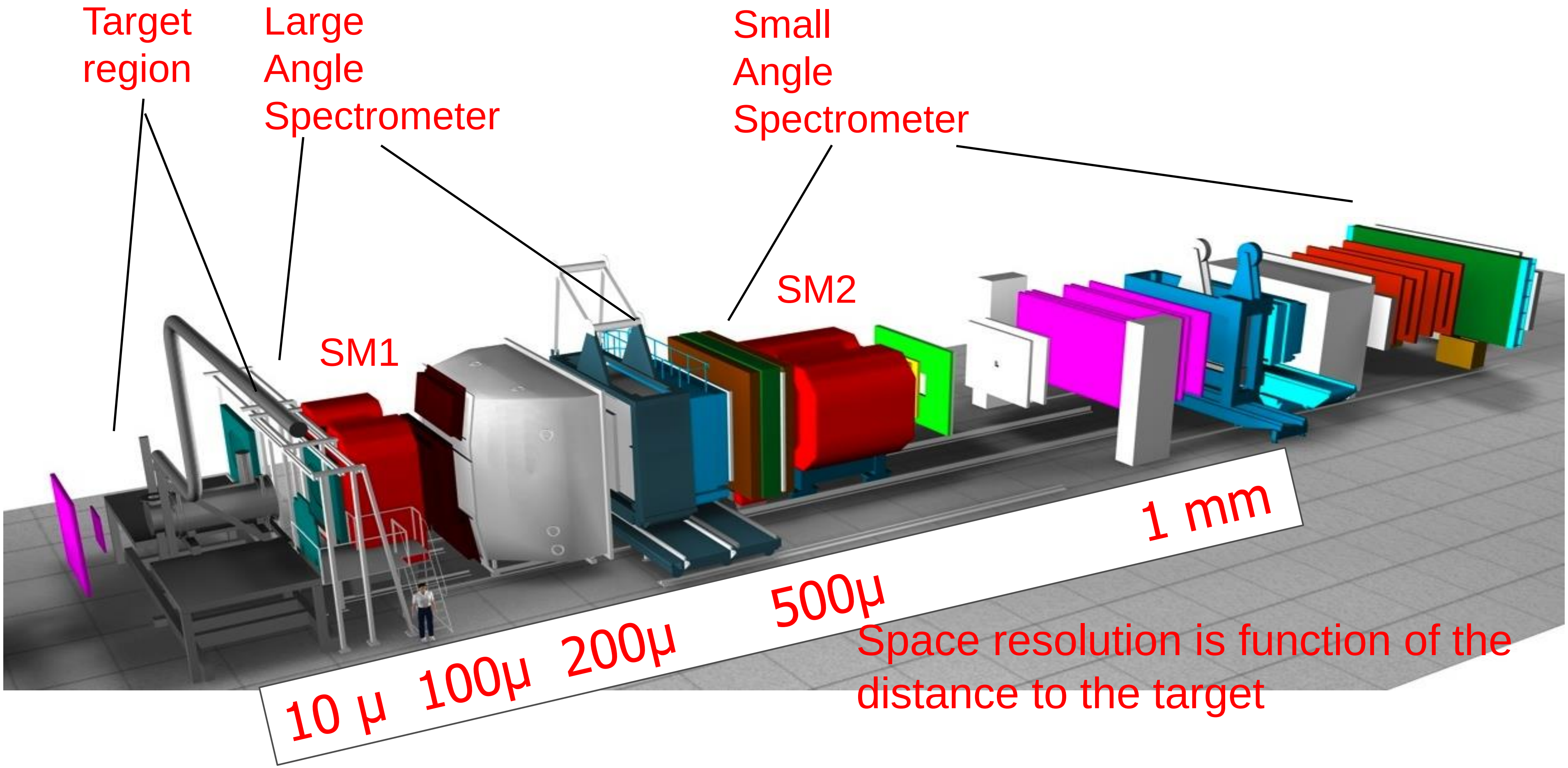
TMD EFFECTS IN SIDIS @ COMPASS

Andrea Bressan
University of Trieste and INFN
(on behalf of the COMPASS Collaboration)

QCD Evolution 2017, Thomas Jefferson National Accelerator Facility
Newport News, VA

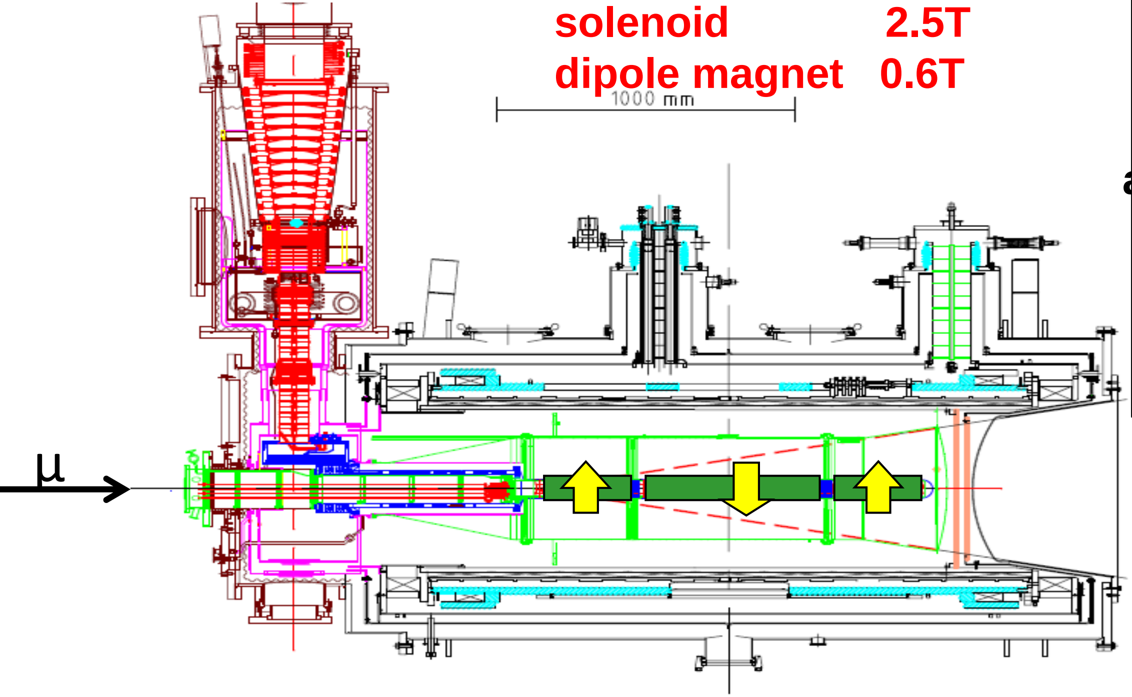
Space resolution



Space resolution is function of the distance to the target

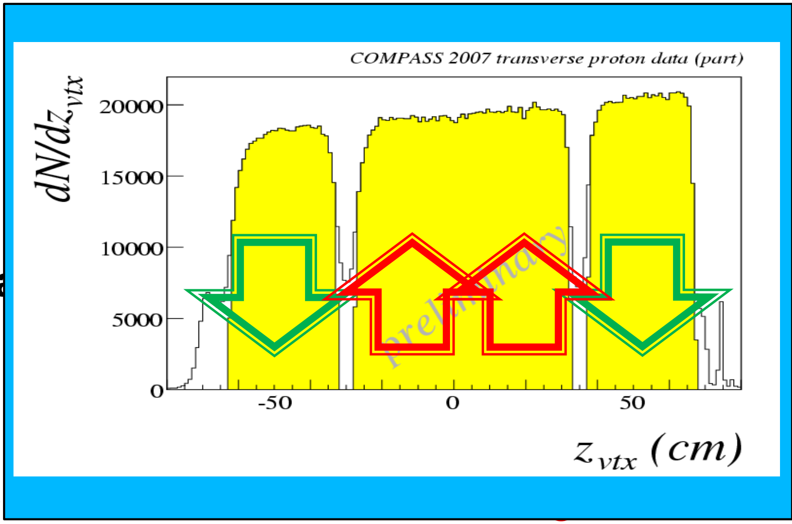
the polarized target system (>2005)

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



solenoid 2.5T

dipole magnet 0.6T



opposite polarisation

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

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

COMPASS data taking

muon beam	deuteron (^{6}LiD) PT	2002 2003 2004	80% L/20% T target polarisation
		2006	L target polarisation
	proton (NH_3) PT	2007	50% L /50% T target polarisation
Hadron	LH target	2008 2009	
muon beam	proton (NH_3) PT	2010	T target polarisation
		2011	L target polarisation
Hadron	Ni target	2012	Primakoff
muon beam	LH2 target	2012	Pilot DVCS & unpol. SIDIS
Hadron	Proton (NH3) DT PT	2014 2015 2018	Pilot DY run DY run 2° year of DY run
muon beam	LH2 target	2016 2017	DVCS & unpol. SIDIS

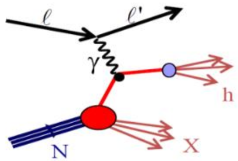
Measurements with the target transversely polarized:

Year	Obs	
2005	$A^{h}_{Siv,d}, A^{h}_{Col,d}$	First ^{6}LiD data
2006	$A^{h}_{Siv,d}, A^{h}_{Col,d}$	Full ^{6}LiD statistics
2009	$A^{\pi^\pm, K^\pm, K_S^0}_{Siv,d}, A^{\pi^\pm, K^\pm, K_S^0}_{Col,d}$	Full ^{6}LiD statistics
2010	$A^{h}_{Siv,p}, A^{h}_{Col,p}$	2007 NH_3 data
2012	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD
2012	$A^{h}_{Siv,p}, A^{h}_{Col,p}$	Full NH_3statistics
2012	$A^{sin(\phi_\rho-\phi_S)}_{UT,d}, A^{sin(\phi_\rho-\phi_S)}_{UT,p}$	Exclusive ρ^0
2013	$A^{(\phi_\rho,\phi_S)}_{UT,d}, A^{(\phi_\rho,\phi_S)}_{UT,p}$	Exclusive ρ^0, all asyms.
2014	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ^{6}LiD and NH_3
2014	$A^{\pi^\pm, K^\pm, K_S^0}_{Siv,d}, A^{\pi^\pm, K^\pm, K_S^0}_{Col,d}$	Full NH_3 statistics
2015	Interplay $A^{sin\phi_{RS}}_{UT,p}$ vs $A^{h}_{Col,p}$	Full NH_3 statistics
2016	$A^{h}_{Siv,p}$ binned in Q^2 to be in DY range	Full NH_3 statistics

Year	Obs	
2013	$dn^h/(dN^\mu dz\, dp_T^2)$	2004, full
2014	$A^{\cos\phi_h}_{UU,d}, A^{\cos 2\phi_h}_{UU,d}, A^{\sin\phi_h}_{LU,d}$	2004, part
2016	$dn^\pi/(dN^\mu dz), dn^K/(dN^\mu dz)$	2006, full
2016	$dn^h/(dN^\mu dz\, dp_T^2)$	2006, full

