Transverse Spin Effects in Semi-Inclusive Deep Inelastic Scattering

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Hadron Structure and Spectroscopy **Freiburg, March 21, 2007**

Content of the talk

- SIDIS Experiments with transversely polarised tgt
  HERMES and COMPASS

- Results on asymmetries
  - transversity Distribution Function
  - Sivers Distribution Function
  - Other TMD Distribution Functions

- Conclusions

mainly experimental results

also,

FANTASTIC PROGRESS IN THEORY, IN THE LAST FEW YEARS

→ *V. Barone, A. Efremov, A. Prokudin*

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  HERMES and COMPASS

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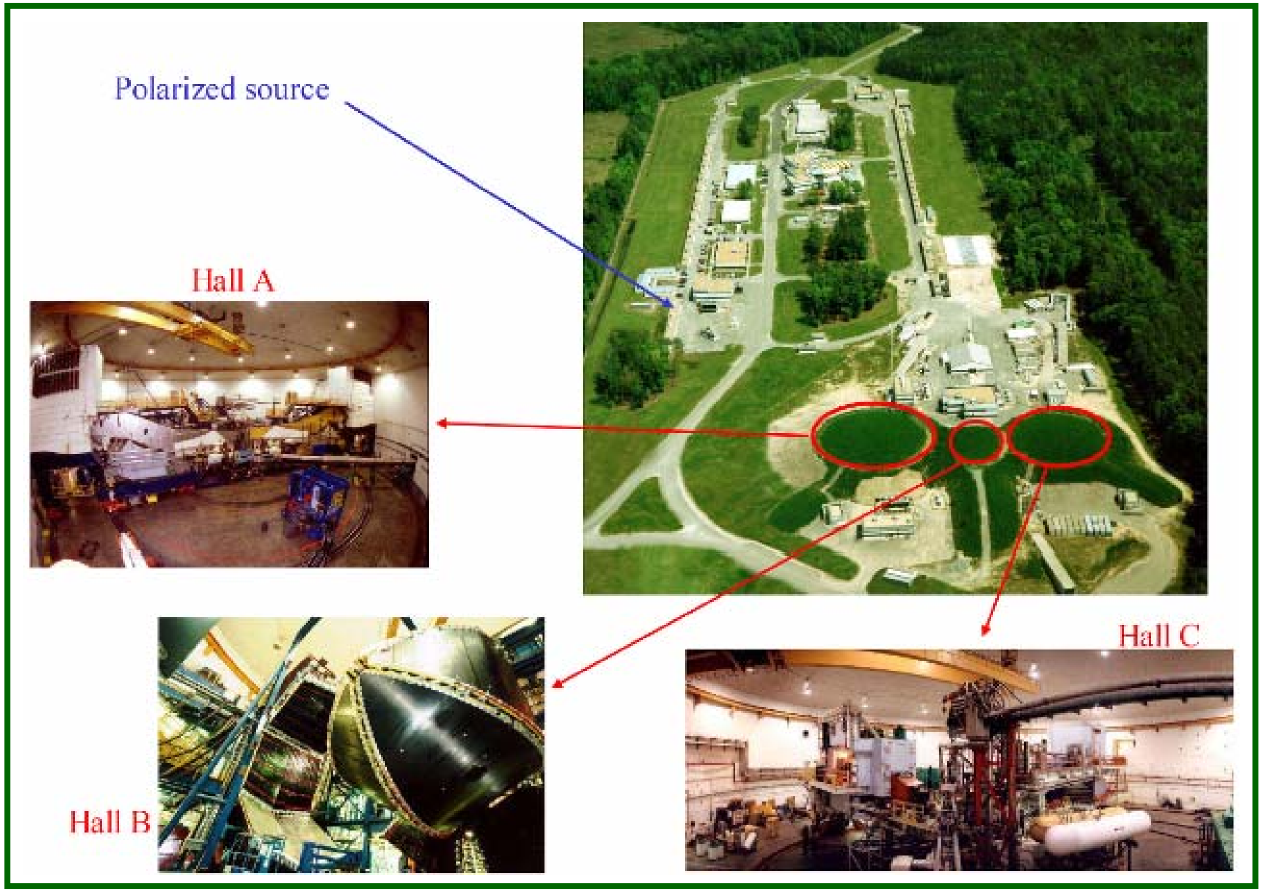
SIDIS Experiments with transversely polarised targets

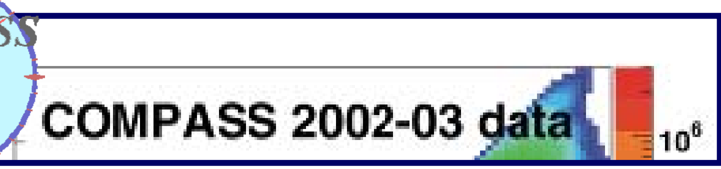
transverse spin effects are an important part of the program of the experiments

HERMES at DESY
electron beam,
energy 27.5 GeV



COMPASS at CERN
long pol μ beam,
energy 160 GeV

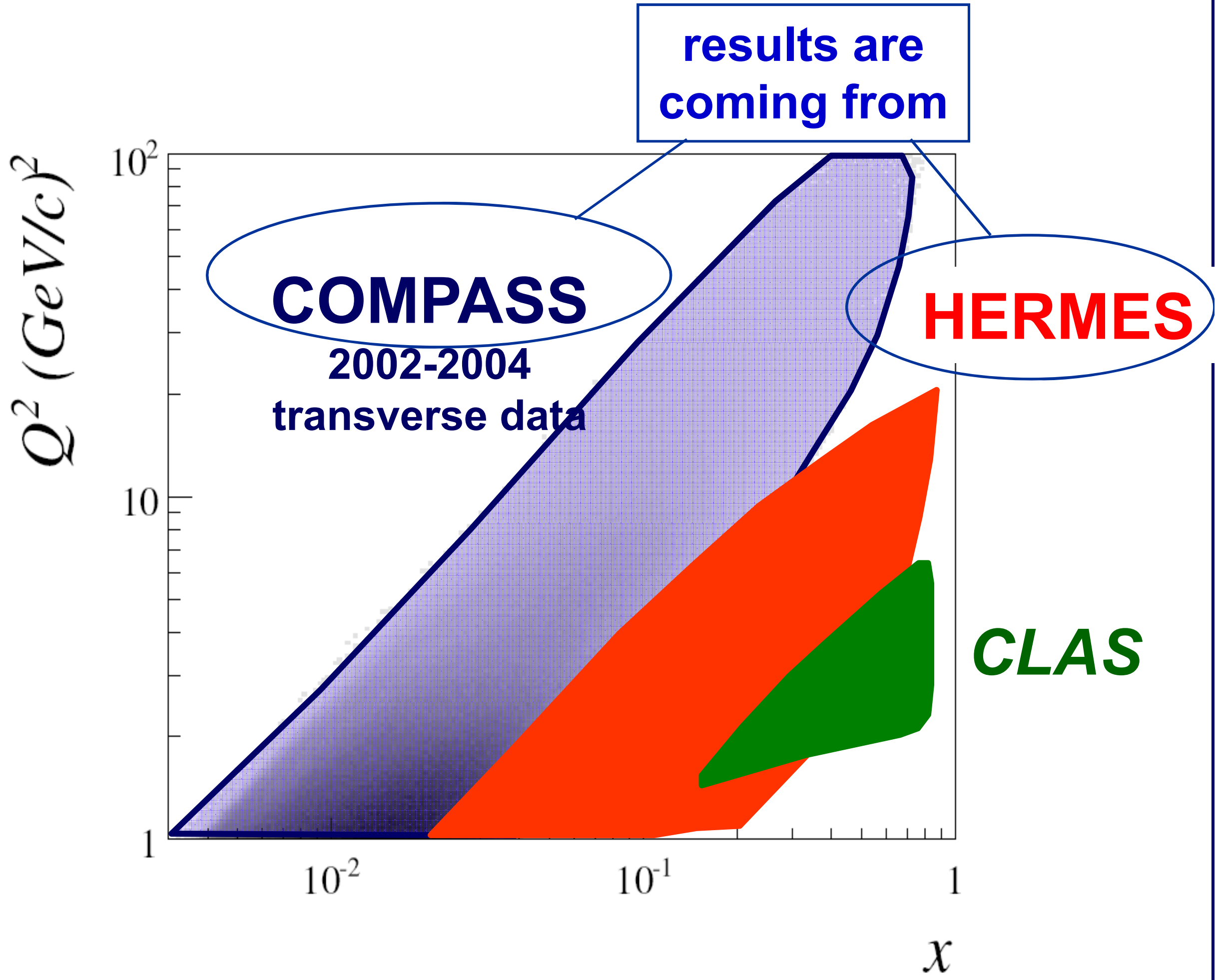
JLAB experiments
electron beam,
energy 6 GeV to be upgraded to 12 GeV
*(**longitudinally polarised target, till now**)*



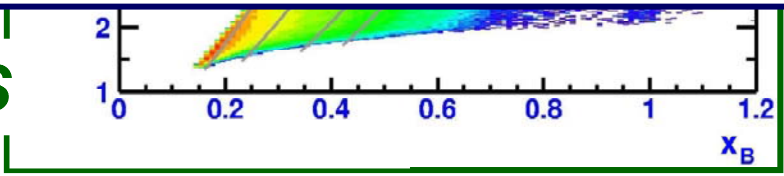
given the different beam energies, the $Q^2 - x$ range is different

→ complementary information,

needed to study energy dependence and to disentangle higher order effects



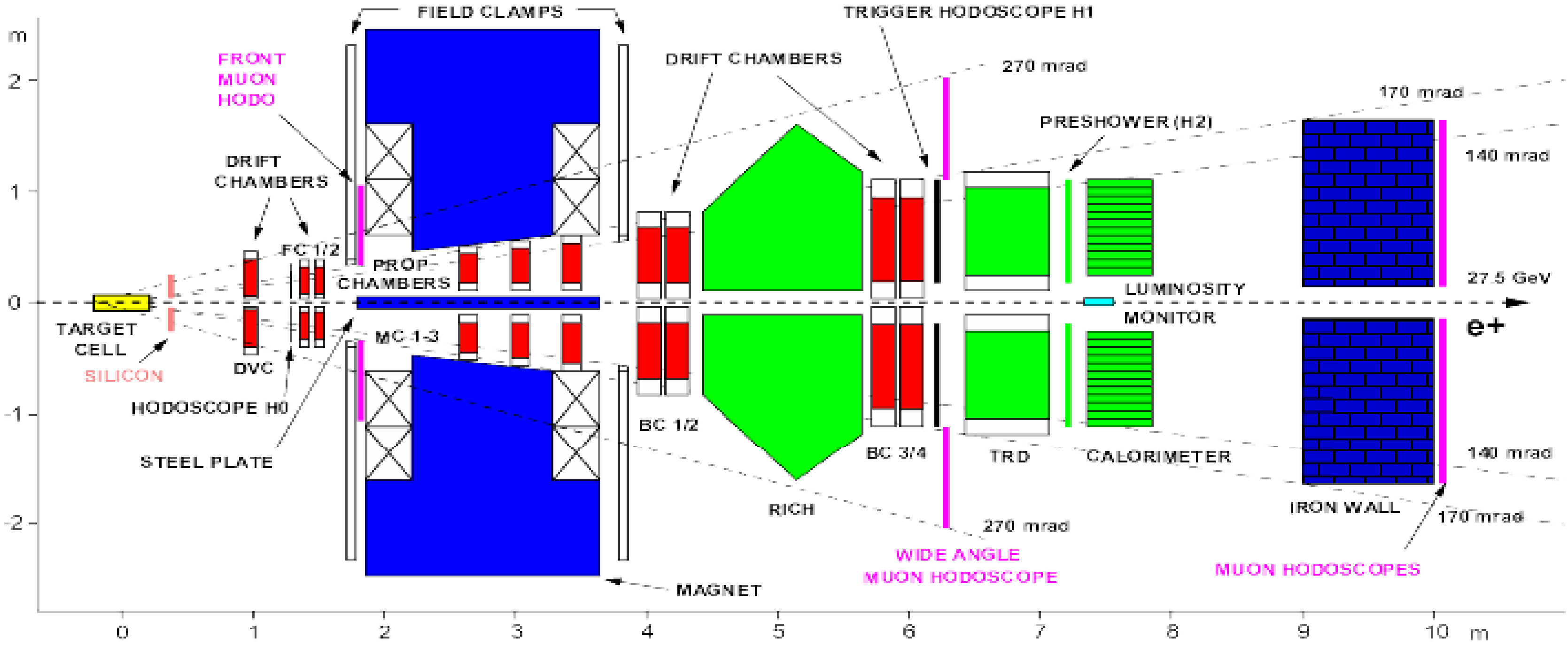
CLAS



HERMES

27.5 GeV e^+

$\sqrt{s}$ = 7 GeV



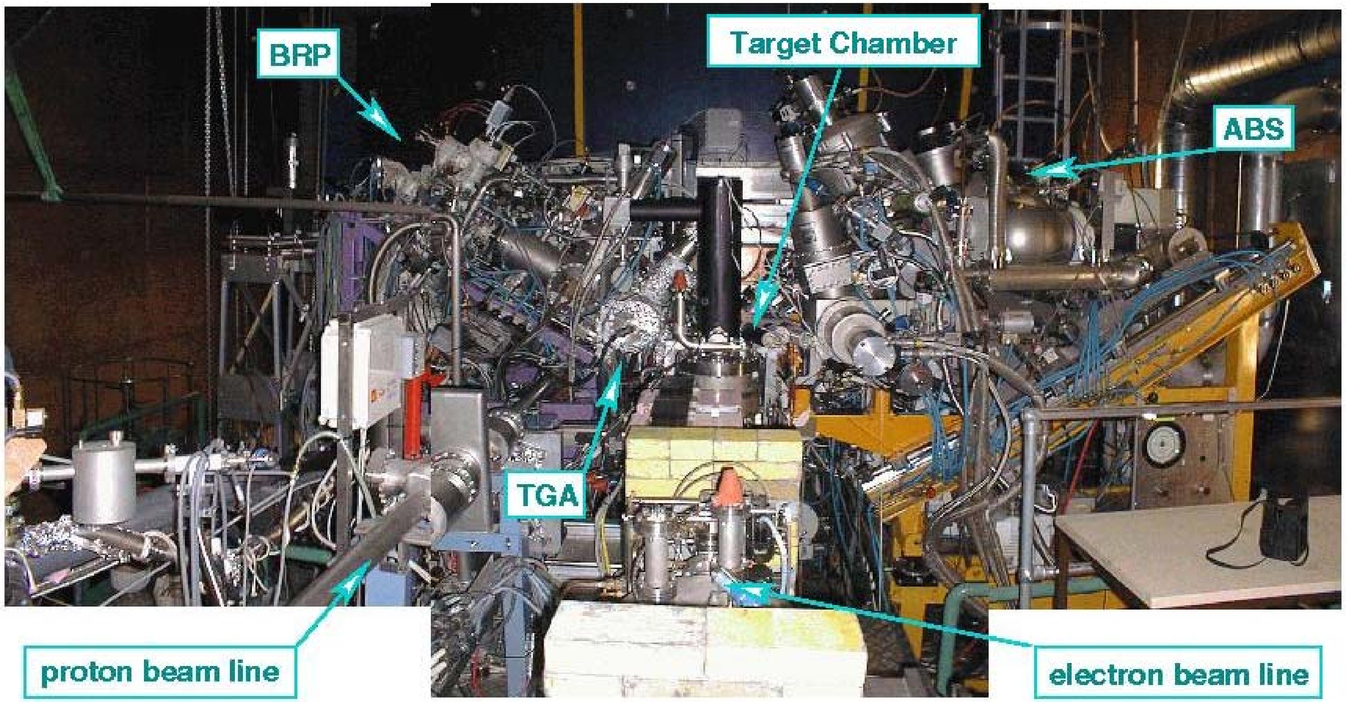
particle ID: lepton ID with ε~98%,

hadron contamination <1%

RICH: π, K, p ID

the HERMES polarised target

pure hydrogen gas target



flipped at high frequency (60- 90 s)

