COMPASS studies of TMDs; recent results and future perspectives

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SAR WORS 2019 – SARDINIAN WORKSHOP ON SPIN STUDIES

JULY 8-10, CAGLIARI ITALY.

Muon beam: SIDIS setup

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

two stages spectrometer

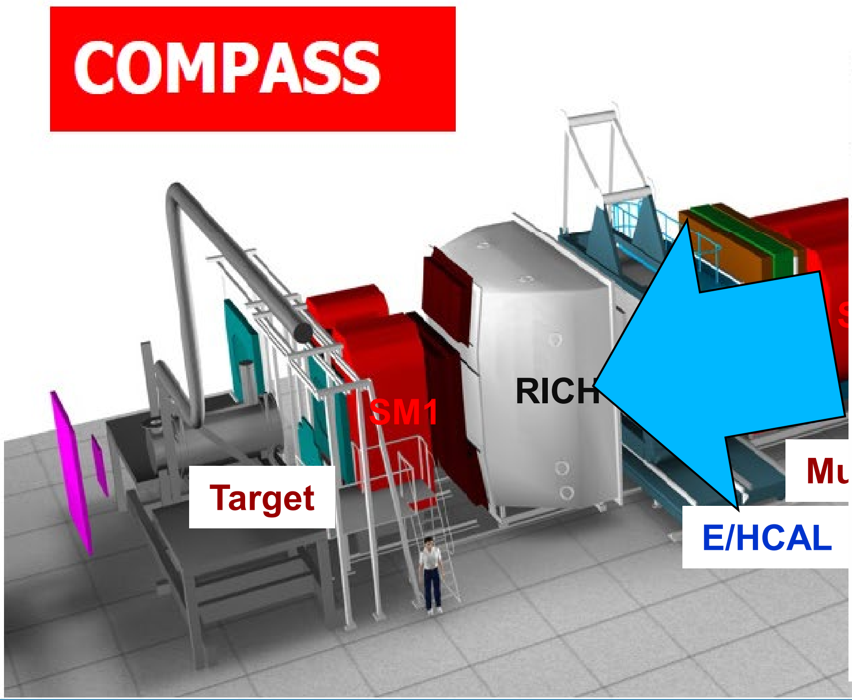
Large Angle Spectrometer (SM1)

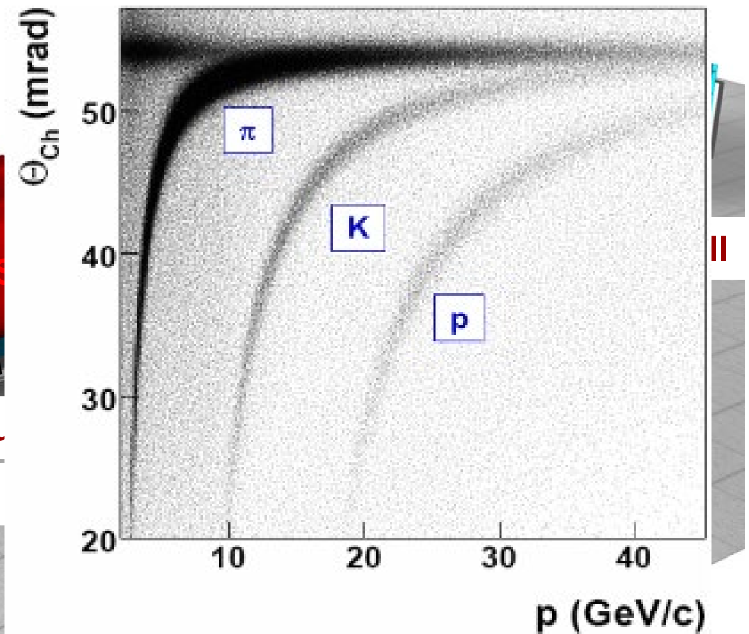
Small Angle Spectrometer (SM2)

