New target transverse spin dependent azimuthal asymmetries from COMPASS experiment

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on behalf of the COMPASS collaboration

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

ECT, Trento, June 11 2007*

Outline

- Target transverse spin asymmetries
- COMPASS experimental setup
- Event selection
- Extraction
  - 1D method
    - Systematic checks
  - 2D method
    - Correlation Coefficients
- Results
- Conclusions

SIDIS Cross-section

$$d\sigma = d\sigma_{00} + P_L^l d\sigma_{L0} + P_L^N (d\sigma_{0L} + P_L^l d\sigma_{LL}) + P_T^N (d\sigma_{0T} + P_L^l d\sigma_{LT})$$

where, P_L^N - target longitudinal polarization, P_T^N - target transverse polarization,
P_L^l - beam longitudinal polarization.

Target transverse spin dependent azimuthal modulations

$$d\sigma_{0T} \propto \underline{A_1 \sin(\varphi_h + \varphi_s)} + A_2 \sin(3\varphi_h - \varphi_s) + \underline{A_3 \sin(\varphi_h - \varphi_s)} + A_4 \sin(2\varphi_h - \varphi_s) + A_5 \sin\varphi_s$$

Published by HERMES & COMPASS

$$d\sigma_{LT} \propto A_6 \cos(\varphi_h - \varphi_s) + A_7 \cos(2\varphi_h - \varphi_s) + A_8 \cos\varphi_s$$

<u>*A.Kotzinian, Nucl. Phys. B441, 234 (1995).*</u>

<u>*A.Bacchetta, M.Diehl, K.Goeke, A.Metz, P.Mulders and M.Schlegel, arXiv:hep-ph/0611265.*</u>

<u>Thursday - *A. Kotzinian*</u>

Within QCD parton model $\rightarrow A_i \propto DF \otimes FF \quad (i = 1,..8)$

For example - $A_6 \propto g_{1T}(x, k_T) \otimes D_1(z, p_\perp)$

g_{1T} − Longitudinally polarized quarks distribution inside the transversely polarized nucleon

$D_1(z, p_\perp)$ − Quark fragmentation function

Transverse spin dependent azimuthal modulations

$$
\left.\begin{aligned}
w_1(\varphi_h,\varphi_s) &= \sin(\varphi_h-\varphi_s)\\
w_2(\varphi_h,\varphi_s) &= \sin(\varphi_h+\varphi_s)\\
w_3(\varphi_h,\varphi_s) &= \sin(3\varphi_h-\varphi_s)\\
w_4(\varphi_h,\varphi_s) &= \sin(\varphi_s)\\
w_5(\varphi_h,\varphi_s) &= \sin(2\varphi_h-\varphi_s)
\end{aligned}\right\} \text{UT}
$$

$$
\left.\begin{aligned}
w_6(\varphi_h,\varphi_s) &= \cos(\varphi_h-\varphi_s)\\
w_7(\varphi_h,\varphi_s) &= \cos(\varphi_s)\\
w_8(\varphi_h,\varphi_s) &= \cos(2\varphi_h-\varphi_s)
\end{aligned}\right\} \text{LT}
$$

8 – modulations.

5 – single spin **3 – double spin**

$$
d\sigma(\varphi_h,\varphi_s) \propto \Big(1 + S_T\sum_{i=1}^{5} D^{w_i(\varphi_h,\varphi_s)}(y)\,A_{UT}^{w_i(\varphi_h,\varphi_s)}\,w_i(\varphi_h,\varphi_s) +
$$

$$
P_{beam}S_T\sum_{i=6}^{8} D^{w_i(\varphi_h,\varphi_s)}(y)\,A_{LT}^{w_i(\varphi_h,\varphi_s)}\,w_i(\varphi_h,\varphi_s) + \ldots\Big).
$$

S_T - target polarization, P_{beam} – beam polarization

$$
A_{U(L),T}^{w_i(\varphi_h,\varphi_s)} = \frac{F_{U(L),T}^{w_i(\varphi_h,\varphi_s)}}{F_{UU,T}}
$$

$D^{w_i(\varphi_h,\varphi_s)}$ – Depolarization factor

Definition of the UT asymmetries

$$\left.\begin{aligned} A_{UT}^{\sin(\varphi_h+\varphi_s)} &= \frac{A_{UT,raw}^{\sin(\varphi_h+\varphi_s)}}{D^{\sin(\varphi_h+\varphi_s)}(y)\, f\,|S_T|} \\ A_{UT}^{\sin(3\varphi_h-\varphi_s)} &= \frac{A_{UT,raw}^{\sin(3\varphi_h-\varphi_s)}}{D^{\sin(3\varphi_h-\varphi_s)}(y)\, f\,|S_T|} \end{aligned}\right\} \quad D^{\sin(\varphi_h+\varphi_S)}(y) = D^{\sin(3\varphi_h-\varphi_S)}(y) = \frac{2(1-y)}{1+(1-y)^2}$$

$$\left.\begin{aligned} A_{UT}^{\sin(2\varphi_h-\varphi_s)} &= \frac{A_{UT,raw}^{\sin(2\varphi_h-\varphi_s)}}{D^{\sin(2\varphi_h-\varphi_s)}(y)\, f\,|S_T|} \\ A_{UT}^{\sin(\varphi_s)} &= \frac{A_{UT,raw}^{\sin(\varphi_s)}}{D^{\sin(\varphi_s)}(y)\, f\,|S_T|} \end{aligned}\right\} \quad D^{\sin(2\varphi_h-\varphi_S)}(y) = D^{\sin(\varphi_S)}(y) = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}$$

$$A_{UT}^{\sin(\varphi_h-\varphi_s)} = \frac{A_{UT,raw}^{\sin(\varphi_h-\varphi_s)}}{D^{\sin(\varphi_h-\varphi_s)}(y)\, f\,|S_T|} \qquad D^{\sin(\varphi_h-\varphi_S)}(y) = \frac{1+(1-y)^2}{1+(1-y)^2} = 1$$

