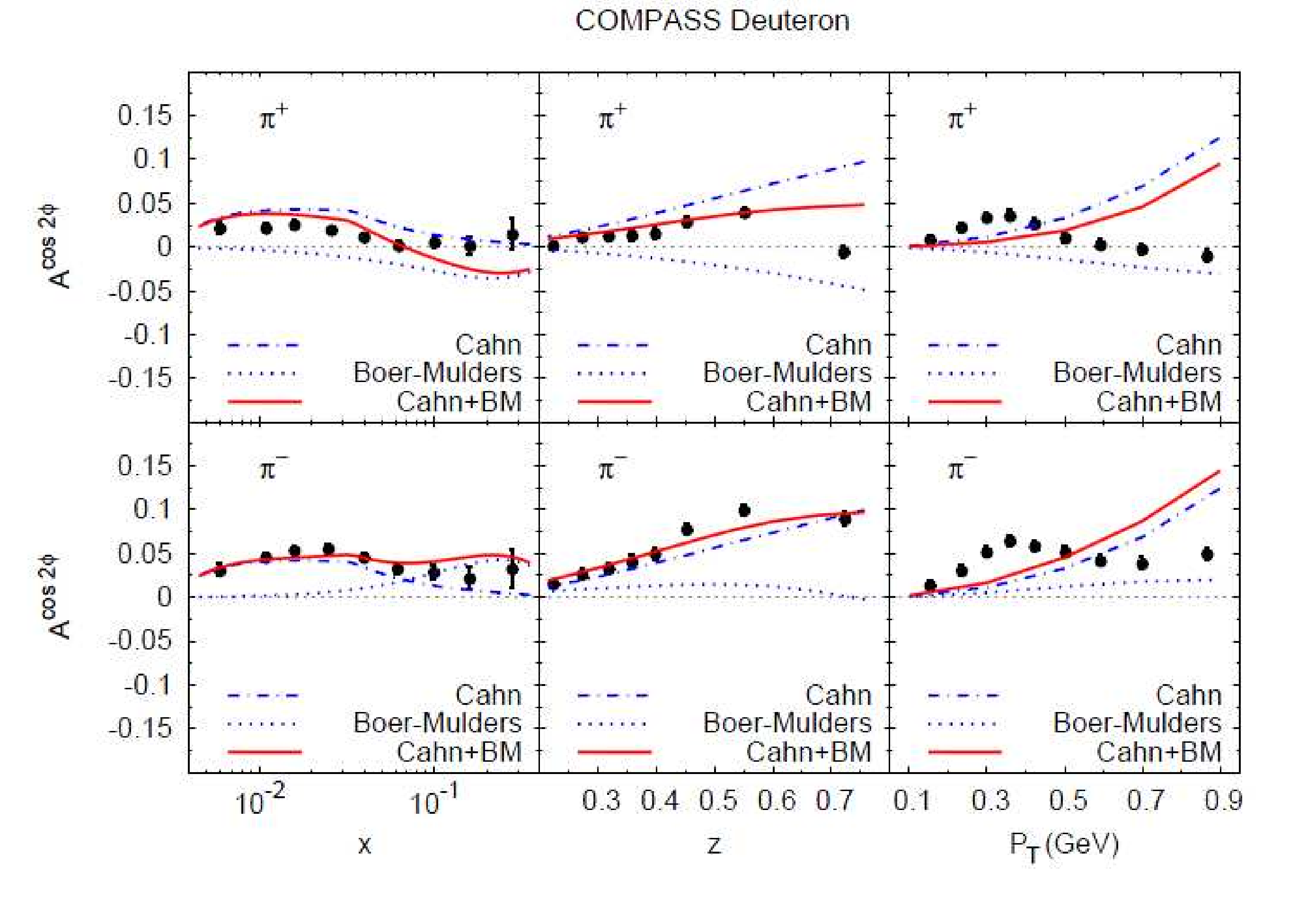
Predictions



total — Boer Mulders
Cahn — pQCD

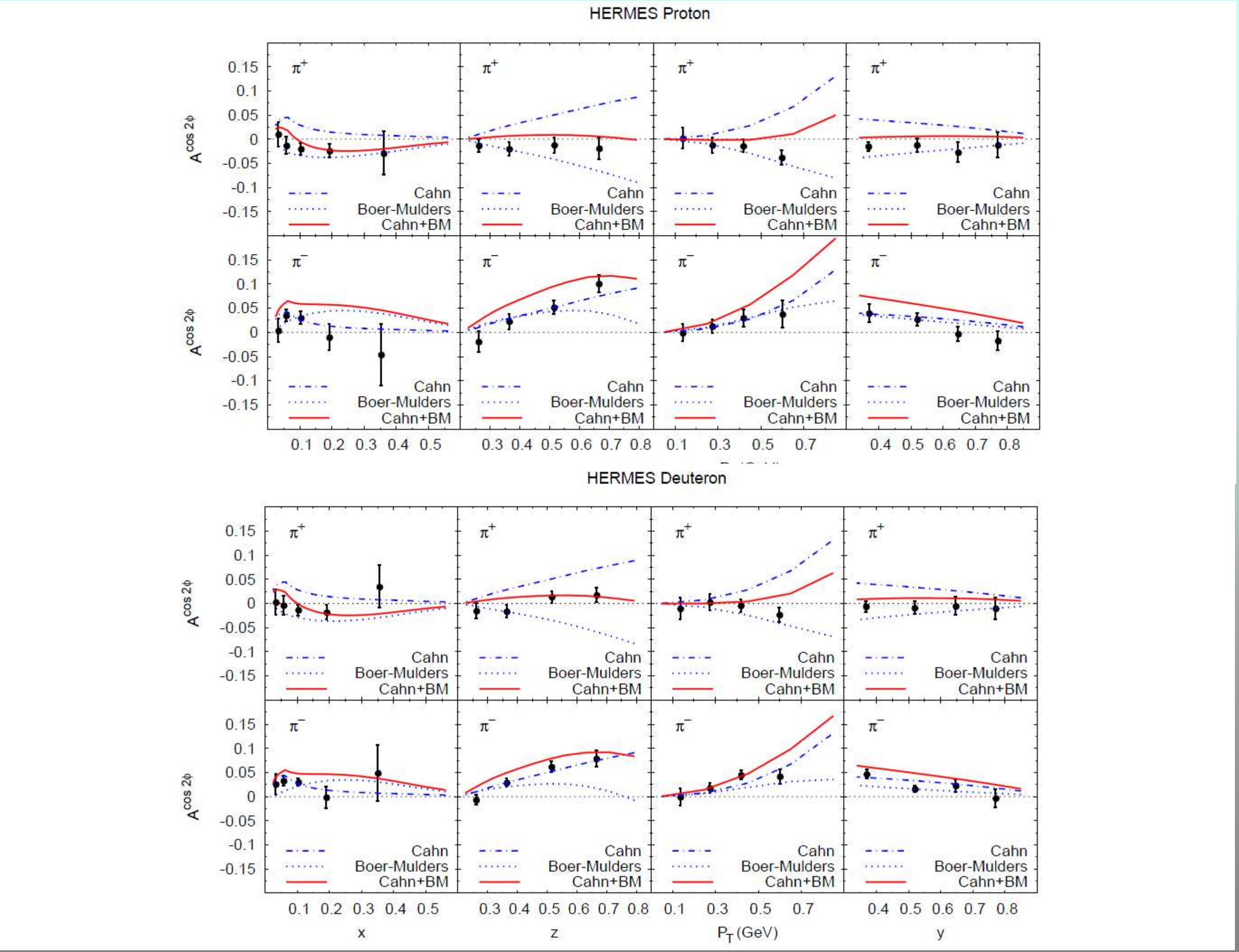
V.Barone, A.Prokudin, B.Q.Ma
arXiv:0804.3024 [hep-ph]

Recent Fits



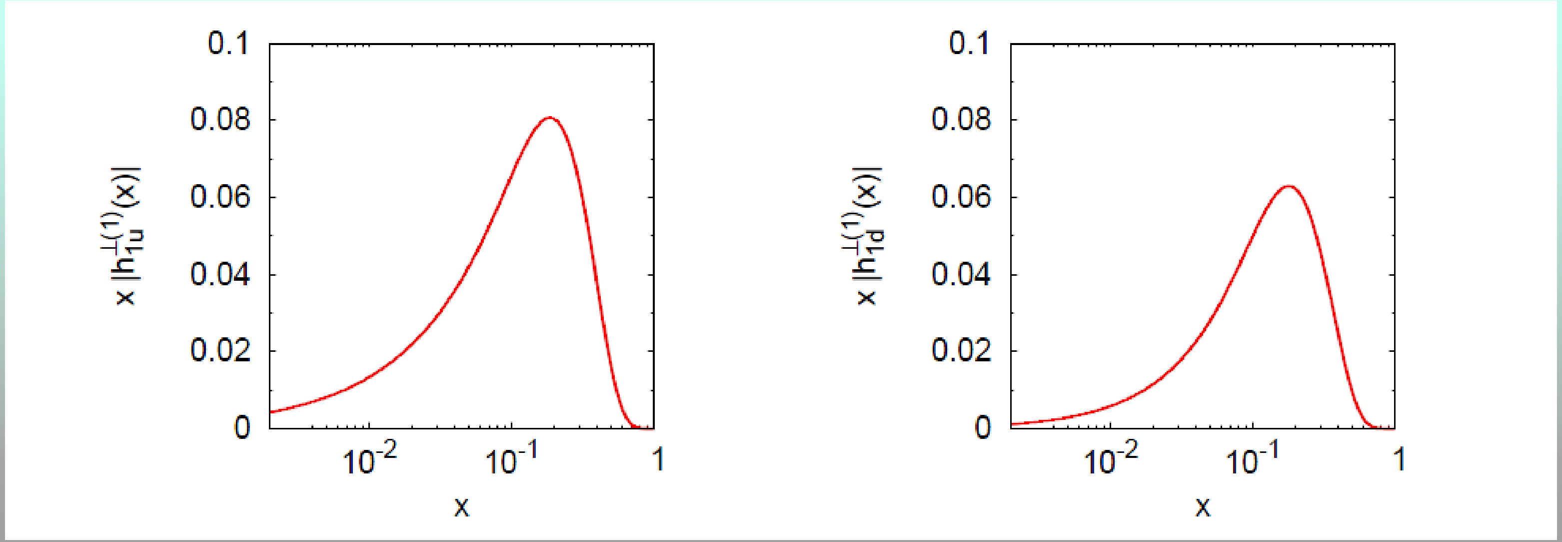
V. Barone arXiv:0912.5194v1 [hep-ph]

Recent Fits



V. Barone arXiv:0912.5194v1 [hep-ph]

Recent Fits



V. Barone arXiv:0912.5194v1 [hep-ph]

Summary Unpolarized

First results on unpolarized asymmetries:

- Results obtained separately for + and - hadrons
- sinϕ modulation compatible with 0
- cosϕ modulation up to 20% (for large z or p_T) and the overall trend is reproduced by the predictions
- cos2ϕ modulation smaller (10% at most). Overall good agreement with the predictions
- There is a difference between +h and –h asymmetries on cosϕ/cos2ϕ ⇒ Boer-Mulders