$^{1}H \rightarrow$ <|P_t|> ~ 85 ±3.8 %

$^{2}H \rightarrow$ <|P_t|> ~ 84 ±3.5 % **$^{1}H \uparrow$ <|P_t|> ~ 74 ±4.2 %**

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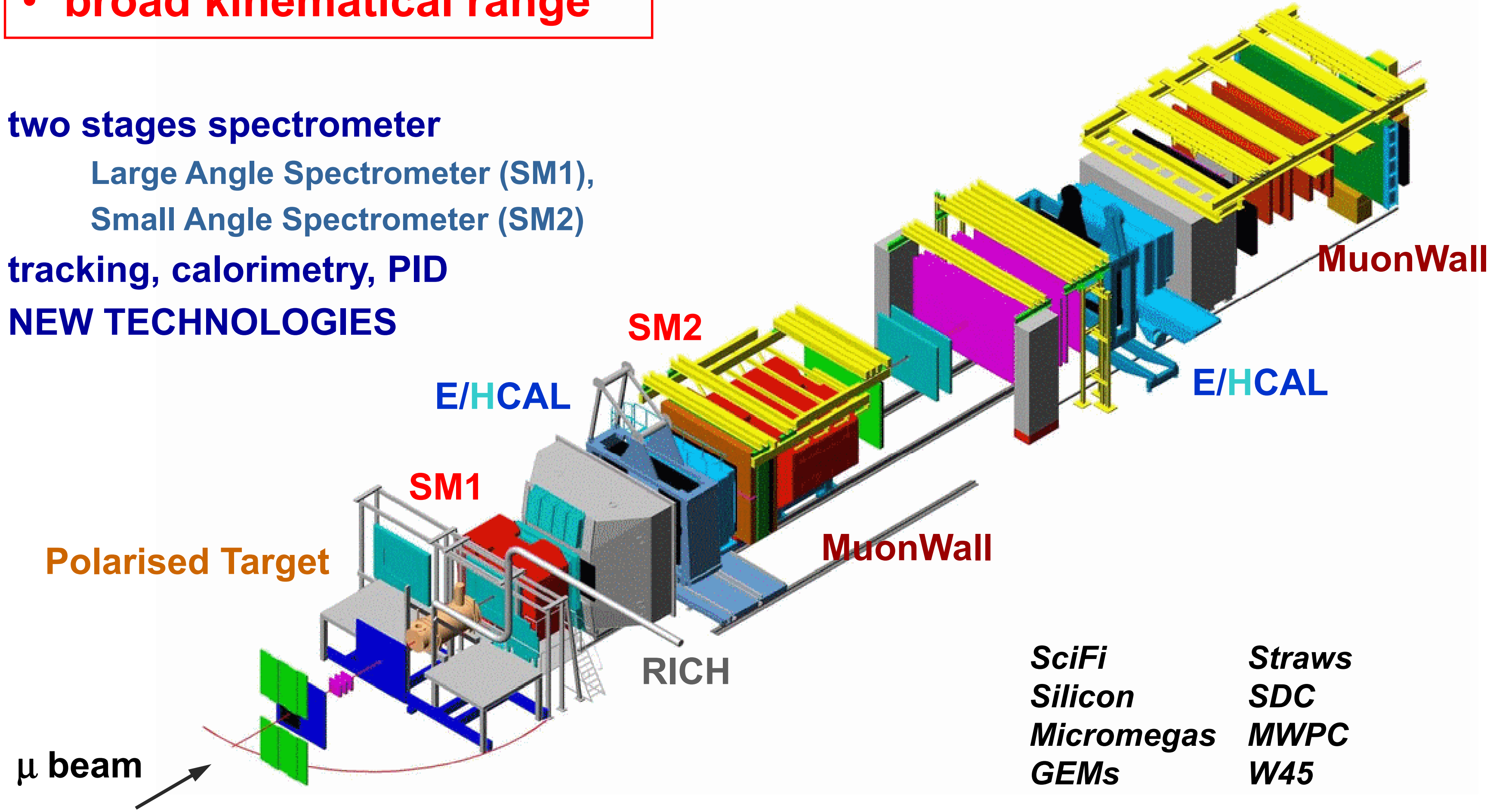
COMPASS

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

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

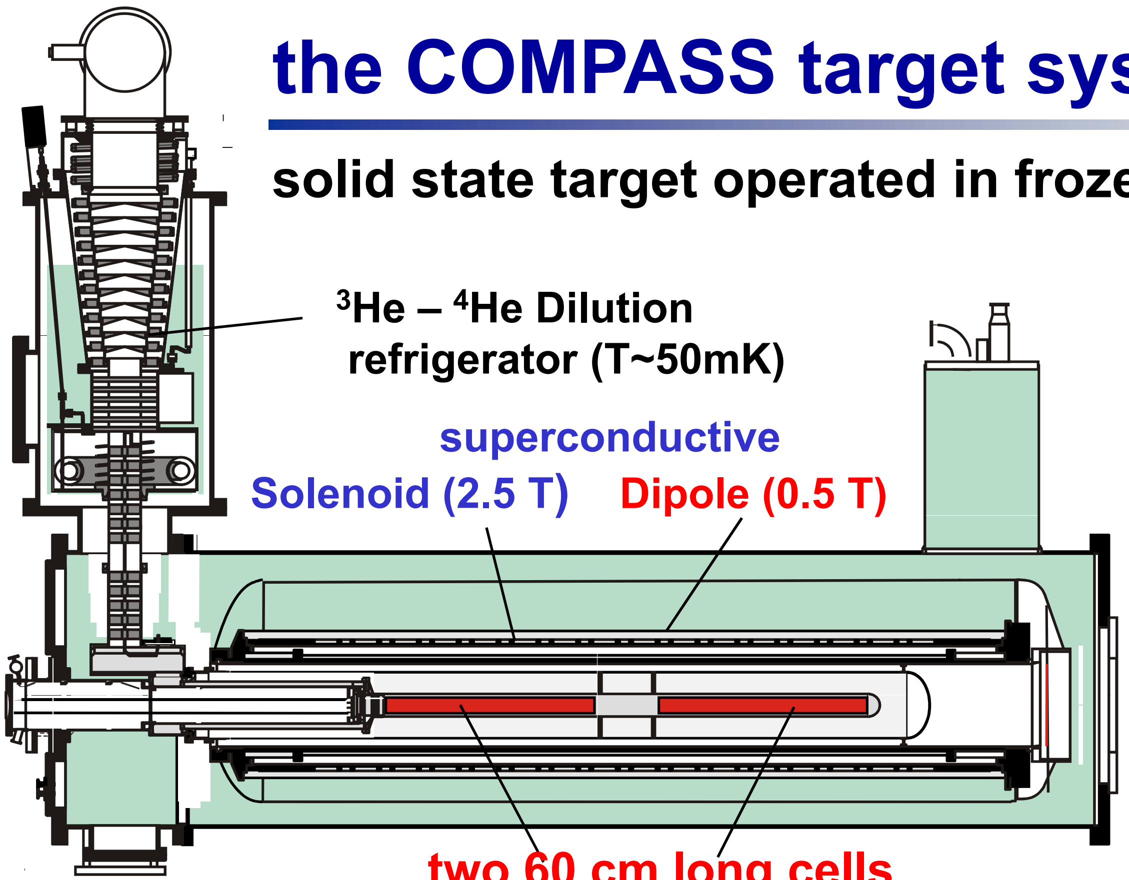
two stages spectrometer
Large Angle Spectrometer (SM1),
Small Angle Spectrometer (SM2)
tracking, calorimetry, PID
NEW TECHNOLOGIES



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

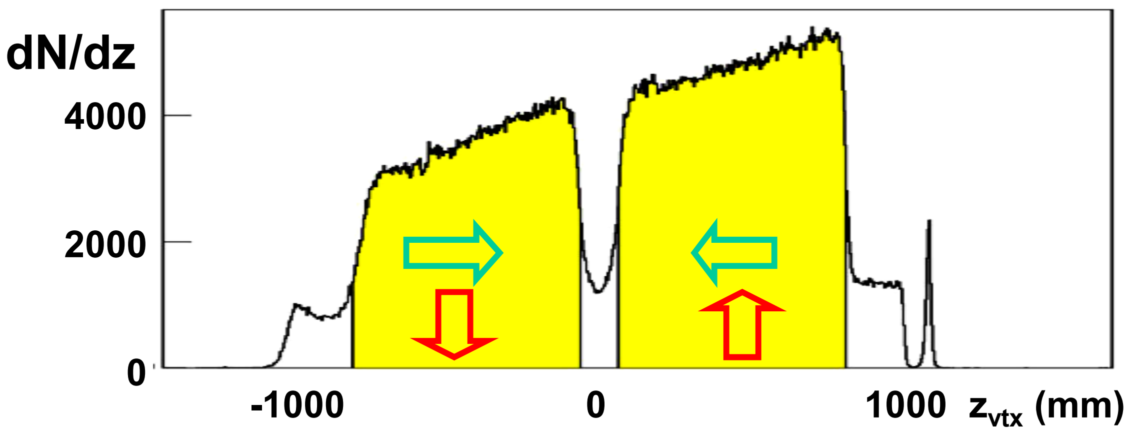
the COMPASS target system (2002-2004)

solid state target operated in frozen spin mode



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

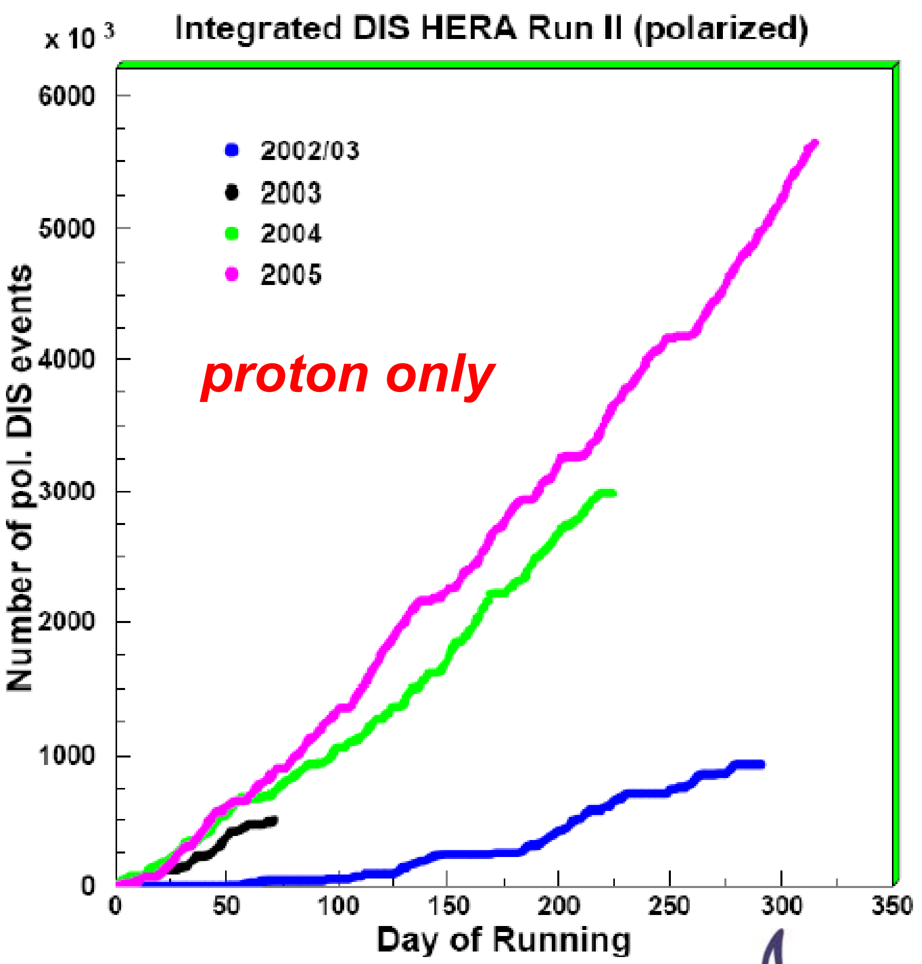
2002-2004: ^{6}LiD
dilution factor f = 0.38
polarization P_T = 50%
~20% of the time transversely polarised



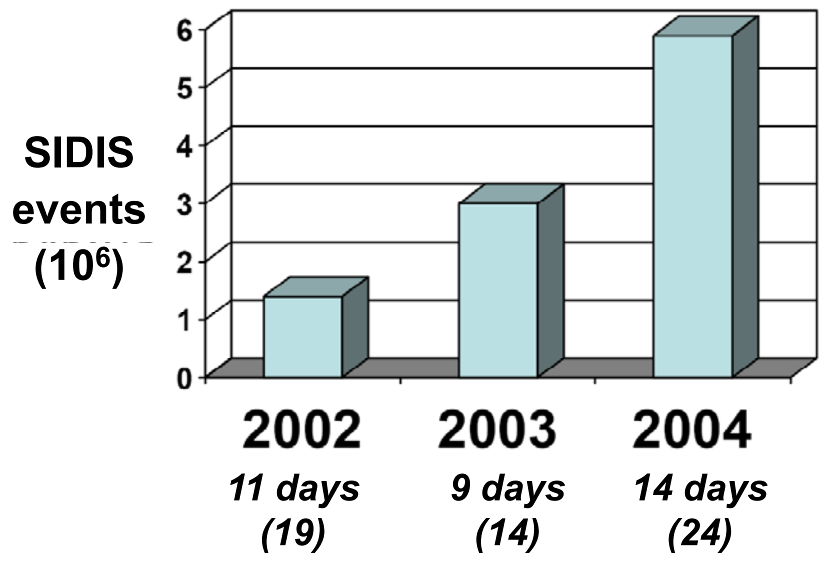
during data taking with transverse polarization

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

data taking with transversely polarised target



2002-2004: ^{6}*LiD only*



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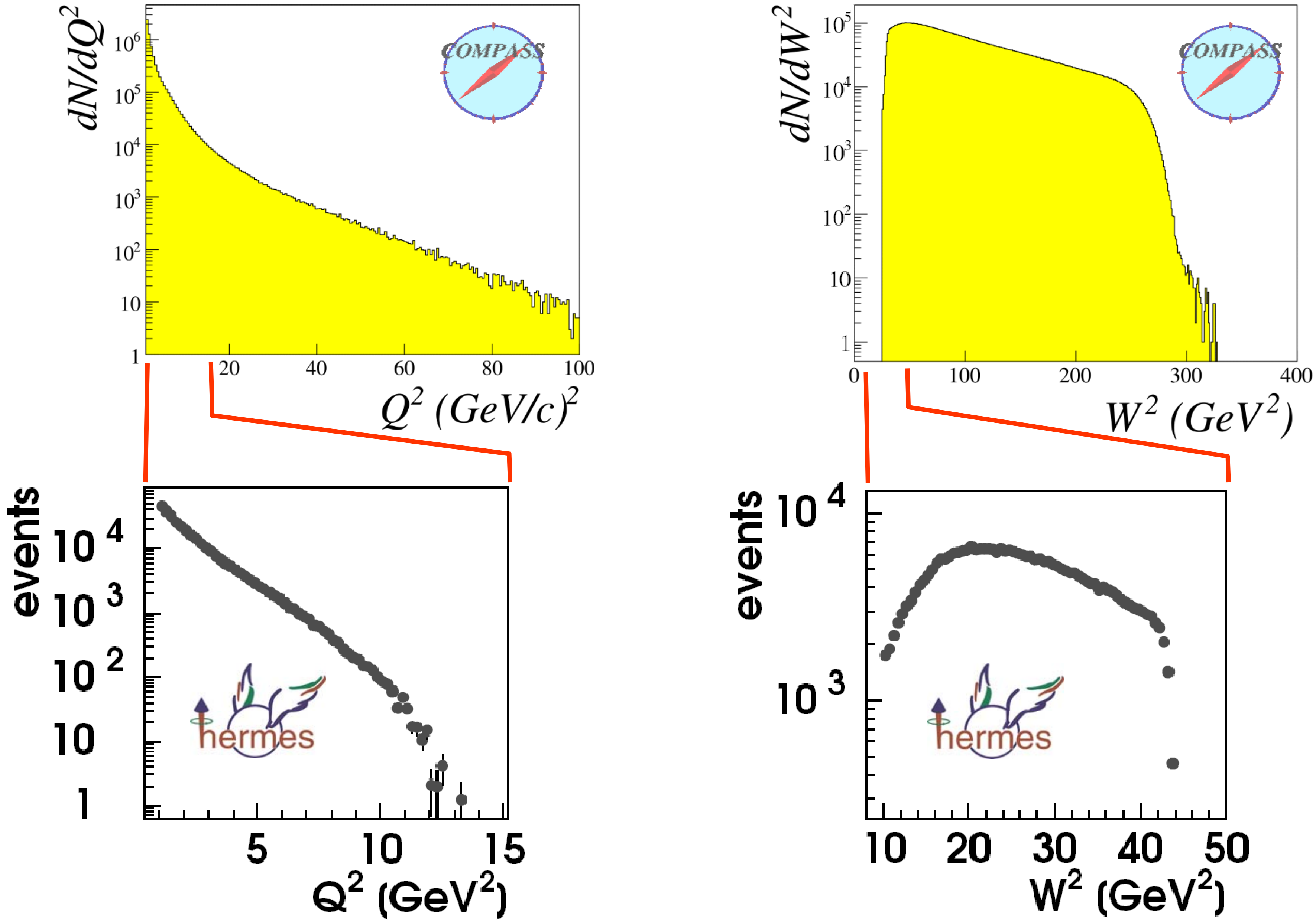
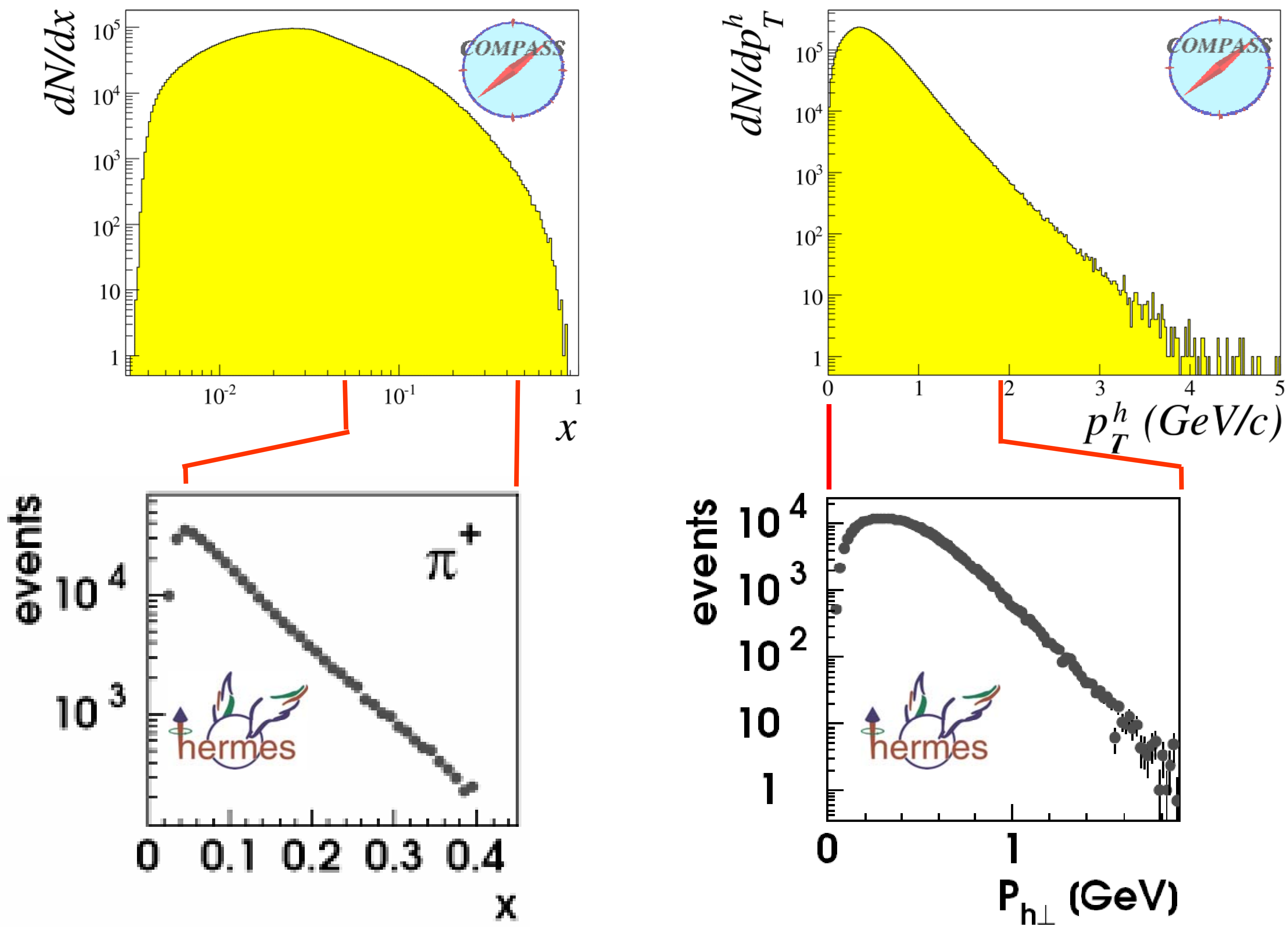
SIDIS kinematics



