Transverse spin measurements in European SIDIS experiments

Outline:

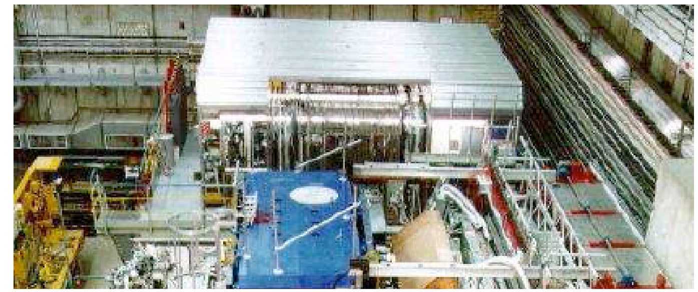
- A short Transverse spin/ TMD overview
- The HERMES and COMPASS detectors
- Transversity/Collins results
  - HERMES (proton)
  - COMPASS (deuteron)
  - A first successful global analysis to extract transversity
  - Transversity/Interference FF
- Sivers asymmetries
- Other TMD measurements
- Outlook

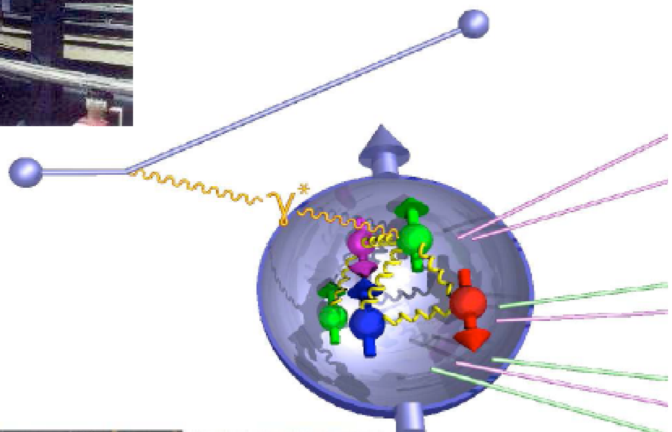
many slides taken from Transversity/TMD workshop last week in Trento
(no new conventions, though)
Presented by an ex-hermesean

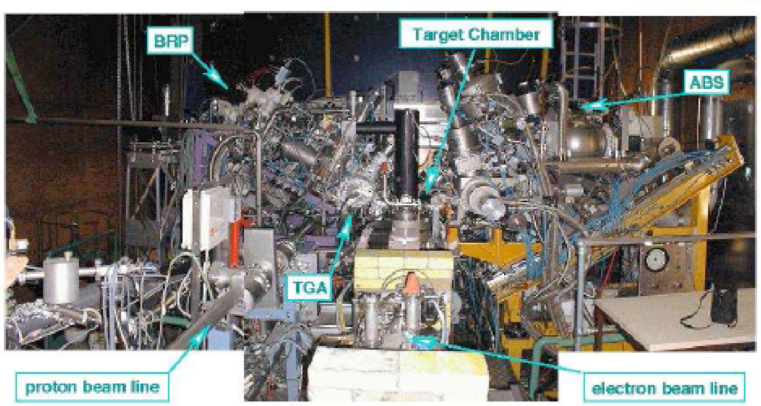
The HERMES Experiment at HERA

27.5 GeV HERA positron beam

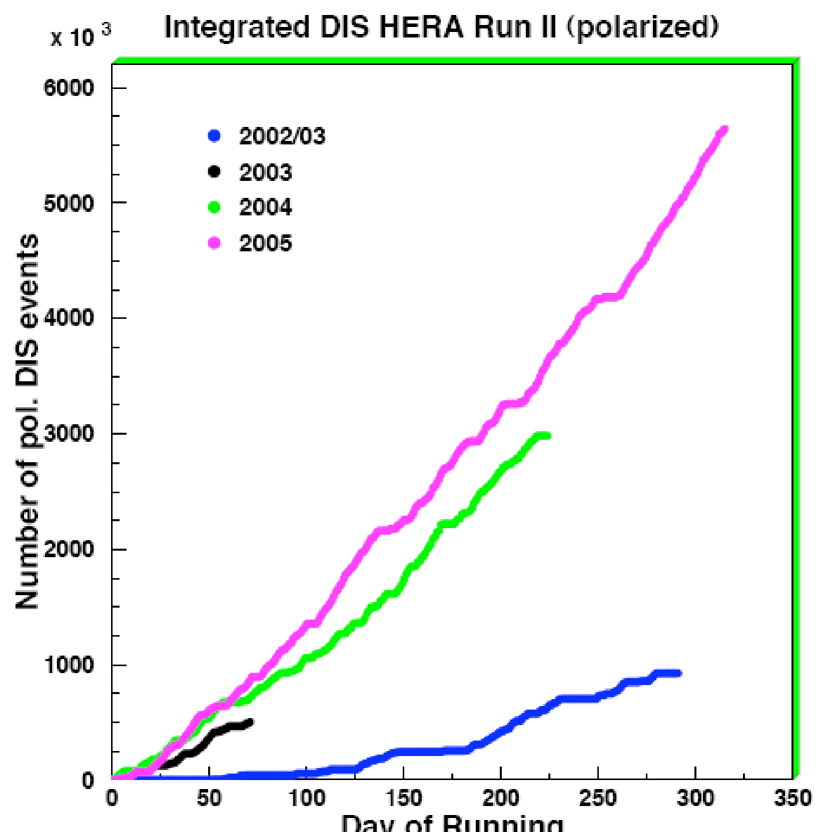
HERMES Spectrometer







2002-200



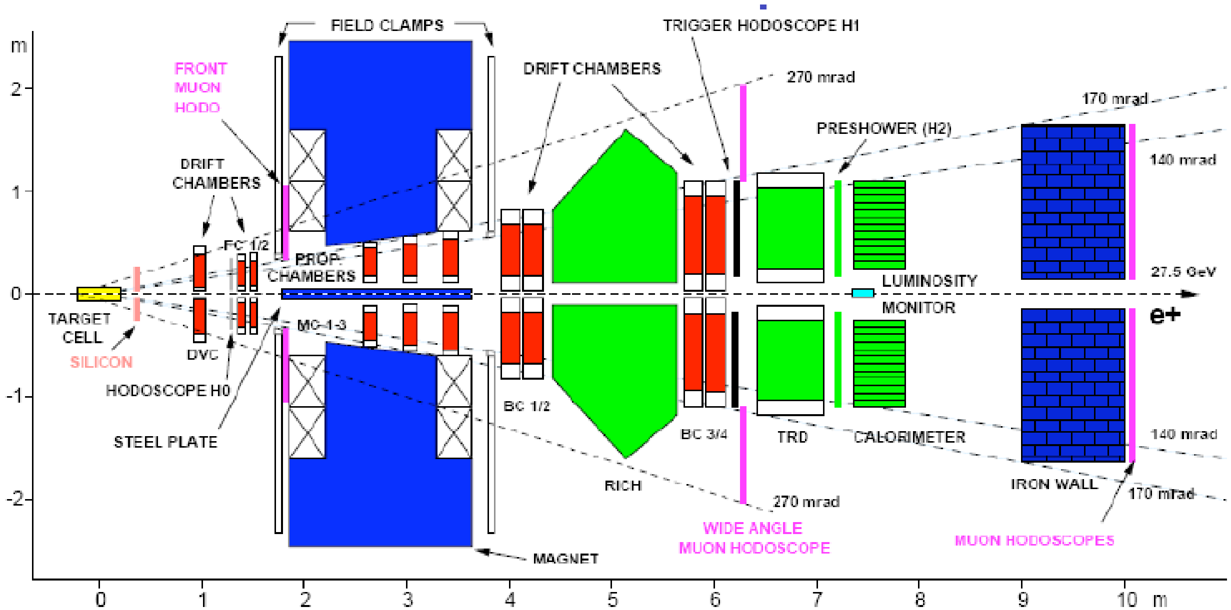
Transversely polarized atomic hydrogen

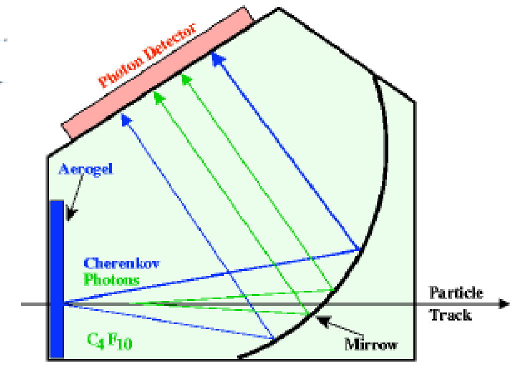
Rapid spin flipping!

The HERMES Spectrometer

Angular acceptance: $40\ mrad < |\theta_y| < 140\ mrad \qquad |\theta_x| < 170\ mrad$

Resolution: $\delta p \leq 2.6\%$; $\quad \delta\vartheta \leq 1\ mrad$





Dual radiator RICH

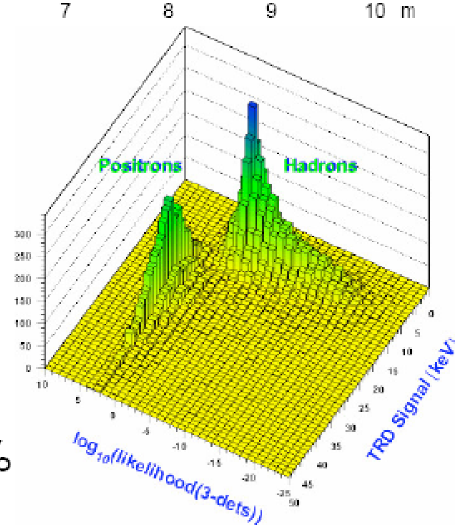
Particle Identification:

TRD, Calorimeter, preshower, RICH:

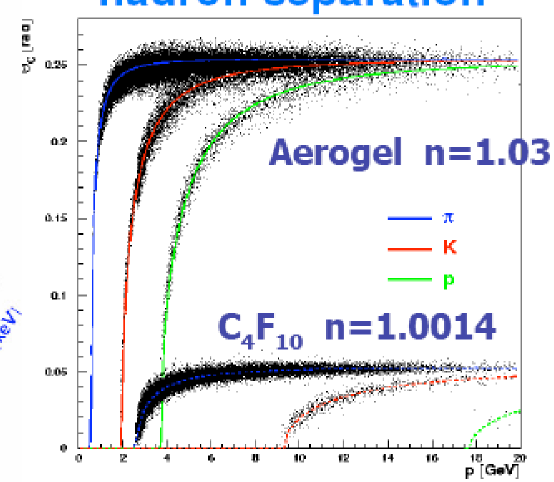
lepton-hadron > 98%

RICH:

Hadron: π ~ 98%, K ~ 88% , P ~ 85%



hadron separation



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)

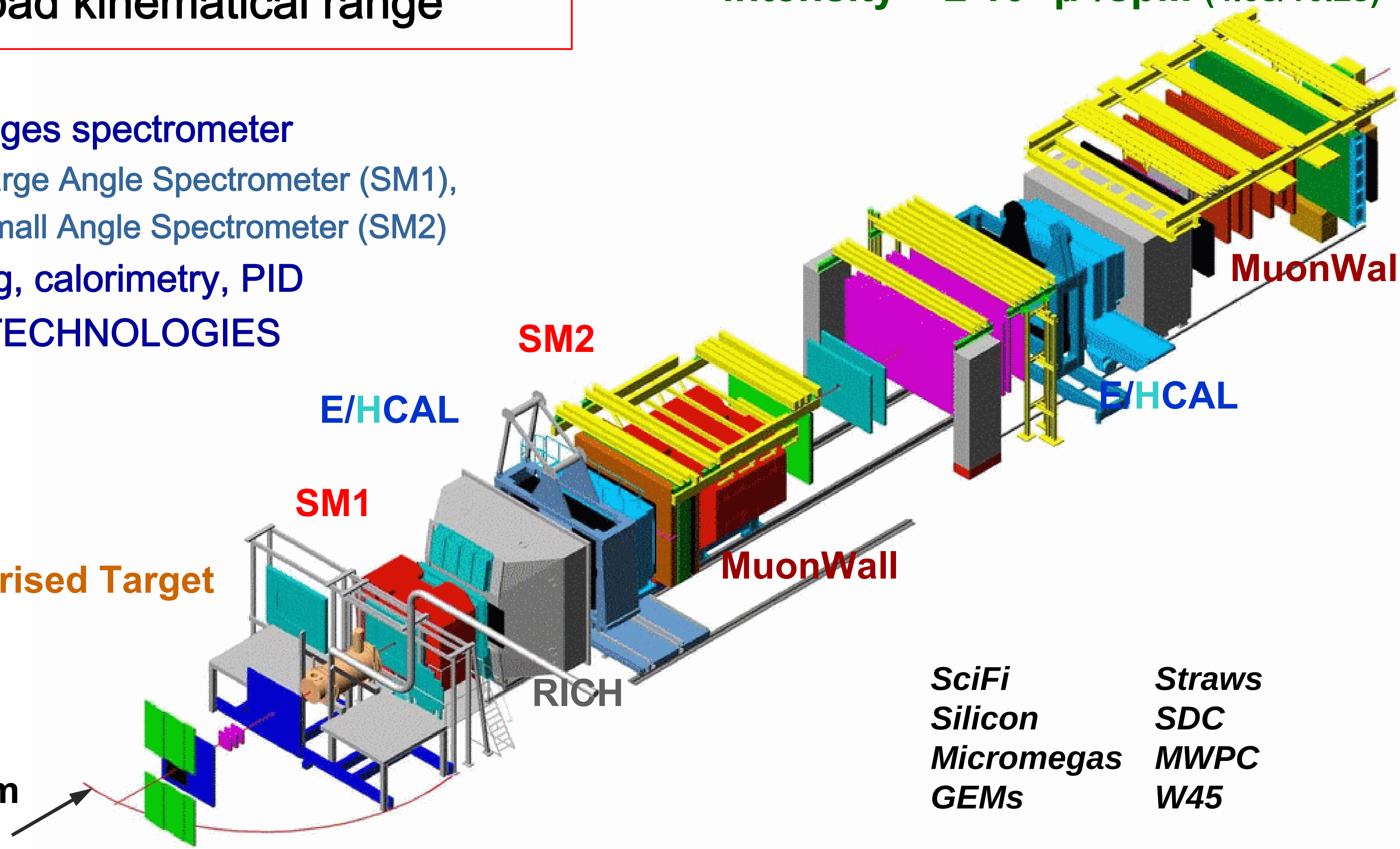
two stages spectrometer

Large Angle Spectrometer (SM1),

Small Angle Spectrometer (SM2)

tracking, calorimetry, PID

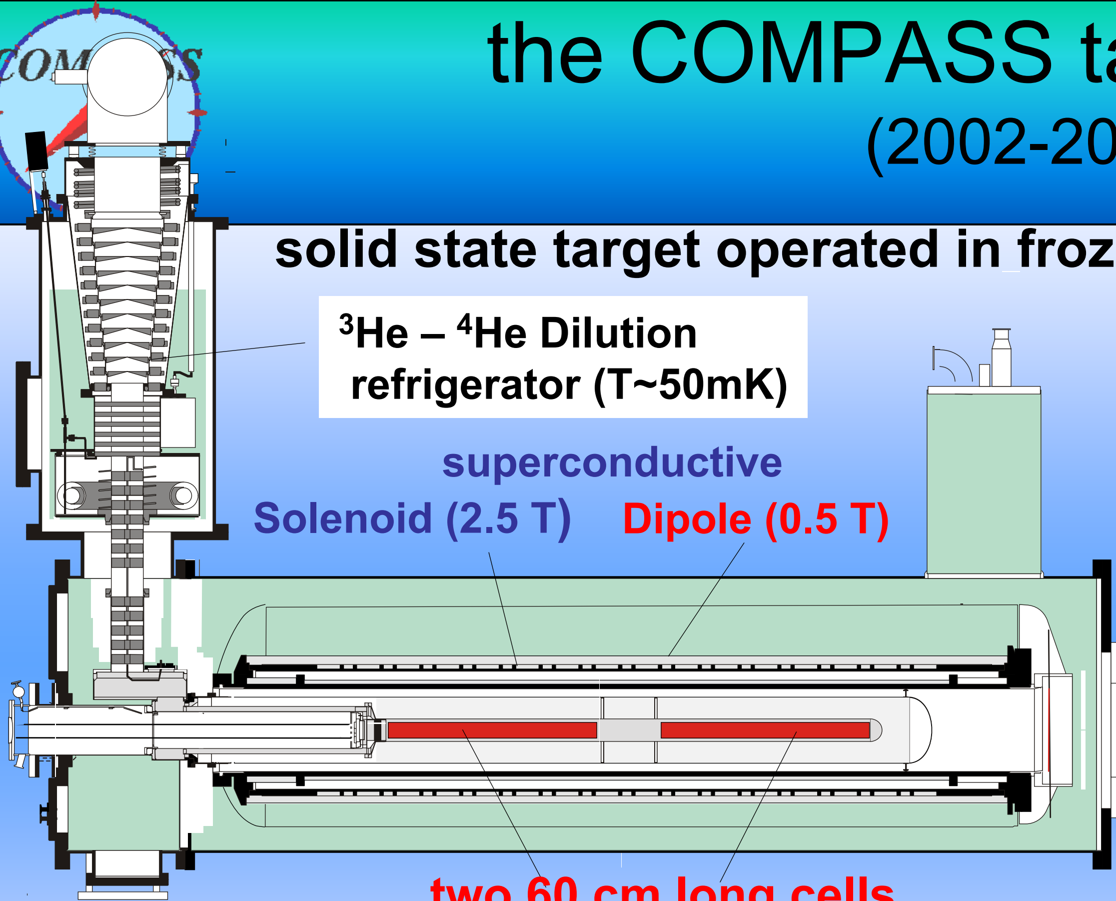
NEW TECHNOLOGIES



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

the COMPASS target system
(2002-2004)

