Transverse Spin and Momentum effects in the COMPASS Experiment

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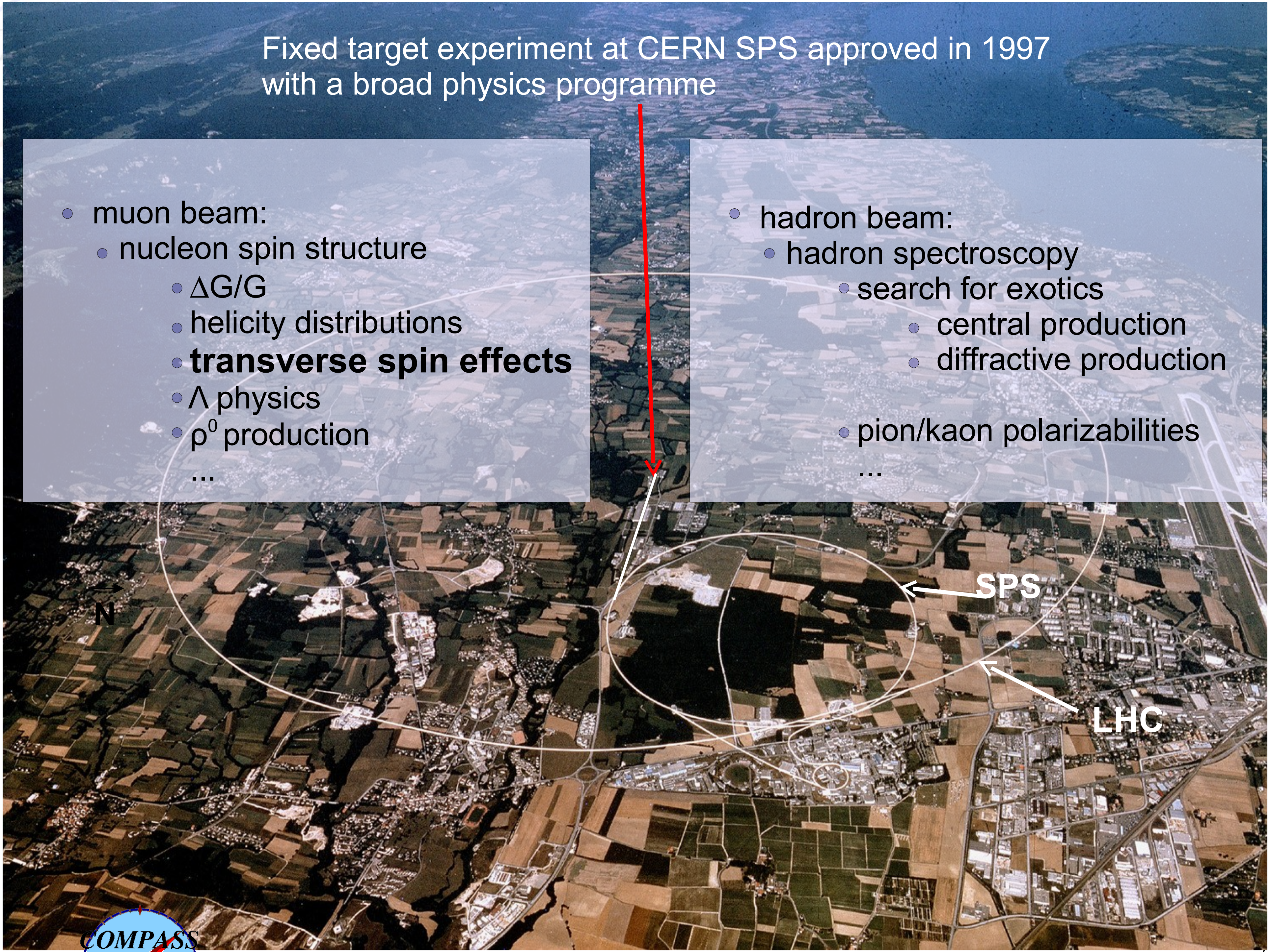
on behalf of the COMPASS Collaboration

International Committee for Spin Physics Symposia
XXIII WORKSHOP ON HIGH ENERGY PHYSICS
Dubna, Russia September 1-5, 2009

OUTLINE

- The COMPASS experiment
- SIDIS
- Hadron azimuthal asymmetries
  - unpolarized target
  - transversely polarized target
- Two hadrons azimuthal asymmetries
- Conclusions and outlook

Fixed target experiment at CERN SPS approved in 1997
with a broad physics programme



- muon beam:
  - nucleon spin structure
    - $\Delta G/G$
    - helicity distributions
    - **transverse spin effects**
    - Λ physics
    - ρ^0 production
    - ...

- hadron beam:
  - hadron spectroscopy
    - search for exotics
      - central production
      - diffractive production
    - pion/kaon polarizabilities
    - ...

Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

Data taking since 2002

muon beam	**deuteron** (^{6}LiD)	2002	L/**T** target polarization
	polarized target	2003	
		2004	
		2006	L target polarization
	proton (NH_3)	2007	L/**T** target polarization
	polarized target		
hadron beam	LH target	2008	
		2009	

longitudinally polarised muon beam

beam intensity: 2.10^8 μ^+/spill (4.8s/16.2s)

beam momentum: **160 GeV/*c***

luminosity: ~5 x 10^{32} cm^{-2} s^{-1}

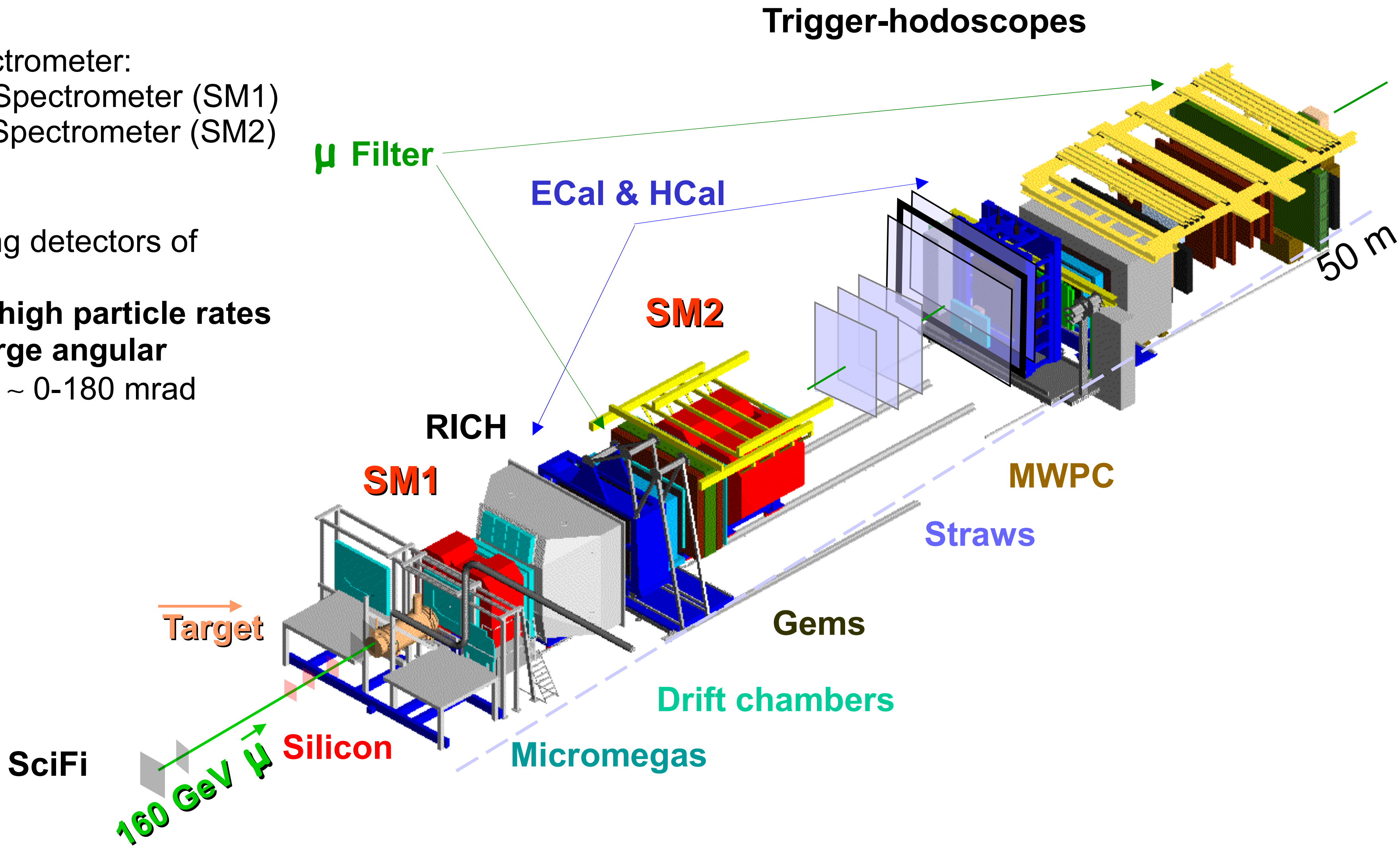
The COMPASS Spectrometer – muon beam

built to cover a large kinematical range

two stage spectrometer:
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

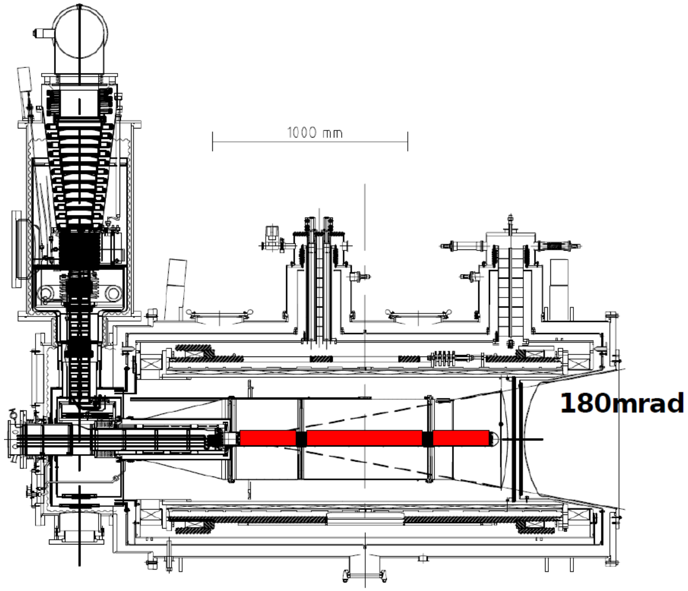
several tracking detectors of different type
- to cope with **high particle rates**
- to cover a **large angular acceptance** ~ 0-180 mrad

particle ID:
- calorimeters
- muon walls
- RICH



Common **M**uon and **P**roton **A**pparatus for **S**tructure and **S**pectroscopy

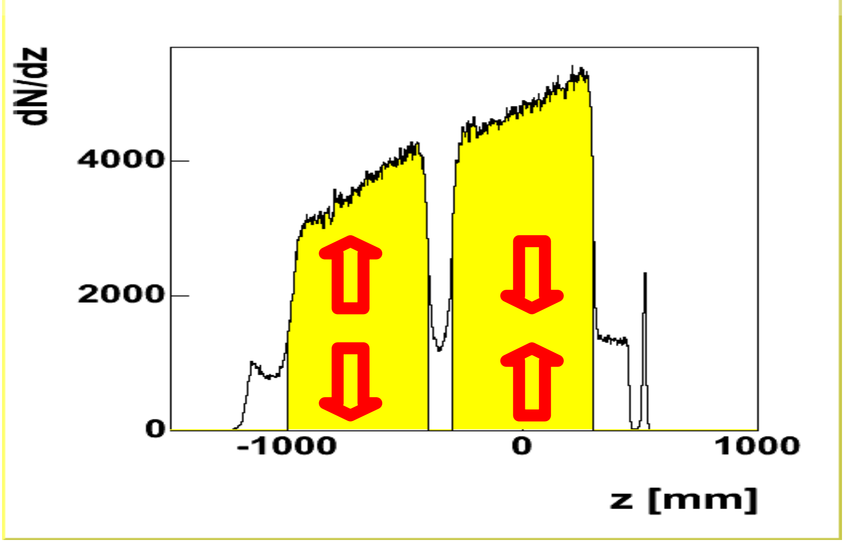
The polarized target



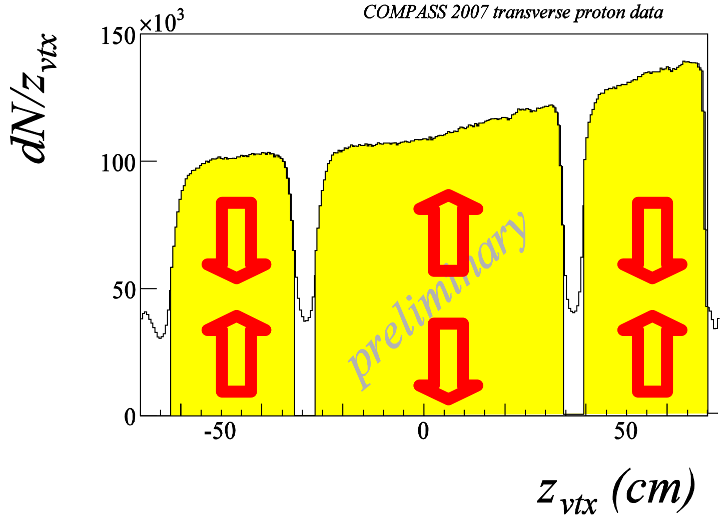
Solid state target operating in **frozen spin mode 120 cm** long

Composed by 2 or 3 cells with **opposite polarization**
reversed every week during transverse data taking

2002-4 ^{6}LiD
dilution factor: 0.38
polarization: 50%



2007 NH_3
dilution factor: 0.14
polarization: 90%



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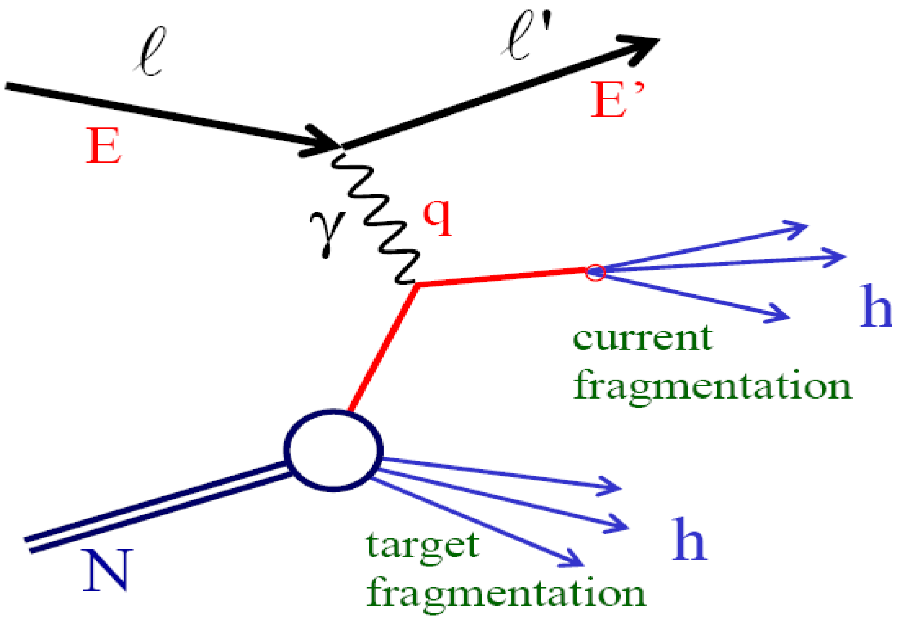
SIDIS: a key process to investigate the spin structure of the nucleon

