Transverse target spin asymmetries on a proton target at COMPASS

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Transverse Spin Physics

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

$q(x) = q_+(x) + q_-(x)$ **well known**

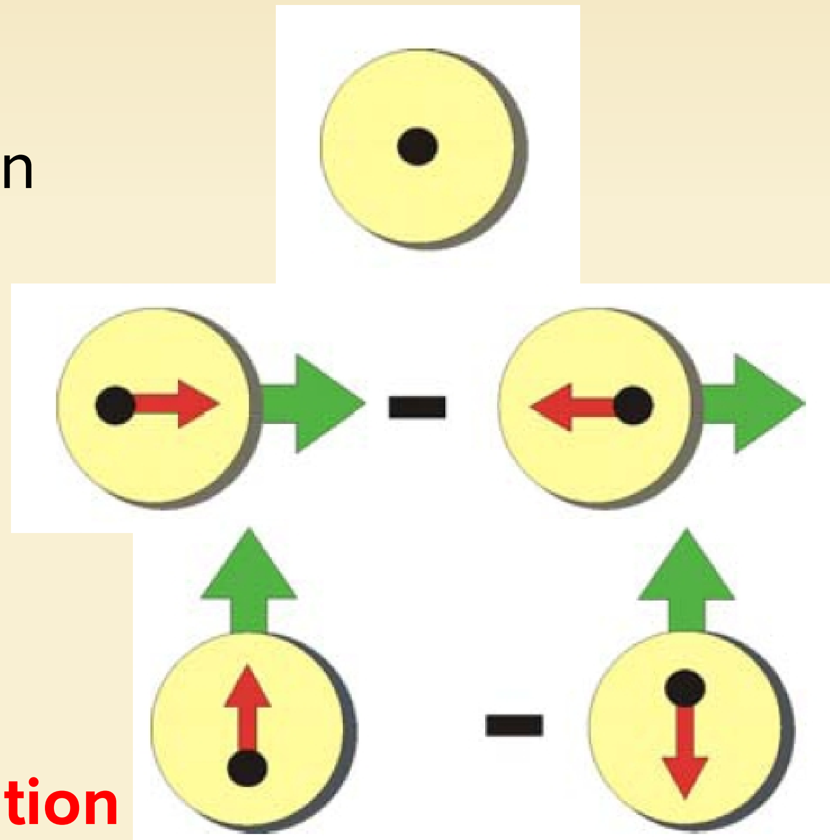
momentum distribution

$\Delta q(x) = q_+(x) - q_-(x)$ **known**

helicity distribution

$\Delta_T q(x) = q_\uparrow(x) - q_\downarrow(x)$ **little known**

transversity distribution



Transverse Spin Physics in SIDIS

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

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

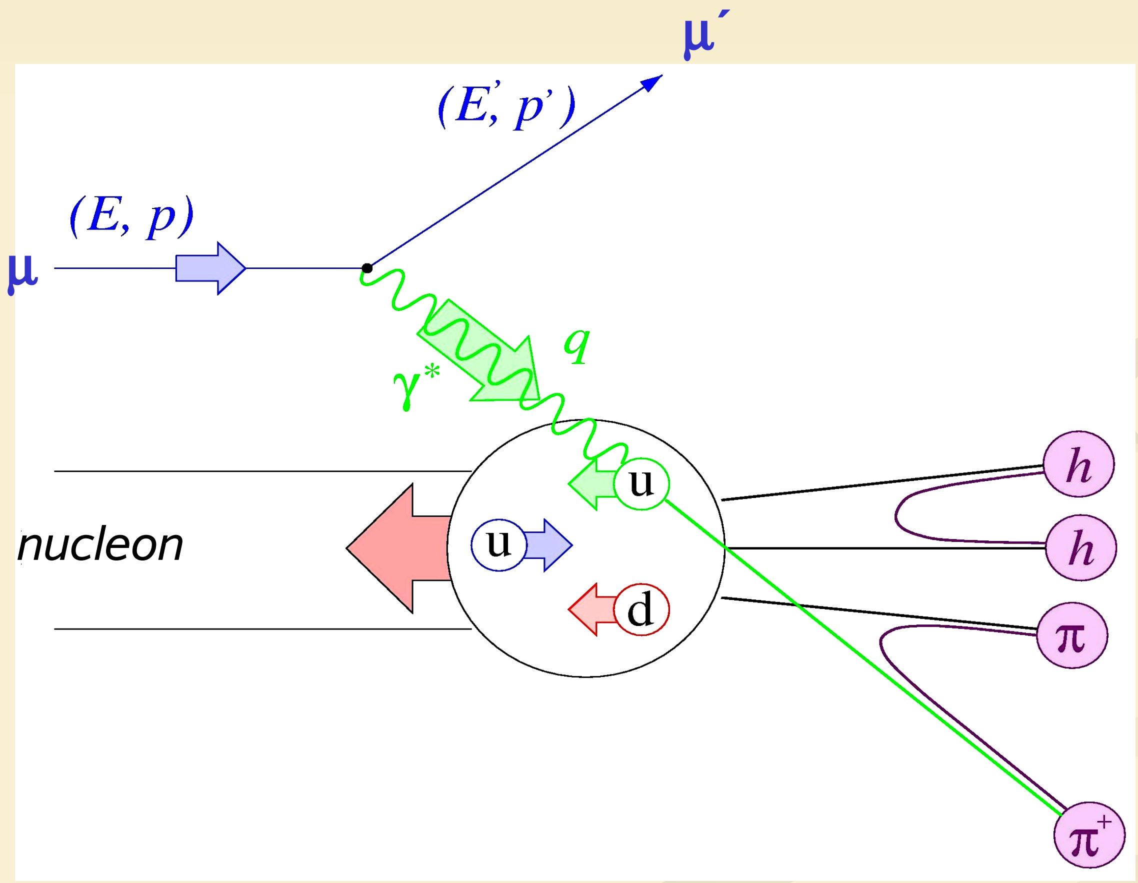
Channels measured by COMPASS:

$l\,N \rightarrow l'\,h\,X$ Collins asymmetry
$l\,N \rightarrow l'\,h\,h\,X$ hadron pair asymmetry
$l\,N \rightarrow l'\,\Lambda\,X$ Λ polarisation

Transverse Spin Physics in SIDIS

Two steps:

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



Kinematic variables:

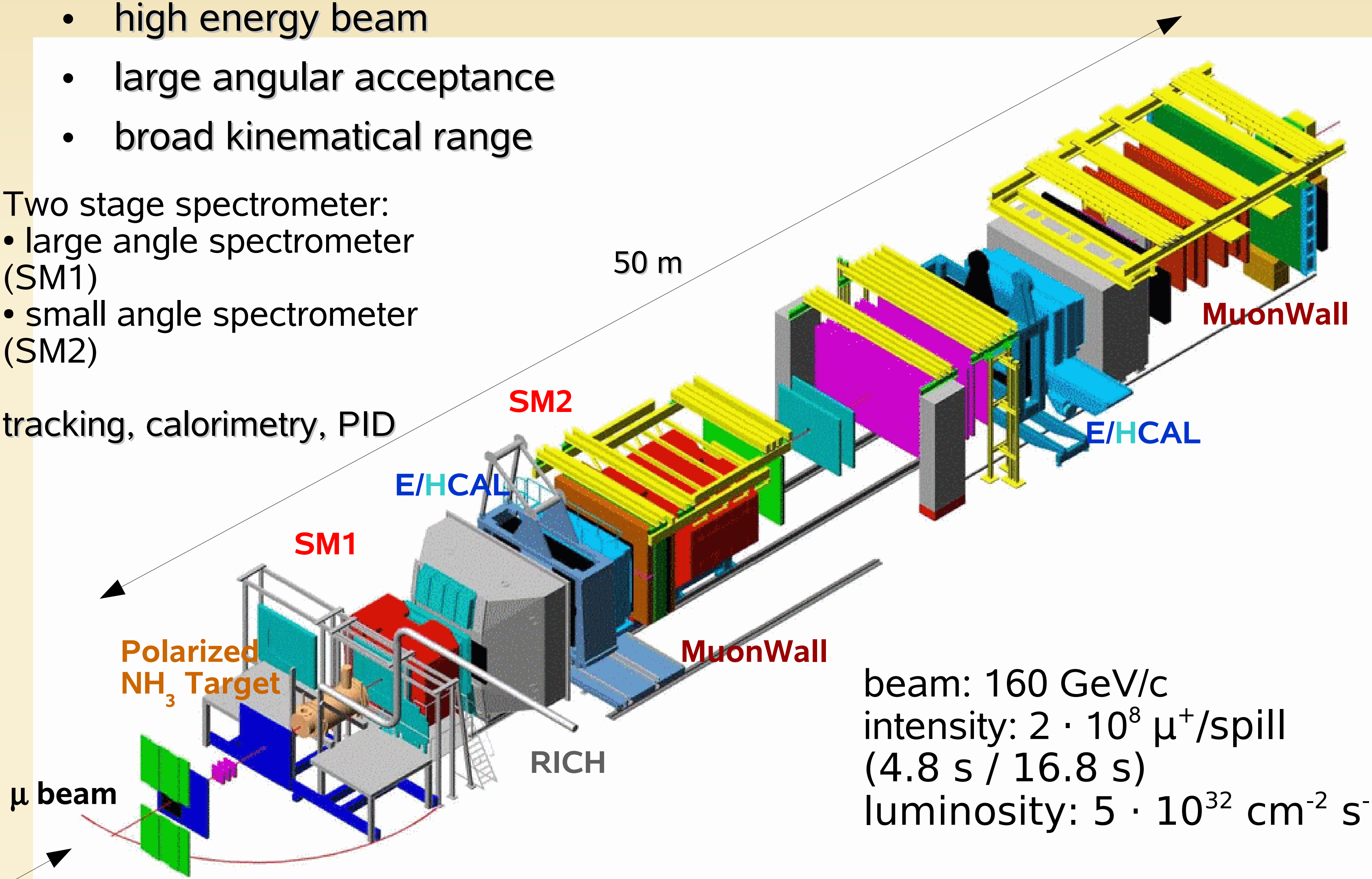
- $Q^2 = -q^2 \approx 4\,E\,E'\,\sin\theta/2$ negative four-momentum transfer squared
- $\nu = E - E'$ photon energy
- $x_{bj} = Q^2/(2M\nu)$ Momentum fraction of struck quark
- $y = \nu/E$ inelasticity
- $z = E_h/\nu$ exclusivity

COMPASS Spectrometer at CERN
(2007 run, proton target)

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

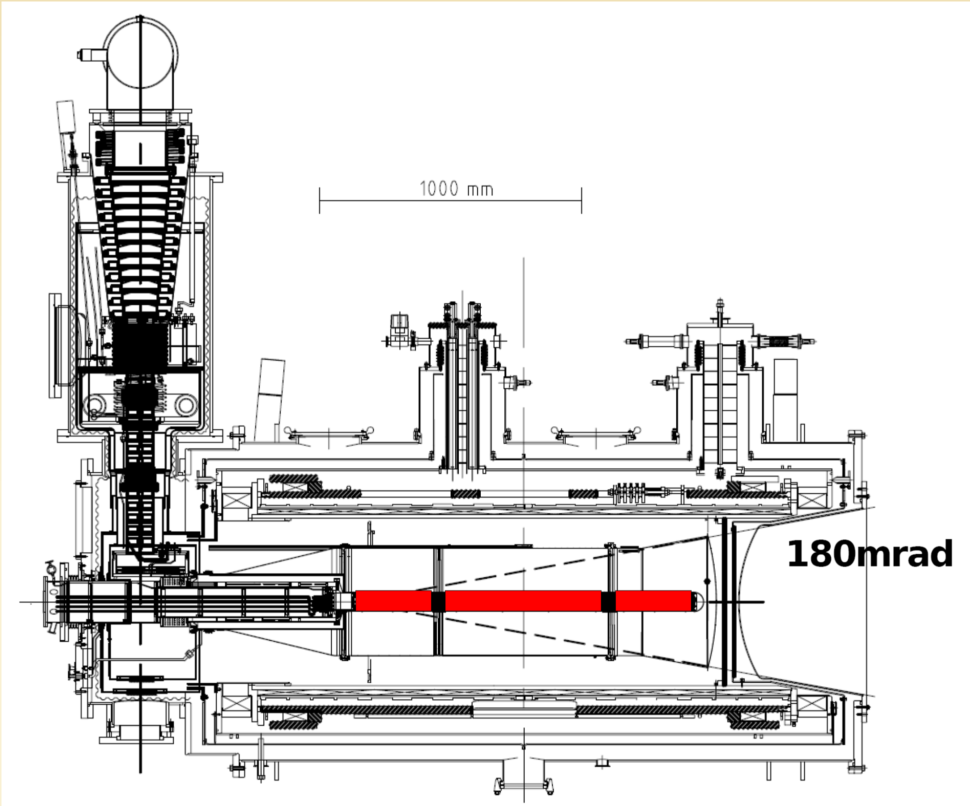
Two stage spectrometer:
• large angle spectrometer (SM1)
• small angle spectrometer (SM2)

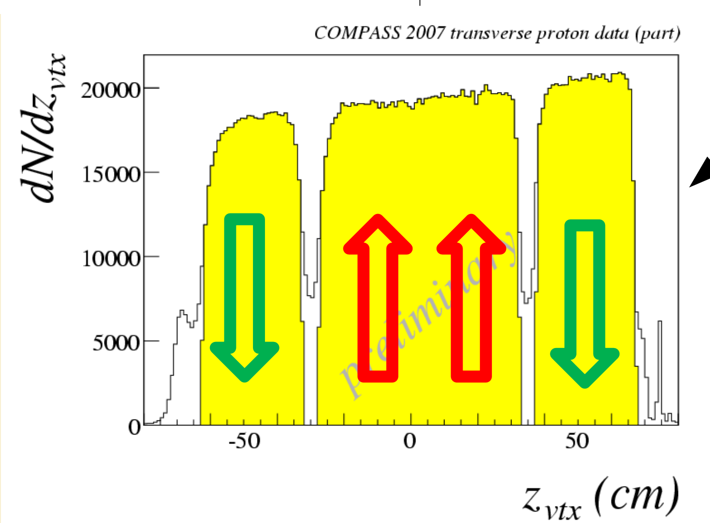
tracking, calorimetry, PID



beam: 160 GeV/c
intensity: $2 \cdot 10^8\ \mu^+$/spill
(4.8 s / 16.8 s)
luminosity: $5 \cdot 10^{32}\ cm^{-2}\ s^{-1}$

Polarized Proton Target (NH_3)





polarization: $P_T \approx 90$ %
dilution factor f ≈ 0.15

3 target cells with opposite polarization

transverse target polarization:
dipole field

changed by microwave reversal:
once a week

Single Hadron Asymmetries

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

a) **Collins effect:**
Fragmentation of a transversely polarized quark with finite transverse momentum into a Spin 0 hadron.