Accessing TMD PDFs and FFs

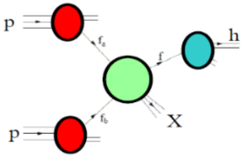
- SIDIS off polarized p, d, n targets



HERMES
COMPASS
JLab
future: ***eN colliders***

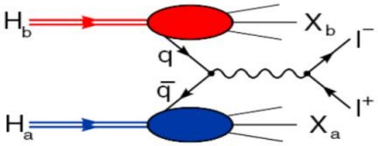
$$\sigma^{\ell p\to\ell' hX} \sim f_{q,p}(x, k_\perp^2\,) \otimes \sigma^{\ell q\to q} \otimes D^h_{1q}(z, p_\perp^2)$$

- hard polarised pp scattering



RHIC

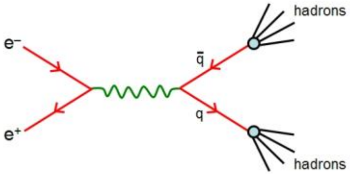
- polarised Drell-Yan



COMPASS
RHIC
FNAL
future: ***FAIR, JPark, NICA***

$$\sigma^{hp\to\ell\ell} \sim \bar{f}_{q,h}(x_1, k_\perp^2) \otimes f_{q,p}(x_2, k_\perp^2) \otimes \hat{\sigma}^{\bar{q}q\to\mu\mu}(\hat{s})$$

- $e^+e^- \to h_1 h_2$

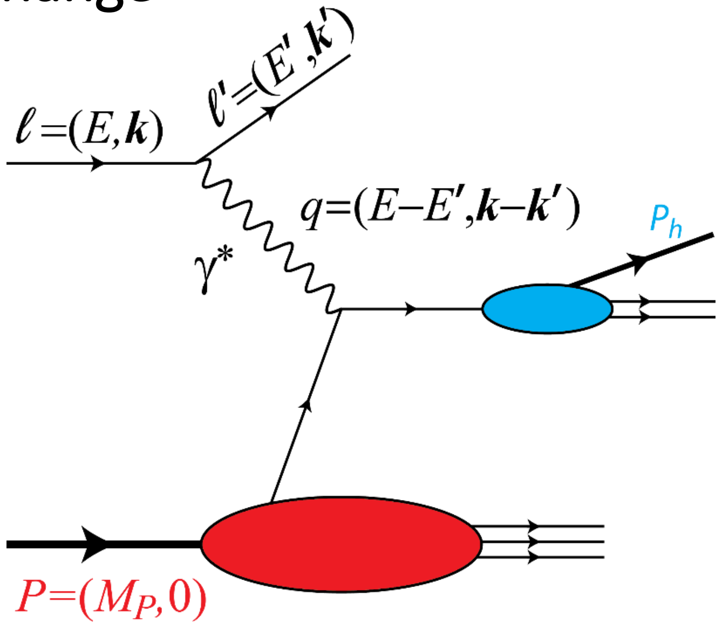


BaBar
Belle
Bes III

$$\sigma^{e^+e^-\to h_1 h_2} \sim \hat{\sigma}^{\ell\ell\to\bar{q}q}(\hat{s}) \otimes D_q^{h_1}(z_1, p_\perp^2) \otimes D_q^{h_2}(z_2, p_\perp^2)$$

SIDIS Measurements

- hard interaction of a lepton with a nucleon via virtual photon exchange



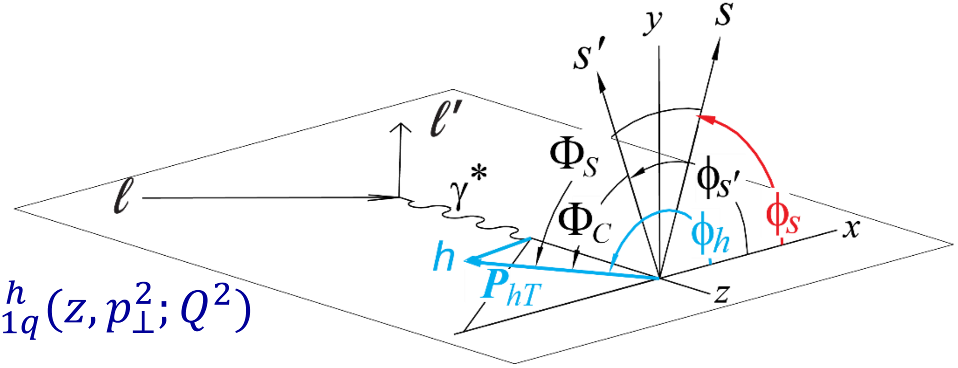
$$Q^2 = -q^2$$

$$x = \frac{Q^2}{2P\cdot q} = \frac{Q^2}{2M_p\nu}$$

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

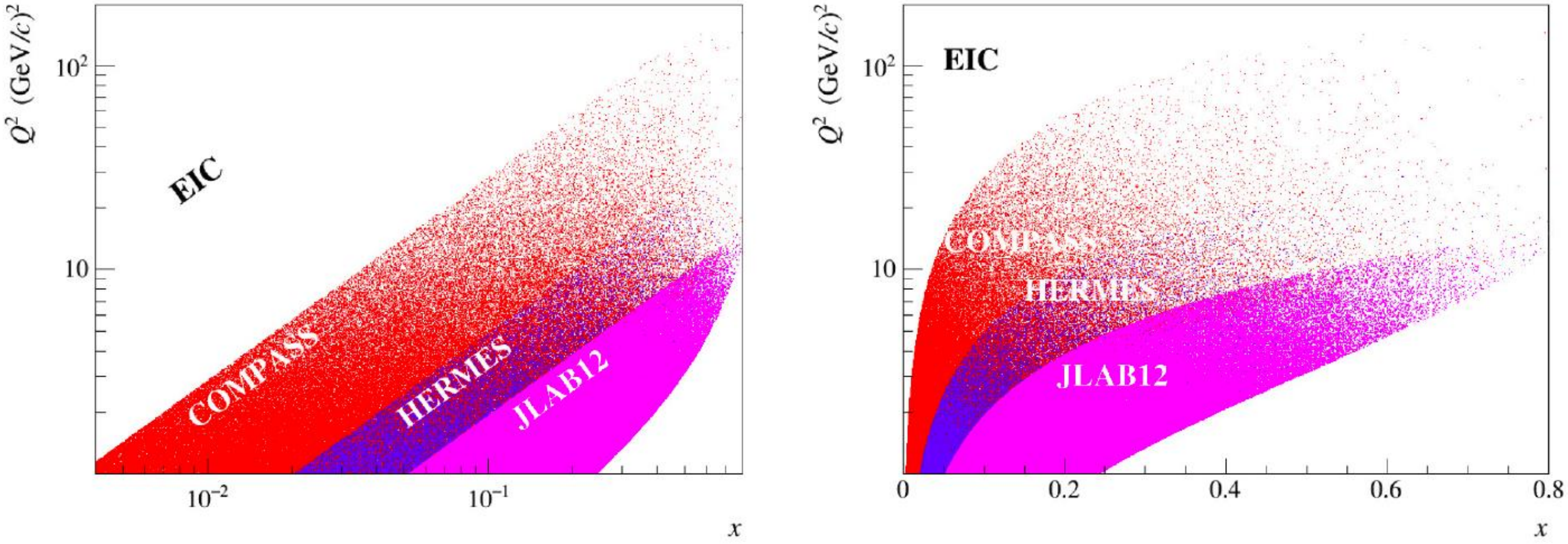
$$W^2 = (P+q)^2 = M_P^2 - Q^2 + 2M_p\nu$$

$$z = \frac{P\cdot P_h}{P\cdot q} = \frac{E_h}{\nu}$$

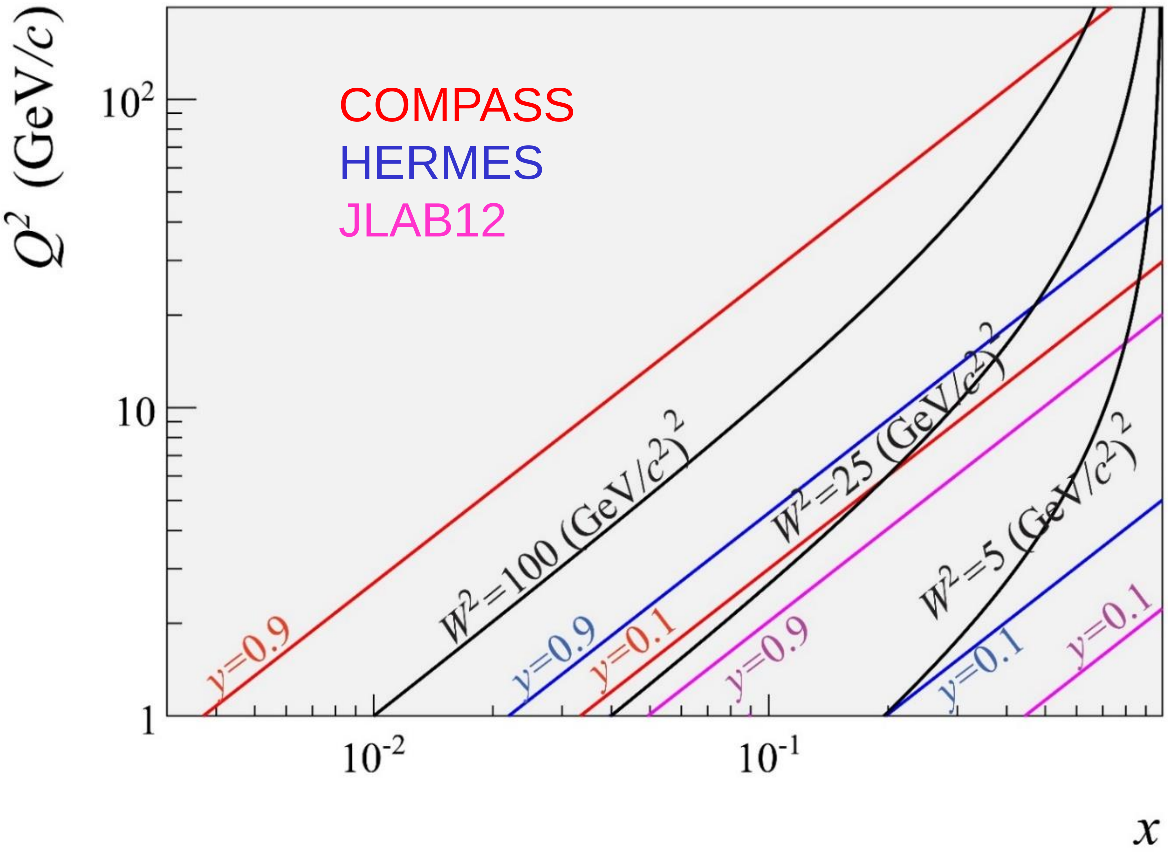


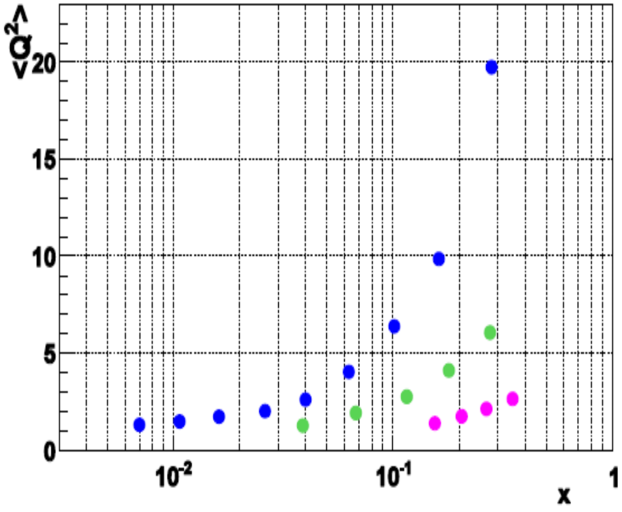
$$\sigma^{\ell P\to \ell h X} \propto \sum\nolimits_q f_q(x,k_\perp^2;Q^2\,) \otimes \sigma^{\ell q\to q} \otimes D_{1q}^h(z,p_\perp^2;Q^2)$$