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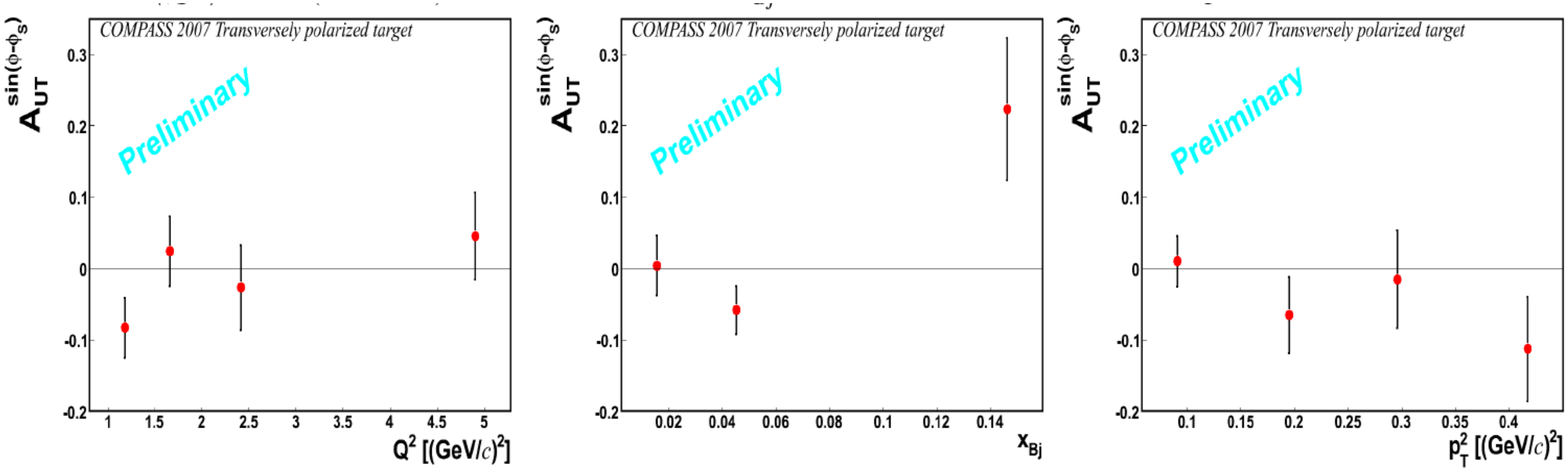
exclusive ρ_0 asymmetries – proton data

$\langle Q^2 \rangle \simeq 2.2 (GeV/c)^2$ $\langle x_{Bj} \rangle \simeq 0.04$ $\langle p_T^2 \rangle \simeq 0.18 (GeV/c)^2$



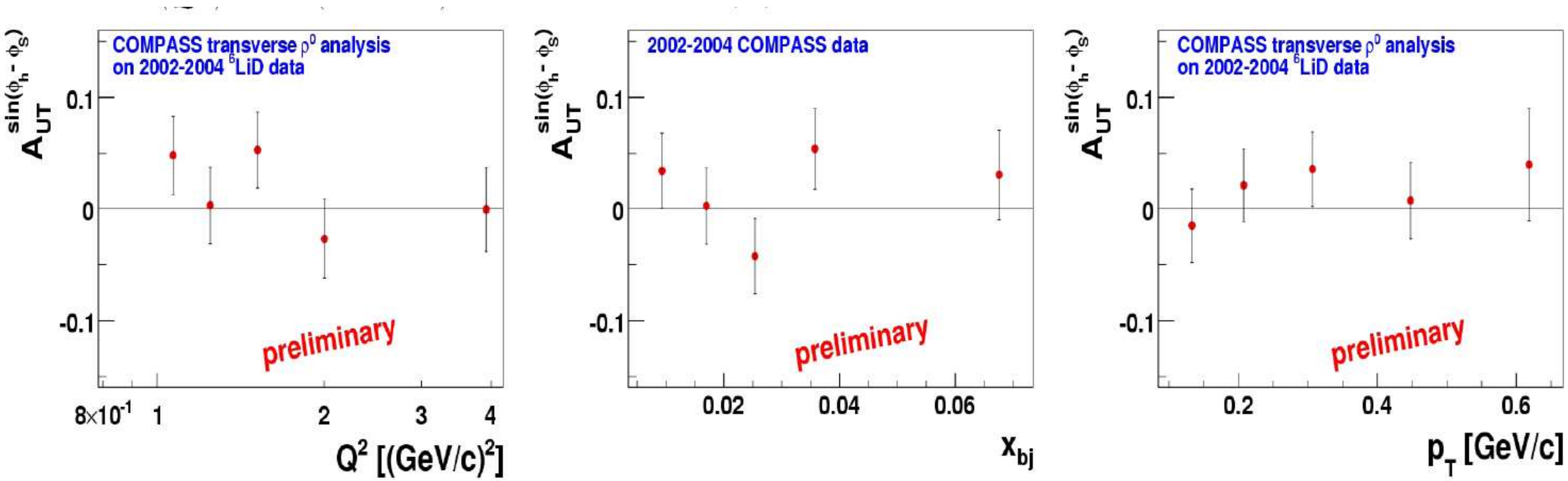
$A_{UT}^{\sin(\phi-\phi_s)}$ compatible with 0

Small value ($A_{UT}(\rho) \simeq$ 0.02) predicted by Goloskokov and Kroll (EPJC59 2009) (hep-ph/0809.4126)

Larger value ($A_{UT}(\omega) \simeq$ 0.1) predicted by Goloskokov and Kroll

exclusive ρ_0 asymmetries – deuteron data

$\langle Q^2 \rangle \simeq 2.0 (GeV/c)^2$ $\langle x \rangle \simeq 0.03$ $\langle p_T \rangle \simeq 0.11\, GeV/c$



without coherent/incoherent scattering separation

OUTLOOK

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  - exclusive ρ asymmetries
- future plans for SIDIS and DY

future COMPASS measurements

motivations

- **SIDIS at high energy provides unique information on the transverse spin and intrinsic momentum structure of the nucleon**
  - high energy and high Q^2, a guarantee for the **hard scale**
  - "easy" flavour separation
  - simple interpretation
  - *access to all the TMD structure functions*
  - broad x range
  - complementary to hard hadron-hadron scattering
- **the high energy muon beam and the COMPASS spectrometer are unique facilities**
- **CERN is the only place where in the next few years SIDIS measurements can be made at high energy**

in the short term, new COMPASS measurements are needed

- **to perform more precise measurements of the Collins asymmetry**
- **to clarify the compatibility of the HERMES and COMPASS measurements of the Sivers asymmetry**

plus precise measurements for all other channels

future COMPASS measurements

- **Letter of Intent** [COMPASS Collaboration]
  CERN-SPSC-2009-003 SPSC-I-238, 21 January 2009:
  - **physics case for further SIDIS data taking with the 160 GeV muon beam and the transversely polarised NH_3 target**
  - further SIDIS measurement with longitudinally polarised NH_3 target
  - Drell-Yan measurements
  - DVCS measurements

    all presented at the CERN Workshop
    "New opportunities in the physics landscape at CERN", May 11-13, 2009.

- **Addendum 2 to the COMPASS Proposal, *June 20, 2009***
  REQUEST TO CERN:
  - **one full year of run (140 days of data taking) with transversely polarised NH3 target with the present muon beam and COMPASS spectrometer**
  - one year with longitudinally polarised target

  starting in 2010 with the transverse part

APPROVED

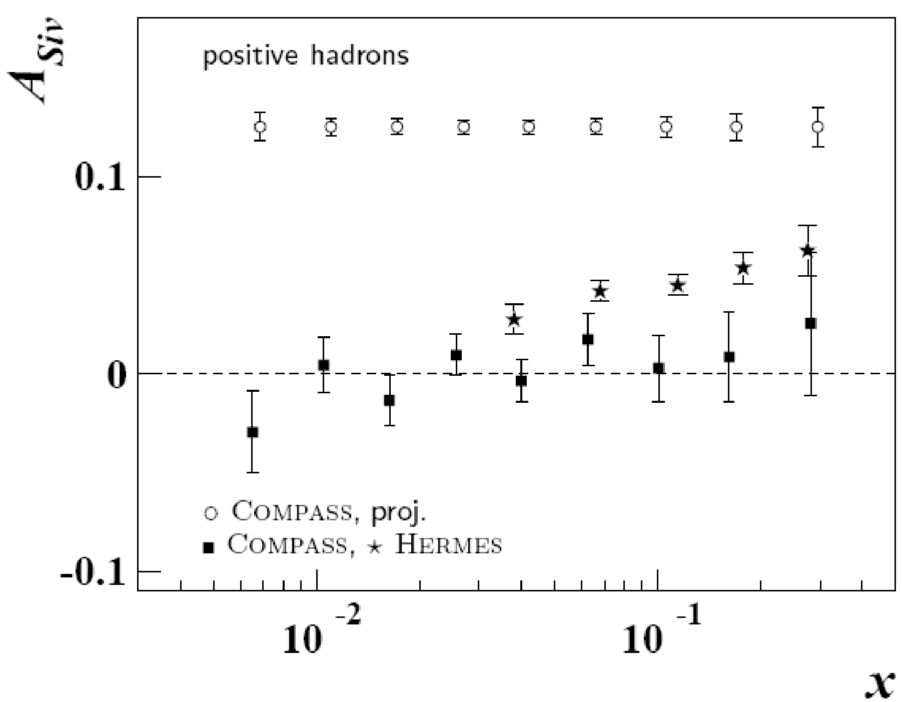
future COMPASS measurements

in 140 days of data taking COMPASS will perform

very precise measurements of transverse spin effects

over the whole x range (0.004 – 0.5)

projected statistical errors for the Sivers asymmetry



COMPASS 2010 h^+, projection

a factor of 3 with respect to the released COMPASS data

more distant future

the 2010 measurement would mostly conclude the exploratory phase of transverse spin effects in SIDIS

more systematic measurements in SIDIS will be needed

today: COMPASS
JLab (6 GeV → 11 GeV)

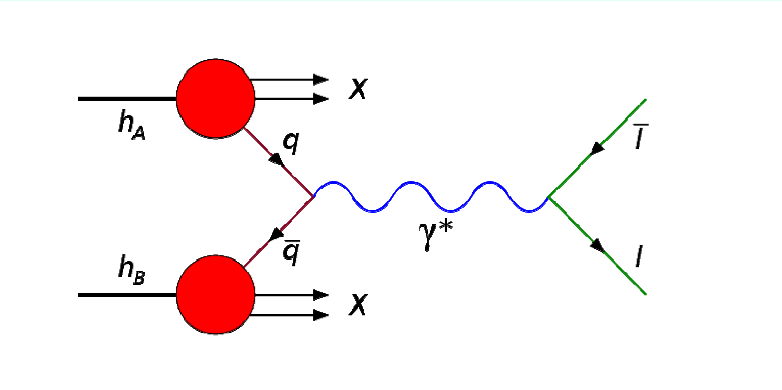
future projects: eRHIC or ELIC
ENC at FAIR

in the mean time CERN could play an important role

".. we are investigating the possibility to increase significantly the muon beam intensity. If the outcome is positive it will be worthwhile to resume with an upgraded COMPASS-like apparatus the SIDIS measurements both with proton and deuteron transversely polarised target."

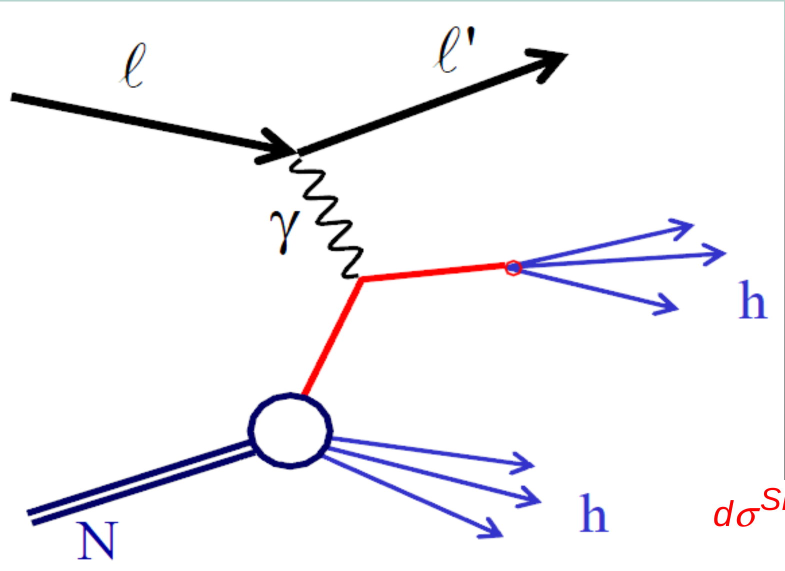
(January 2009 LoI)

