COMPASS RESULTS on TMDs and TRANSVERSITY

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on behalf of the COMPASS Collaboration

SPIN-PRAHA-2006

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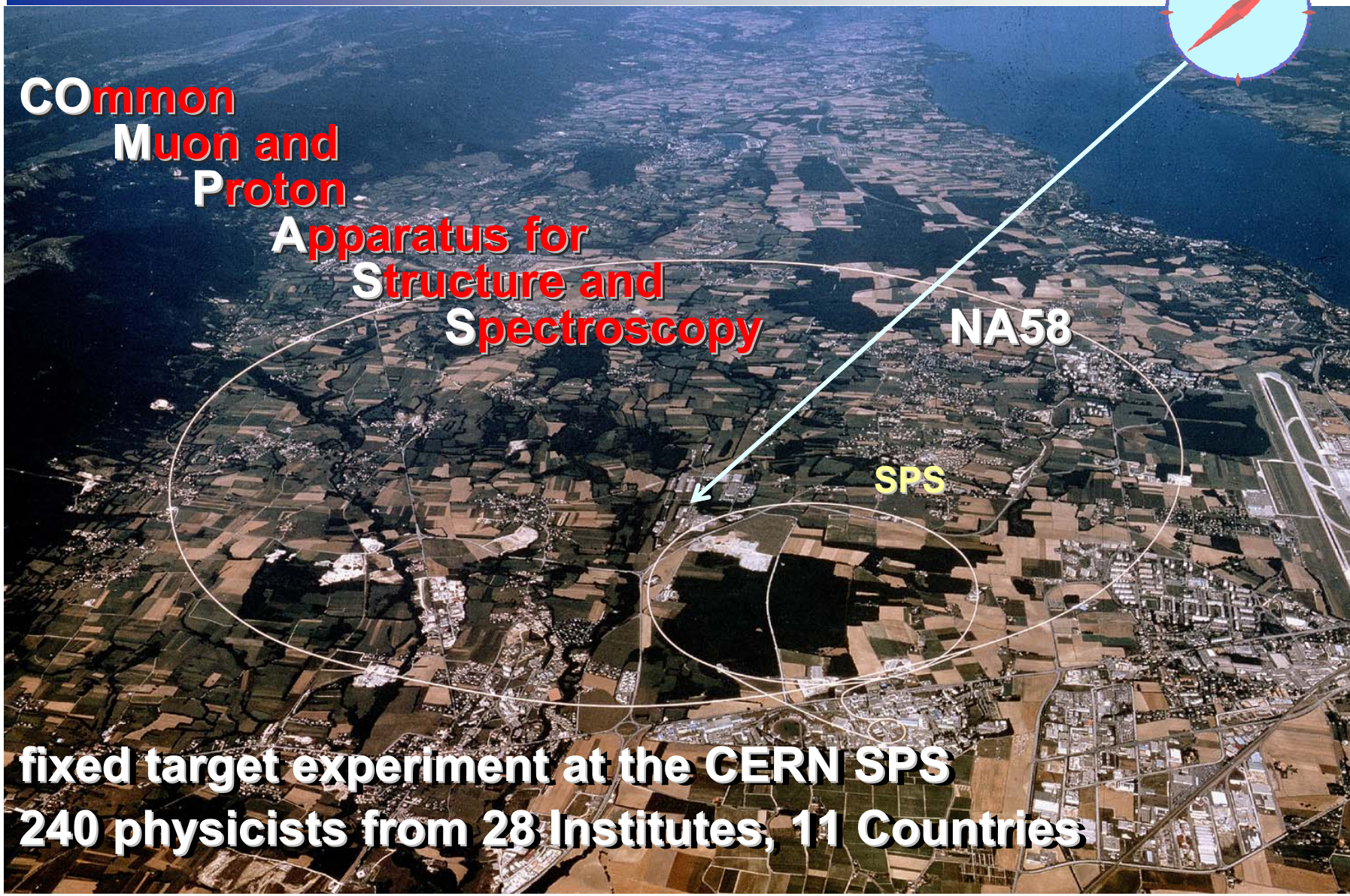
CONTENT

- THE EXPERIMENT
- TRANSVERSE SPIN PHYSICS
- PHYSICS RESULTS
  - Collins and Sivers asymmetries
  - Two hadron asymmetries
  - Λ polarimetry
- SUMMARY AND OUTLOOK

- **THE EXPERIMENT**
- TRANSVERSE SPIN PHYSICS
- PHYSICS RESULTS
  - Collins and Sivers asymmetries
  - Two hadron asymmetries
  - Λ polarimetry
- SUMMARY AND OUTLOOK

the COMPASS experiment



the COMPASS experiment

approved in 1998 with a broad physics programme

- **hadron spectroscopy (π,K,p beams)**
- **nucleon spin structure (muon beam, polarised p and d targets)**
  - **gluon contribution to nucleon spin** → *Grzegorz Brona talk*
  - **g_1, $\Delta\Sigma$, Δq flavour decomposition** → *Helena Santos talk*
  - **Λ physics**
  - ***transversity***

data taking started in 2002

2002-2004 **(pilot run with π beam in 2004)**

- **muon beam** **momentum 160 GeV/c**
  longitudinal polarisation -76%
  intensity $2 \cdot 10^8$ μ^+/spill (4.8s/16.2s)
- **polarised deuteron target** **~80% L, 20% T**

2006: muon beam

2007 - …: hadron and muon beams → *Horst Fischer talk*

the spectrometer (2004)

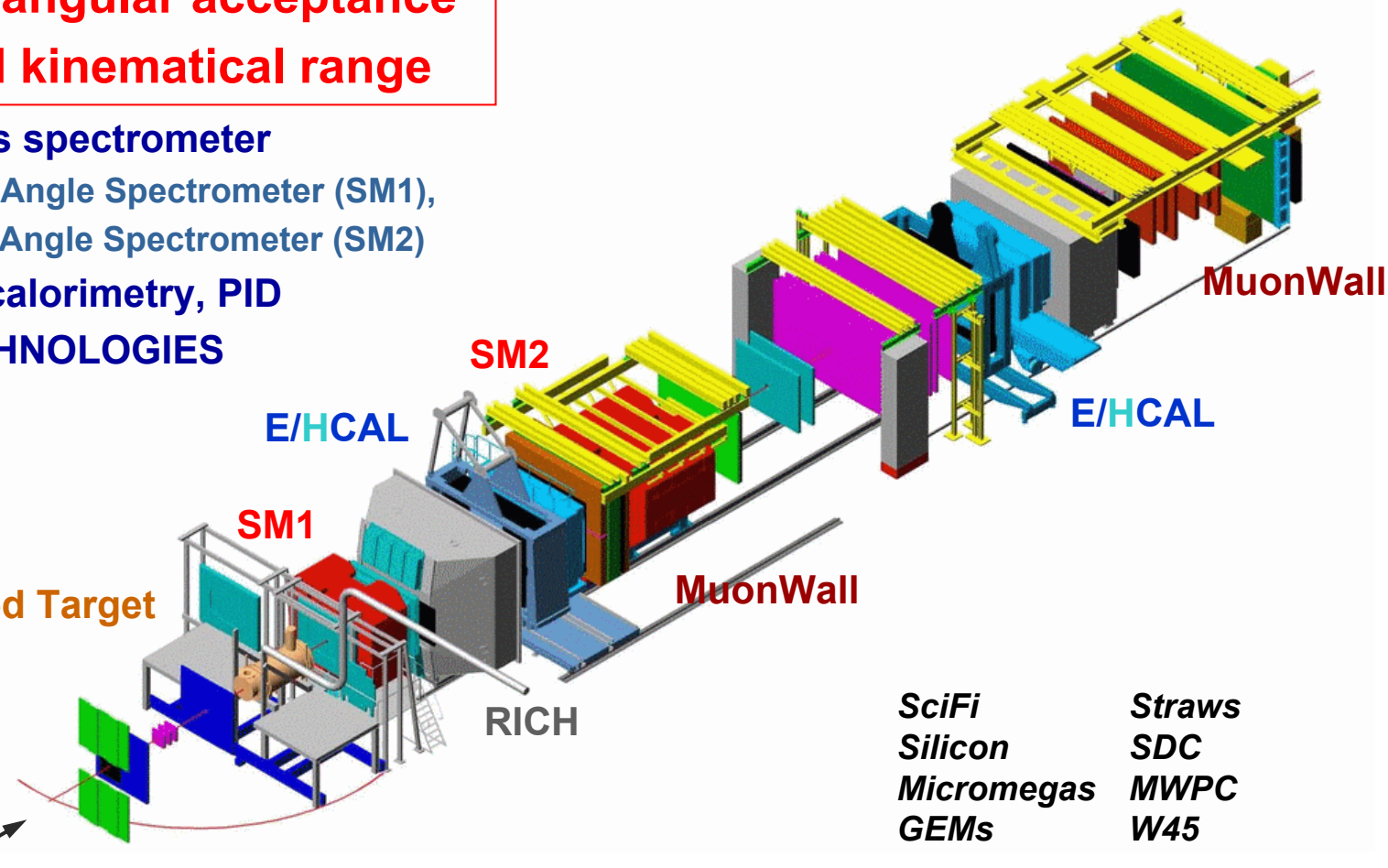
- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

Large Angle Spectrometer (SM1),
Small Angle Spectrometer (SM2)

tracking, calorimetry, PID

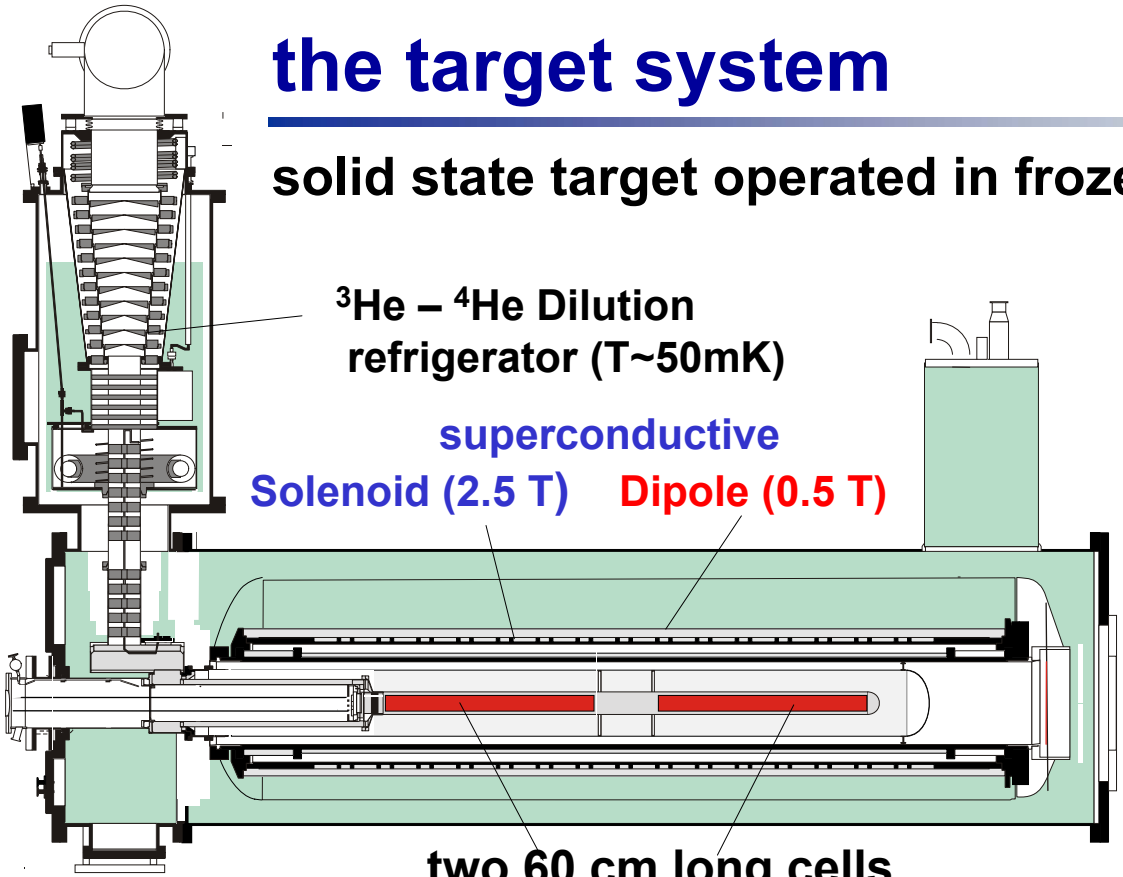
NEW TECHNOLOGIES



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

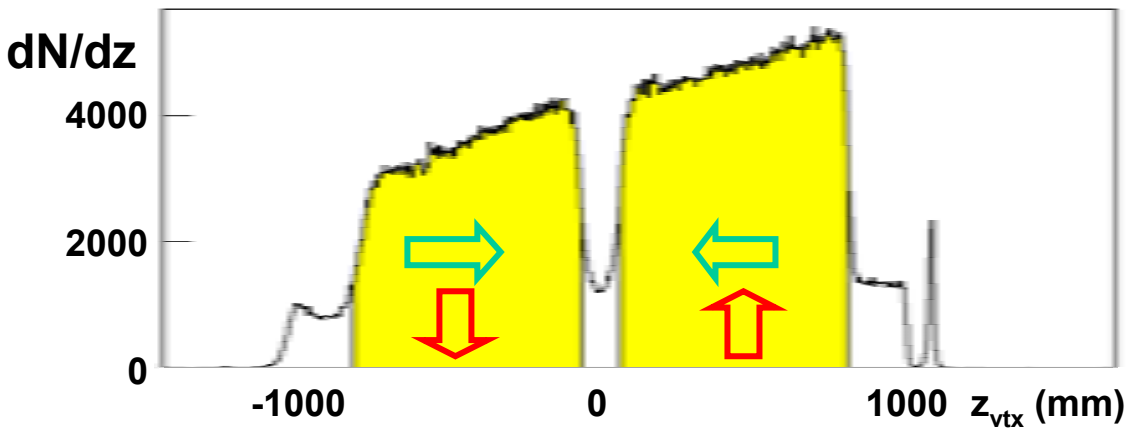
the target system

solid state target operated in frozen spin mode



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

→ *Micheal Finger talk*



during data taking with transverse polarization

- **dipole field always ↑**
- **polarization reversal in the 2 cells after ~ 5 days** (systematics)

data taking 2002-2004

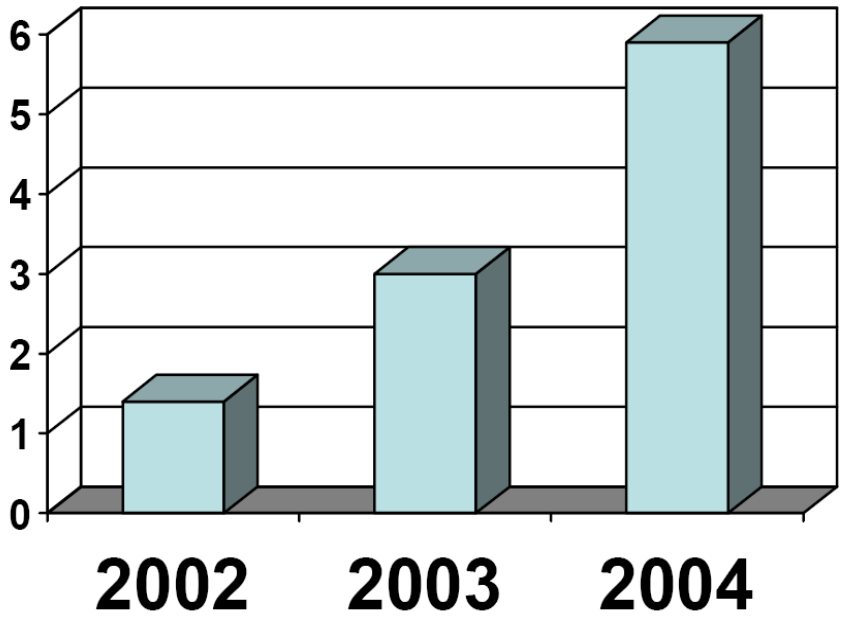
transversely polarised deuteron target
~ 20% of the running time

2002	11 days of data taking (19),	2 periods
2003	9 days of data taking (14),	1 period
2004	14 days of data taking (24),	2 periods

trigger (large x, Q^2)

DAQ, on line filter

reconstructed DIS events (10^6)



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TRANSVERSE SPIN PHYSICS

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

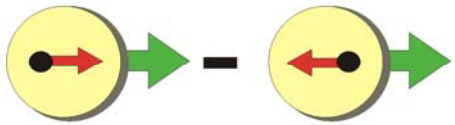
(all of equal importance !)