"raw" – indicates number event asymmetry extracted as an amplitude of the corresponding modulation

f - target dilution factor, S_T - target polarization

$D^{w_i(\varphi_h,\varphi_s)}$ – Depolarization factor

Definition of the LT asymmetries

$$A_{LT}^{\cos(2\varphi_h-\varphi_s)} = \frac{A_{LT,raw}^{\cos(2\varphi_h-\varphi_s)}}{D^{\cos(2\varphi_h-\varphi_s)}(y)\, fP_{beam}\, |S_T|}$$

$$A_{LT}^{\cos(\varphi_s)} = \frac{A_{LT,raw}^{\cos(\varphi_s)}}{D^{\cos(\varphi_s)}(y)\, fP_{beam}\, |S_T|}$$

$$D^{\cos(2\varphi_h-\varphi_S)}(y) = D^{\cos(\varphi_S)}(y) = \frac{2y\sqrt{1-y}}{1+(1-y)^2}$$

$$A_{LT}^{\cos(\varphi_h-\varphi_s)} = \frac{A_{LT,raw}^{\cos(\varphi_h-\varphi_s)}}{D^{\cos(\varphi_h-\varphi_s)}(y)\, fP_{beam}\, |S_T|}$$

$$D^{\cos(\varphi_h-\varphi_S)}(y) = \frac{y(2-y)}{1+(1-y)^2}$$

f **- target dilution factor,** S_T **- target polarization**

$D^{w_i(\varphi_h,\varphi_s)}$ **– Depolarization factor**

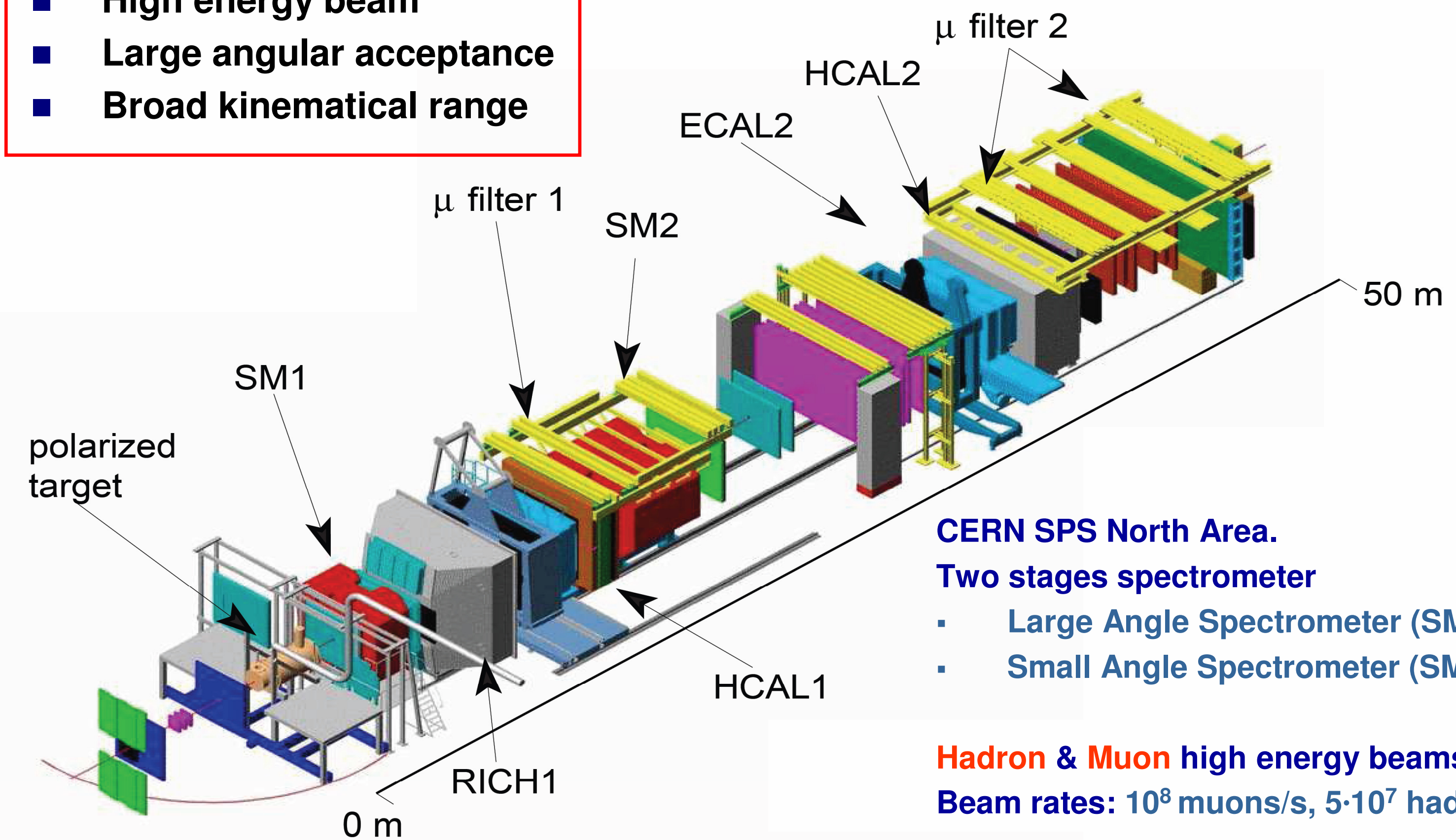
$$A_{UT,raw}^{w_i(\varphi_h,\varphi_s)} = D^{w_i(\varphi_h,\varphi_s)}(y)\, f\, |S_T|\, A_{UT}^{w_i(\varphi_h,\varphi_s)}, \quad (i=1,..,5)$$ **- Single Spin Asymmetries**

$$A_{LT,raw}^{w_i(\varphi_h,\varphi_s)} = D^{w_i(\varphi_h,\varphi_s)}(y)\, fP_{beam}\, |S_T|\, A_{LT}^{w_i(\varphi_h,\varphi_s)}, \quad (i=6,..,8)$$ **- Double Spin Asymmetries**

COmmon Muon Proton Apparatus for Structure and Spectroscopy

- Longitudinally polarized μ^+ beam (160 Gev/c).
- Longitudinally or Transversely polarized ^{6}LiD target
- Momentum, tracking and calorimetric measurements, PID

