TMD and Transverse Spin Measurements at COMPASS: status and perspectives

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Trieste University and INFN

on behalf of the COMPASS Collaboration

Transverse momentum, spin, and position distributions of partons in hadrons

ECT*
June 11, 2007

Outlook

- COMPASS
- Results on asymmetries
  - Transversity Distribution Function
  - Sivers Distribution Function
  - Other TMD Distribution Function
- Conclusions and future programs

COMPASS

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

beam: 160 GeV/c
polarisation - 76% (2002-03)
- 80% (2004)
intensity $2\cdot10^{8}$ μ^{+}/spill (4.8s/16.2s)

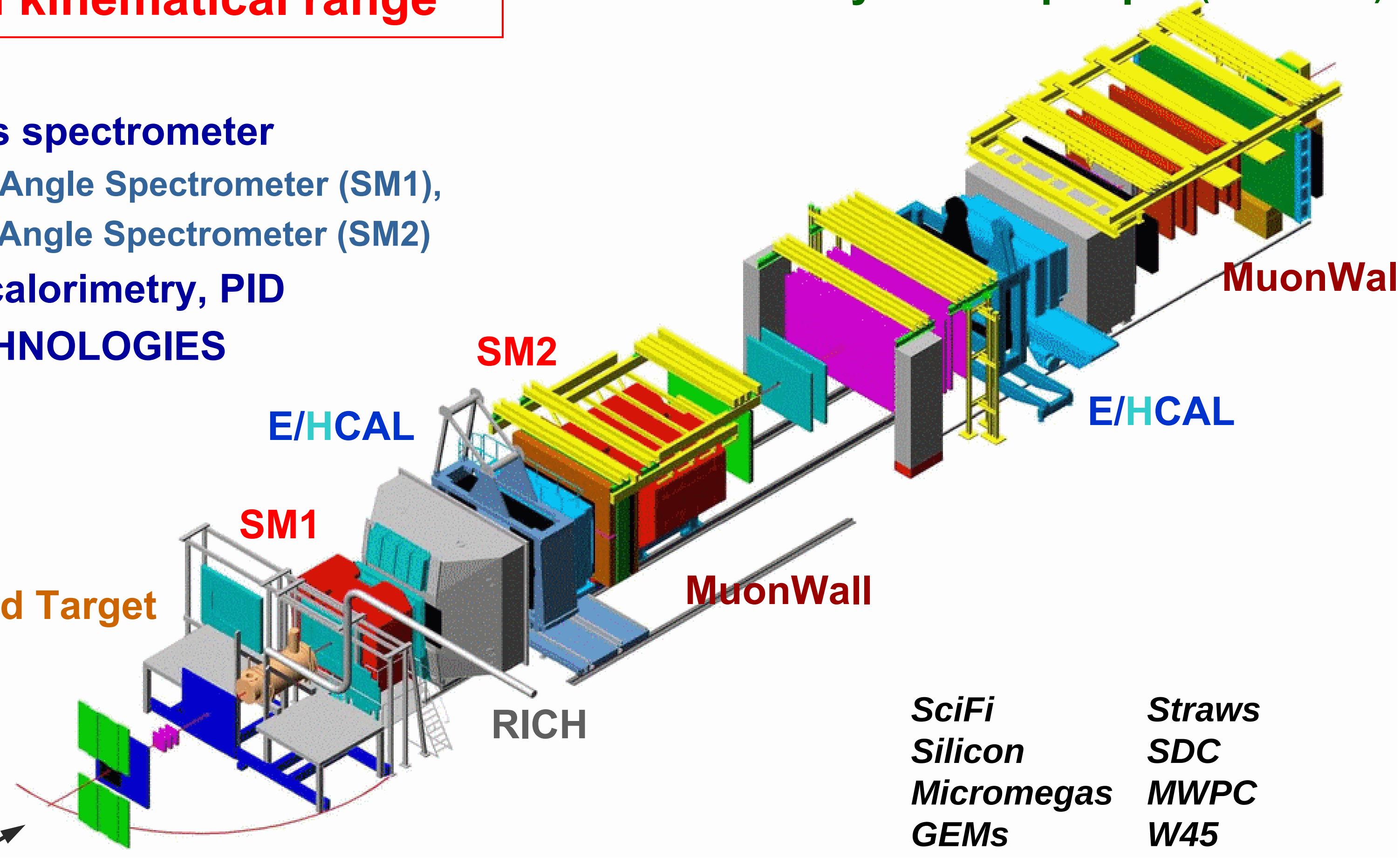
two stages spectrometer

Large Angle Spectrometer (SM1),

Small Angle Spectrometer (SM2)

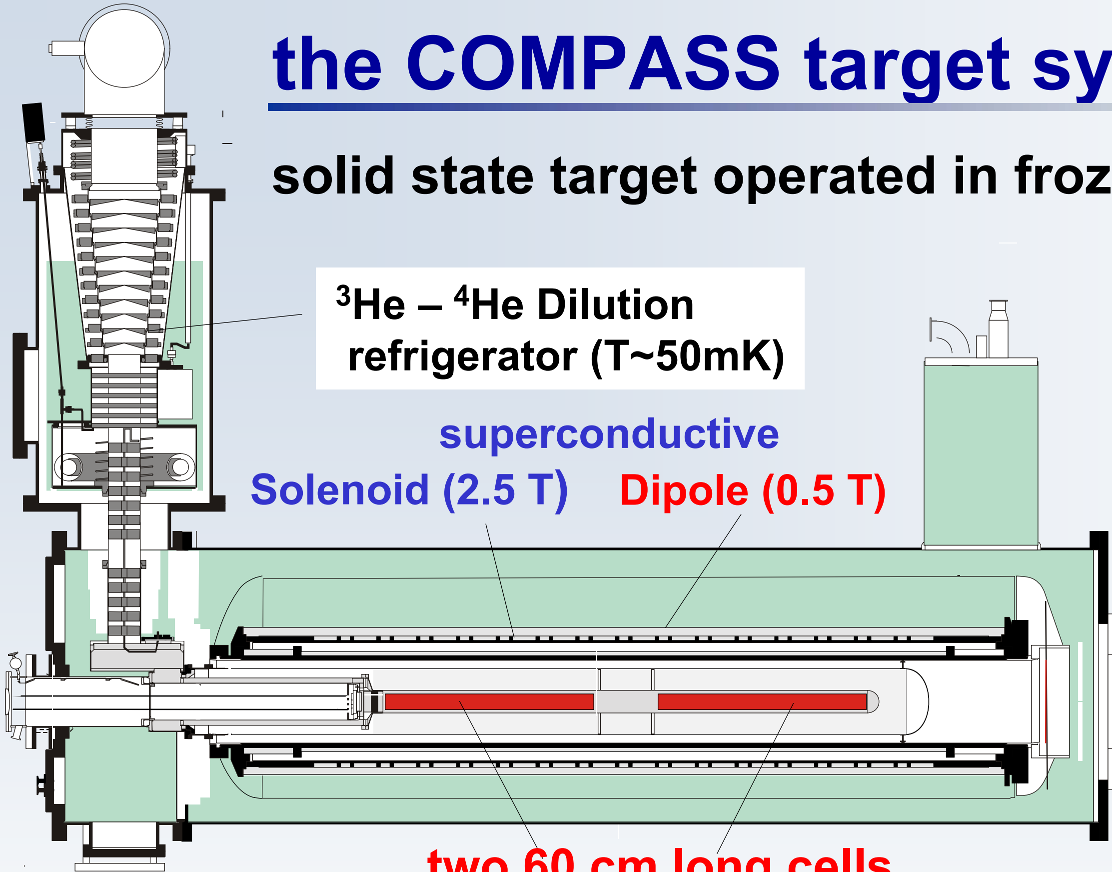
tracking, calorimetry, PID

NEW TECHNOLOGIES

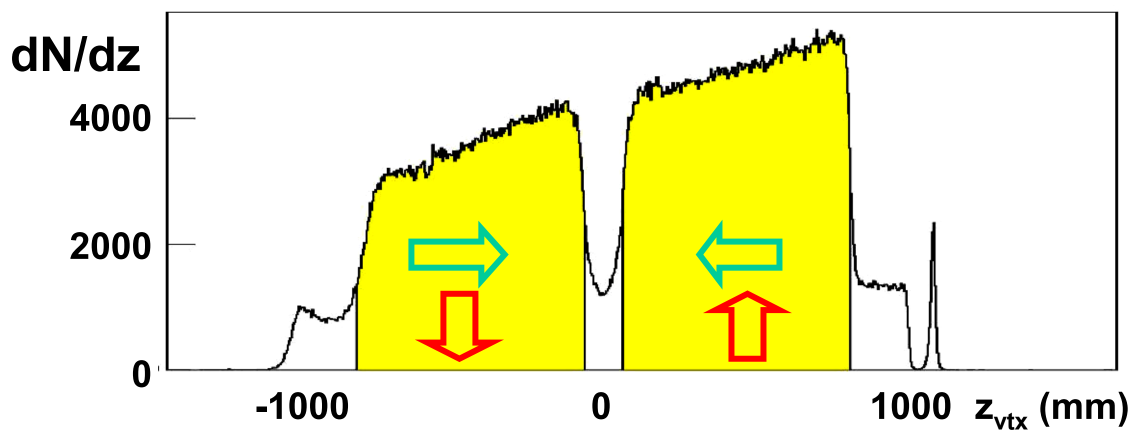


the COMPASS target system (2002-2004)

solid state target operated in frozen spin mode



two 60 cm long cells
with *opposite polarisation* (systematics)



2002-2004: ^{6}LiD
dilution factor f = 0.38
polarization P_T = 50%
~20% of the time
transversely polarised

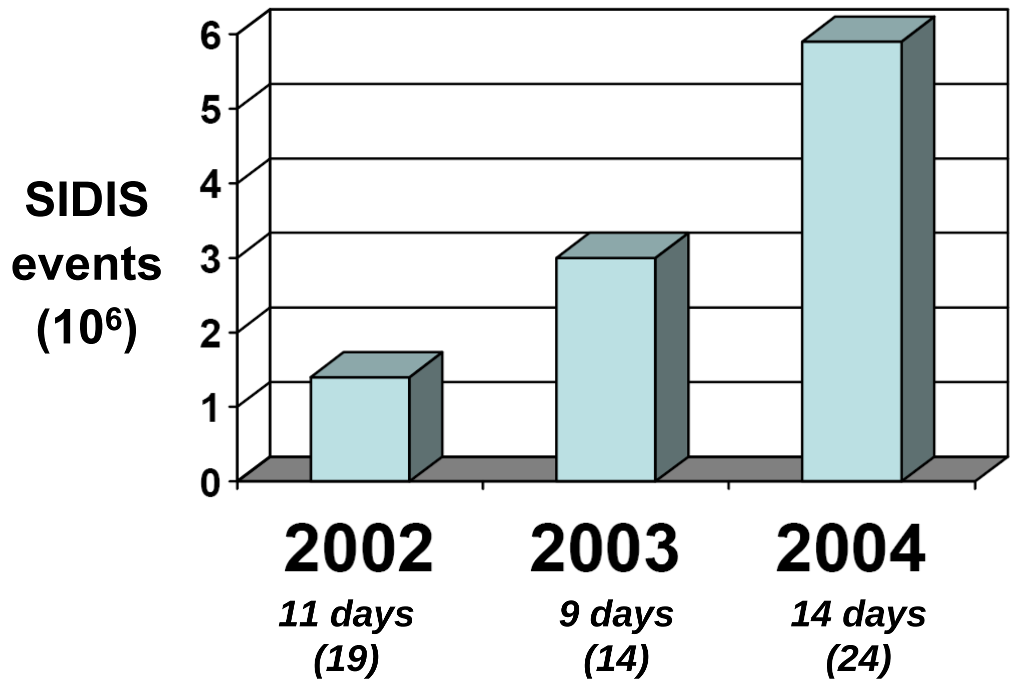
2006:
- PTM replaced with the large acceptance COMPASS magnet
- 2 ➔ 3 cells

during data taking with transverse polarization
- dipole field always ↑
- polarization reversal in the 2 cells after ~ 5 days