SIDIS kinematics



- SIDIS Experiments with transversely polarised tgt

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Transversity distribution function

reminder:

1993: first proposals to measure the transversity DFs:

the RHIC-Spin Collaboration, BNL — Drell-Yan

the HELP Collaboration, CERN — SIDIS

today: SIDIS

transversity (and transverse spin effects) is being studied at HERMES and COMPASS

proposals to measure it at JLAB (12 GeV)

Christine Aidala

Drell-Yan: measurements planned at RHIC

Oleg Denissov

being planned at COMPASS

proposed at GSI

complementary to SIDIS

flavour separation: unique feature in SIDIS

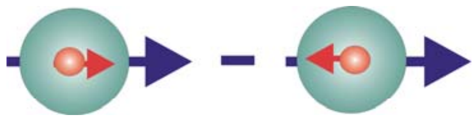
Transversity Distribution Function

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

$q(x)$
$f_1^q\,(x)$

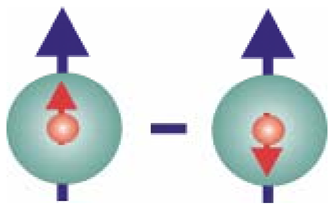
unpolarised DF
quark with momentum *xP* in a nucleon
well known – unpolarised DIS

$\Delta q(x)$
$g_1^q(x)$



helicity DF
quark with spin parallel 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
quark with spin parallel 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 dinamics**
- **no contribution from the gluons $\rightarrow$ 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 $q\!\uparrow \rightarrow \Lambda$

....

Measurement of the Transversity DF in SIDIS

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

the "quark polarimetry" relies on the **Collins effect**

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

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

$$D_q^h(z,\vec{p}_T^{\,h}) = D_q^h(z,p_T^h) + \underbrace{\Delta_T^0 D_q^h(z,p_T^h)}_{\text{"Collins" FF: } H_1^{\perp q},\ \delta\hat{q}^{\,h},\ \ldots} \cdot \sin(\varphi_h - \varphi_s)$$

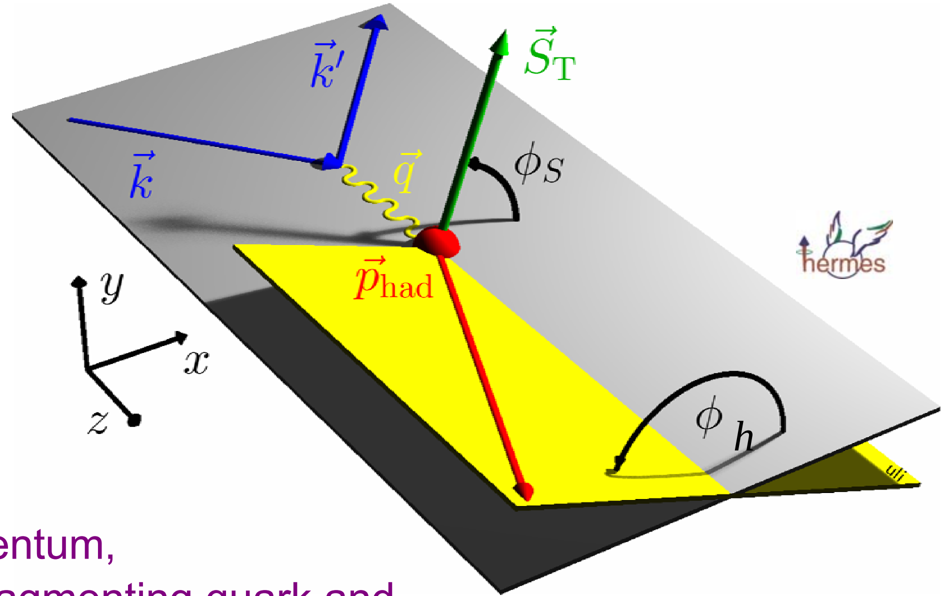
Collins effect in SIDIS

the "Collins angle" is

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

$= \phi_h + \phi_S - \pi$

hermes: $\Phi_C = \phi_h + \phi_S$ (Trento)



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

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

Collins effect in SIDIS

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

in each angular bin one measures the quantities

hermes

$$A_{\mathrm{UT}}^{\pi^\pm}(\phi,\phi_S) = \frac{1}{\langle P_z \rangle} \cdot \frac{N^{\Uparrow}_{\pi^\pm}(\phi,\phi_S) - N^{\Downarrow}_{\pi^\pm}(\phi,\phi_S)}{N^{\Uparrow}_{\pi^\pm}(\phi,\phi_S) + N^{\Downarrow}_{\pi^\pm}(\phi,\phi_S)}$$

COMPASS

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

2 cells oppositely polarised:
- 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**

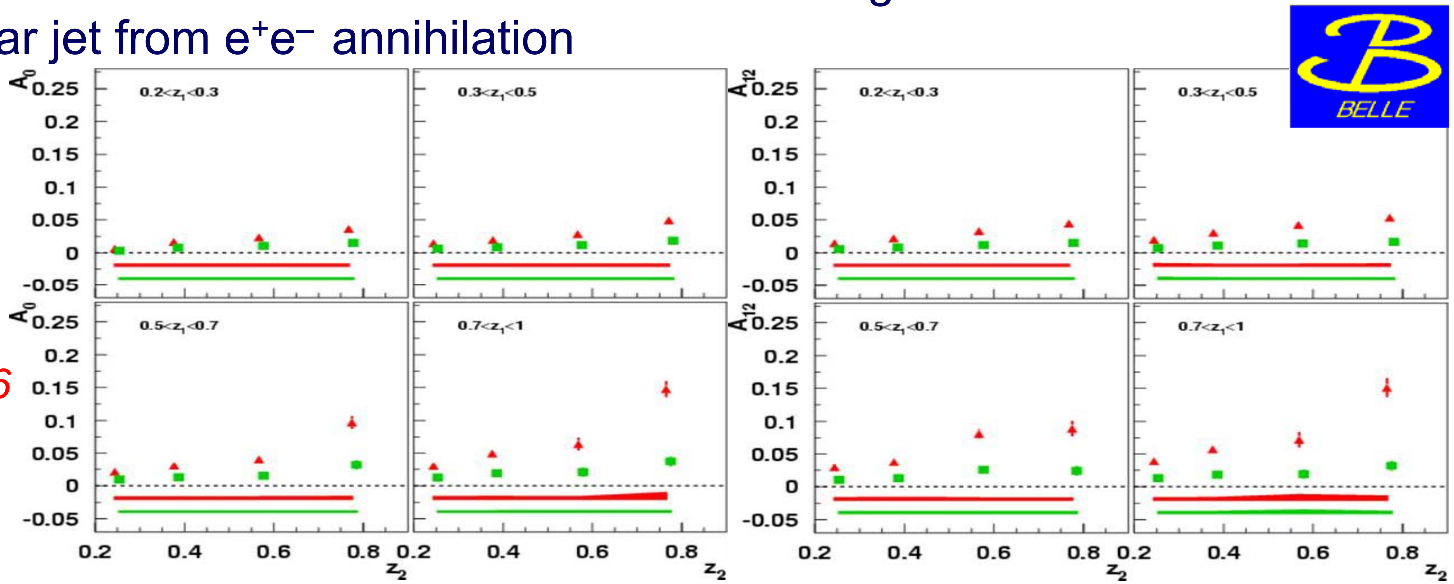
last year: great news from BELLE

the Collins FF is being 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

- 547 fb^{-1} charm corrected data sample,
- UL and UC double ratios

R. Seidl, SPIN2006

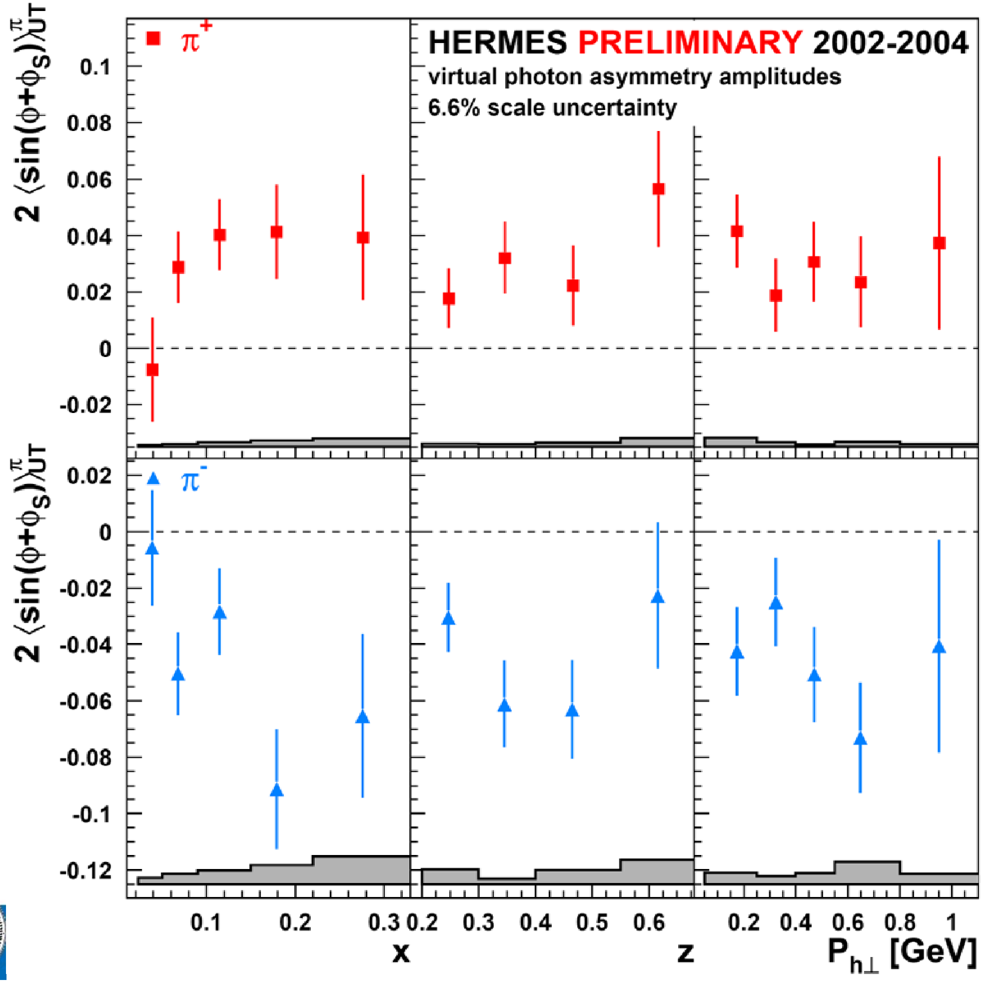


Matthias GP

Collins asymmetry

transversely polarised proton target - charged pions

- *first attempt with longitudinally polarised target*
- **2004: results from 2002-2003 data** PRL94 (2005) 012002 **confirmed by**
- **2005: results from 2002-2004 data**



a very clear signal:

transversity is ≠ 0,

the Collins FF is ≠ 0

positive π^+

and

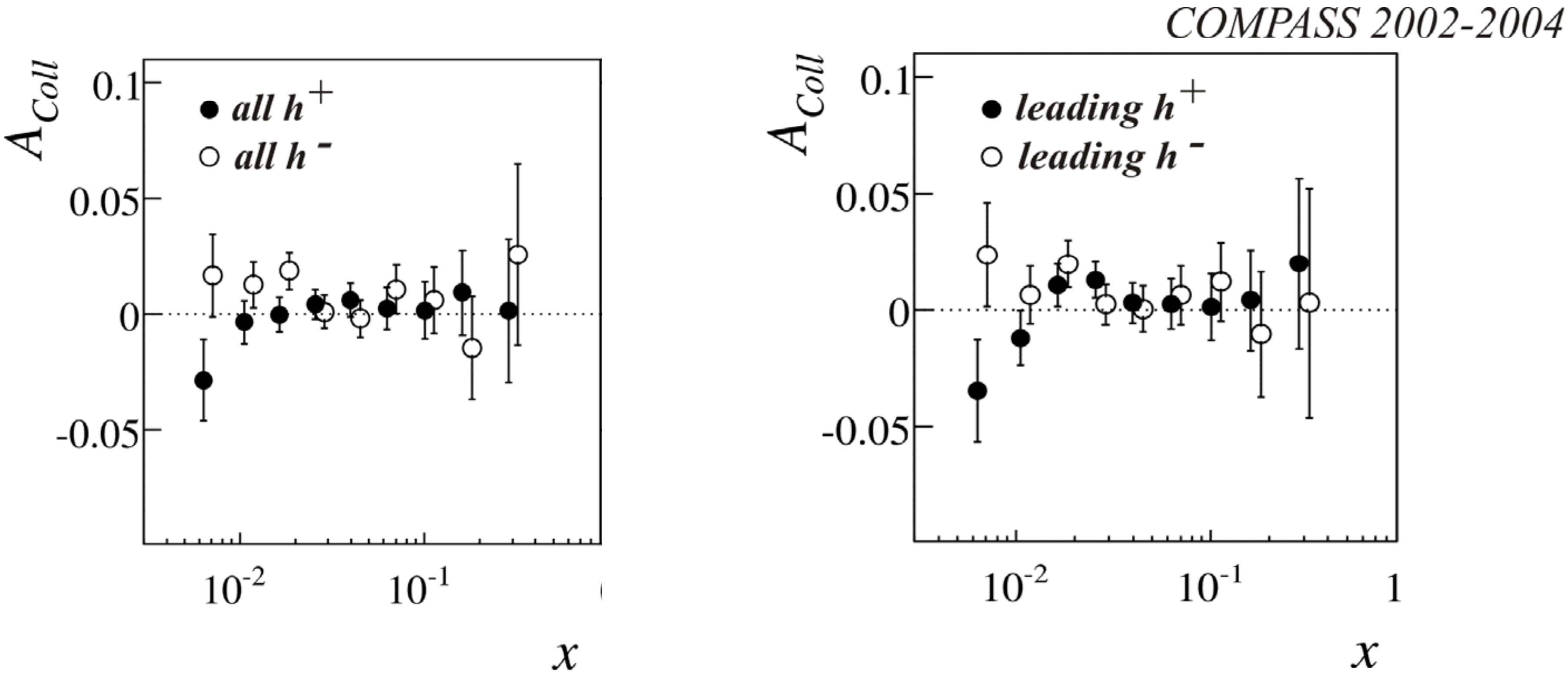
negative π^- *(unexpected large)*

asymmetries

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)

