COMPASS results on unpolarized SIDIS

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Trieste University & INFN
on behalf of the COMPASS Collaboration

Structure of nucleons and nuclei

Como, 10-14 June 2013

OUTLINE

- the COMPASS experiment
- results from SIDIS off unpolarised deuteron
  - hadron multiplicities vs p_T^2
  - hadron pair multiplicities
  - azimuthal asymmetries

the COMPASS spectrometer

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

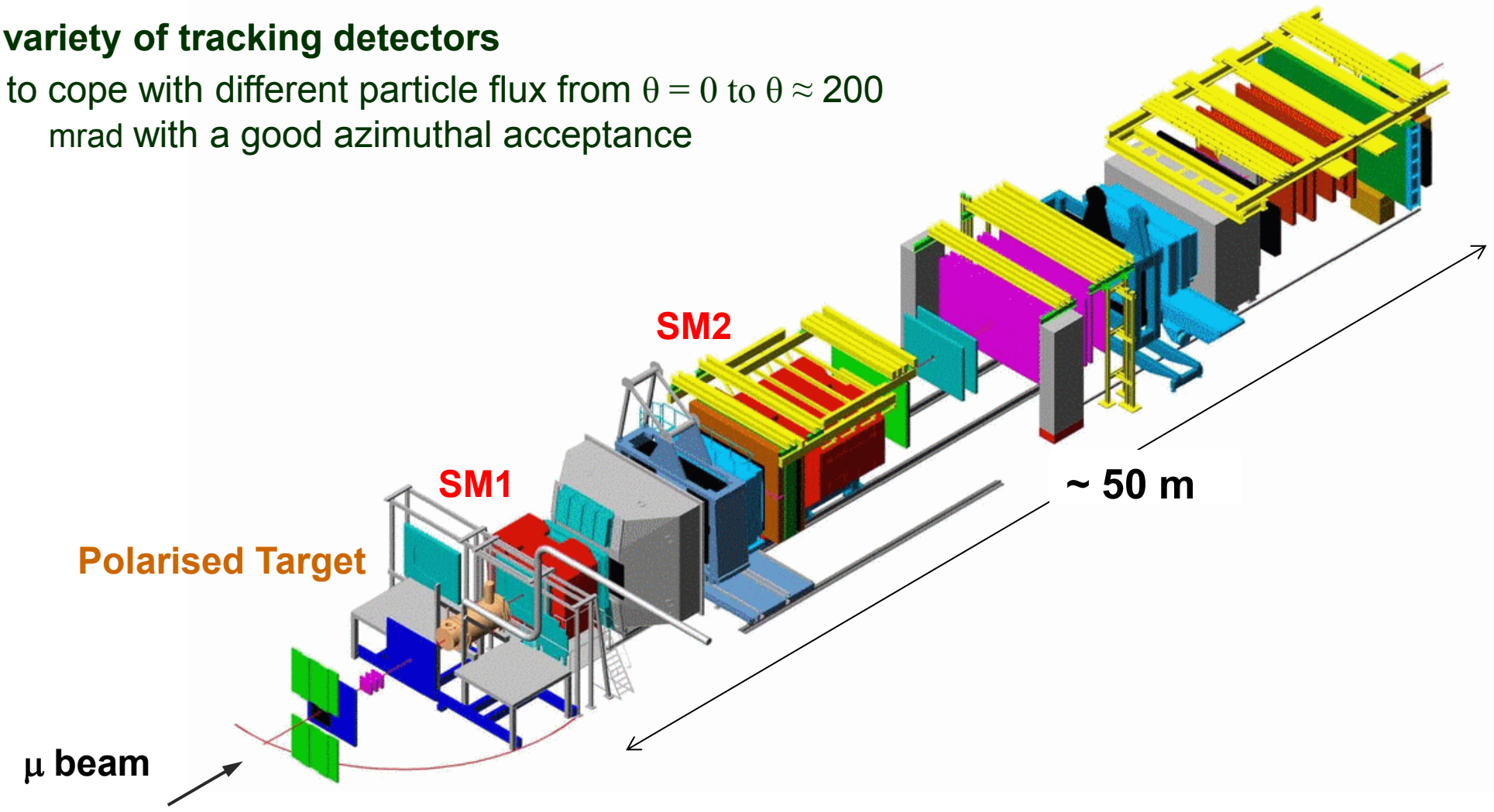
two stages spectrometer

Large Angle Spectrometer (SM1)

Small Angle Spectrometer (SM2)

variety of tracking detectors

to cope with different particle flux from $\theta = 0$ to $\theta \approx 200$ mrad with a good azimuthal acceptance



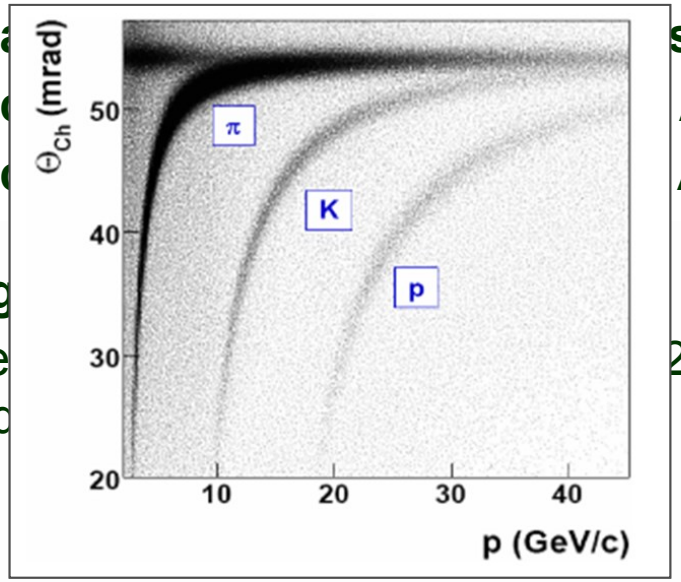
the COMPASS spectrometer

- high energy bea… s spectrometer
- large angular ac… Angle Spectrometer (SM1)
- broad kinematic… Angle Spectrometer (SM2)

variety of tracking…

to cope with differe… 200 mrad with a good…

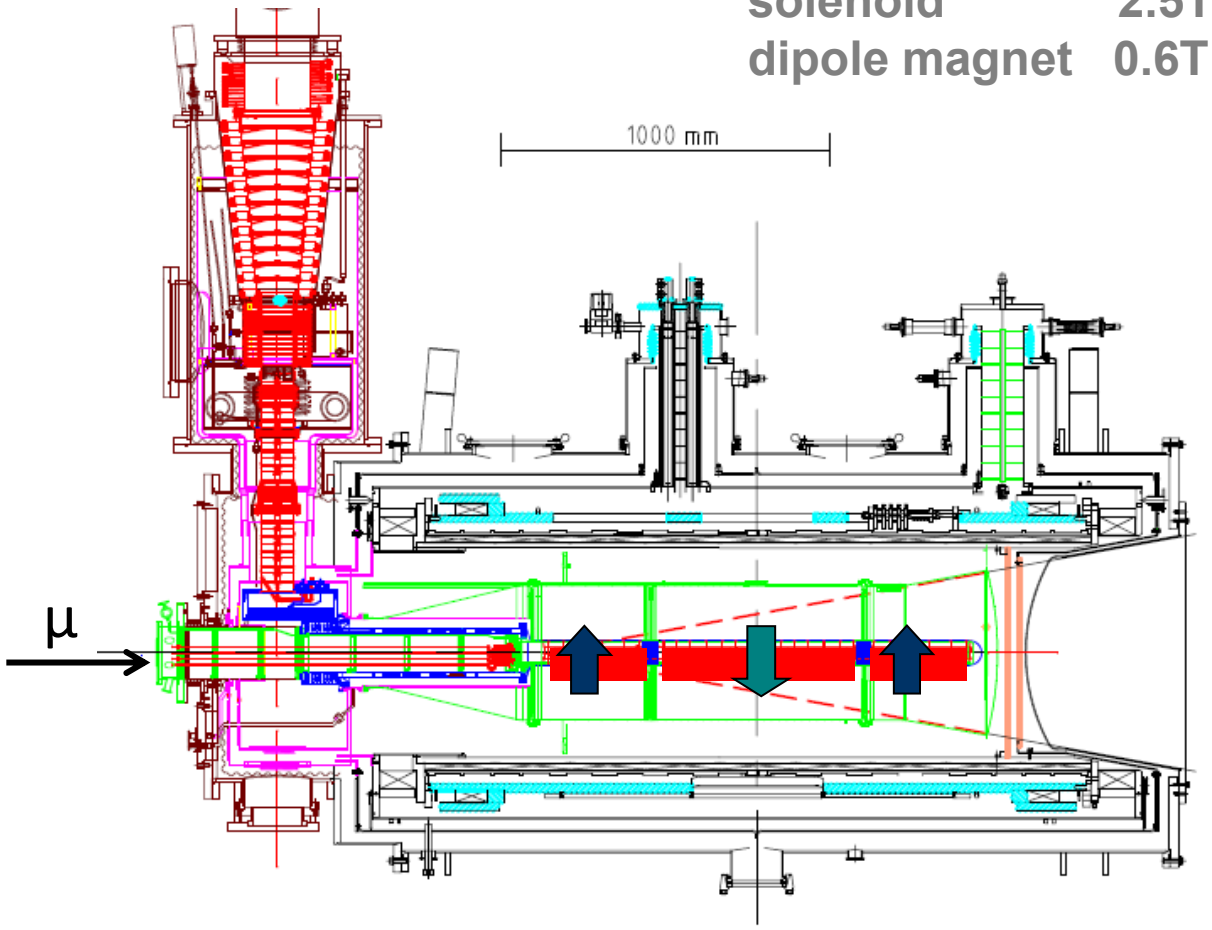
calorimetry, μID



the polarized target system (>2005)

^{3}He – ^{4}He dilution refrigerator (T~50mK)

solenoid	2.5T
dipole magnet	0.6T



acceptance > ± 180 mrad

3 target cells
30, 60, and 30 cm long

opposite polarisation

	d (^{6}LiD)	p (NH_3)
polarization	50%	90%
diliution factor	40%	16%

no evidence for relevant nuclear effects *(160 GeV)*

COMPASS data taking

2002 2003 2004	SIDIS with L & T	polarised deuteron (^{6}LiD)	160 GeV μ
2005	*CERN shutdown / spectrometer upgrade*		
2006	SIDIS with L	polarised deuteron	160 GeV μ
2007	SIDIS with L & T	polarised proton (NH_3)	160 GeV μ
2008 / 2009	hadron spectroscopy		
2010	SIDIS with T	polarised proton	160 GeV μ
2011	SIDIS with L	polarised proton	190 GeV μ
2012	Primakoff / DVCS test (LH_2)		

results from SIDIS off unpolarised deuteron

hadron multiplicities vs p_T^2

released in 2010, Spin-Prague

sent for publication

CERN-PH-EP/2013-052 **hep-ex/1304.0952**

hadron multiplicities vs p_T^2

hadron multiplicity per interaction:

differential SIDIS cross-section / differential DIS cross-section

$$\left.\frac{d^2 n^{h\pm}(z, p_T^2, x_{Bj}, Q^2)}{dz\, dp_T^2}\right|_{\Delta x_{Bj}\Delta Q^2} \approx \frac{\Delta^4 N^{h\pm}(z, p_T^2, x_{Bj}, Q^2)/(\Delta z \Delta p_T^2 \Delta x_{Bj} \Delta Q^2)}{\Delta^2 N^{\mu}(x_{Bj}, Q^2)/(\Delta x_{Bj}\Delta Q^2)}$$

p_T **transverse momentum of the hadron wrt the photon direction**

hadron multiplicities vs p_T^2

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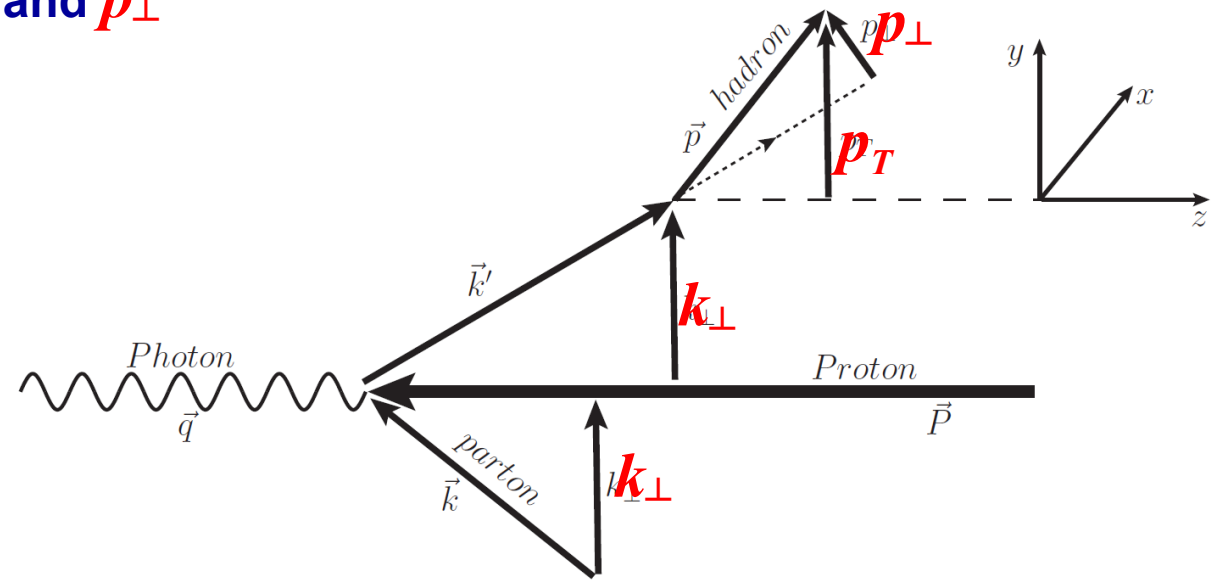
p_T **transverse momentum of the hadron wrt the photon direction**

it is due to $k_\perp$ **and** $p_\perp$

p_T^2 **distributions give information on** $k_\perp$ **and** $p_\perp$



hadron multiplicities vs p_T^2

SIDIS data collected in 2004 with ^{6}LiD target

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

$0.1 < y < 0.9$

$W > 5$ GeV/c

45.8×10^6 DIS events

hadron multiplicities vs p_T^2

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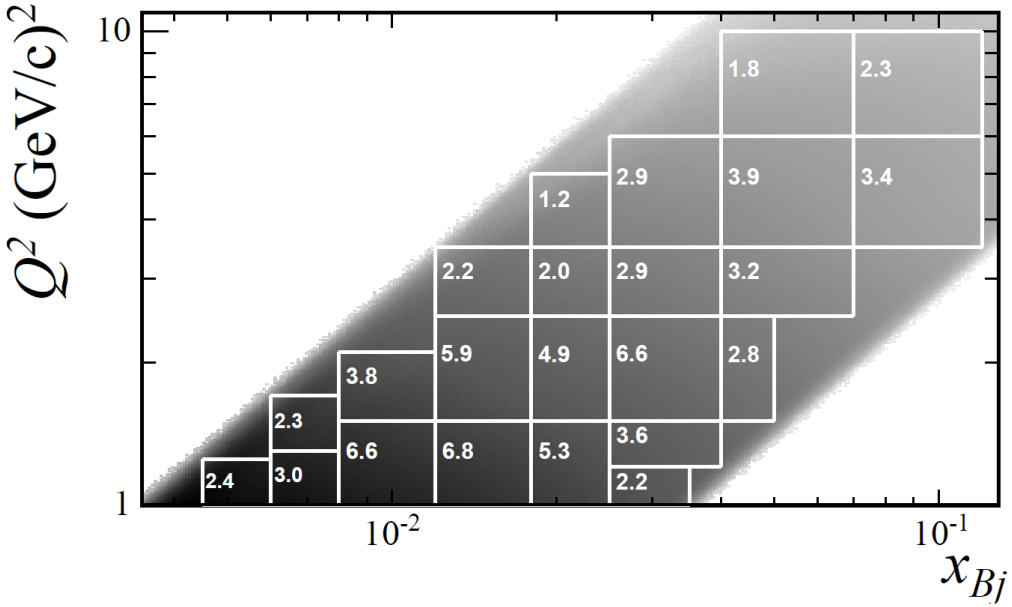
23 x , Q^2 intervals