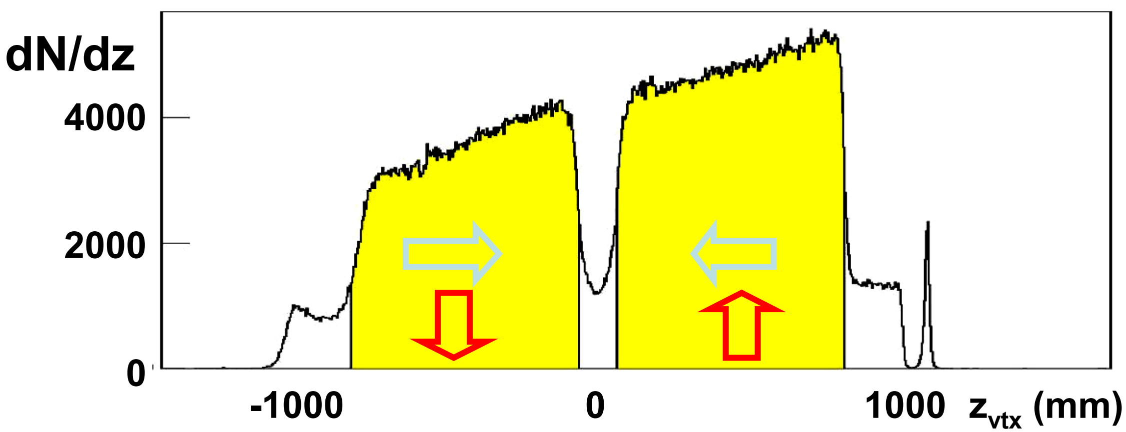
solid state target operated in frozen spin mode



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

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

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

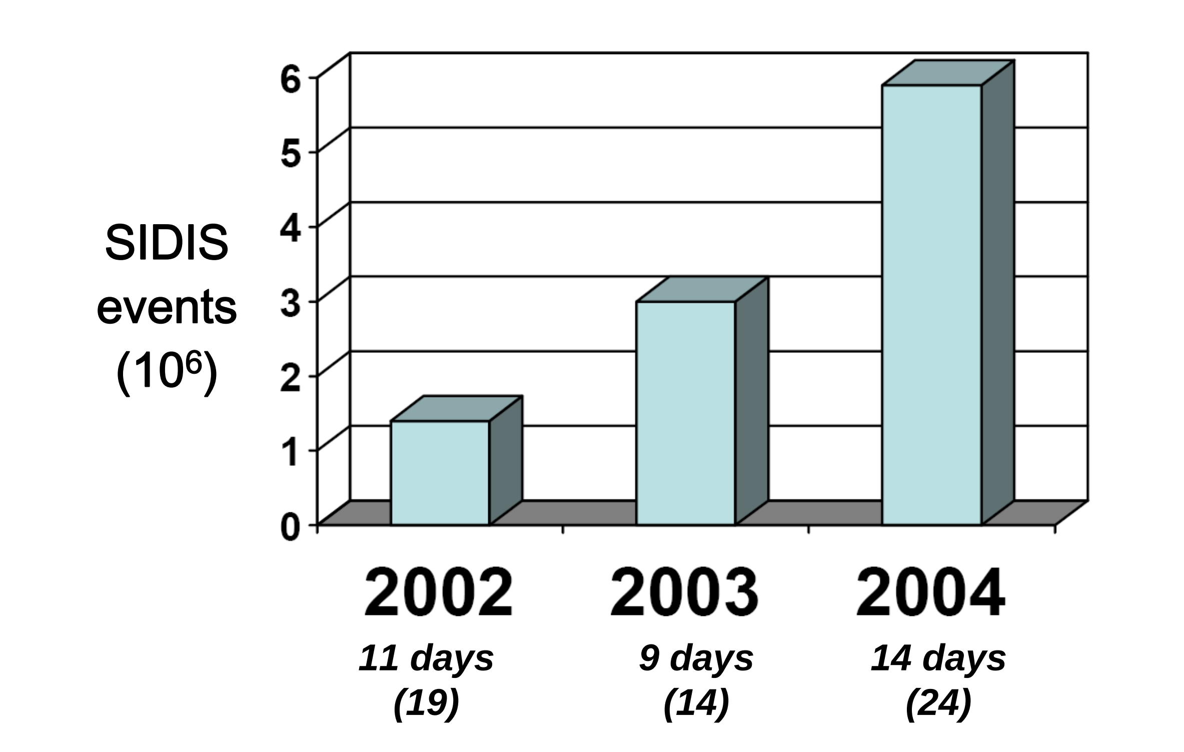


during data taking with transverse polarization
- **dipole field always ↑**
- **polarization reversal in the 2 cells after ~ 5 days**

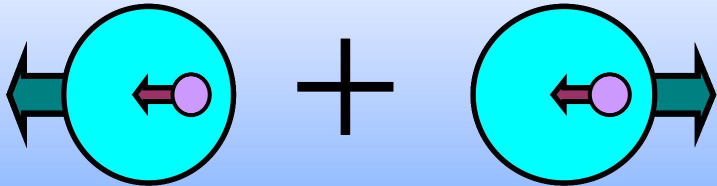
data taking with transversely polarized target

2002-2004: ^{6}LiD

2007: NH_3



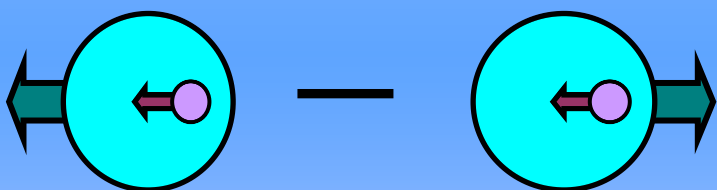
Quark distributions



Unpolarized distribution function q(x)

Sum of quarks with parallel and antiparallel polarization relative to proton spin
(well known from Collider DIS experiments)

q(x), G(x)



Helicity distribution function $\Delta q(x)$

Difference of quarks with parallel and antiparallel polarization relative to longitudinally polarized proton
(known from fixed target (SI)DIS experiments)

$\Delta q(x), \Delta G(x)$

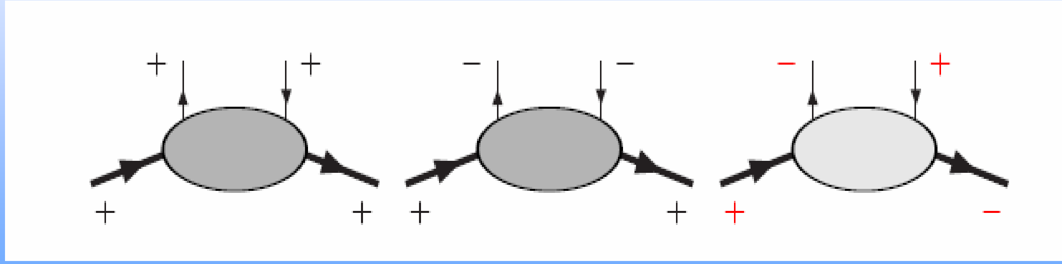
Difference of quarks with parallel and antiparallel polarization relative to transversely polarized proton
(first results from HERMES and COMPASS – with the help of Belle)

$\delta q(x)$

Transversity distribution function $\delta q(x)$

Transversity properties:
Three notations in use: $\delta q(x)$, $h_1(x)$, $\Delta_T q(x)$

- Helicity flip amplitude
- Chiral odd ➔ needs other chiral odd partner:
  - Transversity in DY
  - Collins fragmentation function
  - Interference fragmentation function
  - Λ Polarization
- Since all interactions conserve chirality one needs another chiral odd object
- Does not couple to gluons ⇨different QCD evolution than $\Delta q(x)$
- Valence dominated⇨ Comparable to Lattice calculations, especially tensor charge



$$q(x) = \quad q_+(x) + q_-(x) \quad \sim Im(\mathcal{A}_{++,++} + \mathcal{A}_{+-,+-})$$

$$\Delta q(x) = \quad q_+(x) - q_-(x) \quad \sim Im(\mathcal{A}_{++,++} - \mathcal{A}_{+-,+-})$$

$$\delta q(x) = \quad q_\uparrow(x) - q_\downarrow(x) \quad \sim Im \mathcal{A}_{+-,-+}$$

Positivity bound:

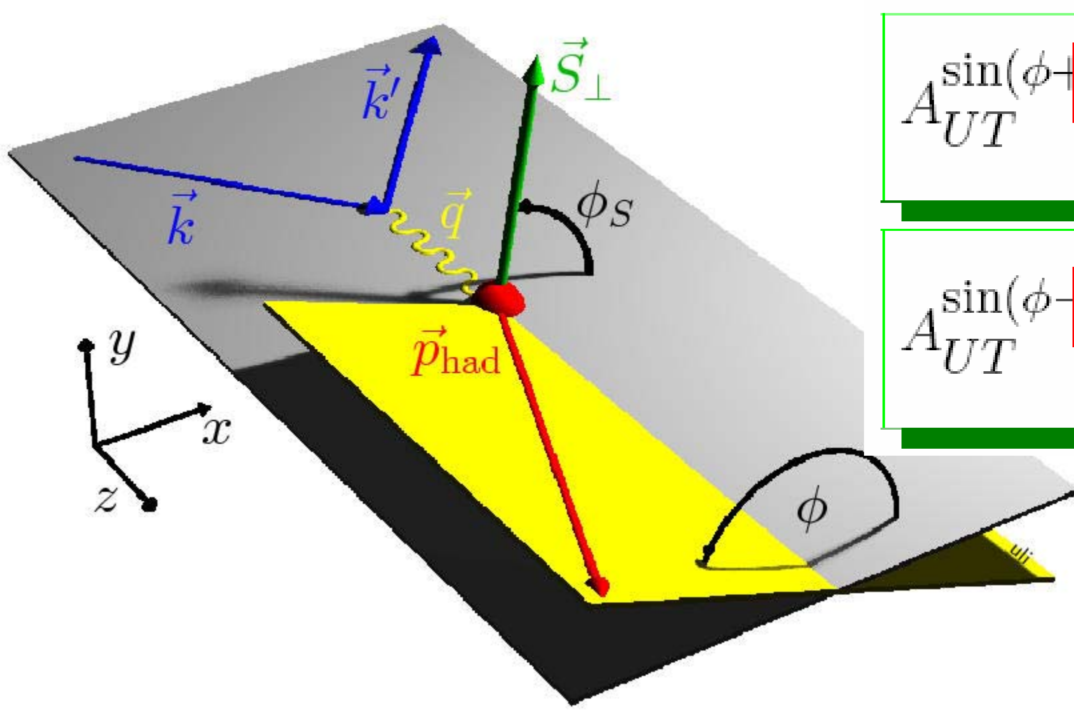
$$|\delta q(x)| \leq q(x)$$

Soffer bound:

$$|\delta q(x)| \leq \tfrac{1}{2}\left(q(x) + \Delta q(x)\right)$$

Azimuthal asymmetries in SIDIS

- Sivers and Collins effect are not distiguishable with longitudinally polarized target
- Higher Twist effects are kinematically favored in longitudinal case
- With transversely polarized target a 2nd angle allows to distinguish effects

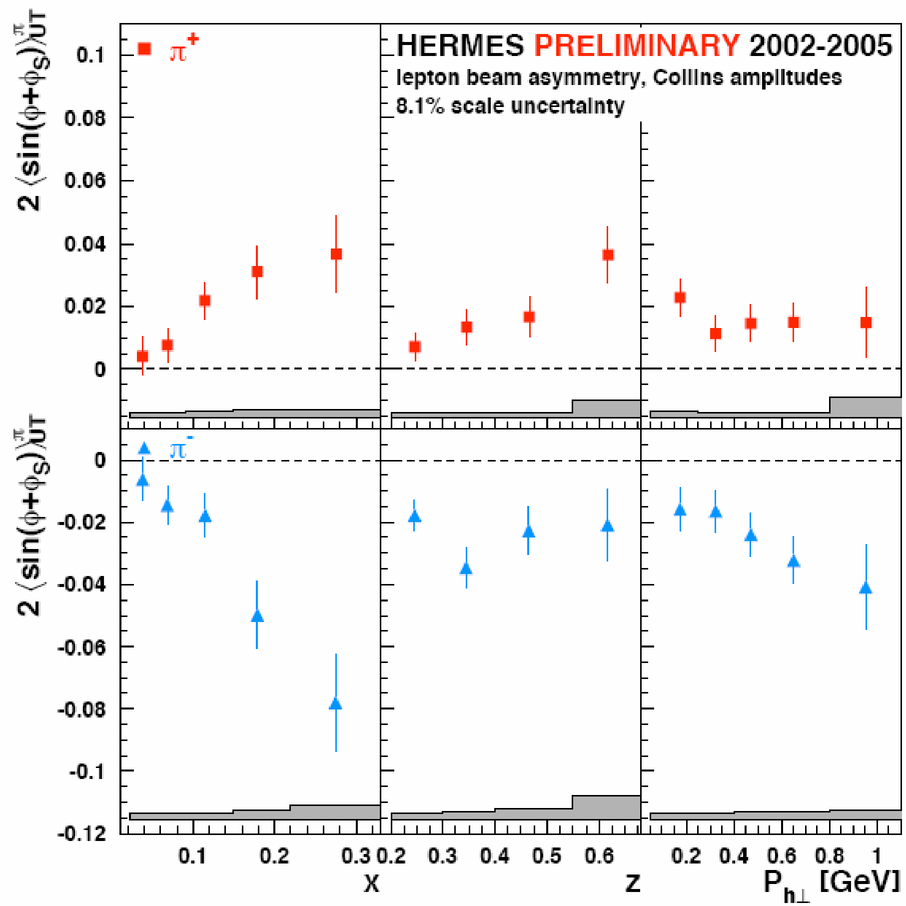


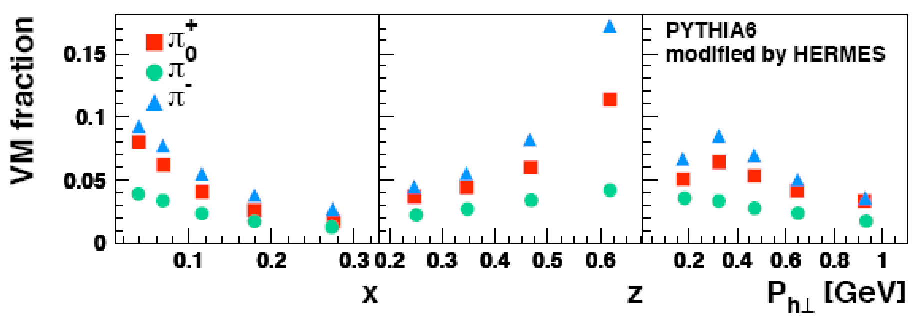
$$A_{UT}^{\sin(\phi+\text{[redacted]})} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 \delta q(x)\, H_1^\perp(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\, D_1(z)}$$

$$A_{UT}^{\sin(\phi-\text{[redacted]})} \propto S_\perp \frac{\sum_{q,\bar{q}} e_q^2 f_{1T}^{\perp,q}(x) \cdot D_1(z)}{\sum_{q,\bar{q}} e_q^2 q(x)\, D_1(z)}$$