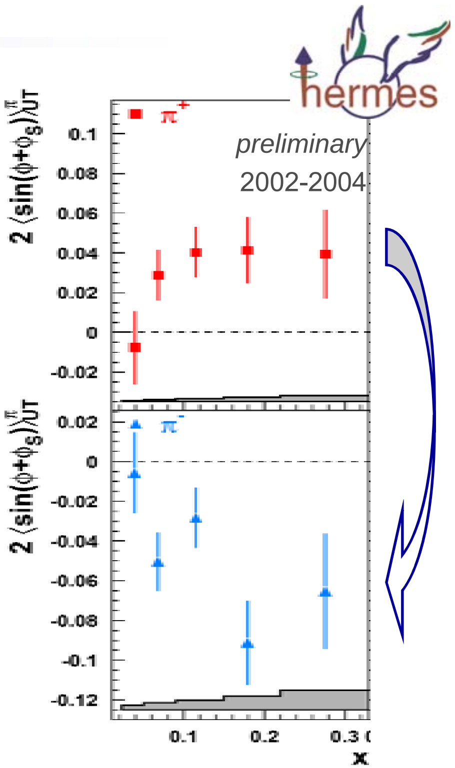
the same with leading h

Collins asymmetry

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

- **proton data**

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

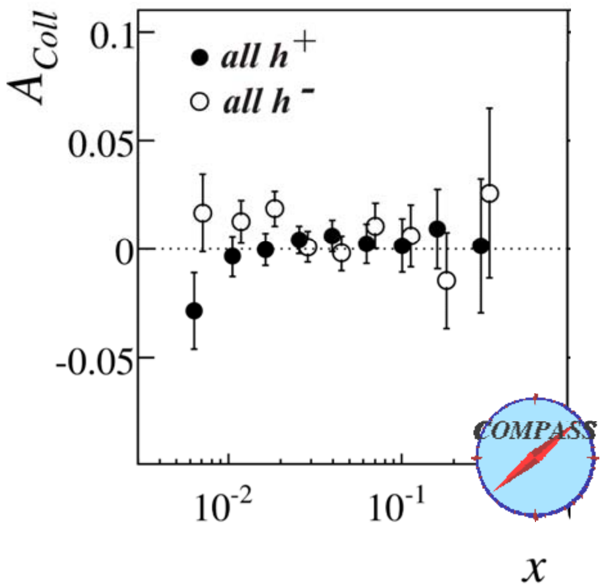


→ **unfavored Collins FF ~ – favored Collins FF**

$\Delta_T^0 D_2 \approx -\Delta_T^0 D_1$ *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 $\Delta_T^0 D_2 \approx -\Delta_T^0 D_1$

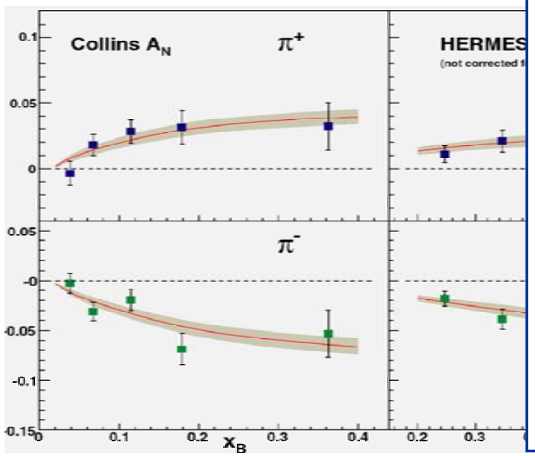
→ **cancellation between $\Delta_T u\ (x)$ and $\Delta_T d\ (x)$**

access to $\Delta_T d\ (x)$

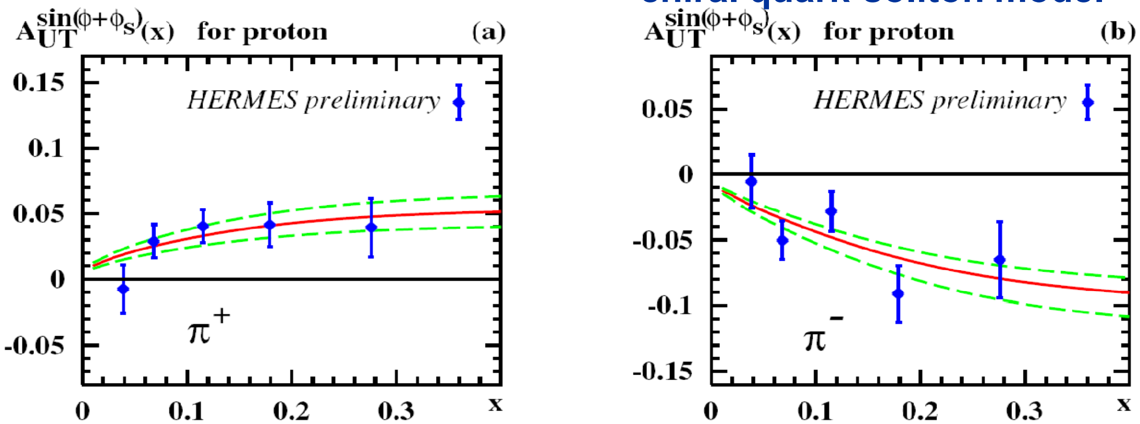
Collins asymmetry

2005-2006: theoretical work mainly

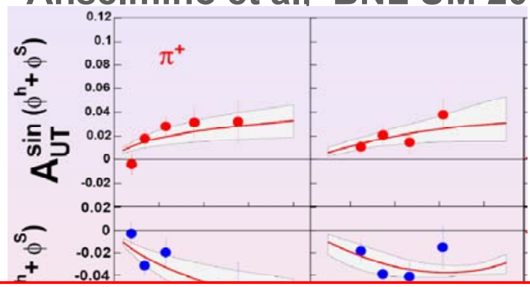
Vogelsang Yuan, PRD 7



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*

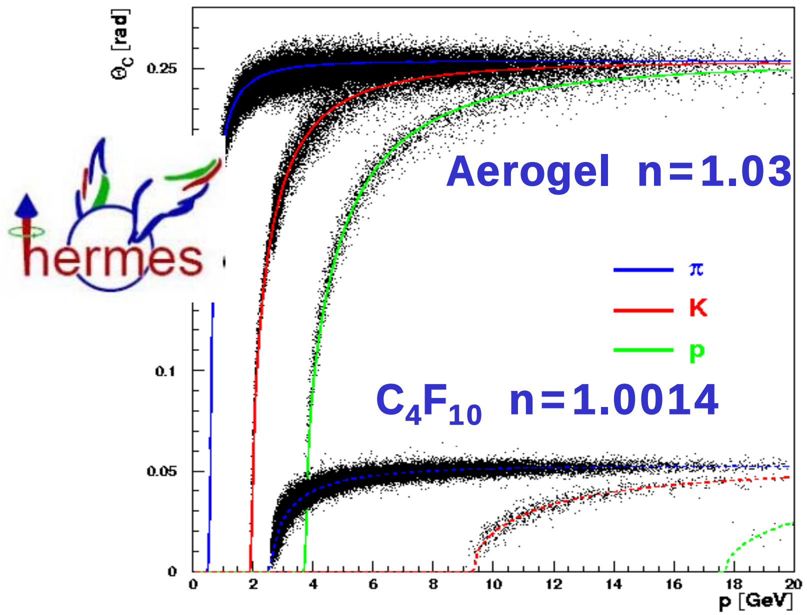
using the new Belle, the HERMES and the COMPASS 2002-2004 data
first extraction from transverity from a global analysis
Anselmino et al (2007) → *A. Prokudin*

Also new: Collins asymmetry for $K^{\pm}$

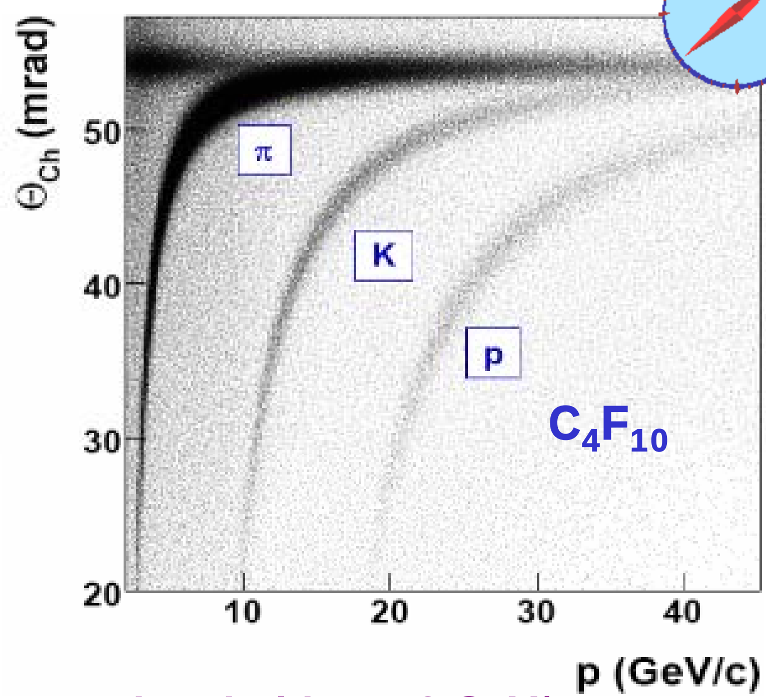
**together with measurements on different targets,
relevant for flavour decomposition**

there are very recent results for the Collins asymmetry

- **on proton for K^+ and K^-**
- **on deuteron for π^+ and π^-, K^+ and K^- (2003-2004)**



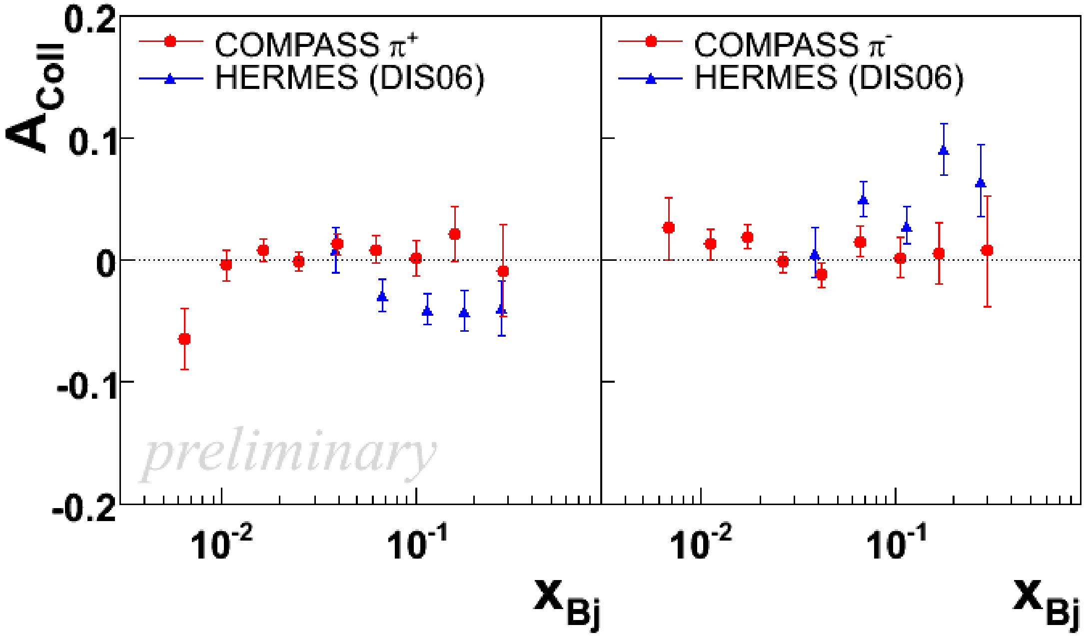
π, K, p ID within $2<E_h<15$ GeV



**threshold: π ~2 GeV/c
K ~ 10 GeV/c**

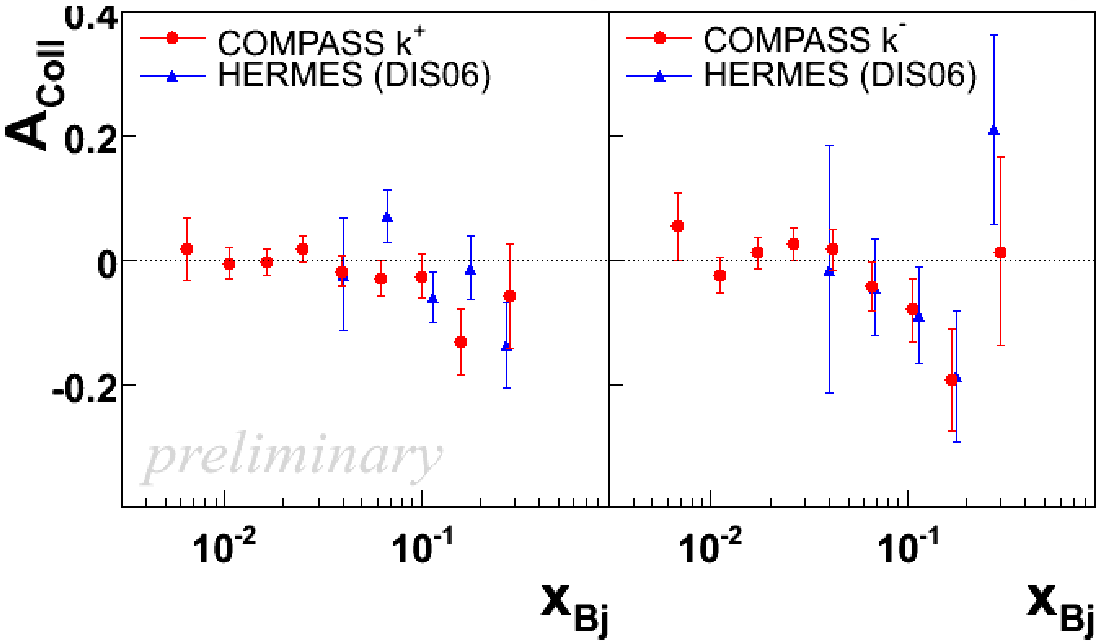
Collins Asymmetry for pions and kaons

preliminary
2002-2004 data
proton



preliminary
2003-2004 data
deuteron

COMPASS
sign
convention



Transversity DF: how to measure it

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

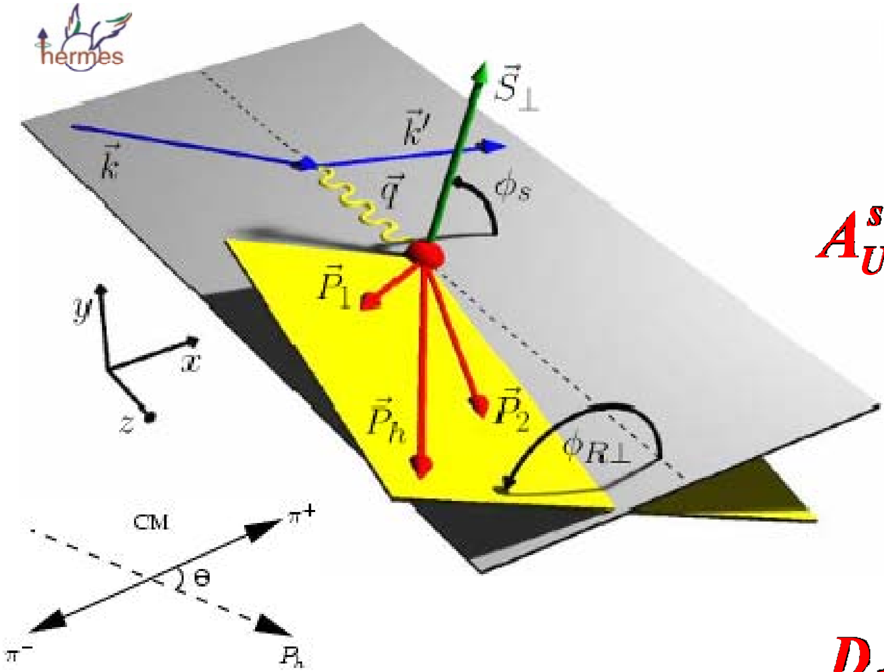
$l\,N^{\uparrow} \rightarrow l'\,\Lambda\,X$ **Λ polarisation**
Fragmentation Function of $q\uparrow \rightarrow \Lambda$

alternative way to access transversity
not sensible to transverse momenta

M. Radici

two-hadron asymmetries

in inclusive production of hadron pairs, one can define the angle $\phi_{R\perp}$ and measure an azimuthal asymmetry from the modulation of the number of events in $\phi_{RS} = \phi_{R\perp} - \phi_S$,
or $\phi_{RS} = \phi_{R\perp} + \phi_S$



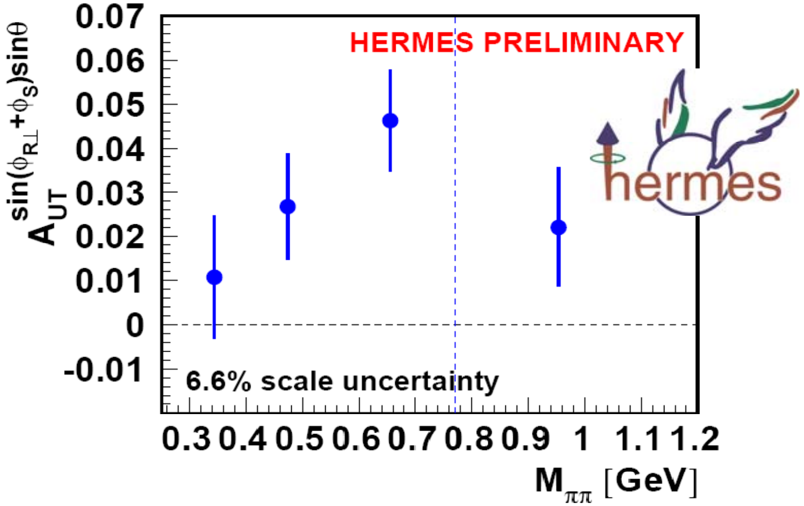
$$A_{UT}^{\sin(\phi_{R\perp}+\phi_S)\sin\theta} \propto \frac{\sum h_1(x) H_1^{\perp\angle}(z)}{\sum q(x) D_1(z)}$$

D_1, $H_1^{\perp\angle}$ presently unknown
being measured in e^+e^- (BELLE)

