TRANSVERSE SPIN MEASUREMENTS IN COMPASS

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on behalf of the COMPASS Collaboration

QCD-N '06

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CONTENT

- **THE EXPERIMENT**
- **PHYSICS RESULTS**
  three different ways to access transversity
  - **Collins and Sivers asymmetries**
    - ***positive and negative hadrons***
    - **$\pi^{\pm}$, $K^{\pm}$**

    NEW
  - **Two hadron asymmetries**
    - ***all pairs***
    - ***leading hadrons***

    NEW
  - **Λ polarimetry**
- **SUMMARY AND OUTLOOK**

COMPASS

the COMPASS experiment

fixed target experiment at the CERN SPS
240 physicists from 28 institutes, 11 Countries

approved in 1998 with a broad physics programme

- **hadron beams** π,K,**p** (2004) 2007, …
- **muon beam** **2002-2004**, 2006, ….

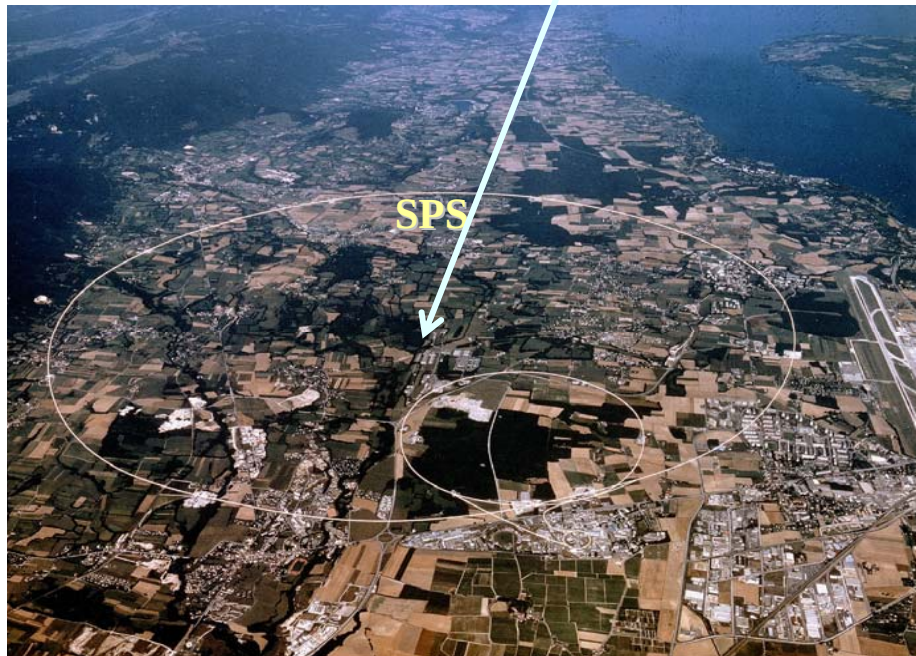
  transversity

  gluon contribution to nucleon spin

  g_1, $\Delta\Sigma$, Δq flavour decomposition

  ….

  ρ^0 production → A. Sandacz



muon beam:
momentum 160 GeV/c
longitudinal polarisation -76%
intensity $2 \cdot 10^8$ μ^+/spill (4.8s/16.2s)

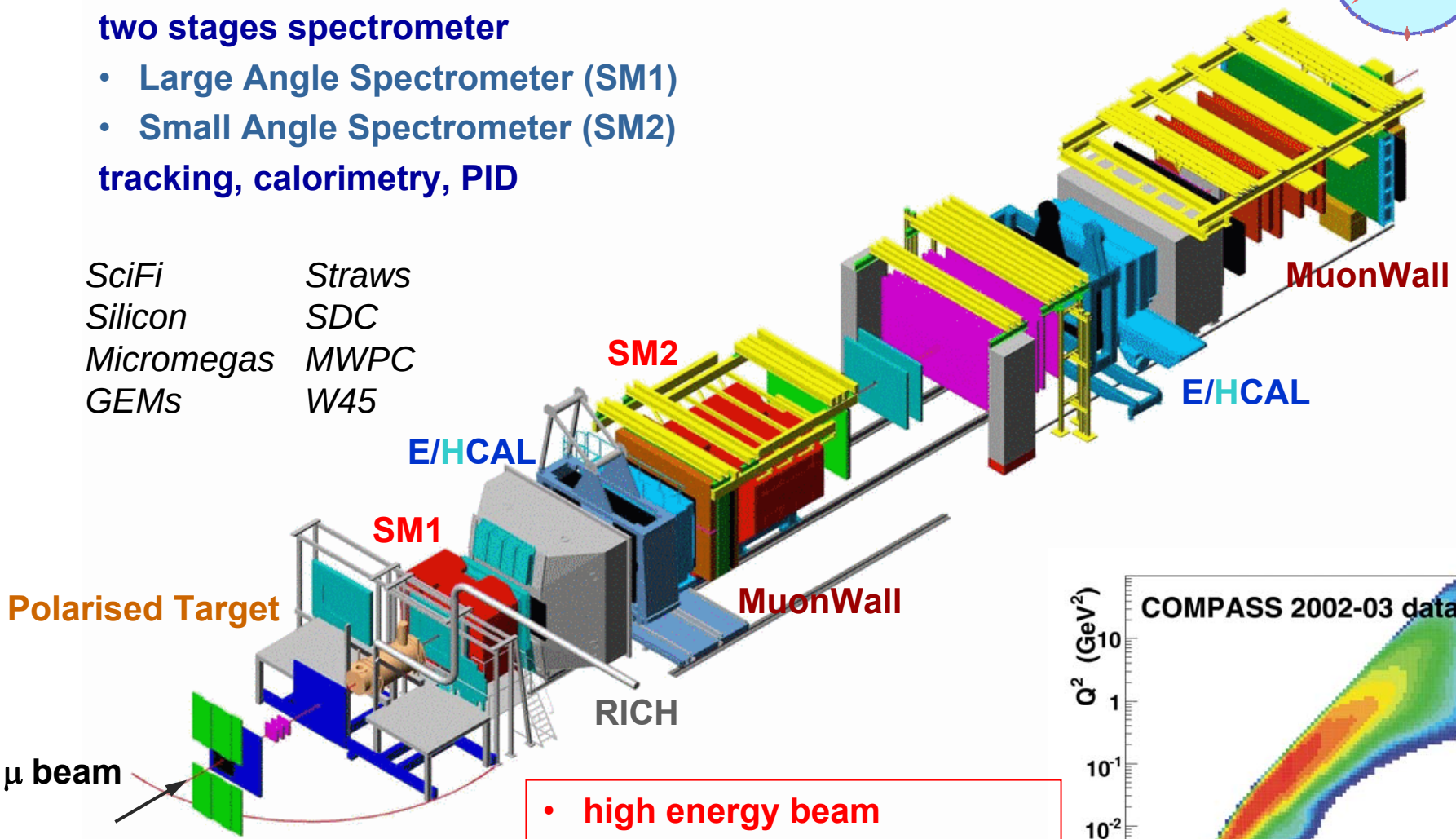
the spectrometer

two stages spectrometer

- **Large Angle Spectrometer (SM1)**
- **Small Angle Spectrometer (SM2)**

tracking, calorimetry, PID

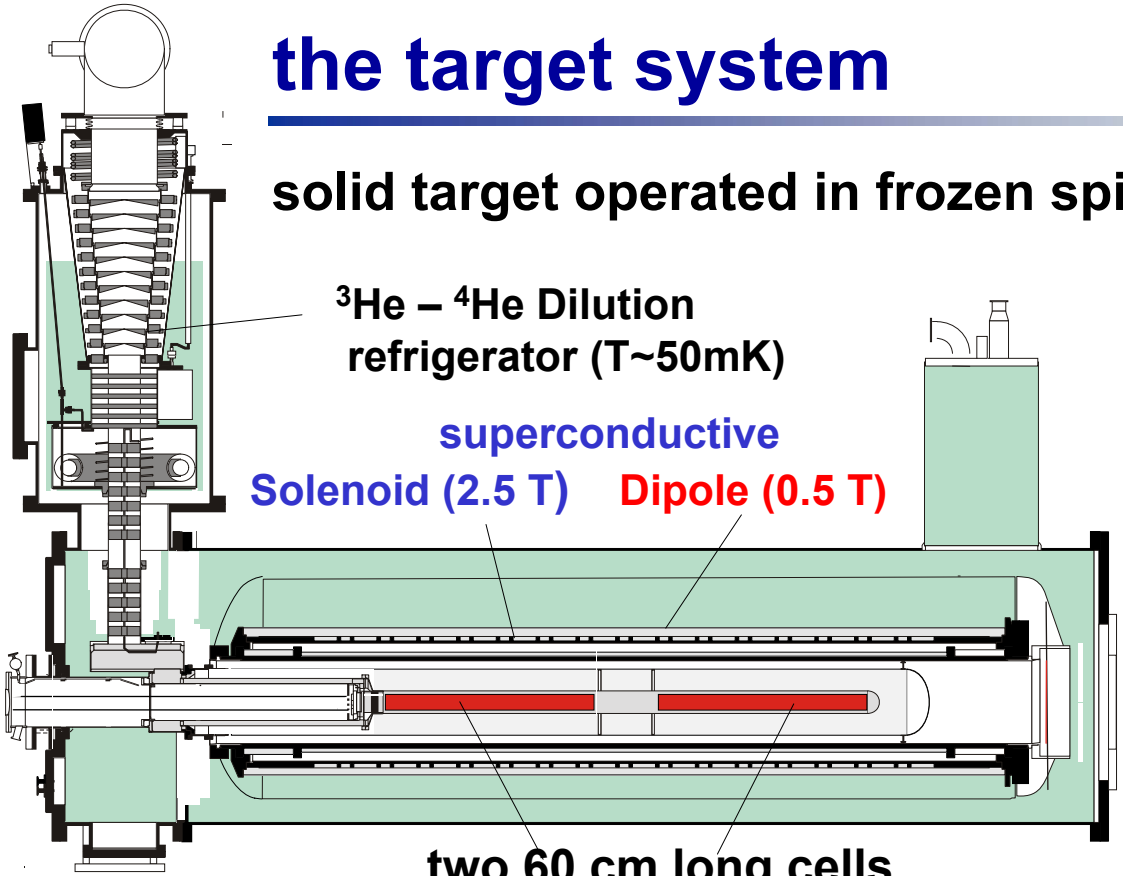
SciFi	*Straws*
Silicon	*SDC*
Micromegas	*MWPC*
GEMs	*W45*



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

the target system

solid target operated in frozen spin mode

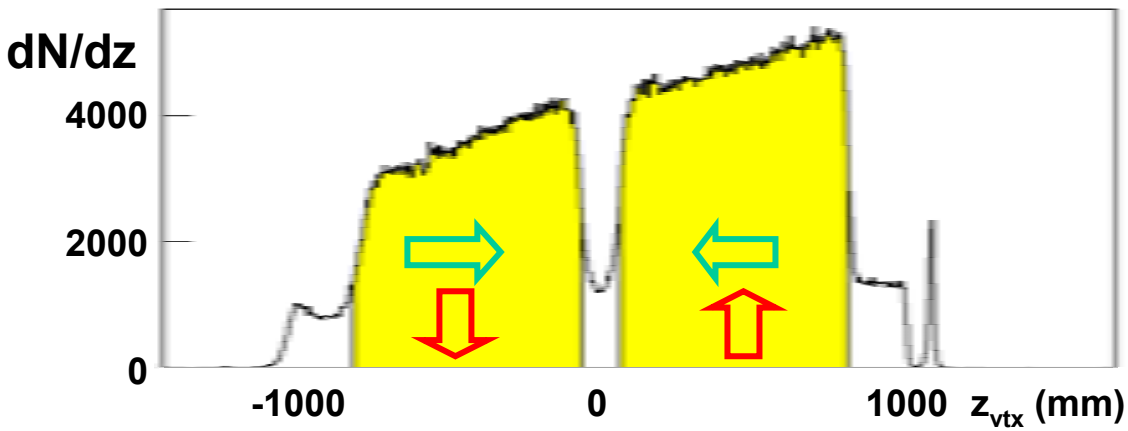


^{6}LiD:

polarization P_T = 50%

dilution factor f = 0.38

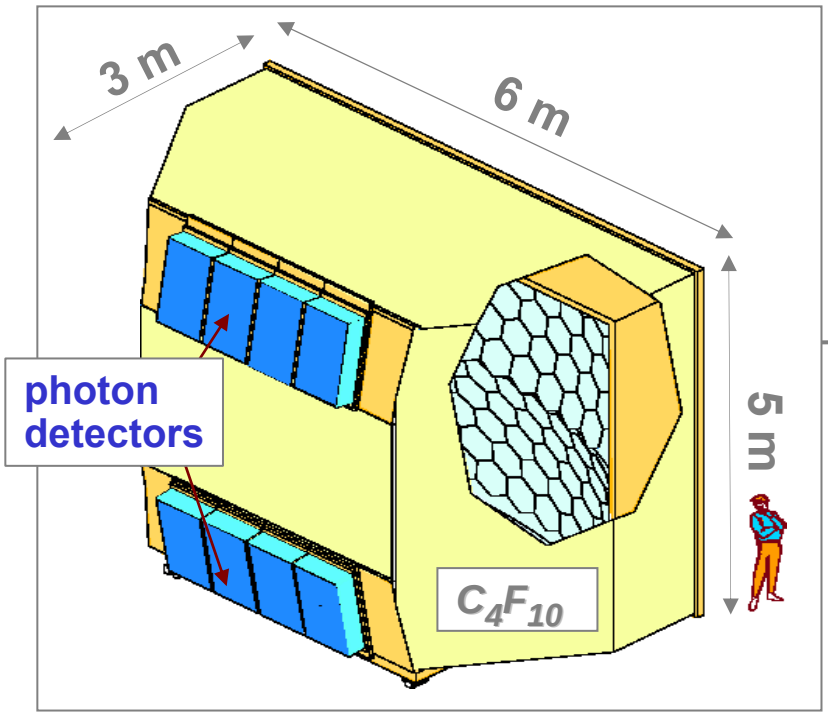
relaxation time > 2000 hrs

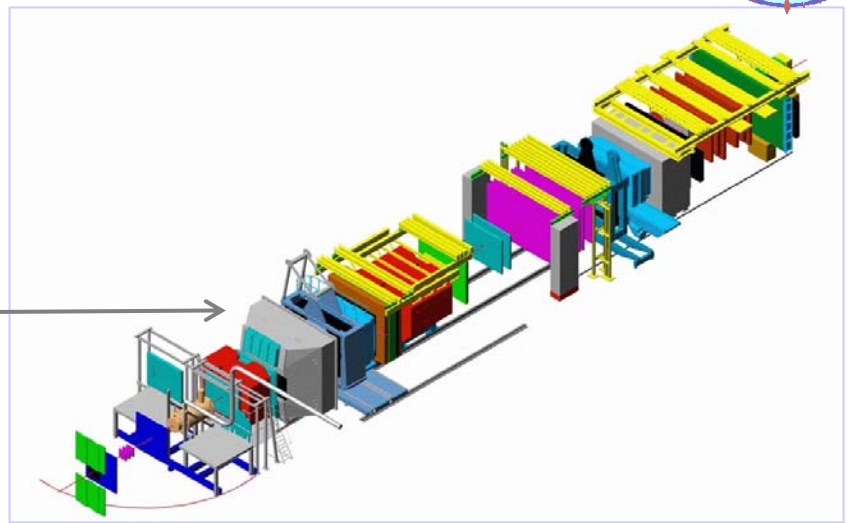


during data taking with transverse polarization

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

the RICH detector

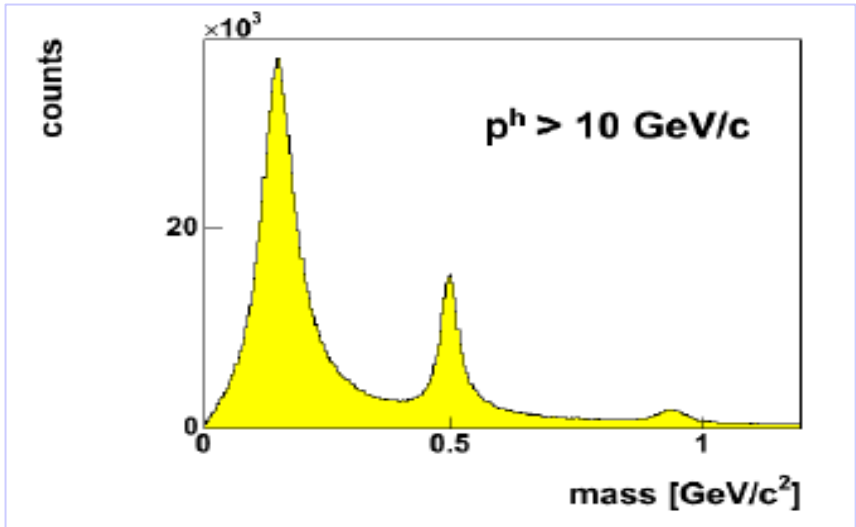




threshold momenta:

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

fully efficient for transverse data in 2003 and 2004



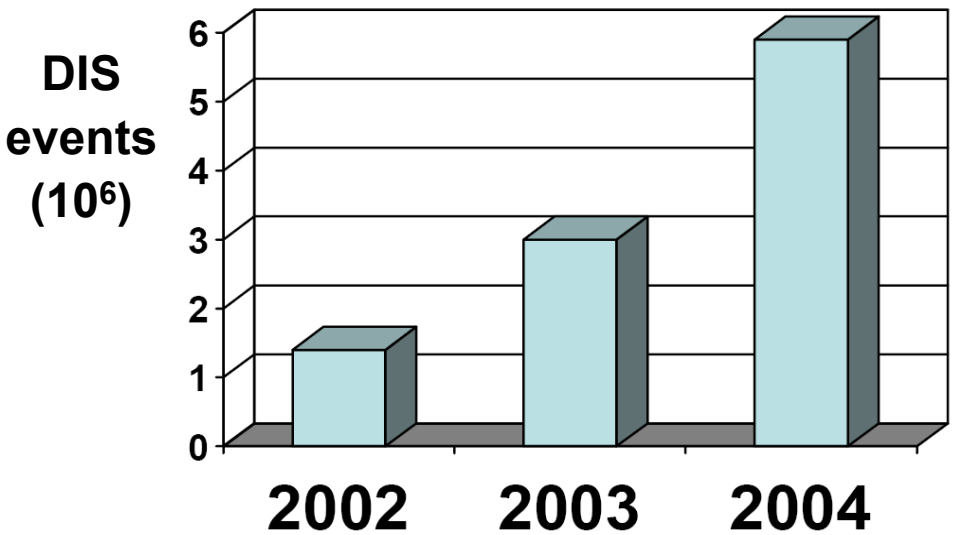
data taking 2002-2004

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



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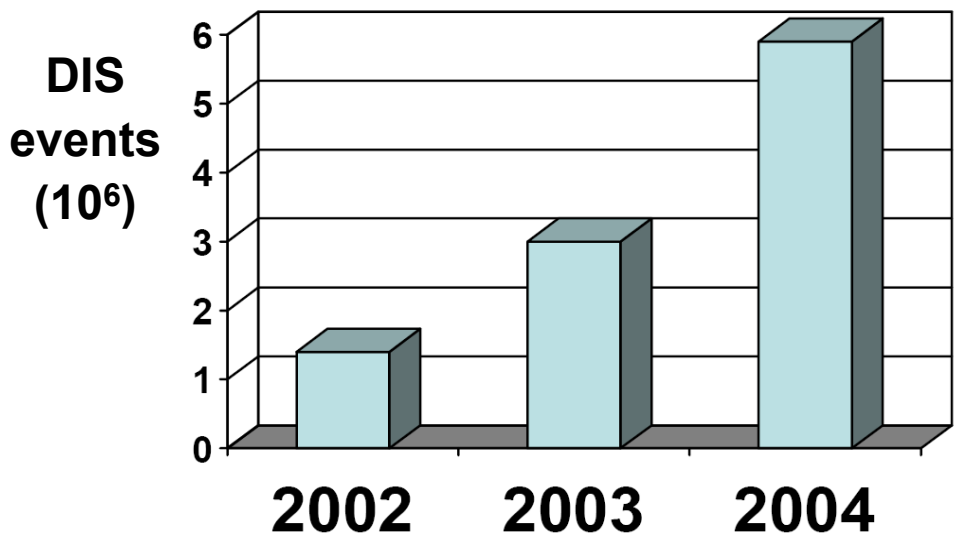


Collins and Sivers asymmetries
- published results 2002
- prel results 2002-2004 with RICH PID

Two hadron asymmetries
- prel results 2002-2004

Λ polarimetry
- prel results 2002-2003

PHYSICS RESULTS

Collins and Sivers asymmetries

positive and negative hadrons

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

Two hadron asymmetries

all pairs

leading hadrons

Λ polarimetry

single hadron asymmetries

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

unpol B and T — *long pol B and/or T*

transvely polarised target

ϕ_h azimuthal angle of the hadron

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

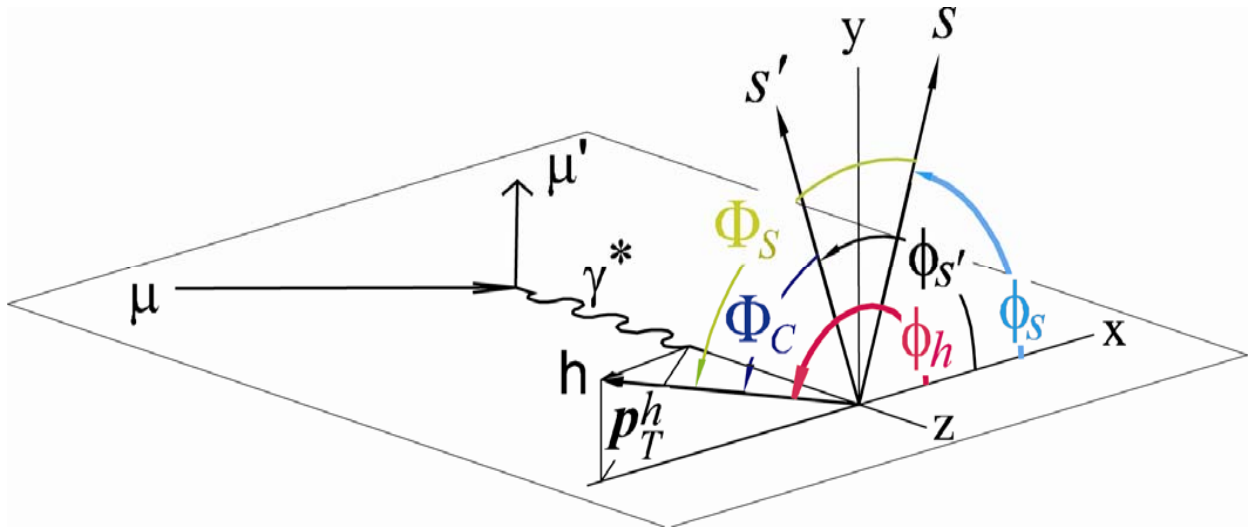
ϕ_s azimuthal angle of the transverse spin of the initial quark $\quad \phi_{s'} = \pi - \phi_s$

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

Collins angle

$\Phi_S = \phi_h - \phi_s$

Sivers angle



single hadron asymmetries

SIDIS cross-section $d\sigma = d\sigma_0 + d\sigma_L + d\sigma_T$ (*unpol B and T*; *long pol B and/or T*; **transvely polarised target**)

ϕ_h azimuthal angle of the hadron

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

ϕ_s azimuthal angle of the transverse spin of the initial quark $\quad \phi_{s'} = \pi - \phi_s$

$$\Phi_c = \phi_h - \phi_{s'} = \phi_h + \phi_s - \pi \qquad \Phi_s = \phi_h - \phi_s$$

at leading order

$$d\sigma_T \propto S_T \cdot \Big[\underbrace{a_1 \cdot \sin\Phi_c}_{\text{Collins}} + \underbrace{a_2 \cdot \sin\Phi_s}_{\text{Sivers}} + a_3 \cdot \sin(3\phi_h - \phi_s) + \lambda_b \cdot a_4 \cdot \cos(\phi_h - \phi_s) \Big]$$

λ_b: **beam polarization**

independent angles → independent extraction of the asymmetries

Collins asymmetry

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

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

D spin transfer parameter
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** (h_1^q, δq, δq_T, …)

$\Delta_T^0 D_q^h$ **Collins fragmentation function (BELLE)**

$$F(\Phi_C) = \frac{N_{h,u}^+(\Phi_C) \cdot N_{h,d}^+(\Phi_C)}{N_{h,u}^-(\Phi_C) \cdot N_{h,d}^-(\Phi_C)} \cong 1 + 4 \cdot A_C^h \cdot \sin\Phi_C$$

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

A_{Coll} evaluated as function of x, z and p_t for *Leading Hadrons* and *All Hadrons*

Sivers asymmetry

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

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

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**

A_{Sivl} evaluated as function of x, z and p_t for
Leading Hadrons* and *All Hadrons