U: unpolarized beam
T: transversely polarized target

Collins measurements I



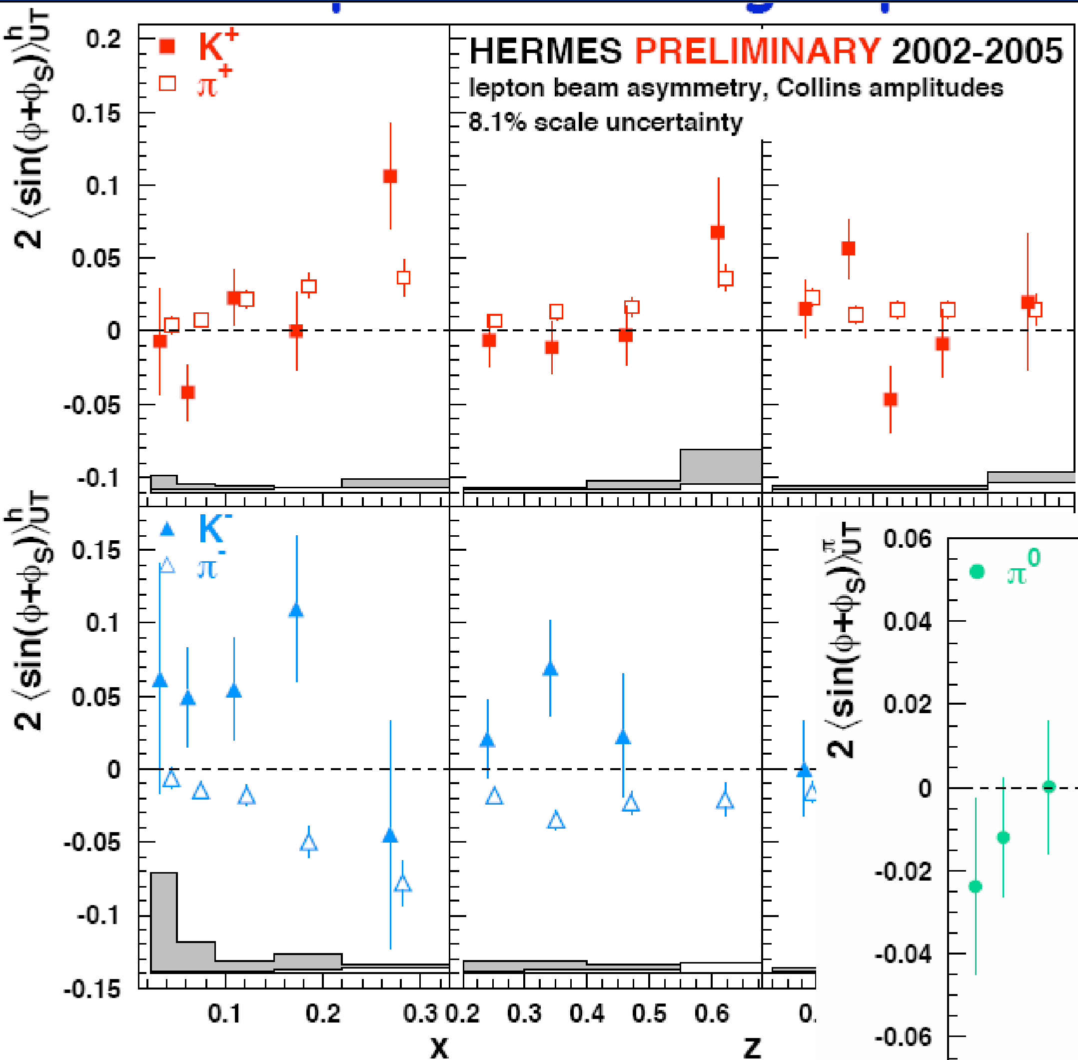


- Large, positive π^+ asymmetries:

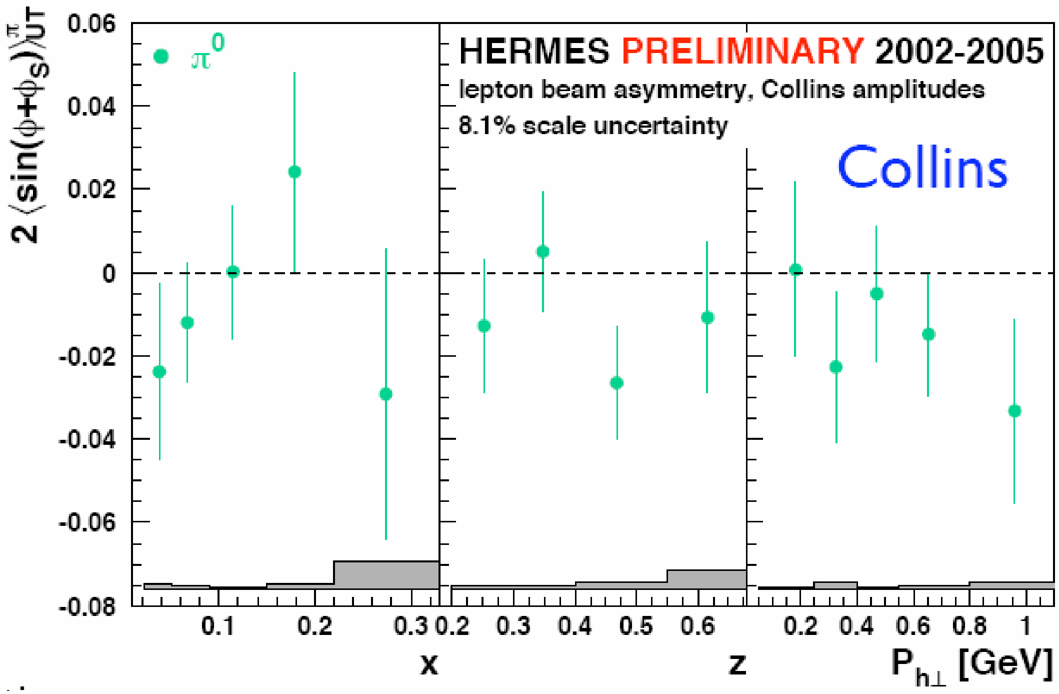
  no surprise from u-quark dominance
- Large, negative π^- asymmetries:

  first a surprise, now understood by large, negative disfavored Collins function
- Contamination from decay of exclusive vector mesons

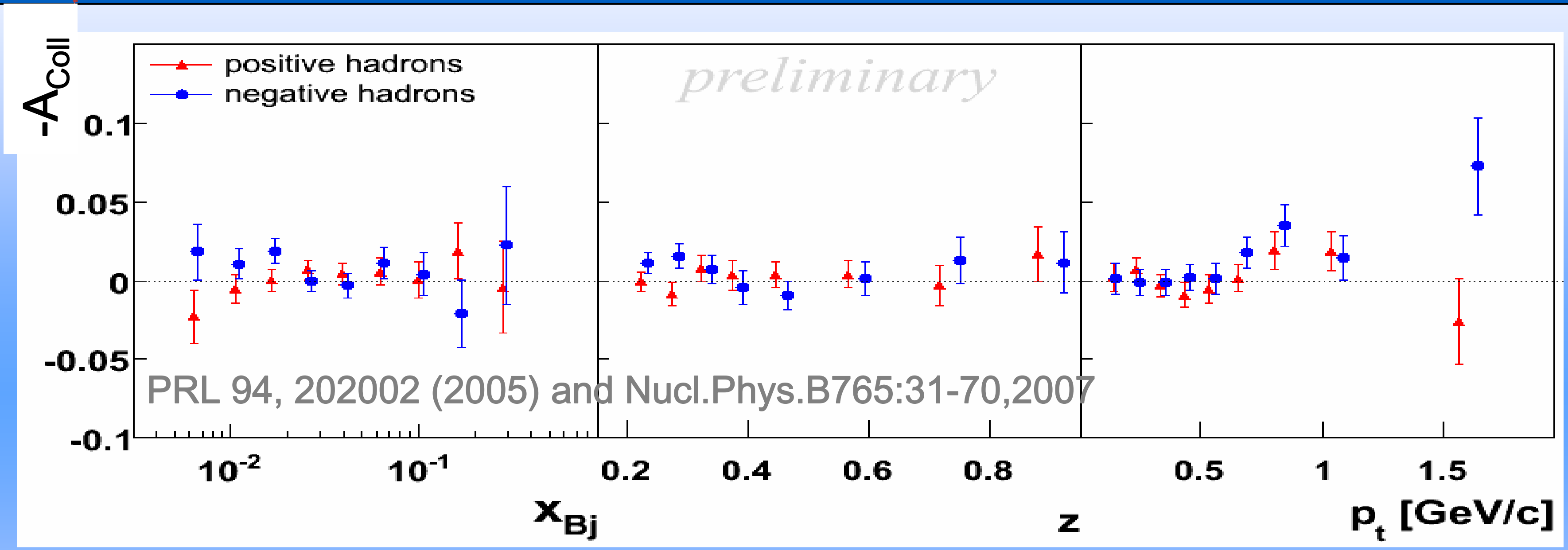
Collins measurements II



- K^+ asymmetries compatible with π^+ asymmetries (through u quark dominance)
- K^- asymmetries maybe slightly positive



Collins measurements III



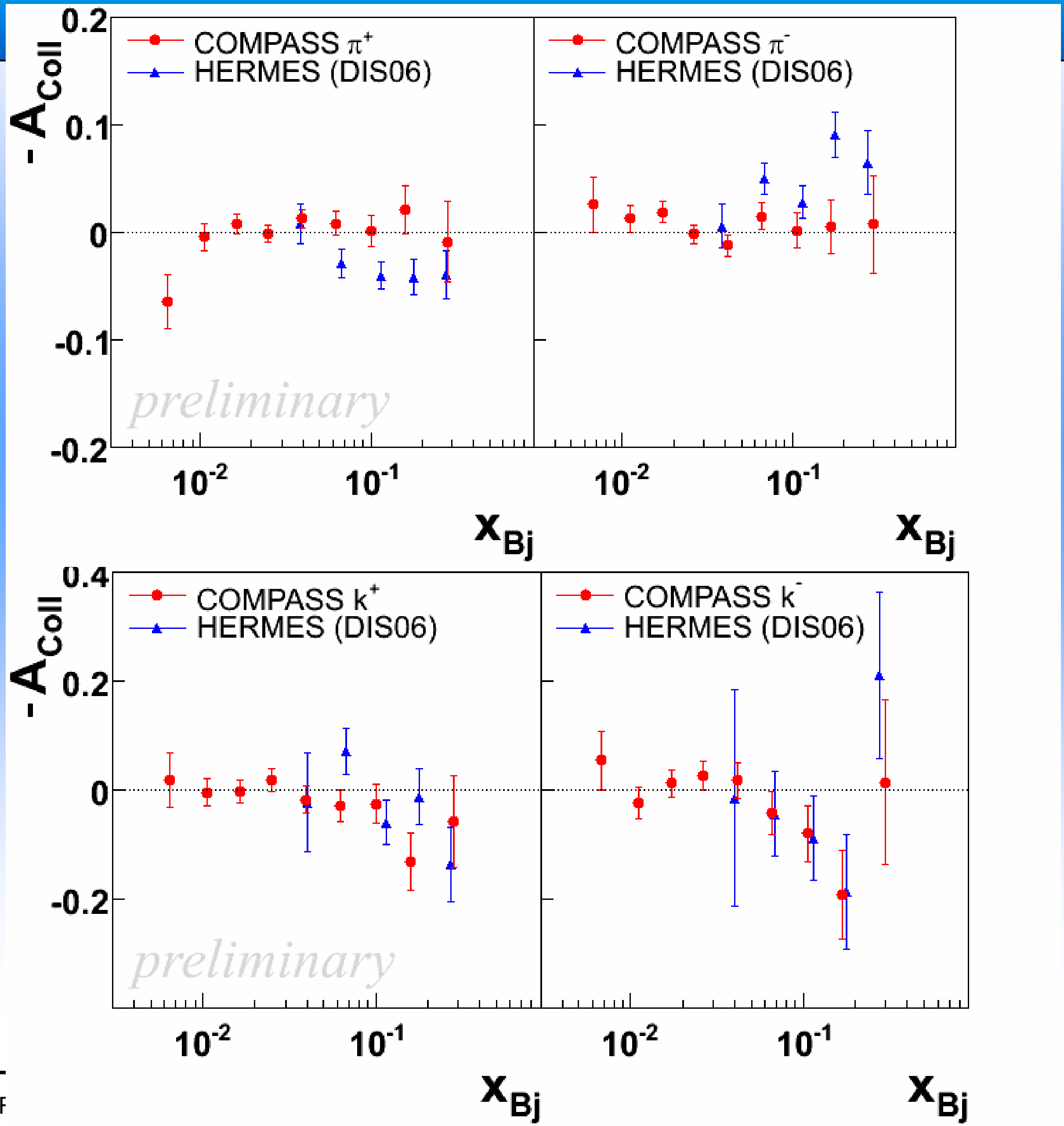
- Smaller asymmetries than in proton case

→ Hint of cancellation of transversity in isoscalar target

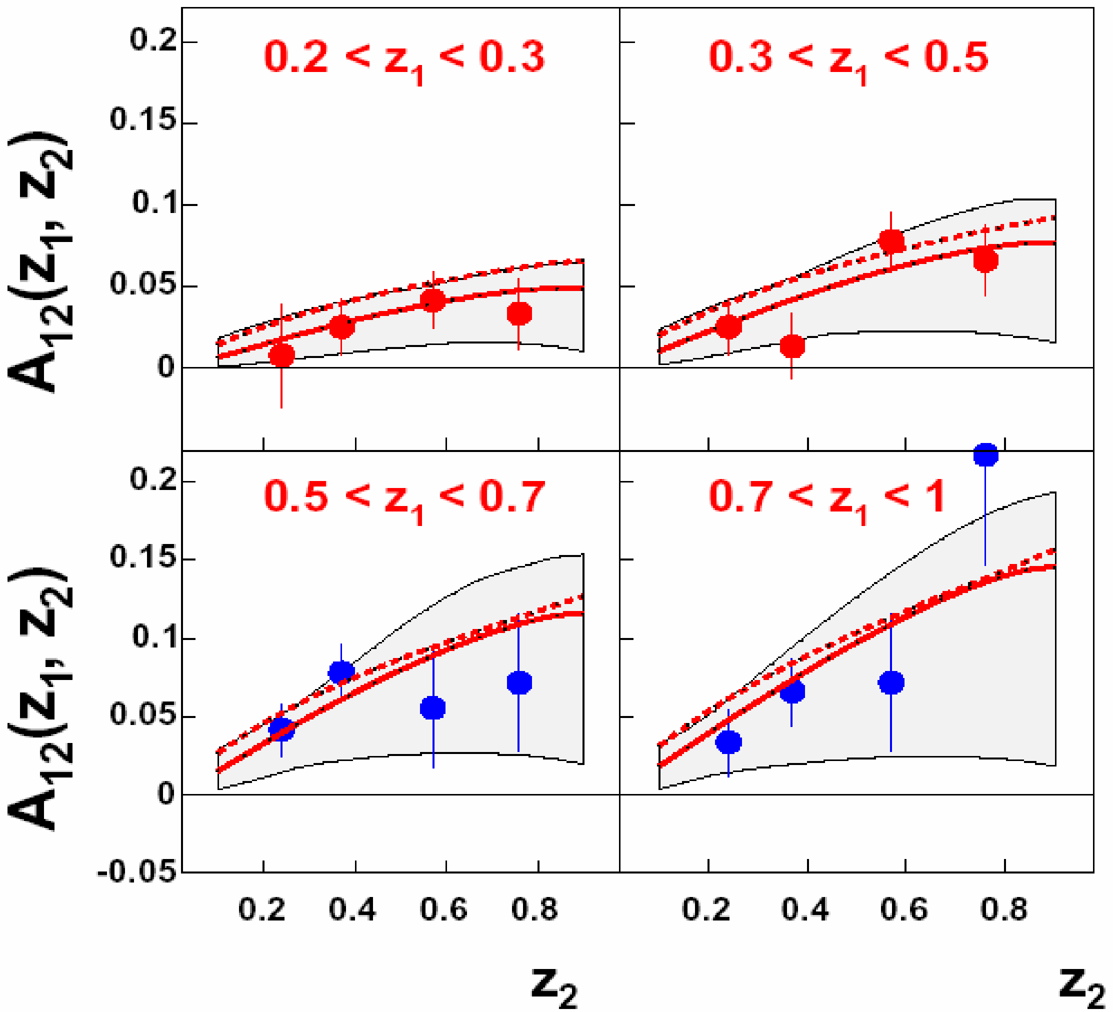
- First fits to HERMES and COMPASS data using assumptions on Transversity show results consistent with each other

