OVERVIEW OF COMPASS RESULTS IN SIDIS AND FUTURE PLANS

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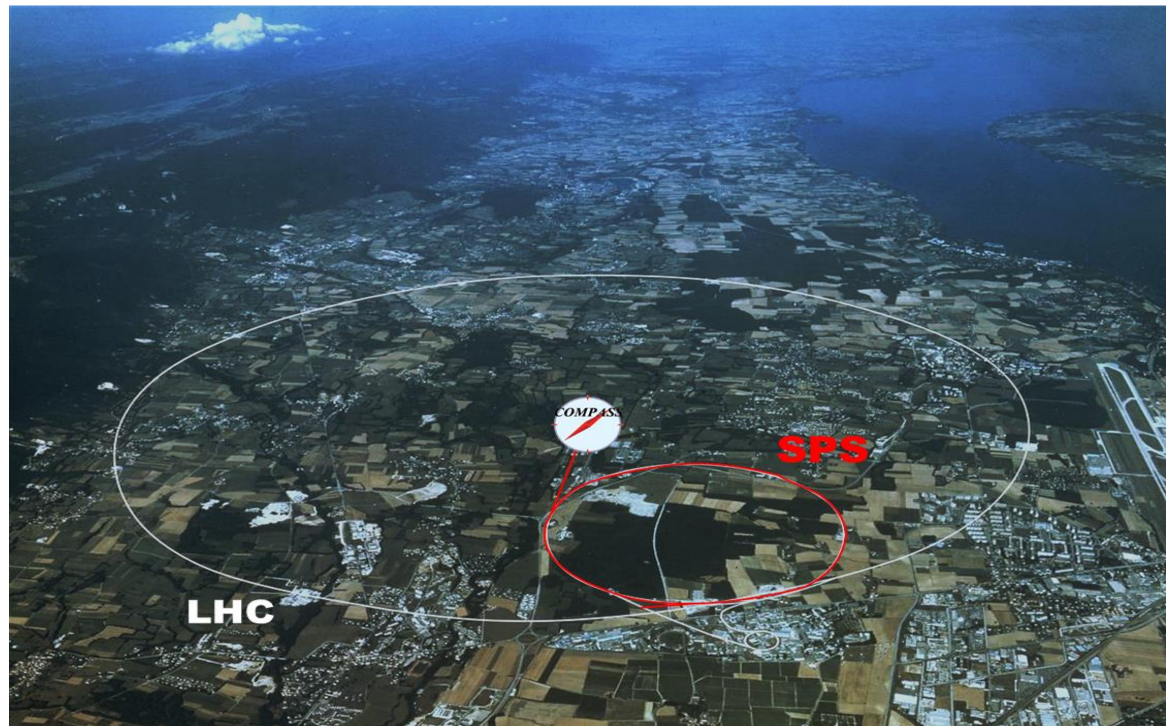
INFN-LABORATORI NAZIONALI DI FRASCATI

fixed target experiment at the CERN SPS

data taking: since 2002

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy



COMPASS Collaboration

Дубна (LPP and LNP), Москва (INR, LPI, State University), Протвино

CERN

Bochum, Bonn (ISKP & PI), Erlangen, Freiburg, Mainz, München TU

Warsawa (NCBJ), Warsawa (TU) Warsawa (U)

Yamagata

USA (UIUC)

Praha (CU/CTU)

Liberec (TU)

Brno (ISI-ASCR)

Lisboa/Aveiro

Saclay

Calcutta (Matrivian)

Tel Aviv

Torino (University,INFN), Trieste (University,INFN)

Taipei (AS)

About 250 physicists from 24 Institutions of 13 Countries

COMPASS-I

- high energy beam
- large angular acceptance
- broad kinematical range

two stages spectrometer

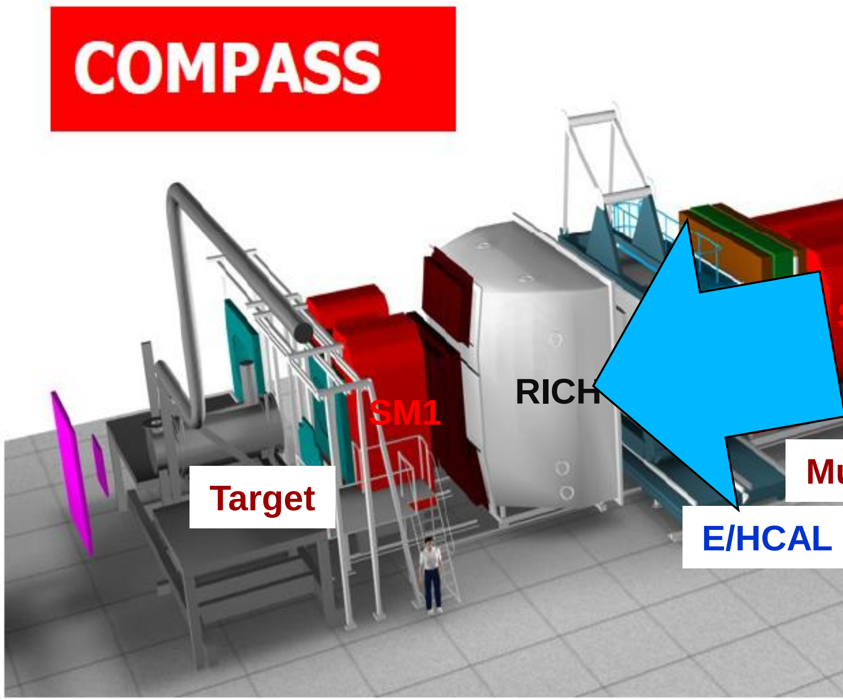
Large Angle Spectrometer (SM1)

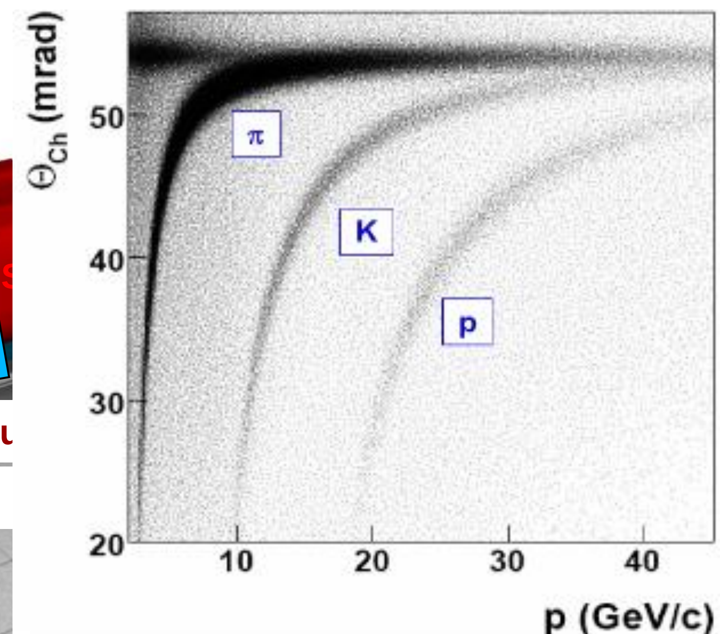
Small Angle Spectrometer (SM2)

radiator C_4F_{10}

threshold: π ~2 GeV/c

K ~ 10 GeV/c

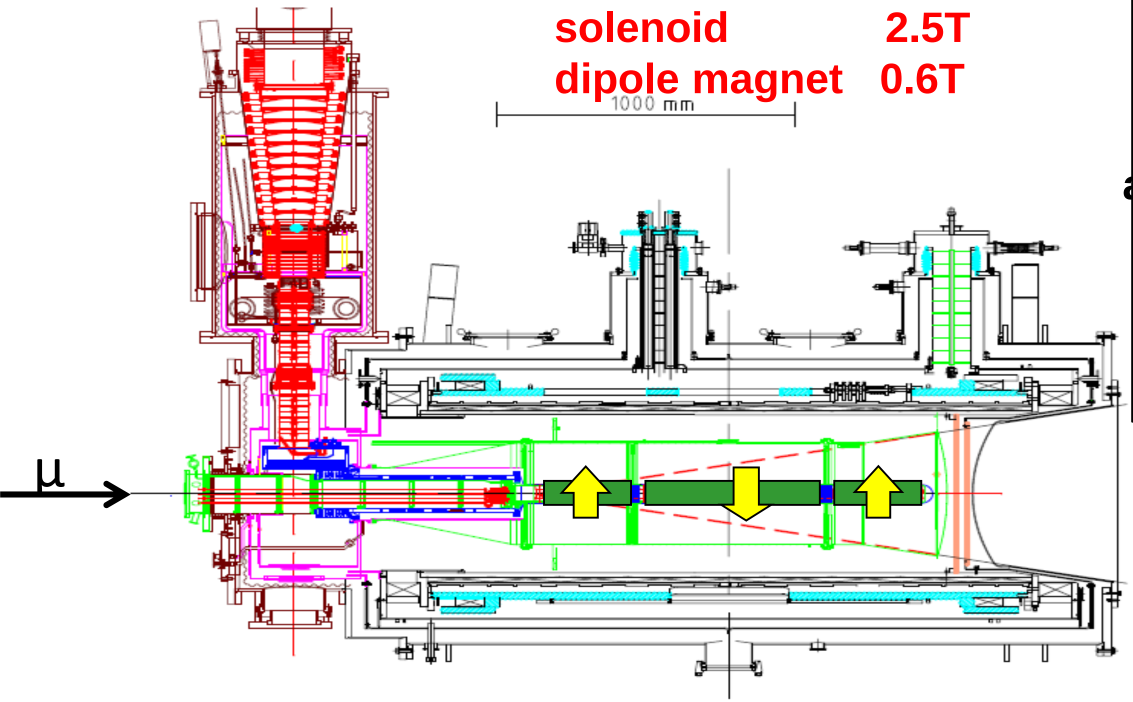


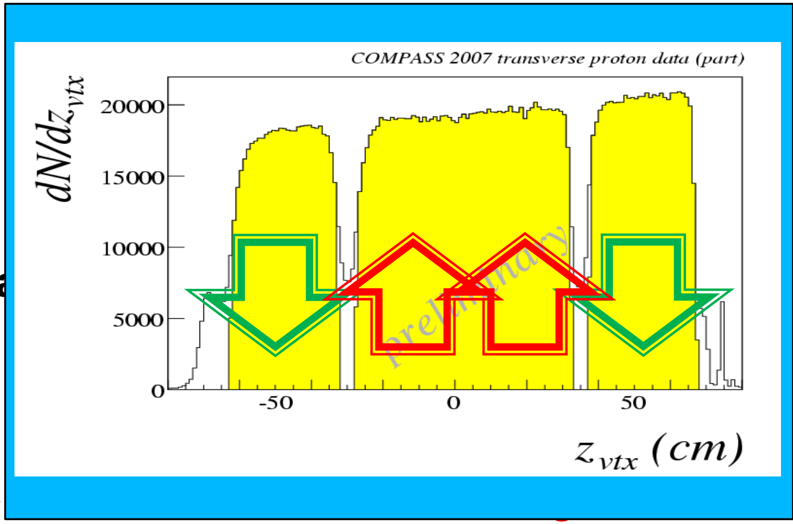


the polarized target system (>2005)