$q(x)$

momentum distribution

distribution of unpolarised partons in an unpolarised nucleon — **well known**

$\Delta q(x)$



helicity distribution

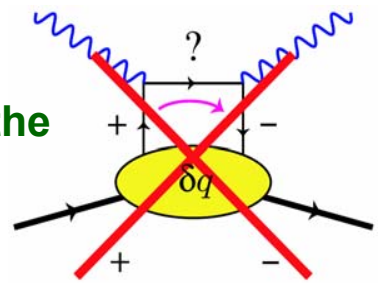
distribution of longitudinally polarised partons in a longitudinally polarised nucleon — **~ known**

$\Delta_T q(x)$
or h_1 or δq

transversity distribution

distribution of transversely polarised quarks in a transversely polarised nucleon — **unknown !**

$\Delta_T q(x)$ decouples from leading twist DIS because the helicity of quark must flip



06, A. Martin

measuring $\Delta_T q(x)$

chiral-odd: requires another chiral-odd partner
→ cannot be measured in inclusive DIS

can be measured in

- **semi-inclusive DIS** **(e.g. COMPASS, HERMES, JLAB)**
  convolution with a spin dependent fragmentation function

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

- **hard pp scattering** **(e.g. RHIC)**
  Drell-Yan → $\Delta_T q \cdot \Delta_T \bar{q}$ ***small effect***
  single spin asymmetries ***Sivers***

- **hard p pbar scattering** **(e.g. GSI)**
  Drell-Yan → $\Delta_T q \cdot \Delta_T q \cong \Delta_T u \cdot \Delta_T u$ ***flavor separation ?***

measuring $\Delta_T q(x)$ in SIDIS

use “quark polarimetry”, i.e. spin dependent fragmentation functions

possible channels:

- single hadron asymmetries (using the “Collins effect”)
- two hadron asymmetries
- Λ polarisation

from COMPASS, results for all of them

- THE EXPERIMENT
- TRANSVERSE SPIN PHYSICS
- **COMPASS RESULTS**
  - **Collins and Sivers asymmetries**
    - **positive and negative hadrons**
    - $\pi^{\pm}$, $K^{\pm}$
  - Two hadron asymmetries
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single hadron asymmetries

Collins effect:

fragmentation function of a transversely polarised quark q into an unpolarised hadron h: $D_q^h + \Delta_T^0 D_q^h \sin \Phi_C$

spin dependent part

"Collins fragmentation function"

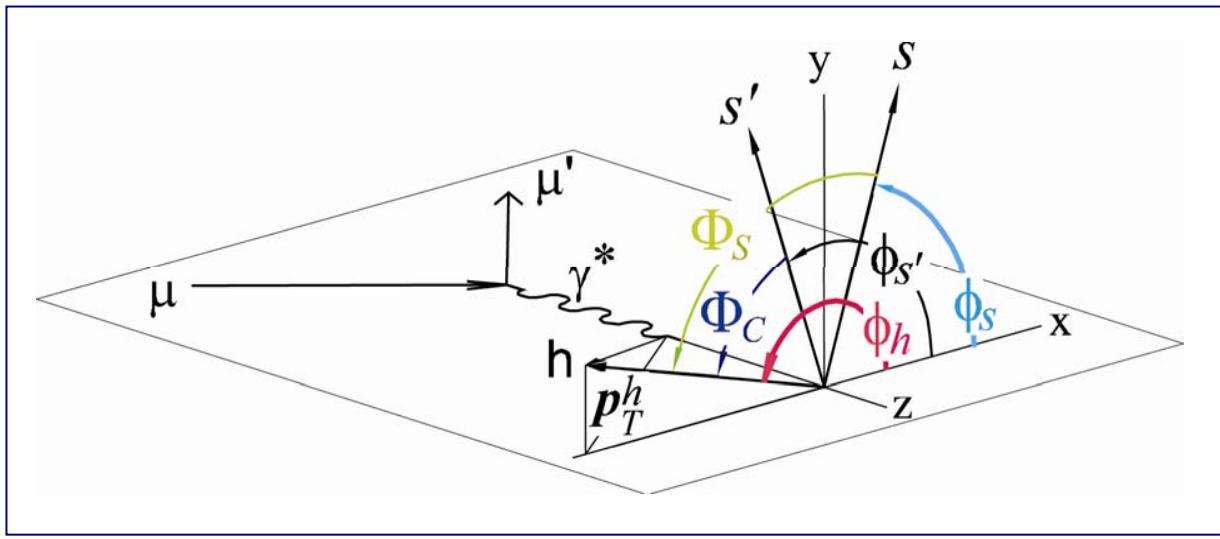
"Collins angle" $\Phi_C = \phi_h - \phi_{s'} = \phi_h + \phi_s - \pi$

ϕ_h azimuthal angle of the **hadron**

$\phi_{s'}$ azimuthal angle of the transverse spin of the **struck quark**

$\phi_{s'} = \pi - \phi_s$

ϕ_s azimuthal angle of the transverse spin of the **initial quark** (nucleon spin)



single hadron Collins asymmetry

in SIDIS $N_h^{\pm}(\Phi_C) = N_h^0 \cdot \left\{ 1 \pm A_C^h \cdot \sin\Phi_C \right\}$

measured asymmetry:

$A_C^h = f \cdot P_T \cdot D \cdot A_{Coll}$

D spin transfer coefficient
P_T target polarisation

f target polarisation dilution factor

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

$\Delta_T q$ **transversity distribution function**

$\Delta_T^0 D_q^h$ **Collins fragmentation function**
(being measured at BELLE: different from zero)

single hadron Sivers asymmetry

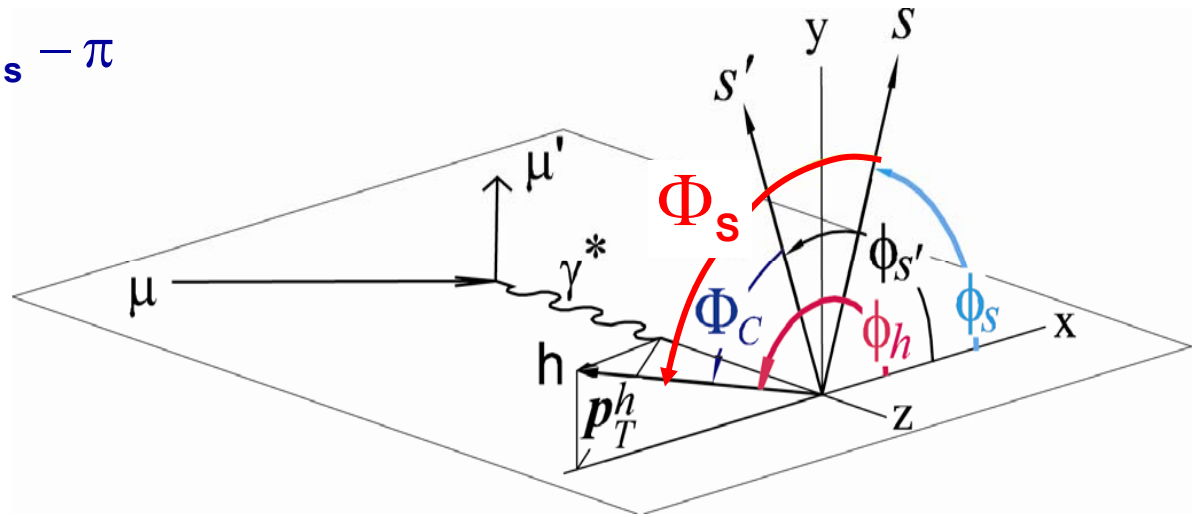
Sivers effect: correlation between the nucleon spin and the quark motion

the parton density inside a transversely polarised nucleon depends on the relative azimuthal angle between the nucleon spin and the quark transverse momentum

modulation in Φ_S of the hadron distribution

"Sivers angle" $\Phi_S = \phi_h - \phi_s$

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



single hadron Sivers asymmetry

modulation in Φ_S of the hadron distribution

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

measured asymmetry:

$$A_S^h = f \cdot P_T \cdot A_{Siv}$$

f target polarisation dilution factor

P_T target polarisation

$$A_{Siv} \cong \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}$$

$\Delta_0^T q$ **Sivers distribution function**

single hadron asymmetries

SIDIS cross-section $d\sigma = d\sigma_0 + d\sigma_L + d\sigma_T$

unpol B and T — $d\sigma_0$; *long pol B and/or T* — $d\sigma_L$; **transvely polarised target** — $d\sigma_T$

at leading order

$$d\sigma_T \propto S_T \cdot \left[\underbrace{a_1 \cdot \sin\Phi_{\mathbf{c}}}_{\textbf{Collins}} + \underbrace{a_2 \cdot \sin\Phi_{\mathbf{s}}}_{\textbf{Sivers}} + a_3 \cdot \sin\left(3\phi_{\mathbf{h}} - \phi_{\mathbf{s}}\right) + \lambda_{\mathbf{b}} \cdot a_4 \cdot \cos\left(\phi_{\mathbf{h}} - \phi_{\mathbf{s}}\right) \right]$$

long. beam polarization

independent angles

→ **independent extraction of the asymmetries from the same data**

single hadron asymmetries

2005: published *[PRL 94 (2005) 202002]*

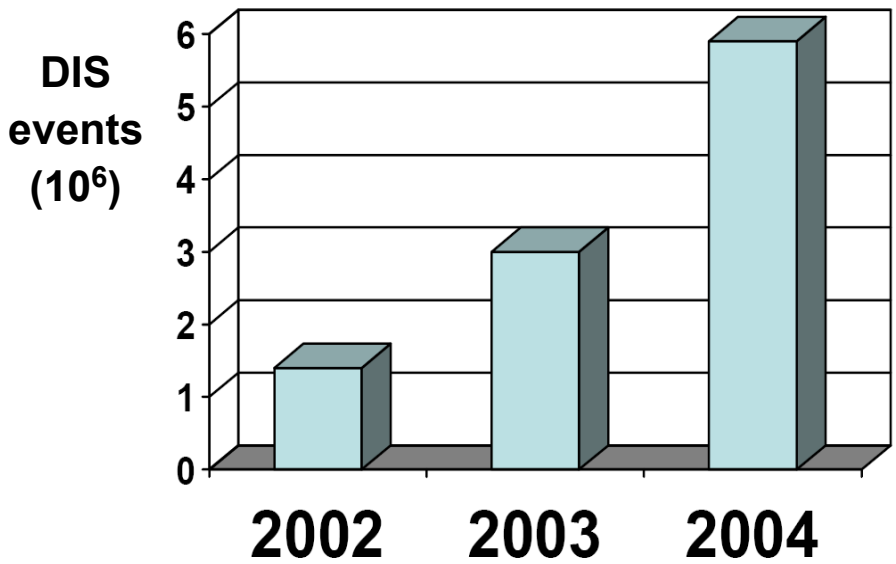
Collins and Sivers asymmetries from 2002 data

March 2006: preliminary results for

Collins and Sivers asymmetries from 2002-2004 data

(DIS06)

factor ~ 8 in statistics !



single hadron asymmetries

data analysis essentially the same as for 2002 data

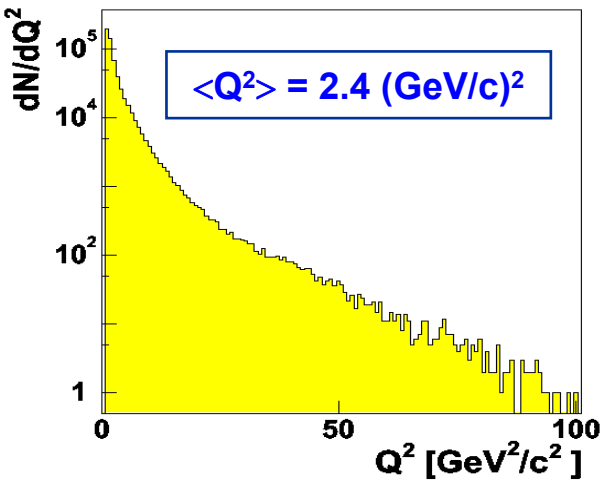
event selection

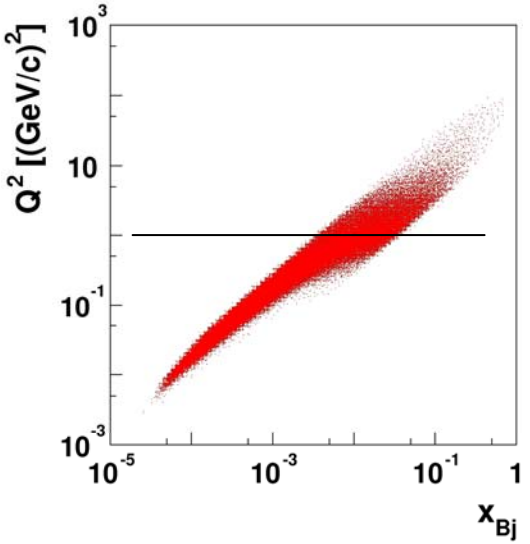
DIS events

$Q^2 > 1$ GeV^2

$W^2 > 25$ GeV^2

$0.1 < y < 0.9$





2002 data

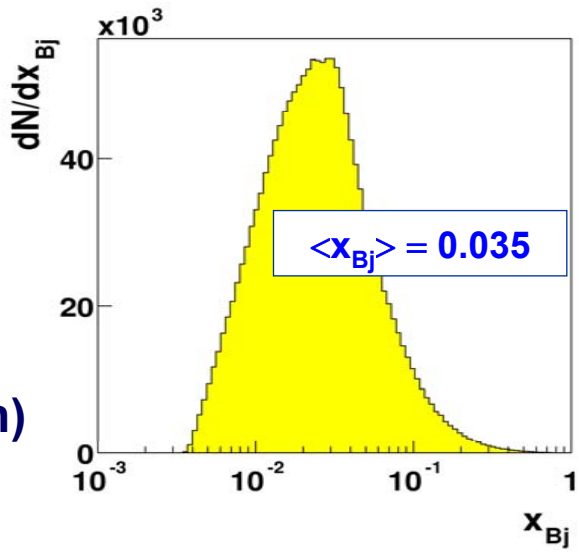
identified hadrons

$p^h_t > 0.1$ GeV/c

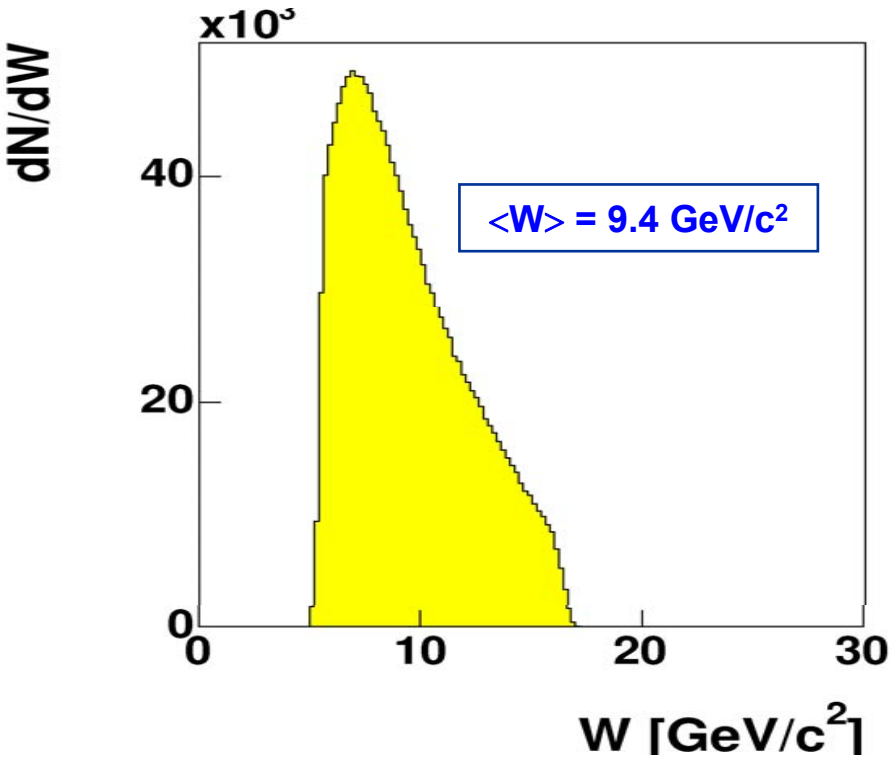
$z > 0.2$ (all h)

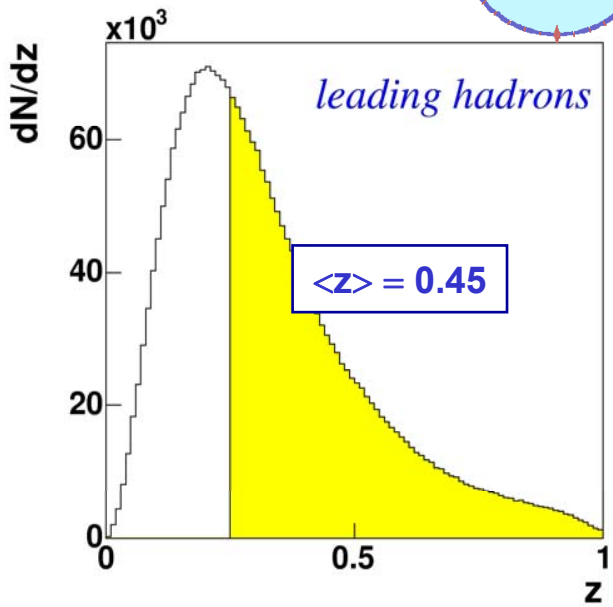
or

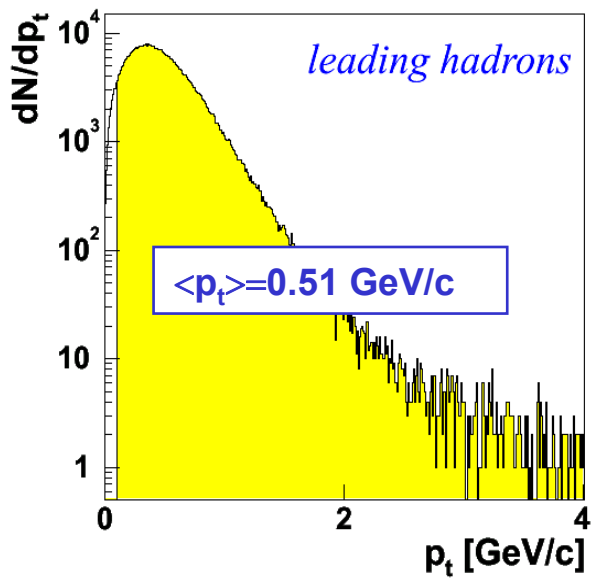
$z > 0.25$ (leading h)



single hadron asymmetries







2002 data

single hadron asymmetries

systematics

estimator $$F(\Phi_C) = \frac{N^{+}_{h,u}(\Phi_C)\cdot N^{+}_{h,d}(\Phi_C)}{N^{-}_{h,u}(\Phi_C)\cdot N^{-}_{h,d}(\Phi_C)} \cong 1 + 4\cdot A^{h}_{C}\cdot \sin\Phi_C$$