$1 < Q^2 < 10$ (GeV/c)^2

$0.004 < x < 0.12$

8 x 40 z , p_T^2 intervals



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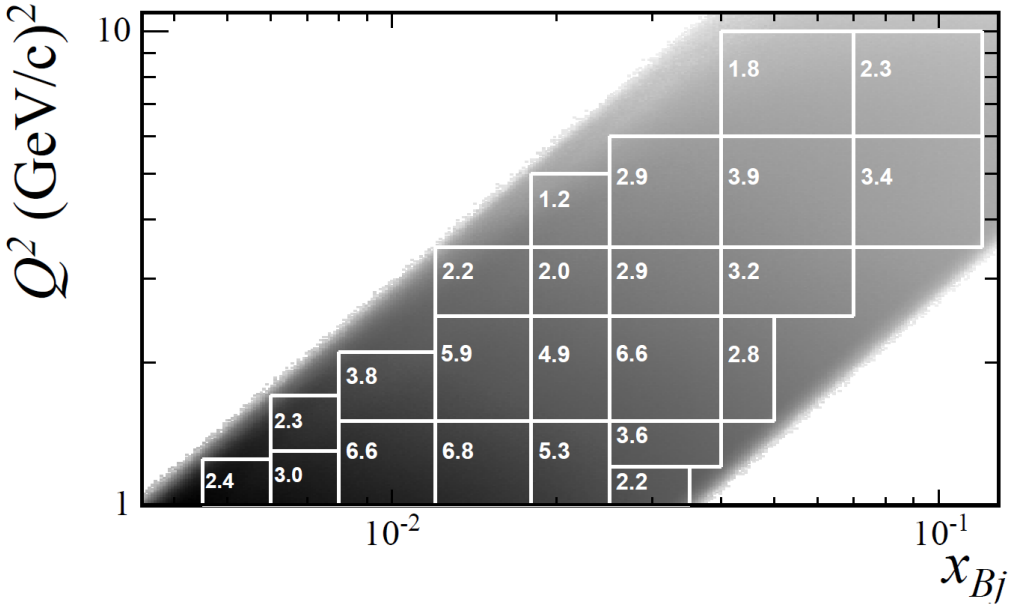
8 x 40 z , p_T^2 intervals

in each of them

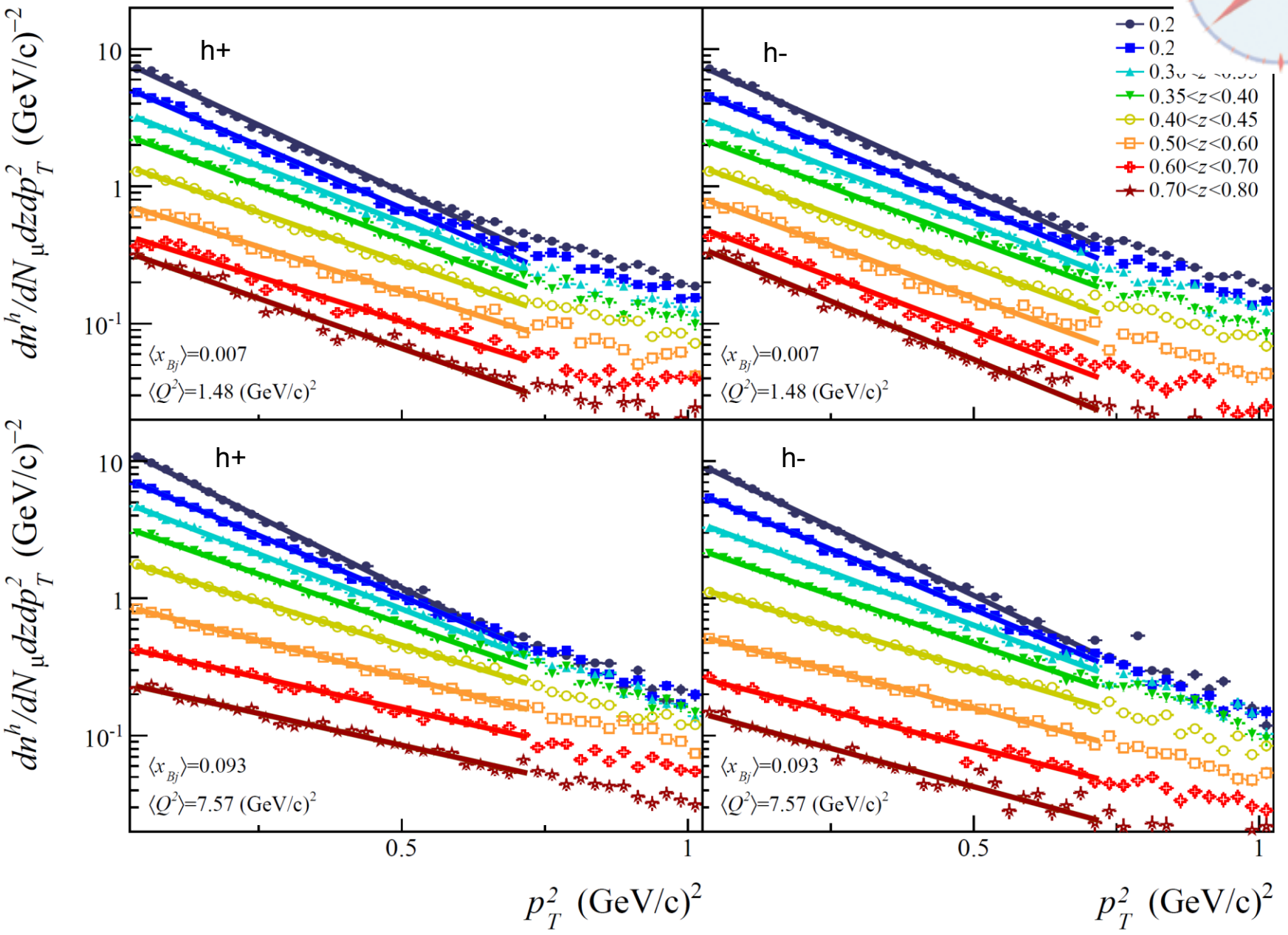


$$\left.\frac{d^2 n^{h\pm}(z, p_T^2, x_{Bj}, Q^2)}{dz\, dp_T^2}\right|_{\Delta x_{Bj}\Delta Q^2} \approx \frac{\Delta^4 N^{h\pm}(z, p_T^2, x_{Bj}, Q^2)/(\Delta z \Delta p_T^2 \Delta x_{Bj} \Delta Q^2)}{\Delta^2 N^{\mu}(x_{Bj}, Q^2)/(\Delta x_{Bj}\Delta Q^2)}$$