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

solenoid 2.5T
dipole magnet 0.6T





opposite polarisation

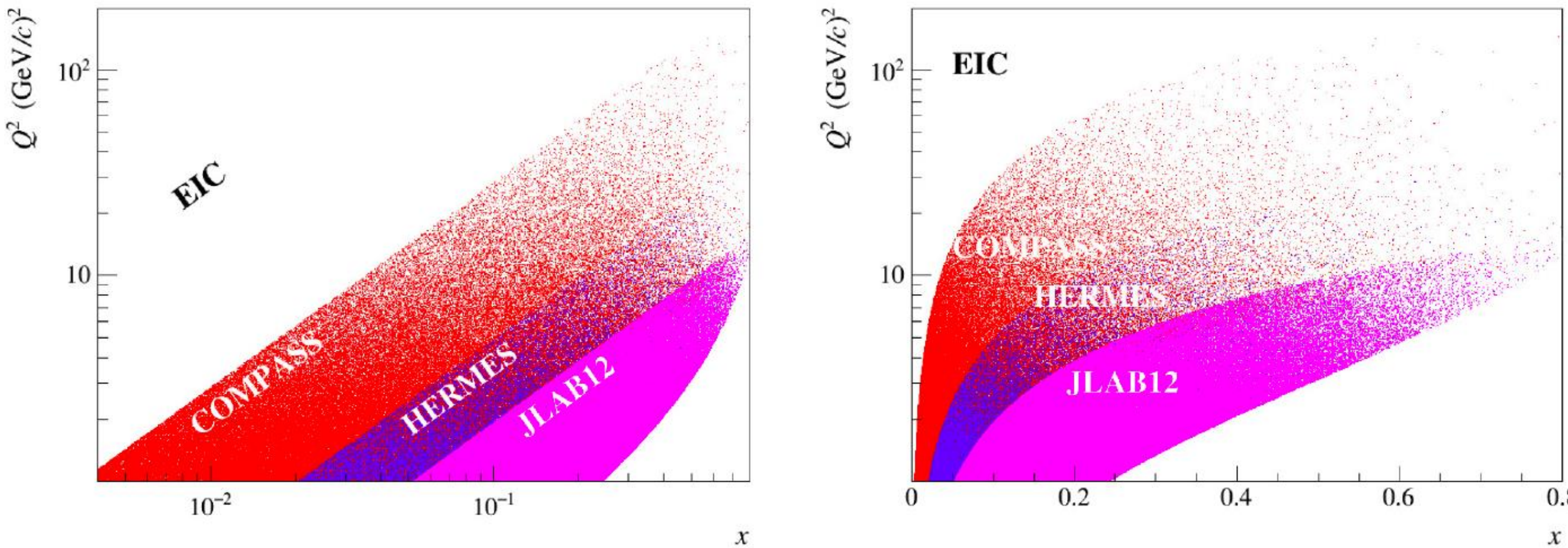
	d (^6LiD)	p (NH_3)
polarization	50%	90%
dilution factor	40%	16%

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	LH_2 target	2012	Pilot DVCS & unpol. SIDIS
Hadron	Proton (NH_3) DT PT	2014 2015	Pilot DY run DY run
Muon beam	LH_2 target	2016 2017	DVCS & unpol. SIDIS
Hadron	Proton (NH_3) PT	2018	DY run

Kinematic coverage



Measurements with the target transversely polarized:

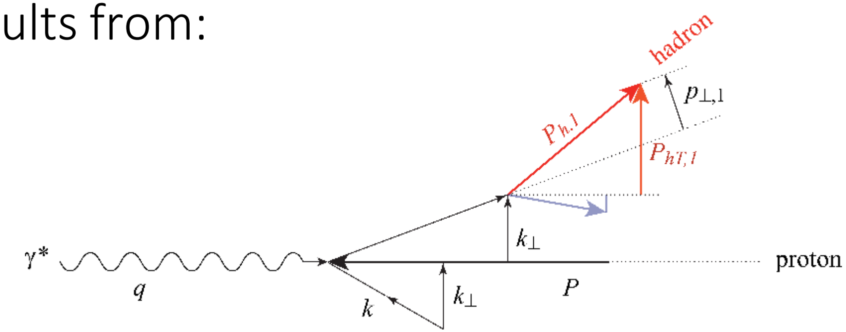
Year	Obs	
2005	$A^h_{Siv,d}, A^h_{Col,d}$	First ⁶LiD data
2006	$A^h_{Siv,d}, A^h_{Col,d}$	Full ⁶LiD statistics
2009	$A^{\pi^\pm,K^\pm,K^0_S}_{Siv,d}, A^{\pi^\pm,K^\pm,K^0_S}_{Col,d}$	Full ⁶LiD statistics
2010	$A^h_{Siv,p}, A^h_{Col,p}$	2007 NH_3 data
2012	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	Full ⁶LiD
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 ⁶LiD and NH_3
2014	$A^{\pi^\pm,K^\pm,K^0_S}_{Siv,d}, A^{\pi^\pm,K^\pm,K^0_S}_{Col,d}$	Full NH_3 statistics
2015	Interplay $A^{sin\phi_{RS}}_{UT,p}$ vs $A^h_{Col,p}$	Full NH_3 statistics
2016	P_{hT}-weighted Sivers asyms	Full NH_3 statistics
2017	P_Λ	Full NH_3 statistics

Measurements with unpolarised targets:

Year	Obs	
2013	$dn^h/(dN^\mu dz\, dp_T^2)$	Unpolarized multiplicities on d, 2004
2014	$A_{UU,d}^{\cos\phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin\phi_h}$	2004, part
2016	$dn^\pi/(dN^\mu dz)$	Unpolarized multiplicities on d, 2006
2016	$dn^h/\left(dN^\mu dz\, dP_{hT}^2\right)$	Unpolarized multiplicities on d, 2006
2016	$dn^K/(dN^\mu dz)$	Unpolarized multiplicities on d, 2006

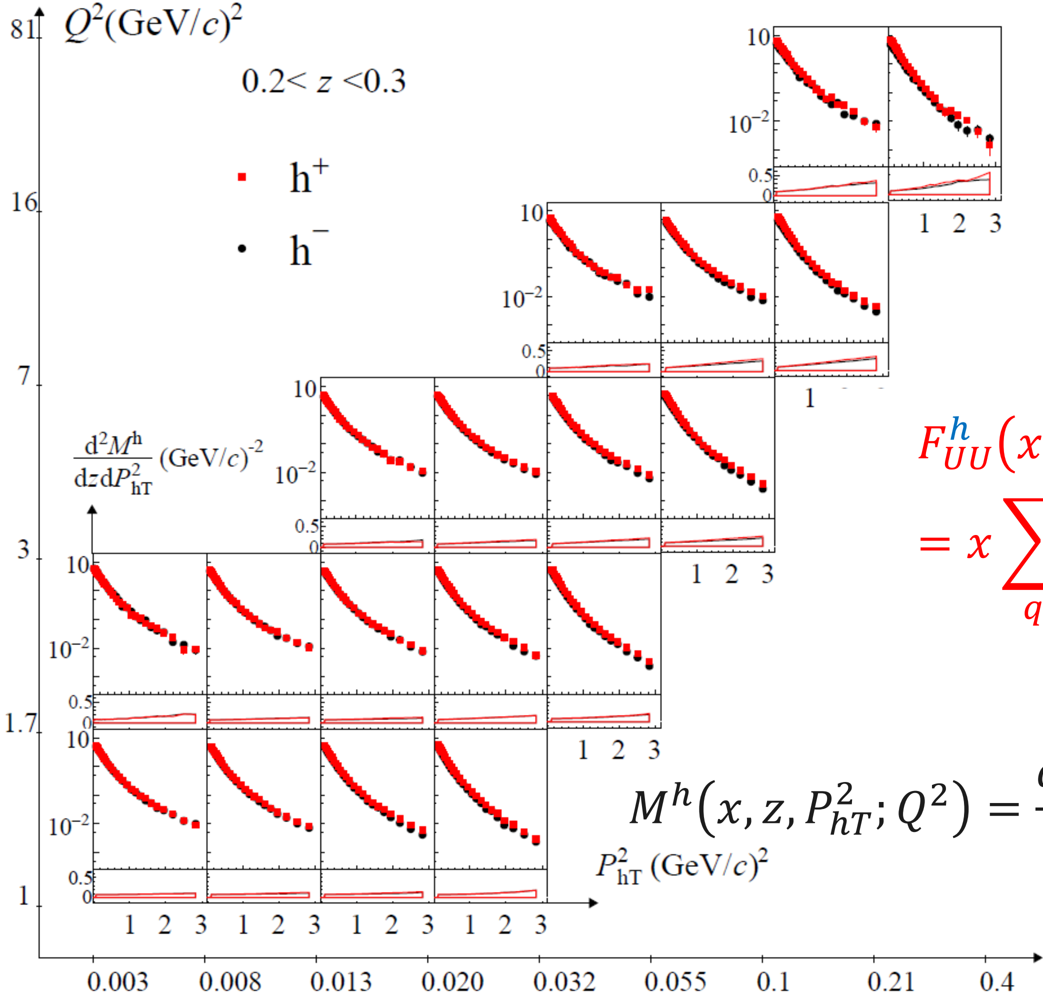
Importance of unpolarized SIDIS

- The cross-section dependence from p_T^h 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
  - $\langle P_{hT}^2 \rangle = z^2 \langle k_\perp^2 \rangle + \langle p_\perp^2 \rangle$

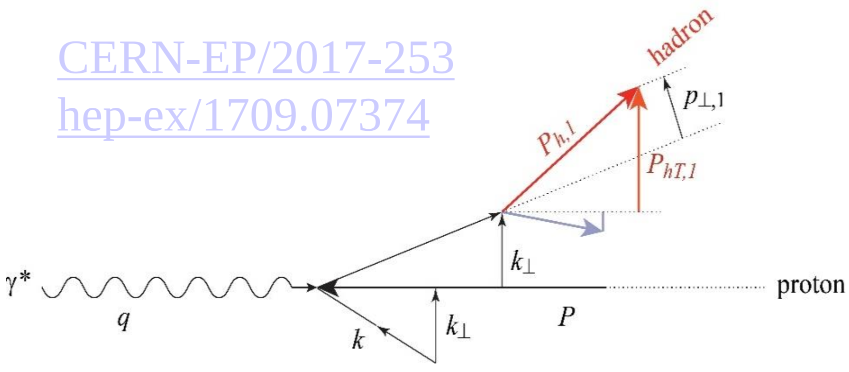


- The azimuthal modulations in the unpolarized cross sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF
- Difficult measurements were one has to correct for the apparatus acceptance
- COMPASS and HERMES have
  - results on $^6LiD\ (\sim d)$ and d and on p (Hermes only)
  - 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