Kinematic coverage

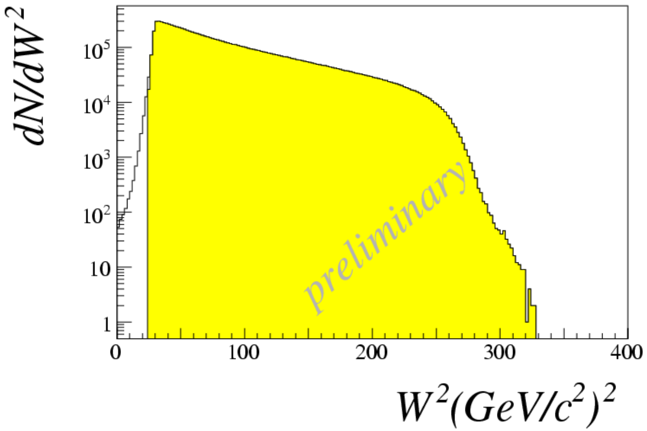


Kinematic coverage



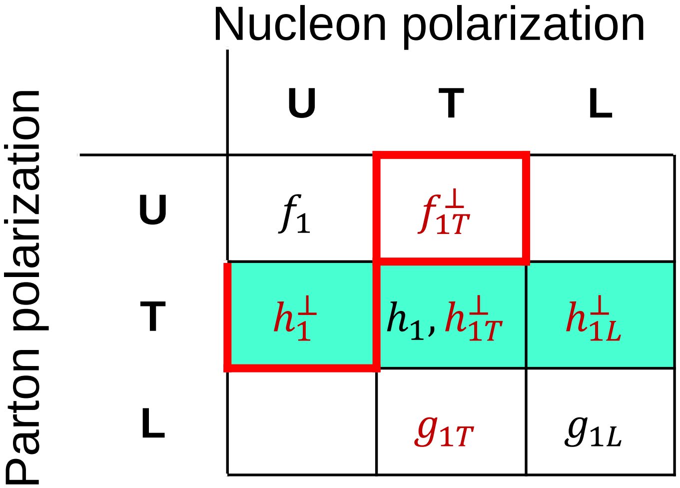


COMPASS 2007 transverse proton data (part)



SIDIS access to TMDs

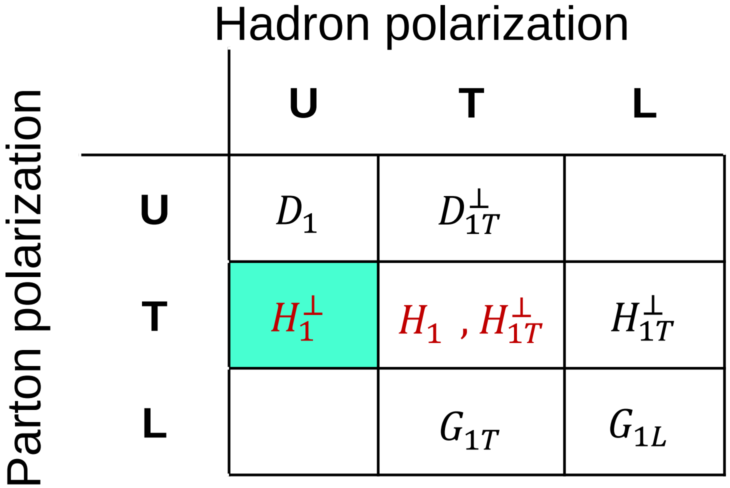
$$\sigma^{\ell p\to\ell' hX}\sim f_{q,p}(x,k_\perp^2)\otimes\sigma^{\ell q\to q}\otimes D_{1q}^h(z,p_\perp^2)$$



Nucleon polarization

Parton polarization

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



Hadron polarization

Parton polarization

	U	T	L
U	D_1	$D_{1T}^\perp$	
T	$H_1^\perp$	H_1 , $H_{1T}^\perp$	$H_{1T}^\perp$
L		G_{1T}	G_{1L}

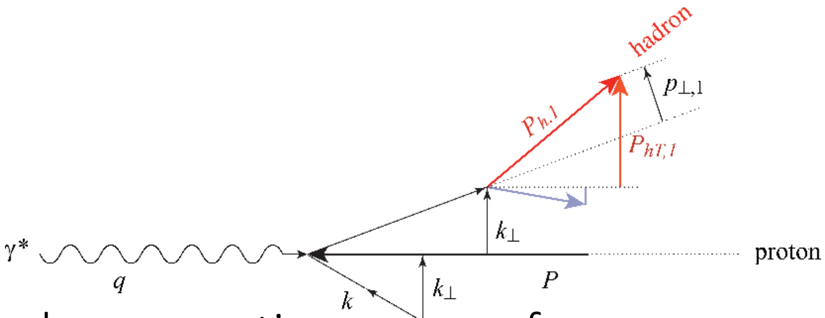
🟥 T odd

🟩 chiral odd

Factorisation (Collins & Soper, Ji, Ma, Yuan, Qiu & Vogelsang, Collins & Metz...)

Importance of unpolarised SIDIS

- The cross-section dependence from P_{hT} results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation
  - A Gaussian ansatz for $k_\perp$ and $p_\perp$ leads to
  - $\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$



- The azimuthal modulations in the unpolarised cross sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF
- Difficult measurements were one has to correct for the apparatus acceptance
- COMPASS and HERMES have
  - results on ^6LiD $(\sim d)$ and d and on p (Hermes only)
  - No COMPASS measurements on p since on NH_3 $(\sim p)$ nuclear effects may be important
- ⇒COMPASS-II, measurements on LH_2 in parallel with DVCS

Unpolarised Azimuthal Modulation

The full cross section for the unpolarised case is written as:

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

Bacchetta, Diehl, Goeke, Metz, Mulders and Schlegel JHEP 0702:093 (2007)

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

$$A_{UU}^{x}\left(x,z,dP_{hT}^2,Q^2\right)=\frac{F_{UU}^{x}}{F_{UU,T}+\varepsilon F_{UU,L}} \qquad \varepsilon=\frac{1-y-\frac{1}{4}y^2\gamma^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}y^2\gamma^2} \quad and \quad \gamma=\frac{2xM}{Q}$$

$$F_{UU}=C[f_1D_1]=x\sum_q e_q^2\int d\vec{p}_\perp d\vec{k}_\perp\,\delta^2\left(z\vec{k}_\perp+\vec{p}_\perp-\vec{P}_{hT}\right)f_1^q(x,k_\perp^2,Q^2)D_{1,q}^h(z,p_\perp^2,Q^2)$$

Unpolarised Azimuthal Modulation

When looking at the content of the structure functions/modulations in terms of TMD PDFs for the $\cos\phi_h$ and $\cos 2\phi_h$ we can write:

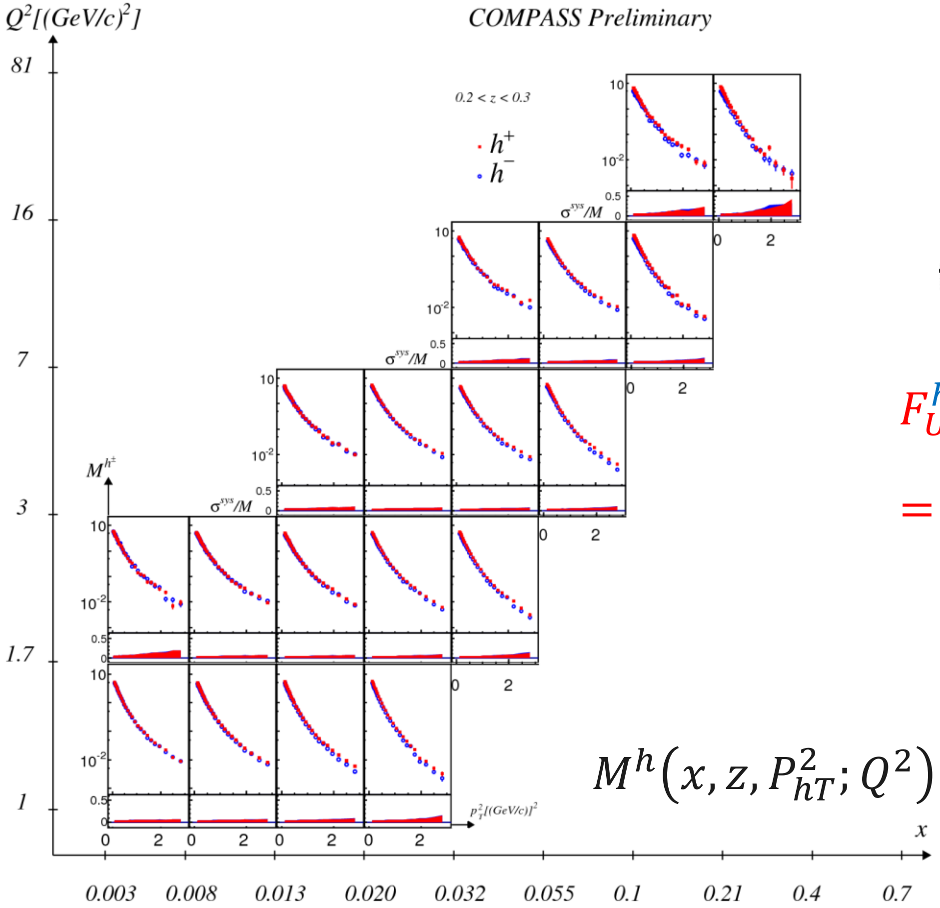
$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q} C\left[\frac{\hat{h}\cdot\vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M}\frac{\vec{P}_{hT} - z\left(\hat{h}\cdot\vec{k}_\perp\right)}{zM_h M} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

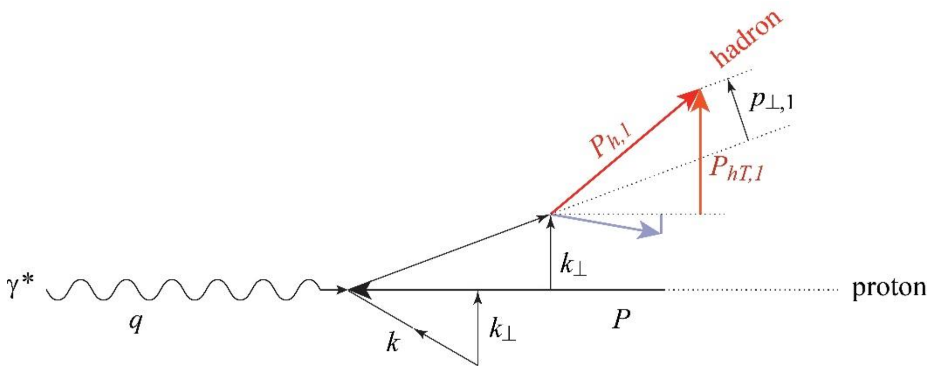
$$F_{UU}^{\cos 2\phi_h} = C\left[\frac{\left(\hat{h}\cdot\vec{k}_\perp\right)\left(\hat{h}\cdot\vec{p}_\perp\right) - \vec{p}_\perp\cdot\vec{k}_\perp}{MM_h} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