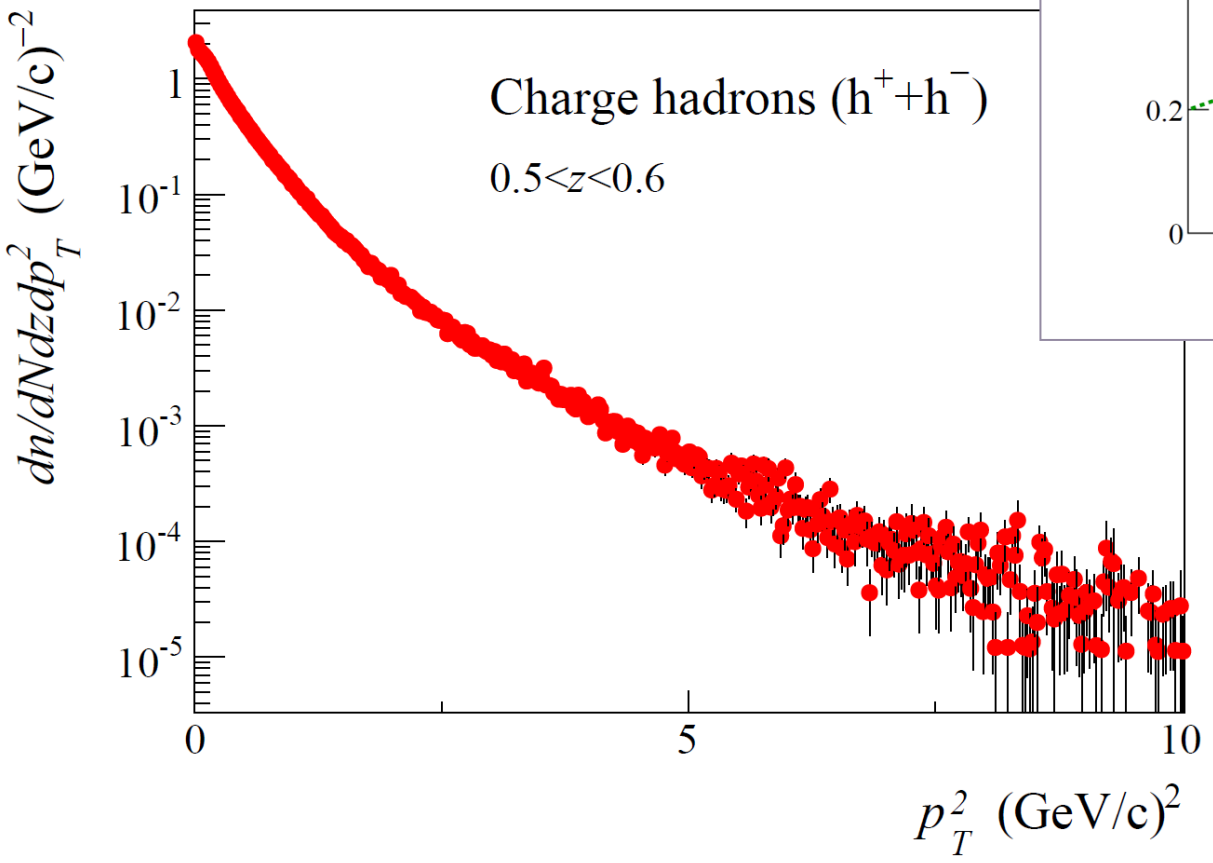
4d acceptance corrected

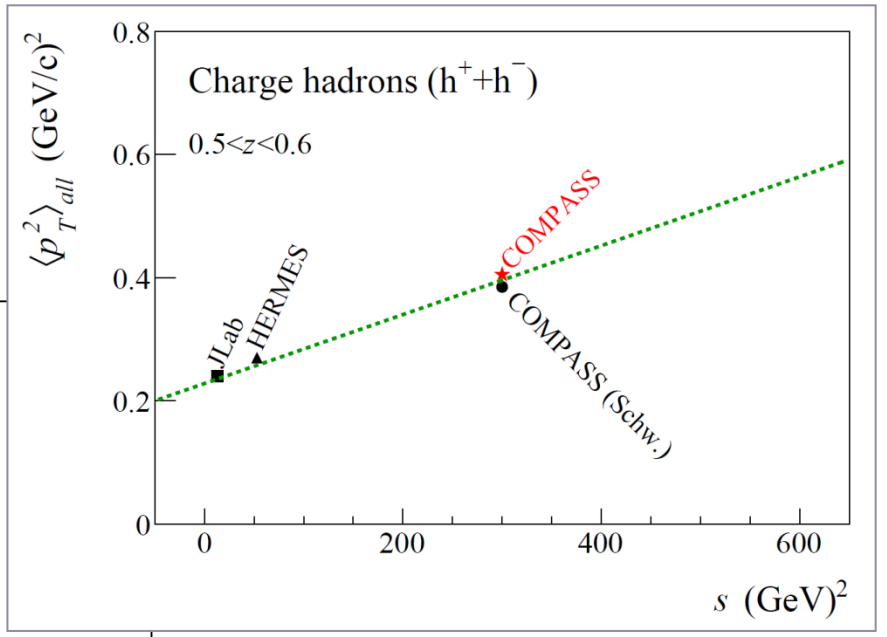
5% systematic uncertainties

hadron multiplicities vs p_T^2

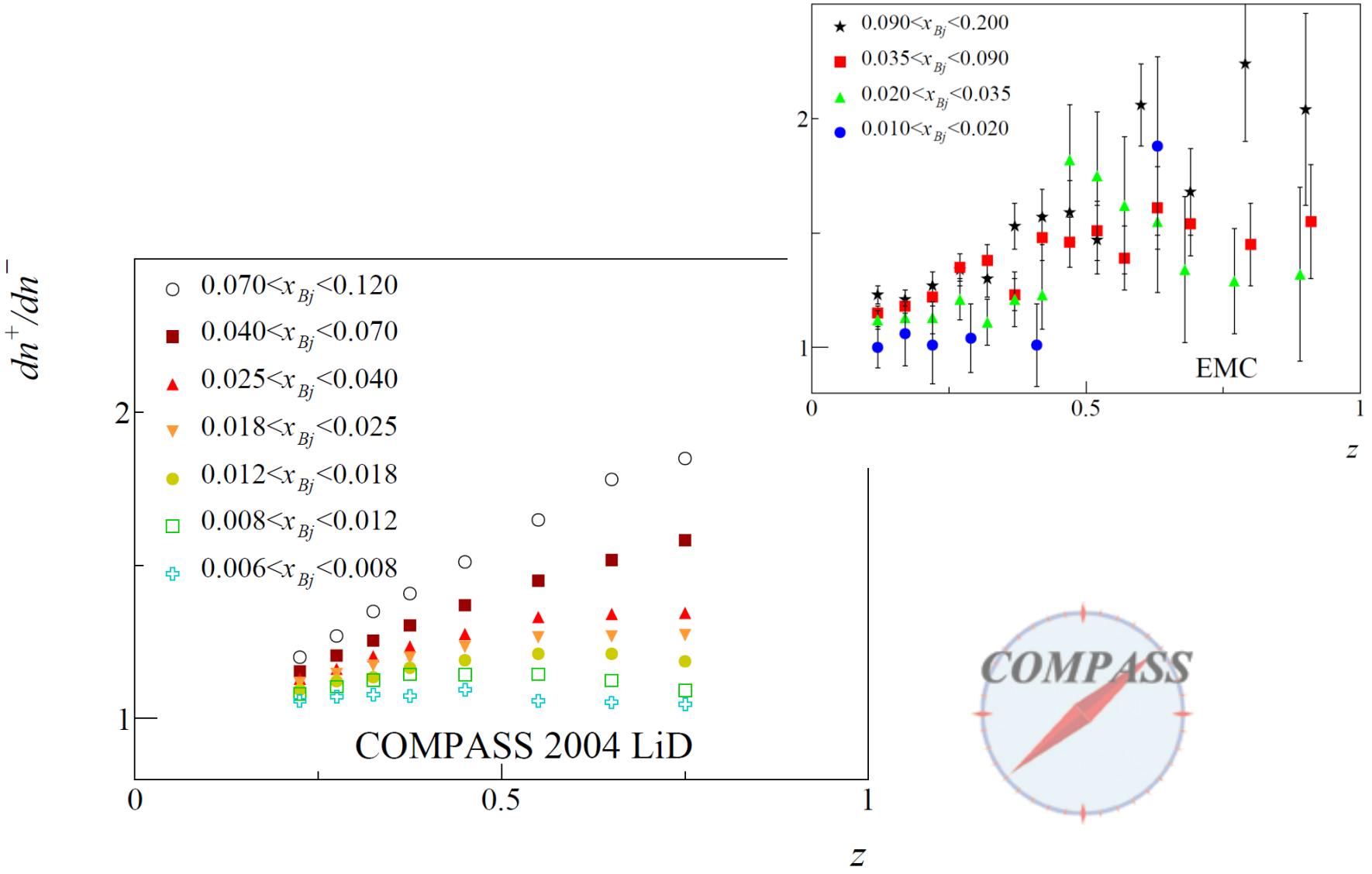


hadron multiplicities vs p_T^2

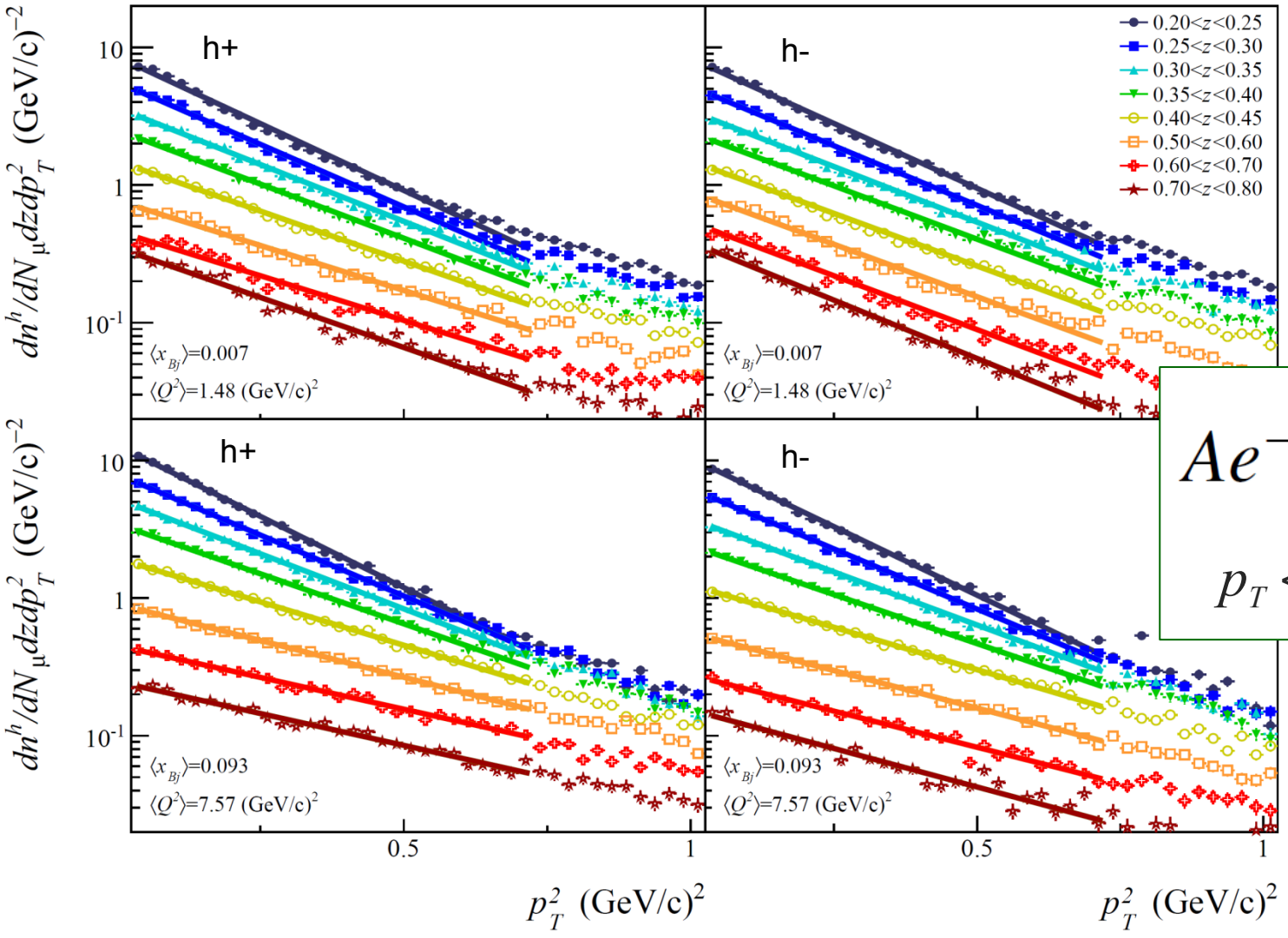




hadron multiplicities vs p_T^2



hadron multiplicities vs p_T^2

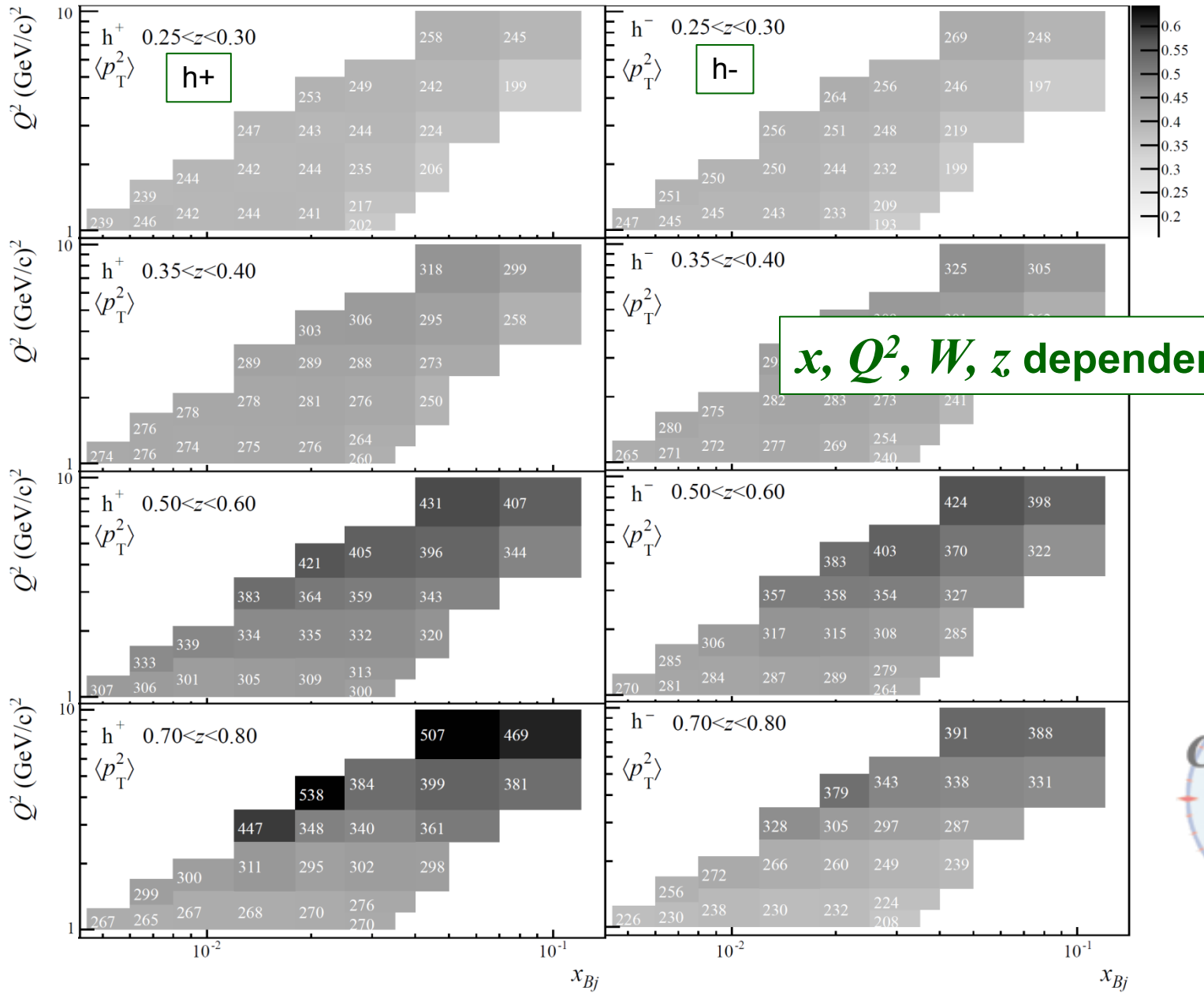


$$Ae^{-p_T^2/\langle p_T^2\rangle}$$

p_T < 0.85 GeV/c

hadron multiplicities vs p_T^2

$\langle p_T^2 \rangle$



x, Q^2, W, z dependence

different for h+ and h-

strong dependence on kin. variables

hadron multiplicities vs p_T^2

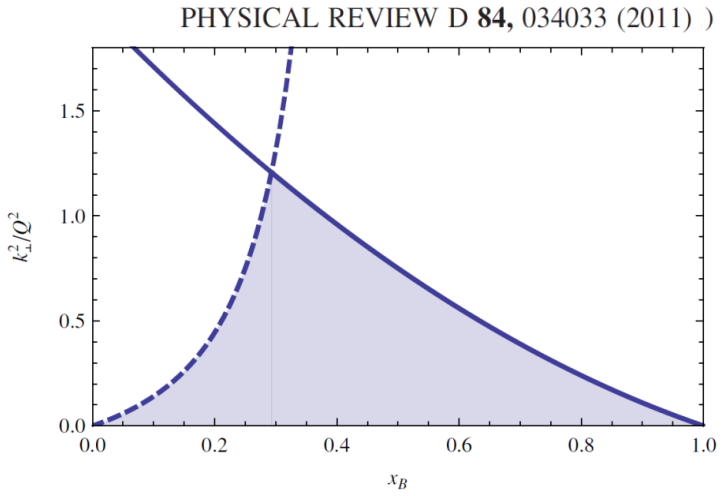
z dependence

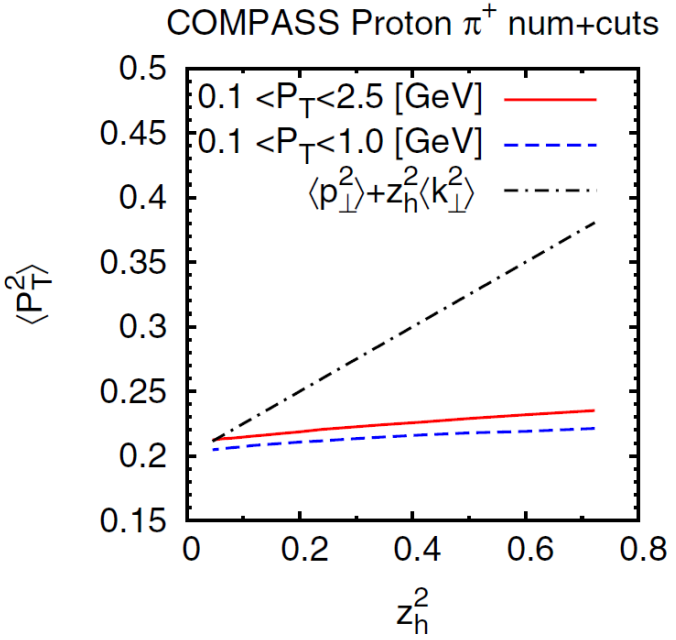
usual assumption:

$$\langle p_T^2 \rangle_q = \langle p_\perp^2 \rangle_q + z^2 \langle k_\perp^2 \rangle_q$$

constant and flavor independent

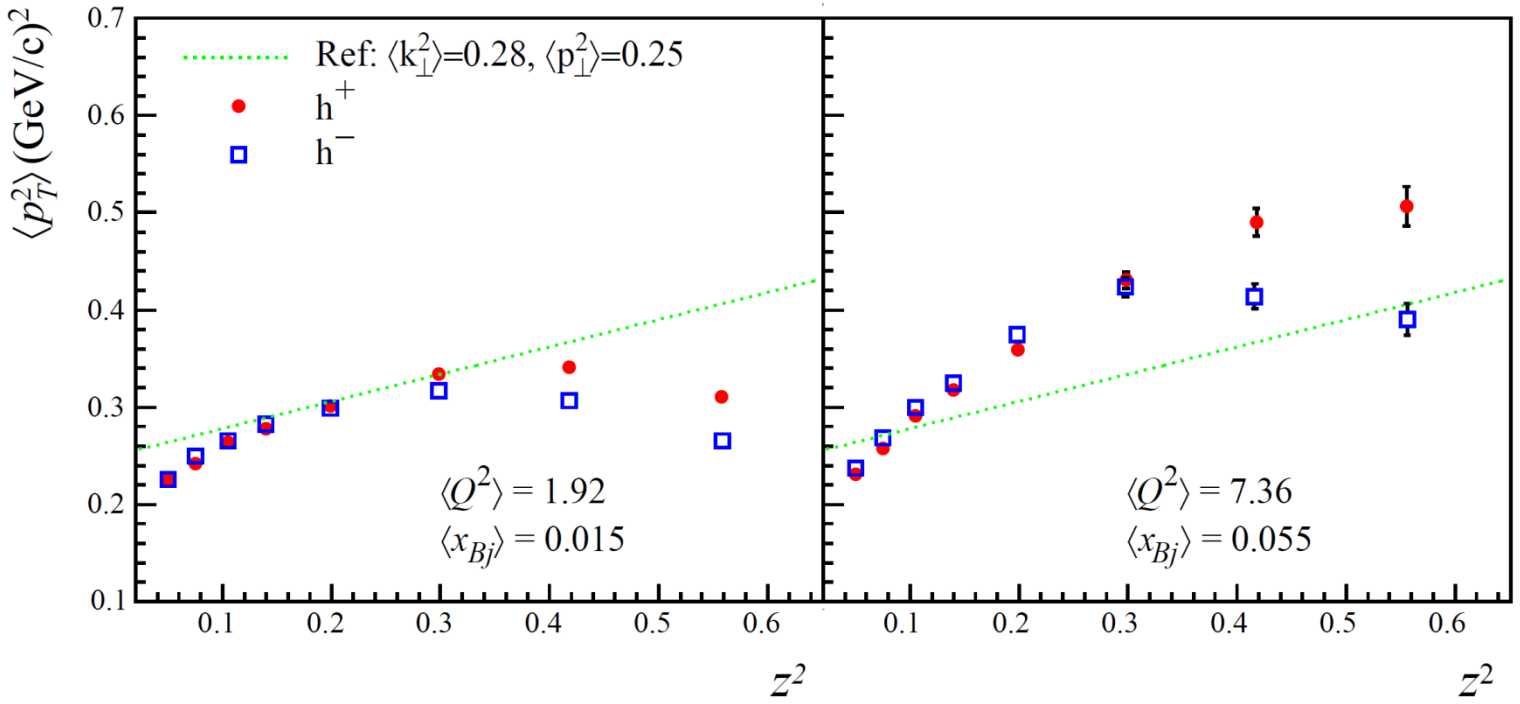
M. Boglione,[1] S. Melis,[2] and A. Prokudin[3]





hadron multiplicities vs p_T^2

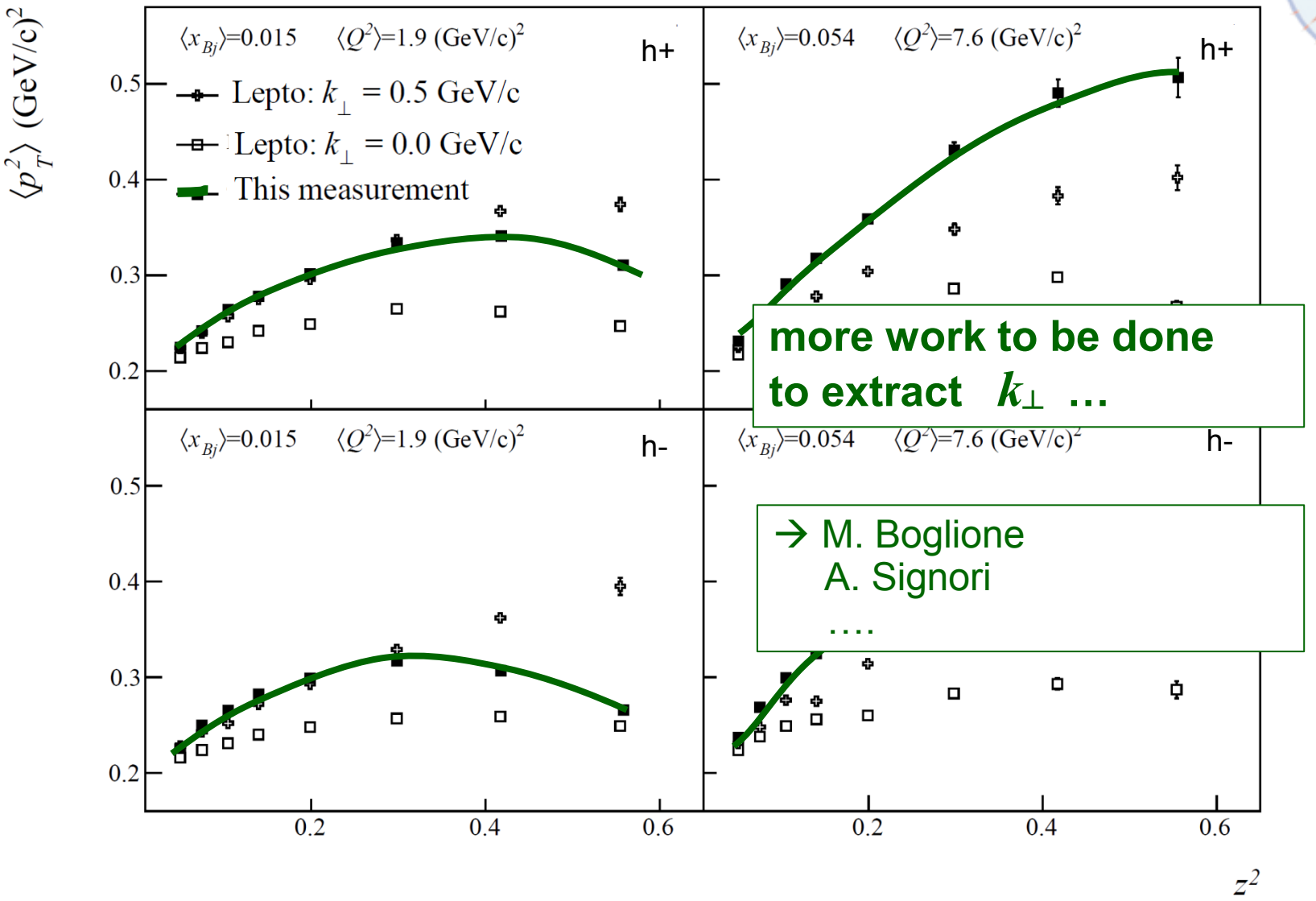
z dependence



$$\langle p_T^2(z)\rangle = \langle p_\perp^2(z)\rangle + z^2\langle k_\perp^2\rangle$$

should be taken from other measurements
i.e. from DIS event generators which are supposed to incorporate all known properties of jet fragmentation

hadron multiplicities vs p_T^2



more work to be done to extract $k_\perp$ …

→ M. Boglione
A. Signori
….