Importance of unpolarized SIDIS



CERN-EP/2017-253
hep-ex/1709.07374

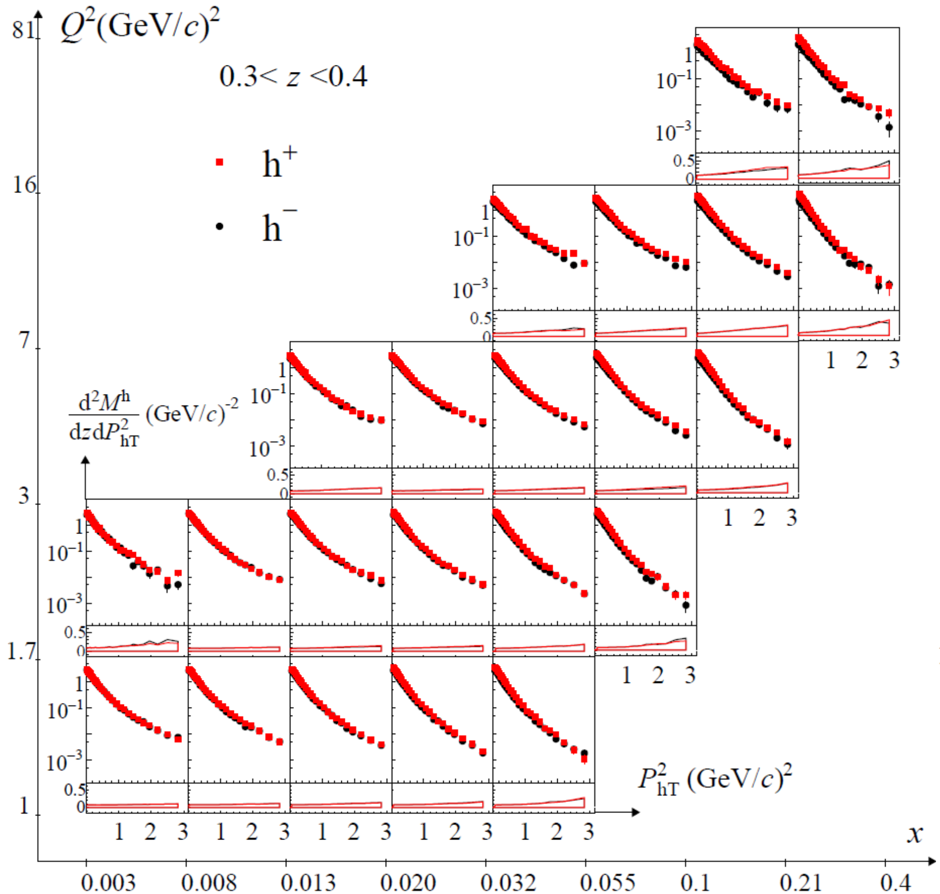


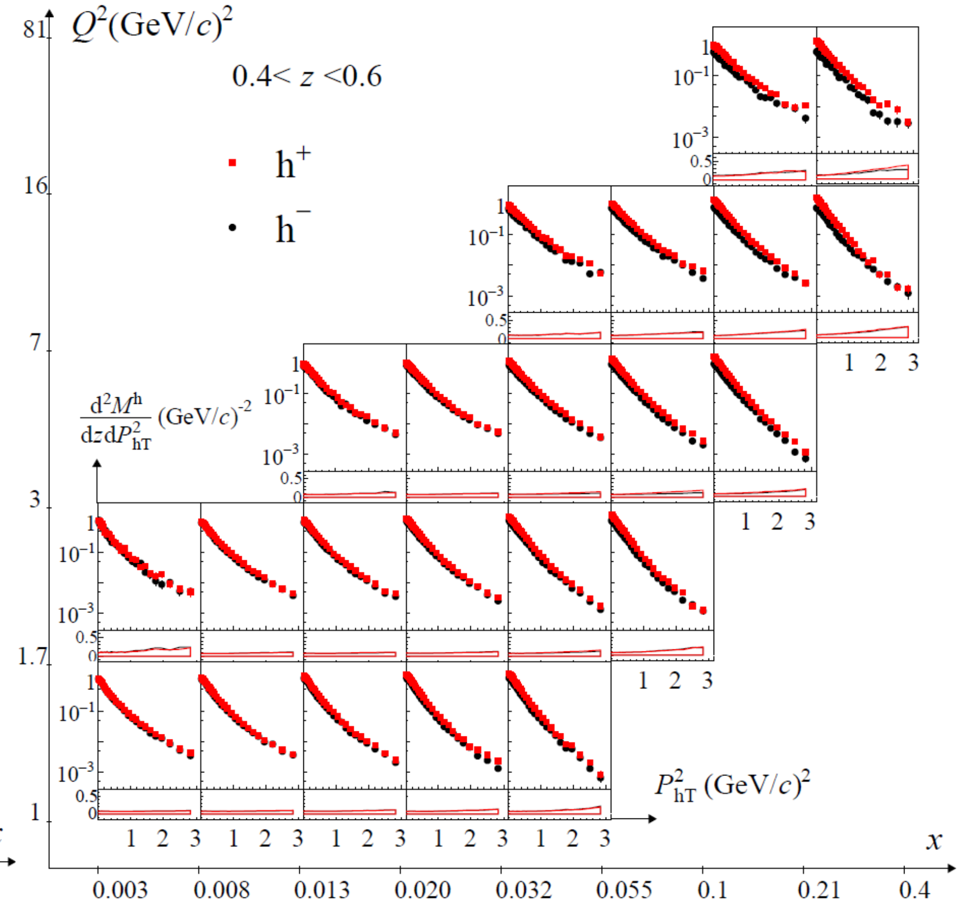
$$F^h_{UU}(x,z,P^2_{hT};\ Q^2) = x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp - z\vec{k}_\perp$$