DY vs SIDIS



DY
cross section
~ convolution of PDFs

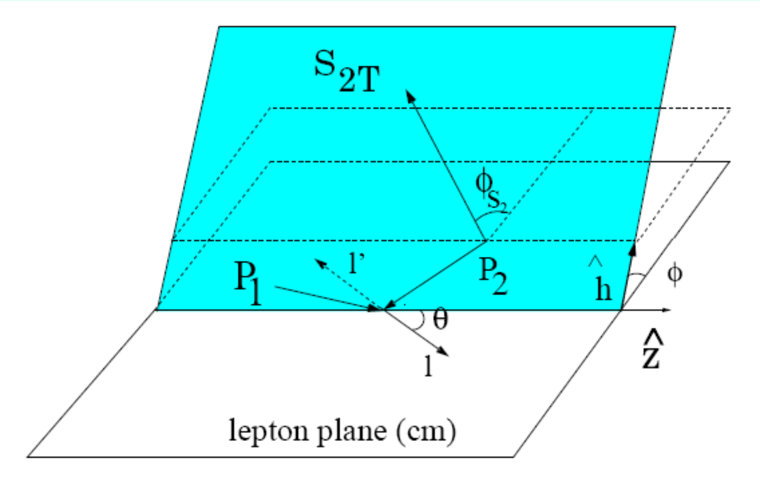
$$d\sigma^{DY} = \sum_a f_q\left(x_1, k_{\perp 1}; Q^2\right) \otimes f_{\bar{q}}\left(x_2, k_{\perp 2}; Q^2\right) d\hat{\sigma}^{q\bar{q} \to \ell^+\ell^-}$$



SIDIS
cross section
~ convolution of PDF and FF

$$d\sigma^{SIDIS} = \sum_Q f_q\left(x, k_\perp; Q^2\right) \otimes d\hat{\sigma}^{\ell q \to \ell q}\left(y, k_\perp; Q^2\right) \otimes D_q^h\left(z, p_\perp; Q^2\right)$$

DY on a trasversely polarized target



Collins-Soper frame
θ, ϕ
ϕ_{S2} ***target transverse spin vector***
S_{2T} wrt lepton plane

$$d\sigma^{DY} \propto \bar{f}_1(x_1, k_{T1}^2) \otimes f_{1T}^{\perp}(x_2, k_{T2}^2)\sin(\phi - \phi_{S2}) +$$

↑ Sivers

$$+ \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_1(x_2, k_{T2}^2)\sin(\phi + \phi_{S2}) +$$

↑ Boer-Mulders ↑ Transversity

$$+ \bar{h}_1^{\perp}(x_1, k_{T1}^2) \otimes h_{1T}^{\perp}(x_2, k_{T2}^2)\sin(3\phi - \phi_{S2})$$

↑ Boer-Mulders ↑ Pretzelosity

Sivers from DY at COMPASS

With a beam intensity $I_{beam} = 6 \times 10^7$ particles/second,
a luminosity of $L = 1.7 \times 10^{33}\ cm^{-2} s^{-1}$ can be obtained.

↪ Assuming 2 years of data-taking, one can collect > 200000 DY events in the region $4 < M_{\mu\mu} < 9.$ GeV/c^2.

Predictions for the Sivers asymmetry in the COMPASS phase-space, for the mass region $4. < M < 9.$ GeV/c^2, compared to the expected statistical errors of the measurement:

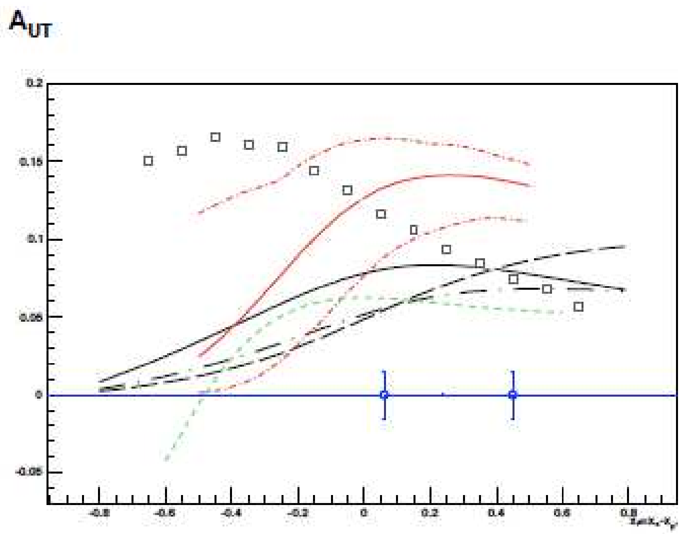
– solid and dashed: Efremov et al, PLB612(2005)233;

– dot-dashed: Collins et al, PRD73(2006)014021;

– solid, dot-dashed: Anselmino et al, PRD79(2009)054010;

– boxes: Bianconi et al, PRD73(2006)114002;

– short-dashed: Bacchetta et al, PRD78(2008)074010.



COMPASS Plans

Starting in 2010:
- **SIDIS measurements with transversely pol protons (1 year)**
- **SIDIS measurements with longitudinally pol protons (1year)**

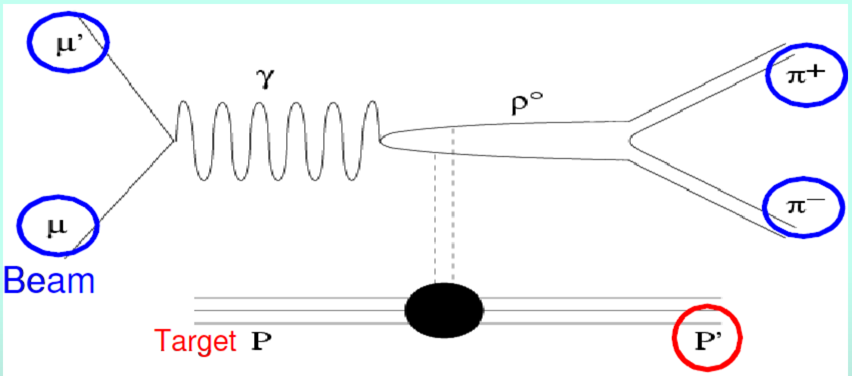
Proposal in preparation
- **DY on transversely polarised p target**
- **DVCS with LH target and polarised p target**

Hadron program: not over
further measurements mainly depending on the results from the 2008-2009 data taking


Thank You

BACK UP

exclusive ρ_0 asymmetries



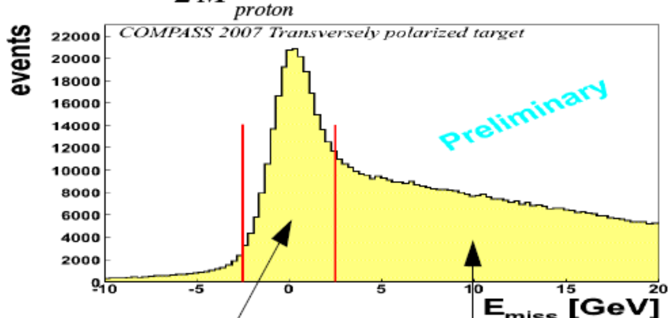
proton data analysis

selection of exclusive ρ_0 production

Exclusive ρ_0 Production

Recoil proton (p') is not detected,
Check if the proton is intact :

$$E_{miss} = \frac{M_X^2 - M_{proton}^2}{2M_{proton}} \in [-2.5, 2.5] GeV$$

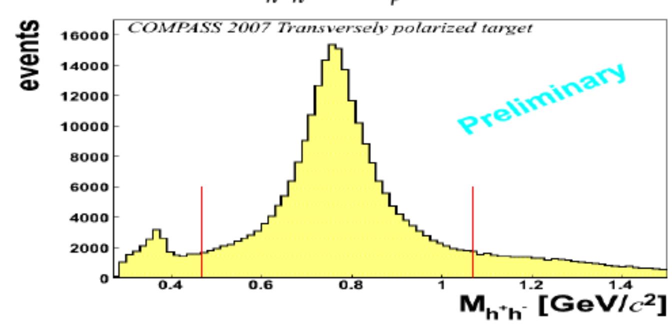


Exclusive peak

Non exclusive background

Invariant mass selection

$$0.3 < M_{h^+h^-} - M_\rho < 0.3 GeV$$

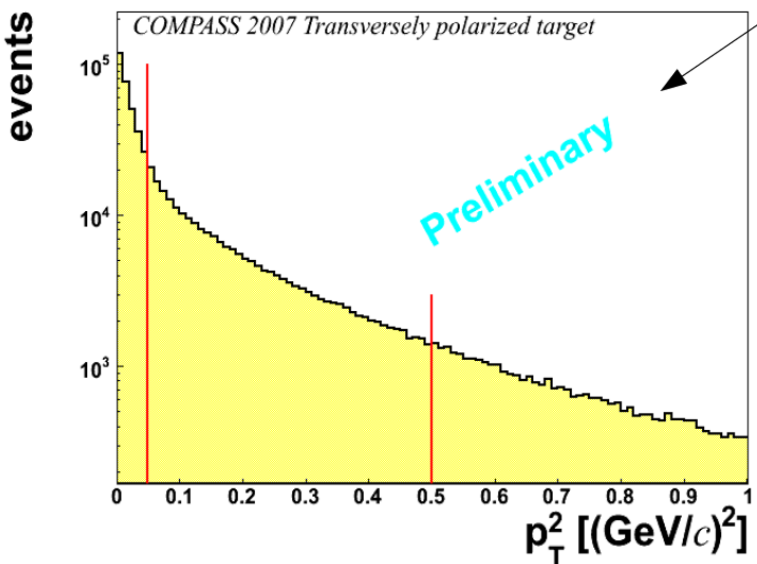


exclusive ρ_0 asymmetries

- **selection of exclusive ρ_0 production**
- **selection of incoherent ρ_0 production**

proton data analysis

Incoherent ρ_0 Production



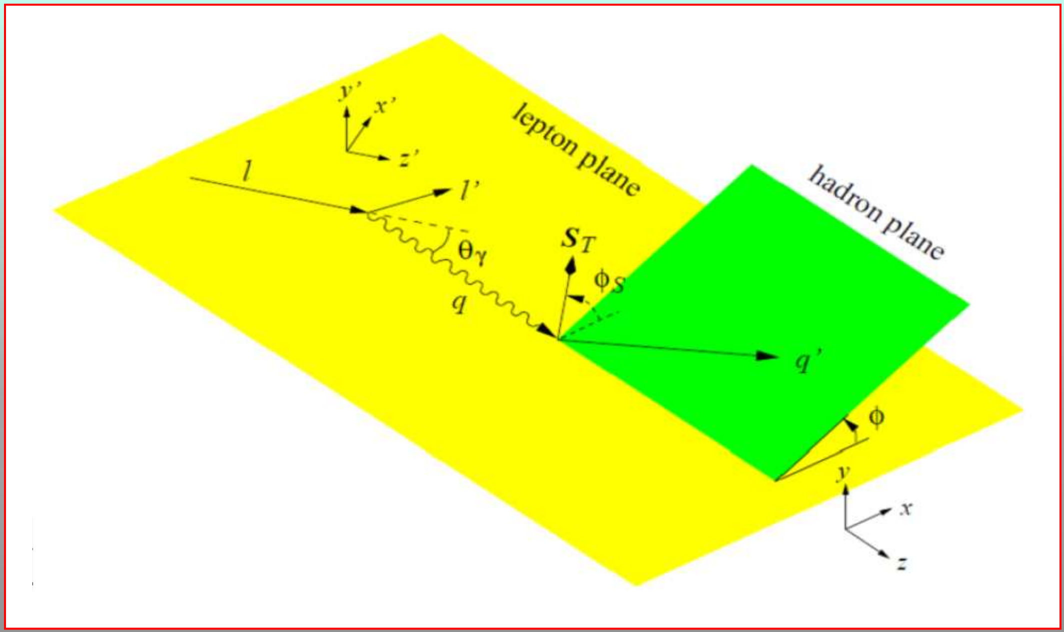
Coherent scattering on nitrogen rejected by selecting events with $p_T^2 > 0.05$ (GeV/c)²

