Unpolarized azimuthal asymmetries in SIDIS at COMPASS

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on behalf of the COMPASS Collaboration

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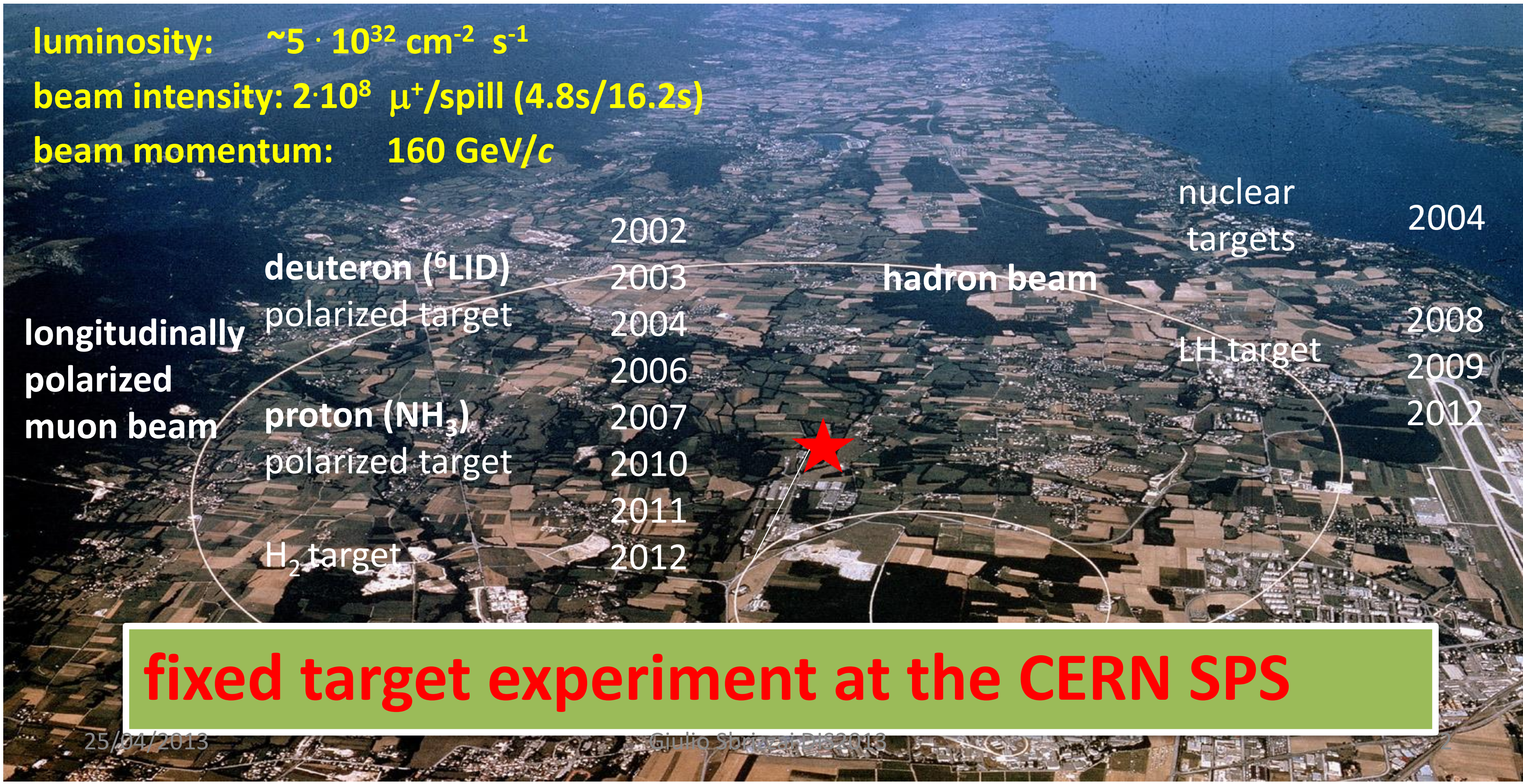
COmmon Muon and Proton Apparatus for Structure and Spectroscopy

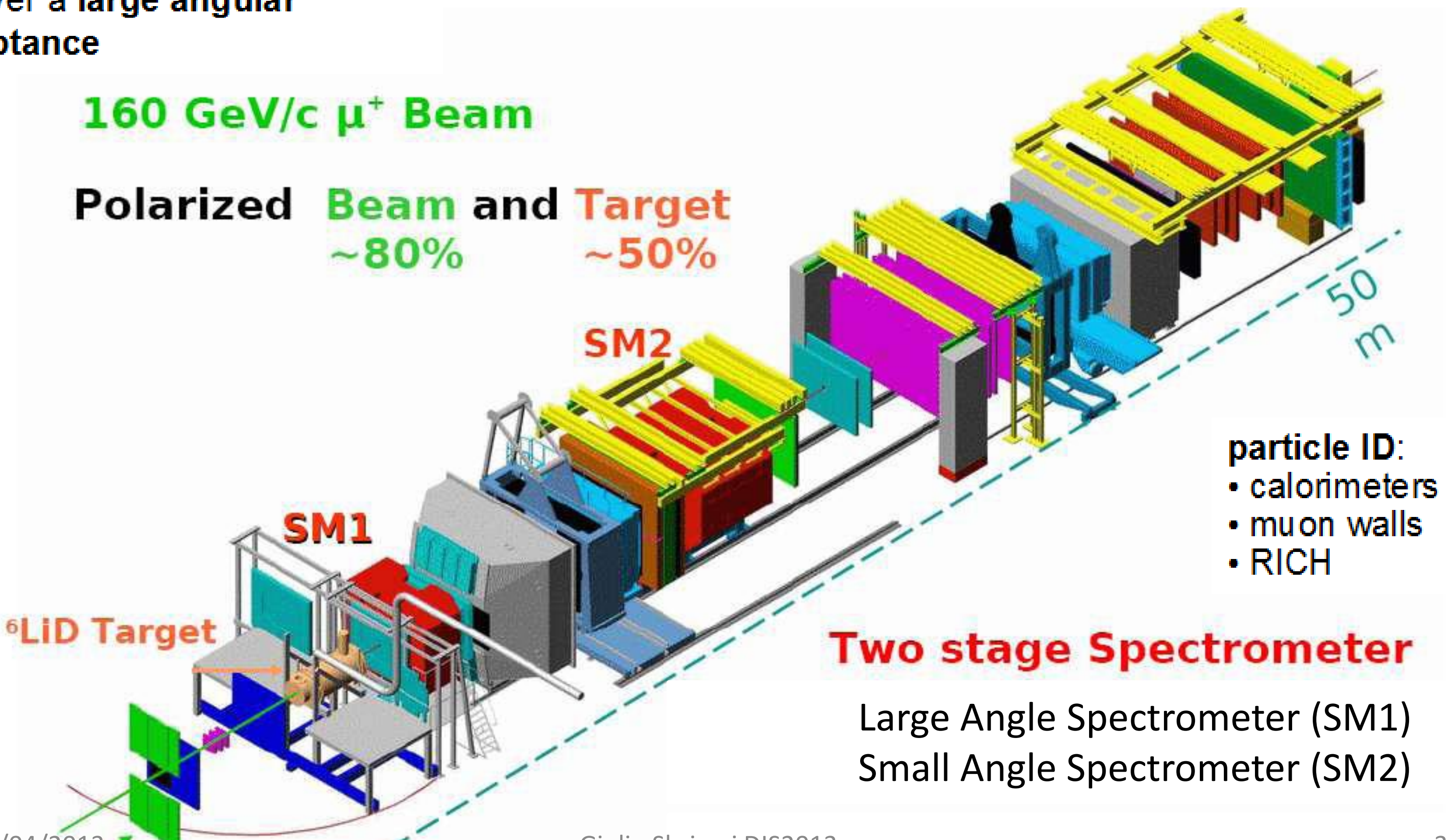
wide physics program carried on using both muon and hadron beam



This talk will focus on the results extracted from the 2004 data (longitudinally pol. muon beam, transversely pol. deuteron target)

The COMPASS experiment (2004 setup)

several tracking detectors of different type
- to cope with **high particle rates**
- to cover a **large angular acceptance**



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

OUTLINE

- ❑ Introduction
- ❑ The Analysis
  - asymmetries extraction
  - systematic errors
- ❑ Results
- ❑ Conclusions

SIDIS: a key process to investigate the structure of the nucleon

lepton interacts with a **single constituent** of the nucleon ($Q^2 > 1 GeV^2/c^2$)