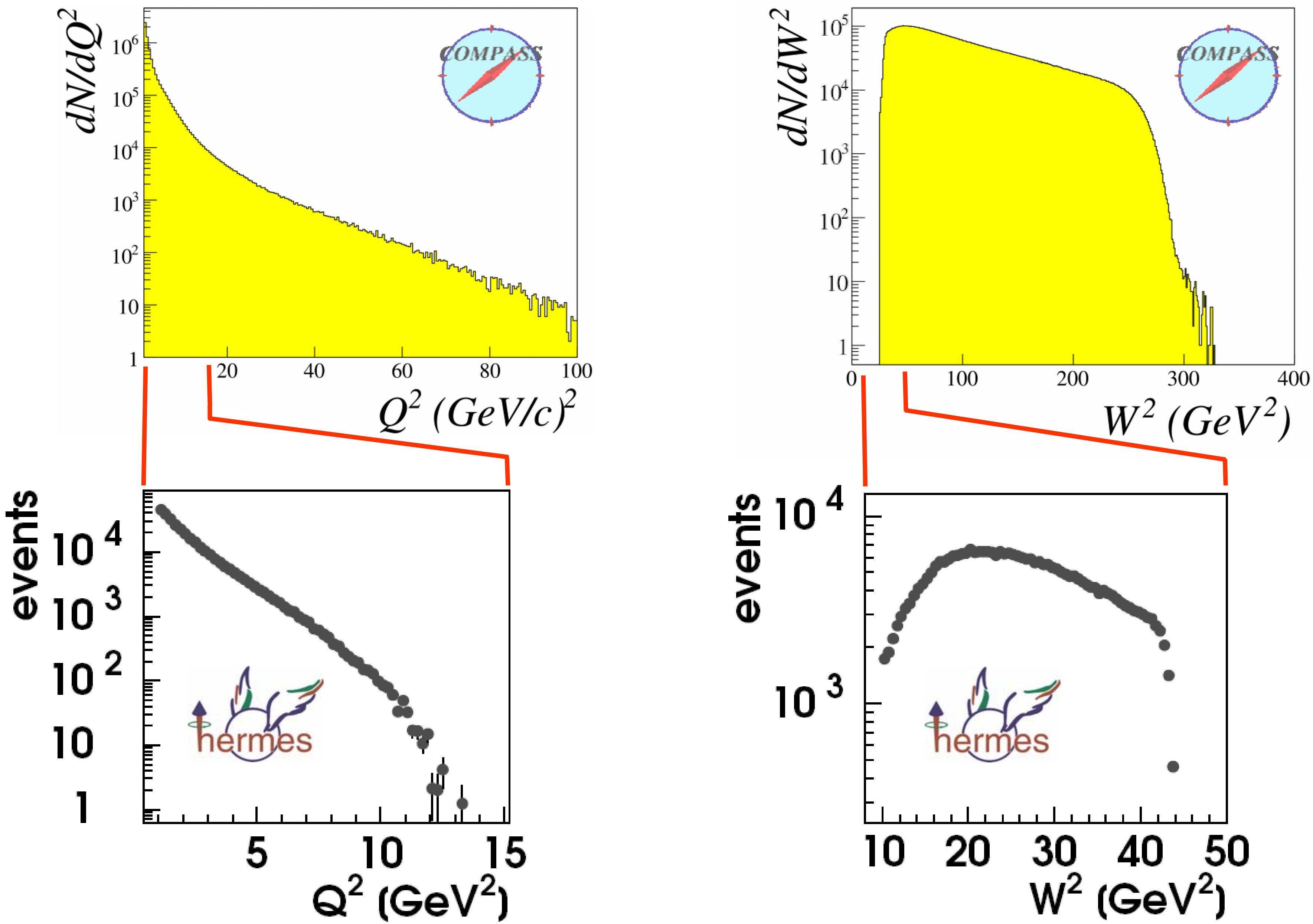
F. Bradamante

data taking
with transversely polarised target

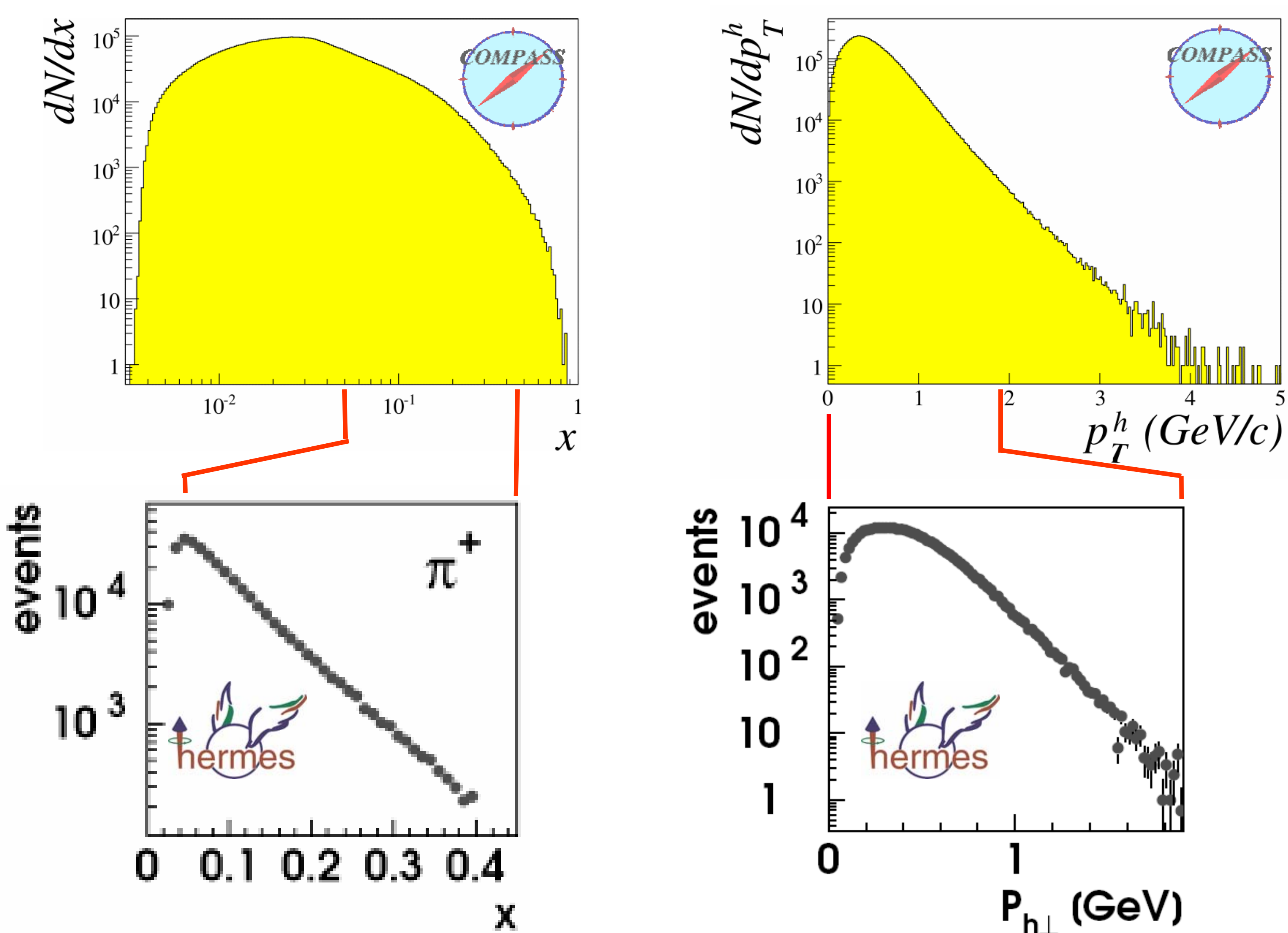
2002-2004: ^{6}LiD



SIDIS kinematics



SIDIS kinematics



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  - Sivers Distribution Function
  - Other TMD Distribution Function

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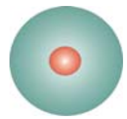
Transversity Distribution Function

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

$q(x)$

$f_1^q(x)$



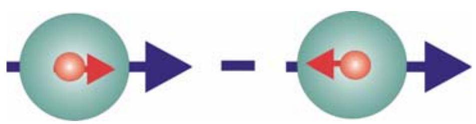
unpolarised DF

DF of a quark with momentum *xP* in a nucleon

well known – unpolarised DIS

$\Delta q(x)$

$g_1^q(x)$



helicity DF

difference of DF of quarks with spin parallel or anti parallele to the nucleon spin in a longitudinally polarised nucleon

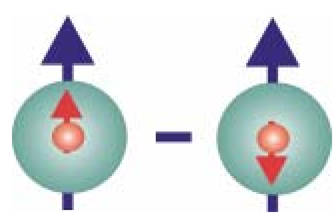
known – polarised DIS

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

$h_1^q(x)$,

$\delta q(x)$,

$\delta_T q(x)$



transversity DF

difference of DF of quarks with spin parallel or anti parallele to the nucleon spin in a transversely polarised nucleon

largely unknown

ALL 3 OF EQUAL IMPORTANCE

Transversity Distribution Function

$\Delta_T q(x)$, $h_1^q(x)$, $\delta q(x)$, $\delta_T q(x)$, $q = u_v, d_v, q_{sea}$

properties:

- **probes the relativistic nature of quark dynamics**
- **no contribution from the gluons → simple Q^2 evolution**
- **positivity (Soffer) bound** $2|\Delta_T q| \leq q + \Delta q$
- **first moments: tensor charge** $\Delta_T q \equiv \int dx \, \Delta_T q(x)$
- **sum rule for transverse spin in Parton Model framework** $\frac{1}{2} = \frac{1}{2}\sum \Delta_T q + L_q + L_g$

  Bakker, Leader, Trueman, PRD 70 (04)
- **it is related to GPD's**

- **is chiral-odd: decouples from inclusive DIS**

Transversity DF: how to measure it

the Transversity DF is chiral-odd:

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

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

$l\ N^{\uparrow} \rightarrow l'\ h\ X$ "Collins" asymmetry
"Collins" Fragmentation Function

$l\ N^{\uparrow} \rightarrow l'\ h\ h\ X$ two-hadron asymmetry
"Interference" Fragmentation Function

$l\ N^{\uparrow} \rightarrow l'\ \Lambda\ X$ Λ polarisation
Fragmentation Function of $q\uparrow\rightarrow\Lambda$

....

all measured in COMPASS

Collins asymmetry

the "quark polarimetry" relies on the Collins effect

→ **the fragmentation function of a transversely polarised quark has a spin dependent part**

a quark moving "horizontally" and polarized "upwards" would emit the leading meson preferentially on the "left" side of the jet

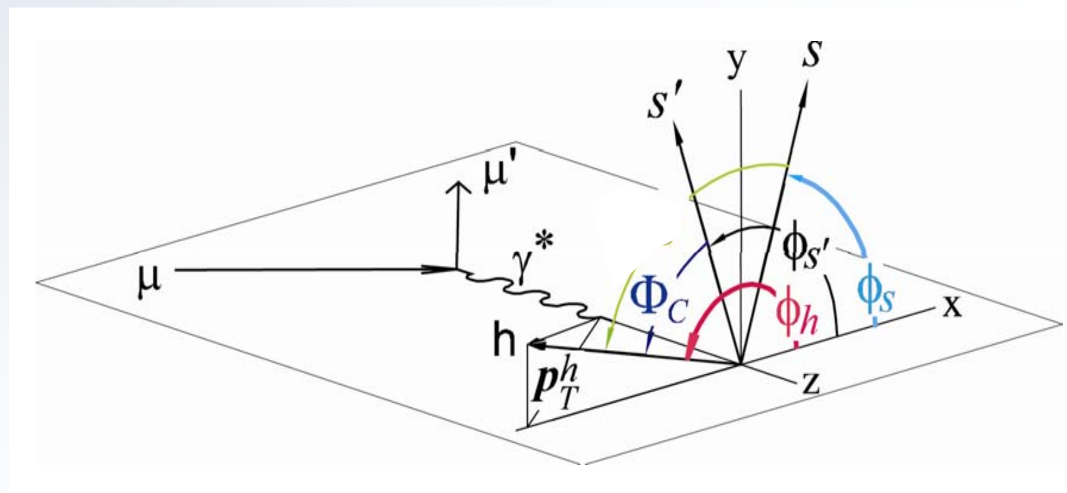
$$D_q^h(z,\vec{p}_T^{\,h}) = D_q^h(z,p_T^h) + \underbrace{\Delta_T^0 D_q^h(z,p_T^h)}\cdot \sin(\varphi_h - \varphi_s)$$

"Collins" FF: $H_1^{\perp q}$, $\delta\hat{q}^h$, ...

in SIDIS

the "Collins angle" is

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



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

Collins asymmetry

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

± refer to the opposite orientation of the transverse spin of the nucleon
P_T ($f \cdot P_T$) is the target polarisation;
D_{NN} is the transverse spin transfer coefficient initial → struck quark

in each angular bin one measures the quantities

$$A_j(\phi_h, \phi_S) = \frac{N^+_{j,u}(\phi_h, \phi_S)}{N^-_{j,u}(\phi_h, \phi_S)} \cdot \frac{N^+_{j,d}(\phi_h, \phi_S)}{N^-_{j,d}(\phi_h, \phi_S)}$$

- reduces acceptance variation effects
- at first order, spin independent effects cancel out

and fitting them the "Collins Asymmetry" is extracted

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

Collins Fragmentation Function

measurable in e^+e^- annihilation

- **first attempts to measured it from the correlation between the azimuthal angles of π's from e^+e^- annihilation using LEP data**

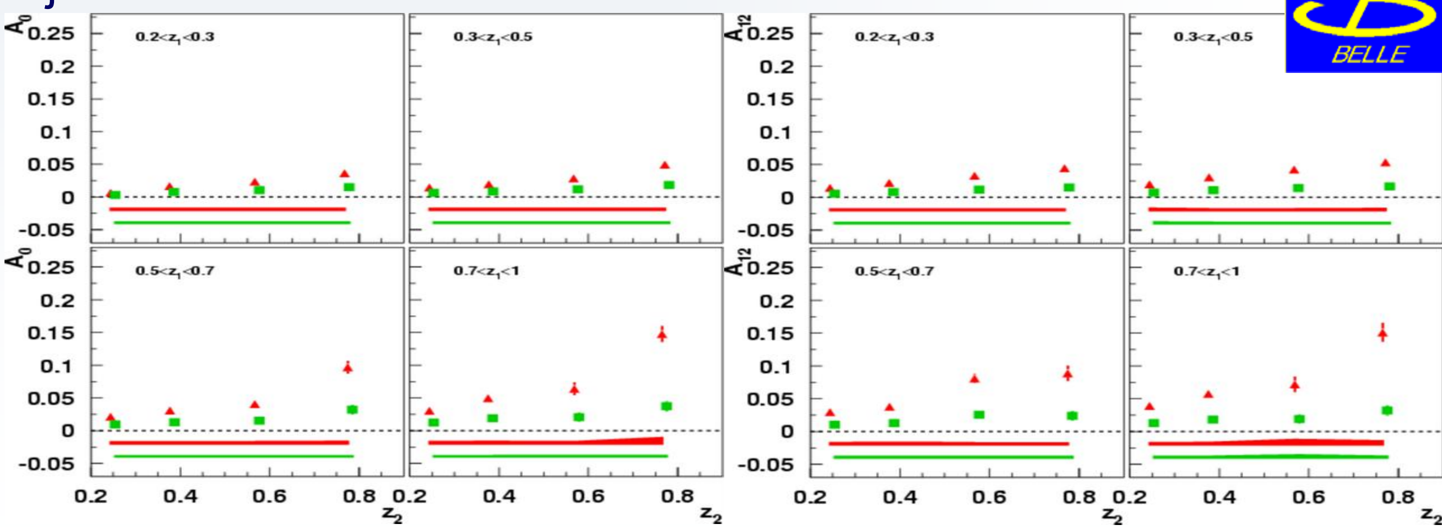
last year: great news from BELLE

the Collins FF has been measured in e^+e^- annihilation, and it is different from zero!

measurement of the correlation between the azimuthal angles of π's in the near jet and in the far jet from e^+e^- annihilation

most recent data, shown at SPIN2006

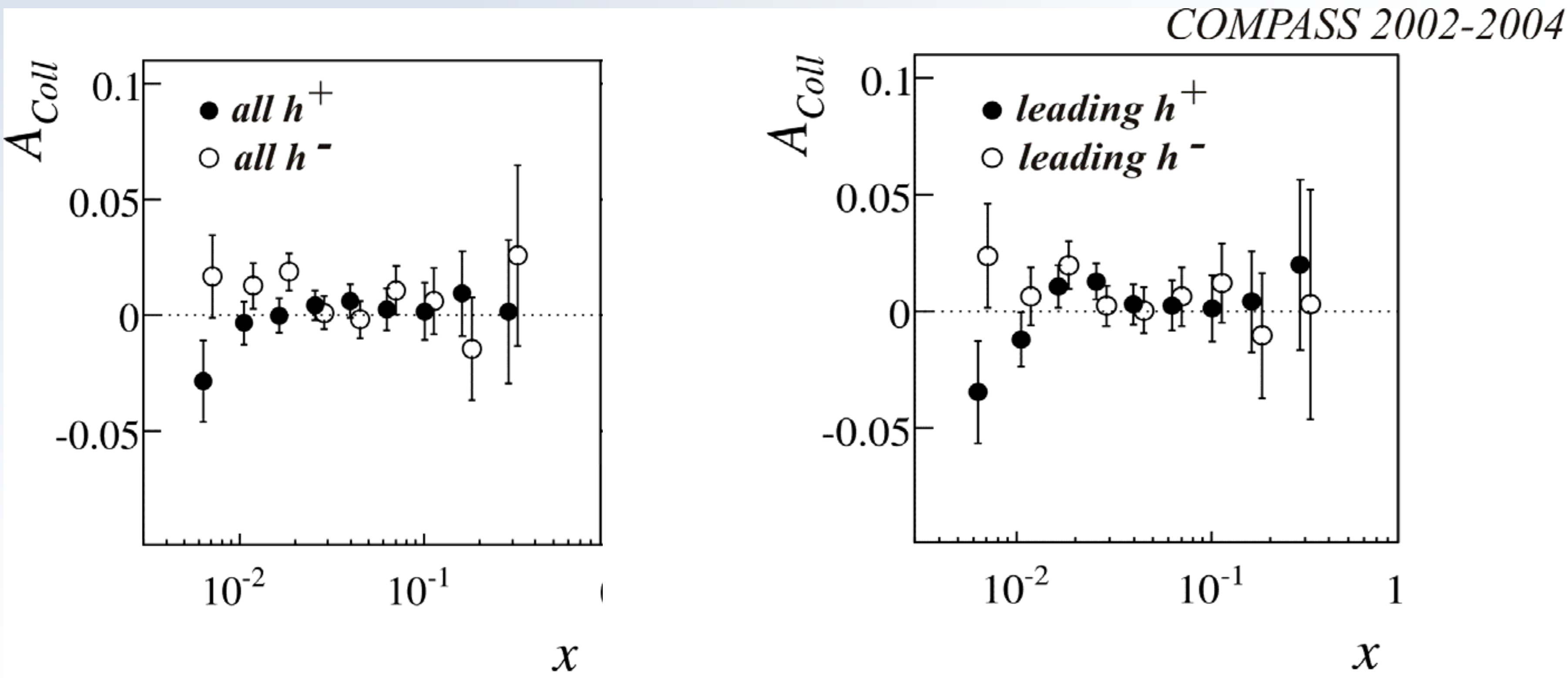
UL and UC double ratios



Collins asymmetry

transversely polarised deuteron target
charged hadrons (mostly pions)

- **2004: first results from 2002 data** PRL94 (2005) 202002 **confirmed by**
- **2006: final results from 2002-2004 data** NPB765 (2007)31



asymmetries compatible with zero within the statistical errors
(syst. errors much smaller)

the same with leading h

Collins asymmetry

naïve interpretation of the data (parton model, valence region)