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

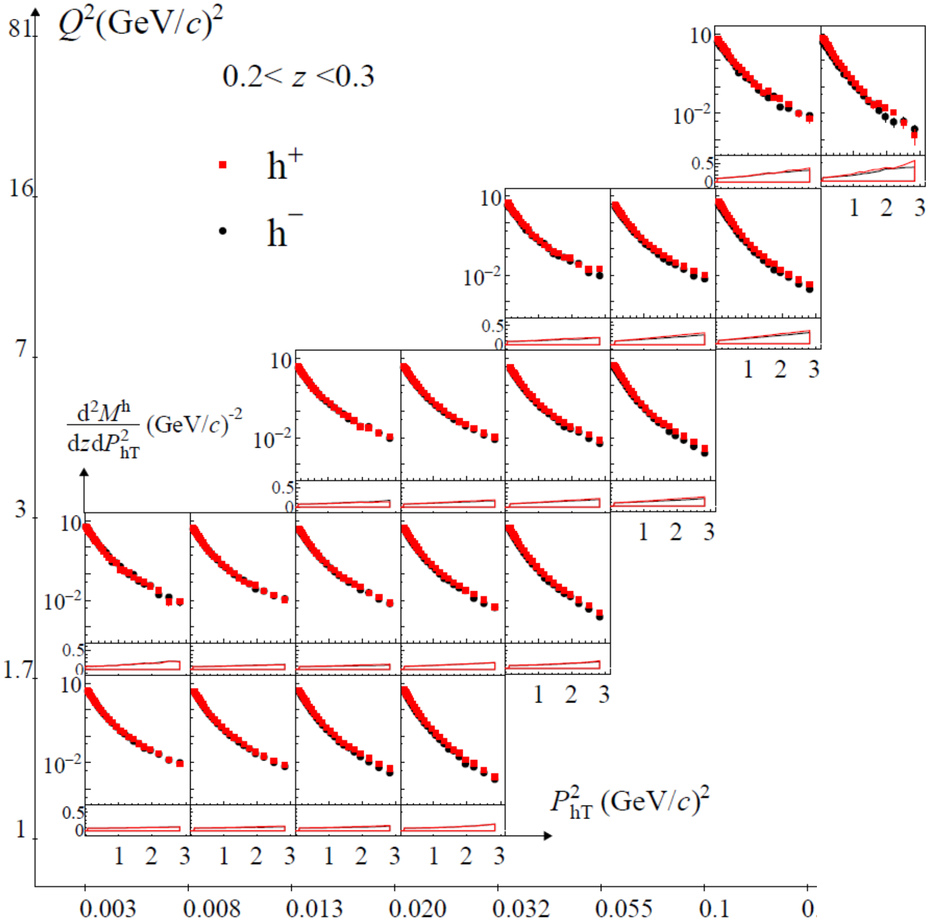
4918 data points

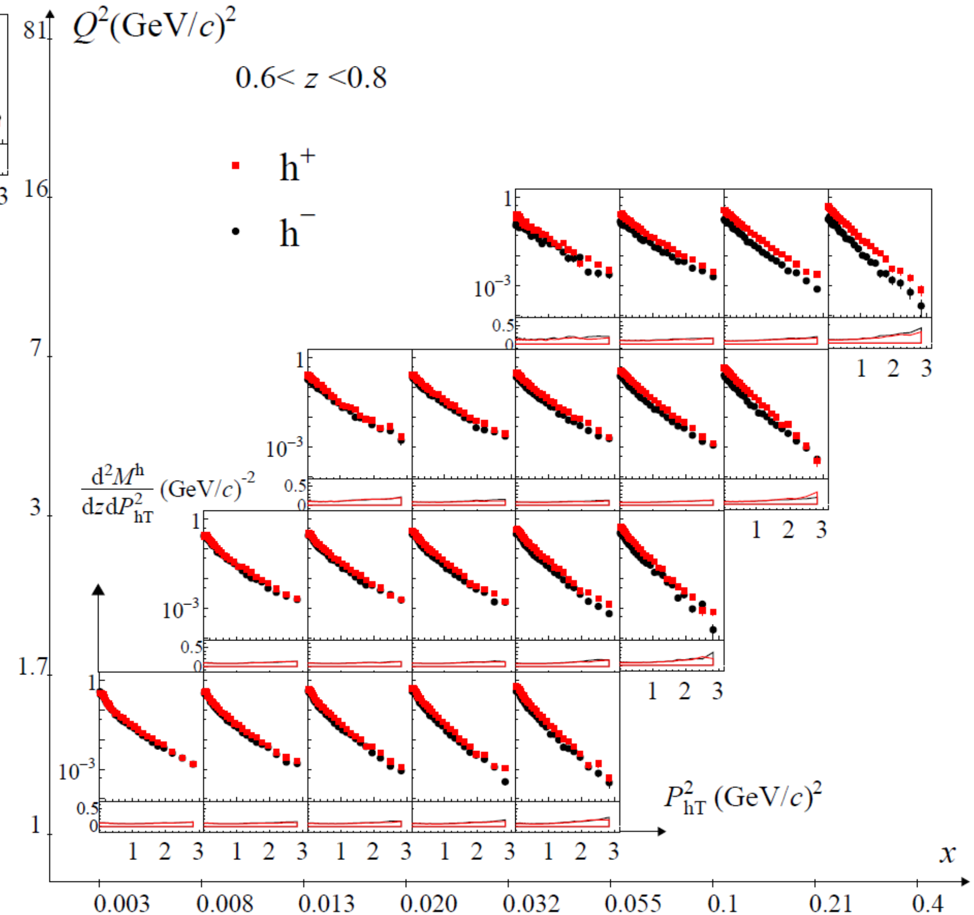
Importance of unpolarized SIDIS





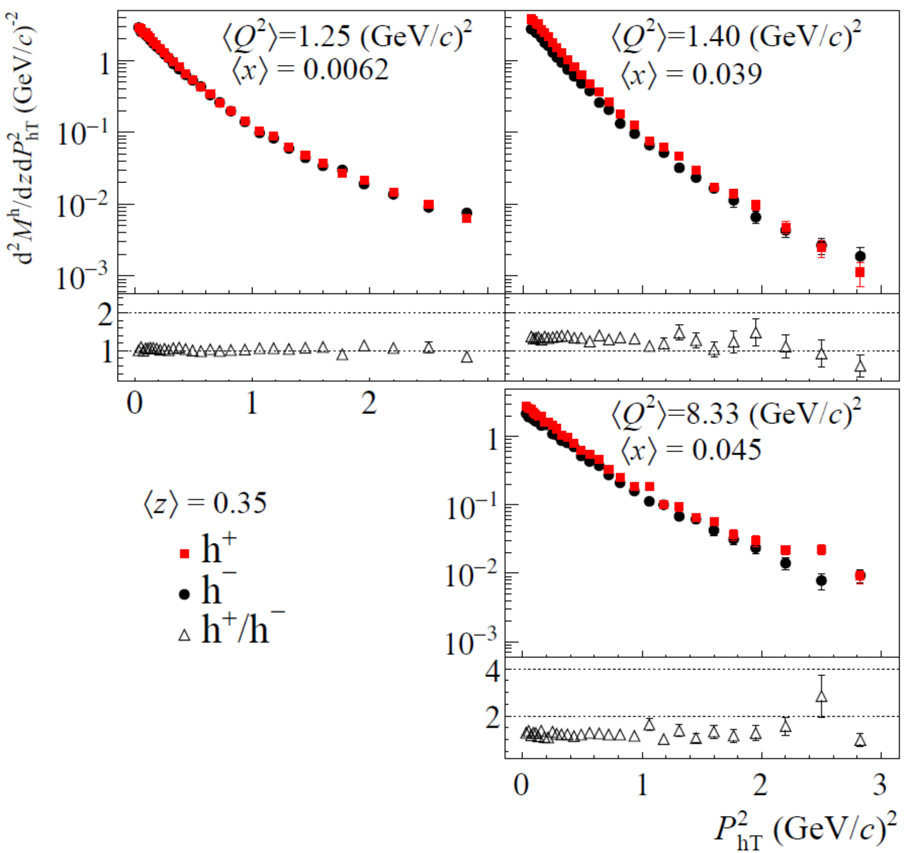
Importance of unpolarized SIDIS

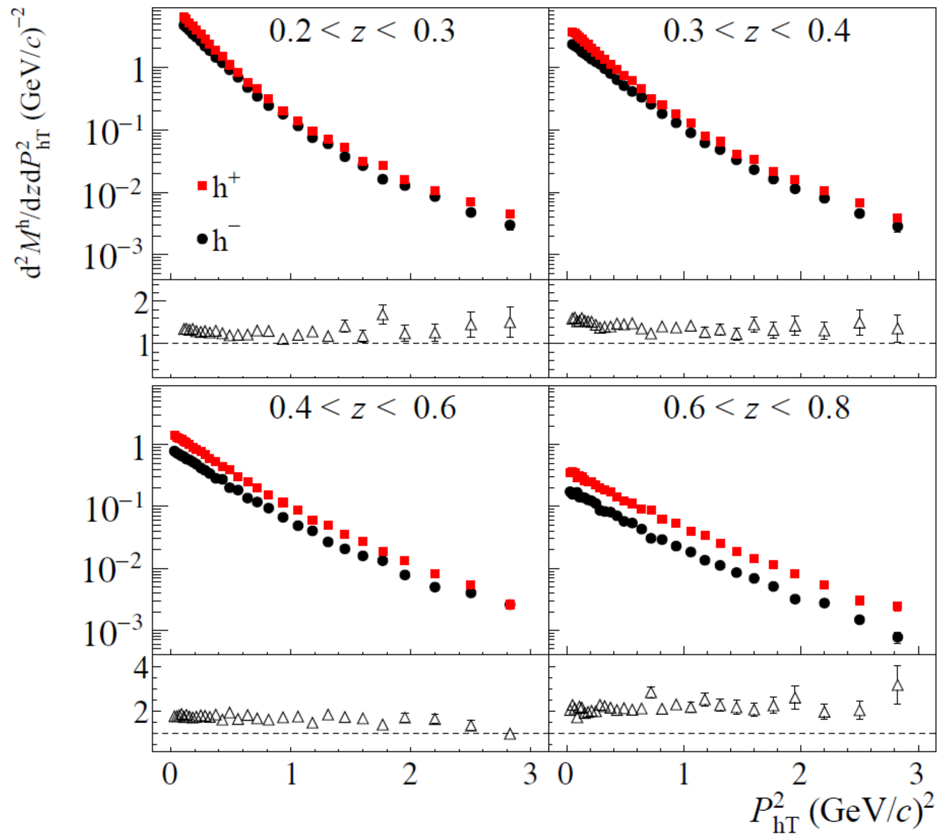




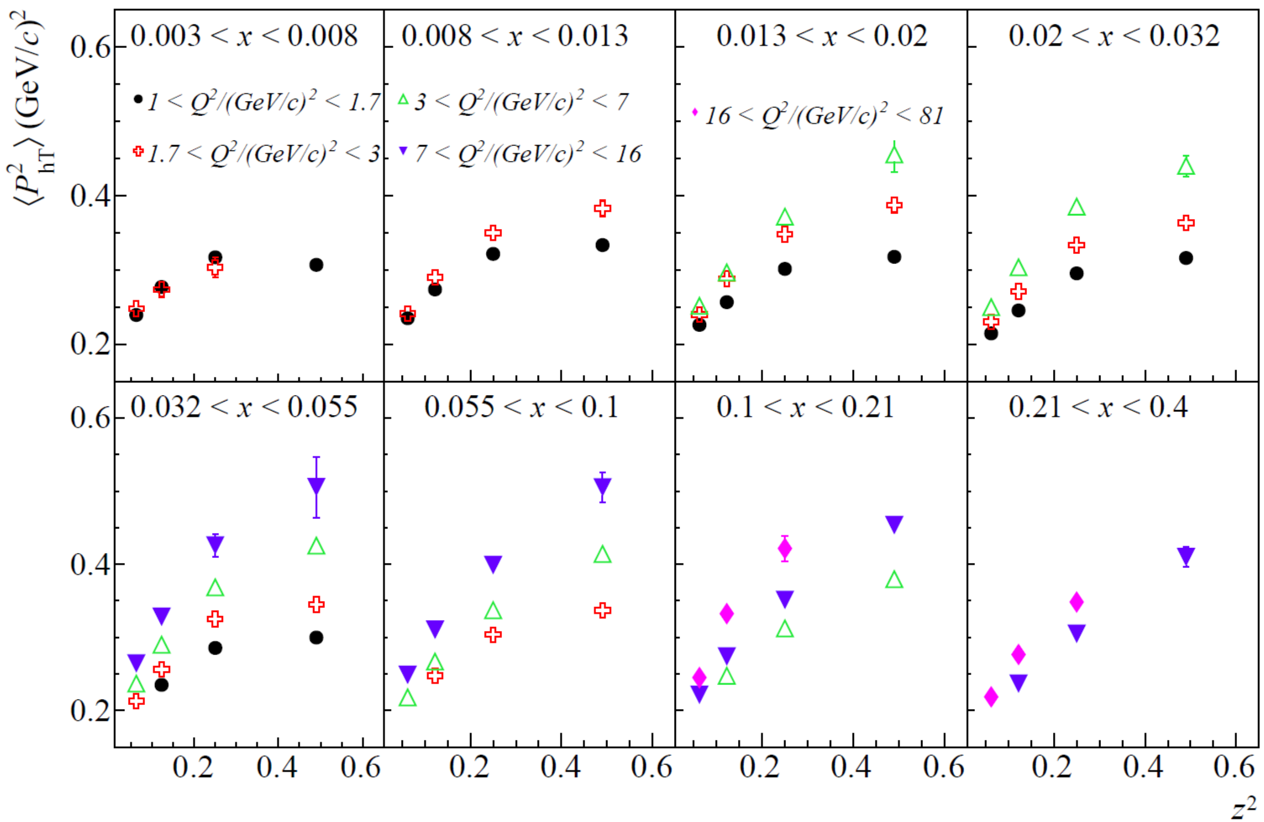
Positive vs Negative charged hadrons

$\langle Q^2 \rangle = 9.78\ (\mathrm{GeV}/c)^2$ and $\langle x \rangle = 0.149$

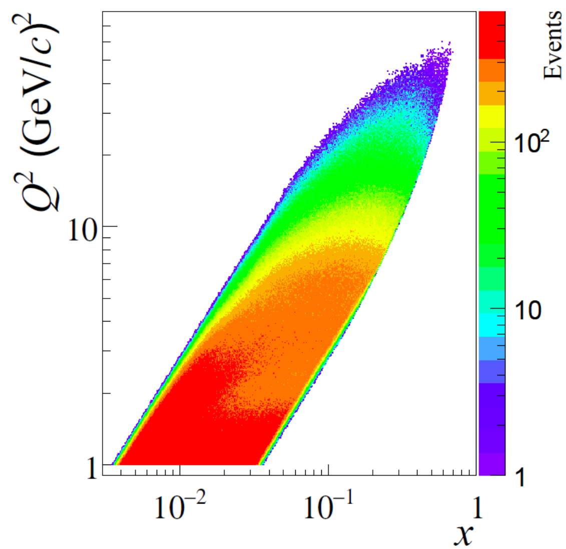




Mean values



$\langle P_{hT}^2 \rangle$ (GeV/c)^2
0.003 < x < 0.008
0.008 < x < 0.013
0.013 < x < 0.02
0.02 < x < 0.032
0.032 < x < 0.055
0.055 < x < 0.1
0.1 < x < 0.21
0.21 < x < 0.4
1 < Q²/(GeV/c)² < 1.7
1.7 < Q²/(GeV/c)² < 3
3 < Q²/(GeV/c)² < 7
7 < Q²/(GeV/c)² < 16
16 < Q²/(GeV/c)² < 81
0.2
0.4
0.6
z²



Q² (GeV/c)²
Events
10
1
10⁻²
10⁻¹
1
x
10²
10
1

Transversity

is chiral-odd:

observable effects are given only by the product of h_1^q (x) and an other chiral-odd function

can be measured in SIDIS on a transversely polarised target via "quark polarimetry"