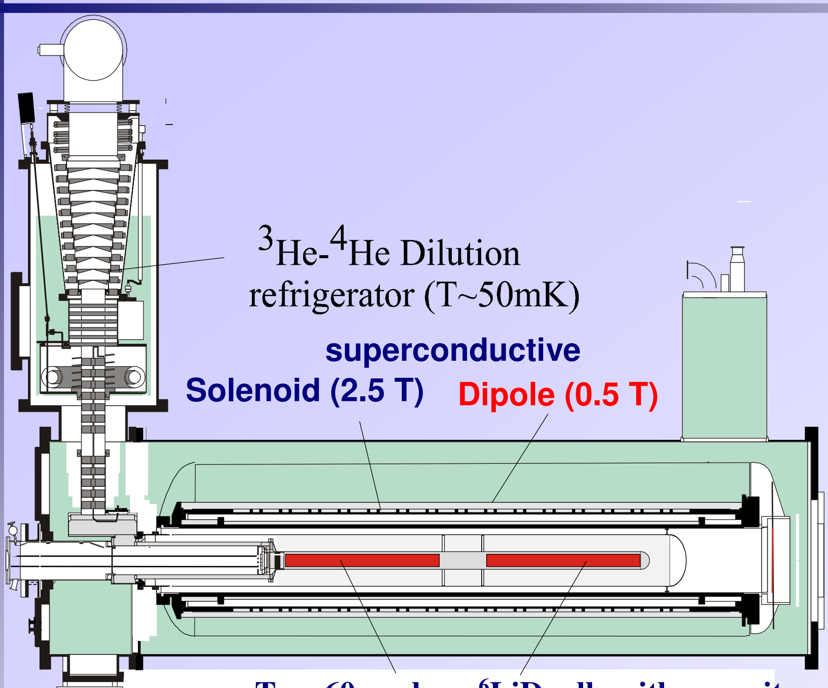
- High energy beam
- Large angular acceptance
- Broad kinematical range



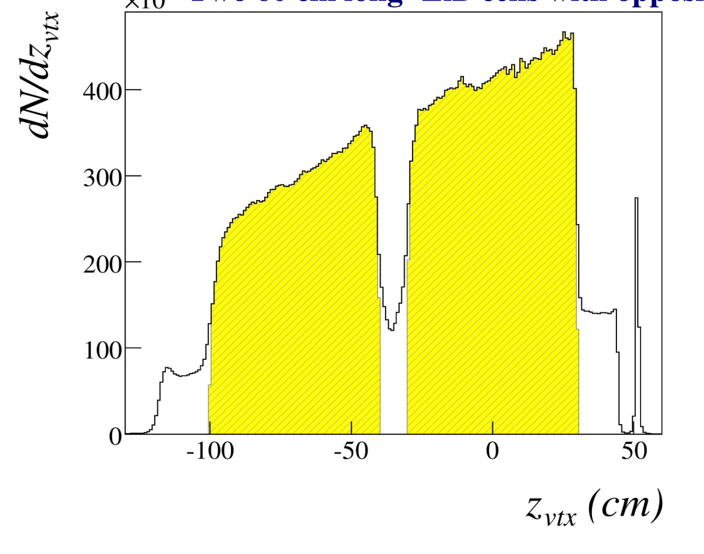
CERN SPS North Area.
Two stages spectrometer
- Large Angle Spectrometer (SM1)
- Small Angle Spectrometer (SM2)

Hadron & Muon high energy beams.
Beam rates: 10^8 muons/s, $5{\cdot}10^7$ hadrons/s.

Polarized target



Two 60 cm long ^{6}LiD cells with opposite polarization

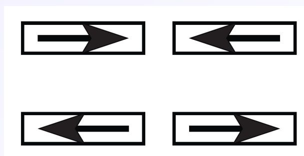


2002-2004 ^{6}LiD:

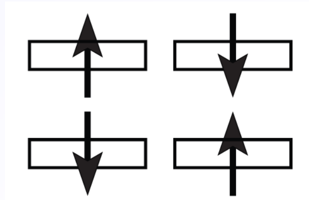
- **Target Polarization ±50%**
- **dilution factor $f \approx 0.4$**
- **~20% of the time transversely polarized**
  - **For transverse runs polarization reversal in two cells each ~ 5days**

Data collected simultaneously for the two target spin orientations.