results from SIDIS off unpolarised deuteron

hadron-pair multiplicities

hadron pair (h+h-) multiplicities

main motivation:

transversity from

hadron pair transverse spin asymmetry

$$A_{UT}^{\sin(\phi_R+\phi_S)\,\sin\theta}(x,z,M_h;Q) = -C_y\,\frac{|\boldsymbol{R}|}{M_h}\,\frac{\sum_q e_q^2\, h_1^q(x;Q^2)\, H_{1,sp}^{\sphericalangle\, q}(z,M_h;Q^2)}{\sum_q e_q^2\, f_1^q(x;Q^2)\, D_1^q(z,M_h;Q^2)}$$

hadron pair (h+h-) multiplicities

SIDIS data collected in 2004 with ^{6}LiD target

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

$0.1 < y < 0.9$

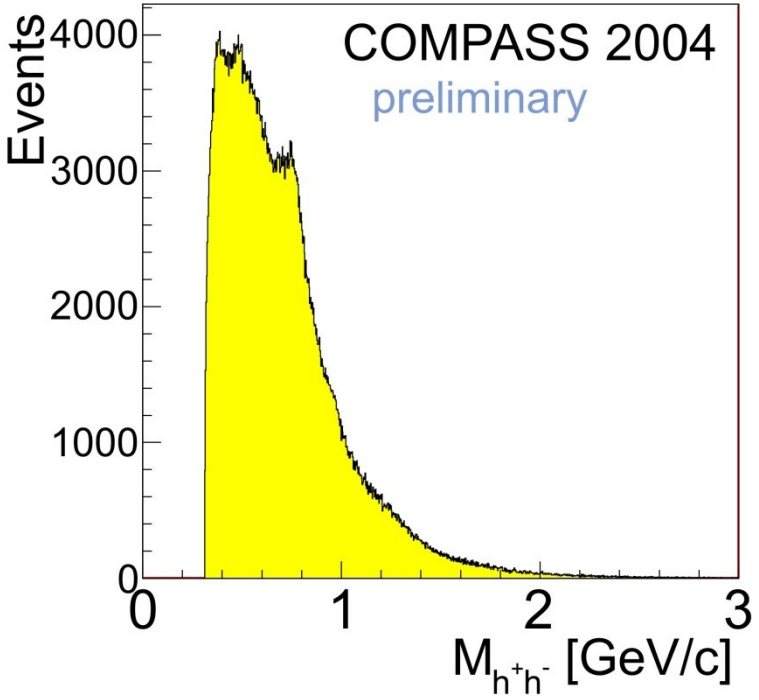
$W > 5$ GeV/c

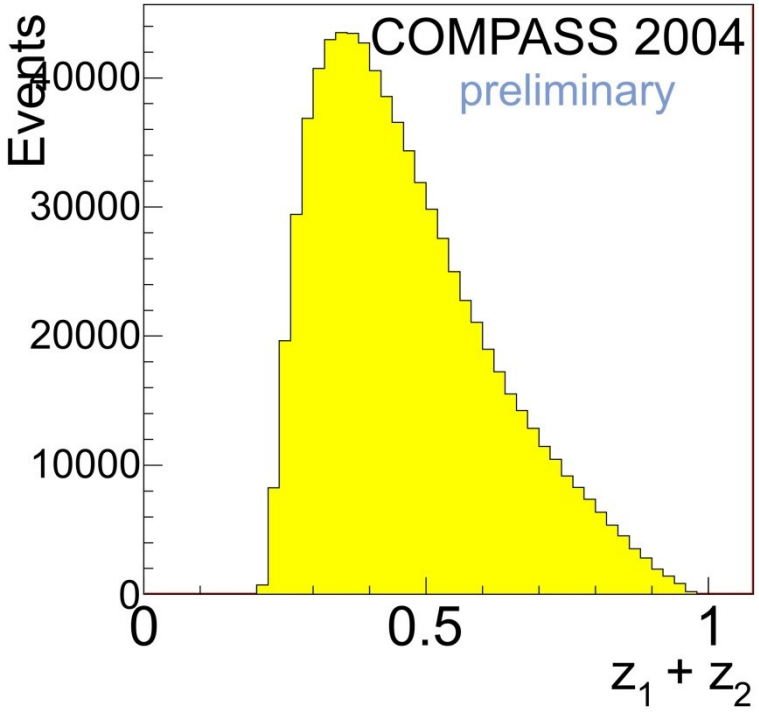
hadron selection: **as for the transverse spin asymmetry measurement**

→ *Christopher Braun*

$z_1, z_2 > 0.1$

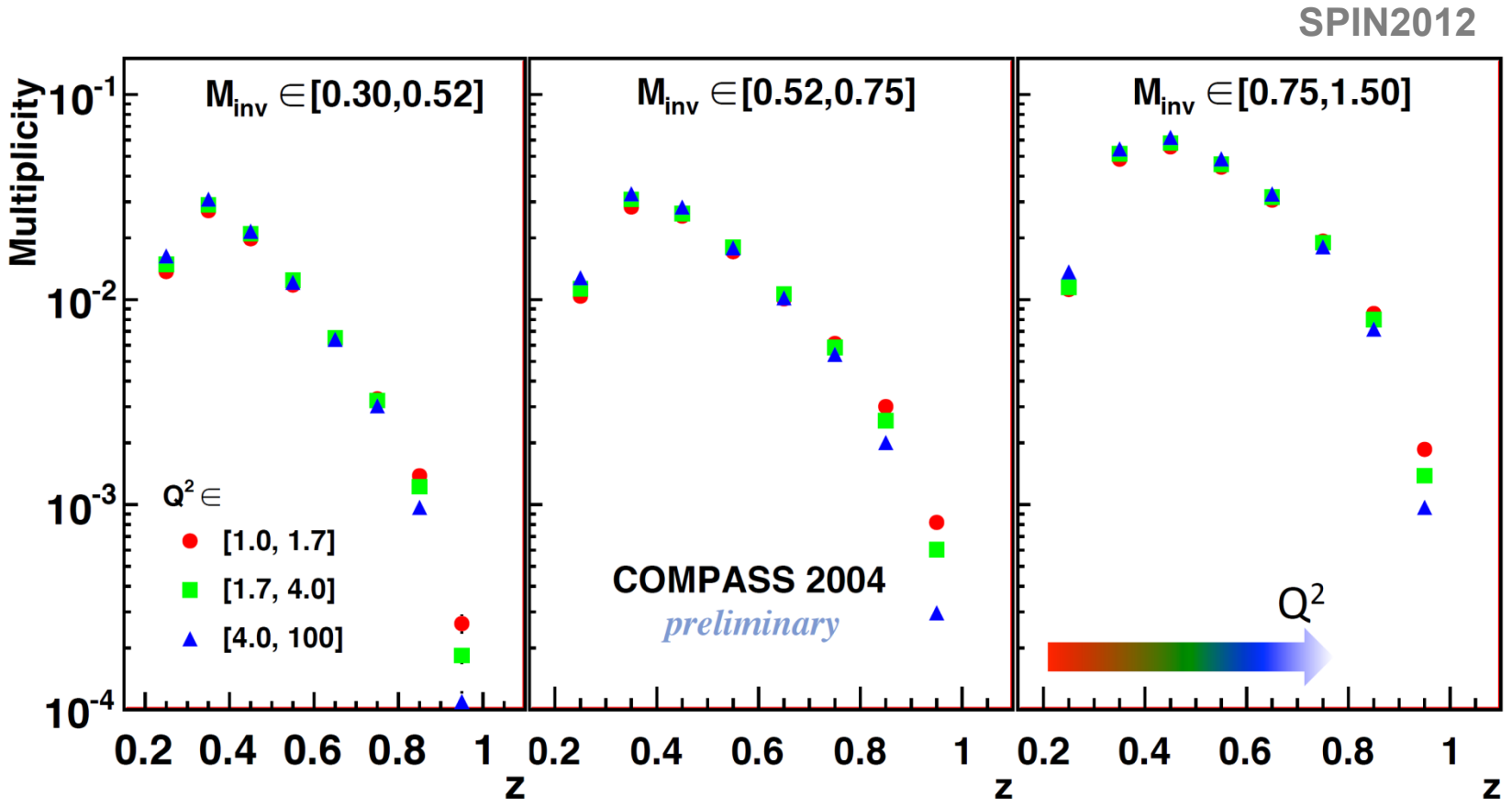
hadron pair (h+h-) multiplicities





hadron pair (h+h-) multiplicities

first measurements in M_{inv}, $z=z_1+z_2$, Q^2 bins

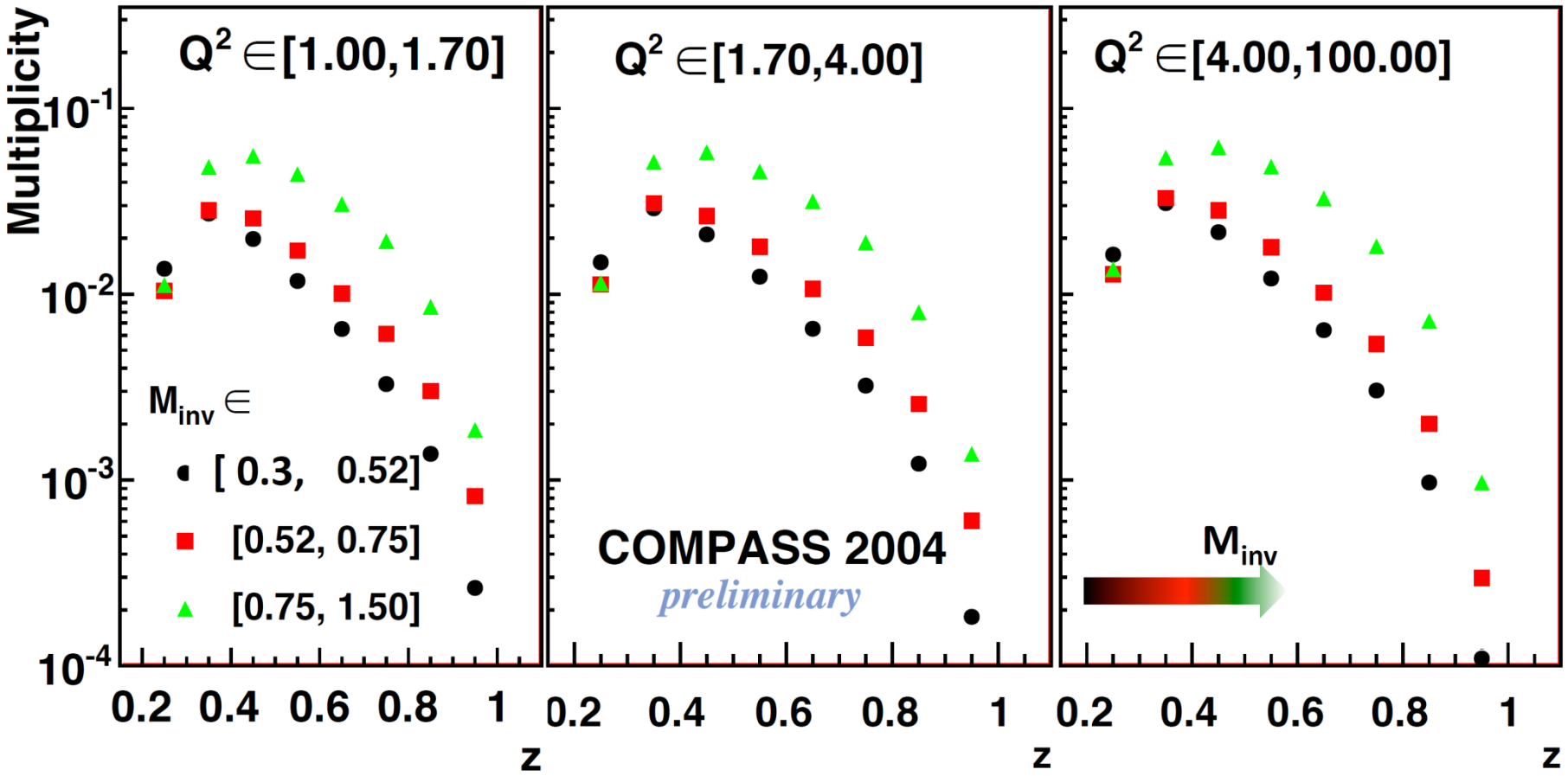


week Q^2 dependence

hadron pair (h+h-) multiplicities

first measurements in M_{inv}, $z=z_1+z_2$, Q^2 bins

SPIN2012



not negligible M_{inv}, z dependence

~ in agreement with Lepto

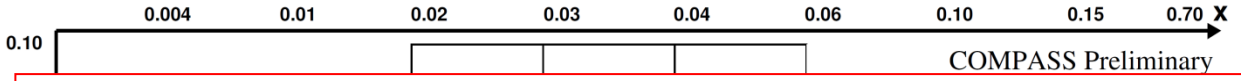
hadron multiplicities

future

from 2006 ^{6}LiD data

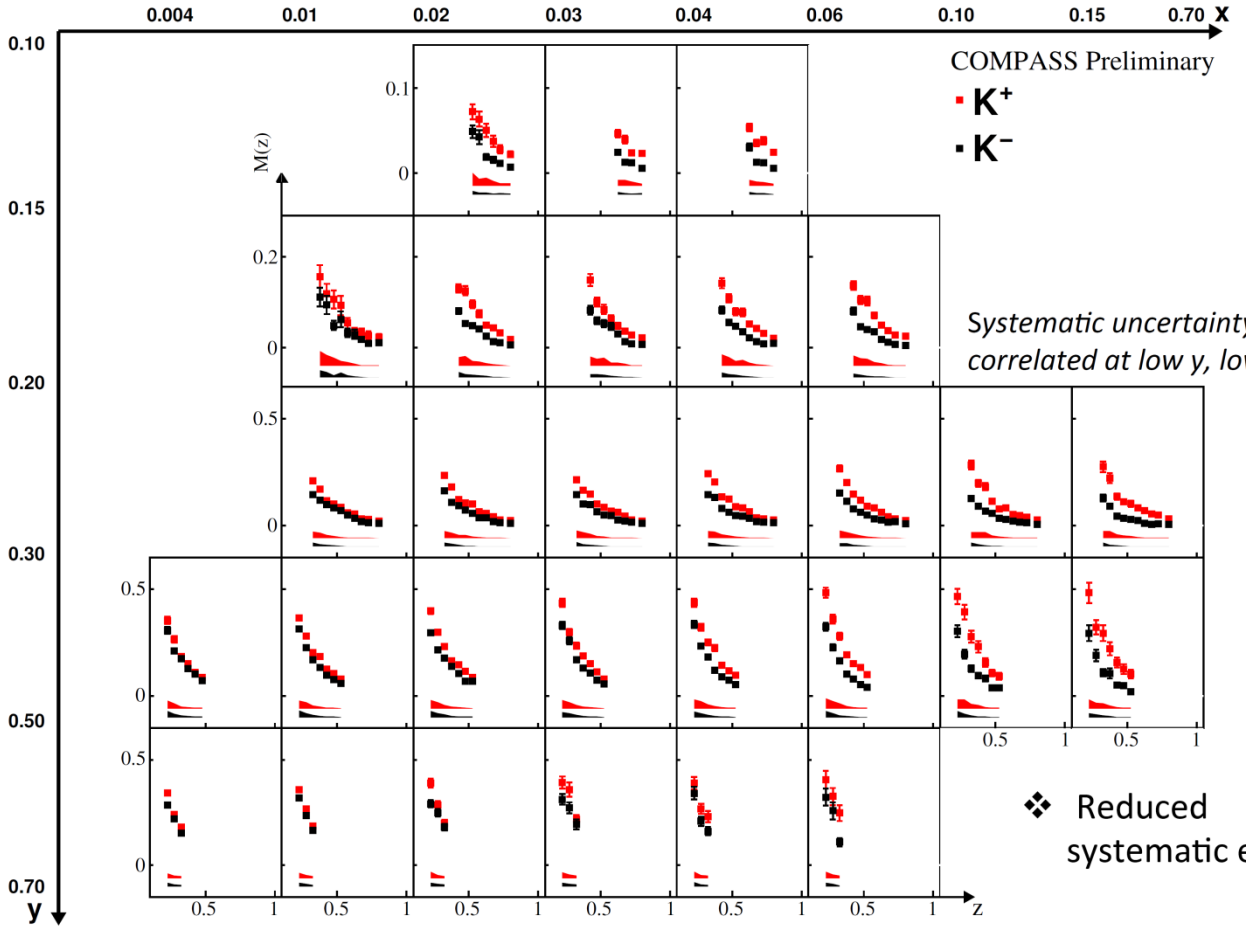
New

Charged pion multiplicities vs (x,y,z)