radiator C_4F_{10}

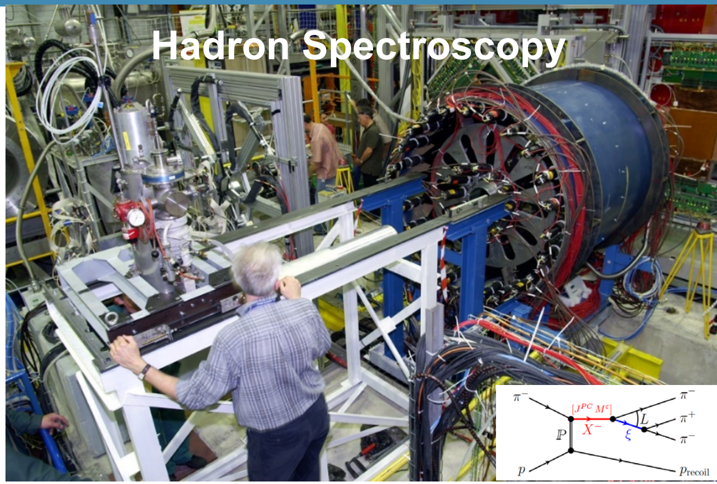
threshold: π ~2 GeV/c

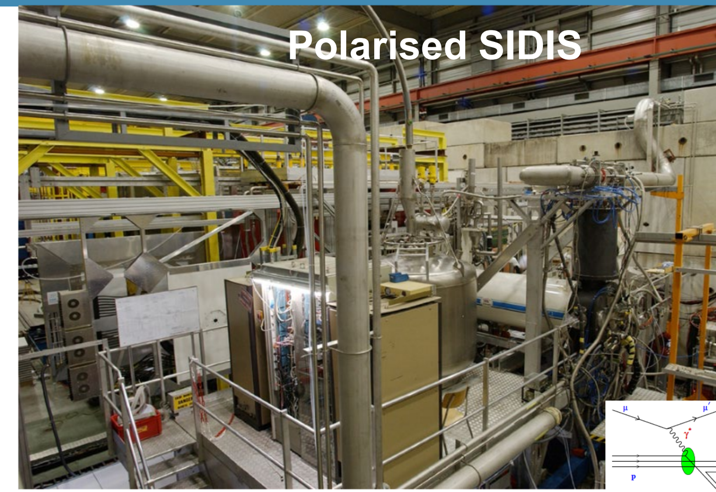
K ~ 10 GeV/c



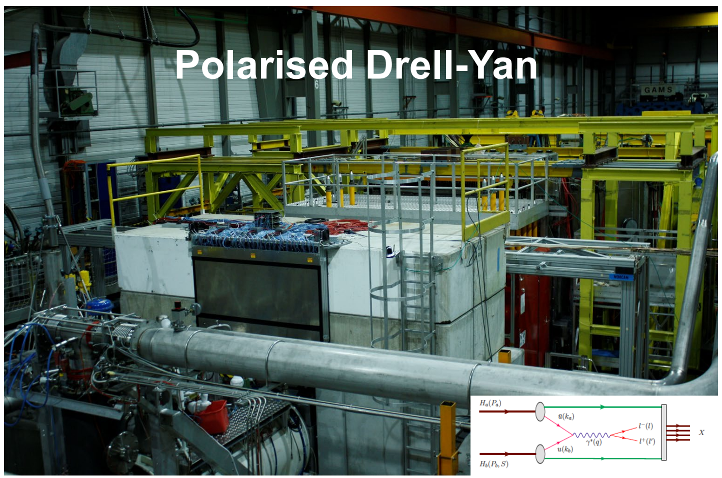