Longitudinal polarization



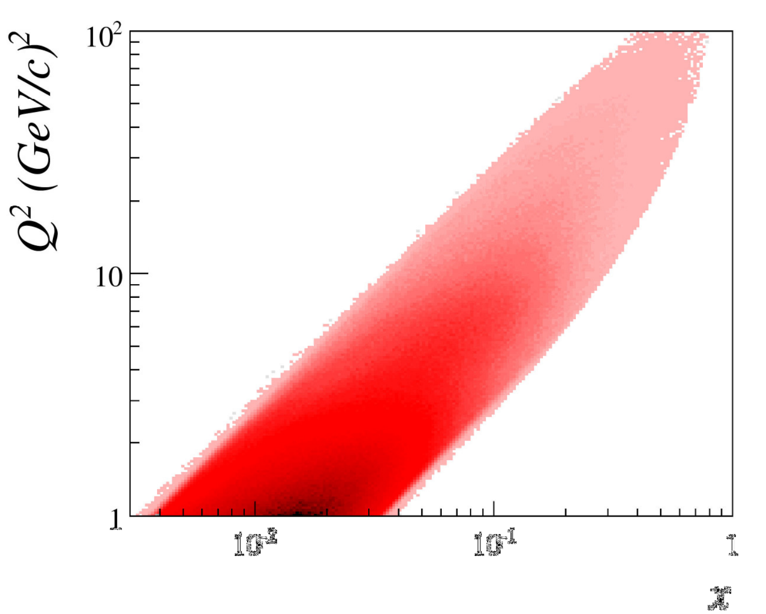
Transverse polarization

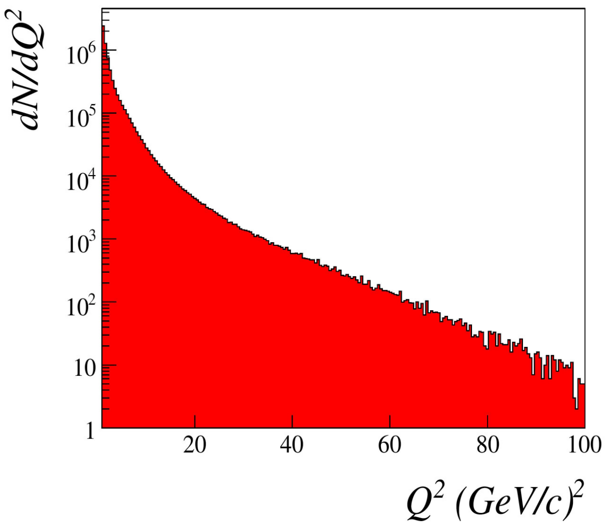


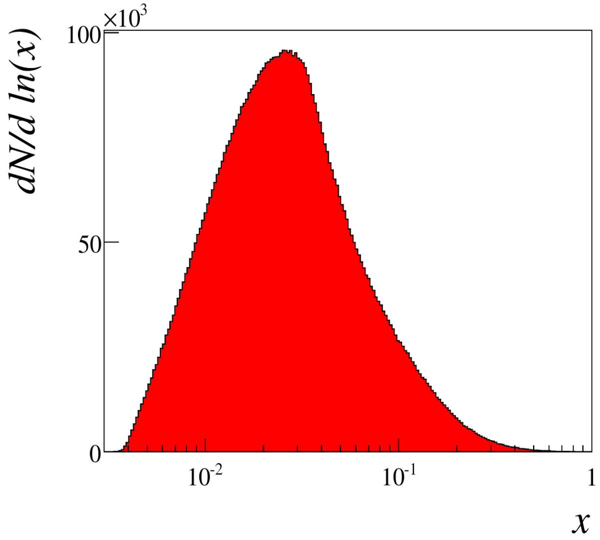
Event selection (2002-2004 deuteron data)

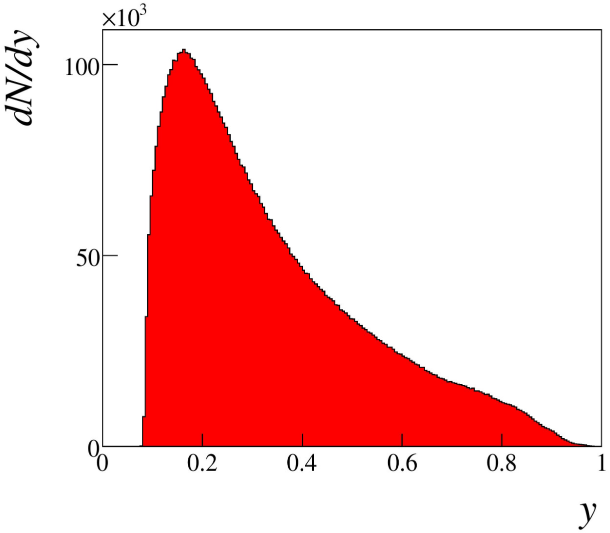
- DIS cuts :
  - $Q^2 > 1$ GeV^2
  - $0.1 < y < 0.9$
  - $W > 5$ GeV
- All Hadrons :
  - $z > 0.2$
  - $p_t > 0.1$ GeV/c

Year	Period	Positive hadrons	Negative hadrons
2002	P2B/P2C	$0.71 \cdot 10^6$	$0.59 \cdot 10^6$
2002	P2H	$0.48 \cdot 10^6$	$0.40 \cdot 10^6$
2003	P1G/P1H	$2.46 \cdot 10^6$	$2.03 \cdot 10^6$
2004	W33/W34	$2.12 \cdot 10^6$	$1.74 \cdot 10^6$
2004	W35/W36	$2.75 \cdot 10^6$	$2.26 \cdot 10^6$
Sum		$8.52 \cdot 10^6$	$7.02 \cdot 10^6$









Extraction of the asymmetries

$$\frac{d\sigma^{\uparrow}-d\sigma^{\downarrow}}{d\sigma^{\uparrow}+d\sigma^{\downarrow}} = A_{UT,raw}^{w_i(\varphi_h,\varphi_s)} \quad (i=1,..,5) \qquad \frac{d\sigma^{\uparrow}-d\sigma^{\downarrow}}{d\sigma^{\uparrow}+d\sigma^{\downarrow}} = A_{LT,raw}^{w_i(\varphi_h,\varphi_s)} \quad (i=6,..,8)$$

8 modulations → 5 combinations of φ_h and φ_S

$$\begin{cases} \Phi_1 = \varphi_h - \varphi_s \\ \Phi_2 = \varphi_h + \varphi_s \\ \Phi_3 = 3\varphi_h - \varphi_s \\ \Phi_4 = \varphi_s \\ \Phi_5 = 2\varphi_h - \varphi_s \end{cases}$$

$$W_1(\Phi_1) = A_{UT,raw}^{w_1(\varphi_h,\varphi_s)} \sin(\Phi_1) + A_{LT,raw}^{w_6(\varphi_h,\varphi_s)} \cos(\Phi_1)$$

$$W_2(\Phi_2) = A_{UT,raw}^{w_2(\varphi_h,\varphi_s)} \sin(\Phi_2)$$

$$W_3(\Phi_3) = A_{UT,raw}^{w_3(\varphi_h,\varphi_s)} \sin(\Phi_3)$$

$$W_4(\Phi_4) = A_{UT,raw}^{w_4(\varphi_h,\varphi_s)} \sin(\Phi_4) + A_{LT,raw}^{w_7(\varphi_h,\varphi_s)} \cos(\Phi_4)$$

$$W_5(\Phi_5) = A_{UT,raw}^{w_5(\varphi_h,\varphi_s)} \sin(\Phi_5) + A_{LT,raw}^{w_8(\varphi_h,\varphi_s)} \cos(\Phi_5)$$

Double Ratio method (NP B765 (2007) 31)

For each data taking period, each cell and polarization state the Φ_j distribution of the number of events can be presented like:

$$N^{\pm}_{u/d}(\Phi_j) = N^{\pm}_{0u/d}(\Phi_j)(1 \pm W_j(\Phi_j))$$

u - Up Stream cell, d - Down Stream cell,

+/- - target polarization

"ratio product" quantities $\longrightarrow$ $$F(\Phi_j) = \frac{N_u^+(\Phi_j)N_d^+(\Phi_j)}{N_u^-(\Phi_j)N_d^-(\Phi_j)}$$