Non-exclusive background reduced by selecting events with $p_T^2 < 0.5$ (GeV/c)²

exclusive ρ_0 asymmetries

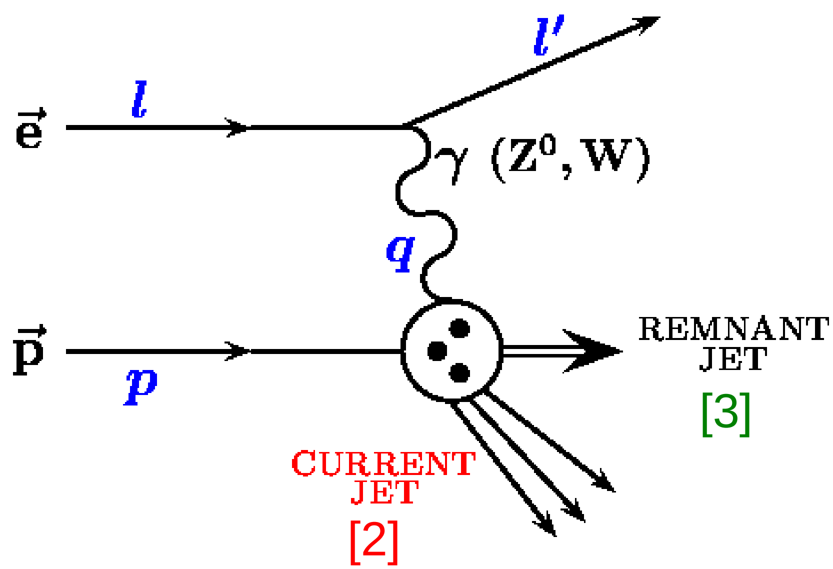
proton data analysis

- **selection of exclusive ρ_0 production**
- **selection of incoherent ρ_0 production**
- **measured asymmetry**



$$N(\phi-\phi_S)=F\,a(\phi-\phi_S)\sigma_0(1\pm f\langle P_T\rangle A_{UT}^{\exp}\sin(\phi-\phi_S))$$

DEEP INELASTIC SCATTERING



$$Q^2 = -q^2 = sxy$$

$$x = \frac{Q^2}{2p \cdot q}$$

$$y = \frac{p \cdot q}{p \cdot l}$$

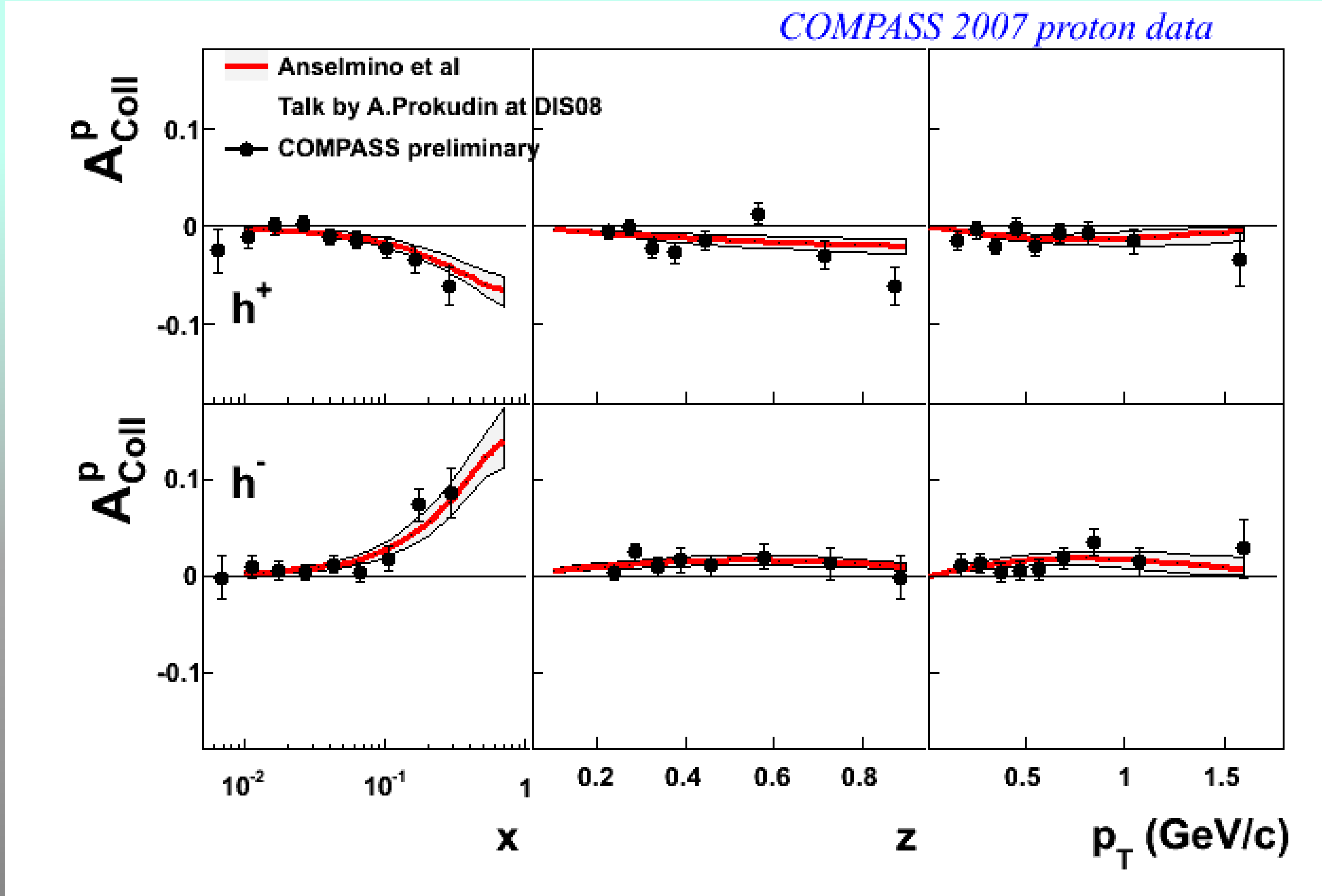
$$s = 4E_e E_p$$

$$W = (q + p)^2$$

- Observe scattered electron/muon [1] → inclusive
- Observe current jet [1]+[2] → semi-inclusive
- Observe remnant jet as well [1]+[2]+[3] → exclusive

Compass proton data

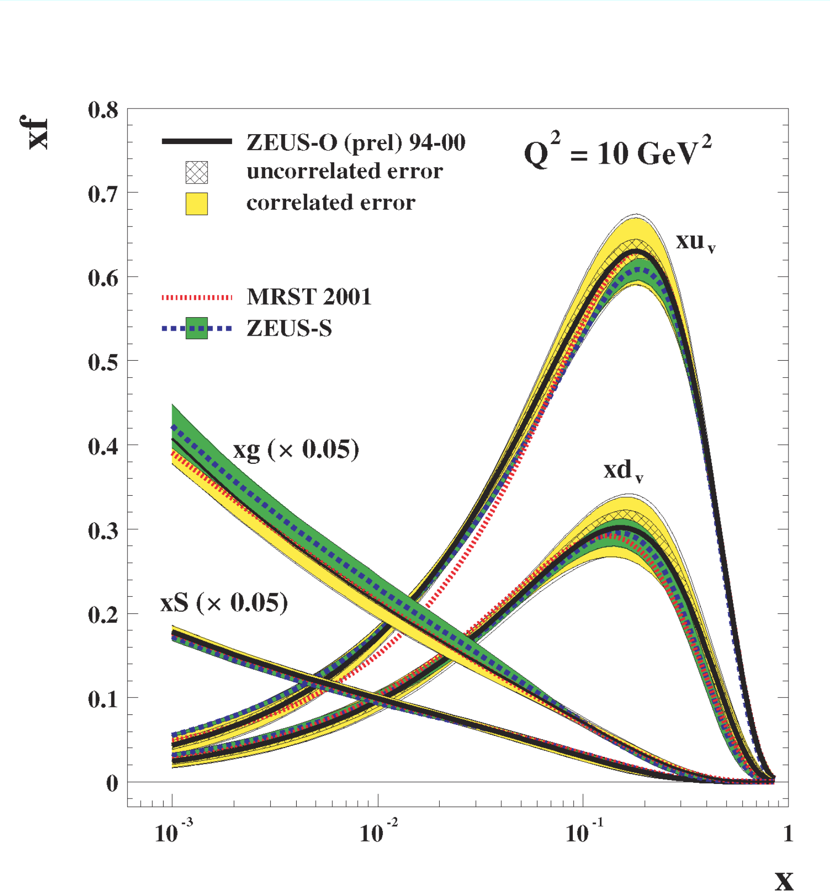
comparison with M. Anselmino et al. predictions



PDF AND STRUCTURE FUNCTIONS

Inclusive DIS: unpolarised

$$\frac{d\sigma}{dx\,dy} = \frac{e^4}{4\pi^2 Q^2} \cdot \left\{ \frac{y}{2} \cdot F_1 + \frac{1}{2xy} \cdot \left(1 - \frac{y}{2} - \frac{y^2}{4} \cdot \gamma^2 \right) \cdot F_2 \right\}$$



$F_2(x) = 2x \cdot F_1(x)$ Callan-Gross

in the parton model

$$F_1(x) = \frac{1}{2} \sum_q e_q^2 \cdot \left[q(x) + \bar{q}(x) \right]$$

$$q = u, d, s$$

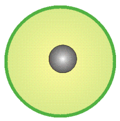
⇒ q(x) from global analysis of DIS and hard scattering data (QCD fits)

The nucleon structure

three distribution functions

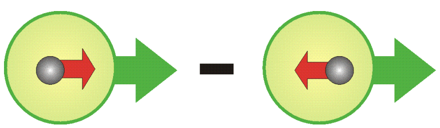
are necessary to describe the structure of the nucleon at LO:

$q(x)$: number density or **unpolarised distribution**



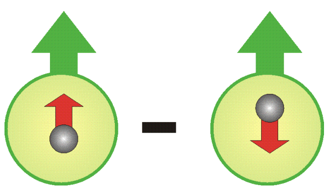
probability of finding a quark with a fraction x of the longitudinal momentum of the parent nucleon

$\Delta q(x) = q^{\rightrightarrows} - q^{\leftrightarrows}$: longitudinal polarization or **helicity distribution**



in a longitudinally polarised nucleon, probability of finding a quark with a momentum fraction x and spin parallel to that of the parent nucleon

$\Delta_T q(x) = q^{\uparrow\uparrow} - q^{\downarrow\uparrow}$: transverse polarization or **transversity distribution**

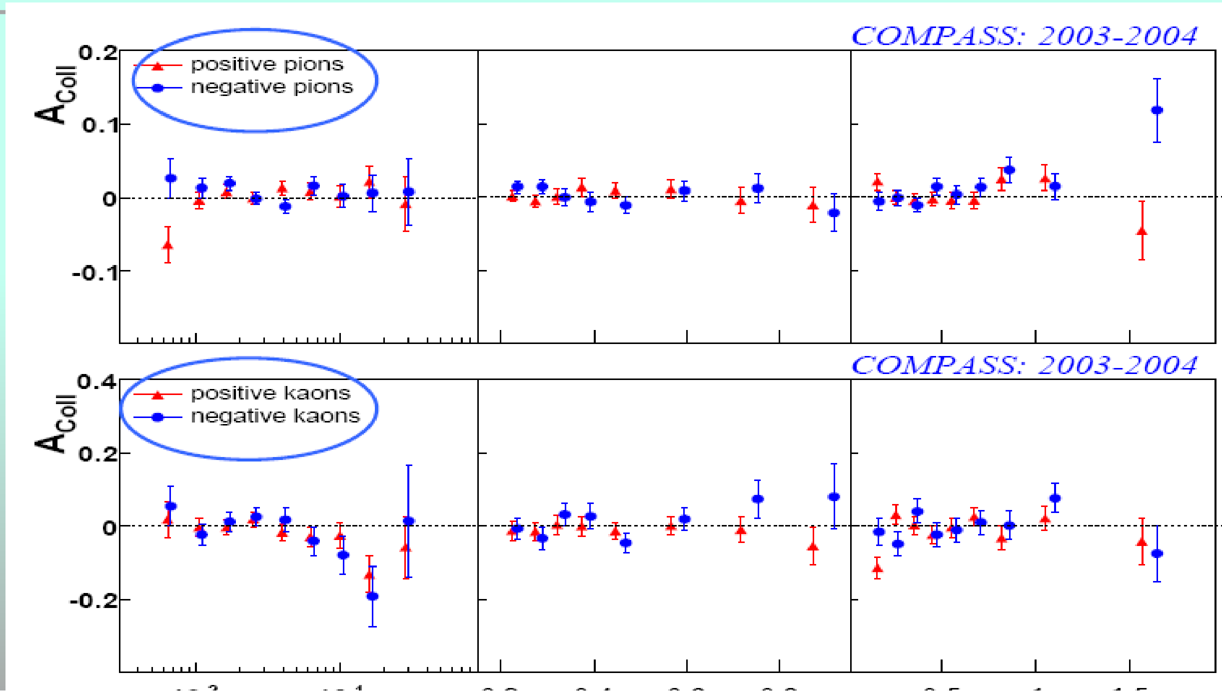


in a transversly polarised nucleon, probability of finding a quark with a momentum fraction x and spin parallel to that of the parent nucleon

q quark or antiquark with a specific flavor [*notation: Barone, Drago, Raftcliffe 2001*]

ALL OF EQUAL IMPORTANCE!