In the $\cos 2\phi_h$ Cahn effects enters only at twist4

$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$

Importance of unpolarised SIDIS



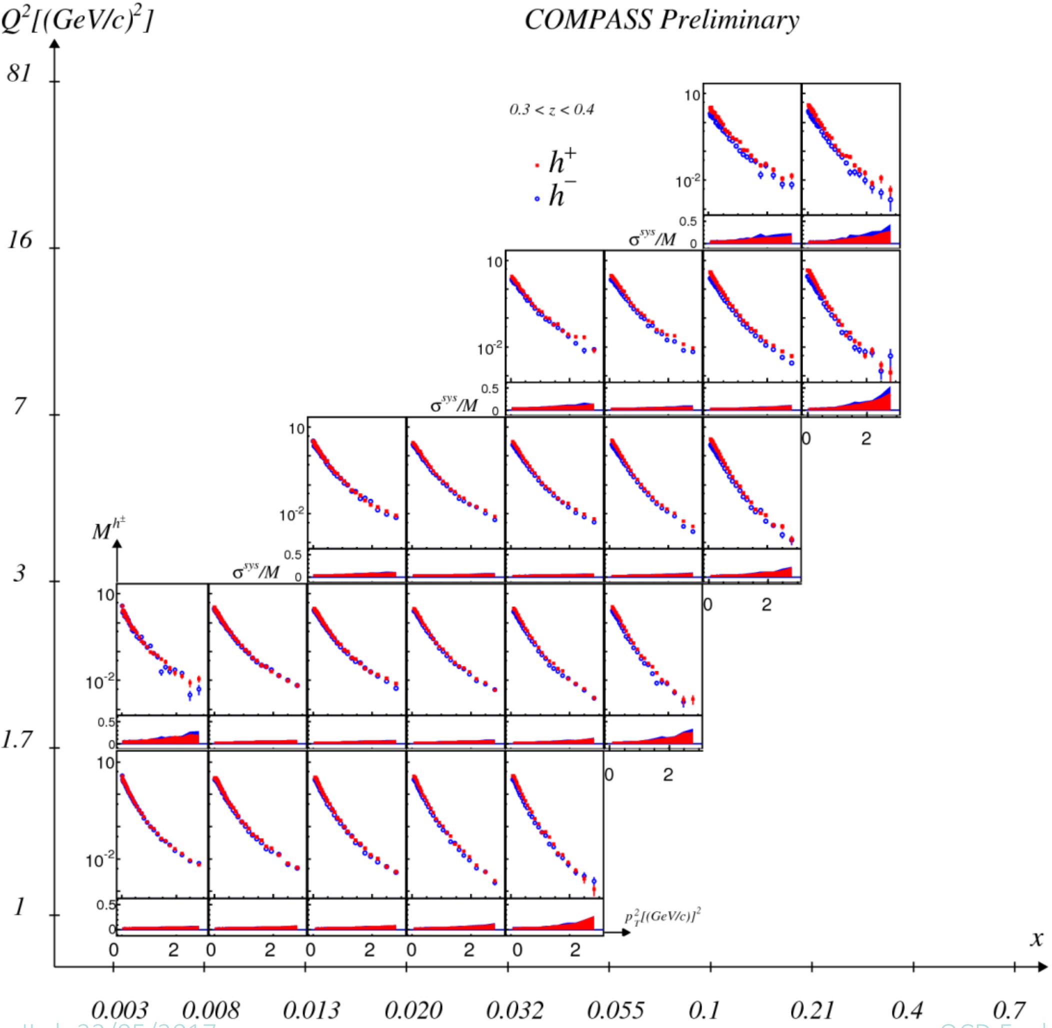


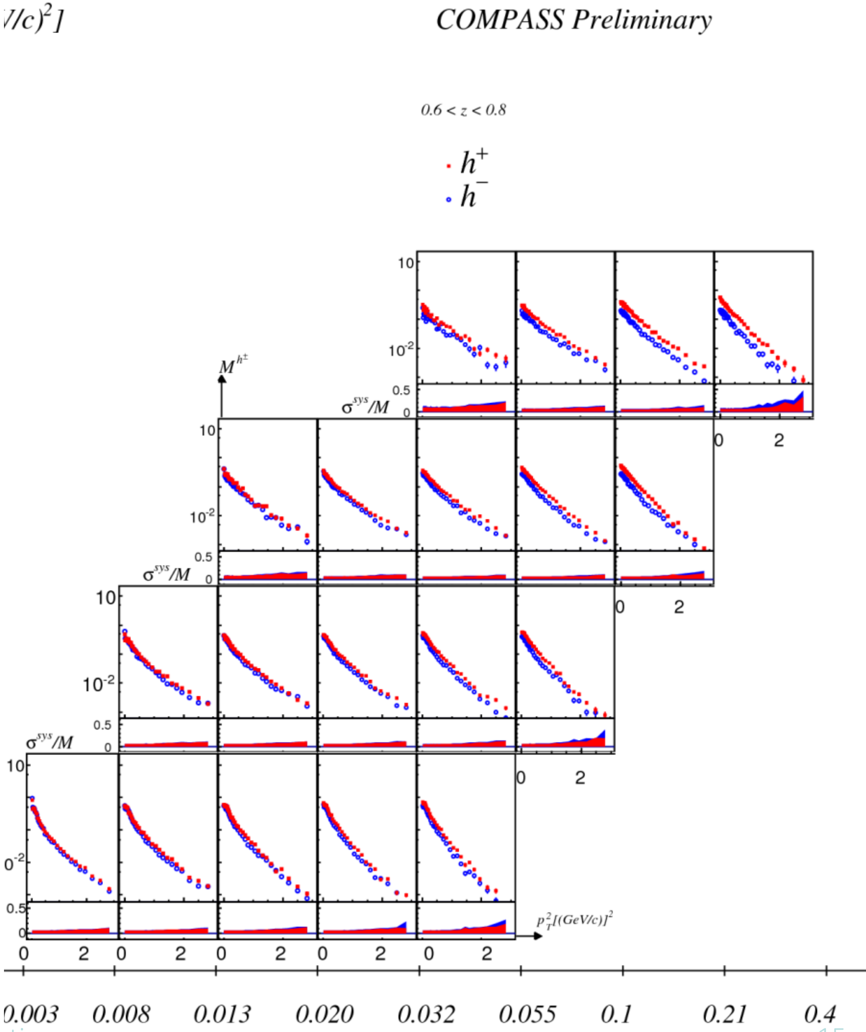
$$F_{UU}^{h}(x,z,P_{hT}^2;\ Q^2)$$

$$= x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp - z\vec{k}_\perp$$

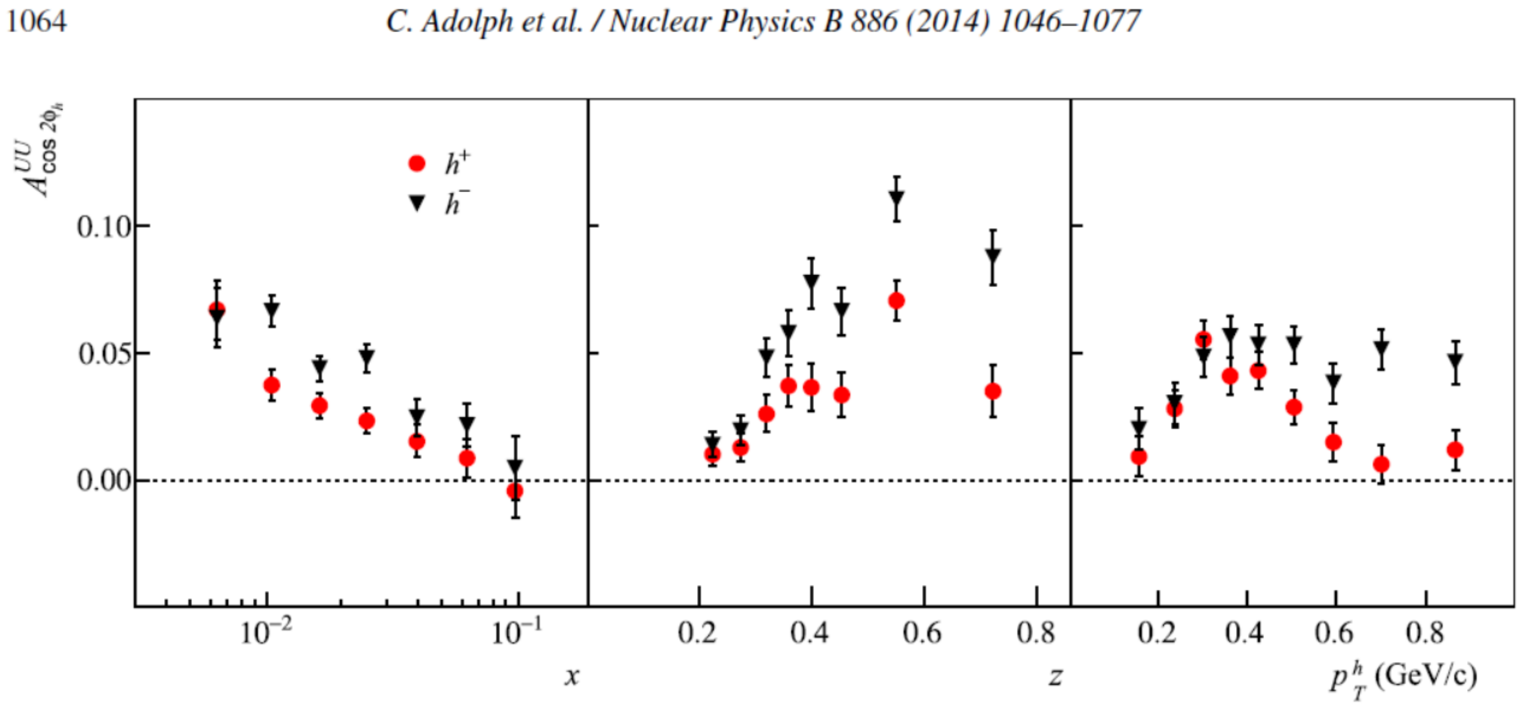
$$M^h(x,z,P_{hT}^2;Q^2) = \frac{d^5\sigma^h/dxdQ^2dzd^2\vec{p}_T}{d^2\sigma^{DIS}/dxdQ^2} \sim \frac{F_{UU}^{h}(x,z,P_{hT}^2;\ Q^2)}{F_{UU,T}+\varepsilon F_{UU,L}}$$