New

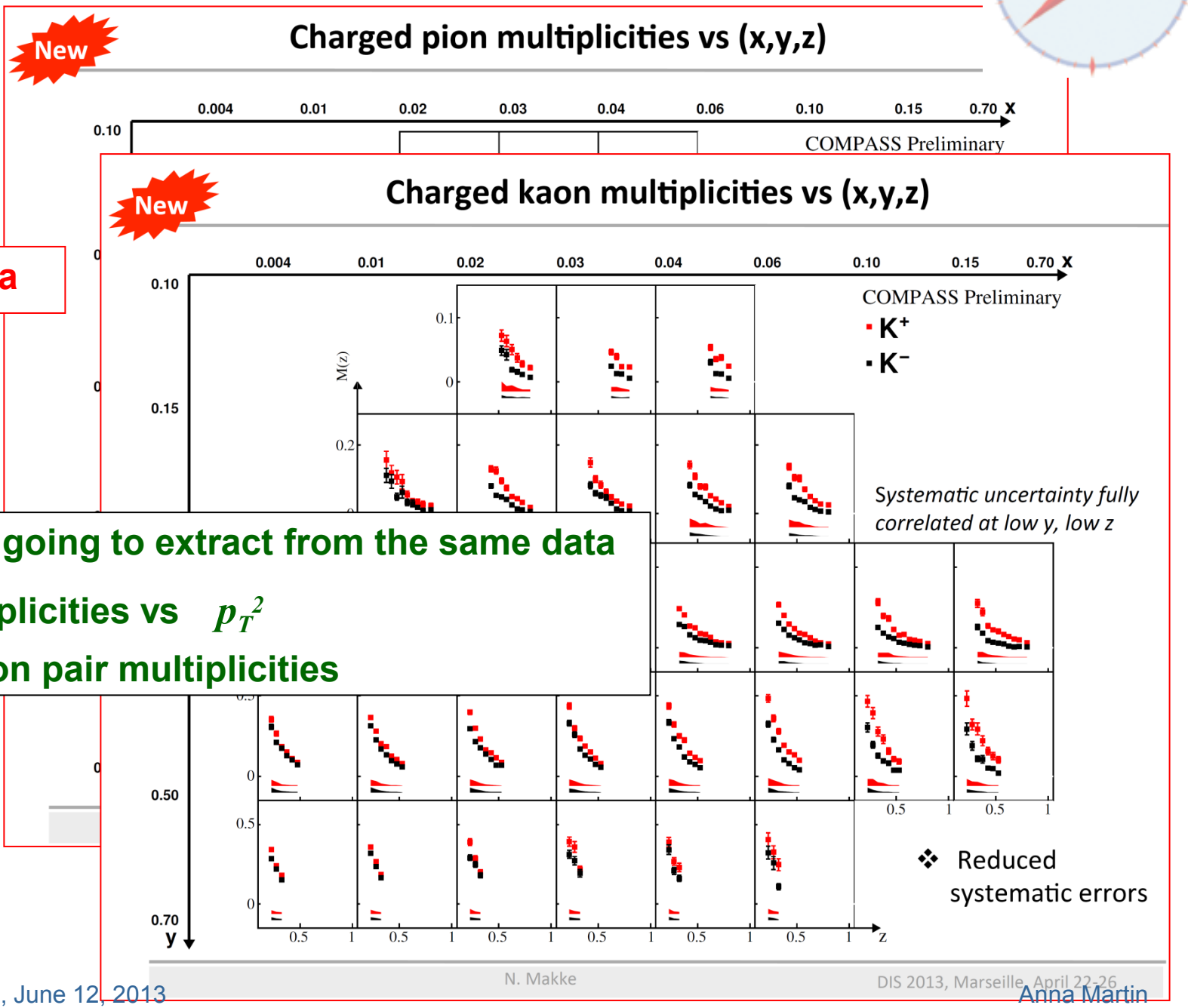
Charged kaon multiplicities vs (x,y,z)



hadron multiplicities

future

from 2006 ^{6}LiD data



work ongoing to extract from the same data

- **multiplicities vs p_T^2**
- **hadron pair multiplicities**

results from SIDIS off unpolarised deuteron

azimuthal asymmetries

azimuthal asymmetries

SIDIS cross-section unpolarised nucleons

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\,\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon\,F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\,\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\,\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + \ldots$$

azimuthal asymmetries

SIDIS cross-section unpolarised nucleons

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h\perp}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2\,(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\,\varepsilon(1+\varepsilon)}\,\cos\phi_h\,F_{UU}^{\cos\phi_h} + \varepsilon\cos(2\phi_h)\,F_{UU}^{\cos 2\phi_h} + \lambda_e\sqrt{2\,\varepsilon(1-\varepsilon)}\,\sin\phi_h\,F_{LU}^{\sin\phi_h} + \dots\Big\}$$

twist3

Boer-Mulders DF

Cahn effect

→ $\langle k_T^2 \rangle$ M. Aghasyan

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h}\left(x h\,H_1^\perp + \frac{M_h}{M}\,f_1\frac{\tilde{D}^\perp}{z}\right) - \frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\left(x f^\perp D_1 + \frac{M_h}{M}\,h_1^\perp\frac{\tilde{H}}{z}\right)\right]$$

$$xh = x\tilde{h} + \frac{p_T^2}{M^2}\,h_1^\perp \qquad xf^\perp = x\tilde{f}^\perp + f_1$$

$$F_{UU}^{\cos\phi_h} \approx \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_T}{M}\,f_1 D_1\right]$$

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

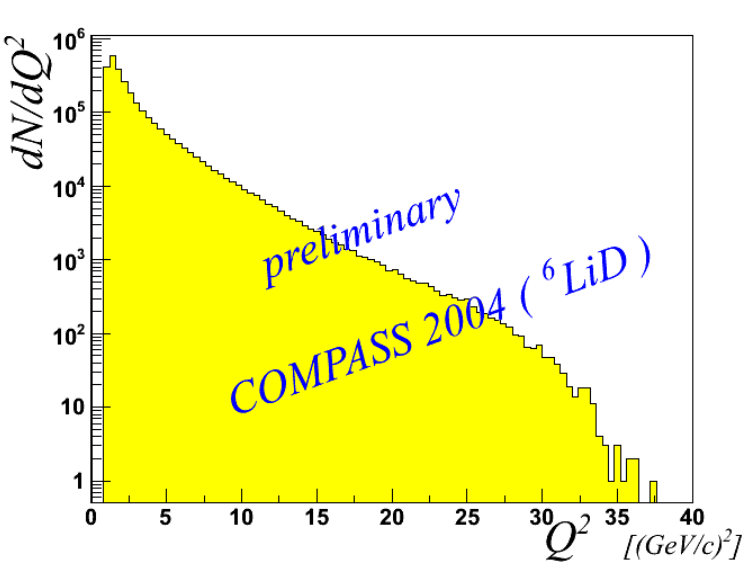
Boer-Mulders PDF x Collins FF
+ Cahn effect (twist 4, $1/Q^2$)

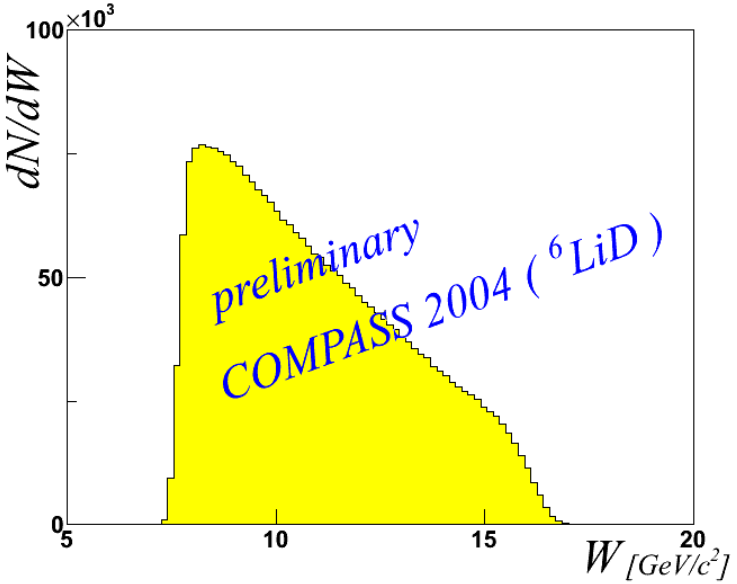
azimuthal asymmetries

SIDIS data collected in 2004 with ^{6}LiD target

event / hadron selection

$$W > 5GeV/c^2$$
$$Q^2 > 1GeV^2$$
$$0.003 < x < 0.13$$
$$0.2 < y < 0.9$$
$$0.2 < z < 0.85$$
$$0.1 < P_T^h < 1.0GeV/c$$
$$\theta_{\gamma^*}^{lab} < 0.06rad$$





azimuthal asymmetries

SIDIS data collected in 2004 with ^{6}LiD target

first results for h^+ and h^- separately presented at Transversity2008

paper in preparation

azimuthal asymmetries

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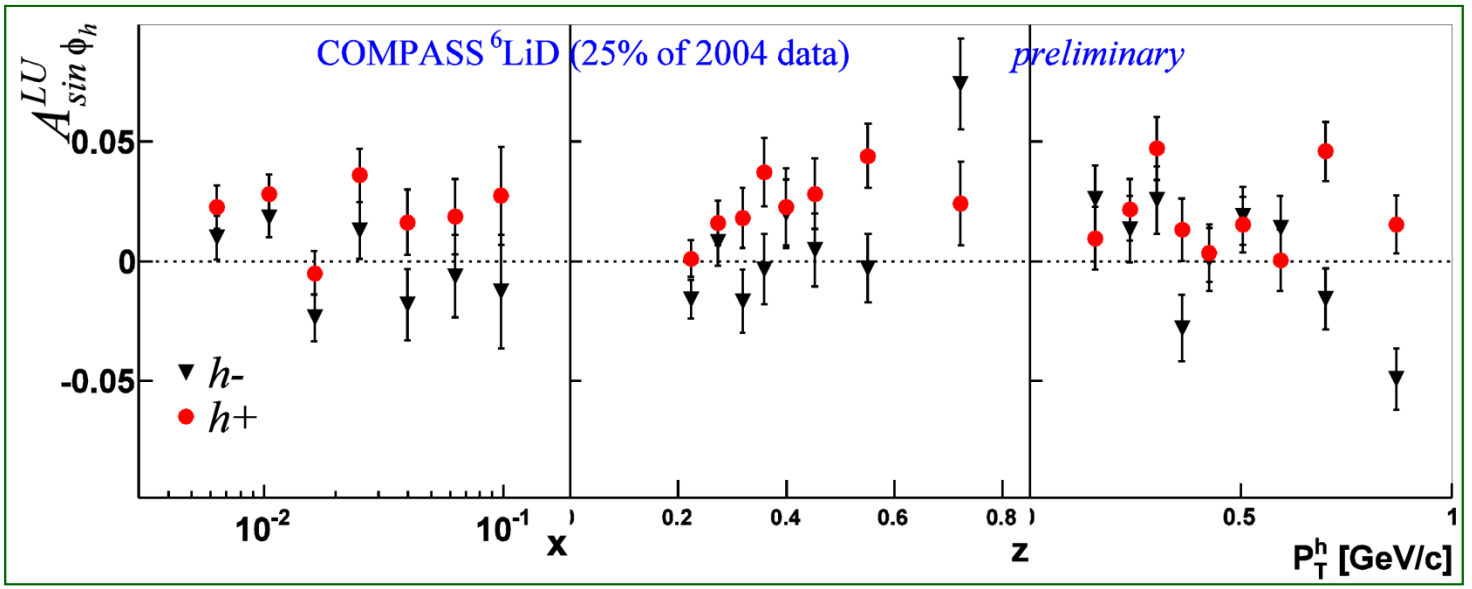
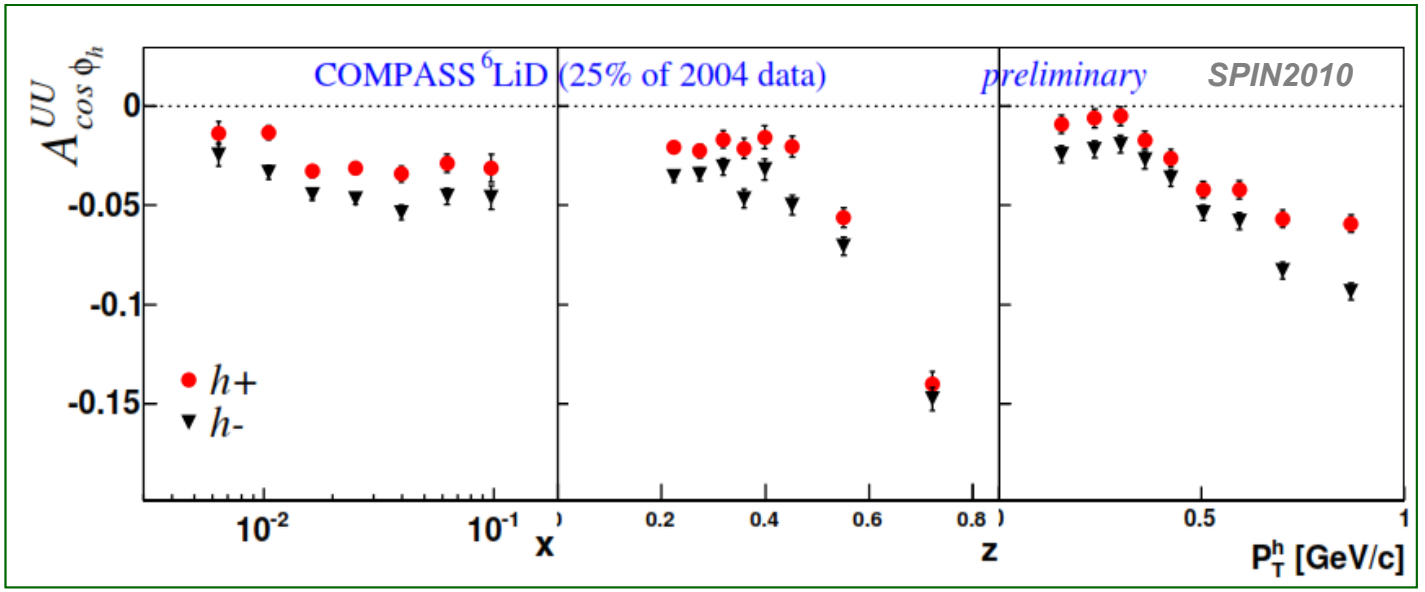


sin ϕ

h- compatible with zero

h+ slightly positive signal higher twist

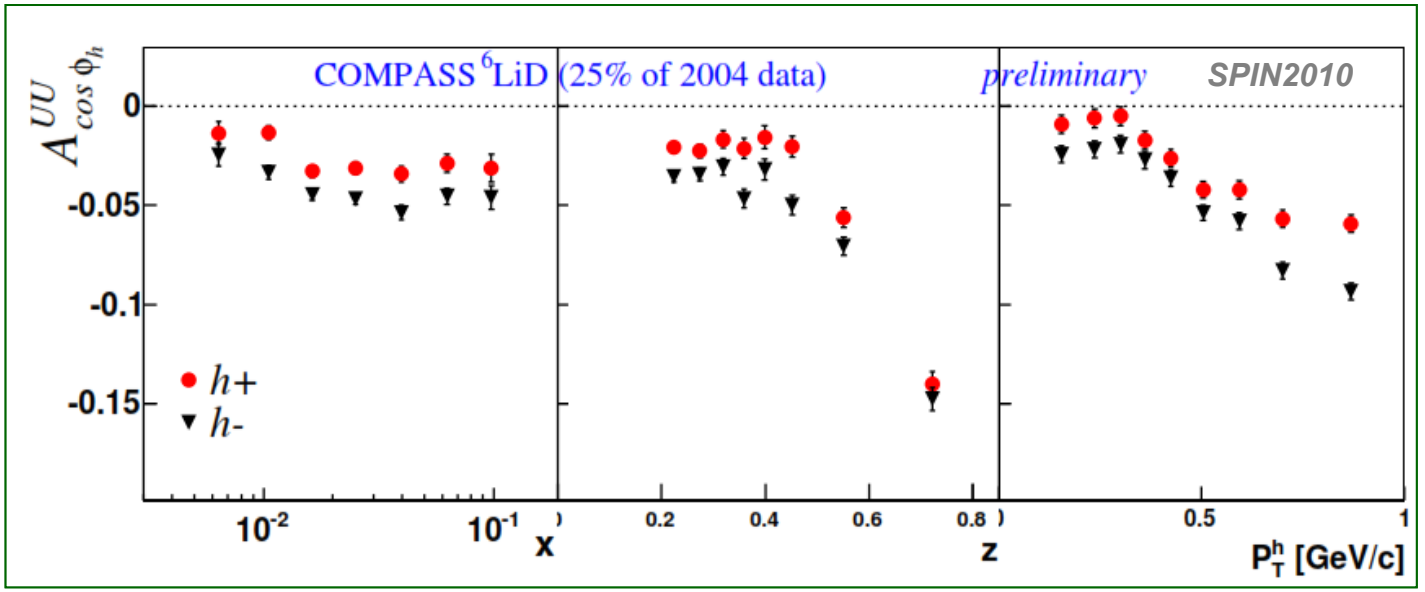
azimuthal asymmetries



cos ϕ

- large signals over all the x range

azimuthal asymmetries



cos ϕ

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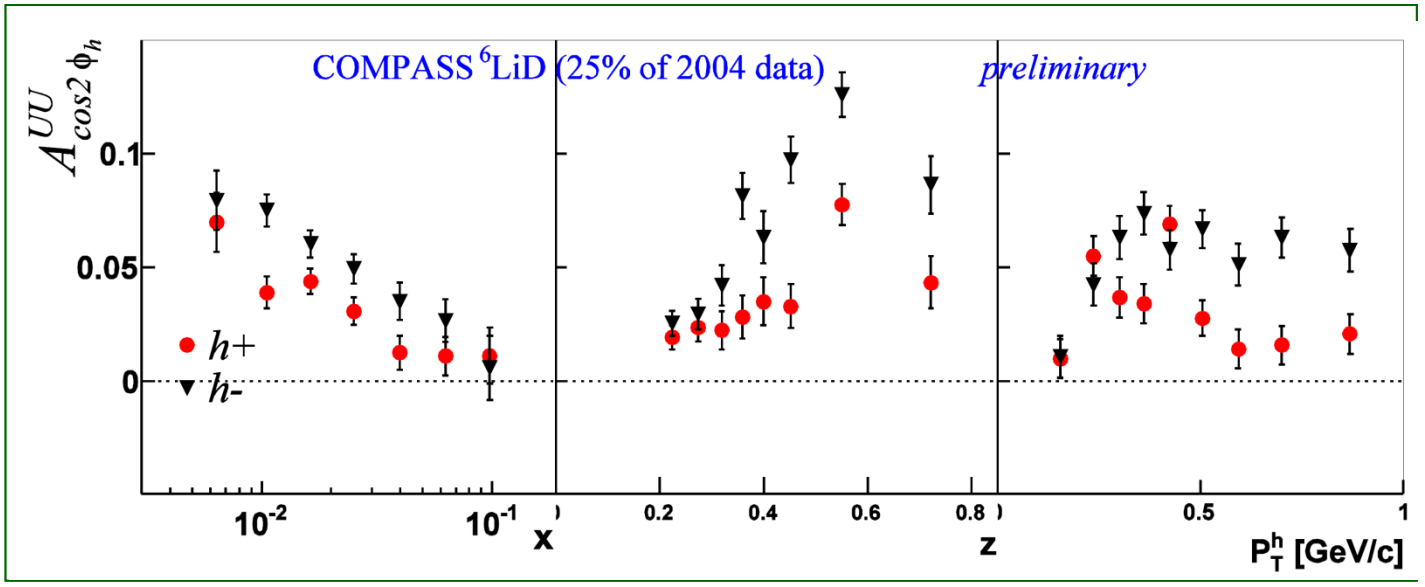