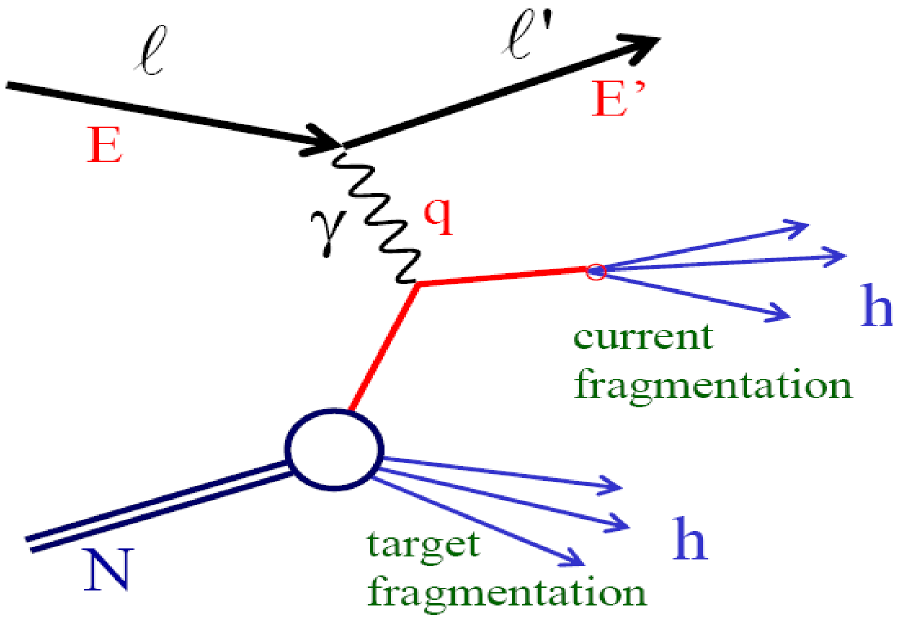
$$q = \ell - \ell'$$

$$Q^2 = -q^2 \qquad W^2 = (P + q)^2$$

$$x = \frac{Q^2}{2P \cdot q}$$ *Bjorken scaling variable*

$$y = \frac{P \cdot q}{P \cdot \ell} =_{LAB} \frac{E - E'}{E}$$

$$z = \frac{P \cdot P_h}{P \cdot q} =_{LAB} \frac{E_h}{E - E'}$$



at least one hadron is detected in the final state
*(information on the **struck quark**)*

azimuthal asymmetries

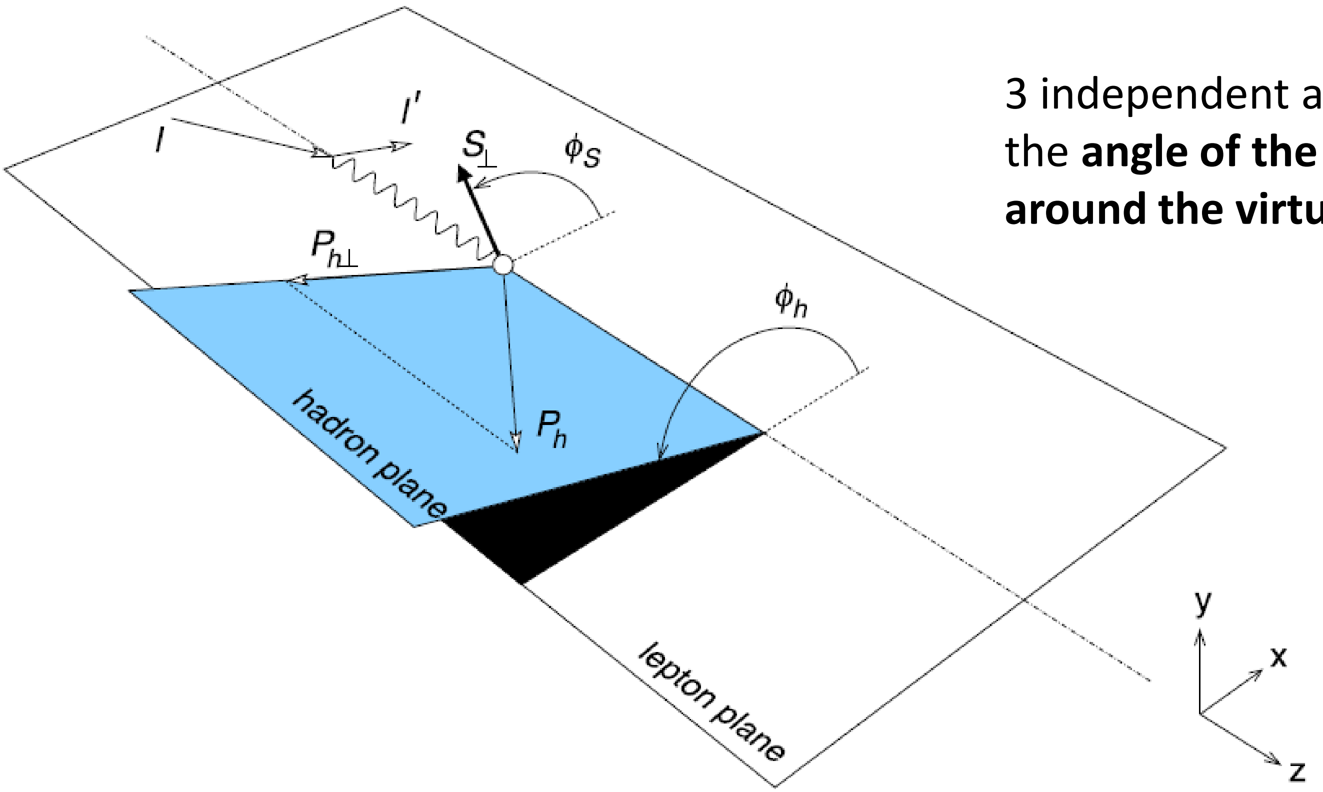
unpolarized target

$$\varepsilon_1 = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2} \qquad \varepsilon_3 = \frac{2y\sqrt{1-y}}{1+(1-y)^2}$$

$$\varepsilon_2 = \frac{2(1-y)}{1+(1-y)^2}$$

λ_l beam polarization

$$N(\phi_h) \propto N_0 \cdot (1 + \varepsilon_1 A^{UU}_{\cos\phi_h} \cos\phi_h + \varepsilon_2 A^{UU}_{\cos 2\phi_h} \cos 2\phi_h + \lambda_l \varepsilon_3 A^{LU}_{\sin\phi_h} \sin\phi_h)$$



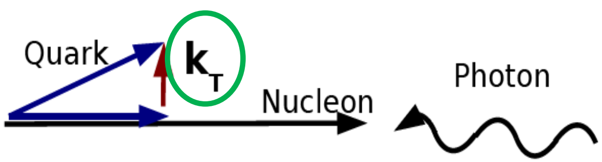
3 independent azimuthal modulations of the **angle of the hadron ϕ_h around the virtual photon direction**

QPM — **convolution on the TM of the quark between different PDFs and a FFs**

$$\sum_q e_q^2 f_q(x, k_\perp) \otimes D_q^h(z, p_\perp)$$

$$N(\phi_h) \propto N_0 \cdot (1 + \varepsilon_1 A^{UU}_{\cos\phi_h} \cos\phi_h + \varepsilon_2 A^{UU}_{\cos 2\phi_h} \cos 2\phi_h + \lambda_l \varepsilon_3 A^{LU}_{\sin\phi_h} \sin\phi_h)$$

mainly **Cahn** effect: **kinematical effect** proportional to the **quark transverse momentum**



$$d\sigma^{lq\to lq} \propto \hat{s}^2 + \hat{u}^2 \propto \left(1 + \varepsilon_1 \frac{k_\perp}{Q}\cos\varphi\right)$$

Boer-Mulders (*T-odd !*) function, one of the most famous **TMD PDF**, convoluted with the **Collins FF**

the **Boer-Mulders function correlates** the **quark transverse momentum** and the **quark spin** in an **unpolarized nucleon**

higher twist effect proportional to beam polarization

no clear interpretation in terms of PM

QPM **convolution on the TM of the quark between different PDFs and a FFs**

$$\sum_q e_q^2 f_q(x, k_\perp) \otimes D_q^h(z, p_\perp)$$

$$N(\phi_h) \propto N_0 \cdot (1 + \varepsilon_1 A_{\cos\phi_h}^{UU} \cos\phi_h + \varepsilon_2 A_{\cos 2\phi_h}^{UU} \cos 2\phi_h + \lambda_l \varepsilon_3 A_{\sin\phi_h}^{LU} \sin\phi_h)$$

$$A_{\dots}^{\dots} = \frac{F_{\dots}^{\dots}}{F_{UU}}$$

$$F_{UU,\text{Cahn}}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\mathbf{h}}\cdot\mathbf{k}_T}{M} f_1 D_1\right]$$

$$F_{UU,\text{BM}}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{(\hat{\mathbf{h}}\cdot\mathbf{k}'_T)\,\mathbf{k}_T^2}{M_h M^2} h_1^\perp H_1^\perp\right]$$

$$F_{UU,\text{Cahn}}^{\cos 2\phi_h} = \frac{M^2}{Q^2}\,\mathcal{C}\left[\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)^2 - \mathbf{k}_T^2}{M^2} f_1 D_1\right]$$

$$F_{UU,\text{BM}}^{\cos 2\phi_h} = \mathcal{C}\left[-\frac{2(\hat{\mathbf{h}}\cdot\mathbf{k}_T)(\hat{\mathbf{h}}\cdot\mathbf{k}'_T) - \mathbf{k}_T\cdot\mathbf{k}'_T}{M M_h} h_1^\perp H_1^\perp\right]$$

$$A_{\cos\phi_h}^{UU} = \frac{1}{Q}\,\text{Cahn} + \frac{1}{Q}\,\text{BM}$$

$$A_{\cos 2\phi_h}^{UU} = \text{BM} + \frac{1}{Q^2}\,\text{Cahn}$$

different Q^2 dependencies

other higher twist effects ?