Under the reasonable assumption on the ratio of the acceptances - to be constant before and after polarization reversal in each Φ_j bin:

$$\frac{a_u^+(\Phi_j)}{a_d^-(\Phi_j)} = \frac{a_u^-(\Phi_j)}{a_d^+(\Phi_j)} = const$$ $\longrightarrow$ **Acceptance differences cancel out**

$$F(\Phi_j) = \frac{N_u^+(\Phi_j)N_d^+(\Phi_j)}{N_u^-(\Phi_j)N_d^-(\Phi_j)} \approx 1 + 4W_j(\Phi_j)$$

- **minimizes acceptance effects**
- **spin independent terms cancel at 1st order (Cahn)**

1-D fitting procedure (MINUIT with χ^2 minimization method)

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

Fitting the "ratio product" quantities

$$\begin{cases} F(\Phi_j) = \dfrac{N_u^+(\Phi_j)N_d^+(\Phi_j)}{N_u^-(\Phi_j)N_d^-(\Phi_j)} \\[2ex] \sigma_R(\Phi_j) = \sqrt{\dfrac{1}{N_u^+(\Phi_j)} + \dfrac{1}{N_u^-(\Phi_j)} + \dfrac{1}{N_d^+(\Phi_j)} + \dfrac{1}{N_d^-(\Phi_j)}} \end{cases}$$

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

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

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

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

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

$par[1]$ - "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)

Systematic checks

- Periods compatibility
  - Asymmetries from each period were compared with the weighed mean from all periods.
- Par[0] test
  - Extracted from the fit par[0] ≈ 1 (acceptance cancellation)
- Stability of the acceptance in Φ_j angles

$$R(\Phi_j) = \frac{N_u^+(\Phi_j) N_d^-(\Phi_j)}{N_u^-(\Phi_j) N_d^+(\Phi_j)} \simeq const(\Phi_j) \quad \text{(acceptance assumption)}$$

- The quality of the fit
  - χ^2 - distribution

Systematic errors are smaller than statistical

2-D fitting procedure (9 parameter fit using MINUIT)

9 – X_{Bj}, 8 - z, 9 - P_{hT} bins and 8x8 – φ_h,φ_S bins.

Fitting function

$$F(\varphi_h,\varphi_s) = par[0](1+4(par[1]\sin(\varphi_h+\varphi_s)+par[2]\sin(3\varphi_h-\varphi_s)+ par[3]\sin(\varphi_h-\varphi_s)+par[4]\sin(2\varphi_h-\varphi_s)+par[5]\sin\varphi_s+ par[6]\cos(\varphi_h-\varphi_s)+par[7]\cos(2\varphi_h-\varphi_s)+par[8]\cos\varphi_s))$$

Fitting the "ratio product" quantities

$$\left\{\begin{aligned} F &= \frac{N_u^+(\varphi_h,\varphi_S)N_d^+(\varphi_h,\varphi_S)}{N_u^-(\varphi_h,\varphi_S)N_d^-(\varphi_h,\varphi_S)} \\ \sigma_R &= \sqrt{\frac{1}{N_u^+(\varphi_h,\varphi_S)}+\frac{1}{N_u^-(\varphi_h,\varphi_S)}+\frac{1}{N_d^+(\varphi_h,\varphi_S)}+\frac{1}{N_d^-(\varphi_h,\varphi_S)}} \end{aligned}\right.$$

$$by\ F(\varphi_h,\varphi_S) = par[0](1+4(par[i]\sin(\Phi_i)+par[j]\cos(\Phi_j)))$$

$$,\ldots,\ par[i],\ldots,\ par[j],\ldots \longrightarrow \textit{Raw Asymmetries}$$

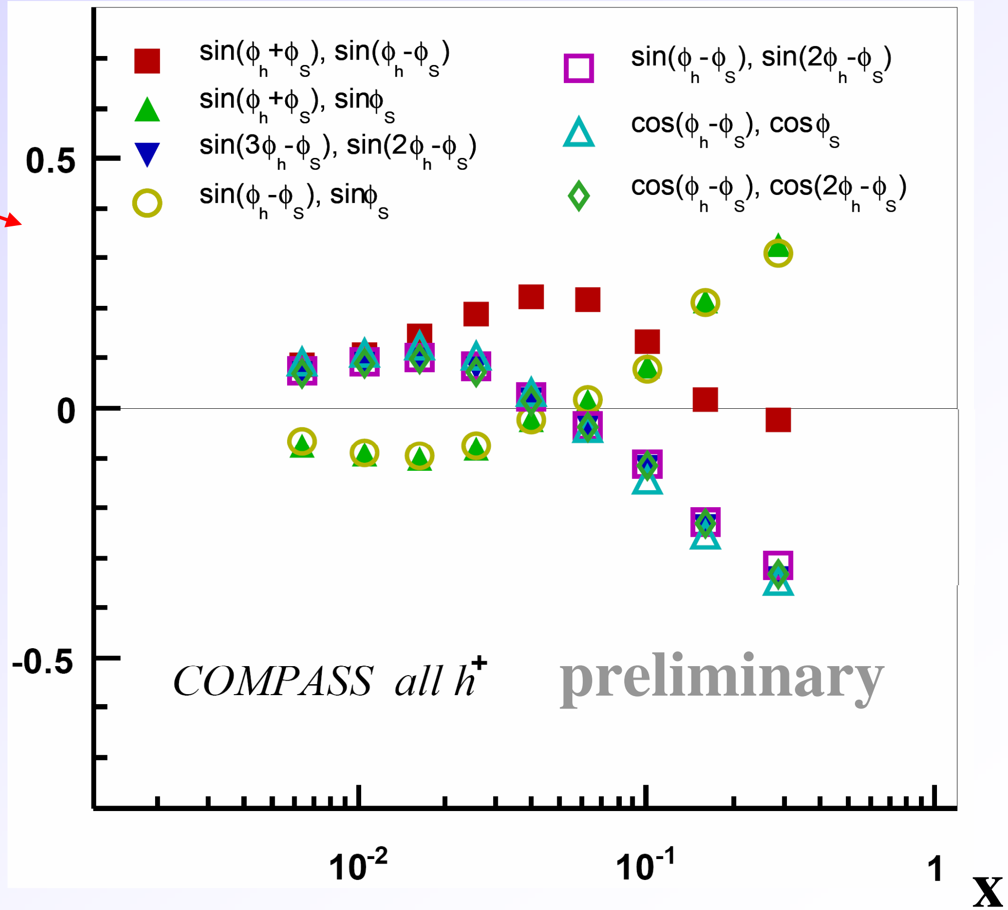
Results from 1D and 2D fits are in good agreement, only 1D results have been released