cos 2ϕ

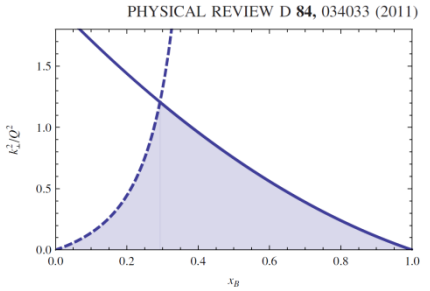
- large signals at small x

different for h^+ and h^-

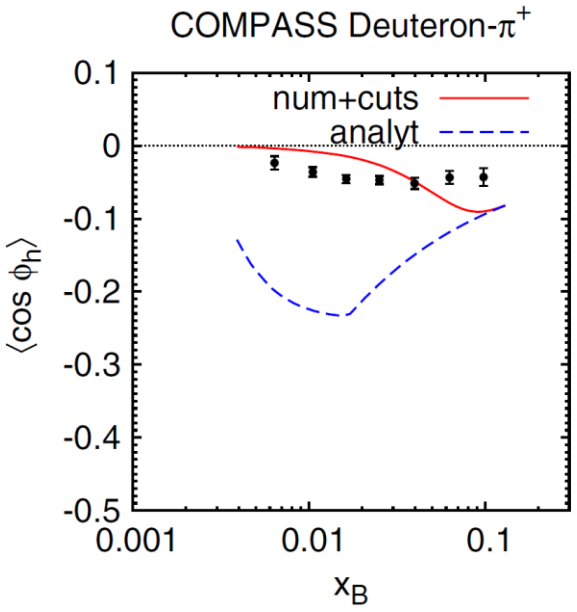
strong dependence on x, z, P_T^h

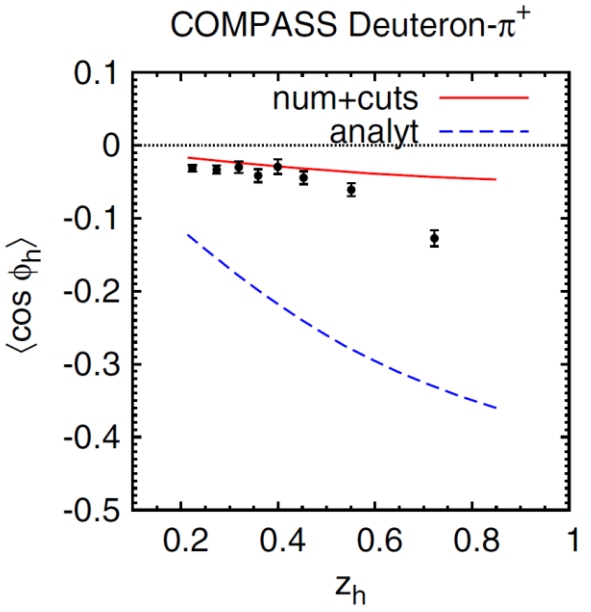
azimuthal asymmetries - cos ϕ

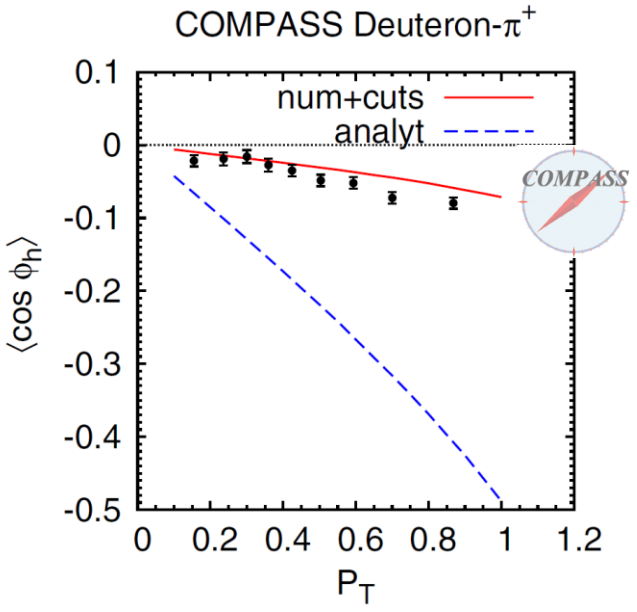
PHYSICAL REVIEW D **84,** 034033 (2011)



M. Boglione,[1] S. Melis,[2] and A. Prokudin[3]



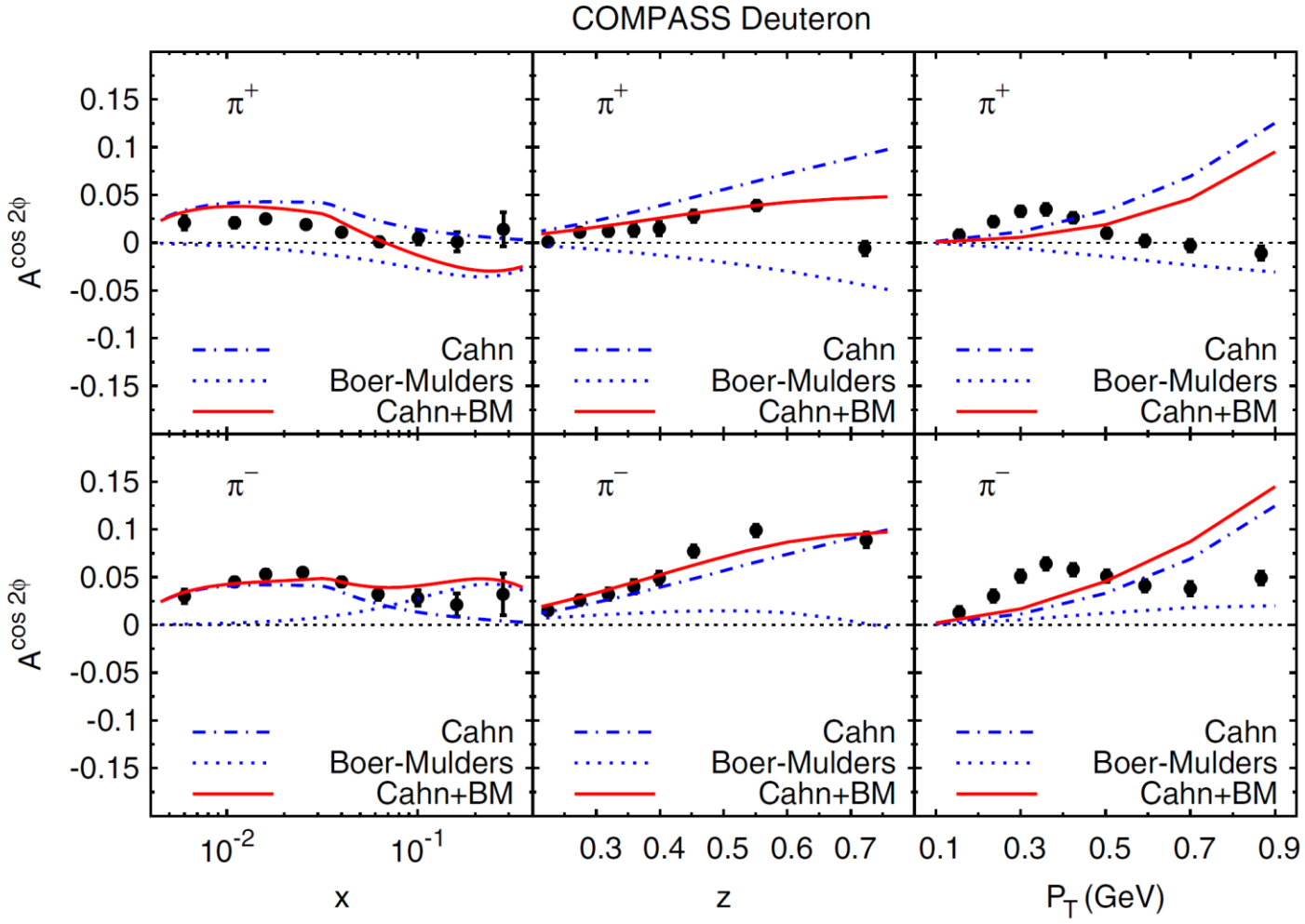




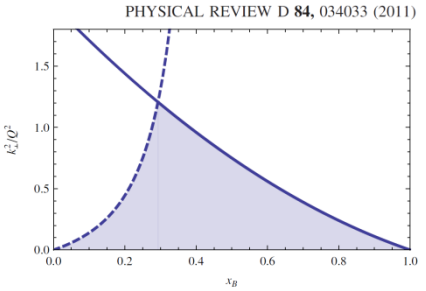
azimuthal asymmetries - cos 2ϕ

Vincenzo Barone,[1,2] Stefano Melis,[1,2] and Alexei Prokudin[3]

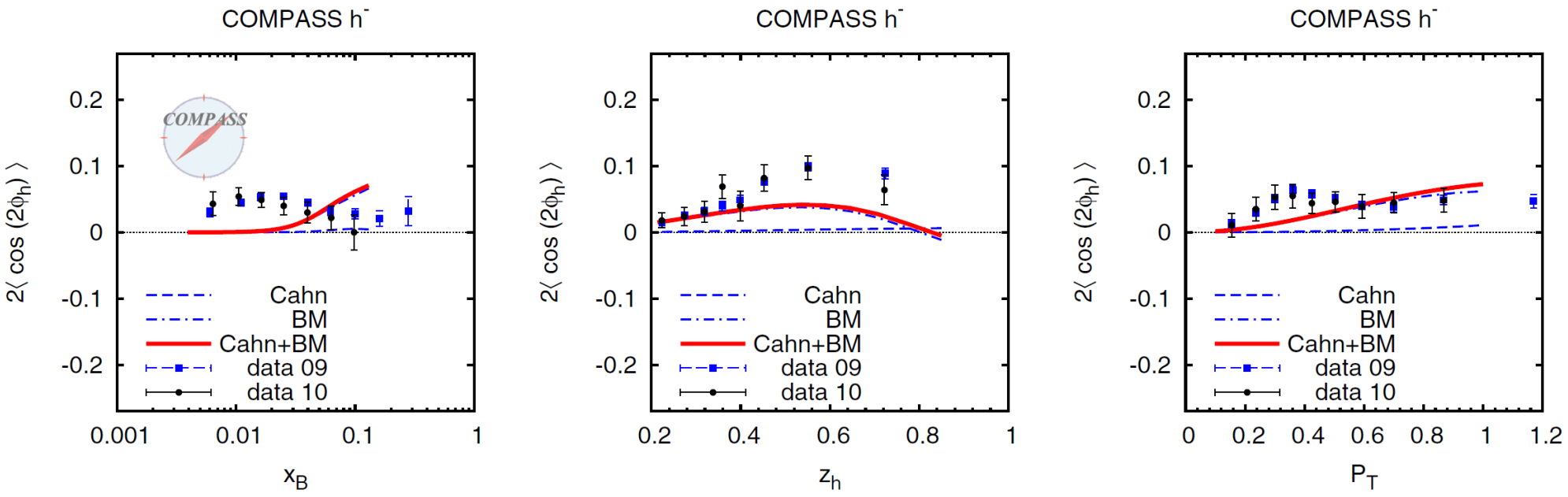
PHYSICAL REVIEW D **81,** 114026 (2010)



azimuthal asymmetries - cos 2ϕ



M. Boglione,[1] S. Melis,[2] and A. Prokudin[3]



azimuthal asymmetries

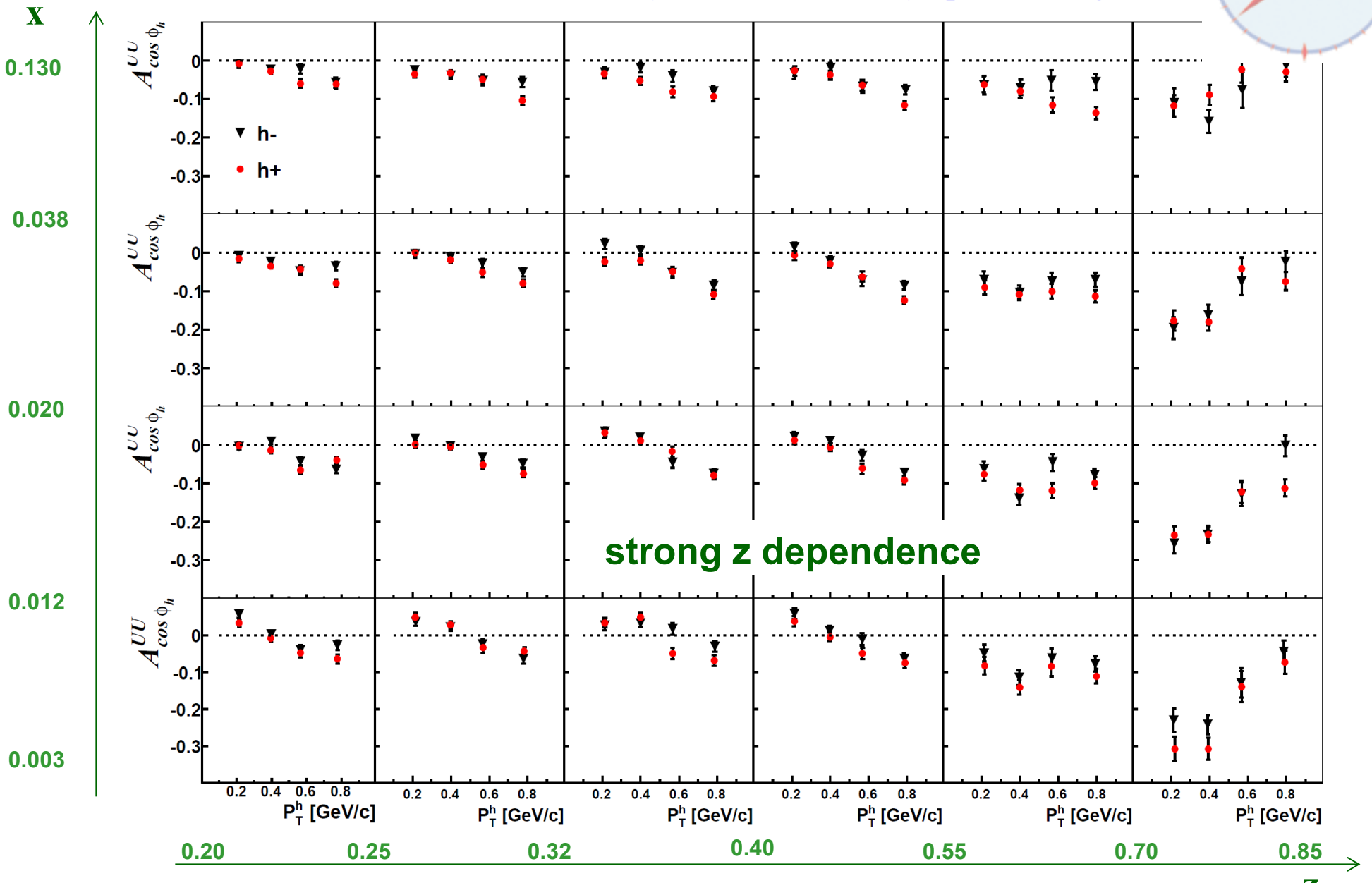
→ **multidimensional analysis**

x	z	$P_T^h\ (GeV/c)$
0.003	0.20	0.10
0.012	0.25	0.30
0.020	0.32	0.50
0.038	0.40	0.64
0.130	0.55	1.00
	0.70	
	0.85	