The **amplitudes of the 3 azimuthal modulations** have been **measured at COMPASS** separately for **positive and negative hadrons**, as functions of the kinematical variables **x,z** and $\mathbf{P^h_T}$ (transv. mom. of the hadron w.r.t. the virtual photon)

Basic idea of the method

• To measure those amplitudes from experimental data
the **apparatus acceptance is needed** (unlike transverse spin asymmetries measurement)

• **for each bin** (k) in **x, z** and $\mathbf{P_T^h}$

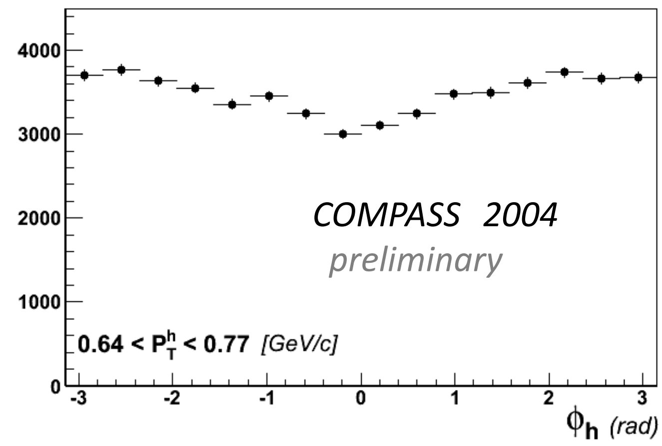
- The **measured azimuthal distributions** need to be **corrected** for the **apparatus acceptance** which may depend on ϕ_h

$$N_k^{corr}(\phi_h) = \frac{N_k(\phi_h)}{Acc_k(\phi_h)}$$

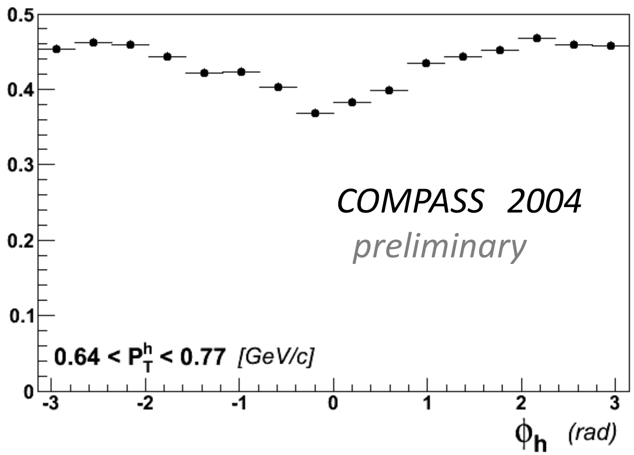
- Azimuthal acceptance calculated from **dedicated MC simulations**

$$Acc_k(\phi_h) = \frac{R_k^{mc}(\phi_h)}{G_k^{mc}(\phi_h)}$$

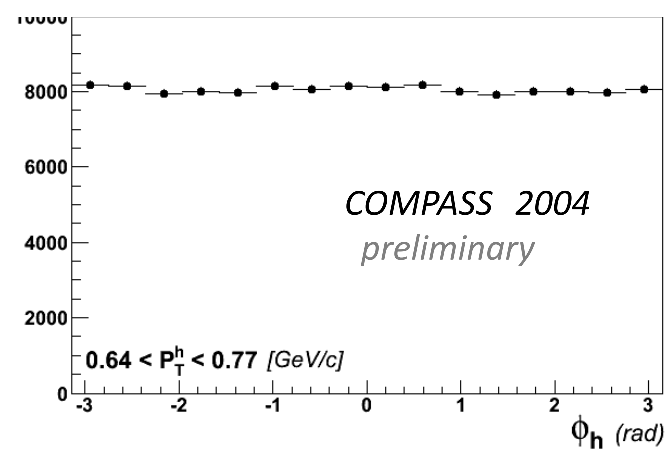
MC rec. azimuthal distribution



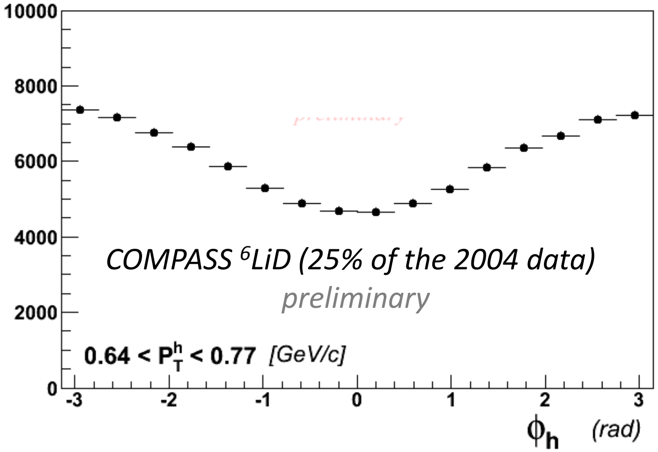
azimuthal acceptance



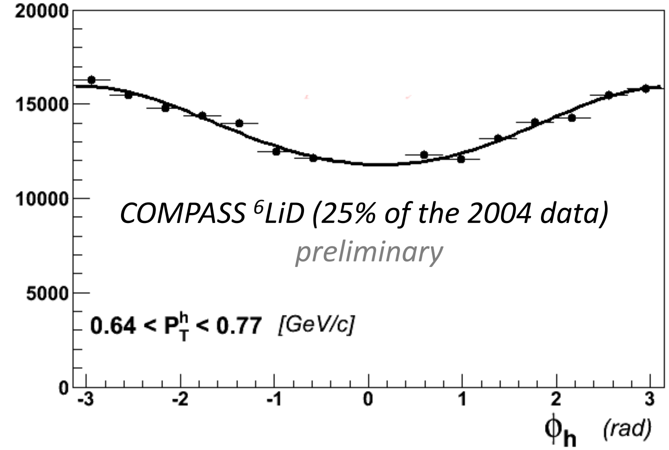
MC gen. azimuthal distribution



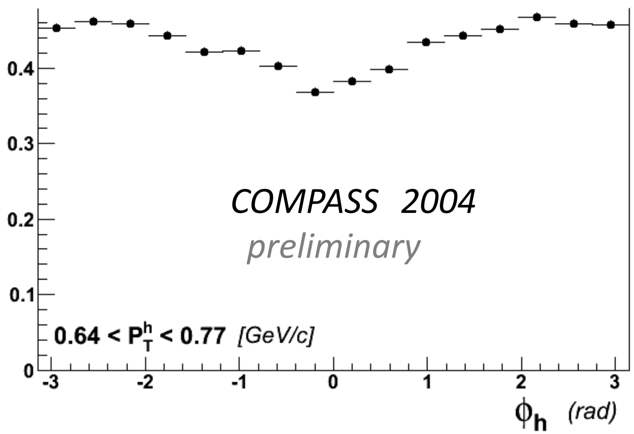
measured azimuthal distribution



measured azimuthal distributions corrected by the acceptance



azimuthal acceptance



amplitudes extracted with a fit:

$$p_0 \cdot (1 + p_1 \cdot \cos\phi_h + p_2 \cdot \cos 2\phi_h + p_3 \cdot \sin\phi_h)$$

The apparatus azimuthal acceptance *as a function of the event kinematics has been* ***studied*** *at length* ***in order to exclude*** *the regions giving rise to* ***large azimuthal modulations in the acceptance*** *(above 50% for some bin)*