Collins measurements IV

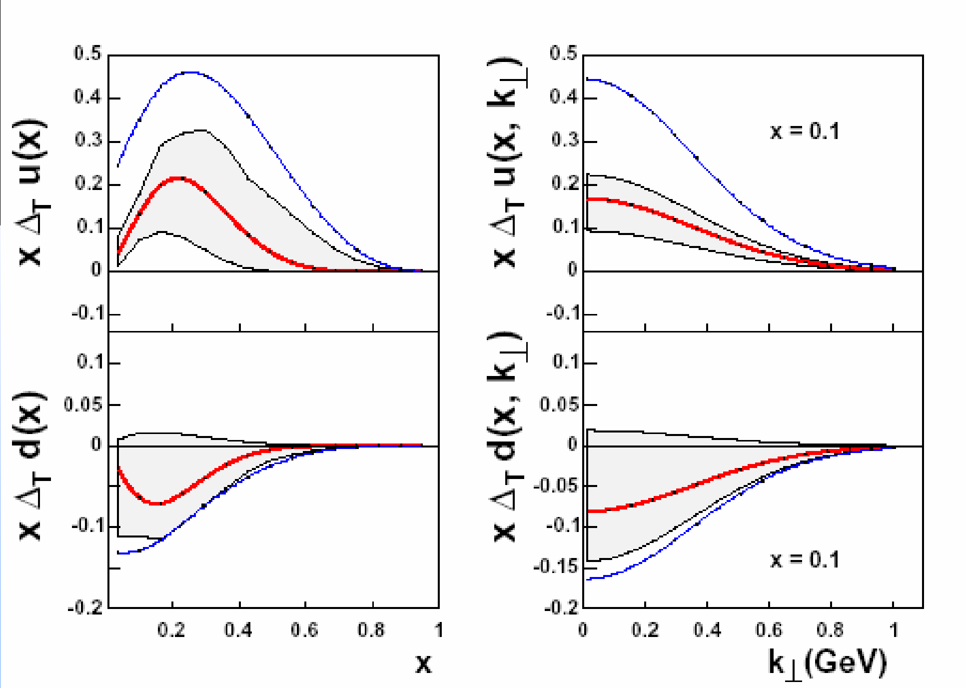
COMPASS preliminary
2003-2004 data from deuteron for identified hadrons



Global Fit of HERMES, COMPASS and BELLE data

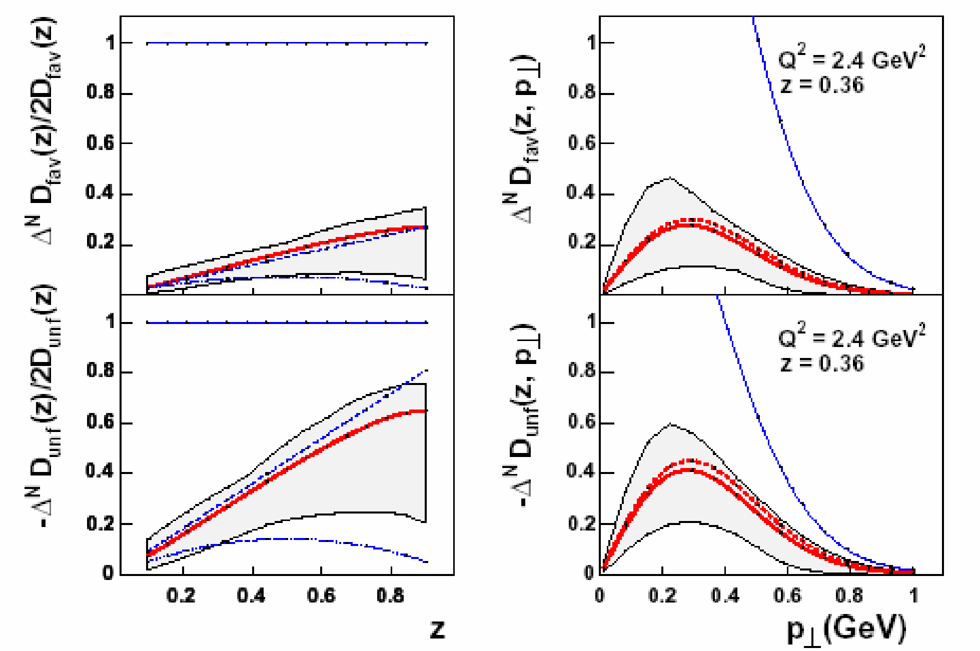


$$A_{12} \propto \Delta^N D_{\pi/q^{\uparrow}}(z_1) \otimes \Delta^N D_{\pi/q^{\uparrow}}(z_2)$$

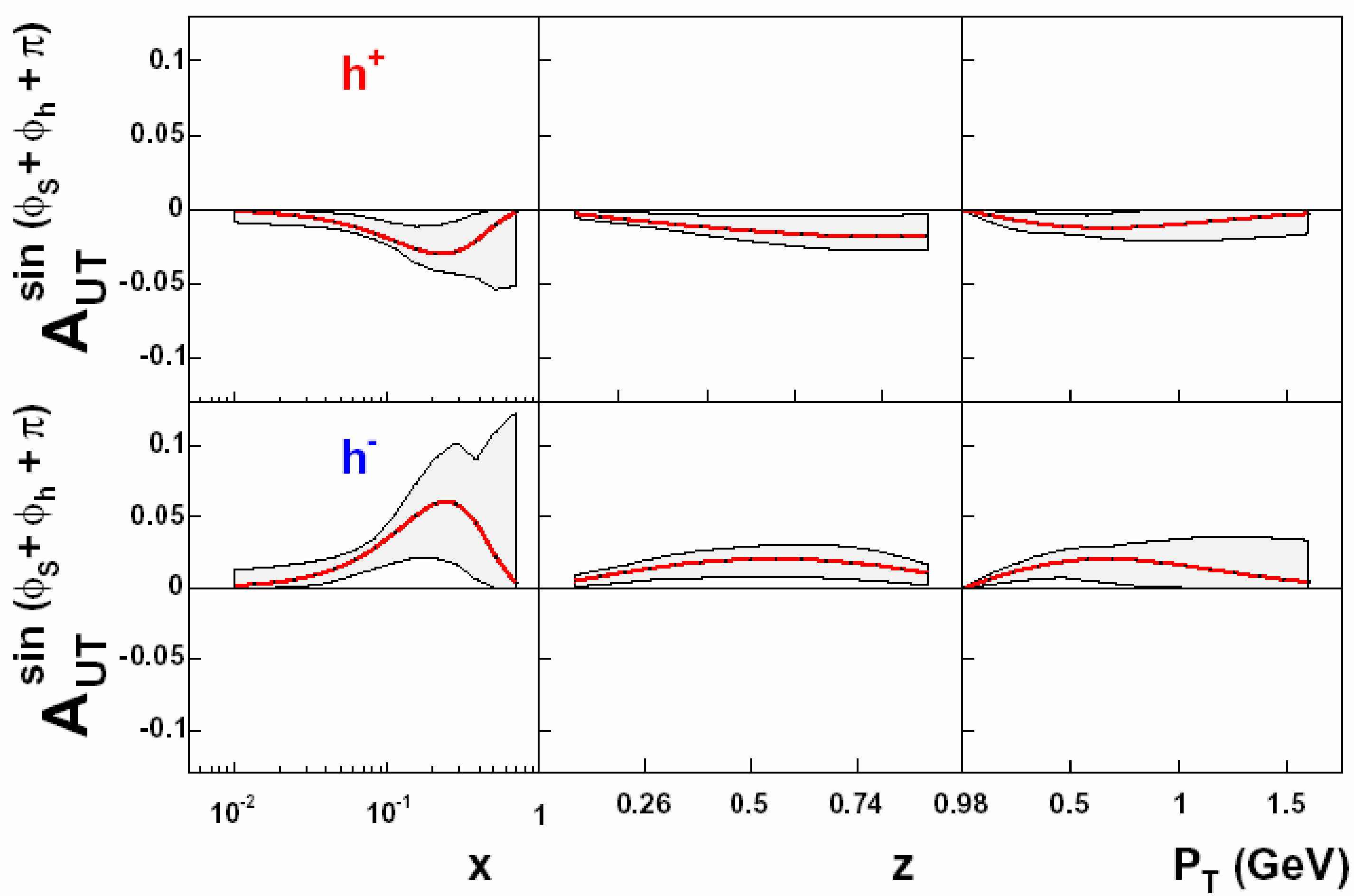


First extraction of Collins functions and transversity distributions from fitting HERMES + COMPASS + BELLE data

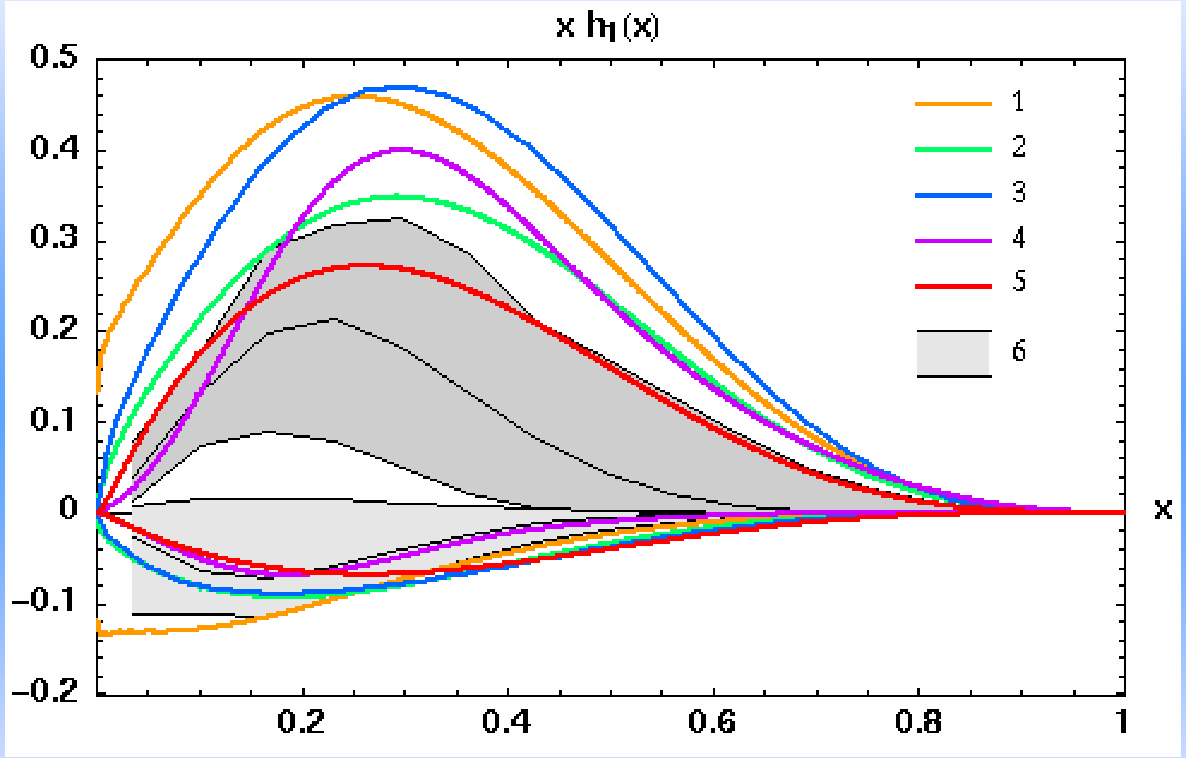
By Anselmino et al., PRD 75 (07)



Predictions for COMPASS data on a proton target from global fit



Comparison with some models



[1] Soffer et al. PRD 65 (02)

[2] Korotkov et al. EPJC 18 (01)

[3] Schweitzer et al., PRD 64 (01)

[4] Wakamatsu, PLB 509 (01)

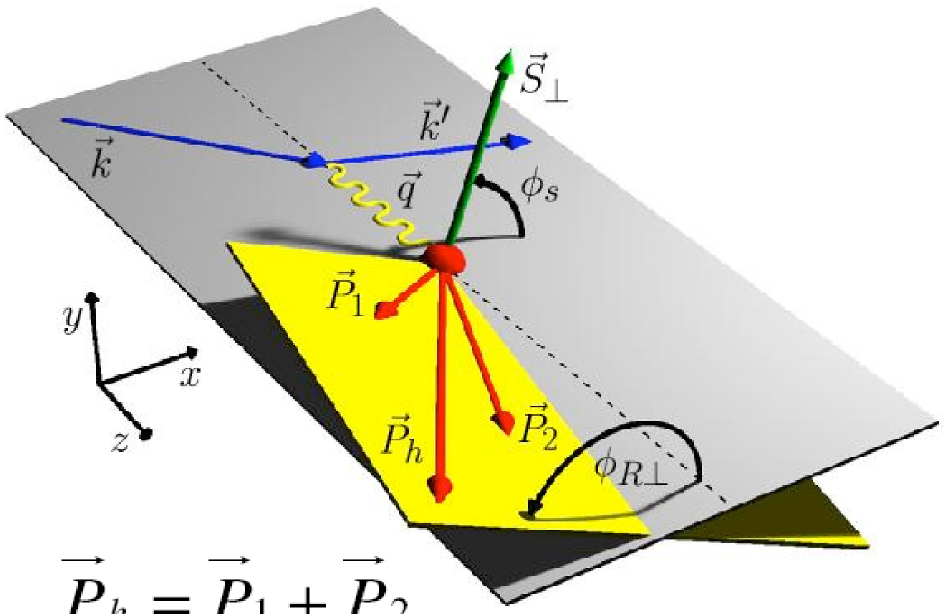
[5] Pasquini et al., PRD 72 (05)

[6] Anselmino et al., PRD 75 (07)

Transversity from di-hadrons – Interference fragmentation function

$$A_{UT} = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}} \propto |\mathbf{S}_{\perp}| \sin(\phi_{R\perp} + \phi_S) \frac{\sum_q e_q^2 \, h_1^q H_1^{\sphericalangle, sp}}{\sum_q e_q^2 \, f_1^q D_1^q}$$

$$H_1^{\sphericalangle, sp}(z, M_h^2) =$$ interference fragmentation between pion pair in s-wave and p-wave

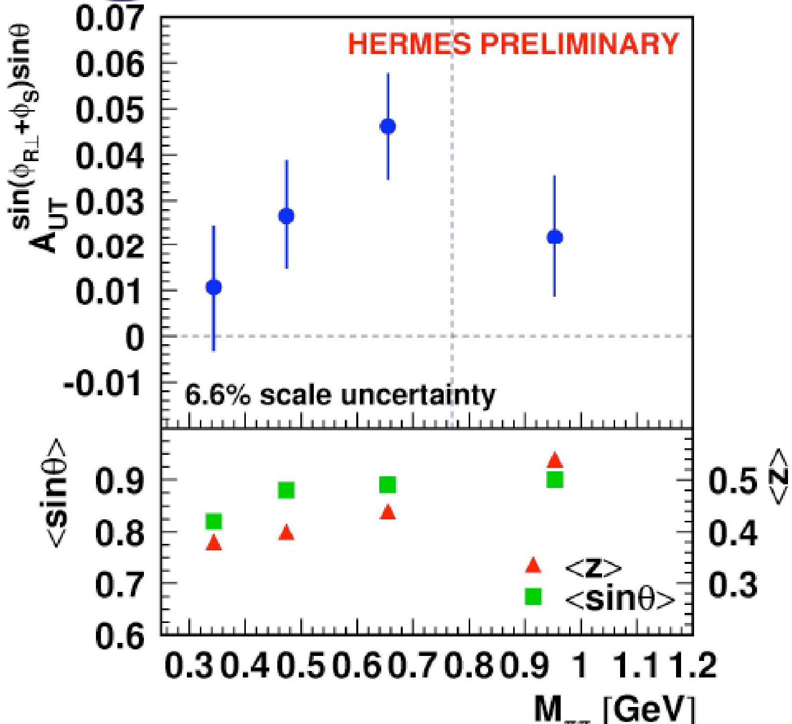


$$\overrightarrow{P_h} = \overrightarrow{P_1} + \overrightarrow{P_2}$$

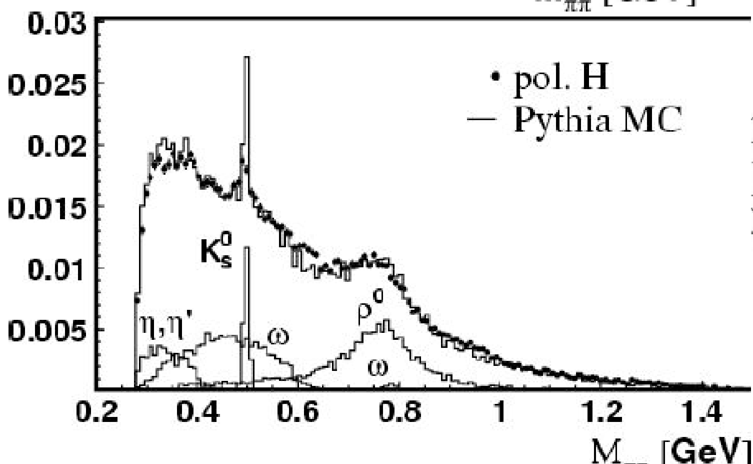
Advantages:
- direct product of transversity and fragmentation function (no convolution)
- easier to calculate Q^2 evolution

Disadvantages:
- less statistics
- cross section depends on 9 variables (sensitive to detector acceptance effects)