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

Collins fragmentation function: being measured at Belle

→ **possibility to measure transversity!**

b) **Sivers effect:**
Fragmentation of an "unpolarized" (unknown spin state) quark inside a transversely polarized nucleon.

→ Gives a measure of the correlation between transverse momentum and transverse spin.

A non-zero Sivers function needs orbital angular momentum of the quarks.

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

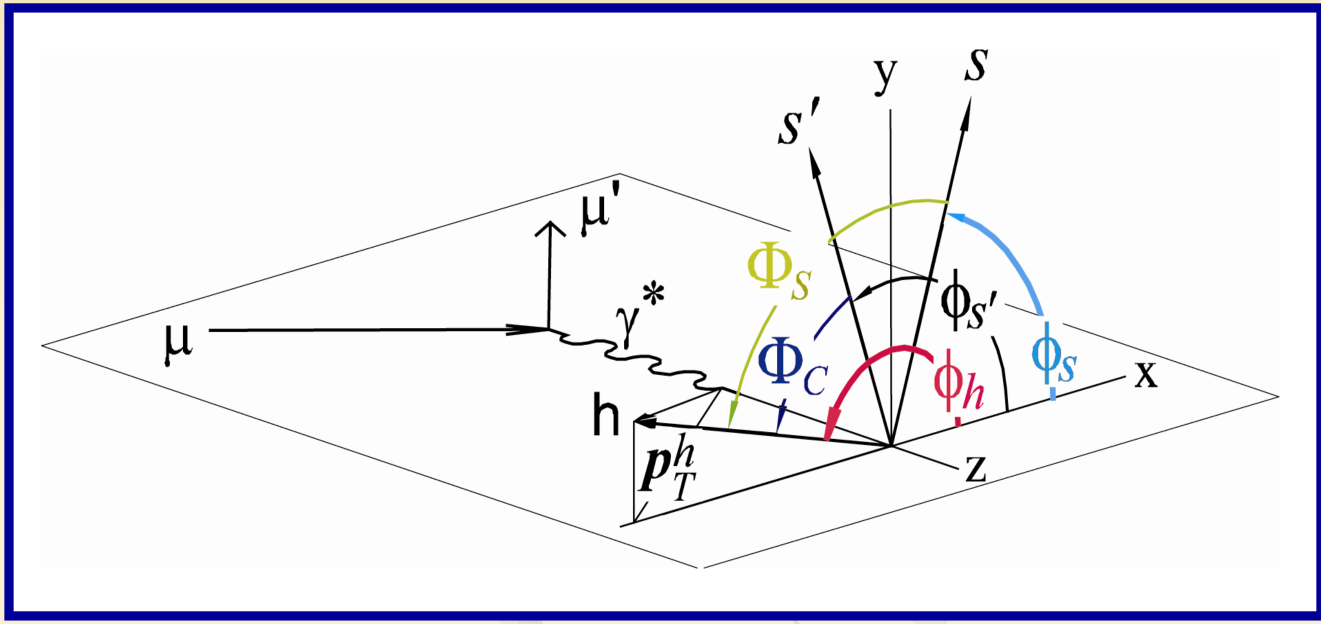
f: dilution factor
P_T: target polarization
D_{nn}: depolarization factor

D_q^h: unpolarized fragmentation function

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

The Coordinate System

Collins and Sivers terms depend on different combination of angles:



Collins:

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

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

$\phi_h + \phi_S - \pi$

Sivers:

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

$\Phi_S = \phi_h - \phi_S$

ϕ_h: azimuthal angle of the hadron

ϕ_S: azimuthal angle of the spin of the initial quark

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

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

Data Taking

Statistics after all cuts:

2002-04 (deuteron target)	hadrons for Collins	hadrons for Sivers
Total statistics	$15.5 \cdot 10^6$	$15.5 \cdot 10^6$

2007 (proton target)		
statistics of first results (Transversity 08)	$11 \cdot 10^6$	$11 \cdot 10^6$
reproduction of data with improved quality (used for Collins)	$29 \cdot 10^6$	$11 \cdot 10^6$

→ for Collins: usable statistics improved by a factor of 3

Data Quality and Systematic Checks

Tests on data for constant detector performance:

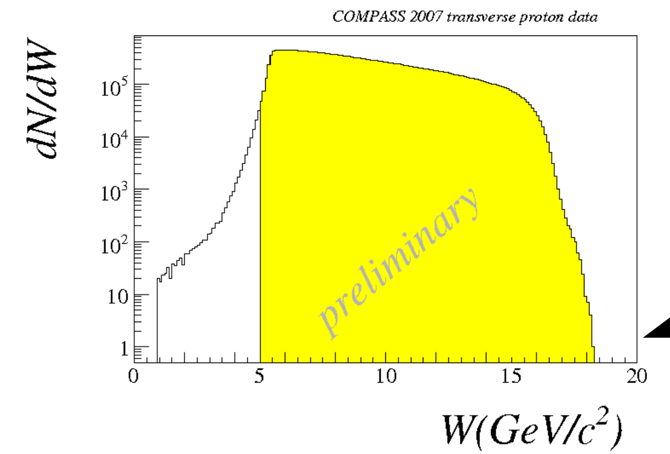
1. A dedicated set of **quality checks** has been developed and applied to satisfy this condition

- Detector and trigger performances
- Event reconstruction
- K^0 reconstruction
- Stability of many kinematical variables:
  (Z_{vtx}, $E_{\mu'}$, $\phi_{\mu'}$, x_{Bj} Q^2, y, W, E_{had} , $\phi_{had_{Lab}}$, $\theta_{had_{Lab}}$, $\phi_{had_{GNS}}$, $\theta_{had_{GNS}}$, p_T)

2. Several **systematics tests** have been performed:

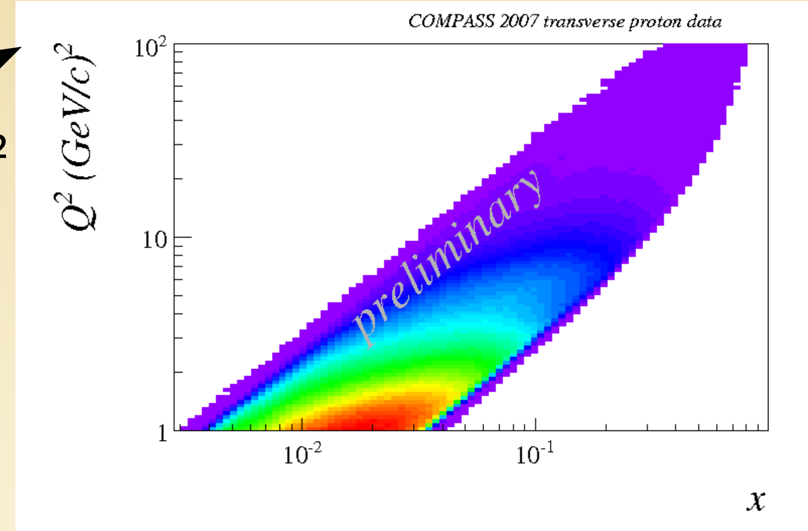
- Splitting of the target into sectors
- False asymmetries tests
- Different methods for asymmetry extraction

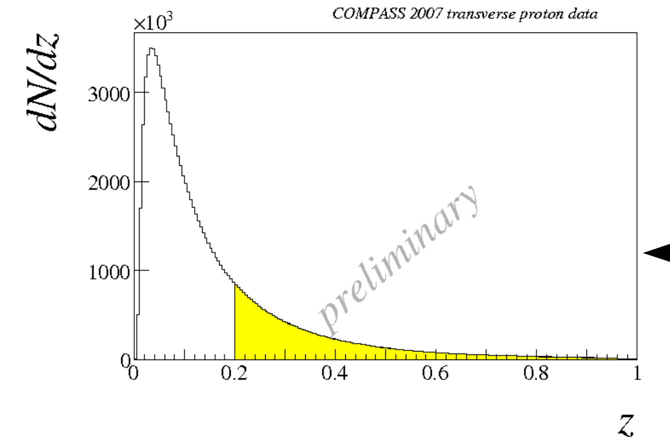
Event Selection



DIS cuts:

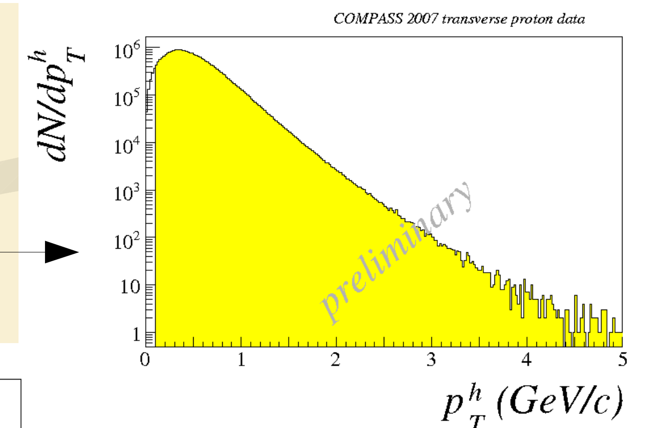
- $Q^2 > 1\ (\mathrm{GeV}/c)^2$
- $0.1 < y < 0.9$
- $W > 5\ \mathrm{GeV}/c^2$



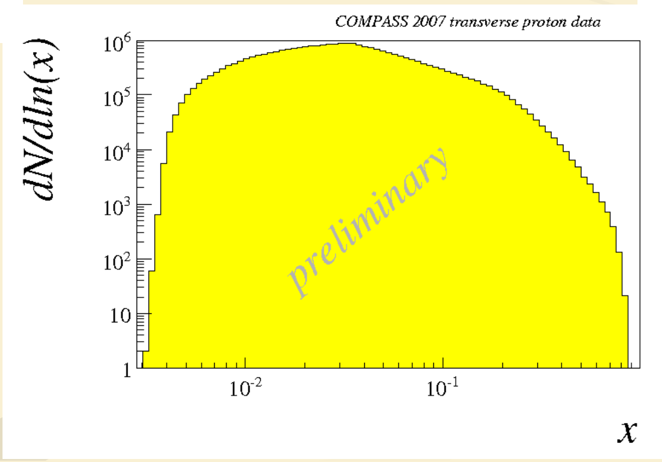


Hadron cuts:

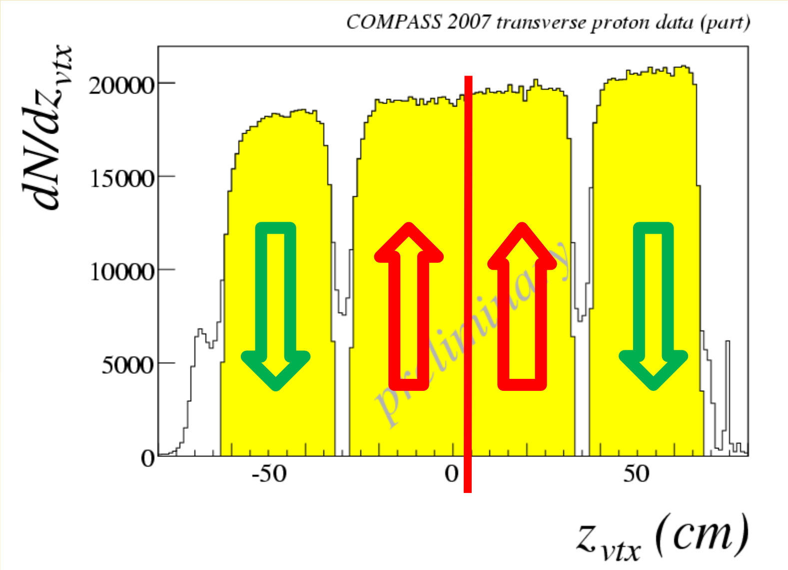
- $z > 0.2$
- $p_T > 0.1\ \mathrm{GeV}/c$



after cuts:
distribution of x_{bj}



Asymmetry Extraction



Splitting middle cell into two parts
- two pairs of cells with opposite polarization
- two independent values for the asymmetries per period

Extraction: 2D Binned Maximum Log-Likelihood Fit:

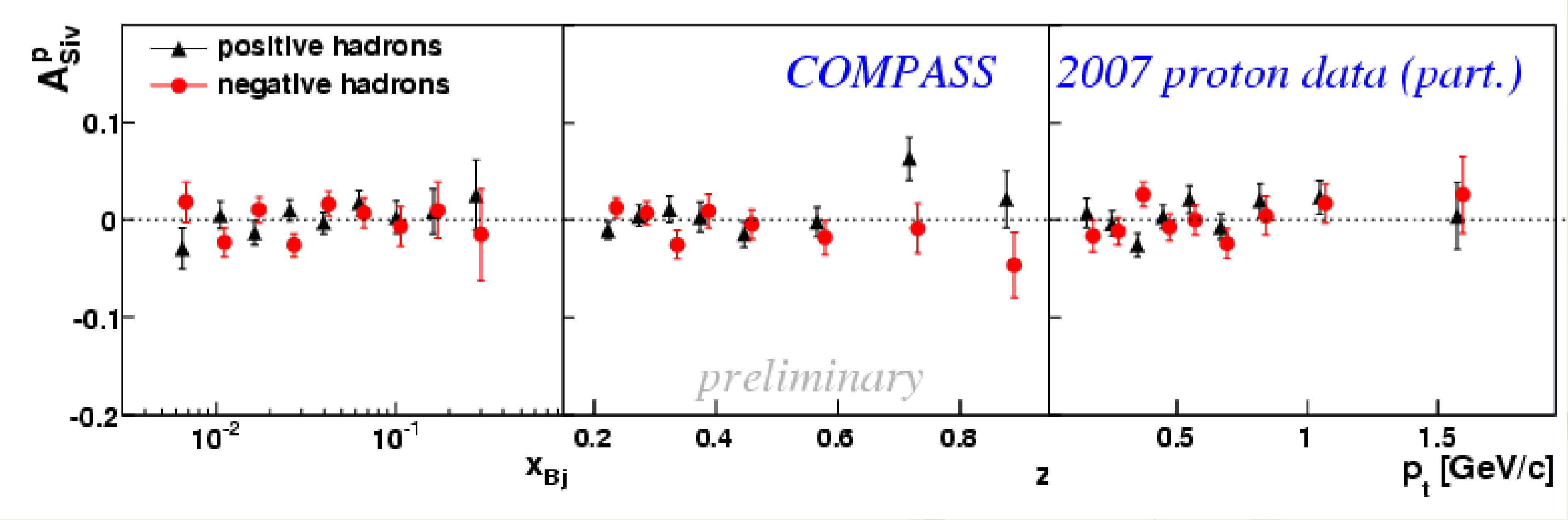
8 X 8 grid in Φ_h and Φ_S

In each bin j = {1,2, ... 64} one expects N_j counts:

$N_j^{\uparrow\downarrow} = a_j g_j^{\uparrow\downarrow}(\vec{A})$ with:

$\uparrow\downarrow$	sign of the target polarization
a_j	acceptance in bin j
$g_j^{\uparrow\downarrow}(\vec{A})$	all 8 spin dependent modulations of the cross section in bin j

Sivers Asymmetries Proton Data

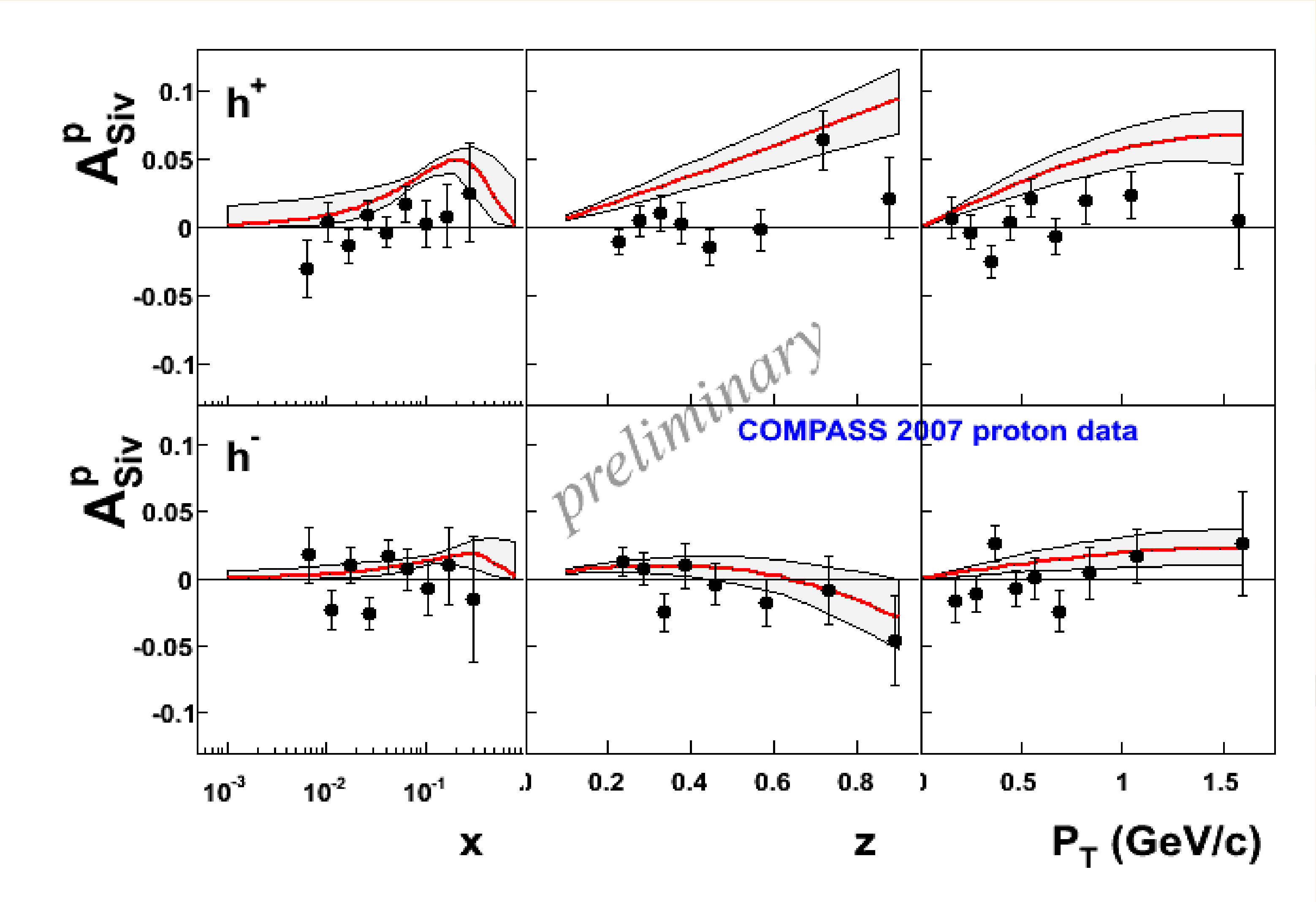


Asymmetries compatible with 0 within present statistical errors

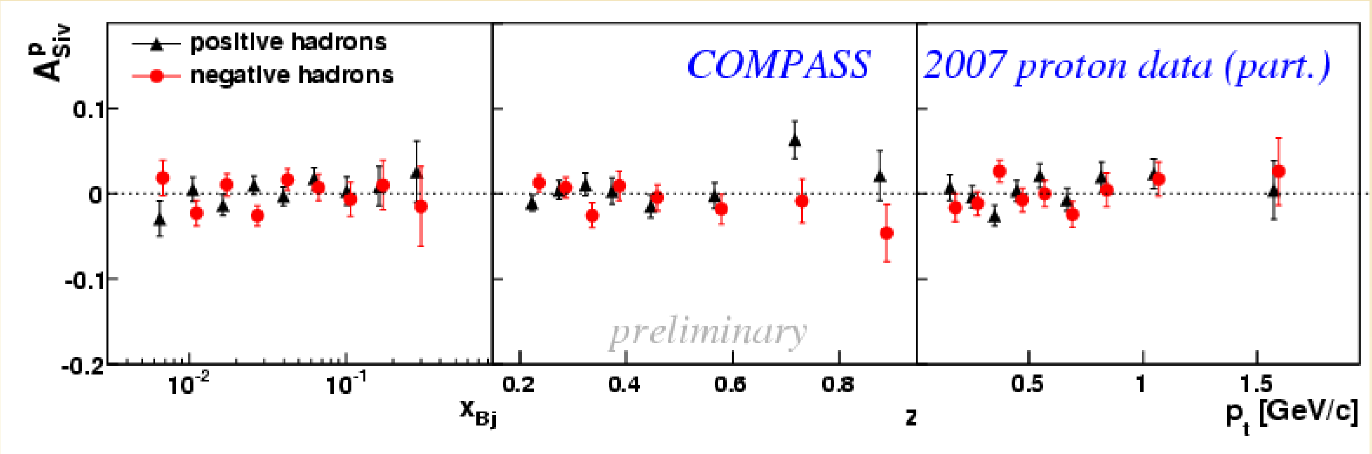
Only statistical errors shown, systematic errors: 0.5 σ_{stat}

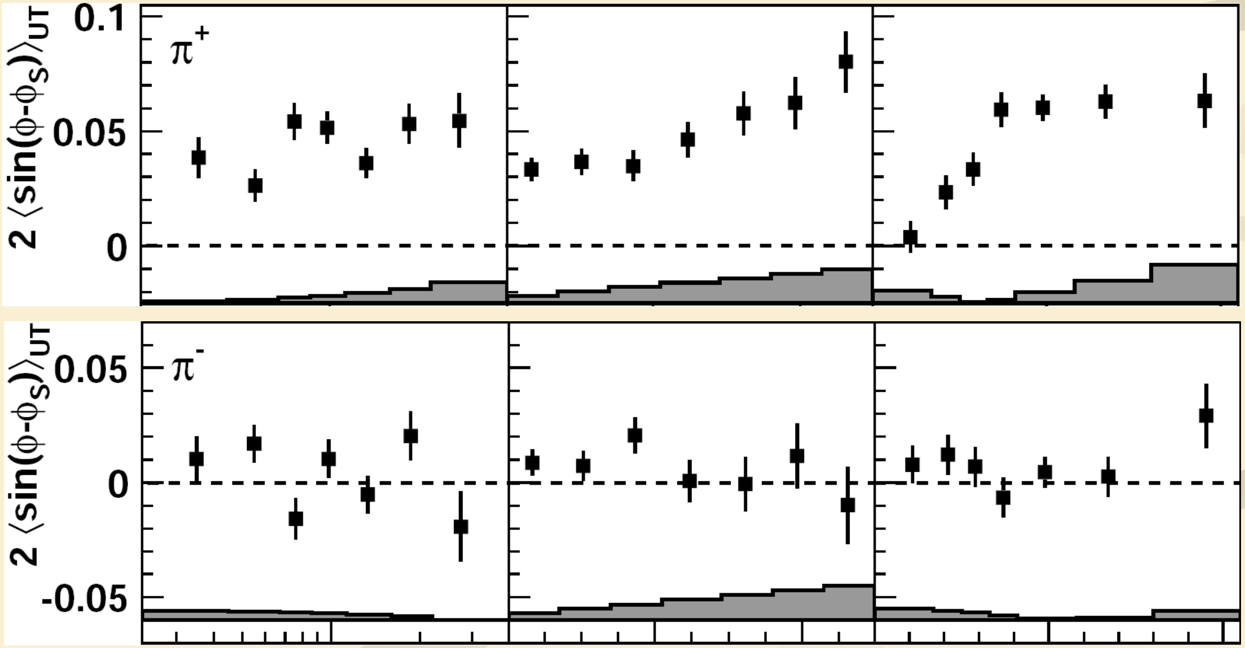
Sivers Asymmetries Proton Data

Comparison with predictions of Anselmino et al.:
Eur. Phys. J.A 39: 89-100, 2009



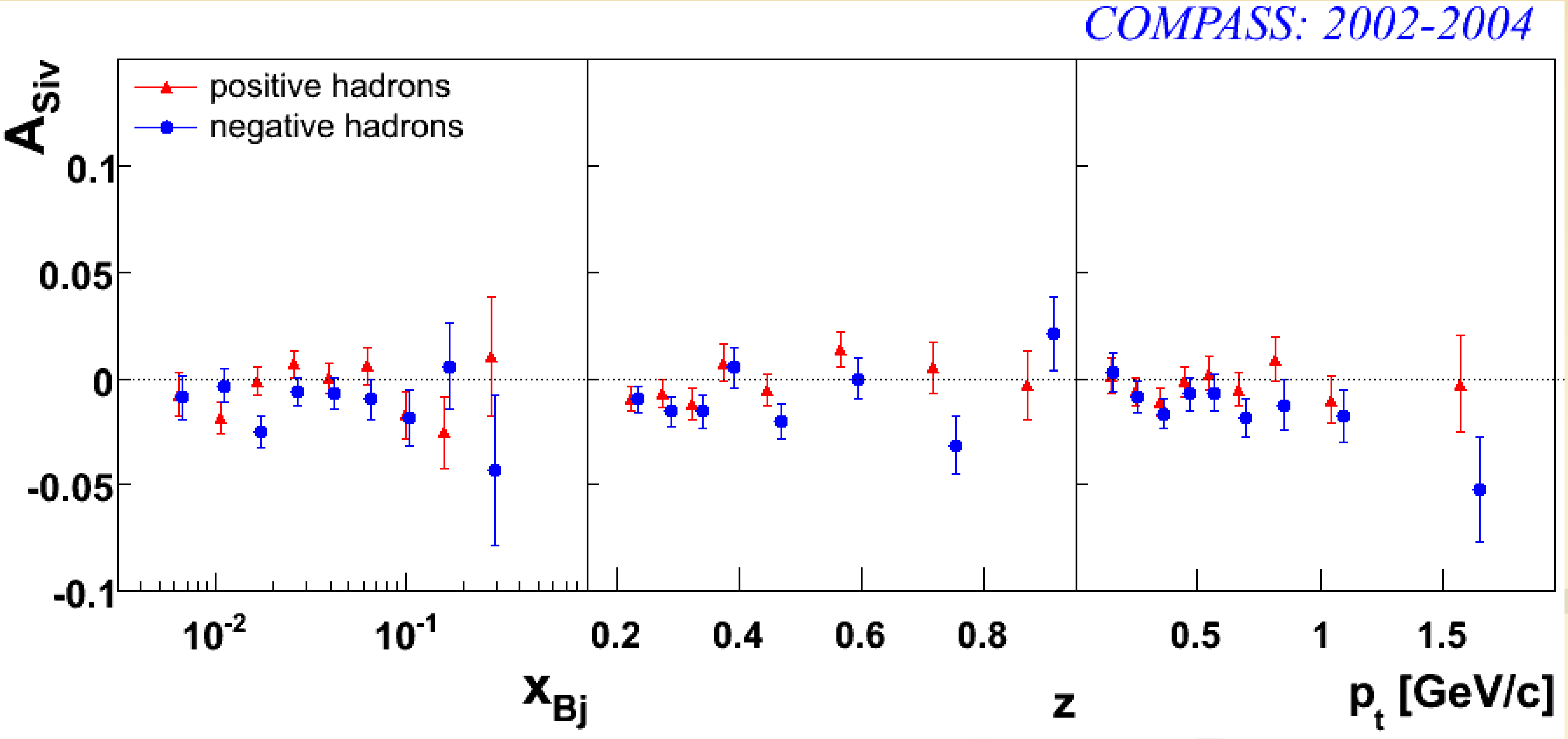
Sivers Asymmetries – Comparison with HERMES





HERMES:
arxiv:0906.3918

Sivers Asymmetries Deuteron Data



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

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

→ the result was interpreted as a strong indication for cancellation of u and d quark Sivers function

Reproduced Data

- Reproduction with improved quality
- Improved quality checks
- Increased systematic checks

Instabilities of the spectrometer in the first part of the run
→ for Sivers: extraction for full 2007 data difficult

Asymmetry extraction:
Extended Unbinned Maximum Likelihood Fit:

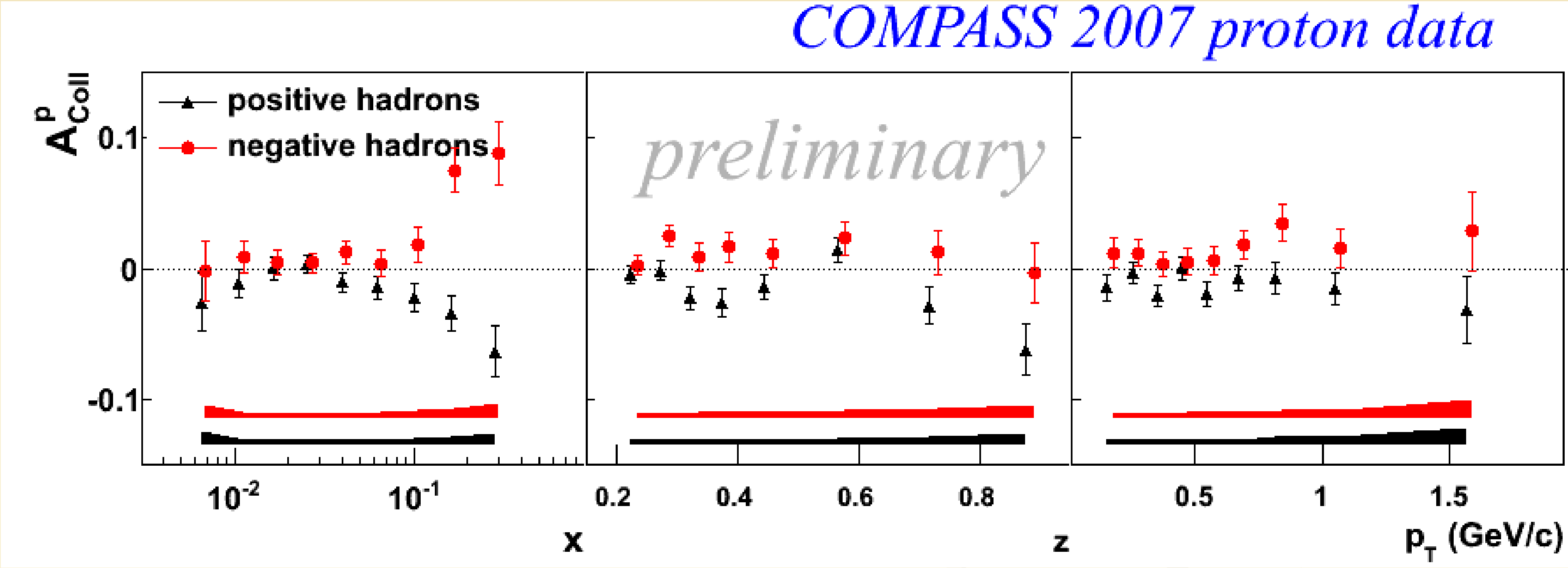
$$L = e^{-N_e} \prod_{i=1}^{N} p(\varphi_S^i, \varphi_h^i; a_1 \cdots a_m)$$

with N: number of hadrons
N_e: expected number of hadrons
(a_1 … a_m) the unknown parameters
p: probability density of the sampling variables Φ_S and Φ_h

$$\int \int p(\varphi_S \varphi_h; a_1 \cdots a_m) d\varphi_S d\varphi_h = N_e(a_1 \cdots a_m)$$

p parametrization contains the single hadron cross-section

Collins Asymmetries - Proton Data

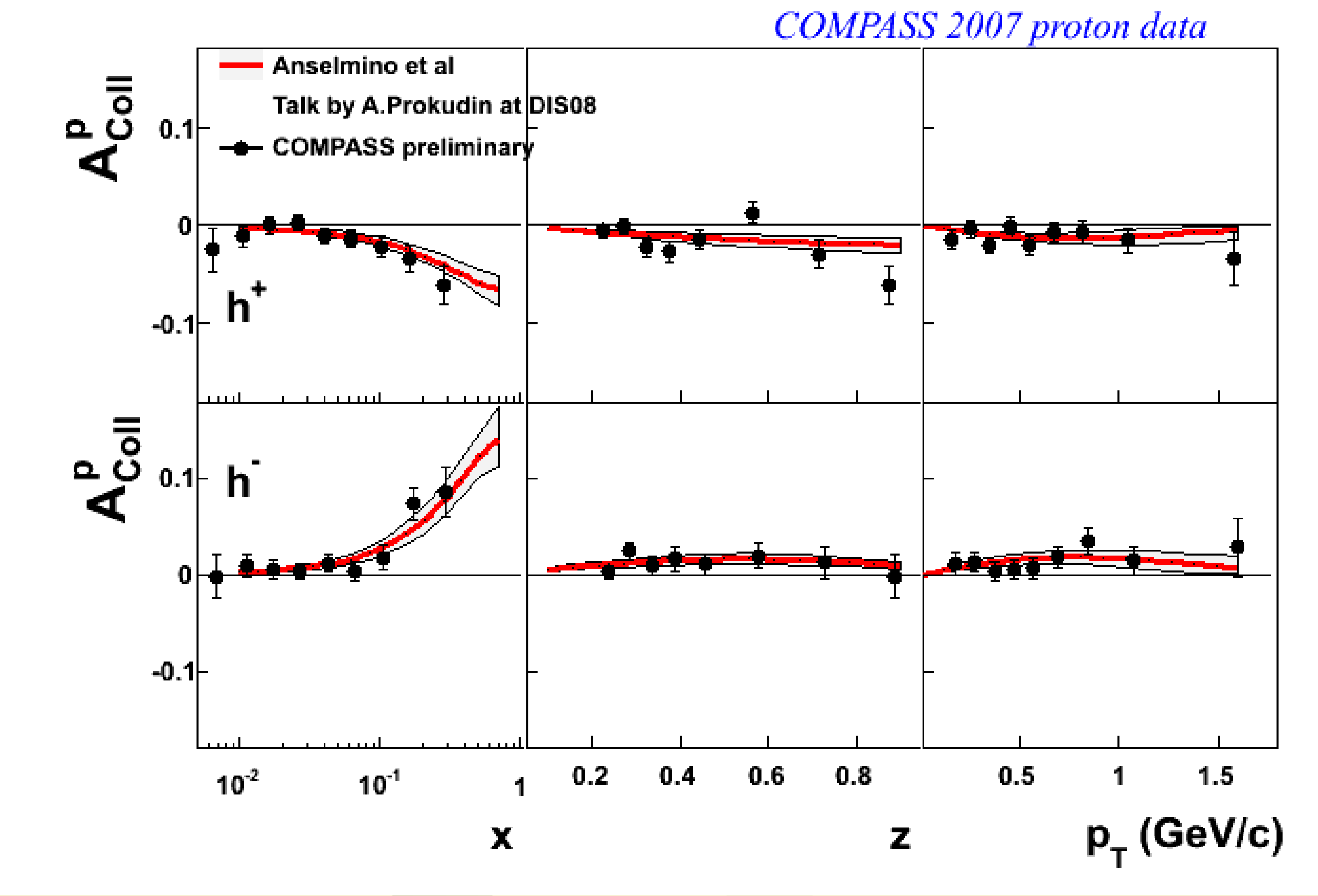


Asymmetries different from 0 for valence region

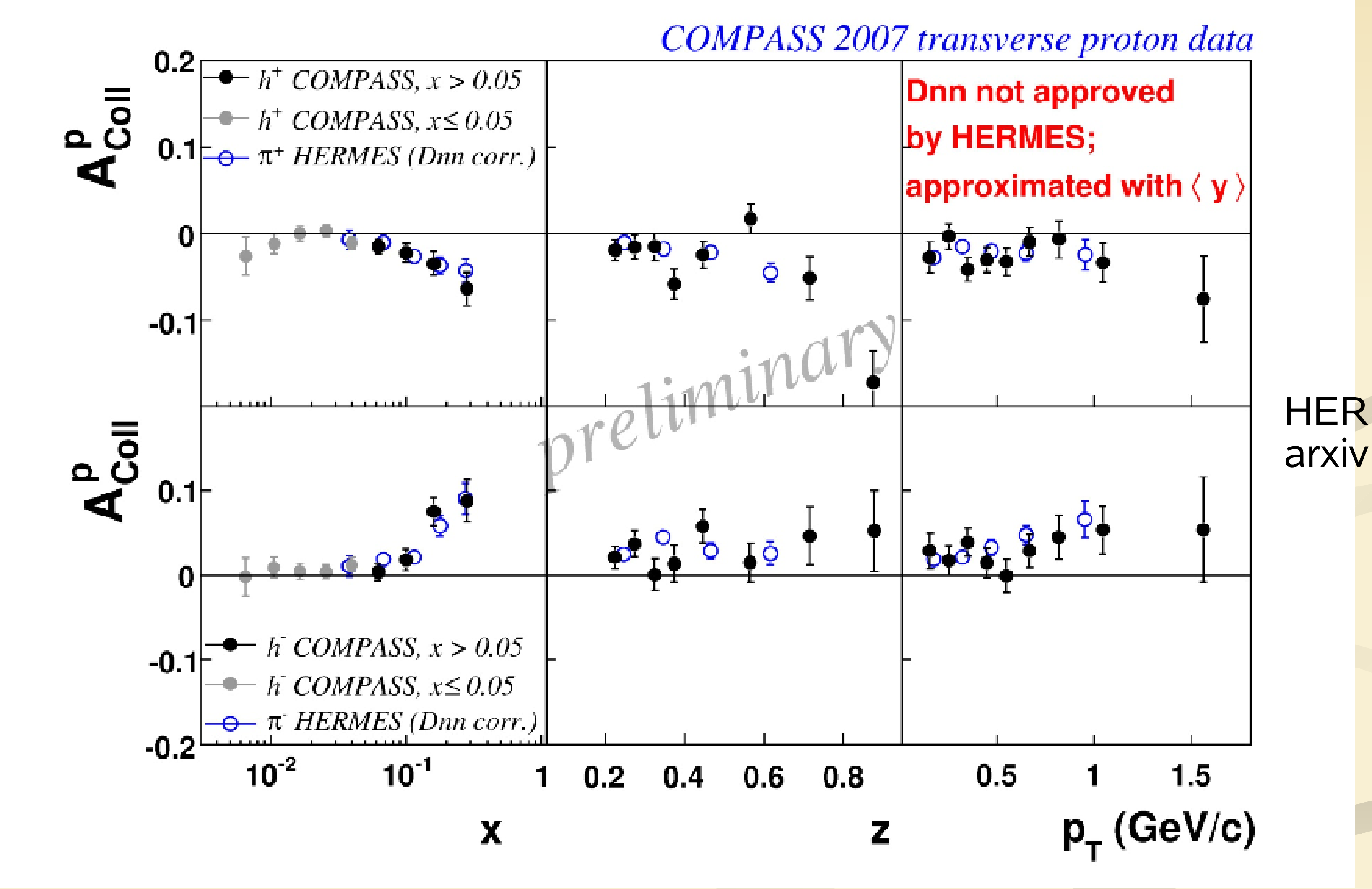
- asymmetries of opposite sign for positive and negative hadrons
- systematic errors: 0.5 σ_{stat}
- small asymmetries, compatible with 0 at small x_{bj}

Collins Asymmetries - Proton Data

Comparison with predictions of Anselmino et al.:



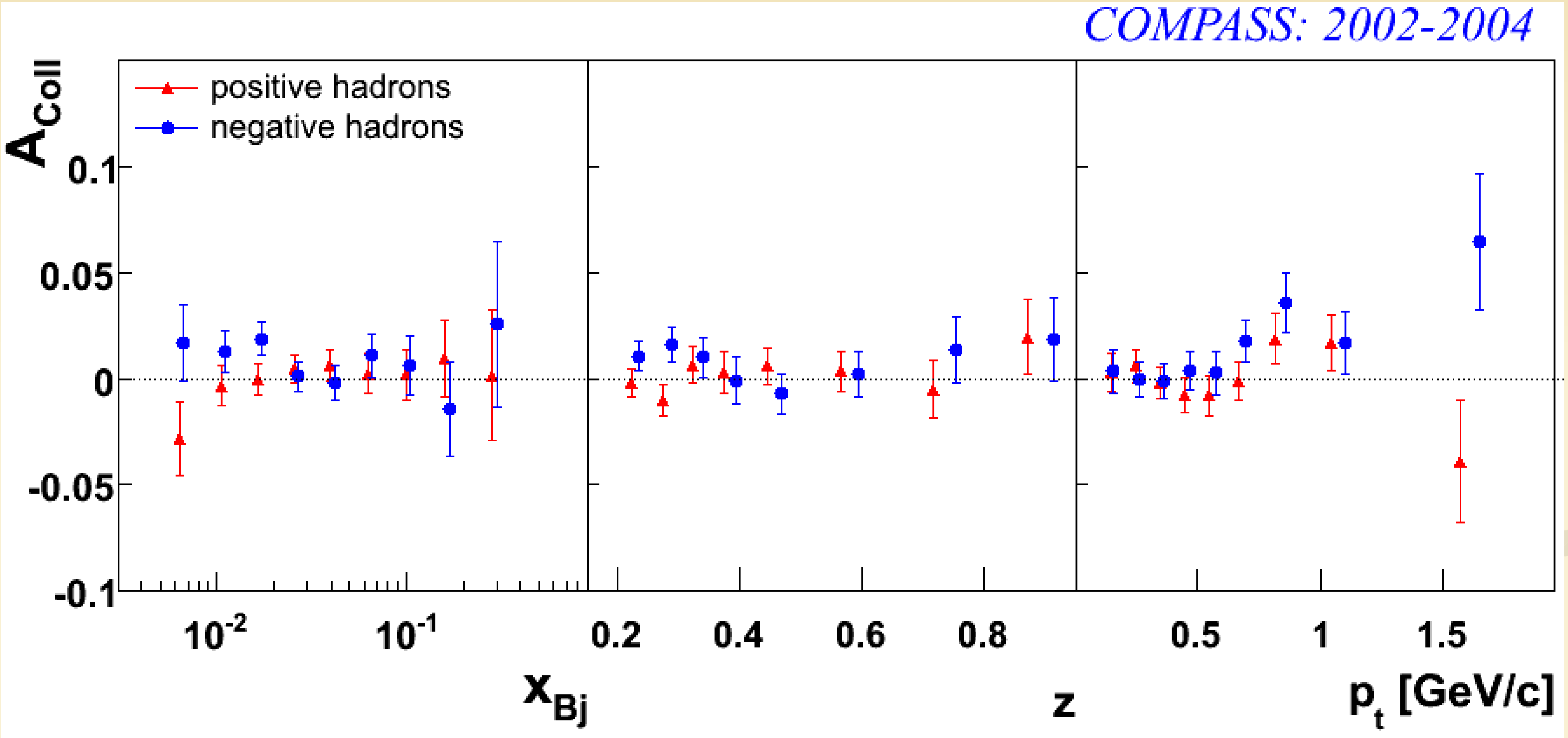
Collins Asymmetries – Comparison with HERMES