- minimizes acceptance effects
- spin independent terms cancel at 1st order

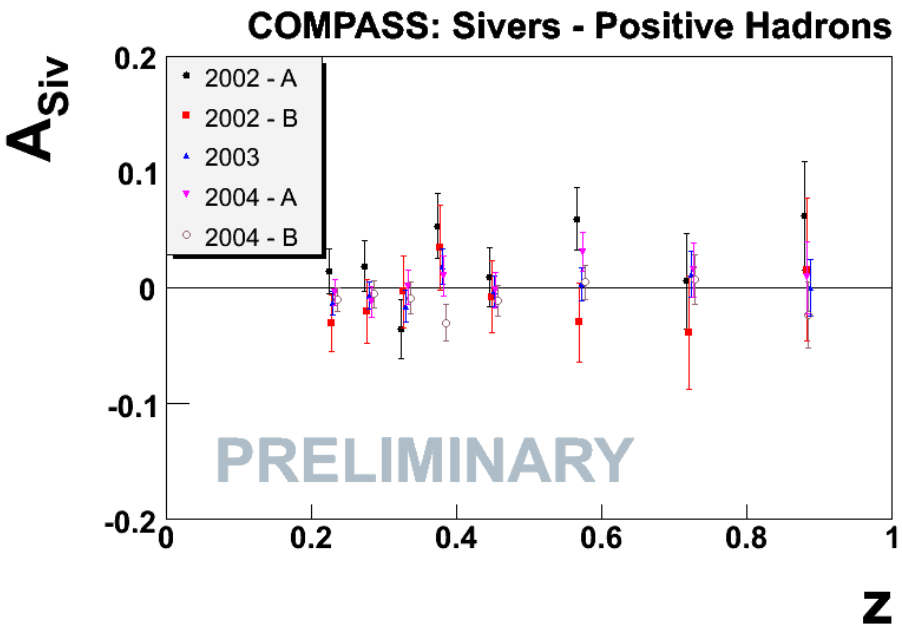
extensive studies

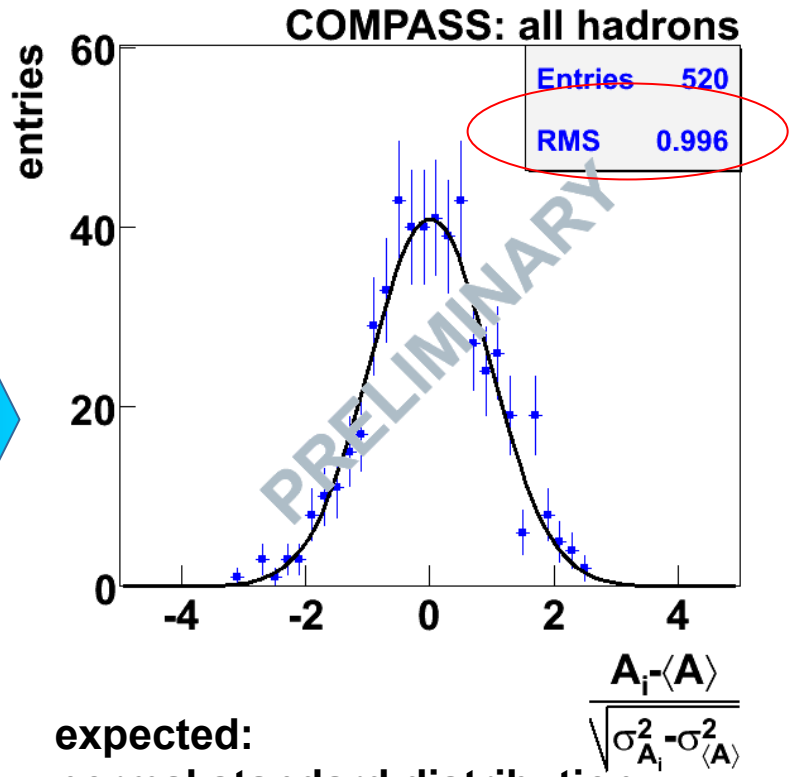
- **false asymmetries**
  splitting target cells and scrambling the data
- **stability in time of acceptance / efficiency**
  R-test
- **stability of the measured asymmetries**
  dividing periods in time, splitting target cells and spectrometer, making bins in z and p_t ,changing Φ binning, …
- **use of different estimators**
- **2-dimensional fit to look for correlations**
- **quality of the fit**
- **….**

single hadron asymmetries

systematics (cont)

- ....
- consistency of the results from the different data taking periods



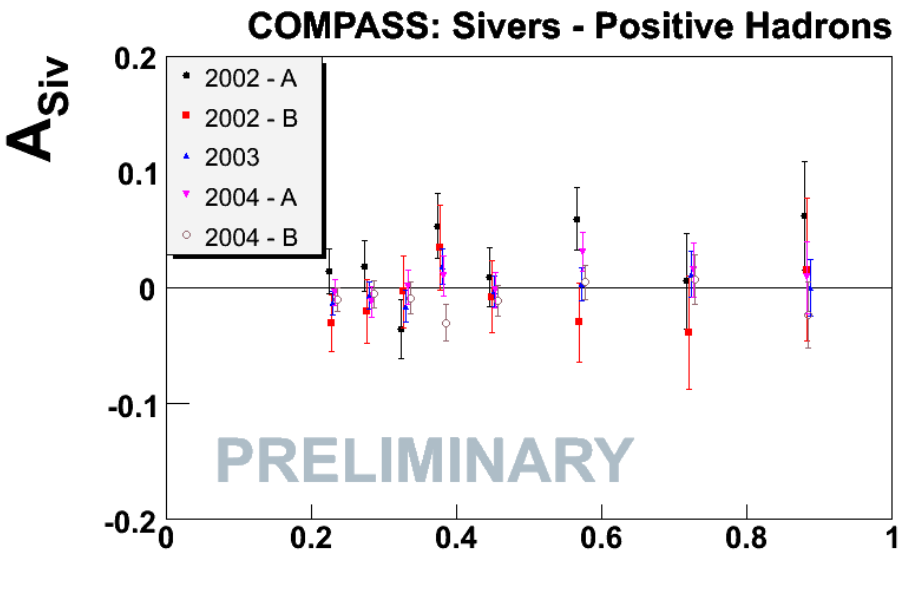


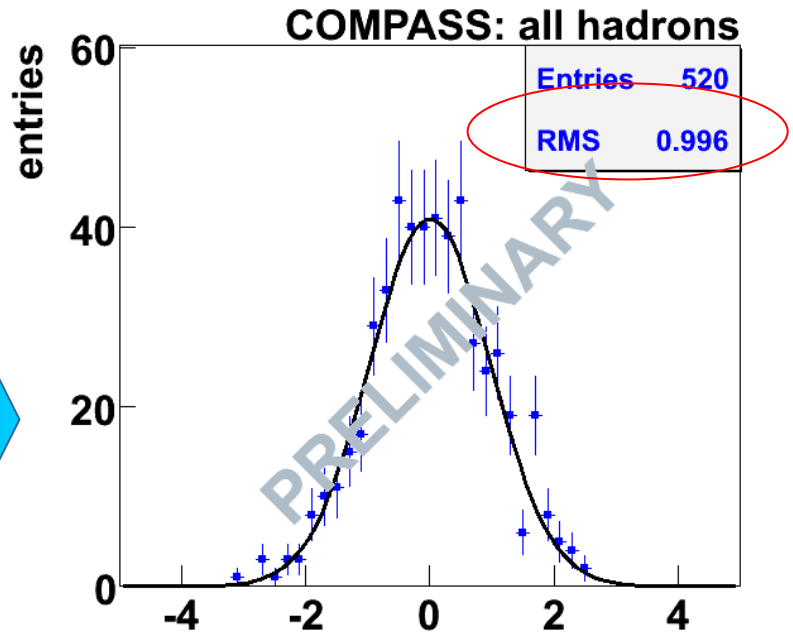
expected:
normal standard distribution

single hadron asymmetries

systematics (cont)

- ....
- consistency of the results from the different data taking periods



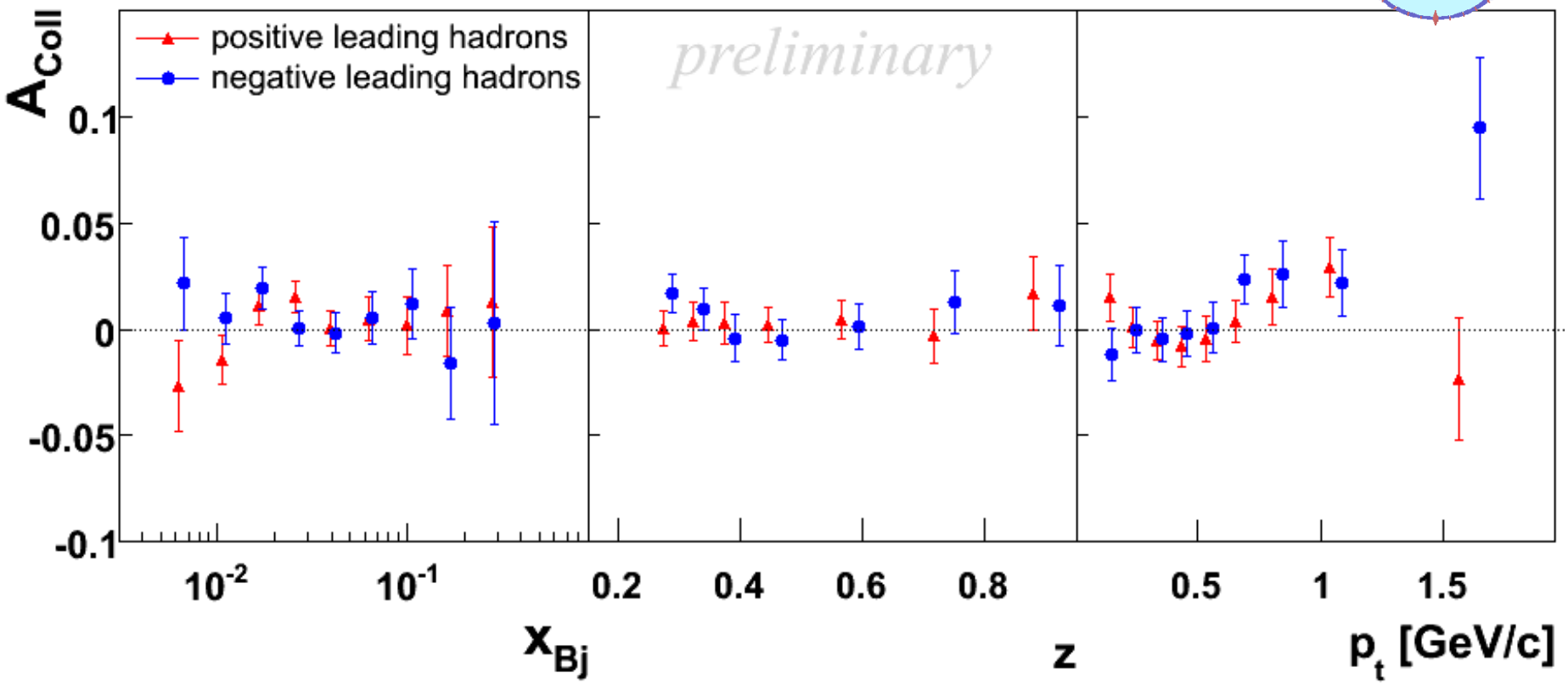


CONCLUSION:

all the effects are compatible with the statistical fluctuations

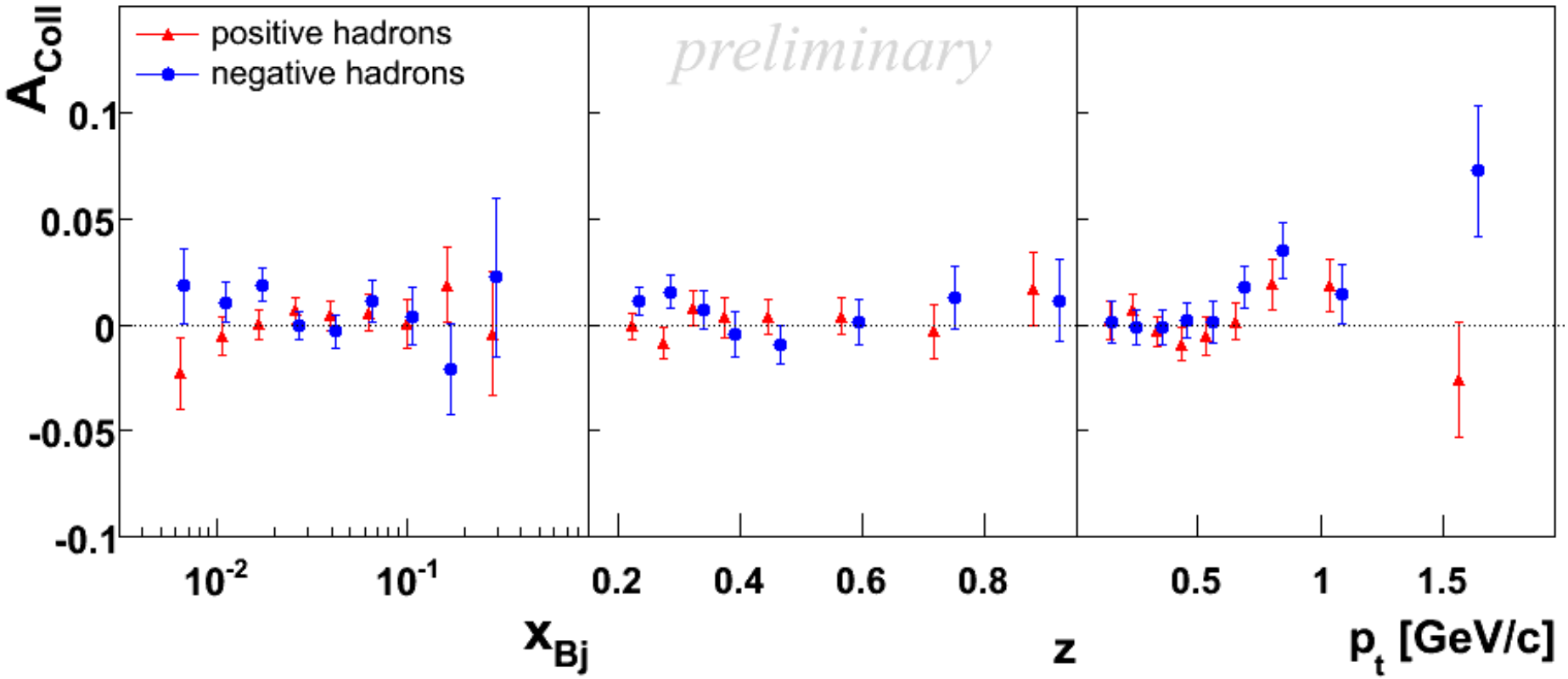
our systematic errors are considerably smaller than the statistical errors

Collins Asymmetries 2002-2004



- small errors (~1%)
- small asymmetries, compatible with 0, for +ve and -ve hadrons

Collins Asymmetries 2002-2004



- small errors (~1%)
- small asymmetries, compatible with 0, for +ve and -ve hadrons

cancellation between p and n?

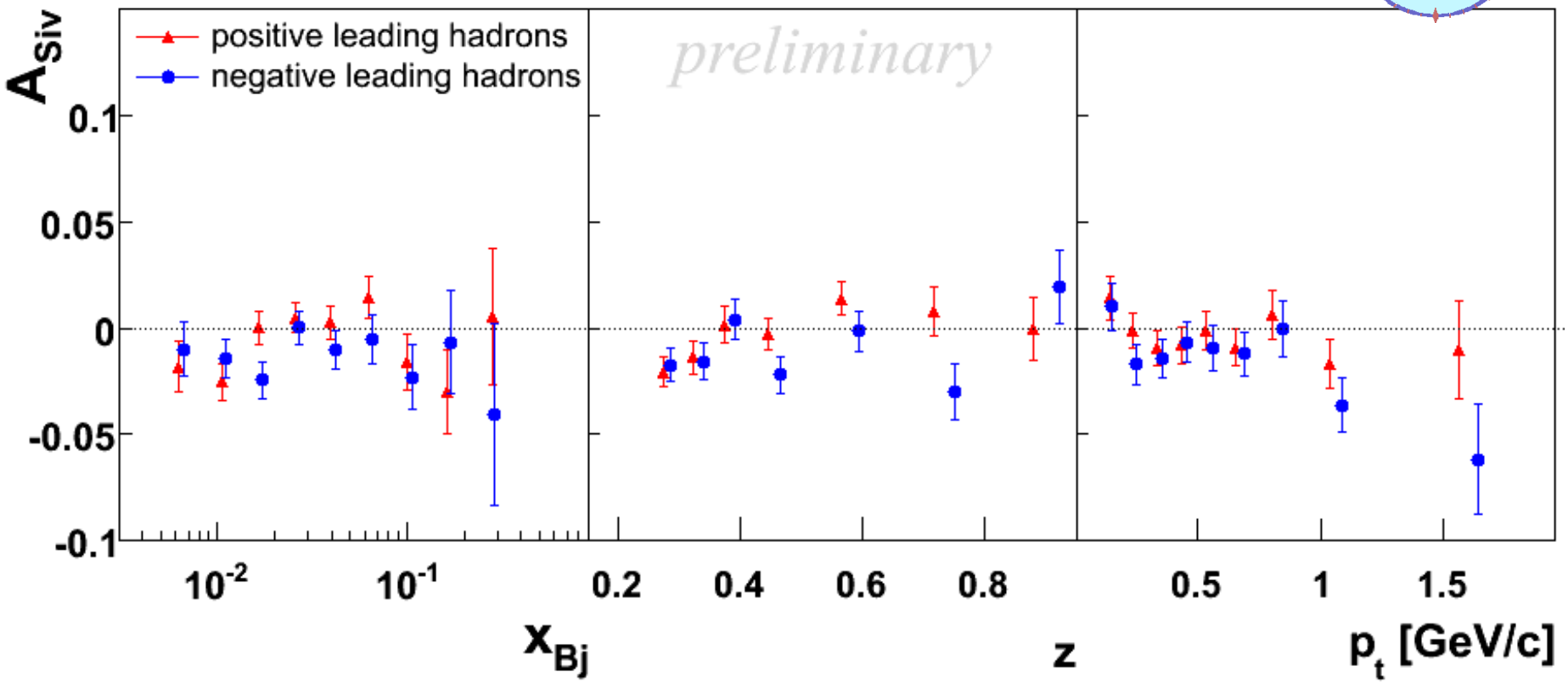
(lh and ah)

HERMES: u quark contribution

$$A_{Coll,d}^{\pi^+} \approx \left(\Delta_T u + \Delta_T d\right)\cdot\left(4\Delta_T^0 D_u^{\pi^+} + \Delta_T^0 D_d^{\pi^+}\right)$$