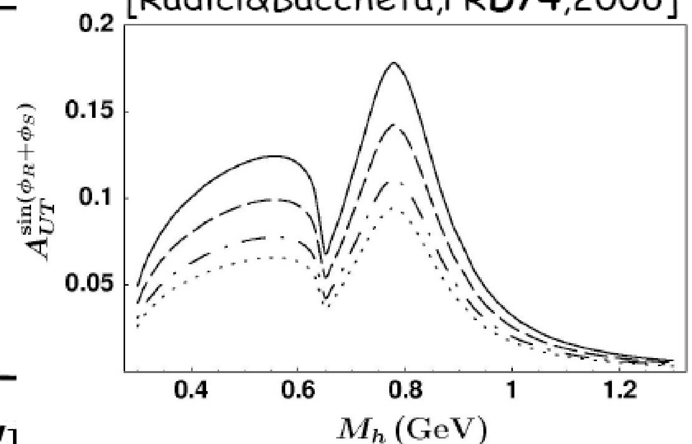
2-hadron asymmetries for 2002-2004



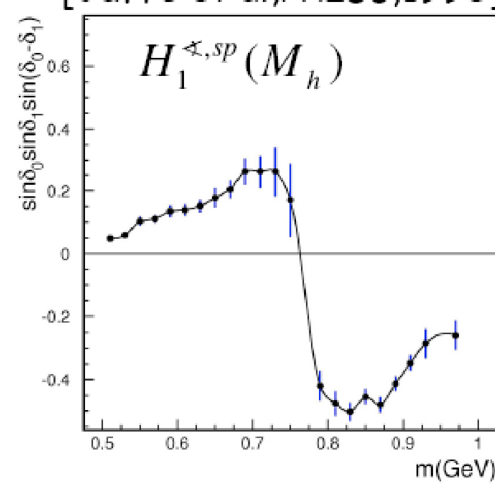
- significantly non-zero amplitudes (2002-2004):
  2-hadron fragmentation probes transversity!
- result disfavors model of Jaffe et al. for $H_1^{\sphericalangle,sp}$
- model of Bacchetta & Radici:
  - overestimates amplitudes
  - consistent with mass dependence
- MC studies: nonlinear mass dependence of amplitude
  → [0%,+44%] (rel.) systematic uncertainty
  (detector acceptance effect)
- BELLE intends to measure 2-hadron FF's



[Radici&Baccheta,PRD**74**,2006]

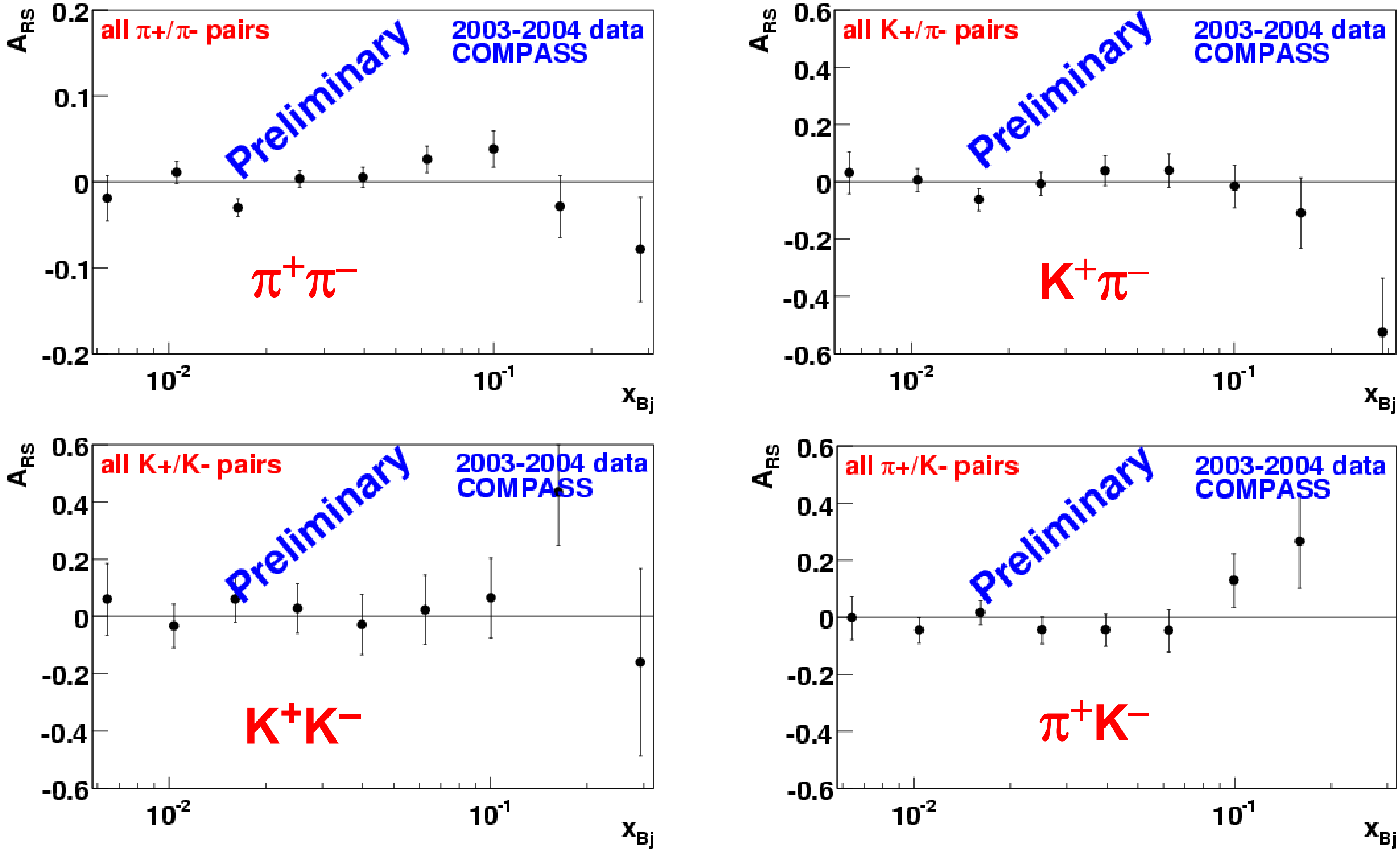


[Jaffe et al,PRL**80**,1998]



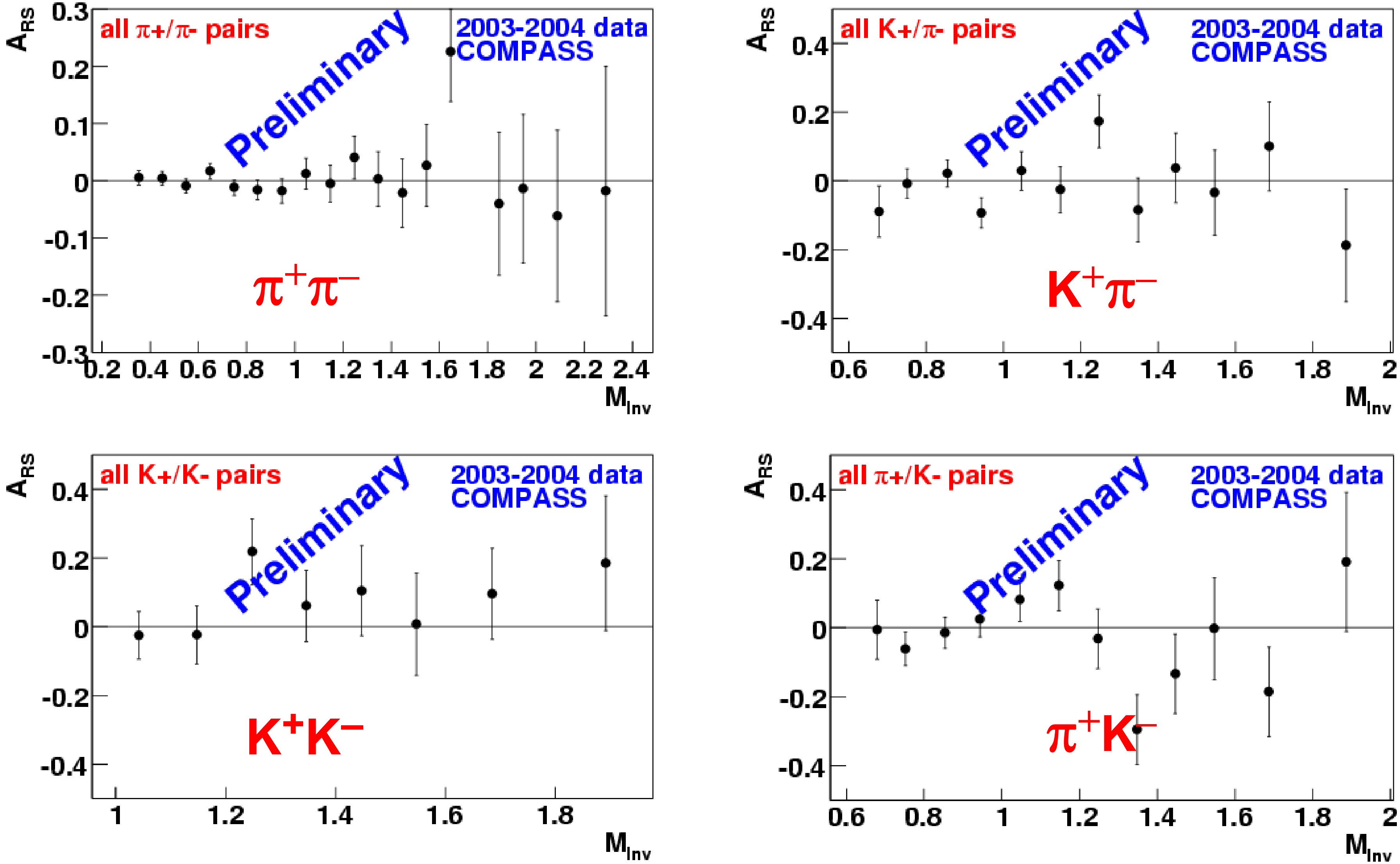
di-hadron asymmetries

identified hadrons on the deuteron target



di-hadron asymmetries

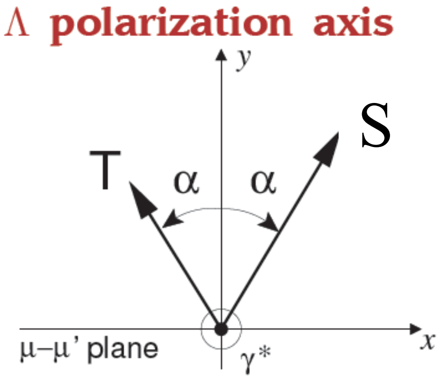
identified hadrons on the deuteron target

