INFN

The COMPASS program with the muon beam: past, present and future

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

The 11th Circum-Pan-Pacific Symposium on High Energy Spin Physics
27-30 August 2019, Miyazaki, Japan

Muon beam: SIDIS setup

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

two stages spectrometer

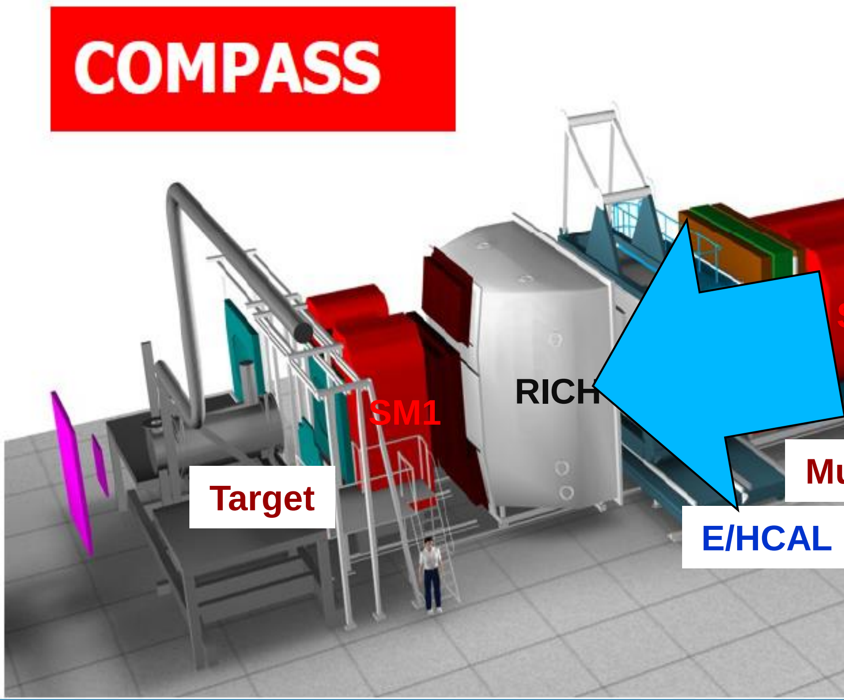
Large Angle Spectrometer (SM1)

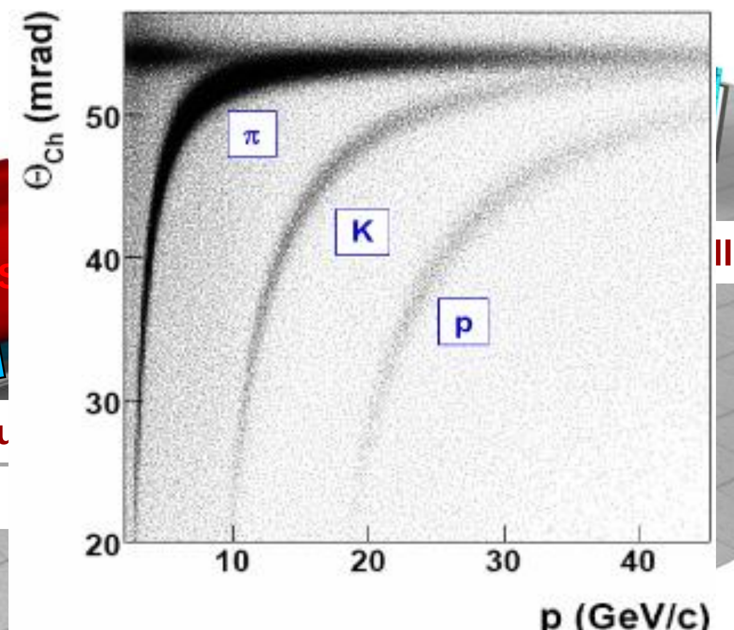
Small Angle Spectrometer (SM2)