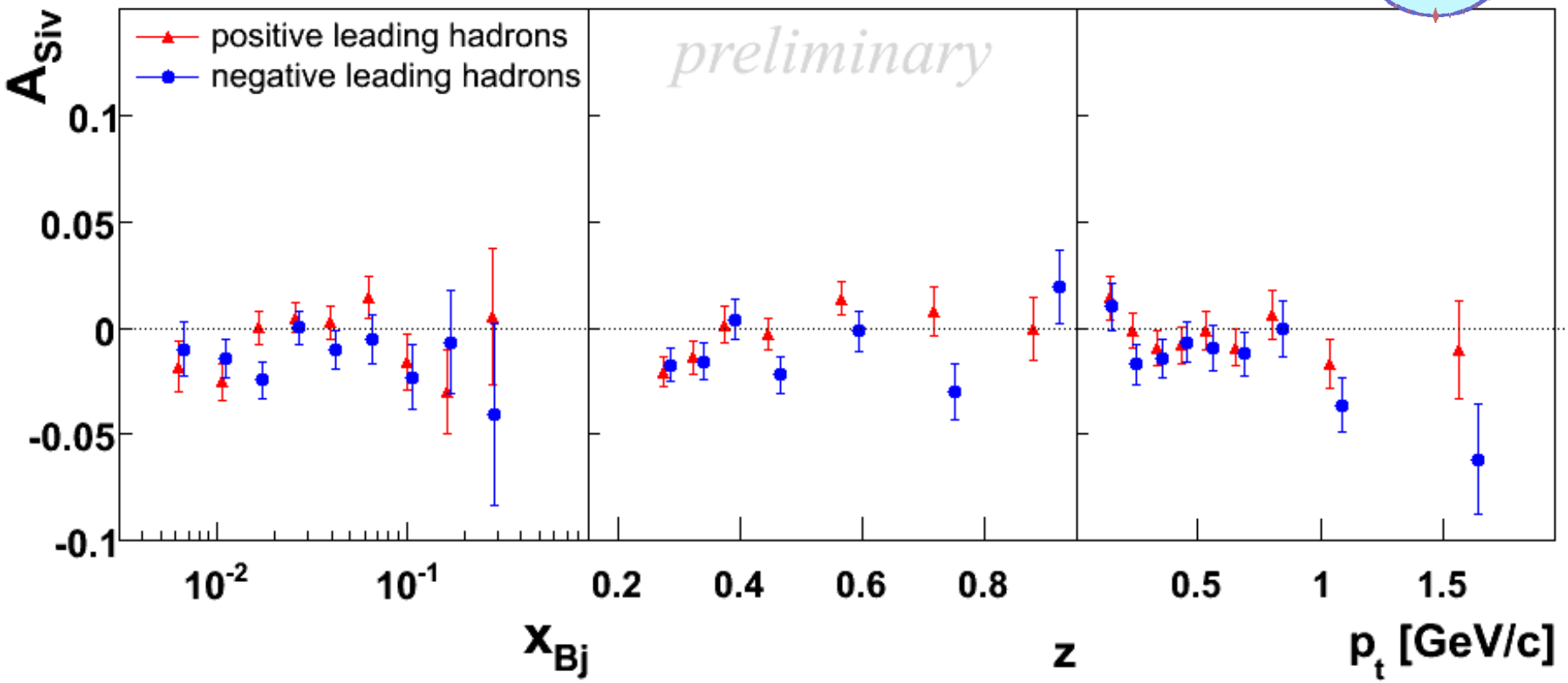
$$A_{Coll,d}^{\pi^-} \approx \left(\Delta_T u + \Delta_T d\right)\cdot\left(\Delta_T^0 D_u^{\pi^+} + 4\Delta_T^0 D_d^{\pi^+}\right)$$

Sivers Asymmetries 2002-2004



- small errors (~1%)
- small asymmetries, compatible with 0, for +ve and -ve hadrons

Sivers Asymmetries 2002-2004



- small errors (~1%)
- small asymmetries, compatible with 0, for +ve and -ve hadrons

~ cancellation between p and n

$$A_{Siv,d} \approx \left(\Delta_0^T u + \Delta_0^T d\right) \cdot D$$

(lh and ah)

in agreement with HERMES

SPIN-PRAHA-2006, A. Martin

Collins - comparison with theory

some of the recent phenomenological studies

W. Vogelsang and F. Yuan
PRD72 (2005) 054028

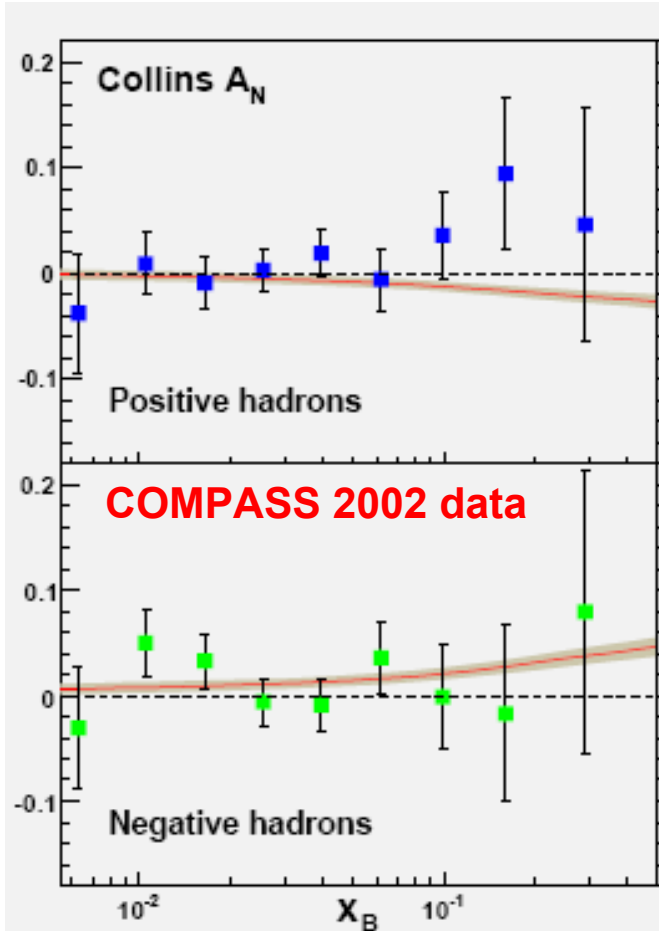
- $\Delta_T q$ from saturation of Soffer inequality
- 2 parameter fit to HERMES π data to extract the Collins FF

  → unfav FF ~ - fav FF

  (χ^2/ν ~ 0.8)

→ very small asymmetries for d target
comparison with COMPASS 2002 data ok

in agreement with the new data



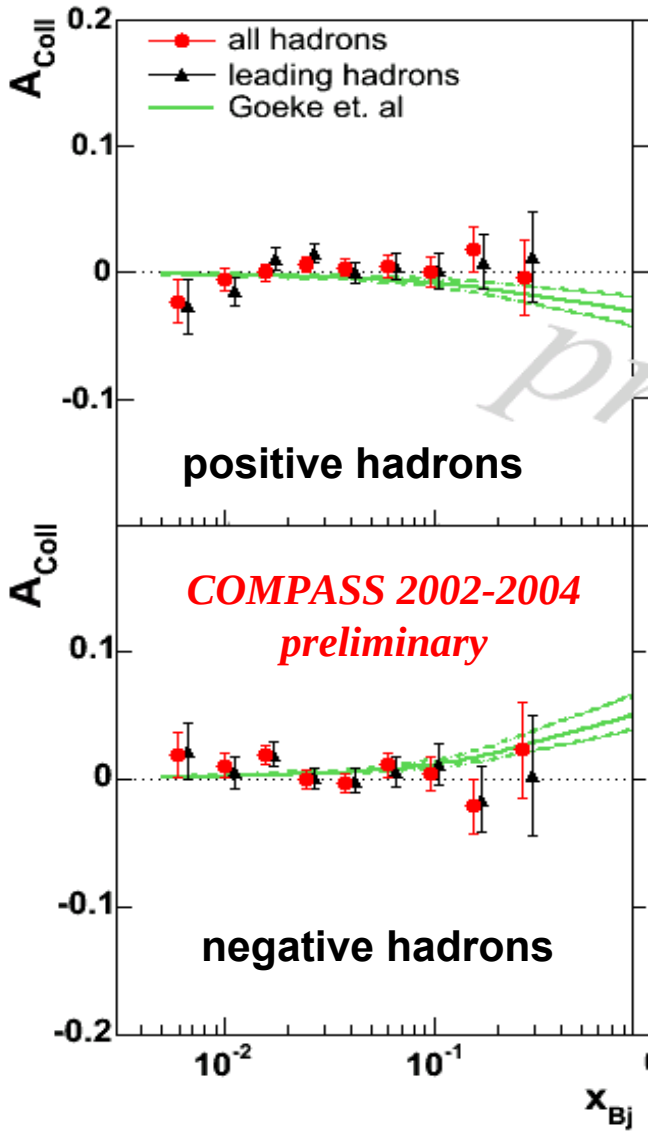
Collins - comparison with theory

A.V. Efremov, K. Goeke and P. Schweitzer,
PRD73 (2006) 094025

- including transverse momenta
- $\Delta_T q$ from chiral quark soliton model
- fit to HERMES data to get Collins FF
  → unfav FF ~ - fav FF

- agreement (absolute values) with BELLE data
- $\Delta_T d$ ~ unconstrained

→ comparison with COMPASS 2002 and 2002-2004 data ok



M. Anselmino et al.

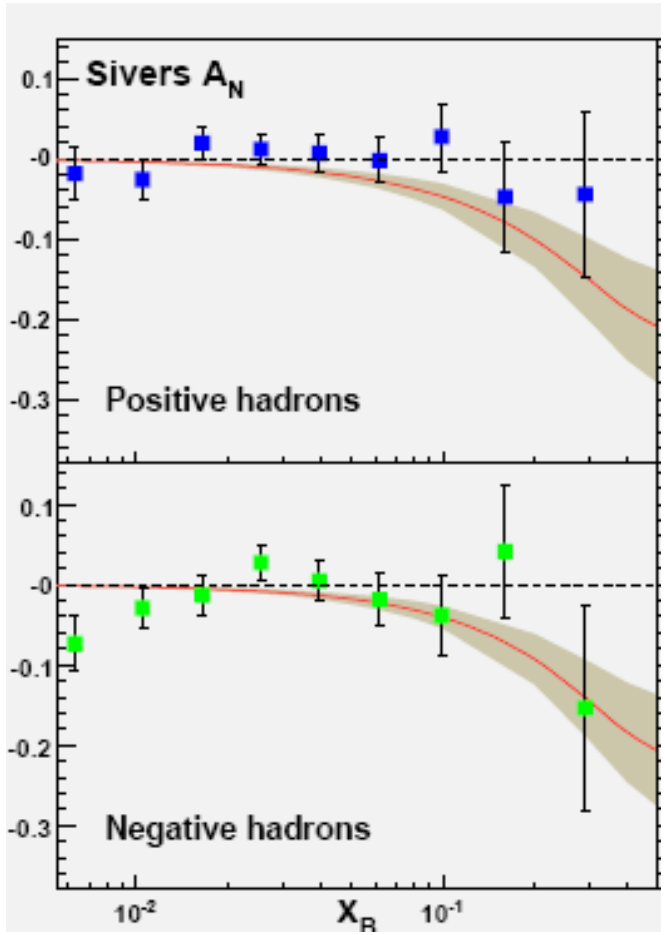
→ E. Boglione presentation at QCD-N'06

Sivers - comparison with theory

W. Vogelsang and F. Yuan
PRD72 (2005) 054028

- **2 parameter fit to HERMES π data to extract Sivers function (u and d)**
  → $\Delta_0^T d \approx -2\,\Delta_0^T u$
  due to the large π^- asymmetry
  ($\chi^2/\nu \sim 1.2$)

→ comparison with COMPASS 2002 data ok



Sivers - comparison with theory

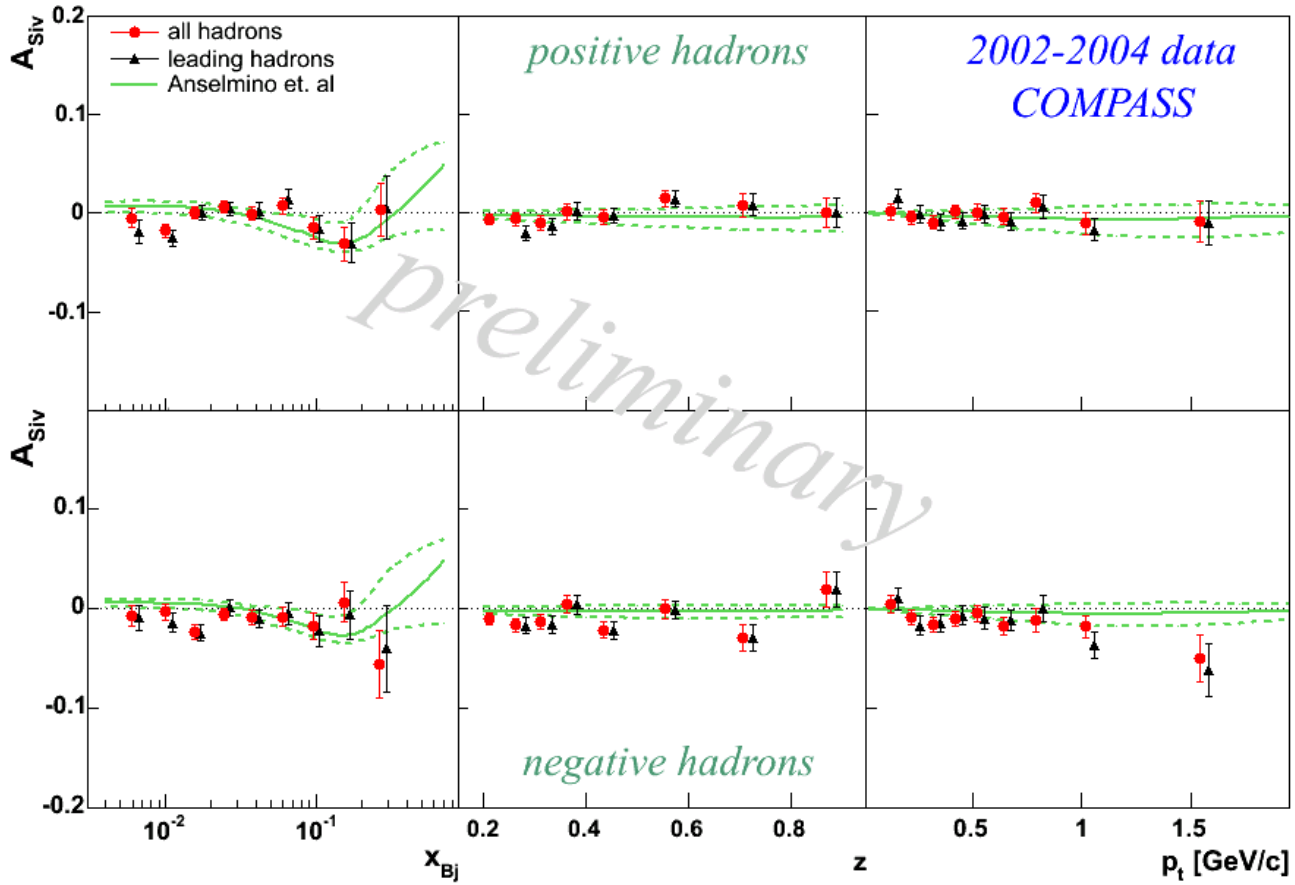
M. Anselmino et al., PRD73 (2006) 094025

- **including transverse momenta, FF from literature**
- **13 parameter fit to HERMES and COMPASS 2002 data to extract the Sivers functions**

→ $\Delta_0^T u \approx - \Delta_0^T d$

($\chi^2/\nu \sim 1.06$)

comparison with COMPASS 2002-2004 data ok



Sivers - comparison with theory

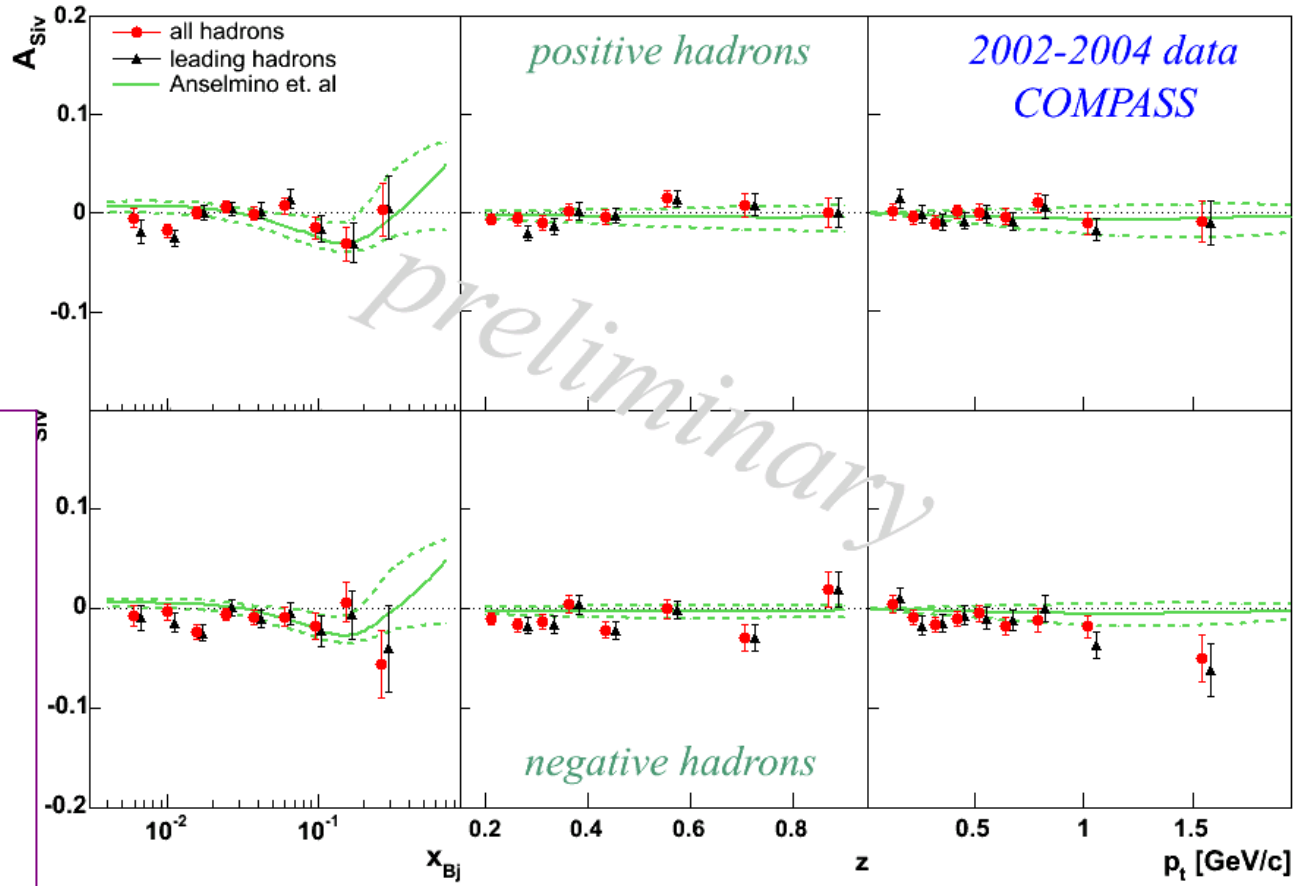
M. Anselmino et al., PRD73 (2006) 094025