$l\ N \longrightarrow l'\ h\ X$



lepton interacts with a single parton of the nucleon (via photon exchange)

q virtual photon four-momentum

$Q^2 = -q^2 > 0$ **$v = E - E'$**

$x = Q^2 / 2Mv$ **$y = v/E$**

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

at least one hadron is detected in the final state

$z = E_h / v$

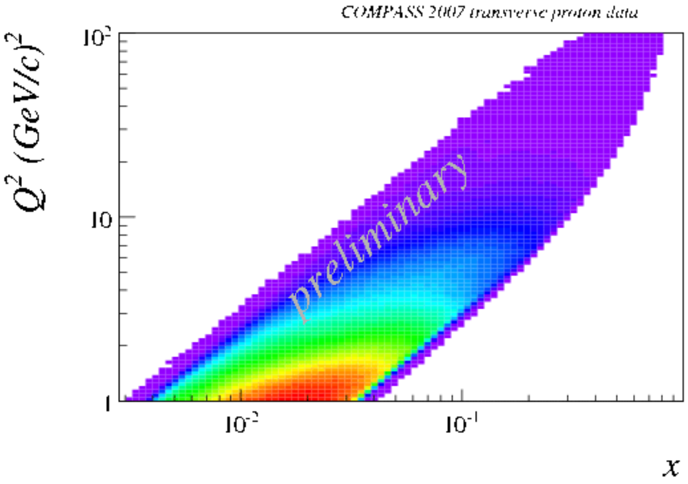
Data selection and kinematics

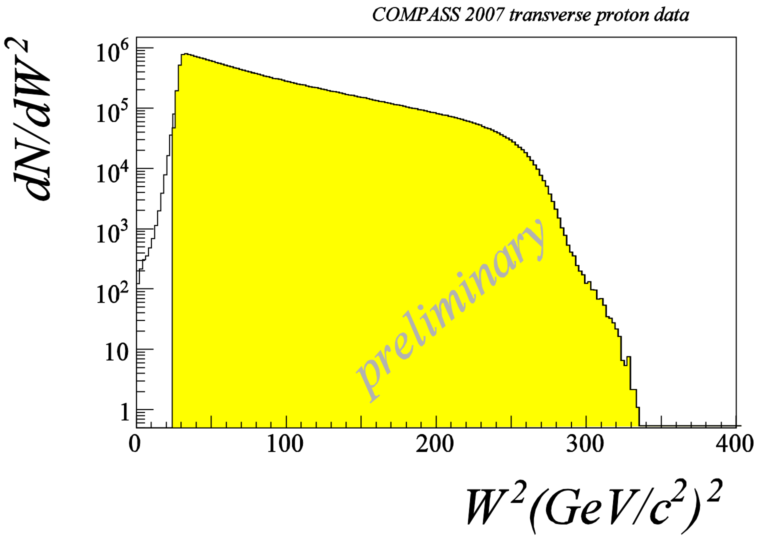
DIS event selection:

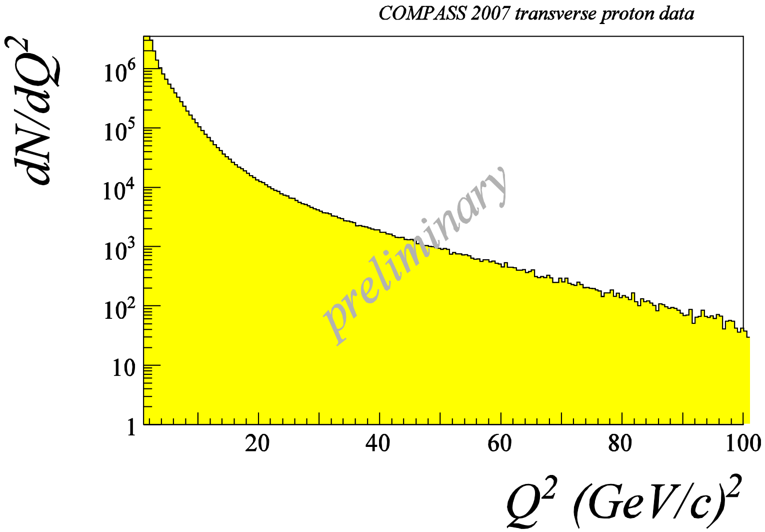
$Q^2 > 1\ (\mathrm{GeV}/c)^2$

$0.1 < y < 0.9$

$W > 5\ \mathrm{GeV}/c^2$







Data selection and kinematics

DIS event selection:

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

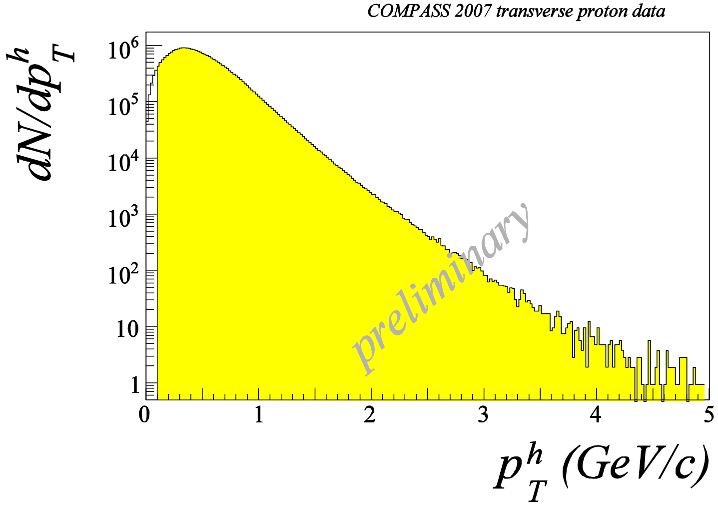
$0.1 < y < 0.9$

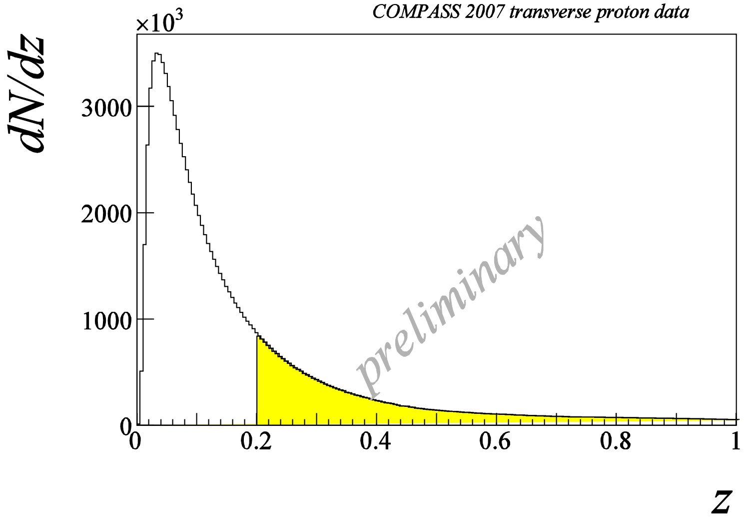
$W > 5\ GeV/c^2$

Hadron selection

$p_T > 0.1\ GeV/c$

$z > 0.2$





SIDIS cross section

From **A. Bacchetta** et al., **JHEP 0702:093,2007**.

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

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

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

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

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

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

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

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

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

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

unpolarized

these modulations
will be addressed in this talk

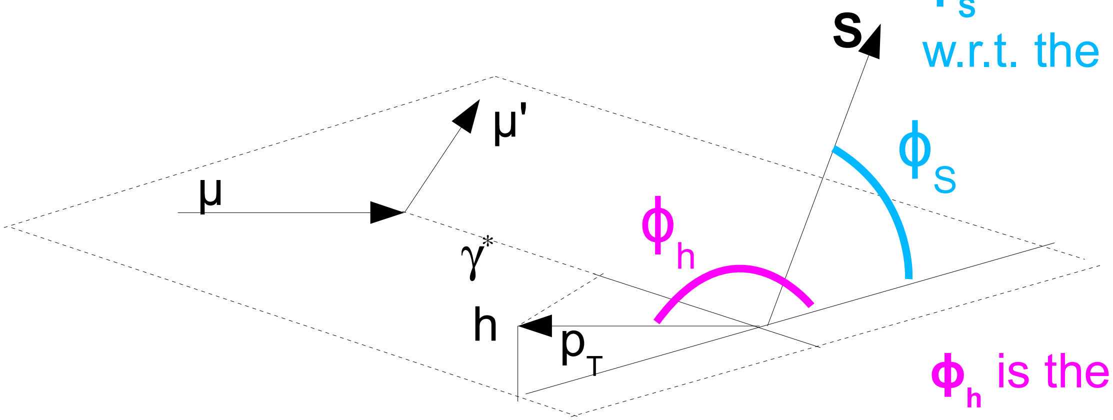
transverse polarization

SIDIS cross section

$$\sigma^{l\,N \to l'\,h\,X} \propto \sum_q \underset{\underset{\text{PDF}}{\uparrow}}{q(x)} \otimes \sigma^{l\,q \to l'\,q'} \otimes \underset{\underset{\text{FF}}{\uparrow}}{D(z)}$$

the complete **SIDIS cross section**, including the quarks transverse momentum, has **18 structure functions** (PDF ⊗ FF), 8 leading order

most of them can be accessed by measuring the corresponding azimuthal modulation (**independent** azimuthal modulations in ϕ_s ϕ_h)



ϕ_s is the azimuthal angle of the **nucleon spin** w.r.t. the scattering plane

ϕ_h is the azimuthal angle of the **hadron momentum** w.r.t. the scattering plane

the relevant **azimuthal angles** ϕ_s ϕ_h are evaluated in the **G**amma **N**ucleon **S**ystem

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three **azimuthal modulations** in the **unpolarized** cross section:

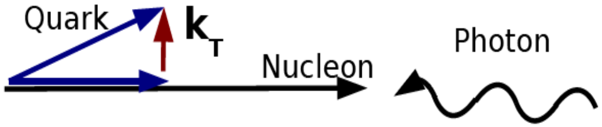
$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} =$$

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

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

$F_{UU}^{\mathbf{cos\phi}}$

mainly **Cahn** effect
kinematical effect due to the **quark transverse momentum**



$F_{UU}^{\mathbf{cos2\phi}}$

given by **Boer-Mulders** function, one of the most famous **TMD PDF**, convoluted with the **Collins FF**

recently increasing interest !

the **Boer-Mulders** function correlates the
quark transverse momentum and
the **quark spin**
in an **unpolarized nucleon**

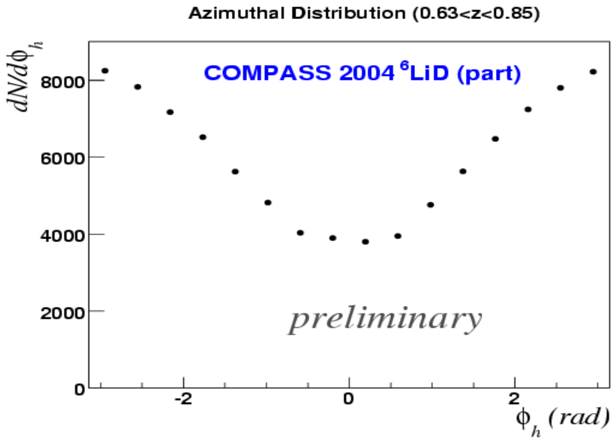
$F_{UU}^{\mathbf{sin\phi}}$

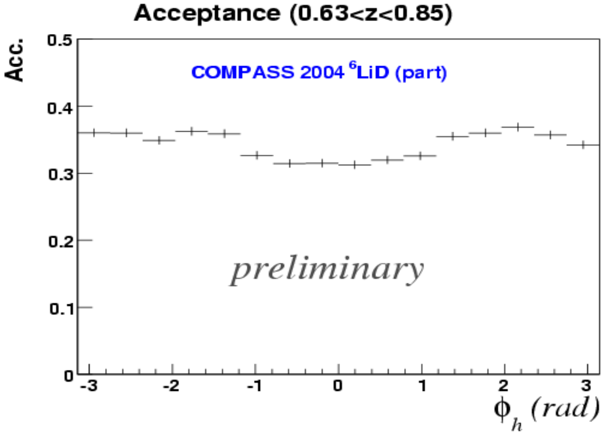
kinematical effect proportional to the beam polarization
(no clear interpretation in term of PM)