HERMES:
arxiv:0706.2242

→ same strength and sign as HERMES

Collins Asymmetries - Deuteron Data



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

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

Interpretation Collins Deuteron

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

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

Phenomenological models can describe data from COMPASS on deuteron, HERMES on proton and BELLE at the same time:

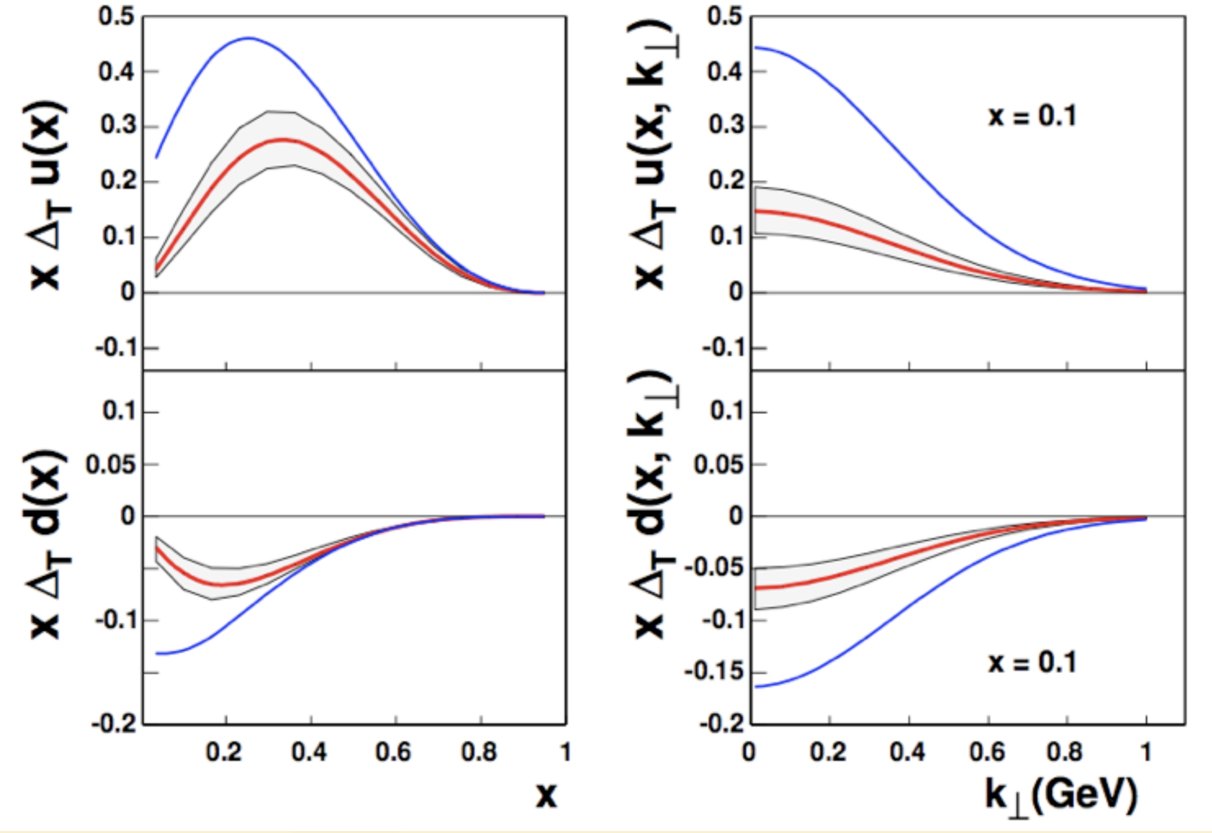
- *Vogelsang, Yuan: hep-ph/0507266*
- *Efremov, Goeke, Schweitzer: hep-ph/0603054*
- *Anselmino, Prokudin at SPIN 2008*

Now also possible with COMPASS (d), COMPASS (p) and BELLE.

HERMES (p), COMPASS (d), BELLE

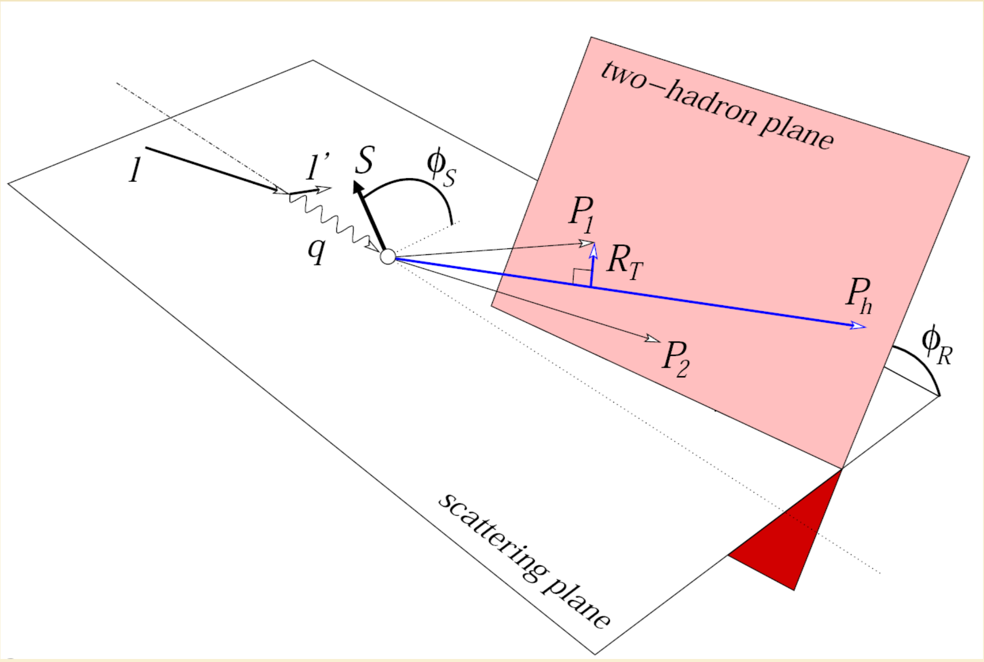
global fit

Soffer bound



Two Hadron Asymmetries

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



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

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

ϕ_R: azimuthal angle of R_T

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

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

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

Transversity distribution function

Interference fragmentation function, being measured at BELLE

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

Two Hadron Asymmetries – Proton Data

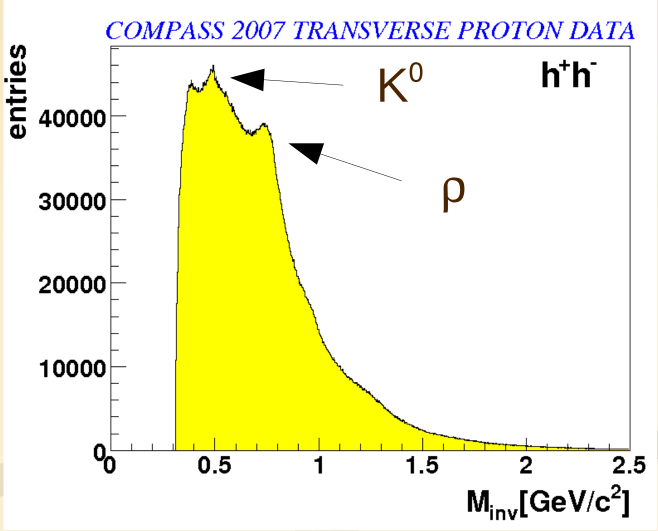
Hadron cuts:

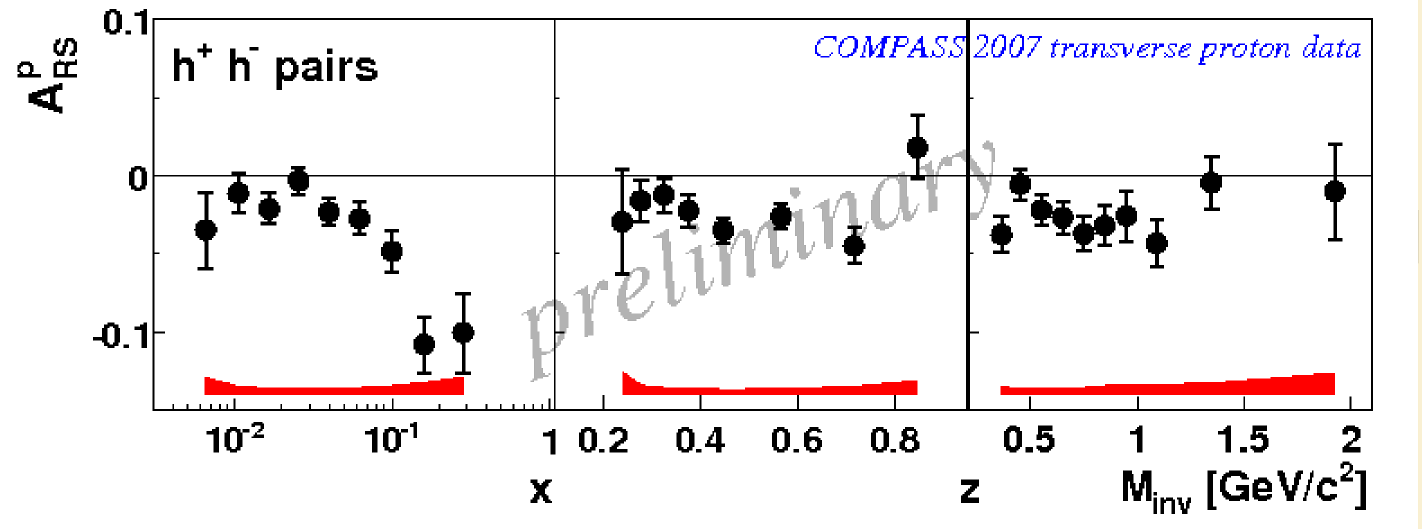
- $z_{1,2} > 0.1$
- $x_{F1,2} > 0.1$
- $z_1 + z_2 < 0.9$ (exclusive ρ)
- $R_T > 0.07$ GeV/c

Statistics after all cuts:

proton target h^+h^- pairs
$11.28 \cdot 10^6$

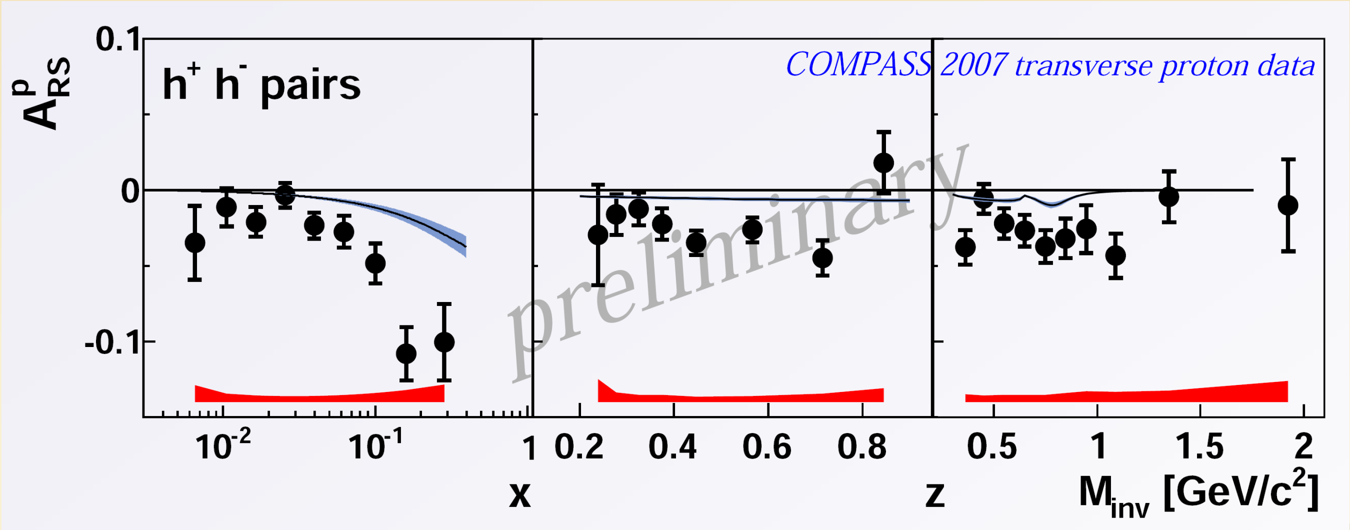
Invariant mass spectra



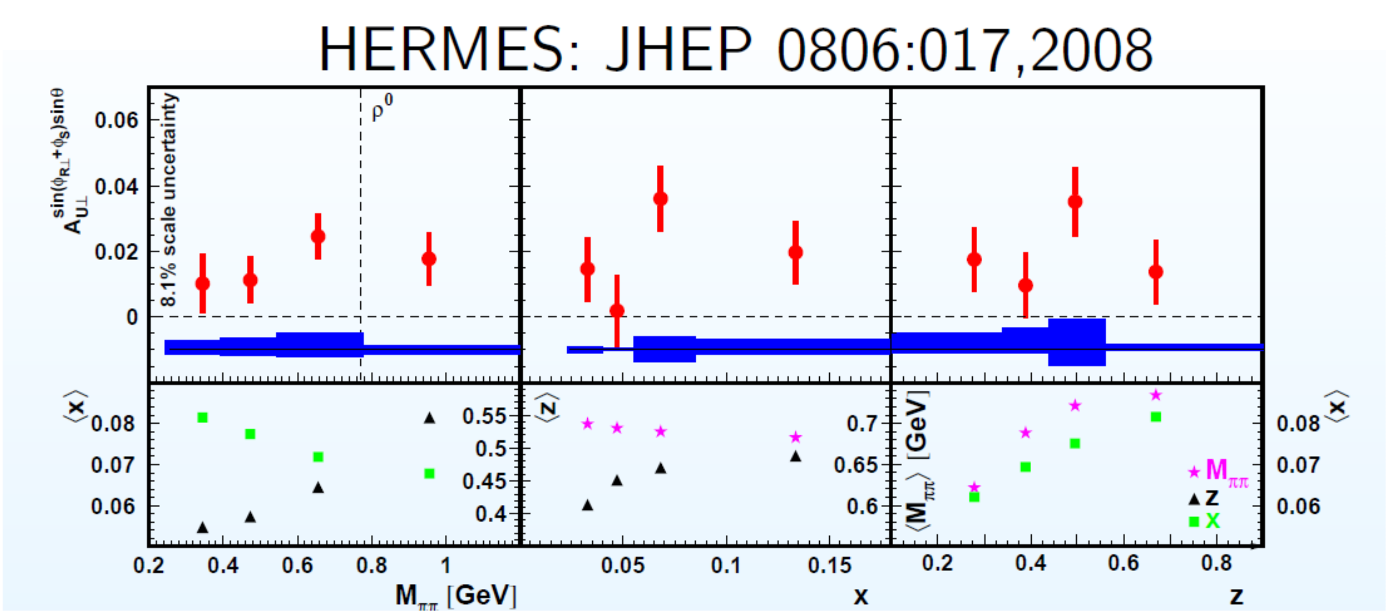


Two Hadron Asymmetries – Proton Data

Comparison with predictions of Bacchetta (Courtesy of A. Bacchetta):



