COMPASS news on unpolarized SIDIS

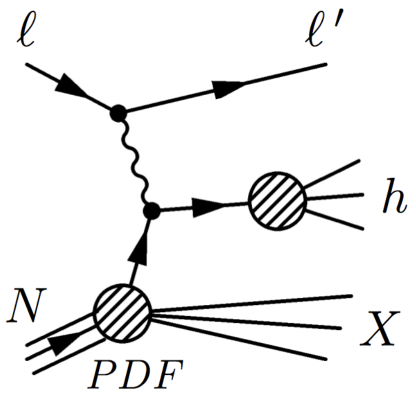
N. Makke for the COMPASS Collaboration

INFN/University of Trieste
International Center for Theoretical Physics, Trieste

Fourth International workshop on
Transverse Polarization Phenomena in Hard Processes
June 9-13, Chia, Cagliari

Semi-inclusive DIS

$$\boxed{\ell N \rightarrow \ell' h(X)}$$



DIS with unpolarized hadron detected in final state

Powerful tool

- PDF and FF dependent
- Allows flavor & charge separation of FFs
- Covers wide scale (Q^2) range
- Relevant for spin physics kinematics

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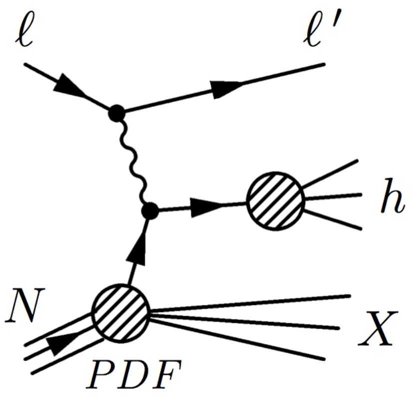

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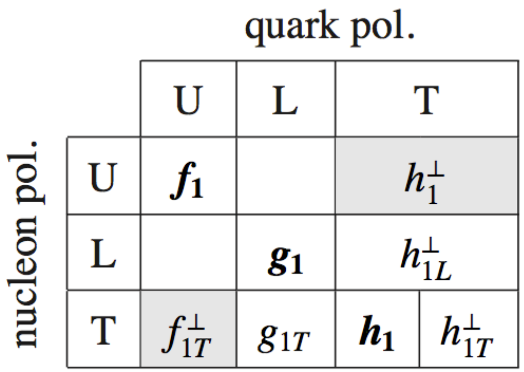
At Leading twist:



quark pol.

nucleon pol.

	U	L	T	
U	f_1		$h_1^\perp$	
L		g_1	$h_{1L}^\perp$	
T	$f_{1T}^\perp$	g_{1T}	h_1	$h_{1T}^\perp$

- 8 intrinsic-transverse-momentum dependent PDFs
- Azimuthal asymmetries with different angular modulations in the hadron and spin azimuthal angles, Φ_h and Φ_s
- Vanish upon integration over k_T except f_1 , g_1 , and h_1

Semi-inclusive DIS

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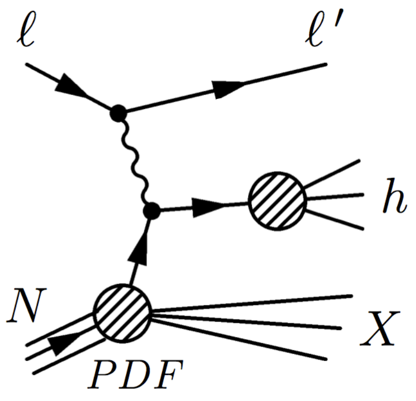

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At Leading twist:

8 TMD PDFs

2 TMD FFs

Unpolarized PDFs & FFs

Boer-Mulders effects

		quark pol.			
		U	L	T	
nucleon pol.	U	f_1		$h_1^\perp$	
	L		g_1	$h_{1L}^\perp$	
	T	$f_{1T}^\perp$	g_{1T}	h_1	$h_{1T}^\perp$

	quark pol.		
	U	L	T
U	D_1		$H_1^\perp$

Relevance of unpolarized SIDIS

Very good knowledge of PDFs and FFS is a key element for a reasonably precise determination of polarized quantities, e.g. polarization of quarks in

- Longitudinally polarized nucleon
- Transversely polarized nucleon

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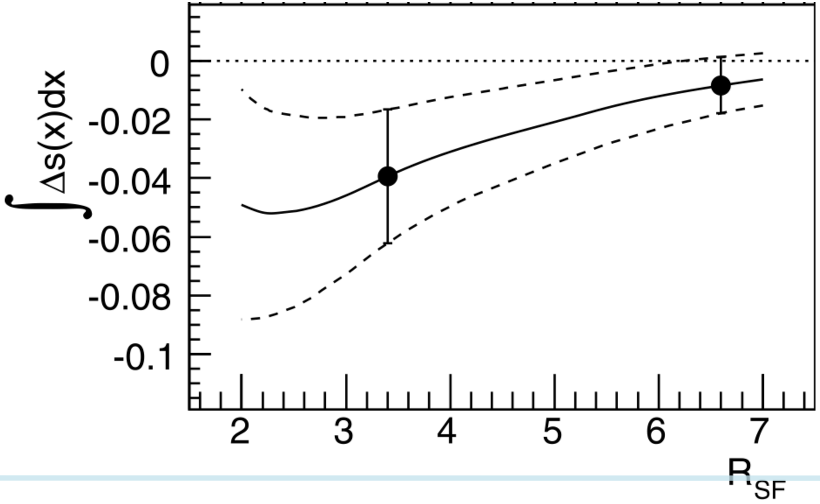
$$A_h^1(x,z) = \frac{\sum_q e_q^2 \left(\Delta q(x) D_q^h(z) + \Delta\bar{q}(x) D_{\bar{q}}^h(z)\right)}{\sum_q e_q^2 \left(\boxed{q(x) D_q^h(z)} + \bar{q}(x) D_{\bar{q}}^h(z)\right)}$$

  - Strange quark polarization and its strong dependence on FFs parameterizations
  - Poor knowledge of S(x) (c.f. M. Contalbrigo's talk)

PLB 693 (2010) 227–235



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- Longitudinally polarized nucleon

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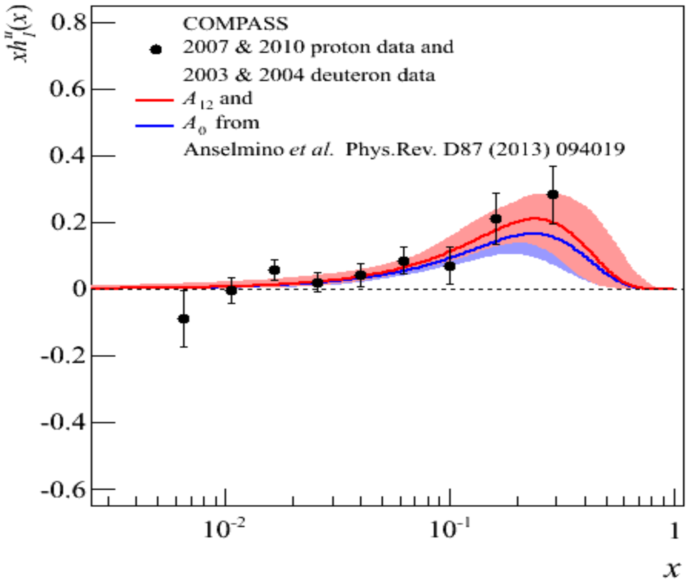
  - Strange quark polarization and its strong dependence on FFs parameterizations
  - Poor knowledge of S(x) (c.f. M. Contalbrigo's talk)

- Transversely polarized nucleon

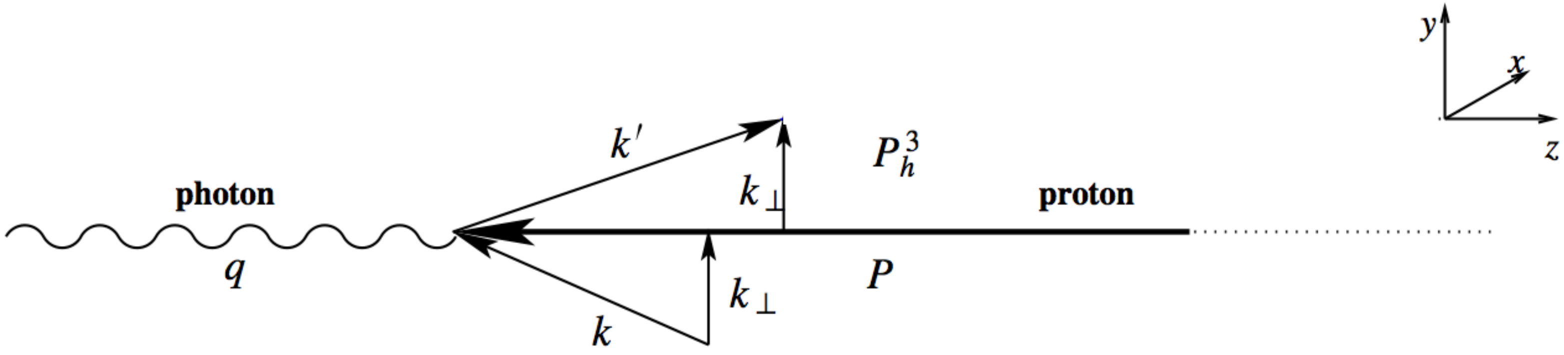
$$A_{\text{Coll}} = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 \cdot \boxed{q(x) \cdot D_q^h(z, p_T^h)}}$$

  - Extraction of transversity function



Transverse Momentum dependence

- Transverse momenta of unpolarised final-state hadron generated by
  ⇒ Transverse momentum of the quark (k) in the target proton

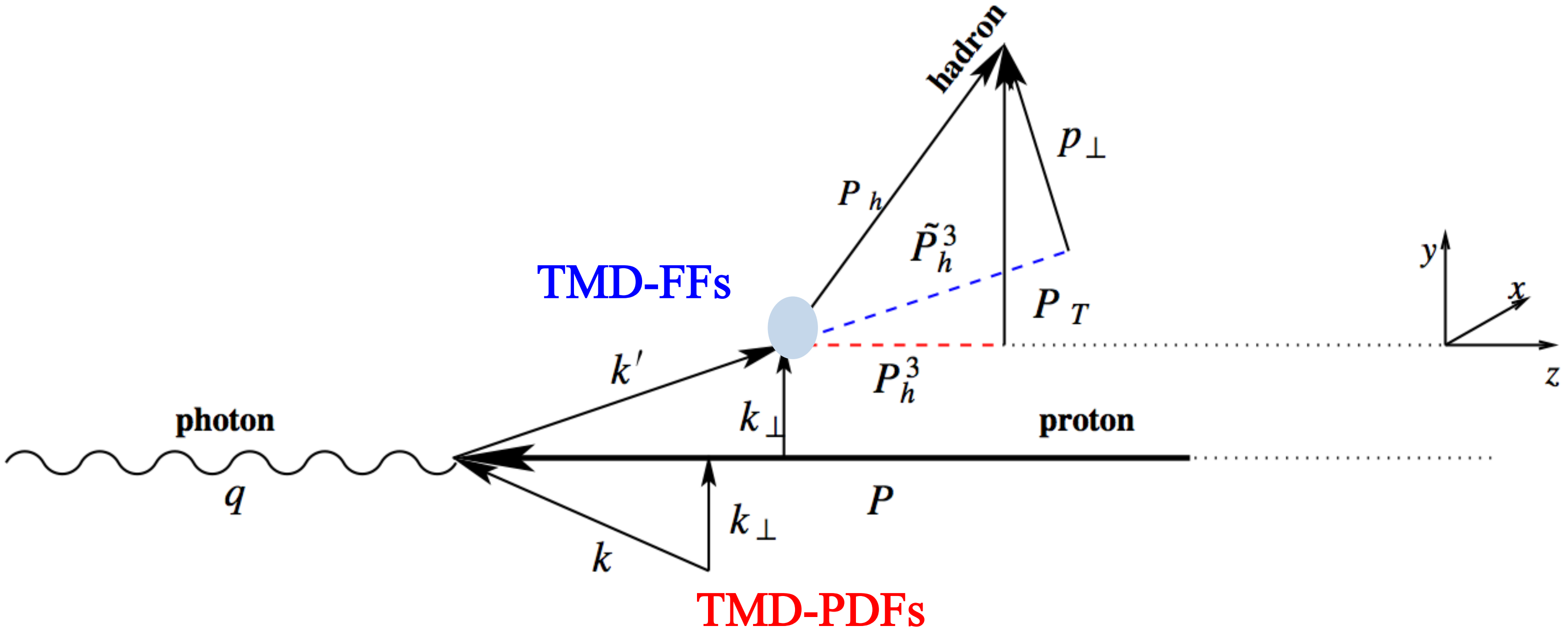


TMD-PDFs

PRD 71, 074006, (2005)