radiator C_4F_{10}

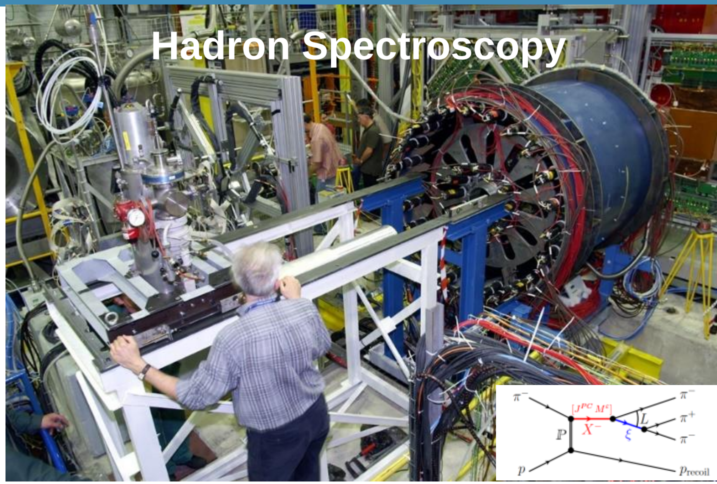
threshold: π ~2 GeV/c

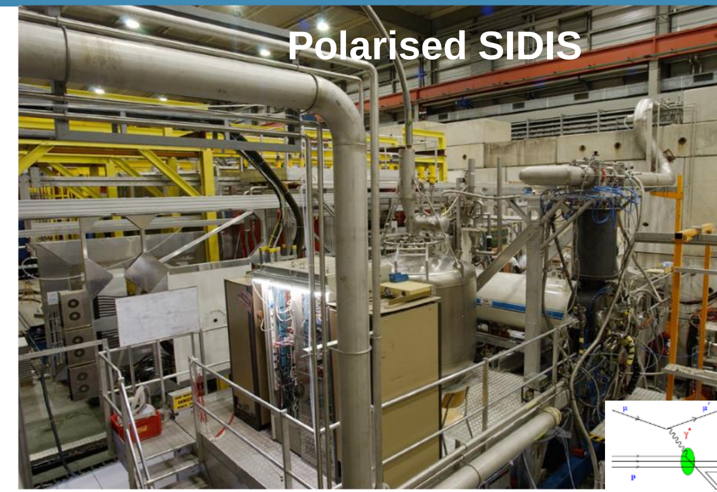
K ~ 10 GeV/c



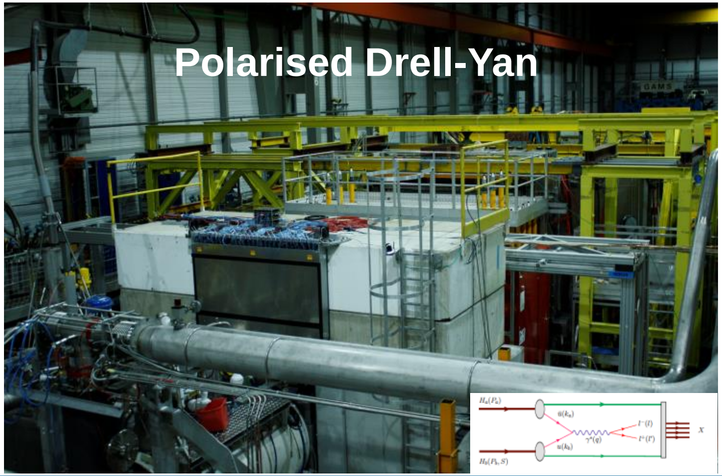


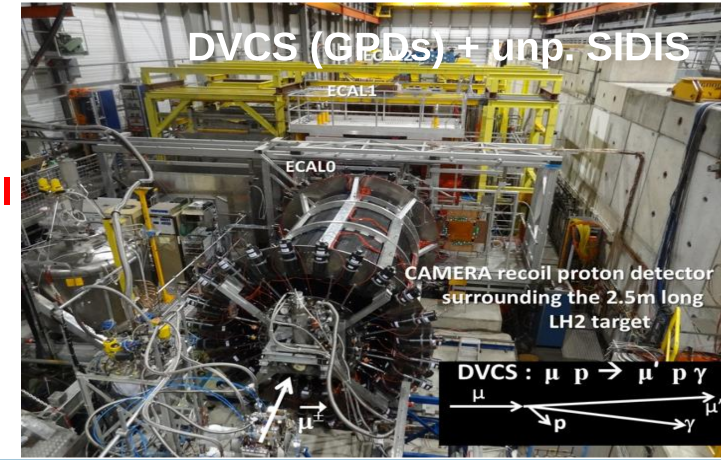
COMPASS target area





COMPASS-I
1997-2011



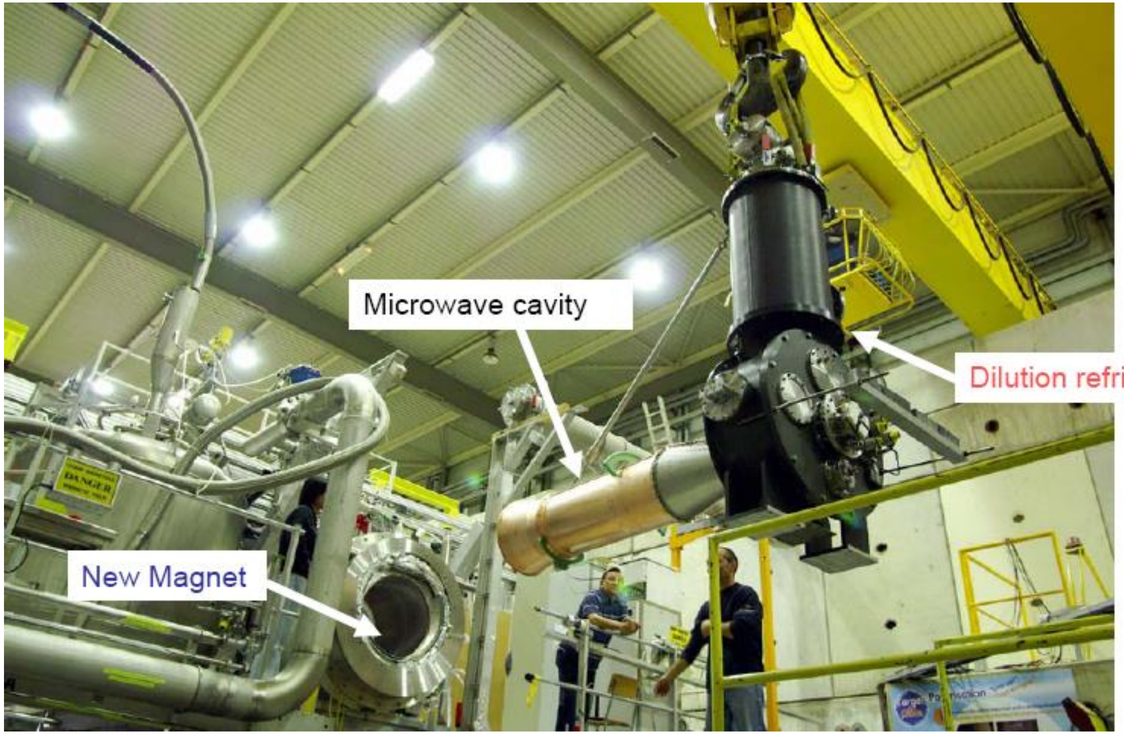


COMPASS-II
2012-2020

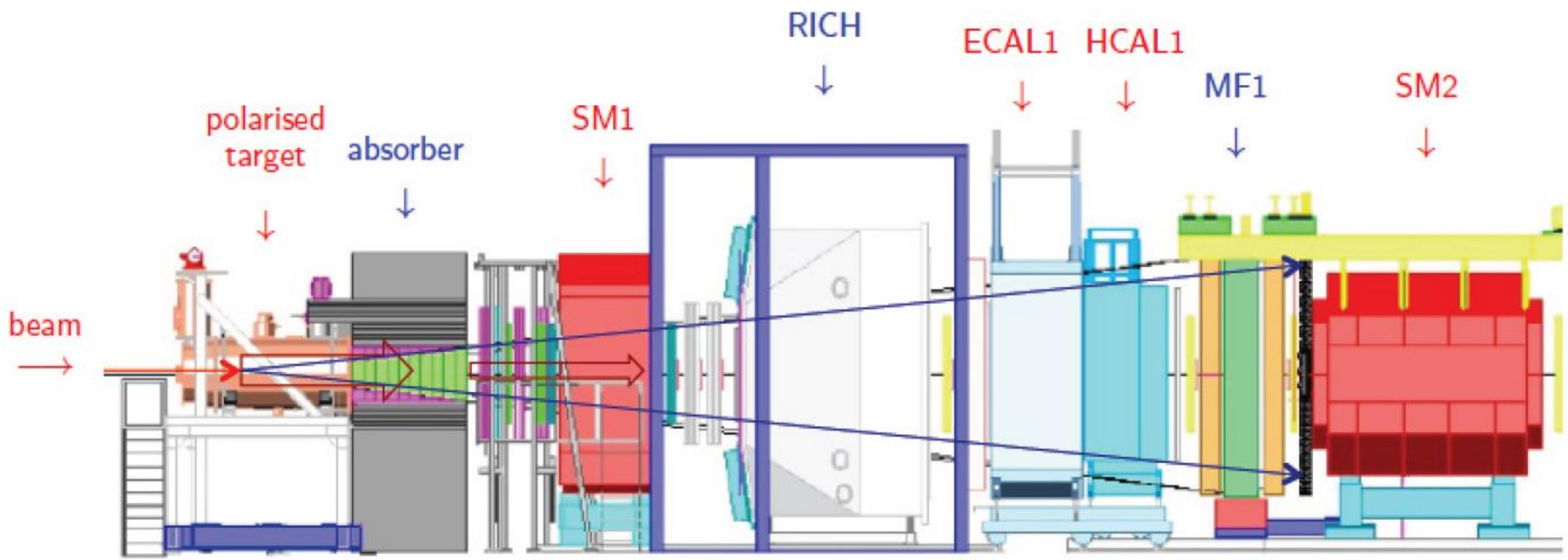
Operations on the target area

Targets

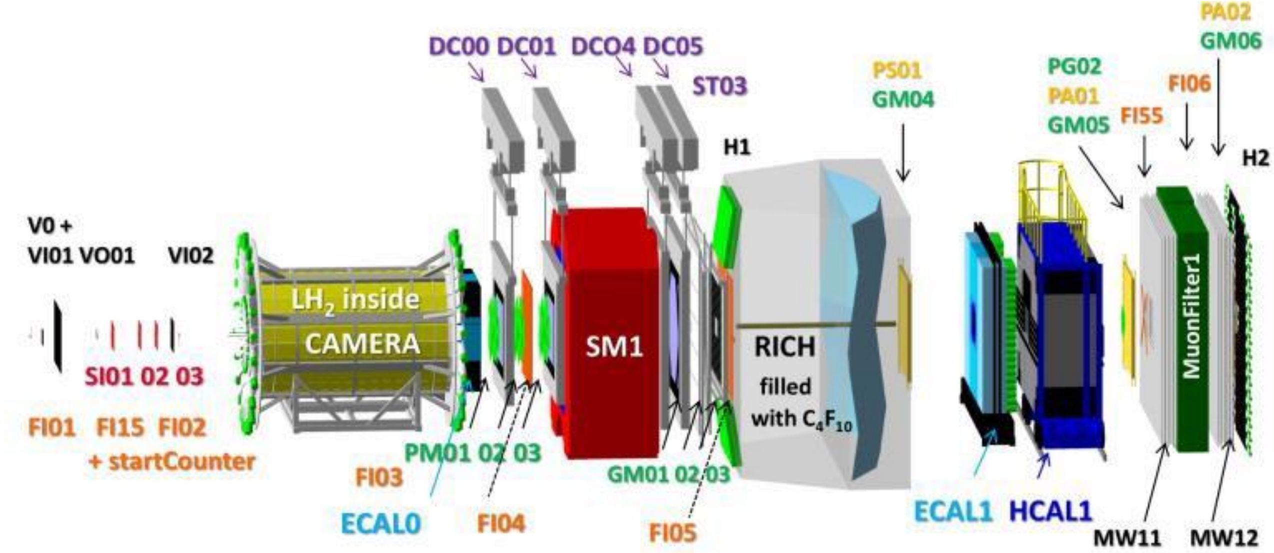

27 09 2012

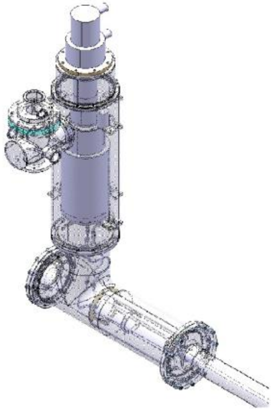

Microwave cavity
Dilution refrigerator
New Magnet

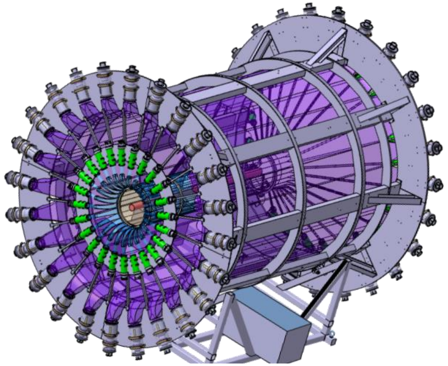
Hadron beam: Drell-Yan setup

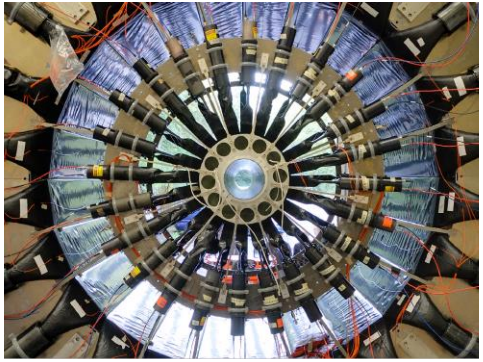


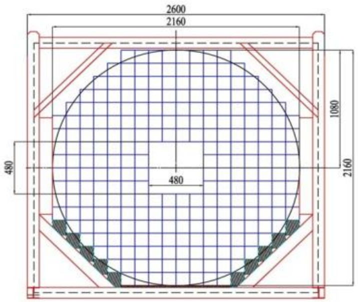
Muon beam – DVCS setup



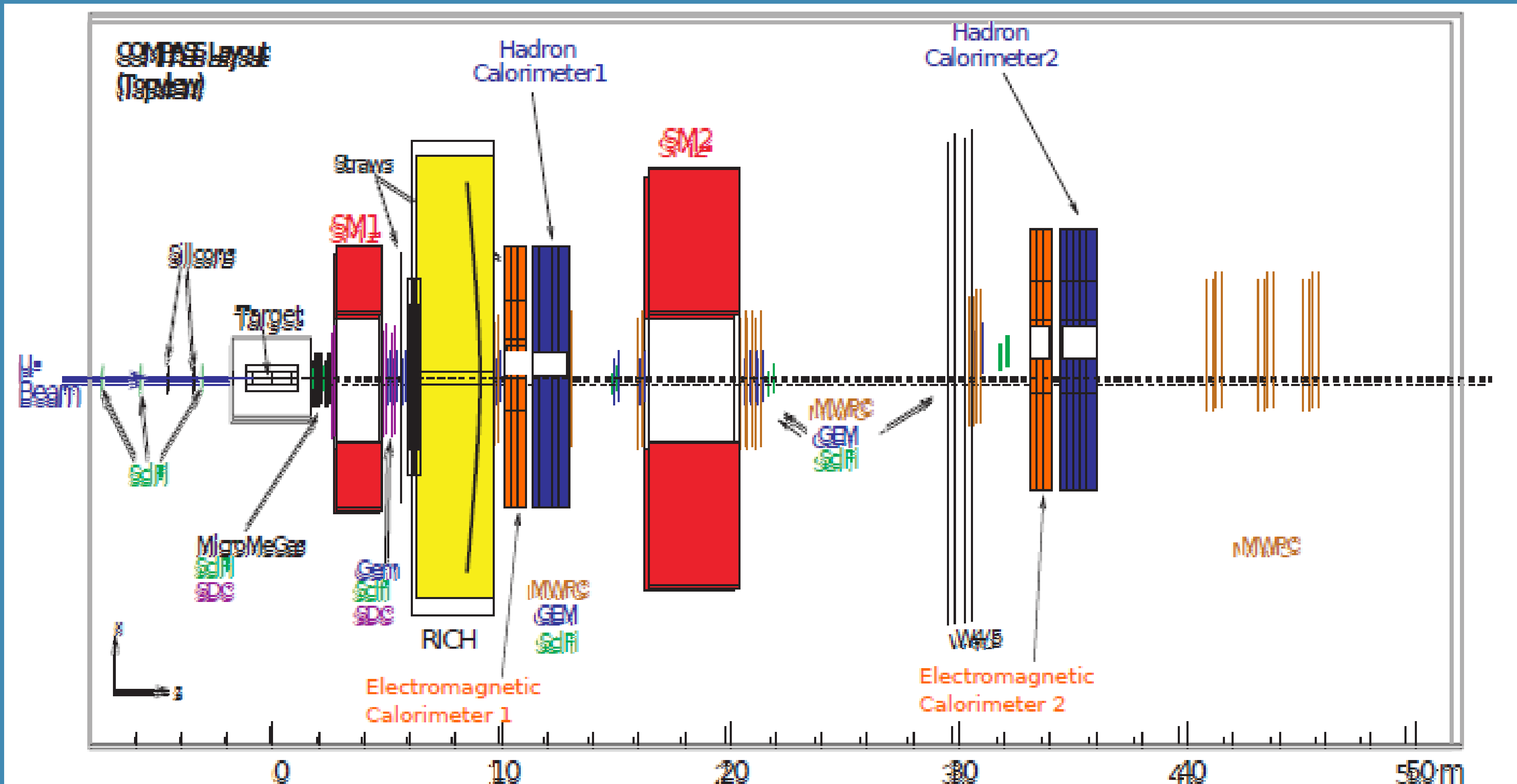




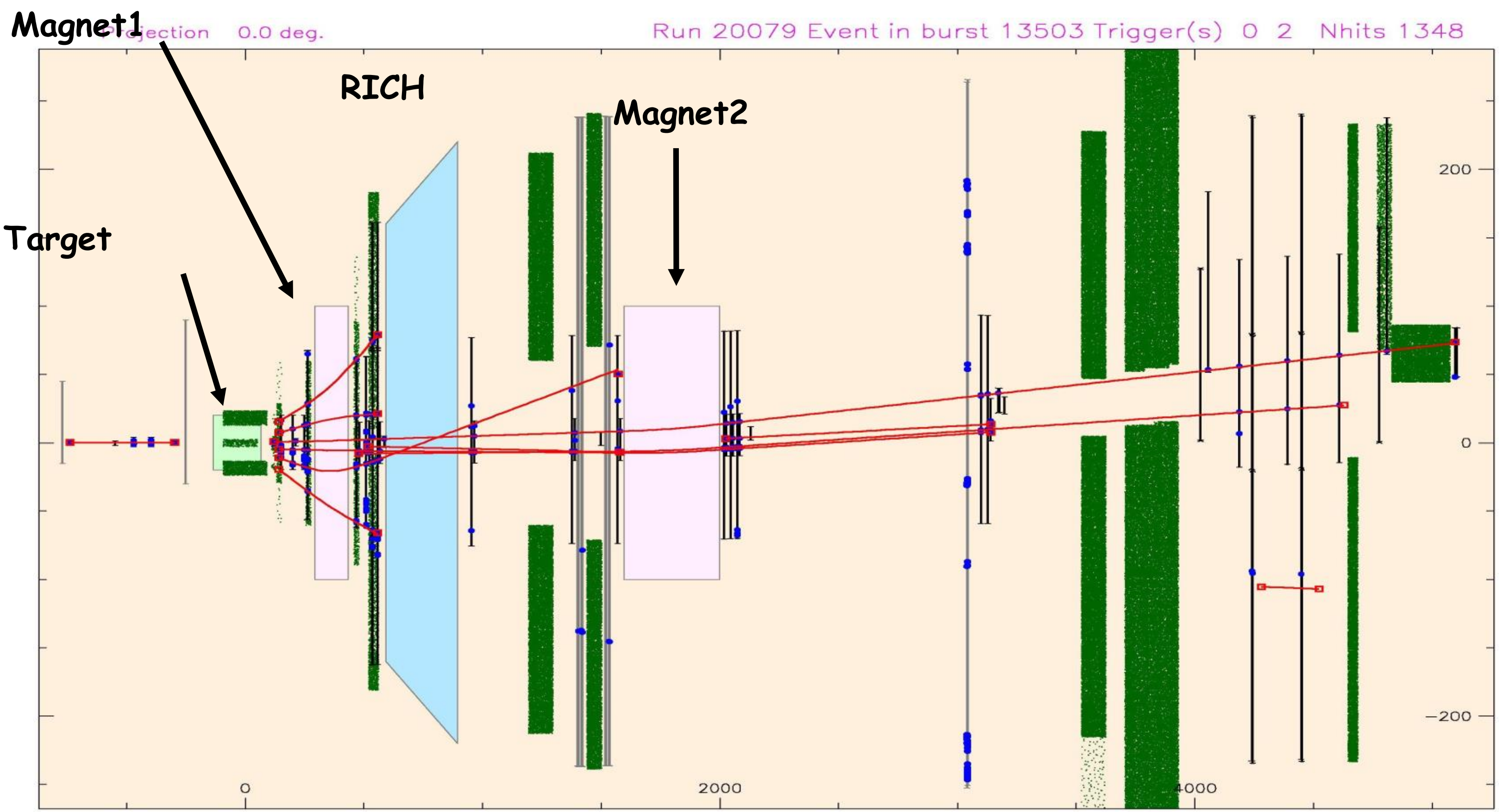




Spectrometer elements

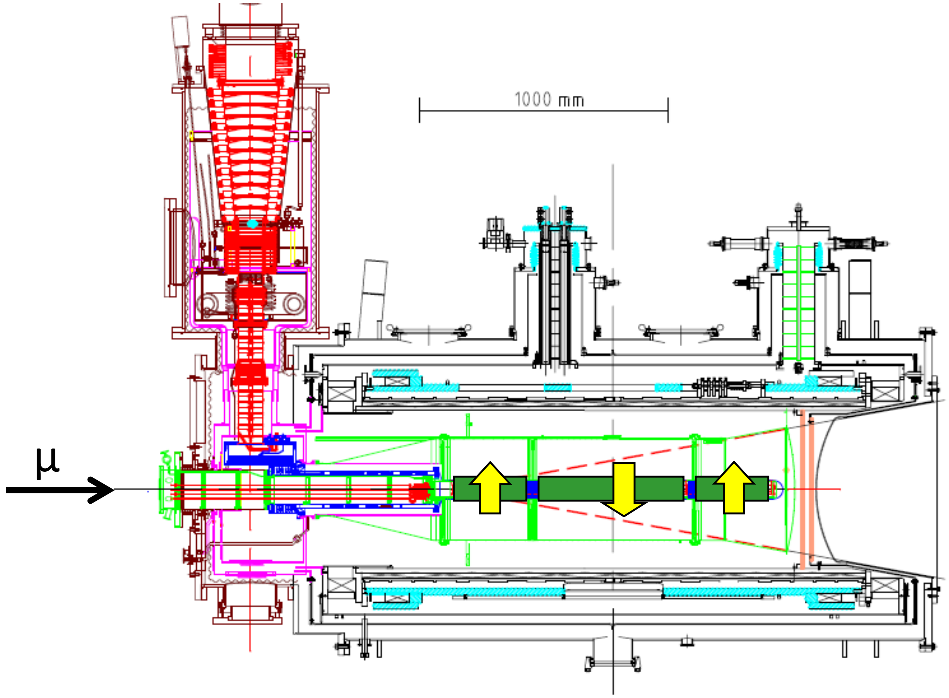


Spectrometer: momentum determination

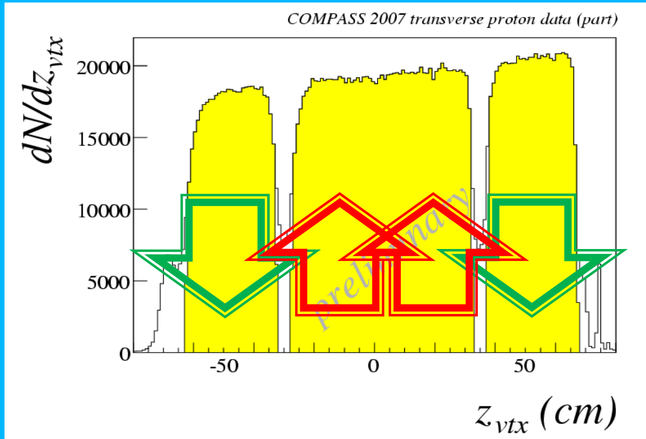


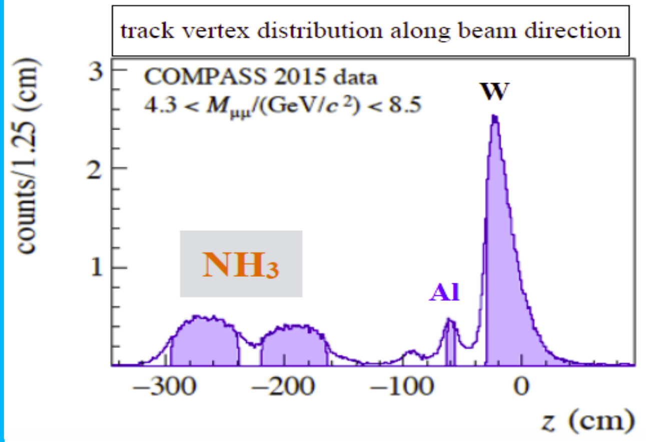
the polarized target system (>2005)

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

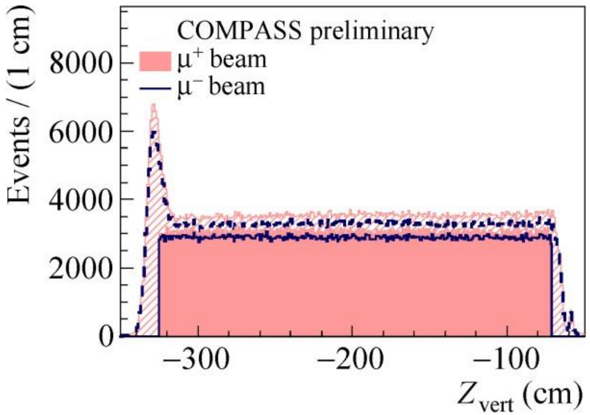


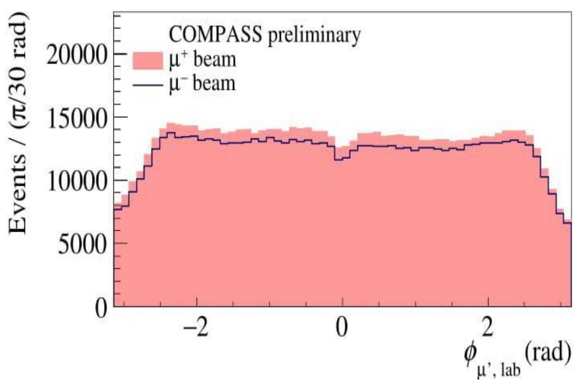
solenoid 2.5T
dipole magnet 0.6T

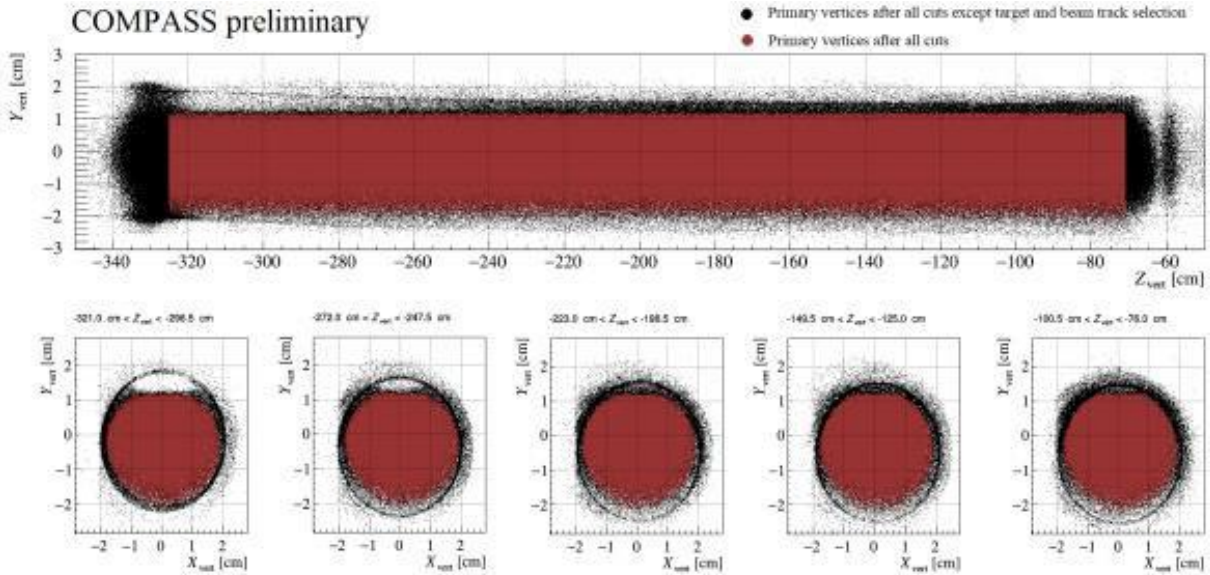


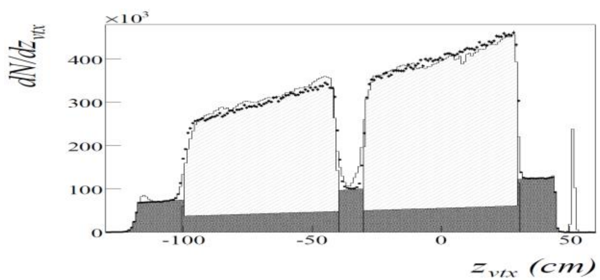


Vertex determination









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 DY run
muon beam	LH2 target	2016 2017	DVCS & unpol. SIDIS

Measurements with the target longitudinally polarized:

Year	Obs.	
2006	$A_{LL}^{2h}(Q^2 < 0)$	$\Delta g/g$
2007	$g_1^d(x)$,	$\Gamma_1^d, \Delta\Sigma$
2008	$A_{1,d}^{h^+ - h^-}$	$\Delta u_v + \Delta d_v$
2009	$A_{1,d}$, $A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}$	$\Delta u_v + \Delta d_v, \Delta\bar{u} + \Delta\bar{d}, \Delta s (= \Delta\bar{s})$
2010	$g_1^p(x)$,	$\Gamma_1^{NS}, \lvert g_A/g_V \rvert$
2010	$A_{1,d}$, $A_{1,d}^{\pi^\pm}, A_{1,d}^{K^\pm}, A_{1,p}$, $A_{1,p}^{\pi^\pm}, A_{1,p}^{K^\pm}$	$\Delta u, \Delta d, \Delta\bar{u}, \Delta\bar{d}, \Delta\bar{d}, \Delta s, \Delta\bar{s}$
2010	$\sin\phi$, $\sin 2\phi$, $\sin 3\phi$, $\cos\phi$ asyms	h_L, $f_L^\perp$, h_1, $f_{1T}^\perp$, $h_{1L}^\perp$, $h_{1T}^\perp$, $h_{1L}^\perp$, $g_L^\perp$, g_{1T}
2013	A_{LL}^{2h}	$\Delta g/g$
2013	$A_D^{\gamma N}$	$\Delta g/g$ in LO and NLO
2015	$g_1^p(x)$	$\Gamma_1^{NS}, \Delta\Sigma, \Delta u + \Delta\bar{u} \cdots$
2015	A_{LL}^p	NLO QCD fits for $\Delta g/g$
2016	$A_{UL}^{\sin\phi_h}, A_{UL}^{\sin 2\phi_h}, A_{UL}^{\cos\phi_h}$ ...	TSA on L polarized NH_3 target

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	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	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	$A^{\pi^\pm, K^\pm, K^0_S}_{Siv,d}, A^{\pi^\pm, K^\pm, K^0_S}_{Col,d}$	Full NH_3 statistics
2015	Interplay $A^{sin\phi_{RS}}_{UT,p}$ vs $A^h_{Col,p}$	Full NH_3 statistics

Measurements with the target transversely polarized :

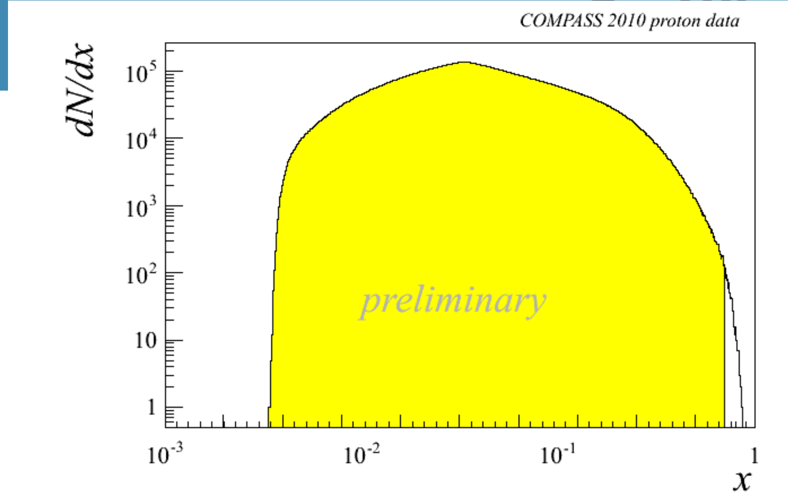
Year	Obs	
2016	P_{hT}-weighted $A^{h}_{Siv,p}$	2010 NH_3 data
2016	$A^{g}_{Siv,p}, A^{g}_{Col,p}$	2010 NH_3 data, gluon Sivers
2017	$P_{\Lambda}(x, z)$	Transversely transmitted Λ 2010 NH_3

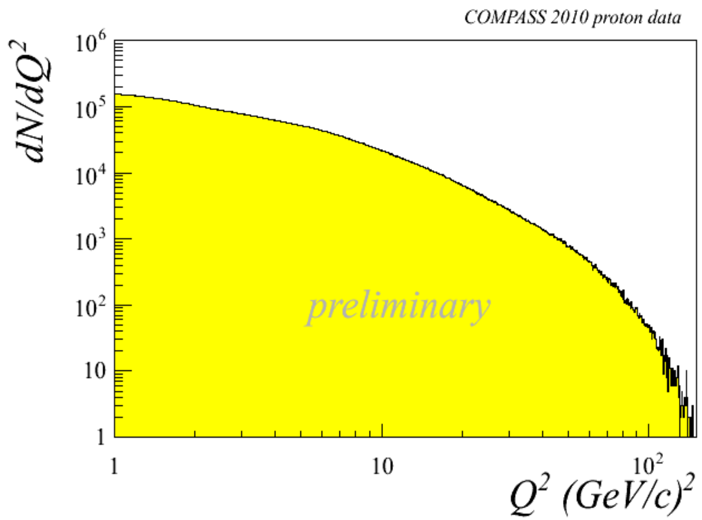
Measurements with unpolarised targets:

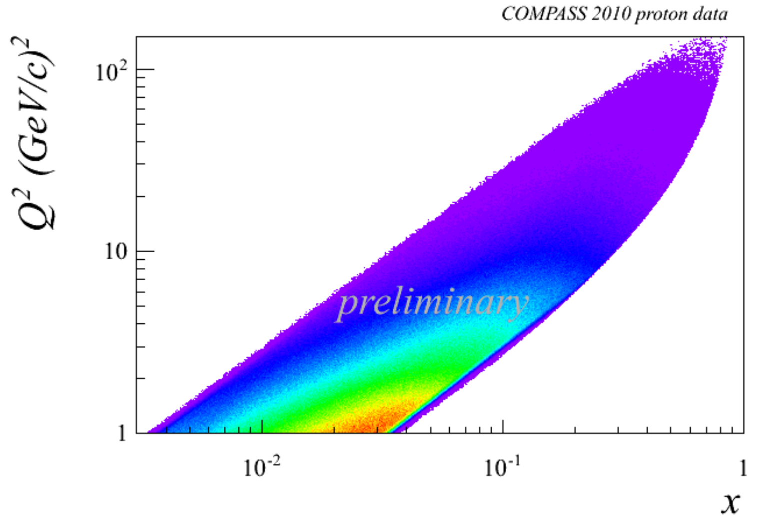
Year	Obs	
2013	$dn^h/(dN^\mu dz\, dp_T^2)$	multiplicities on d, 2004
2014	$A_{UU,d}^{\cos\phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin\phi_h}$	2004, part
2016	$dn^\pi/(dN^\mu dz)$	multiplicities on d, 2006
2016	$dn^h/(dN^\mu dz\, dp_T^2)$	multiplicities on d, 2006
2016	$dn^K/(dN^\mu dz)$	multiplicities on d, 2006
2017	$[dn^{K^+}/(dN^\mu dz)]/[dn^{K^-}/(dN^\mu dz)]$	Multiplicity ratios for k on d, 2006
2018	SDME modulation for ω	Liquid H_2, 2012 data
2018	$A_{UU,d}^{\cos\phi_h}, A_{UU,d}^{\cos 2\phi_h}, A_{LU,d}^{\sin\phi_h}$	Liquid H_2, 2016 data, part
2019	$dn^{\pi,K,p}/(dN^\mu dz)$	multiplicities on p, 2016
2019	$dn^h/(dN^\mu dz\, dp_T^2)$	p_T^2-dep multiplicities on p, 2016

Kinematic distributions

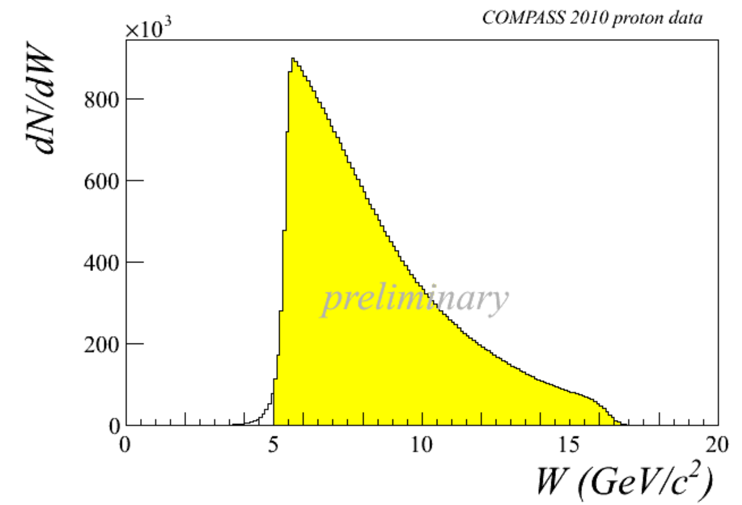
DIS cuts: $Q^2 > 1\ (GeV/c)^2$
$0.1 < y < 0.9$
$W > 5\ GeV/c^2$





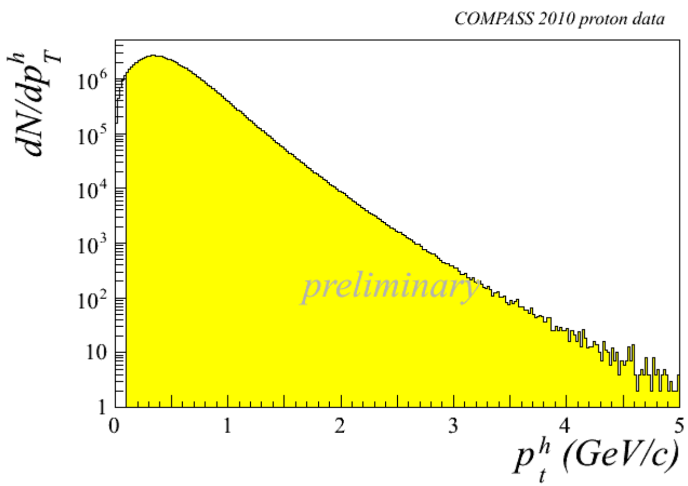


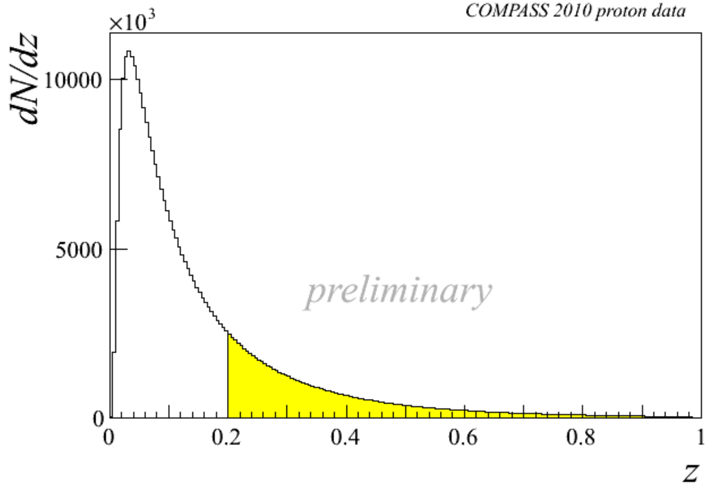
Kinematic distributions - 2



DIS cuts: $Q^2 > 1\ (\mathrm{GeV}/c)^2$
$0.1 < y < 0.9$
$W > 5\ \mathrm{GeV}/c^2$