Collins Final on Deteron - COMPASS

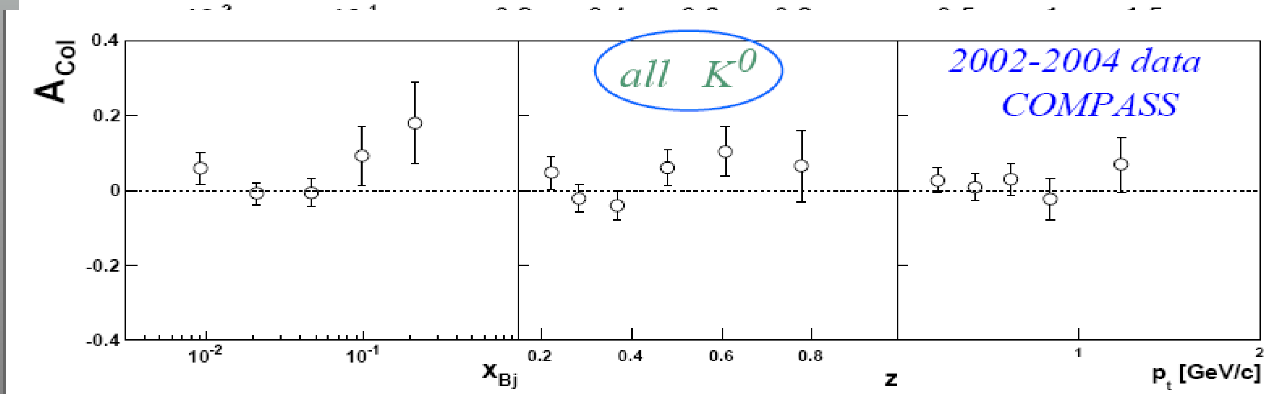


Final Results

all deuteron data

hep-ex/0802.2160

(subm. PLB)



Final Results

all deuteron data

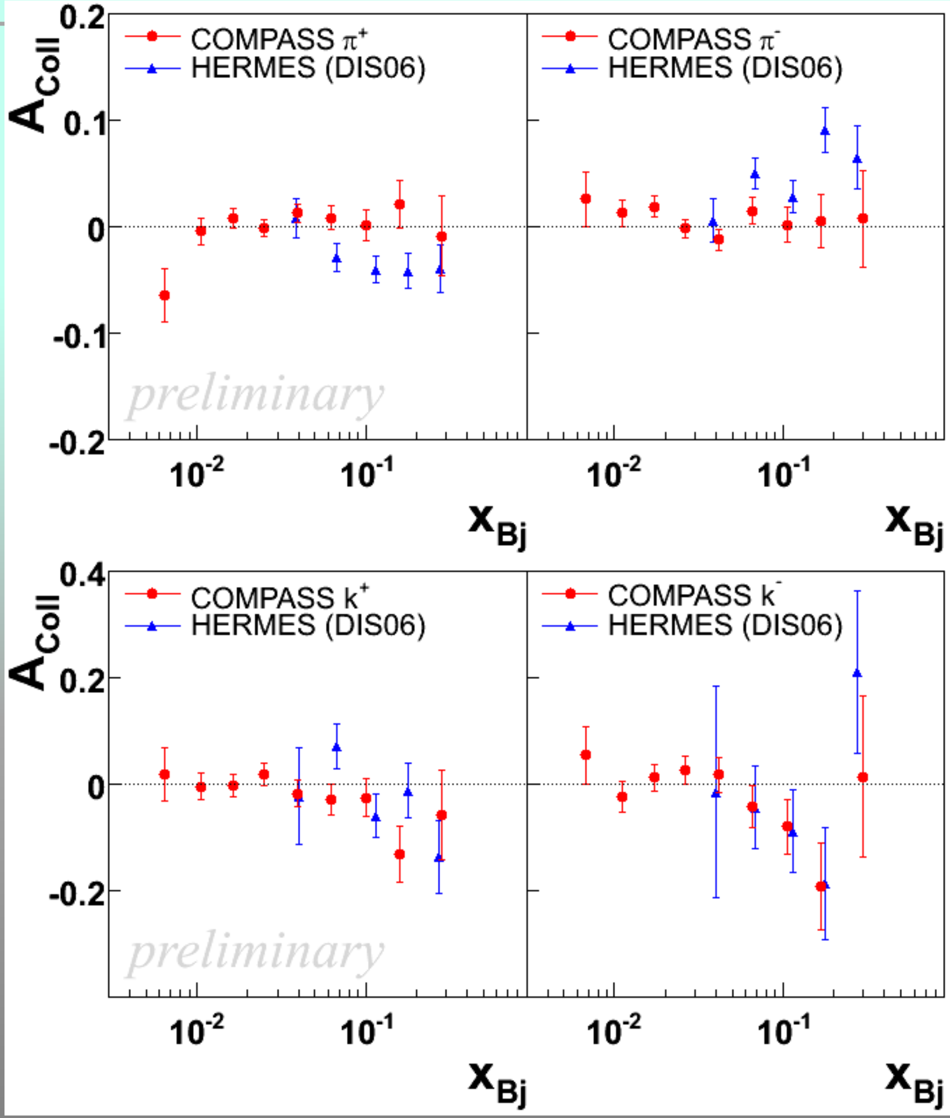
hep-ex/0802.2160

(subm. PLB)

Collins asymmetry for pions and kaons

preliminary
2002-2004 data
proton
(virtual photon asymm)
(*lepton beam 2002-05 → DIS07*)

final *CERN-PH-EP/2008-002*
hep-ex/0802.2160 (PRL)
2003-2004 data
deuteron
(virtual photon asymm)



Collins asymmetries: SUMMARY

The facts:

- **HERMES has measured on a proton target non-zero Collins asymmetries for π^+ and π^-**
- **COMPASS has measured on a deuteron target Collins asymmetries compatible with zero**
- **BELLE has produced the first results on Collins FF**

Conclusion:

- **Collins mechanism is a real phenomenon**
- **universality of Collins FF**
- **transversity can be measured in SIDIS**

Present picture

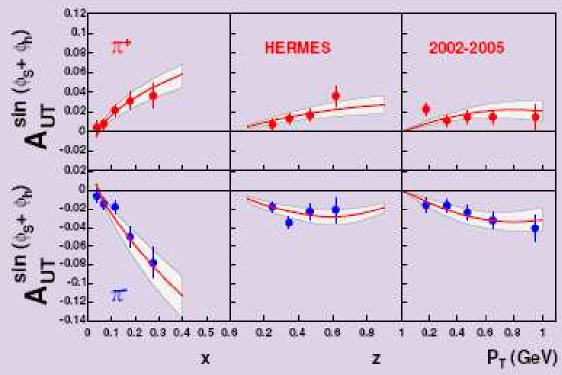
- **Collins:** $\Delta_T u \sim - \Delta_T d$
  $\Delta_T{}^0 D(fav.) \sim - \Delta_T{}^0 D(unfav)$

To extract TMD DF and FF GLOBAL ANALISYS are necessary

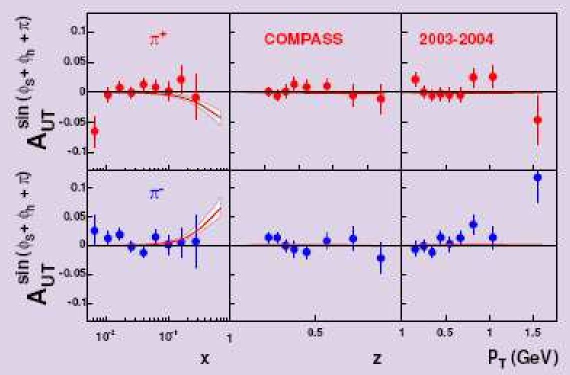
Global Fits

Preliminary results

HERMES $A_{UT}^{sin(\phi_h+\phi_S)}$

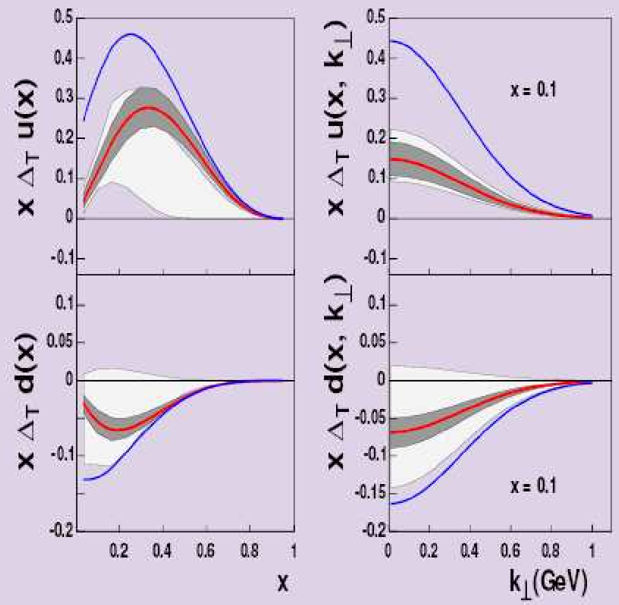


COMPASS $A_{UT}^{sin(\phi_h+\phi_S+\pi)}$



First Extraction of $\Delta_T q$

Transversity

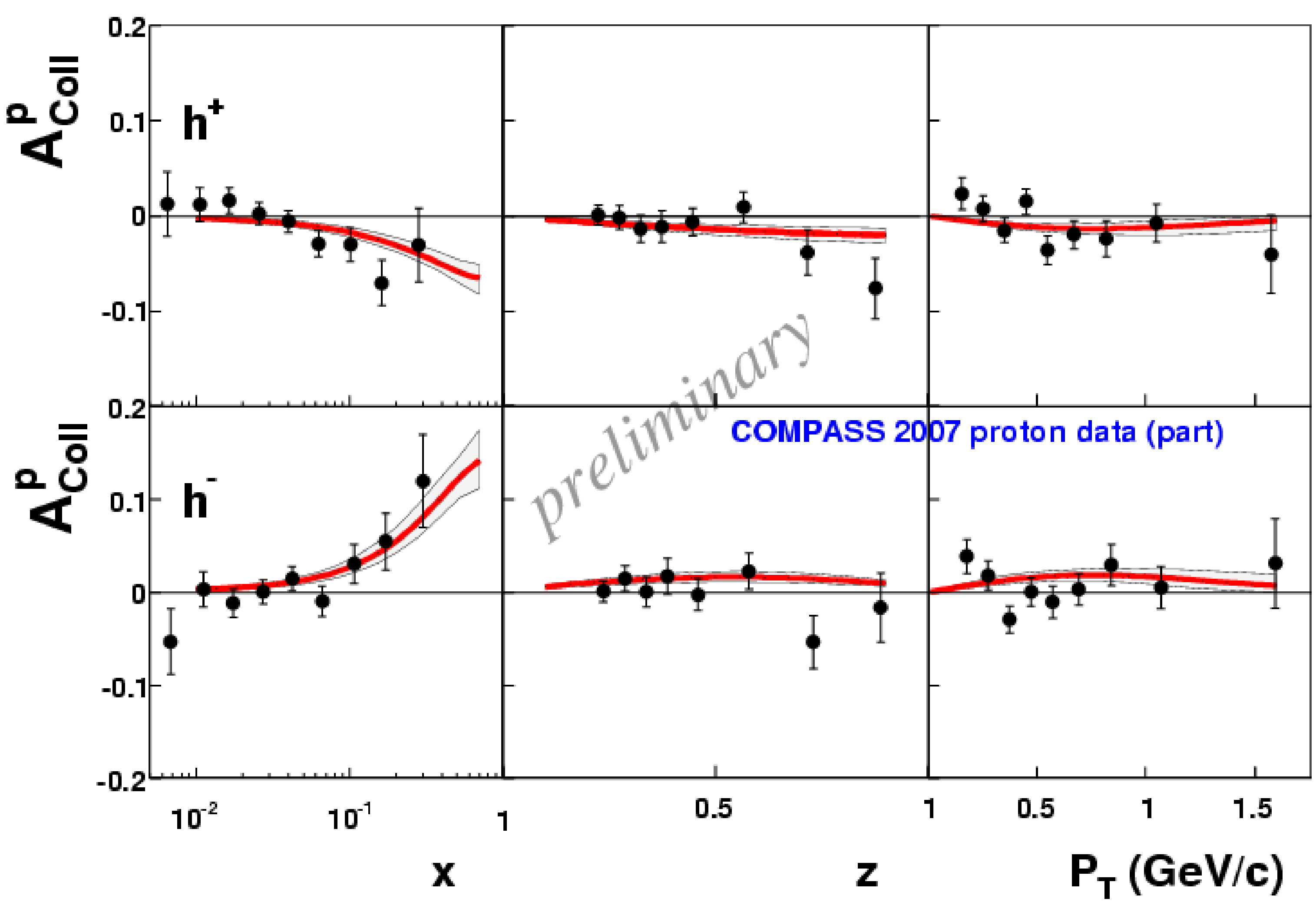


- This is the extraction of transversity from new experimental data.
- Compared to previous extraction PRD75:054032,2007
- $\Delta_T u(x) > 0$ and $\Delta_T d(x) < 0$ The errors are diminished significantly.
- $\Delta_T u(x)$ became larger than that of the previous fit.