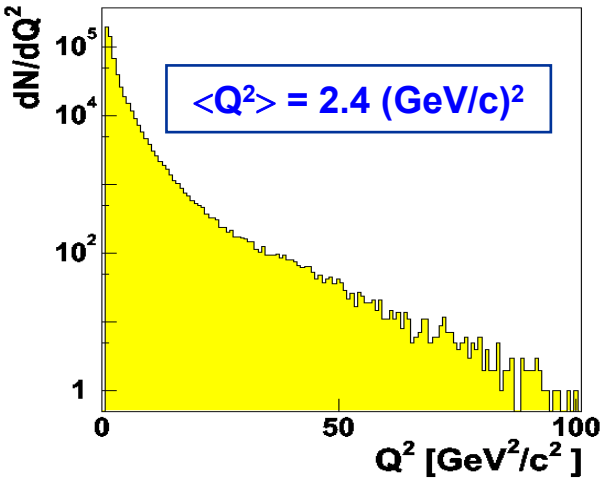
event selection

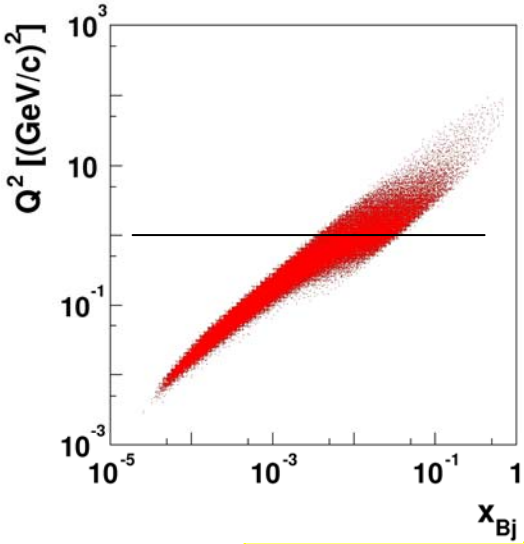
DIS events

$Q^2 > 1$ GeV^2

$W^2 > 25$ GeV^2

$0.1 < y < 0.9$





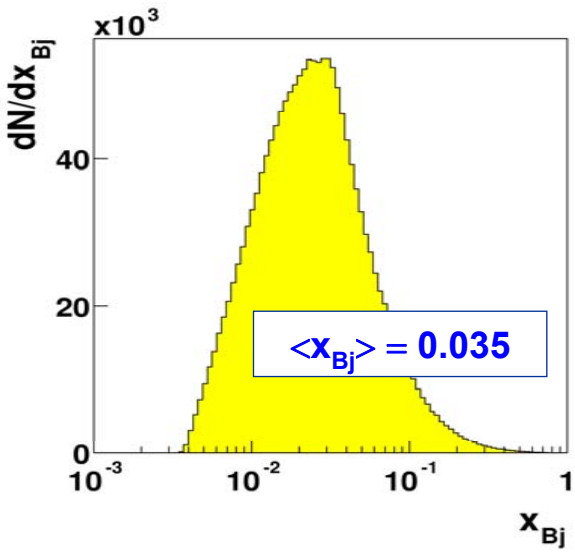
2002 data

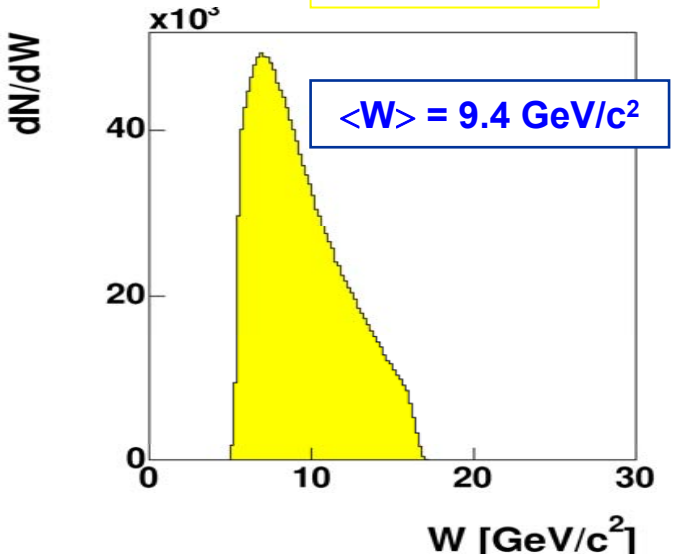
hadrons

$p^h_t > 0.1$ GeV/c

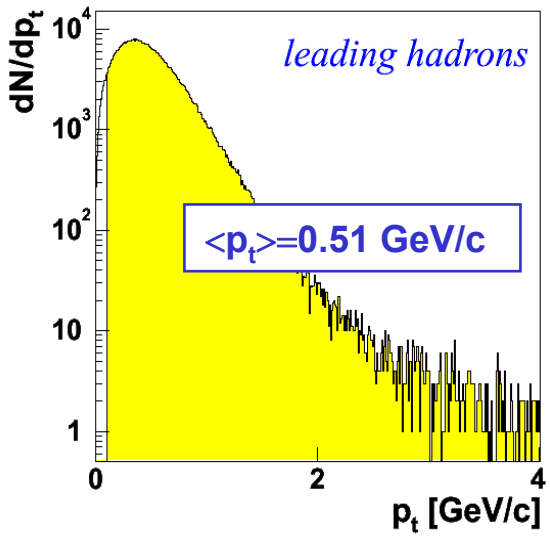
$z > 0.2$ (all h)

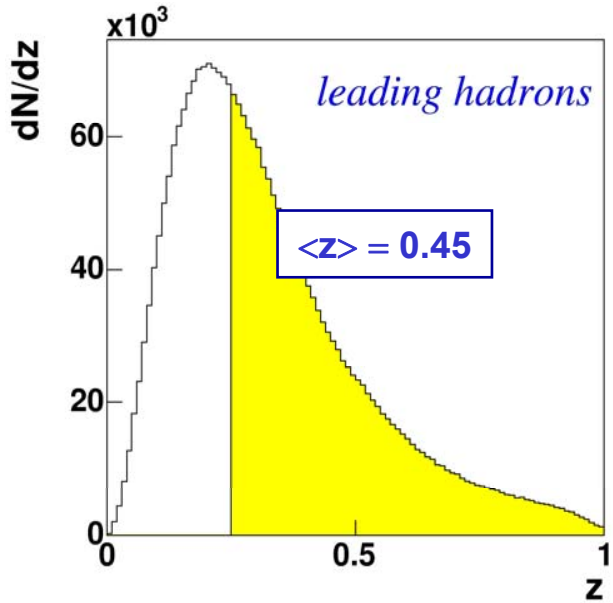
$z > 0.25$ (leading h)





event selection cont



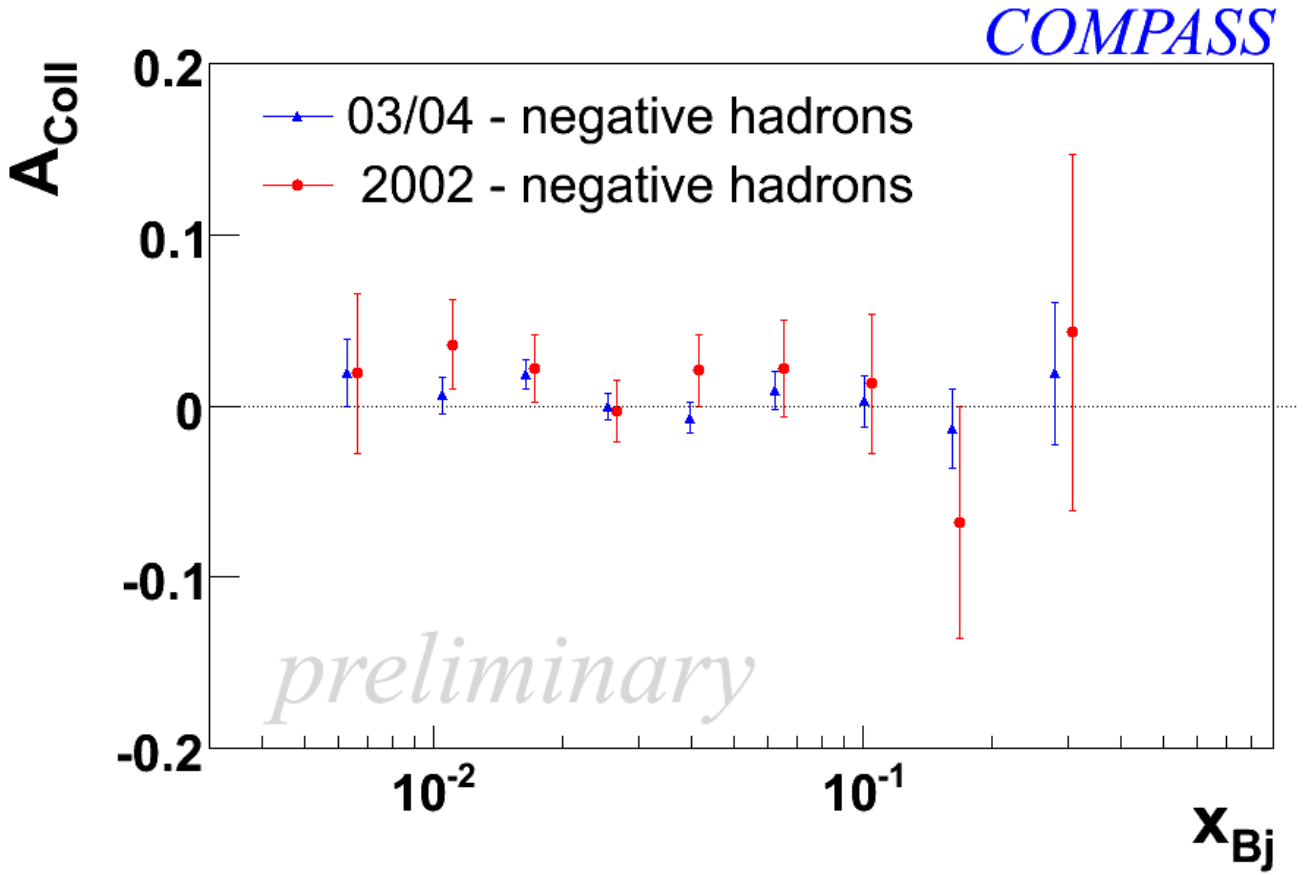


2002 data

Asymmetries 2003-2004 vs 2002

results from 2003-2004 data released in April (DIS2006)

comparison with the published 2002 data ***PRL 94 (2005) 202002***



increase in statistics by a factor of 7!

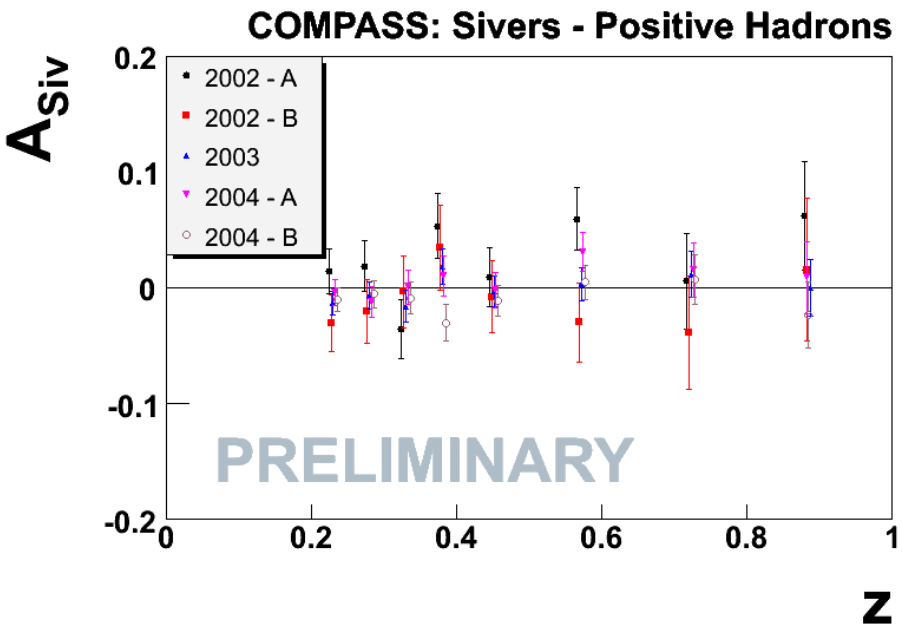
systematics

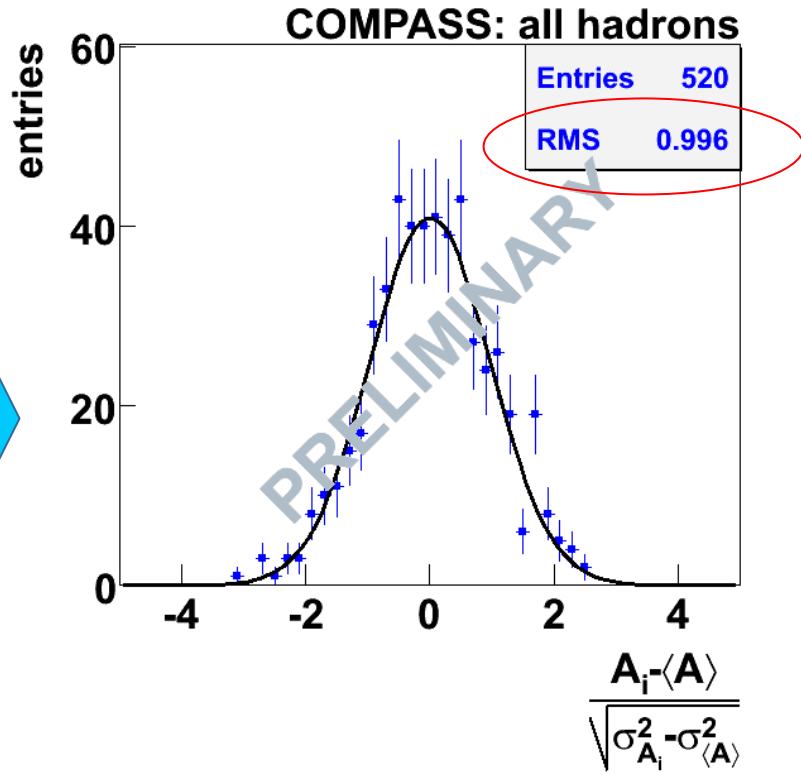
extensive studies, in view of the small statistical errors:

- **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**
- **quality of the fit**
- **….**

systematics (cont)

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

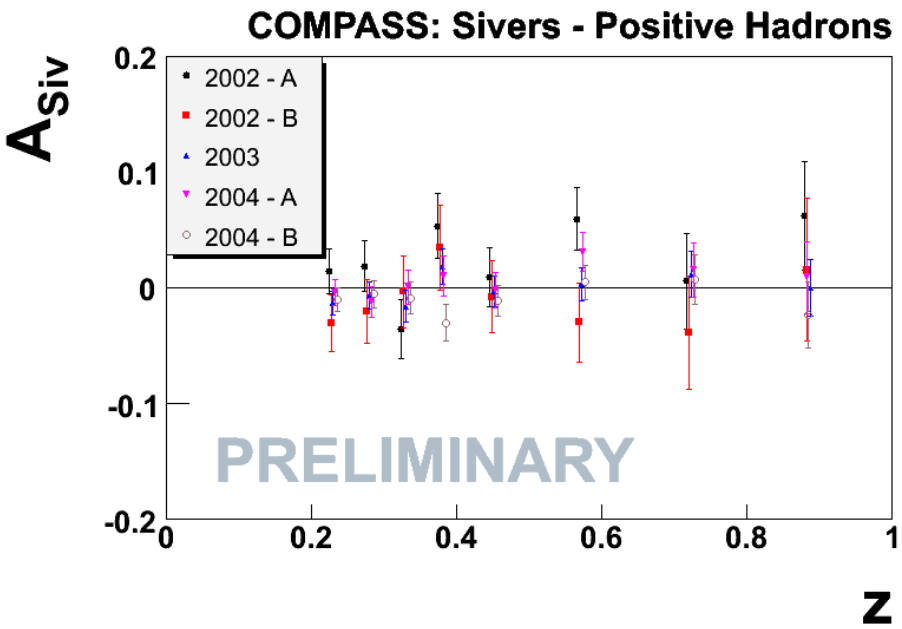


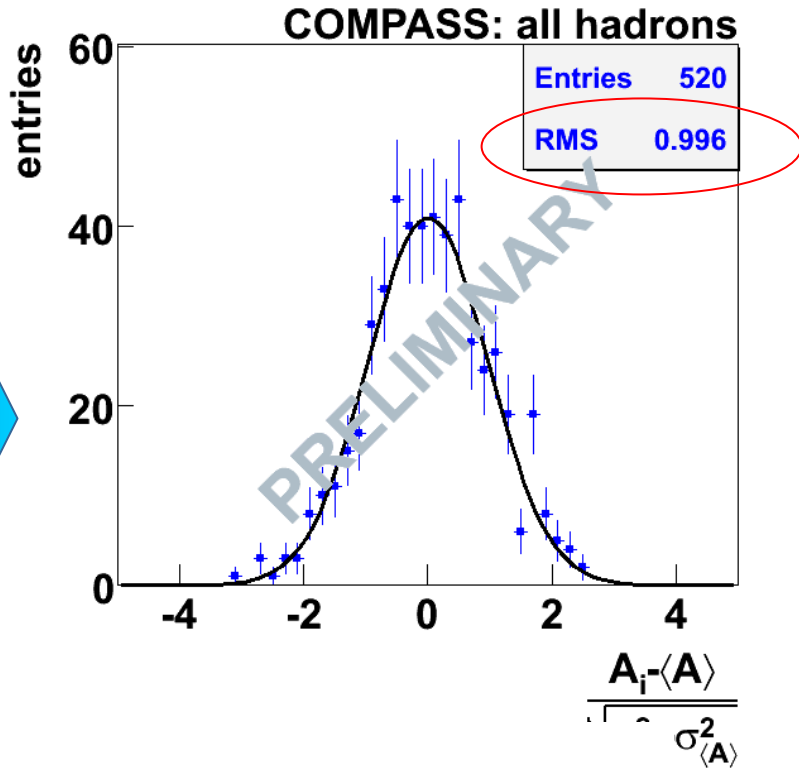


expected:
normal standard distribution

systematics (cont)