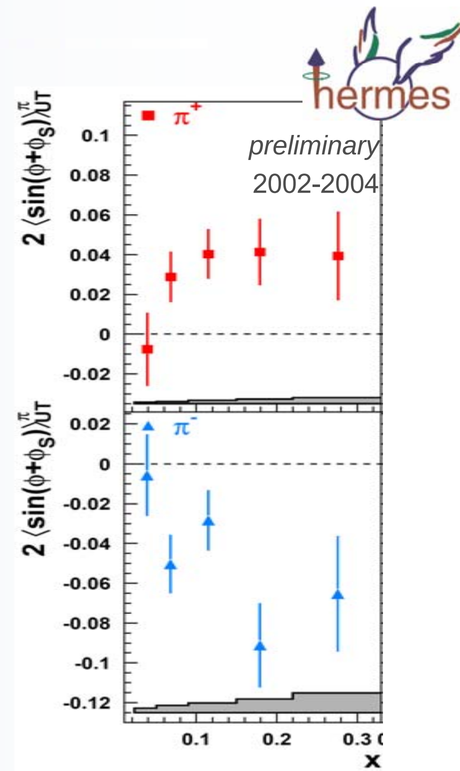
- proton data

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

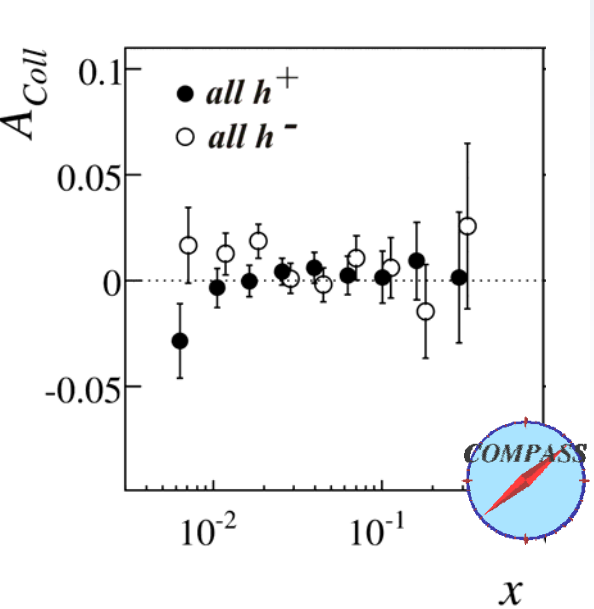
→ unfavored Collins FF ~ – favored Collins FF

$\Delta_T^0 D_2 \approx -\Delta_T^0 D_1$ *at variance with unpol case*

u quark dominance (d quark DF ~ unconstrained)



- deuteron data



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

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

some (small) effect expected even if $\Delta_T^0 D_2 \approx -\Delta_T^0 D_1$

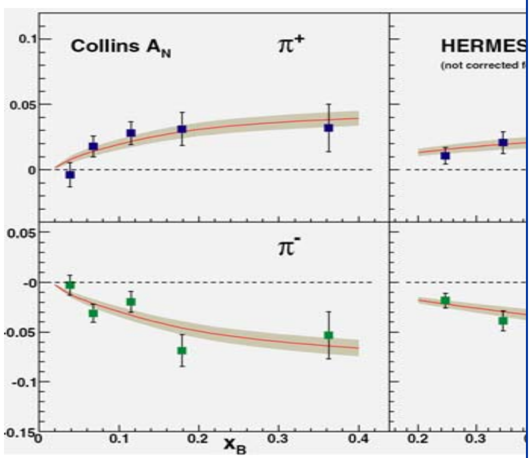
→ cancellation between $\Delta_T u(x)$ and $\Delta_T d(x)$

access to $\Delta_T d(x)$

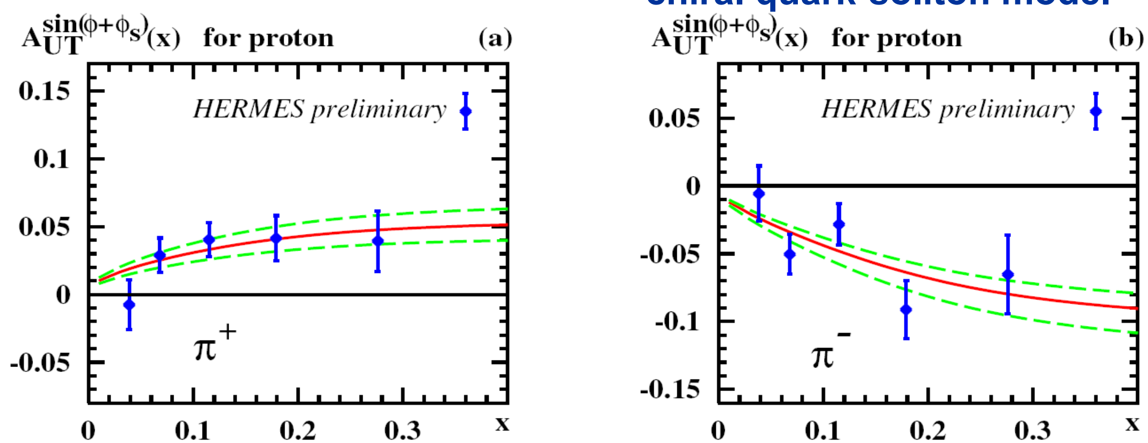
Collins asymmetry

2005-2006: theoretical work mainly

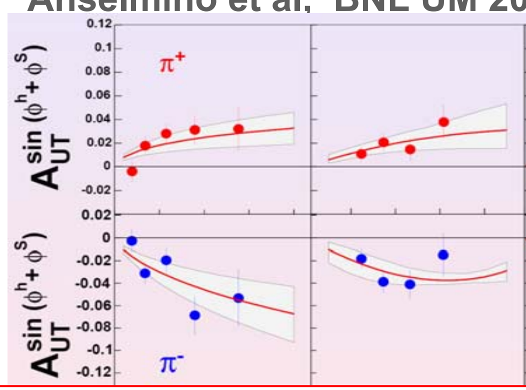
Vogelsang Yuan, PRD 7



Efremov et al, PRD 73, 094025 (2006)
chiral quark-soliton model



Anselmino et al, BNL UM 2006



Soffer bound
& $\Delta_T q = \Delta q$

- favored Collins FF ~
  – unfavored Collins FF
- u-dominance
- agreement with the first Belle and COMPASS 2002 data
- *marginal agreement with the new deuterium data*

using the new Belle, the HERMES and the COMPASS 2002-2004 data
first extraction from transverity from a global analys
A. Efremov, A. Prokudin, P. Schweitzer

Collins asymmetry for pions and kaons

together with measurements on different targets, relevant for flavour decomposition

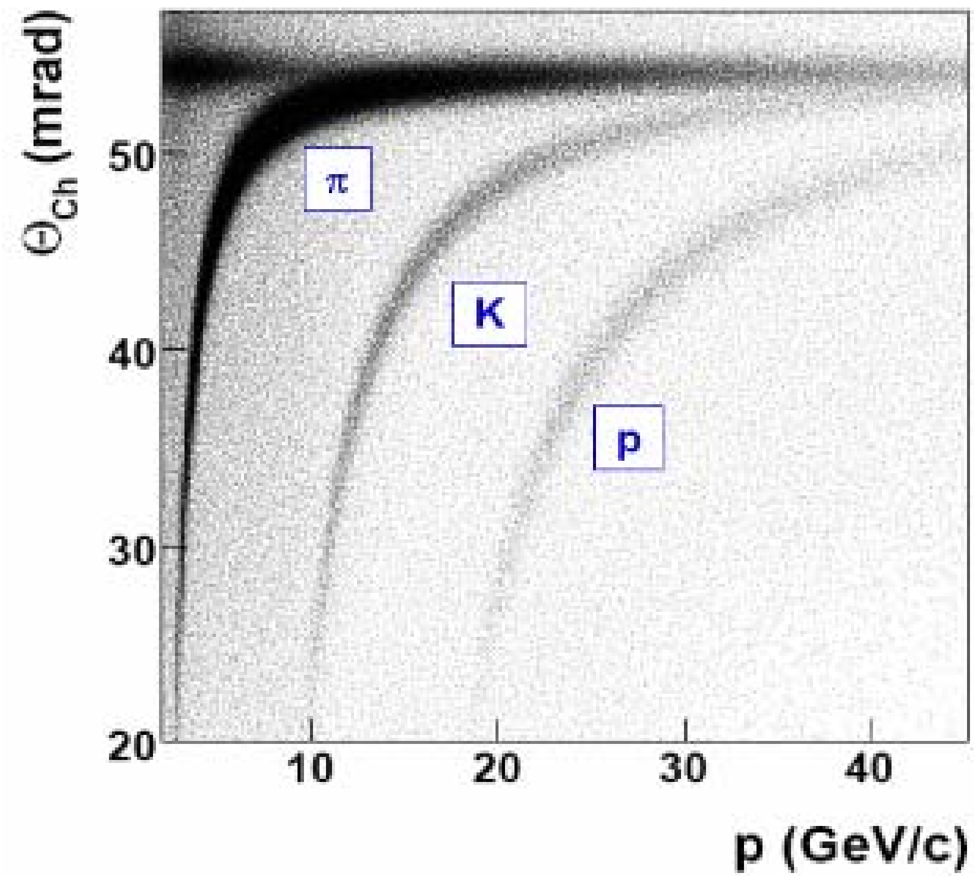
results on deuteron

for π^+ and π^-, K^+ and K^-

from 2003-2004 data

C_4F_{10}

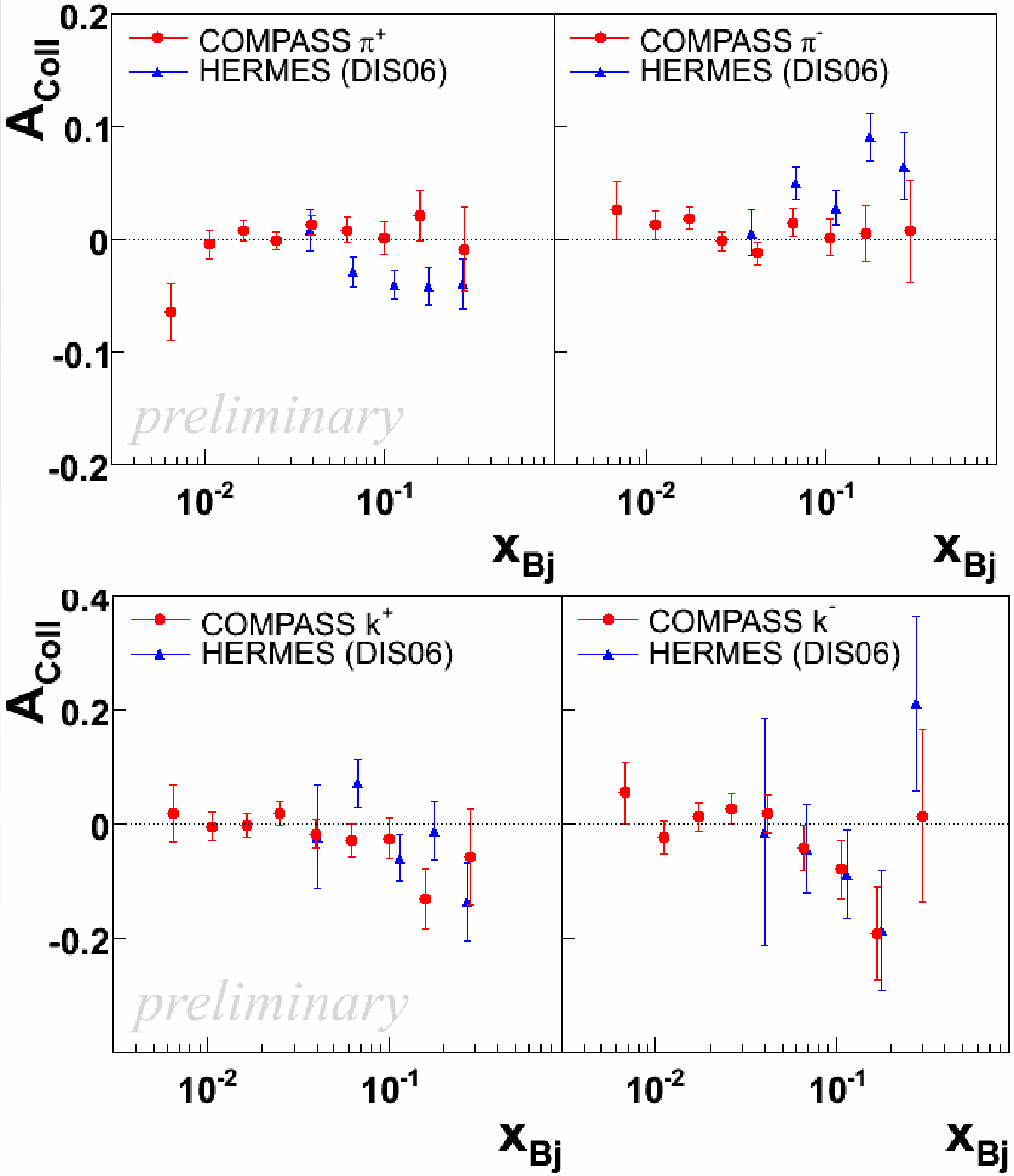
threshold: π ~2 GeV/c
K ~ 10 GeV/c



Collins asymmetry for pions and kaons

preliminary
2002-2004 data
proton

(2002-05 → DIS07)



preliminary
2003-2004 data
deuteron

COMPASS
sign convention

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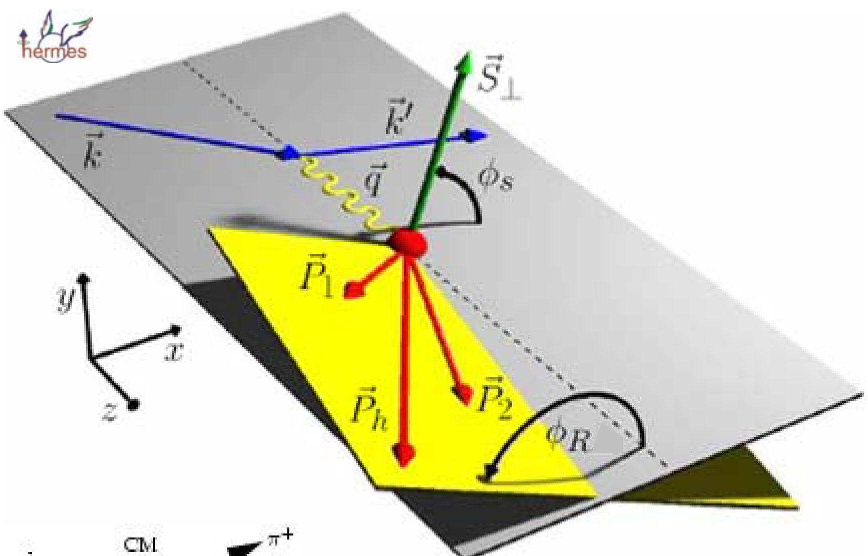
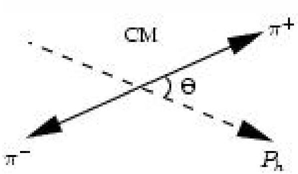
....

alternative way to access transversity
not sensible to transverse momenta

two-hadron asymmetries

in inclusive production of hadron pairs, one can define the angle ϕ_R and measure an **azimuthal asymmetry** from the **modulation of the number of events in $\Phi_{RS} = \phi_R - \phi_S$,**