HERMES, COMPASS BELLE

Compass proton data

comparison with M. Anselmino et al. predictions



What else?

When k_T is taken into account…

- **Transverse momentum dependend PDFs and FFs**
  - Transverse momentum dependent (TMD) parton distributions and fragmentation functions are currently under intense investigation both from the experimental and theoretical side
  - The knowledge of correlations of transverse momentum of partons and spin are crucial for the understanding of the spin structure of the nucleon in terms of the quark and gluon degrees of freedom of QCD.

Three parton distributions describing quark's TM and/or TS

Three transverse quantities:

1) Nucleon transverse spin

$\vec{S}_\perp^N$

2) Quark transverse spin

$\vec{s}_\perp^q$

3) Qaurk transverse momentum

$\vec{k}_\perp^q$

$\Rightarrow$ Three different correlations

1) Transversity

h_{1T} = –

Correlation between $\vec{s}_\perp^q$ and $\vec{S}_\perp^N$

COMPASS HAS RESULTS ON SIVERS AND OTHER TMDs

2) Sivers function

$f_{1T}^\perp$ = –

Correlation between $\vec{S}_\perp^N$ and $\vec{k}_\perp^q$

but too long…

3) Boer-Mulders function

$h_1^\perp$ = –

Correlation between $\vec{s}_\perp^q$ and $\vec{k}_\perp^q$

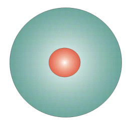
The 3rd Twist-2 structure function

three quark distribution functions (DF) are necessary to describe the structure of the nucleon at LO

$q(x)$

$f_1^q(x)$

→ vector charge



unpolarised DF

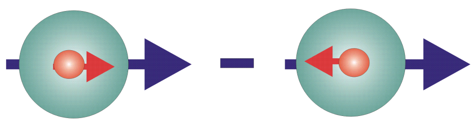
quark with momentum *xP* in a nucleon

well known – unpolarised DIS

$\Delta q(x)$

$g_1^q(x)$

→ axial charge



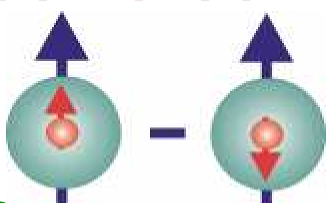
helicity DF

quark with spin parallel to the nucleon spin in a longitudinally polarised nucleon

known – polarised DIS

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

$h_1^q(x)$,



→ tensor charge

transversity DF

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

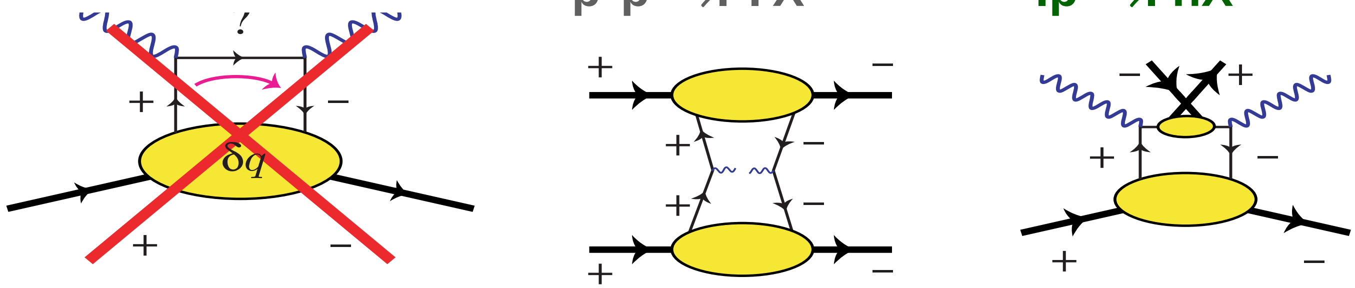
largely unknown

ALL 3 OF EQUAL IMPORTANCE

Misura di $\Delta_T q(x)$

Chiral-odd: requires another chiral-odd partner

Inclusive DIS	$p^\uparrow p^\uparrow \to l^+ l^- X$	$lp^\uparrow \to l' h X$



$lp^\uparrow \to l' h_1 h_2 X$
$lp^\uparrow \to l' \Lambda X$

impossible	direct measurement $\Sigma \Delta_T q(x) \cdot \Delta_T q(x)$	convolution with spin dependent fragment. func.

SIDIS
(e.g. COMPASS and HERMES)

$$\Delta_T q(x) \otimes FF$$

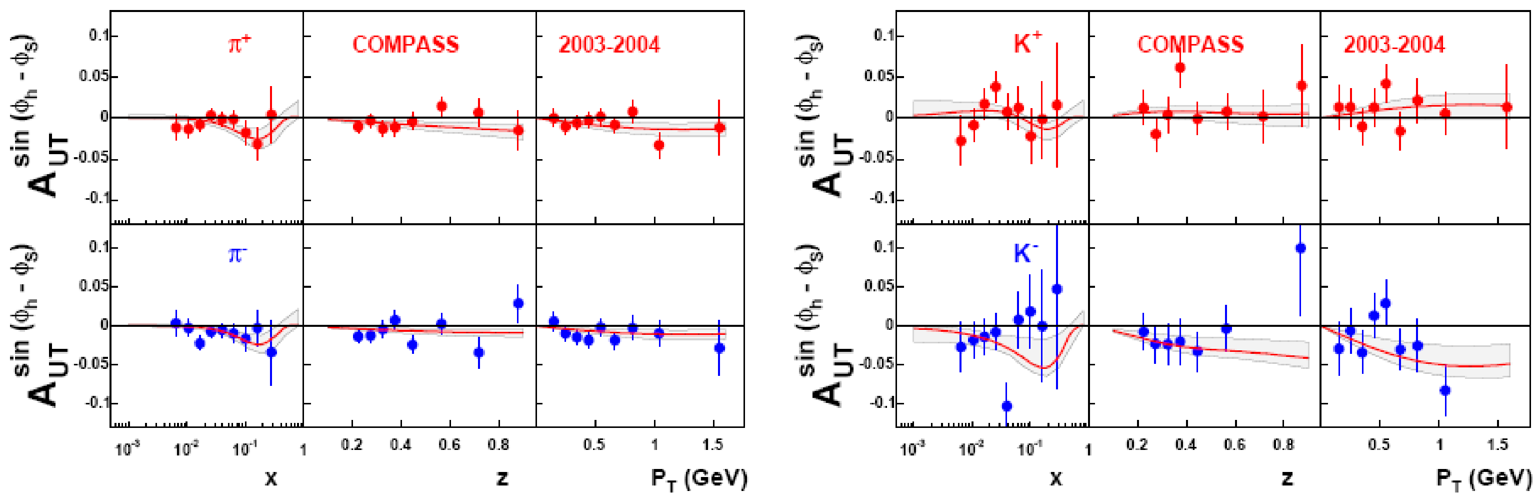
Hard scattering NN (e.g. RHIC)
- **Drell-Yan** $\Delta_T q \cdot \Delta_T q$
- **Single Spin Asym (e.g. $p^\uparrow p \to \pi X$)**

Hard scattering $N\bar{N}$ (e.g. GSI)
- **Drell-Yan** $\Delta_T q \cdot \Delta_T q$

Global Analysis II

➢ COMPASS data◇ fit

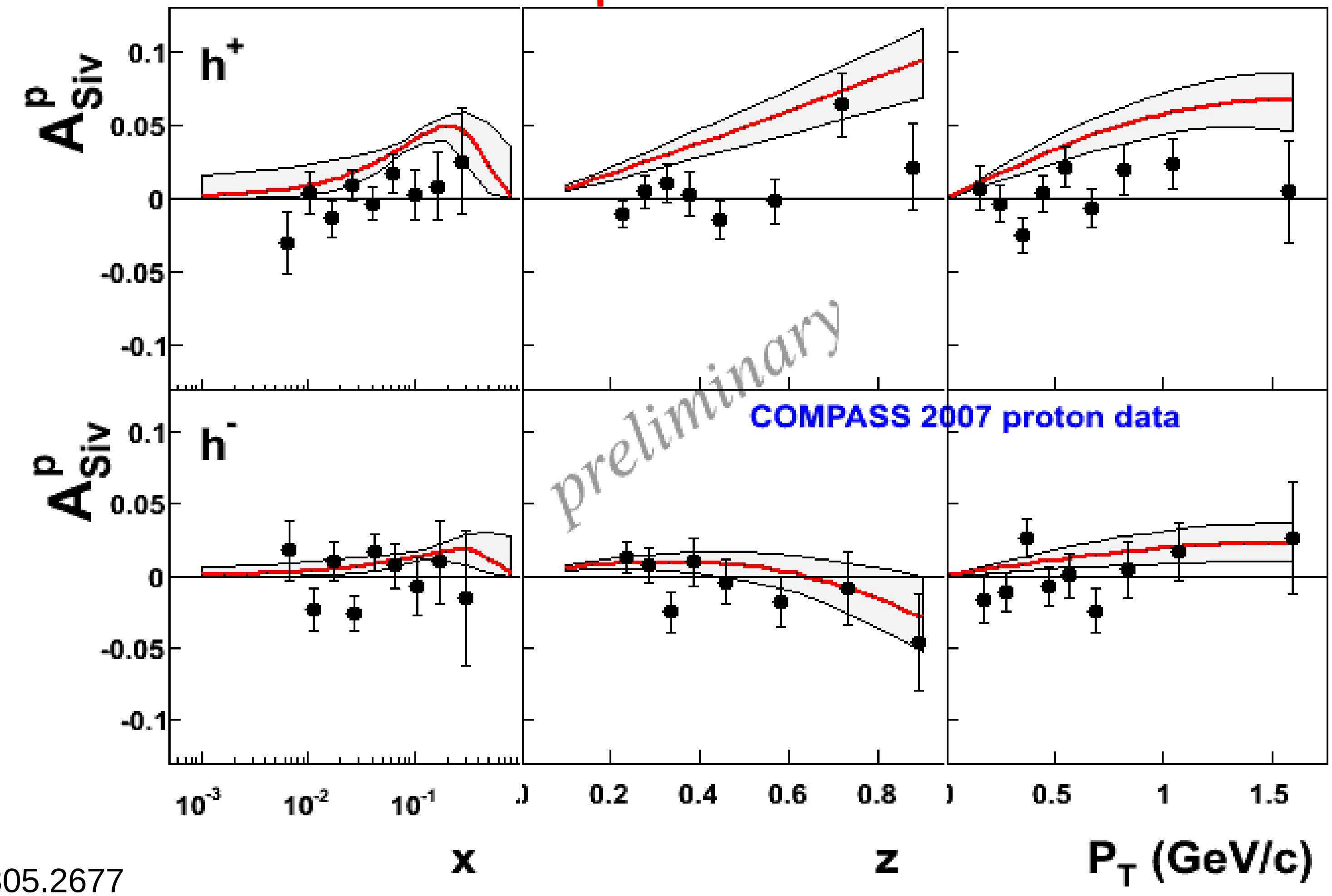
$eD \to e\pi X$ $\quad p_{lab} = 160$ GeV/c $\quad eD \to eKX$