Transverse Momentum dependence

- Transverse momenta of unpolarised final-state hadron generated by
  - ⇒ Transverse momentum of the quark (*k*) in the target proton
  - ⇒ Transverse momentum of hadron wrt fragmenting quark (*k*')



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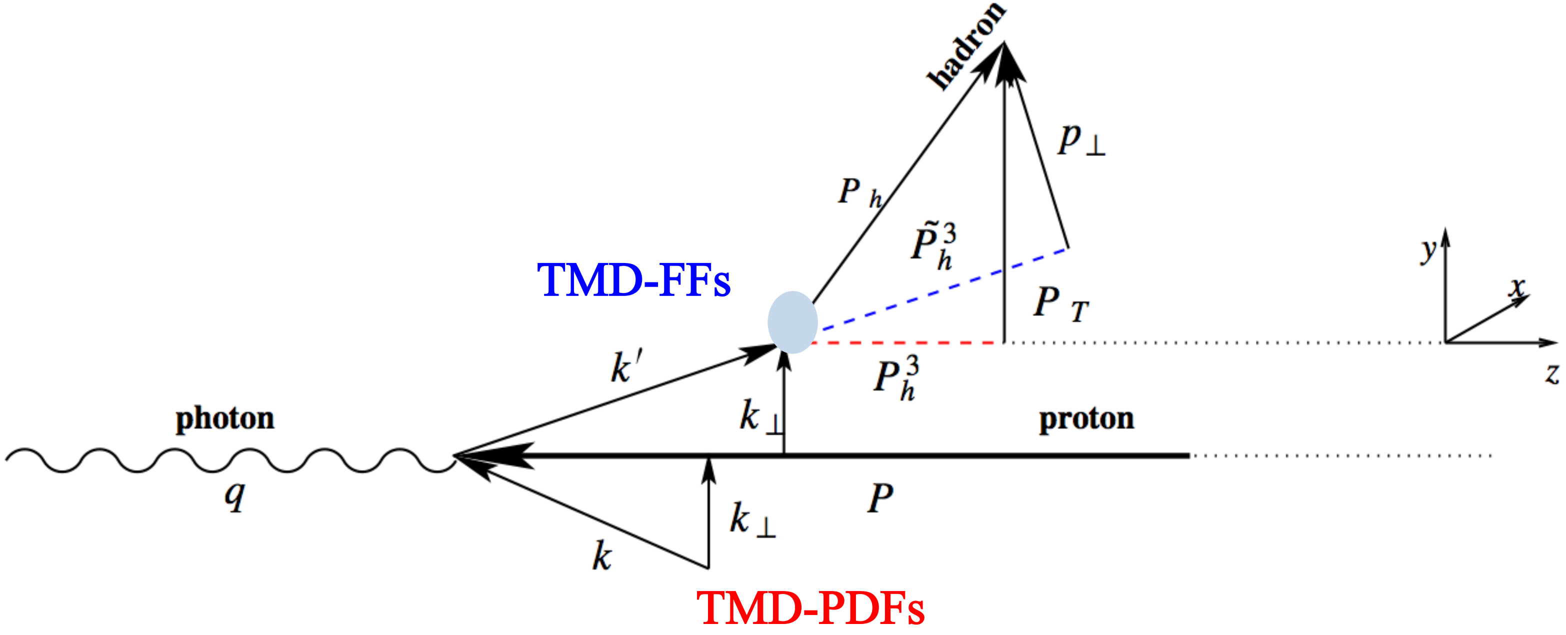
Parton model

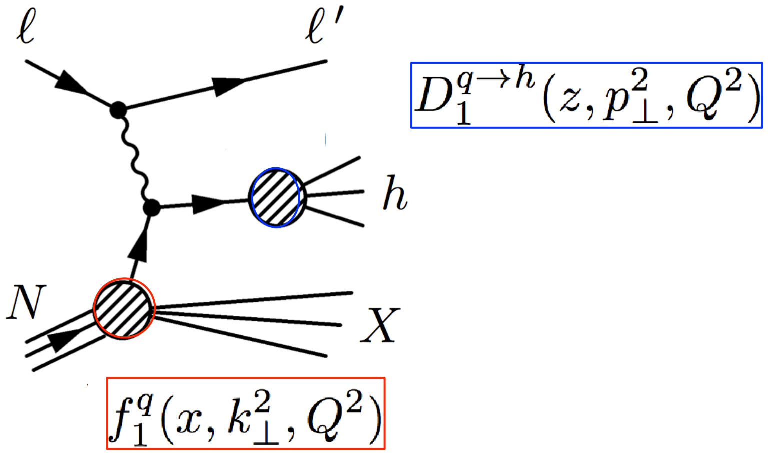
$$F_{UU}(x,z,p_T^2;Q^2)=\sum_q e_q^2 x\int dk_\perp dp_\perp \delta(zk_\perp+p_\perp-p_T) f_1^q(x,k_\perp^2,Q^2) D_1^{q\to h}(z,p_\perp^2,Q^2)$$



PRD 71, 074006, (2005)

Experimental observable: Multiplicity

Defined as average number of hadrons
produced per DIS event



$$D_1^{q\to h}(z,p_\perp^2,Q^2)$$

$$f_1^q(x,k_\perp^2,Q^2)$$

$$M_N^h(x,z,p_T^2,Q^2) = \frac{d^4\sigma_N^h/(dx\,dz\,dp_T^2\,dQ^2)}{d^2\sigma_{DIS}/(dx\,dQ^2)} \sim \frac{F_{UU}(x,z,p_T^2;Q^2)}{F_T(x,Q^2)}$$

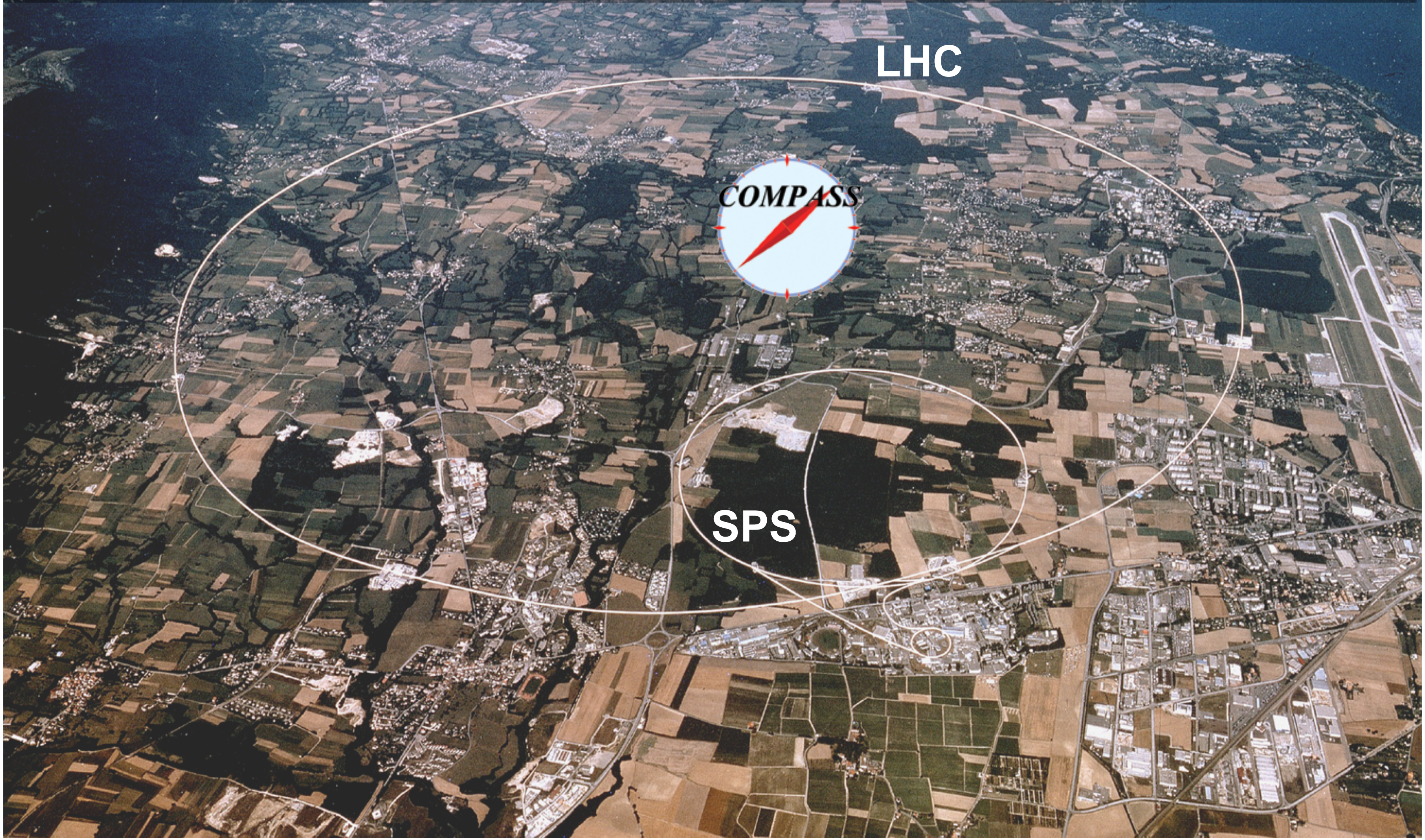
$$\sim f_1^q(x,k_\perp^2,Q^2) \times D_1^{q\to h}(z,p_\perp^2,Q^2)$$

TMD-PDFs TMD-FFs

p_T integrated multiplicities ==> M. Contalbrigo’s talk

COMPASS:

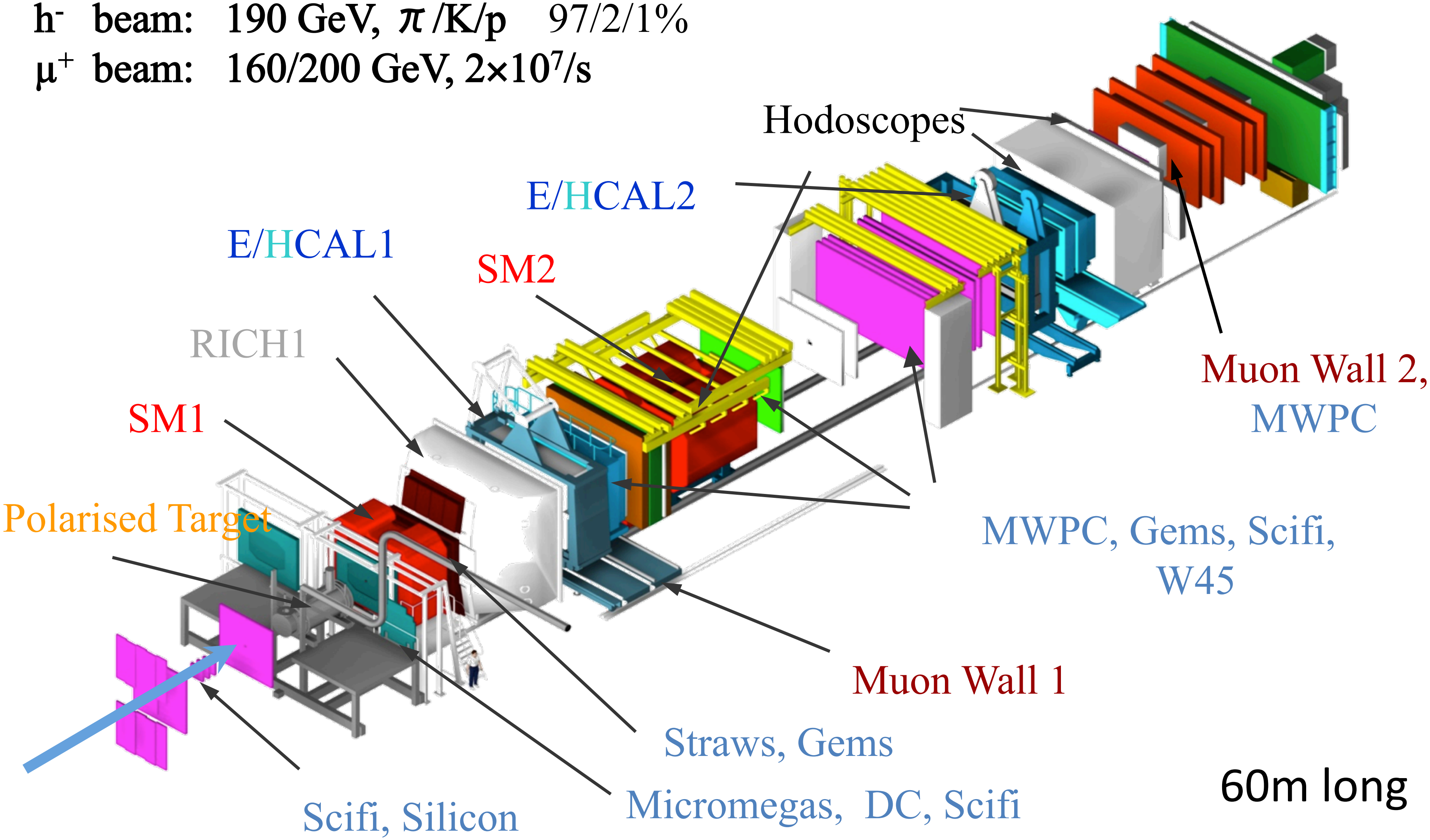
COmmon Muon and Proton Apparatus for Structure and Spectroscopy"



COMPASS spectrometer

h^+ beam: 190 GeV, p/ π /K 75/24/1%
h^- beam: 190 GeV, π /K/p 97/2/1%
μ^+ beam: 160/200 GeV, 2×10^7/s