→ **new cuts have been tuned:**

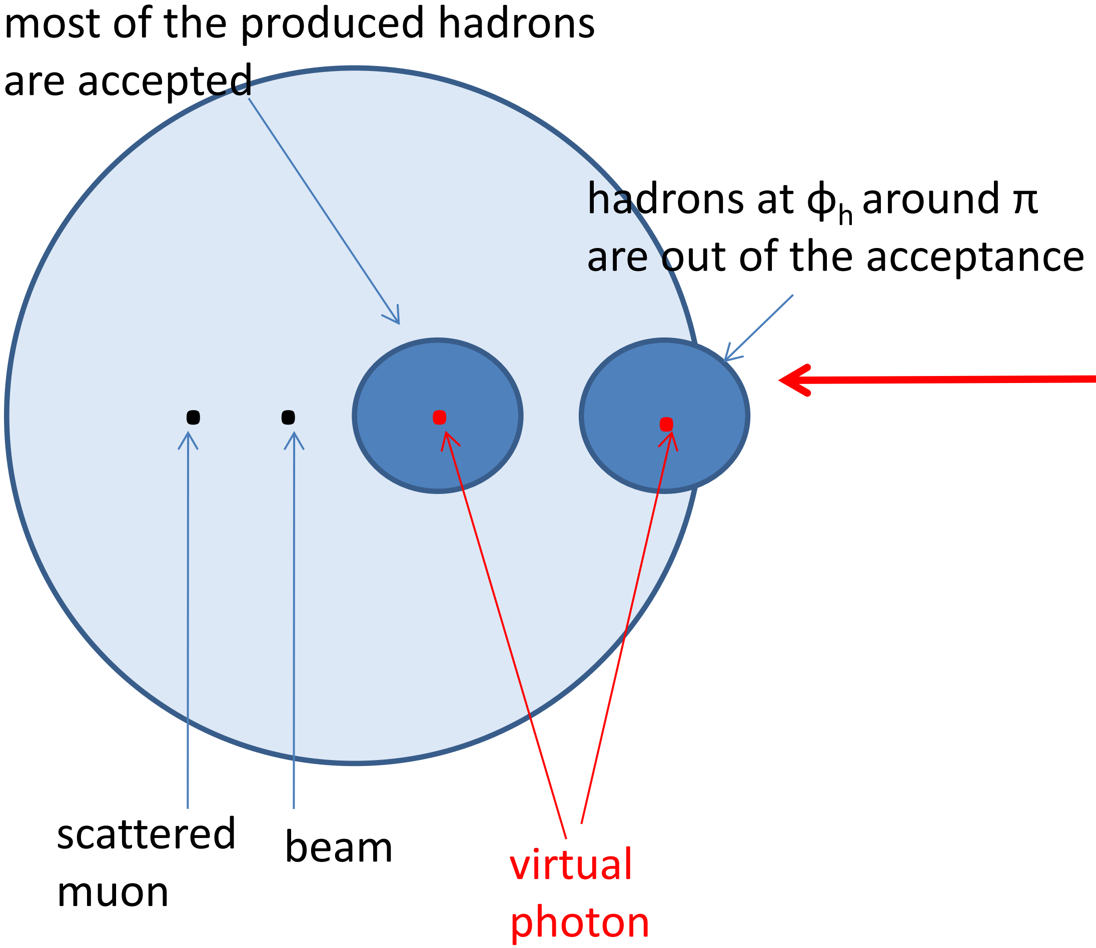
$Q^2 > 1$ (GeV/c)^2

$< y < 0.9$

$W > 5$ GeV/c^2

$0.2 < z < 0.85$

$0.1 < P^T_h$ GeV/c



$Q^2 > 1$ (GeV/c)^2

$\theta_\gamma^{lab} < 0.06$

$0.003 < x < 0.13$

$0.2 < y < 0.9$

$W > 5$ GeV/c^2

$0.2 < z < 0.85$

$0.1 < P^T_h < 1$ GeV/c

the **large corrections** given by the acceptance **disappeared**

SYSTEMATIC ERROR

the sources of the systematic error which have been checked and included in the evaluation are the following:

- differences between amplitudes of the azimuthal modulations extracted using the 3 different MC samples

- differences between amplitudes of the azimuthal modulations extracted from transverse and longitudinal data (different apparatus setup → 2 different MC descriptions)

- estimation of possible azimuthal effects from unknown inefficiencies of detectors in low redundancies region

the different contributions calculated in each kinematical bin have been summed in quadrature :

$$\sigma_{sys} = 2 \cdot \sigma_{stat}$$

other studies ...

• a first calculation of the possible effects of radiative corrections have been performed using RADGEN and have been found to be relatively small

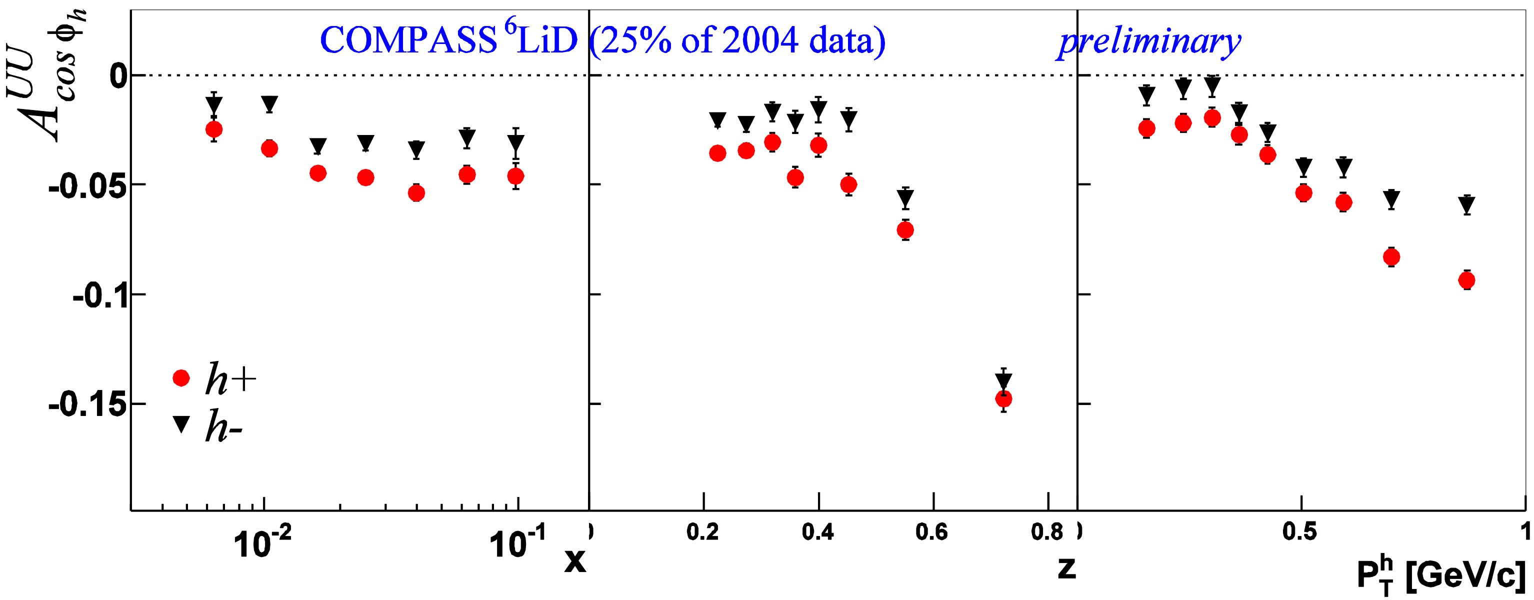
• more amplitudes have been added in the fitting function to the ones expected from the unpolarized cross section → compatible with zero

... not included in the systematic errors

RESULTS

Results extracted binning alternatively in x, z and P_T^h

shown
at SPIN2010



sys ≈ 2 · stat

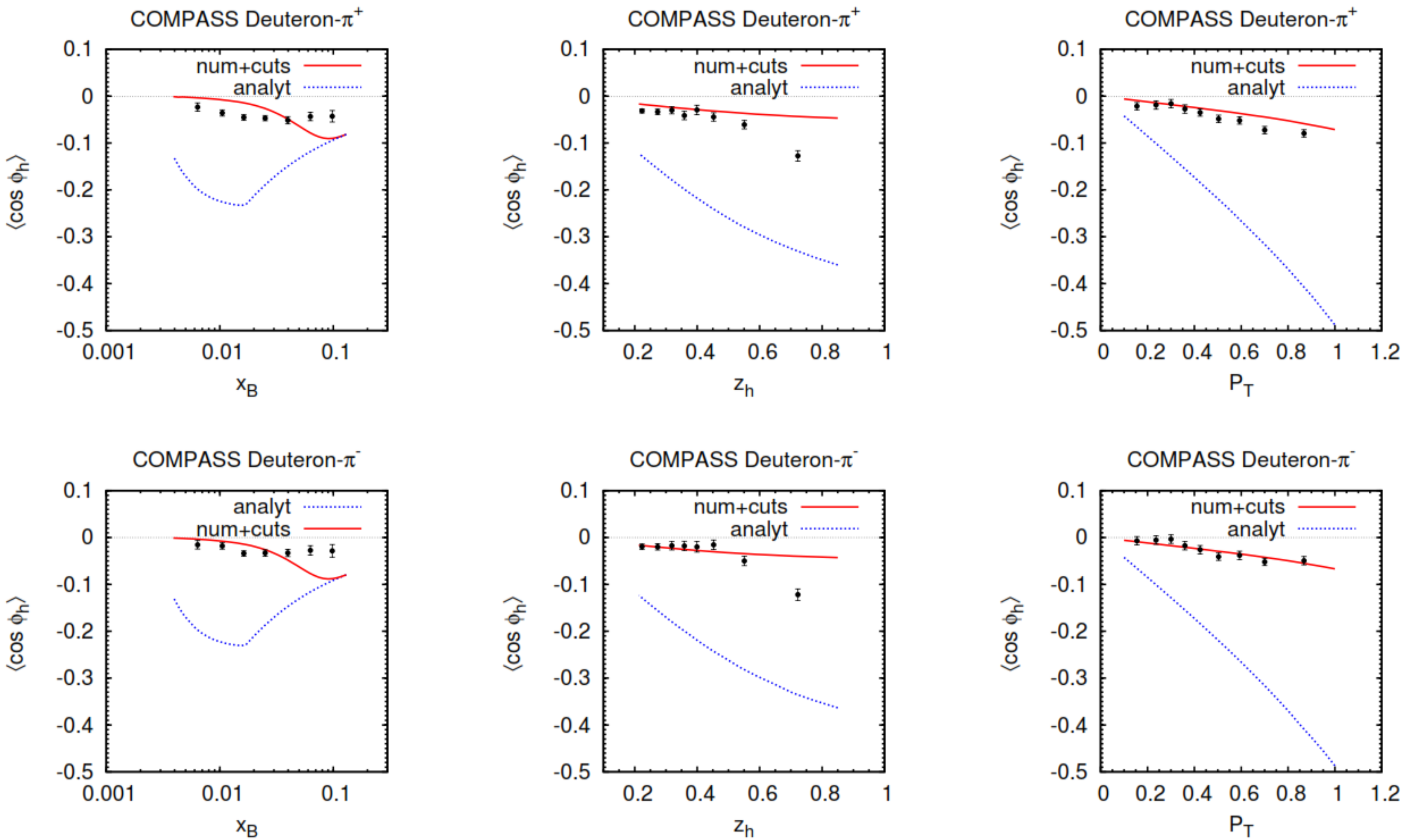
$$A^{UU}_{\cos\phi_h} = \frac{1}{Q}\,\text{Cahn} + \frac{1}{Q}\,\text{BM}$$