hadron selection: $P_{hT} > 0.1$ GeV/c,
$z > 0.2$



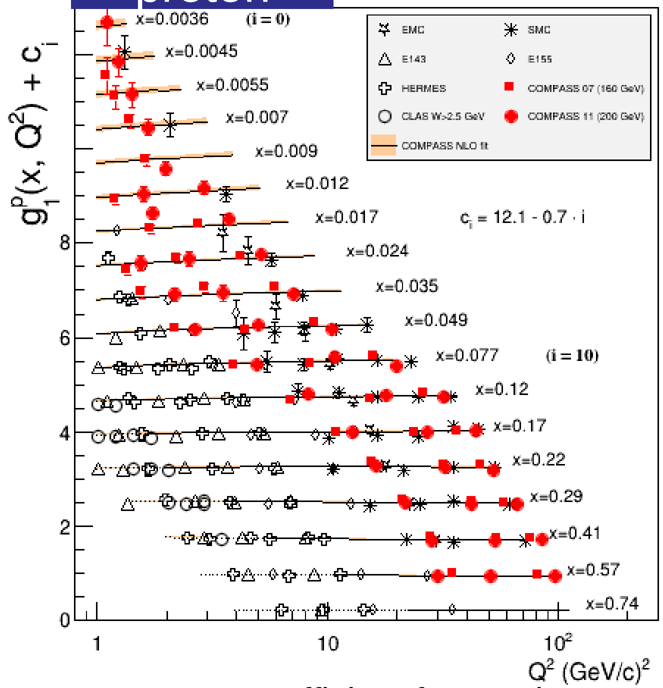


QCD fits- World data on g_1^p and g_1^d

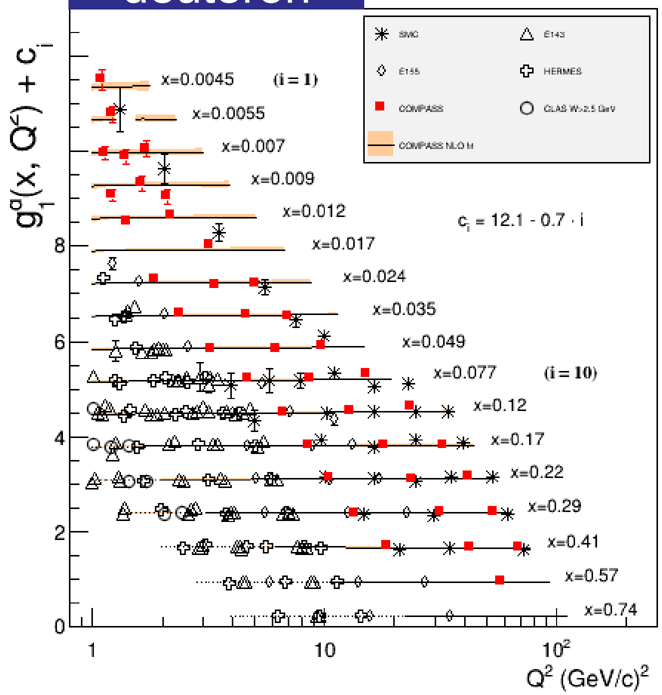
→ $g_1(x,Q^2)$ as input to global QCD fits
for extraction of $\Delta q_f(x)$ and $\Delta g(x)$

$$\frac{dg_1}{d\ln Q^2} \propto -\Delta g(x,Q^2)$$

proton



deuteron

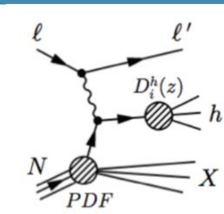


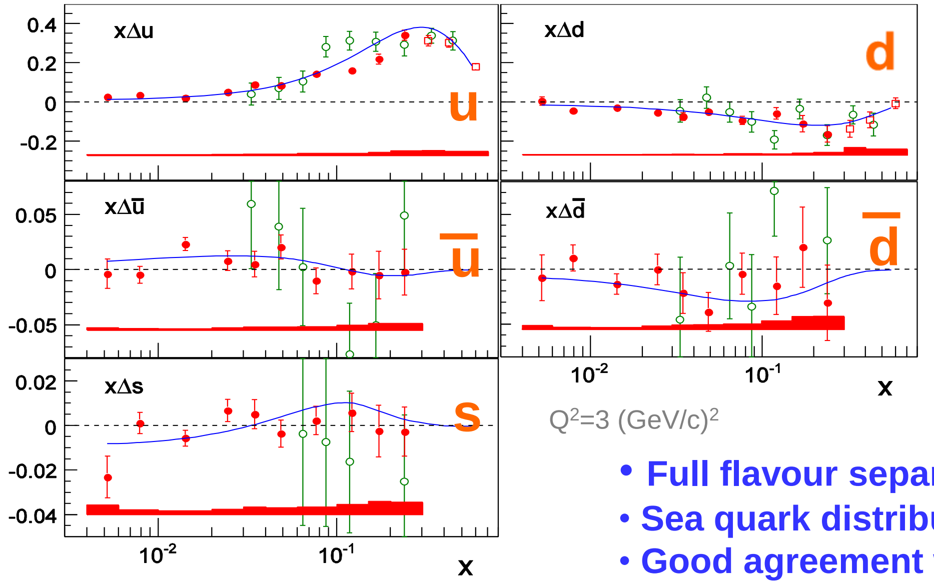
x and Q^2 coverage not yet sufficient for precise Δg
Can be improved by constraining from pp data (as DSSV, NNPDF…)

PLB753 (2016) 18

Quark helicities from semi-inclusive DIS

Leading order extraction of quark helicities from spin asymmetries:





- **COMPASS**
  PLB693(2010)227, using DSS FFs
- o **HERMES**
  PRD71(2005)012003
- ___ DSSV at NLO

$$\vec{l}\,\vec{p} \rightarrow l\, h^{\pm} X$$

- **Full flavour separation → x~0.004**
- **Sea quark distributions ~ zero**
- **Good agreement with global fits**

What about Δs? Integral is found negative from ***inclusive*** data, when imposing SU3 while here from ***semi-inclusive*** data, $x > \sim 0.005$ Δs is compatible with zero.

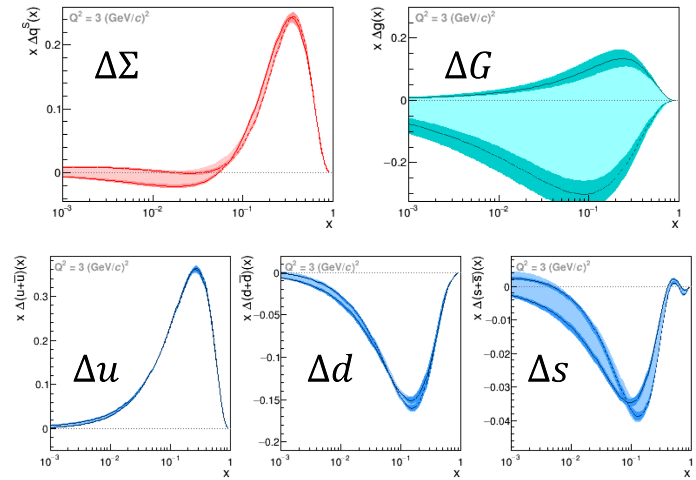
NB: - The extraction assumes quark Fragmentation Functions known (DSS here)
- No measurement at lower x

A NLO pQCD fit to g_1 DIS world data

- Assumes functional forms for $\Delta\Sigma$, ΔG and Δq^{NS} and SU3 symmetry
- Use DGLAP equations.
- Fit g_1^p, g_1^d, g_1^n DIS world data

→ Quark spin contribution :

$\Delta\Sigma = 0.31 \pm 0.05$ at $Q^2 = 3\ (\mathrm{GeV}/c)^2$



$0.82 \le \Delta U \le 0.85$ $-0.45 \le \Delta D \le -0.42$ $-0.11 \le \Delta S \le -0.08$

Uncertainties are dominated by the bad knowledge of the functional forms.

→ Gluon spin contribution: ΔG not well constrained, even the sign, using DIS only

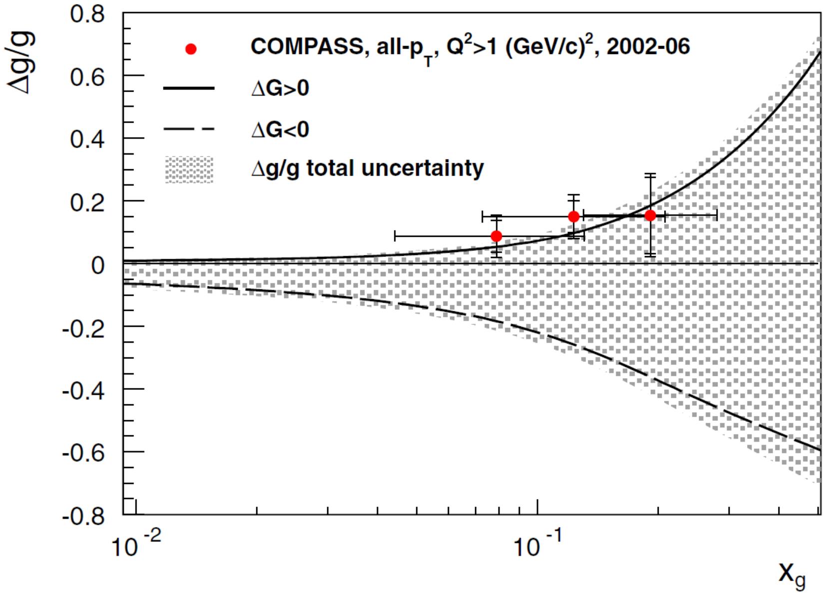
Solution with ΔG>0 agrees with result from DSSV++ using RHIC pp data

PLB 753 (2016) 18

Gluon helicity $\Delta g/g$ from SIDIS

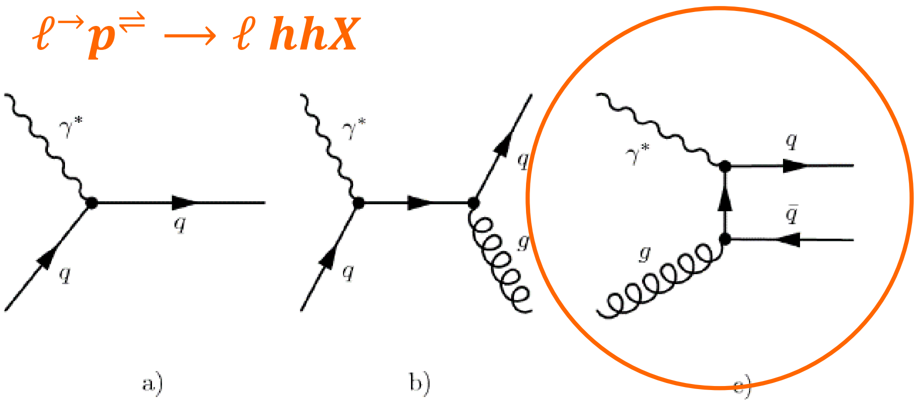
Extraction at LO:

$$\Delta G/G\ (x = 0.1) = 0.11 \pm 0.04 \pm 0.04$$



EPJC 77 (2017) 209

$\ell^{\rightarrow} p^{\rightleftarrows} \longrightarrow \ell\, hhX$



Photon Gluon Fusion

Summary on nucleon SPIN

$$\frac{1}{2} = \frac{1}{2}(\Delta u_v + \Delta u_v + \Delta q_s) + \Delta G + L_q + L_g$$

Quarks $\frac{1}{2}\Delta\Sigma \sim 0.15$ from g_1 measurements and global analysis at NLO. Largest uncertainty on $\Delta\Sigma$ due to uncertainty on ΔG

Gluons $\Delta G \sim 0.2$ integrated between $0.05 < x < 0.2$: precise result from RHIC. ΔG/G positive at $x \sim 0.1$ (from data of γg fusion process, at LO). Low-x contribution to integral still unknown. Not enough constrain from g_1 global analysis at NLO.

Orbital momenta: $L_q + L_q = ?$ Ongoing studies of GPDs.

Promising results from lattice QCD calculations:

→ The main question raised in 'Nucleon spin crisis' is resolved:

- Quark spin represents a non zero fraction (0.3) of nucleon spin **(measurements and lattice QCD calculations)**
- The hypothesis of very large ΔG (2 to 3, associated to $L \sim -2 \div -3$) rejected

→ Puzzle still pending: share between ΔG and L

The spin content of the proton: where we stand

Gluons PDF are accessed using DGLAP! Equations

$$\frac{d}{dt}\Delta\Sigma(x,t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{qq}^S\left(\frac{x}{y},\alpha_s(t)\right)\Delta\Sigma(y,t) + 2n_f P_{qg}\left(\frac{x}{y},\alpha_s(t)\right)\Delta g(y,t)\right]$$

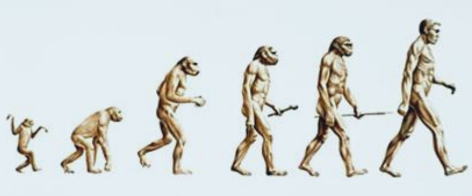
$$\frac{d}{dt}\Delta g(x,t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y}\left[P_{gq}\left(\frac{x}{y},\alpha_s(t)\right)\Delta\Sigma(y,t) + P_{gg}\left(\frac{x}{y},\alpha_s(t)\right)\Delta g(y,t)\right]$$

$$\frac{d}{dt}\Delta q_{NS}(x,t) = \frac{\alpha_s(t)}{2\pi}\int_x^1 \frac{dy}{y} P_{qq}^{NS}\left(\frac{x}{y},\alpha_s(t)\right)\Delta q_{NS}(x,t)$$

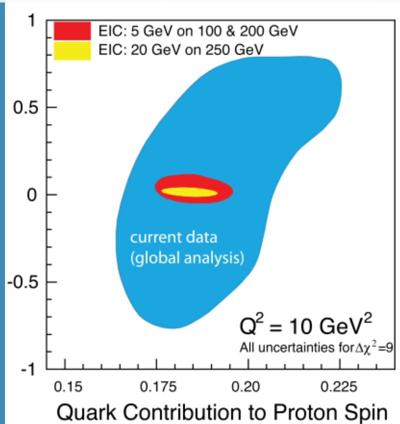
With $t = \ln Q^2/\Lambda^2$, $\Delta\Sigma(x,t) = \sum_{i=1}^{n_f}\Delta q_i$ and $\Delta q_{NS}(x,t) = \sum_{i=1}^{n_f}(e_i^2/\langle e^2\rangle - 1)\Delta q_i$,

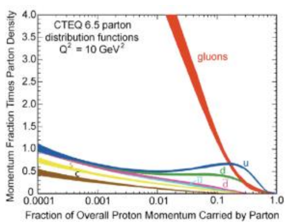
where $\langle e^2\rangle = \frac{1}{n_f}\sum_{i=1}^{n_f} e_i^2$

A very powerful tool access Δg, but limited by the present experimentally available phase space

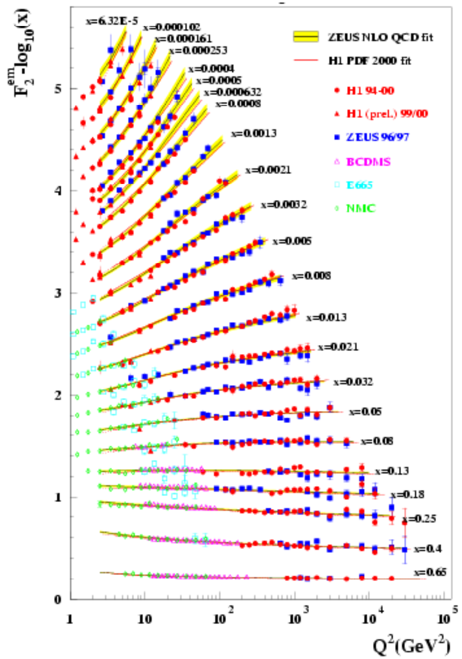


To answer to this we need and EIC



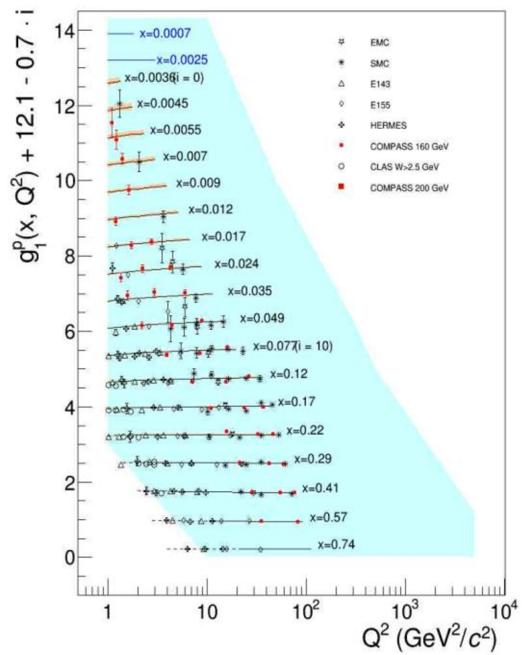


World Data on F_2^p



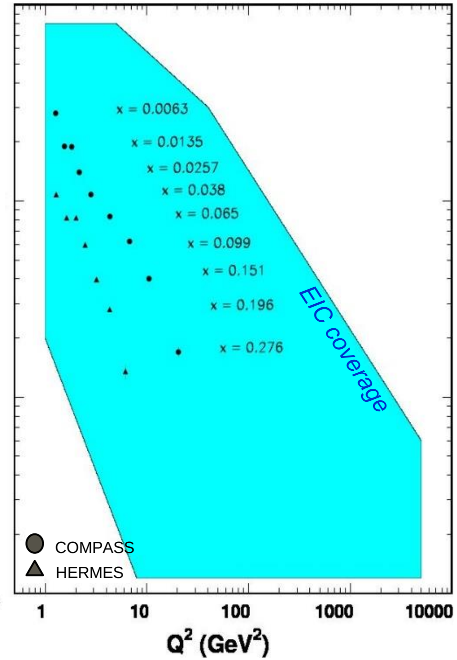
momentum

World Data on g_1^p



spin

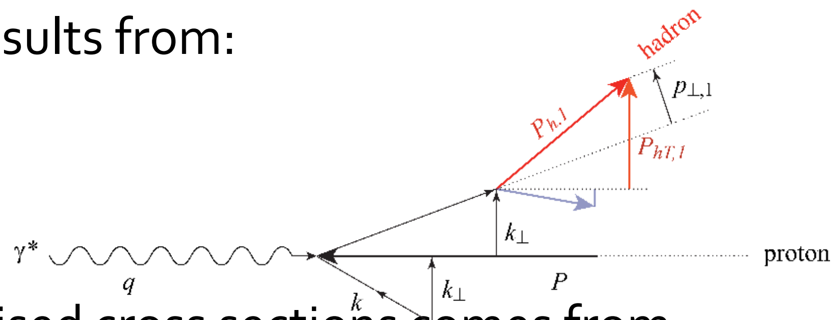
World Data on h_1^p



transverse spin ~ angular momentum

Importance of unpolarized SIDIS

- The cross section dependence from P_{hT} results from:
  - intrinsic $k_\perp$ of the quarks
  - $p_\perp$ generated in the quark fragmentation



- The azimuthal modulations in the unpolarised cross sections comes from:
  - Intrinsic $k_\perp$ of the quarks
  - The Boer-Mulders PDF

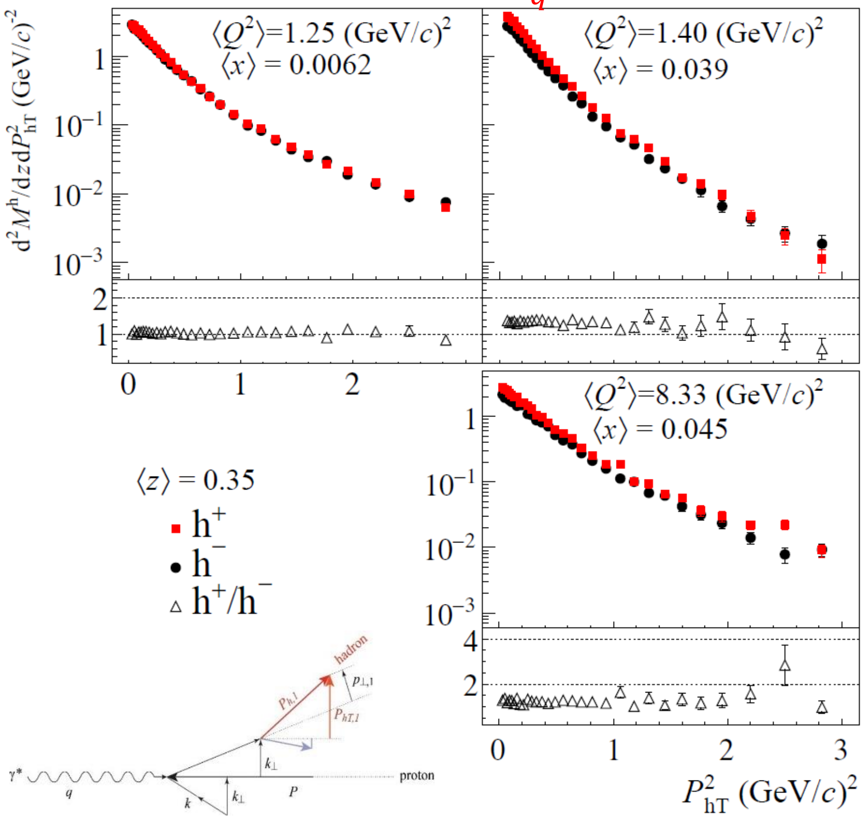
- Difficult measurements were one has to correct for the apparatus acceptance

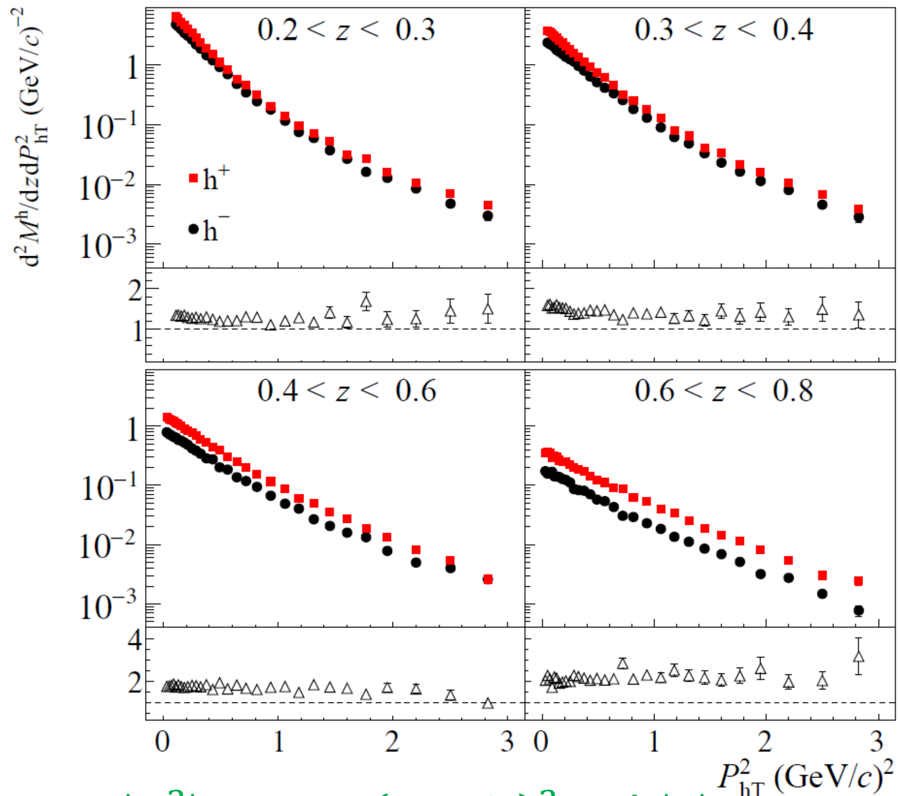
- COMPASS and HERMES have
  - results on ^6LiD $(\sim d)$ and preliminary on p from COMPASS
  - d and p from HERMESS

- ⇒COMPASS-II, measurements on LH_2 in parallel with DVCS

Positive vs Negative charged hadrons (^6LiD)