Data taking since 2002



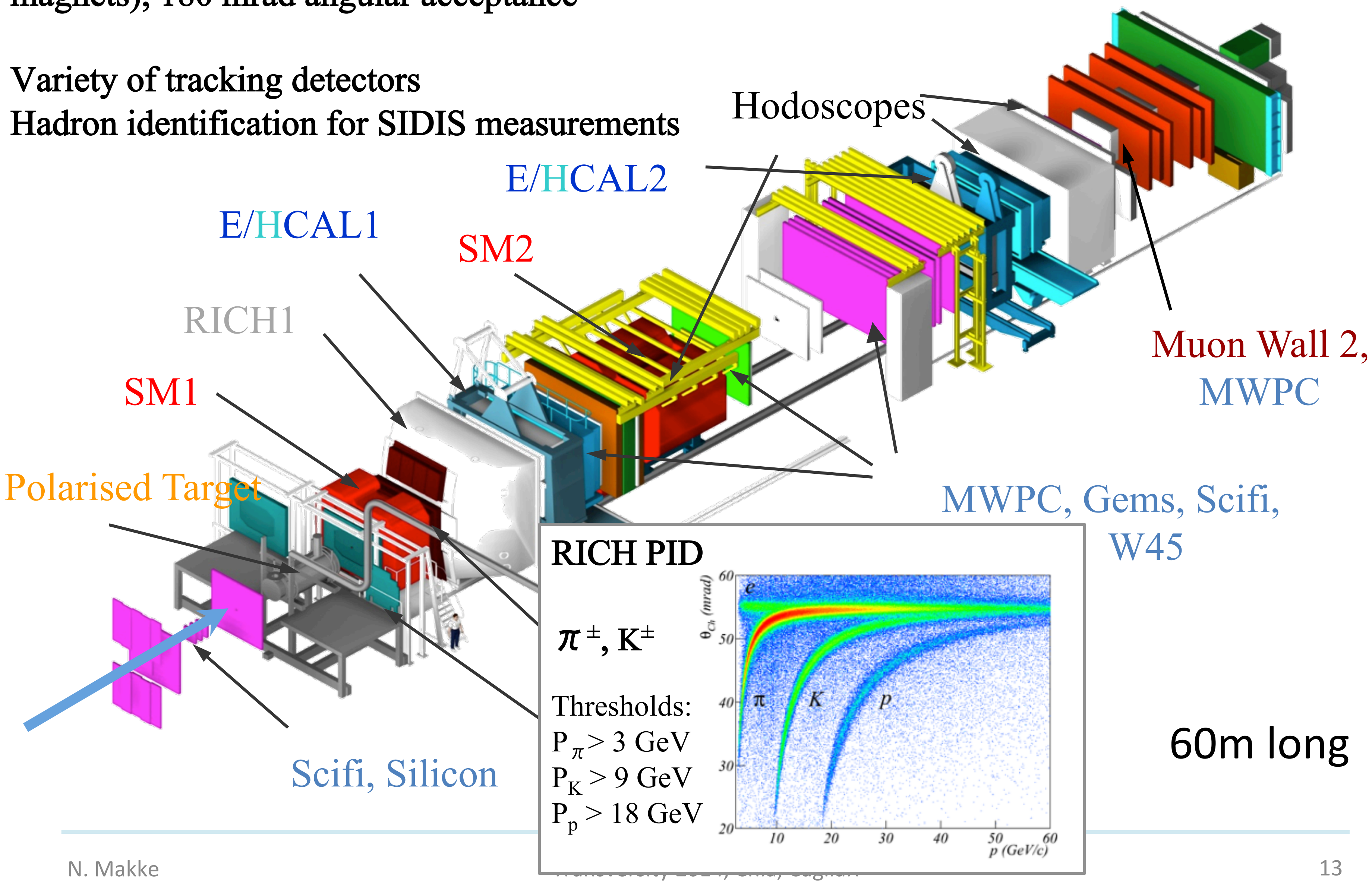
60m long

COMPASS spectrometer

Two stages spectrometer (with SM1/2 magnets), 180 mrad angular acceptance

Variety of tracking detectors
Hadron identification for SIDIS measurements

Data taking since 2002



Hodoscopes

E/HCAL2

E/HCAL1

SM2

RICH1

SM1

Muon Wall 2, MWPC

Polarised Target

MWPC, Gems, Scifi, W45

Scifi, Silicon

RICH PID

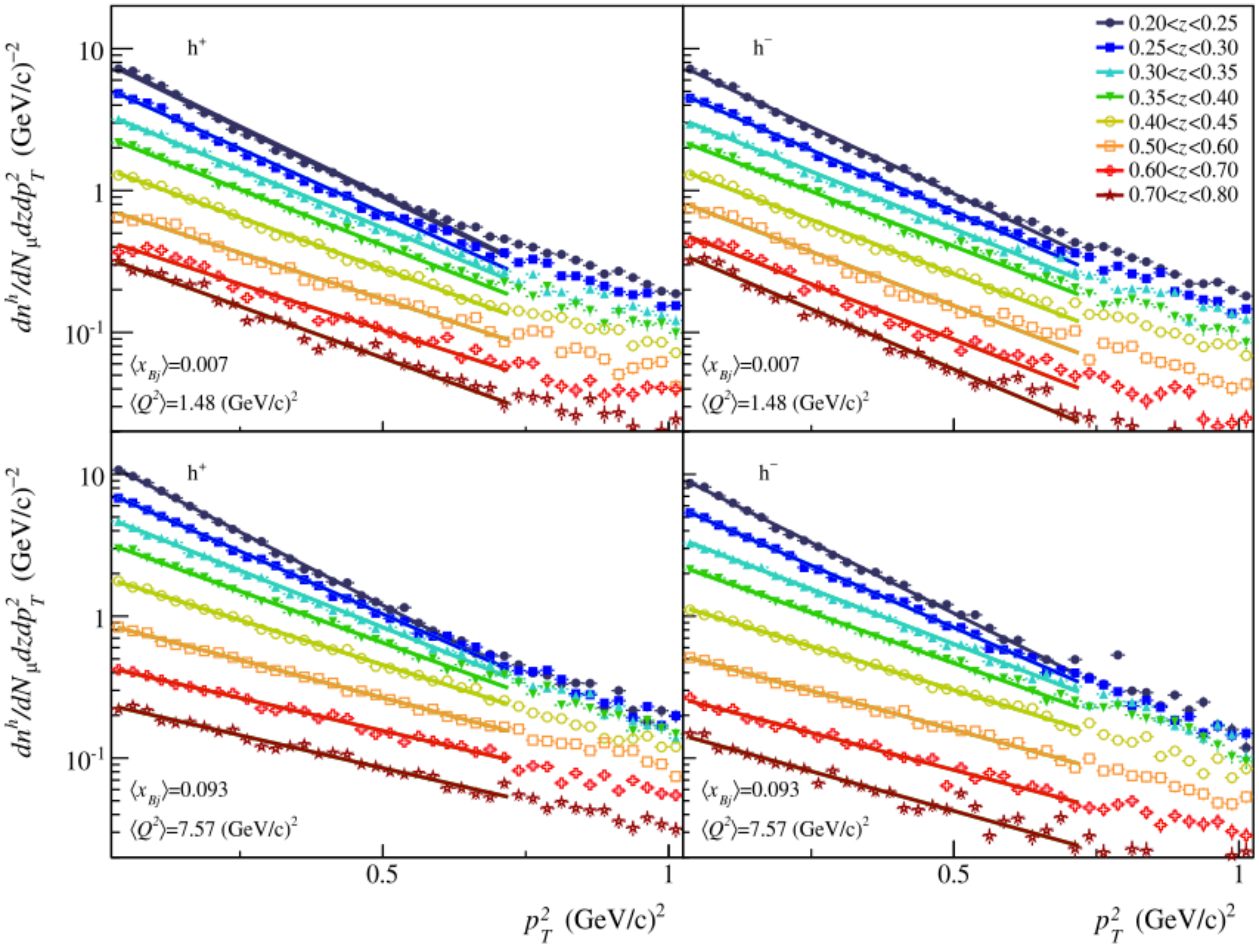
$\pi^{\pm}$, $K^{\pm}$

Thresholds:
$P_{\pi} > 3$ GeV
$P_{K} > 9$ GeV
$P_{p} > 18$ GeV

60m long

p_T^2 dependent multiplicities

SIDIS data collected in 2004 using deuteron target EPJC 73 (2013) 2531



- $Q^2 > 1$ (GeV)^2
- $W > 5$ (GeV/c^2
- $0.1 < y < 0.9$
- $0.0044 < x < 0.12$

2004 kinematic coverage

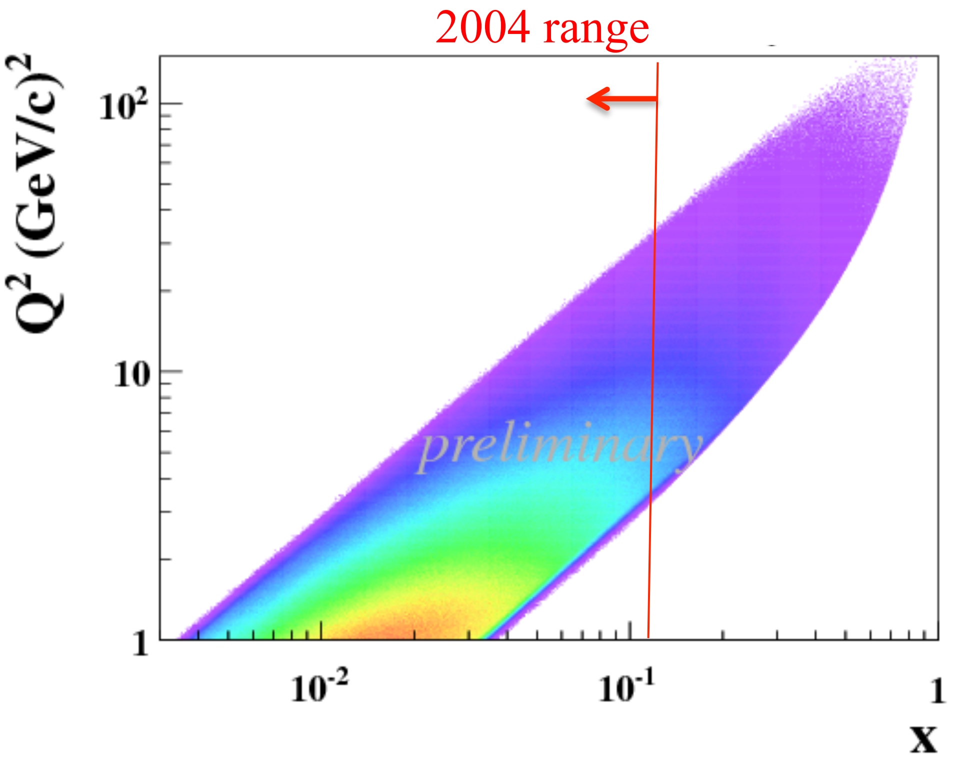
- $p_T < 1.3$ (GeV)^2

Lack of statistics at large p_T

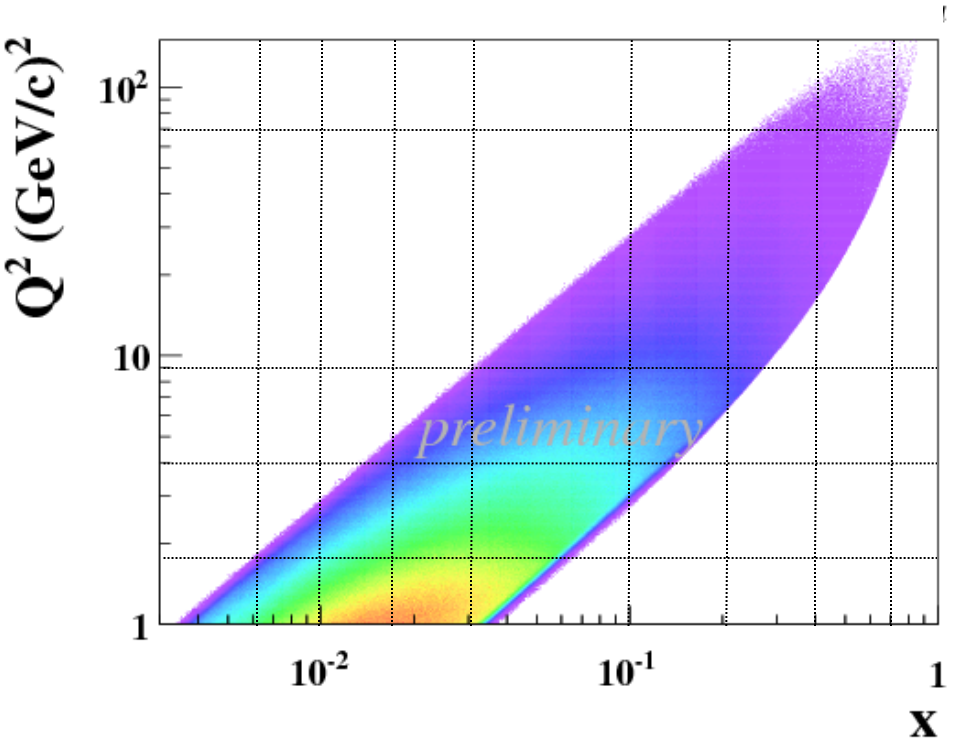
New analysis with 2006 SIDIS data

New SIDIS data sample collected in 2006 (on deuterons)

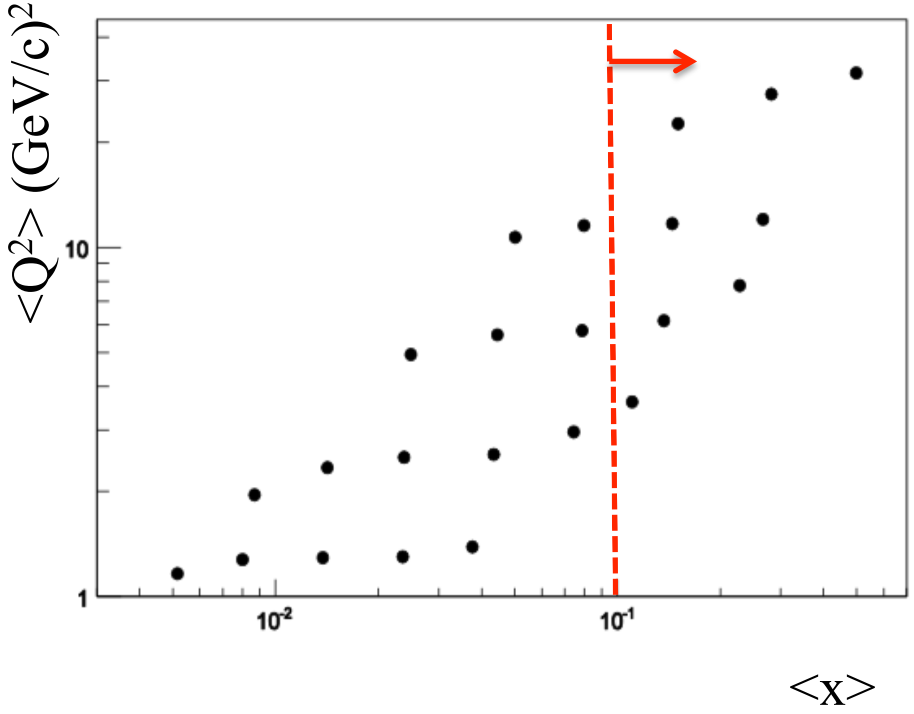
- Larger angular acceptance
- Very good π /K PID efficiency
- Larger statistics sample



Multi-dimensional analyses



2006 extended kinematic range



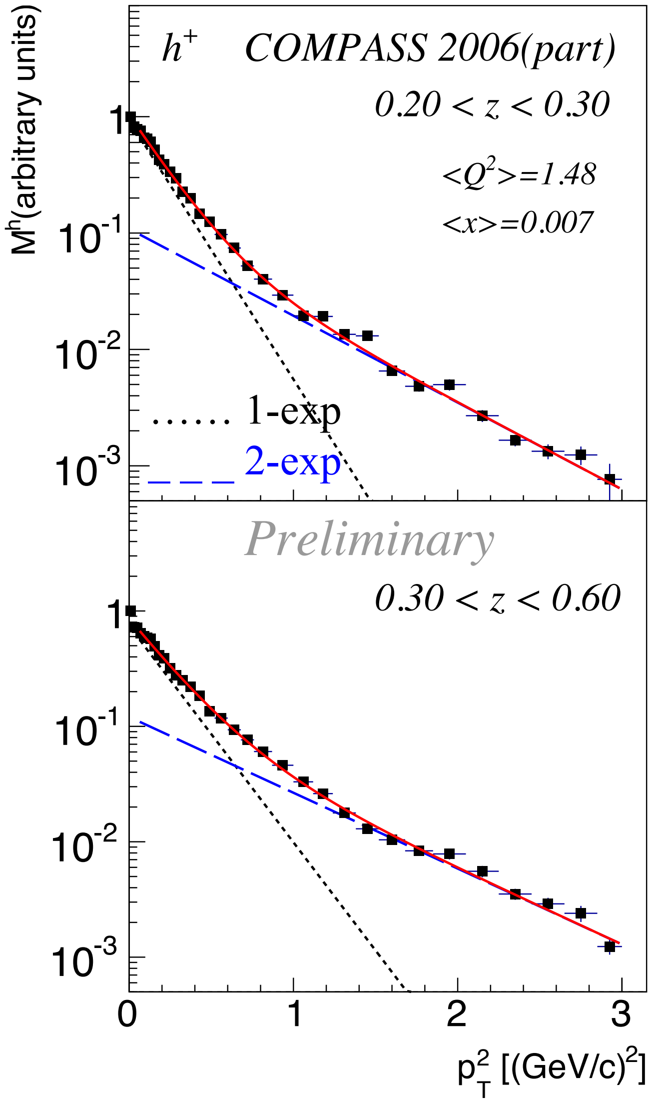
Multi dimensions: 9 x . 5 Q^2 . 8 z . 7 p_T Bins

Common binning for **SSAs** and **unpolarized measurements**

Ongoing analyses, results to come soon

h$^+$ distributions, $Q^2 \in [1.5, 2.5]$, $x \in [0.018, 0.025]$

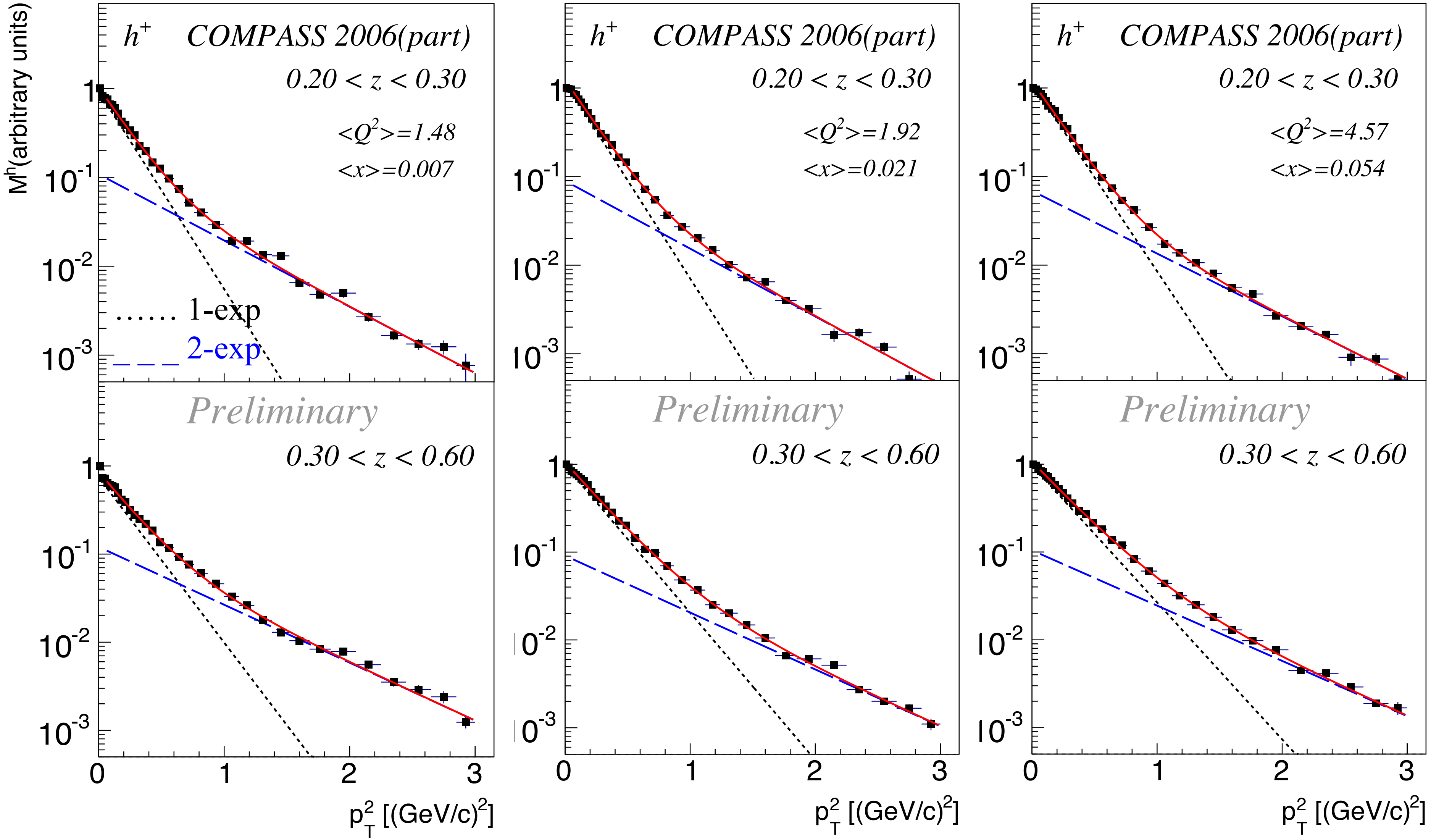
NEW



- Precise measurement using 2006 data with larger angular acceptance
- p_T^2 range extended to 3 (GeV/c)^2
- Very promising to extract physics on transverse momentum dependent PDFs and FFs
- Fit multiplicities with
  - ○ 1-exponential for $p_T^2 \in [0.05, 0.68]$
  - ○ 2-exponentials for $p_T^2 \in [0.05, 3]$
  - ⇒ Need 2-exponentials to describe p_T^2 shape of COMPASS data
- Ongoing analysis to extract complete set of multiplicities in full kinematic domain