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



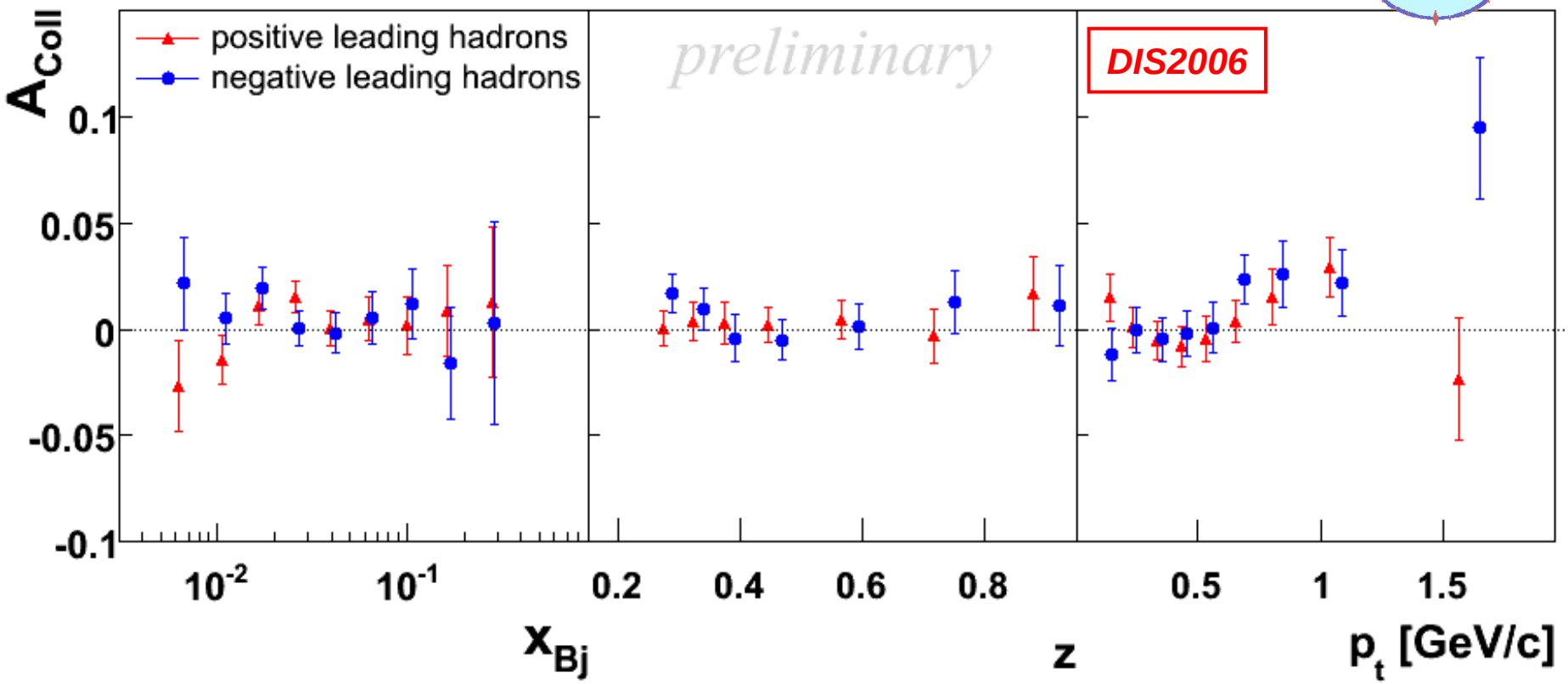


CONCLUSION:

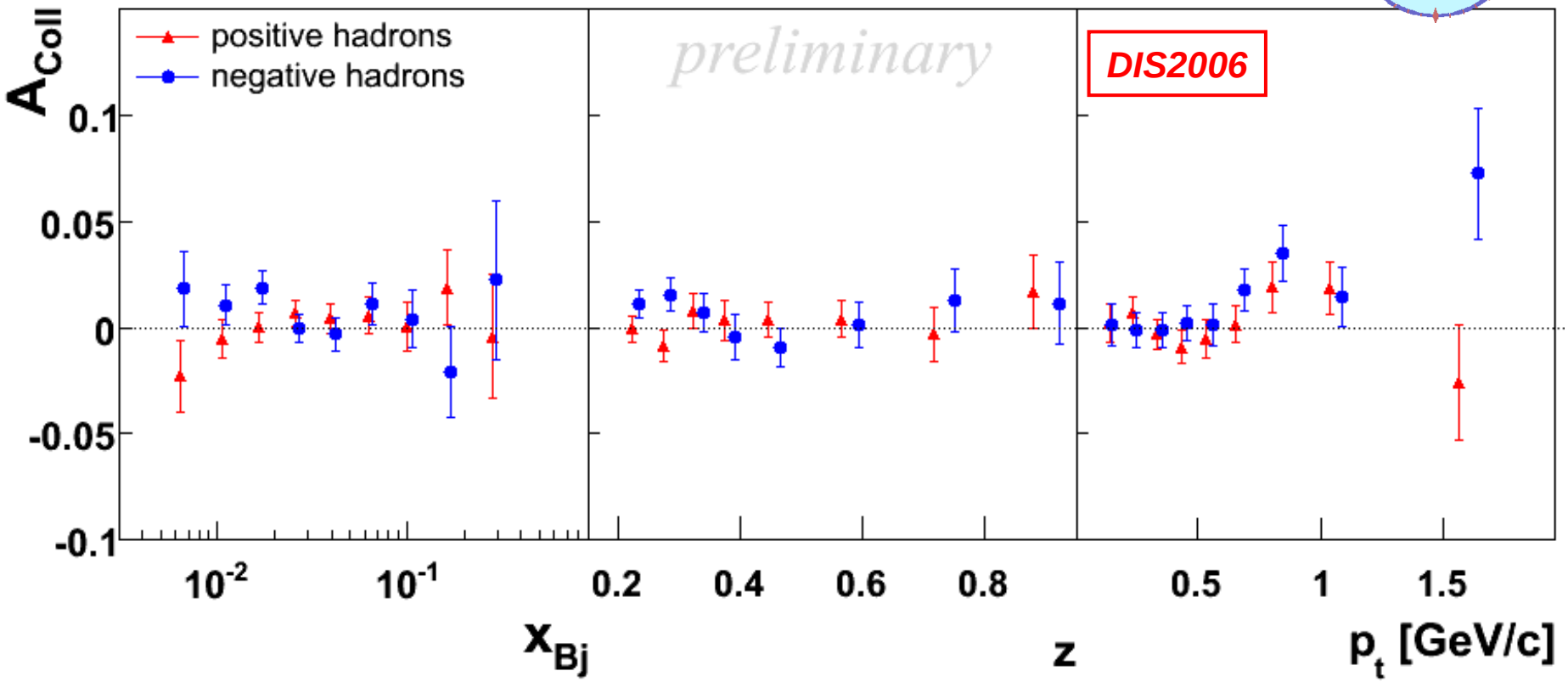
all the effects are compatible with the statistical fluctuations →

our systematic errors are considerably smaller than the statistical errors

Collins Asymmetries 2002-2004



Collins Asymmetries 2002-2004



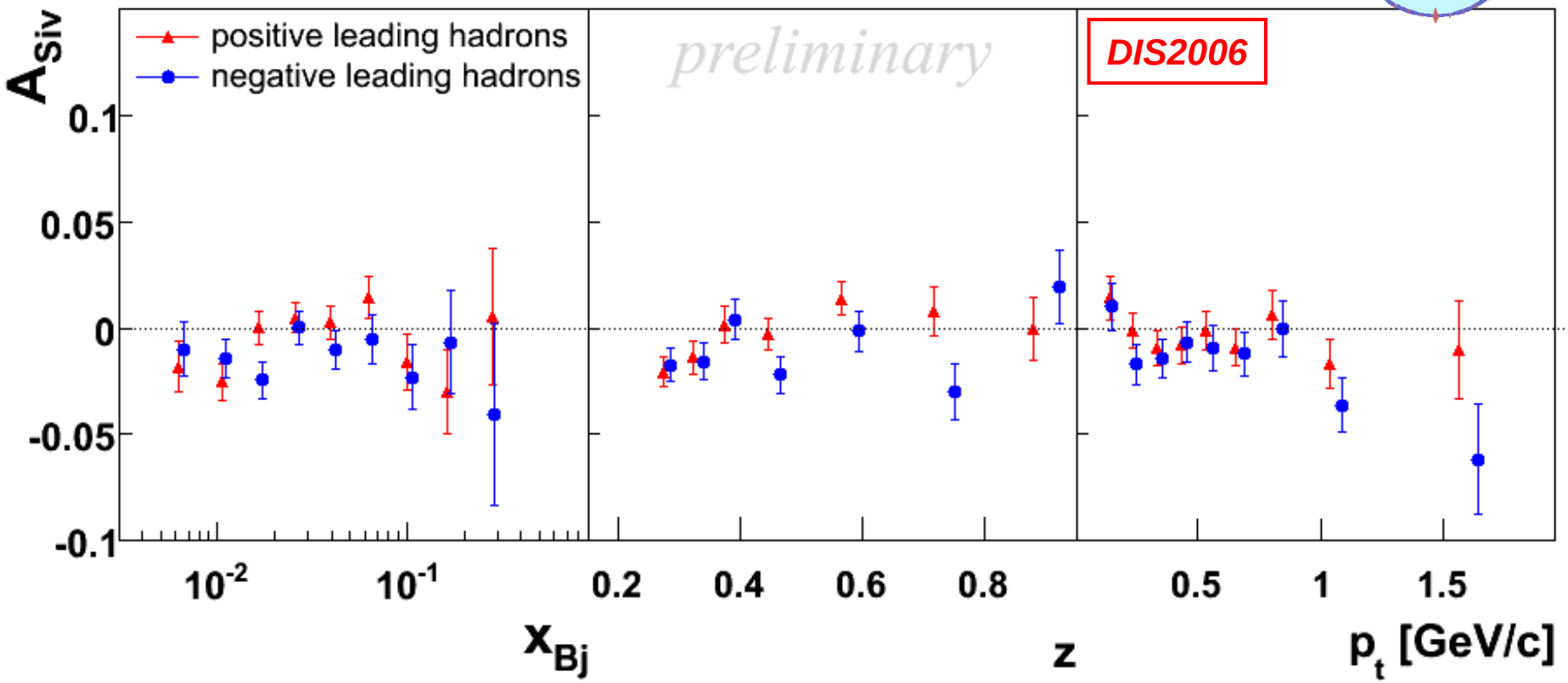
- **small errors (~1%)**
- **small asymmetries**
- **cancellation between p and n**

(lh and ah)

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

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

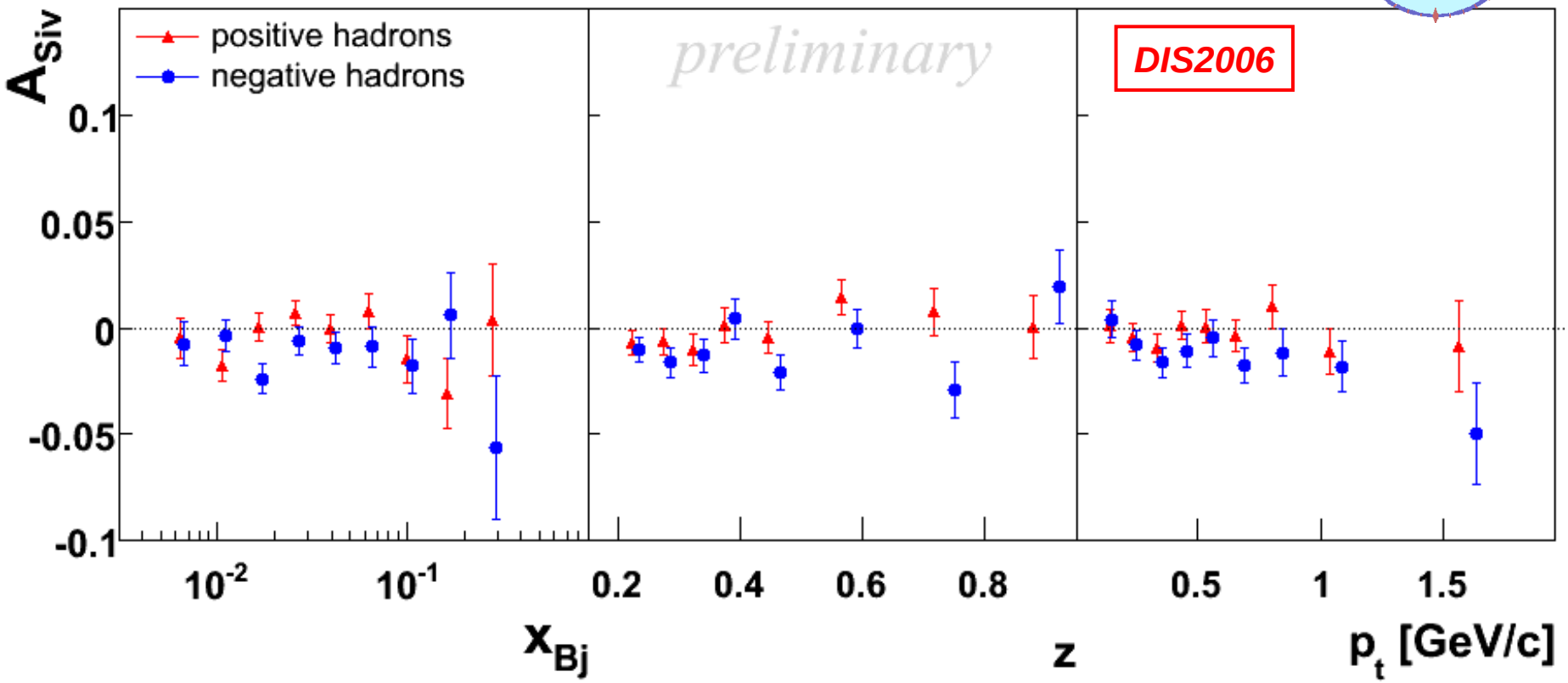
Sivers Asymmetries 2002-2004



- **small errors (~1%)**
- **small asymmetries**
- **cancellation between p and n** $A_{Siv,d} \approx \left(\Delta_0^T u + \Delta_0^T d\right) \cdot D$