Stefano Melis

Sivers asymmetry– proton data

comparison with the most recent predictions from M. Anselmino et al.



arXiv:0805.2677

GLOBAL FIT

This paper presents the first "global" NLO analysis of the data from DIS, SIDIS, and RHIC in terms of the helicity PDFs. While there have been quite a few NLO

deFlorian, Sassot, Stratmann, Vogelsang

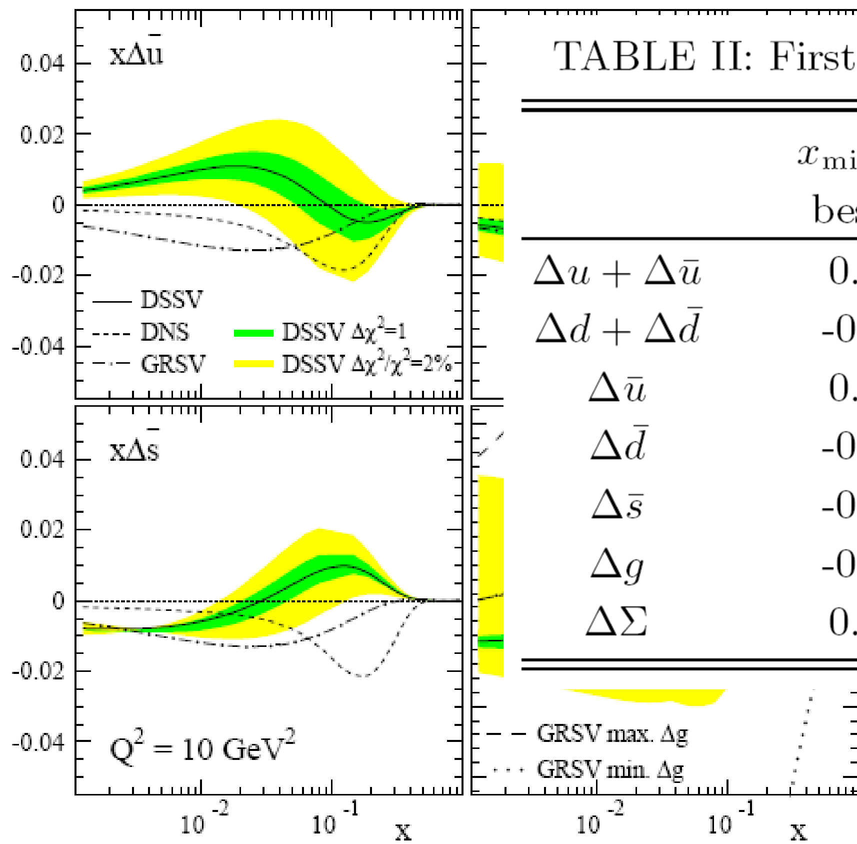


TABLE II: First moments $\Delta f_j^{1,[x_{\min}-1]}$ at $Q^2 = 10\,\mathrm{GeV}^2$.

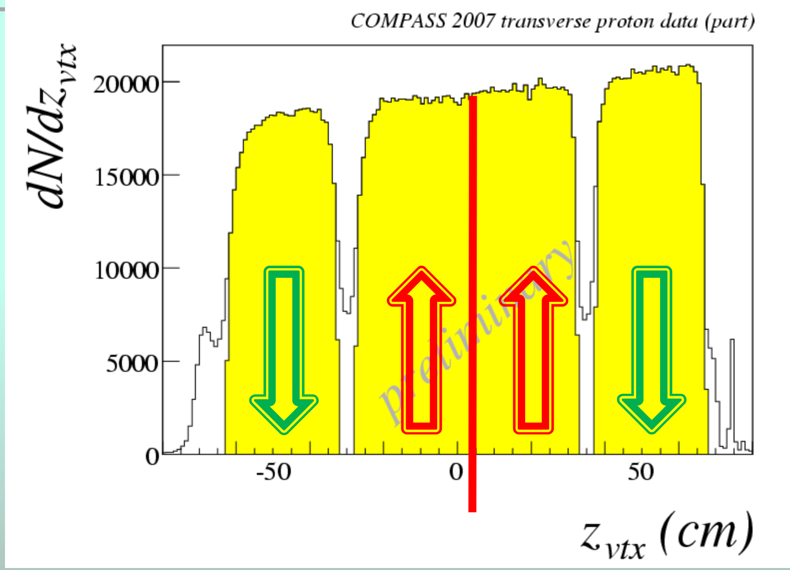
	$x_{\min} = 0$ best fit	$x_{\min} = 0.001$ $\Delta\chi^2 = 1$	$\Delta\chi^2/\chi^2 = 2\%$
$\Delta u + \Delta\bar{u}$	0.813	$0.793\ ^{+0.011}_{-0.012}$	$0.793\ ^{+0.028}_{-0.034}$
$\Delta d + \Delta\bar{d}$	-0.458	$-0.416\ ^{+0.011}_{-0.009}$	$-0.416\ ^{+0.035}_{-0.025}$
$\Delta\bar{u}$	0.036	$0.028\ ^{+0.021}_{-0.020}$	$0.028\ ^{+0.059}_{-0.059}$
$\Delta\bar{d}$	-0.115	$-0.089\ ^{+0.029}_{-0.029}$	$-0.089\ ^{+0.090}_{-0.080}$
$\Delta\bar{s}$	-0.057	$-0.006\ ^{+0.010}_{-0.012}$	$-0.006\ ^{+0.028}_{-0.031}$
Δg	-0.084	$0.013\ ^{+0.106}_{-0.120}$	$0.013\ ^{+0.702}_{-0.314}$
$\Delta\Sigma$	0.242	$0.366\ ^{+0.015}_{-0.018}$	$0.366\ ^{+0.042}_{-0.062}$

FIG. 2: Our polarized sea and gluon densities compared to previous fits [6, 8]. The shaded bands correspond to alternative fits with $\Delta\chi^2 = 1$ and $\Delta\chi^2/\chi^2 = 2\%$ (see text).

Asymmetry Extraction

Splitting middle cell into two parts

- two couples of cells with opposite polarization
- two independent values for the asymmetries per period



Extraction: 2D Binned Maximum Log-Likelihood Fit:

eight by eight grid in ϕ_h and ϕ_S;
in each bin of the matrix one expects N_j counts :

$$N_j^{\uparrow\downarrow} = a_j \, \Delta_j^{\uparrow\downarrow}(\vec{A}) \quad \text{with:} \begin{cases} \uparrow\downarrow & = \text{orientation of the target polarization} \\ a_j & = \text{acceptance in bin j} \\ \Delta_j^{\uparrow\downarrow}(\vec{A}) & = \text{all 8 spin dependent modulations in bin j} \end{cases}$$

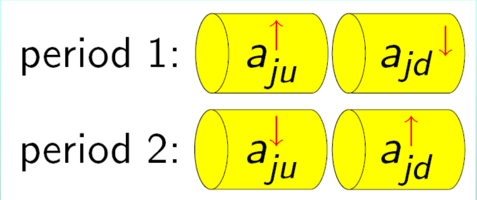
Asymmetry Extraction - II

Separation of acceptance and spin dependent modulations:

Coupling of two cells (u,d) with opposite polarization (↑↓)

and two periods (p_1,p_2) with opposite target polarization:

Reasonable assumption: $$\frac{a_{ju}^{\uparrow}}{a_{ju}^{\downarrow}} = C\,\frac{a_{jd}^{\downarrow}}{a_{jd}^{\uparrow}}$$



$4 \cdot 64 = 256$ nonlinear equations $\left(\vec{f}\,(\vec{a})\right)$

$1 + 8 + 3 \cdot 64 = 201$ fit parameter, $(\vec{a})$

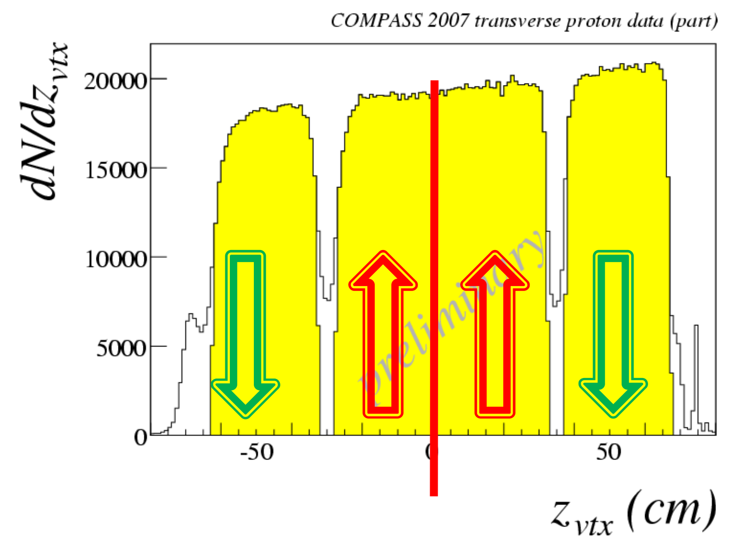
Poisson distribution to account for low statistics: $$P_j(\vec{a}) = \frac{f_j(\vec{a})^{N_j}\; e^{-f_j(\vec{a})}}{N_j!}$$

Tests for systematic errors:

- For false asymmetries: combination of cells with same polarization
- Comparison of 5 estimators for asymmetry extraction included the one used in previous analysis (deuteron data)

For this analysis: overall systematic error is 30% and 50% of the statistical error for Collins and Sivers respectively

Asymmetry Extraction



Splitting middle cell into two parts

- two couples of cells with opposite polarization
- two independent values for the asymmetries per period

Extraction: Extended Unbinned Maximum Likelihood Fit

$$L = e^{-N_e} \prod_{i=1}^{N} p(\phi_S^i, \phi_h^i; a_1 \cdots a_m)$$

Where N is the number of hadrons, N_e is the expected n.of.h, $\{a_1 \ldots a_m\}$ are the unknown parameters and p describes the probability density of the sampling variables ϕ_S and ϕ_h

$$\int\int p(\phi_S \phi_h; a_1 \cdots a_m) d\phi_S d\phi_h = N_e(a_1 \cdots a_m)$$

i.e. p describes also the size of the distribution, not only the shape

p parameterization contains the single hadron cross-section

Collins over the full 2007

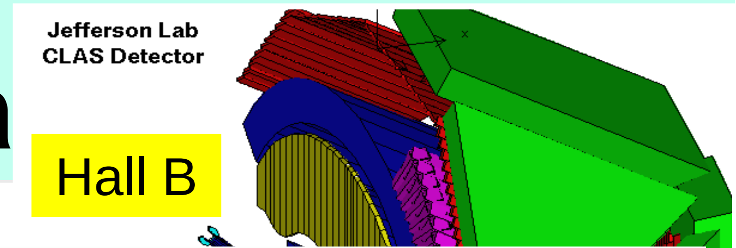
1 year have been spend to further analyse the data collected in the first part of the 2007 run to

- reproduce the data with improved quality
- Improve quality checks
- Increase systematic checks

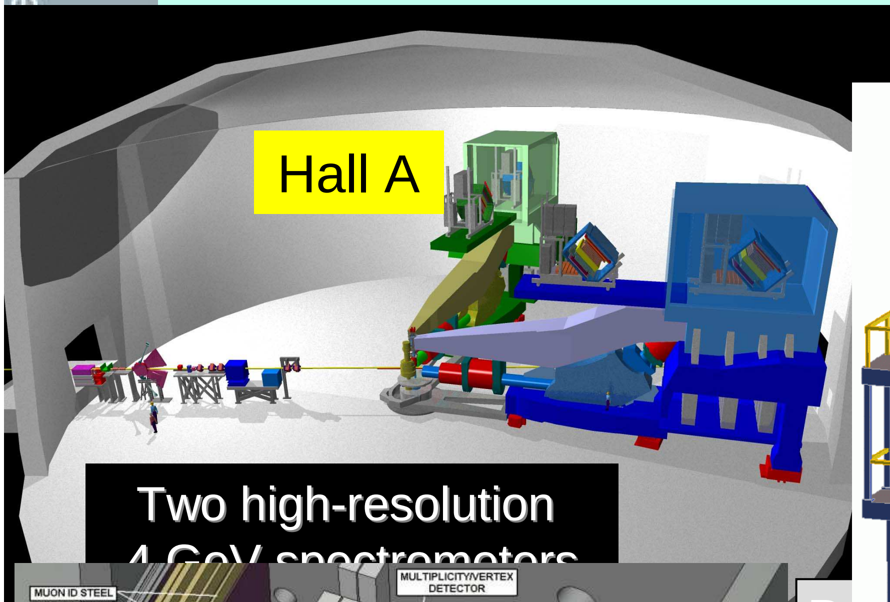
resulting in an increase of usable statistics for the Collins asymmetries by ~ a factor 3, while previous results for Sivers have been confirmed