4 **6** **4**

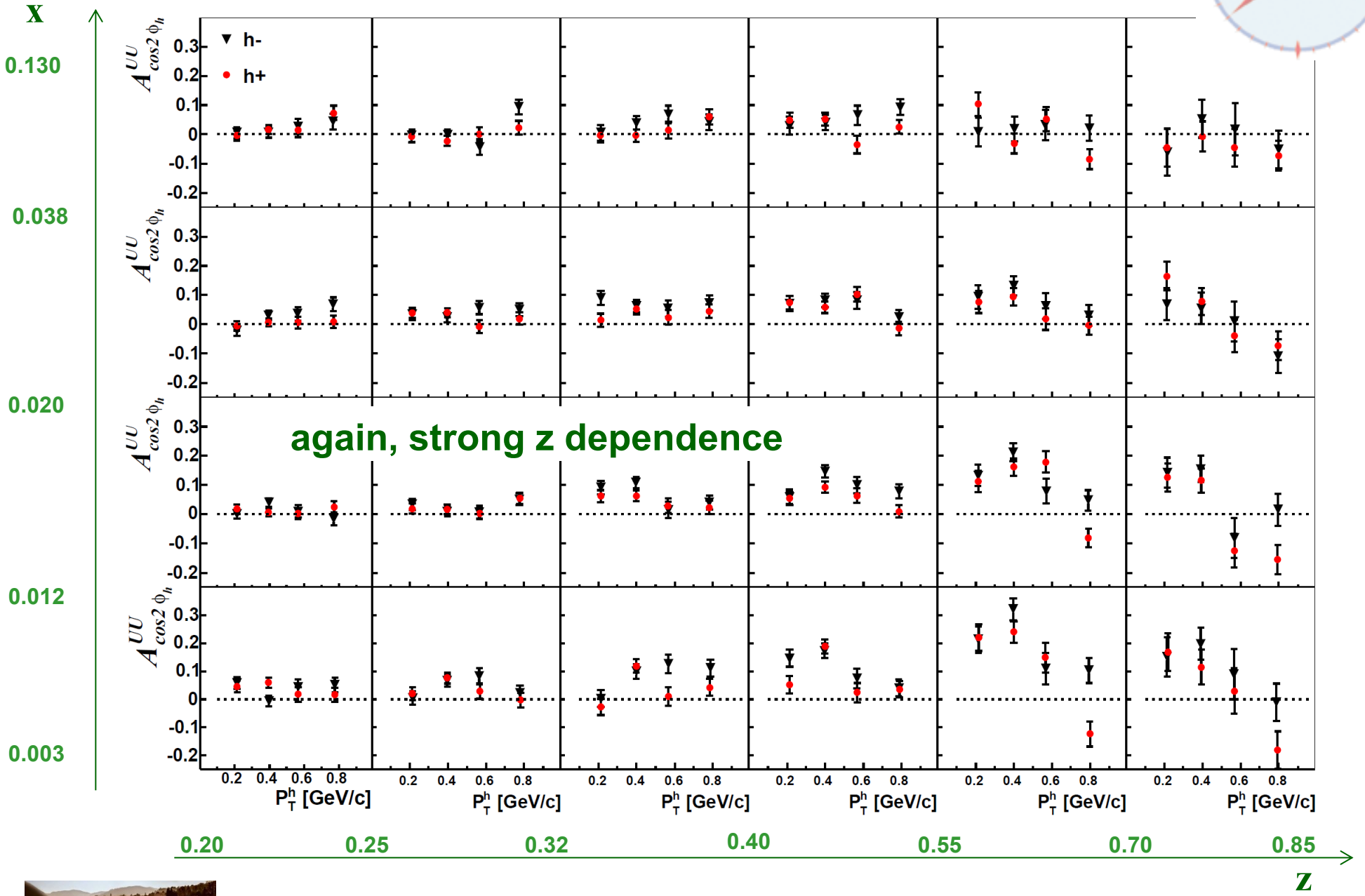
azimuthal asymmetries - cos ϕ

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



azimuthal asymmetries - cos 2ϕ

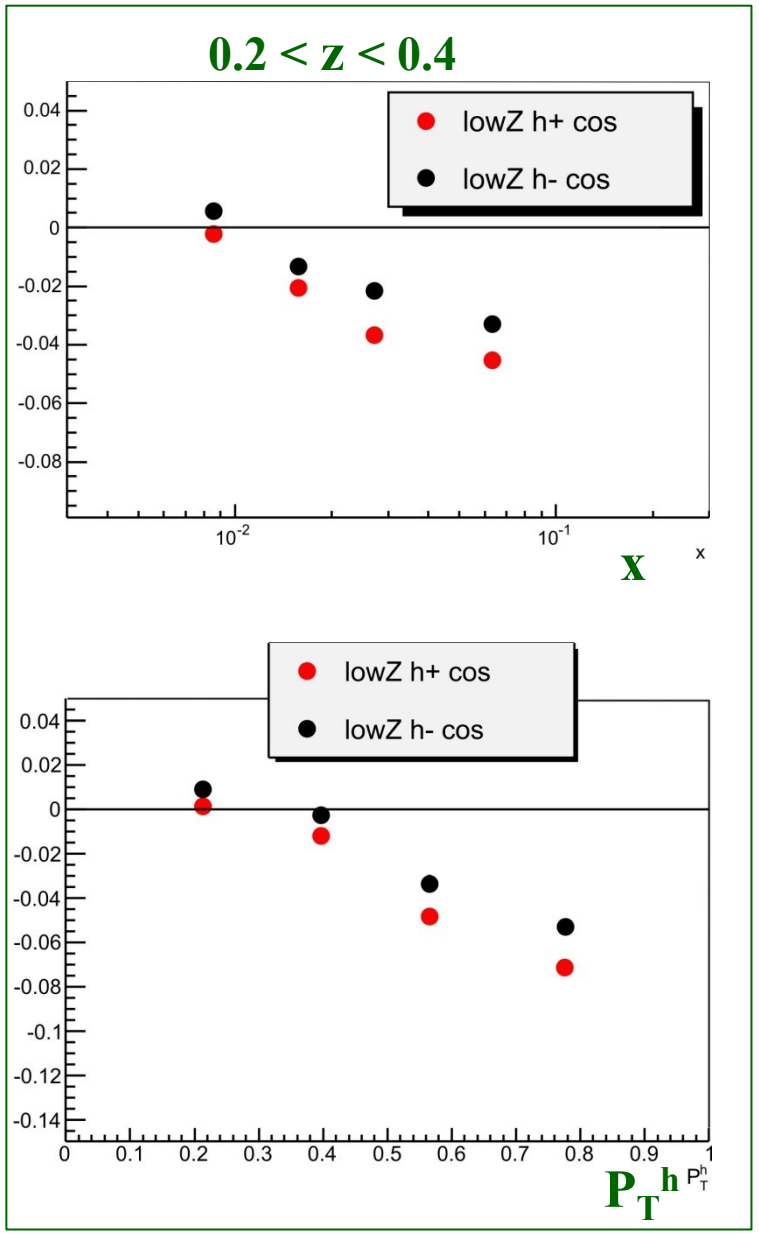
COMPASS ^{6}LiD (25% of 2004 data) preliminary