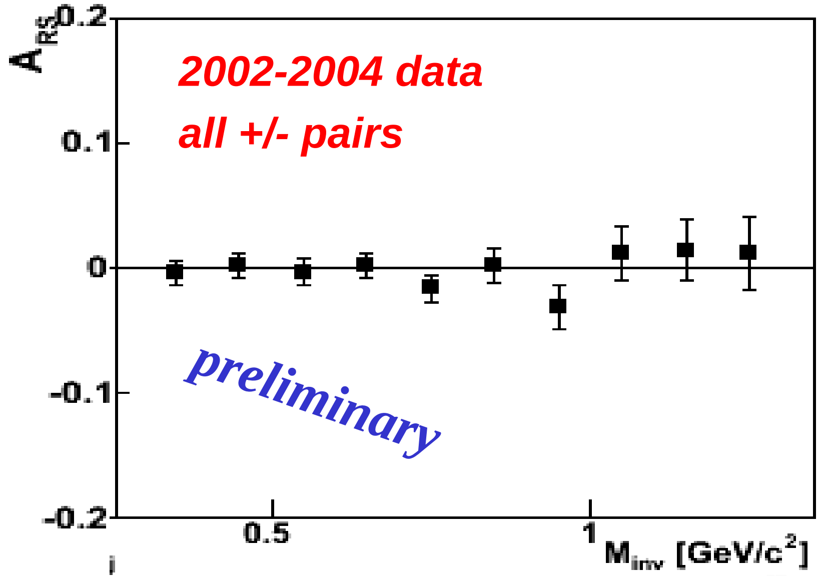
$$\vec{R} = \frac{z_1 \vec{P}_2 - z_2 \vec{P}_1}{z_1 + z_2}$$

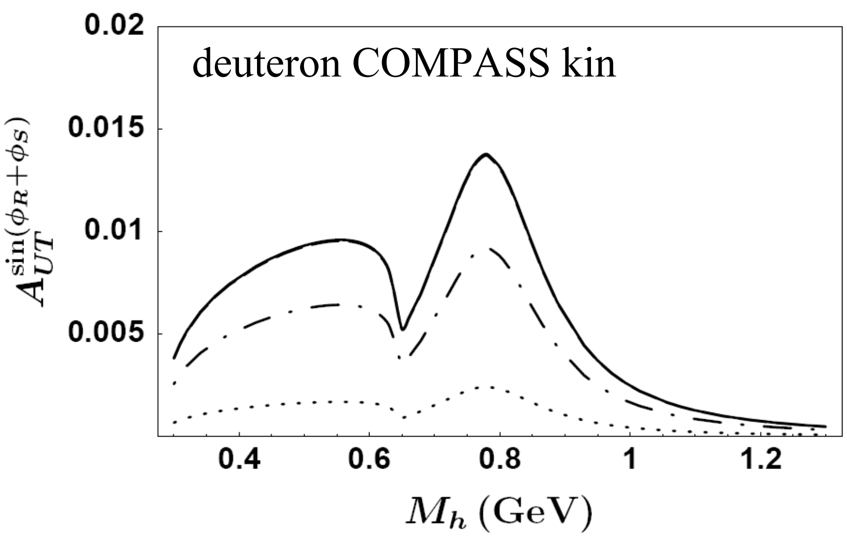
$$A_{RS} \propto \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot H_1^{\angle}}{\sum_q e_q^2 \cdot q \cdot D_q}$$

D_q, $H_1^{\angle}$ presently unknown being measured in e^+e^- (BELLE)

expected to depend on the hadron pair invariant mass

two-hadron asymmetries





deuteron target

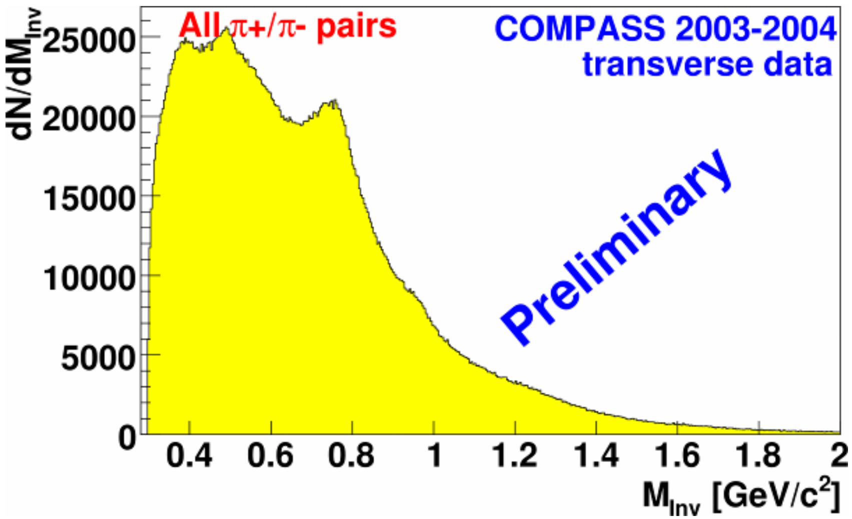
as expected from the measured values of the Collins asymmetry, also the two hadron asymmetry ~ 0

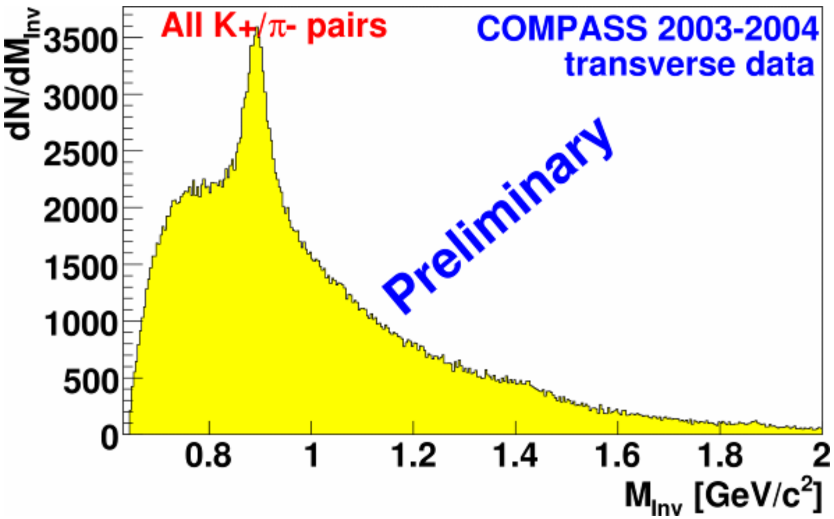
(whatever the size of the Interference Fragmentation Function)

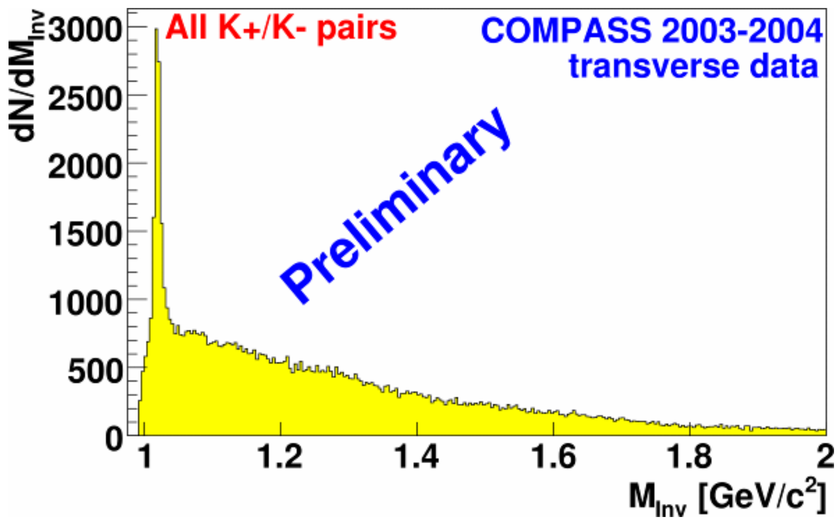
A. Bacchetta, M. Radici
PRD74(2006)114007
model for DiFF

two-hadron asymmetries

identified hadrons on the deuteron target







two-hadron asymmetries

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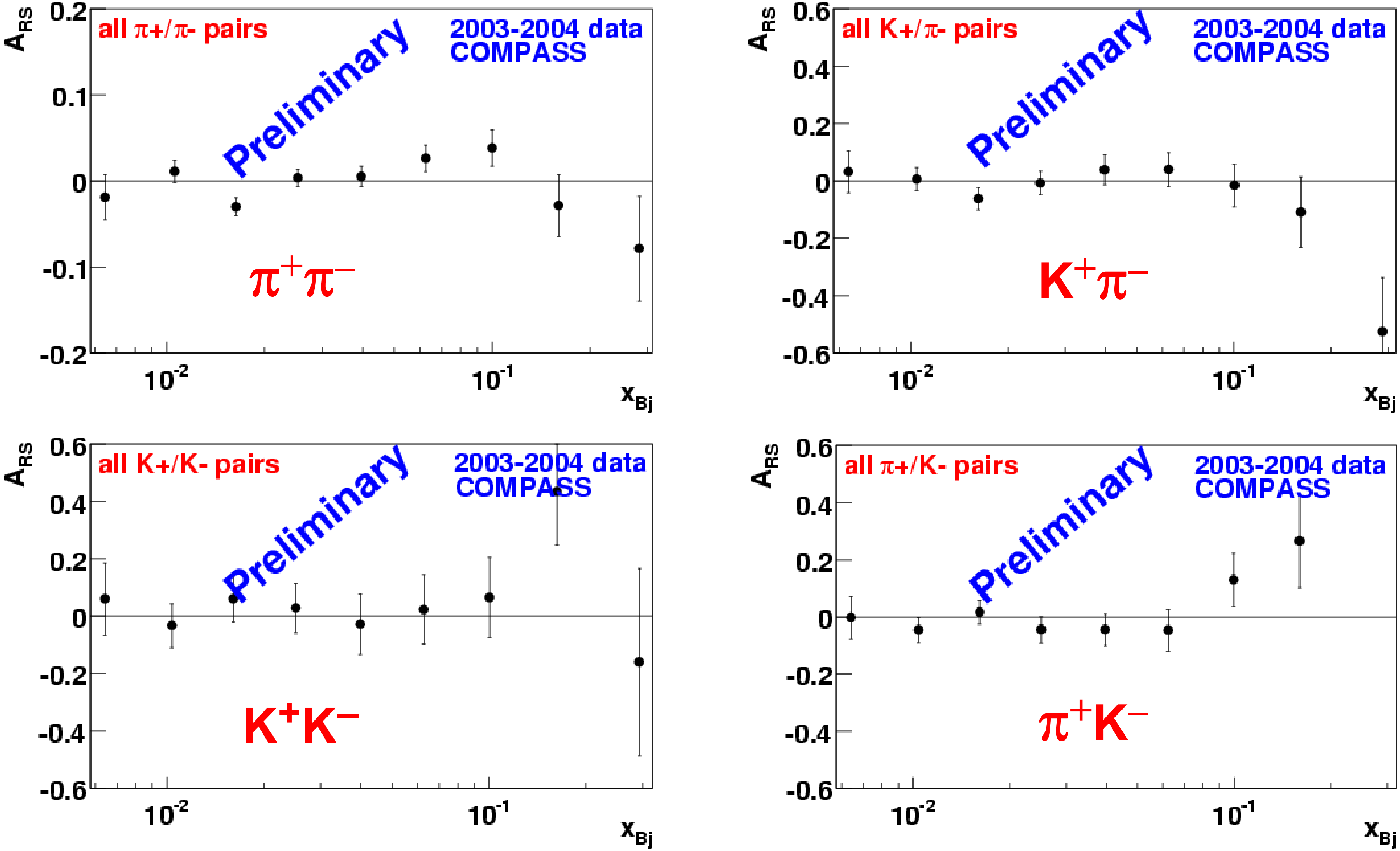

two-hadron asymmetries

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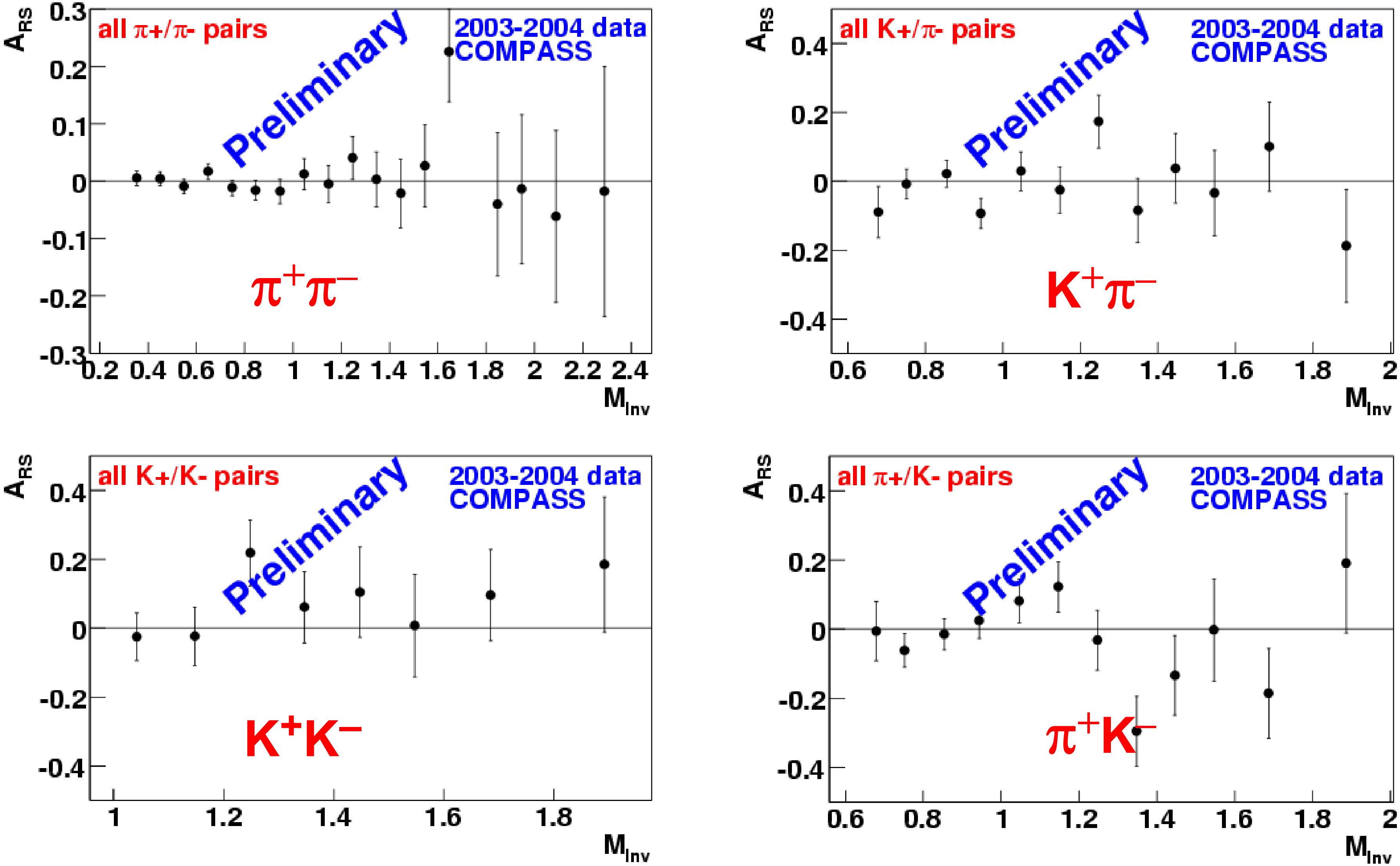
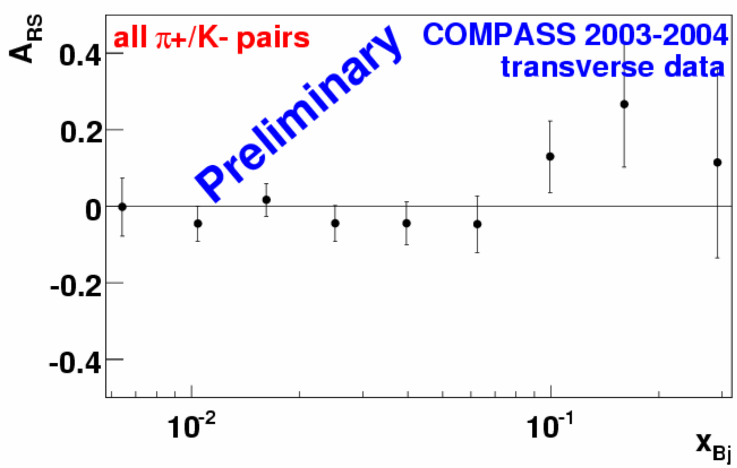
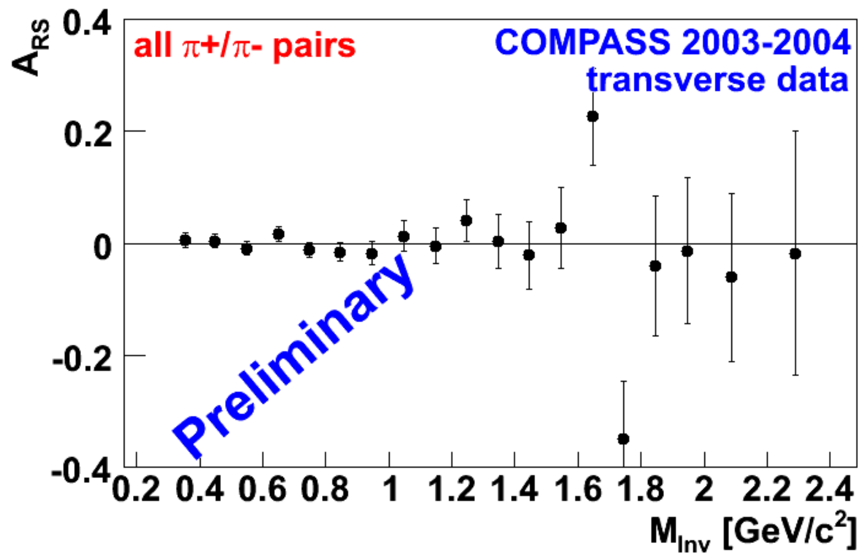