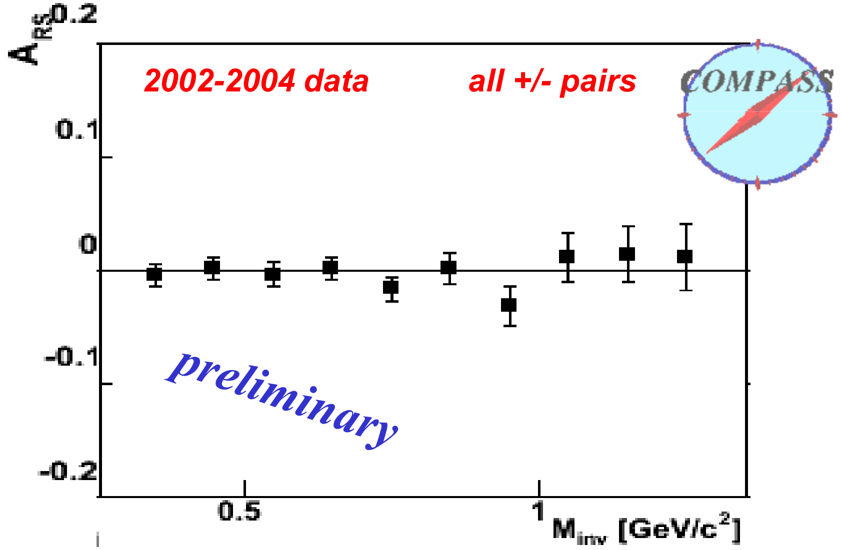
expected to depend on the hadron pair invariant mass

two-hadron asymmetries

proton target

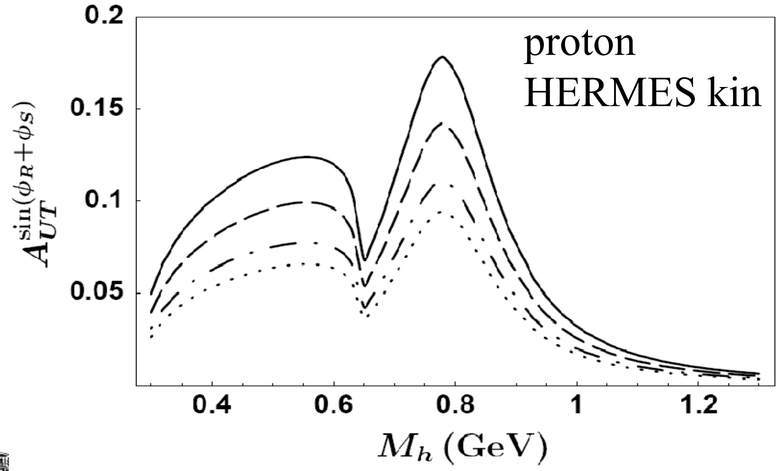


deuteron target



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

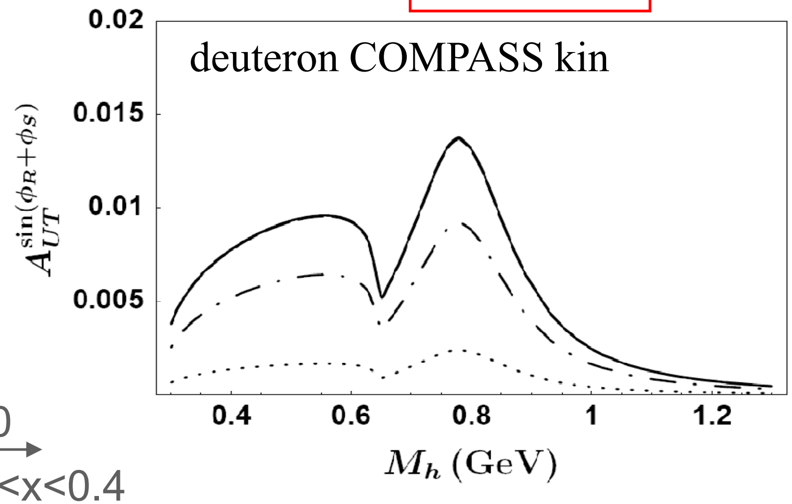
M. Radici



1/10

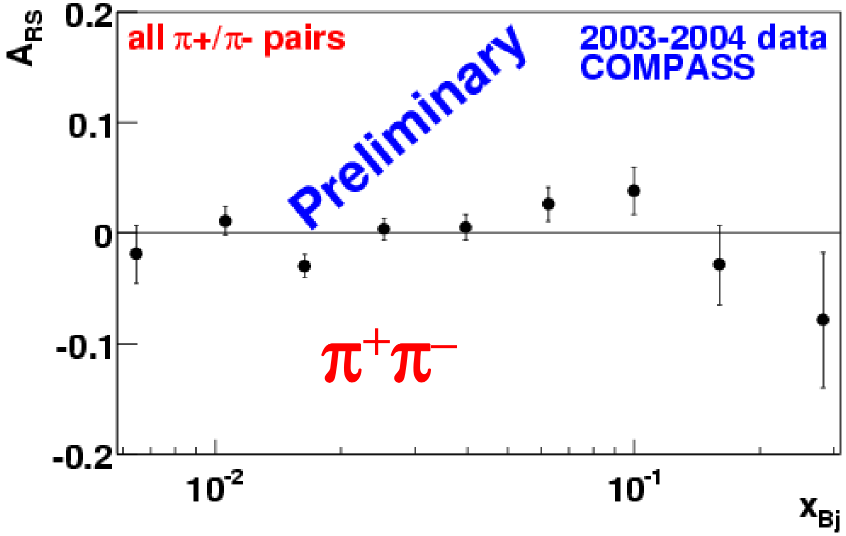
0.004<x<0.4

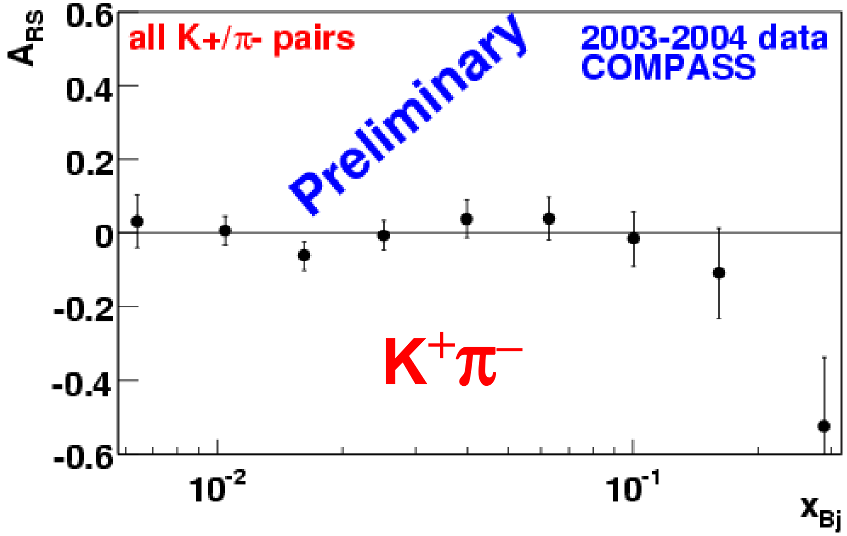
AND deuteron target

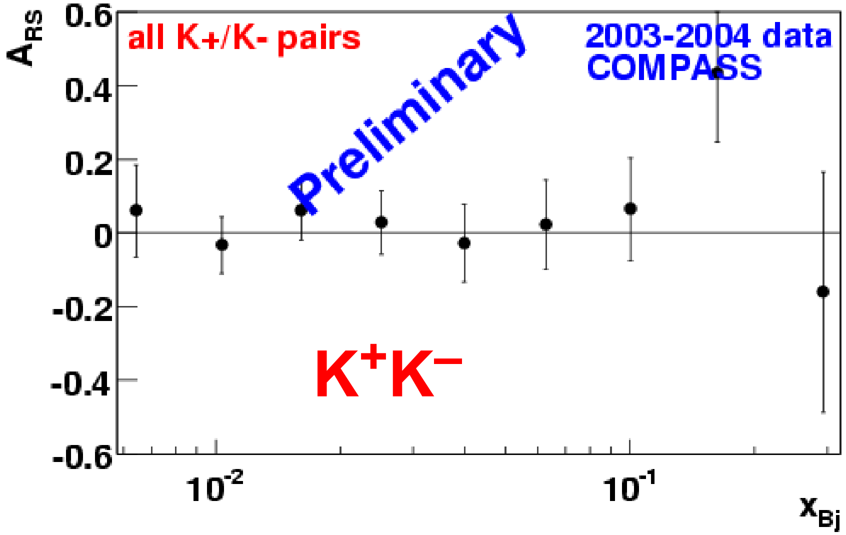


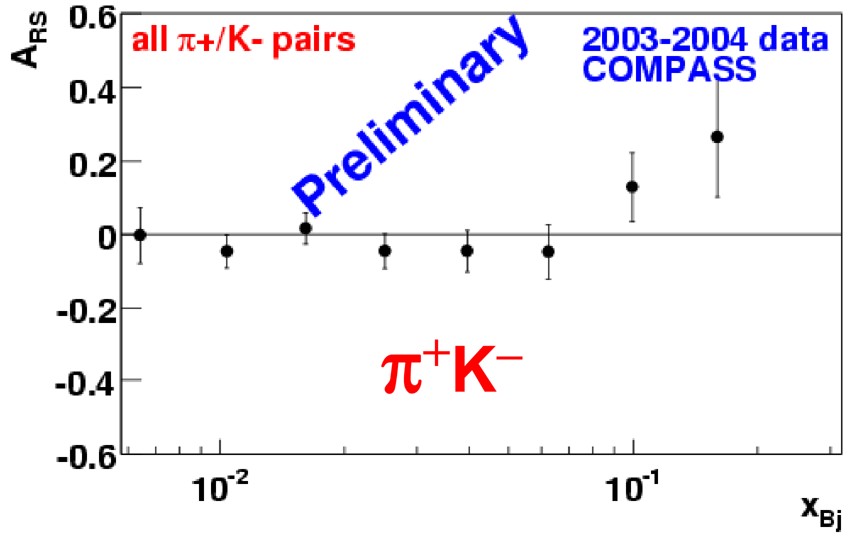
two-hadron asymmetries

new results from COMPASS with deuteron target (2007)

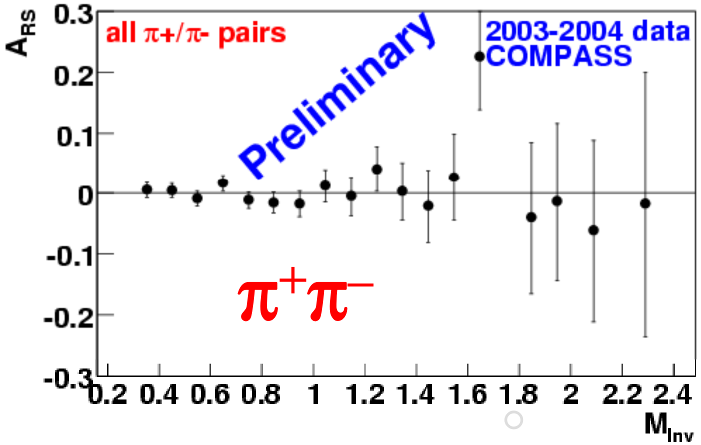


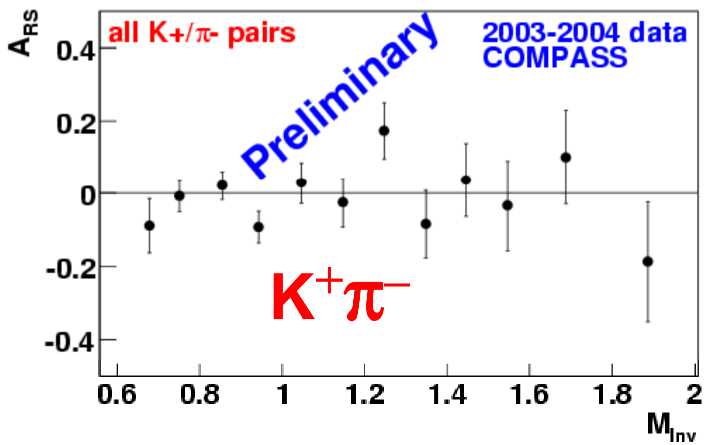


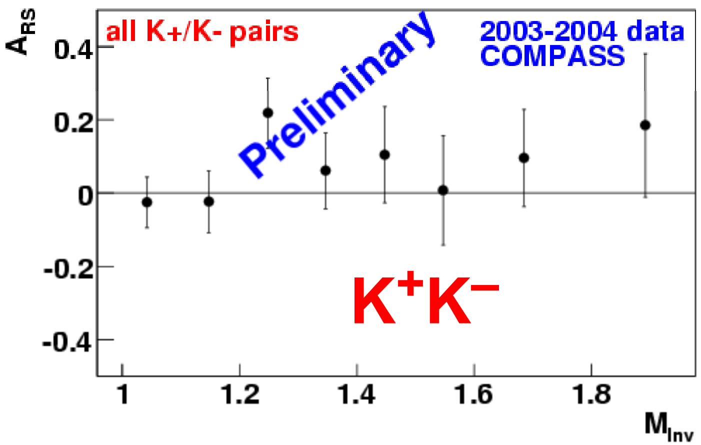


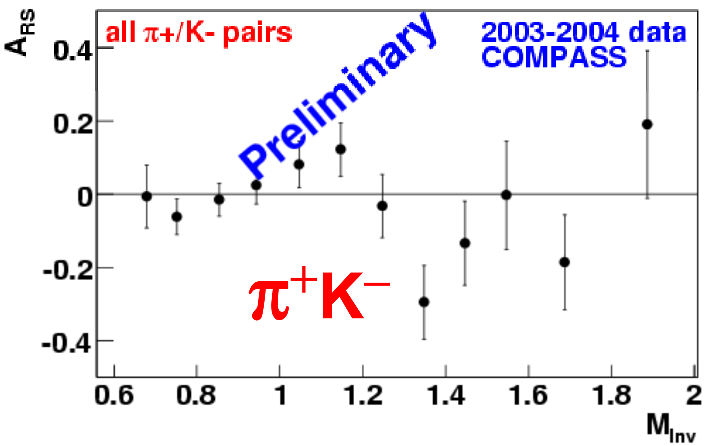


two-hadron asymmetries

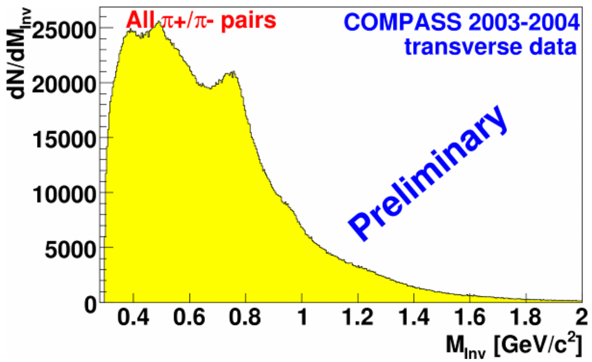


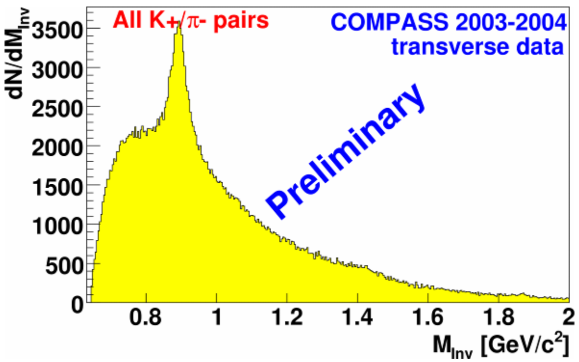


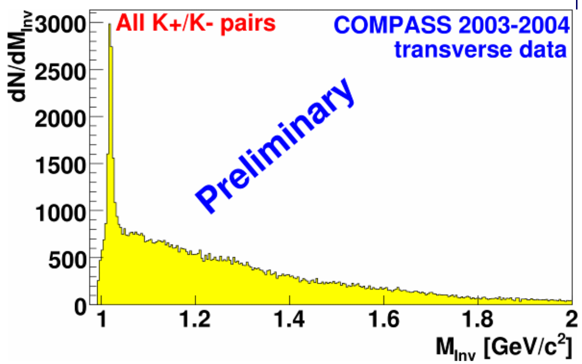




deuteron
target







Transversity DF: how to measure it

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

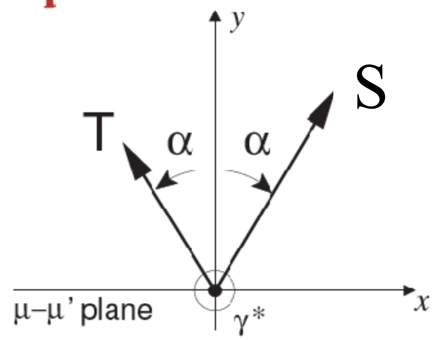
$l\,N^{\uparrow} \rightarrow l'\,\Lambda\,X$ **Λ polarisation**
Fragmentation Function of $q\uparrow \rightarrow \Lambda$

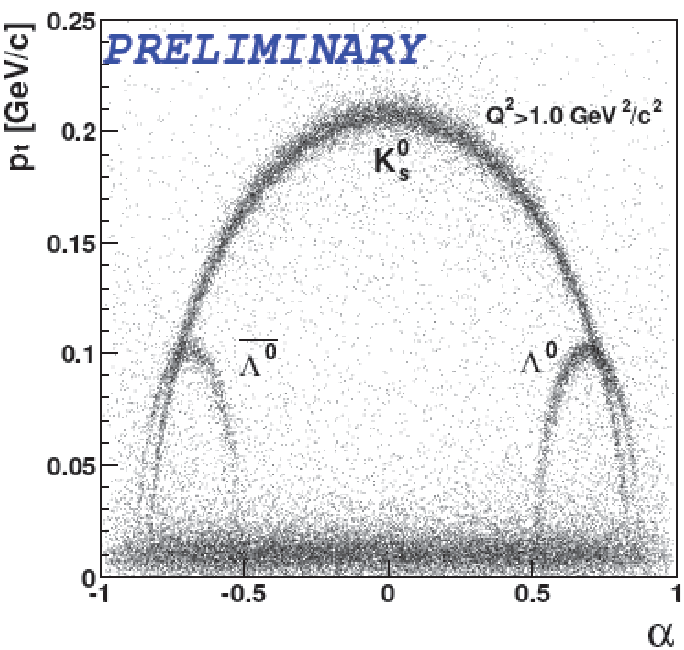
alternative way to access transversity
independent on Transverse Momentum …
the favorite in some models
(statistics)