Importance of unpolarised SIDIS





Boer-Mulders in cos 2ϕ

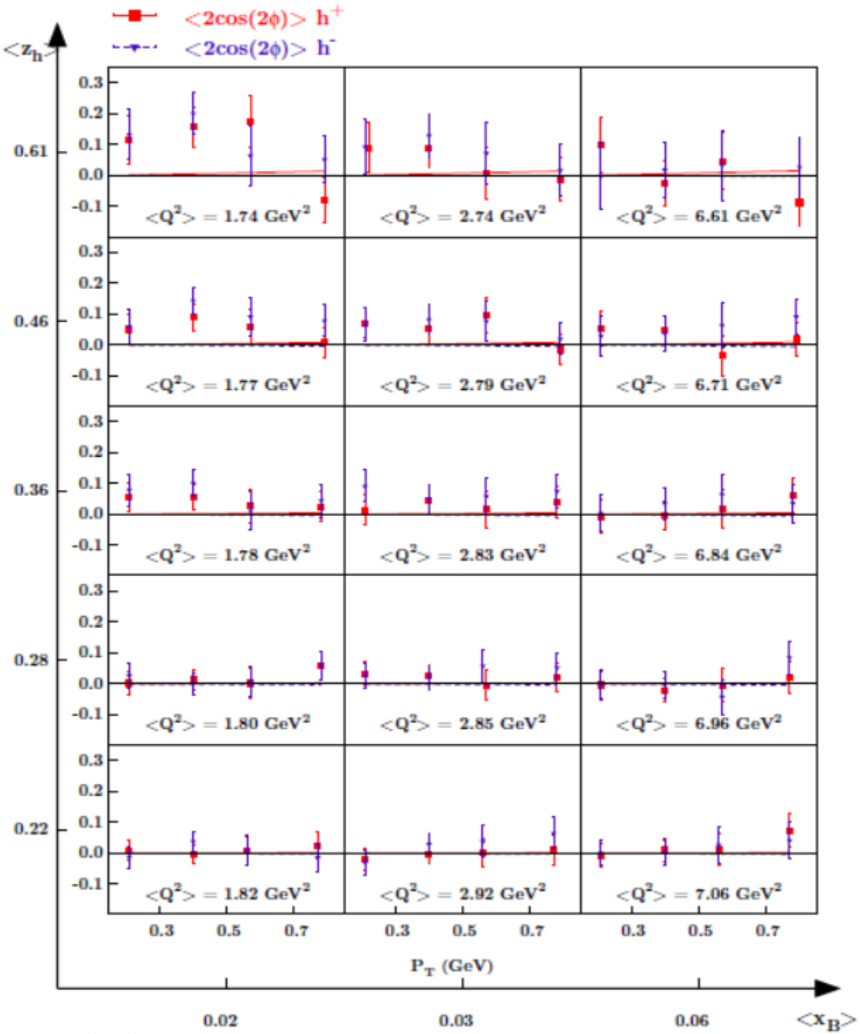


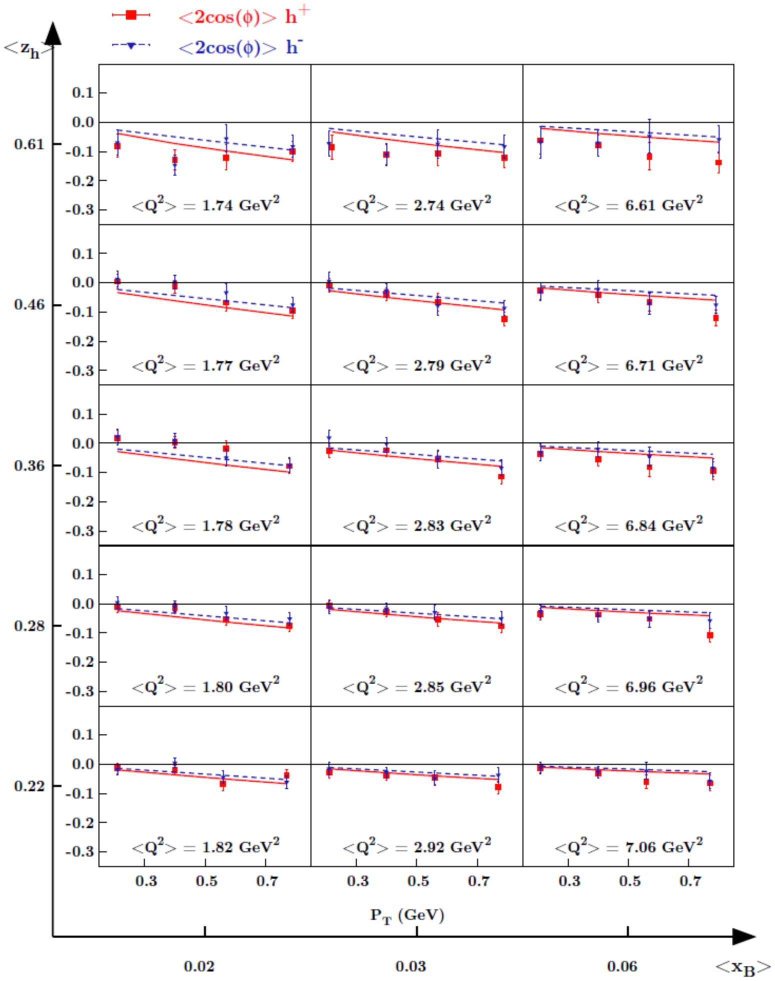
1064 C. Adolph et al. / Nuclear Physics B 886 (2014) 1046–1077

$$F_{UU}^{\cos 2\phi}\left(x,z,P_{hT}^2;\ Q^2\right)$$

$$= -x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \frac{2\left(\hat{h}\cdot\vec{k}_\perp\right)\left(\hat{h}\cdot\vec{k}_\perp\right) - \vec{k}_\perp\cdot\vec{p}_\perp}{M m_h}\ h_1^{\perp,q}(x,k_\perp^2;Q^2)H_{1q}^{\perp}(z,p_\perp^2;Q^2)$$

Boer-Mulders in cos 2ϕ and in cos ϕ



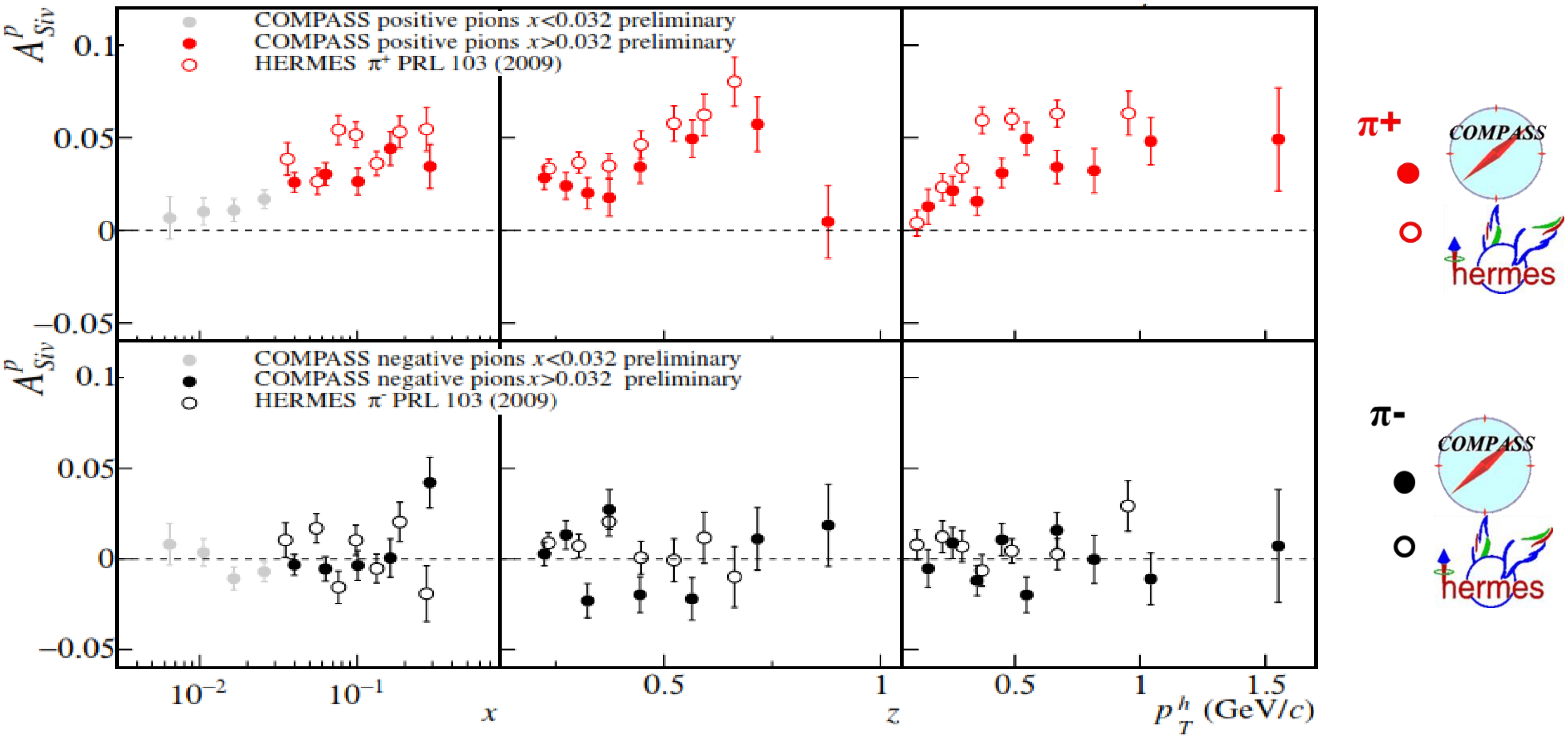


Sivers Asymmetry

- Sivers: correlates nucleon spin & quark transverse momentum k_T /T-ODD: at LO for $\boldsymbol{\mu p^{\uparrow} \rightarrow \mu X h^{\pm}}$
- $A_{Siv}(x,z) = \frac{F_{UT}^{\sin\Phi_{Siv}}(x,z)}{F_{UU}(x,z)} = \frac{\sum_q e_q^2 x f_{1T}^{\perp q}(x,k_\perp^2) \otimes D_{1q}^h(z,p_\perp^2)}{\sum_q e_q^2 x f_1^q(x,k_\perp^2) \otimes D_{1q}^h(z,p_\perp^2)}$
- To evaluate it we need to solve the convolutions (i.e. make hypothesis on the transverse momenta dependences of the TMDs)
- Gaussian ansatz: $f_{1T}^{\perp q}(x)\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_S}}{\pi\langle k_\perp^2\rangle_S}$ $\quad D_{1q}^h(z)\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$
- Leading to: $A_{Siv,G}(x,z) = \frac{\sqrt{\pi}M}{\sqrt{z^2\langle k_T^2\rangle_S+\langle p_T^2\rangle}} \frac{\sum_q e_q^2\, x f_{1T}^{\perp(1)q}(x) z D_{1q}^h(z)}{\sum_q e_q^2 x f_1^q(x) D_{1q}^h(z)}$ with $f_{1T}^{\perp(1)q}(x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x,k_T^2)$

Sivers asymmetry on p

charged pions (and kaons), HERMES and COMPASS



The weighted Sivers asymmetry

- If we weight the spin dependent part of the cross-section

$$F_{UT}^{sin\Phi_{Siv}}(x,z) = \Sigma_q\ e_q^2 \int d^2\vec{P}_T P_T F_q(x,z,P_T^2)$$