A_RS
all π+/K- pairs
Preliminary
COMPASS 2003-2004
transverse data
0.4
0.2
0
-0.2
-0.4
10^-2
10^-1
x_Bj


A_RS
all π+/π- pairs
COMPASS 2003-2004
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Preliminary
0.4
0.2
0
-0.2
-0.4
0.2 0.4 0.6 0.8 1 1.2 1.4 1.6 1.8 2 2.2 2.4
M_Inv [GeV/c^2]

Transversity DF: how to measure it

the Transversity DF is chiral-odd:

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

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

$l\,N^{\uparrow} \rightarrow l'\,h\,X$ "Collins" asymmetry
"Collins" Fragmentation Function

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$l\,N^{\uparrow} \rightarrow l'\,\Lambda\,X$ Λ polarisation
Fragmentation Function of $q\uparrow \rightarrow \Lambda$

....

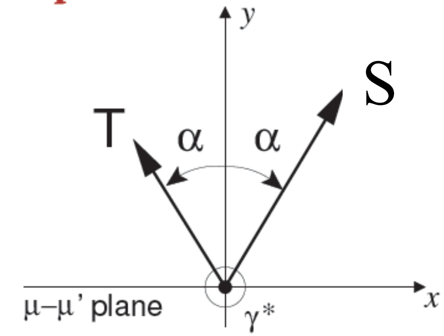
alternative way to access transversity independent on Transverse Momentum …
the favorite in some models (statistics)

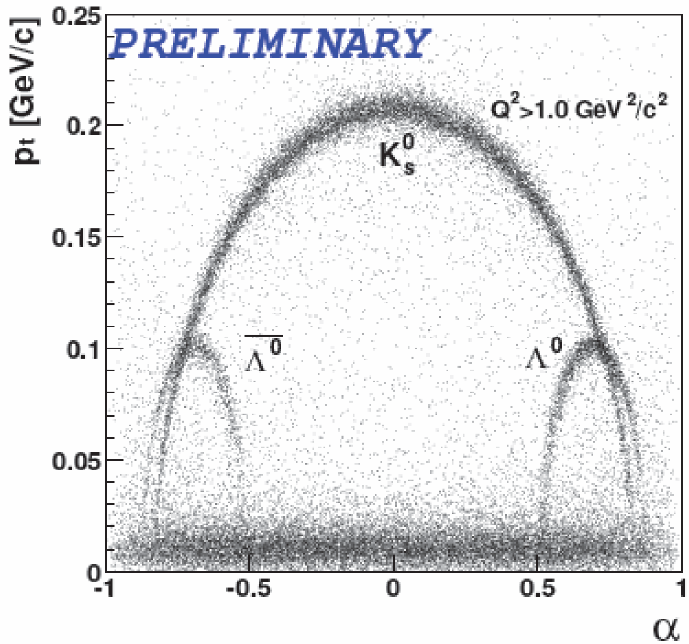
Λ polarimetry

$$P^{\Lambda}_{T,exp} = \frac{d\sigma^{\mu N^{\uparrow}\to\mu'\Lambda^{\uparrow}X} - d\sigma^{\mu N^{\downarrow}\to\mu'\Lambda^{\uparrow}X}}{d\sigma^{\mu N^{\uparrow}\to\mu'\Lambda^{\uparrow}X} + d\sigma^{\mu N^{\downarrow}\to\mu'\Lambda^{\uparrow}X}}$$

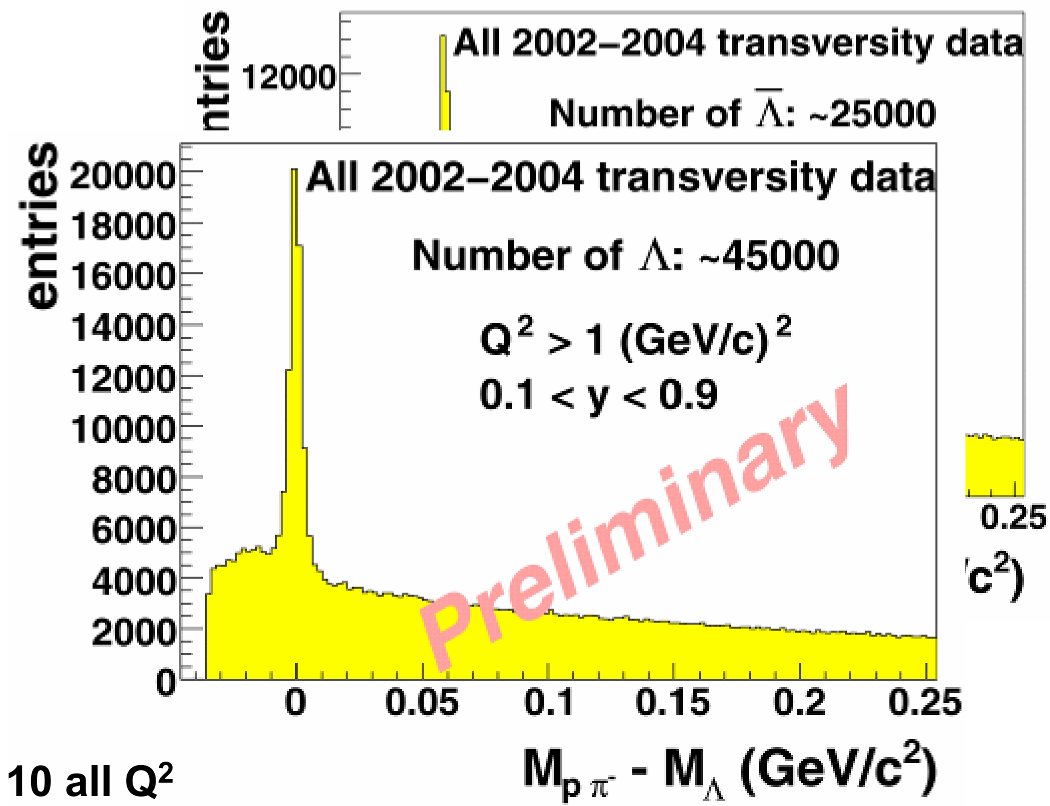
$$= f P_N D(y) \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)}$$

Λ polarization axis

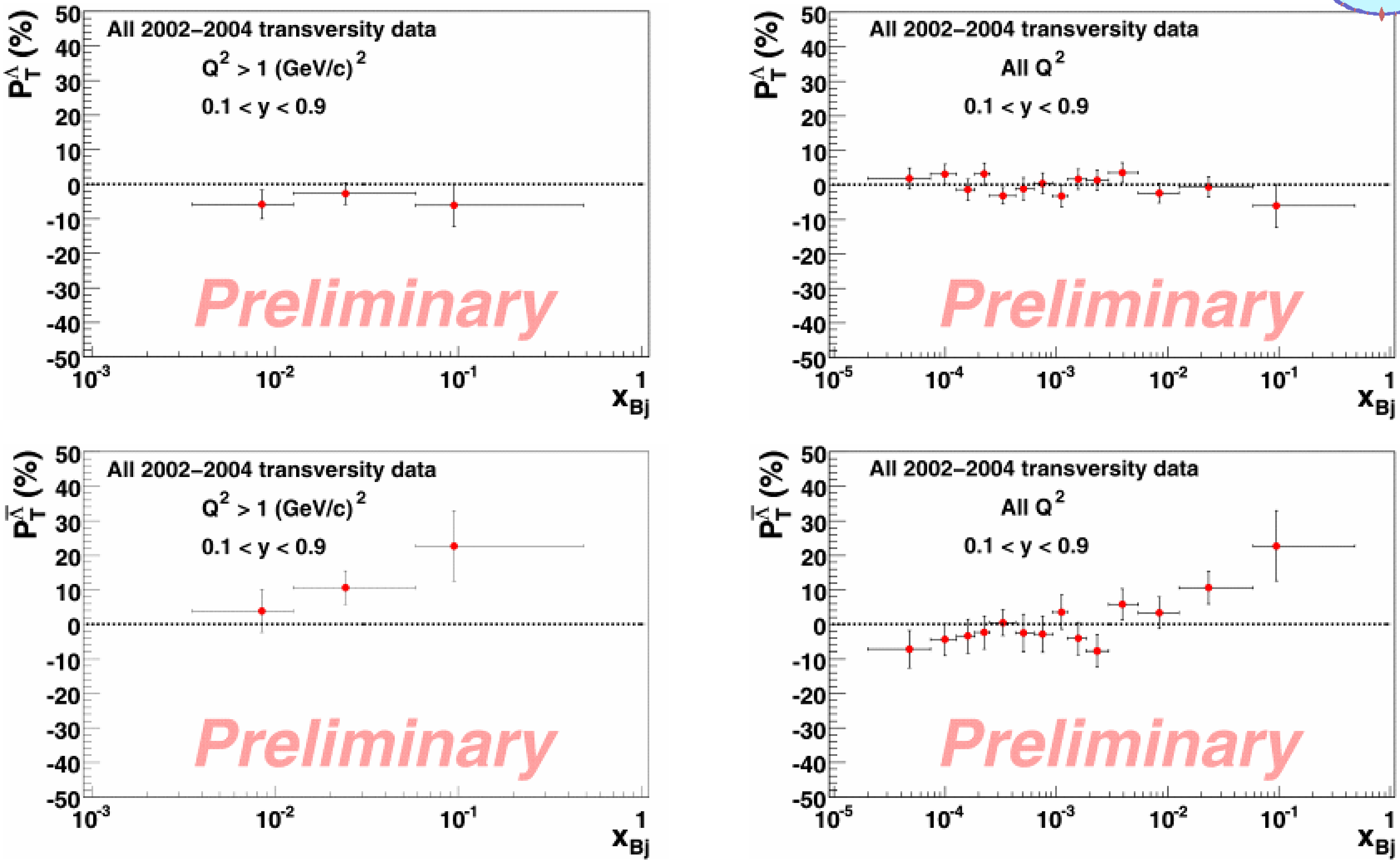




x 10 all Q^2



Λ polarimetry



systematic errors not larger than statistical errors

RICH ID not used yet; some other improvement in selection still foreseen

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Measurement of the Sivers DF in SIDIS

$\Delta_0^T q$ (or $\Delta^N f_{q/N\uparrow}$ or $f_{1T}^{\perp q}$ or q_T)

it is the most famous of the TMD parton distribution functions

it is related to an intrinsic asymmetry in the parton transverse momentum distribution induced by the nucleon spin

- **requires final/initial-state interactions**
  quark rescattering via soft gluon exchange
- **should change sign from SIDIS to DY (important test !!)**
- **it is related to the parton orbital angular momentum in a transversely polarized nucleon**

Sivers asymmetry

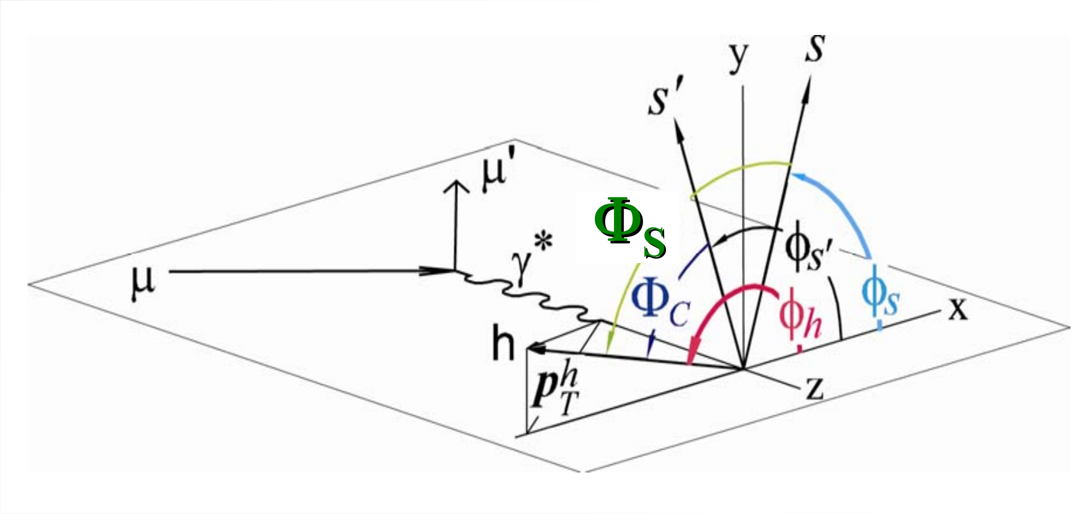
appears in SIDIS as a modulation in the "Sivers angle" Φ_S

$$N_h^{\pm}(\Phi_S) = N_h^0 \cdot \left[1 \pm P_T \cdot A_{Siv} \cdot \sin\Phi_S \right]$$

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

ϕ_h azimuthal angle of hadron momentum
ϕ_S azimuthal angle of the spin of the nucleon

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



the "Sivers angle" Φ_S and the "Collins angle" Φ_C are independent

→ the Collins and Sivers asymmetries can be disentangled and extracted from the same data in SIDIS on a transversely polarised target

Sivers asymmetry

the Collins and Sivers asymmetries can be disentangled and extracted from the same data in SIDIS on a transversely polarised target