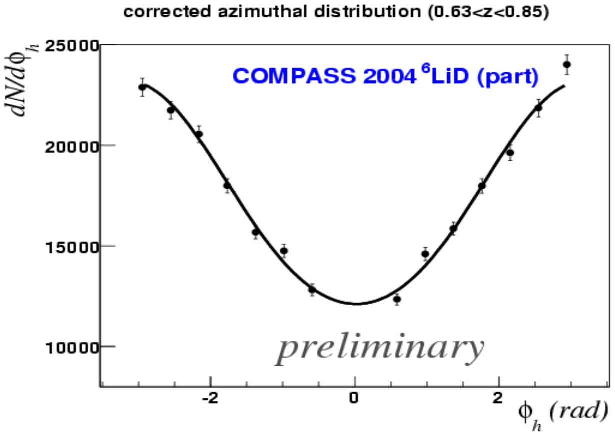
measurement done on deuteron target

data combined to cancel possible polarization dependent terms

To extract the asymmetries:
the azimuthal distributions have to be **corrected by the apparatus acceptance**
➔ **dedicated MC simulations** for L and T target polarization data







fit function

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

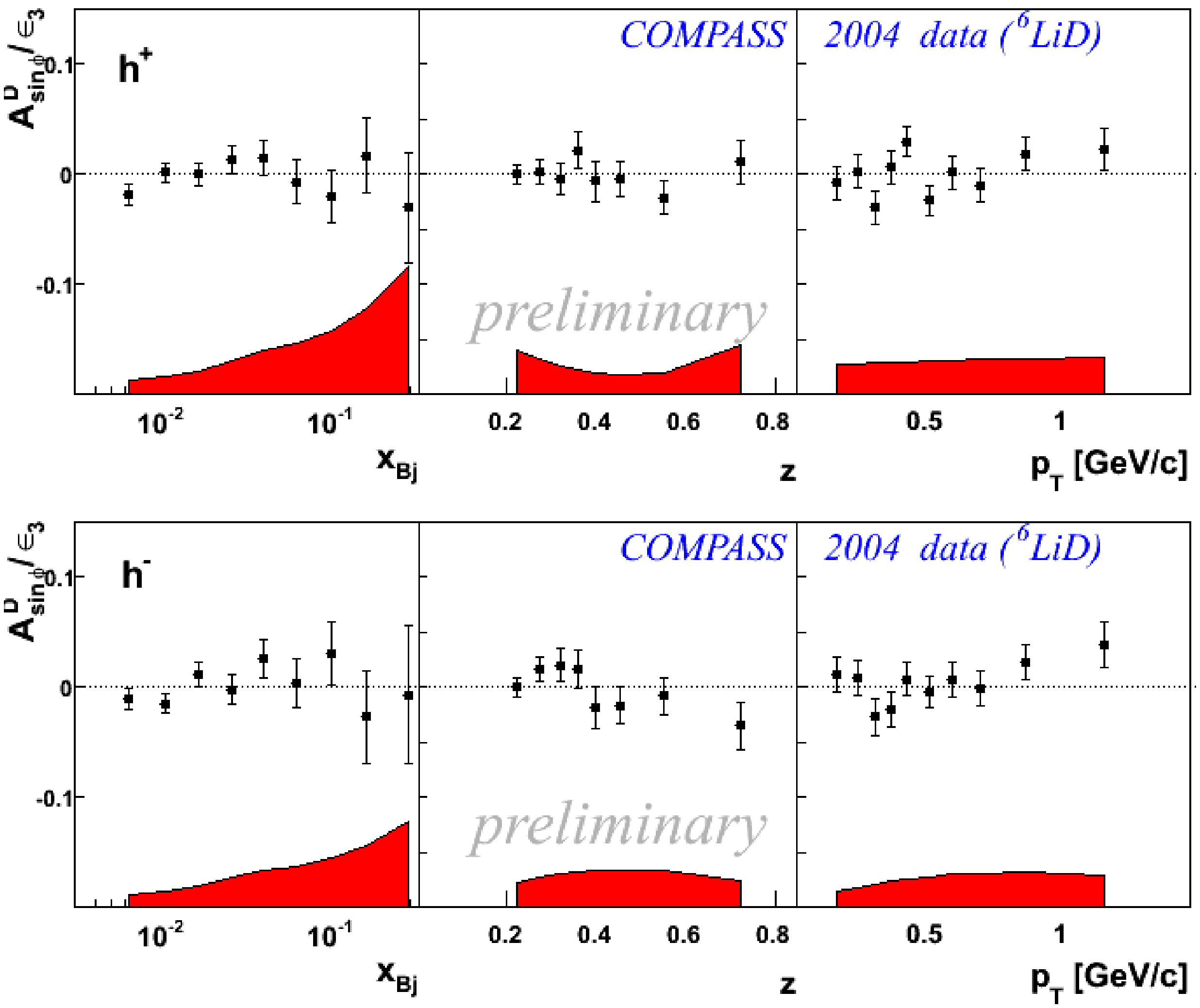
these asymmetries have been measured for the **first time** separately for **positive and negative hadrons**

Results

sinϕ: small amplitudes, compatible with zero

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

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



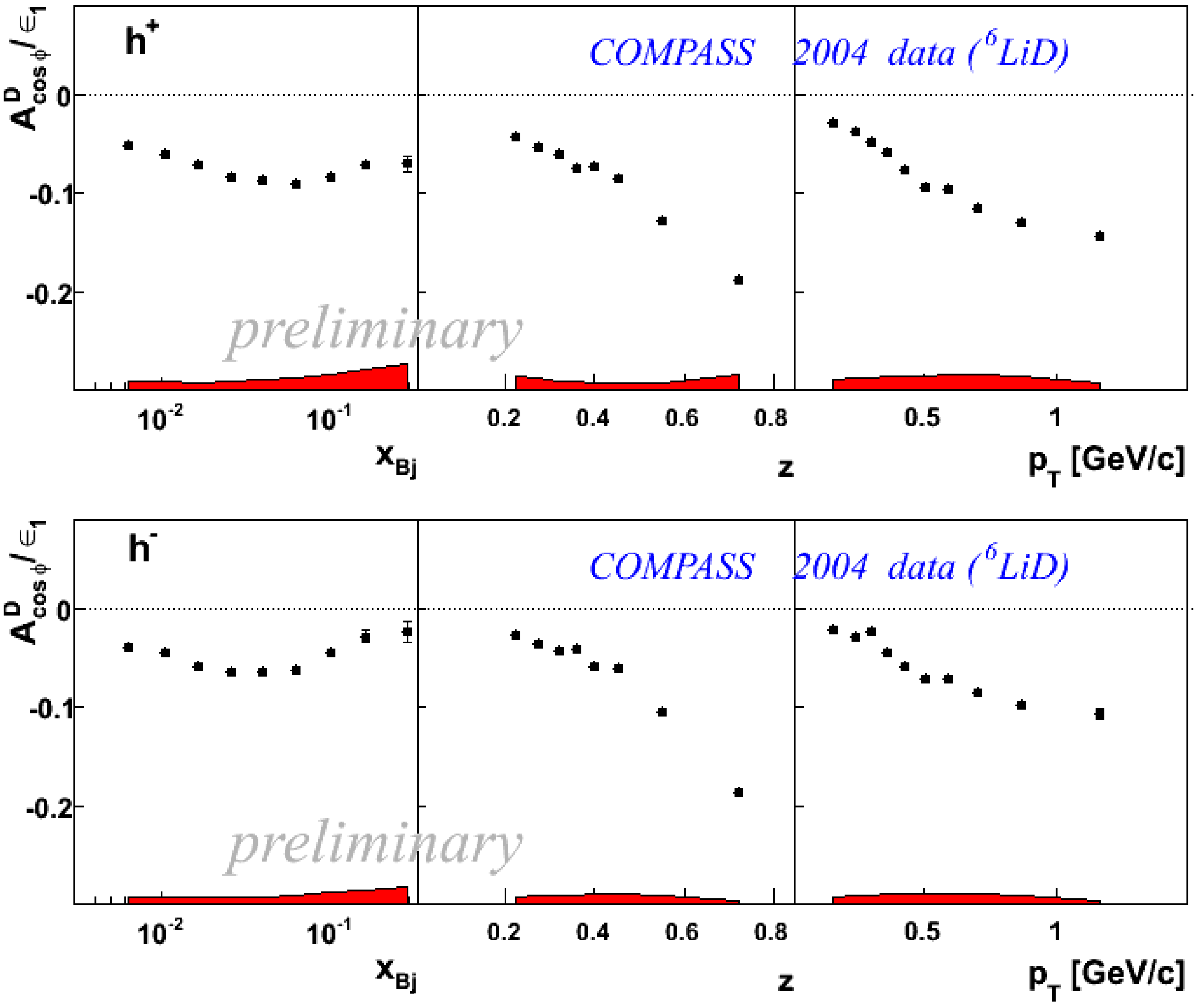
red bands are systematic errors

Results

cosϕ: strong signal both for positive and negative hadrons

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

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



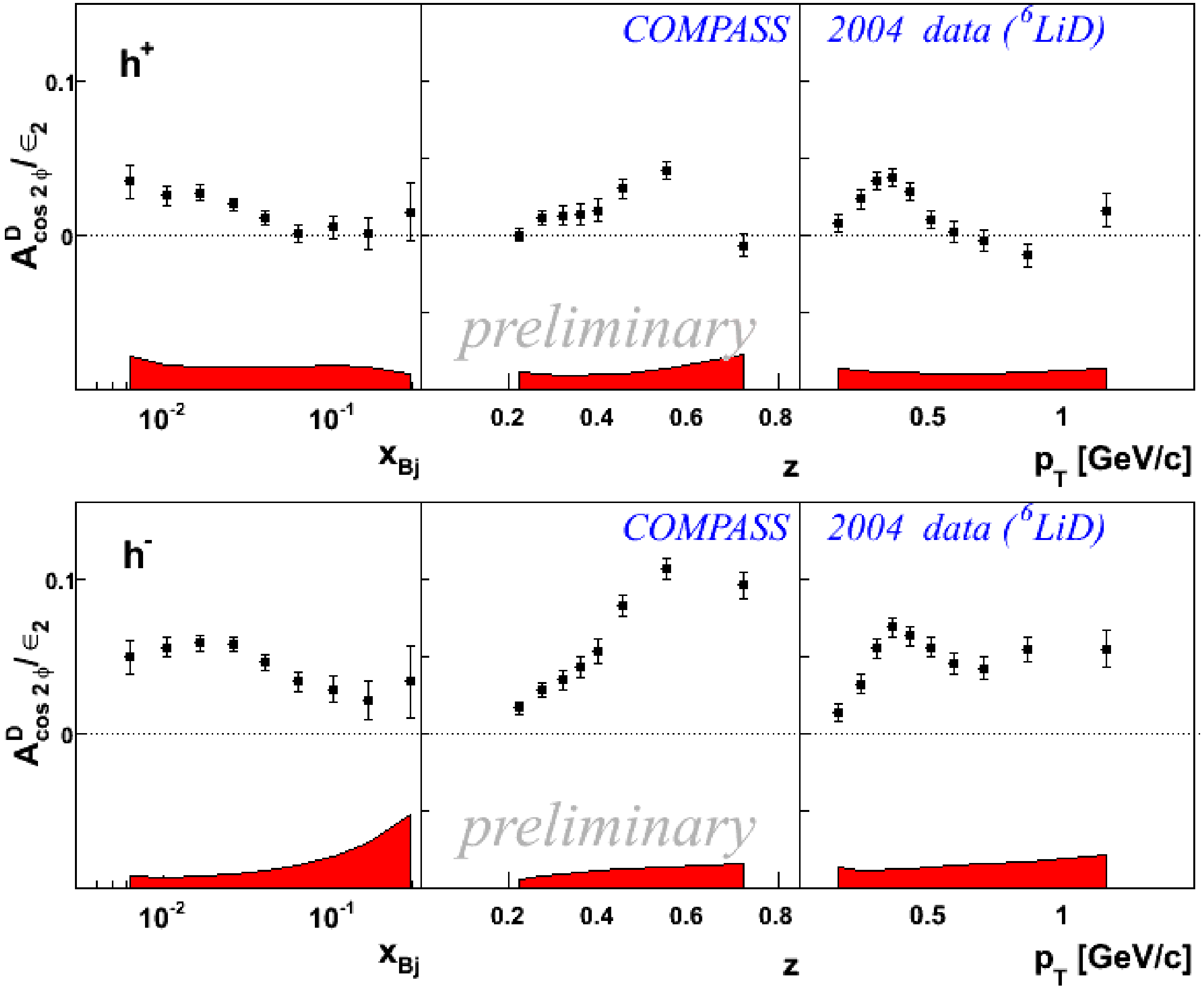
red bands are systematic errors

Results

cos2ϕ: different from zero and different for positive and negative hadrons

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

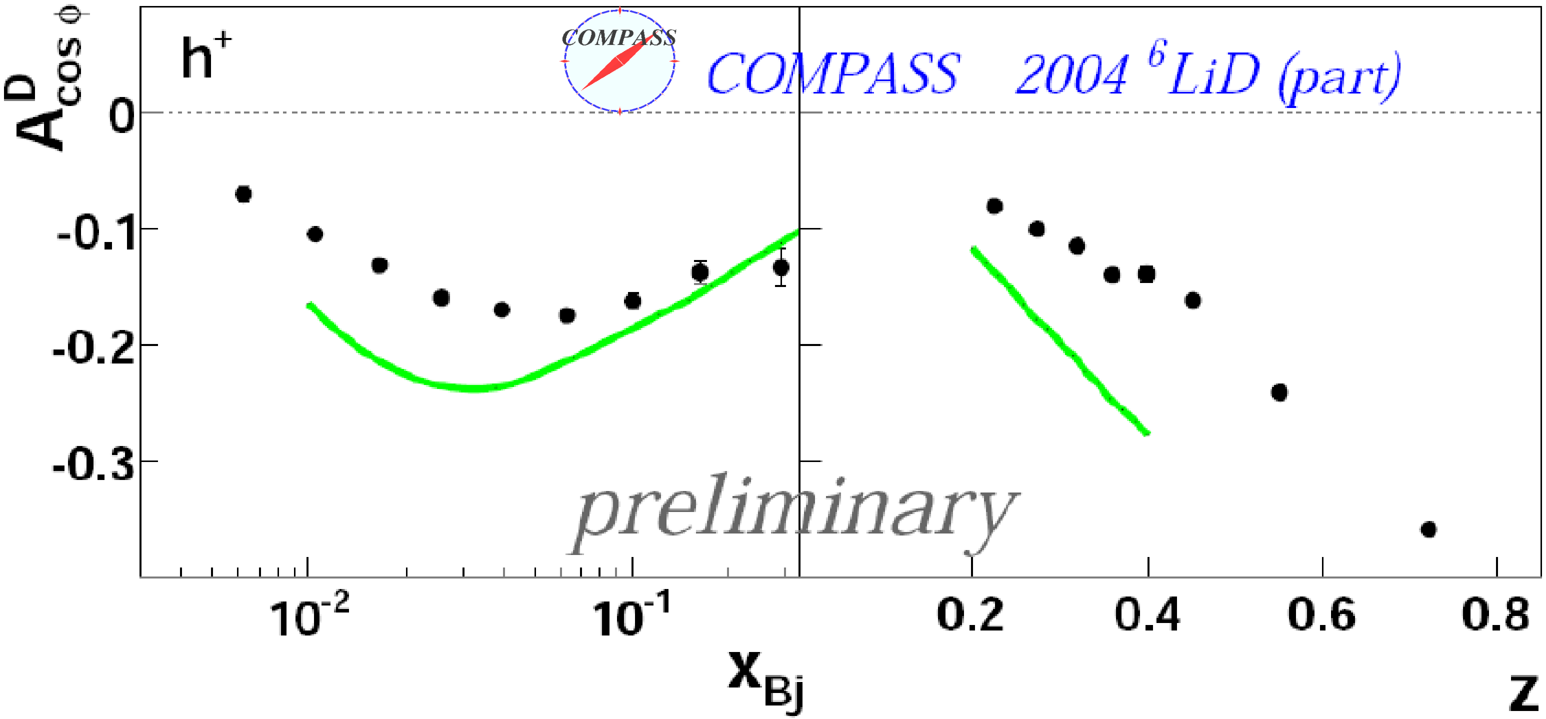
$$\varepsilon_2 = \frac{2(2-y)}{1+(1-y)^2}$$