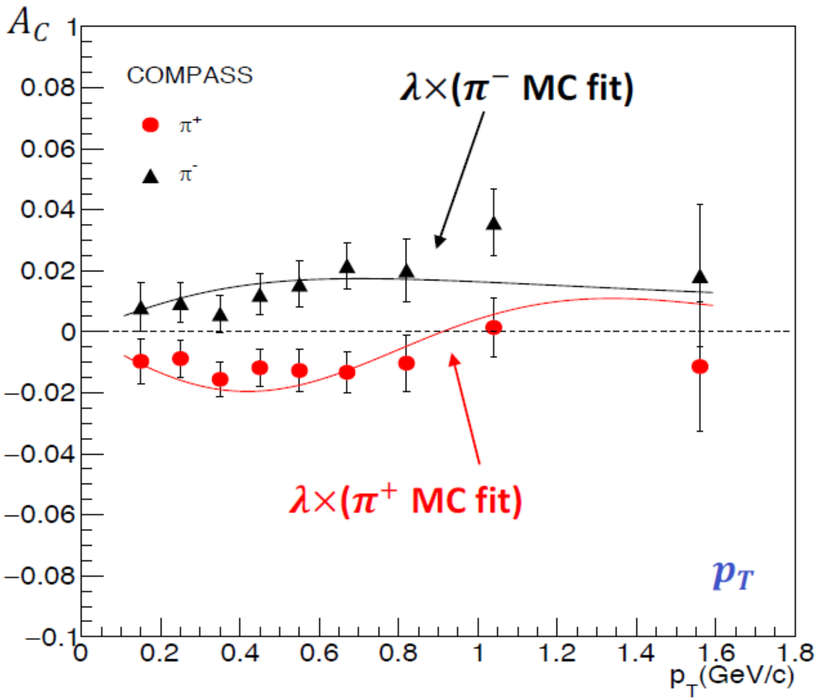
$\ell N^{\uparrow} \rightarrow \ell' h X$ — "Collins" asymmetry
"Collins" Fragmentation Function

$\ell N^{\uparrow} \rightarrow \ell' h h X$ — "two-hadron" asymmetry
"Interference" Fragmentation Function

$\ell N^{\uparrow} \rightarrow \ell' \Lambda X$ — Λ polarisation
Fragmentation Function of $q\uparrow \rightarrow \Lambda$

Collins asymmetry on proton and $^3P_0$ model for FF

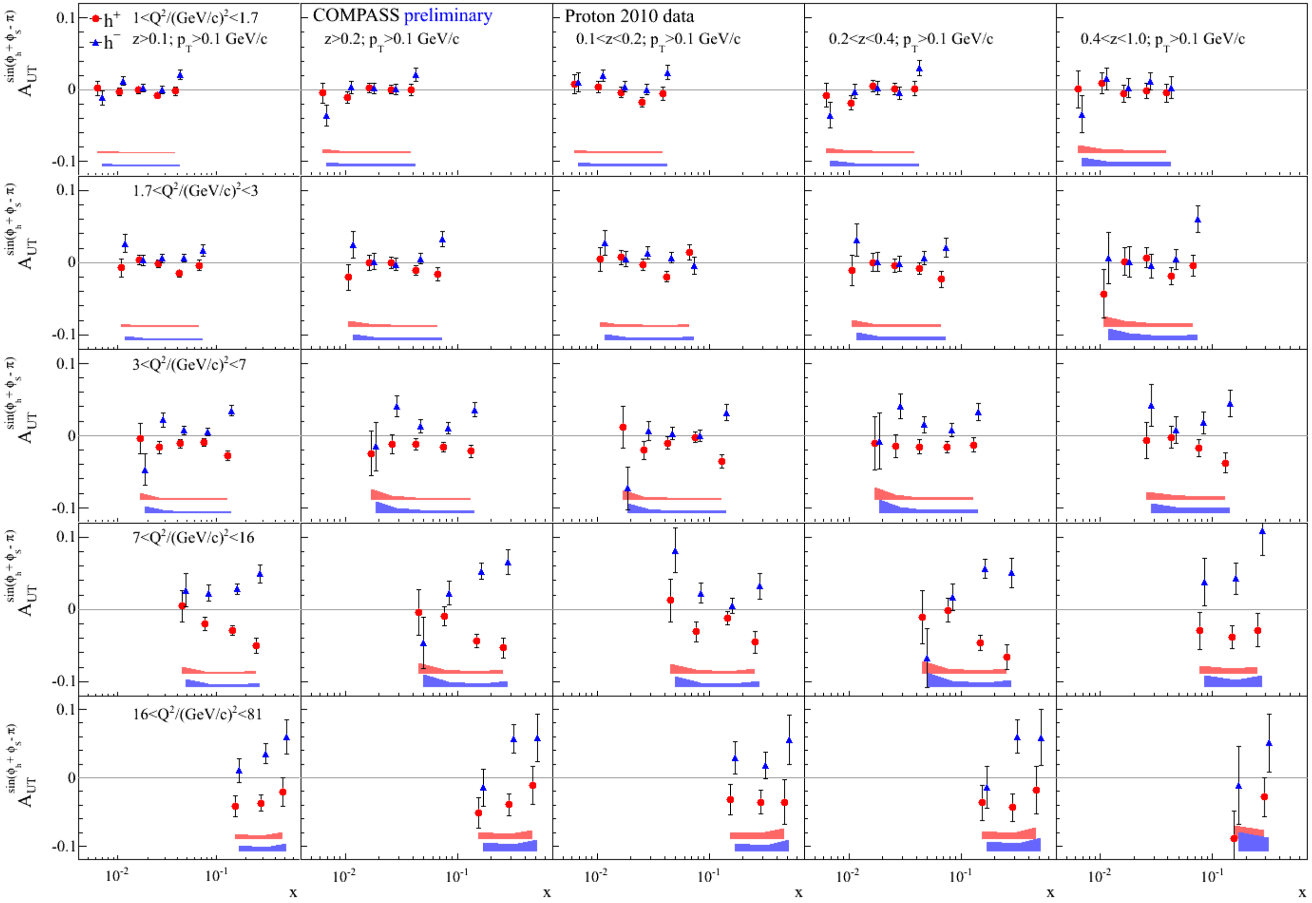
Albi Kerbizi @ DSPIN17 http://theor.jinr.ru/~spin/2017/

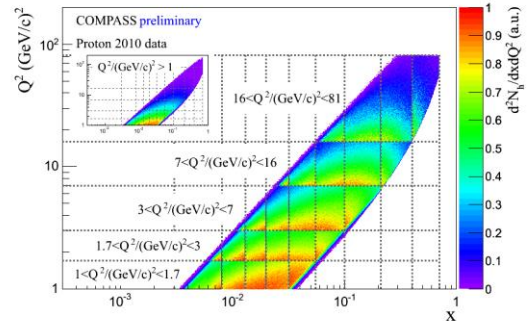


- The curves are fits of the Monte Carlo data, scaled by $\lambda \sim \langle h_1^u / f_1^u \rangle \sim 0.055$
- Agreement with the measured Collins asymmetry is quite satisfactory

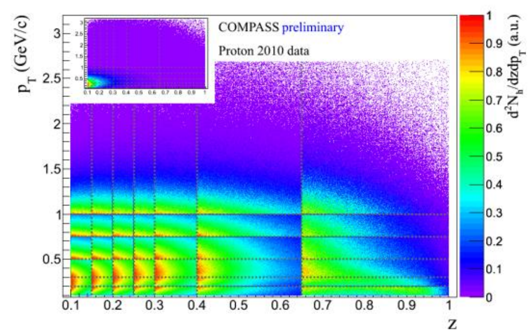
Collins asymmetry on proton. Multidimensional

First extraction of TSAs within a Multi-D $(x{:}\,Q^2{:}\,z{:}\,p_T)$ approach



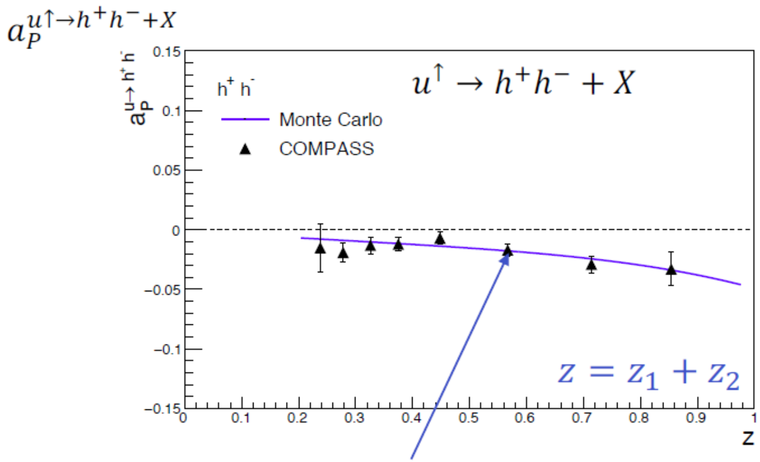


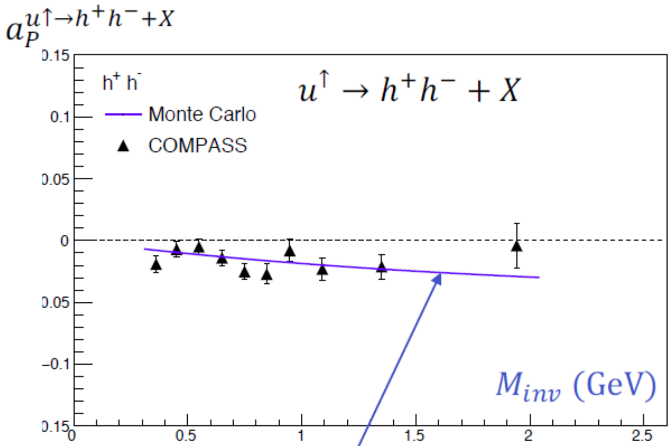
One dense plot out of many



2h asymmetries on p

$$A_{UT}^{\sin(\phi_R+\phi_S-\pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q\to h_1 h_2}^{\sphericalangle}\left(z, \mathcal{M}_{h_1 h_2}^2\right)}{\sum_q e_q^2 q(x) D_q^{h_1 h_2}\left(z, \mathcal{M}_{h_1 h_2}^2\right)}$$

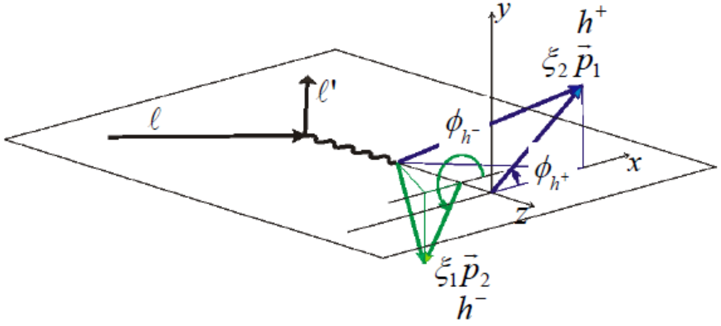


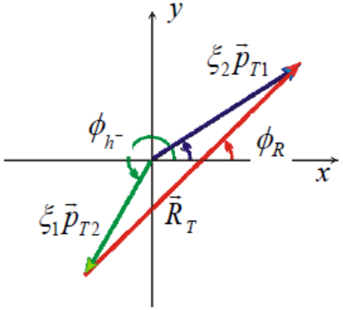


$\lambda\times$MC fit **Points -> Compass (proton)** **$\lambda\times$MC fit**

$a_P^{u\uparrow\to h^+h^-X} = \langle\sin(\phi_R+\phi_S-\pi)\rangle$ and $\vec{R} = \frac{z_2\vec{P}_{h1}-z_1\vec{P}_{h2}}{z_1+z_2}$ and as before $\lambda\sim\langle h_1^u/f_1^u\rangle\sim 0.055$