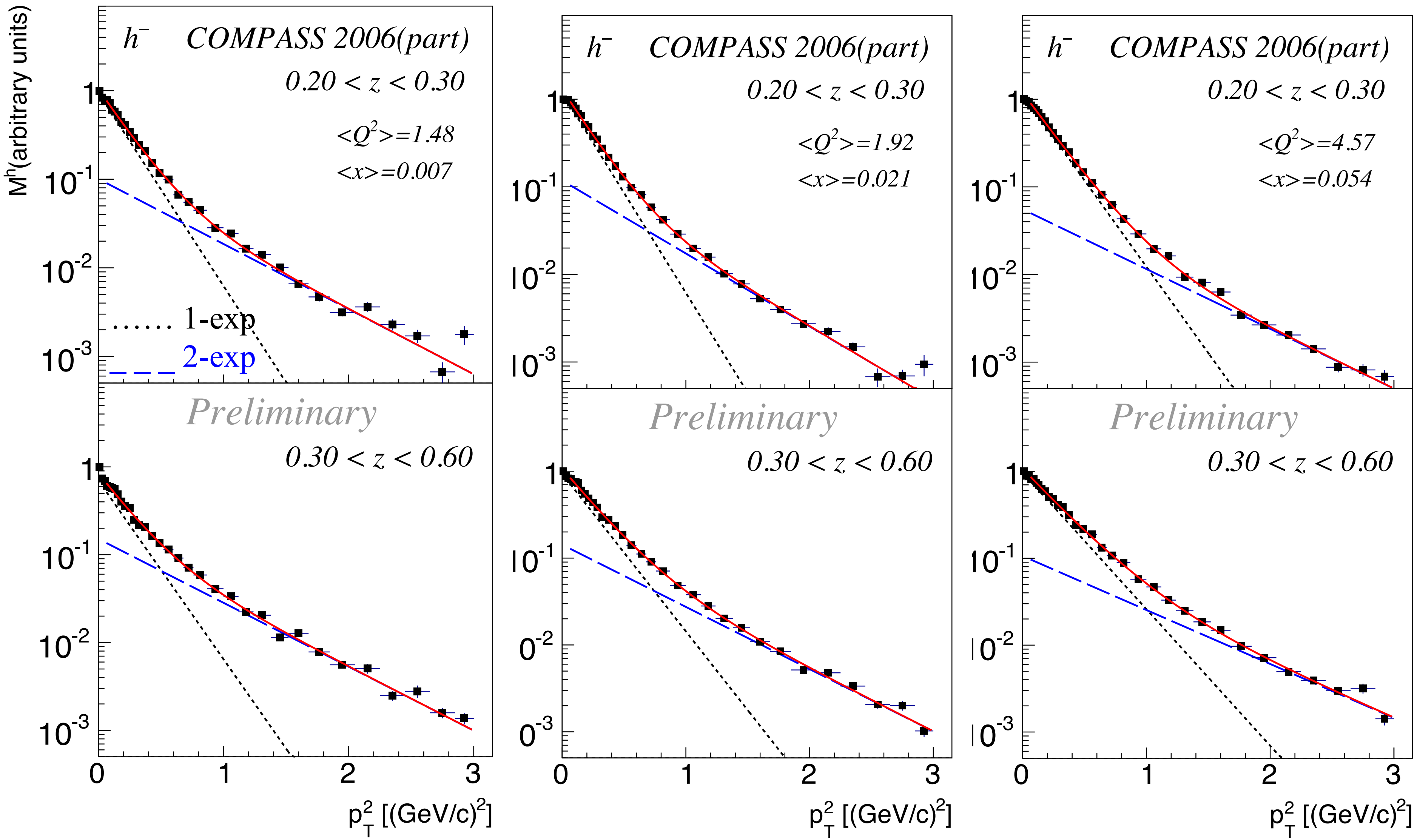
p_T^2 – dependent distributions vs. (x,z,p_T^2,Q^2) for h^+

NEW



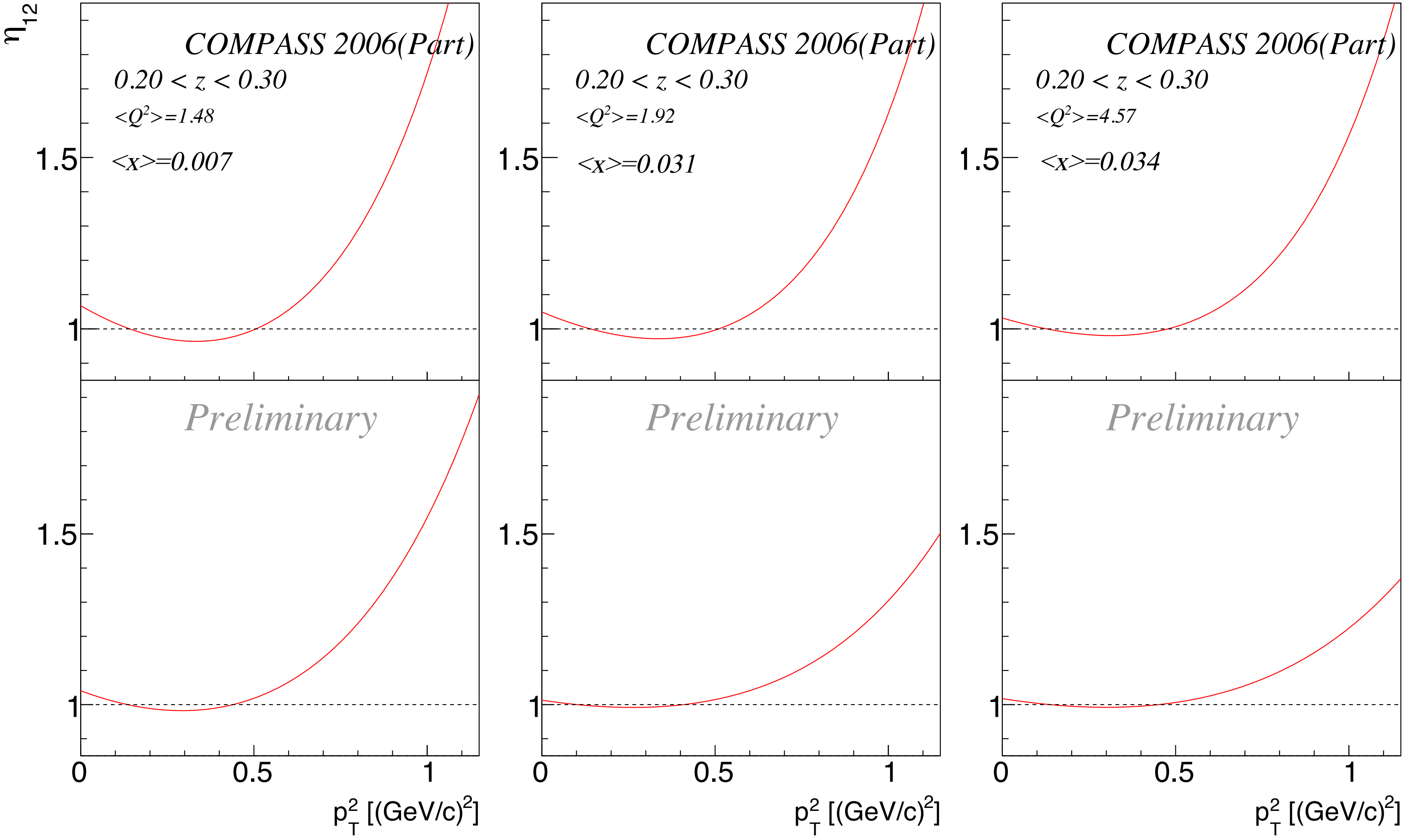
p_T^2 – dependent distributions vs. (x,z,p_T^2,Q^2) for h^-

NEW



h^+: Ratio $(A.e^{-a.pt2} + B.e^{-b.pt2})/A'e^{-a'.pt2}$

NEW



- ○ 1-exponential for $p_T^2 \in [0.05, 0.68]$
- ○ 2-exponentials for $p_T^2 \in [0.05, 3]$

Results from SIDIS off unpolarized deuterons

azimuthal asymmetries

Azimuthal Asymmetries

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

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

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

SIDIS cross-section
unpolarized
nucleons

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SIDIS cross-section
Unpolarized
nucleons

Kinematical effect due to quark intrinsic transverse momentum

Boer-Mulders DF

Cahn effect

→ $\langle k_T^2 \rangle$
M. Aghasyan

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

$$xh = x\tilde{h}+\frac{p_T^2}{M^2}\,h_1^\perp \qquad xf^\perp = x\tilde{f}^\perp + f_1 \qquad F_{UU}^{\cos\phi_h} \approx \frac{2M}{Q}\,\mathcal{C}\left[-\frac{\hat{h}\cdot\boldsymbol{p}_T}{M}\,f_1 D_1\right]$$

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

Boer-Mulders PDF x Collins FF
+ Cahn effect (twist 4, 1/Q²)

Correlation between quark transverse momentum and quark spin inside unpolarized nucleon

Unpolarized asymmetries: kinematic range

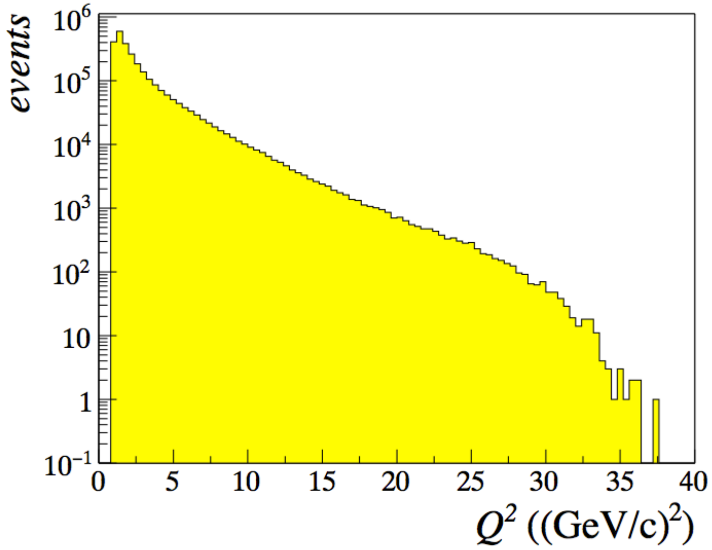
SIDIS data collected in 2004 using ^{6}LiD target

Kinematic selection:

- $Q^2 > 1$ (GeV)^2
- $W > 5$ (GeV/c^2)