strong z dependence, for z > 0.5

important input to phenomenological predictions

kinematical cuts had to be introduced for the quark intrinsic transverse momentum

$$f_{q/p}(x,k_\perp) = f_{q/p}(x)\,\frac{1}{1-e^{-(k_\perp^{\max})^2/\langle k_\perp^2\rangle}}\,\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle}}{\pi\langle k_\perp^2\rangle}$$



Results extracted binning alternatively in x, z and P_T^h

shown
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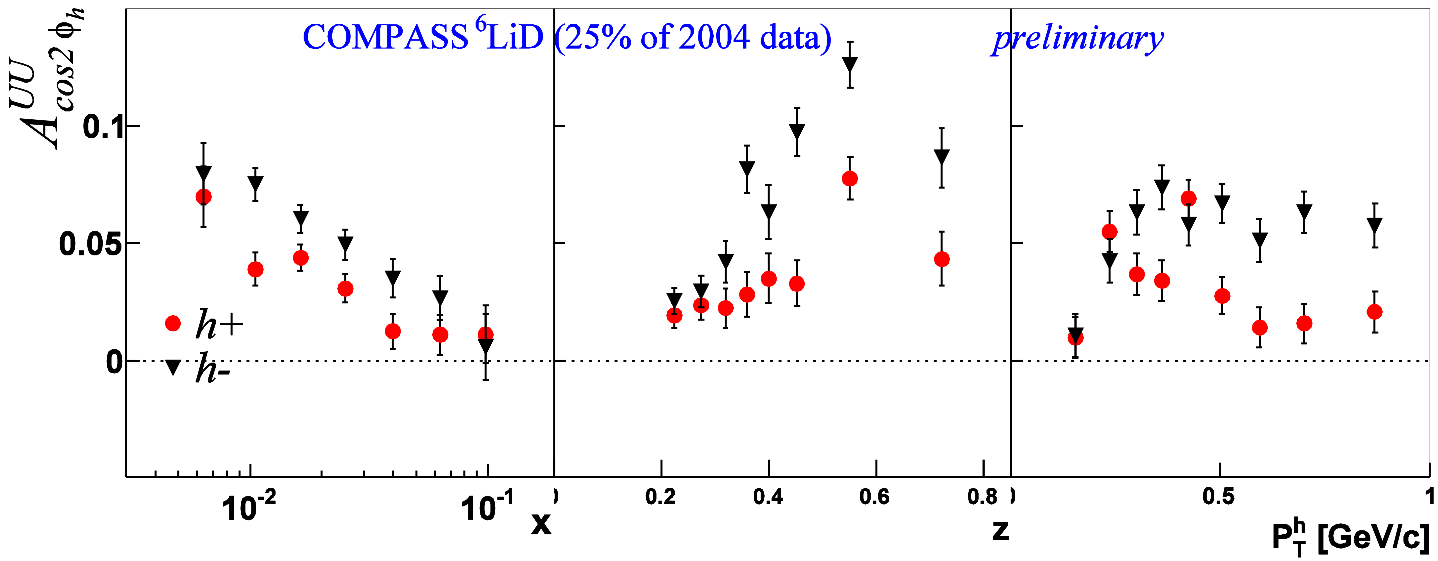
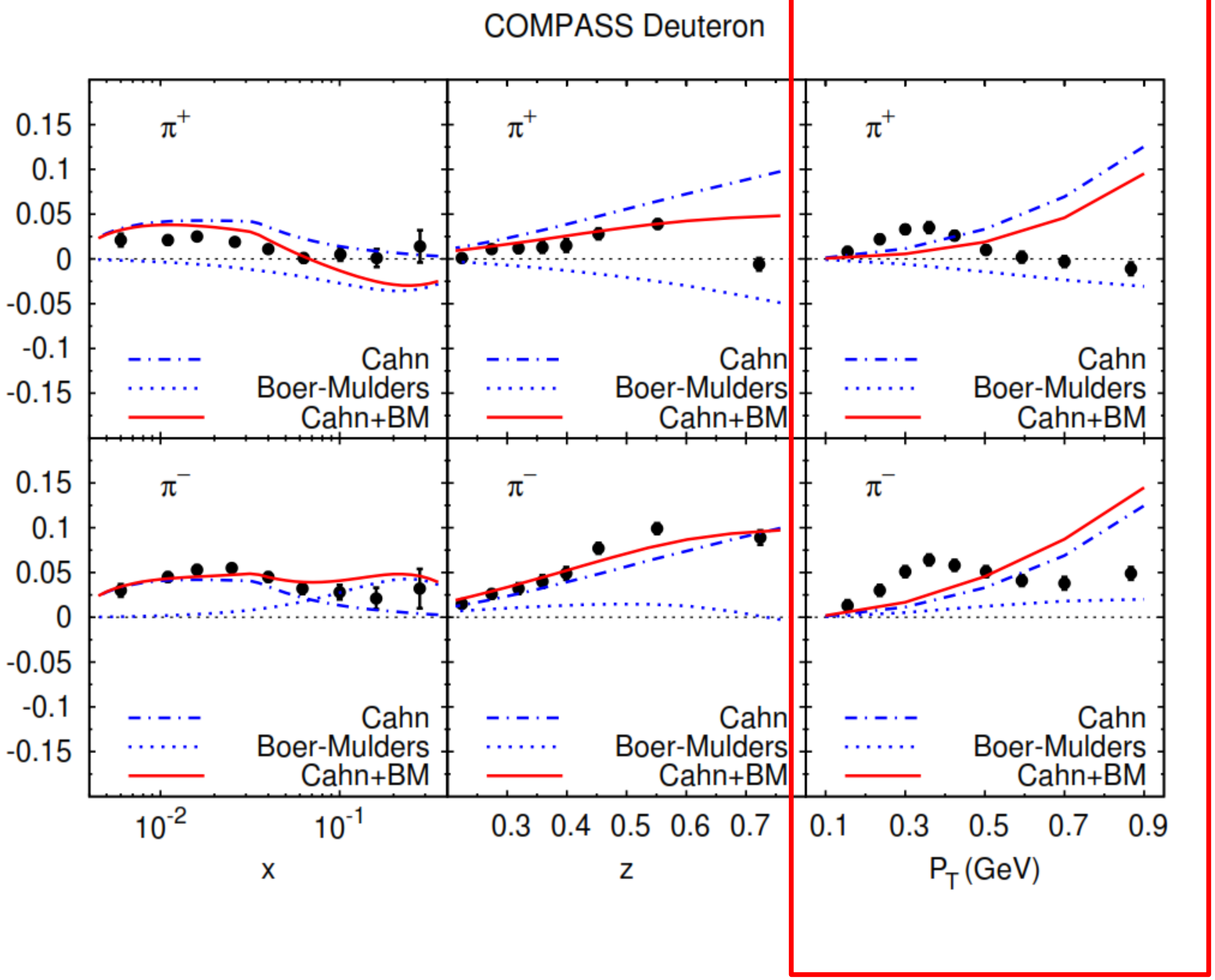


sys ≈ 2 · stat

$$A^{UU}_{\cos 2\phi_h} = \text{BM} + \frac{1}{Q^2}\,\text{Cahn}$$

P_T^h dependence difficult to reproduce (PRD81, Barone,Melis,Prokudin)