- including transverse momenta, FF from literature
- 13 parameter fit to HERMES and COMPASS 2002 data to extract the Sivers functions

→ $\Delta_0^T u \approx - \Delta_0^T d$

($\chi^2/\nu \sim 1.06$)

comparison with COMPASS 2002-2004 data ok



A. Efremov et al., PLB 612 (2005) 233

- assuming $\Delta_0^T u = - \Delta_0^T d$
- fit to HERMES data ok

agreement with COMPASS data (~zero)

comparison with theory – summary

Phenomenological studies can describe at the same time

- **the BELLE FF,**
- **the HERMES (proton) and**
- **the COMPASS (deuteron) Collins and Sivers asymmetries**

First outputs:

Collins asymmetry: indication for unfav FF ~ - fav FF (surprising)

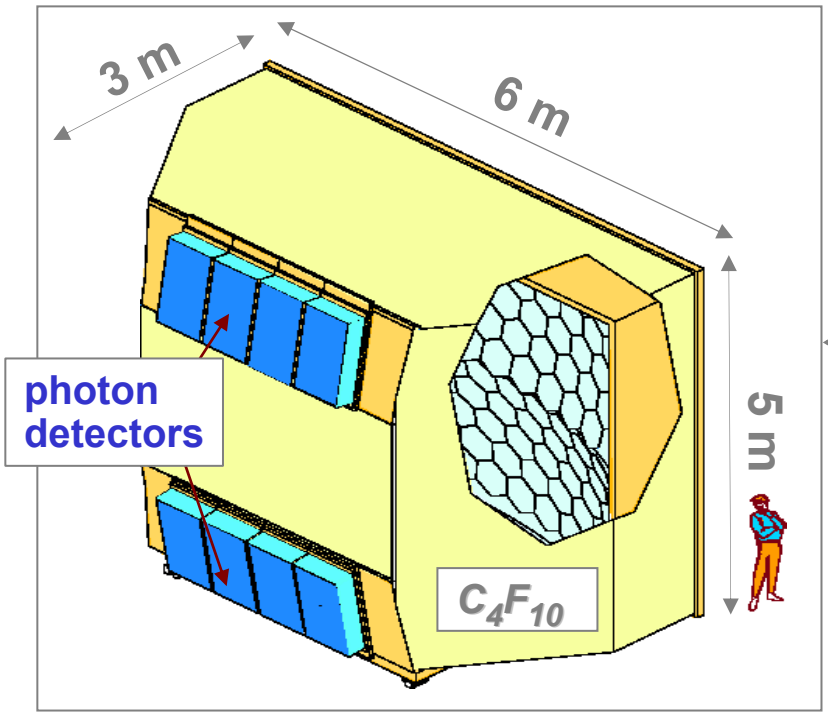
$\Delta_T d$ **small**

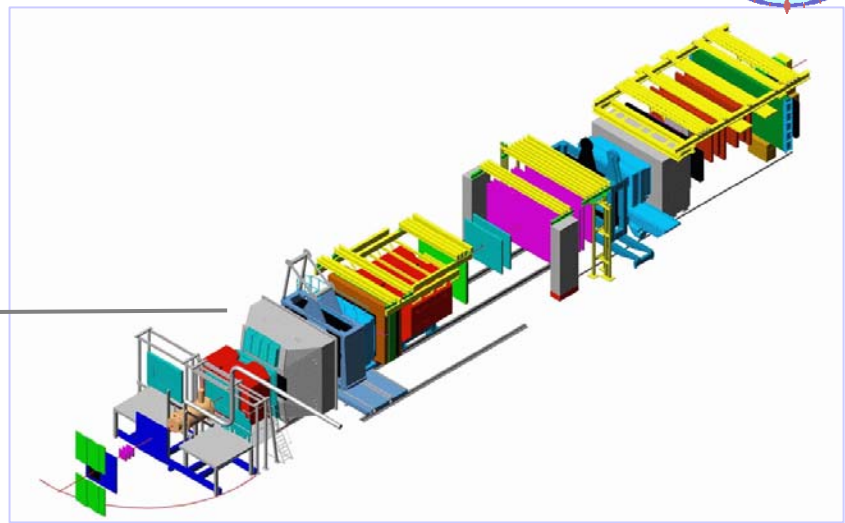
Sivers asymmetries: indication for $\Delta_0^T d \sim -(2)\, \Delta_0^T u$

… several assumptions needed

- THE EXPERIMENT
- TRANSVERSE SPIN PHYSICS
- **COMPASS RESULTS**
  - **Collins and Sivers asymmetries**
    - positive and negative hadrons
    - $\pi^{\pm}$, $K^{\pm}$
  - Two hadron asymmetries
  - Λ polarimetry
- SUMMARY AND OUTLOOK

the RICH detector



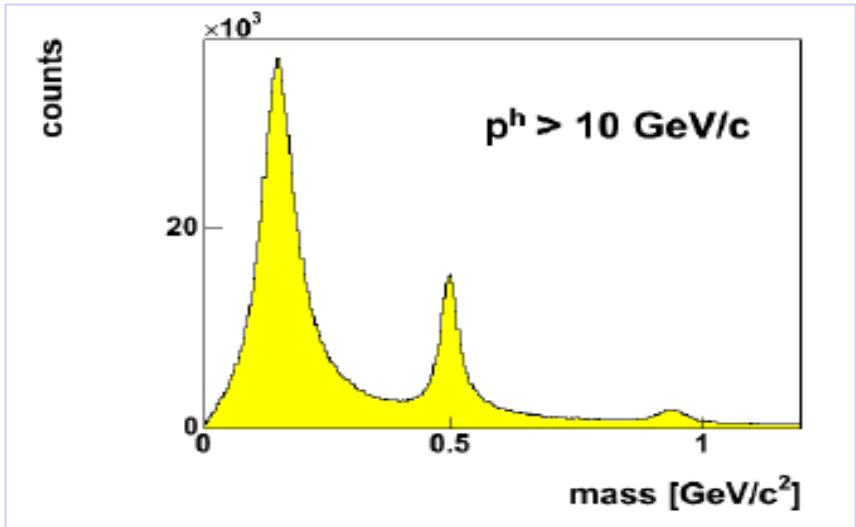


threshold momenta:

- p_π = 2 GeV/c
- p_K = 9 GeV/c
- p_P =17 GeV/c

fully efficient for transverse data in 2003 and 2004

→ *E. Rocco, M. Sulc, J. Polak talks*



$\pi^{\pm}$, $K^{\pm}$ Collins and Sivers asymmetries

new preliminary results from 2003-2004 data (June, GPD06)

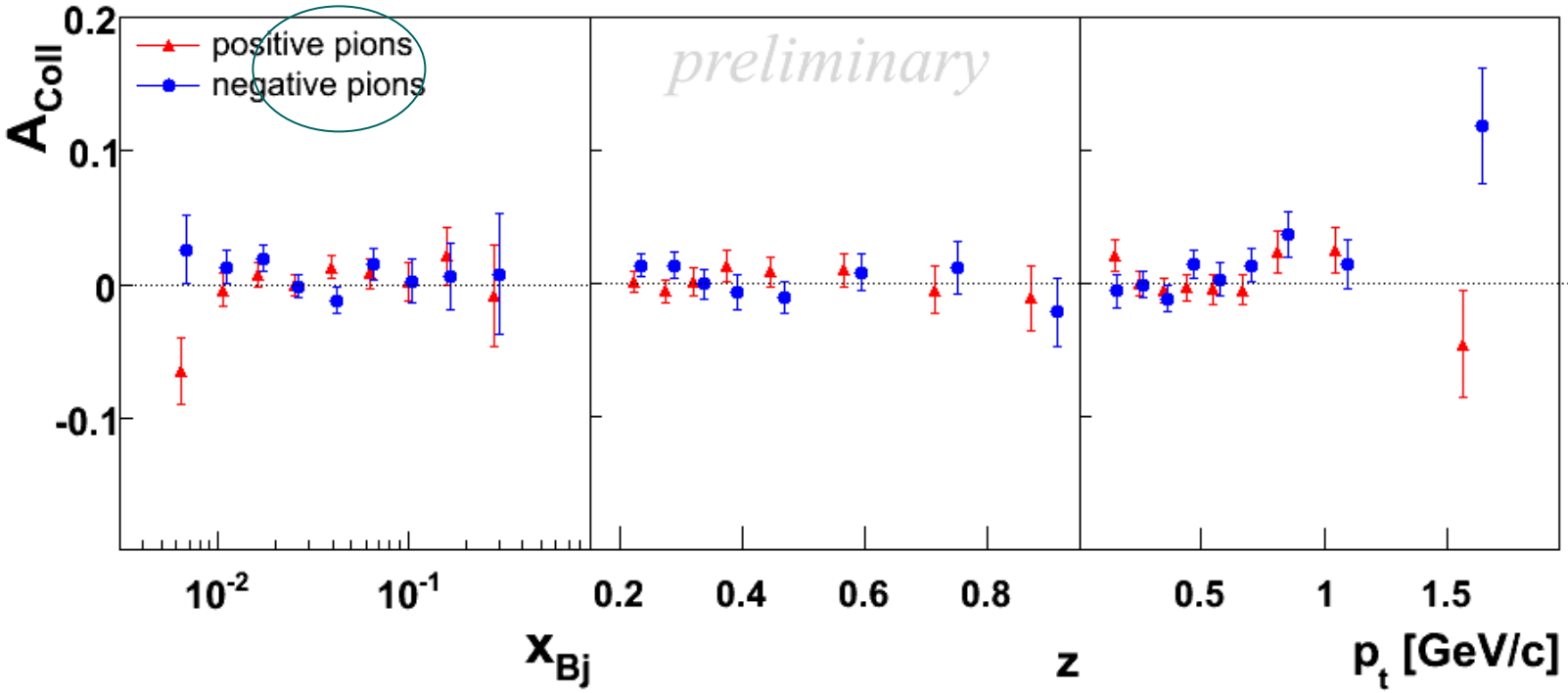
same DIS event selection and hadron definition as before
plus
PID based on RICH response

	hadrons	100%
	no RICH information	5%
after all cuts	pions	77%
after all cuts	kaons	12%
after all cuts	protons	3%

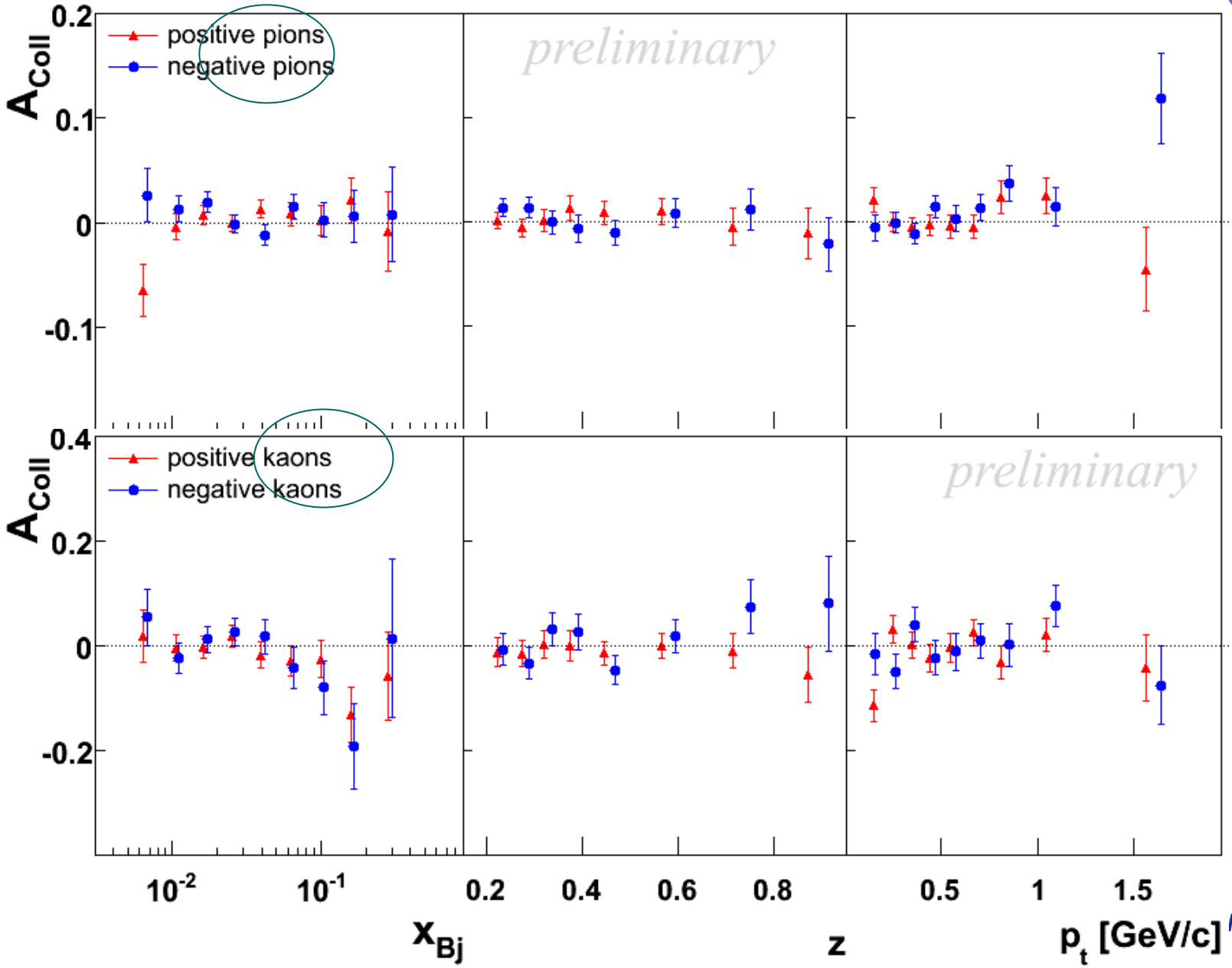
final sample	positive	all	leading	negative	all	leading
	pions	5.3 M	3.4 M	pions	4.2 M	2.8 M
	kaons	0.9 M	0.7 M	kaons	0.6 M	0.4 M

additional systematic tests: RICH stability
→ systematic errors smaller than statistical ones