Λ polarimetry

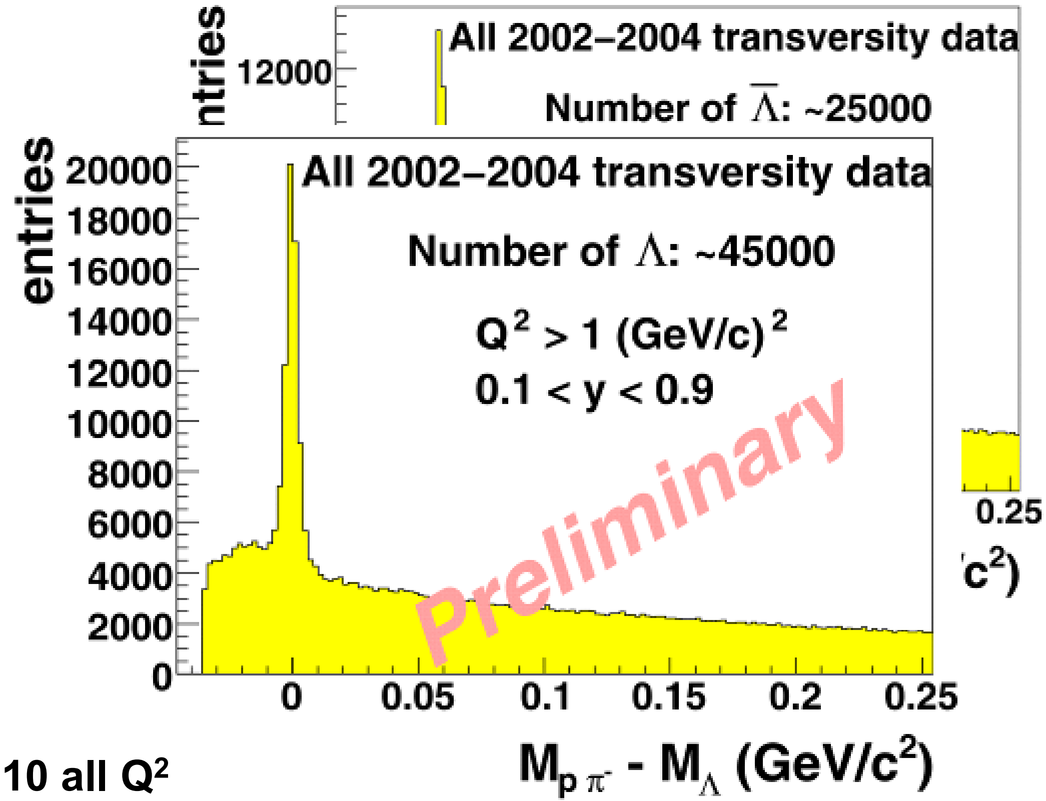
$$
\begin{aligned}
P^{\Lambda}_{T,exp} &= \frac{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} - d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}}{d\sigma^{\mu N^{\uparrow}\rightarrow\mu'\Lambda^{\uparrow}X} + d\sigma^{\mu N^{\downarrow}\rightarrow\mu'\Lambda^{\uparrow}X}}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

Λ polarization axis

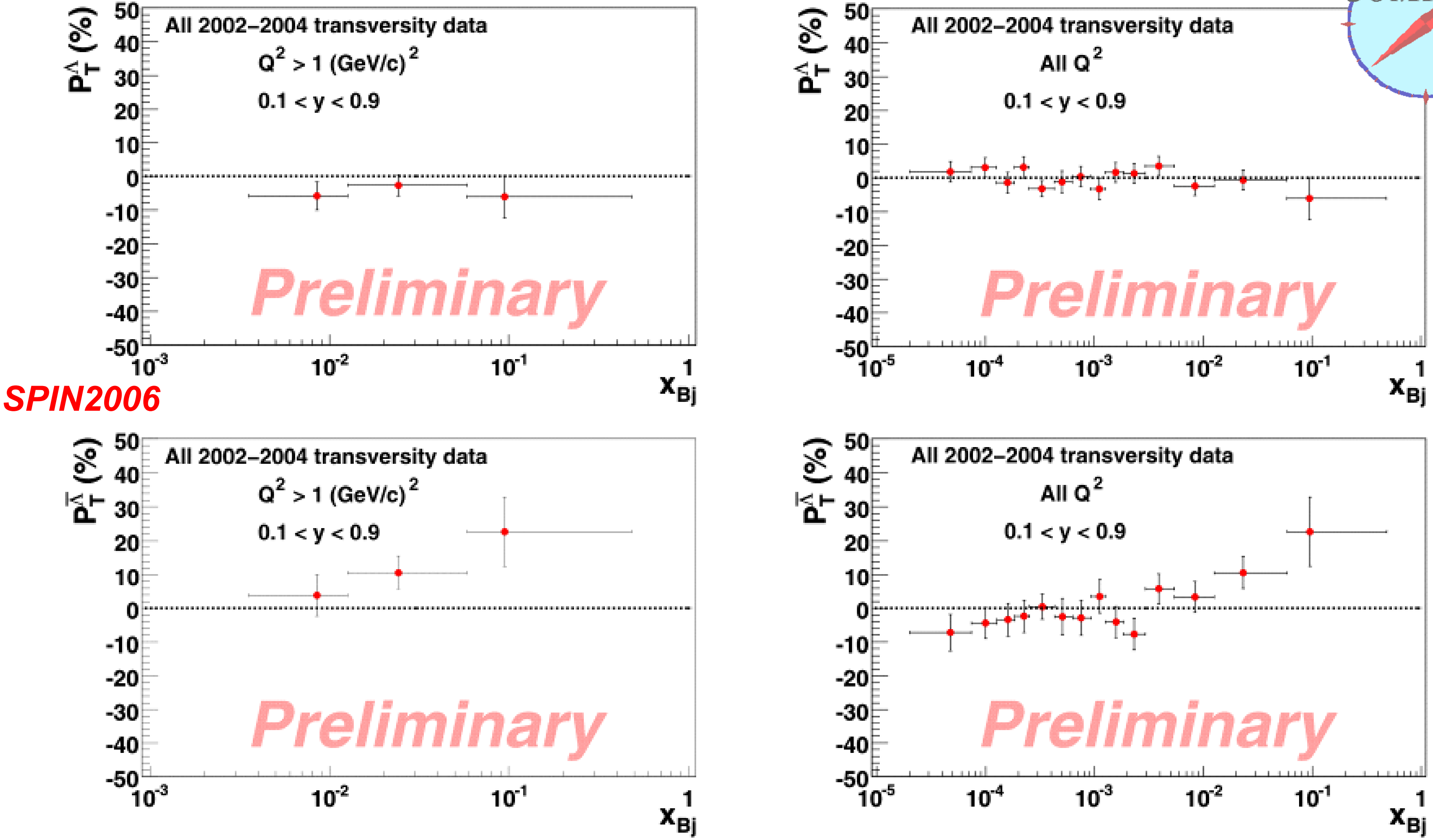




x 10 all Q^2



Λ polarimetry



systematic errors not larger than statistical errors

RICH ID not used yet; someother improvement in selection still foreseen

Anna Martin

- SIDIS Experiments with transversely polarised tgt

  HERMES and COMPASS

- Results on asymmetries
  - transversity Distribution Function
  - Sivers Distribution Function
  - Other TMD Distribution Functions

- Conclusions

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
- it is related to the parton orbital angular momentum in a transversely polarized nucleon

Sivers asymmetry

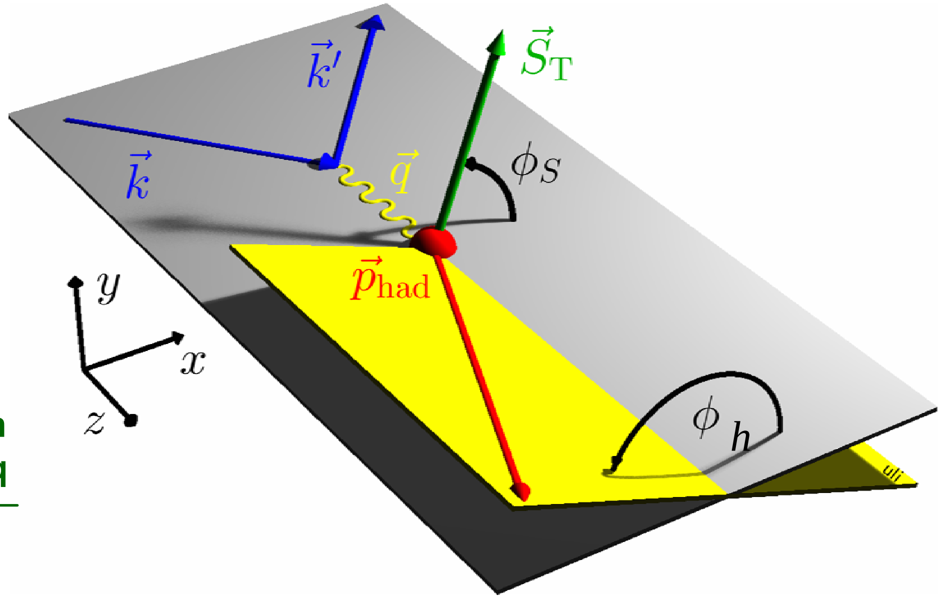
appears in SIDIS as a modulation in the "Sivers angle" Φ_S

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

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

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

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



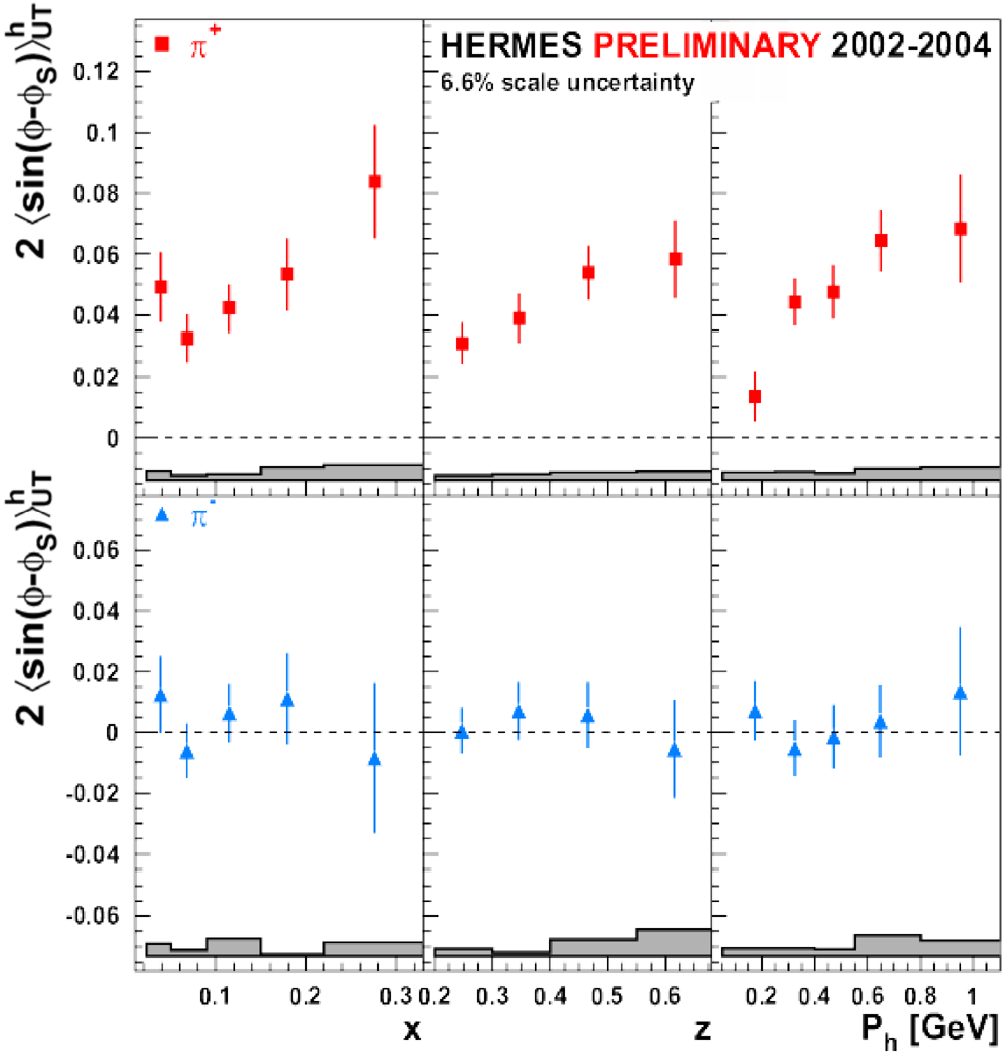
the "Sivers angle" Φ_S and the "Collins angle" Φ_C are independent

→ the Collins and Sivers asymmetries can be disentangled and extracted from the same data in SIDIS

Sivers asymmetry

proton target transversely polarised – charged pions

- **2004: results from 2002-2003 data** PRL94(2005)012002 **confirmed by**
- **2005: results from 2002-2004 data**



π^+ asymmetry > 0

VERY CLEAR SIGNAL

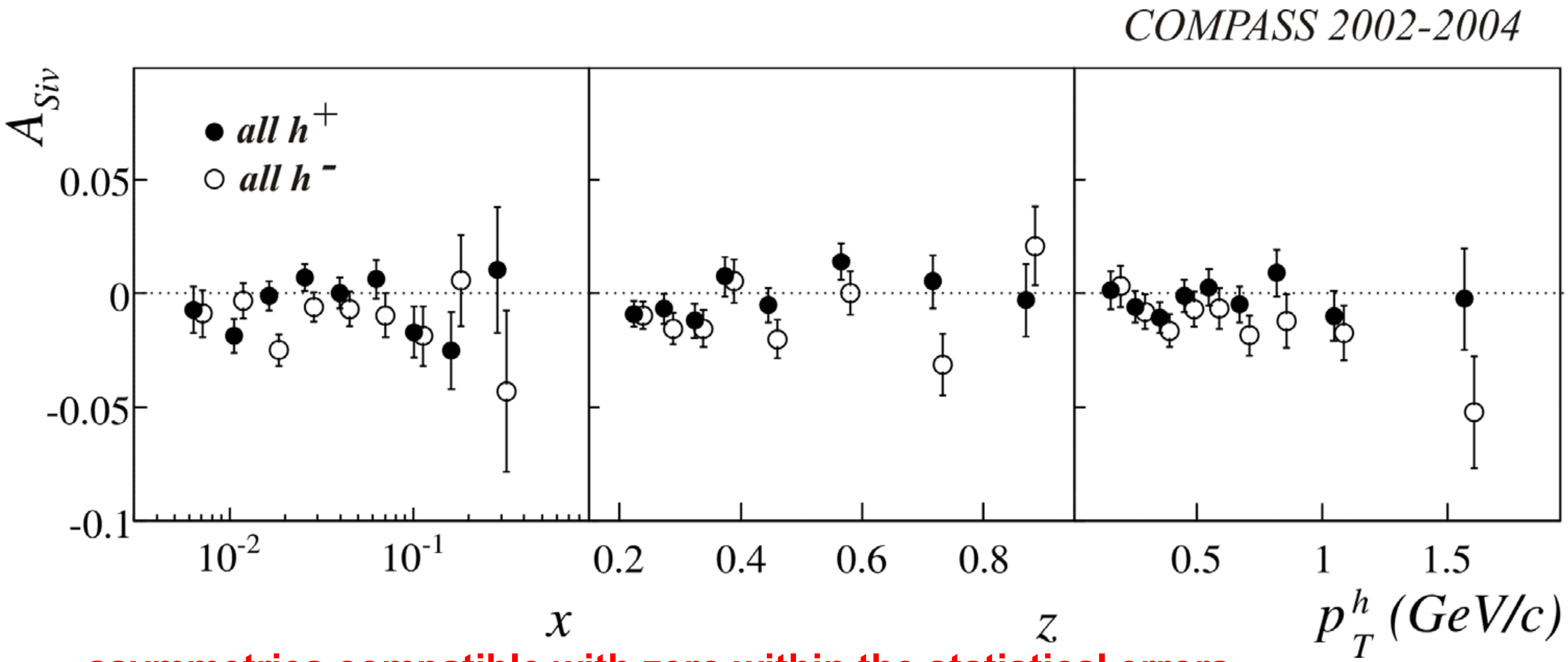
π^- asymmetry ~ 0

the Sivers effect is a real effect !