$A^{UU}_{\cos 2\phi_h}$



P_T^h dependence difficult to reproduce (PRD81, Barone,Melis,Prokudin)

to better understand the interesting and unexpected kinematical dependencies found

a multi dimensional analysis has been done

binning simultaneously in x, z and P_T^h

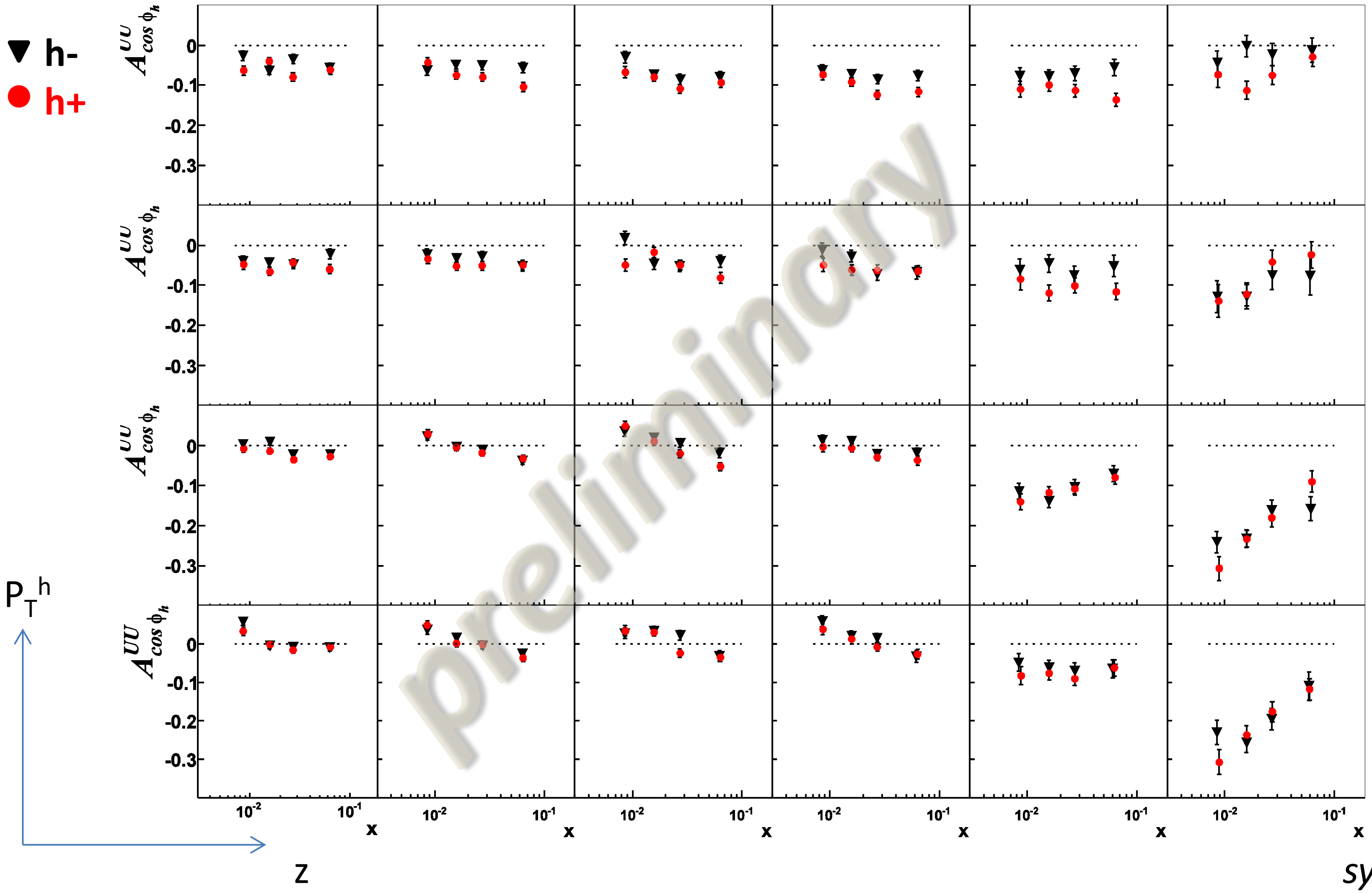
x	P_T^h	z
0.003 - 0.012	0.1 - 0.3	0.2 - 0.25
0.012 - 0.02	0.3 - 0.5	0.25 - 0.32
0.02 - 0.038	0.5 - 0.64	0.32 - 0.40
0.038 - 0.13	0.64 - 1.0	0.40 - 0.55
		0.55 - 0.70
		0.70 - 0.85

results shown at SPIN2012 in Dubna

Results for

$$A^{UU}_{\cos\phi_h}$$

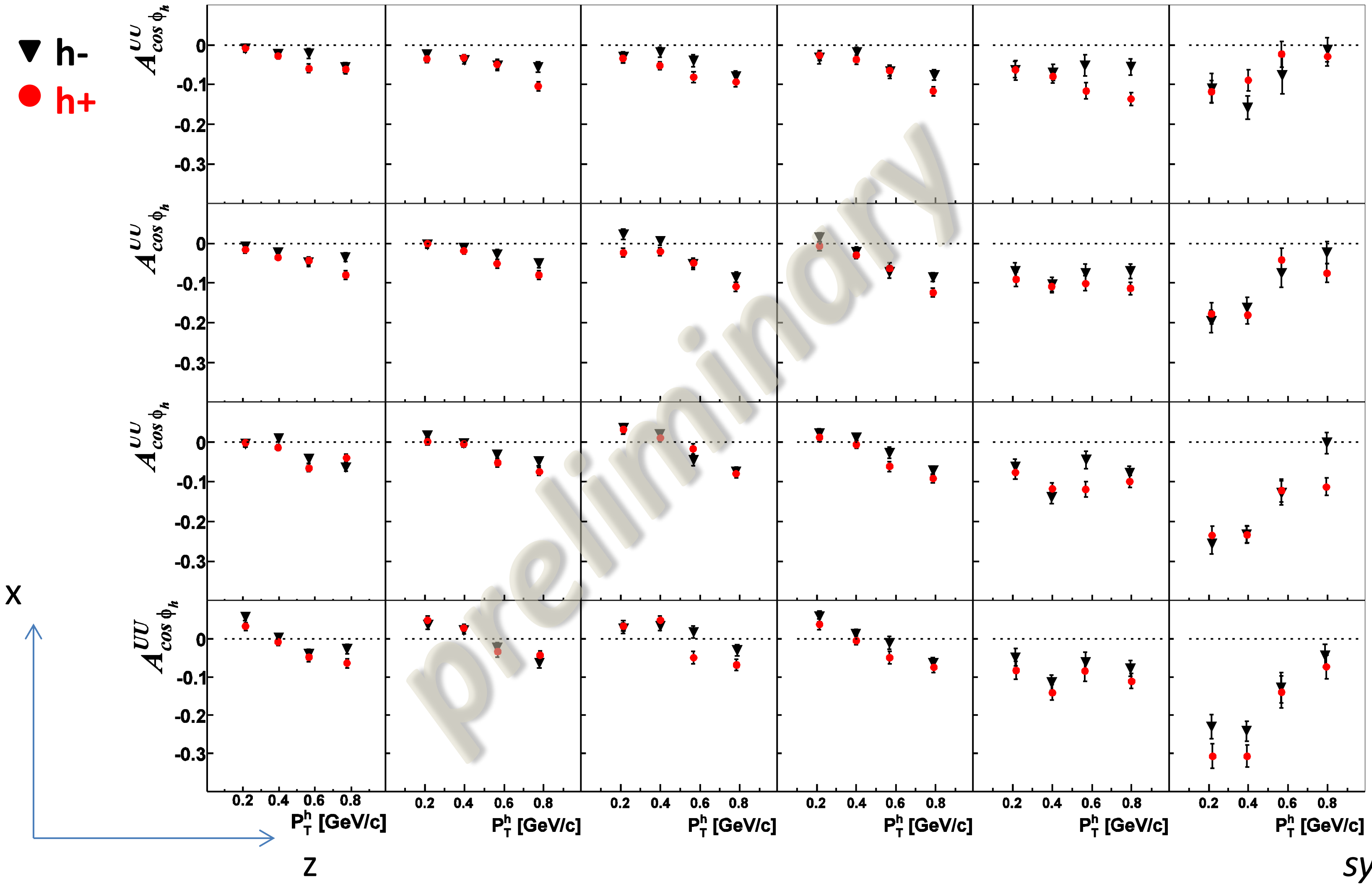
COMPASS ^{6}LiD (25% of 2004 data)



sys ≈ 2 · stat

largest difference between positive and negative hadrons at large P_T^h
x trend changes going from small to large z values