Comparison with HERMES:

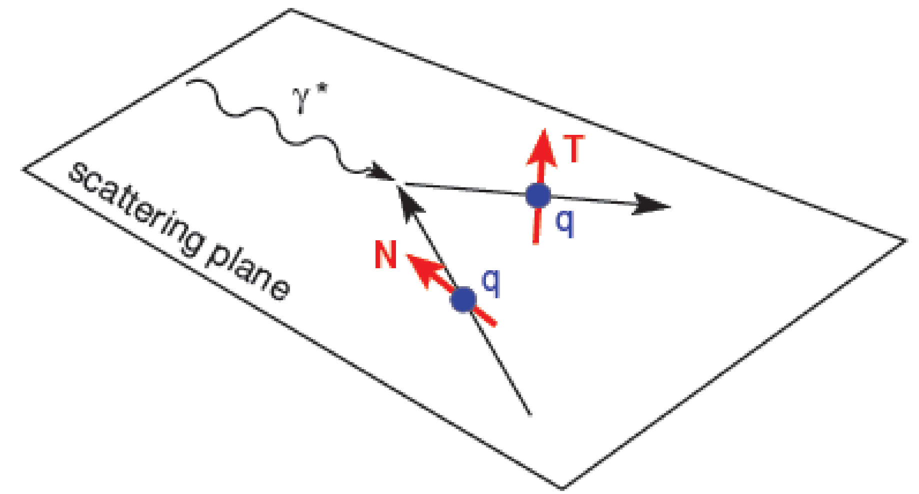


Λ Polarimetry

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

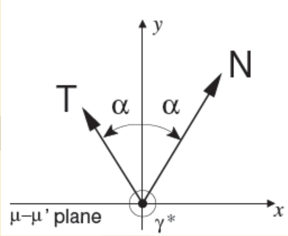
$$\mu\ N^{\uparrow} \rightarrow \mu' \Lambda^{\uparrow} X$$

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



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

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



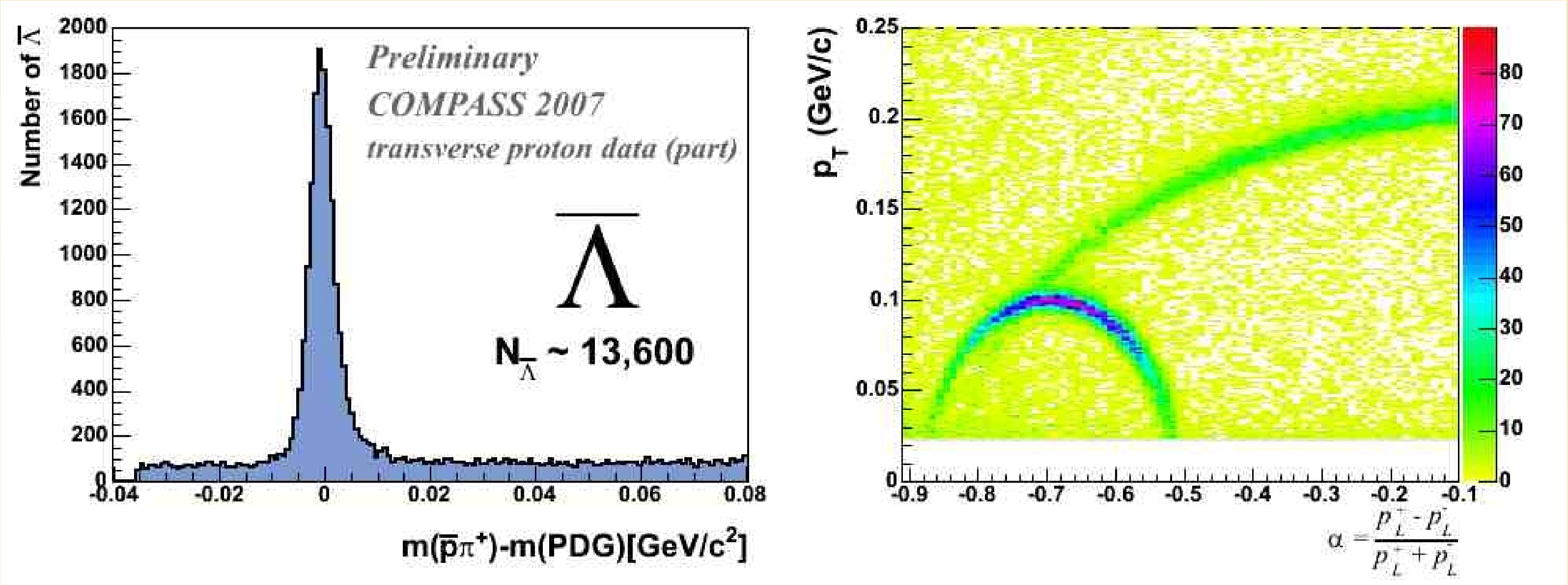
$$P^{\Lambda}_{T,exp} = \frac{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} - d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}}{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} + d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}} = f P_N D(y) \frac{\sum_q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

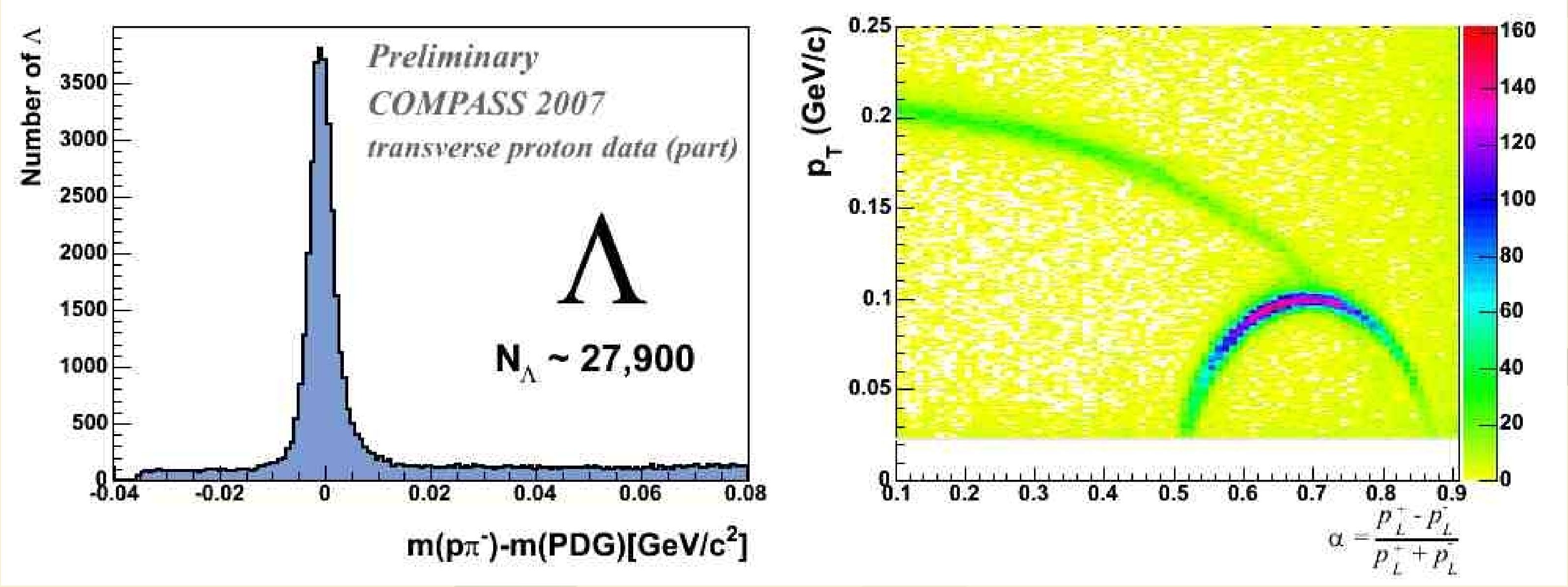
f = target dilution factor, P_N = target polarization,

$D(y)$ = virtual photon depolarization factor

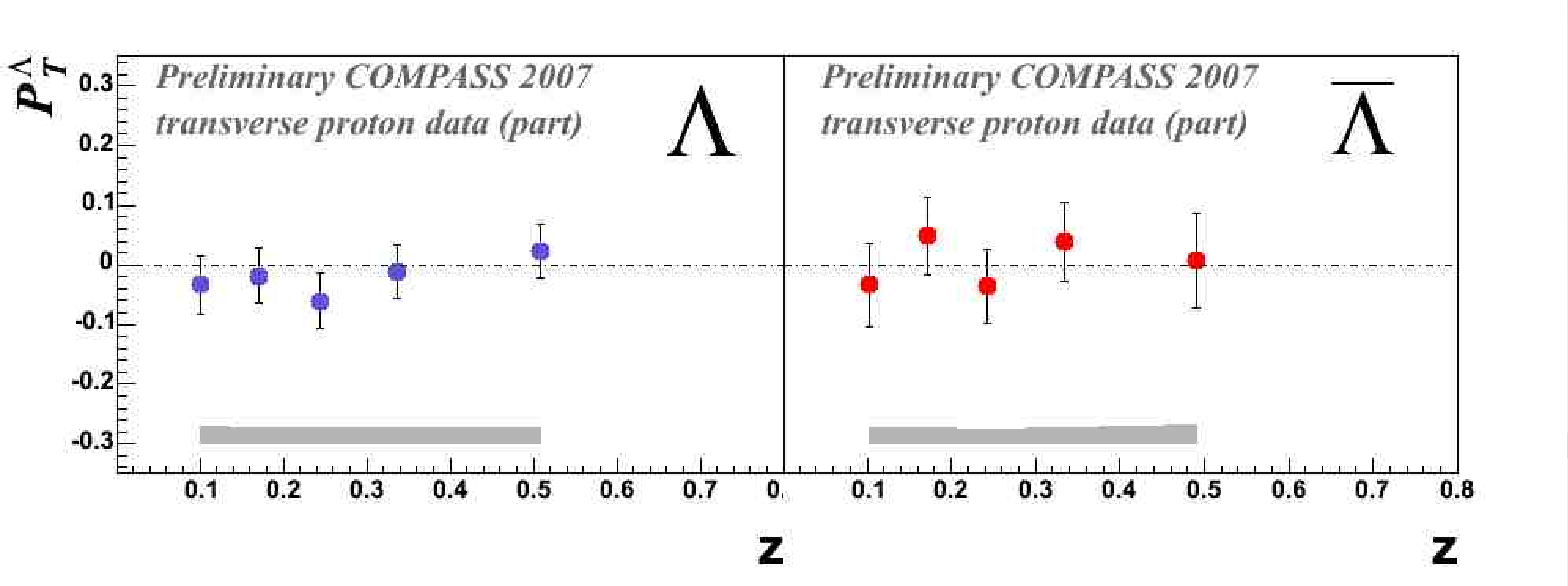
$$\Delta_T D_{\Lambda/q}(z) = D_{\Lambda^{\uparrow}/q^{\uparrow}}(z) - D_{\Lambda^{\downarrow}/q^{\uparrow}}(z)$$

Λ Polarimetry – Proton Data





Λ Polarimetry – Proton Data



- no dependence on x_{bj}
- fragmentation function as function of z seems quite small

Summary and Outlook

Results of the COMPASS 2007 proton transverse run:

- **Collins asymmetry:**
  - different from 0, compatible with HERMES
  - agreement with predictions of Anselmino et al.