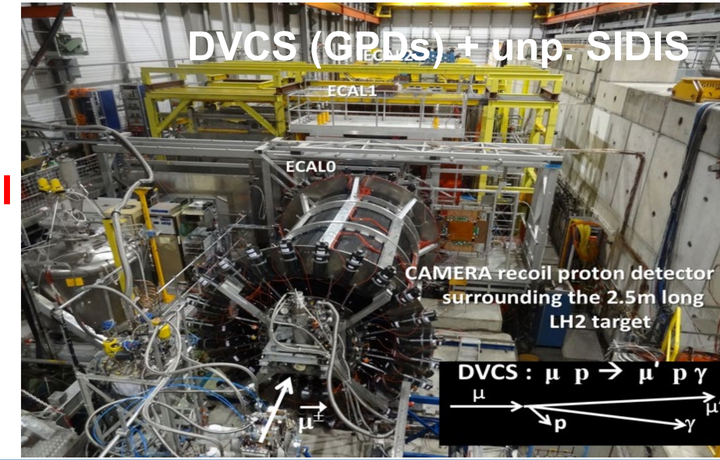
COMPASS target area





COMPASS-I
1997-2011



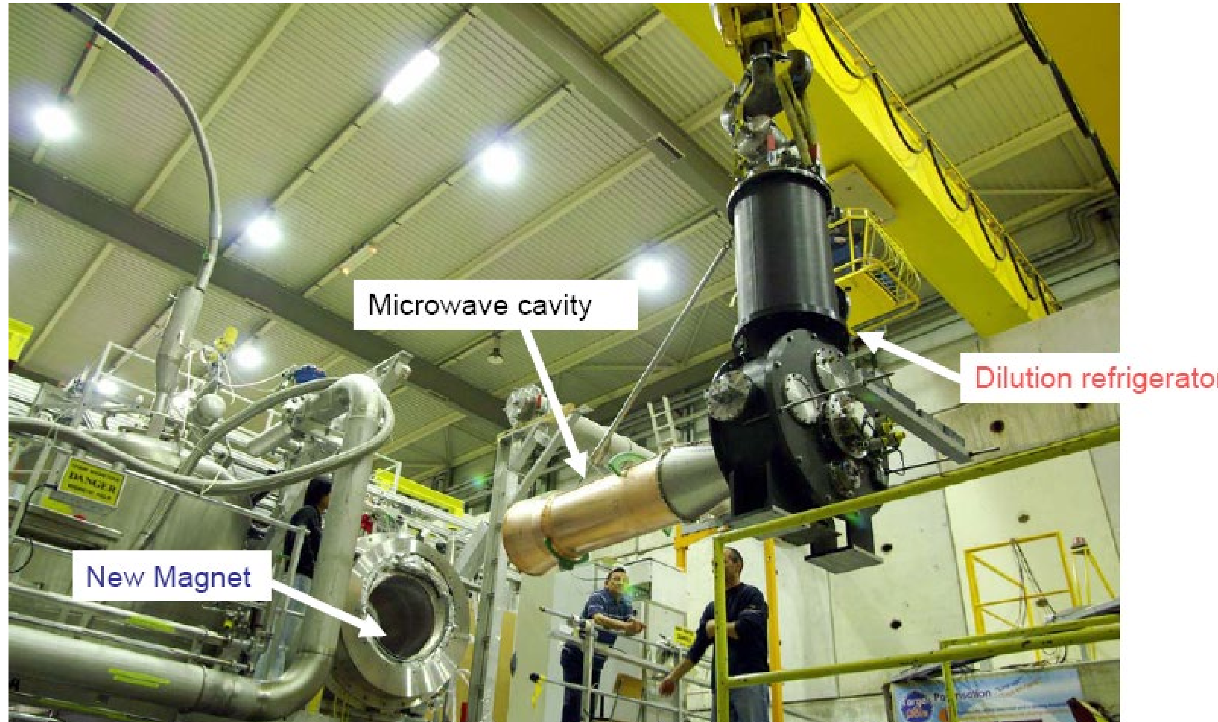


COMPASS-II
2012-2020

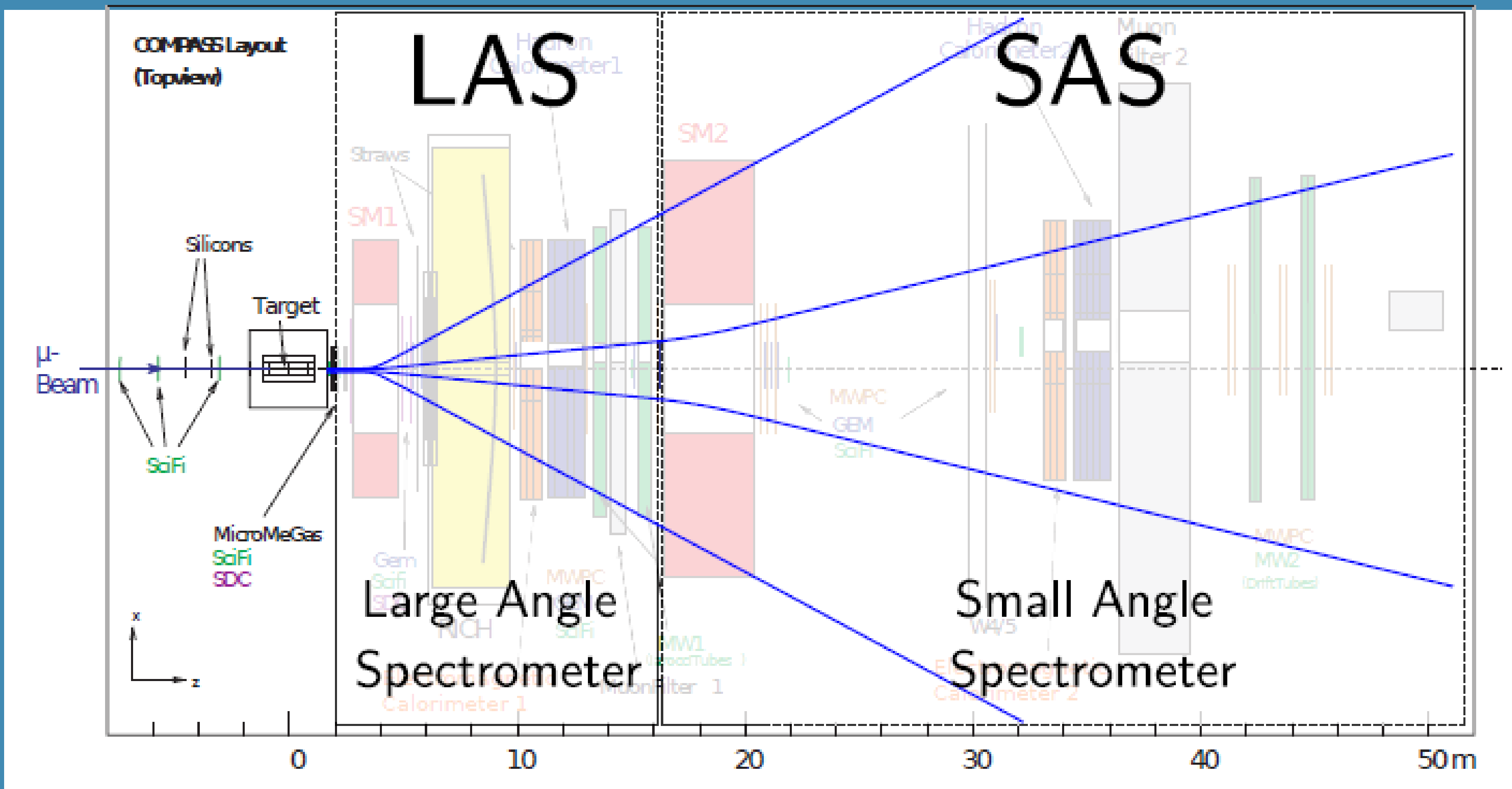