red bands are systematic errors

Comparison with predictions

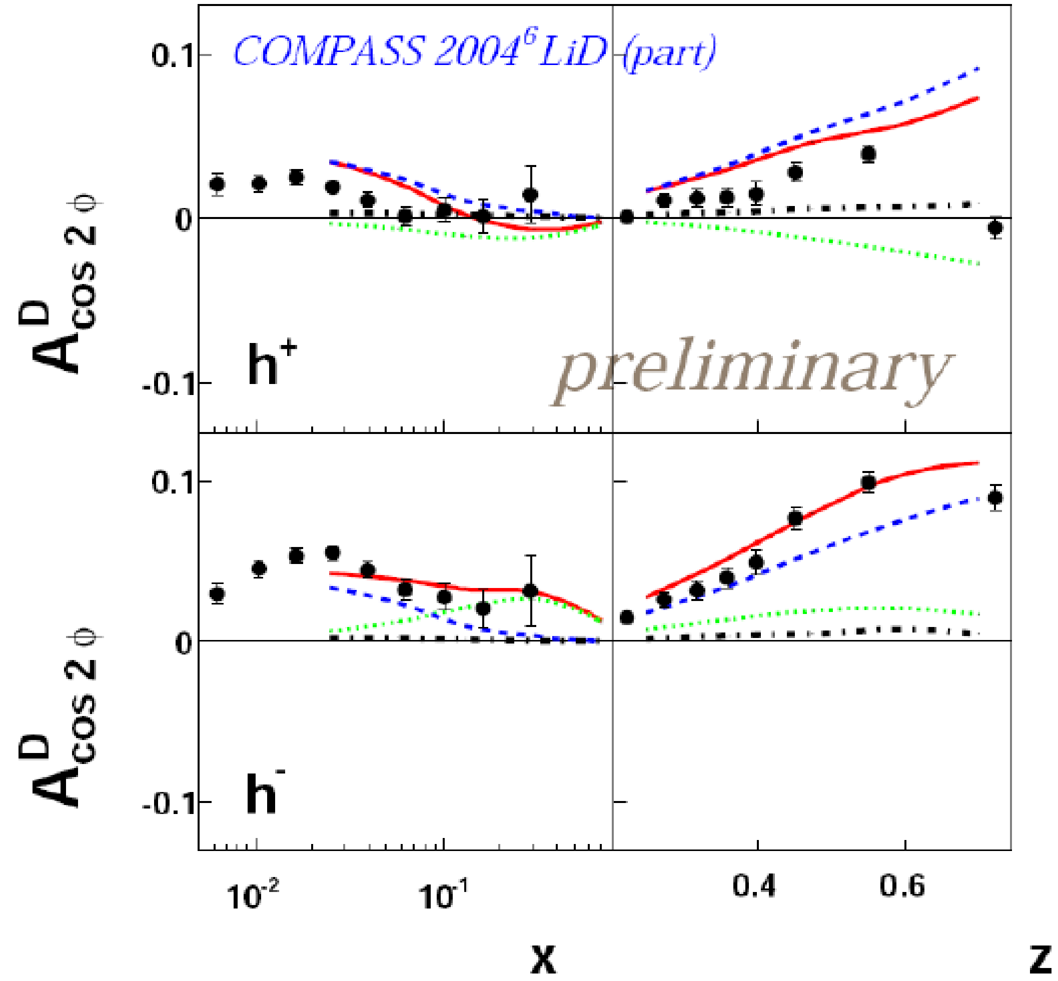
cosϕ



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

Comparison with predictions

cos2ϕ



V. Barone, A. Prokudin, B.Q. Ma
Phys.Rev. D78: 045022, 2008

- sum of all contributions
- Cahn effect
- Boer-Mulders
- QCD (first order)

8 azimuthal modulations can be measured in SIDIS on **transversely polarized target**

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

The most known are:

Sivers asymmetry

Collins asymmetry

Collins asymmetry is a very important measurement
it gives access to the:

Transversity PDF

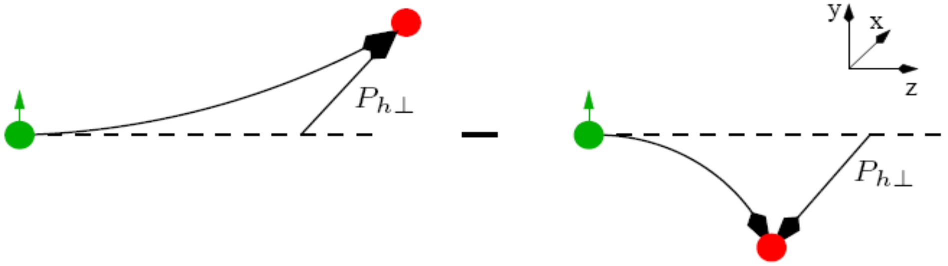
- which is one of the three PDF needed to **describe** the **spin structure of the nucleon** at **leading order** (with helicity PDF and unpolarized PDF)

- it gives the probability to find a **quark** with **spin parallel or anti-parallel to the nucleon's spin** in a **transversely polarized** nucleon

- it is **chiral odd** → can be measured only in **SIDIS** on transversely polarized target (convoluted with another chiral odd function)

Transversity ⊗ **Collins FF**

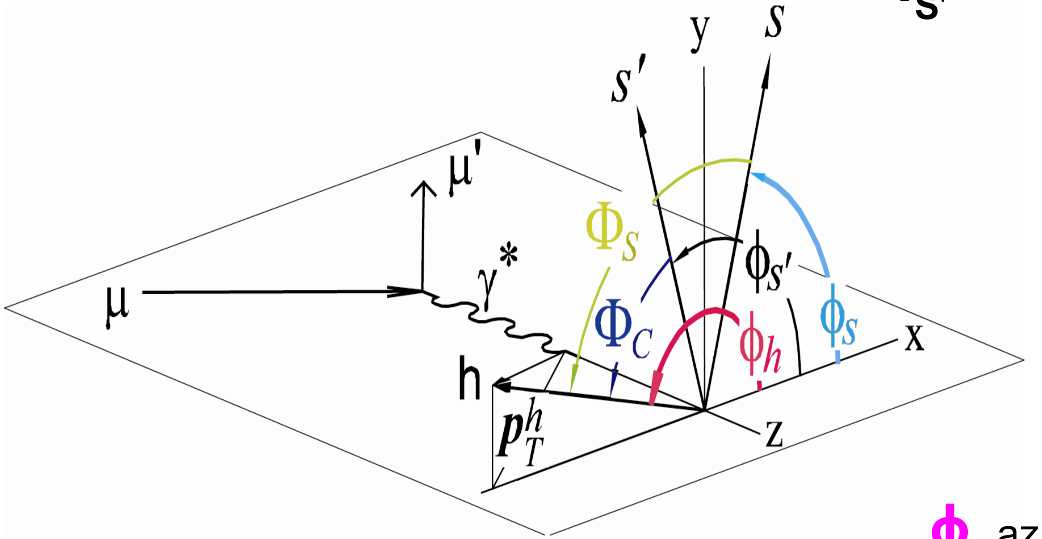
left right asymmetry in the fragmentation of the transversely polarized quark in an unpol. hadron



Collins asymmetry appears as a modulation in Φ_C

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

$$\phi_{S'} = \pi - \phi_S$$



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

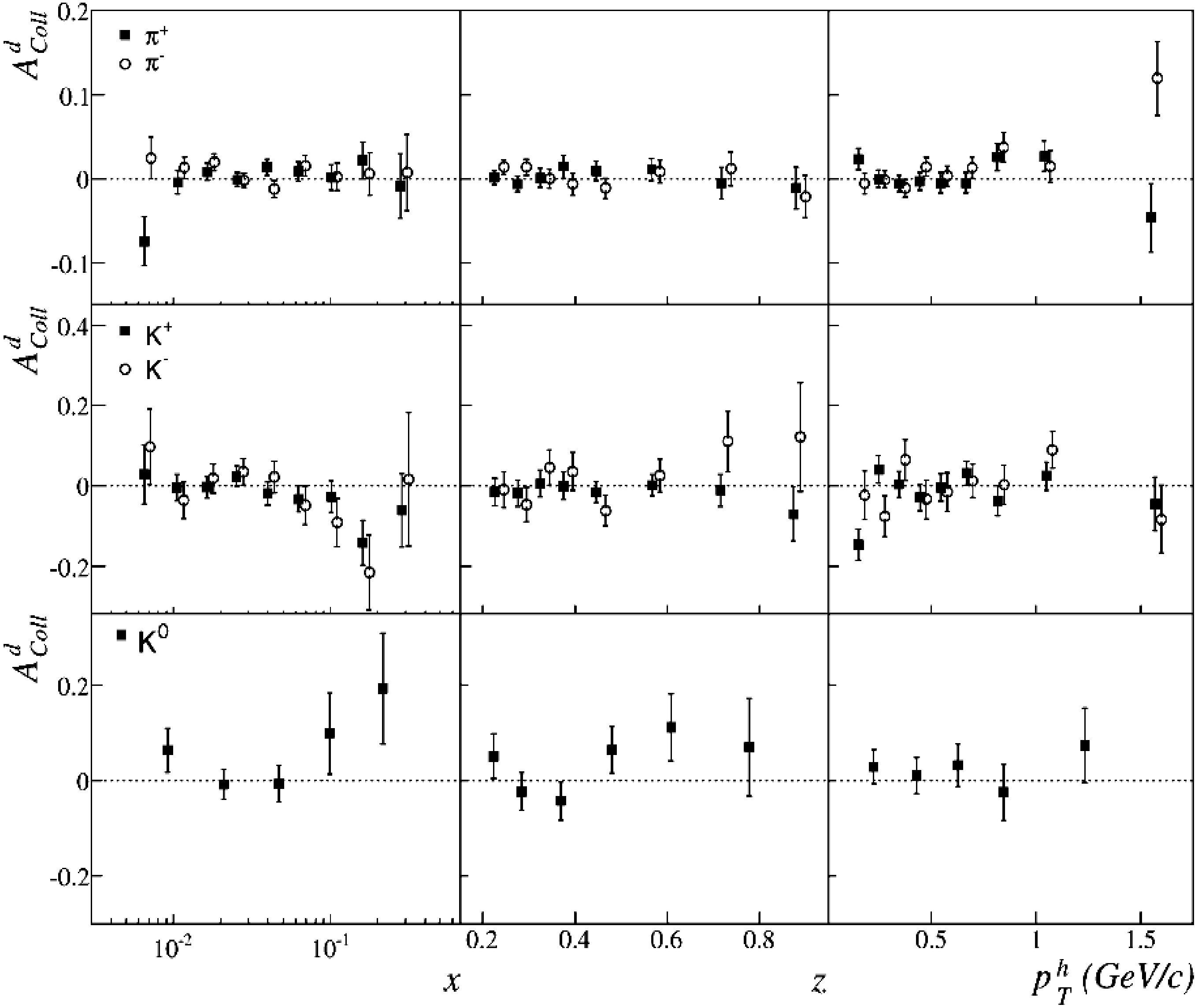
Collins angle

ϕ_h azimuthal angle of the **hadron momentum**

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

← “transversity” PDF ⊗ Collins FF

COMPASS measurement on
transversely polarized deuteron (2002-2004 data)



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

Values corrected for the purity; systematic error below 30% of the statistical one

Collins asymmetries on deuteron are compatible with zero

at variance with **HERMES** which measured a **signal** for both positive and negative hadrons on **transversely polarized proton**

- Naïve interpretation of the results (parton model, valence region)

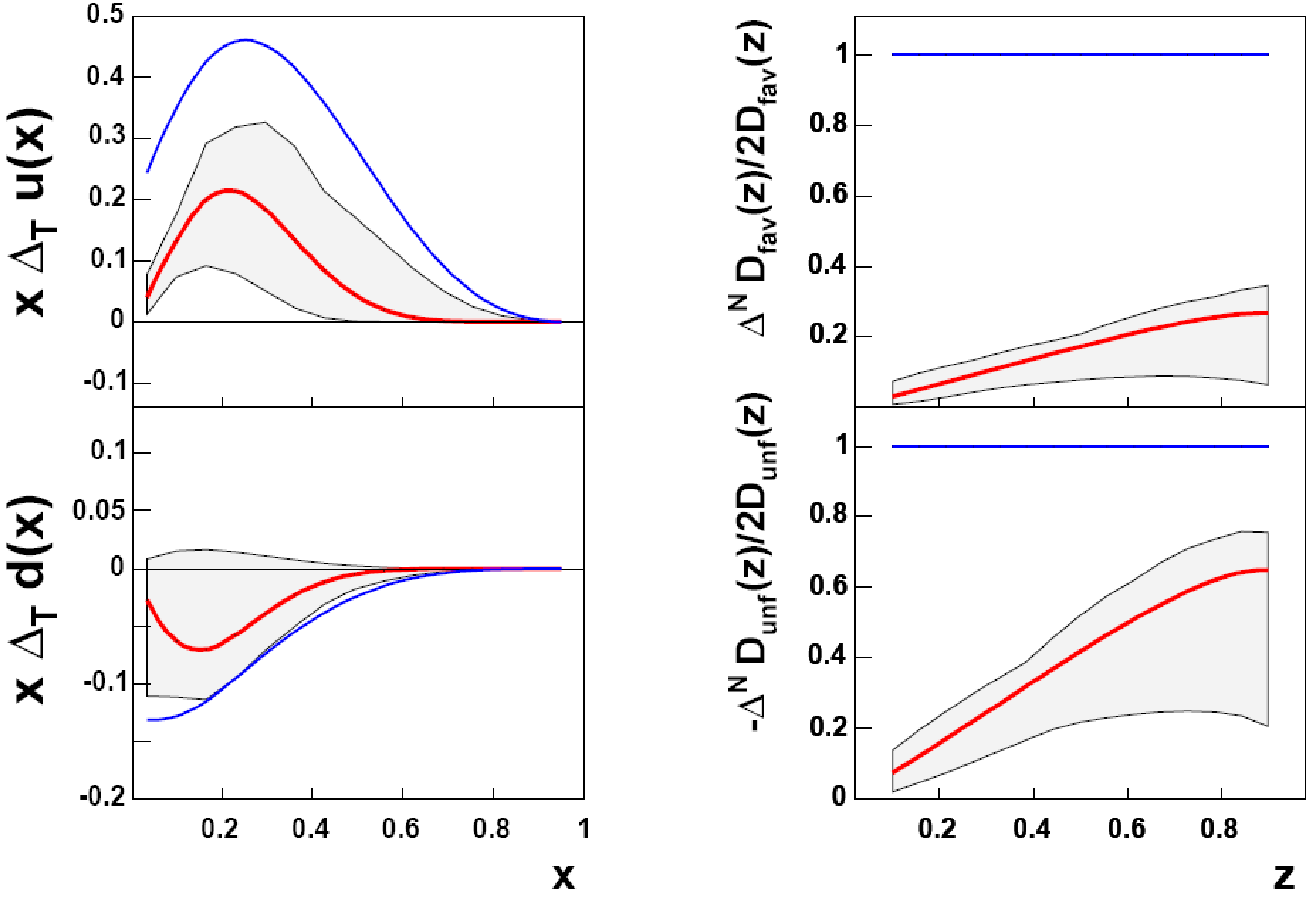
$$A_{Coll}^{d,\pi^+} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{4\Delta_T^0 D_1 + \Delta_T^0 D_2}{4D_1 + D_2} \qquad A_{Coll}^{d,\pi^-} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{\Delta_T^0 D_1 + 4\Delta_T^0 D_2}{D_1 + 4D_2}$$