$\pi^{\pm}$, $K^{\pm}$ Collins Asymmetries 2003-2004

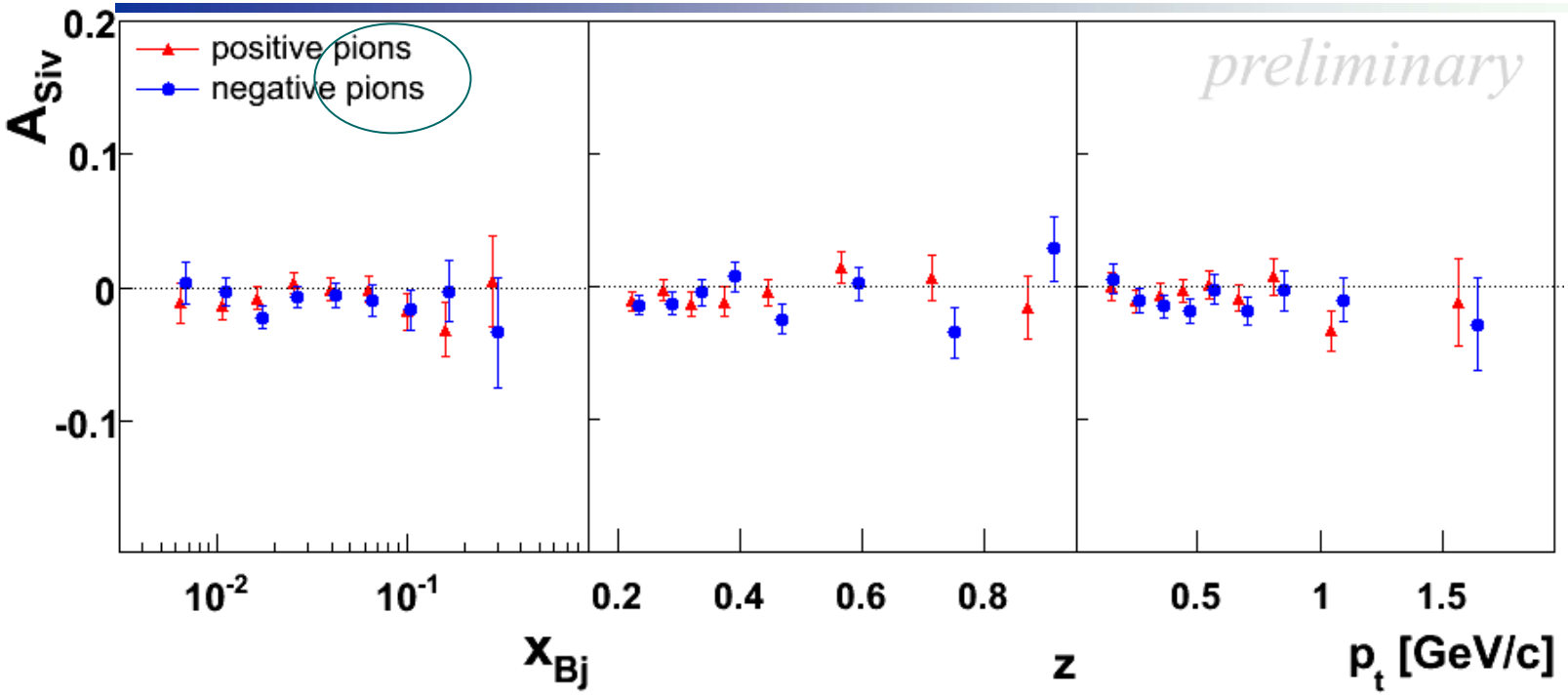


$\pi^{\pm}$, $K^{\pm}$ Collins Asymmetries 2003-2004

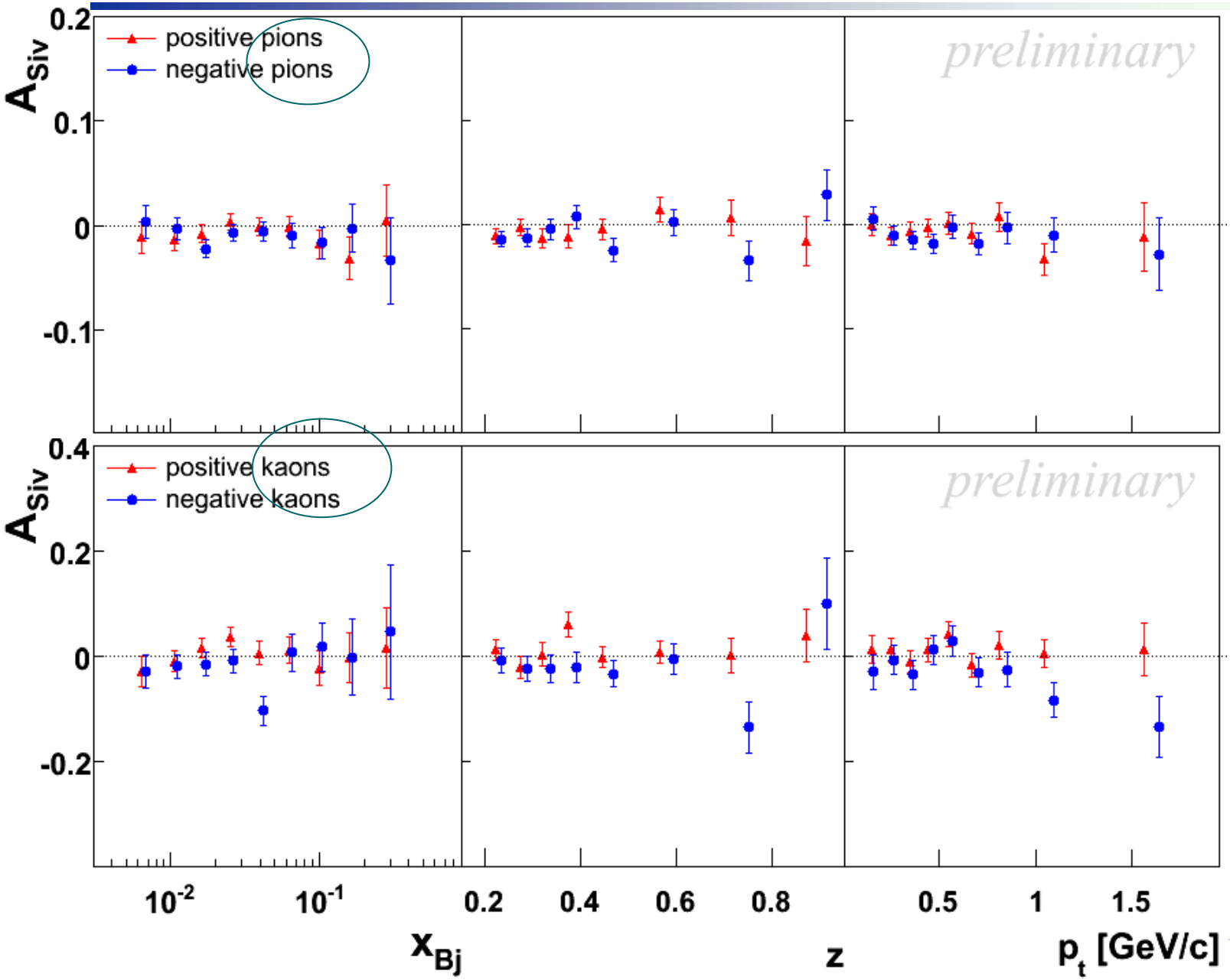


Martin

$\pi^{\pm}$, $K^{\pm}$ Sivers Asymmetries 2003-2004

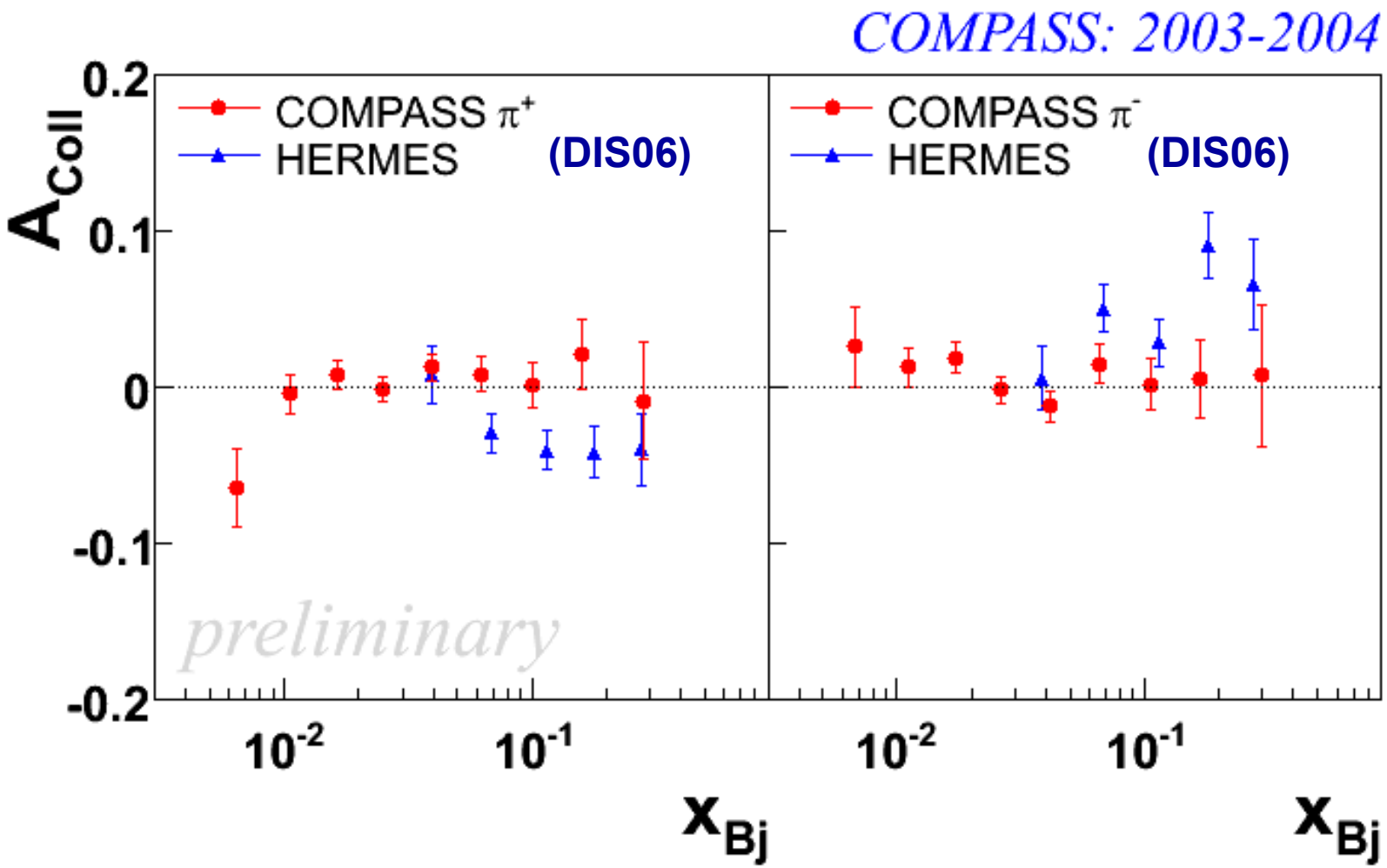


$\pi^{\pm}$, $K^{\pm}$ Sivers Asymmetries 2003-2004

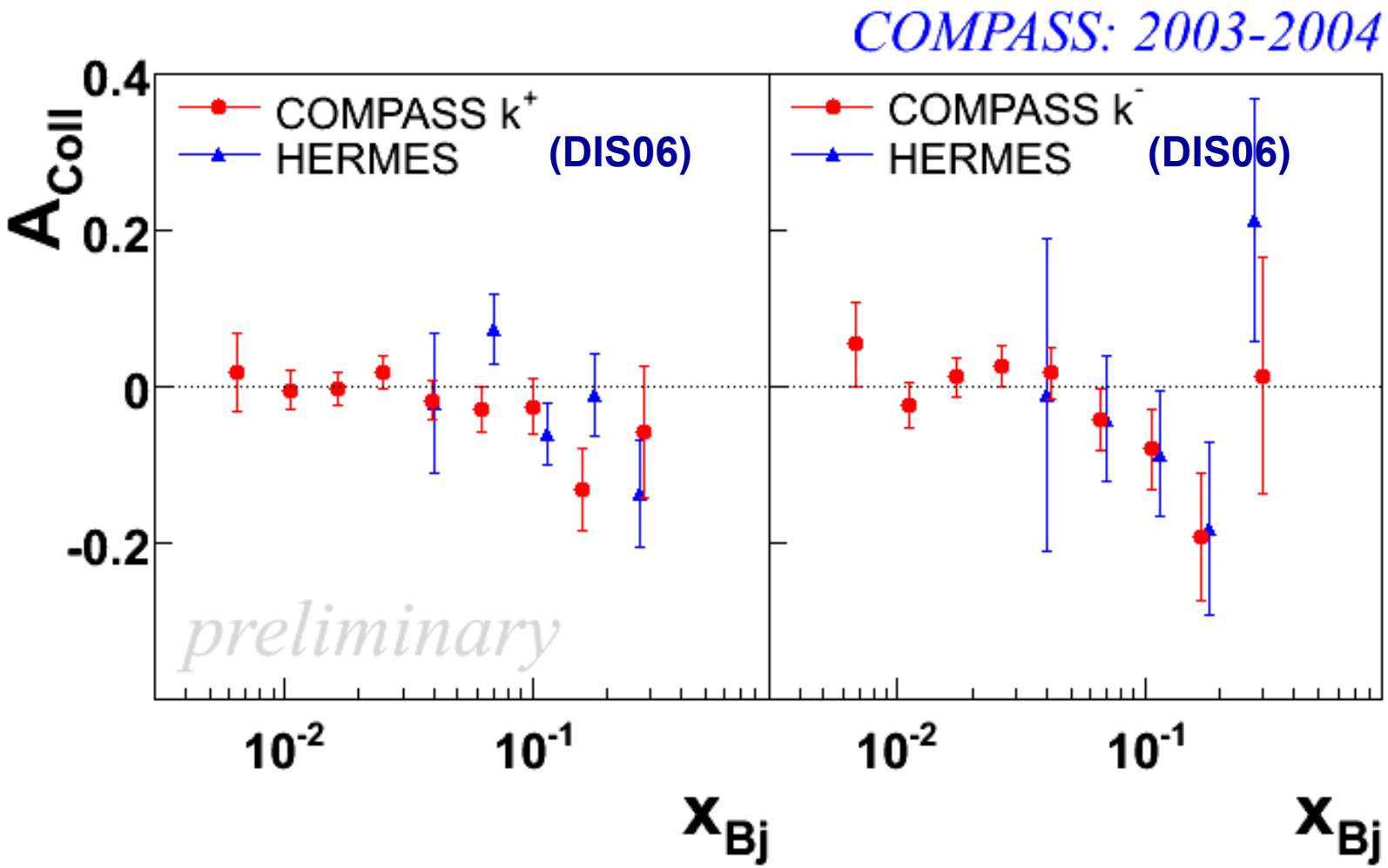


A. Martin

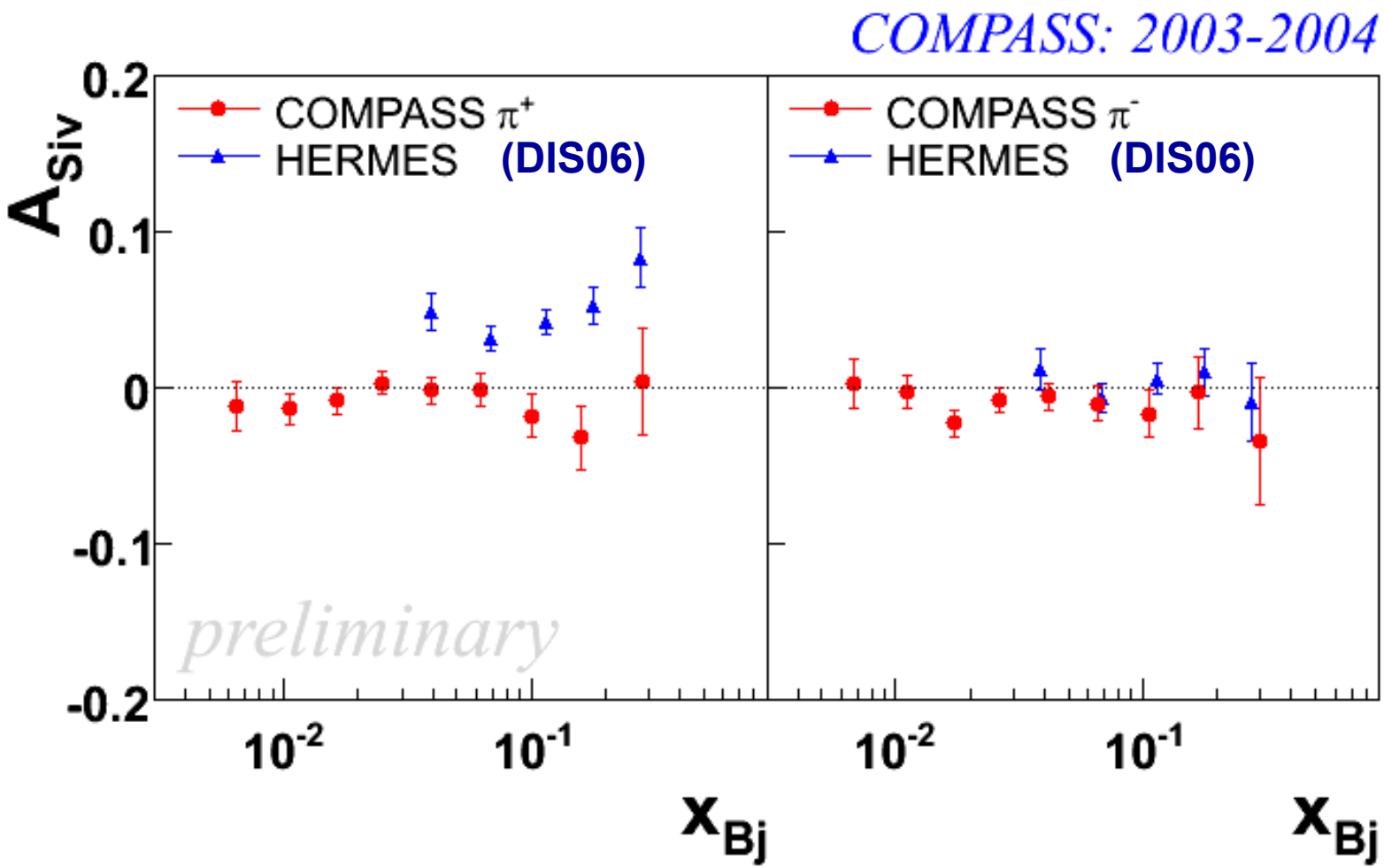
comparison with HERMES



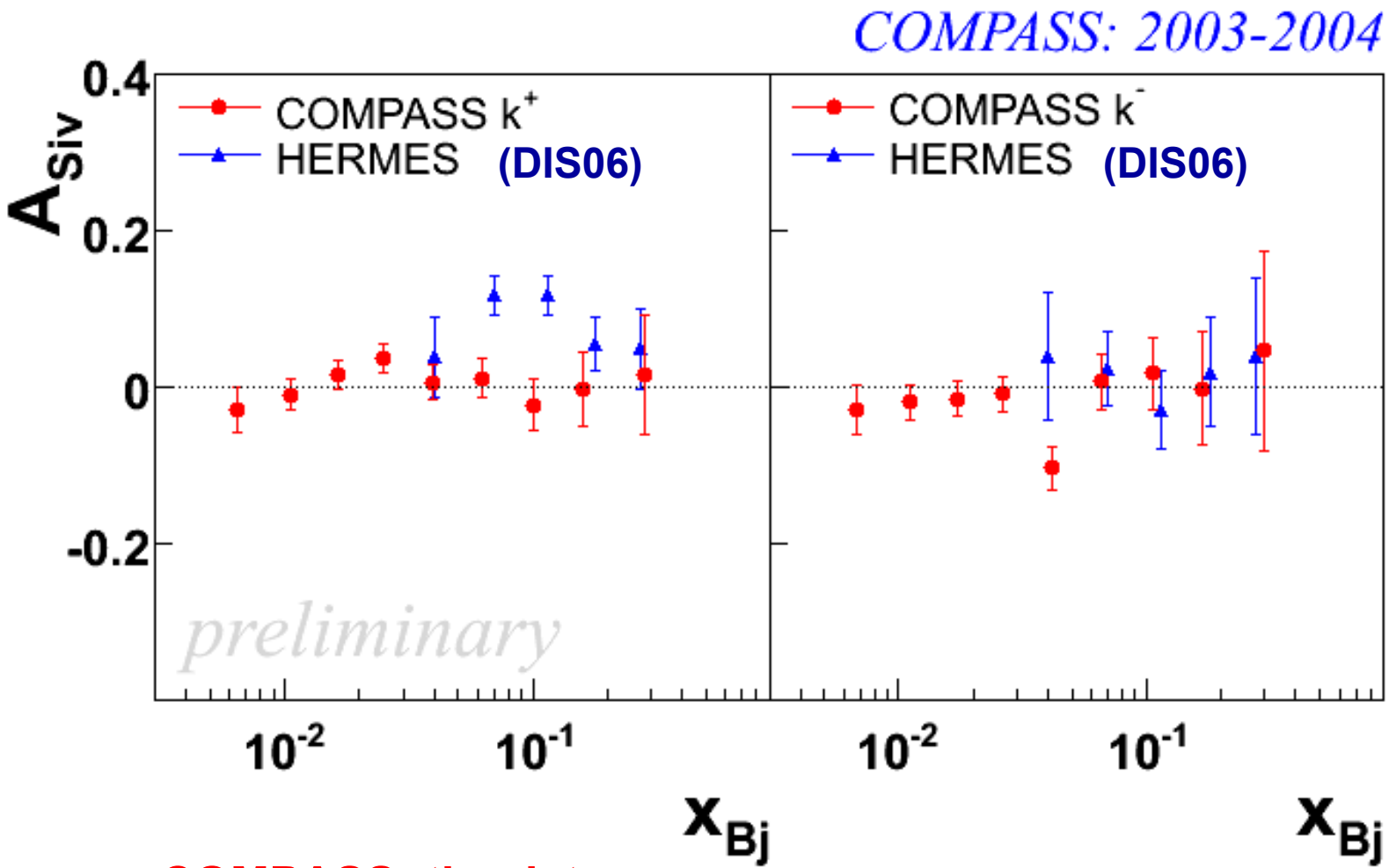
comparison with HERMES



comparison with HERMES



comparison with HERMES



COMPASS: the data are new

comparison with theory not available yet

cancellation between n and p ?