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



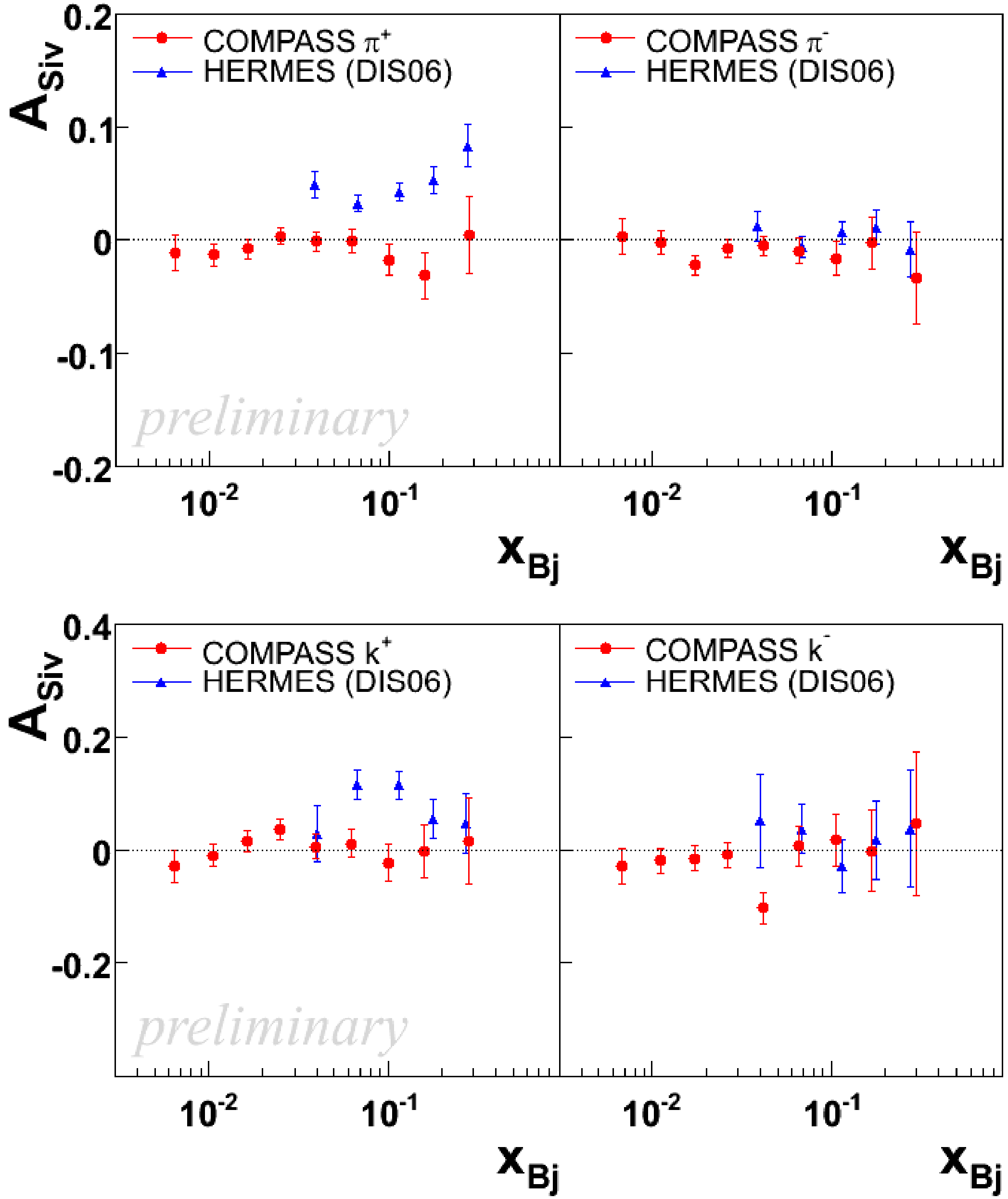
asymmetries compatible with zero within the statistical errors

(syst. errors much smaller)

Also new: Sivers asymmetry for $\pi^{\pm}$, $K^{\pm}$

HERMES
***preliminary* 2002-2004**
K^+ and K^- on proton
(DIS06)

COMPASS
***preliminary* 2003-2004**
π^+ and π^- , K^+ and K^-
on deuteron
(GPD06)



Sivers asymmetry

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

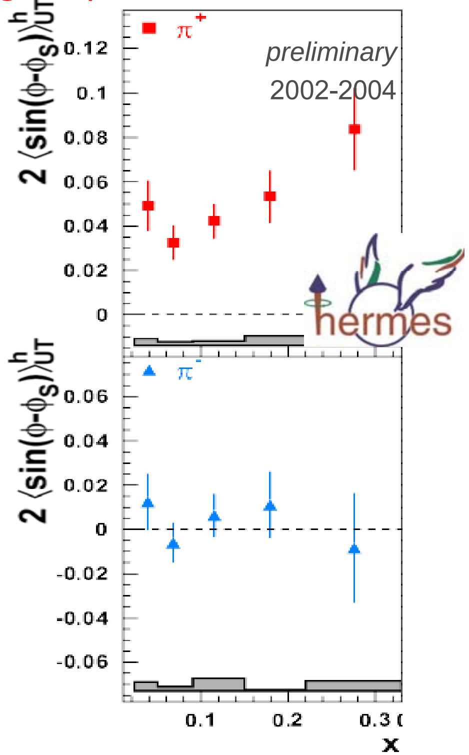
- **proton data**

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

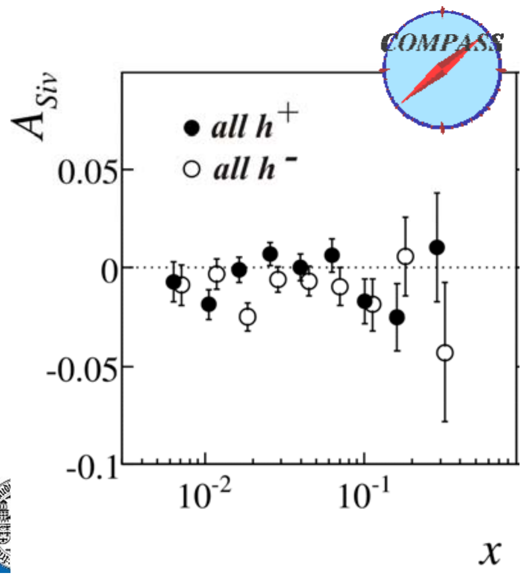
asymmetry for $\pi^+ > 0$, asymmetry for $\pi^- \approx 0$

→ **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

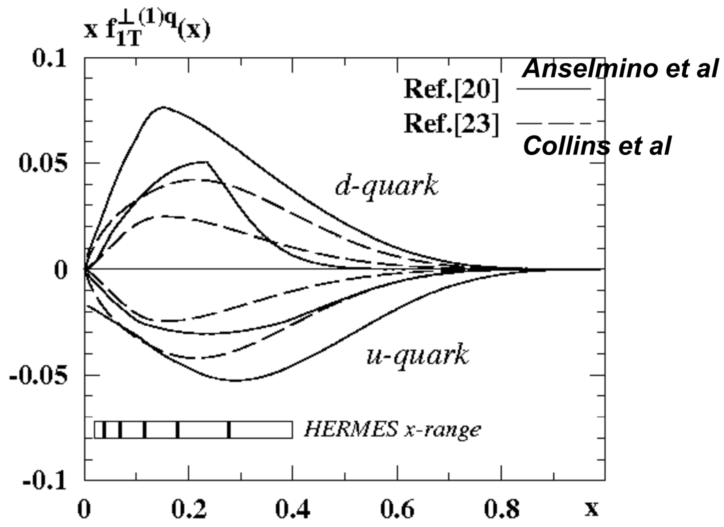
2005-2006: theoretical work on the interpretation of the data

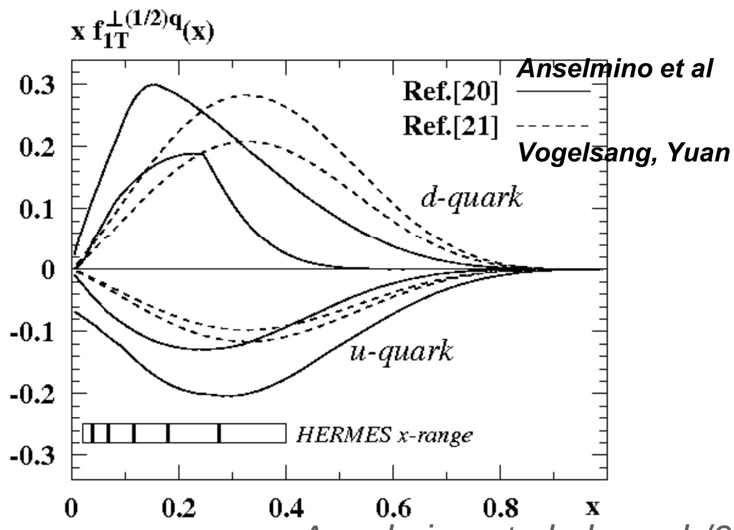
use of the new HERMES results to exctract the Sivers DF

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 $-2\Delta_0^T u$





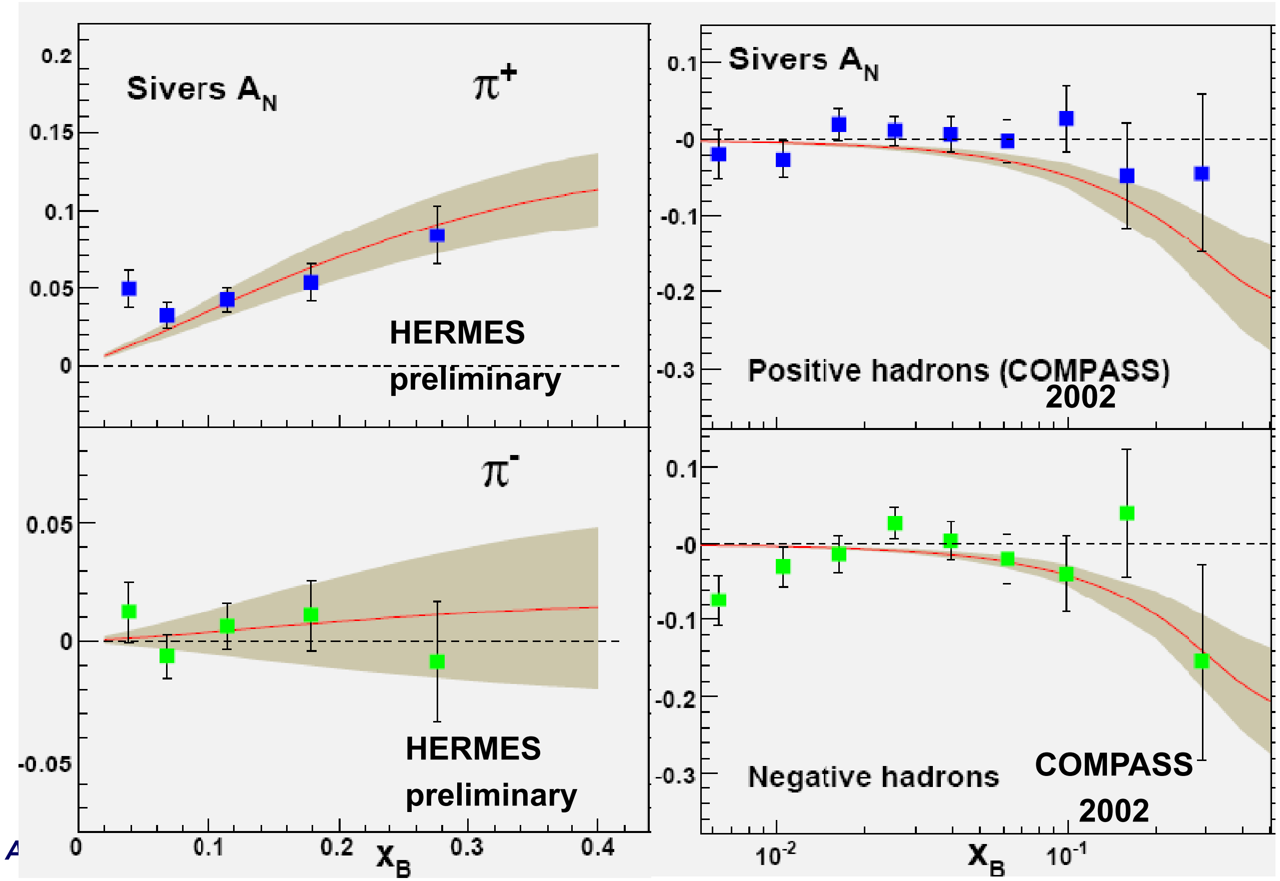
Anselmino et al., hep-ph/0511017

Siver asymmetry – flavour separation

to have a hint about the relevance of the 2002-2004 deuteron data, same fit as in Vogelsang and Yuan, PRD 72, 054028(2005)

$$\Delta_0^T u = S_u x(1-x)u(x)$$
$$\Delta_0^T d = S_d x(1-x)u(x)$$

with HERMES data only: $S_u = -0.81 \pm 0.07$, $S_d = 1.86 \pm 0.28$



$$\boxed{\begin{aligned} S_u &= -0.76 \pm 0.07 \\ S_d &= 1.83 \pm 0.29 \end{aligned}}$$

[Trieste, 2006]

Siver asymmetry – flavour separation

$$\Delta_0^T u = S_u x(1-x)u(x)$$

$$\Delta_0^T d = S_d x(1-x)u(x)$$

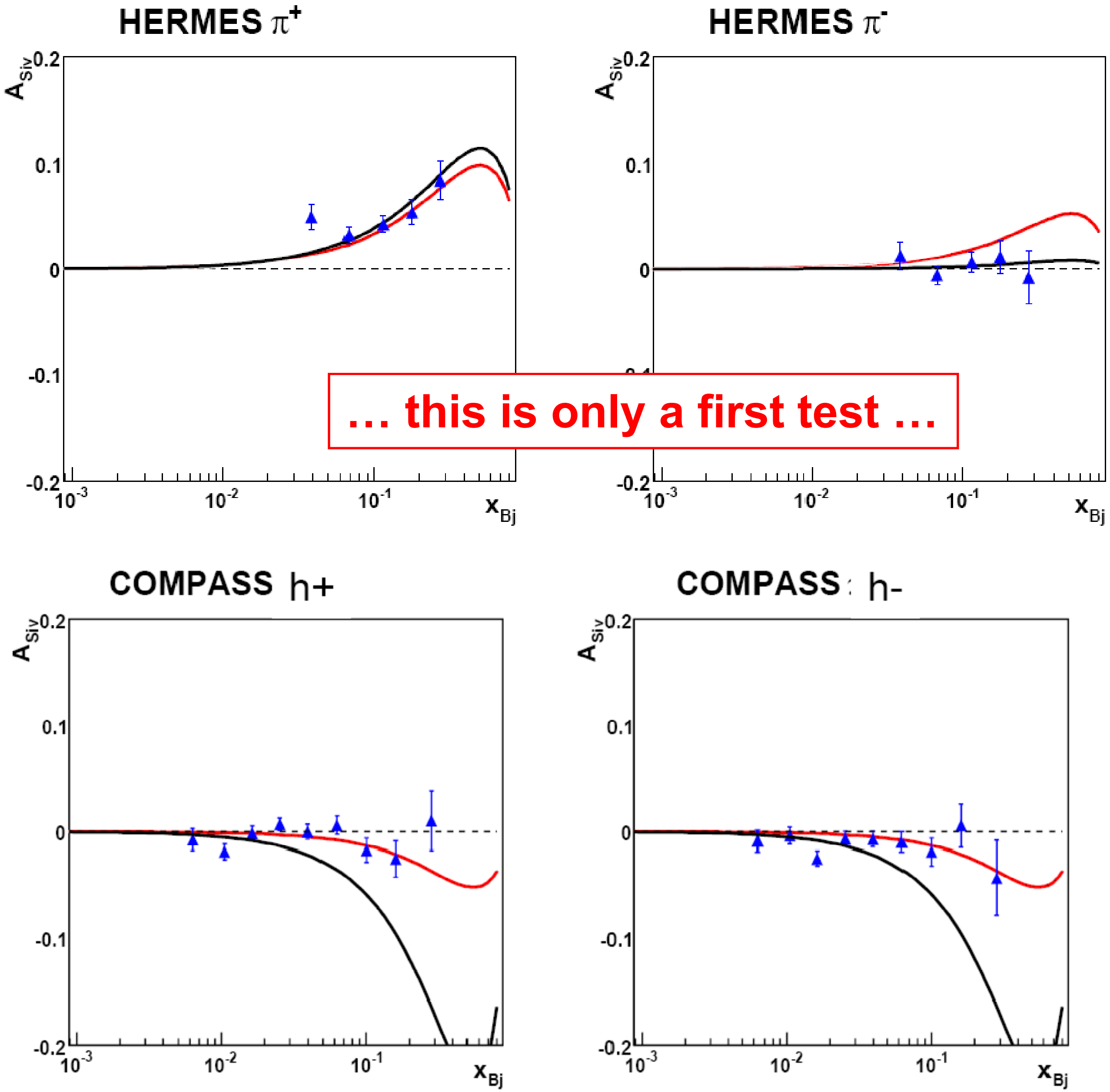
HERMES only

$$\boxed{\begin{aligned} S_u &= -0.76 \pm 0.07 \\ S_d &= 1.83 \pm 0.29 \end{aligned}}$$

HERMES and COMPASS 02-04

$$\boxed{\begin{aligned} S_u &= -0.52 \pm 0.05 \\ S_d &= 0.76 \pm 0.10 \end{aligned}}$$

[Trieste, 2006]



… this is only a first test …

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.