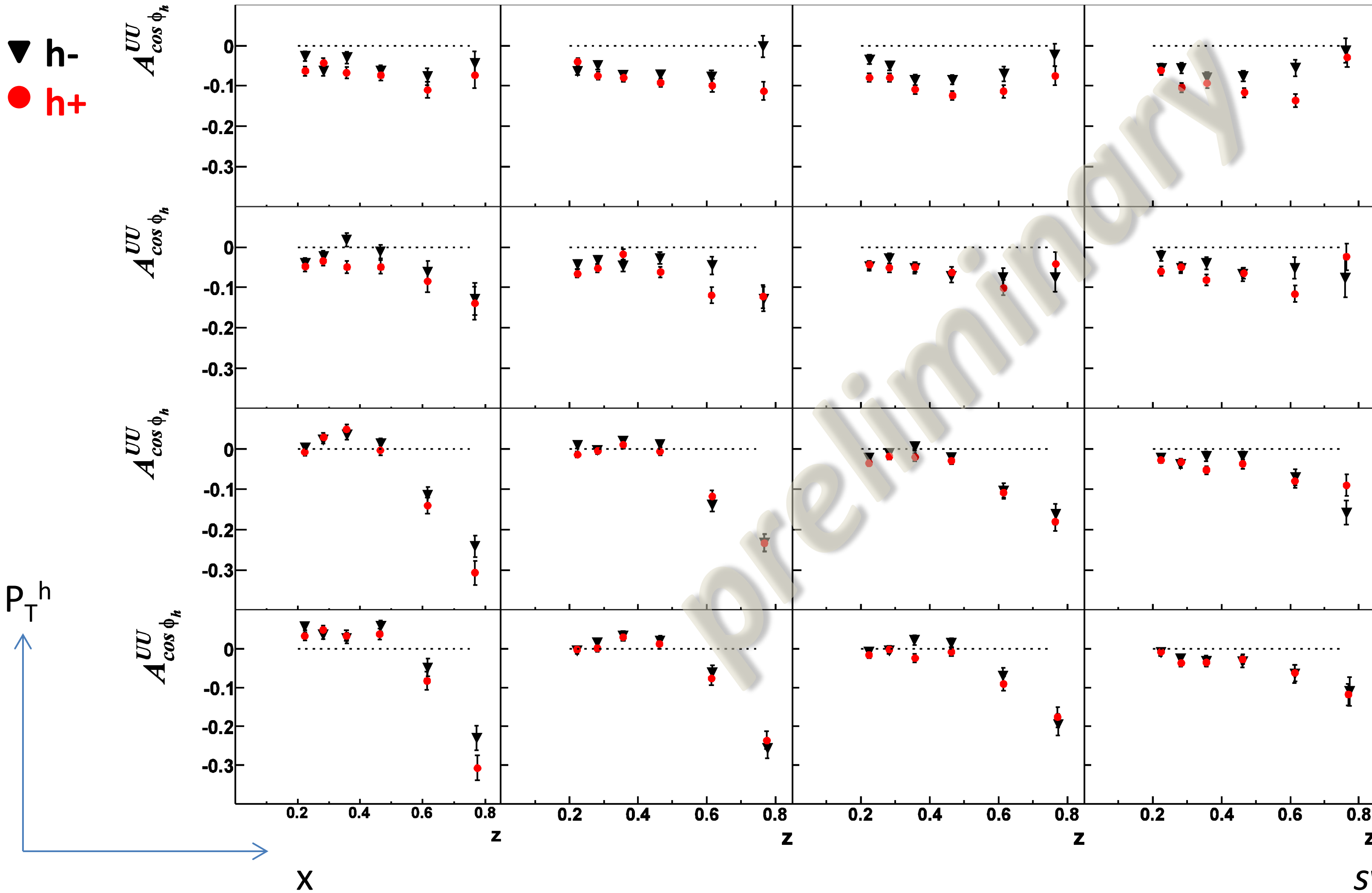
COMPASS ^{6}LiD (25% of 2004 data)



sys ≈ 2 · stat

P_T^h trend changes going from small to large z values
and it is roughly the same for all x intervals

COMPASS ^{6}LiD (25% of 2004 data)