Correlation Coefficients (positive hadrons, x)

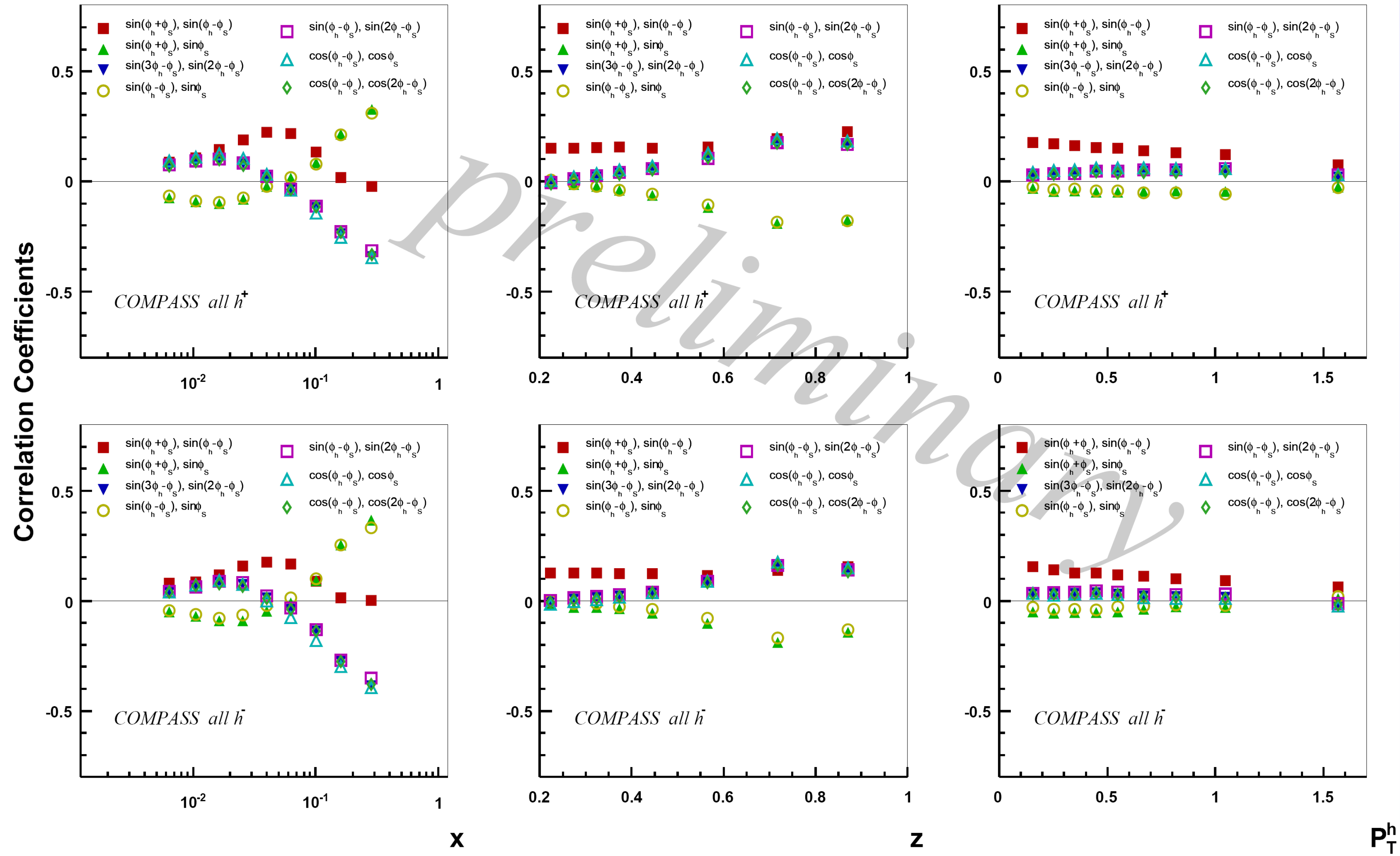
$$\rho = \frac{covarinace_{[i,j]}}{\sqrt{variance_{[i,i]} \cdot variance_{[j,j]}}} \quad i,j = 1,..,8$$

- For the most of the pairs of parameters ρ≈0 and always < 0.4
- Only some correlation coefficients are larger than 0.1
- Correlations are small or negligible