- SIDIS Experiments with transversely polarised tgt

  HERMES and COMPASS

- Results on asymmetries
  - transversity Distribution Function
  - Sivers Distribution Function
  - Other TMD Distribution Functions

    taking into account transverse momentum,

    more terms appear in the SIDIS cross-section

- Conclusions

semi-inclusive cross-section

18 structure functions

A. Metz

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

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

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

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

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

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

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

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

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

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

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

semi-inclusive cross-section

18 structure functions

Cahn

Boer-Mulders

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

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

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

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

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

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

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

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

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

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

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

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

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

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

5

3

by now all measured by COMPASS on deuteron – NEW RESULT

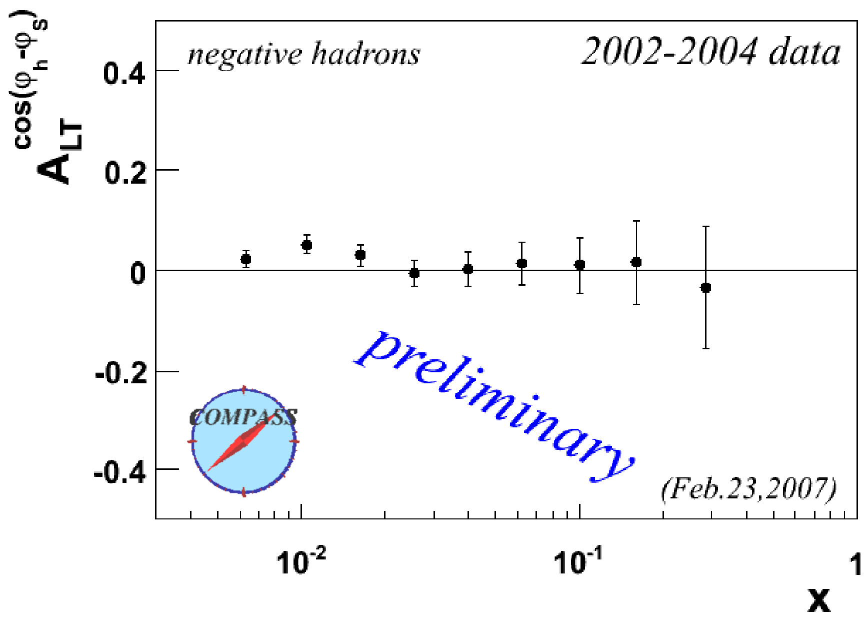
target transverse spin dependent asymmetries (LO)

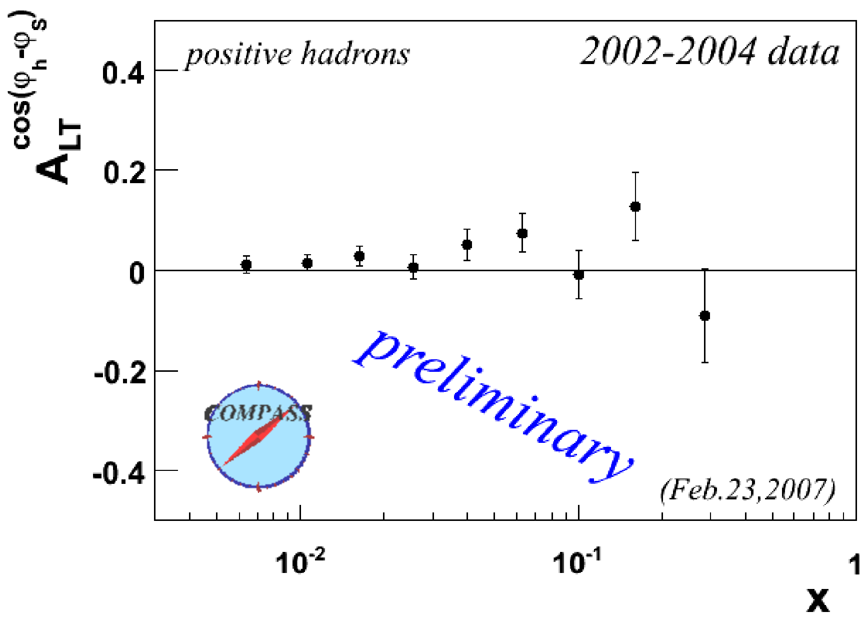
$$\boxed{F_{LT}^{\cos(\phi_h-\phi_s)} \quad \propto \quad g_{1T}^{q} \otimes D_{1q}^{h}}$$

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

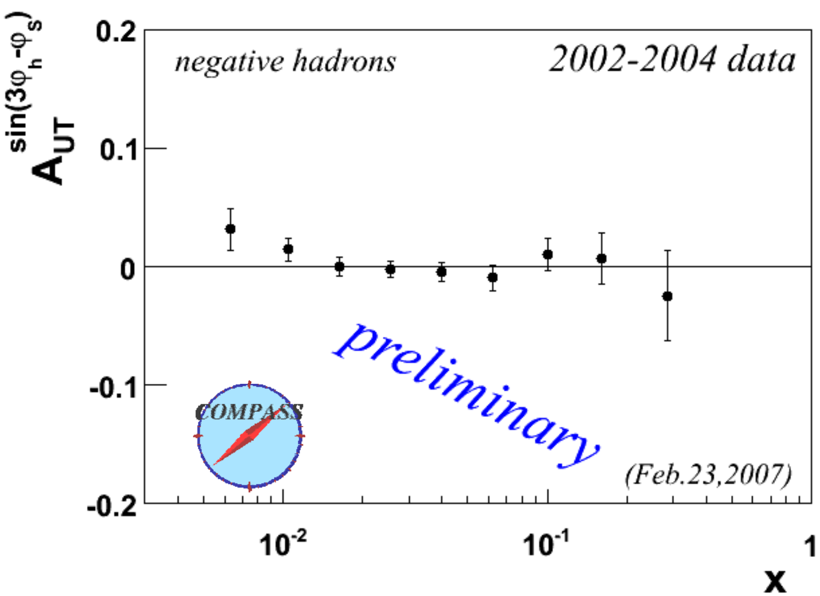


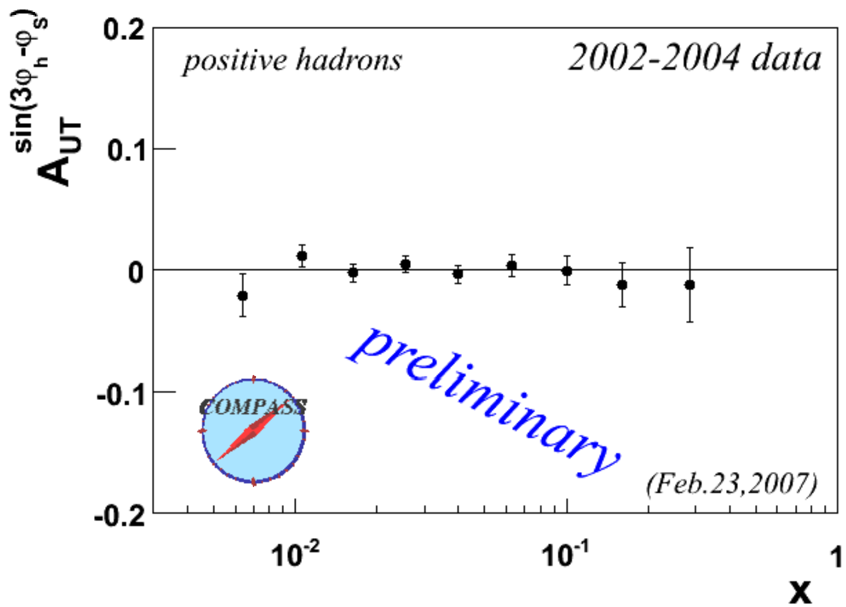


target transverse spin dependent asymmetries (LO)

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

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

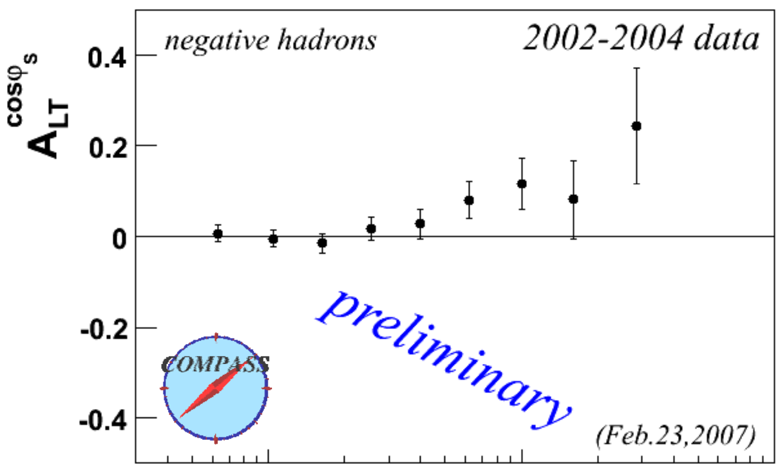


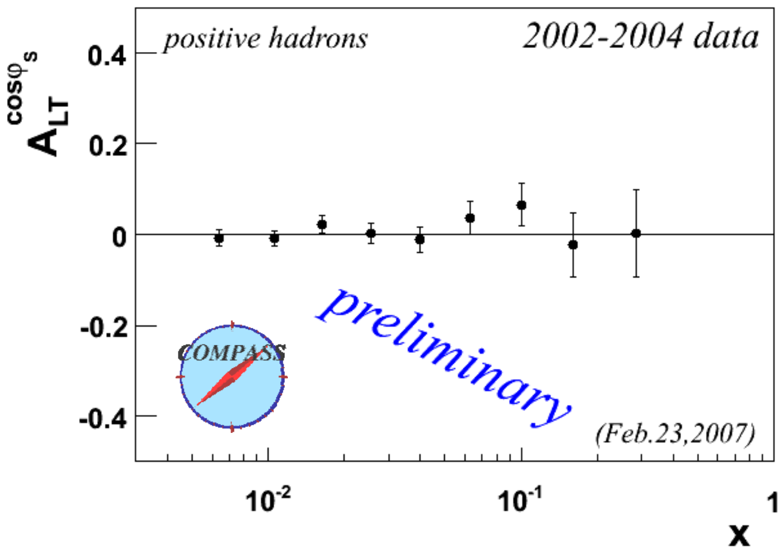


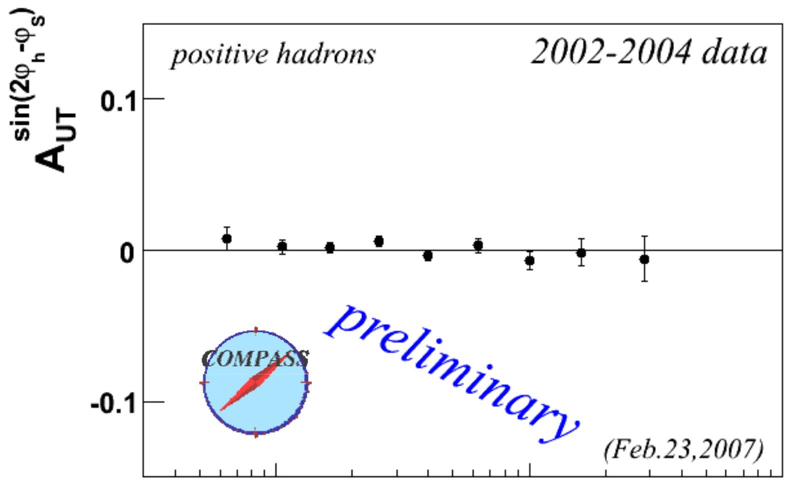
target transverse spin dependent asymmetries /2

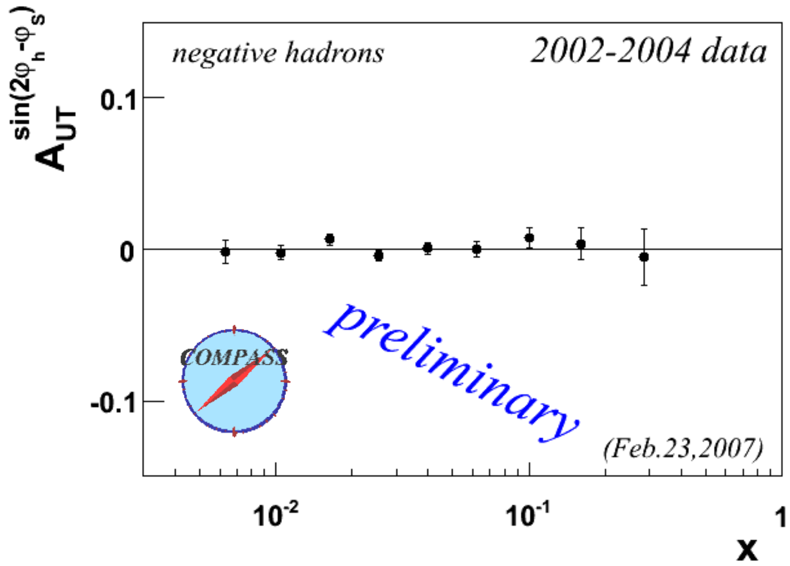
$$F_{LT}^{\cos(\phi_s)} \propto \frac{M}{Q} g_{1T}^q \otimes D_{1q}^h$$

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





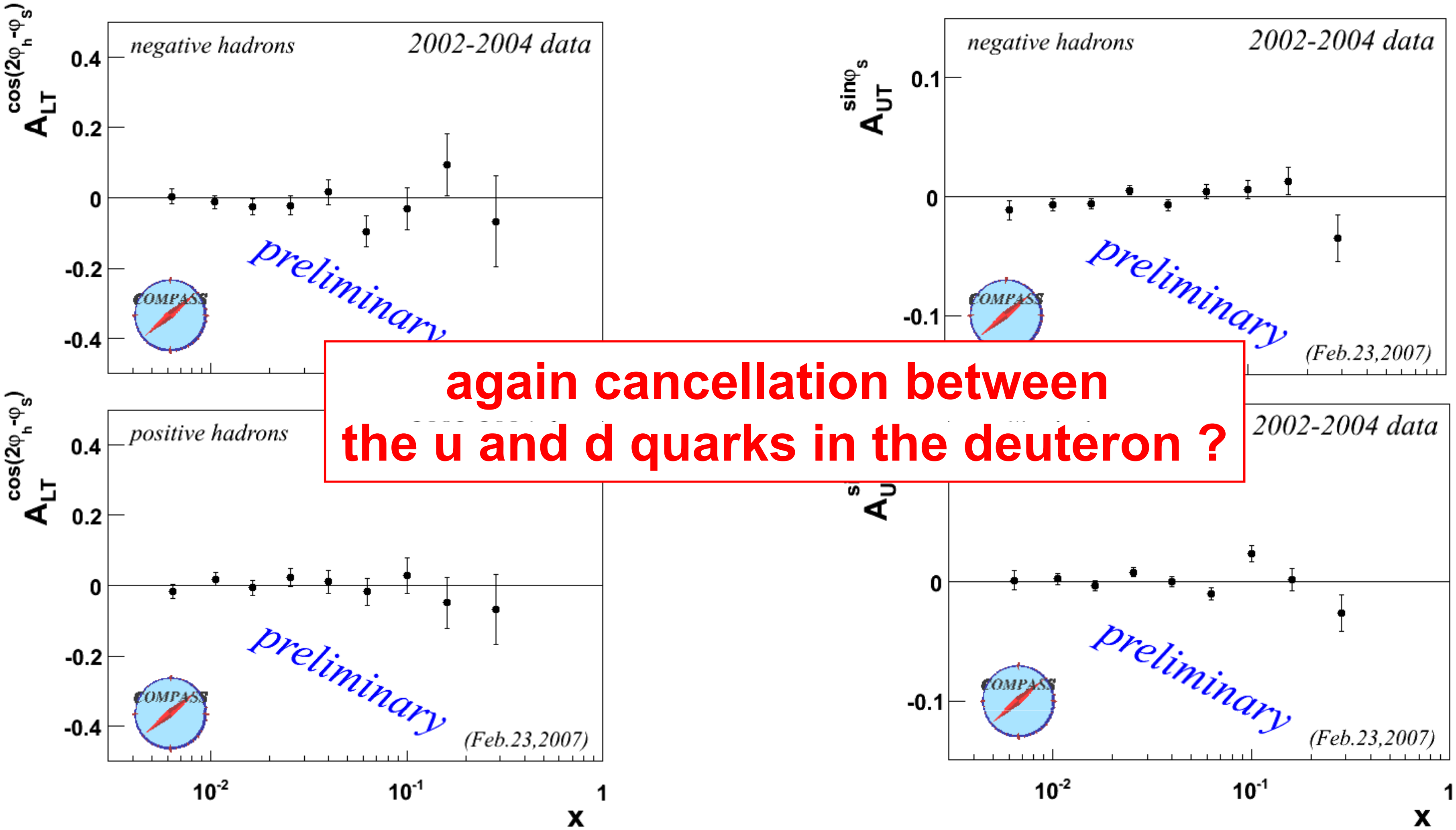




target transverse spin dependent asymmetries /3

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

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



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

- SIDIS Experiments with transversely polarised tgt

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- Results on asymmetries
  - transversity Distribution Function
  - Sivers Distribution Function
  - Other TMD Distribution Functions

- **Conclusions**

summary

after many years of work,

since 2004 measurements of

- Collins asymmetries on p and d
- Collins FF in e^+e^- from Belle

transversity DF

transversity DFs ≠ 0, Collins FF ≠ 0, a new property of matter

- 2hadron asymmetries on p and d
- Λ polarisation on d

- Sivers asymmetries on p and d

Sivers DF ≠ 0, a real effect

<u>first extractions of the u and d quark DFs</u>

- six more target transverse spin asymmetries have been measured on the deuteron

a complete description of the
spin structure of the nucleon is emerging

the work is starting now!

summary 2

<u>new SIDIS data</u> are coming

very soon:

- new results from HERMES from 2005 data (factor 2 in statistics)

soon:

- K^0 asymmetries on deuteron from COMPASS
- *exclusive ρ^0 asymmetries on deuteron from COMPASS ➔ GPDs*
- *Cahn and Boer-Mulders asymmetries ➔ unpol*
- proton asymmetries from COMPASS (the run is about to start)

afterwards, there should be:

- (neutron) data from JLab experiments
- further measurements at CERN (COMPASS2)

and

the measurements of Drell-Yan pairs in πp (COMPASS) and pbar-p (FAIR) scattering

Oleg Denissov

in addition to the transverse spin effects measurements in pp hard scattering at RHIC

Christine Aidala

ALL IN ALL,

A HUGE EXPERIMENTAL EFFORT

and

A CHALLENGING GOAL FOR THEORY