Small asymmetries → $\mathbf{\Delta_T u\ (x) + \Delta_T d\ (x) \sim 0}$

measurements on deuteron (isoscalar target) important to access $\mathbf{\Delta_T d}$

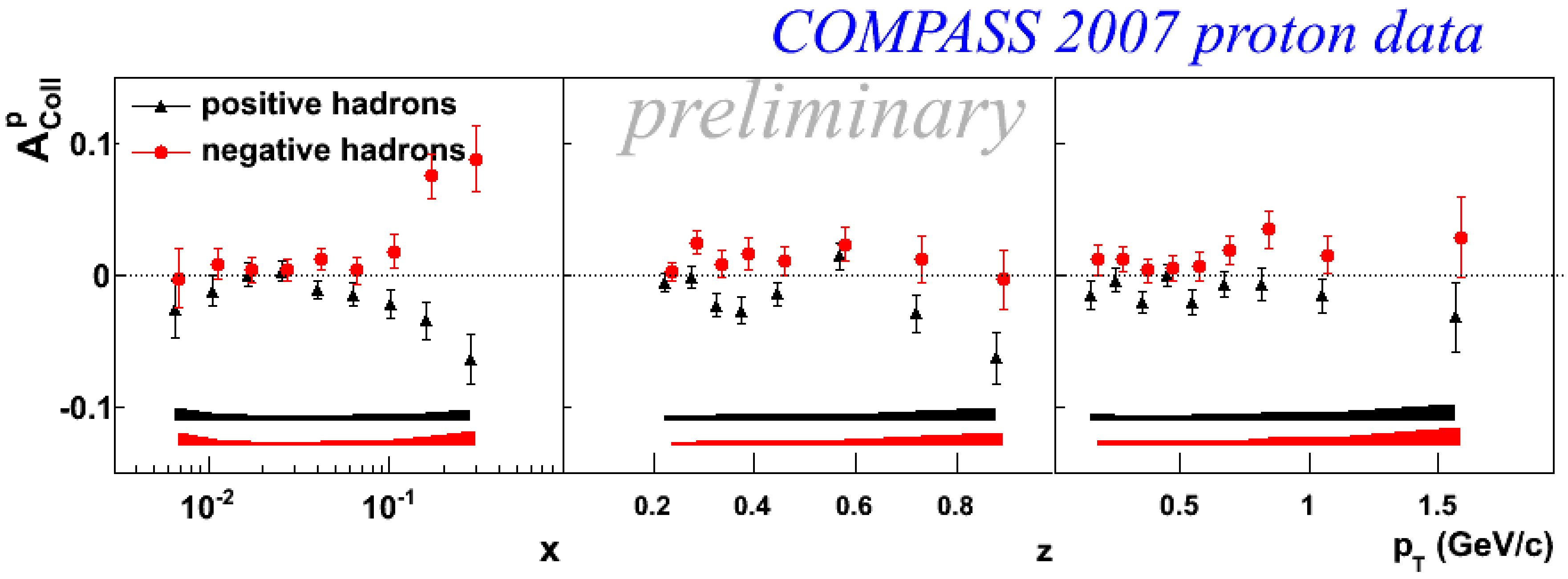
- data taken with deuteron (COMPASS), proton (HERMES) and $e^+ e^- \rightarrow$ hadrons (BELLE) global fit → consistent description

first extraction of the:
transversity PDF and the **Collins FF** for **u** and **d quarks**



Anselmino et al. Phys.Rev. D75 (2007) 054032

COMPASS Collins asymmetry on transversely polarized proton (DIS09)

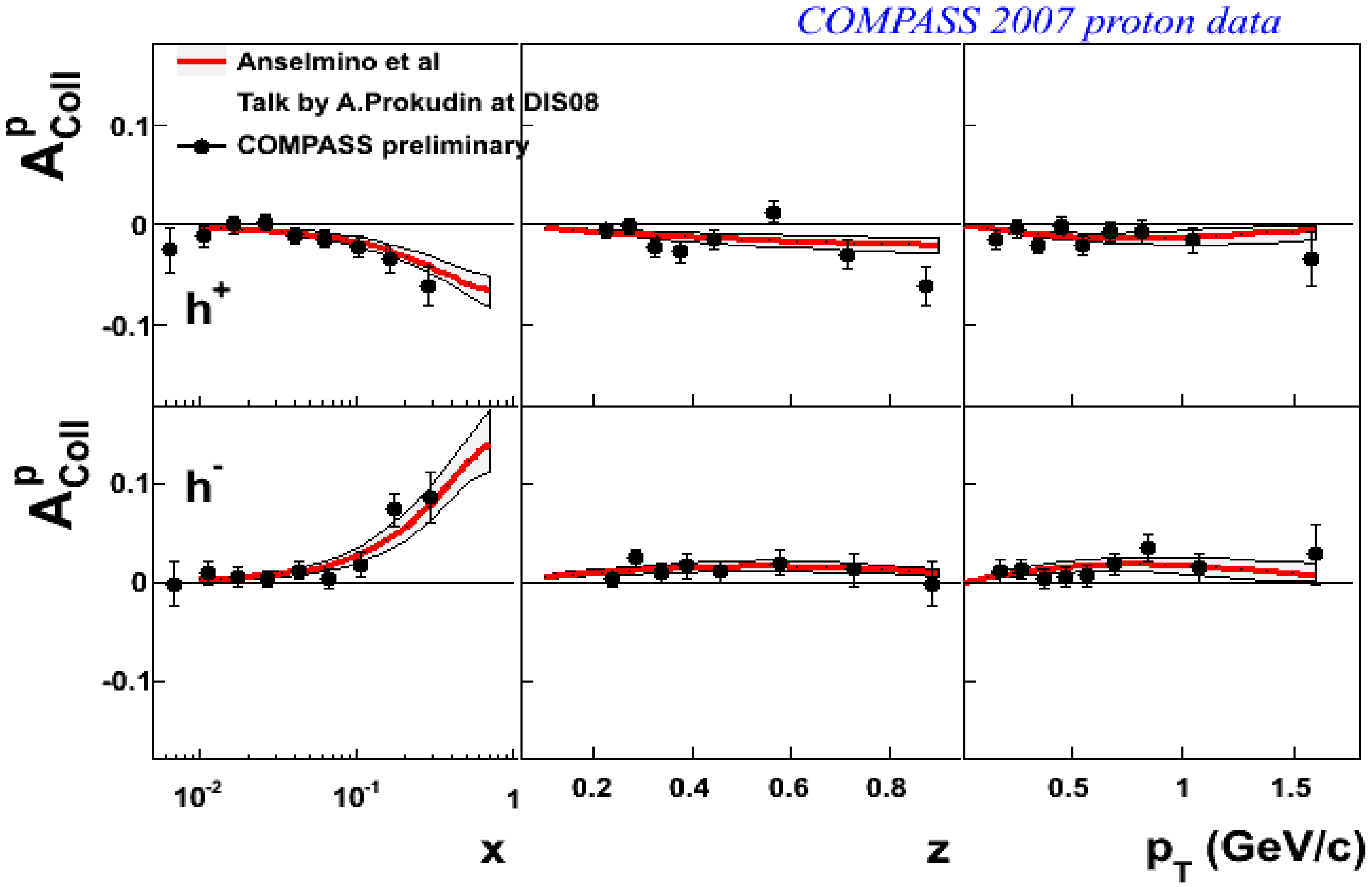


bands are systematic errors

The effect is still there at higher Q^2 (w.r.t. HERMES)

at small x, the asymmetries are compatible with zero
in the valence region the asymmetries are different from zero,
of opposite sign for positive and negative hadrons,
and have the same strength and sign as HERMES

COMPASS measurements on proton confirm present picture and are **consistent with prediction** (from global fit)



last prediction from Anselmino group

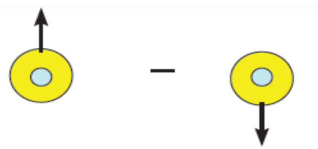
$$
\begin{aligned}
&\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \\
&\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Bigg\{F_{UU,T}+\varepsilon\,F_{UU,L}+\sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} \\
&\quad+\varepsilon\cos(2\phi_h)\,F_{UU}^{\cos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

Sivers asymmetry

Collins asymmetry

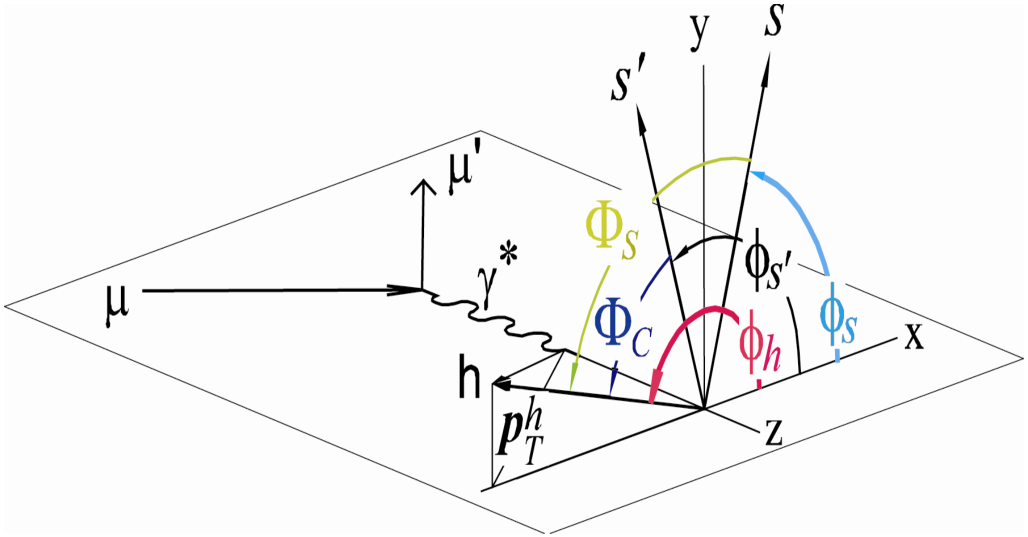
- The **Sivers** function is one of the most studied **TMD** parton distribution functions

- correlates the **quark transverse momentum** and the **nucleon spin** in a transversely polarized nucleon



- it is related to **angular orbital momentum** of the quark in a transversely polarized nucleon

Sivers asymmetry appears as a **modulation** in Φ_S



ϕ_h azimuthal angle of the **hadron momentum**

ϕ_S azimuthal angle of the **nucleon spin**

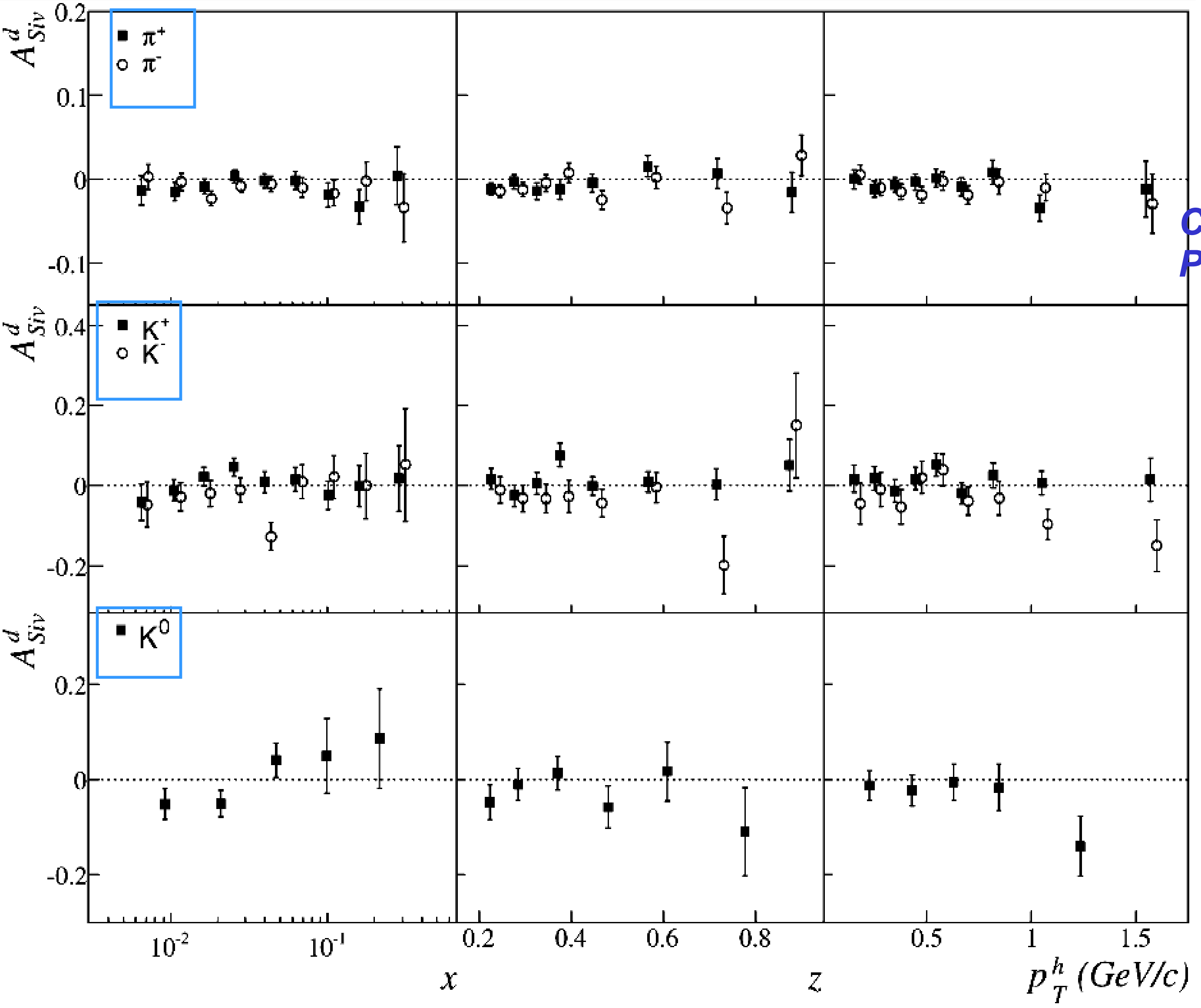
$$\Phi_S = \phi_h - \phi_S$$

Sivers angle ► **measured azimuthal modulation**

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

Sivers TMD PDF ⊗ Unpolarized FF

COMPASS measurement on **transversely polarized deuteron** (2002-2004 data)