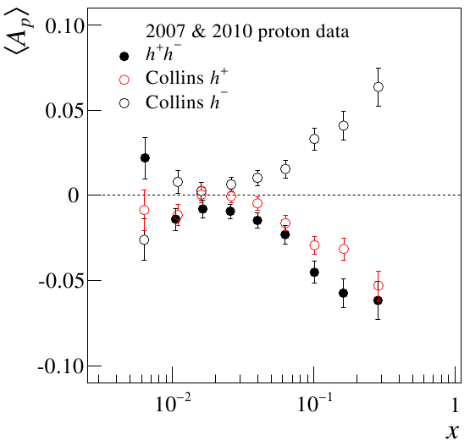
Hadron correlations

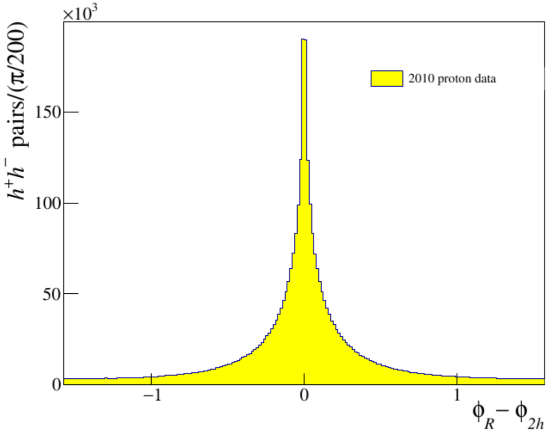


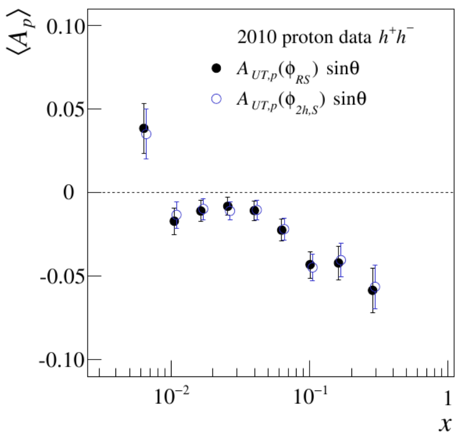


Interplay between Collins and IFF asymmetries

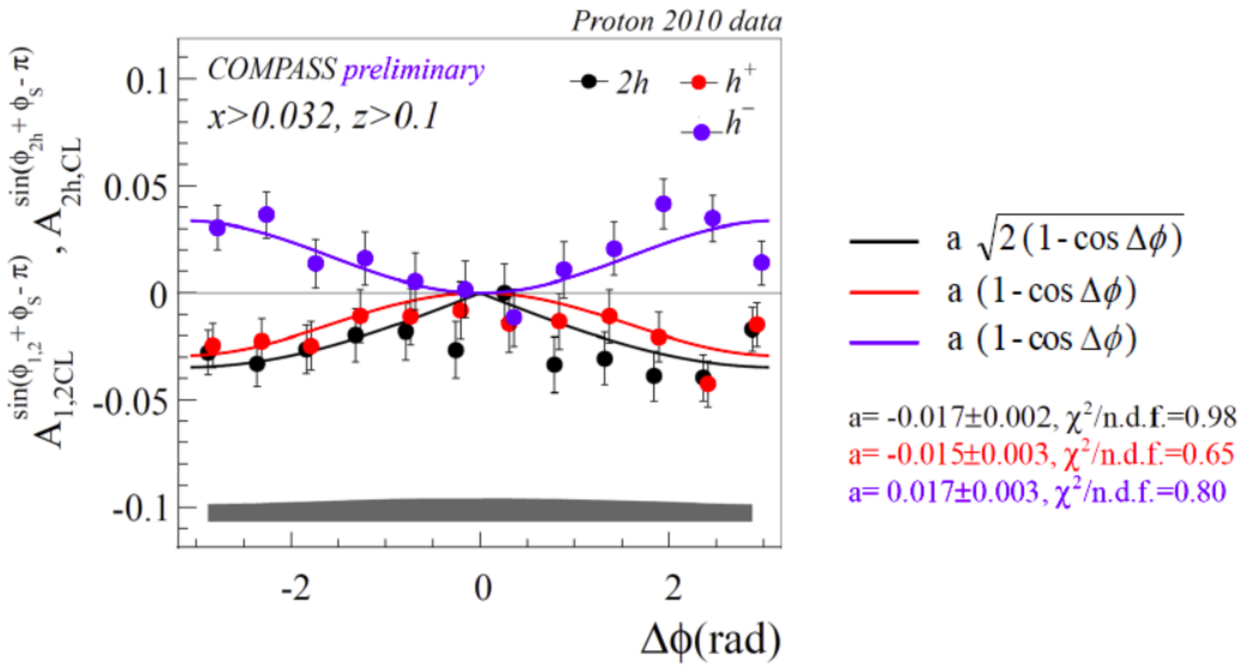
common hadron sample for Collins and 2h analysis







Asymmetries for $x > 0.032$ vs $\Delta\phi = \phi_{h^+} - \phi_{h^-}$



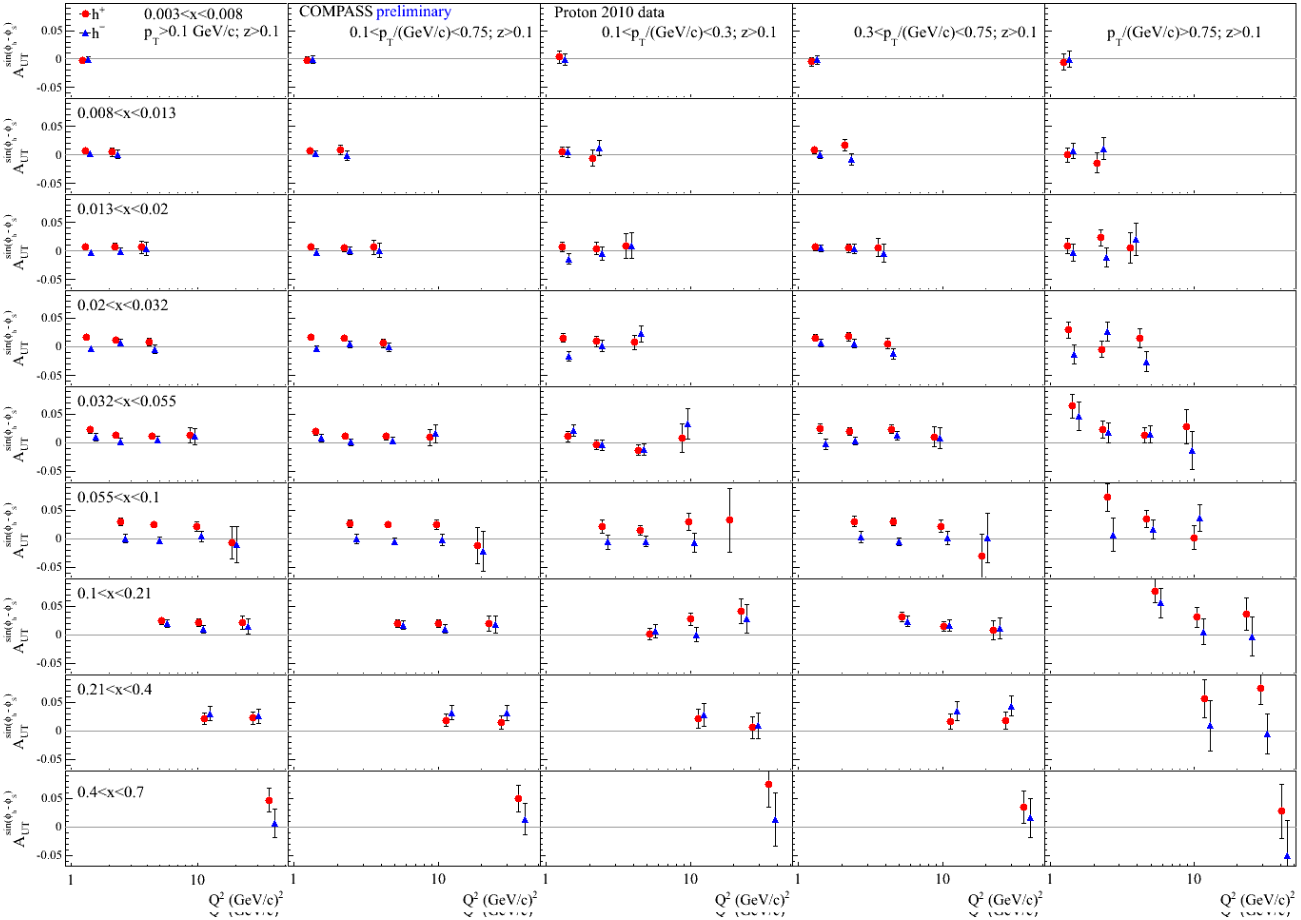
$$a = \frac{\sigma_{1C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)} = -\frac{\sigma_{2C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

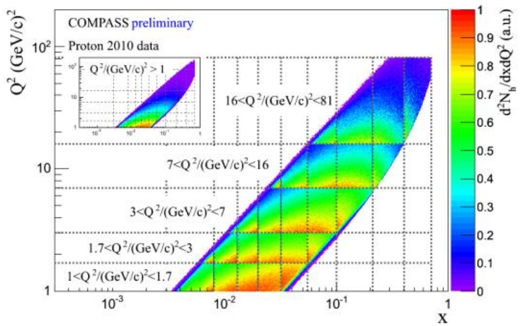
ratio of the integrals compatible with $4/\pi$

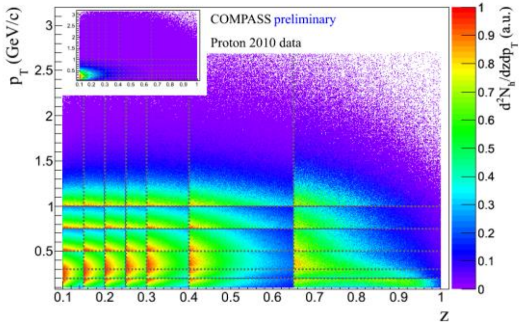
Hints for a common origin of 1h and 2h mechanisms