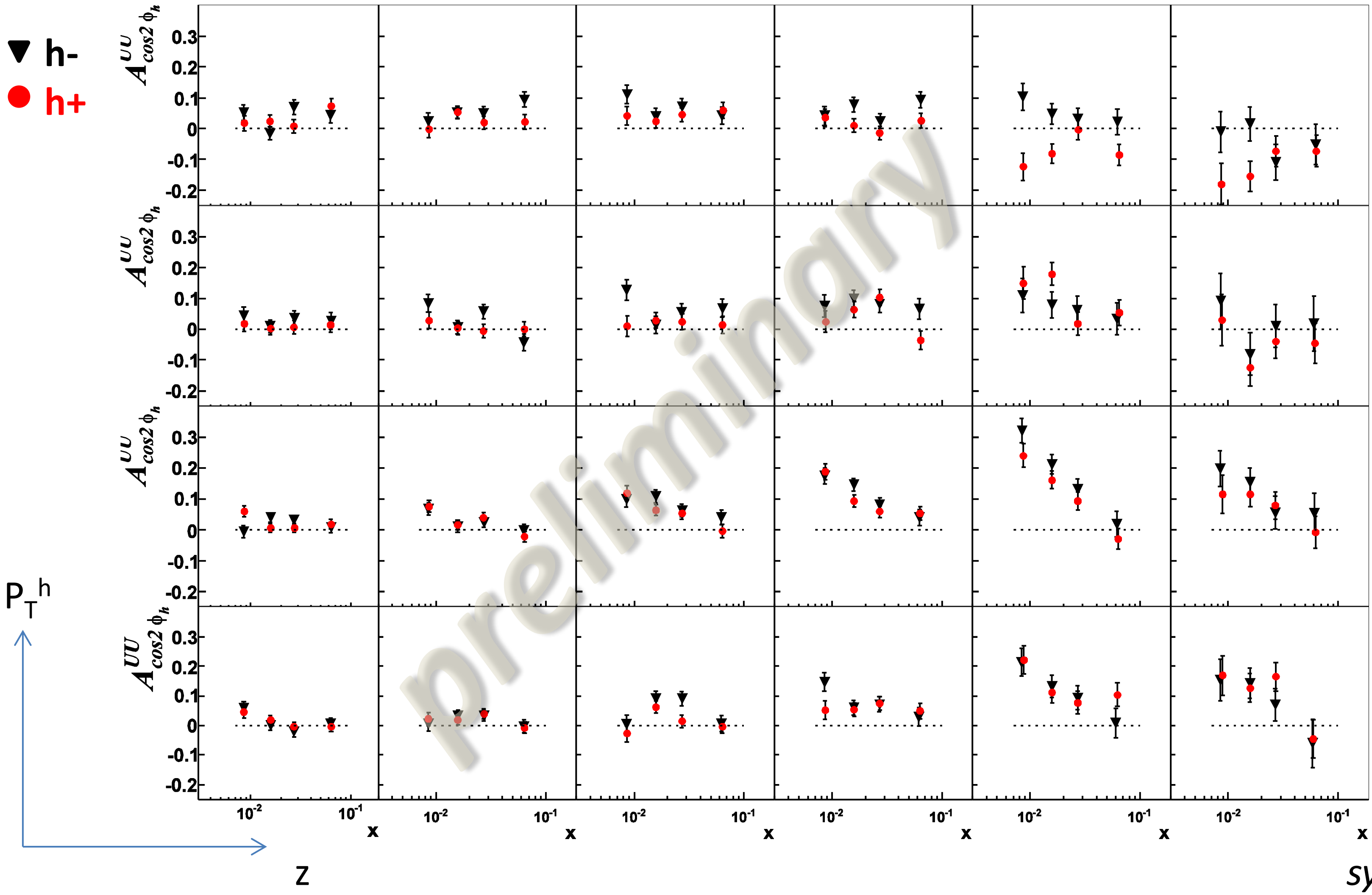
sys ≈ 2 · stat

z strong dependence more evident at small x and small P_T^h

Results for

$$A_{\cos 2\phi_h}^{UU}$$

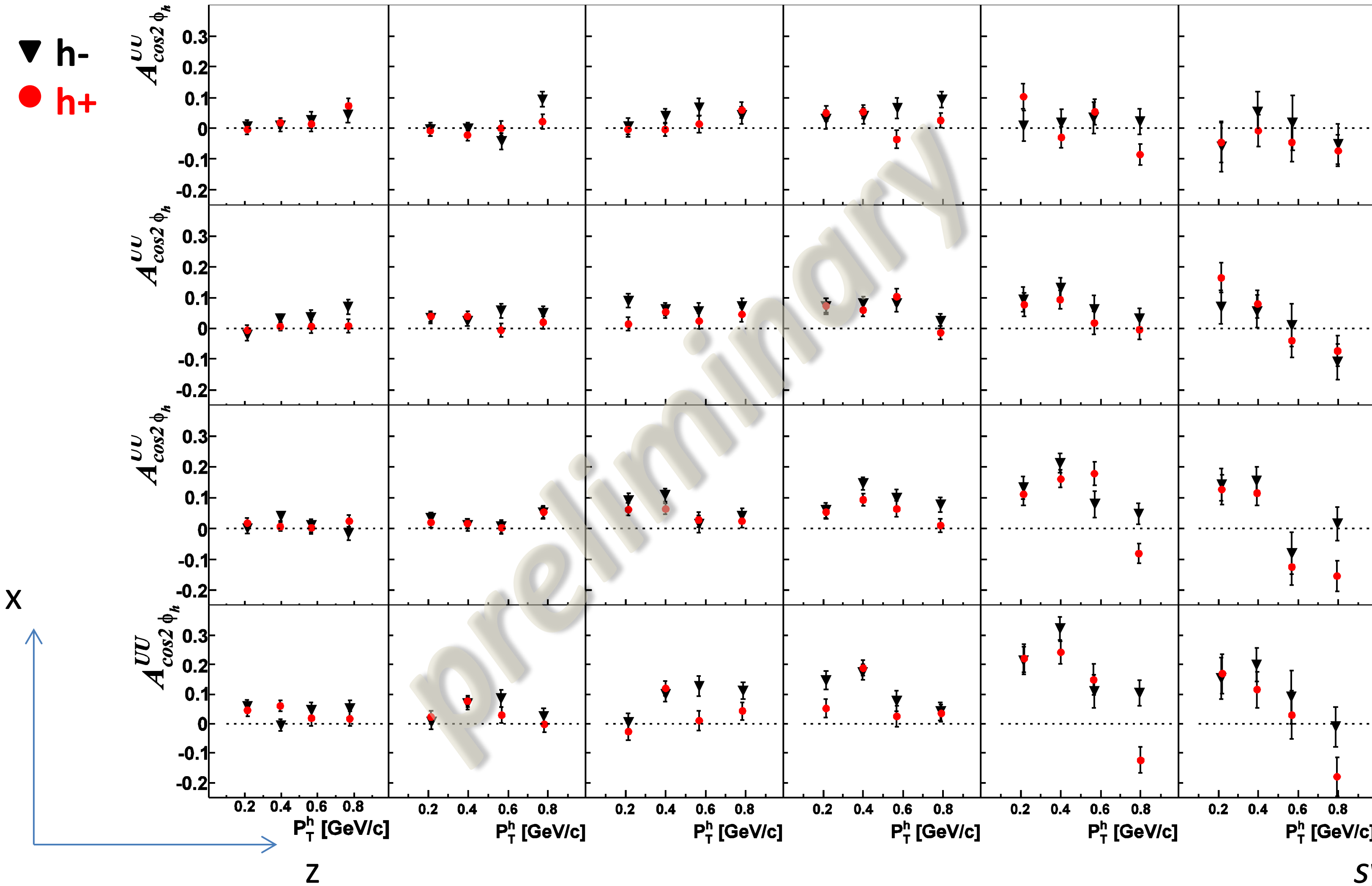
COMPASS ^{6}LiD (25% of 2004 data)



sys ≈ 2 · stat

x trend changes from small to large z values

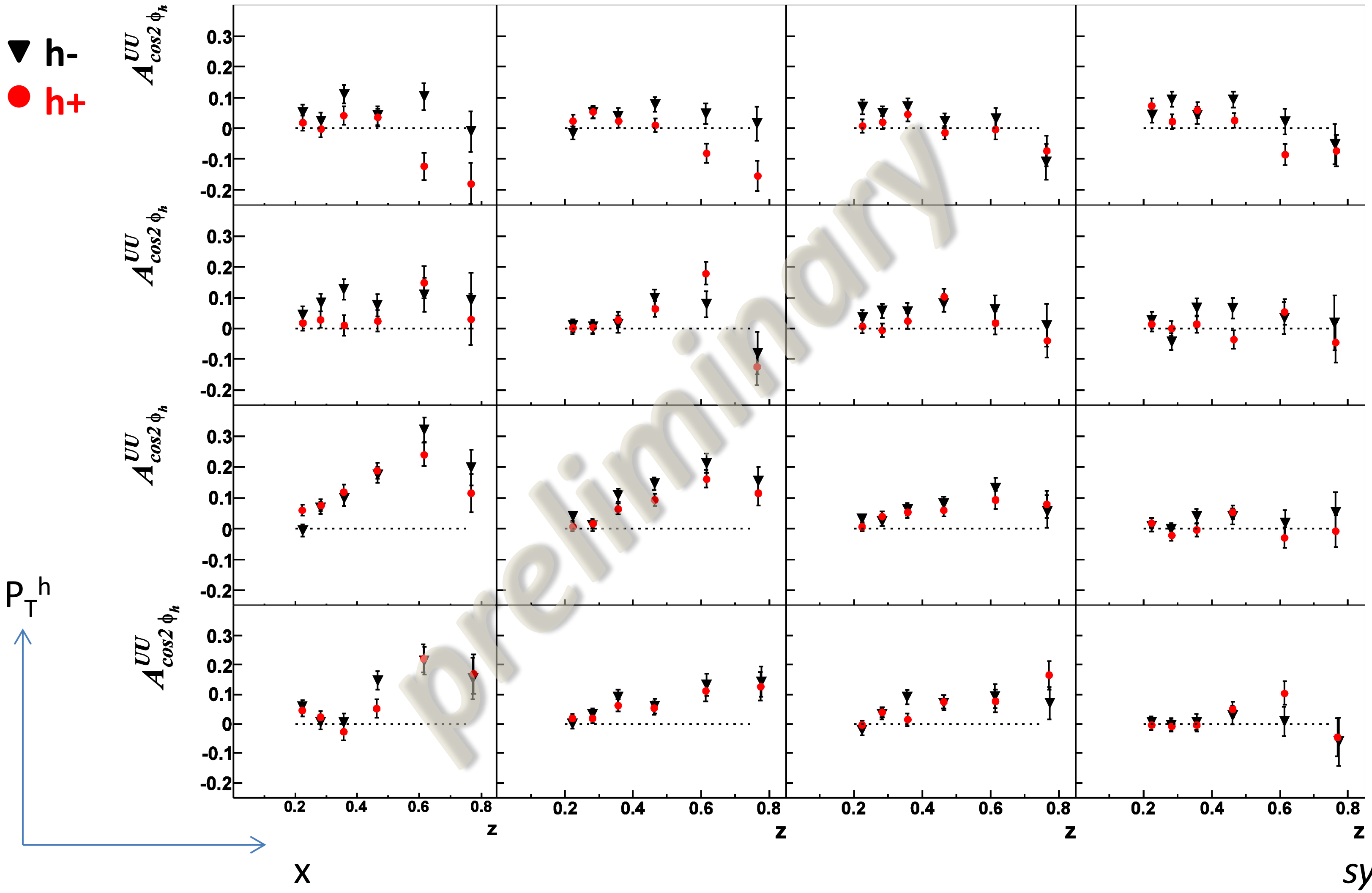
COMPASS ^{6}LiD (25% of 2004 data)



sys ≈ 2 · stat

the $P_T{}^h$ trend difficult to reproduce by models is there for large z and low x

COMPASS ^{6}LiD (25% of 2004 data)



sys ≈ 2 · stat

strongest effect at low x and low P_T^h

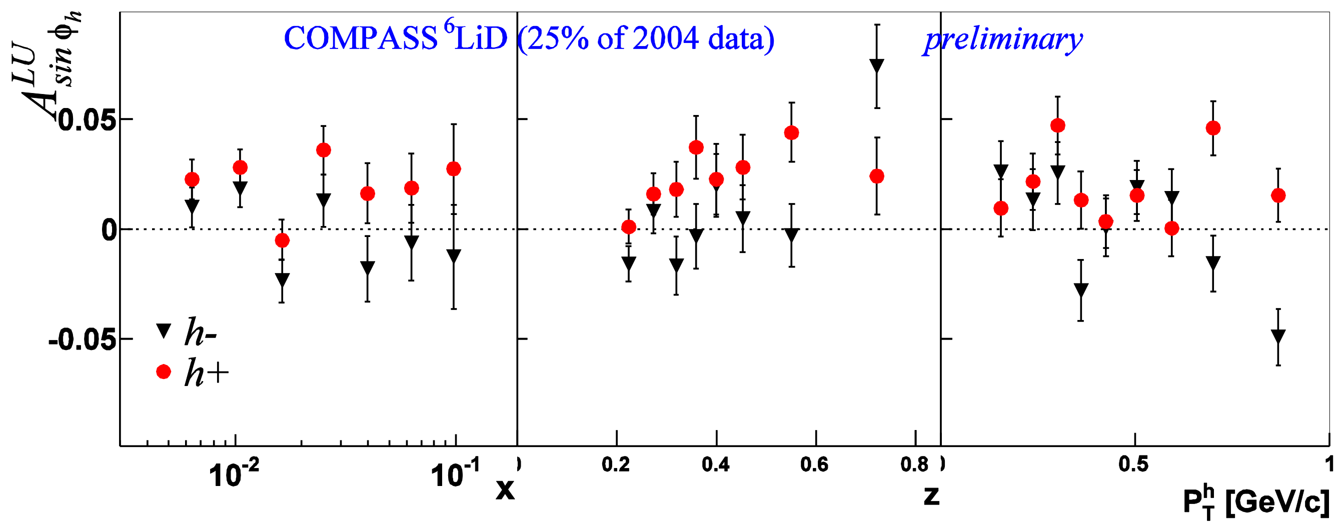
Summary and outlook

- kinematical dependencies investigated in the x, z and P_T^h grid

  → complex picture

- the strong z dependence seems to come from the small x and small P_T^h region
- x dependence clearly change going at large z values ($z > 0.5$)
- the interpretation of the results must also take into account the correlation between x and Q^2
- interesting inputs for theory
- new measurement of the unpolarized azimuthal asymmetries in parallel to DVCS with a LH target measurement in 2012 and at COMPASS II starting from 2015

backup



small amplitudes compatible with zero
slightly positive signal for positive hadrons