SPIN-PRAHA-2006, A. Martin

- THE EXPERIMENT
- TRANSVERSE SPIN PHYSICS
- **COMPASS RESULTS**
  - Collins and Sivers asymmetries
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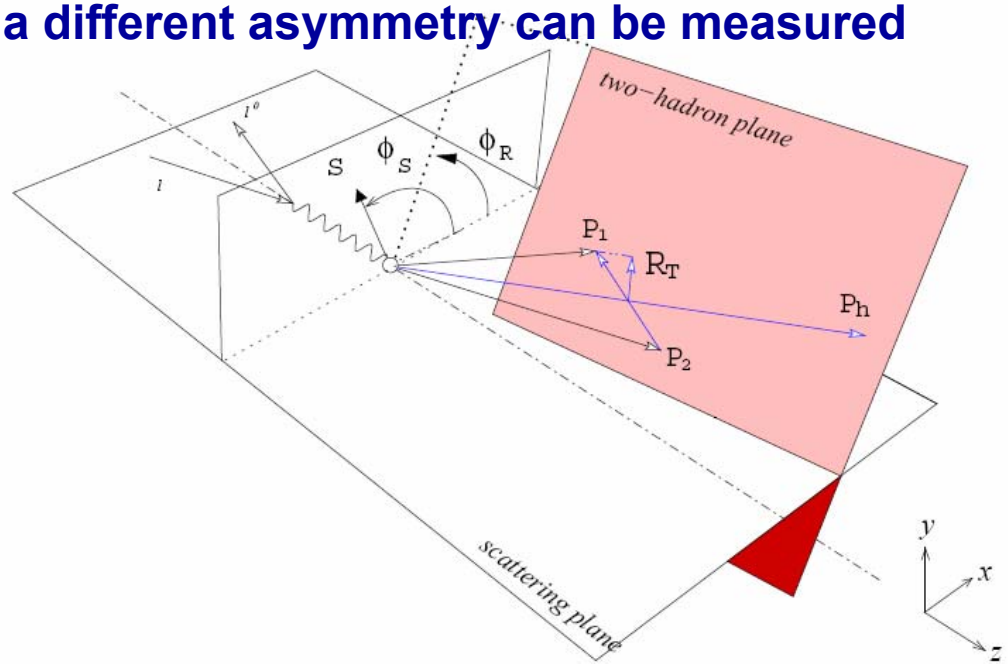
  - **Two hadron asymmetries**
  - Λ polarimetry
- SUMMARY AND OUTLOOK

Two Hadron Asymmetries

looking at two hadron production, a different angle can be defined and a different asymmetry can be measured



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

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

$$\Phi_{RS} = \phi_R - \phi_S,$$

ϕ_R azimuthal angle of $\vec{R}_T$

$\phi_S' = \pi - \phi_S$ azimuthal angle of the fragmenting quark spin wrt the lepton scattering plane

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

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

$$z = z_1 + z_2$$

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

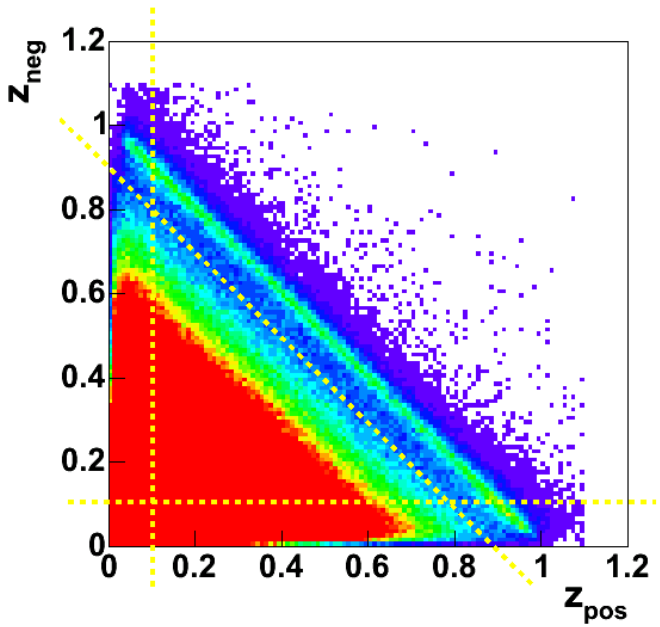
Two Hadron Asymmetries

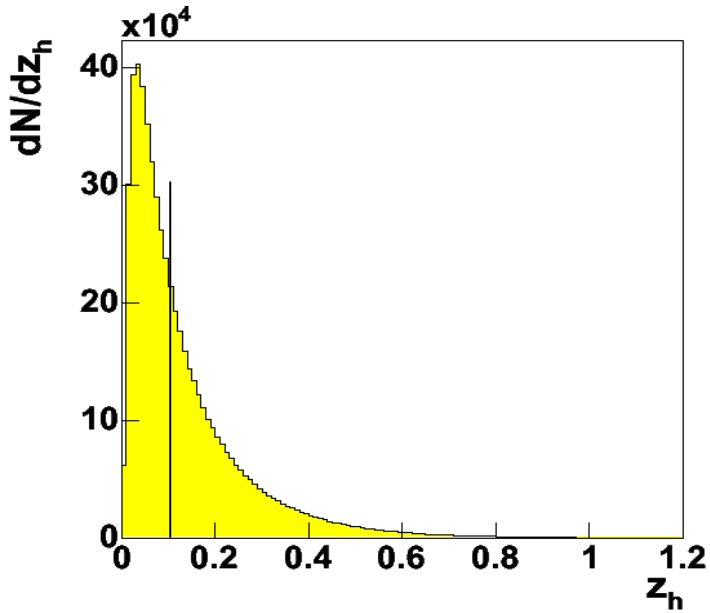
selection of DIS events

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

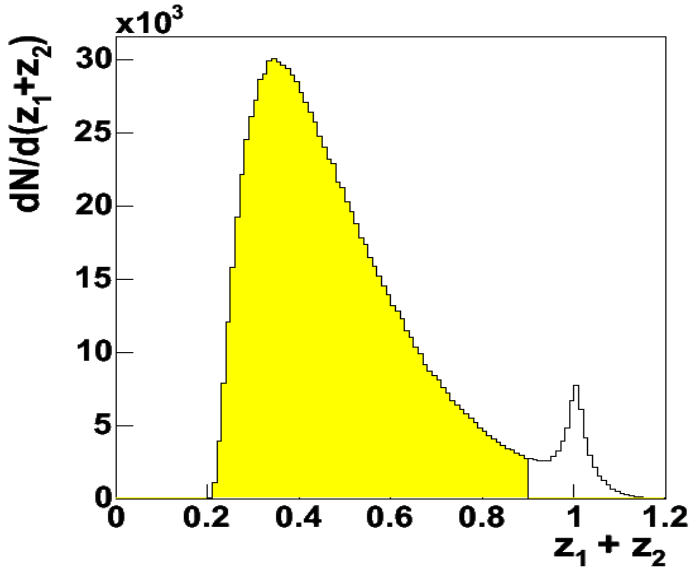
and of hadrons

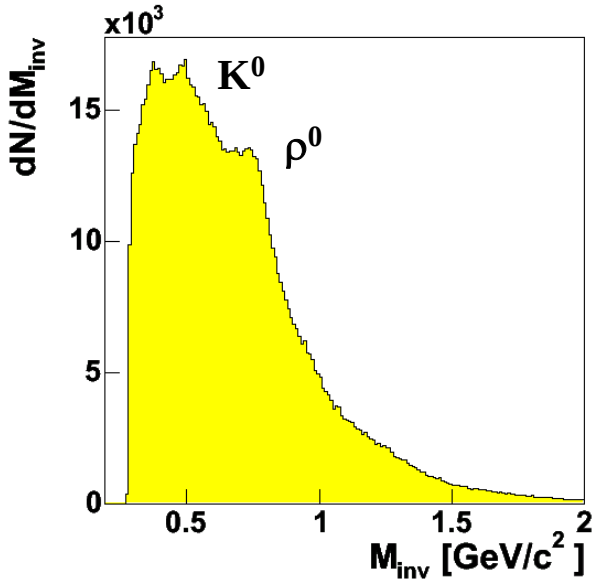
- $z_{1,2} > 0.1$ and $x_{f1,2} > 0.1$
- $z_1 + z_2 < 0.9$
- all combinations of +ve (h_1) and –ve (h_2) hadrons (~1.3/ev)
- presently no RICH PID

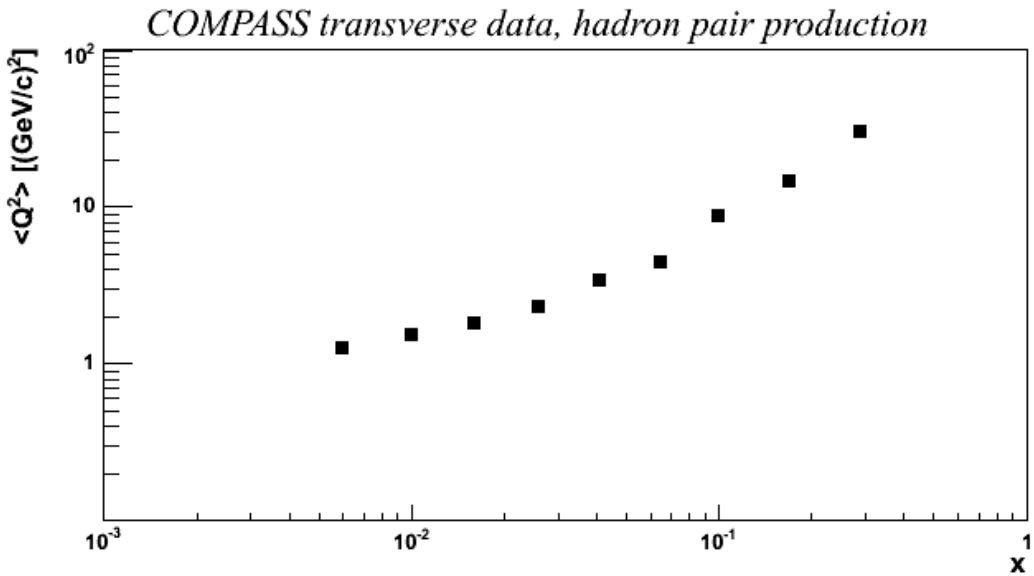




Two Hadron Asymmetries







final sample

total statistics 2002-2004:
6.1 M combinations

2002-2004 data
released in April 06

CIPANP06

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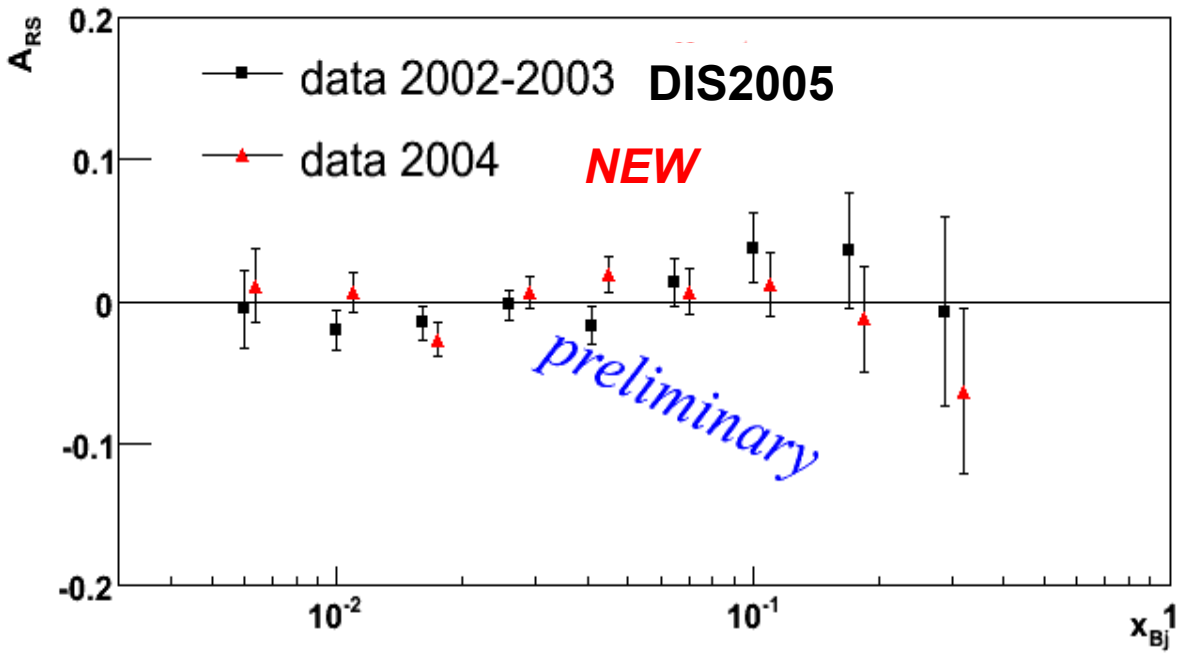
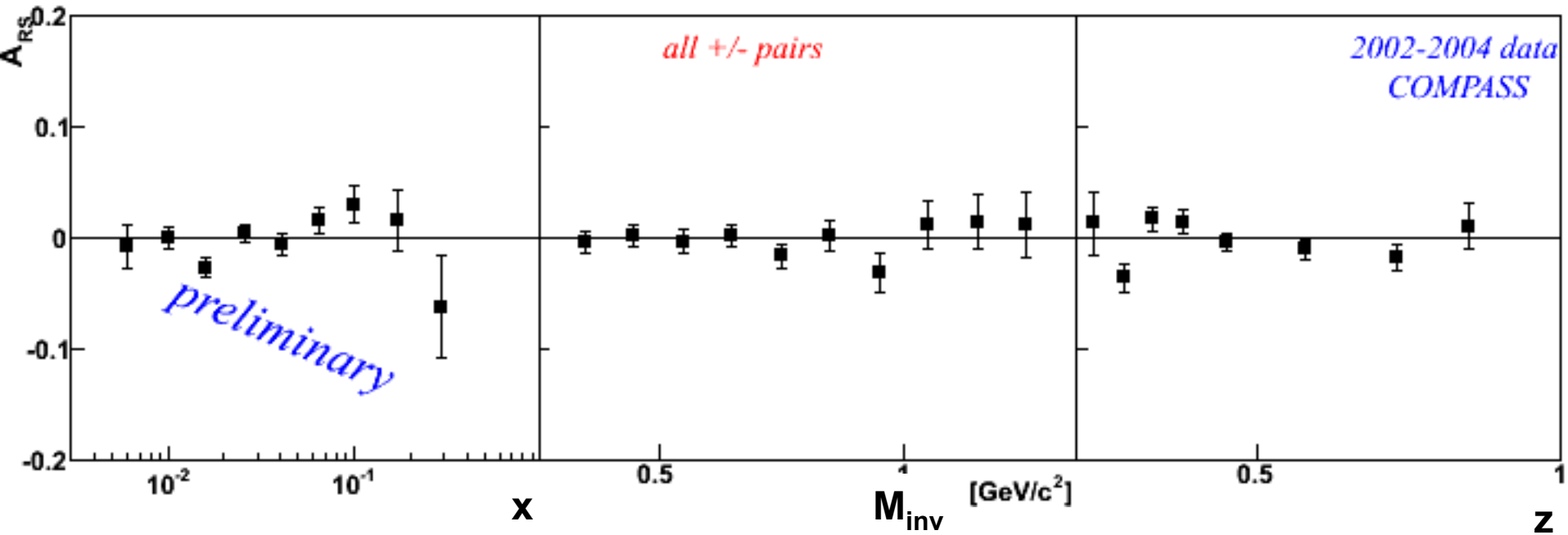
Two Hadron Asymmetries

all combinations
of +ve (h_1) and –ve (h_2) hadrons



Two Hadron Asymmetries

all combinations
of +ve (h_1) and –ve (h_2) hadrons



2002-2004 COMPASS data

- **small errors (order of ~%)**
- **small asymmetries! cancellation?**

work in progress: M. Radici, QCD-N'06

SPIN-PRAHA-2006, A. Martin

Two Hadron Asymmetries 2

different hadron pairs selections have been tried

still based on the string fragmentation model

1 entry/event

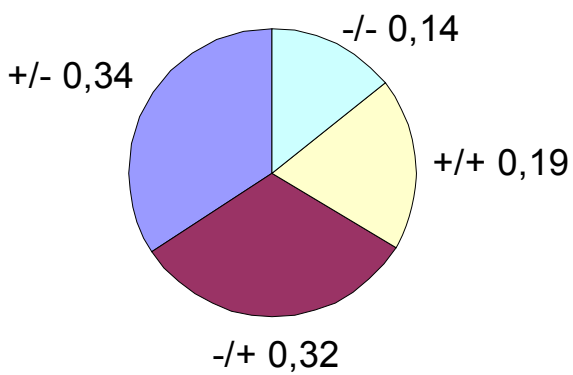
2002-2003 data → *SPIN 2005*

- **p_T - leading hadron pairs**
  h_1 = +ve hadron with largest p_T, h_2 = -ve hadron with second largest p_T
  and
  h_1 = -ve hadron with largest p_T, h_1 = +ve hadron with second largest p_T