- $0.003 < x \underline{\leq 0.13}$
- $0.2 < y < 0.9$

Submitted for publication
CERN-PH-EP-2014-009



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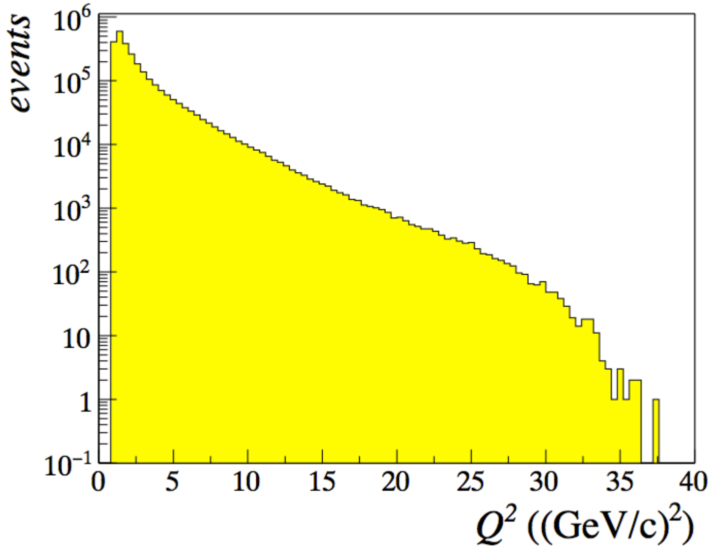
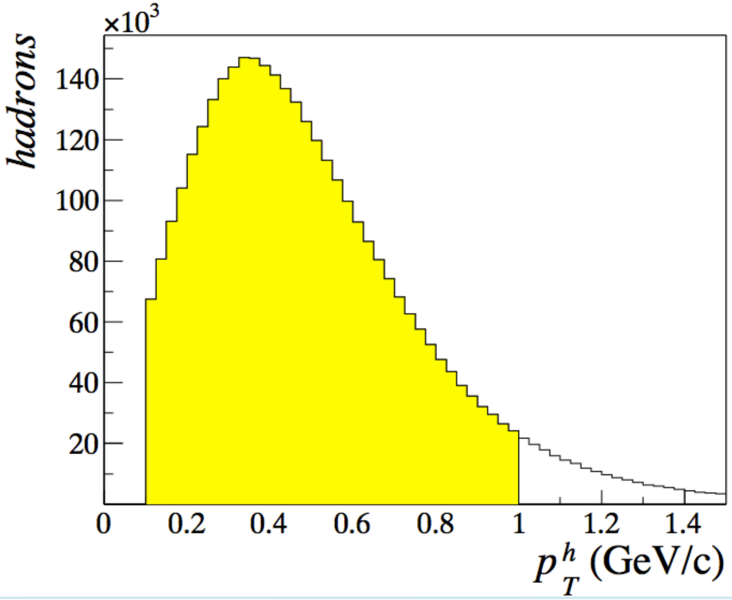
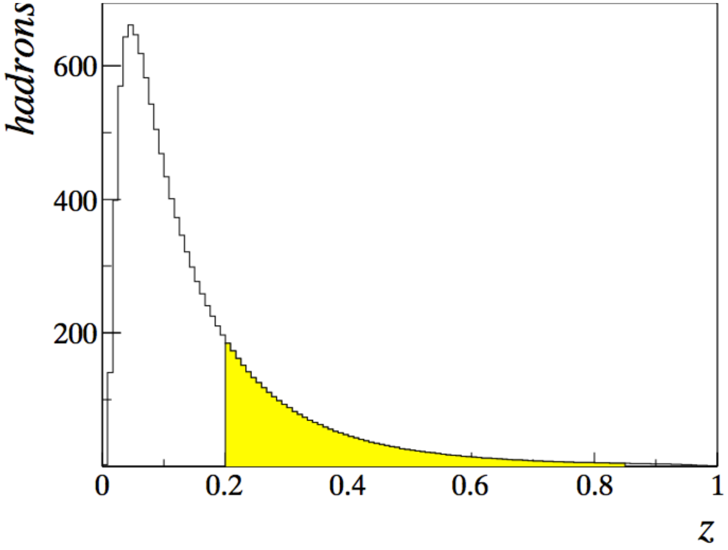
  - $0.2 < z < 0.85$
  - $0.1 < p_T < 1$

CERN-PH-EP-2014-009

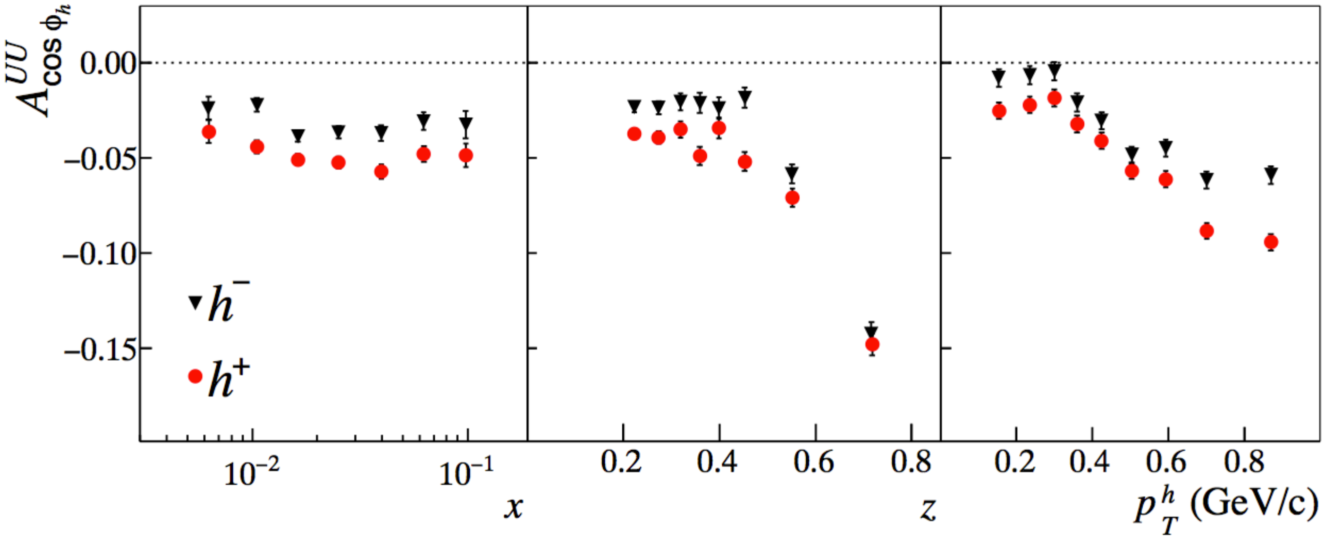






Azimuthal Asymmetries: $A_{UU}^{\cos\Phi}$ and $A_{UU}^{\cos2\Phi}$ amplitudes h^+/h^-

CERN-PH-EP-2014-009



- Negative amplitudes h^+/h^-
- Clear differences between h^+/h^-
    - Larger amplitude for h^+
- Strong z dependence (>0.5)
- Large signal over all x

Azimuthal Asymmetries: $A_{UU}^{\cos\Phi}$ and $A_{UU}^{\cos2\Phi}$ amplitudes h^+/h^-

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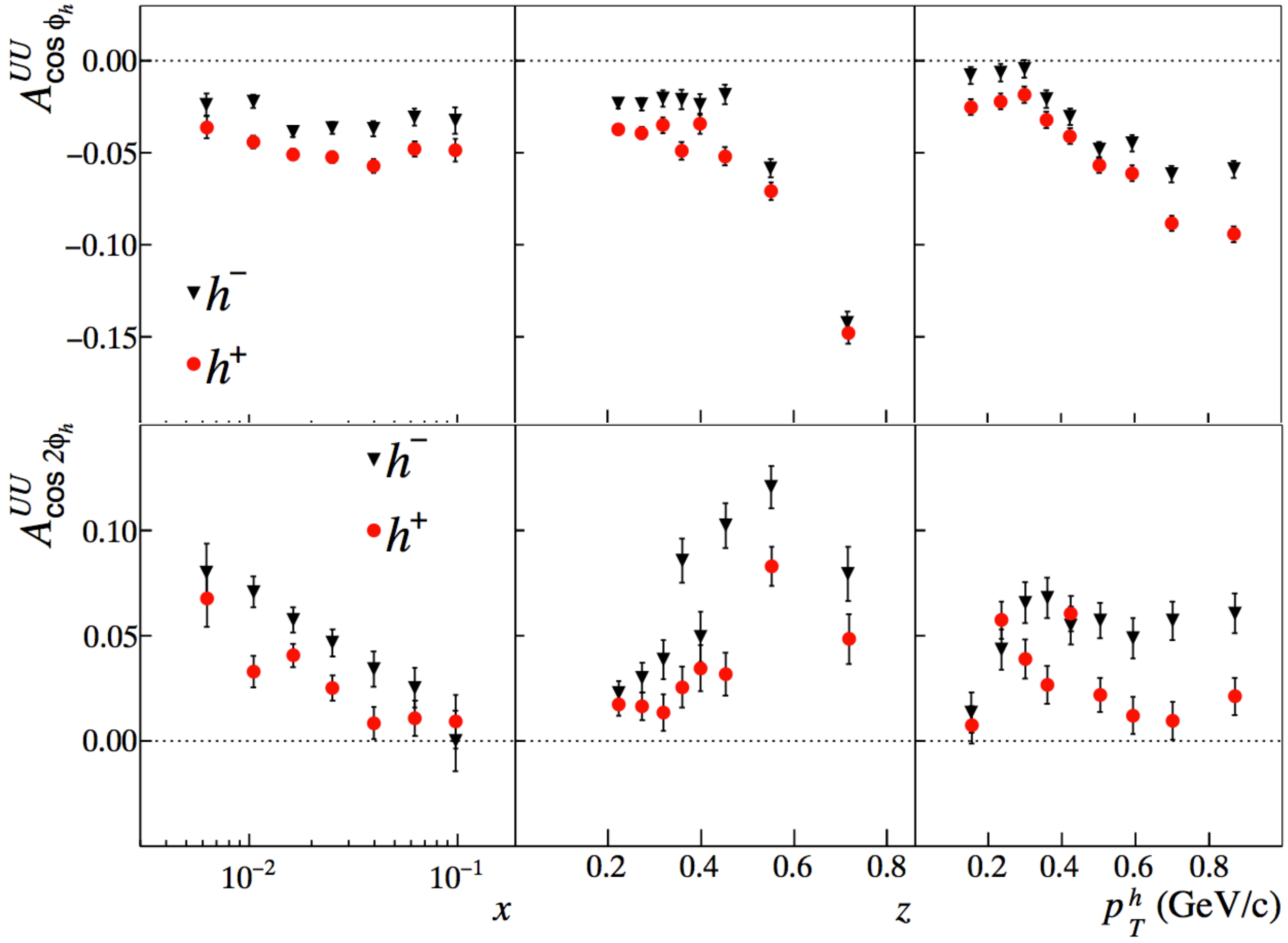