- with $w = P_T/zM$, i.e.

$$F_{UT}^{sin\Phi_{Siv},w}(x,z) = \Sigma_q\ e_q^2 \int d^2\vec{P}_T \frac{P_T^2}{zM} F_q(x,z,P_T^2) = 2\ \Sigma_q\ e_q^2 x f_{1T}^{\perp(1)q}(x) D_{1q}^h(z)$$

and $F_q(x,z,P_T^2) = \int d^2\vec{k}_T \int d^2\vec{p}_T\ \delta^2(\vec{P}_T - z\vec{k}_T - \vec{p}_T) \frac{\vec{P}_T\cdot\vec{k}_T}{MP_T^2} x f_{1T}^{\perp q}(x,k_T^2)\ D_{1q}(z,p_T^2)$

- we have no longer a convolution but a product of two integrals and we can write

$$A_{Siv}^{w}(x,z) = \frac{F_{UT}^{sin\Phi_{Siv},w}(x,z)}{F_{UU}(x,z)} = 2\frac{\Sigma_q e_q^2 x f_{1T}^{\perp(1)q}(x) D_{1q}^h(z)}{\Sigma_q e_q^2 x f_1^q(x) D_{1q}^h(z)}$$

- with $f_{1T}^{\perp(1)q}(x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x,k_T^2)$

The weighted Sivers asymmetry

- In one dimension: for x

$$A^{w}_{Siv}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x)\int D_{1q}^{h}(z)dz}{\sum_q e_q^2 x f_1^{q}(x)\int D_{1q}^{h}(z)dz}$$

and for z

$$A^{w}_{Siv}(z) = 2\frac{\sum_q e_q^2 D_{1q}^{h}(z)\int C(x) x f_{1T}^{\perp(1)q}(x)dx}{\sum_q e_q^2 D_{1q}^{h}(z)\int C(x) x f_1^{q}(x)dx}$$

with $C(x) = \int_{\Omega_y} dy\frac{1-y+y^2/2}{x^2y^2}$

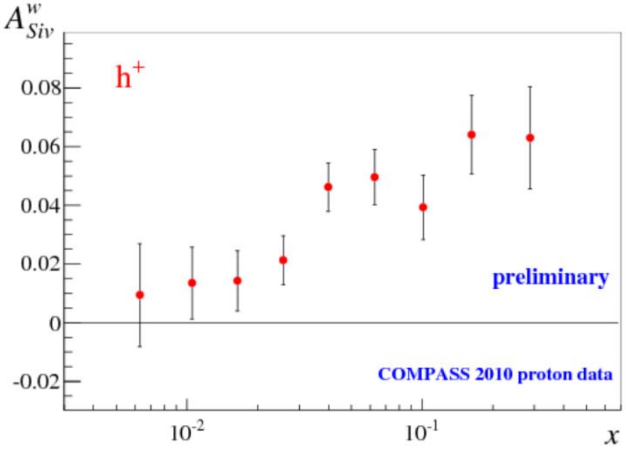
- Note that assuming u-dominance at large x for positive hadrons:

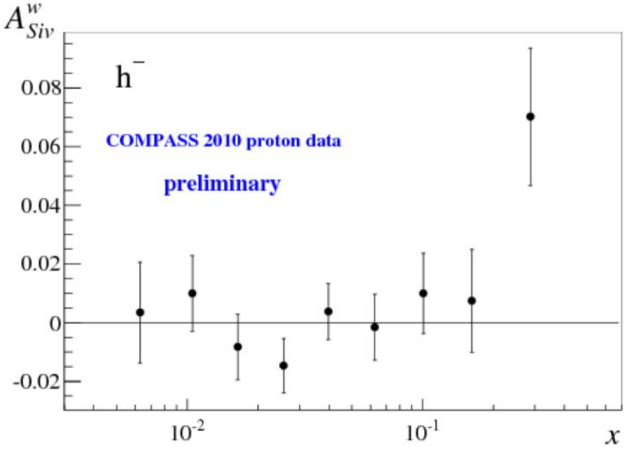
$$A^{w,h^+}_{Siv}(x) \cong 2\frac{f_{1T}^{\perp(1)u}(x)}{f_1^{u}(x)} \quad \text{and} \quad A^{w,h^+}_{Siv}(z) = 2\frac{\int C(x) x f_{1T}^{\perp(1)u}(x)dx}{\int C(x) x f_1^{u}(x)dx}$$

The weighted Sivers asymmetry

$$A^{w}_{Siv}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) \int D_{1q}^{h}(z)dz}{\sum_q e_q^2 x f_1^{q}(x) \int D_{1q}^{h}(z)dz} \qquad w = P_T/zM$$

standard cuts
z>0.2





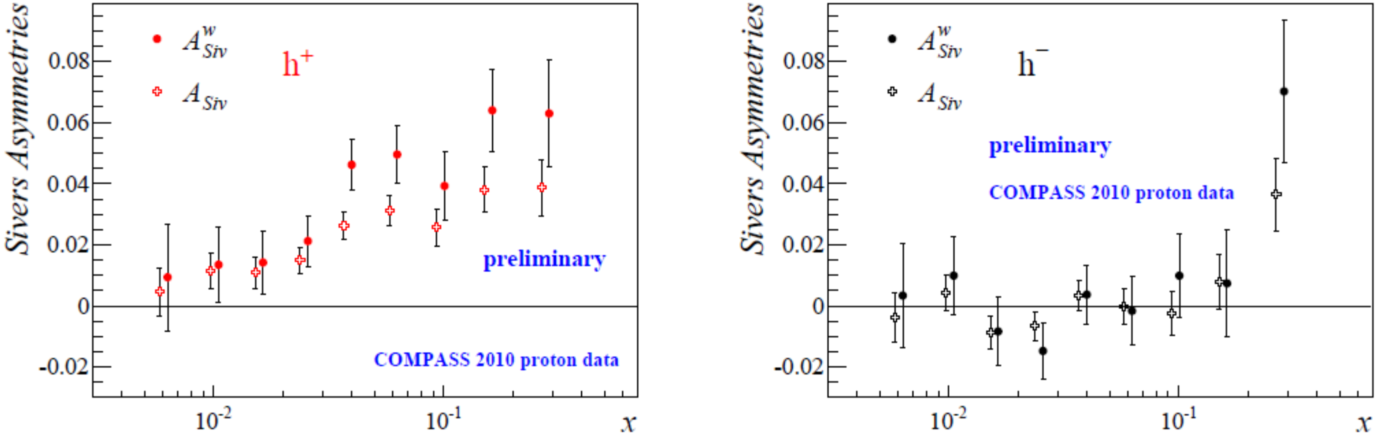
$$\sim 2\frac{f_{1T}^{\perp(1)u}(x)}{f_1^{u}(x)}$$

both $f_{1T}^{\perp(1)u}$ and $f_{1T}^{\perp(1)d}$ contribute

The weighted Sivers asymmetry

$$A_{Siv}^{w}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) \int D_{1q}^{h}(z)dz}{\sum_q e_q^2 x f_1^{q}(x) \int D_{1q}^{h}(z)dz} \qquad w = P_T/zM$$

standard cuts
z>0.2

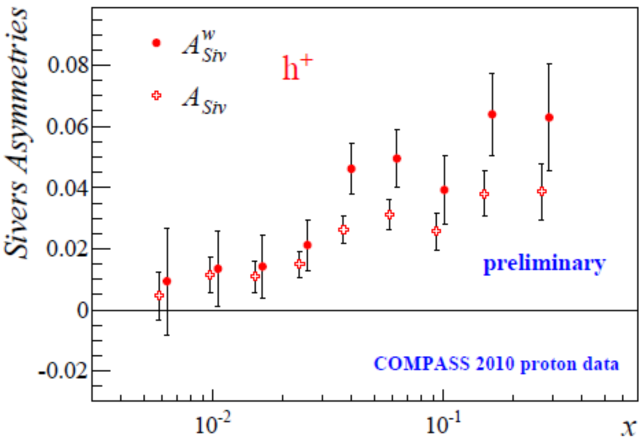


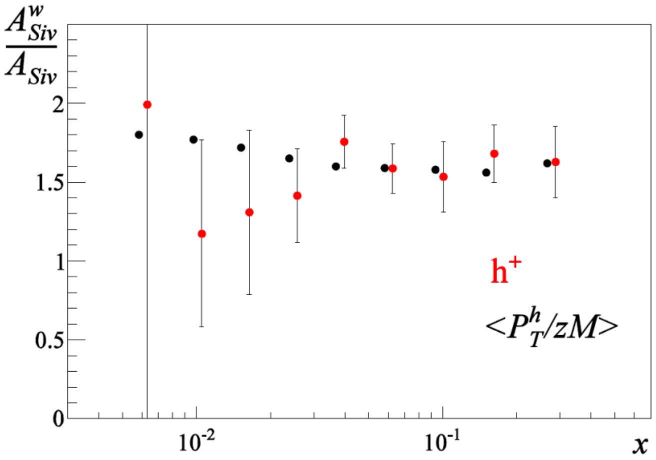
C. Adolph *et al.* [COMPASS Collaboration], Phys. Lett.
B **717** (2012) 383.

The weighted Sivers asymmetry

$$A^{w}_{Siv}(x) = 2\frac{\sum_q e_q^2 x f_{1T}^{\perp(1)q}(x) \int D_{1q}^h(z)dz}{\sum_q e_q^2 x f_1^q(x) \int D_{1q}^h(z)dz} \qquad w = P_T/zM$$

standard cuts
z>0.2

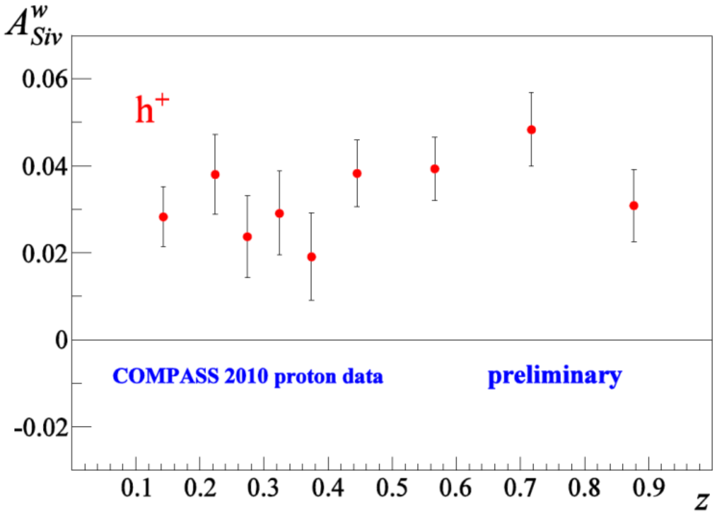


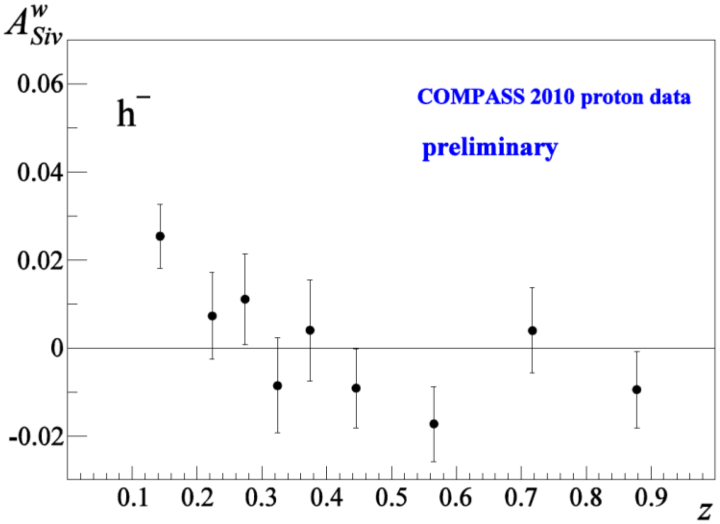


The ratio between weighted and unweighted Sivers asymmetries follows the average of $\left\langle\frac{P_{hT}}{zM}\right\rangle$ of the unpolarised sample