- **z - leading hadron pairs**
  h_1 = +ve hadron with largest z, h_2 = -ve hadron with second largest z
  and
  h_1 = -ve hadron largest z, h_2 = +ve hadron with second largest z
  plus
  equal charge combinations

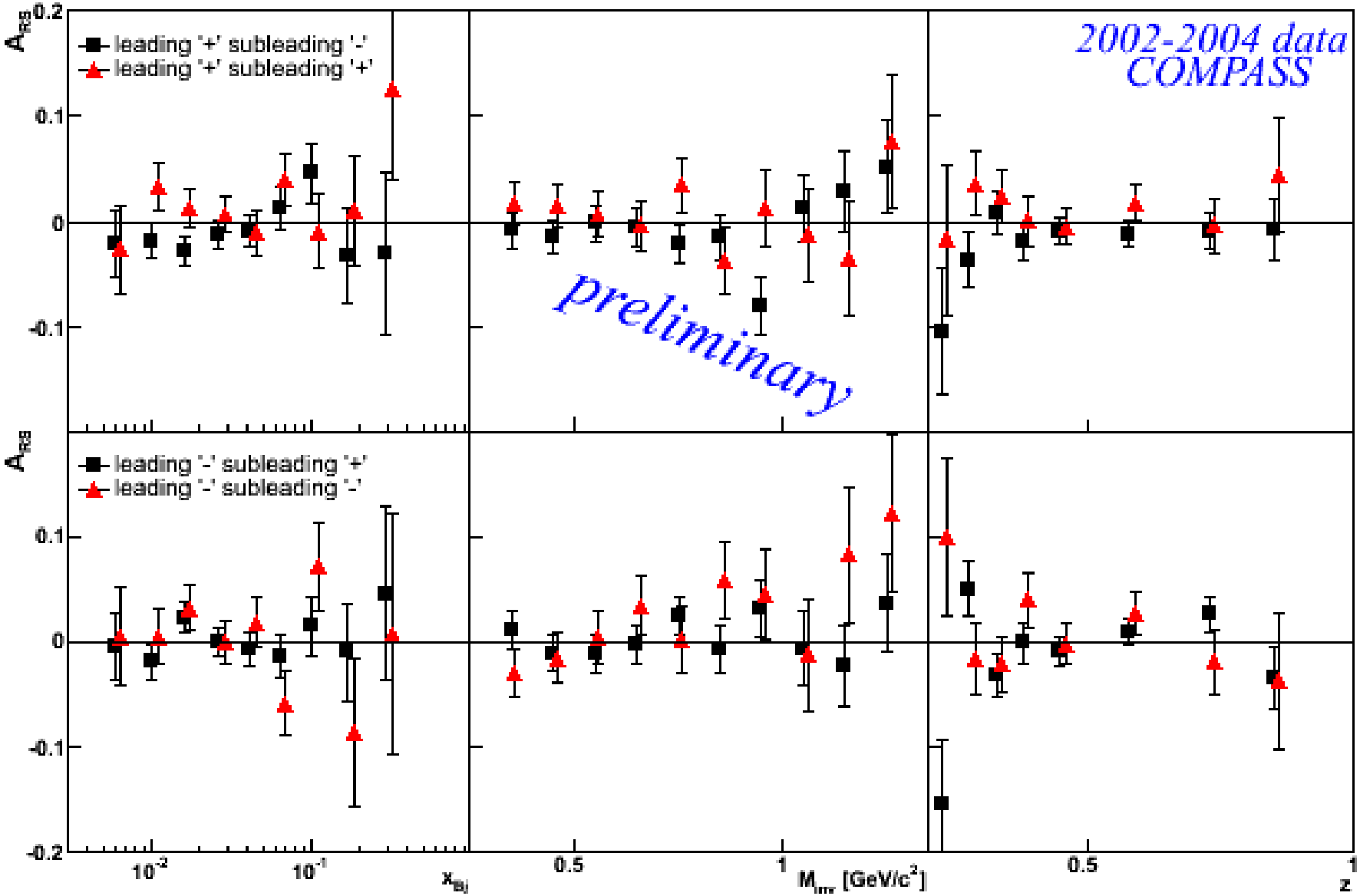
2002-2004 data: 6.4 M events

fractions:



Two Hadron Asymmetries

z-leading hadron pairs



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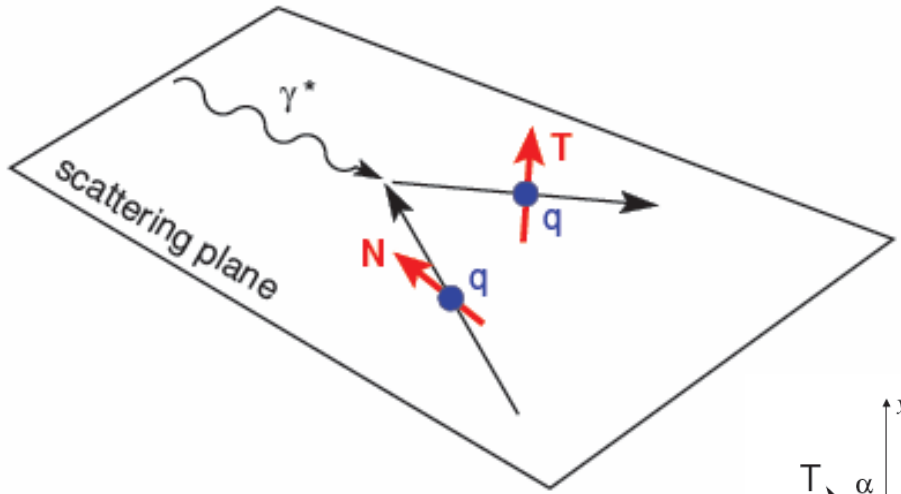
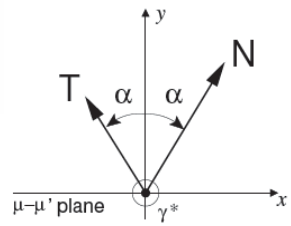
Λ polarimetry

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





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

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

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

f = target dilution factor, P_N = target polarization,

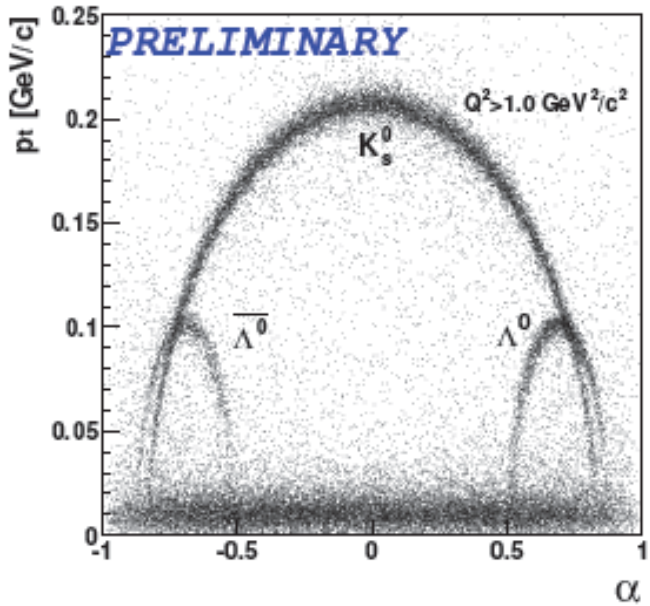
$D(y)$ = virtual photon depolarization factor

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

Λ polarimetry

event selection

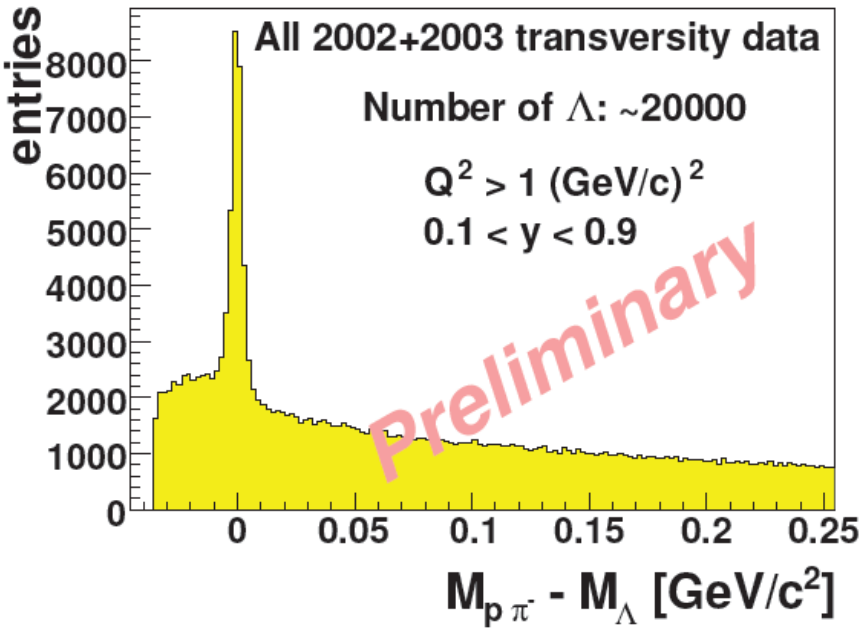
- Primary vertex in target cell material, beam crossing both cells
- μ' traverses at least 30 radiation lengths
- Tracks of p and π^- candidates traverse at least the SM1 magnet
- momentum of both decay particles > 1 GeV/c

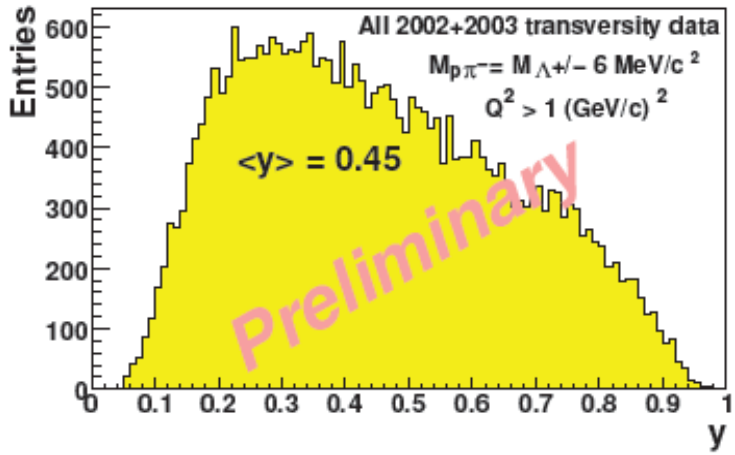


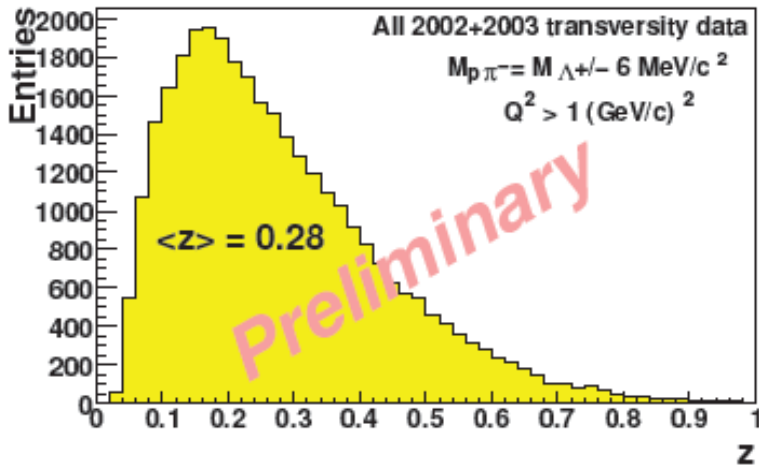
- The candidate Λ decay is downstream of the target and outside of it
- collinearity < 10 mrad
- Armenteros $p_T > 23$ MeV/c
- $0.1 < y < 0.9$

Λ polarimetry

2002-2003 data





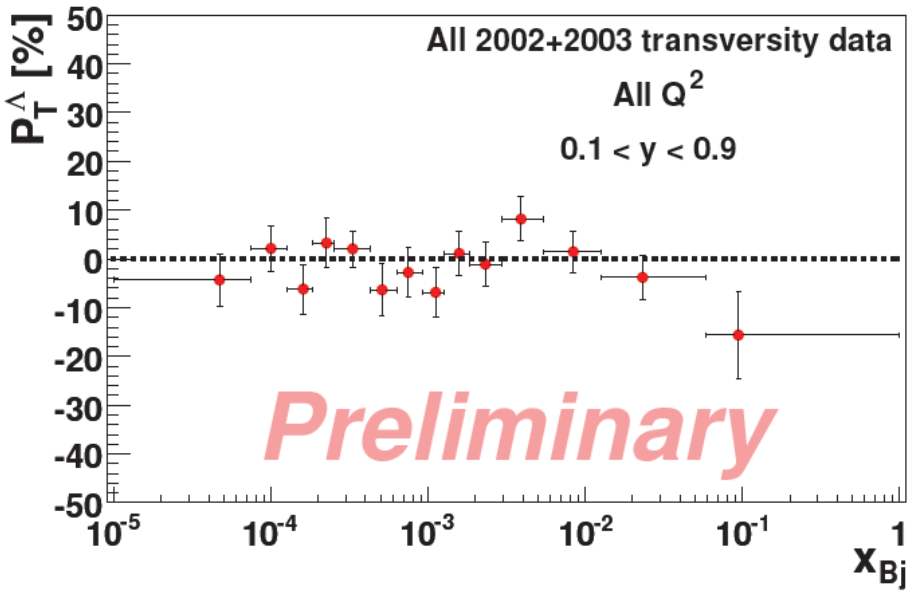


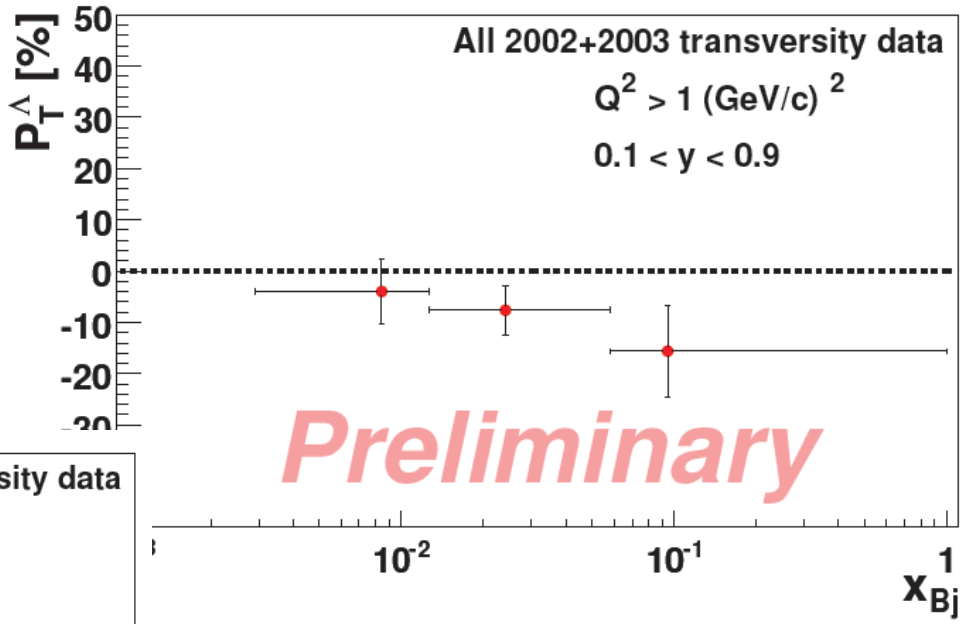
The majority of Lambda events are produced at $x_F > 0$ (current fragmentation region)

Λ polarimetry

TRANSVERSITY 2005

2002-2003 data





analysis of 2004 data ongoing:

results soon !

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summary and outlook

precise deuteron data from COMPASS are now available

Collins and Sivers asymmetries +ve and -ve hadrons, $\pi^{\pm}$, $K^{\pm}$

two hadron asymmetries all pairs, leading hadrons

Λ polarisation

in so far all the measured deuteron asymmetries are very small, compatible with zero

remarkable progress in the theoretical description

present phenomenological studies can describe at the same time the BELLE (FF), the HERMES (proton) and COMPASS (deuteron) with some surprising result

new data and a global analysis is needed to

- **have first information on $\Delta_T q$**
- **evaluate the size of the effort necessary to complete the programme**

summary and outlook

in the near future COMPASS will produce some new results from the present deuteron data:

- **Two hadron asymmetries with RICH PID 2003-2004**
- **Λ polarisation 2004**

plus

- **transverse effects from longitudinal data**
- **all the LO asymmetries from single hadron data**
- **g_2**
- **Cahn effect**
- **exclusive ρ production on transversely polarised target**
- **….**

summary and outlook

in 2006 COMPASS plans to take data with a
transversely polarised proton target (NH_3)

with 30 days running, precision ~ deuteron at small x,
much better at "large" x (new PT magnet) → *H. Fischer*

the COMPASS Collaboration plans to take more proton data
before 2010, and after …

new proposal: physics programme including
spectroscopy
GPDs and
Transverse Spin Asymmetries, DY and SIDIS

Memo to CERN Council Strategy Group (Jan. 15, 2006)

SIDIS essential for flavour separation
i.e. for transversity measurement