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

Values corrected for the purity;
systematic error below
30% of the statistical one

COMPASS mesurements on polarized deuteron
small Sivers asymmetries compatible with zero

global fit together with *HERMES data on proton*
extraction of Sivers function

asymmetries ≠ 0 for π+

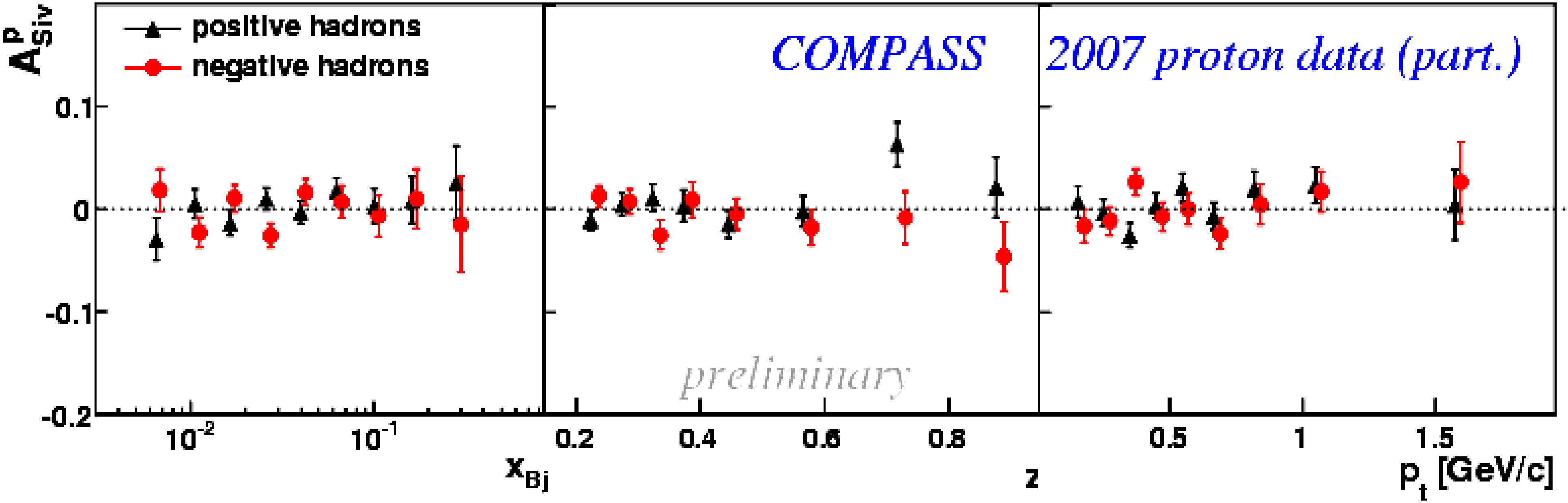
naïve interpretation (parton model, valence region)

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

small asymmetries suggest

$$\boxed{\Delta_0^T d_v \simeq -\Delta_0^T u_v}$$

COMPASS Sivers asymmetry:
measurement on **transversely polarized proton** (DIS09)

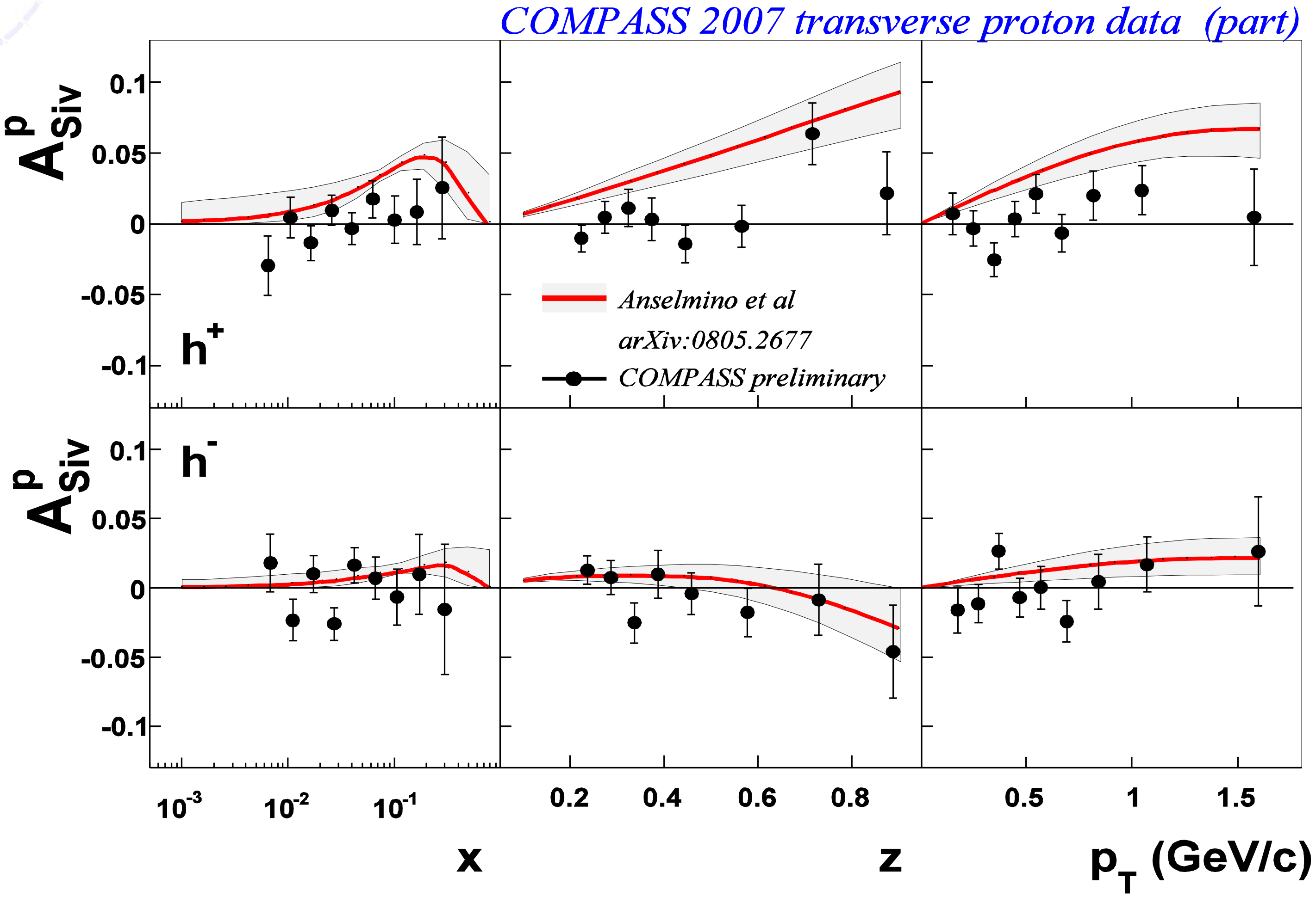


systematic errors ~ 0.5 σ stat

the measured asymmetries are small, compatible with zero

intriguing results , not easy to explain in the present theoretical picture

COMPASS Sivers asymmetries on proton: comparison with prediction from Anselmino et al.



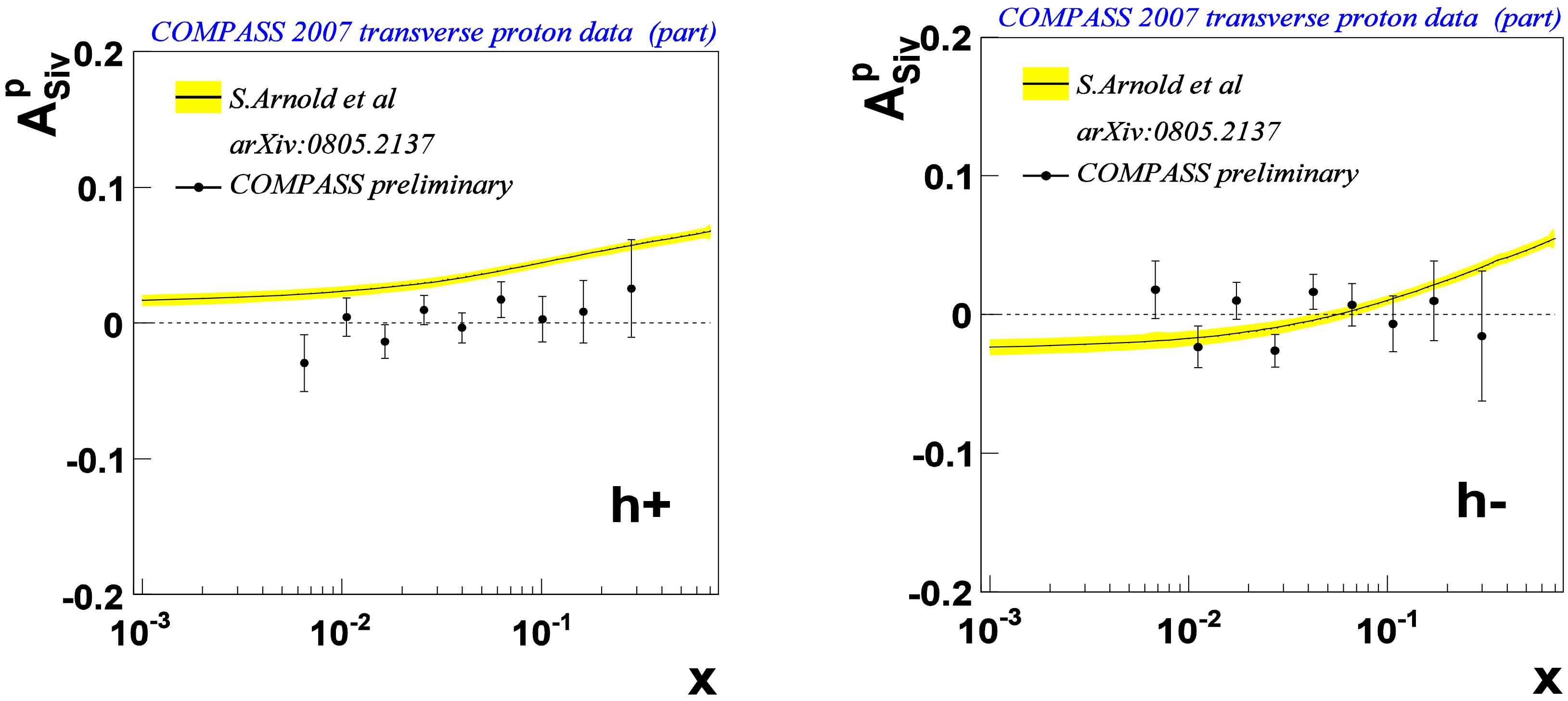
marginal agreement between data and predictions

more precise high energy data urgently needed

COMPASS Sivers asymmetries on proton: comparison with prediction from

based on Quark Soliton Model

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



marginal agreement between data and predictions

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

From **A. Bacchetta** et al.,
JHEP 0702:093,2007.

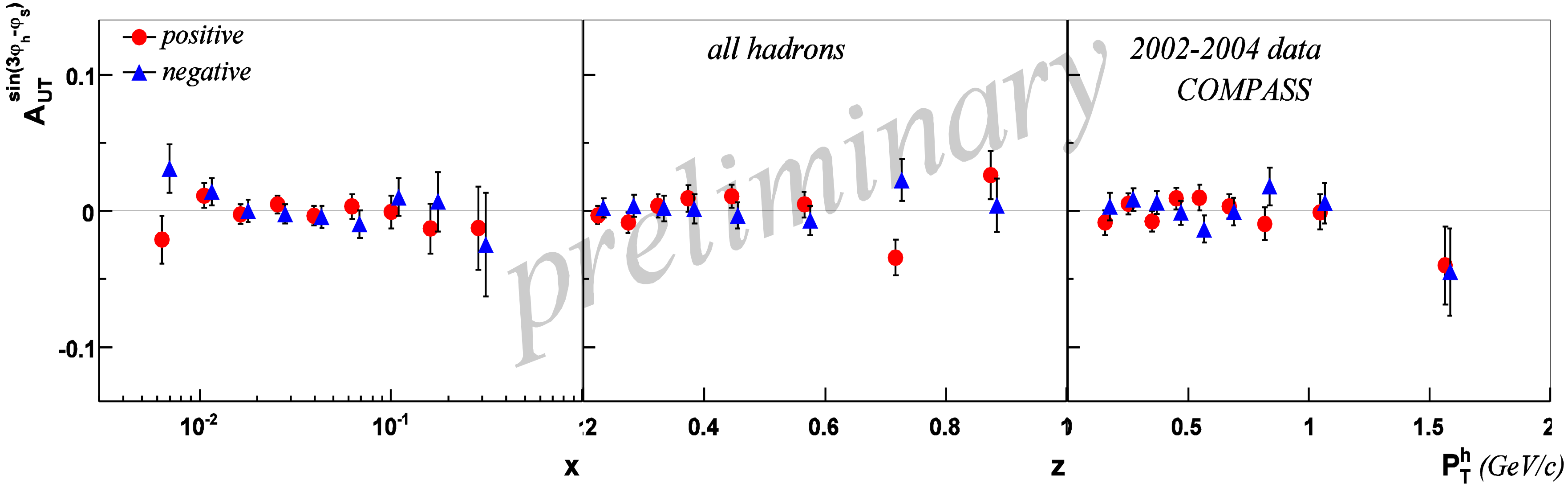
other **6 single spin asymmetries**
on a transversely polarized target,
all measured by **COMPASS** on **deuteron**
and **found to be compatible with zero**

$F_{UT}^{\sin(3\phi h - \phi S)}$

given by the so called “pretzelosity” PDF

correlates the **quark transverse momentum** and the **quark spin** in a transversely polarized nucleon