The weighted Sivers asymmetry

1. weight $w = P_T/zM$ $A^w_{Siv}(z)$ $0.1 < z < 1.0$

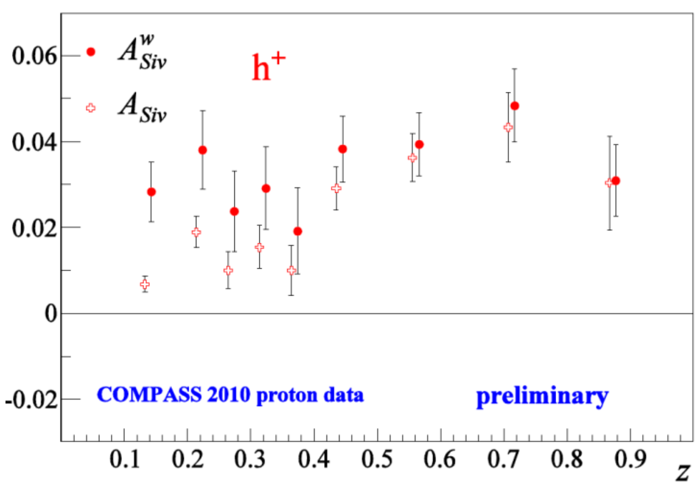


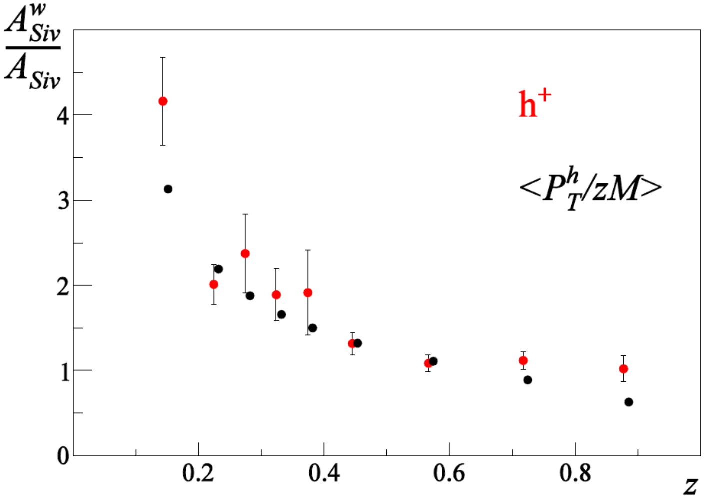


$$2\frac{\int C(x) x f_{1T}^{\perp(1)u}(x)dx}{\int C(x) x f_1^u(x)dx}$$

The weighted Sivers asymmetry

1. weight $w = P_T/zM$ $A^w_{Siv}(z)$ $0.1 < z < 1.0$





The ratio between weighted and unweighted Sivers asymmetries follows the average of $\left\langle \frac{P_{hT}}{zM} \right\rangle$ of the unpolarised sample

The weighted Sivers asymmetry

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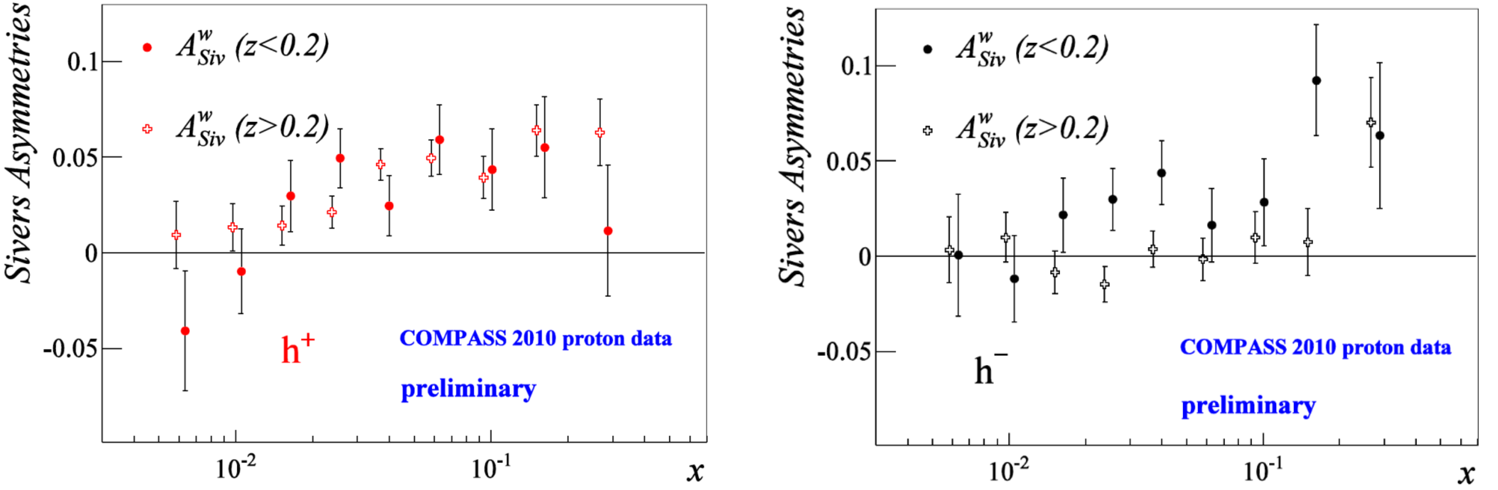


For $0.1 < z < 0.2$ the asymmetries for h^+ and h^- show the same behavior

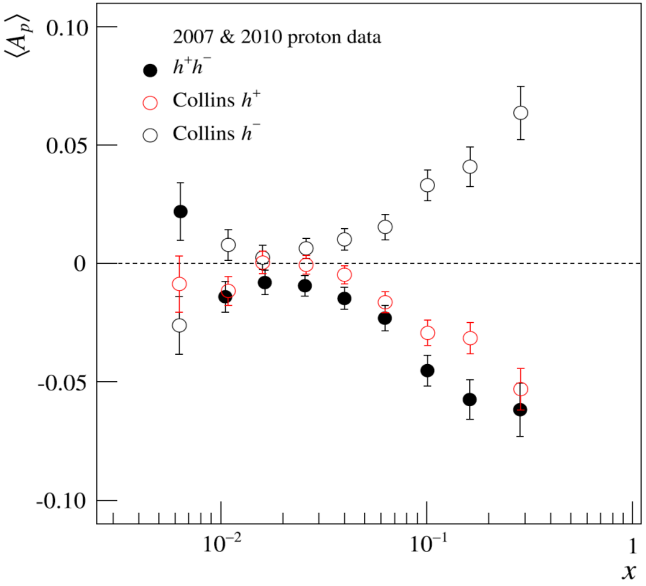
Interplay among dihadron and single hadron asymmetries

- Collins asymmetry for h+ and for h-

  "mirror symmetry"

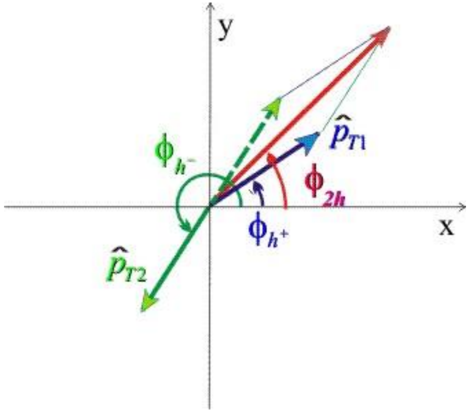
- dihadron asymmetry

  only somewhat larger than h+ Collins



hints for a common origin
of the Collins FF and DiFF

Como 2013, DSpin2013, PLB736 (2014) 124



look at

the $\Delta\phi = \phi_1 - \phi_2$

dependence of the asymmetries

COMPASS

Interplay among dihadron and single hadron asymmetries

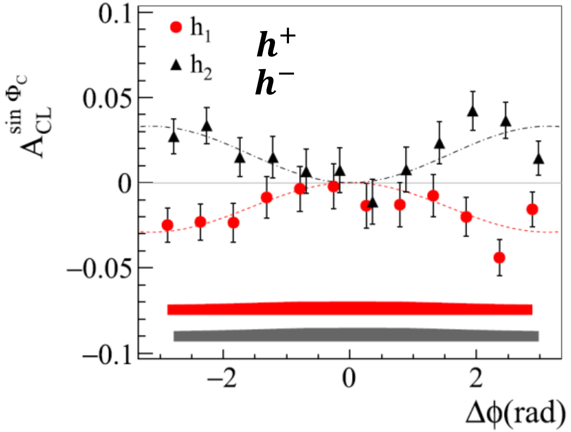
PLB 753 (2016) 406

analitically

$$A^{\sin\Phi_C}_{CL1} = a_1 + a_2 \cos\Delta\phi$$

$$A^{\sin\Phi_C}_{CL2} = a_2 + a_1 \cos\Delta\phi$$

mirror symmetry



agreement with
data if $a_1 = -a_2 = a$

⇩

$$A^{\sin\Phi_{2h,S}}_{CL\,2h} = a\sqrt{2(1-\cos\Delta\phi)}$$

ratio of the $\Delta\phi$ integrated 2h and 1h asymmetries: $4/\pi$

slightly larger than h^+

Interplay among dihadron and single hadron asymmetries

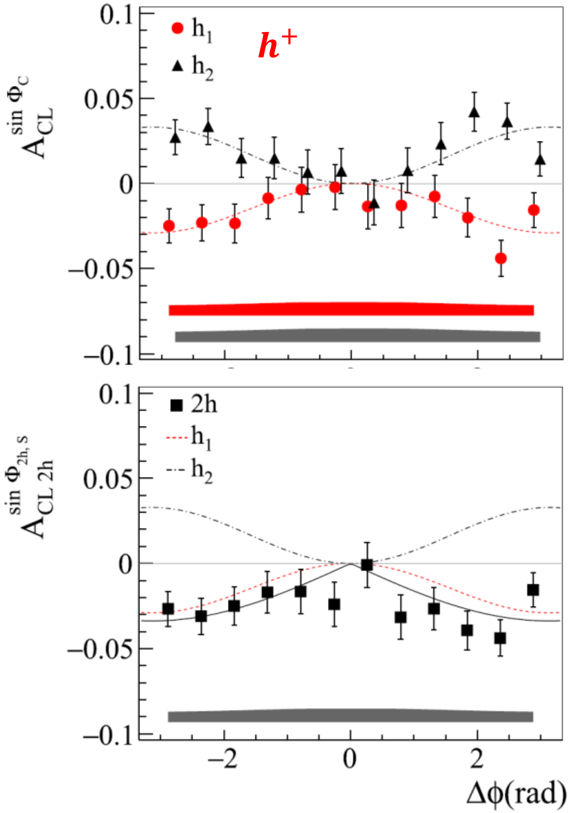
PLB 753 (2016) 406

analitically

$$A_{CL1}^{\sin\Phi_C} = a_1 + a_2\cos\Delta\phi$$

$$A_{CL2}^{\sin\Phi_C} = a_2 + a_1\cos\Delta\phi$$

mirror symmetry



agreement with data if

⇩

$$A_{CL\,2h}^{\sin\Phi_{2h,S}} = a\sqrt{2(1-\cos\Delta\phi)}$$

agreement with data

a very simple relationships among the asymmetries in the “2h sample”

they are driven by the same elementary mechanism.