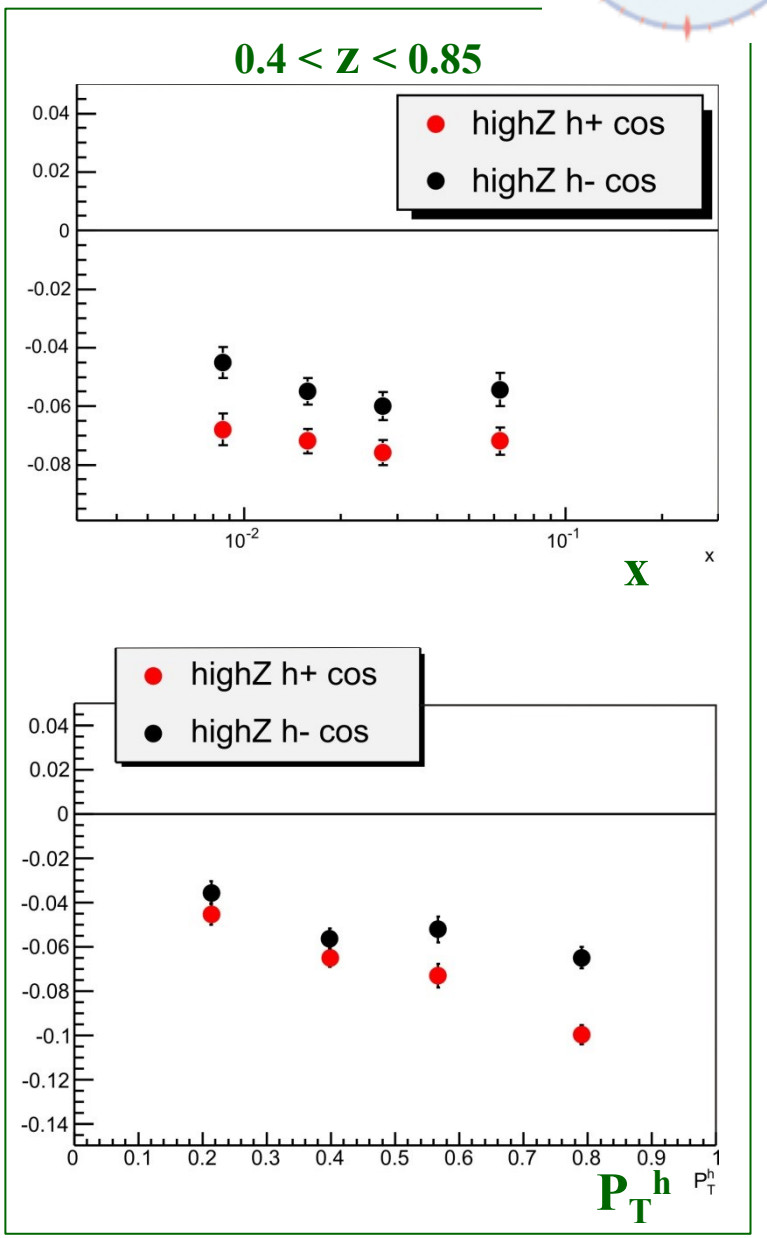


azimuthal asymmetries

z dependence

$A^{\cos\phi}$

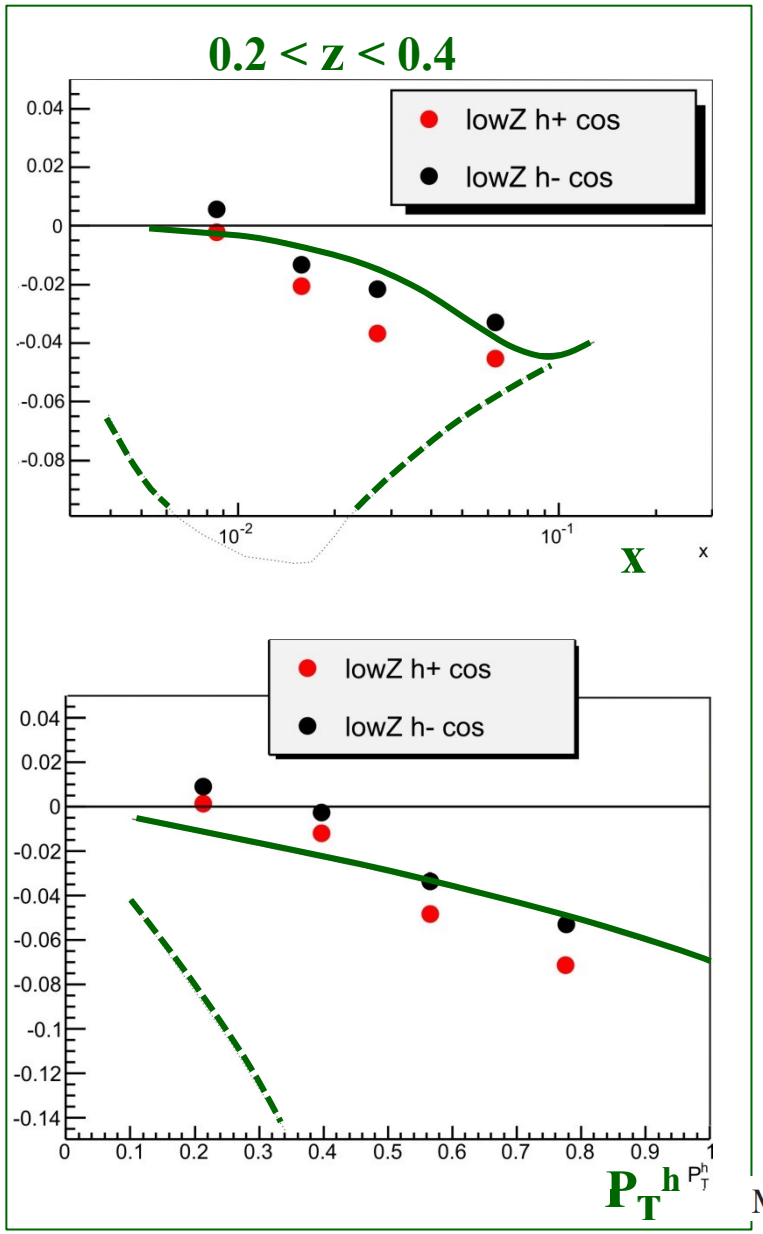


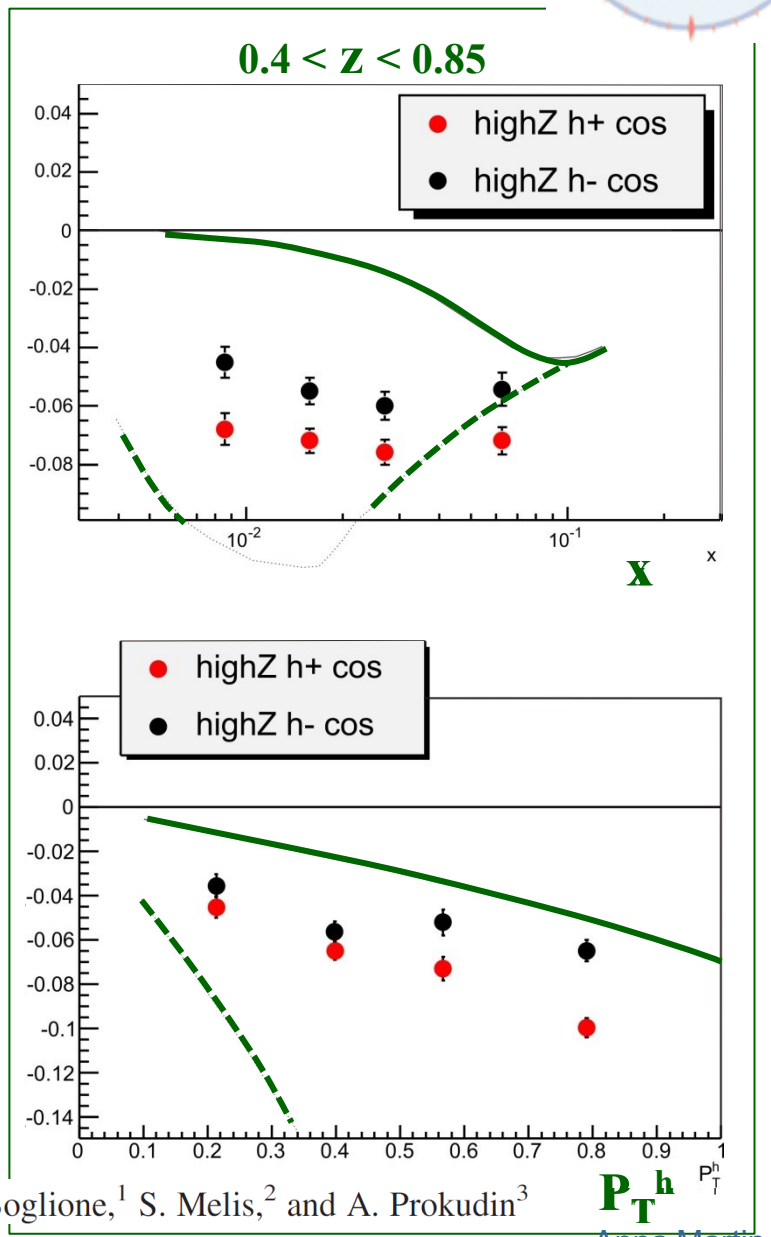


azimuthal asymmetries

z dependence

$A^{\cos\phi}$



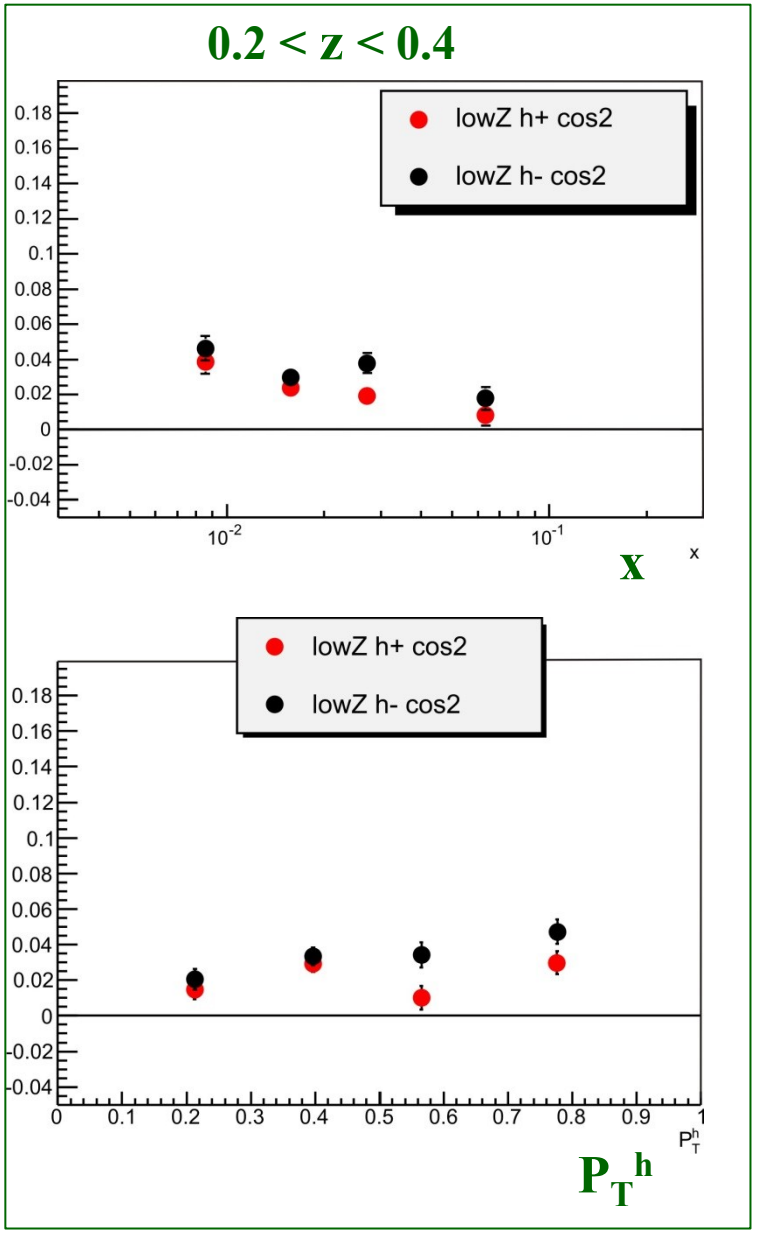


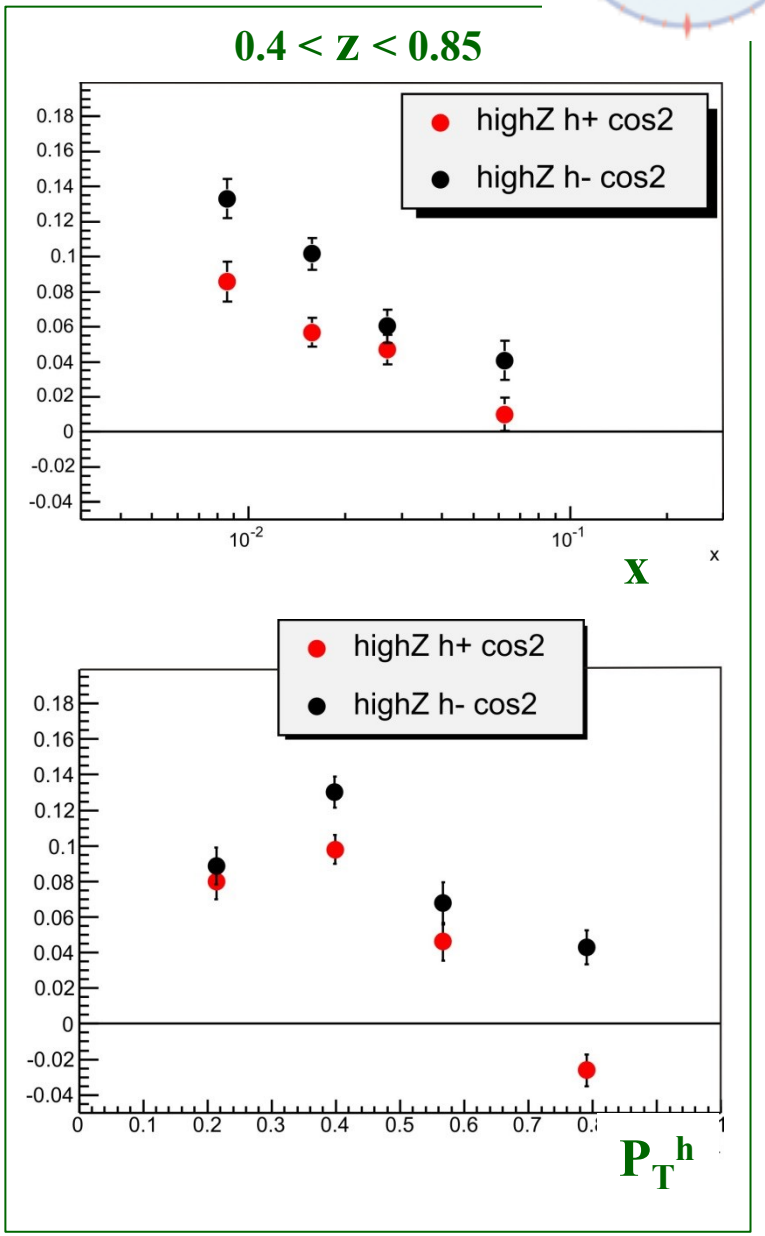
M. Boglione,[1] S. Melis,[2] and A. Prokudin[3]

azimuthal asymmetries

z dependence

$A^{\cos 2\phi}$

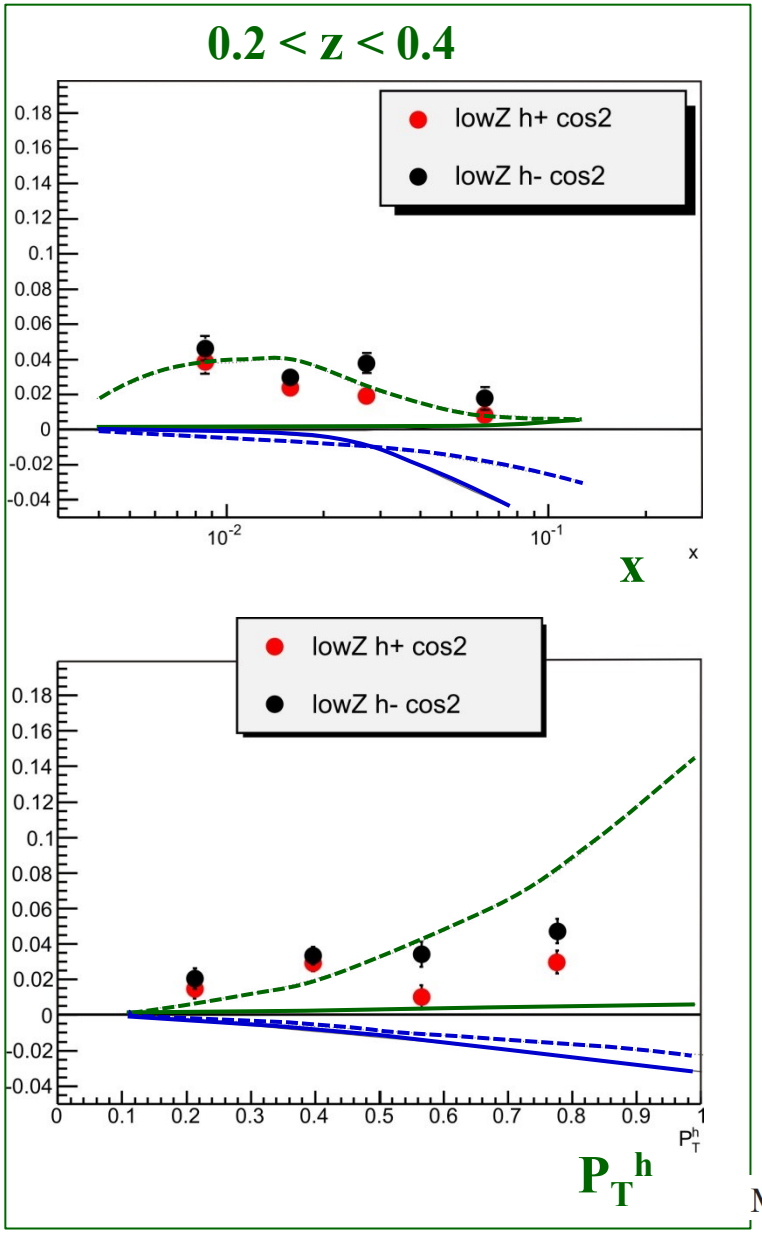


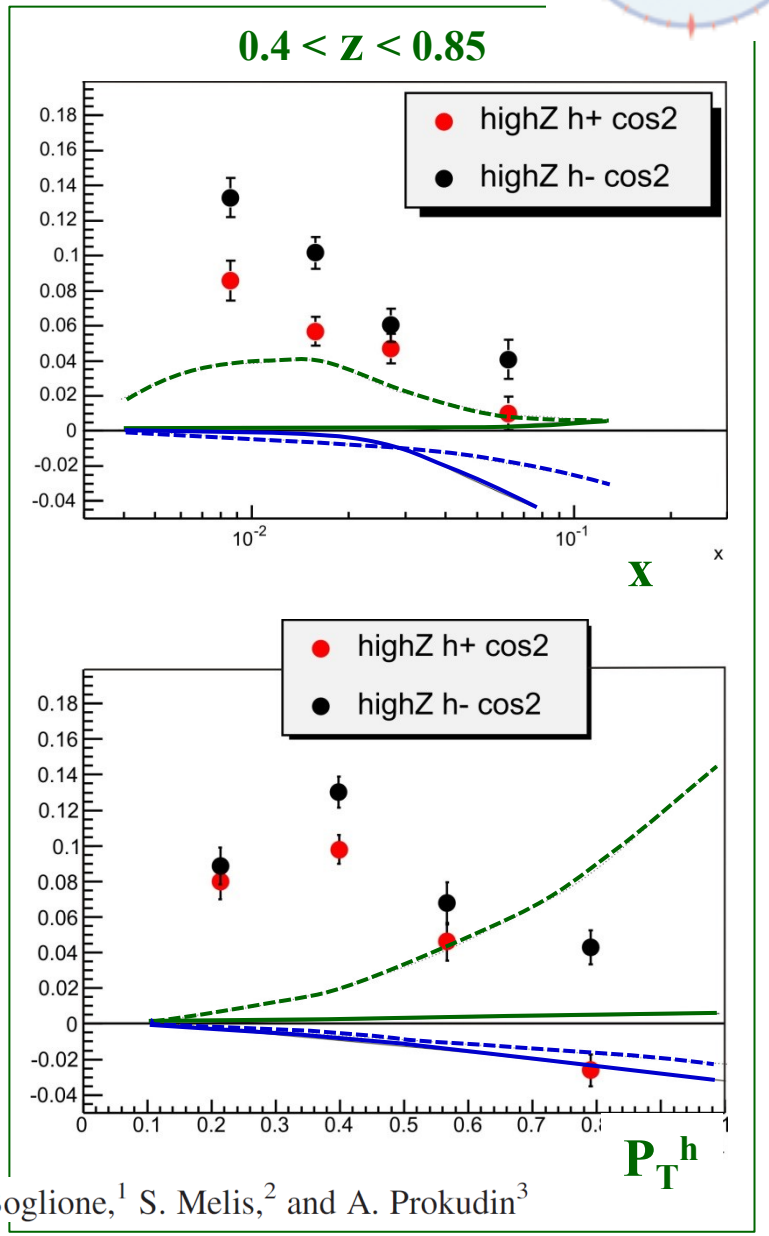


azimuthal asymmetries

z dependence

$A^{\cos 2\phi}$





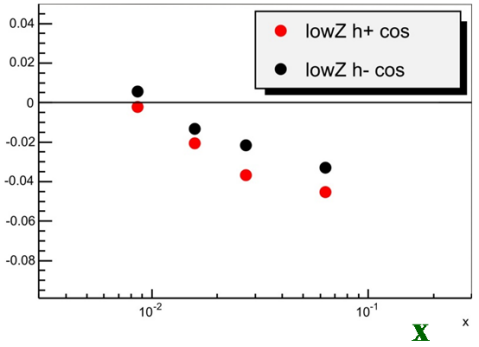
M. Boglione,[1] S. Melis,[2] and A. Prokudin[3]

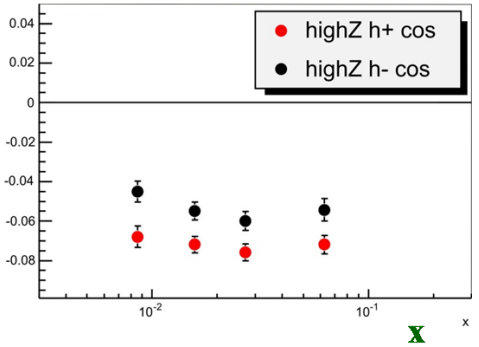
azimuthal asymmetries

different dependences for

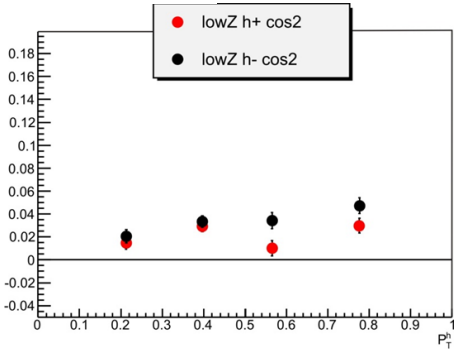
$0.2 < z < 0.4$ $0.4 < z < 0.85$

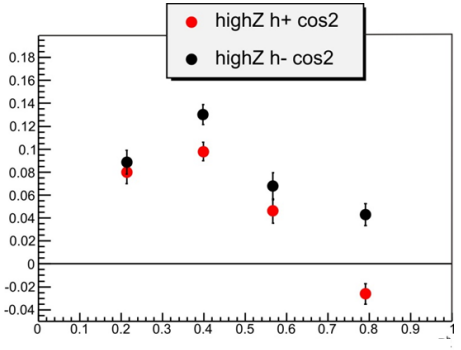
$A^{\cos\phi}$

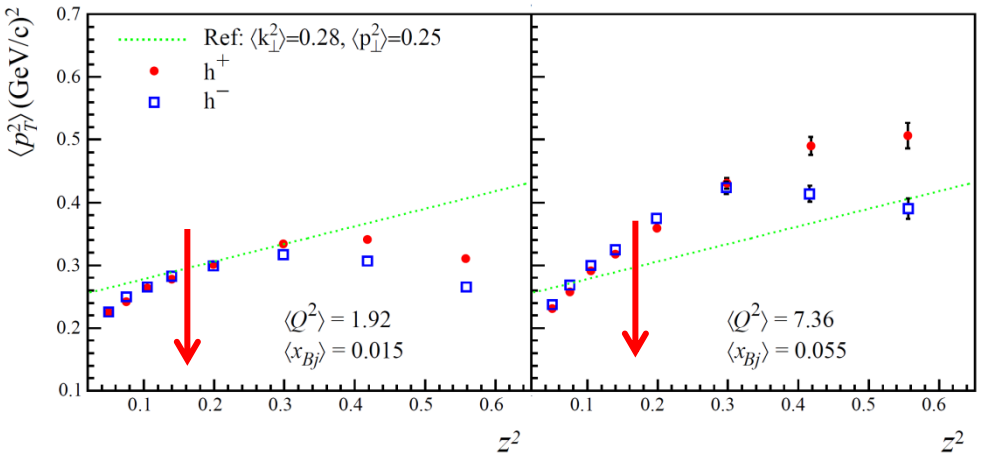




$A^{\cos 2\phi}$







to be understood!

conclusions

COMPASS has produced interesting and "intriguing" results on SIDIS off unpolarised deuteron

- **hadron multiplicities vs p_T^2**
- **hadron pair multiplicities**
- **azimuthal asymmetries**

next steps: results on

- **hadron multiplicities vs p_T^2**
- **hadron pair multiplicities**

from 2006 deuteron data, with PID

on a longer time scale

- **hadron multiplicities vs p_T^2**
- **hadron pair multiplicities**
- **azimuthal asymmetries**

from SIDIS measurements with LH target, in parallel to DVCS (2016-2017)