Operations on the target area

Targets

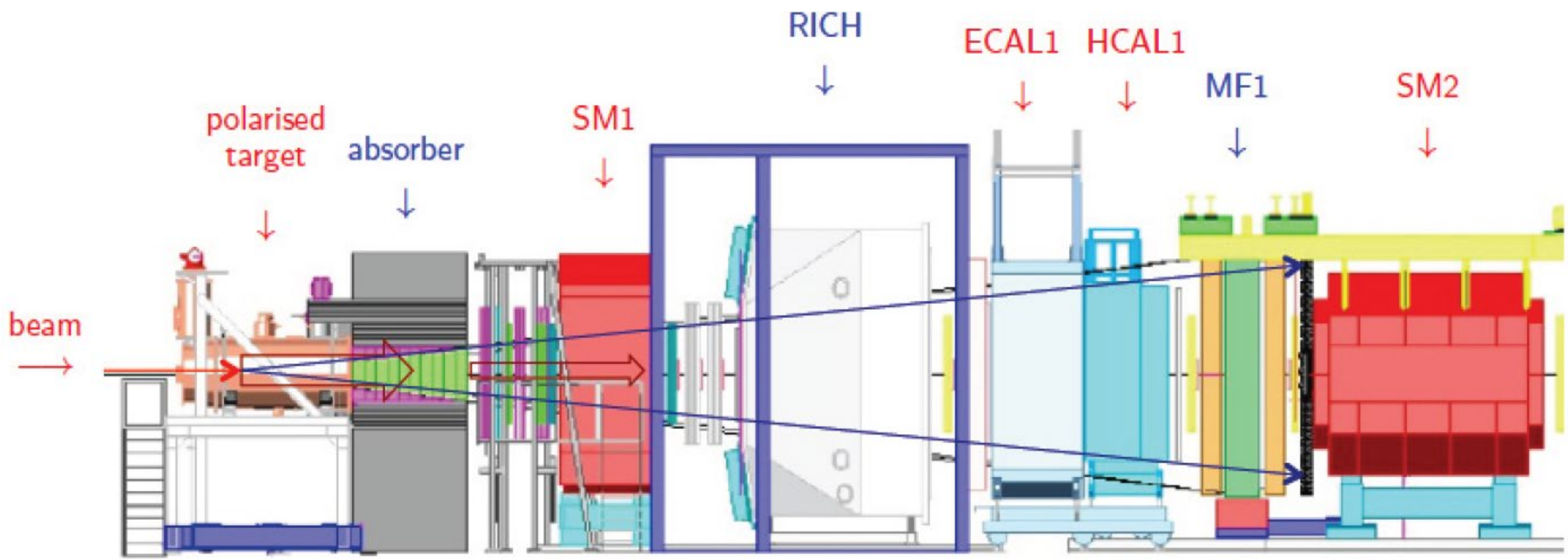

27 09 2012


Microwave cavity
Dilution refrigerator
New Magnet

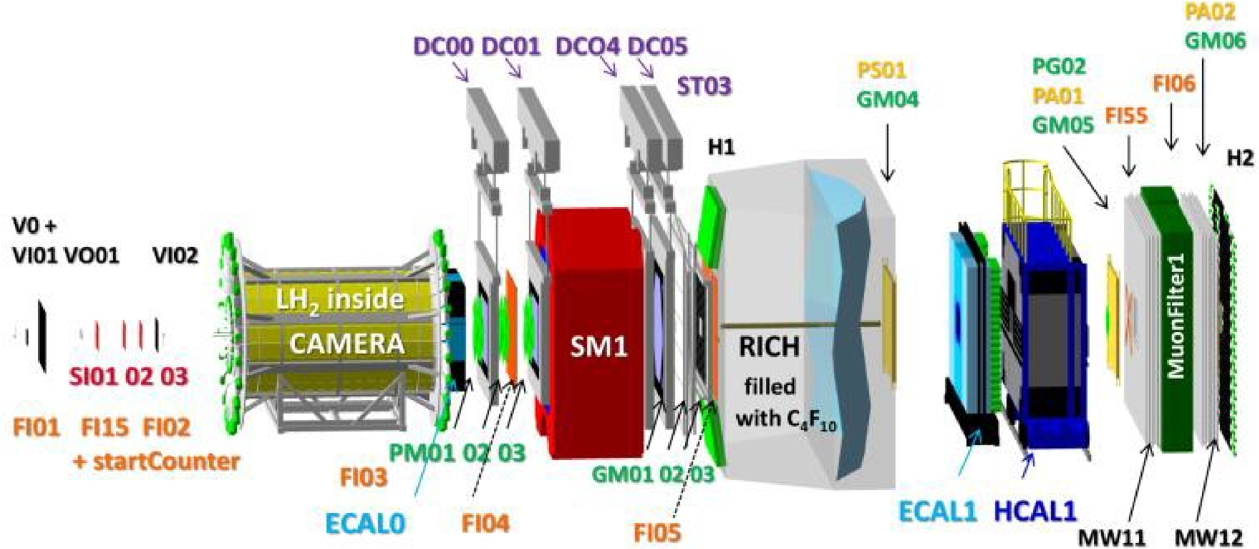