2002-2004 data NPB765(2007)31

to extract the Collins and Sivers asymmetries the measured quantities

$$A_j(\Phi_j) = \frac{N^+_{j,u}(\Phi_j)}{N^-_{j,u}(\Phi_j)} \cdot \frac{N^+_{j,d}(\Phi_j)}{N^-_{j,d}(\Phi_j)}, \qquad j = C, S$$

are fitted separately with the functions

$$p_0 \cdot (1 + A^m_C \cdot \sin\Phi_C) \qquad p_0 \cdot (1 + A^m_S \cdot \sin\Phi_S)$$

check: fit of

$$A_j(\phi_h, \phi_S) = \frac{N^+_{j,u}(\phi_h, \phi_S)}{N^-_{j,u}(\phi_h, \phi_S)} \cdot \frac{N^+_{j,d}(\phi_h, \phi_S)}{N^-_{j,d}(\phi_h, \phi_S)}$$

with ("2D fit")

$$H(\phi_h, \phi_S) = a_1 + a_2 \sin(\phi_h + \phi_S - \pi) + a_3 \sin(3\phi_h - \phi_S) + +a_4 \sin(\phi_h - \phi_S) + a_5 \cos(\phi_h - \phi_S) .$$

excellent agreement

slightly correlated

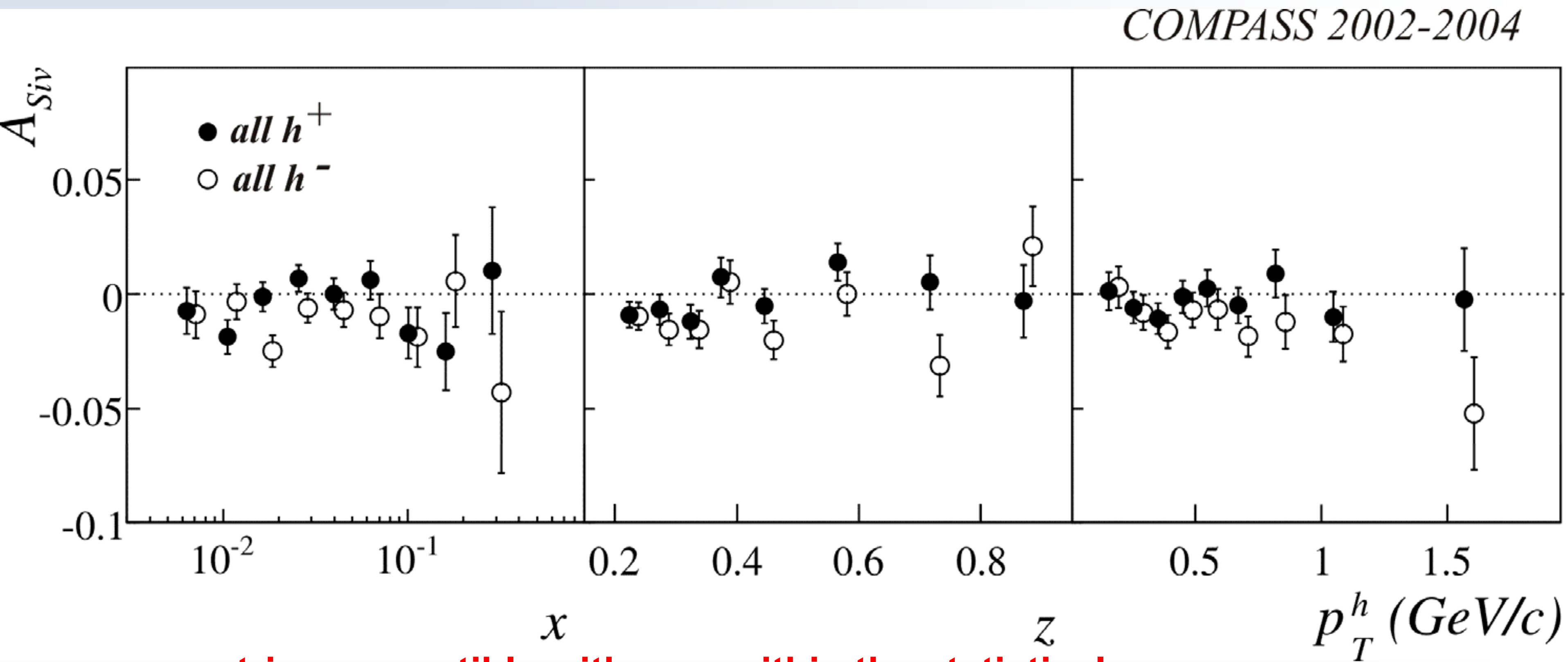
correlation coefficient ranges from -0.25 to 0.25

8 parameter fit → *B. Parsamyan*

Sivers asymmetry

deuteron target transversely polarised
charged hadrons (mostly pions)

- **2004: results from 2002 data** PRL94(2005)202002 **confirmed by**
- **2006: results from 2002-2004 data** NPB765(2007)31



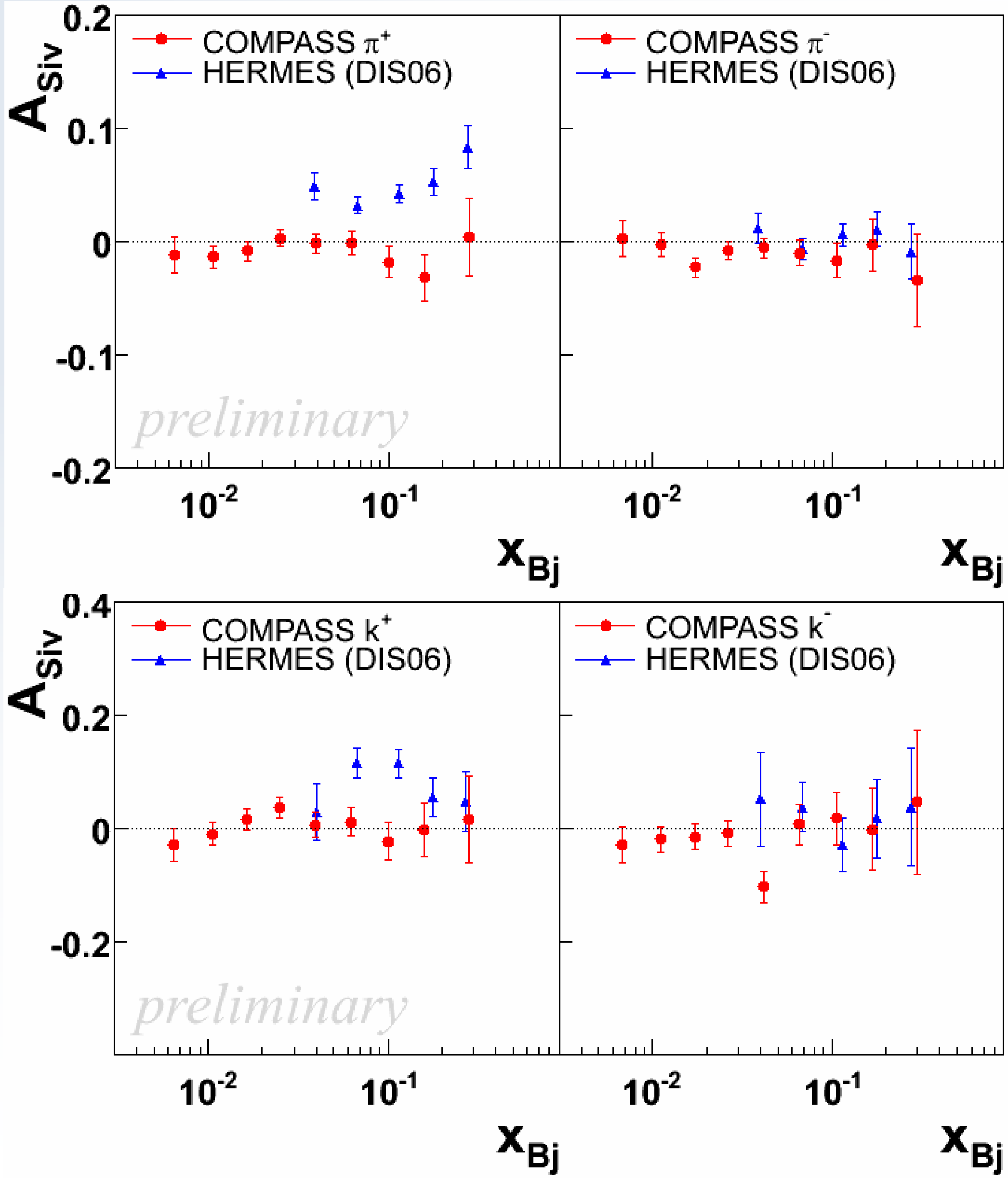
asymmetries compatible with zero within the statistical errors
(systematic errors much smaller)

Sivers asymmetry for pions and kaons

preliminary
2002-2004 data
proton

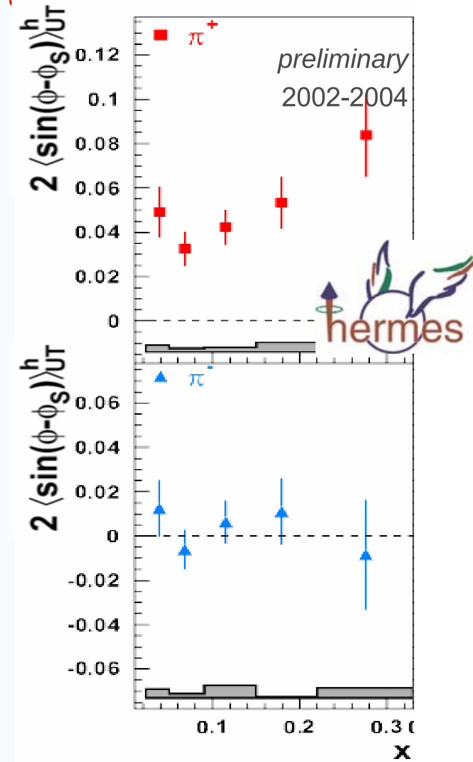
(2002-05 → DIS07)

preliminary
2003-2004 data
deuteron



Sivers asymmetry

naïve interpretation of the data (parton model, valence region)



- **proton data**

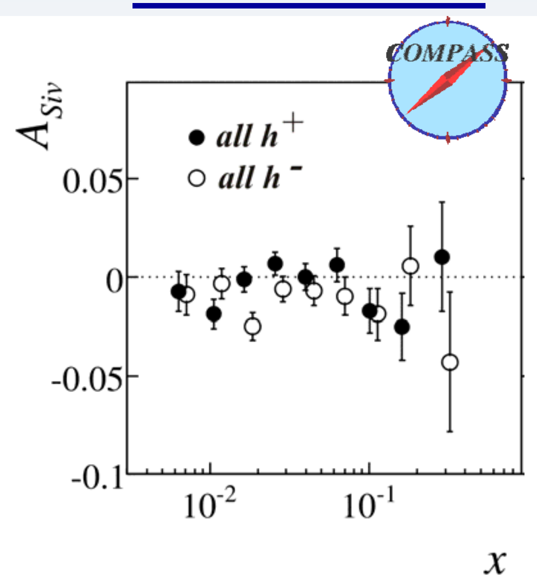
$$A_{Siv}^{p,\pi^+} \simeq \frac{4\Delta_0^T u_v D_1 + \Delta_0^T d_v D_2}{4u_v D_1 + d_v D_2} \qquad A_{Siv}^{p,\pi^-} \simeq \frac{4\Delta_0^T u_v D_2 + \Delta_0^T d_v D_1}{4u_v D_2 + d_v D_1}$$

asymmetry for $\pi^+ > 0$, asymmetry for $\pi^- \approx 0$

→ **Sivers DF for d-quark ≈ - 2 Sivers DF for u-quark**

$$\Delta_0^T d_v \simeq -2\ \Delta_0^T u_v$$

- **deuteron data**



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

the measured asymmetries **compatible with zero** suggest

$$\Delta_0^T d_v \simeq -\Delta_0^T u_v$$

Sivers asymmetry

the measured asymmetry on deuteron compatible with zero has been interpreted as

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

S.J. Brodsky and 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.

Outlook

- COMPASS
- Results on asymmetries
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semi-inclusive cross-section

18 structure functions

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

$$\frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+\sqrt{2\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h}$$ **4**

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

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

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

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

$$+\varepsilon\,\sin(\phi_h+\phi_S)\,F_{UT}^{\sin(\phi_h+\phi_S)}+\varepsilon\,\sin(3\phi_h-\phi_S)\,F_{UT}^{\sin(3\phi_h-\phi_S)}$$ **6**

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

$$+|\boldsymbol{S}_\perp|\lambda_e\Big[\sqrt{1-\varepsilon^2}\,\cos(\phi_h-\phi_S)\,F_{LT}^{\cos(\phi_h-\phi_S)}+\sqrt{2\varepsilon(1-\varepsilon)}\,\cos\phi_S\,F_{LT}^{\cos\phi_S}$$ **3**

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

A Bacchetta, M Diehl, K Goeke, A Metz, P Mulders, M Schlegel (06)

semi-inclusive cross-section

18 structure functions

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

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

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

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

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

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

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

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

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

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

Cahn

Boer-Mulders

EMC
E665
ZEUS
CLAS
HERMES

A Bacchetta, M Diehl, K Goeke, A Metz, P Mulders, M Schlegel (06)

semi-inclusive cross-section

8 tgt transverse spin dependent asymmetries, 4 LO

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

$$\frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{\cdots\cdots$$

$f_{1T}^{\perp q} \otimes D_{1q}^h$ **Sivers**

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

$h_1^q \otimes H_{1q}^{\perp h}$ **transversity**

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

5

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

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

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

3

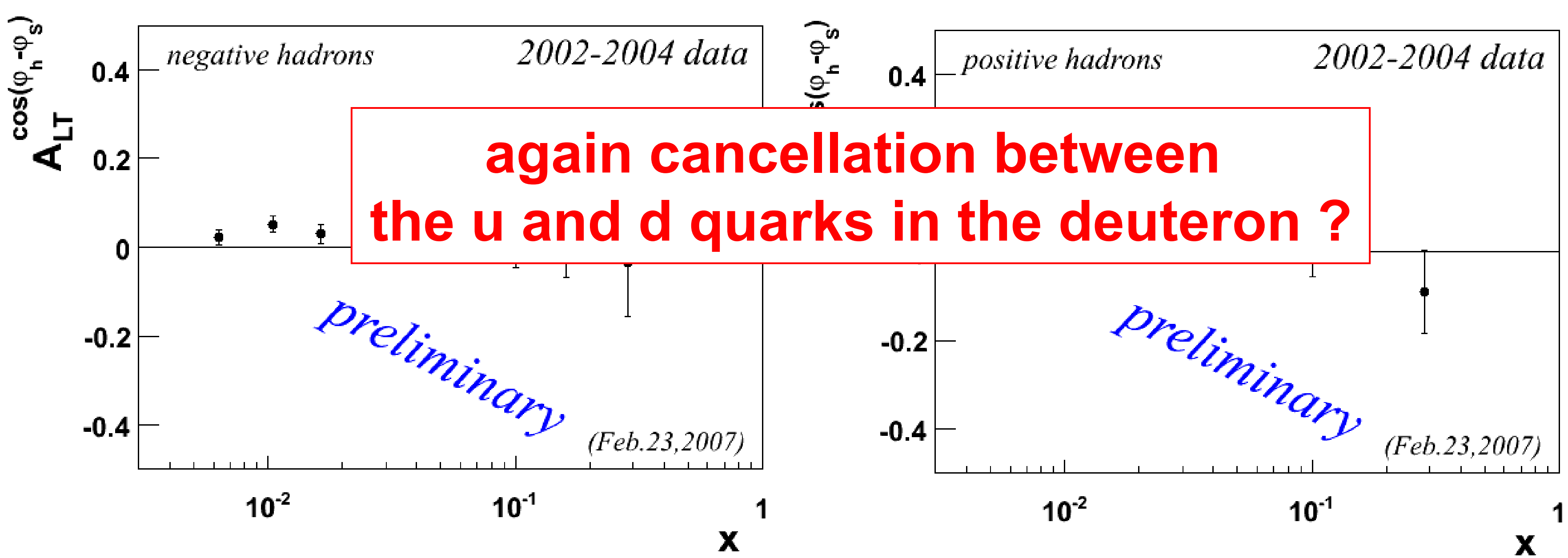
by now all measured by COMPASS on deuteron

talk by B. Parsamyan

target transverse spin dependent asymmetries (LO)

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

g_{1T} is the only parton DF which is
chiral-even, T-even, leading twist function
in addition to the unpolarised DF and to the helicity DF



again cancellation between
the u and d quarks in the deuteron ?

Outlook

- COMPASS

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Conclusions

both Collins effect and Sivers effect have been shown to be there

NEW PROPERTIES of MATTER

TRANSVERSITY CAN BE MEASURED

First global analysis being done

! THE WORK STARTS NOW !