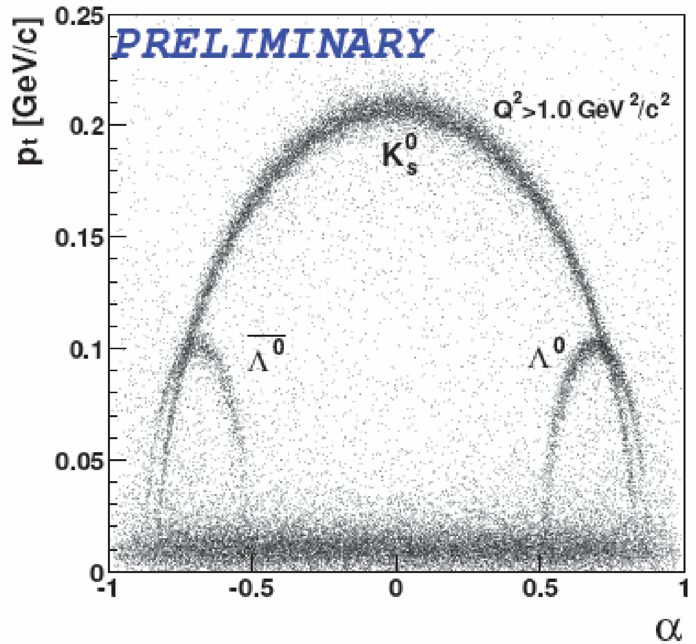


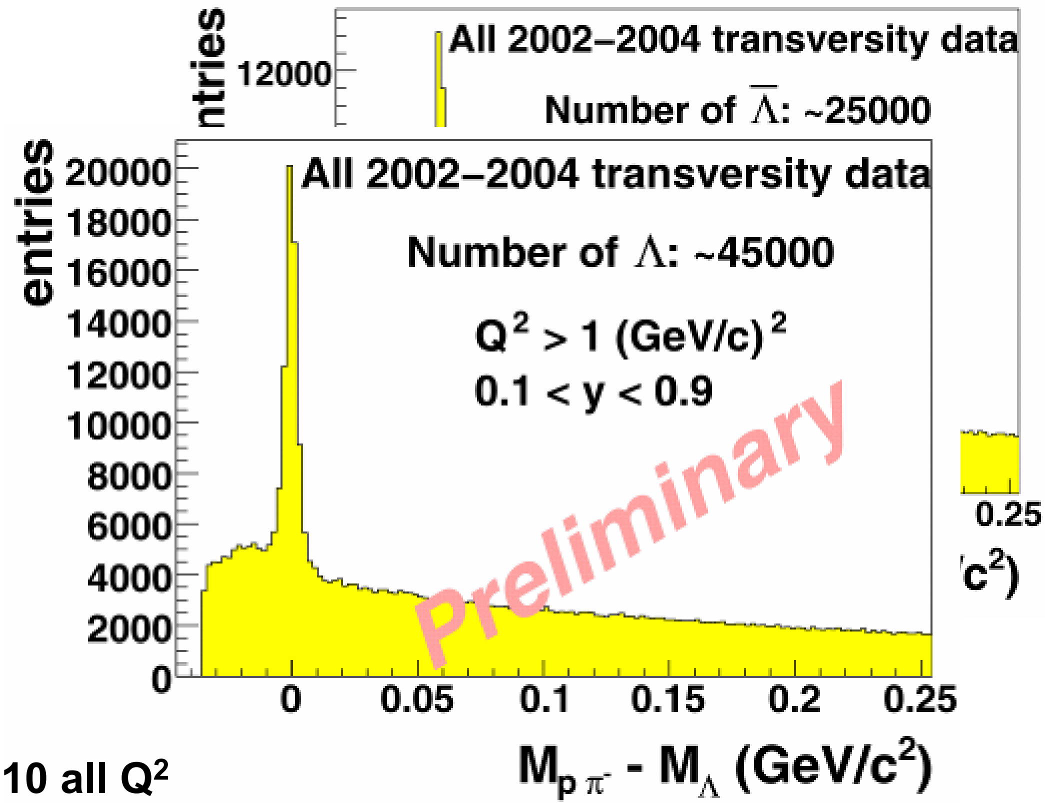
Λ polarimetry

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

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

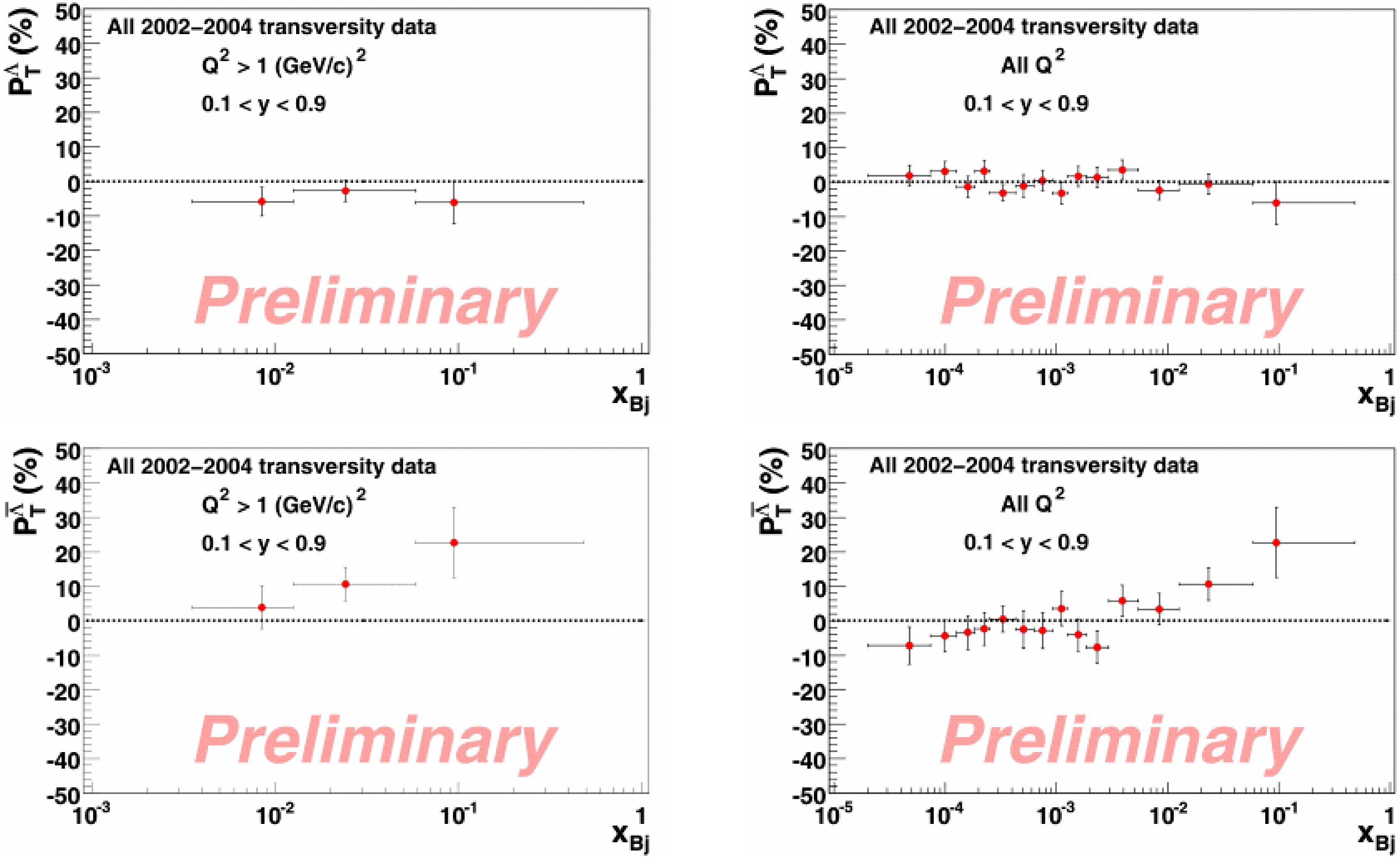






x 10 all Q^2

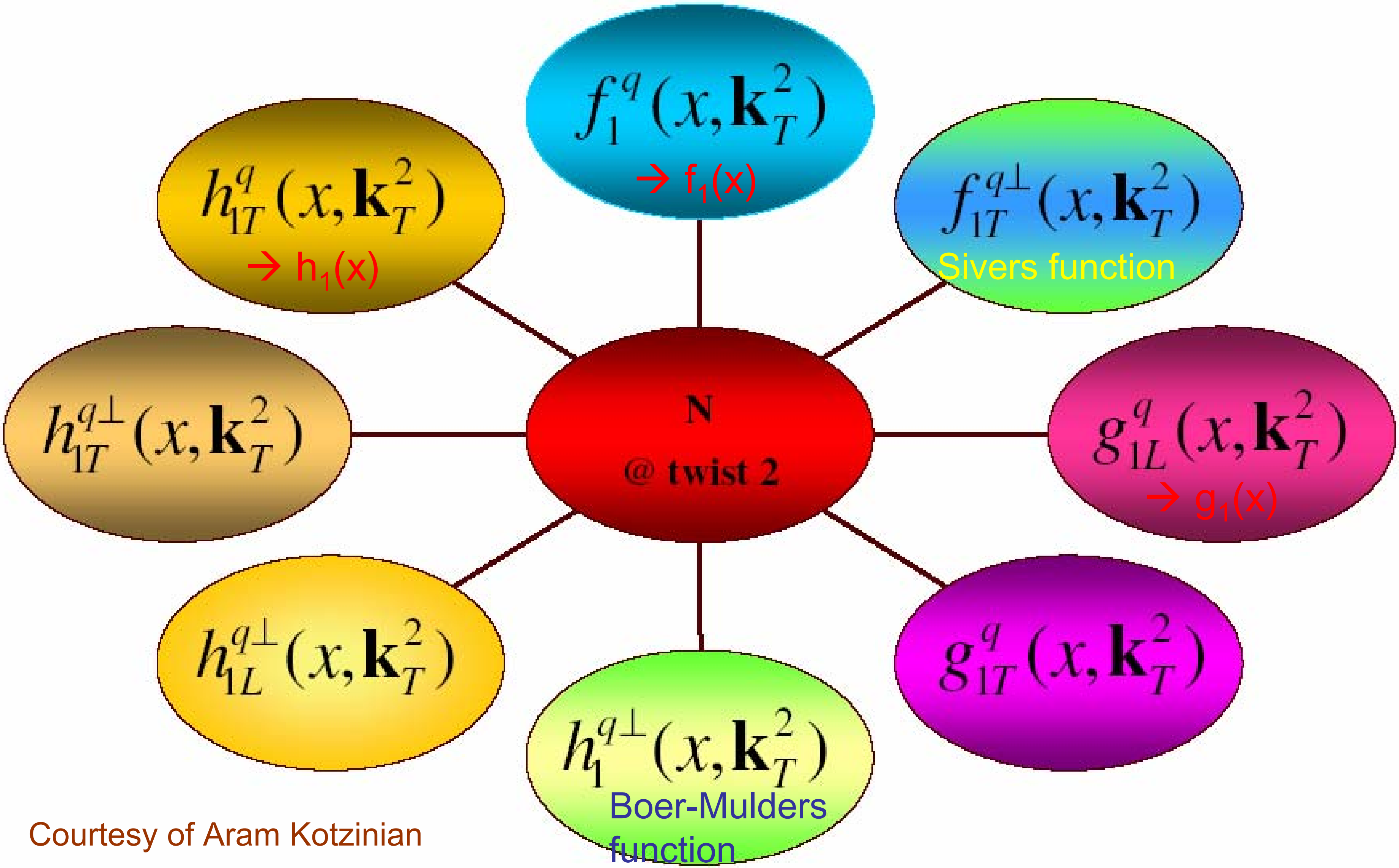
Λ polarimetry



systematic errors not larger than statistical errors

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

8 leading-twist spin-$k_\perp$ dependent (TMD) distribution functions



Courtesy of Aram Kotzinian

Sivers function

$$f_{q/p,\boldsymbol{S}}(x,\boldsymbol{k}_\perp) = f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q/p^\uparrow}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

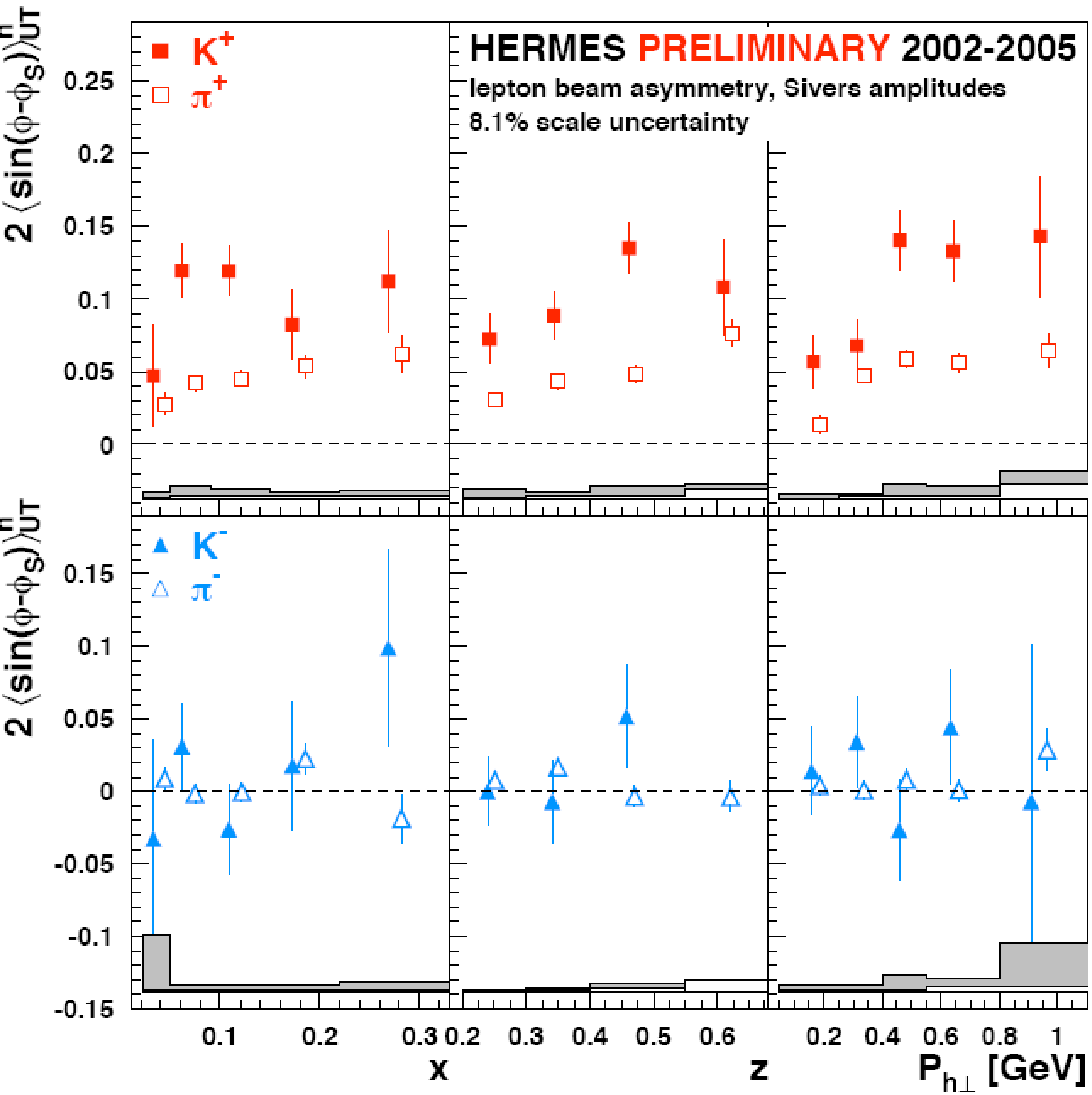
$$= f_{q/p}(x,k_\perp) - \frac{k_\perp}{M} f_{1T}^{\perp q}(x,k_\perp)\,\boldsymbol{S}\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

Boer-Mulders function

$$f_{q,\boldsymbol{s}_q/p}(x,\boldsymbol{k}_\perp) = \frac{1}{2} f_{q/p}(x,k_\perp) + \frac{1}{2}\Delta^N f_{q^\uparrow/p}(x,k_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

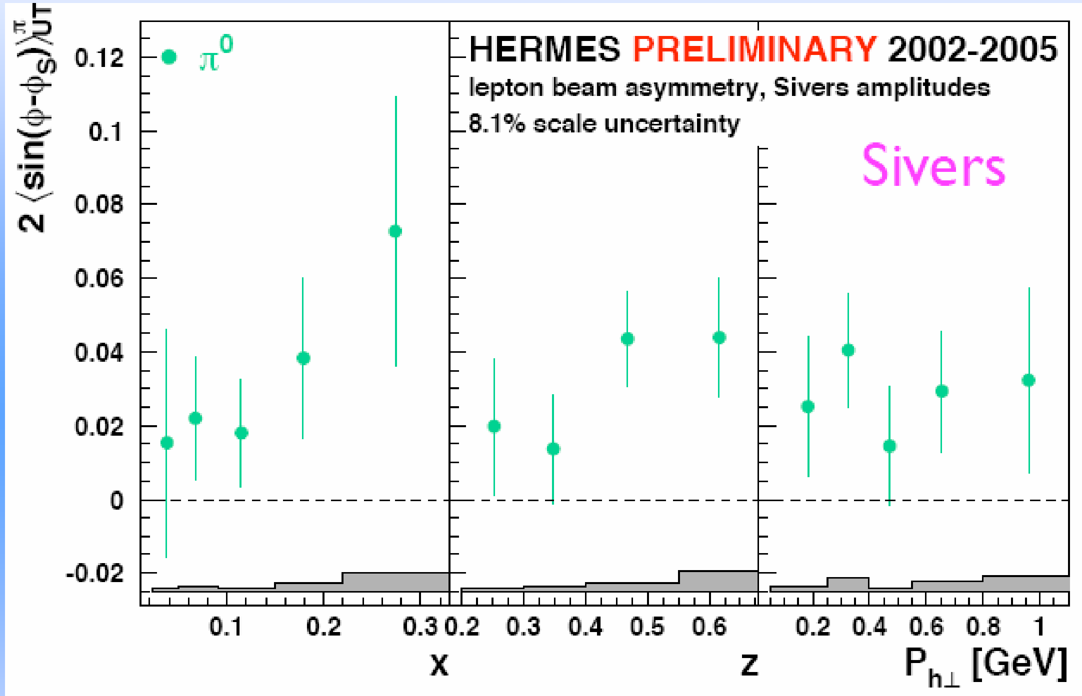
$$= \frac{1}{2} f_{q/p}(x,k_\perp) - \frac{1}{2}\frac{k_\perp}{M} h_1^{\perp q}(x,k_\perp)\,\boldsymbol{s}_q\cdot(\hat{\boldsymbol{p}}\times\hat{\boldsymbol{k}}_\perp)$$

Sivers function measurements I



- π^+ asymmetries clearly positive
- First evidence of a nonzero TMD
- π^- K^- asymmetries consistent with zero
- K^+ asymmetries 2.3 times larger than π^+ hard to explain
- Consistent sign of Sivers functions as from M.Burkhardt's chromodynamic lensing