  (lh and ah)

Sivers Asymmetries 2002-2004



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- **small asymmetries**
- **cancellation between p and n** $A_{Siv,d} \approx \left(\Delta_0^T u + \Delta_0^T d\right) \cdot D$

  (lh and ah)

Collins - comparison with theory

some of the recent phenomenological studies

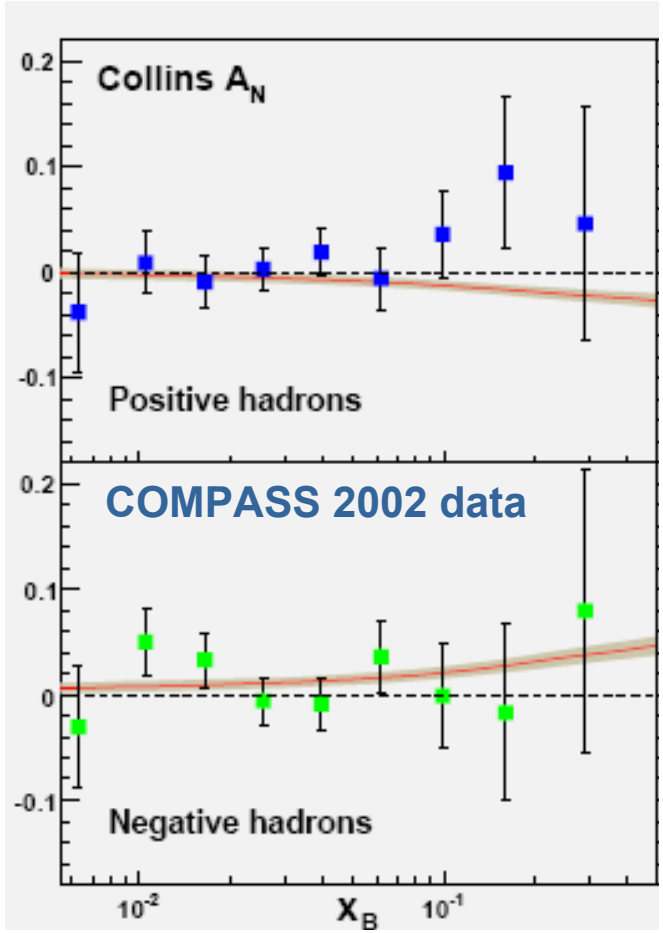
W. Vogelsang and F. Yuan
PRD72 (2005) 054028

- $\Delta_T q$ 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



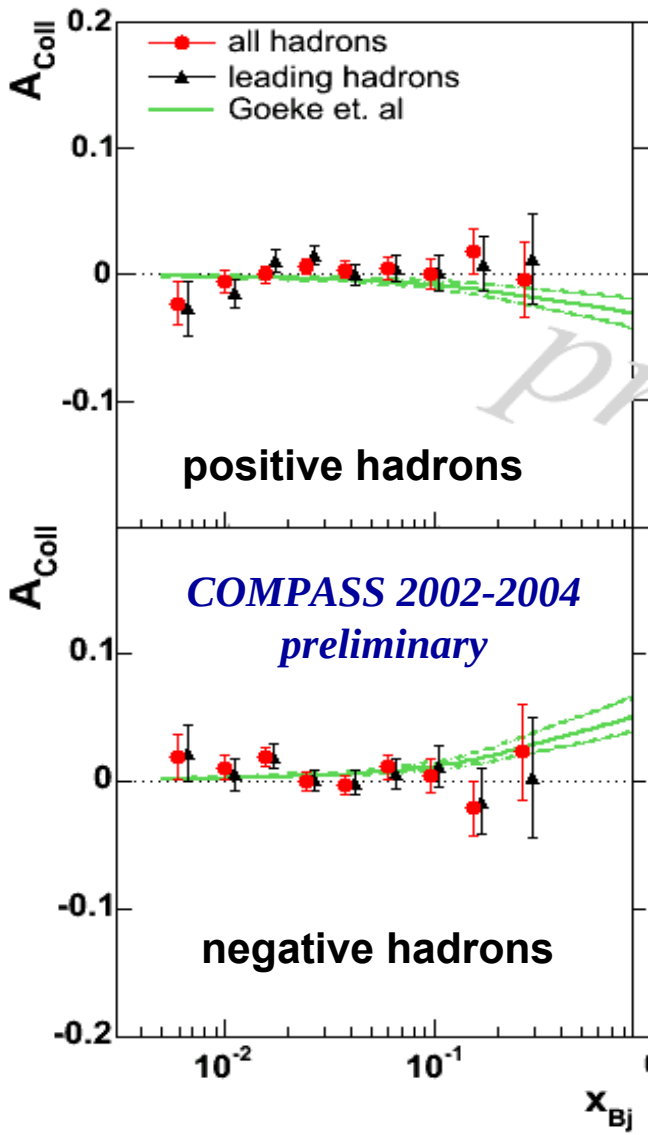
Collins - comparison with theory

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 analysis of BELLE**
- **$\Delta_T d$ ~ unconstrained**

→ comparison with COMPASS 2002 data ok



Sivers - comparison with theory

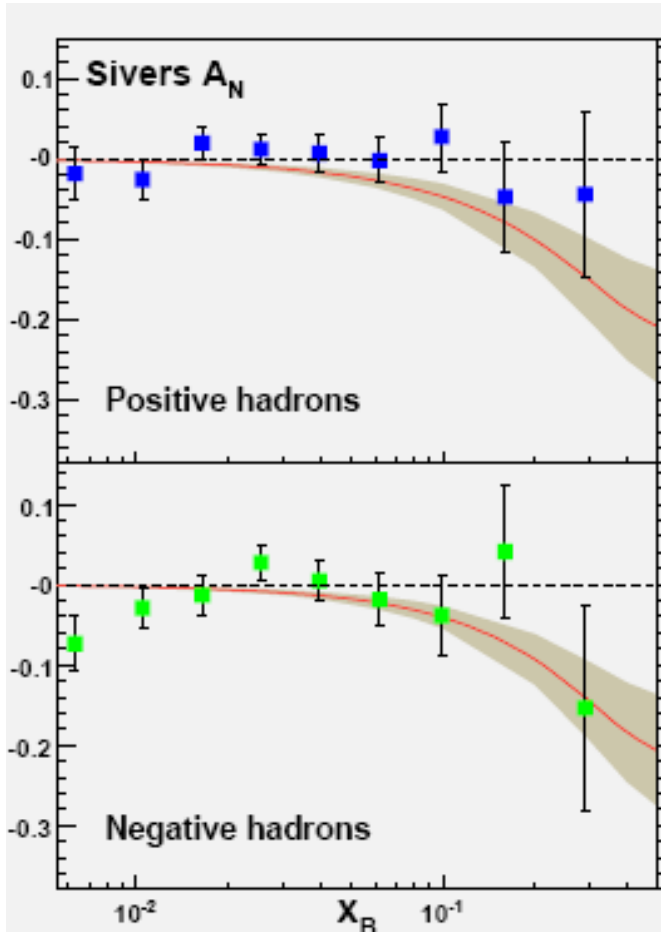
W. Vogelsang and F. Yuan
PRD72 (2005) 054028

- **2 parameter fit to HERMES π data to extract Sivers function (u and d)**

  → d ~ - 2 u

  due to the large π^- asymmetry
  (χ^2/ν ~ 1.2)

→ comparison with COMPASS 2002 data ok

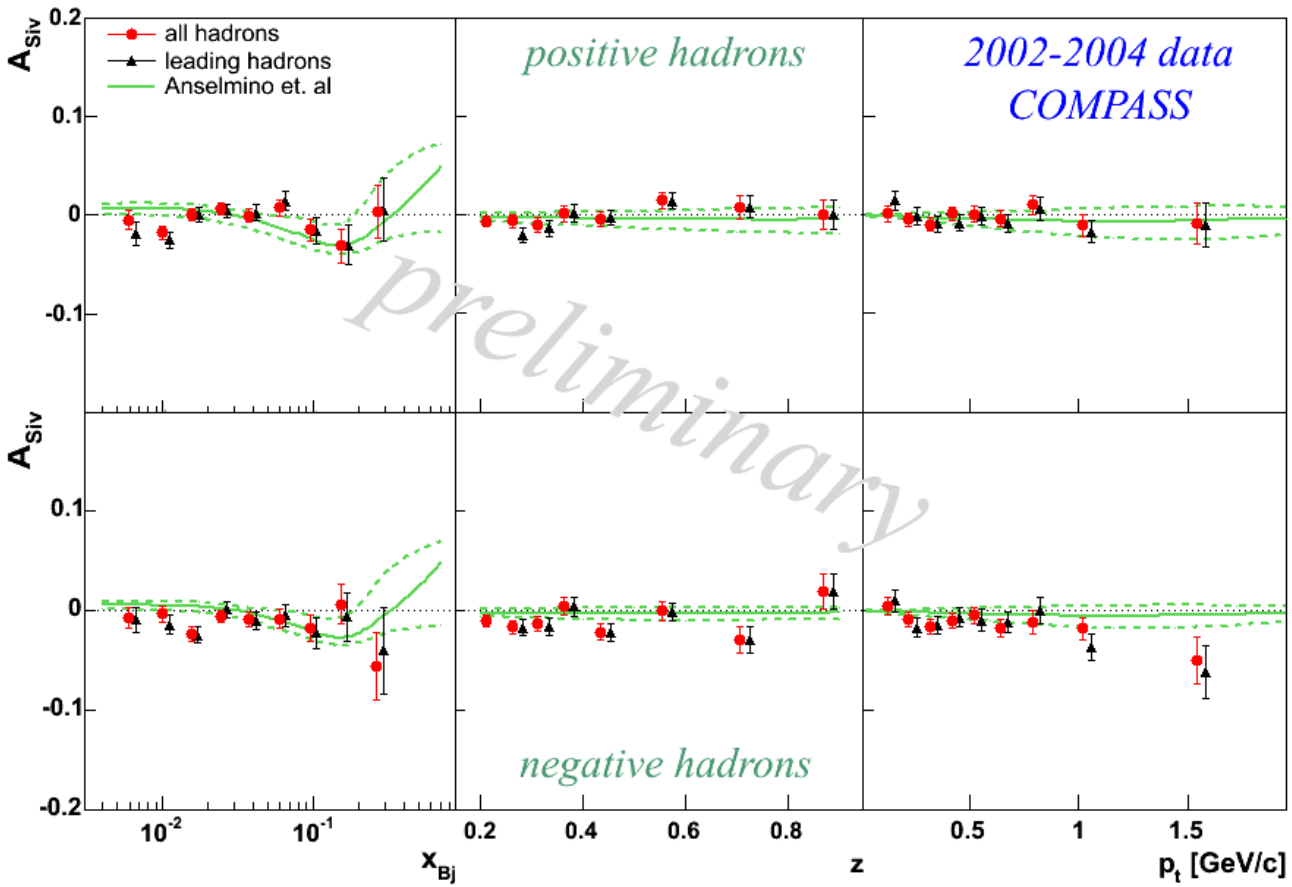


Sivers - comparison with theory

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

- **including transverse momenta**
- **FF from literature**
- **13 parameter fit to HERMES and COMPASS 2002 data to extract Sivers functions → $\Delta_0^T u \approx -\Delta_0^T d$**

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



PHYSICS RESULTS

Collins and Sivers asymmetries

positive and negative hadrons,

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

Two hadron asymmetries

all pairs

leading hadrons

Λ polarimetry

COMPASS

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

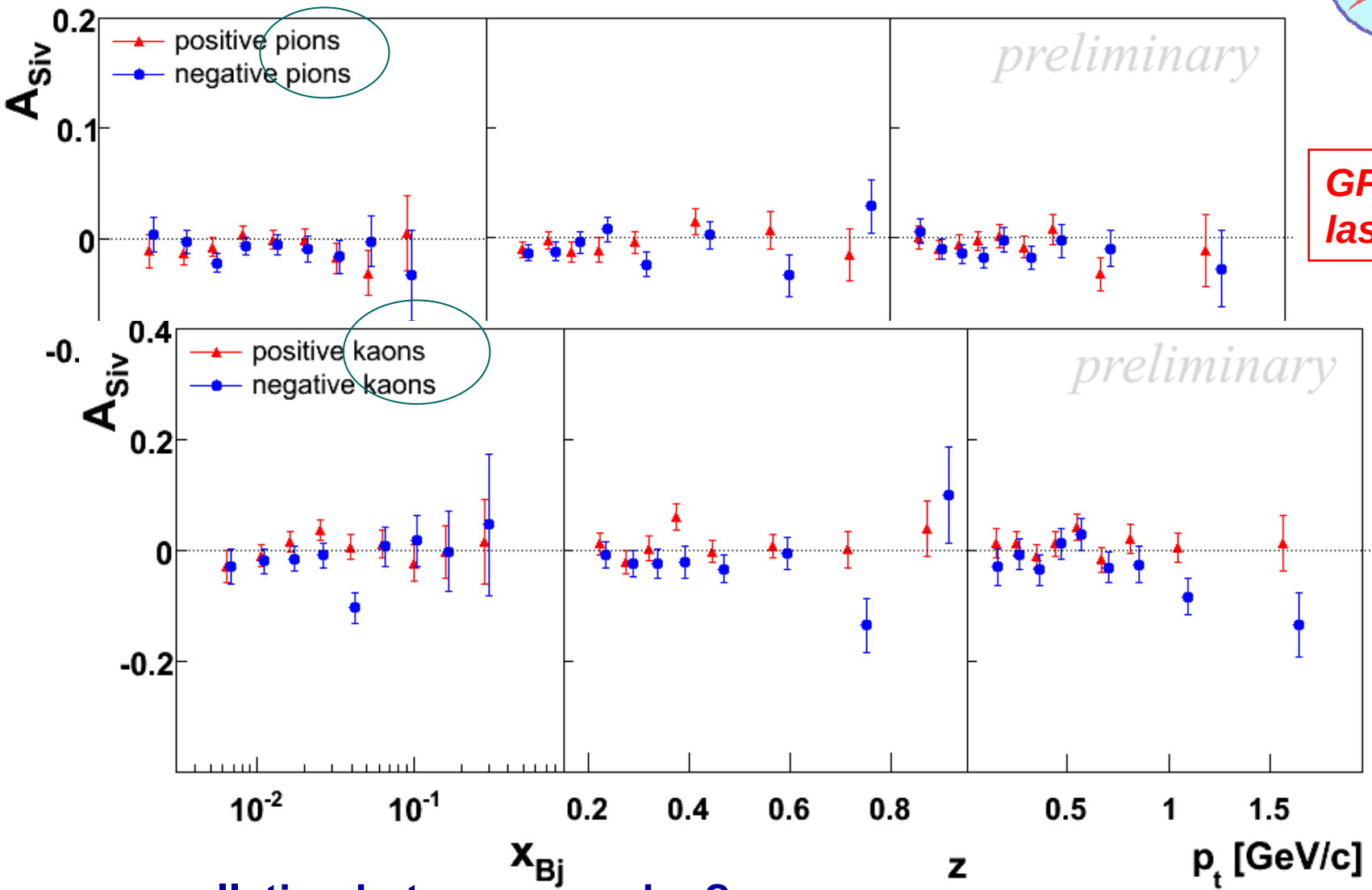
same DIS event selection and hadron definition as before
plus
PID based on RICH response