Two stage spectrometer

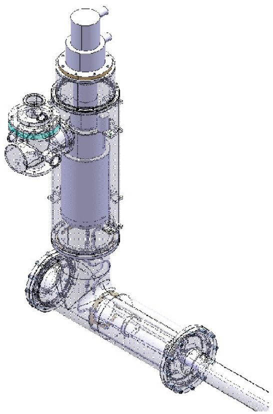


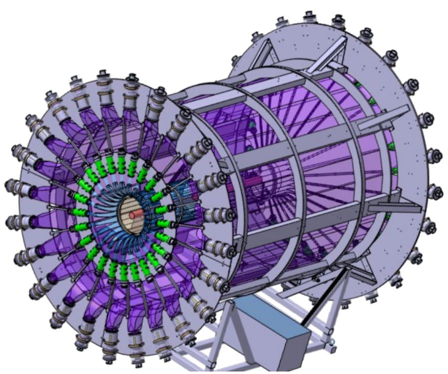
Hadron beam: Drell-Yan setup

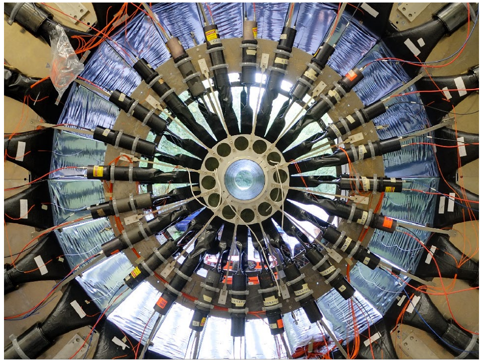