Sivers function measurements II

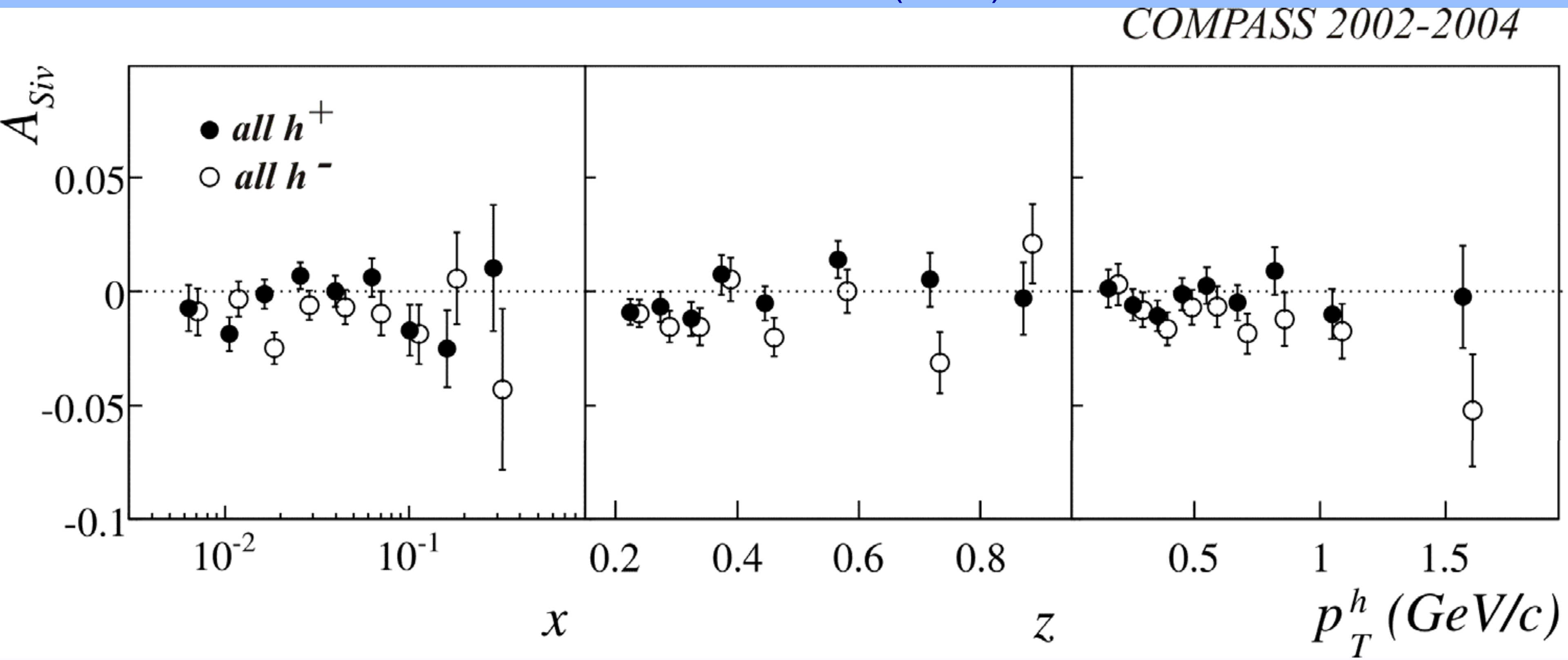


- Results for all 3 pion states consistent with isospin symmetry

Sivers asymmetry III

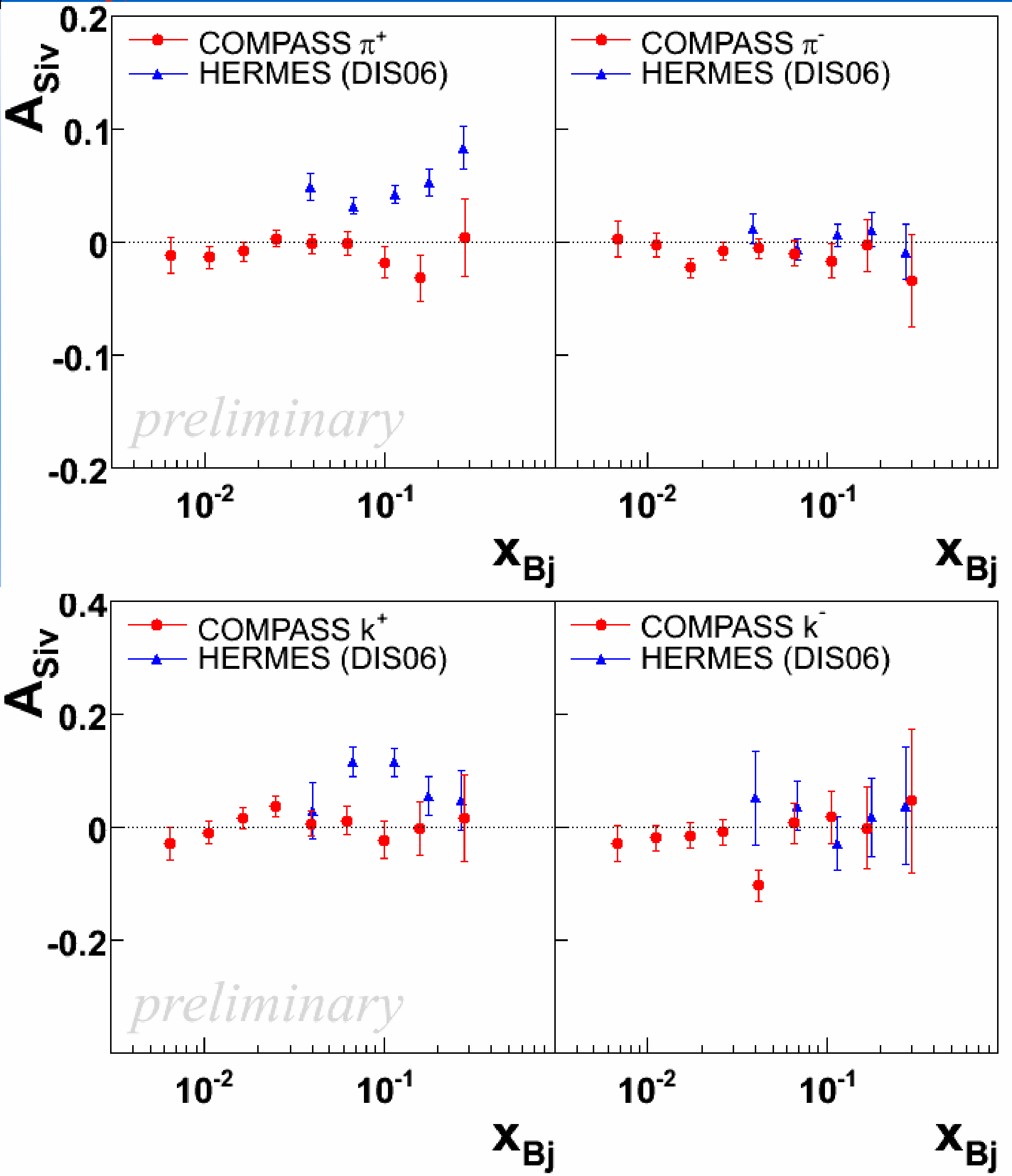
deuteron target transversely polarised
charged hadrons (mostly pions)

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



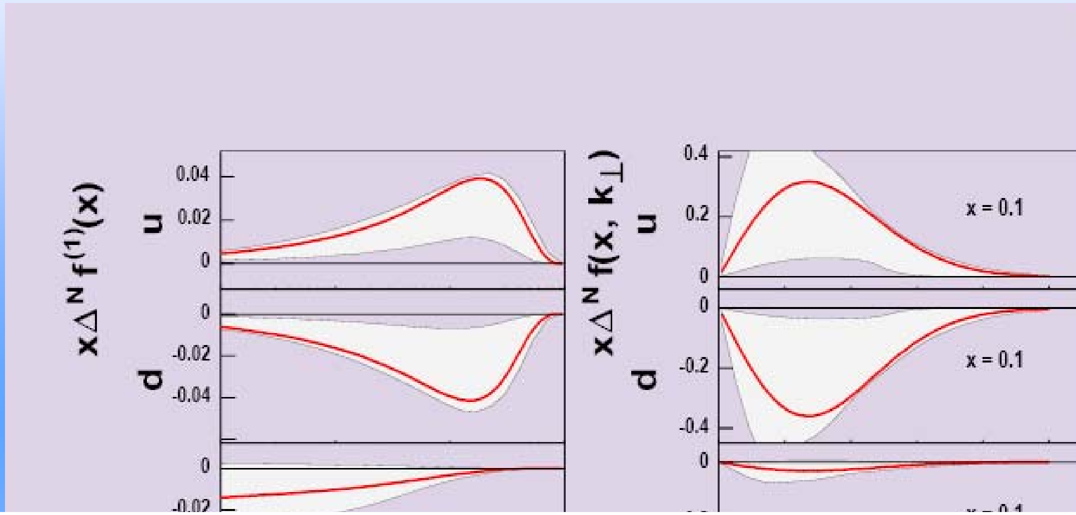
asymmetries compatible with zero within the statistical errors
(systematic errors much smaller)

Sivers measurements IV

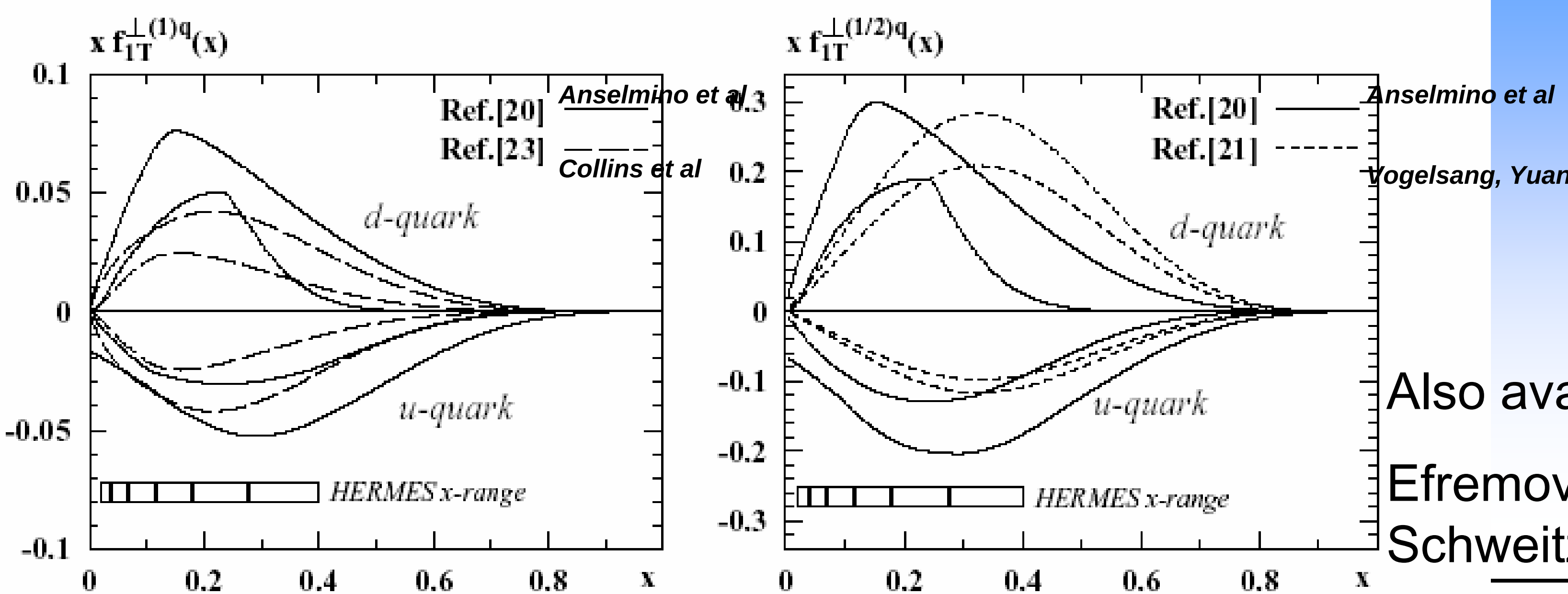


- Again, 2003-2004 data for identified hadrons

Sivers global analysis



- Simultaneous fit of HERMES (02-04) and COMPASS (03-04) data on identified hadrons
- u and d Sivers functions of nearly equal size and opposite sign



Also available:

Efremov,Goeke, Schweitzer

Other TMDs accessible in SIDIS

(leading twist – many more at subleading twist)

SIDIS $[dx dQ^2 dz d^2\boldsymbol{p_T}]$:

$f_1 \otimes D_1 (1 + \cos(\phi_h))$ $\quad$ $h_1^\perp \otimes H_1^\perp \cos(2\phi_h)$

$S_L \, h_{1L}^\perp \otimes H_1^\perp \sin(2\phi_h)$

$S_T \, g_{1T} \otimes D_1 \cos(\phi_h - \phi_S)$ $\quad$ $S_T \, f_{1T}^\perp \otimes D_1 \sin(\phi_h - \phi_S)$

$S_T \, h_1 \otimes H_1^\perp \sin(\phi_h + \phi_S)$ $\quad$ $S_T \, h_{1T}^\perp \otimes H_1^\perp \sin(3\phi_h - \phi_S)$

- 2 unpolarized functions (Cahn effect and Boer Mulders function)
  - Boer Mulders function interesting, models see same sign for u and d, quark spin-orbit correlation
- 2 with longitudinally polarized target

  (g_1 missing from table)
- 4 with transversely polarized target

1-D fitting procedure (MINUIT with $\chi 2$ minimization method)

$9 - X_{Bj}$, $8 - z$, $9 - P_{hT}$ bins and 16 Φ_j bins.

Fitting the "ratio product" quantities

$$F(\Phi_j) = \frac{N_u^+(\Phi_j) N_d^+(\Phi_j)}{N_u^-(\Phi_j) N_d^-(\Phi_j)}$$

$$\sigma_R(\Phi_j) = \sqrt{\frac{1}{N_u^+(\Phi_j)} + \frac{1}{N_u^-(\Phi_j)} + \frac{1}{N_d^+(\Phi_j)} + \frac{1}{N_d^-(\Phi_j)}}$$

in case if $W_j(\Phi_j)$ *contains only* sin *or only* cos *moment.*

by $F(\Phi_j) = par[0](1 + 4\,par[1]\sin(\Phi_j))$, or by $F(\Phi_j) = par[0](1 + 4\,par[1]\cos(\Phi_j))$

$par[1]$ - *Raw Asymmetry value.*

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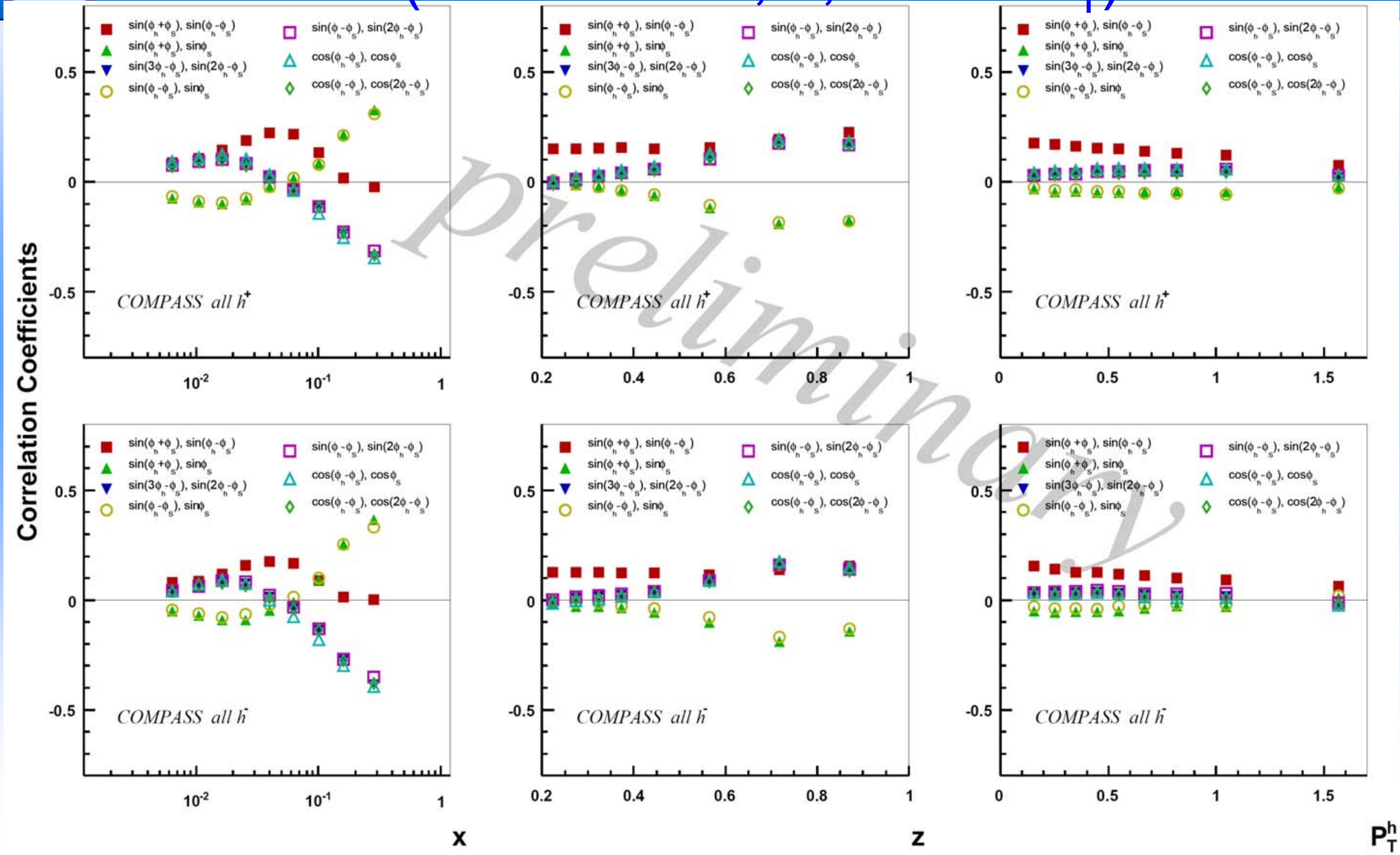
and in case if $W_j(\Phi_j)$ *contains both* sin *and* cos *moments.*

by $F(\Phi_j) = par[0](1 + 4(par[1]\sin(\Phi_j) + par[2]\cos(\Phi_j)))$

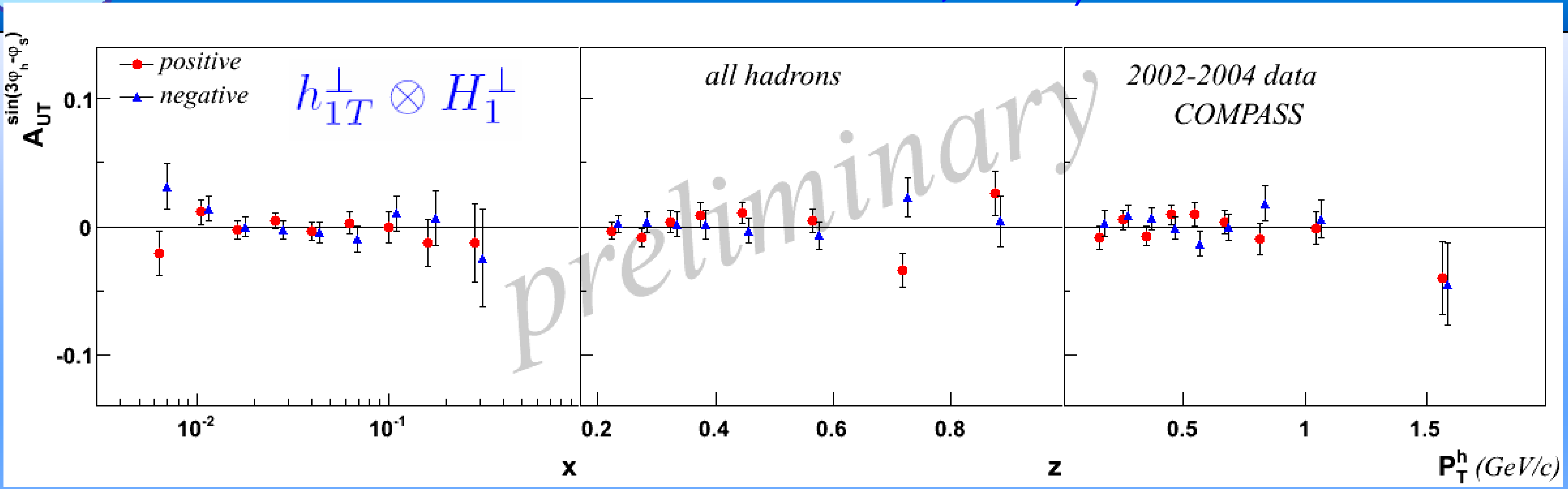
$par[1]$ - "sin" *Raw Asymmetry value and* $par[2]$ - "cos" *Raw Asymmetry.*