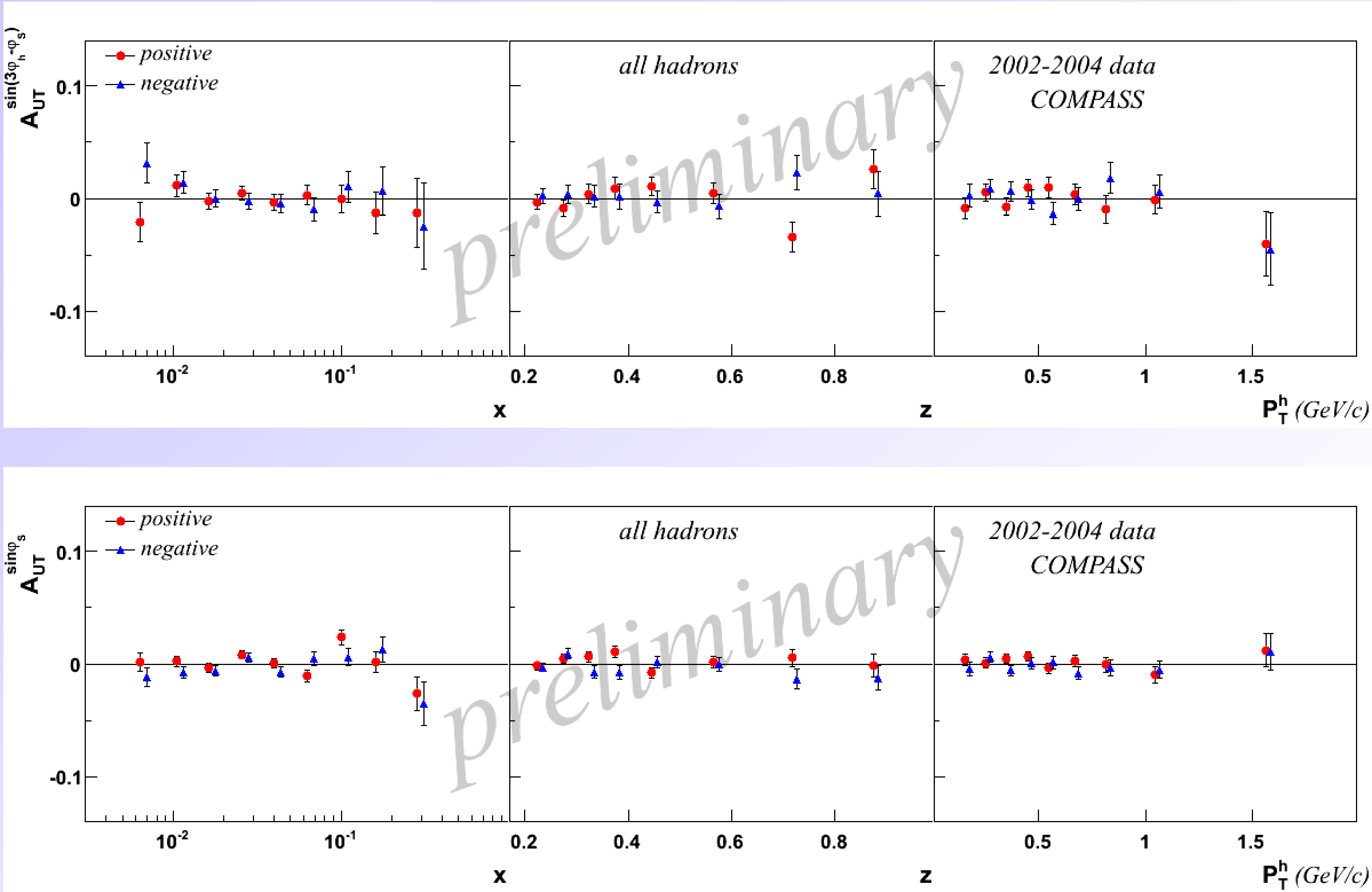
- Correlation between Collins and Sivers asymmetries



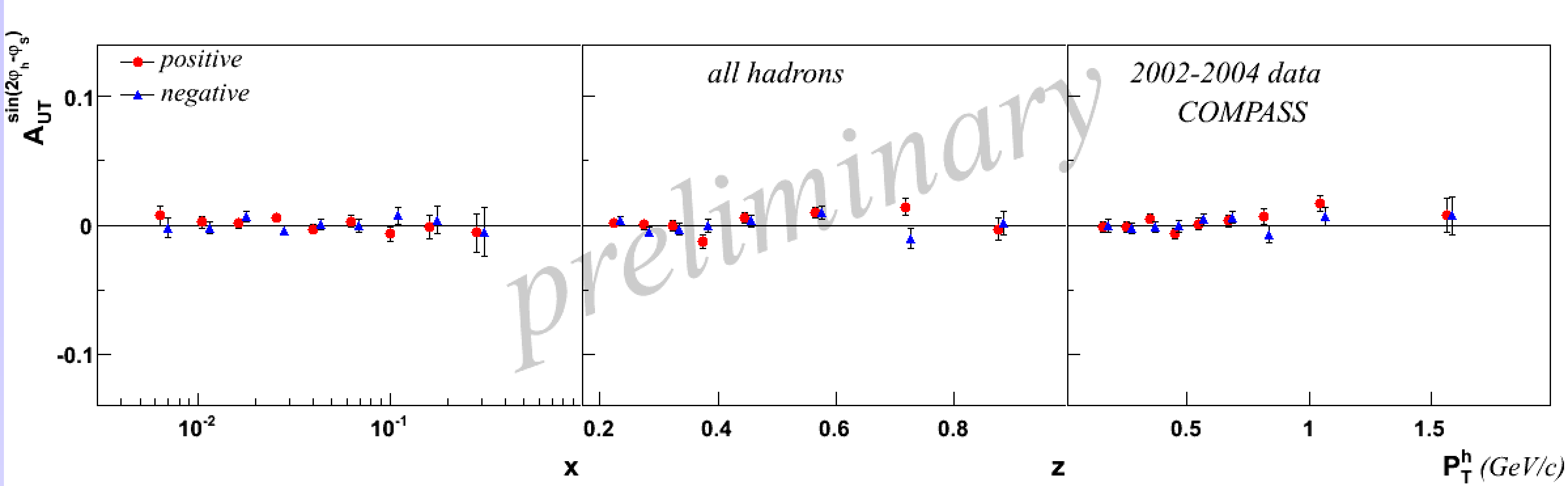
Correlation Coefficients (+/- hadrons, x, z and P_T)