Sivers asymmetry on proton. Multidimensional

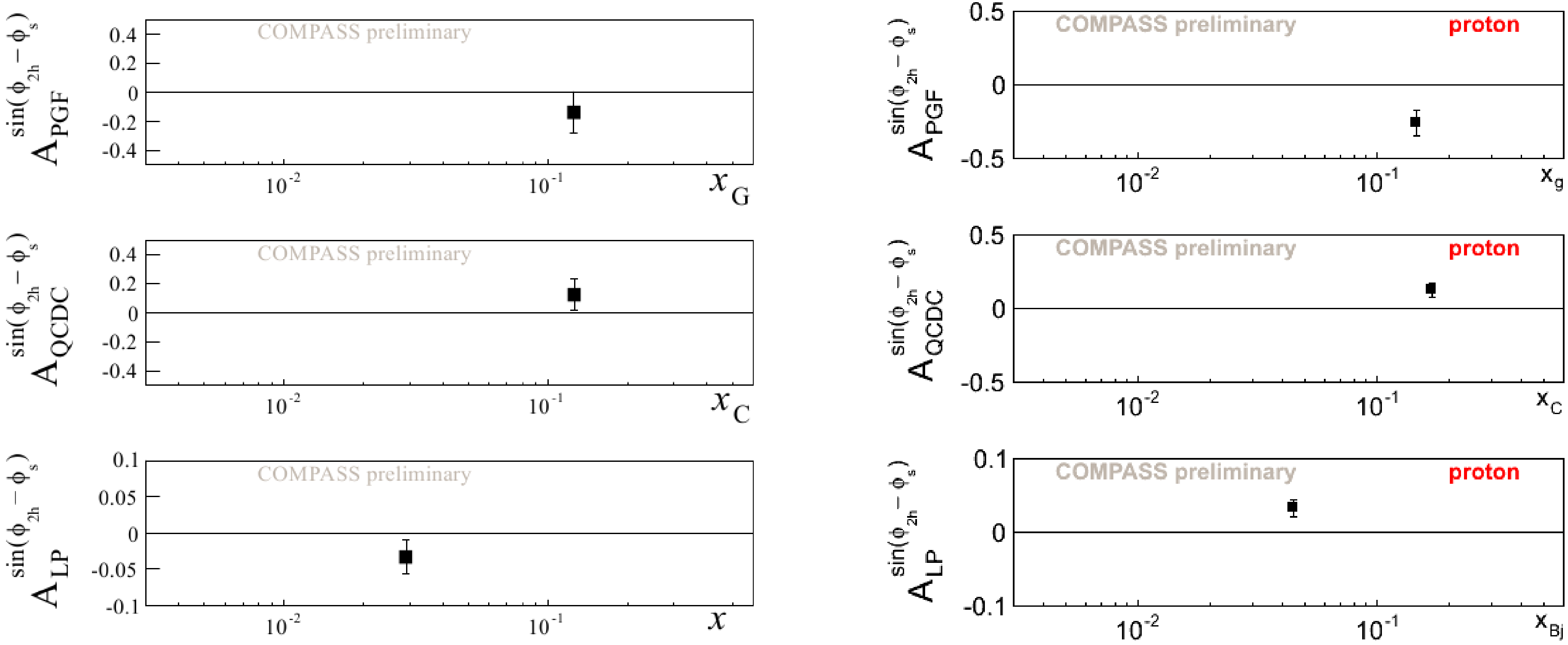
First ever extraction of TSAs within such a Multi-D $(x: Q^2: z: p_T)$ approach







Sivers asymmetry on deuteron and proton for Gluons



COMMENT ON TMD studies

- SIDIS has opened the way to this field more than 10 years ago:
  - Collins and DiHadron asymmetries on protons are sizeable
  - The Sivers asymmetry is also different from zero and we are now probing it's pseudo universality
  - The other TMDs are small, compatible to zero in most of the cases, at present precision
  - We measured sizeable $\cos\phi$ and $\cos 2\phi$ asymmetries but we don't really know yet if the Boer-Mulders TMD PDF is different from zero
  - The measurement of the azimuthal asymmetries on protons is one of the tasks of the analysis of the near future

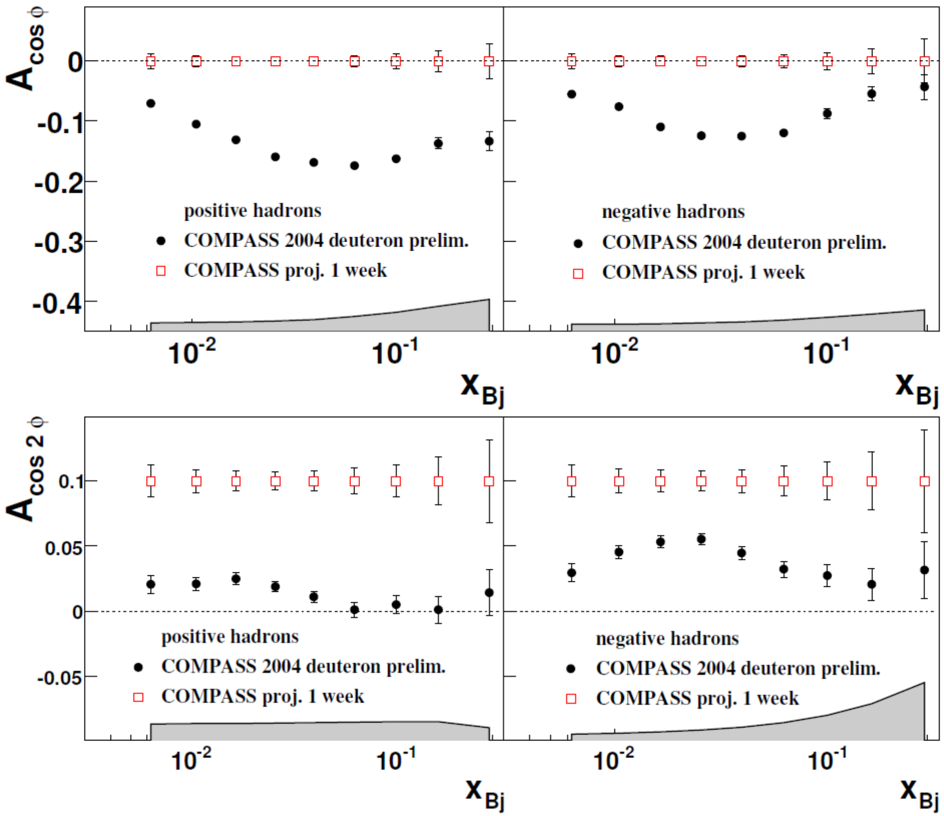
Future

- Let us start with what was sent in 2012 for the European Strategy group

Table 2: Summary of the different physics items for the far and near future. Already approved measurements are in bold.

	physics item	key aspects of the measurement
GPD	**H**	**RPD, Beam Charge and Spin Asymmetries**
	***t*-slope parameter** B	$\boldsymbol{d\sigma/dt}$
	E	transversely polarized proton target
SIDIS	**hadron multiplicities for** π **and** K	**PID and absolute acceptance**
	$\boldsymbol{h_{1,u}^{\perp}, h_{1,d}^{\perp}}$	**azimuthal modulations and PID**
	h_1^d with same accuracy as h_1^u	transversely polarized deuteron target
	$f_1^{\perp}$ evolution	100 GeV and transversely polarized proton target
DY	**sign change for** $f_1^{\perp}$ **and** $h_1^{\perp}$	**transversely polarized proton target**
	universality of TMD PDFs	higher statistics with transversely polarized proton target
	flavor separation	transversely polarized deuteron target
	test of the Lam-Tung relation	hydrogen target
	EMC effect in DY	different nuclear targets

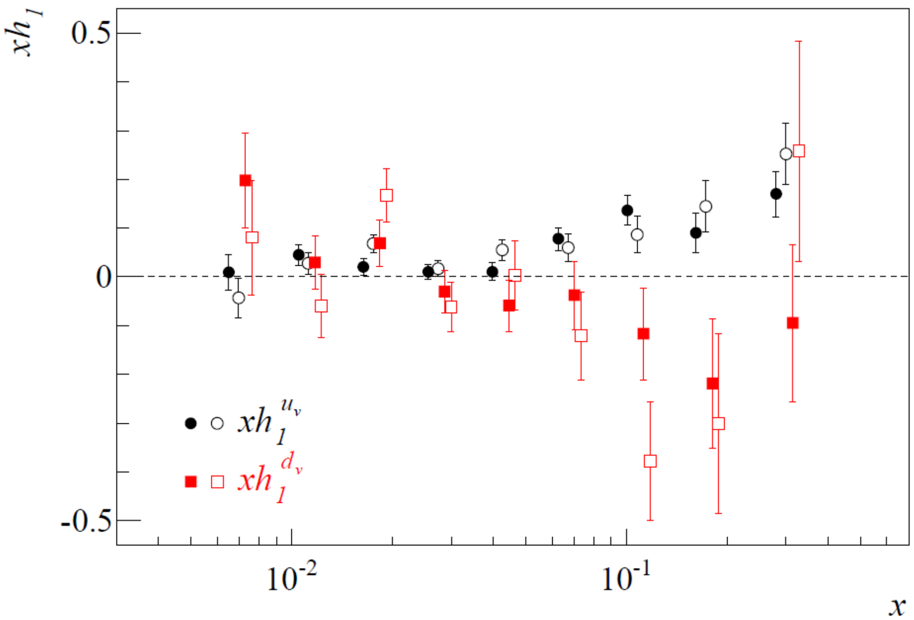
From 2016 and 2017 running with the LH_2 target



Moreover we will extract P_{hT} dependent hadron multiplicities on protons

- Poin-to-poiny extraction [Physical Review D 91, 014034 (2015)]
- Keep in mind that we are the only one to have measured TSA on deuteron

Open points/squares – from dihadron
Closed points/squares – from Collins

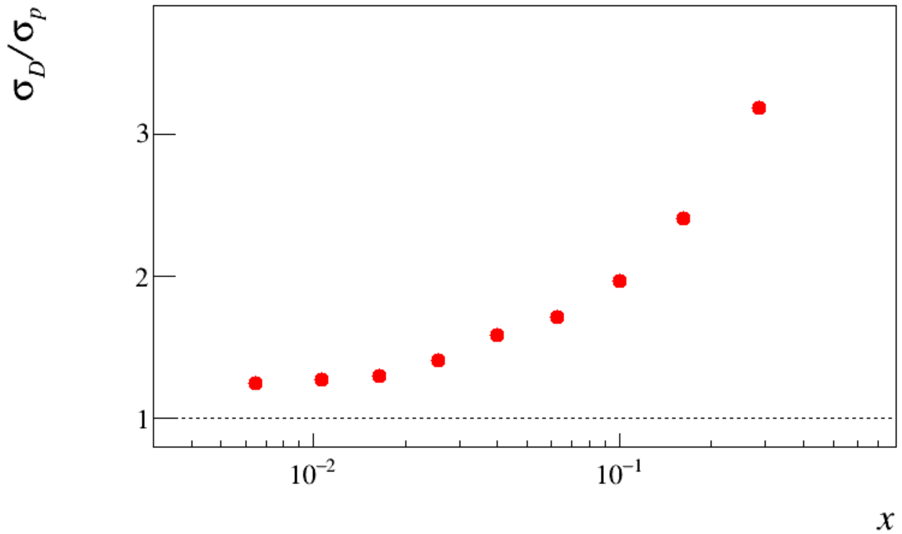


ERRORS ON h_1^d ARE A FACTOR 4 LARGER THAT THE ONES ON h_1^u

From ^{6}LiD (2002 – 2004) to NH_3(2007 – 2010)