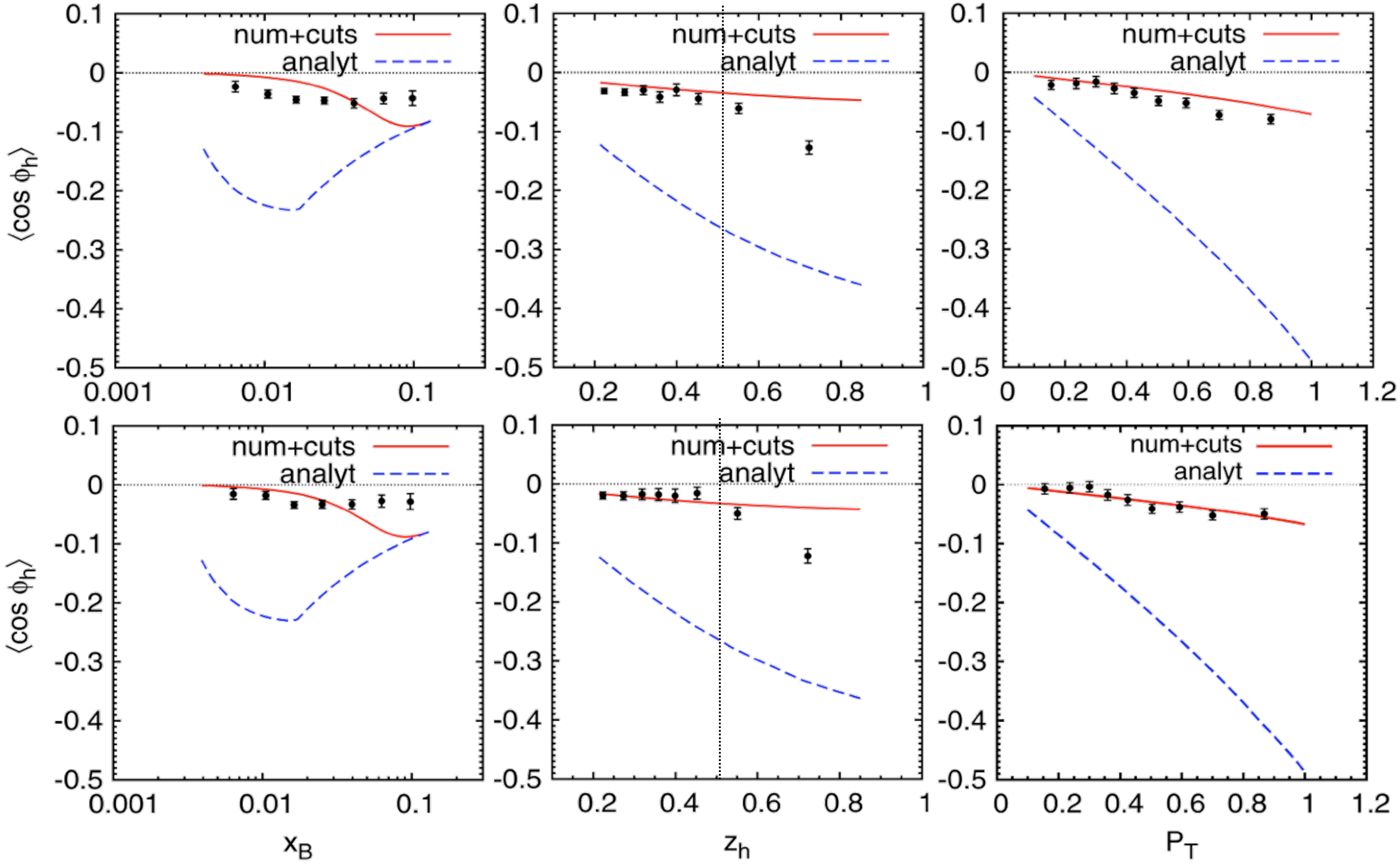
- ➢ Negative amplitudes h^+/h^-
- ➢ Clear differences between h^+/h^-
  - ➢ Larger amplitude for h^+
- ➢ Strong z dependence (>0.5)
- ➢ Large signal over all x

- ➢ Positive amplitudes h^+/h^-
- ➢ Clear differences between h^+/h^-
- ➢ Large signal at small x
- ➢ Strong dependence on kinematic variables x,z,p_T

⇒ Multi-dimensional analysis for a better understanding of kinematic dependences

$A_{UU}^{\cos\Phi}$ – amplitude: comparison with theory h^+/h^-

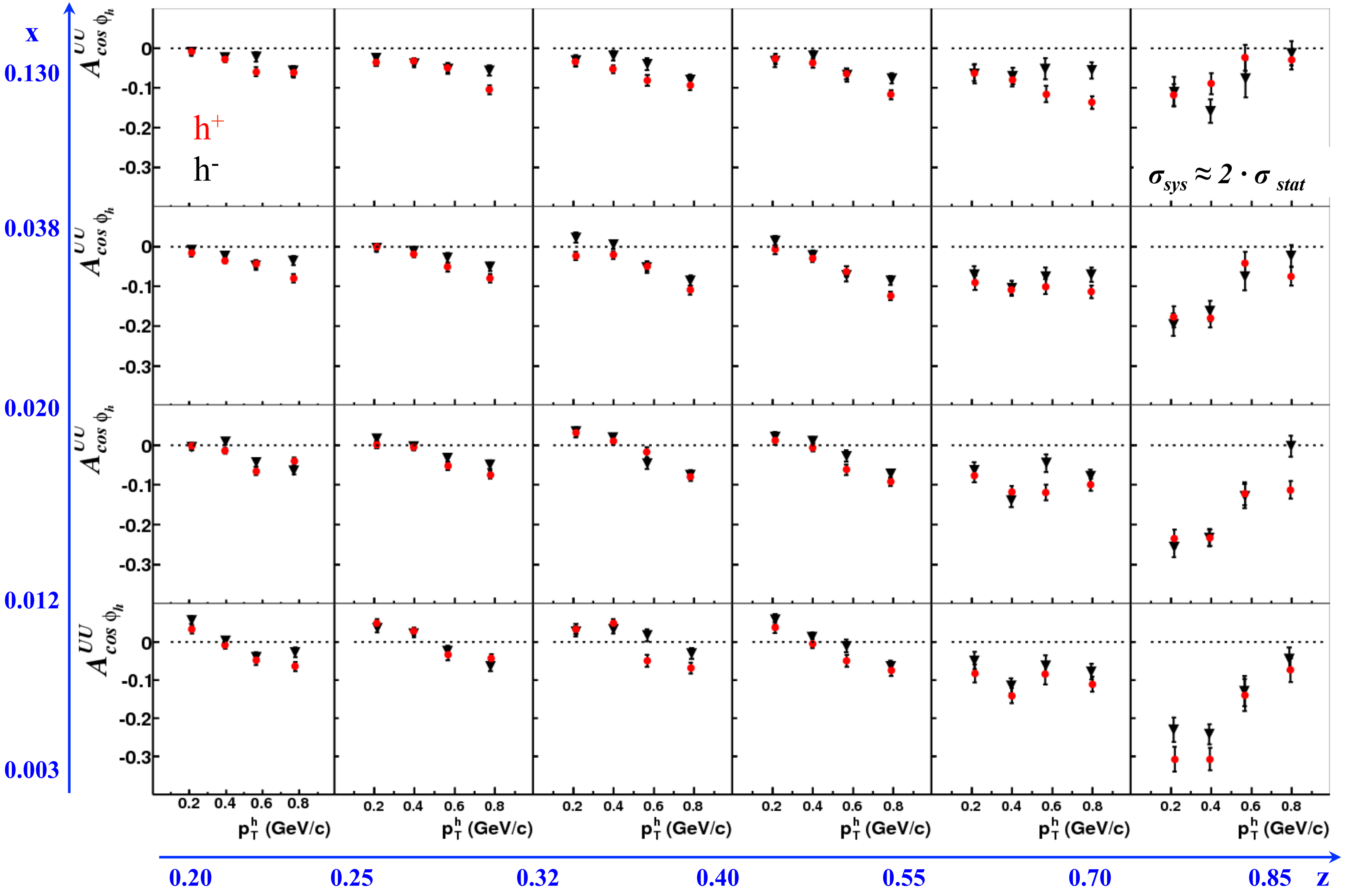
M. Boglione, S. Melis, and A. Prokudin, **Phys. Rev. D 84,** 034033 (2011)



1) the energy of the parton to be less than the energy of the parent hadron → $k_\perp^2 \leq (2 - x_B)(1 - x_B)Q^2, \qquad 0 < x_B < 1.$

2) the parton to move in the forward direction with respect to the parent hadron → $k_\perp^2 \leq \frac{x_B(1 - x_B)}{(1 - 2x_B)^2} Q^2, \qquad x_B < 0.5.$

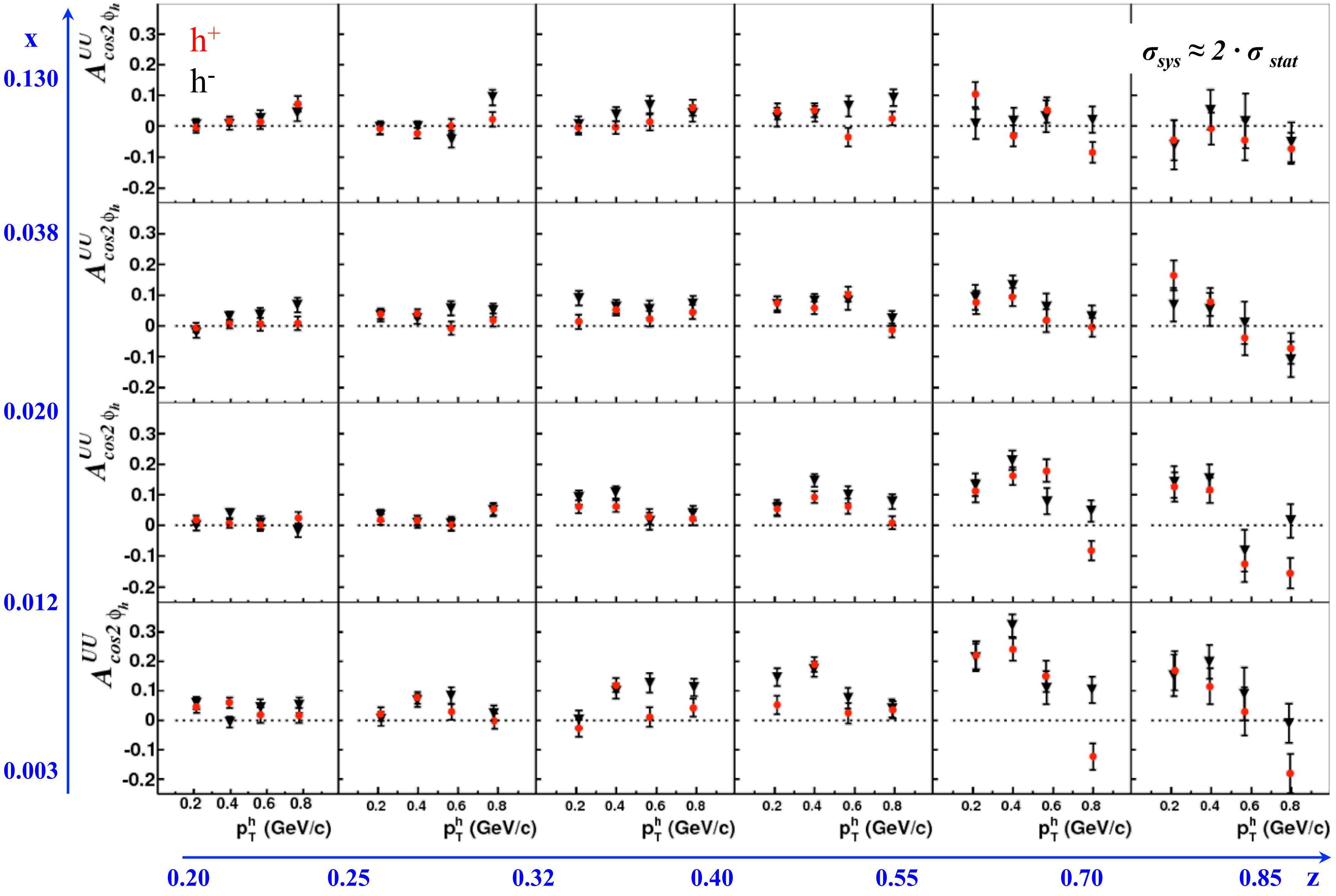
$A_{UU}^{\cos\Phi}$ – asymmetry: p_T dependence