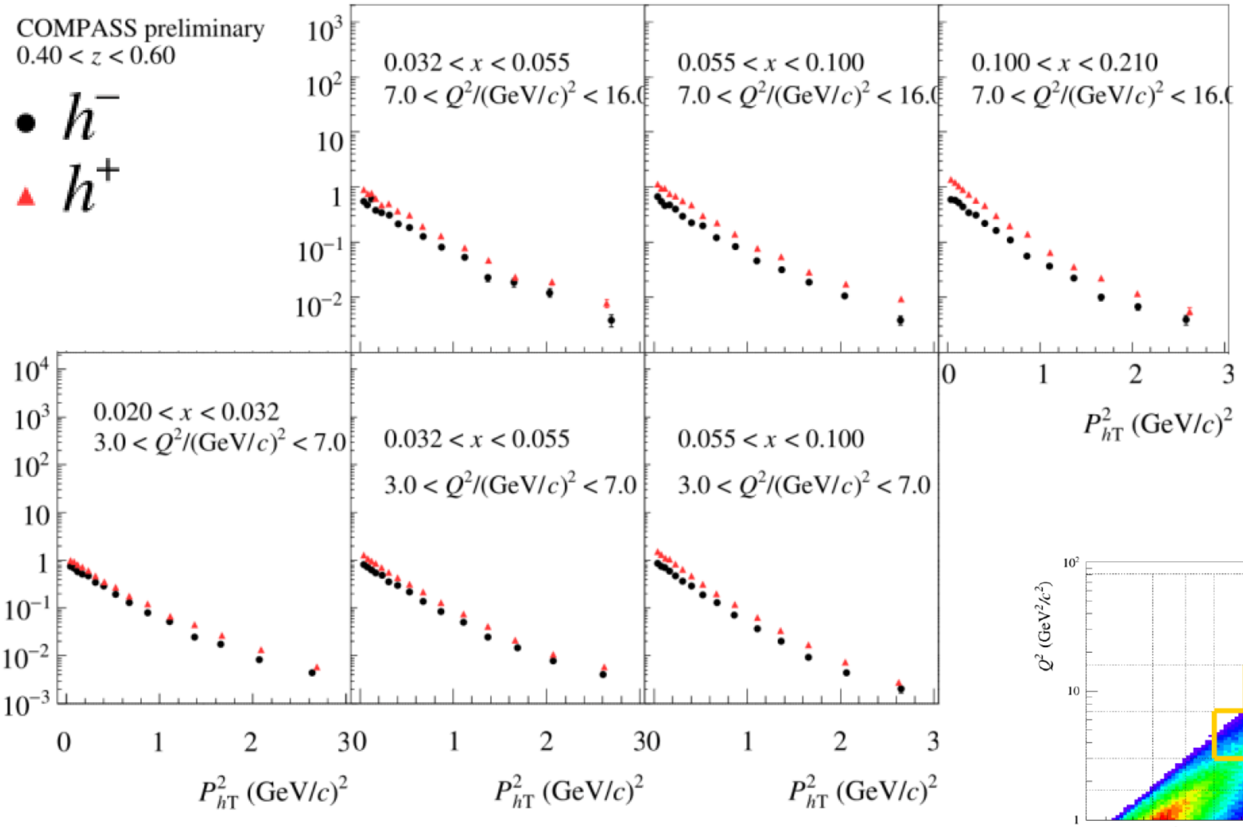
$$F_{UU}^{h}(x,z,P_{hT}^2;\,Q^2) = x\sum_q e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp + z\vec{k}_\perp - \vec{P}_{hT})\; f_1^q(x,k_\perp^2;Q^2)\,D_1^{q\to h}(z,p_\perp^2;Q^2)$$

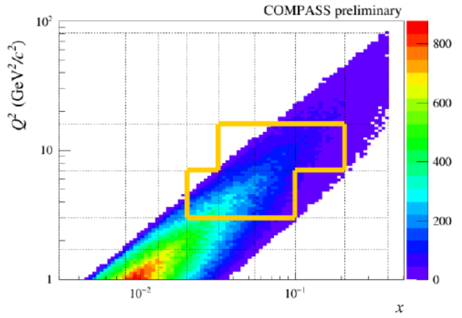




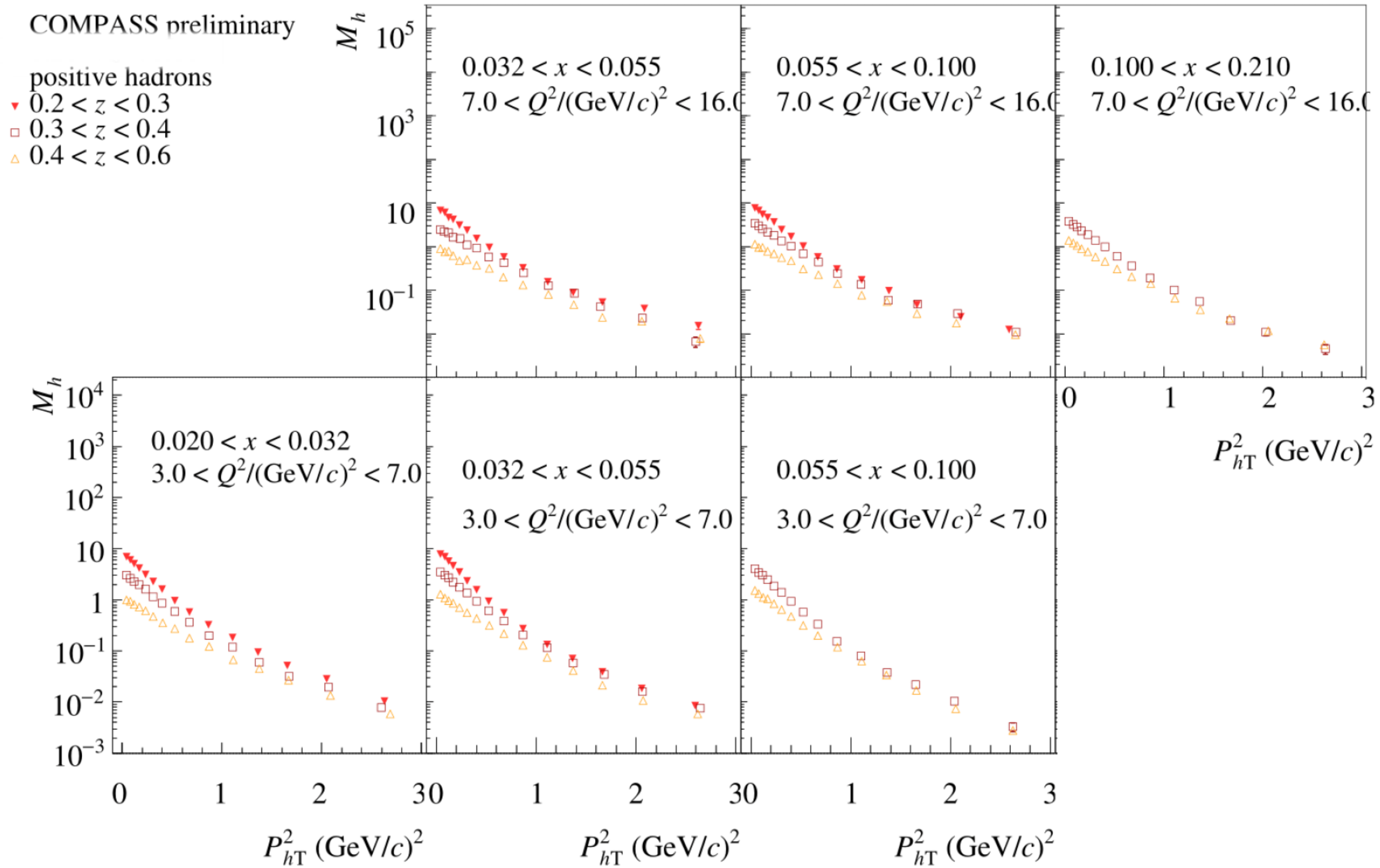
$\langle Q^2\rangle = 9.78\ (\mathrm{GeV}/c)^2$ and $\langle x\rangle = 0.149$

Positive vs Negative charged hadrons (p)

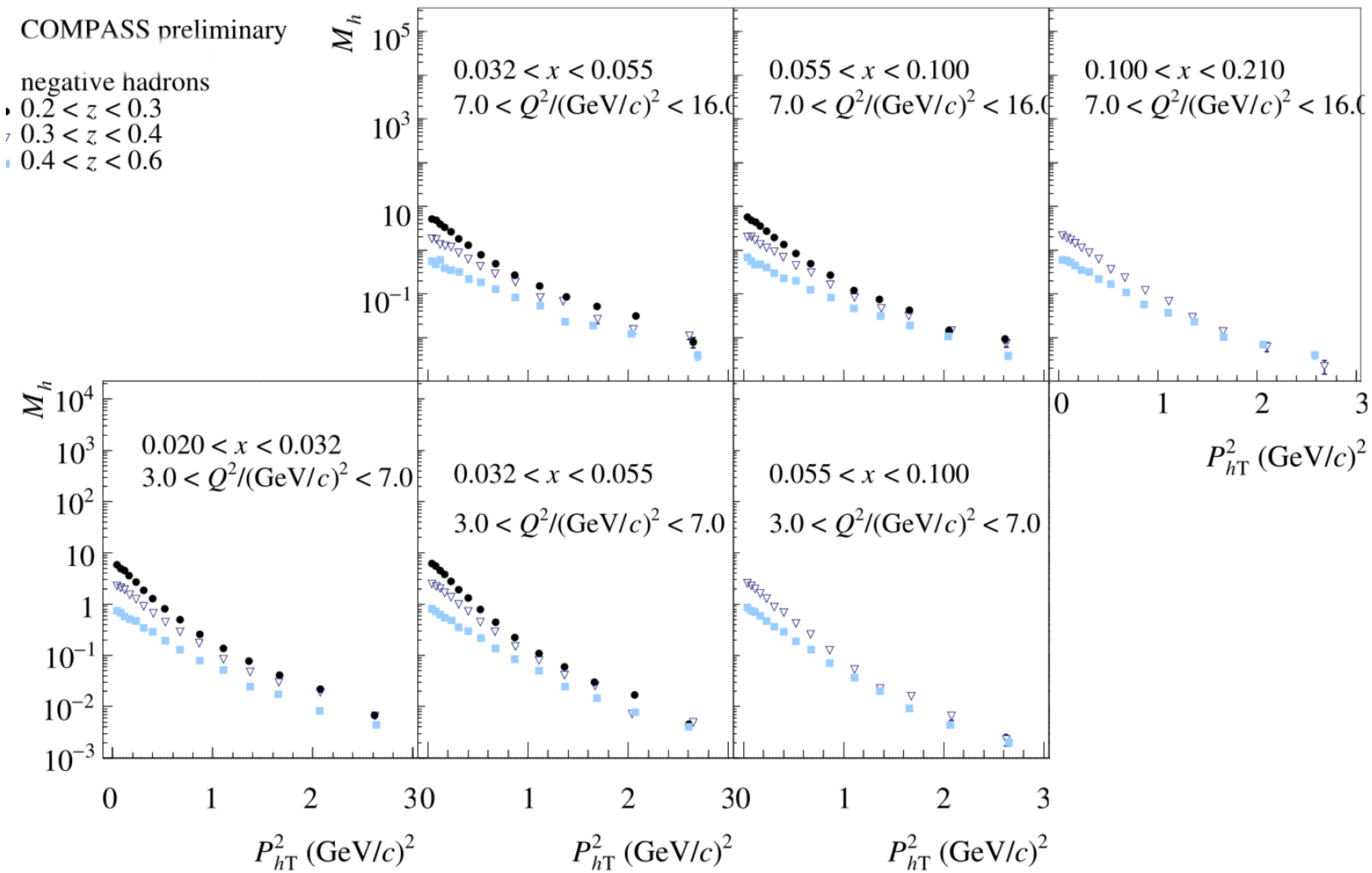




Positive charged hadrons (p)

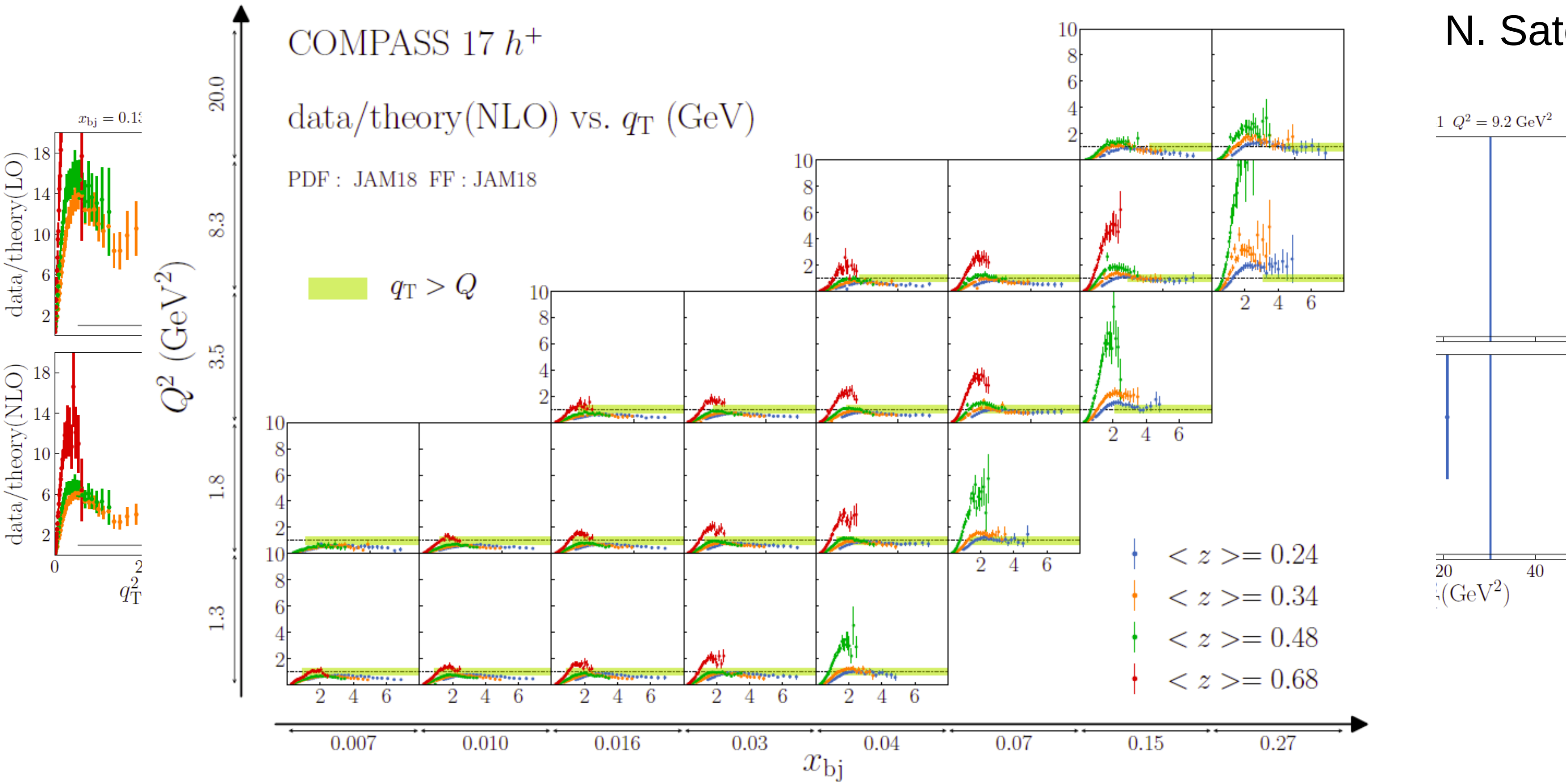


Negative charged hadrons (p)



The matching problem ($q_T/Q > 1$ region)

N. Sato



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:

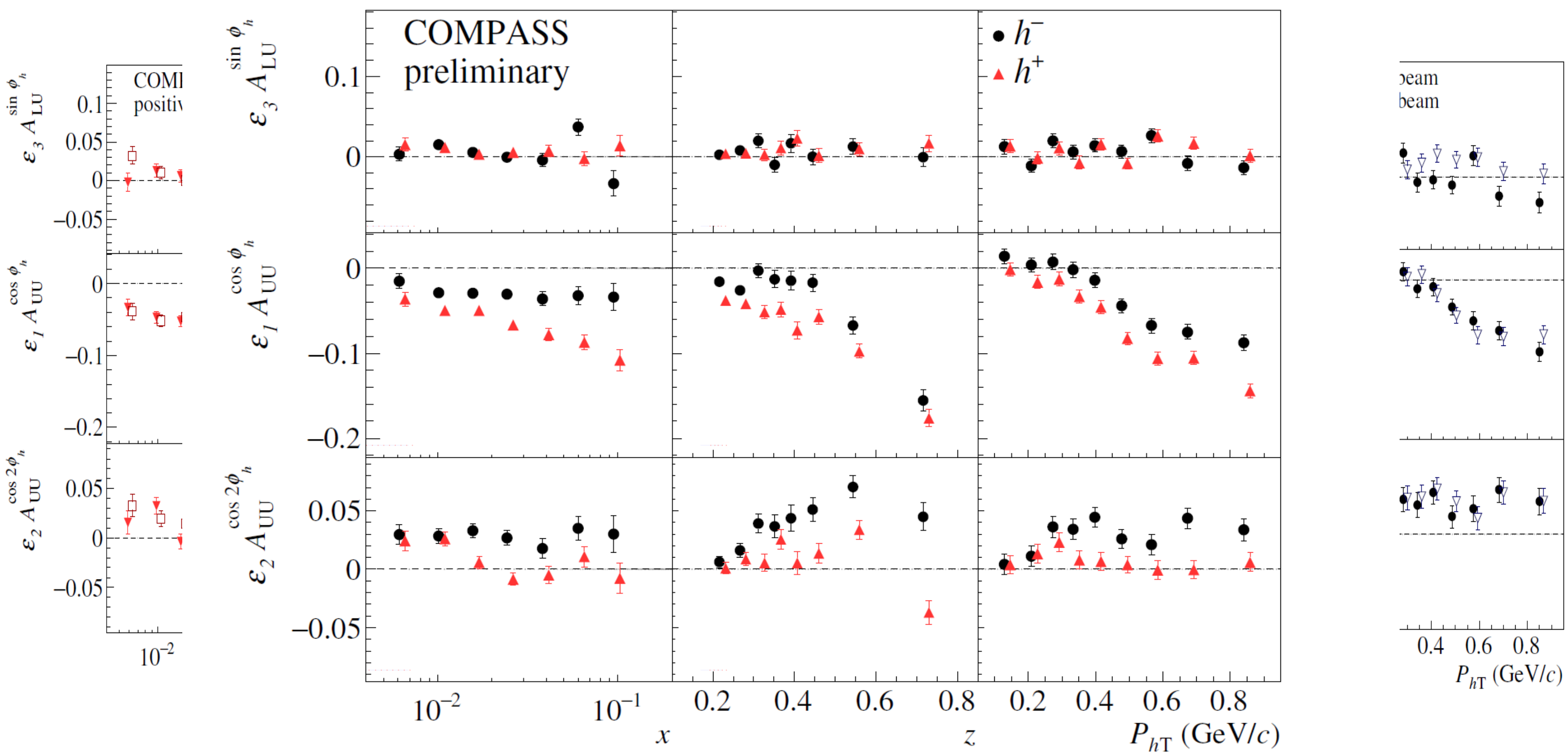
$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q} C\left[\frac{\hat{h}\cdot\vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M}\frac{\vec{P}_{hT} - z(\hat{h}\cdot\vec{k}_\perp)}{zM_h M} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

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

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

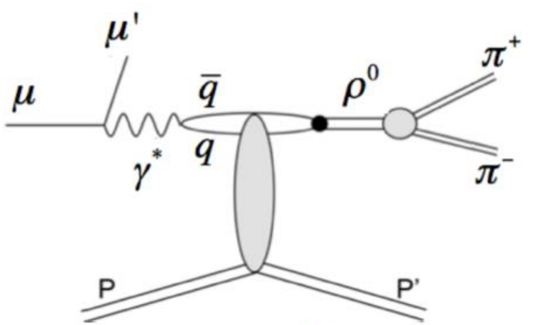
$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$

Azimuthal modulations on p

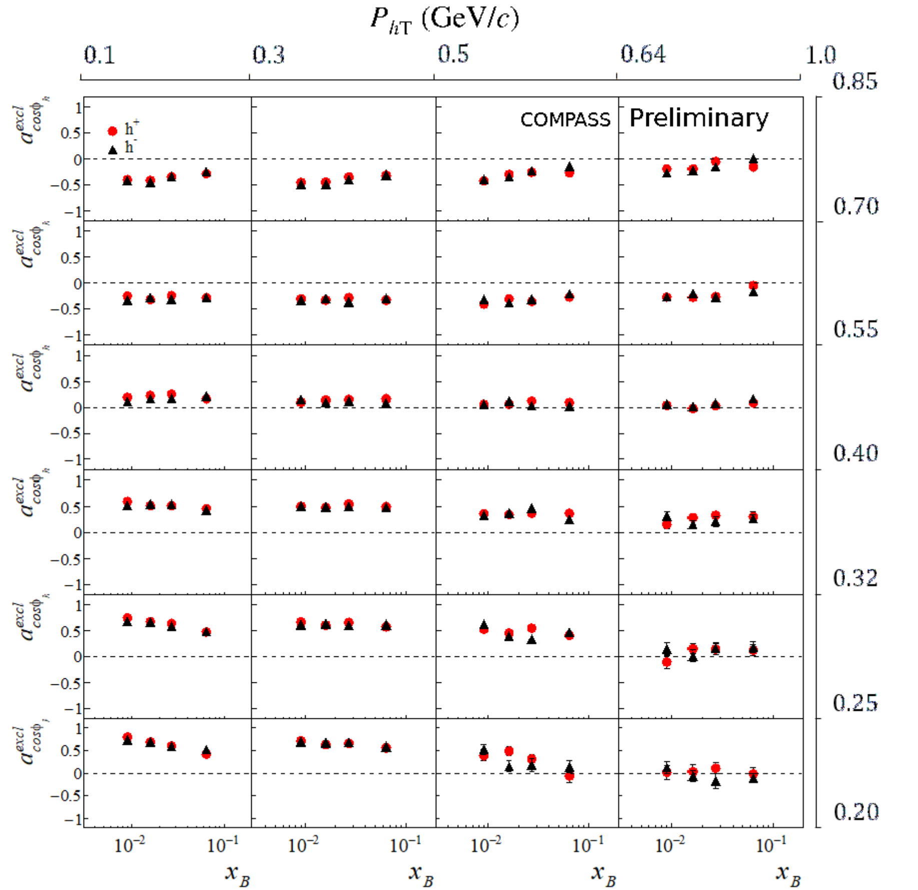


Contribution of diffractive VMs

- Determined from $z_1 + z_2 > 0.95$
- Selecting ρ^0 and ϕ
- Smaller, but not negligible, effect for $\cos 2\phi_h$

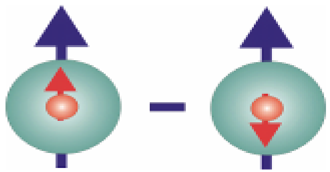


The diffractive ρ^0 production and decay.