ratio of the $\Delta\phi$ integrated 2h and 1h asymmetries: $4/\pi$

slightly larger than h^+

From Collins asymmetries to transversity

- Following Physical Review D 91, 014034 (2015), in the valence region

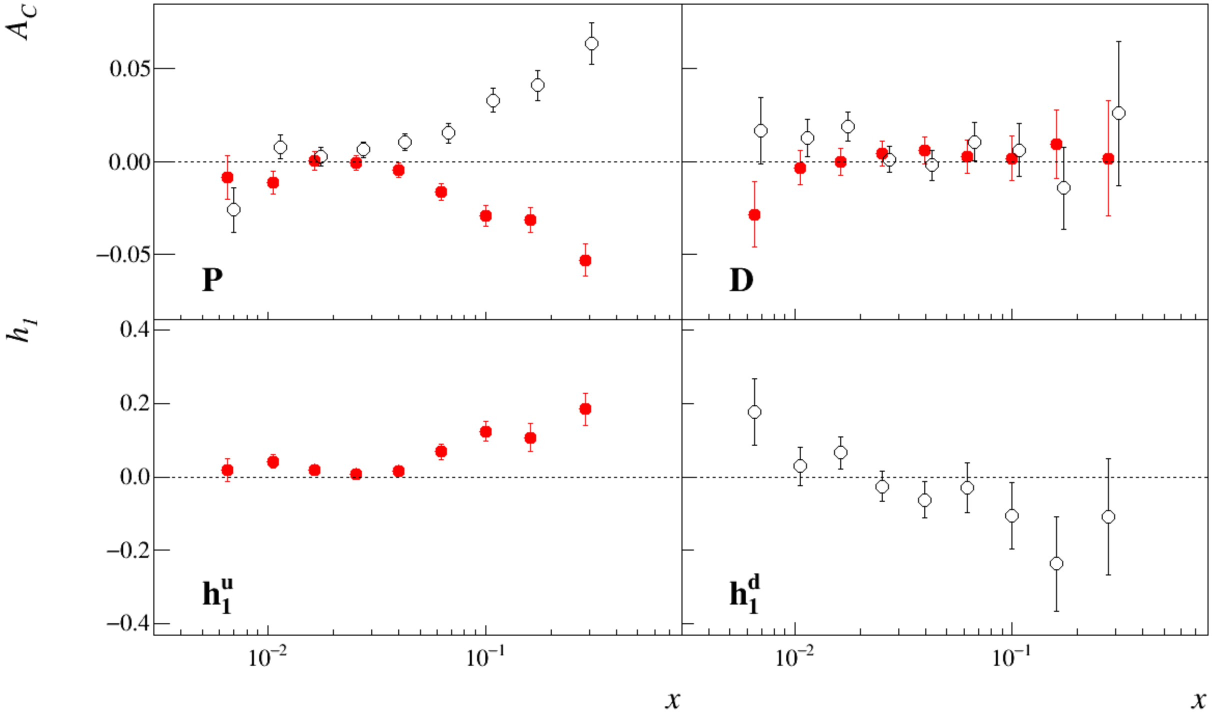
$$xh_1^u = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\left(xf_p^+ A_p^+ - xf_p^- A_p^-\right) + \frac{1}{3}\left(xf_d^+ A_d^+ - xf_d^- A_d^-\right)\right]$$

$$xh_1^d = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\frac{4}{3}\left(xf_d^+ A_d^+ - xf_d^- A_d^-\right) - \left(xf_p^+ A_p^+ - xf_p^- A_p^-\right)\right]$$

With $\tilde{a}_P^h$ and $\tilde{\alpha}$ constants

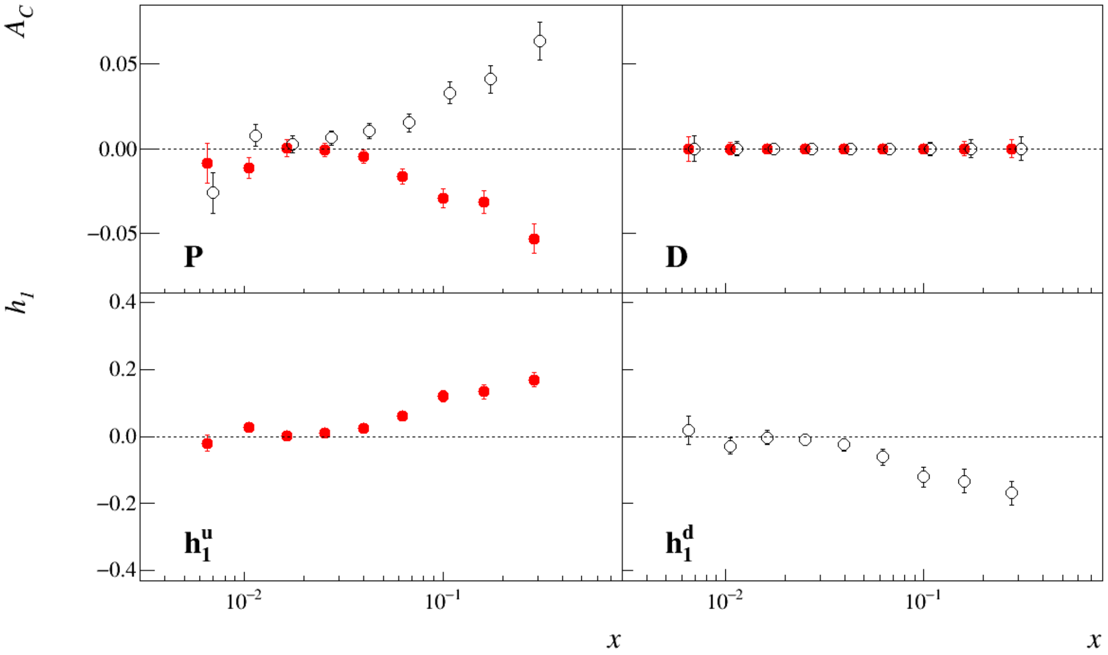
New deuteron data

- Benchmark: extraction from Collins asymmetries



New deuteron data

- 1 full year (same as 2010). We also gain from $\frac{f_p P_{pT}}{f_D P_{DT}} = \frac{0.155\times0.8}{0.40\times0.5} = 0.6$



THIS IS A KEY MEASUREMENT THAT WILL IMPACT OUR KNOWLEDGE,

Conclusions

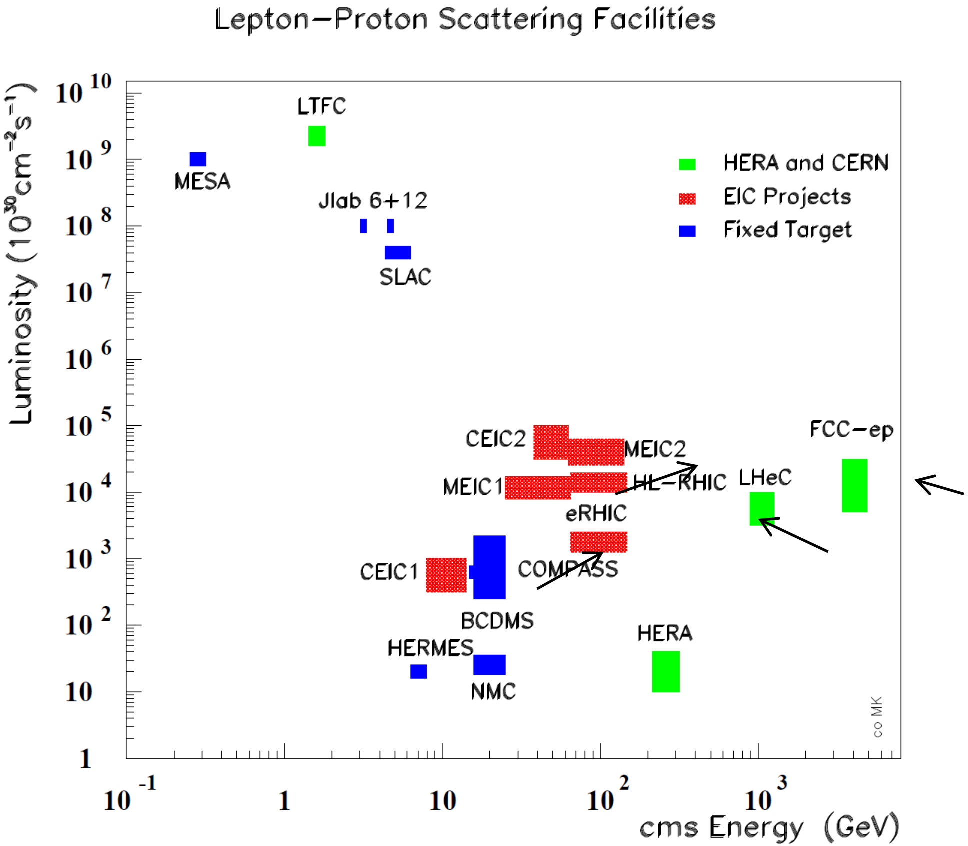
- The study of TMDs has entered the phase of multidimensional analysis
- An important step in this direction is the large sample of precise unpolarised data, both as multiplicities and as azimuthal modulations
- In the next years more of such data will be available both from COMPASS and from JLab12
- One year of deuteron data (something that COMPASS can do after 2020) will strongly impact our knowledge of h_1^d!
- Waiting for the EIC to extend the accessible phase space, the description of such data is a mandatory task for the theory of TMDs

Thank you

and see you all in Trieste for the EICUG meeting (July 18-22, 2017)

eicug2017.ts.infn.it

The CM Energy vs Luminosity Landscape



CEIC1 = Chinese version of Electron-Ion Collider

("A dilution-free mini-COMPASS")

MEIC1 = EIC@Jlab

eRHIC = EIC@BNL

LHeC = ep/eA collider @ CERN

CEIC2
MEIC2
HL-eRHIC
FCC-he

SIDIS Experiments

SIDIS Experiment must:

- Have large acceptances on all the relevant variables x, Q^2, z, P_{hT}, ϕ
- Use different targets (p, d, n) and identify hadrons to allow flavor separation
- Be ad different energies for to cover PDFs from the valence region down to small-x
- Large luminosity to allow multidimensional results needed by the complexity of TMDs

The polarized lepton-nucleon collider will be a mandatory tool to reach the level of ordinary PDF