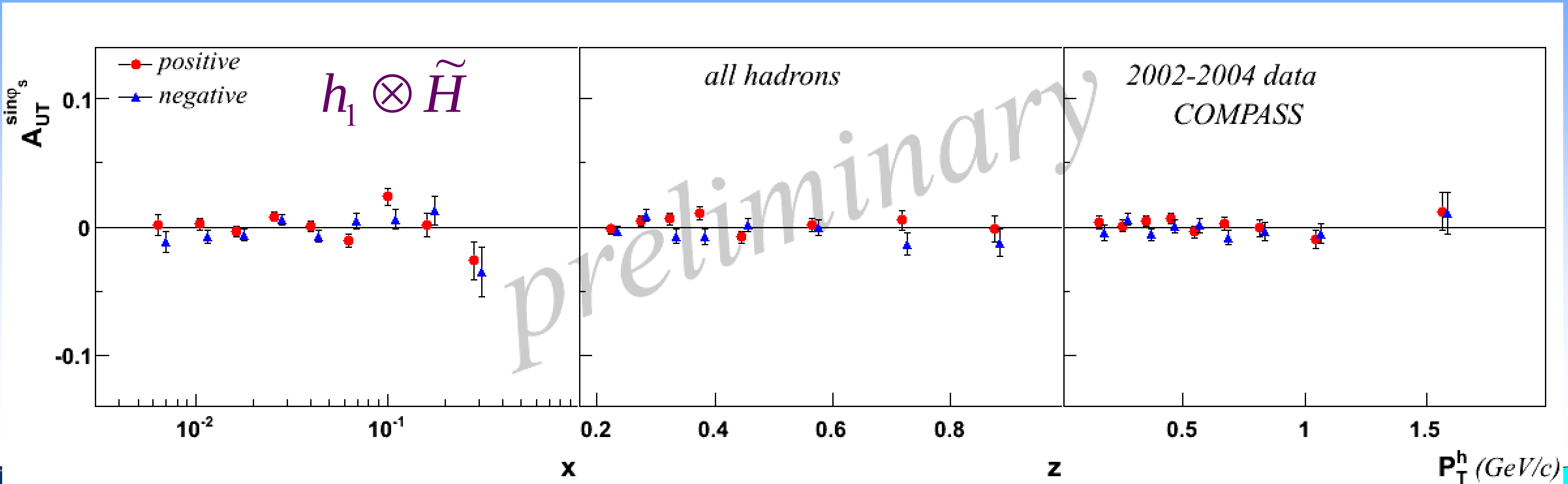
Newly extracted Collins & Sivers asymmetries gave the same result as published (NP B765 (2007) 31)

Correlation Coefficients
(+/- hadrons, x, z and P_T)

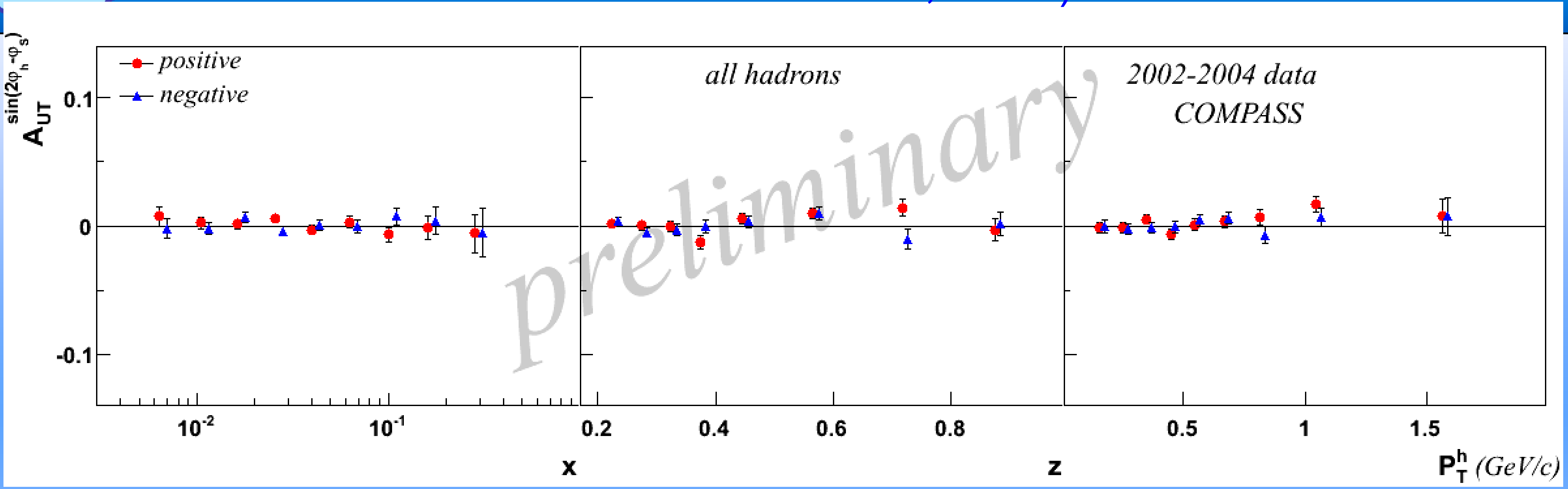


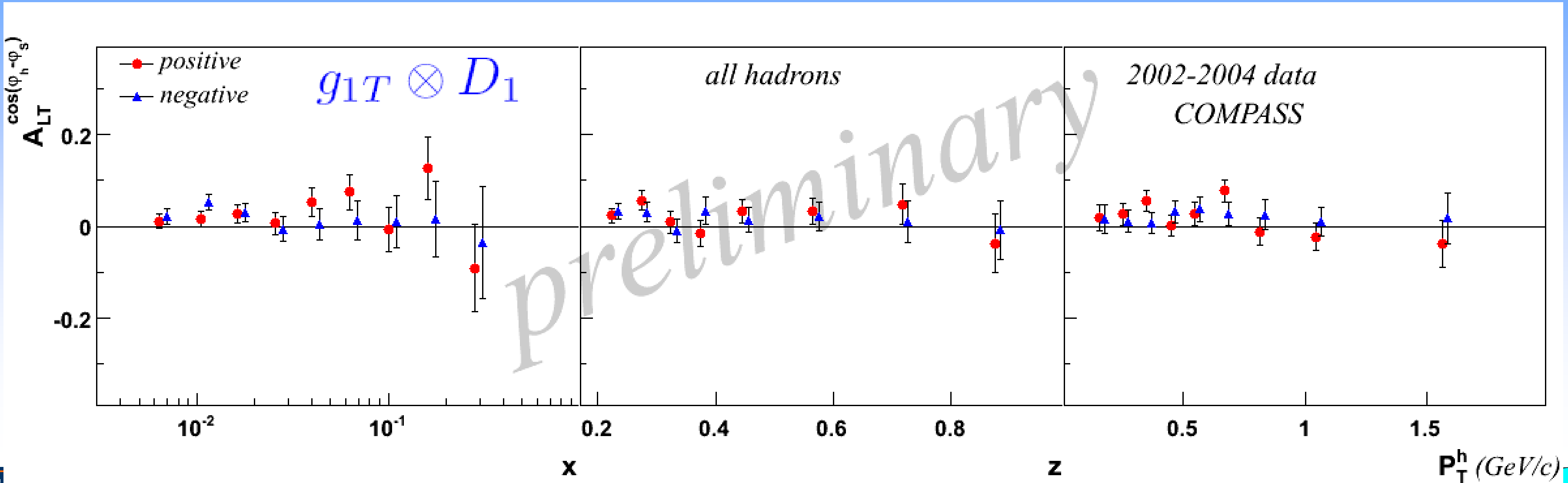
Results for $A_{UT}^{\sin(3\varphi_h-\varphi_s)}$ & $A_{UT}^{\sin(\varphi_s)}$ (2002-2004 deuteron data, 1D fit)



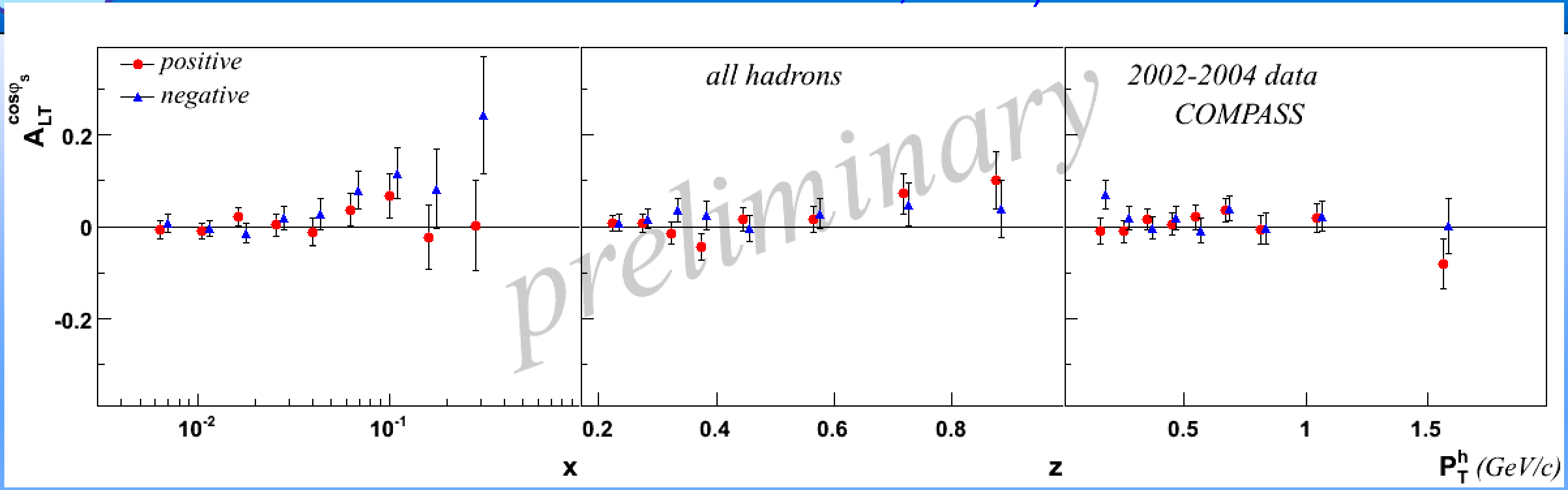


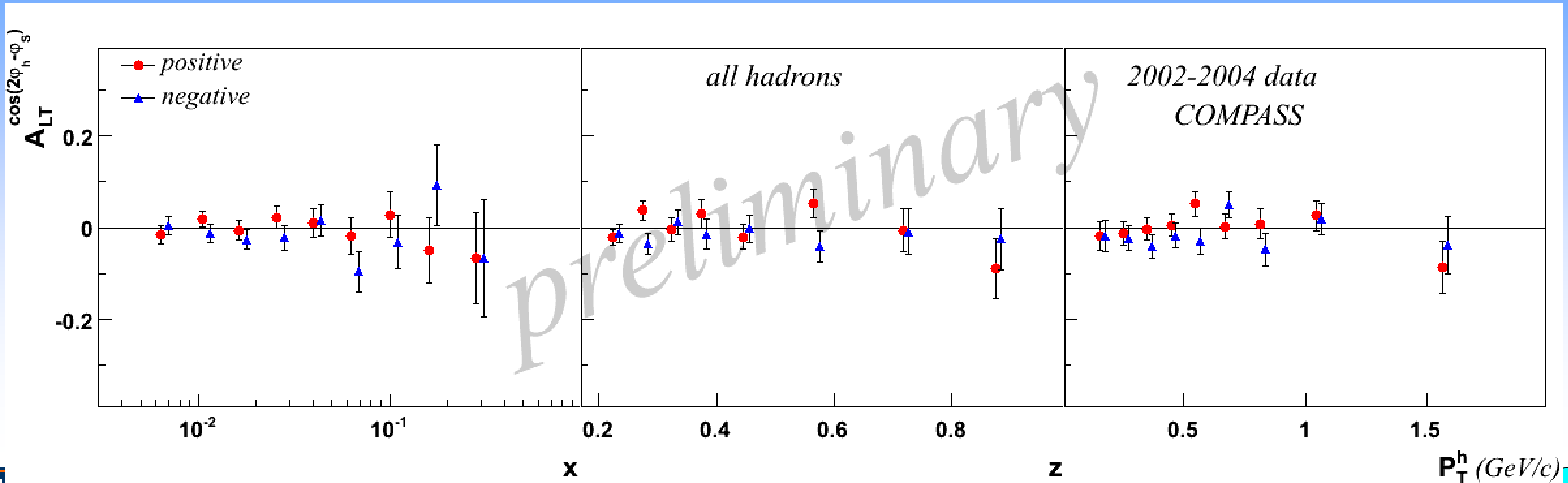
Results for $A_{UT}^{\sin(2\varphi_h-\varphi_s)}$ & $A_{LT}^{\cos(\varphi_h-\varphi_s)}$ (2002-2004 deuteron data, 1D fit)





Results for $A_{LT}^{\cos(\varphi_s)}$ & $A_{LT}^{\cos(2\varphi_h-\varphi_s)}$ (2002-2004 deuteron data, 1D fit)





Summary and Outlook

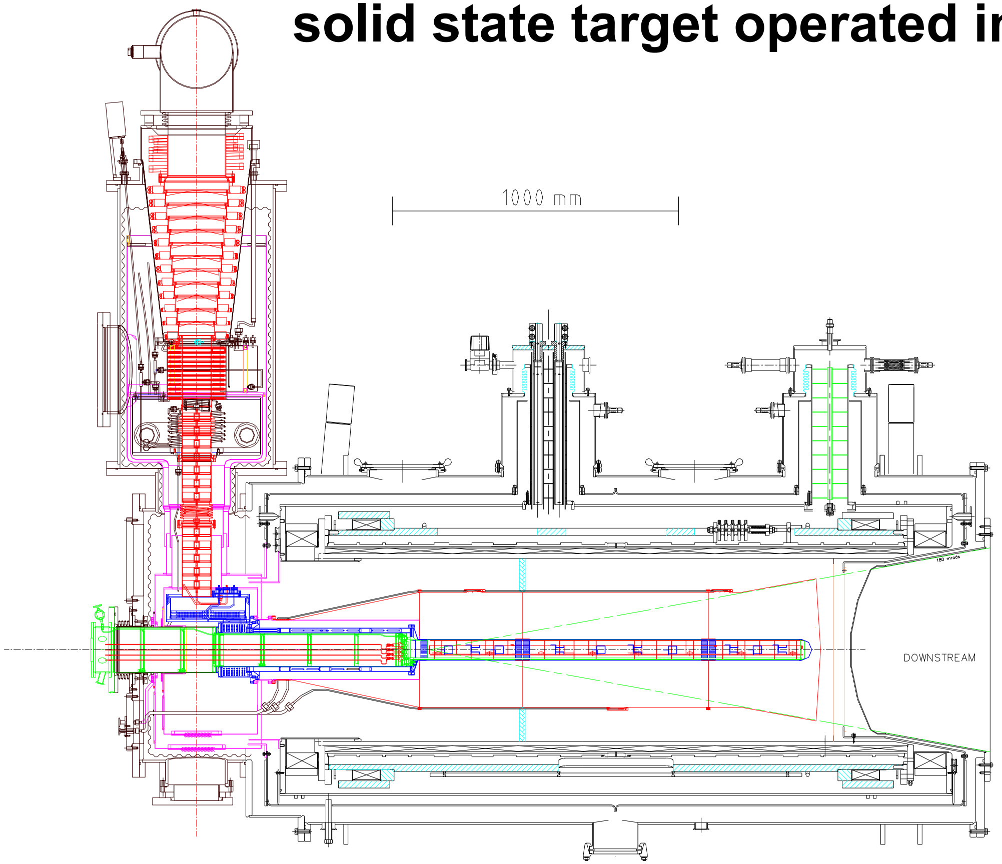
- Nonzero Collins asymmetries measured at HERMES on transversely polarized proton target
- Nearly vanishing Collins asymmetries from COMPASS on deuteron target
- Global transversity analysis on HERMES, COMPASS and BELLE data
  - Confirms large, negative disfavored Collins function
  - Extracts first u and d Transversity distribution
- Interference FF results from HERMES and COMPASS
- Λ polarization results from COMPASS
- Sivers data from HERMES (nonzero) and COMPASS (zero)

- Global Sivers analysis sees large u and d Sivers functions, sea and Gluons seem small
- Efforts to extract further TMDs through distinct azimuthal dependencies

- HERMES has finished taking polarized data
  - Unweighted asymmetries contain full data set
  - Analysis of weighted moments and other azimuthal dependencies ongoing
  - End of HERMES running June 30 ☹
- COMPASS is just starting to run with a transversely polarized proton (NH_3) target

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