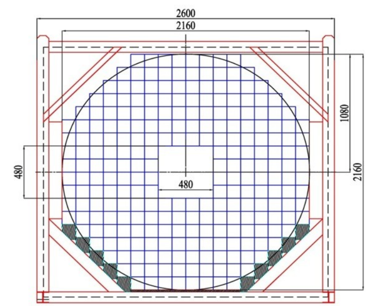
Muon beam – DVCS setup



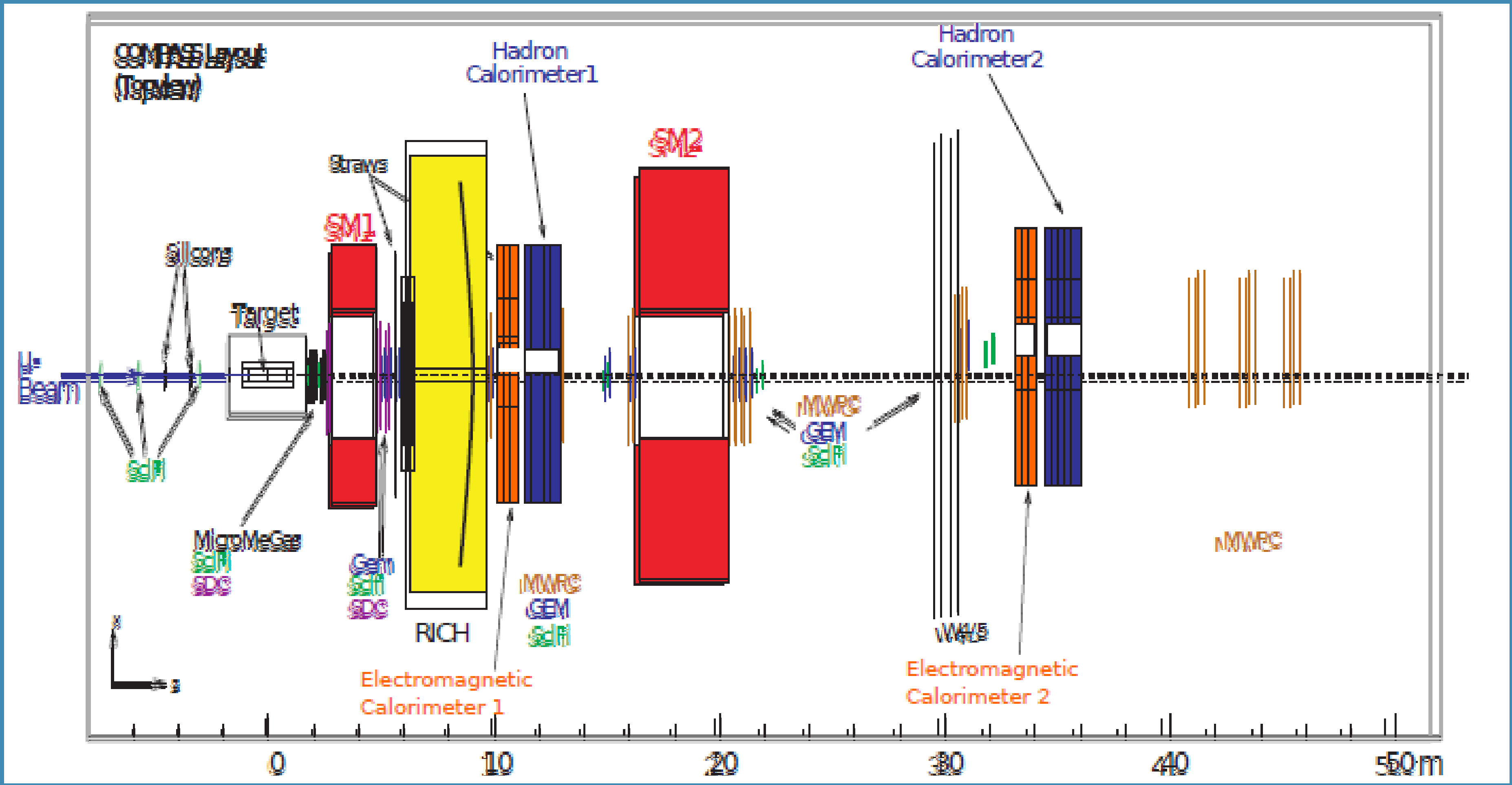




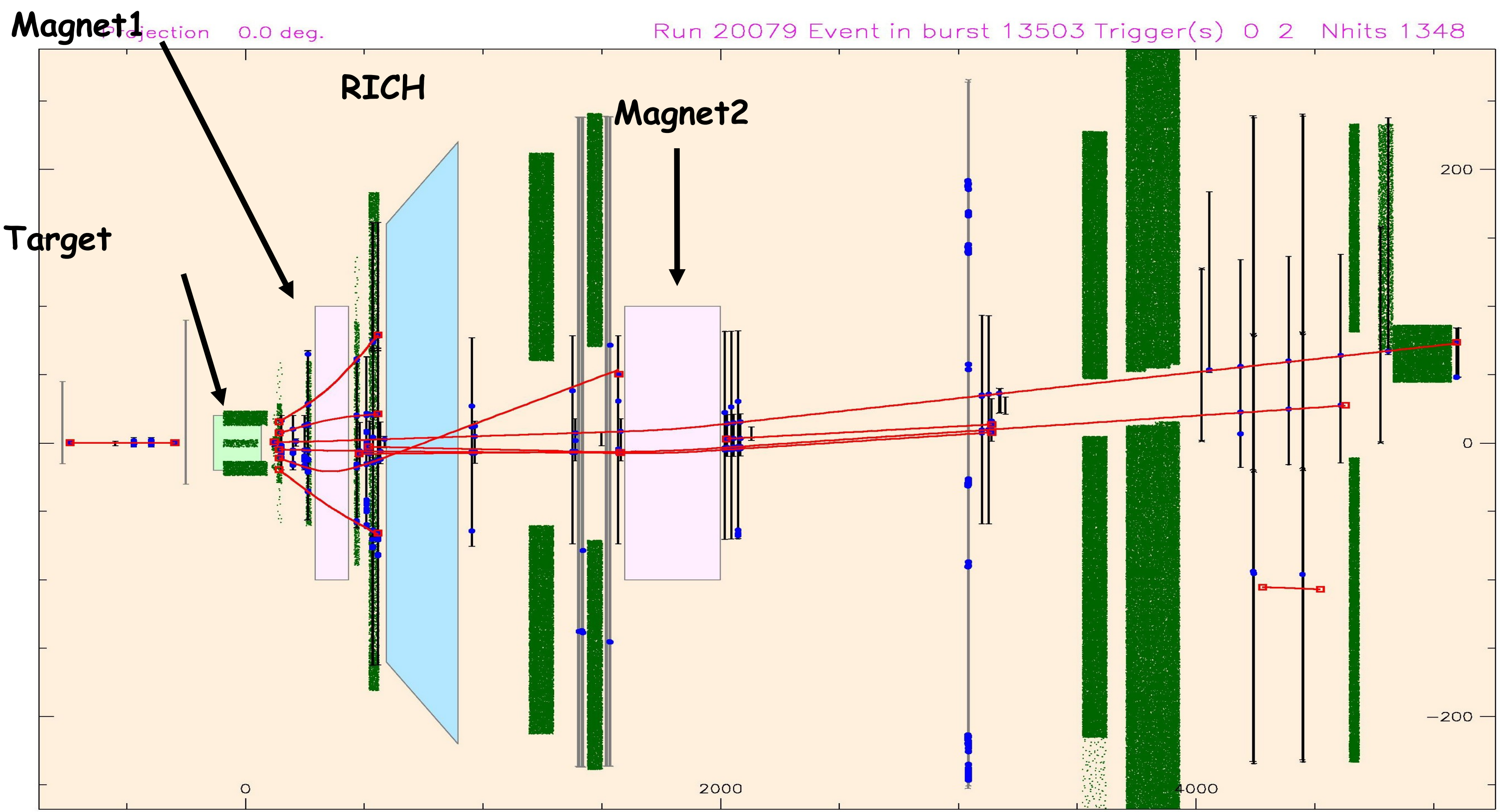




Spectrometer elements