Many TMD PDF and FF to be measured

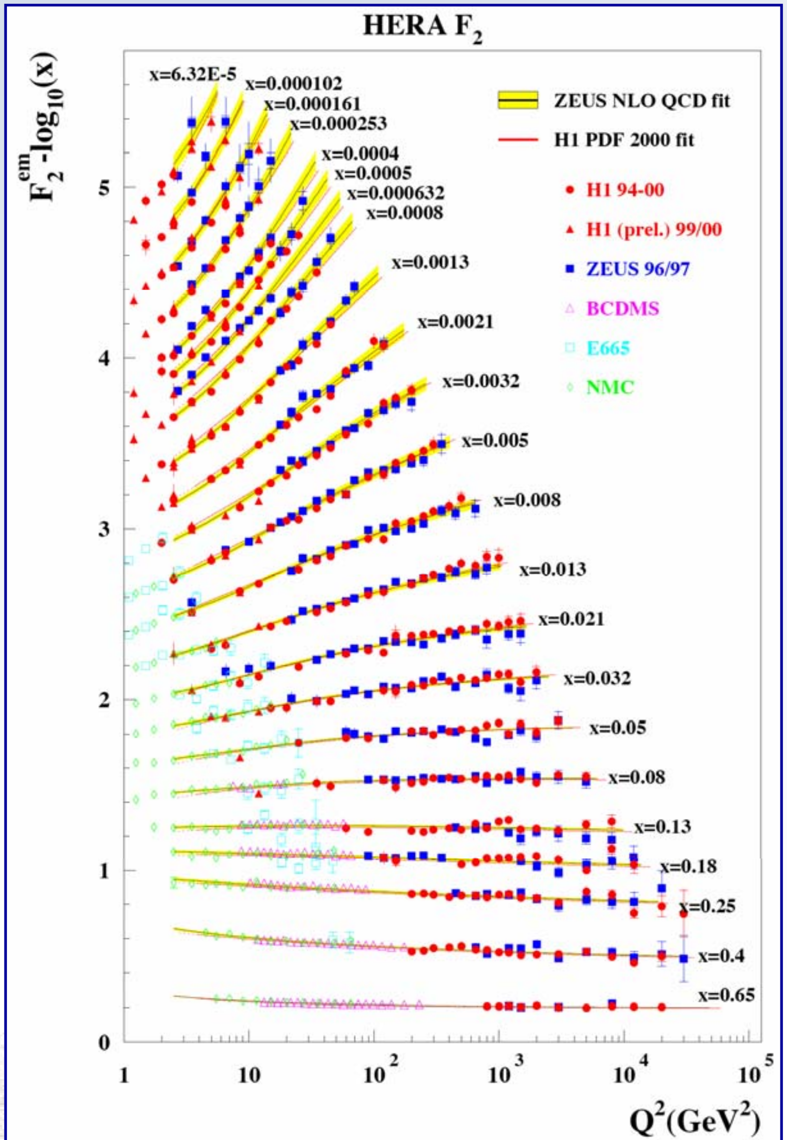
PRECISION NEEDED

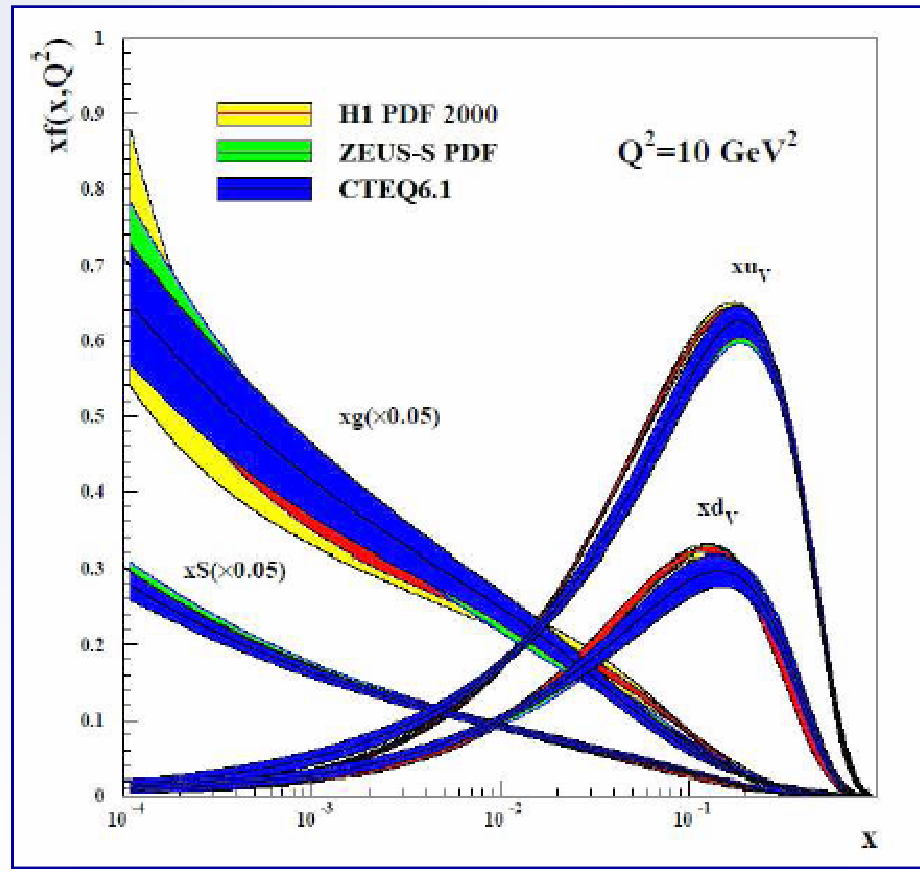
unpolarised PDF

Parton Model

$$\rightarrow F_2^p(x,Q^2) = \tfrac{1}{2} \sum e_i^2 \left[q_i(x,Q^2) + \overline{q}_i(x,Q^2)\right]$$

Unpolarized DIS Structure Function(x,Q²)





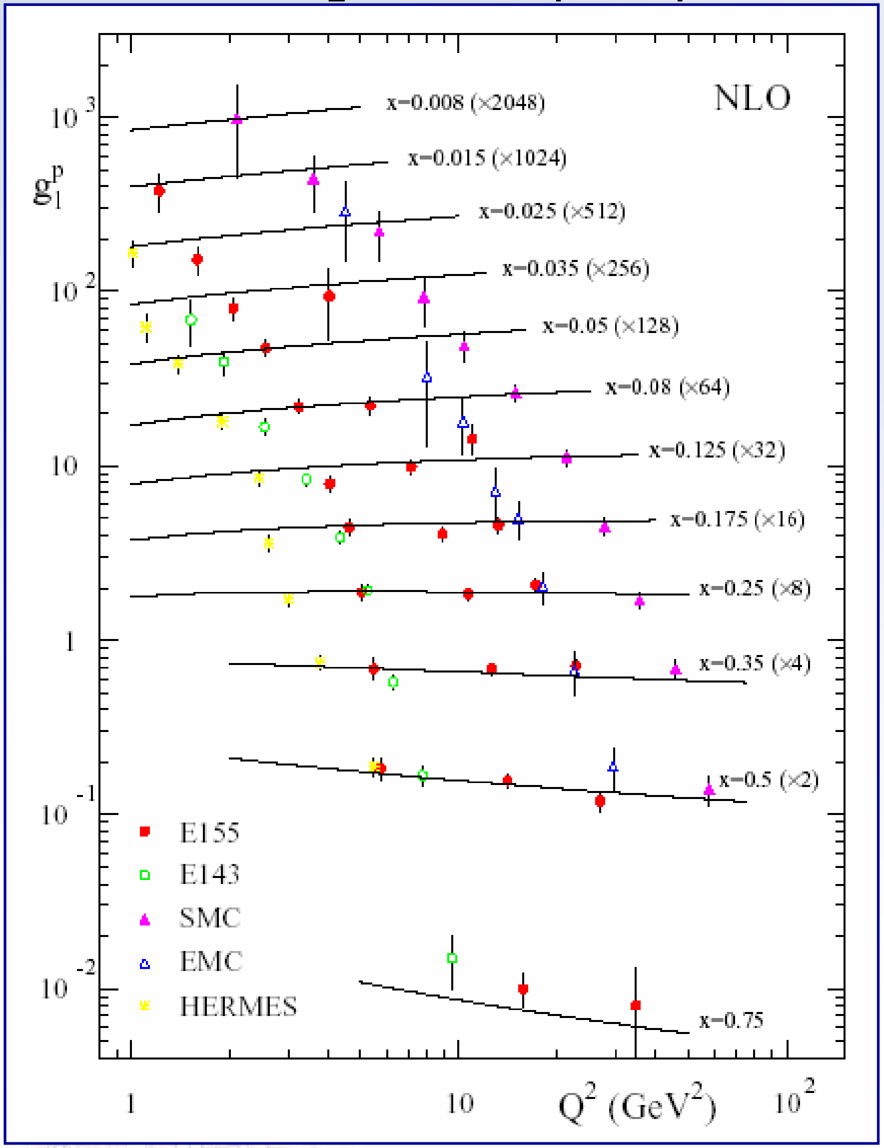
still big uncertainty for G(x) at large x !

F. Bradamante

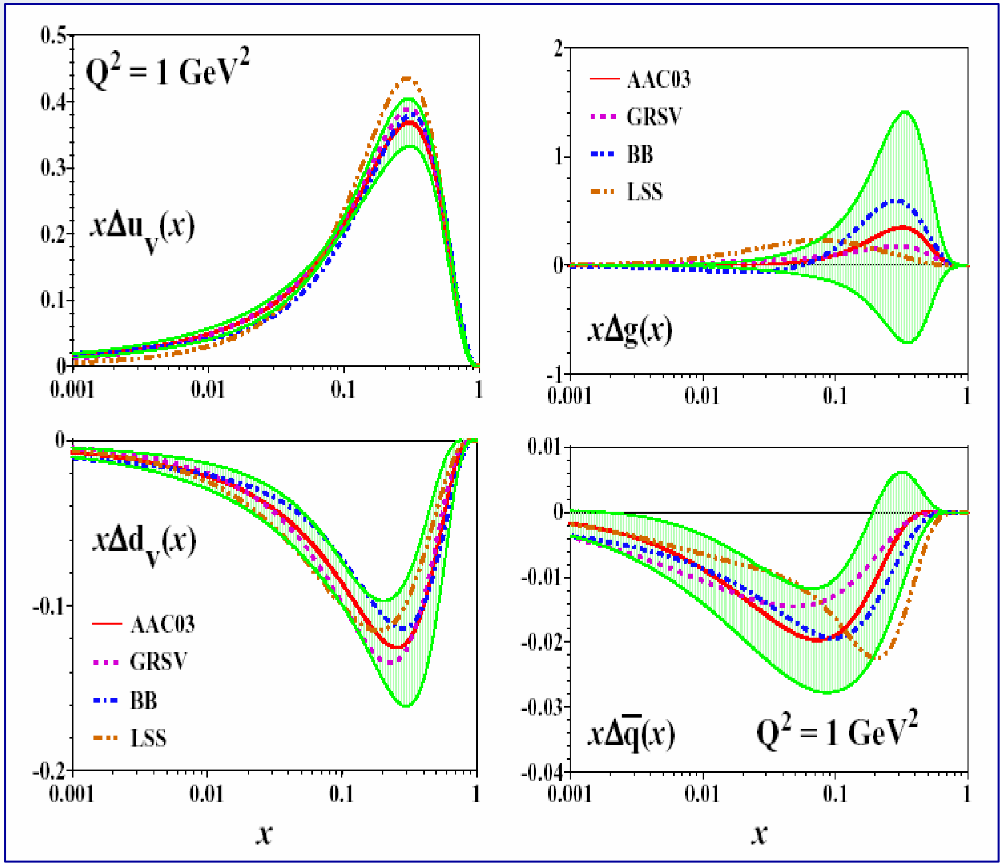
helicity PDF

Parton Model

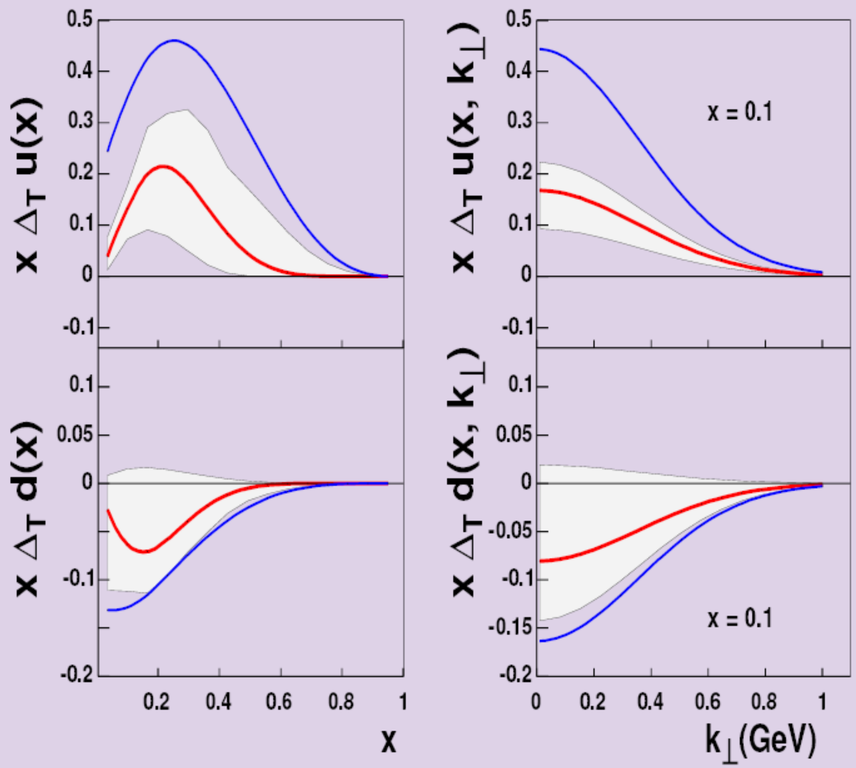
$\rightarrow \quad g_1^p = \frac{1}{2} \sum e_i^2 [\Delta q_i(x,Q^2) + \Delta \bar{q}_i(x,Q^2)]$



Asymmetry **A**nalysis **C**ollaboration,
M. Hirai, S. Kumano and N. Saito, PRD (2004)



Transversity



- This is the first extraction of transversity from experimental data.
- $\Delta_T u(x) > 0$ and $\Delta_T d(x) < 0$
- Both $\Delta_T u(x)$ and $\Delta_T d(x)$ do not saturate Soffer bound.
- HERMES data alone fixes well $\Delta_T u(x)$ while HERMES+COMPASS alows us to extract $\Delta_T d(x)$.