Transversity PDF

$$\boldsymbol{h_1^q(\mathbf{x}) = q^{\uparrow\uparrow}(x) - q^{\uparrow\downarrow}(x)}$$



$\boldsymbol{q = u_v, d_v, q_{sea}}$

quark with **spin** parallel to the nucleon spin in a transversely polarised nucleon

- probes the relativistic nature of quark dynamics
- no contribution from the gluons → simple Q^2 evolution
- Positivity: Soffer bound................. $2|h_1^q| \le f_1^q + g_1^q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge.......... $\delta q(Q^2) = \int_0^1 dx\left[h_1^q(x) - h_1^{\bar{q}}(x)\right]$
- is chiral-odd: decouples from inclusive DIS *Bakker, Leader, Trueman, PRD 70 (04)*

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**

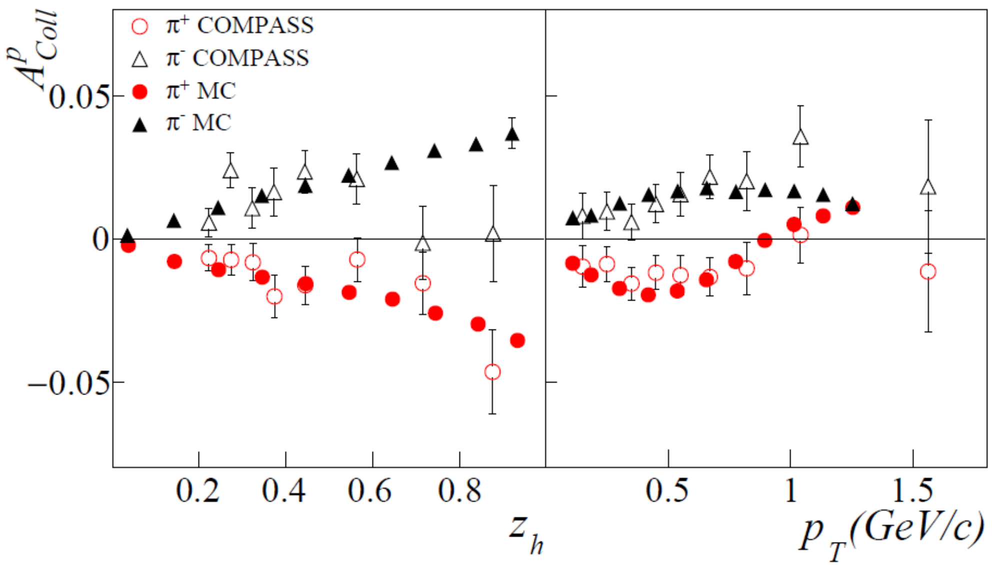
"Interference" Fragmentation Function

$\ell N^{\uparrow} \rightarrow \ell'$ **Λ X** — **Λ polarisation**

Fragmentation Function of q↑→Λ

A^p_{Coll} on proton and $^3P_0$ model for FF

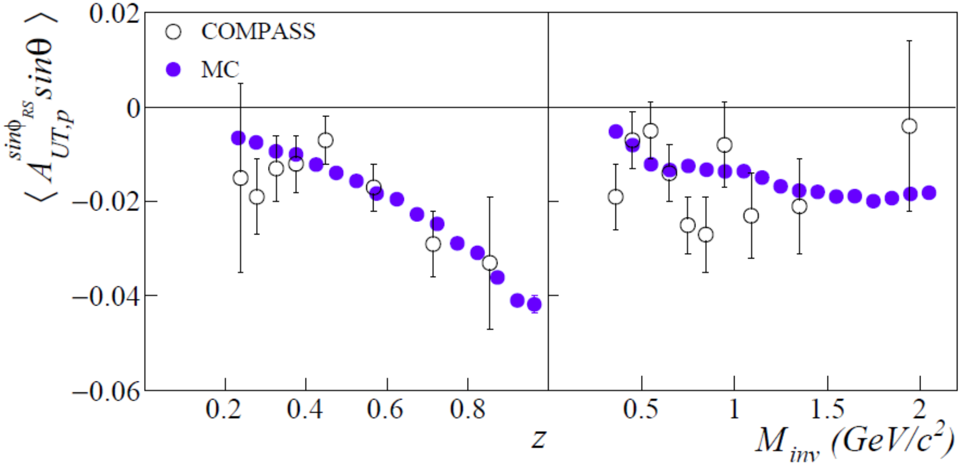
Albi Kerbizi @ DSPIN17 http://theor.jinr.ru/~spin/2017/
Phys. Rev. D 97, 074010 (2018)/**arXiv:1802.00962**

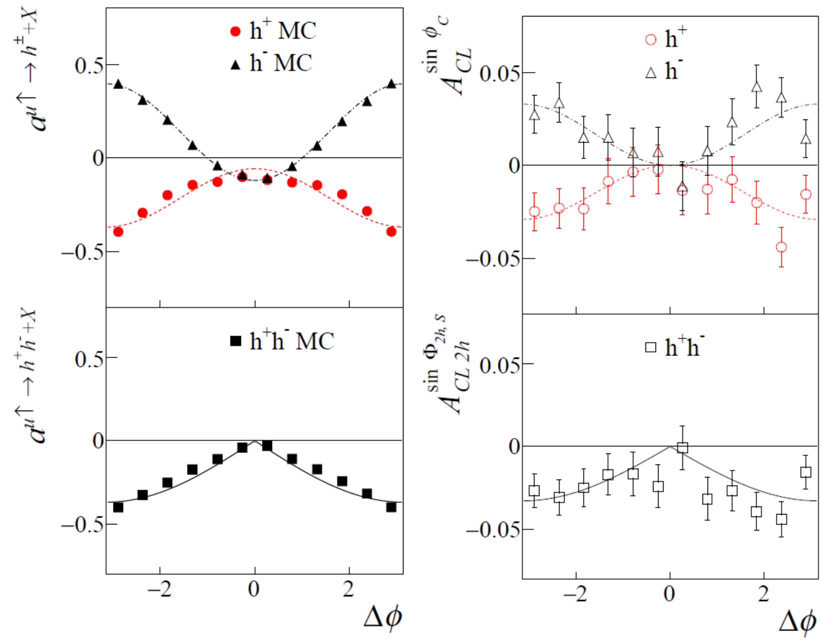


- The curves are fits of the Monte Carlo data, scaled by $\lambda \sim \langle h_1^u / f_1^u \rangle \sim 0.055$
- Agreement with the measured Collins asymmetry is quite satisfactory

2h asymmetries on p and ${}^3P_0$ model for FF

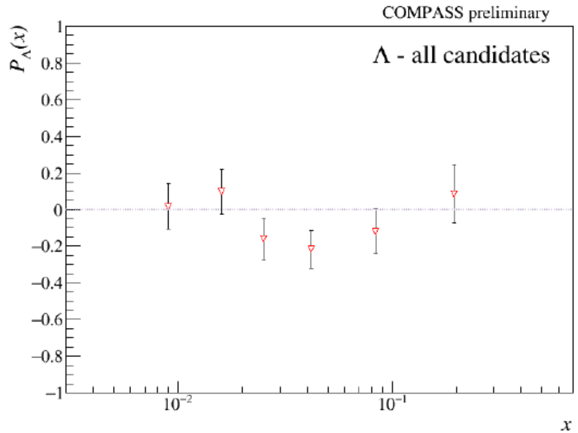
$$A_{UT}^{\sin(\phi_R+\phi_S-\pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q\to h_1h_2}^{\sphericalangle}\left(z,\mathcal{M}_{h_1h_2}^2\right)}{\sum_q e_q^2 q(x) D_q^{h_1h_2}\left(z,\mathcal{M}_{h_1h_2}^2\right)}$$

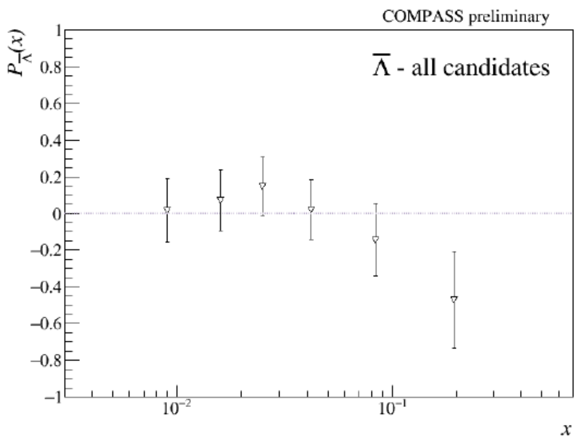




$a_P^{u\uparrow\to h^+h^-X} = \langle\sin(\phi_R+\phi_S-\pi)\rangle$ and $\vec{R} = \frac{z_2\vec{P}_{h1}-z_1\vec{P}_{h2}}{z_1+z_2}$ and as before $\lambda\sim\langle h_1^u/f_1^u\rangle\sim 0.055$

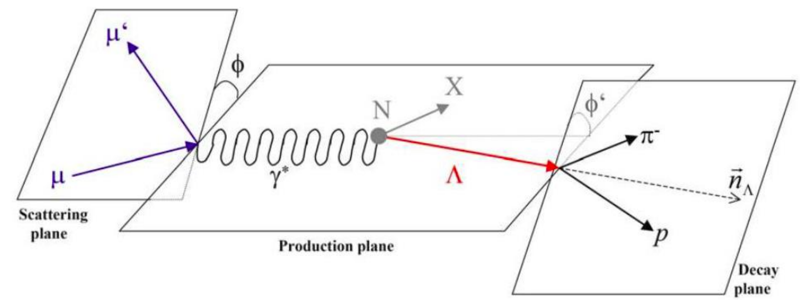
Λ transverse spin transfer from COMPASS





$$P_{\Lambda(\bar{\Lambda})}(x,z) = \frac{\sum_q e_q^2 h_1^q(x)\, H_1^{\Lambda(\bar{\Lambda})}(z)}{\sum_q e_q^2 f_1^q(x)\, D_1^{\Lambda(\bar{\Lambda})}(z)}$$

$$\frac{dN}{d\cos\theta^*} \propto A\left(1 + \alpha P_{\Lambda(\bar{\Lambda})} \cos\theta^*\right)$$



Sivers Asymmetry

Sivers: correlates nucleon spin & quark transverse momentum k_T /T-ODD

at LO:

$$A_{Siv} = \frac{\sum_q e_q^2 f_{1Tq}^{\perp} \otimes D_q^h}{\sum_q e_q^2 q \otimes D_q^h}$$

$$\mu p^{\uparrow} \rightarrow \mu X h^{\pm}$$

The Sivers PDF	
1992	Sivers proposes $f_{1T}^{\perp}$
1993	J. Collins proofs $f_{1T}^{\perp} = 0$ for T invariance
2002	S. Brodsky, Hwang and Schmidt demonstrate that $f_{1Tq}^{\perp}$ may be $\neq 0$ due to FSI
2002	J. Collins shows that $(f_{1T}^{\perp})_{DY} = -(f_{1T}^{\perp})_{SIDIS}$
2004	HERMES on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$
2004	COMPASS on d: $A_{Siv}^{\pi^+} = 0$ and $A_{Siv}^{\pi^-} = 0$
2008	COMPASS on p: $A_{Siv}^{\pi^+} \neq 0$ and $A_{Siv}^{\pi^-} = 0$

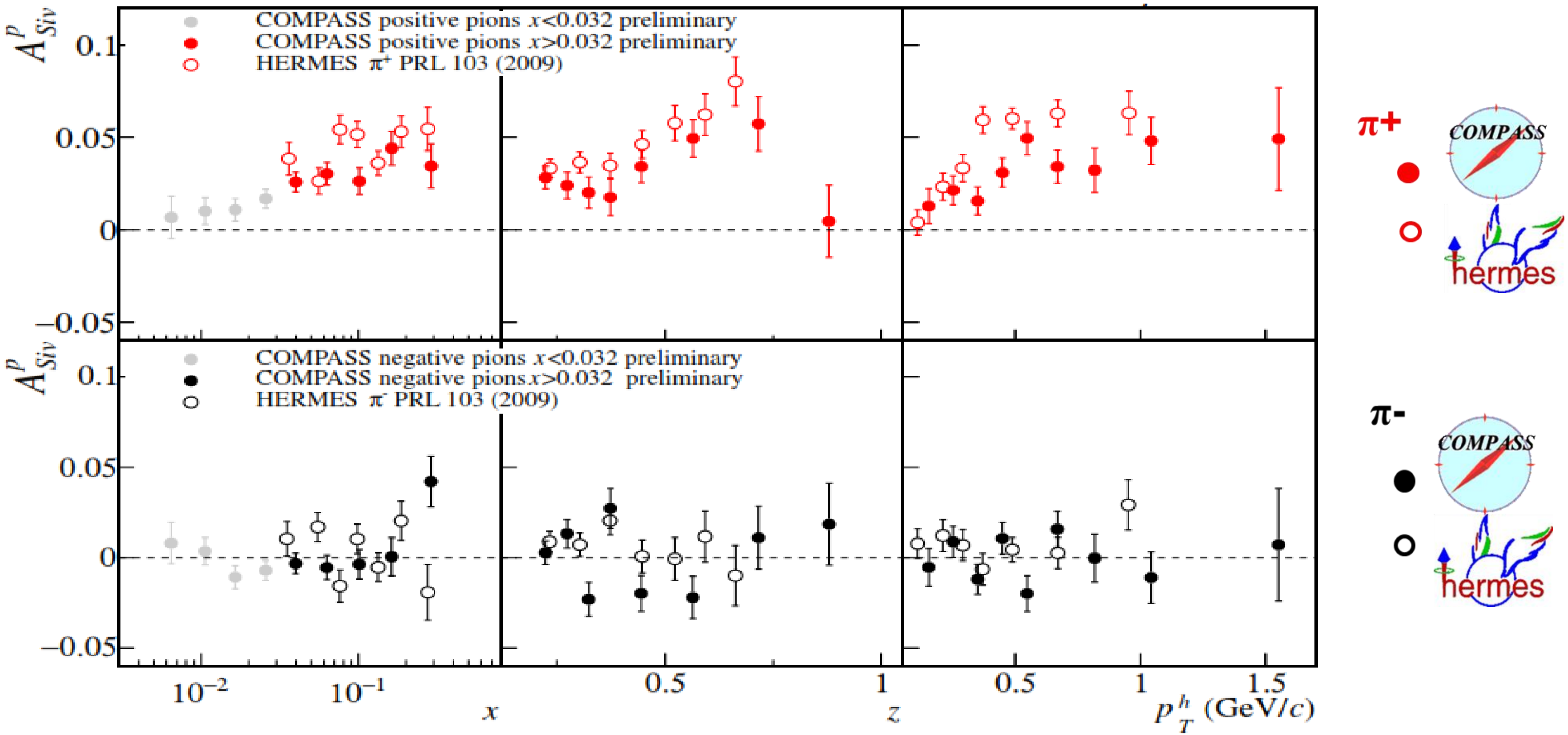
Sivers Asymmetry

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

- To evaluate it we need to solve the convolutions (i.e. make hypothesis on the transverse momenta dependences of the TMDs)
- Gaussian ansatz: $f_{1T}^{\perp q}(x)\frac{e^{-k_\perp^2/\langle k_\perp^2\rangle_S}}{\pi\langle k_\perp^2\rangle_S}$ $D_{1q}^h(z)\frac{e^{-p_\perp^2/\langle p_\perp^2\rangle}}{\pi\langle p_\perp^2\rangle}$
- 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

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

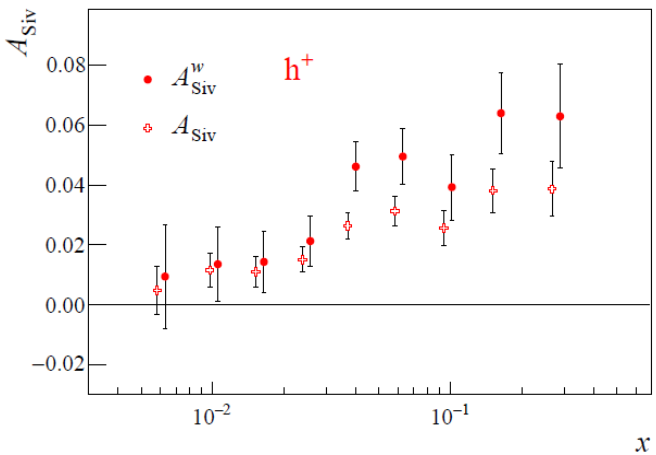
with $f_{1T}^{\perp(1)q}(x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x,k_T^2)$

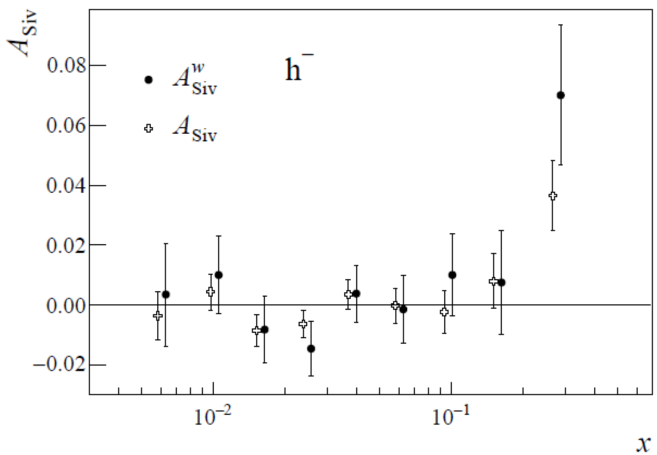
The weighted Sivers asymmetry

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

$w = P_T/zM$

standard cuts
z>0.2





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

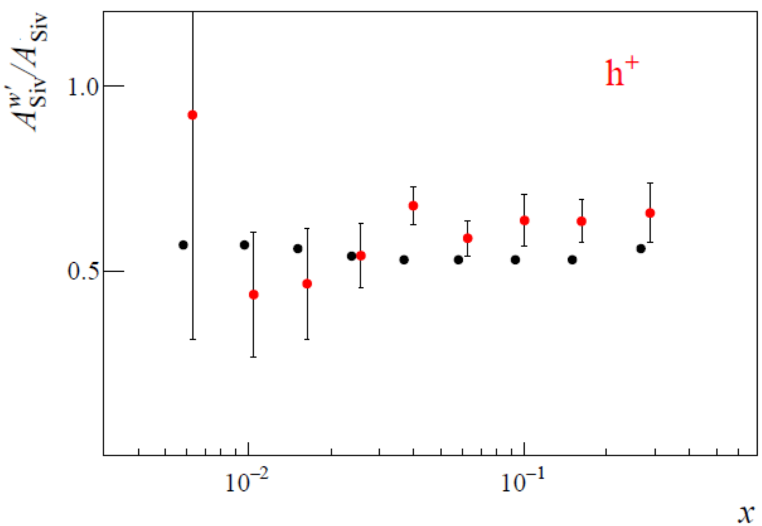
both $f_{1T}^{\perp(1)u}$ and $f_{1T}^{\perp(1)d}$ contribute

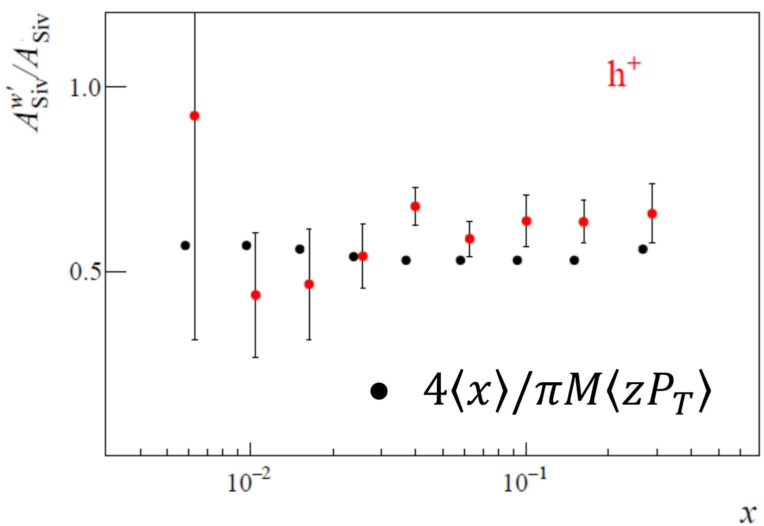
The weighted Sivers asymmetry

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

$w = P_T/zM$

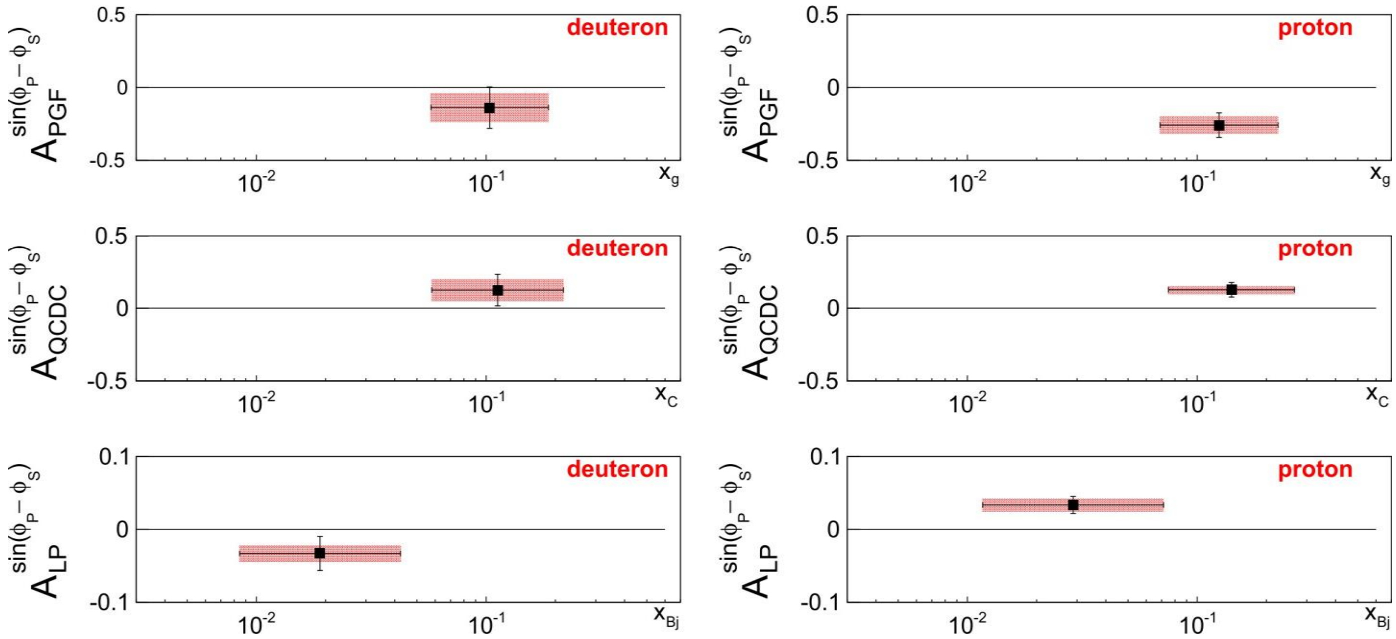
standard cuts
z>0.2





The ratio between weighted and unweighted Sivers asymmetries follows the average of $4\langle x\rangle/\pi M\langle zP_T\rangle$ of the unpolarised sample

Sivers Asymmetry for Gluon from SIDIS



$$A_{PGF}^{Siv,d} = -0.14 \pm 0.15(\text{stat.}) \pm 0.10(\text{syst.})$$
$$\langle x_g \rangle = 0.13$$