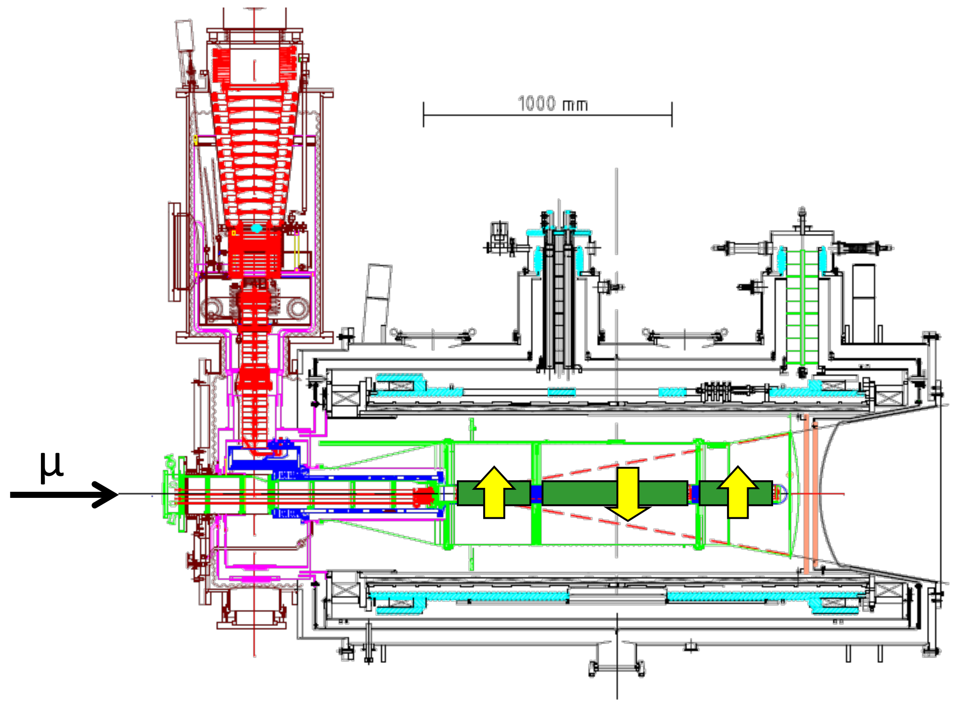


Spectrometer: momentum determination

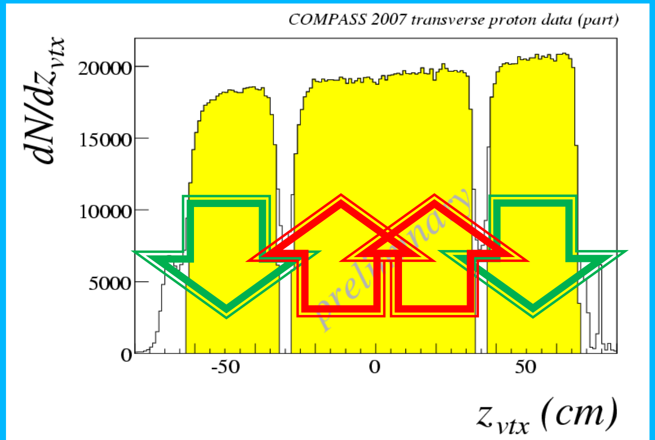


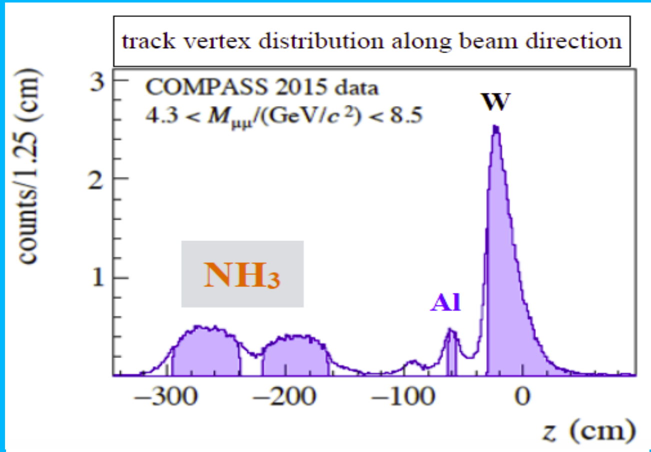
the polarized target system (>2005)