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

Strong z dependence, more evident at small x and small p_T

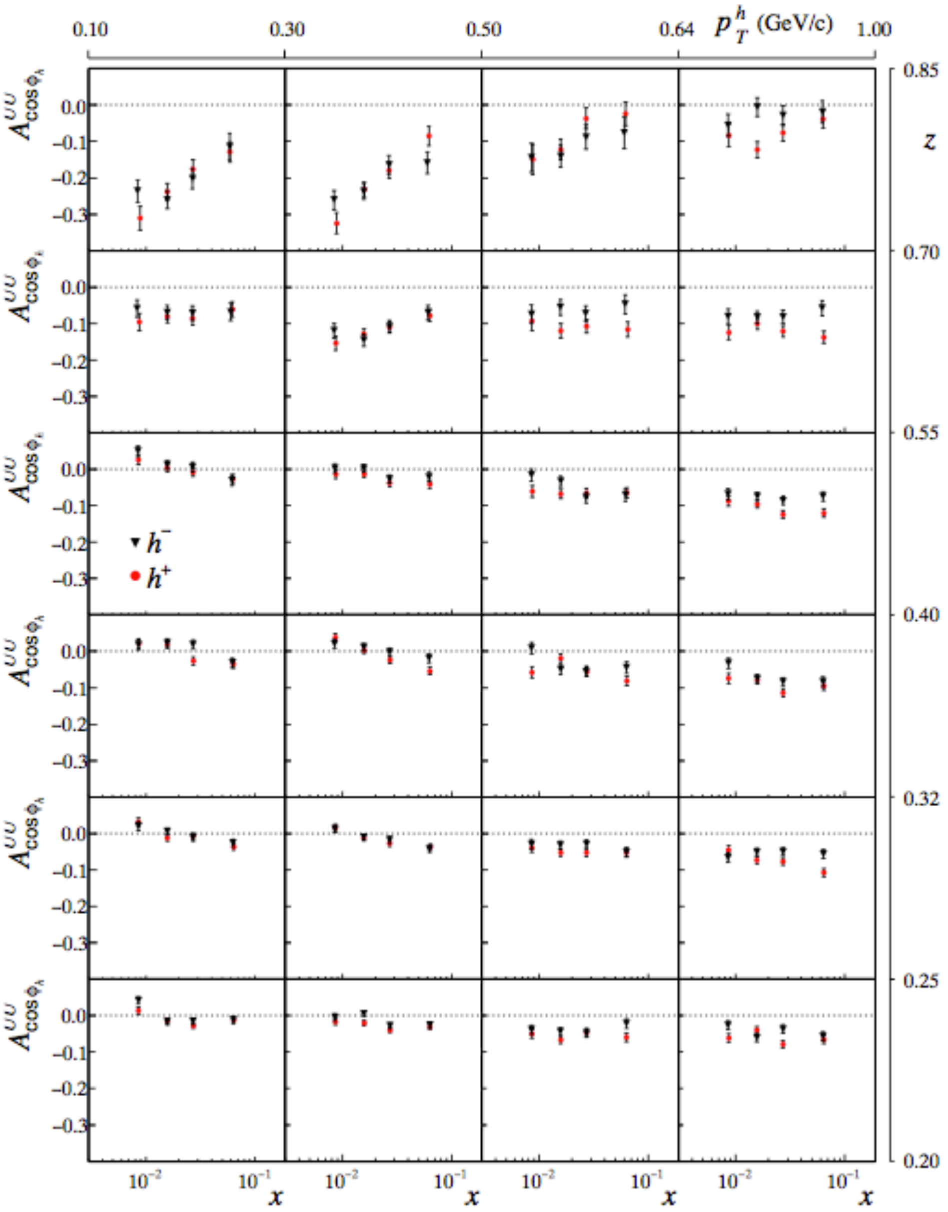
$A_{UU}^{\cos2\Phi}$ – asymmetry: p_T dependence

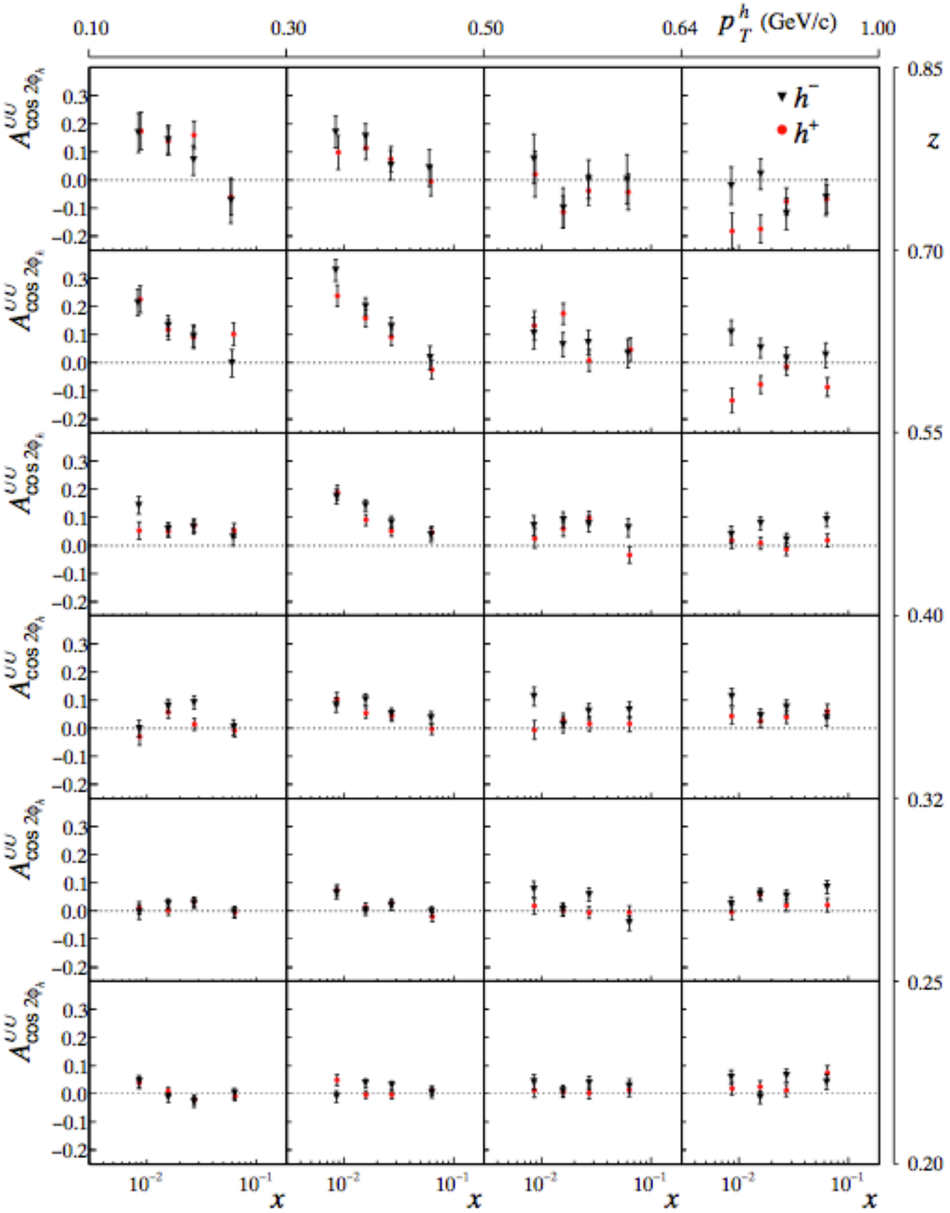


p_T trend not described by the models arises at large z and low x

$A_{UU}^{\cos\Phi}$ & $A_{UU}^{\cos2\Phi}$ – asymmetries: x dependence

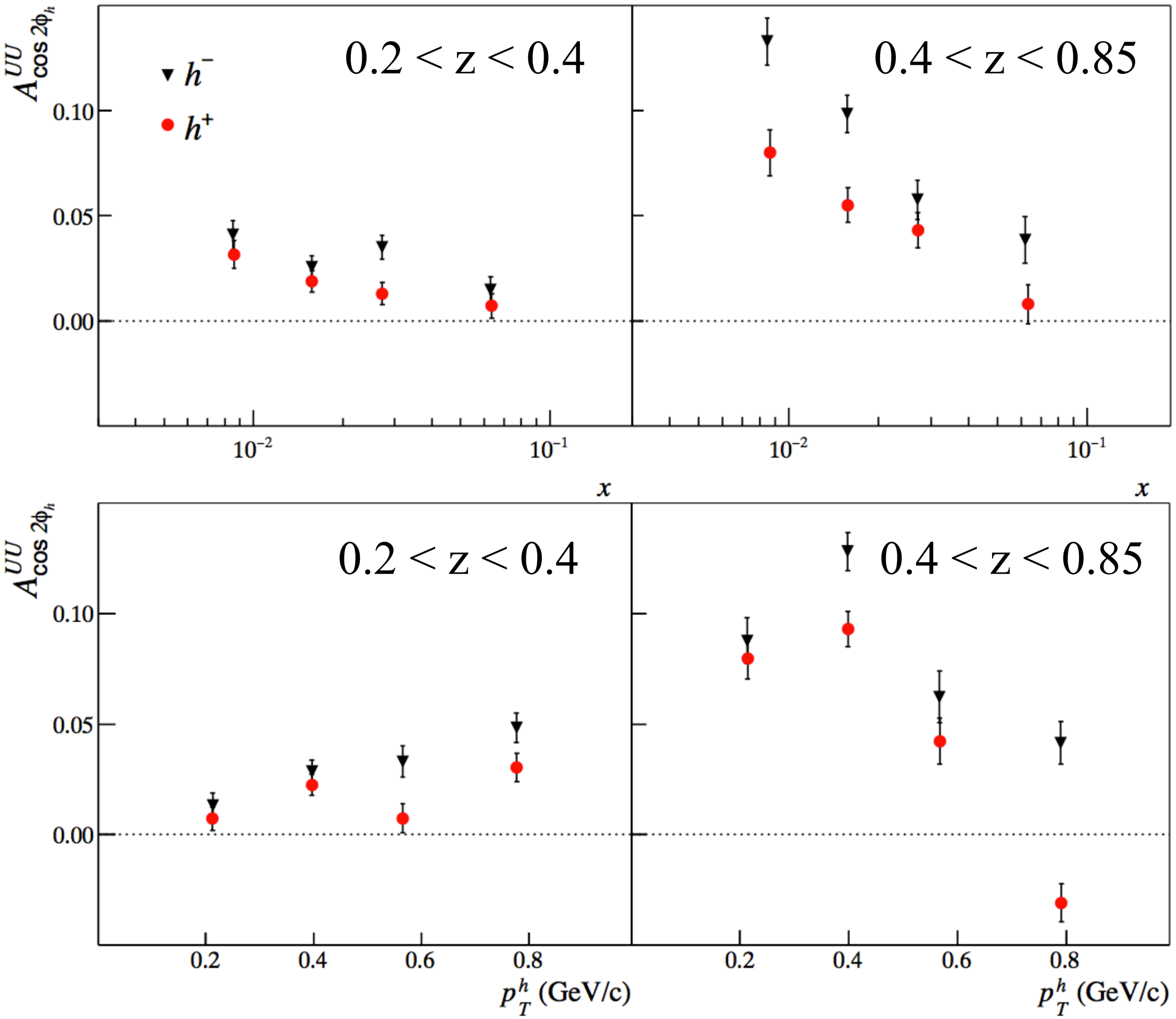
CERN-PH-EP-2014-009





$A_{UU}^{\cos 2\Phi}$ – asymmetry: x and p_T dependence

CERN-PH-EP-2014-009



⇒ Different z and p_T^2 dependencies for different z regimes … to be understood

… more to come from 2006 deuteron data (with PID)

Summary & conclusions

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

- Hadron multiplicities vs. p_T^2
- Azimuthal asymmetries
- Hadron multiplicities vs. z & hadron pair multiplicities

… and more to come from 2006 deuteron data

- p_T^2-dependent multiplicities – Complete set of results
- Fine binning in x, z, p_T/p_T^2, Q^2
- RICH PID facility

on a longer time scale: Measurements with proton (LH) target, in parallel to DVCS (2016-2017)