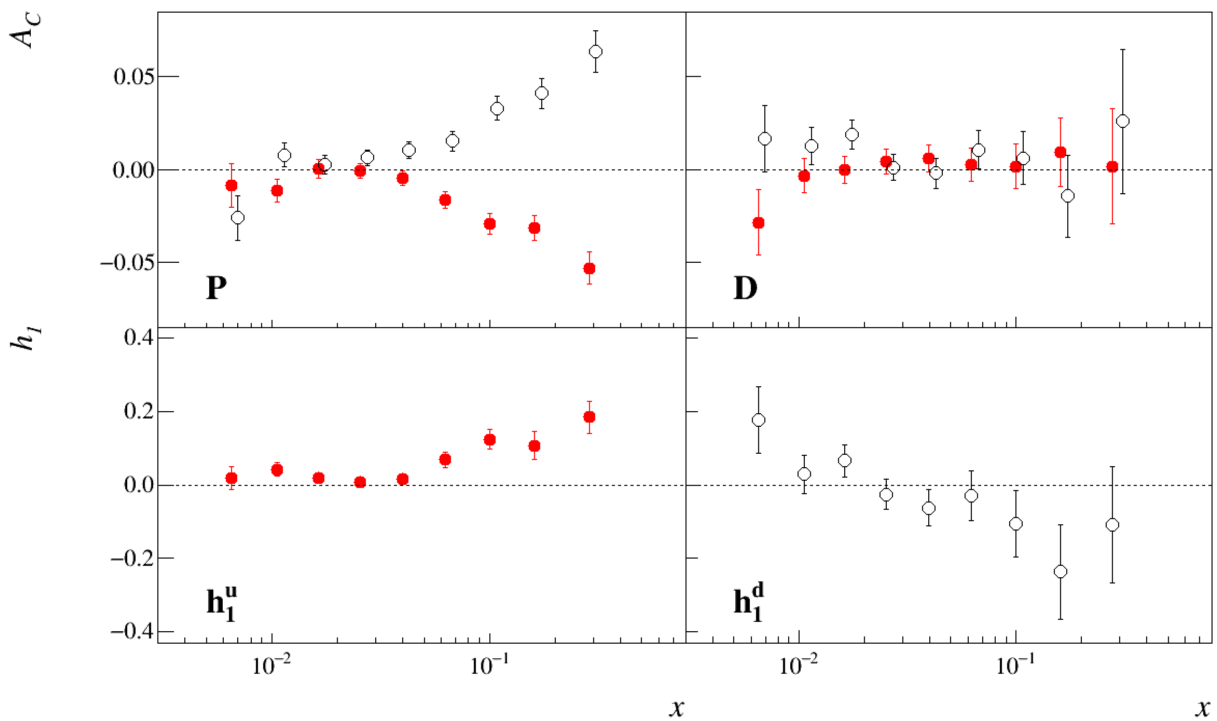
$$A_{PGF}^{Siv,p} = -0.26 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})$$
$$\langle x_g \rangle = 0.15$$

C. Adolph et al. (COMPASS Collaboration), Phys. Lett. B 772, 854 (2017).

WHAT WILL COME NEXT

2021 Deuteron run

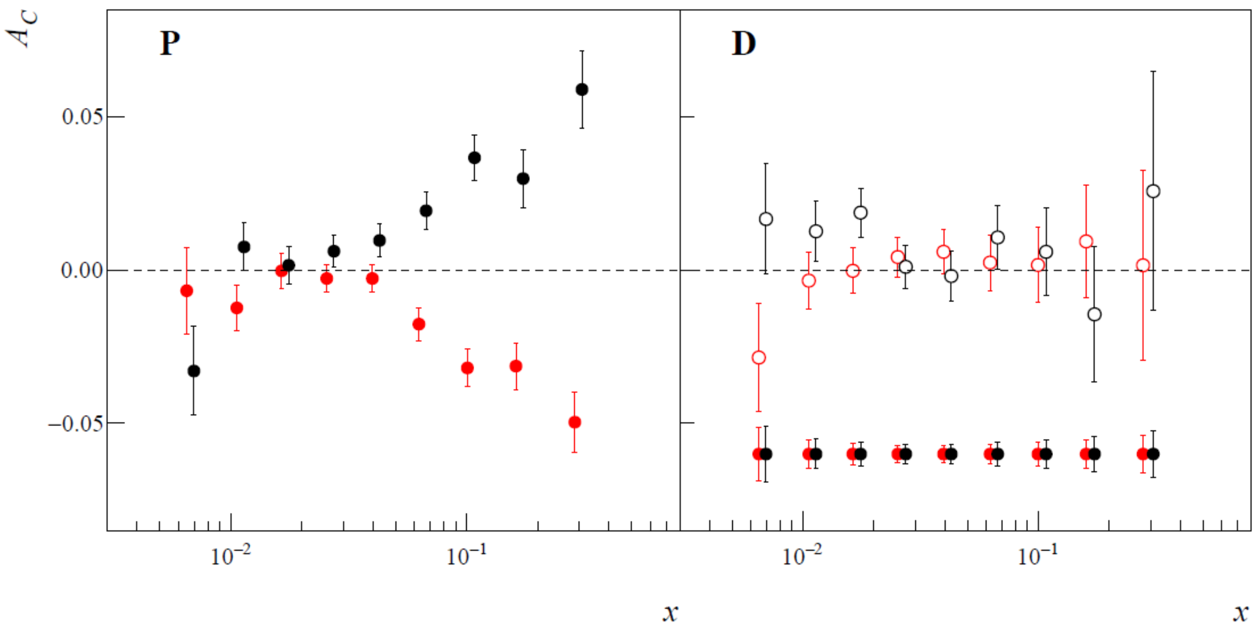
- Benchmark: h_1 extraction from Collins asymmetries



Transversity extracted as in PRD 91(2015) 014034

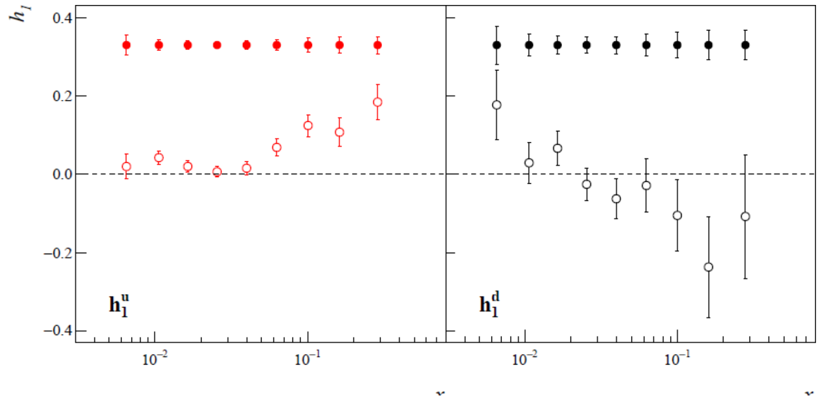
2021 Deuteron Run

- COMPASS proposed to CERN to run a full year with the transversely polarized deuteron target and this proposal has been approved



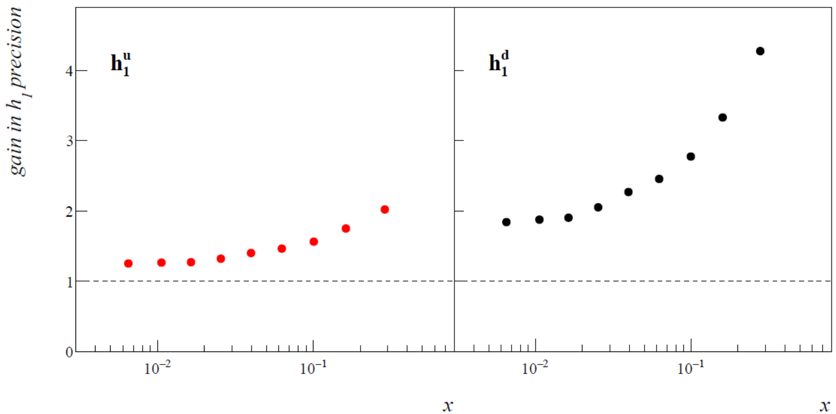
New deuteron data

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



projected

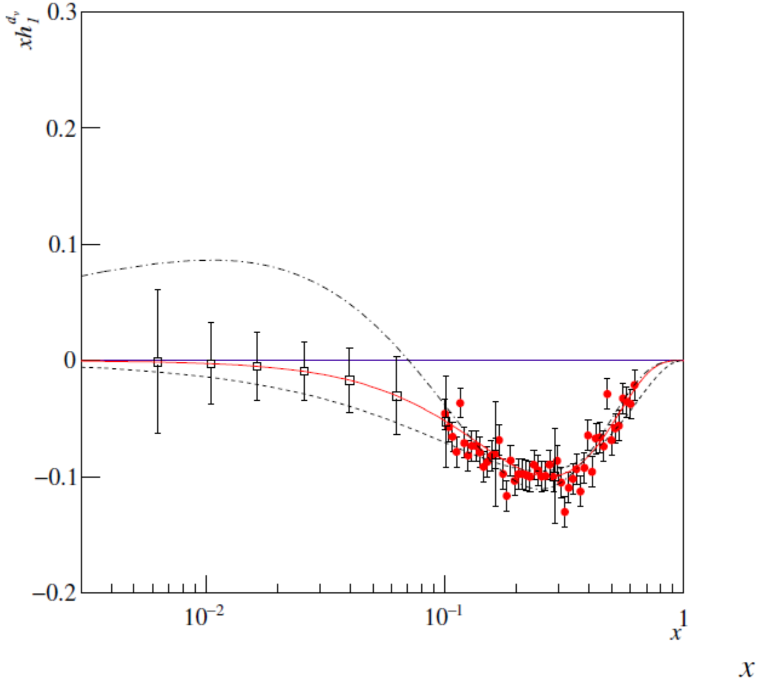
present

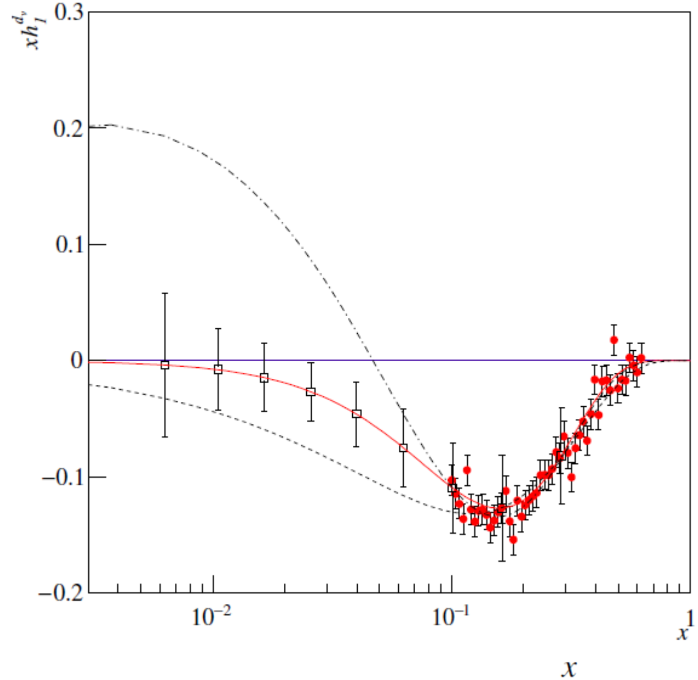


Transversity extracted as in PRD 91(2015) 014034

COMPASS deuteron data in 2021

- Expected gain in precision on u- and d-quark transversity





New QCD facility at CERN M2

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-SPSC-2019–XXX
SPSC-P-XXX
May 31, 2019

Proposal for Measurements at the M2 beam line of the CERN SPS

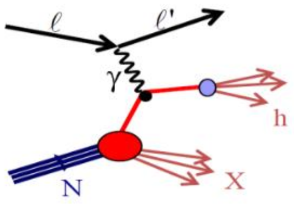
Phase-1: 2022-2024

COMPASS++[*]/AMBER[†]


Thank you

FACTORISATION

- DIS/SIDIS off polarized p, d, n targets



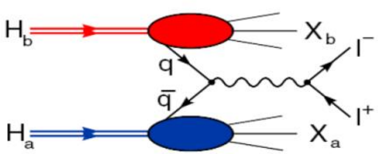
Cern/Hera/Jlab
future: ***eN colliders?***

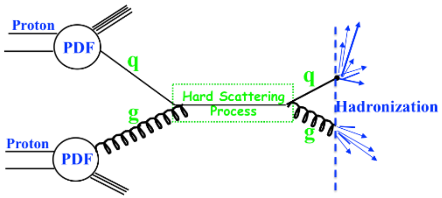
$$\sigma^{\ell p\to\ell' X} \sim q(x) \otimes \hat{\sigma}^{\gamma q\to q}$$

$$\sigma^{\ell p\to\ell' hX} \sim q(x) \otimes \hat{\sigma}^{\gamma q\to q} \otimes D_q^h(z)$$

- Drell-Yan/W/jets in Hadron Hadron

$$\sigma^{hp\to\mu\mu} \sim \bar{q}_h(x_1) \otimes q_p(x_2) \otimes \hat{\sigma}^{\bar{q}q\to\mu\mu}(\hat{s})$$

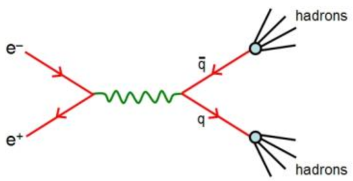




CERN(COMPASS/LHC)/RHIC/*FNAL*
future: ***FAIR, JPark, NICA***

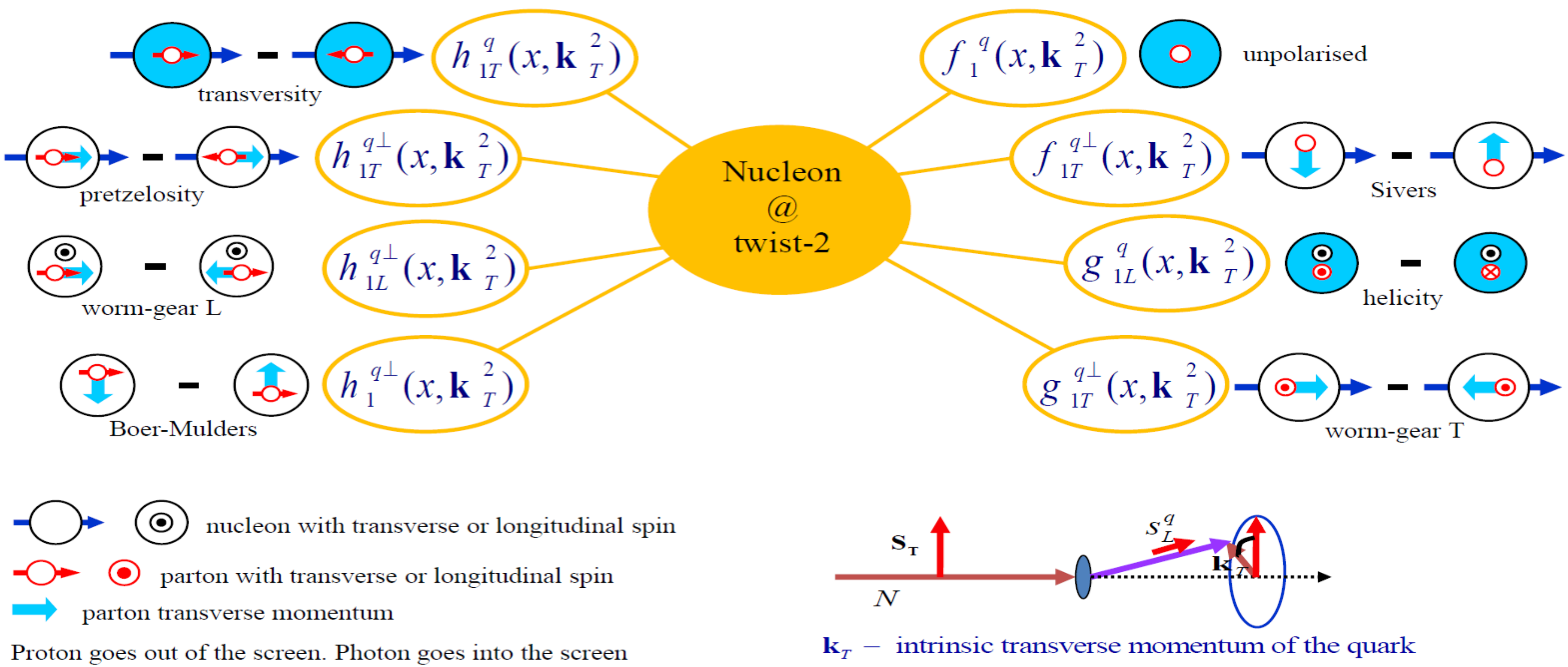
- $e^+e^- \to h_1 h_2$

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

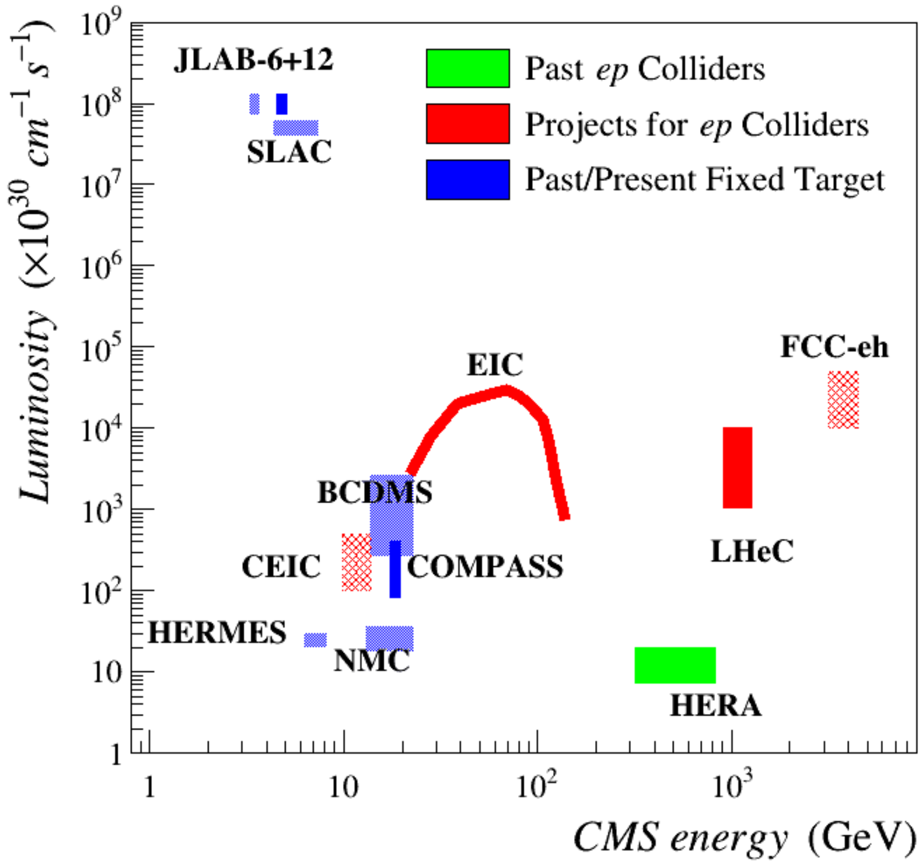


LEP/SLAC/BELLE/BES

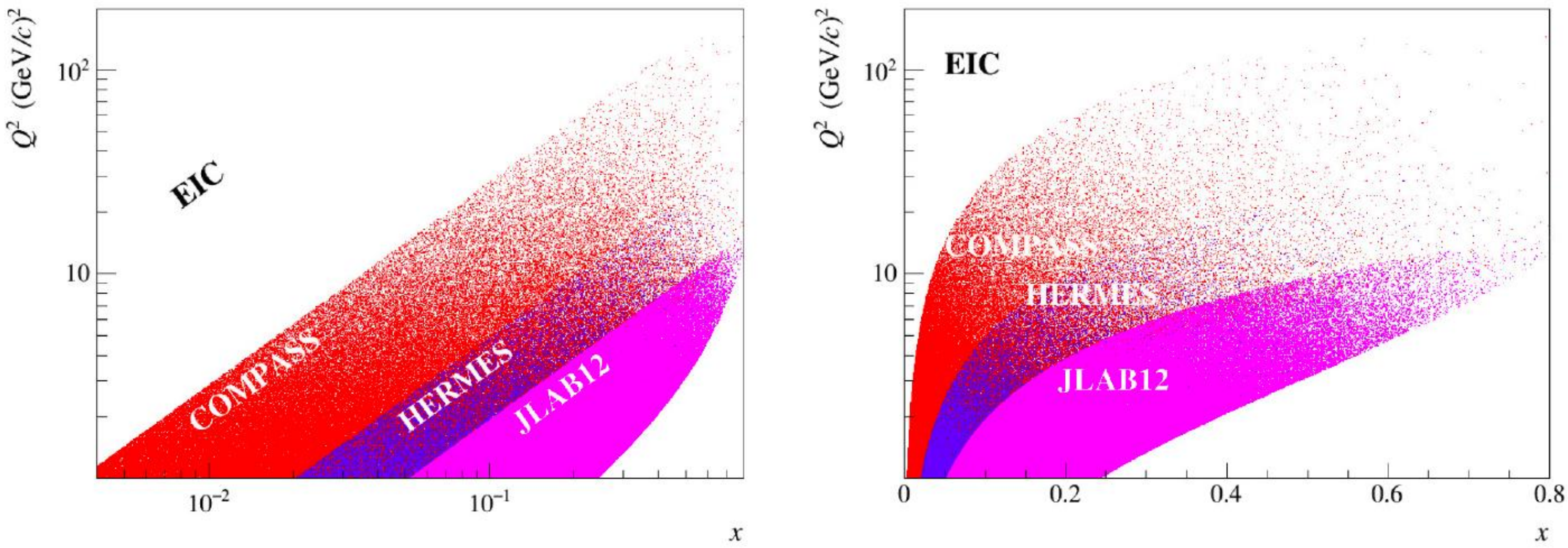
TMD Distribution Functions



DIS around the world



Kinematic coverage



From Collins asymmetries to transversity

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

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

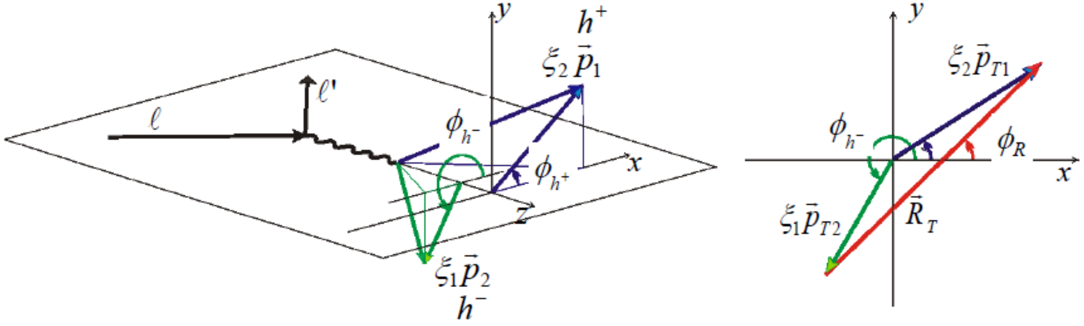
$$xh_1^d = \frac{1}{5}\frac{1}{\tilde{a}_P^h(1-\tilde{\alpha})}\left[\frac{4}{3}\left(xf_d^+ A_d^+ - xf_d^- A_d^-\right) - \left(xf_p^+ A_p^+ - xf_p^- A_p^-\right)\right]$$

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

π^+ in p: $f_p^+ = 4\left(f_1^u + \frac{\widetilde{D}_{unf}}{\widetilde{D}_f} f_1^{\bar{u}}\right) + \left(\frac{\widetilde{D}_{unf}}{\widetilde{D}_f} f_1^d + f_1^{\bar{d}}\right) + \frac{\widetilde{D}_{unf}}{\widetilde{D}_f}\left(f_1^s + f_1^{\bar{s}}\right)$