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

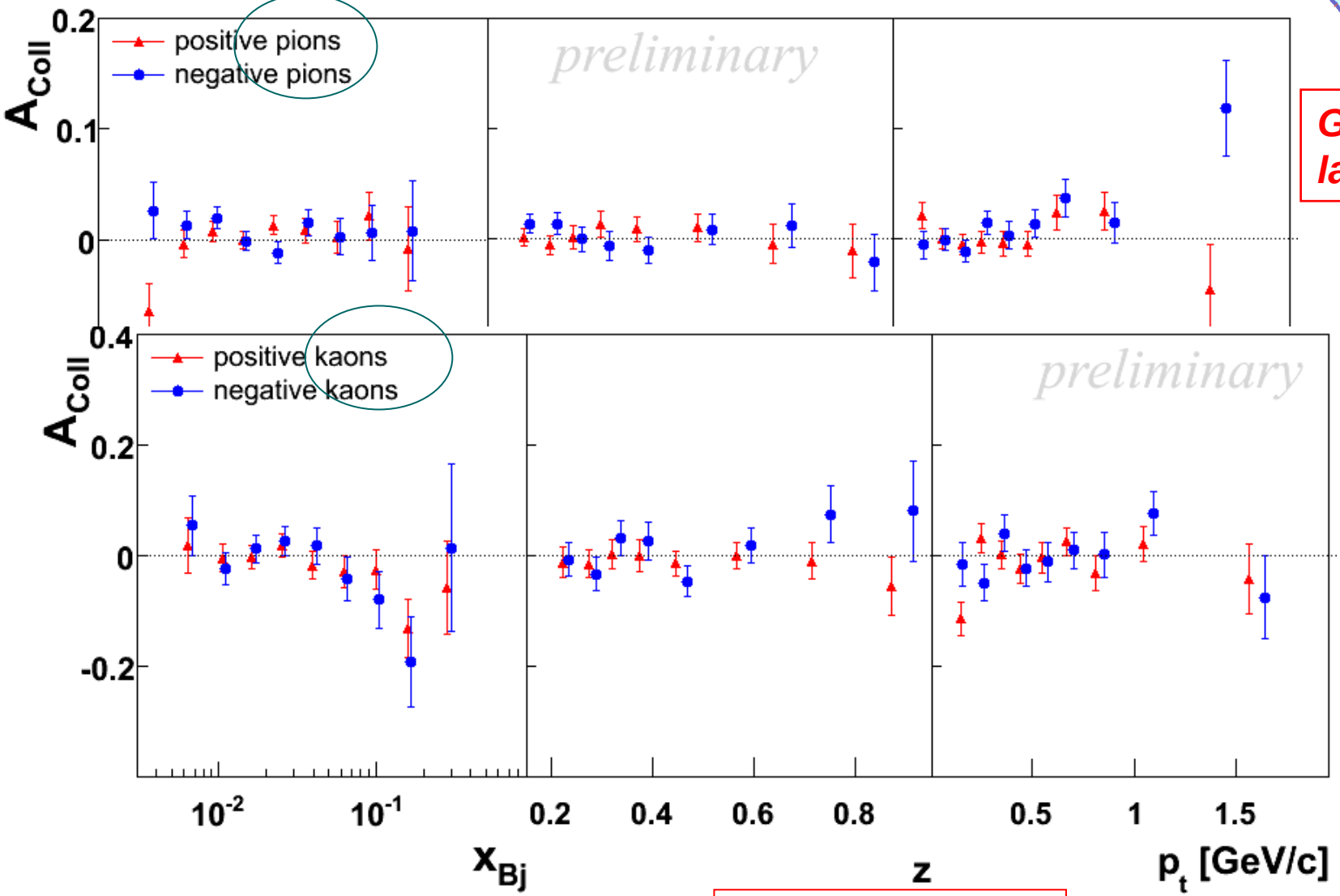
$\pi^{\pm}$, $K^{\pm}$ Sivers Asymmetries 2003-2004



GPD2006 last week

cancellation between p and n ?

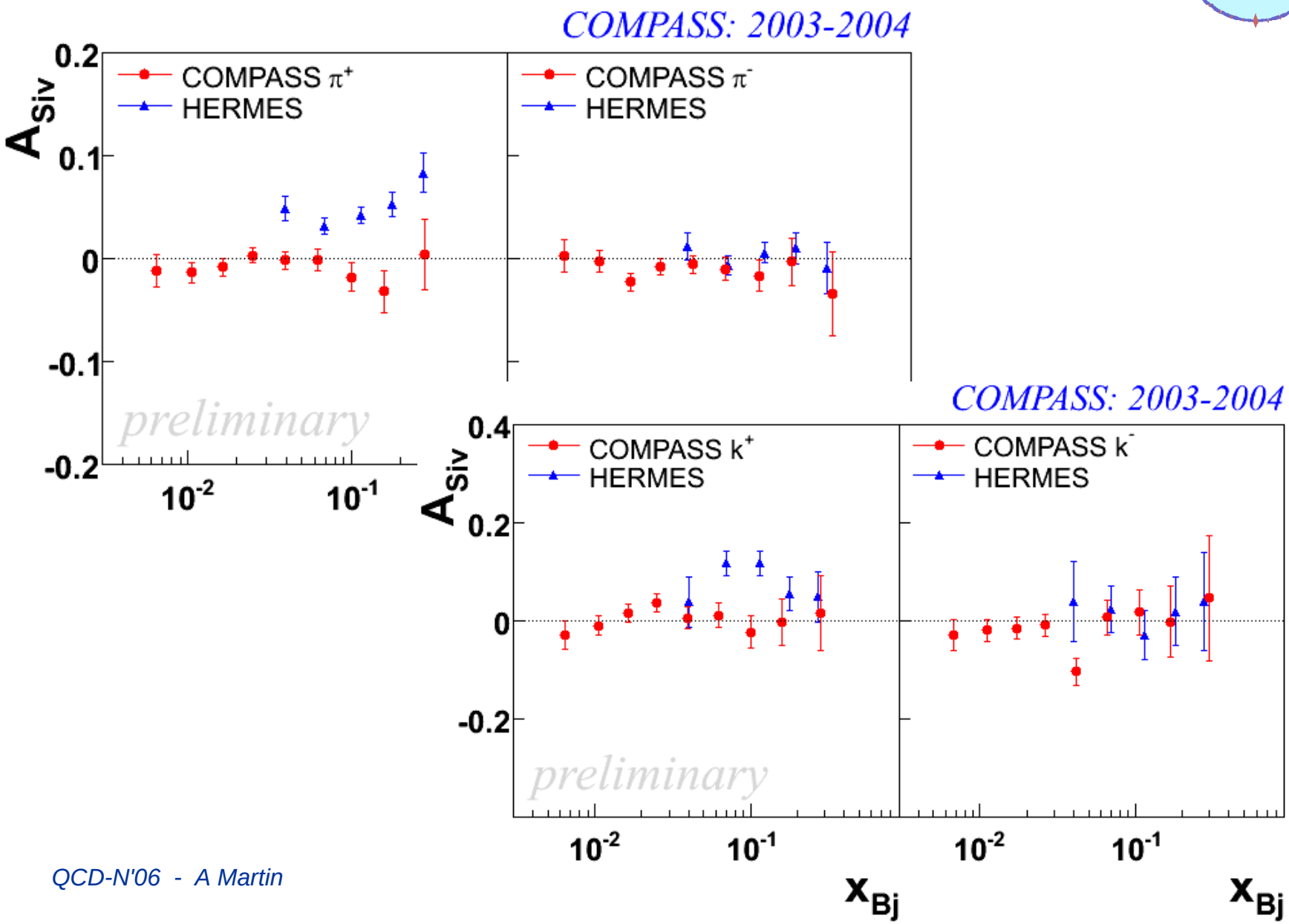
$\pi^{\pm}$, $K^{\pm}$ Collins Asymmetries 2003-2004



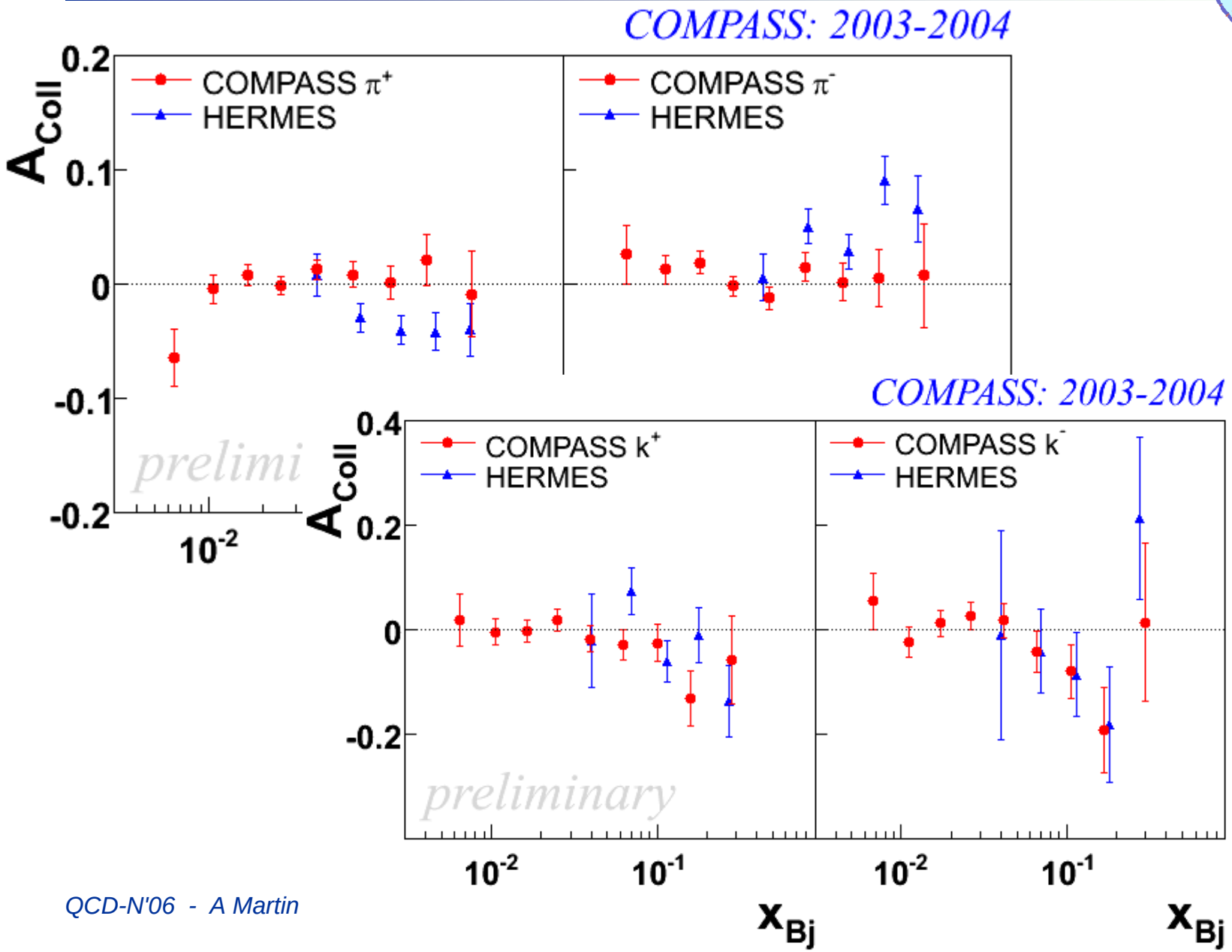
GPD2006 last week

just released …

comparison with HERMES



comparison with HERMES



PHYSICS RESULTS

Collins and Sivers asymmetries

positive and negative hadrons,

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

Two hadron asymmetries

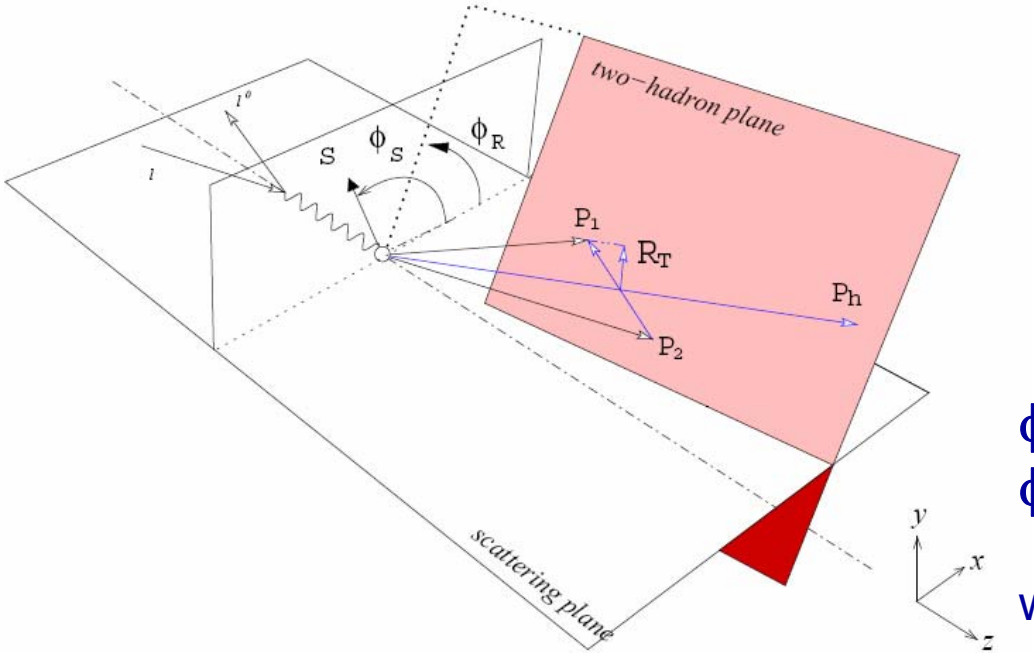
all pairs

leading hadrons

Λ polarimetry

Two Hadron Asymmetries

looking at two hadron production, 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 1