	COLLINS	SIVERS
Total statistics entering the analysis	29×10^6 h	11×10^6 h

Who are the pla

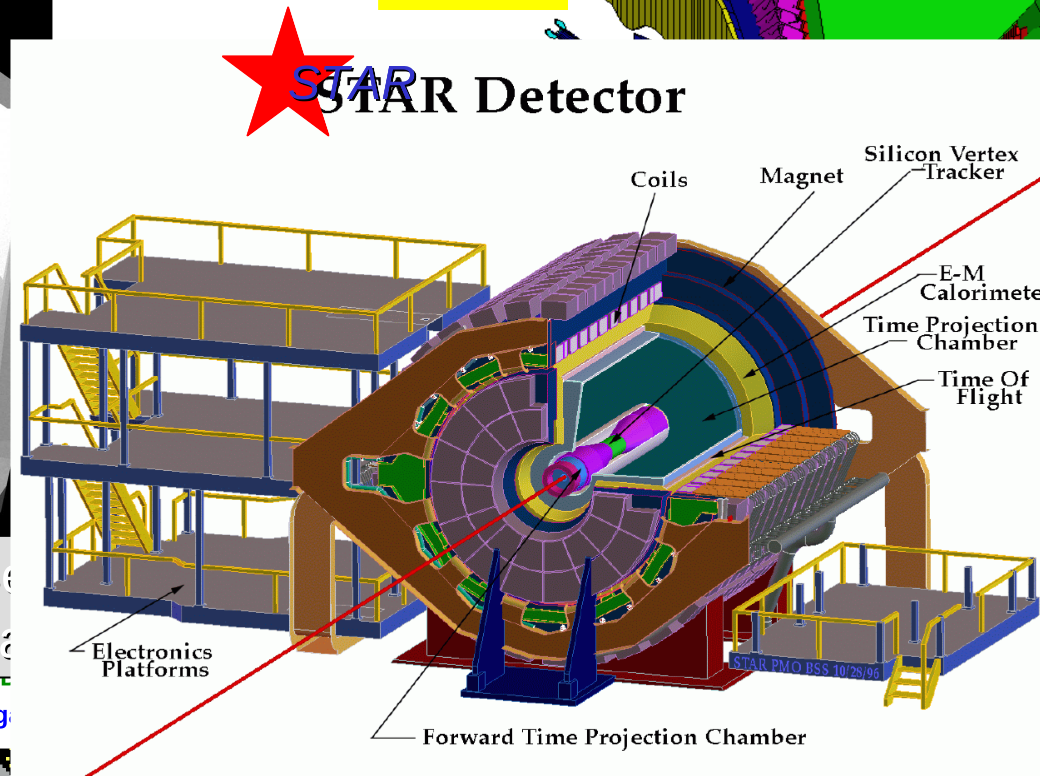


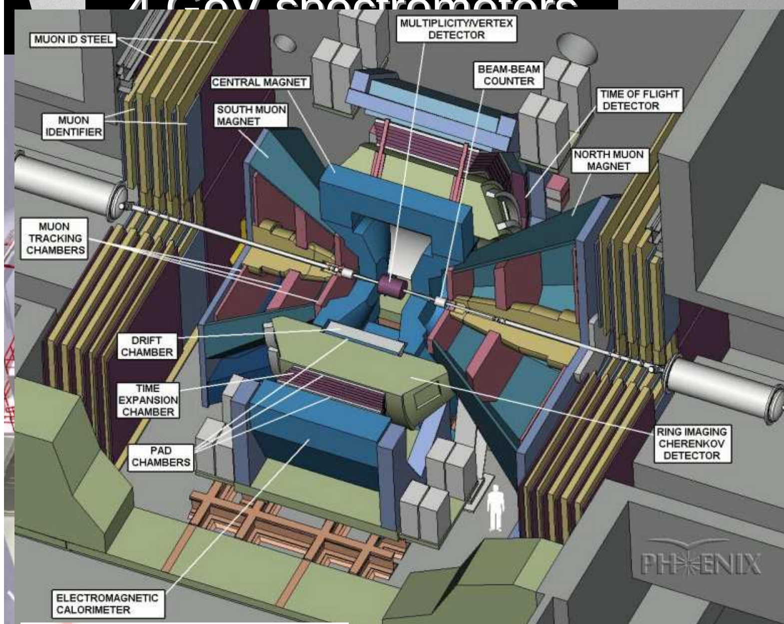
Hall B



Hall A

Two high-resolution
4 GeV spectrometers

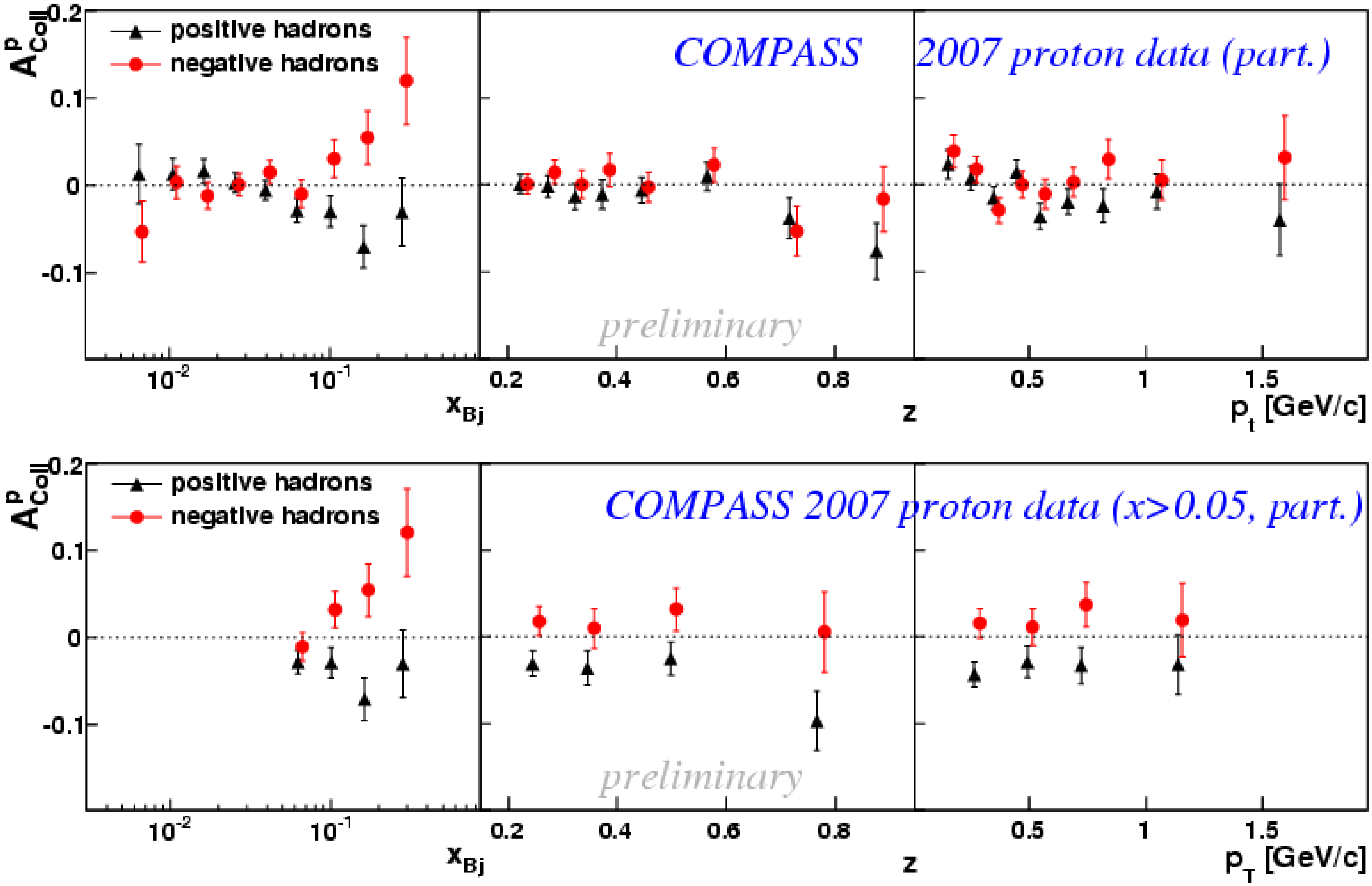




PHENIX

Beams: 250 GeV pp; <60>% polarization
Lumi: 1.2 10^{31}cm^{-2}s^{-1}

Collins asymmetry



A summary

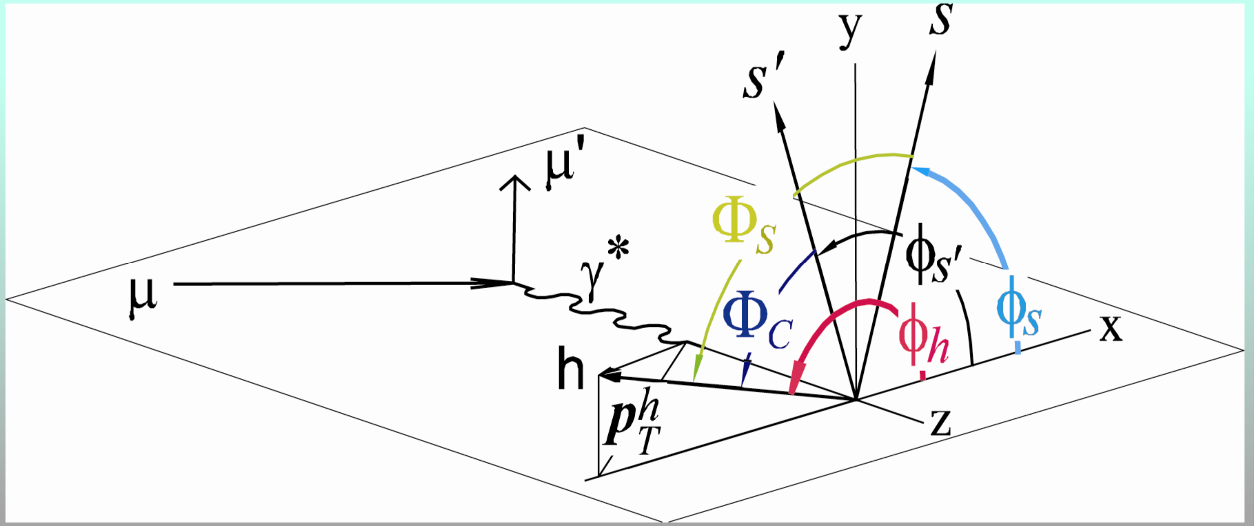
	^{6}LiD (2002-4) 20%		NH_3 (2007) 50%	
	unID	ID	unID	ID
Collins	**X**	**X**	X	
Sivers	**X**	**X**	X	
Other SSA	X			
2hadrons	X	X	X	
Lambda		X		X
Unpolarized	X			

Azimuthal modulations

Collins and Sivers angles

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

$\Phi_S = \phi_h - \phi_S$



$\phi_{S'}$ azimuthal angle of spin vector of fragmenting quark ($\phi_{S'} = \pi - \phi_S$)

ϕ_h azimuthal angle of hadron momentum

2007 Transverse data taking statistics

- 2007 Compass Data taking

  Begin of run: 18 May 2007

  End of run: 11 November 2007

- Split between transverse and longitudinal target polarization:

  - μ on tape for transverse (40.0×10^{12})

  - μ on tape for longitudinal (41.5×10^{12})

- First results on about 20% of the collected statistics shown at Transversity 2008 in Ferrara