$A_{UT}^{\sin(3\phi_h - \phi_S)}$



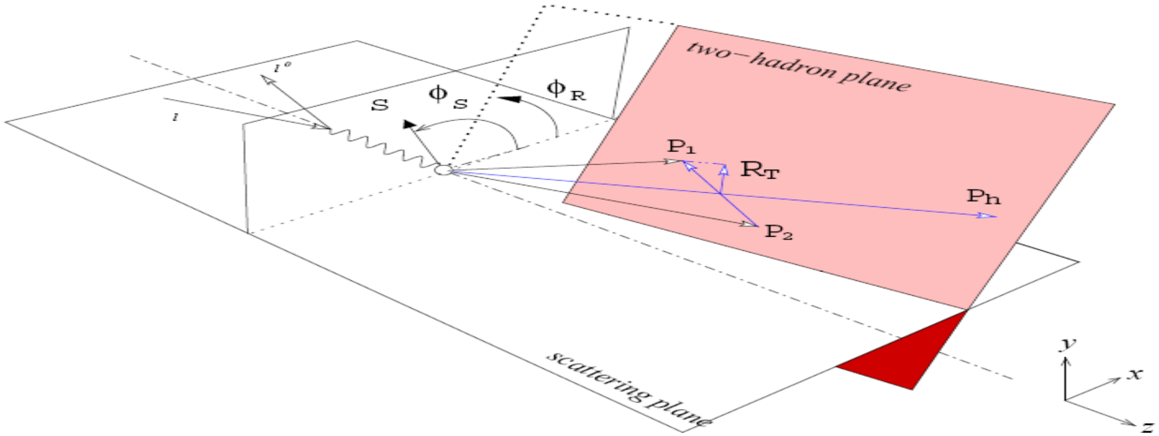
OUTLINE

- The COMPASS experiment
- SIDIS
- Hadron azimuthal asymmetries
  - unpolarized target
  - transversely polarized target
- **Two hadrons azimuthal asymmetries**
- Conclusions and outlook

2 h asymmetries

Transversity can be also accessed in inclusive production of hadron pairs by measuring an **azimuthal asymmetries** in the angle: $\Phi_{RS} = \phi_{R_T} - \phi_{S'}$

is the angle of $\mathbf{R_T}$ w.r.t the gamma



$$R_T = \frac{z_2 P_1 - z_1 P_2}{z_1 + z_2}$$

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

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

transversity distribution function **interference fragmentation** function

COMPASS measured small asymmetries (compatible with zero) on deuteron

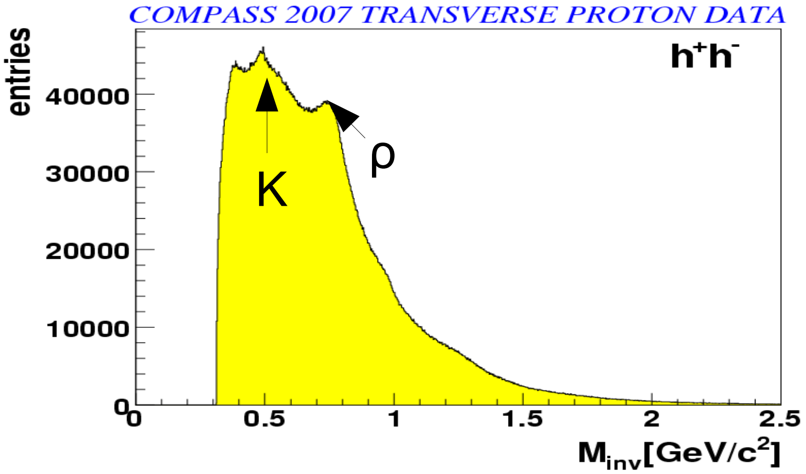
2 hadrons COMPASS asymmetry on transversely polarized proton

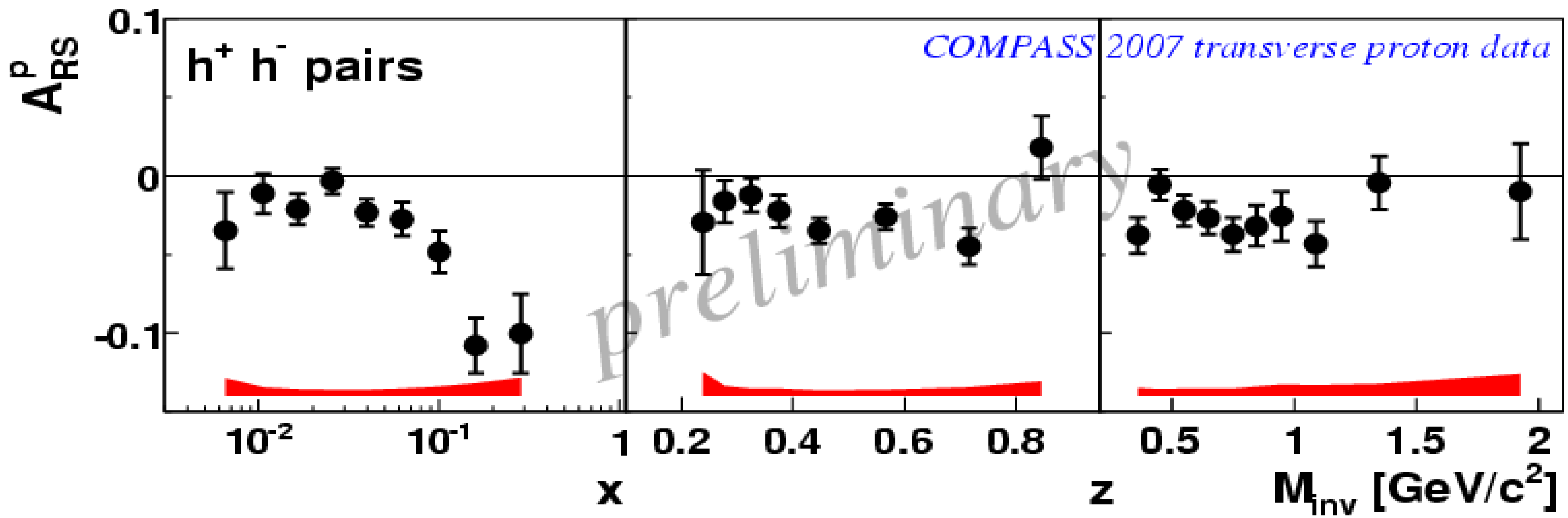
$x_F > 0.1$

$z_1 , z_2 > 0.1$

$Z = z_1 + z_2 < 0.9$

$R_T > 0.07$ GeV/c

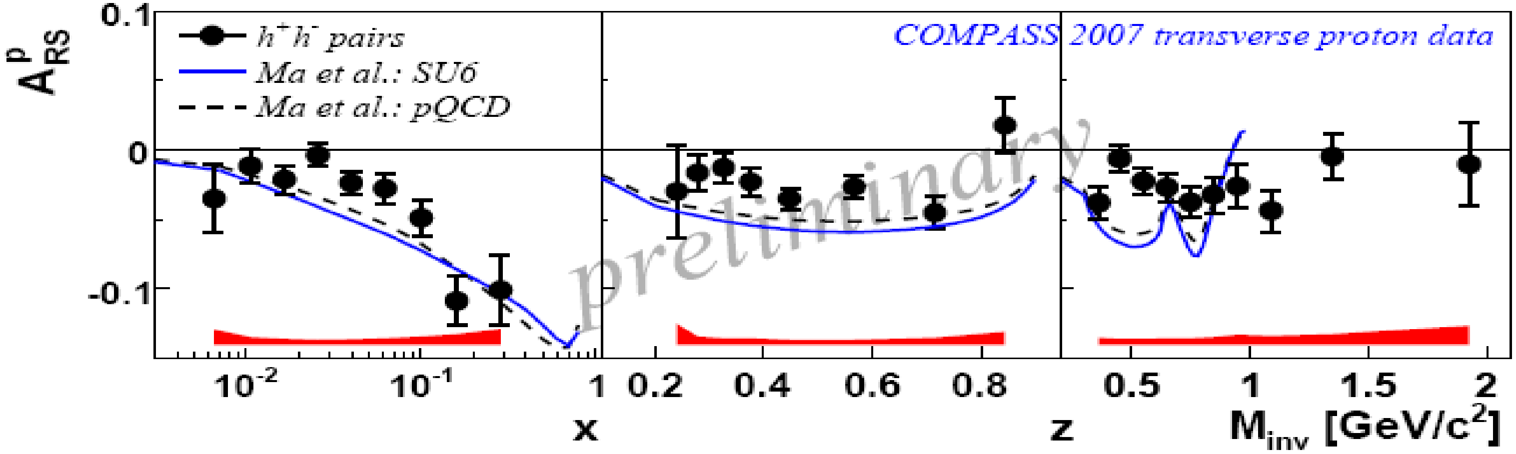




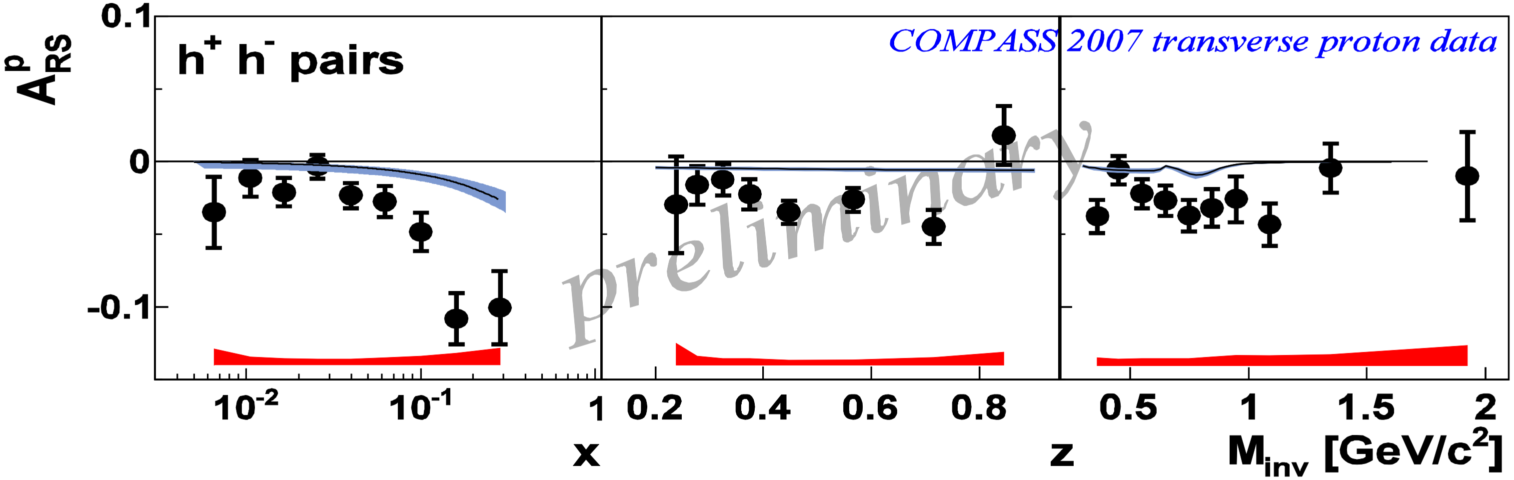
in the valence region the asymmetries are different from zero and the signal is larger than for the Collins asymmetry

2 hadrons : comparison with predictions

Ma et al. private communication



Bacchetta et al. private communication



Conclusions and outlook

- many interesting results on **transverse momentum** and **transverse spin** from **COMPASS** data both on on **deuteron** and **proton** polarized target

  → flavour separation

- **near future**

  - new results on unpolarized azimuthal asymmetries on deuteron (final results)
  - Collins and Sivers asymmetries on identified hadrons
  - 2 hadrons asymmetries on identified hadrons

on proton {

Conclusions and outlook

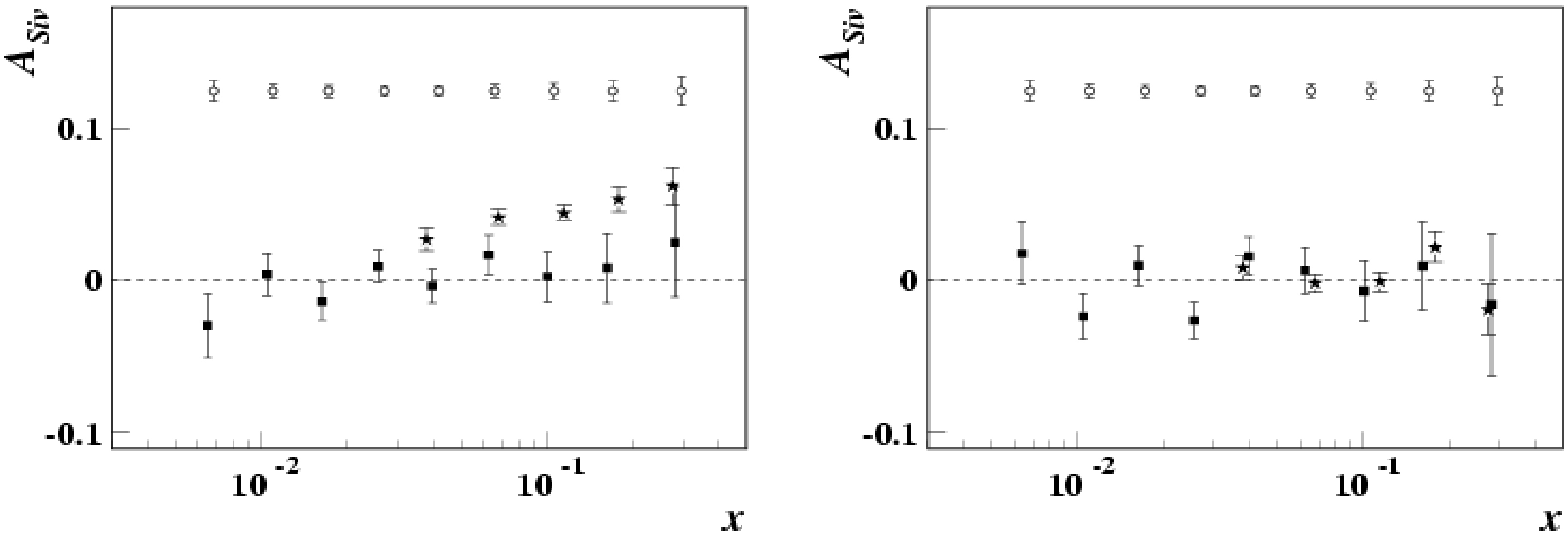
- Next year

• Data taking with transversely polarized proton foreseen
$\rightarrow$ new precise results