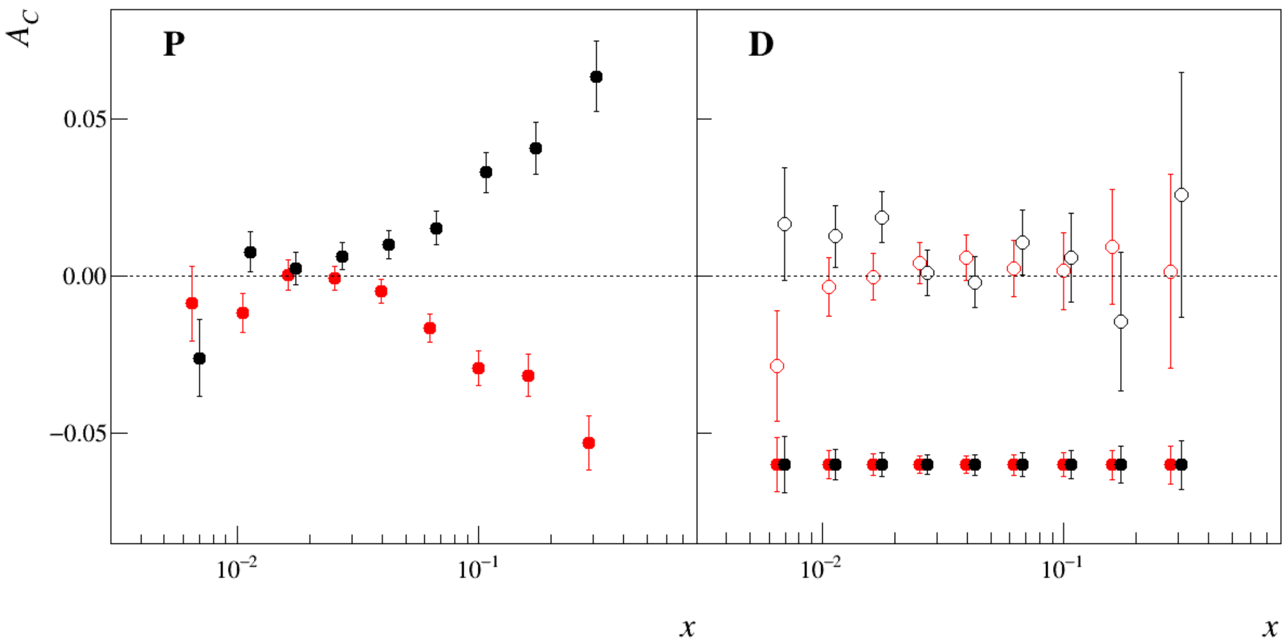
- We have done many progresses:
  - New 3 cells target / 1.3 gain due to larger diameter
  - New superconducting magnet / Factor 2.5 increase of acceptance at large x
  - New large x trigger with LAST / Factor 2 increase at large x
  - Statistics (partially lost given $\frac{f_p P_{pT}}{f_D P_{DT}} = 0.6$)

ALL IN ALL A TOTAL FACTOR OF >10



New deuteron data

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



From Collins asymmetries to transversity

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

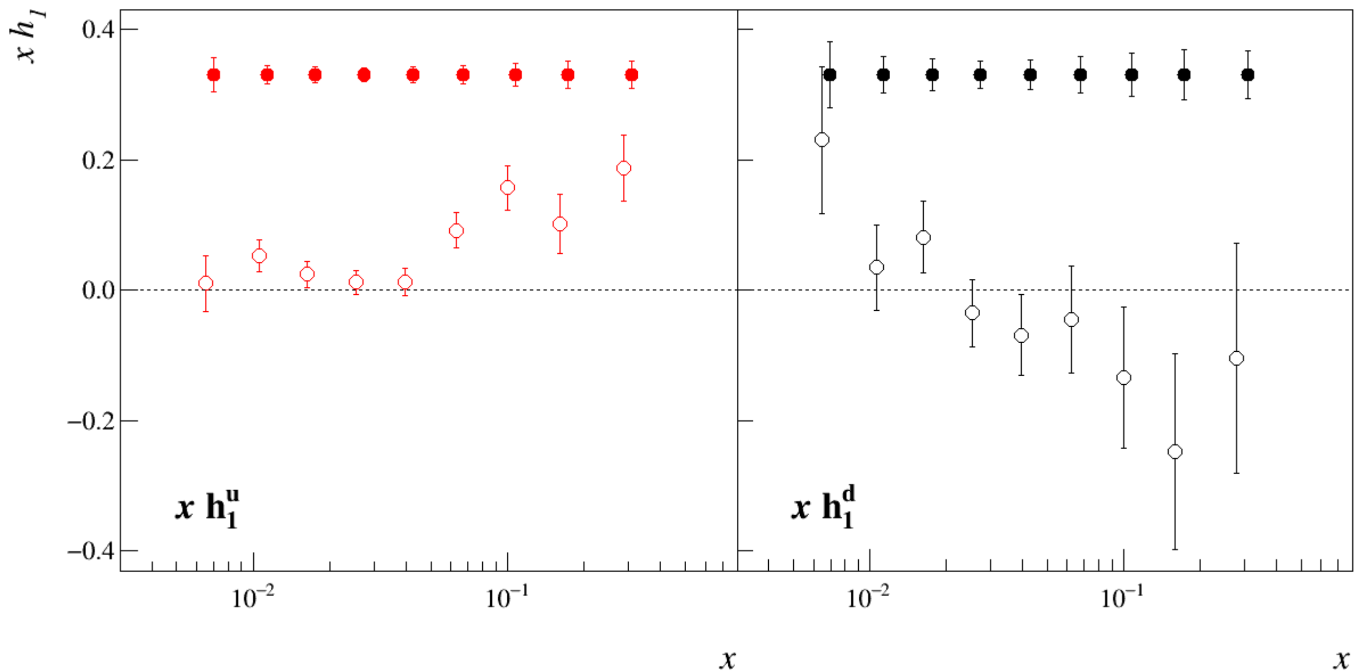
$$x h_1^u = \frac{1}{5} \frac{1}{\tilde{a}_P^h (1-\tilde{\alpha})} \left[\left(x f_p^+ A_p^+ - x f_p^- A_p^- \right) + \frac{1}{3} \left(x f_d^+ A_d^+ - x f_d^- A_d^- \right) \right]$$

$$x h_1^d = \frac{1}{5} \frac{1}{\tilde{a}_P^h (1-\tilde{\alpha})} \left[\frac{4}{3} \left(x f_d^+ A_d^+ - x f_d^- A_d^- \right) - \left(x f_p^+ A_p^+ - x f_p^- A_p^- \right) \right]$$

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

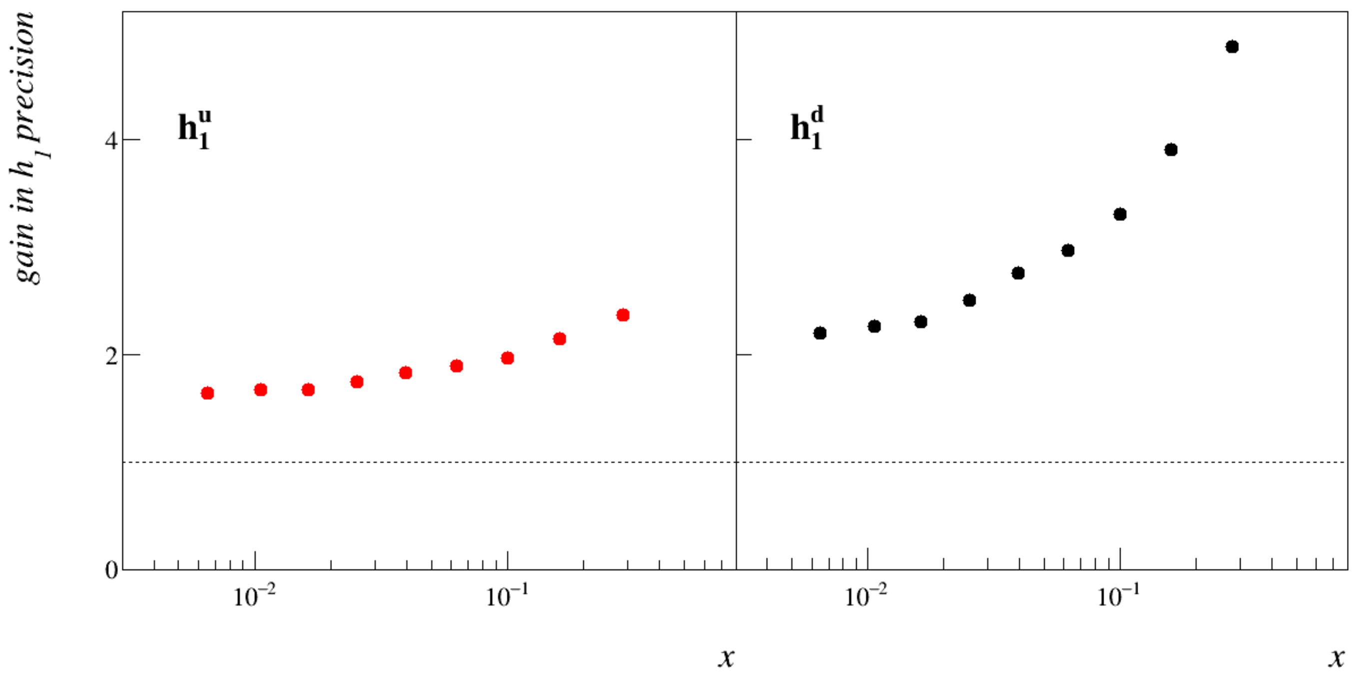
New deuteron data

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



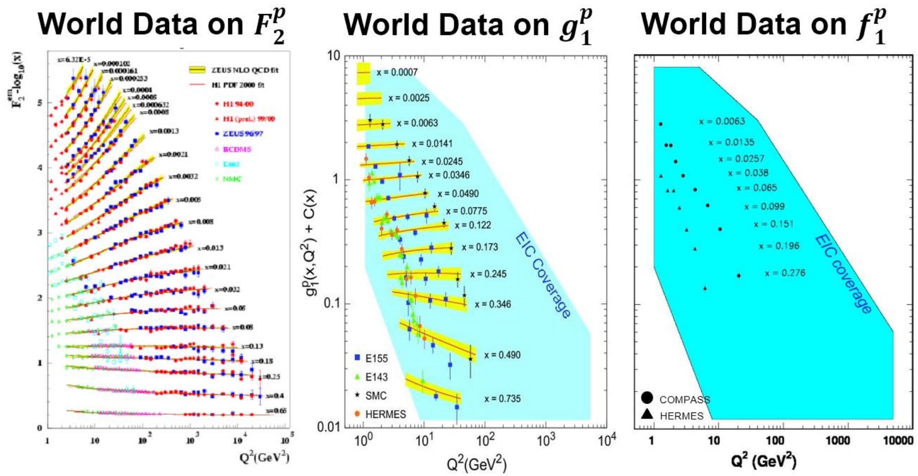
THIS IS A MEASUREMENT THAT WILL IMPACT OUR KNOWLEDGE, BEFORE THE START OF AN EIC

New deuteron data



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
- 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