  → **access to transversity!**

- **Sivers asymmetry:**
  - compatible with 0 within present statistical errors in difference to Hermes for h^+

  → to be understood

- **Two Hadron Asymmetries**
  - different from 0, signal stronger than HERMES

- **Λ Polarization**
  - fragmentation function as function of z seems quite small

- **Near future:**
  - identified hadrons
  - further transverse data taking (2010)

Just in case…

Systematic Studies

Several systematics tests have been performed:

Splitting of the target into sectors:

1. Left right
2. Up down

False asymmetries test:

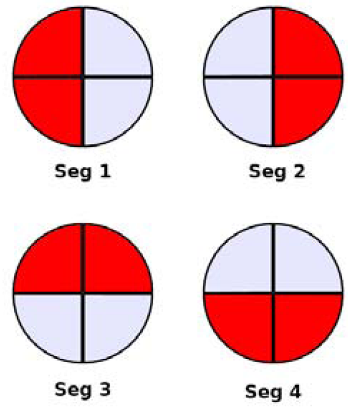
1. Combining cells with the same polarization

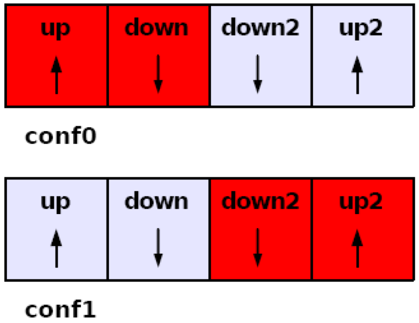
Target split: different target sectors

1. Combining half upstream target cells (conf 0)
2. Combining half downstream target cells (conf 1)

Different methods for asymmetry extraction

1. 5 different methods



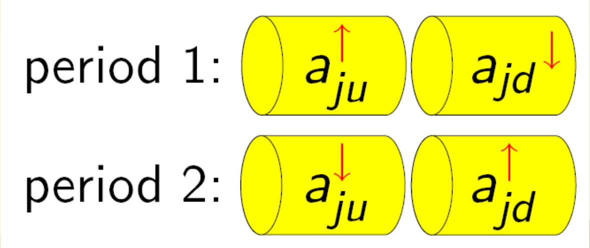


Asymmetry Extraction

Separation of acceptance and spin dependent modulations:

Coupling of two cells (u, d) with opposite polarization (↑↓) and two periods (p1, p2) with opposite target polarization

Reasonable assumption:



$$\frac{a_{ju}^{\uparrow}}{a_{ju}^{\downarrow}} = C \frac{a_{jd}^{\downarrow}}{a_{jd}^{\uparrow}}$$

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

1 + 8 + 3 • 64 = 201 fit parameters $\left(\vec{a}\right)$

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

Solution: $max\, \Pi_{j=1}^{256} P_j\left(\vec{a}\right)$

Interpretation Sivers Deuteron

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

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

Small asymmetries → $\Delta_0^T d_v \simeq -\Delta_0^T u_v$

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

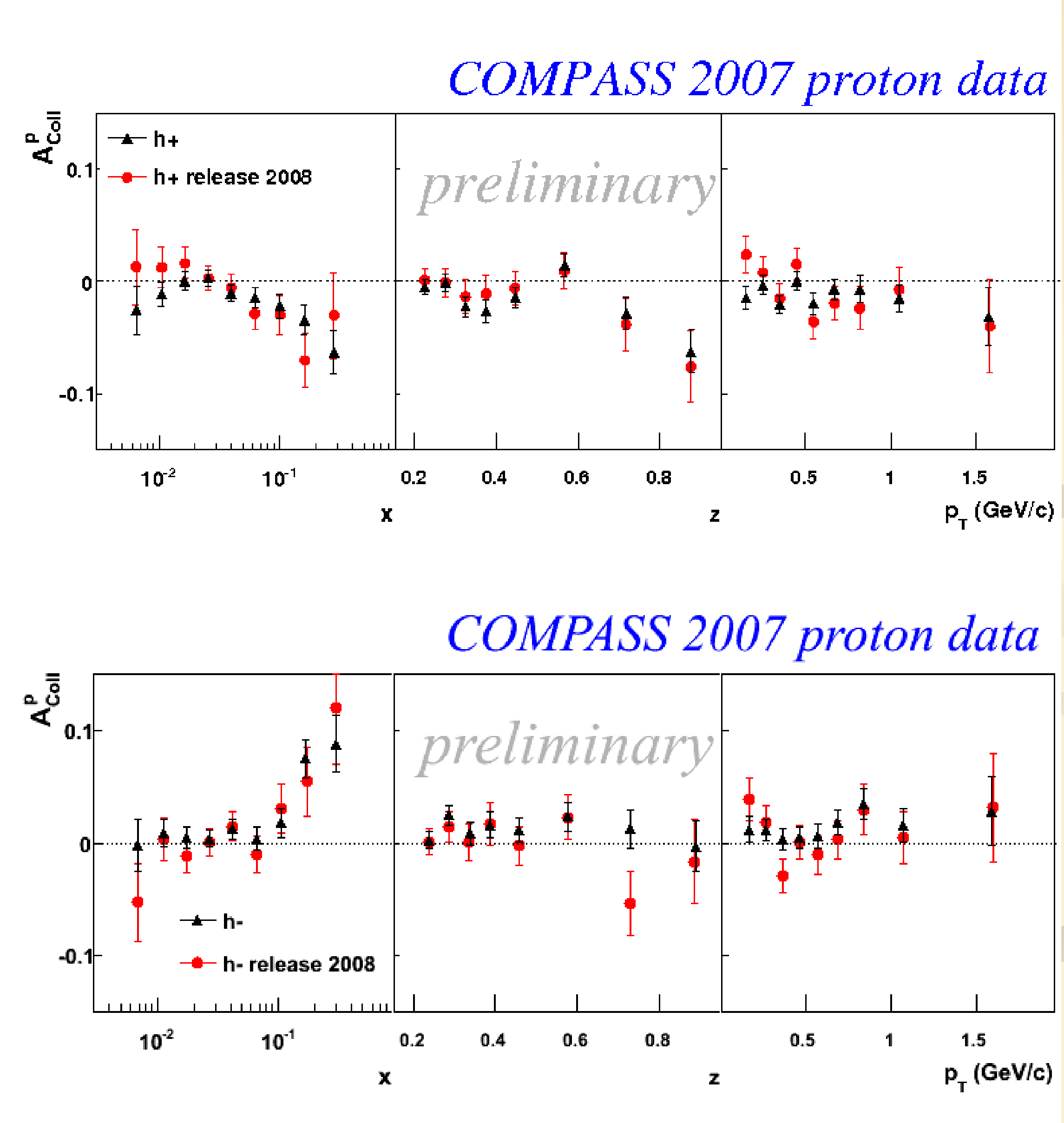
measured asymmetry on deuteron compatible with 0 has been interpreted as

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

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

The approximate cancellation of the SSA measured on a deuterium target suggests that the gluon mechanism, and thus the orbital angular momentums carried by gluons in the nucleon, is small.

Collins – Proton Data: Comparison Release 08 - Reproduction



Interpretation Collins Deuteron

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

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

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

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

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

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

Other Single Spin Asymmetries

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

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

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

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

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

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

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

Other Single Spin Asymmetries

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

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

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

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

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

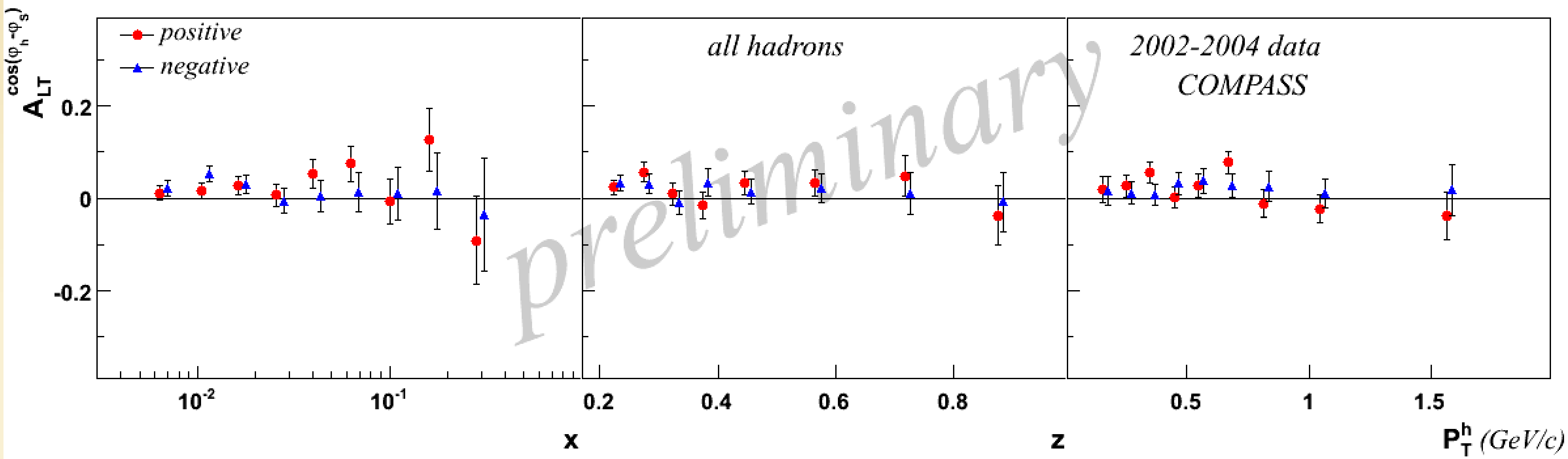
$$F_{UT}^{\sin(2\phi_h-\phi_s)} \propto \frac{M}{Q} \left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h \right)$$

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

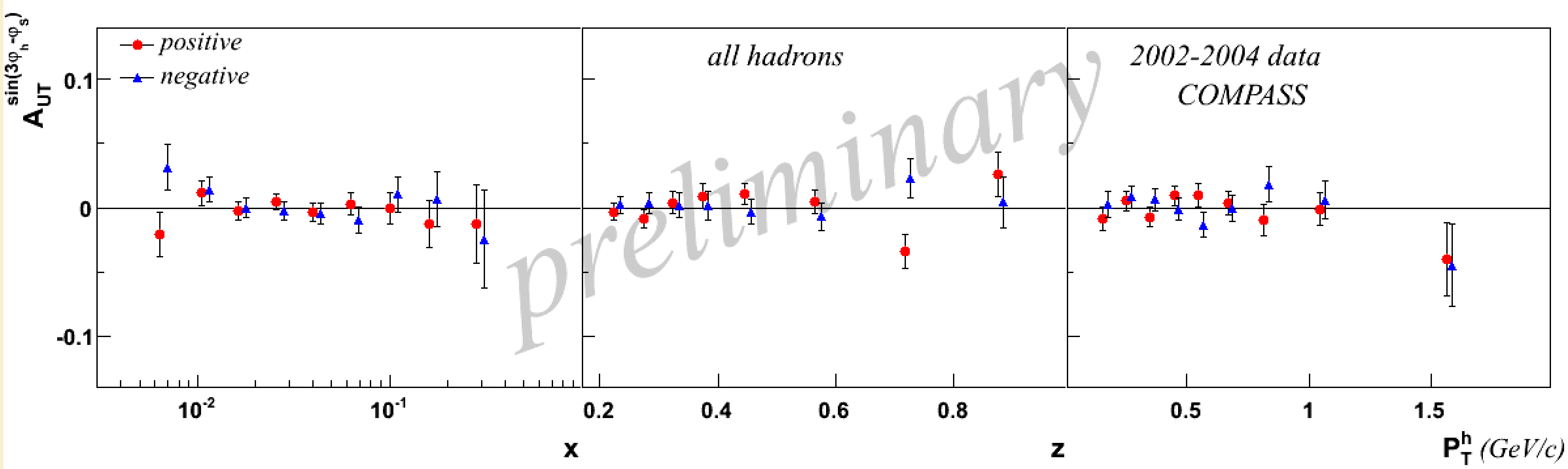
The four remaining ones can be interpreted as twist-3 contributions.

Other SSA: Twist-2 - Deuteron

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

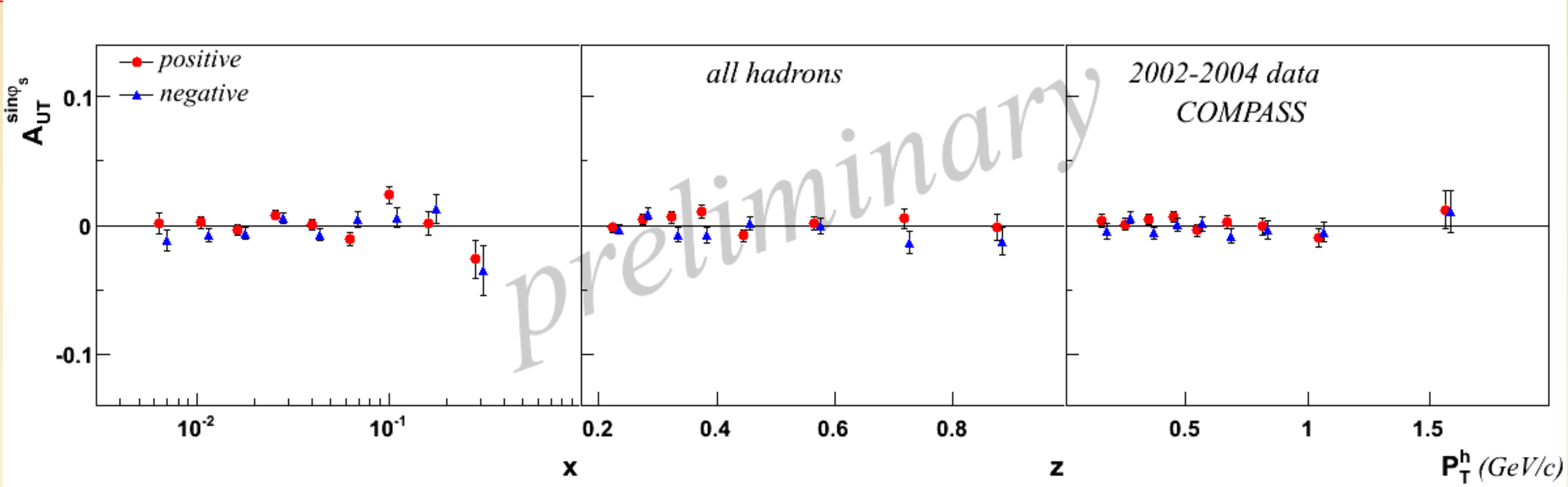


$$F_{UT}^{\sin(3\phi_h-\phi_s)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$$