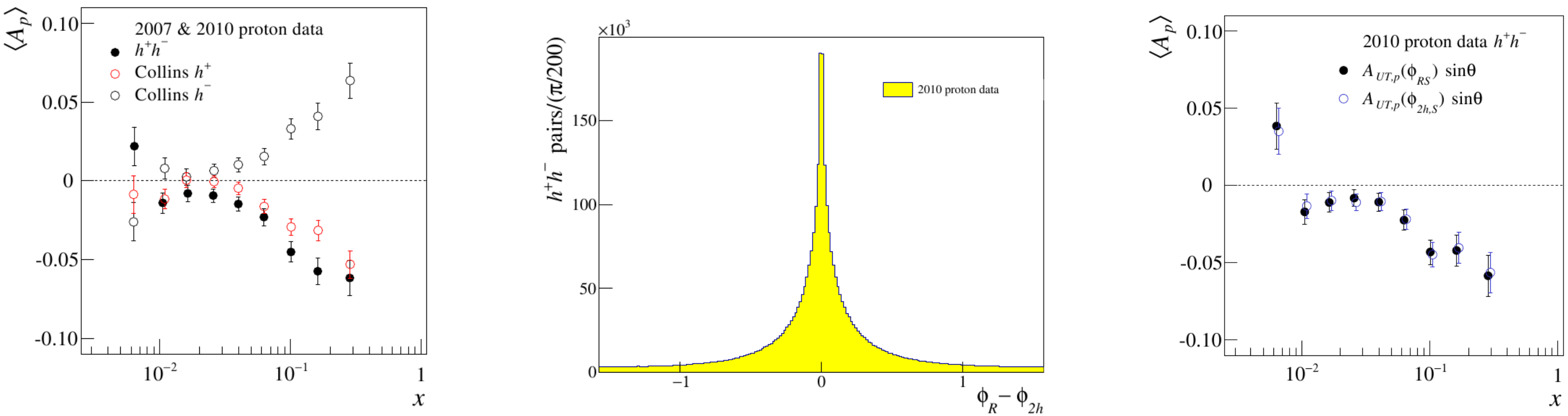
π^- in p: $f_p^+ = 4\left(\frac{\widetilde{D}_{unf}}{\widetilde{D}_f} f_1^u + f_1^{\bar{u}}\right) + \left(f_1^d + \frac{\widetilde{D}_{unf}}{\widetilde{D}_f} f_1^{\bar{d}}\right) + \frac{\widetilde{D}_{unf}}{\widetilde{D}_f}\left(f_1^s + f_1^{\bar{s}}\right)$

Hadron correlations

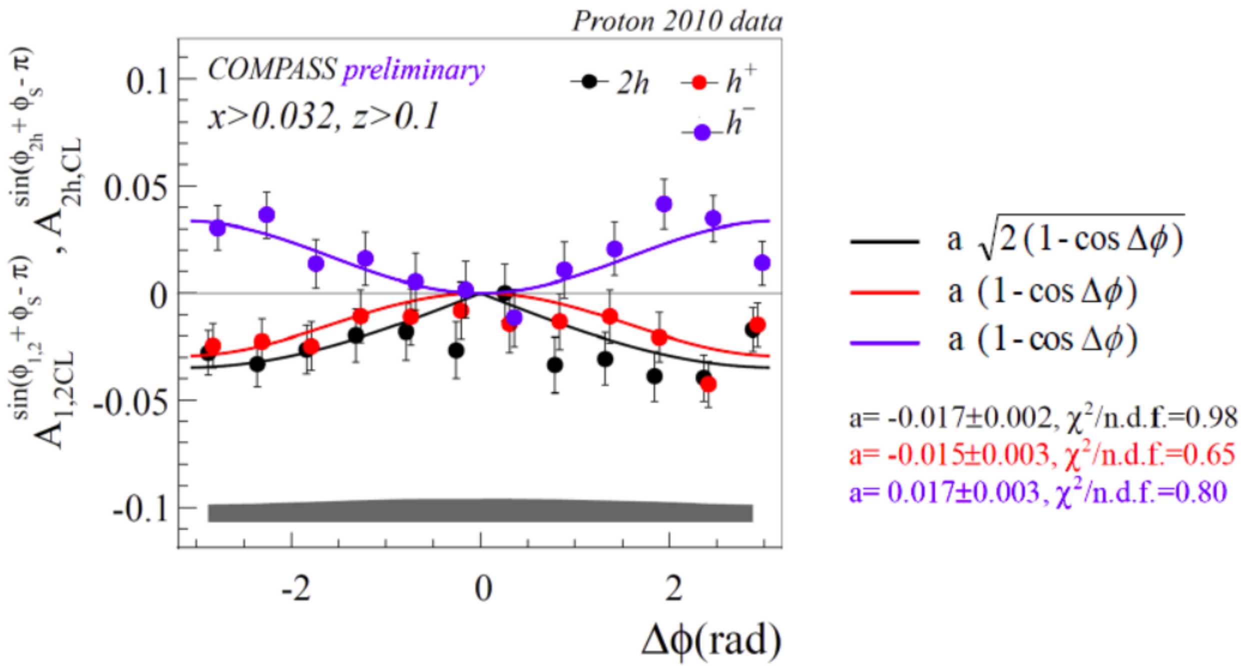


Interplay between Collins and IFF asymmetries

common hadron sample for Collins and 2h analysis



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



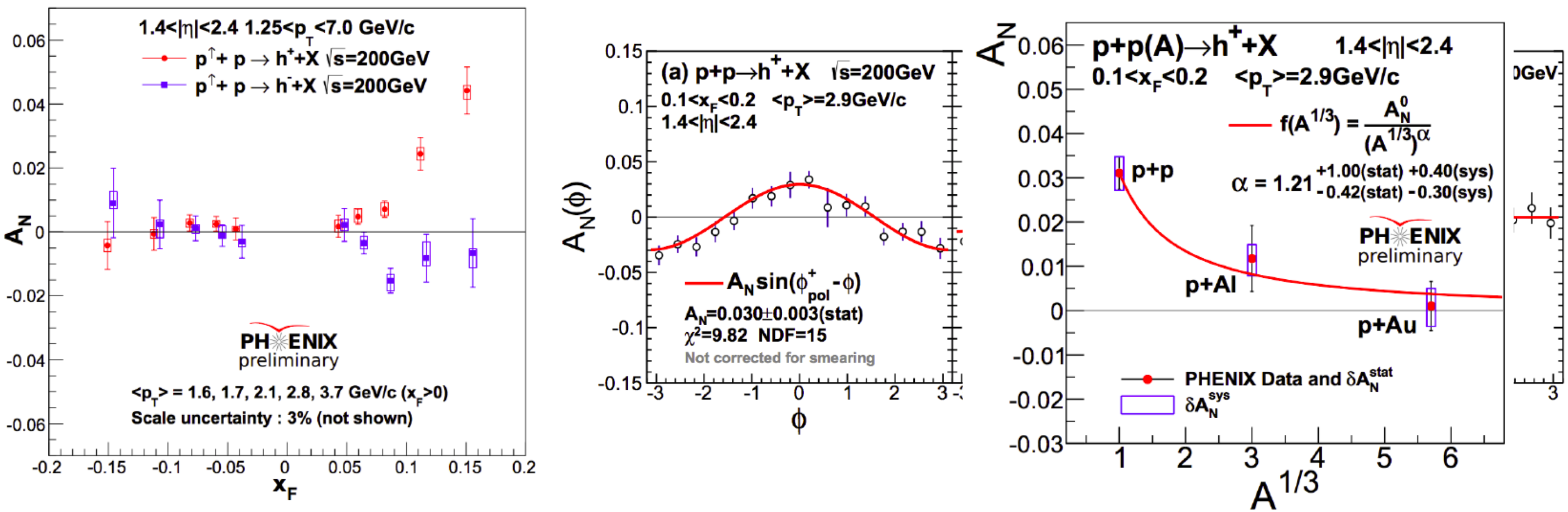
$$a = \frac{\sigma_{1C}^{h^+h^-}(\Delta\phi)}{\sigma_U(\Delta\phi)}$$

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

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

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

TSSA A_N studies at PHENIX

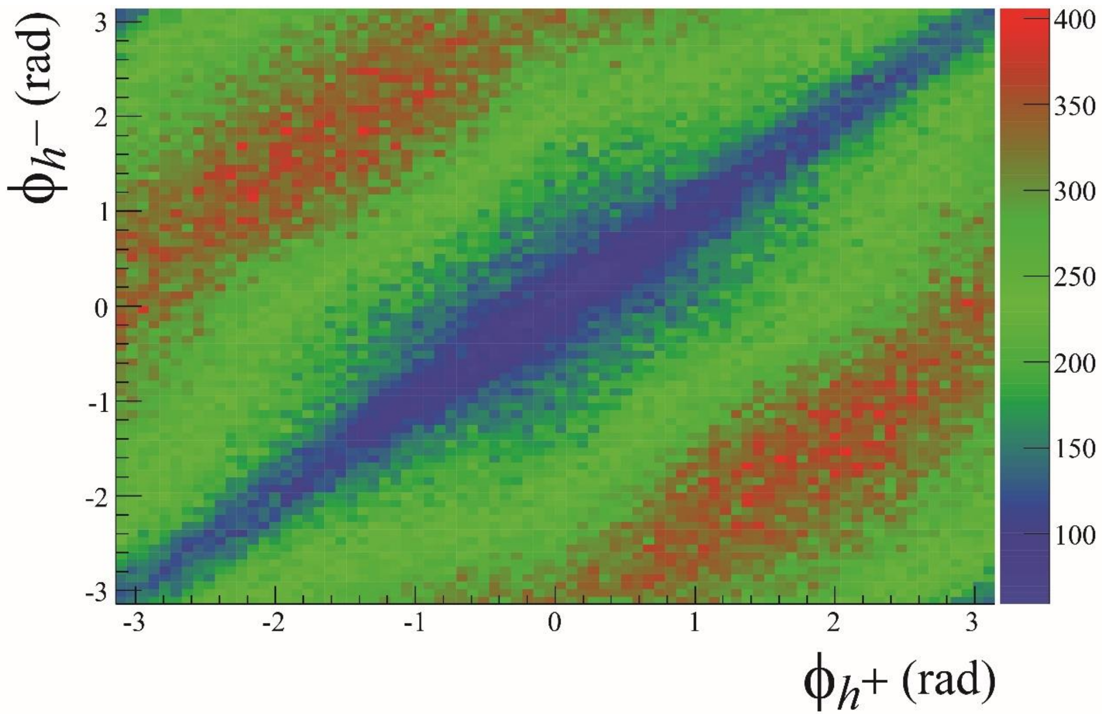


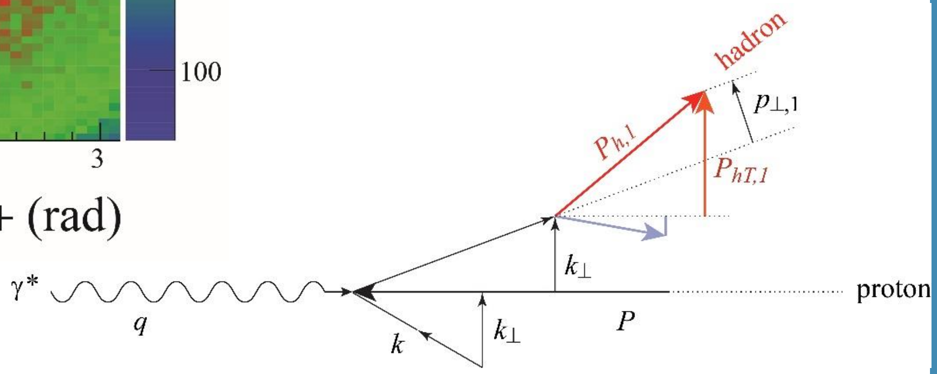
Described by twist 3 collinear approach (1 scale, high p_T)

Suppresion in $p^{\uparrow}A$ expected by gluon saturation ($\propto A^{1/3}$)

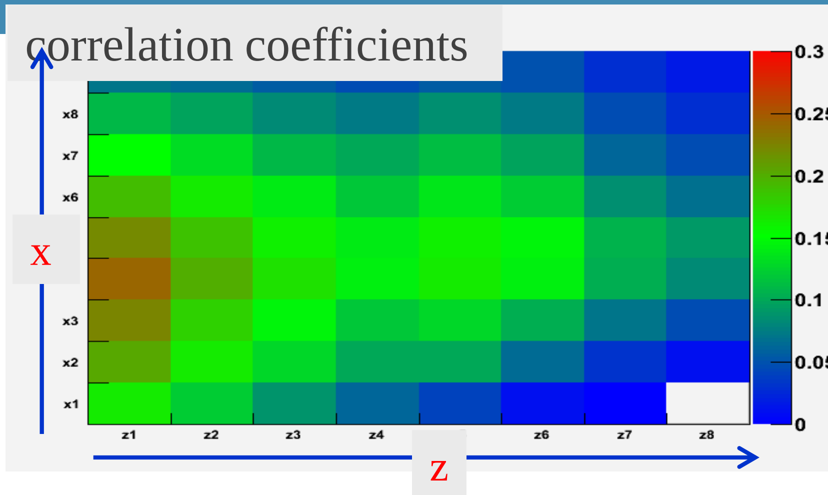
Hybrid approach: twist-3 and CGC

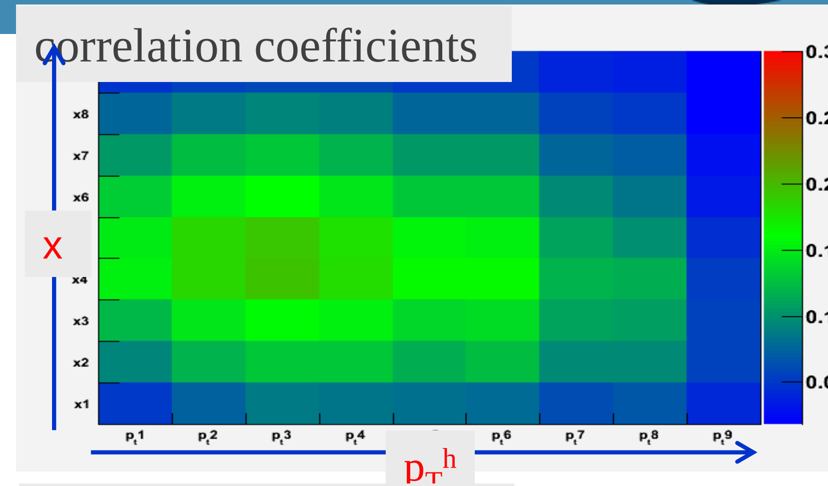
Is correlation having an impact?

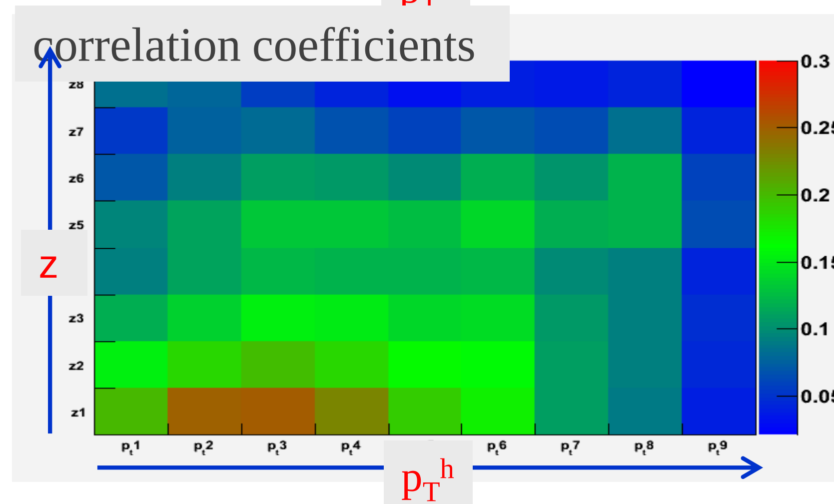




Statistical correlations







charged pions

also available for

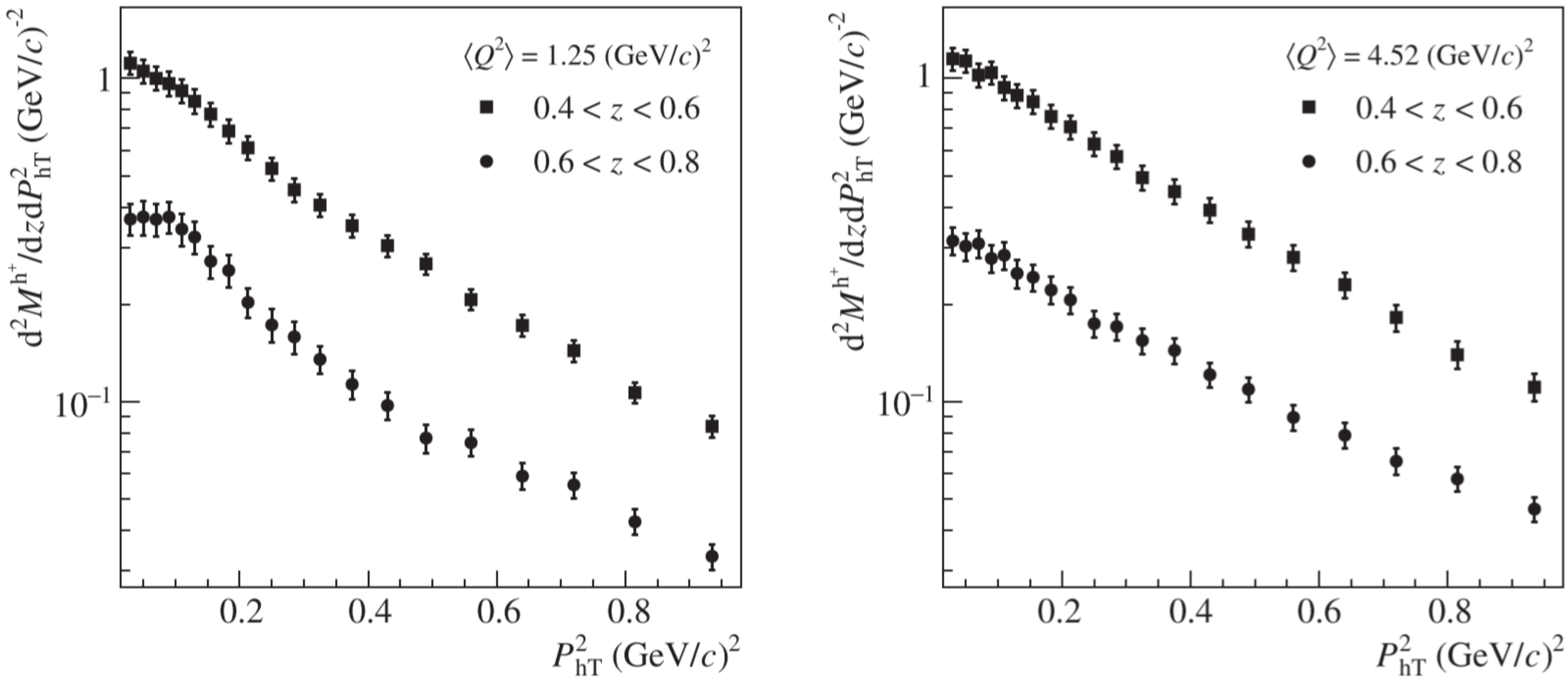
charged hadrons

charged kaons

have to be taken into account

Low P_{hT} behavior

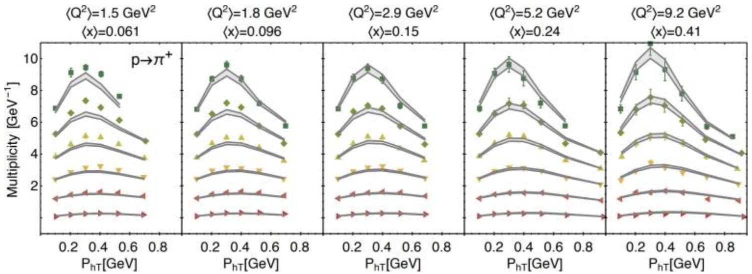
$\langle x \rangle = 0.006$ $\langle x \rangle = 0.043$



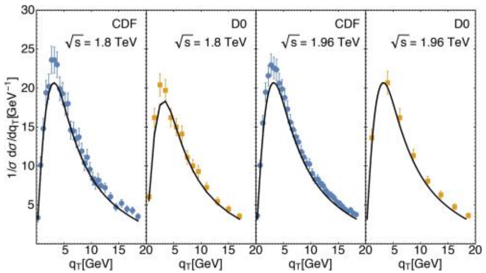
Global Analysis: Unpolarized TMD

Global analysis of semi-inclusive DIS, Drell-Yan and Z production data with TMD evolution

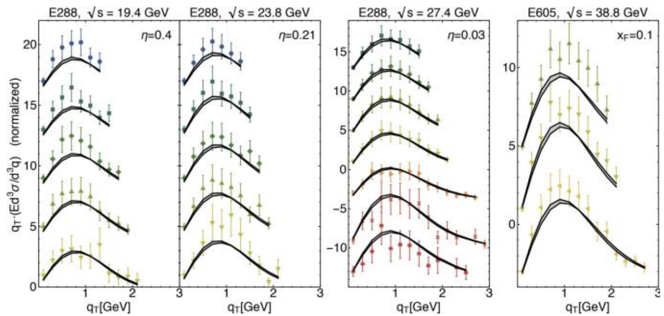
SIDIS multiplicity (example)



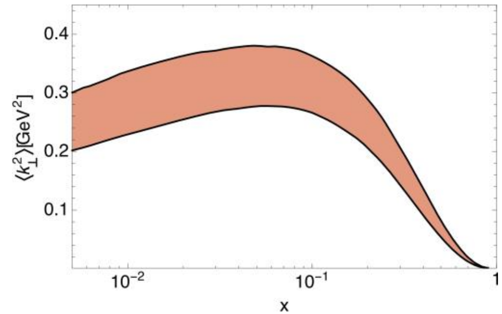
Z production



Drell-Yan cross section



Transverse momentum distribution



A. Bacchetta *et al.*, J. High Energy Phys. 06 (2017) 081.

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TMD evolution:

- QCD evolution of TMDs in Fourier space (solution of equation)

$$F(x,b;Q) \approx C \otimes F(x,c/b^*) \exp\left\{-\int_{c/b^*}^{Q_f} \frac{d\mu}{d}\left(A \ln\frac{Q_f^2}{\mu^2} + B\right)\right\} \times \exp\left[-S_{\text{non-pert}}(b,Q)\right]$$

Evolution of longitudinal/ collinear part

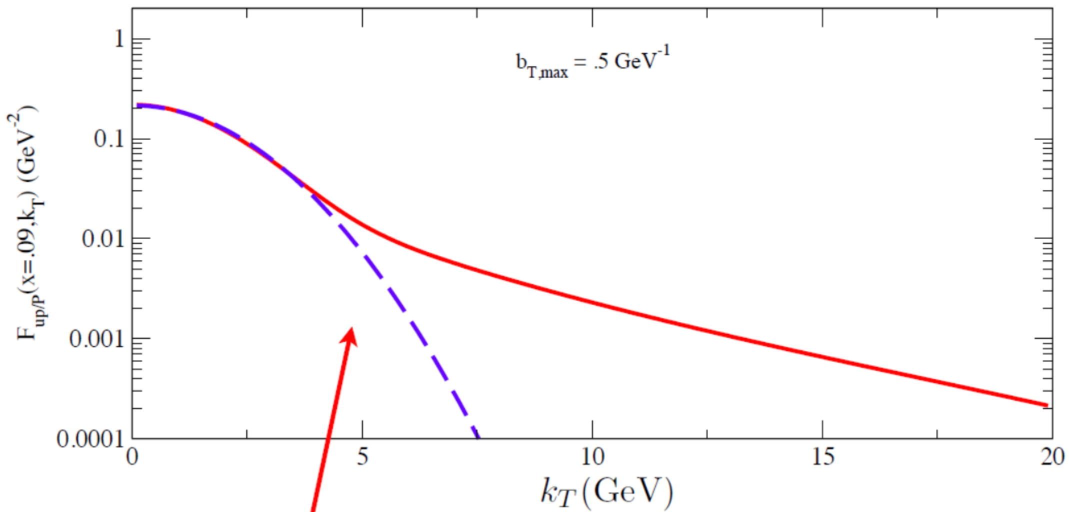
Evolution of transverse part (Sudakov form factor)