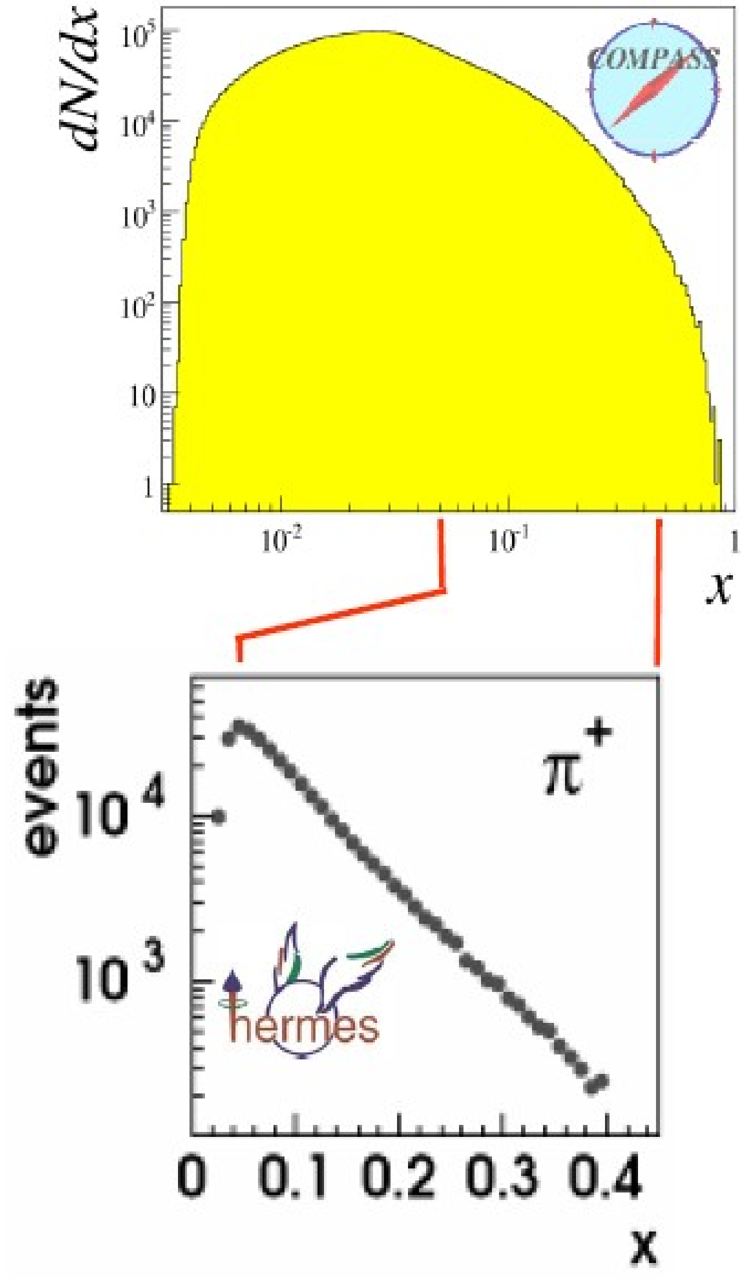
☐ compass 2010 projected errors

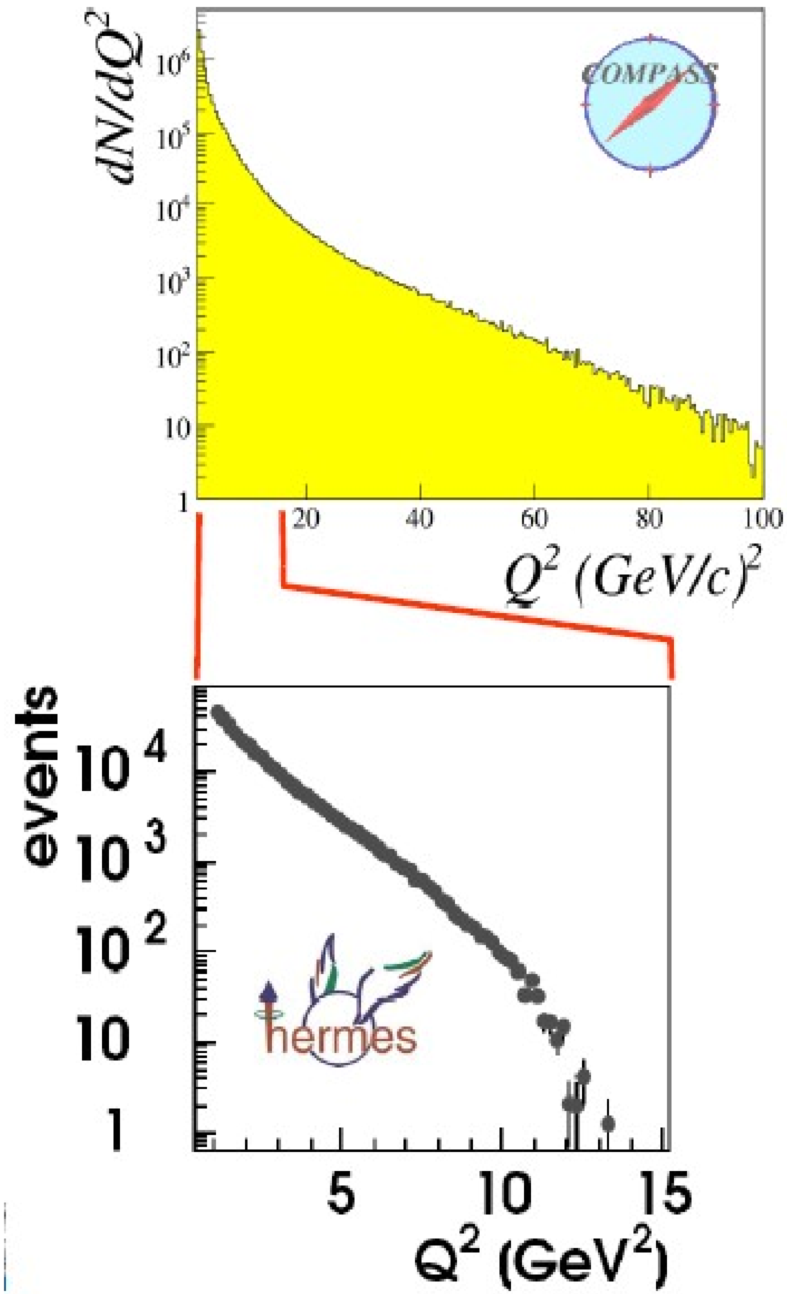
● compass 2007

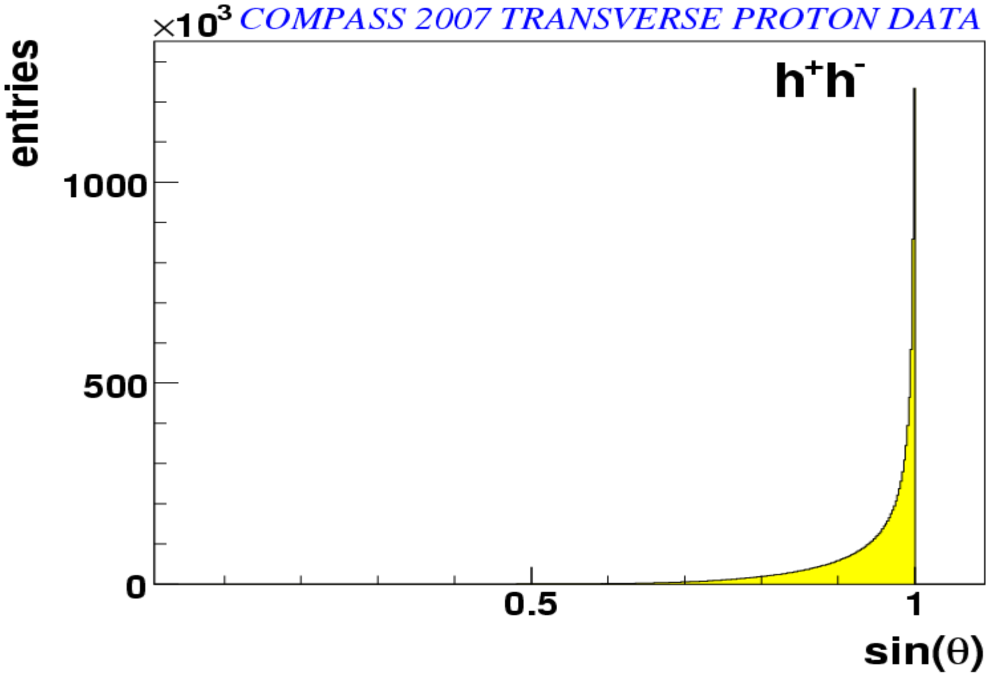
★ hermes

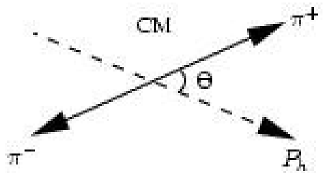


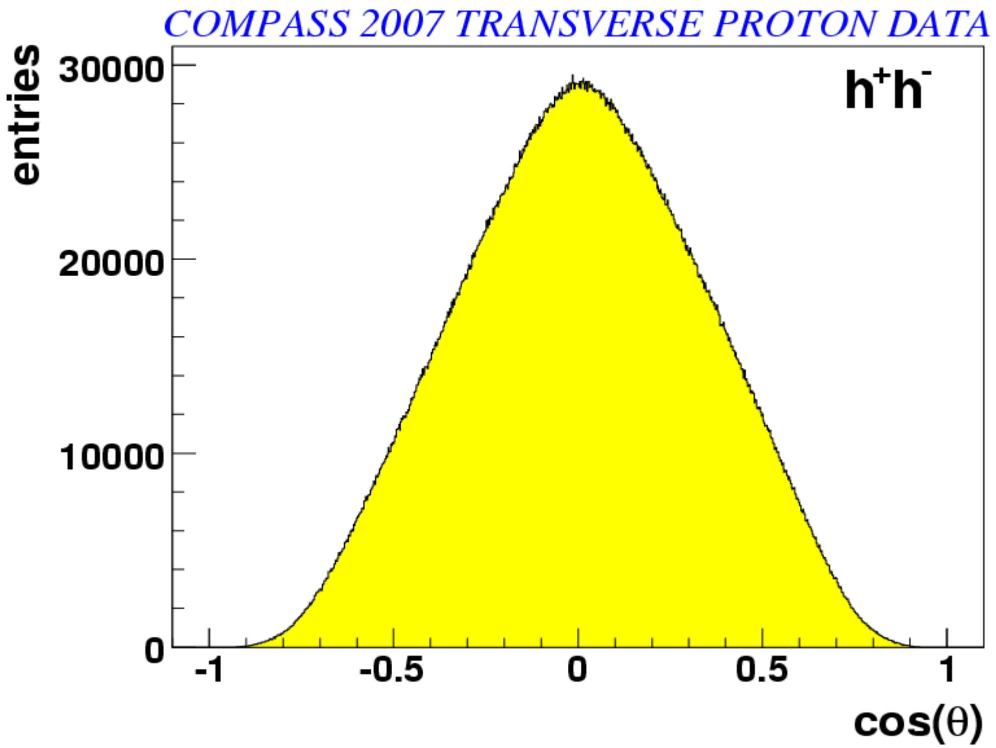
BACKUP


dN/dx
10^5
10^4
10^3
10^2
10
1
10^{-2}
10^{-1}
1
x
COMPASS
events
10^4
10^3
π^+
hermes
0
0.1
0.2
0.3
0.4
x


dN/dQ^2
10^6
10^5
10^4
10^3
10^2
10
1
20
40
60
80
100
Q^2 $(GeV/c)^2$
COMPASS
events
10^4
10^3
10^2
10
1
5
10
15
Q^2 (GeV^2)
hermes

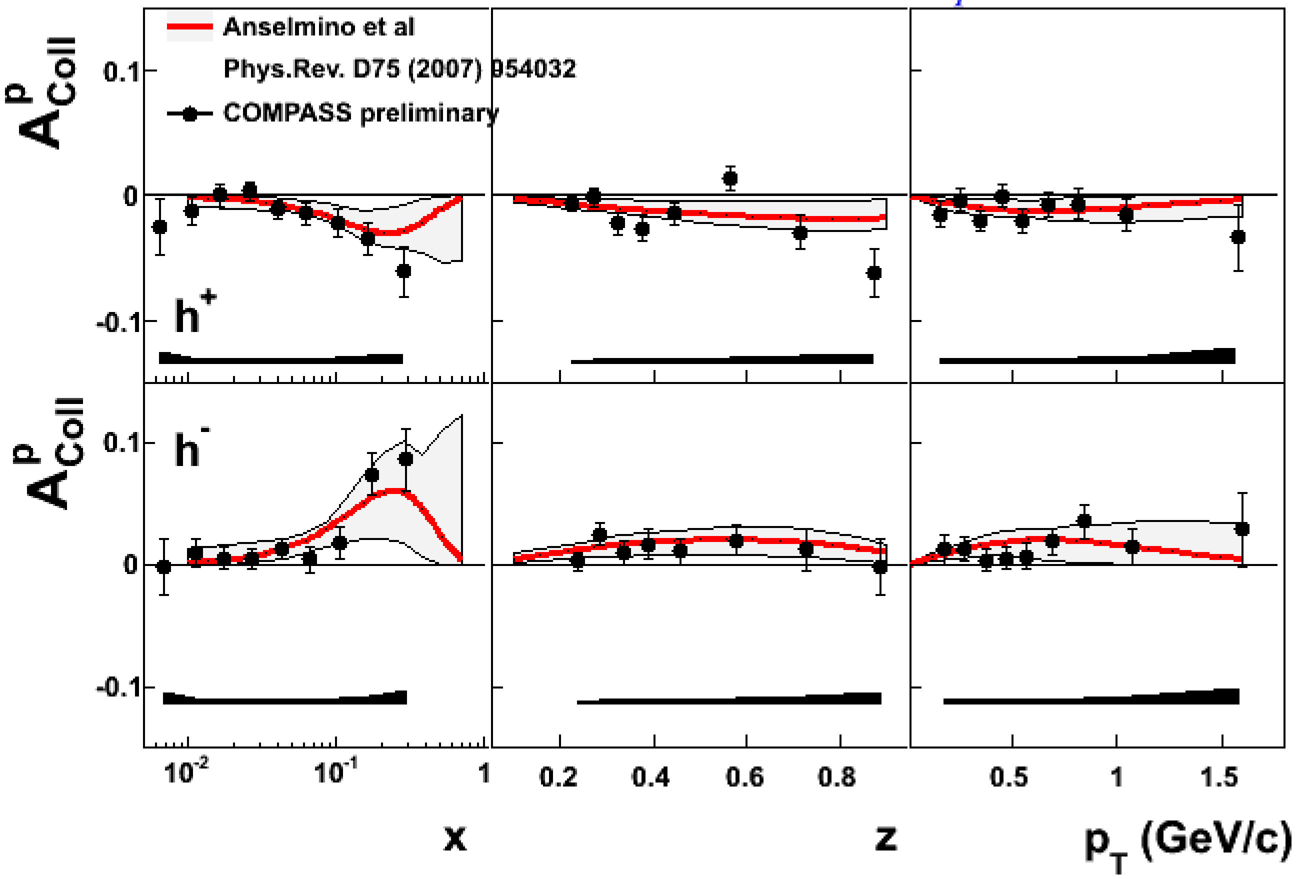

×10^3 COMPASS 2007 TRANSVERSE PROTON DATA
entries
h+h-
1000
500
0
0.5
1
sin(θ)


CM
π+
θ
π−
P_h


COMPASS 2007 TRANSVERSE PROTON DATA
entries
h+h-
30000
20000
10000
0
-1
-0.5
0
0.5
1
cos(θ)

prediction by Anselmino group in Phys. Rev. D

COMPASS 2007 proton data



Anselmino et al. Phys.Rev. D75 (2007) 054032