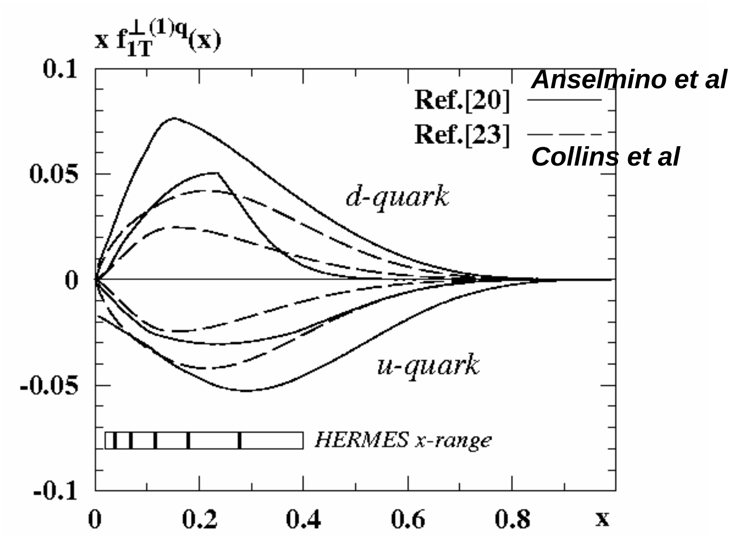
Sivers asymmetry

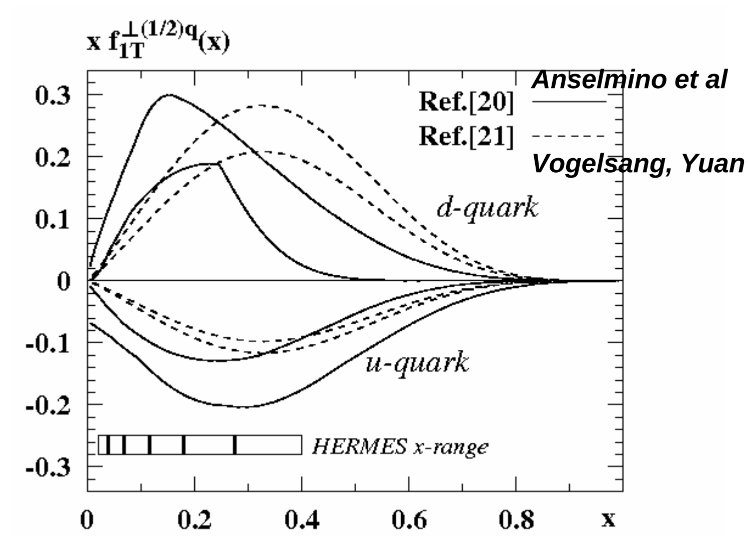
2005-2006: theoretical work on the interpretation of the data
use of the new HERMES results to exctract the Sivers DF

Vogelsang Yuan (2005), Anselmino et al (2005), Collins et al (2006)

- **good fits to the new proton from HERMES**
- **comparison (or fit) with the deuteron COMPASS 2002 data ok**

with $\Delta_0^T d$ ranging from $-\Delta_0^T u$ to $-2\Delta_0^T u$





Anselmino et al., hep-ph/0511017

“Global” fits

work on global fits ongoing also in Trieste

see talk of A. Martin in Freiburg, March 2007
“International Workshop on Hadron Structure and Spectroscopy”

interesting problems:

Correlation between Cfav and Cunf in BELLE measurement

Error bands in DF’s and FF’s

Outlook

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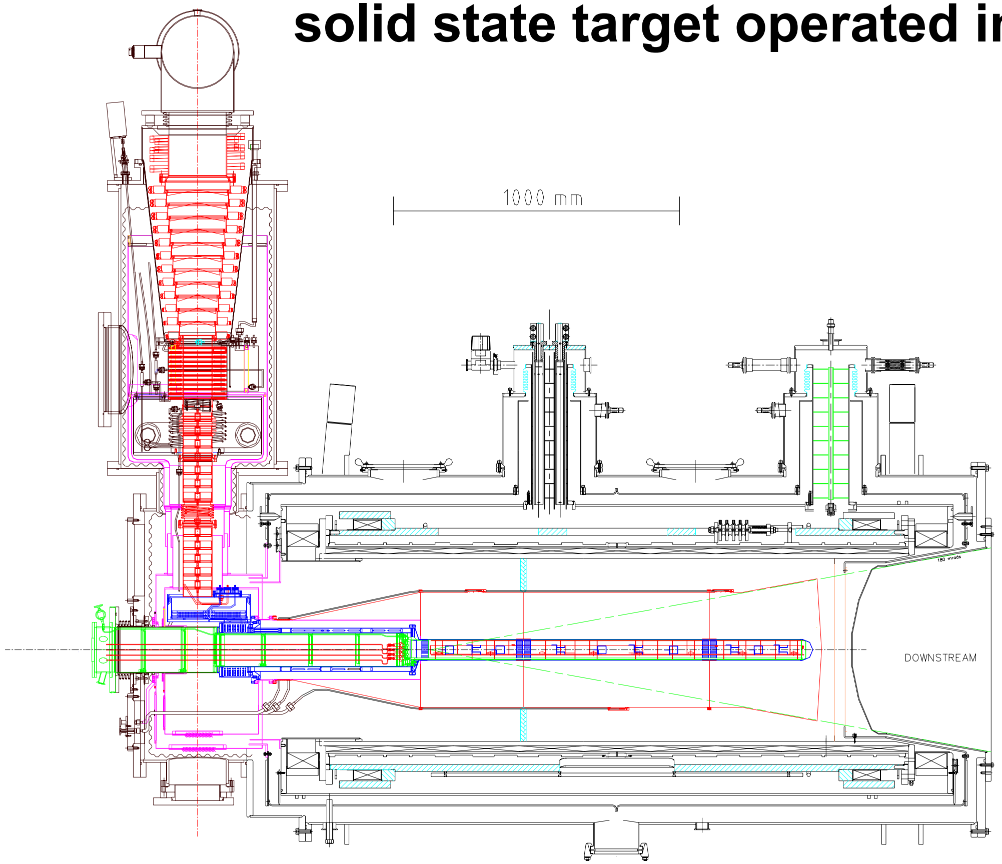
COMPASS proton run 2007

solid state target operated in frozen spin mode

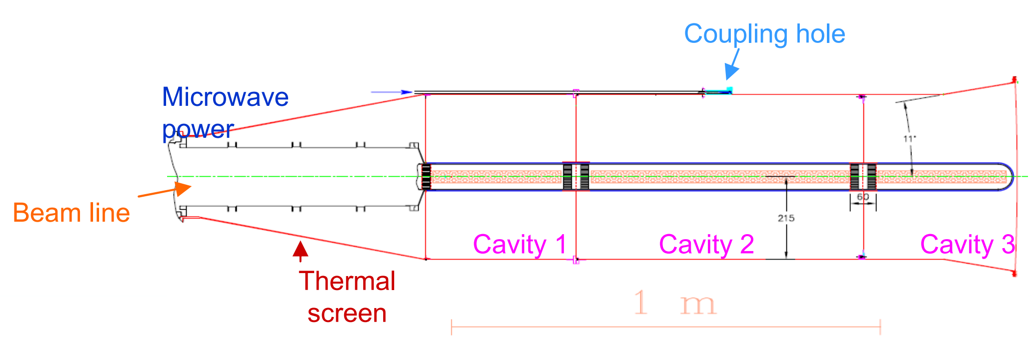


2007: NH_3

dilution factor f = 0.14

polarization P_T = 90%

2 ➔ 3 cells



COMPASS Programme, 2007 to 2010

The COMPASS Collaboration - January 23, 2007

5 Longer term projects

Other lines of research are presently under consideration as already mentioned in a document submitted January 15, 2006 to the CERN Council Strategy Group:

- The measurements of Generalised Parton Distribution functions with muon beams will, in particular, give access to the orbital momentum contribution to the nucleon spin, as described in the Expression Of Interest submitted (SPSC-2005-007, SPSC-EOI-005).

- The transverse spin effects were unveiled only recently and measurements are very preliminary. The next decade could cover systematic studies.

- The measurements of single spin observables in Drell–Yan processes with hadron beams will allow to check fundamental predictions of QCD. An EOI is being prepared.

- The double charm production with hadron beams will be accessible once a more refined vertex reconstruction is achieved.

GPD's at COMPASS2

Villars SPSC Meeting, september 2004

"COMPASS with high intensity muon beams and unpolarized target"

and

"Expression of Interest": SPSC-E0I-005

and

CERN-SPSC-2007-002
SPSC-M-754

proposed channels:

- **Exclusive meson electroproduction:**
  - **Vector mesons (ρ^0)**
  - **Pseudoscalar mesons (π)**
- **Deeply Virtual Compton Scattering (DVCS)**

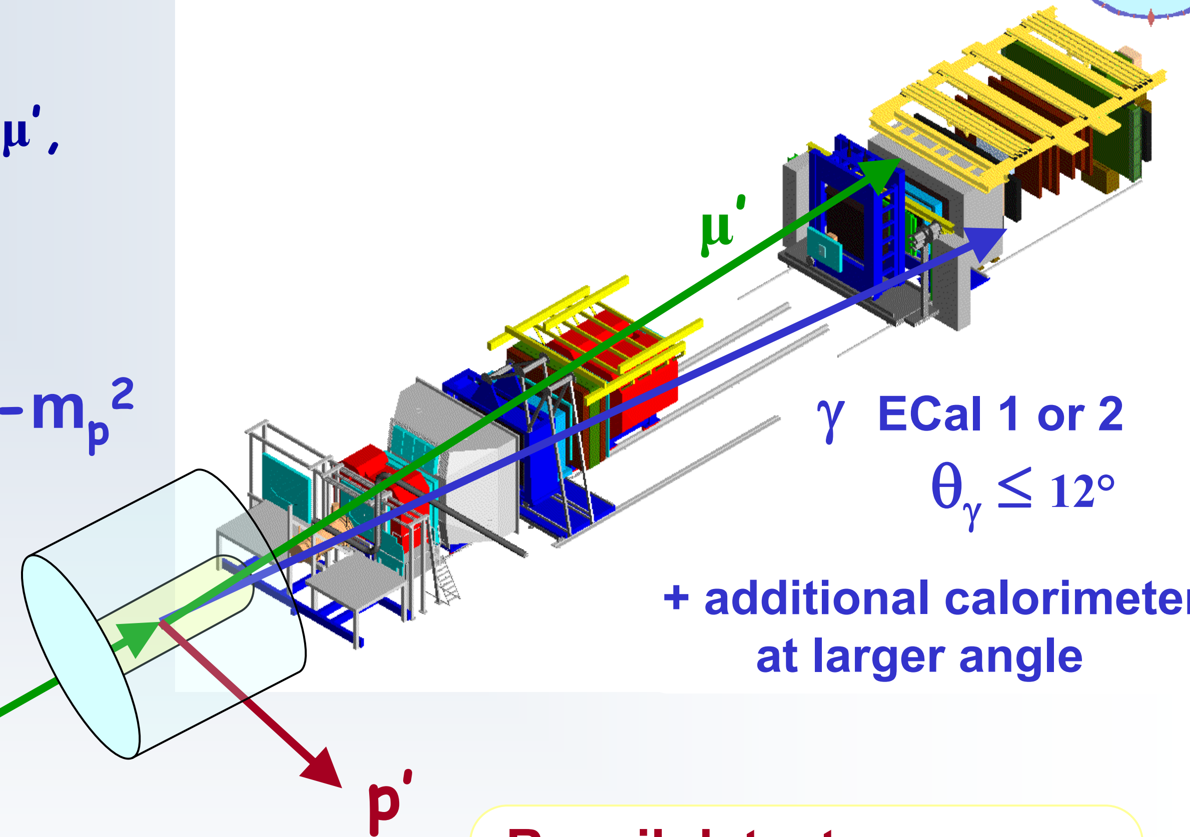
Additional equipment to the COMPASS set up

DVCS $\mu p \rightarrow \mu' p' \gamma$

At these energies (for μ, μ', and γ) the missing mass technique is not adapted

$$\Delta M^2_{required} = (m_p + m_\pi)^2 - m_p^2 = 0.25 \text{ GeV}^2$$

$$\Delta M^2_{observed} > 1 \text{ GeV}^2$$



$N\mu = 2\cdot 10^8$/SPS cycle
(duration 5.2s, each 16.8s)

Recoil detector
to insure exclusivity
to be designed and built

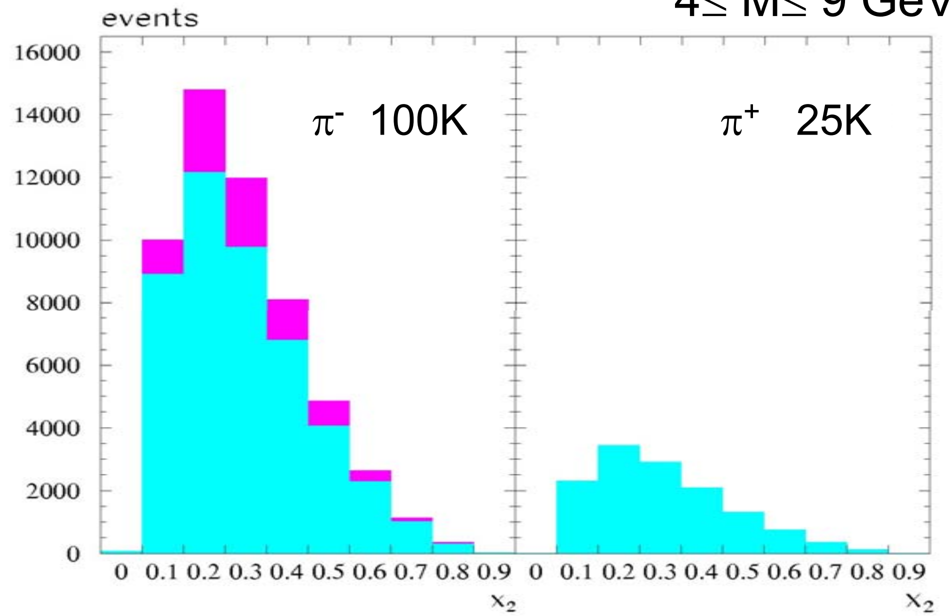
2.5m liquid H2 target
to be designed and built

$L = 1.3\ 10^{32}\ cm^{-2}\ s^{-1}$

$\pi^{\pm} p^{\uparrow} \rightarrow \mu^{+} \mu^{-} X$

100K events (before dilut.) E_{π}=100 GeV s=200 GeV²

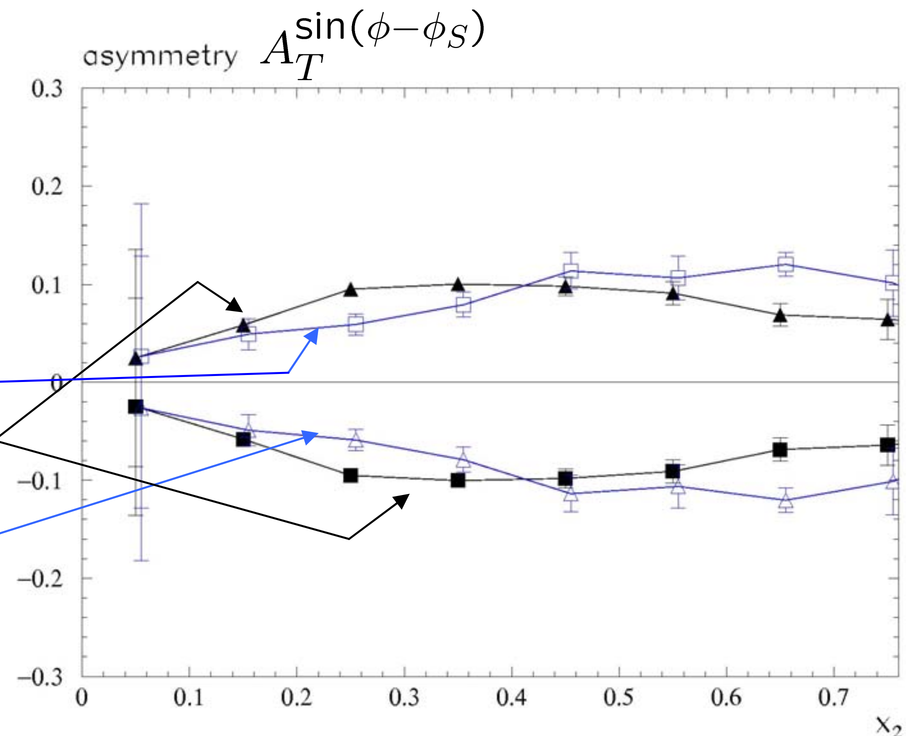
4≤ M≤ 9 GeV 0.5≤ q_T ≤ 2.5 GeV/c



$\sin(\phi - \phi_{S_p}) > 0$

$\sin(\phi - \phi_{S_p}) < 0$

Bianconi & Radici
P.R. D**73** (06) 114002



param. # 2

$$f_{1T}^{\perp q}\Big|_{SIDIS} = +f_{1T}^{\perp q}\Big|_{Drell-Yan}$$

$$f_{1T}^{\perp q}\Big|_{SIDIS} = -f_{1T}^{\perp q}\Big|_{Drell-Yan}$$

N_u = 0.7 N_d = -0.7

from M.. Radici Talk in Freiburg, March 2007

AGAIN,

THE WORK HAS ONLY STARTED