Non-perturbative part has to be fitted to experimental data
The key ingredient is spin-independent

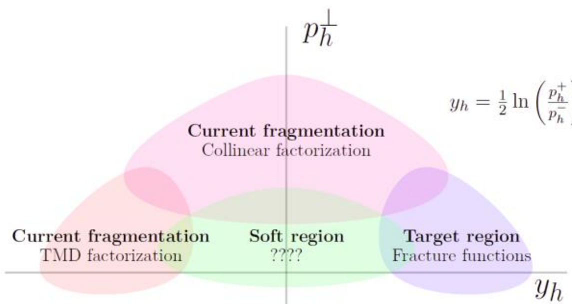
- Polarized scattering data comes as ratio: e.g. $A_{UT}^{\sin(\phi_h-\phi_s)} = F_{UT}^{\sin(\phi_h-\phi_s)}/F_{UU}$
- Unpolarized data is very important to constrain/extract the key ingredient for the non-perturbative part

Effect of QCD evolution

- What evolution does
  - Spread out the distribution to much larger $k_\perp$. At low $k_\perp$, the distribution decreases due to this spread

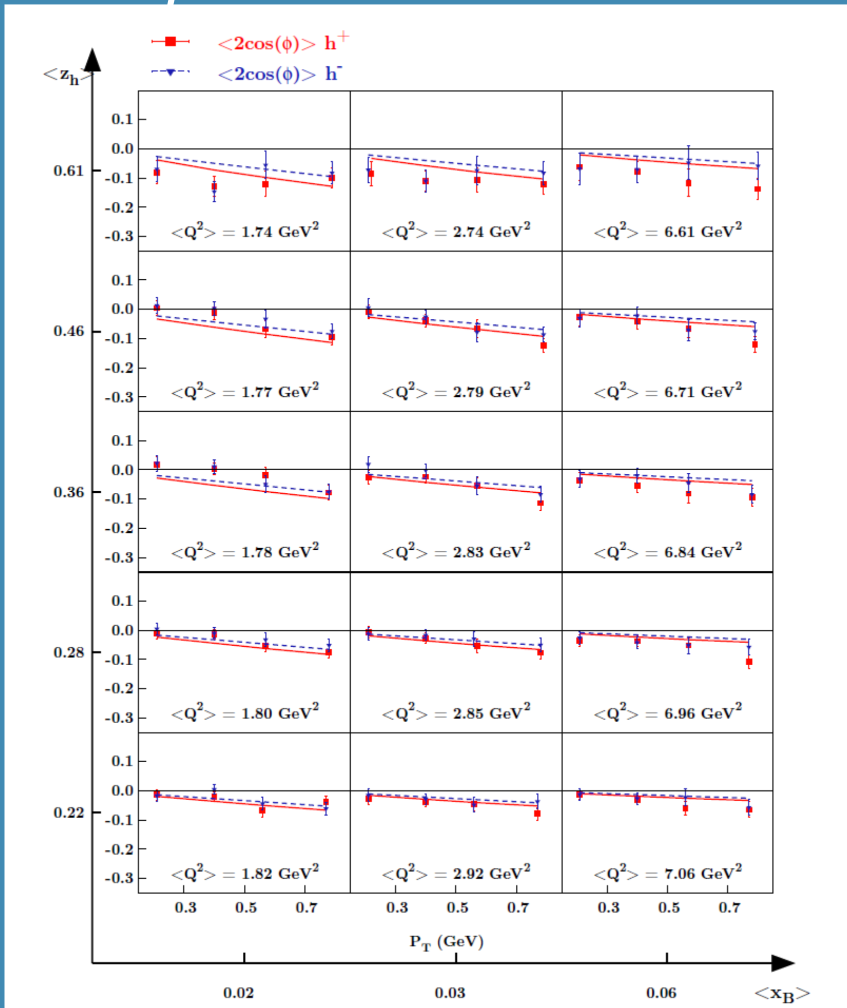


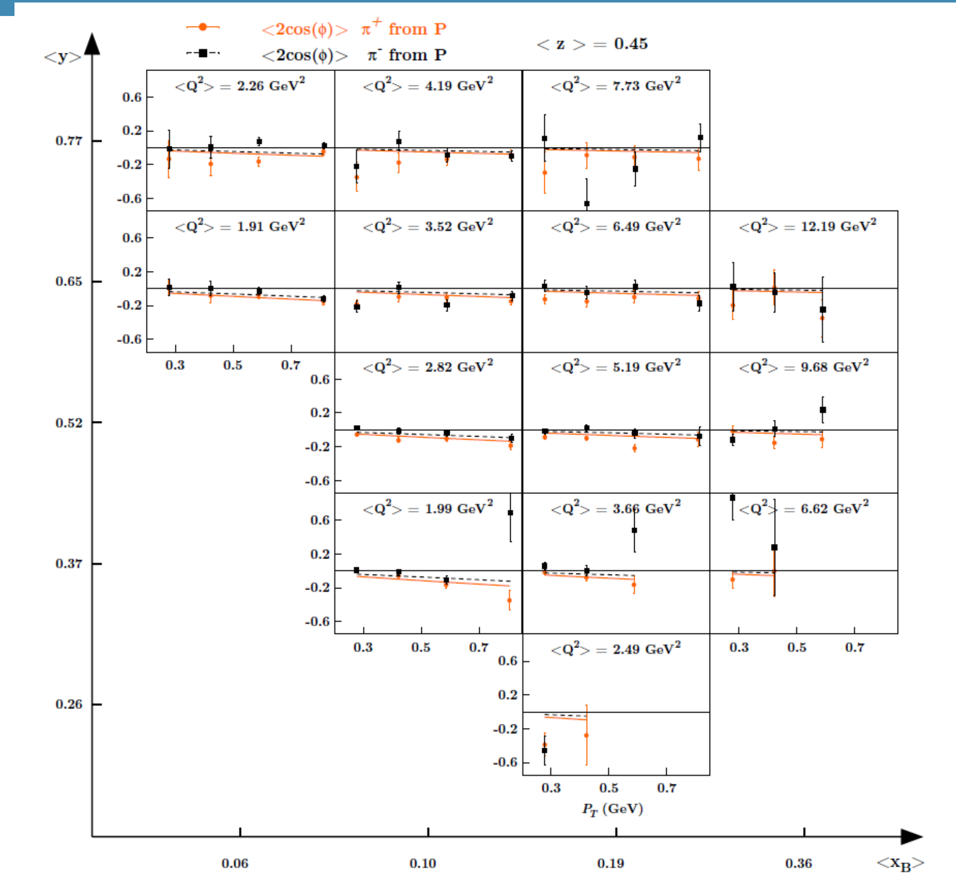
gaussian fit does not capture the effects of evolution quite well



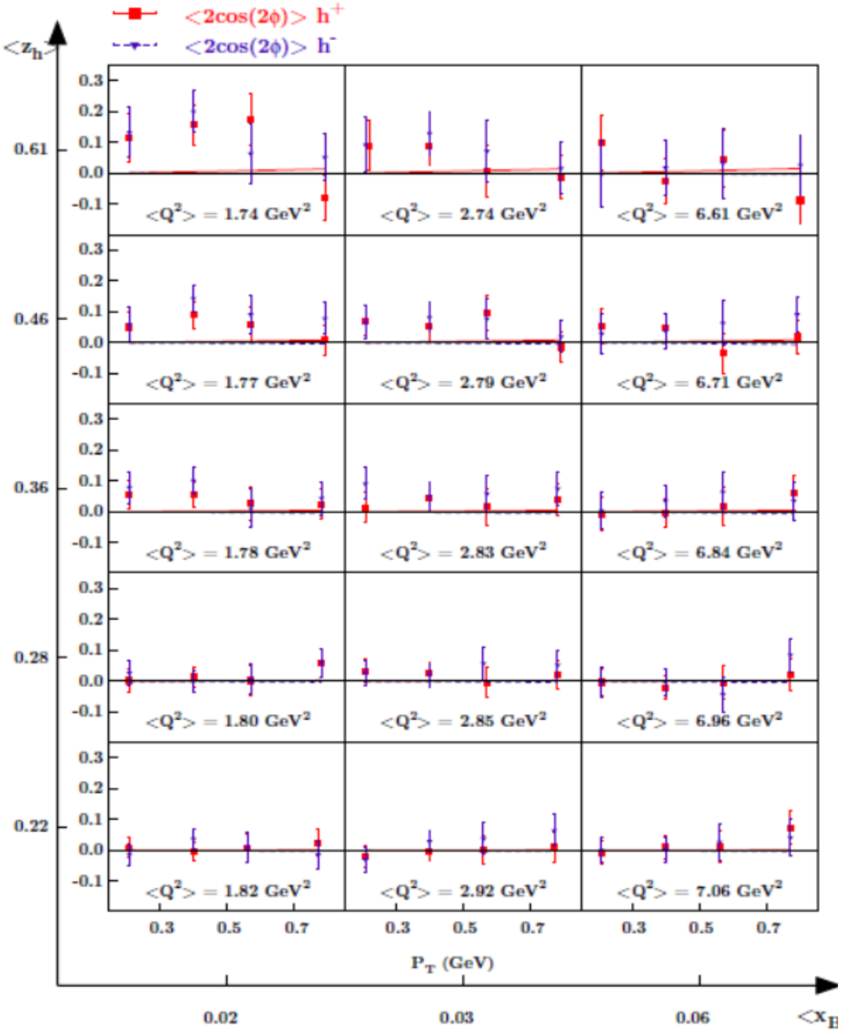
Echevarria, Idilbi, Kang, Vitev. Kang, Prokudin, Sun, Yuan

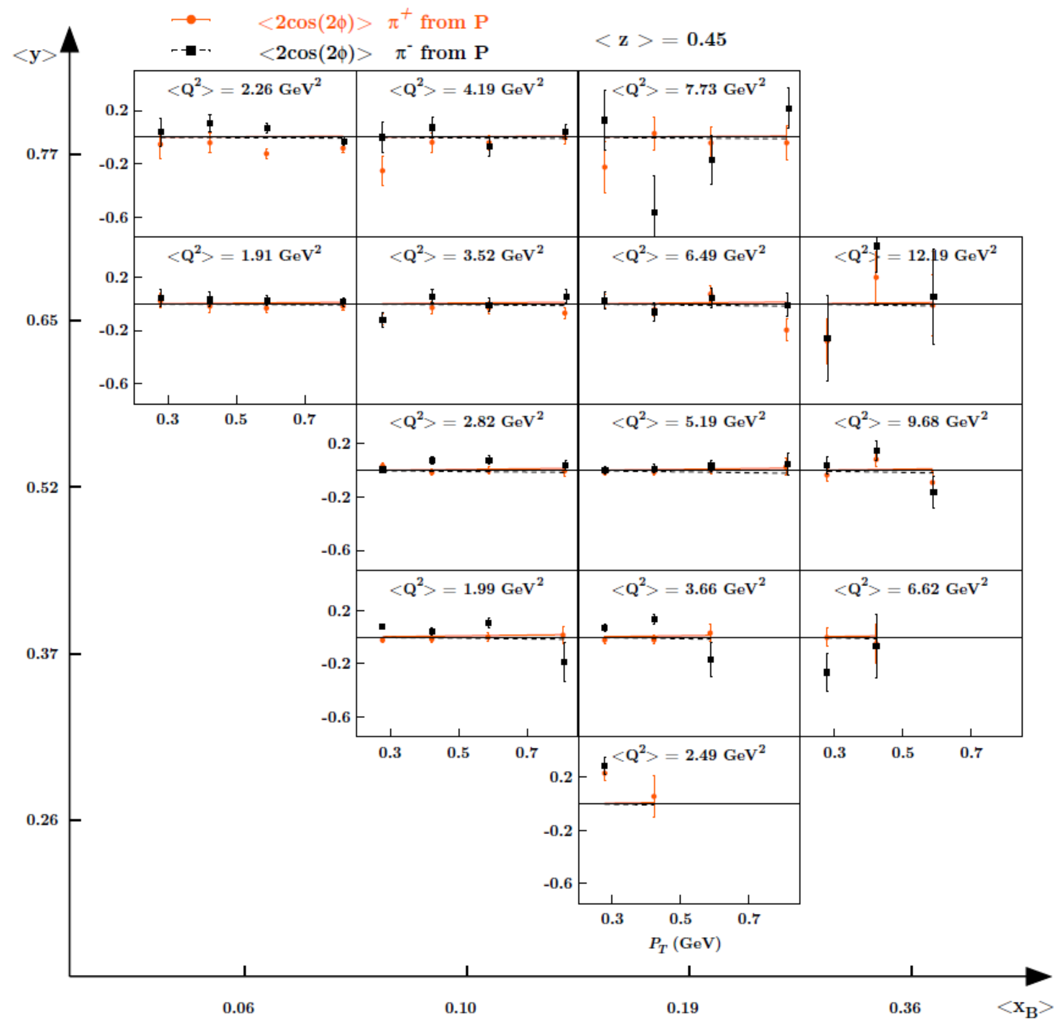
cos ϕ modulation





Boer-Mulders in $\cos 2\phi$ and in $\cos \phi$



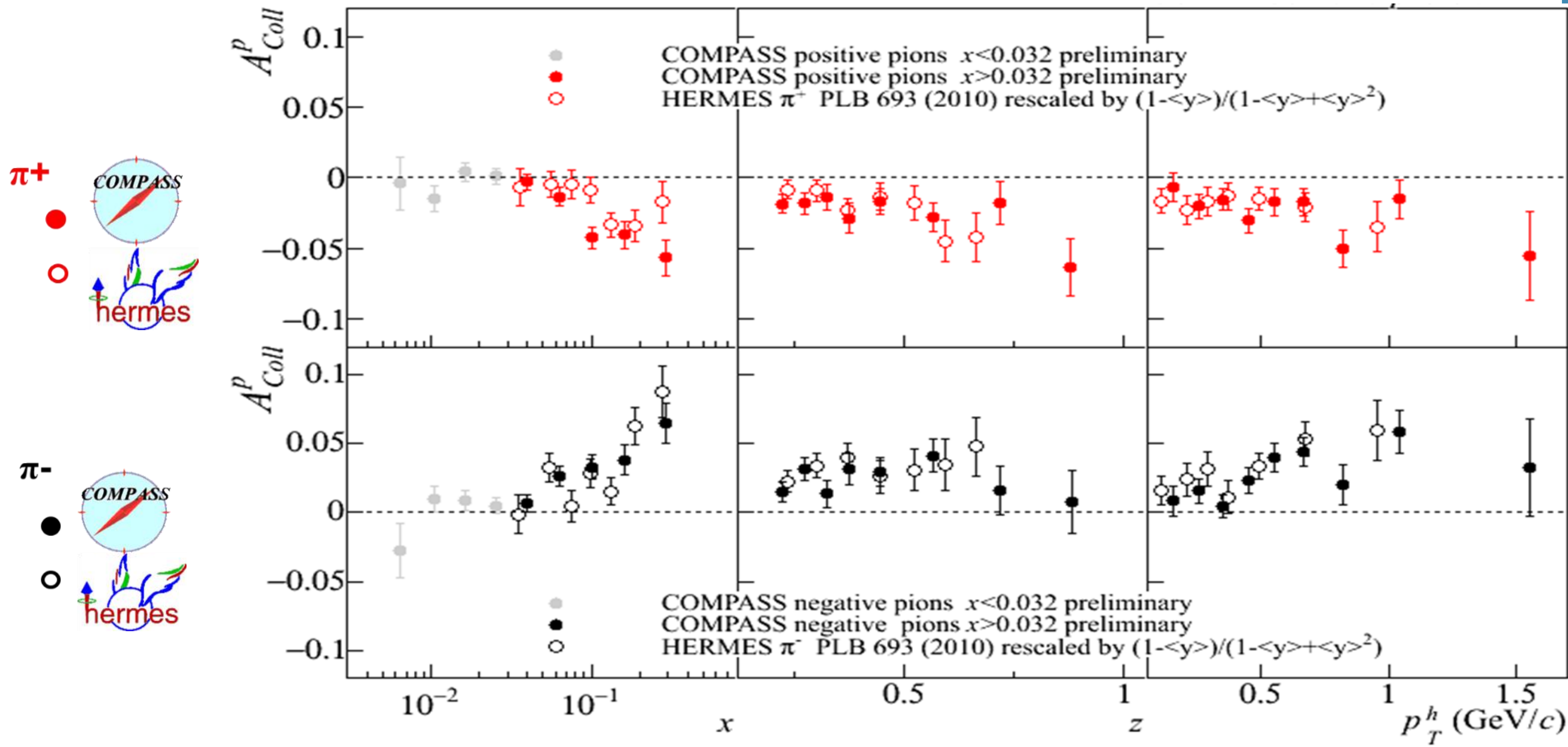


Collins asymmetry on proton

x > 0.032 region

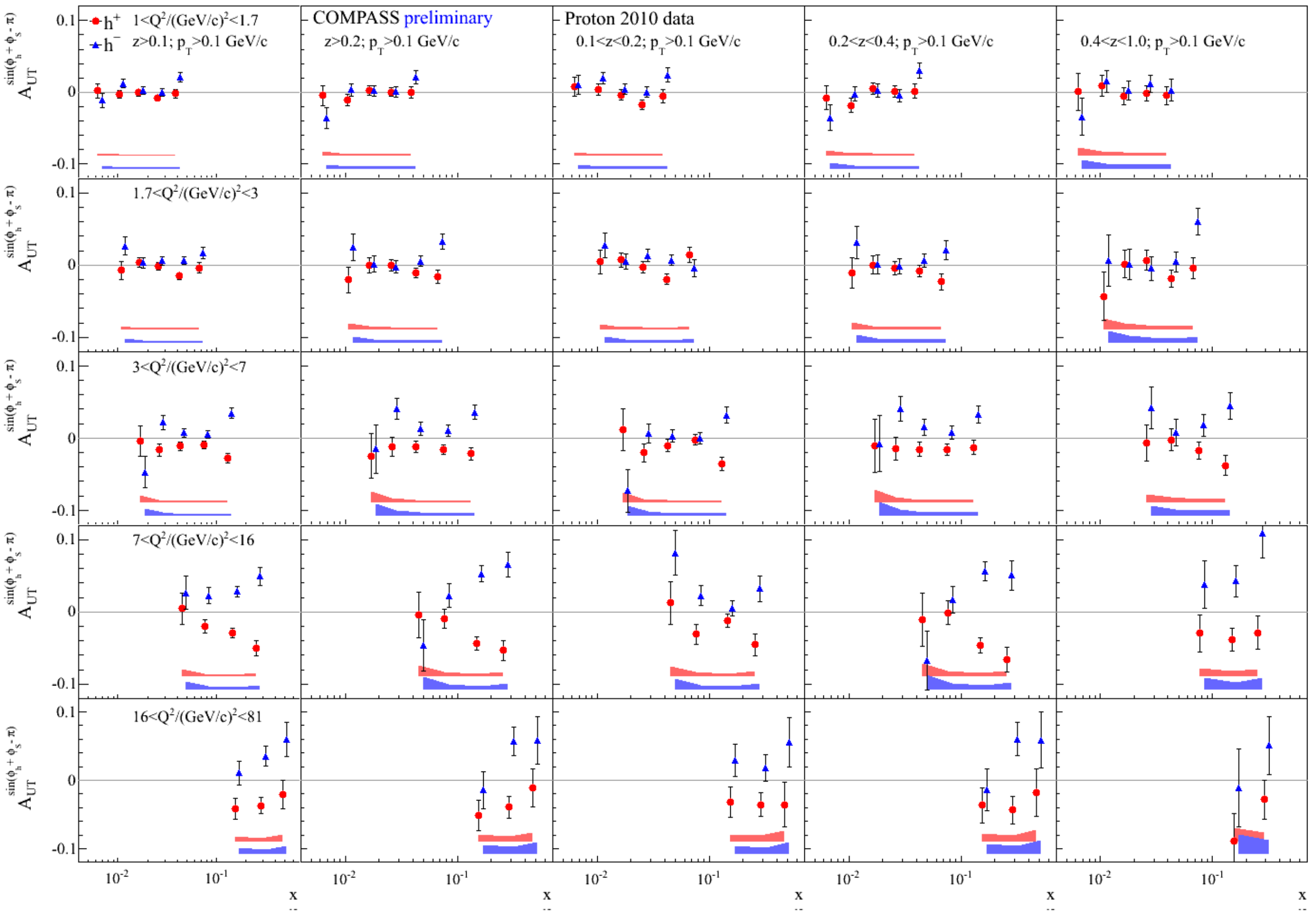
charged pions

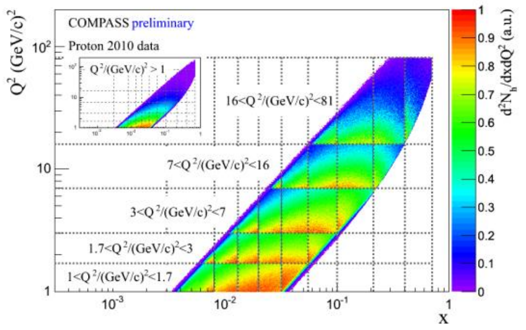
COMPASS and HERMES results



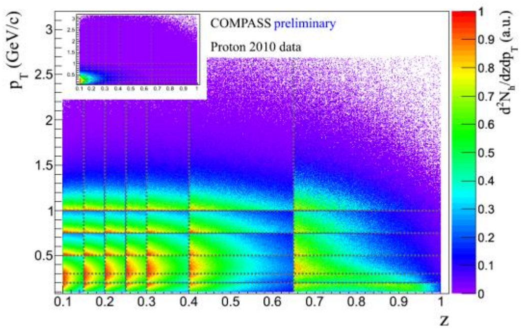
Collins asymmetry on proton. Multidimensional

Extraction of TSAs with a Multi-D $(x{:}\ Q^2{:}\ z{:}\ p_T)$ approach





One dense plot out of many



TMD PDFs

- The theoretical expression of TMDs has a more complicated structure of the gauge link, connecting two space-time points with a transverse separation

$$f_{q/N}(x,k_\perp) = \frac{1}{8\pi}\int dr^- \frac{dr_\perp^2}{(2\pi)^2} e^{-iMxr^-/2+ik_\perp\cdot r_\perp}$$

$$\langle N(P)|\bar{q}(r^-,r_\perp)\gamma^+ W[r^-,r_\perp;0]q(0)|N(P)\rangle|_{r^+\sim 1/\nu\to 0}$$

- The Wilson line W is no longer on the light-cone axis and may introduce a **process dependence**

Parity and Time reversal invariance ⇒

$$\left(f_{1Tq}^{\perp}\right)_{DY} = -\left(f_{1Tq}^{\perp}\right)_{SIDIS}$$

Most critical test to TMD approach to SSA