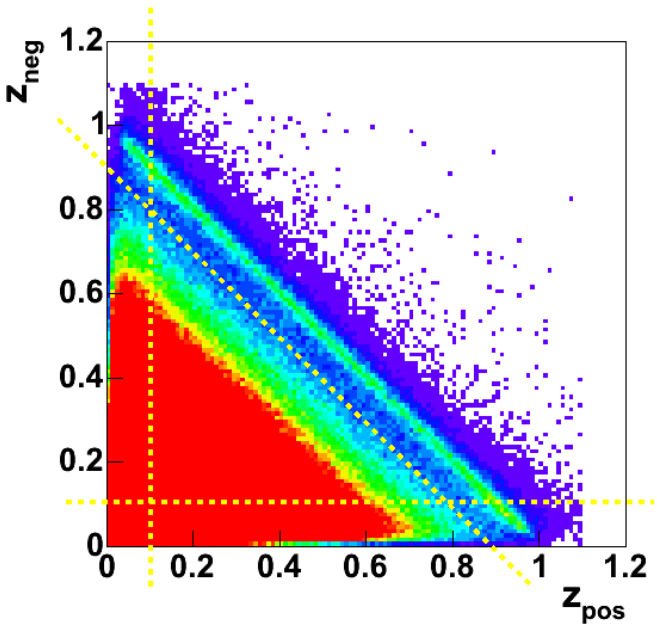
selection of DIS events

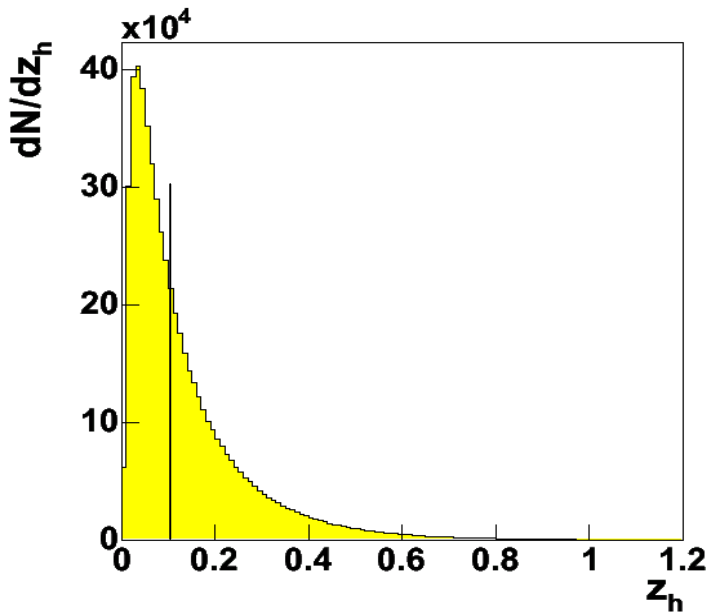
- $Q^2 > 1\ (GeV/c)^2$
- $0.9 > y > 0.1$
- $W > 5$ GeV

and hadrons

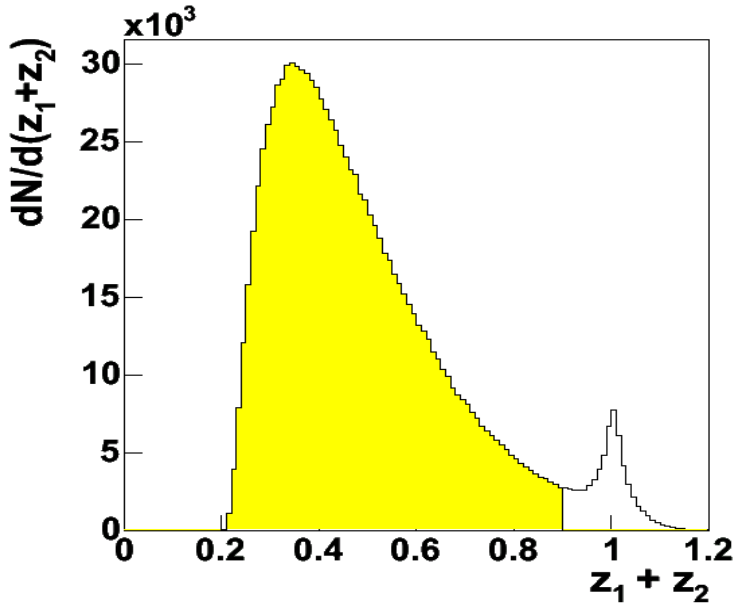
- $z_{1,2} > 0.1$ and $x_{f1,2} > 0.1$
- $z_1 + z_2 < 0.9$
- all combinations of +ve (h_1) and –ve (h_2) hadrons (~1.3/ev)
- presently no RICH PID

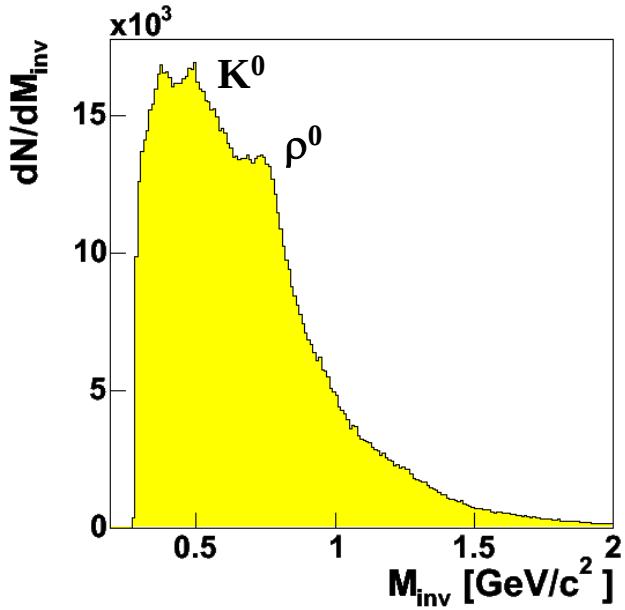
total statistics 2002-2004: 6.1 M combinations