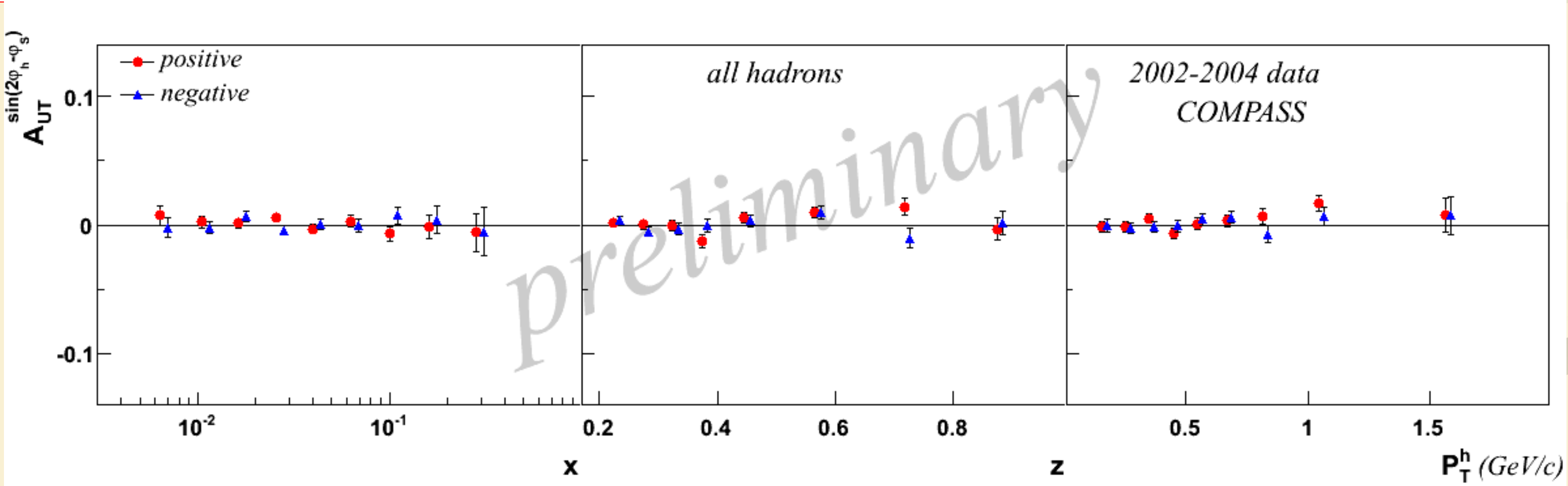


Other SSA: Twist-3 - Deuteron

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

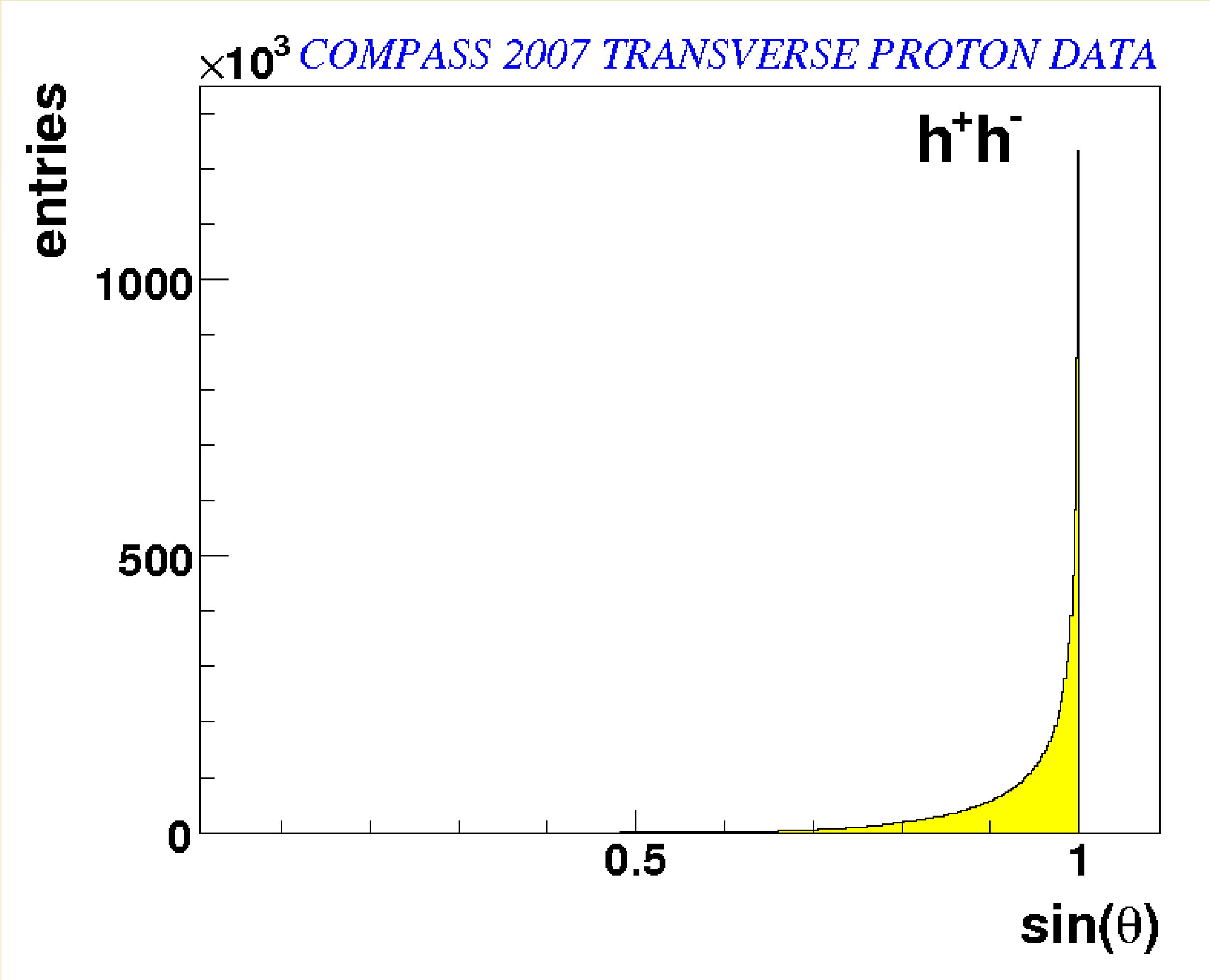


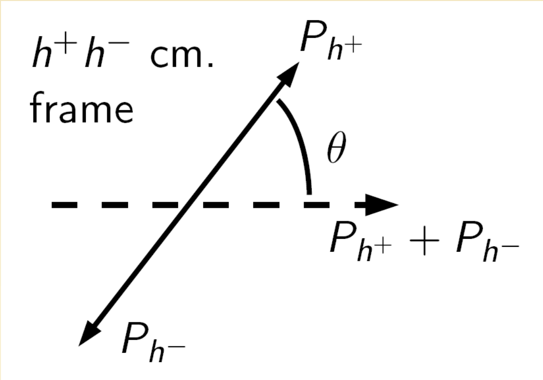
$$F_{UT}^{\sin(2\phi_h-\phi_s)} \propto \frac{M}{Q}\left(h_{1T}^{\perp q} \otimes H_{1q}^{\perp h} + f_{1T}^{\perp q} \otimes D_{1q}^h\right)$$



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

Two Hadron Asymmetries – Proton Data



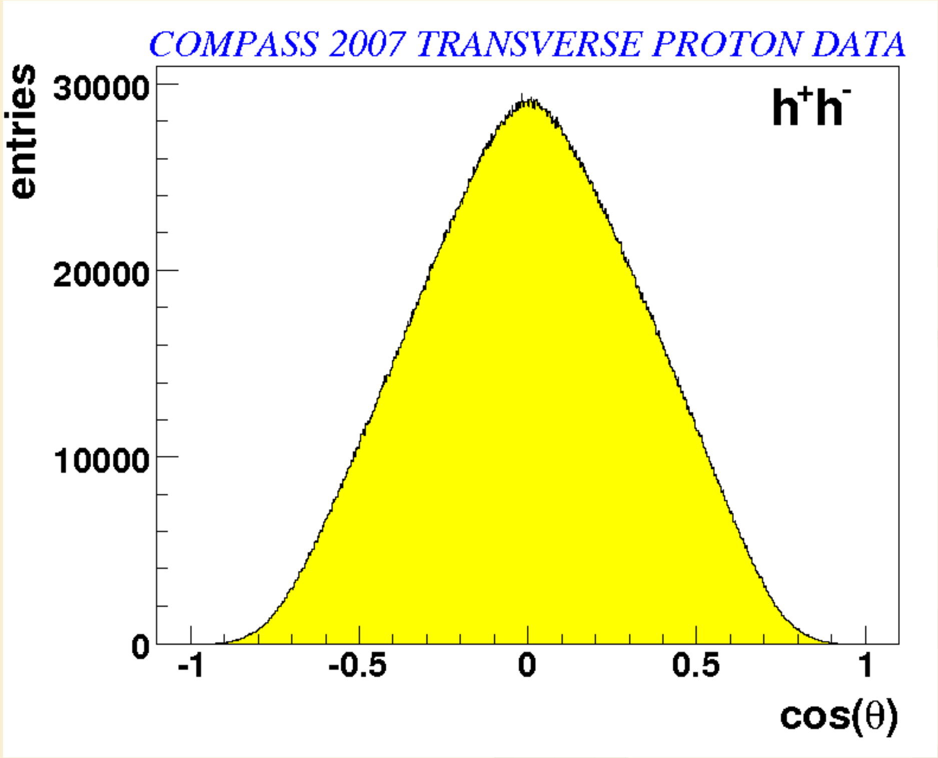


sinθ can be neglected

Two Hadron Asymmetries: Partial Wave Expansion – Proton Data

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

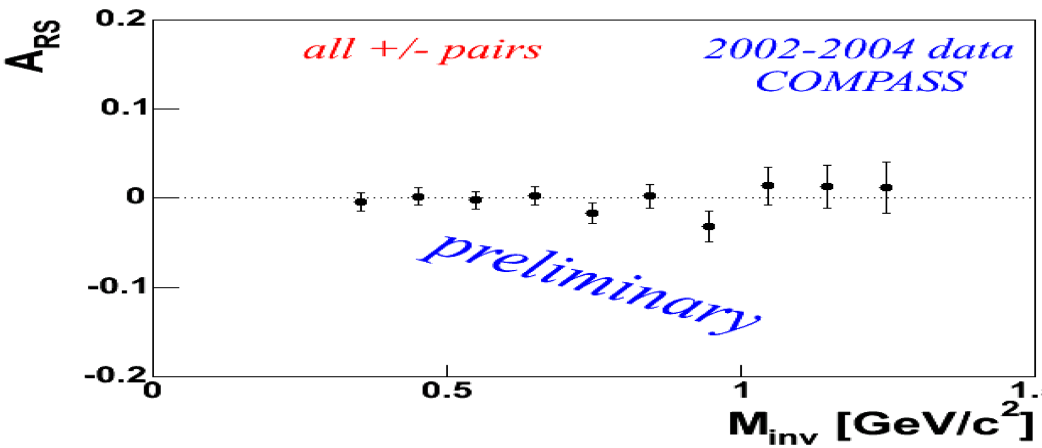
A. Bacchetta, hep-ph/0708037

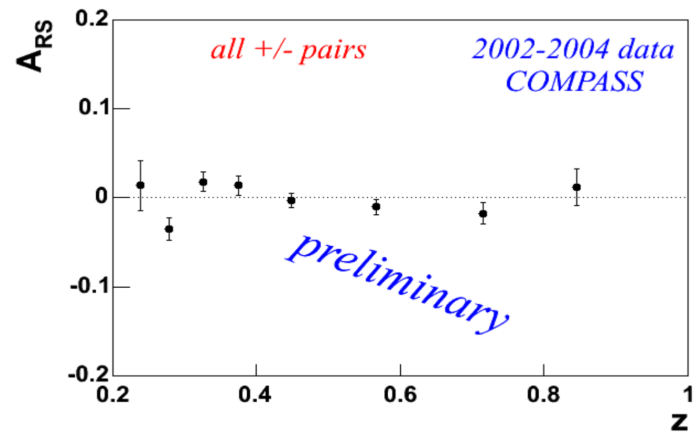


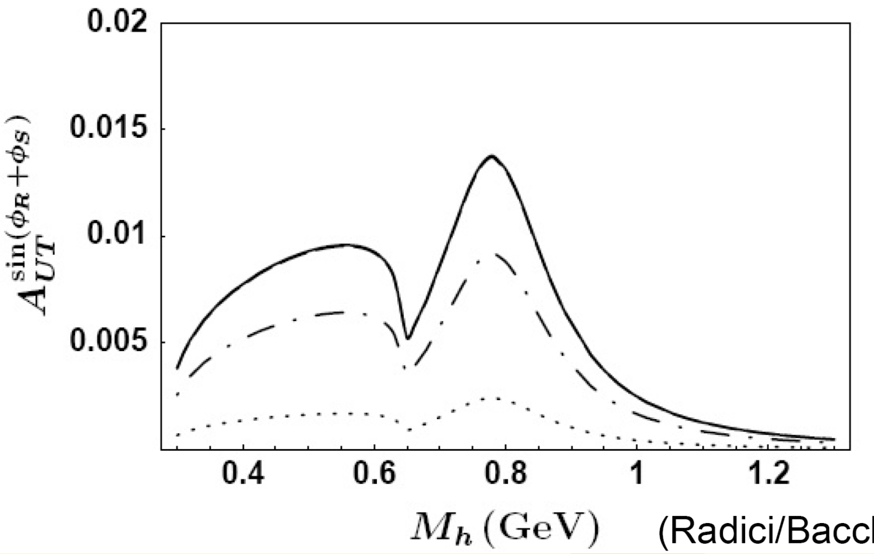
$\langle\cos\theta\rangle = 0.01$

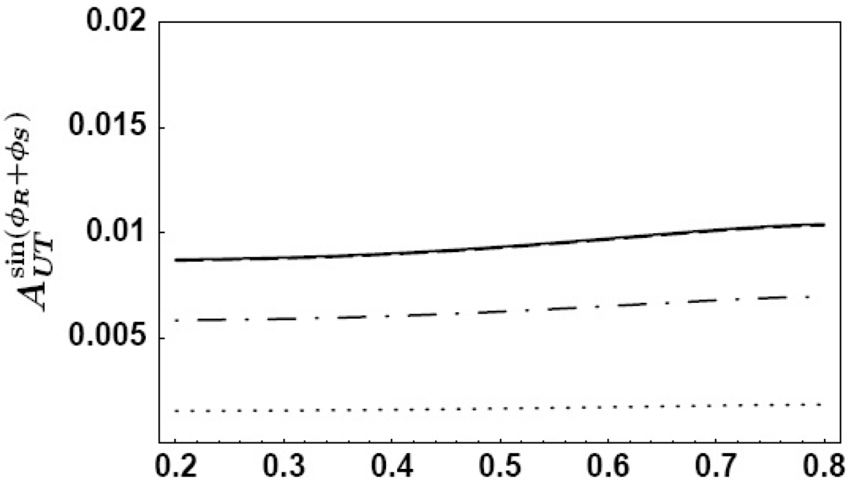
Two Hadron Asymmetries – Deuteron Data

Small asymmetries are expected:









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

Λ Polarimetry – Proton Data
Event Selection

- Secondary vertex downstream of primary vertex.
- $P_T > 23$ MeV/c to exclude e^+e^- pairs
- Proton and pion momenta > 1 GeV/c
- $Q^2 > 1$ $(GeV/c)^2$
- $0.1 < y < 0.9$
- Use of RICH (2007 data)
- Λ decay distance $D_\Lambda > 7\ \sigma_D$
- Collinearity < 10 mrad

Λ Polarimetry – Deuteron Data