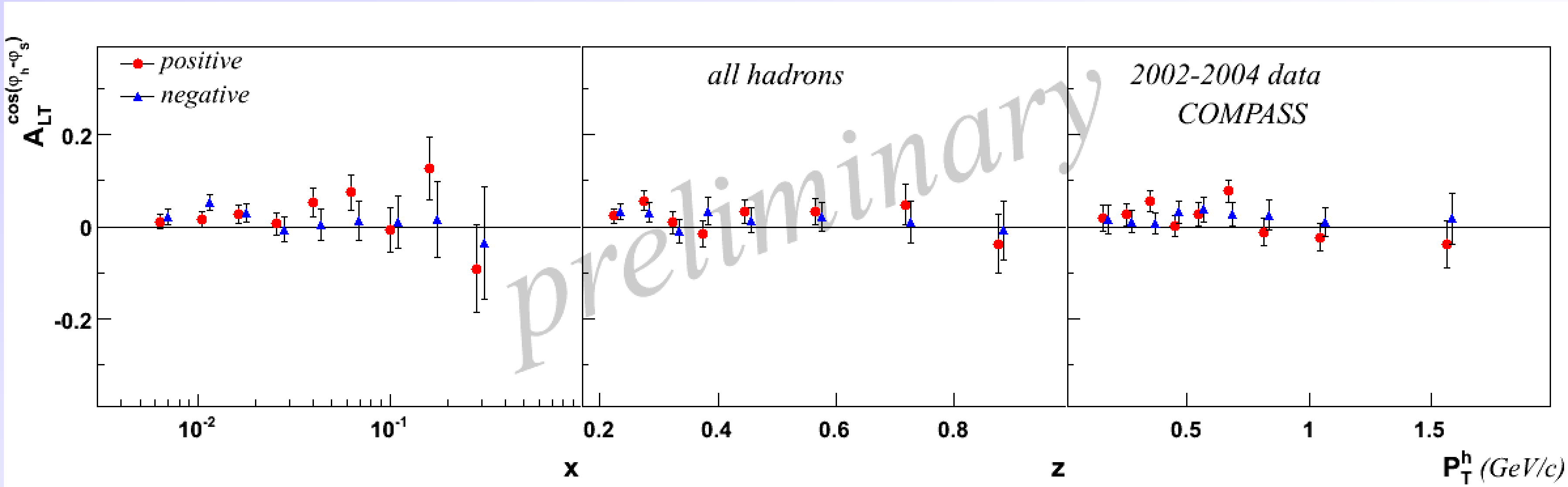


Results for $A_{UT}^{\sin(3\varphi_h-\varphi_s)}$ & $A_{UT}^{\sin(\varphi_s)}$ (2002-2004 deuteron data, 1D fit)

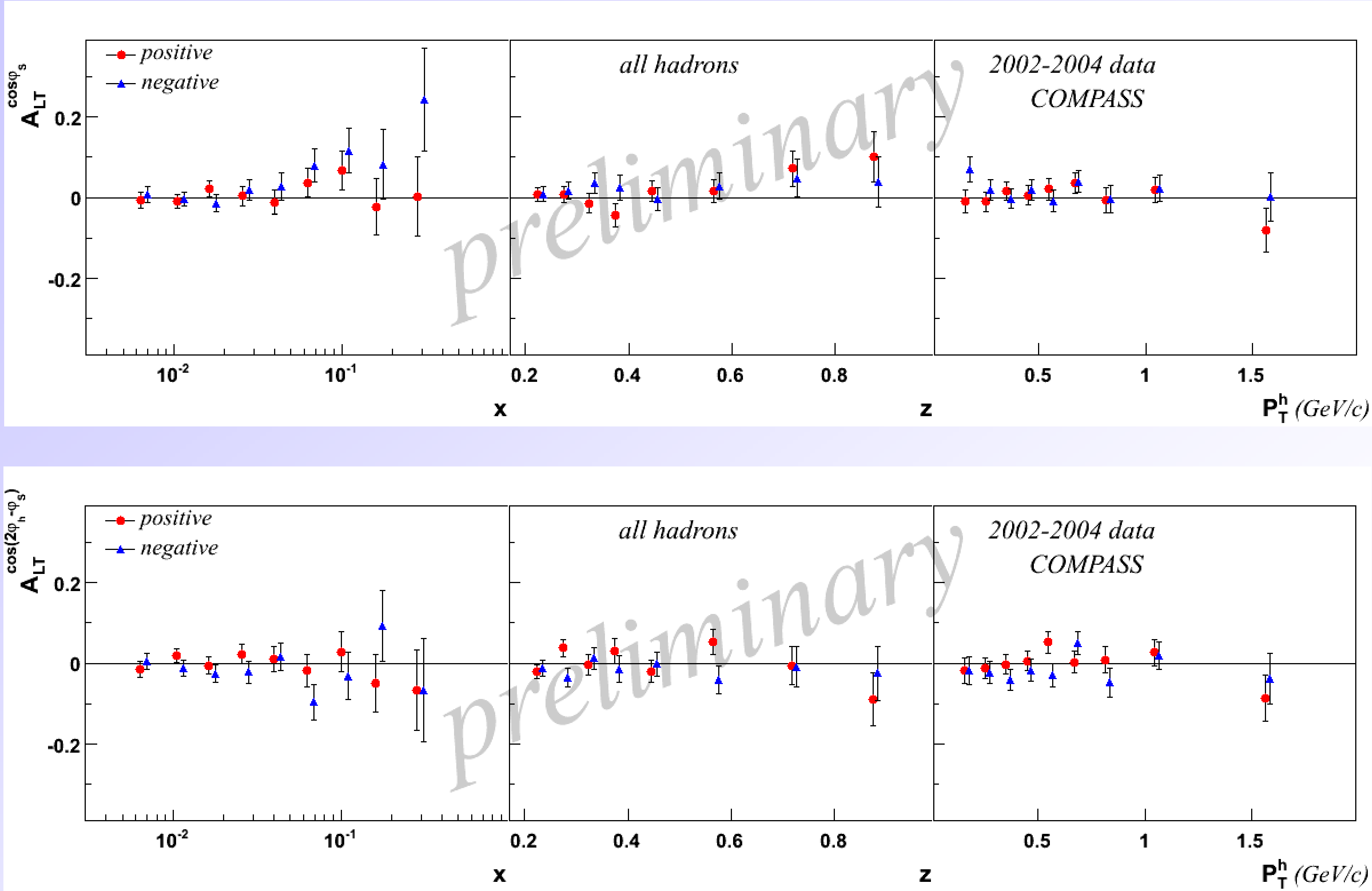


Results for $A_{UT}^{\sin(2\varphi_h-\varphi_s)}$ & $A_{LT}^{\cos(\varphi_h-\varphi_s)}$ (2002-2004 deuteron data, 1D fit)





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



Conclusions

- 6 new asymmetries were measured in COMPASS (2002-2004 deuteron data)

$$A_{UT}^{\sin(3\varphi_h-\varphi_s)},\ A_{UT}^{\sin\varphi_s},\ A_{UT}^{\sin(2\varphi_h-\varphi_s)},\ A_{LT}^{\cos(\varphi_h-\varphi_s)},\ A_{LT}^{\cos\varphi_s}\ \&\ A_{LT}^{\cos(2\varphi_h-\varphi_s)}$$

- Analysis was done using 1 dimensional and 2 dimensional fitting procedures
- Asymmetries obtained from both methods shows the same trend and point to the same physical result.
  - Only 1D results have been released
- Correlation coefficients obtained from 2 dimensional fit are negligible or small
  - In most of the cases $\rho \approx 0$ and always < 0.4
- Results have been checked for systematic effects
  - Systematical errors appears to be smaller than statistical
- All measured asymmetries are compatible with zero within statistical accuracy…

The end

Thank you!!!