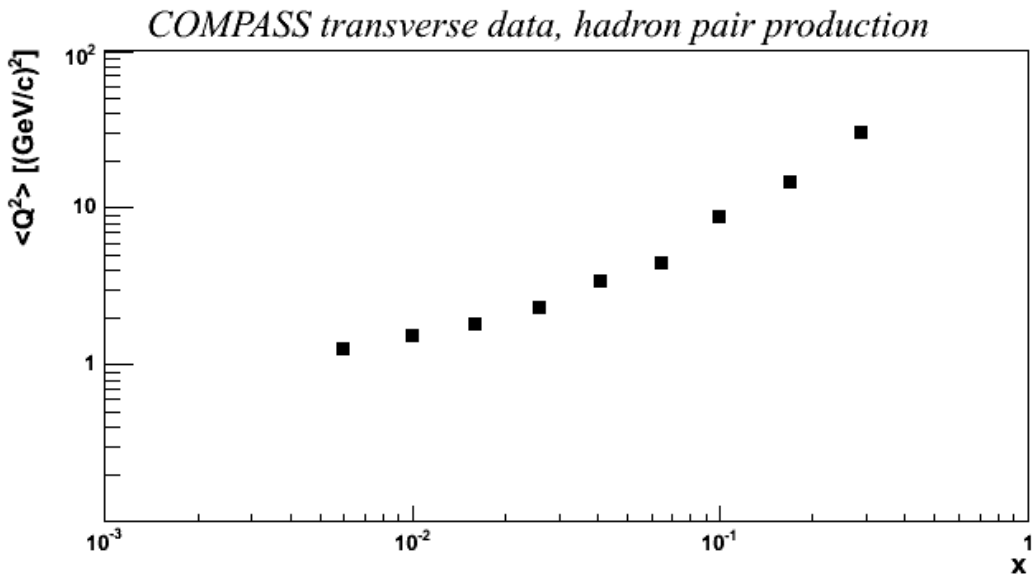


Two Hadron Asymmetries 1



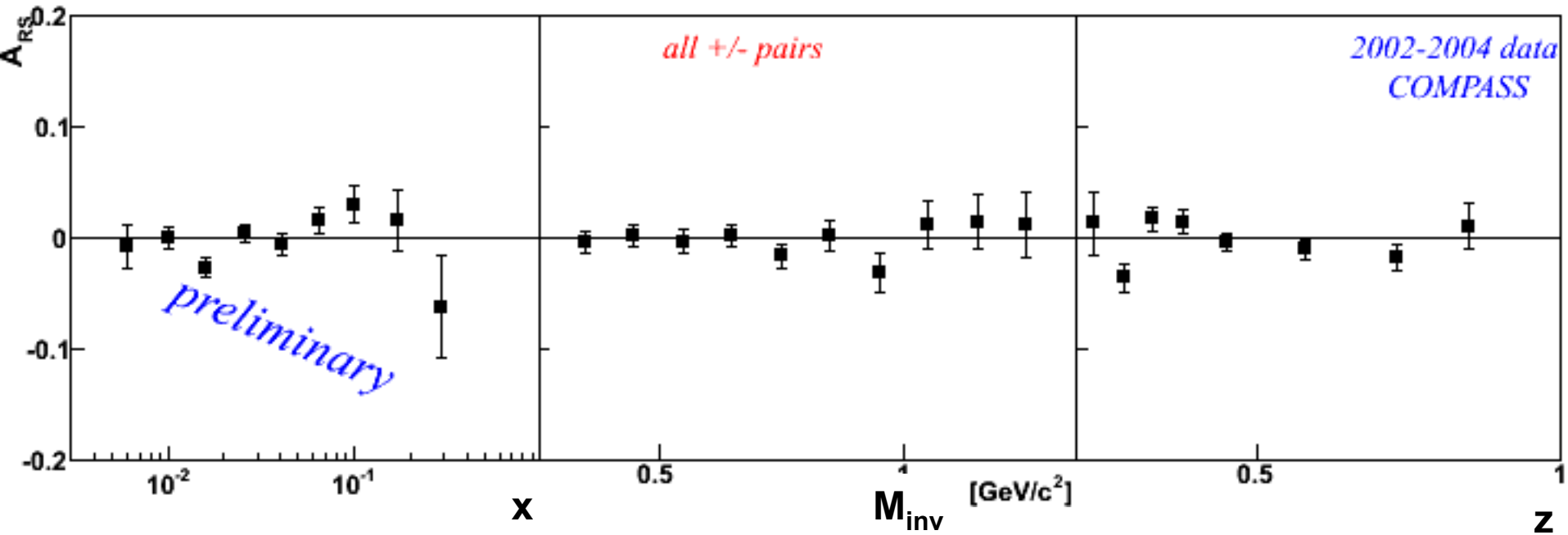


final sample



Two Hadron Asymmetries 1

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



2002-2004 COMPASS data

CIPANP06, May-June

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

PHYSICS RESULTS

Collins and Sivers asymmetries

positive and negative hadrons,

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

Two hadron asymmetries

all pairs

leading hadrons

Λ polarimetry

Two Hadron Asymmetries 2

different hadron pairs selections have been tried

still based on the string fragmentation model

1 entry/event

- **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

→ *SPIN 2005*

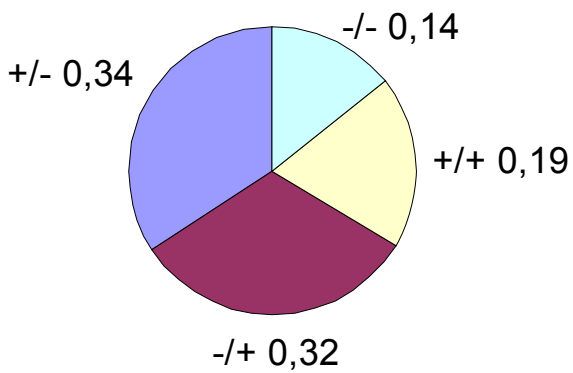
- **z - leading hadron pairs**

  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

CIPANP06

2002-2004 data: 6.4 M events

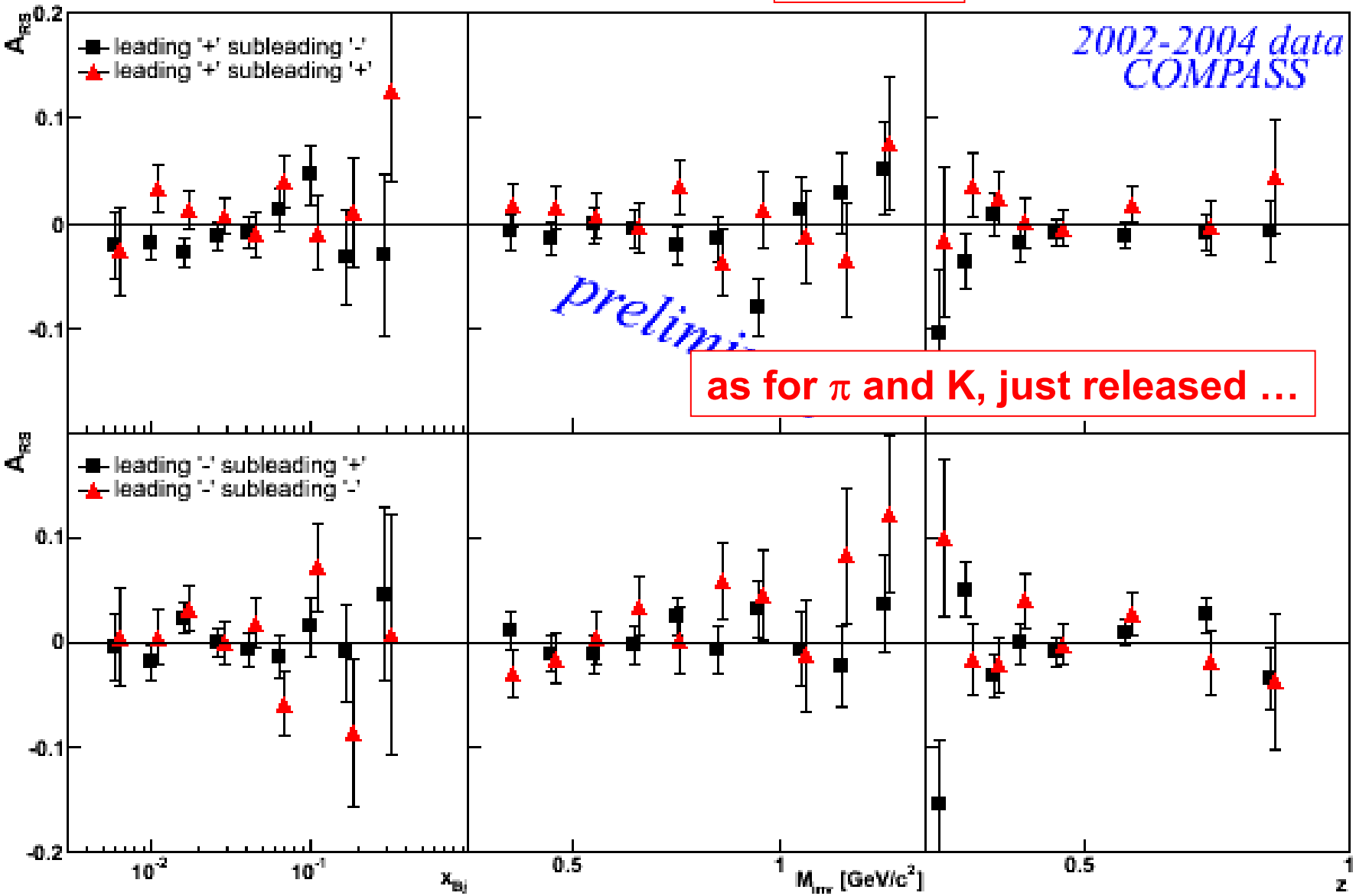
fractions:



Two Hadron Asymmetries / 2

z-leading hadron pairs

CIPANP06



as for π and K, just released …

PHYSICS RESULTS

Collins and Sivers asymmetries

positive and negative hadrons,

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

Two hadron asymmetries

all pairs

leading hadrons

Λ polarimetry

COMPASS

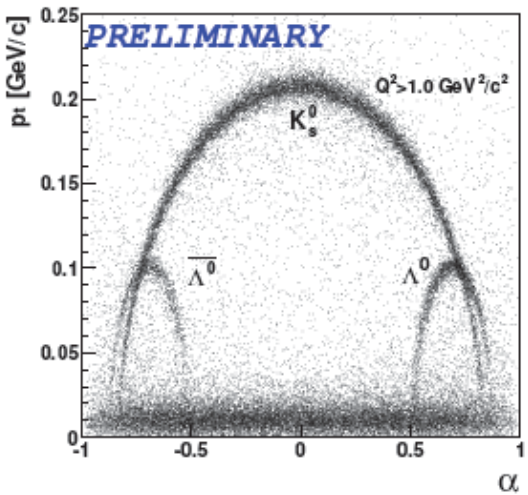
Λ polarimetry

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

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

event selection

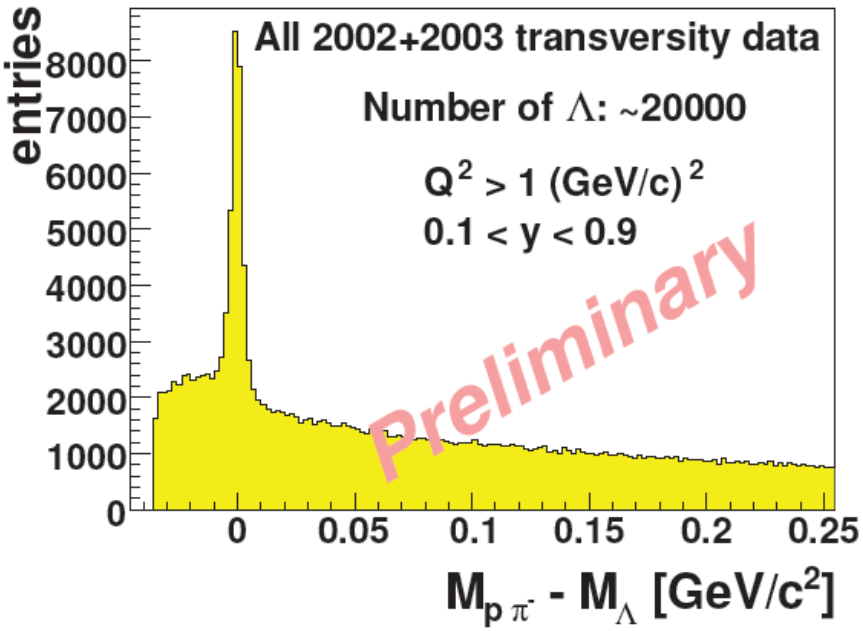
- Primary vertex in target cell material, beam crossing both cells
- μ' traverses at least 30 radiation lengths
- Tracks of p and π^- candidates traverse at least the SM1 magnet
- momentum of both decay particles > 1 GeV/c

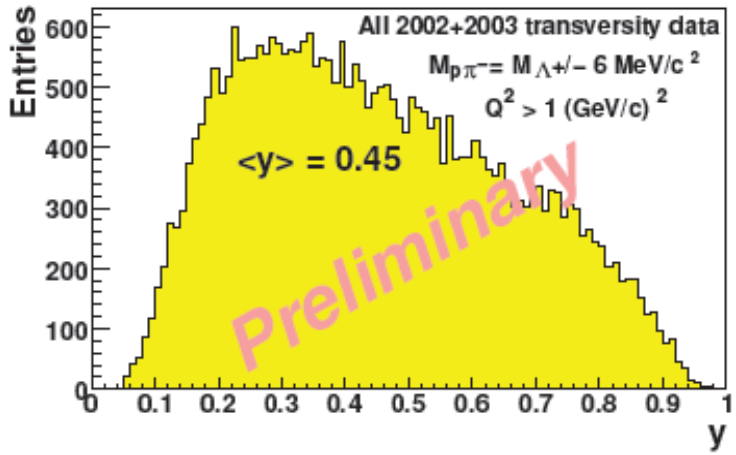


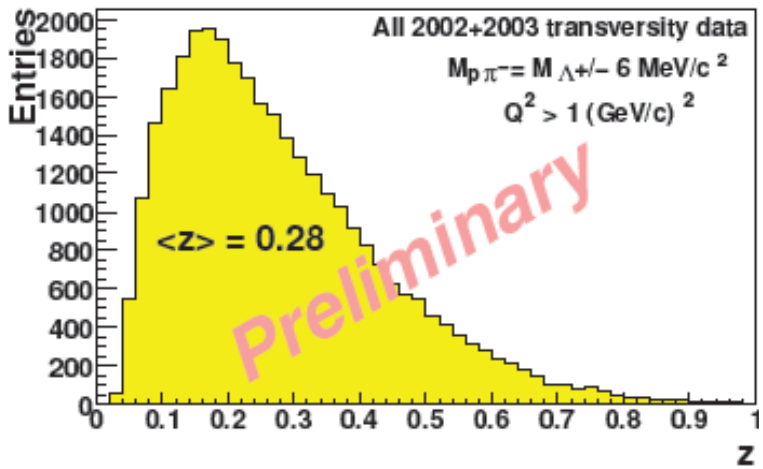
- The candidate Λ decay is downstream of the target and outside of it
- collinearity < 10 mrad
- Armenteros $p_T > 23$ MeV/c
- $0.1 < y < 0.9$

Λ polarimetry

2002-2003 data







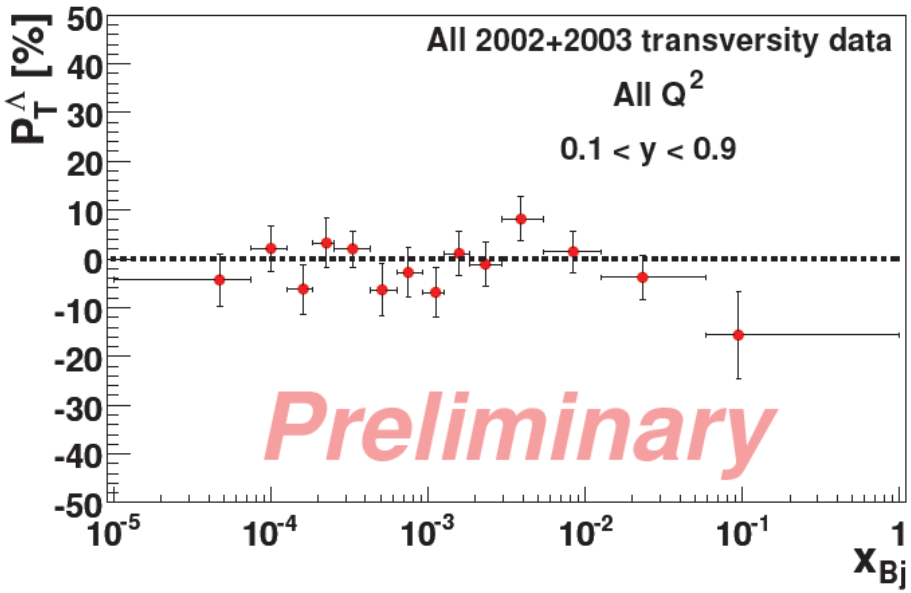
The majority of Lambda events are produced at $x_F > 0$ (current fragmentation region)

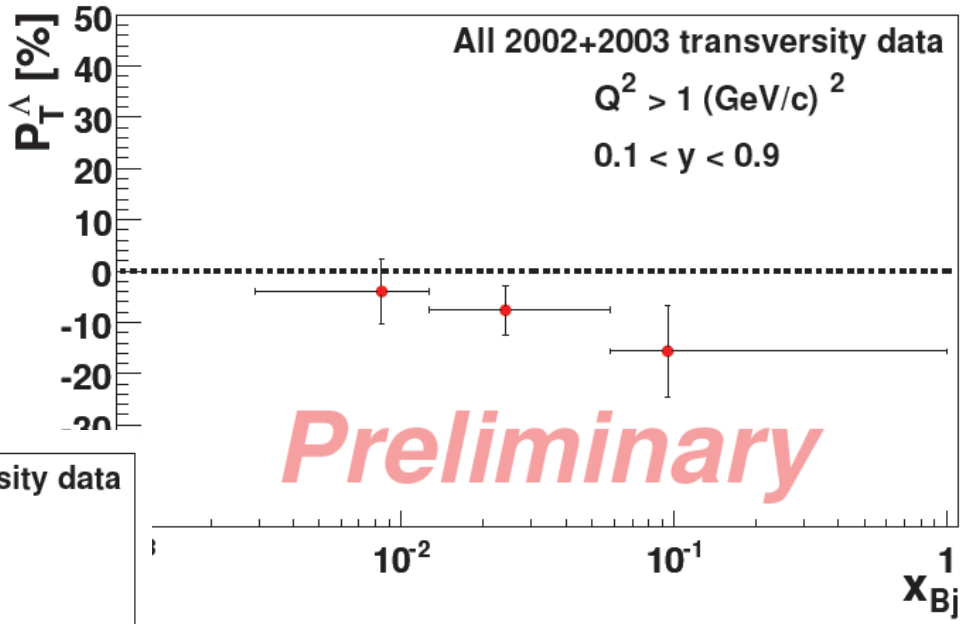
TRANSVERSITY 2005

Λ polarimetry

TRANSVERSITY 2005

2002-2003 data





2004 data: analysis ongoing

SUMMARY AND OUTLOOK

summary

New precise DIS deuteron data from COMPASS are now available

In all the channels investigated in so far

- **Collins and Sivers asymmetries** *+ve and -ve hadrons,* $\pi^{\pm}$, $K^{\pm}$
- **Two hadron asymmetries** *all pairs, leading hadrons*
- **Λ polarimetry**

the measured deuteron asymmetries are very small, compatible with zero

SURPRISING RESULTS FROM KAON ASYMMETRIES

Phenomenological studies can describe at the same time the BELLE (FF), the HERMES (proton) and 2002 COMPASS (deuteron) Collins and Sivers asymmetries

Is the emerging picture satisfactory ?!!

outlook 1

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

- Two hadron asymmetries

  RICH PID 2003-2004

- Λ polarimetry 2004

plus

- transverse effects from longitudinal data
- other two asymmetries from single hadron data
- g_2
- Cahn effect
- exclusive ρ production on transversely polarised target
- ….

outlook 2

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

with 30 days running, precision ~ deuteron
in 2006, new PT magnet (larger acceptance at large x)

The COMPASS Collaboration
is considering a new proposal (*) based on spectroscopy,
GPDs, and TRANSVERSITY

SIDIS essential for flavour separation !

→ *H. Fischer*

(*) Input to CERN Council Strategy Group (Jan. 15, 2006)
SPSC-EOI-005 (Jan. 18, 2005)