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

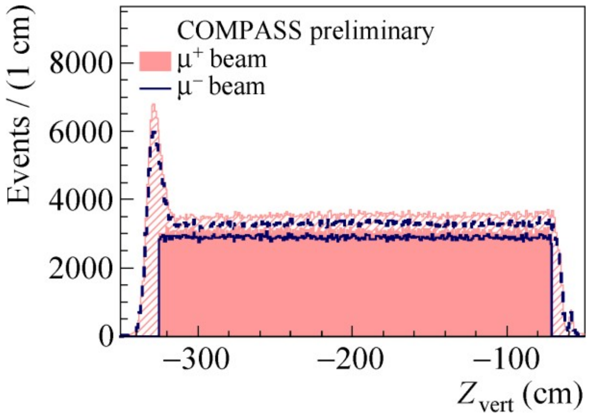


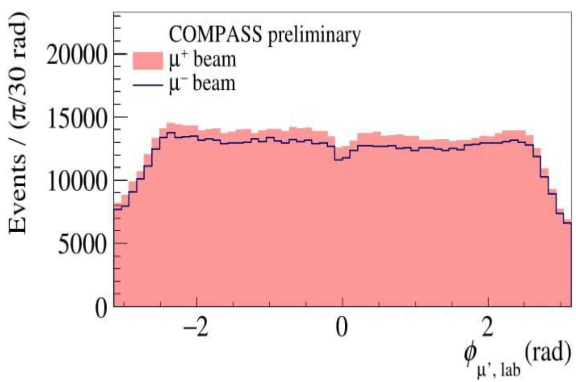
solenoid 2.5T
dipole magnet 0.6T

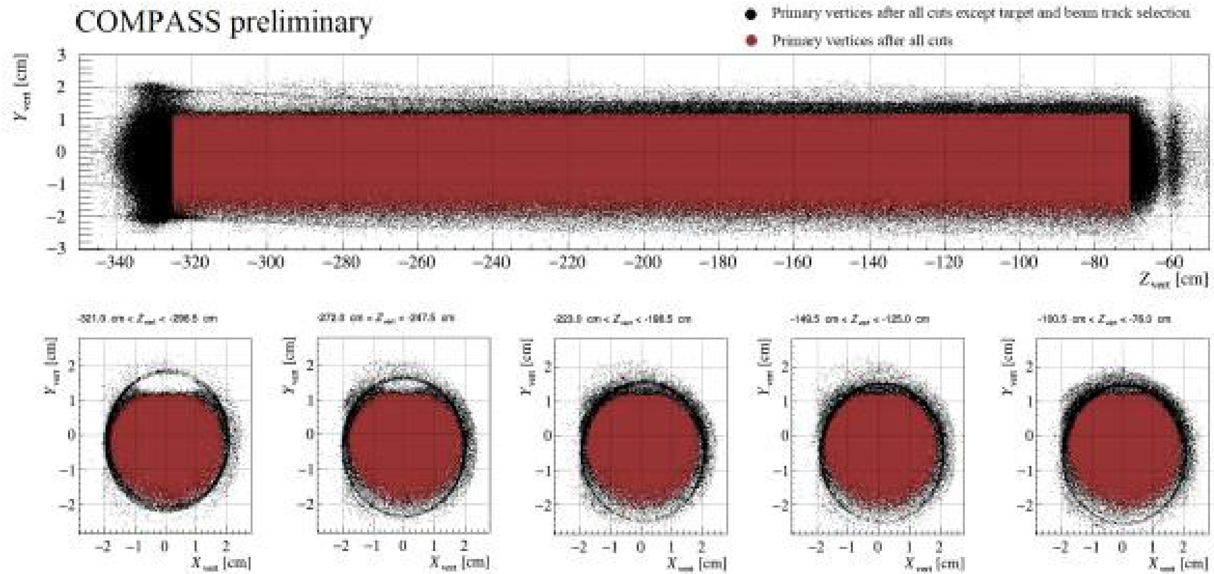


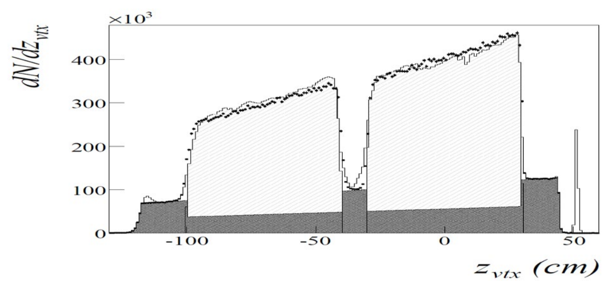


Vertex determination



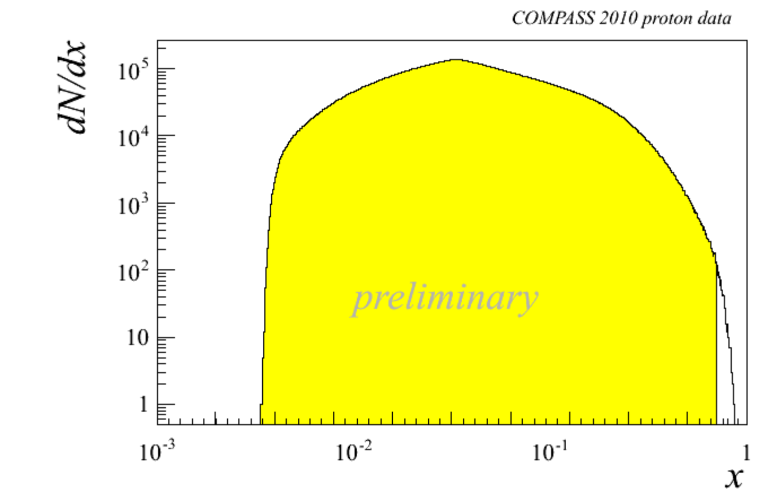


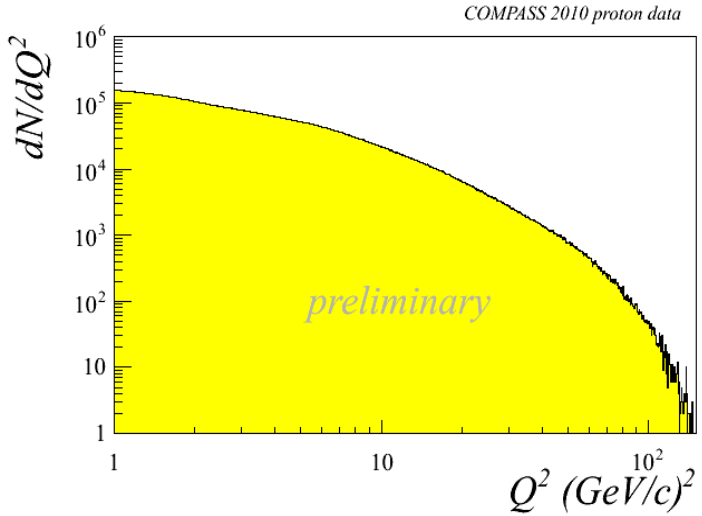


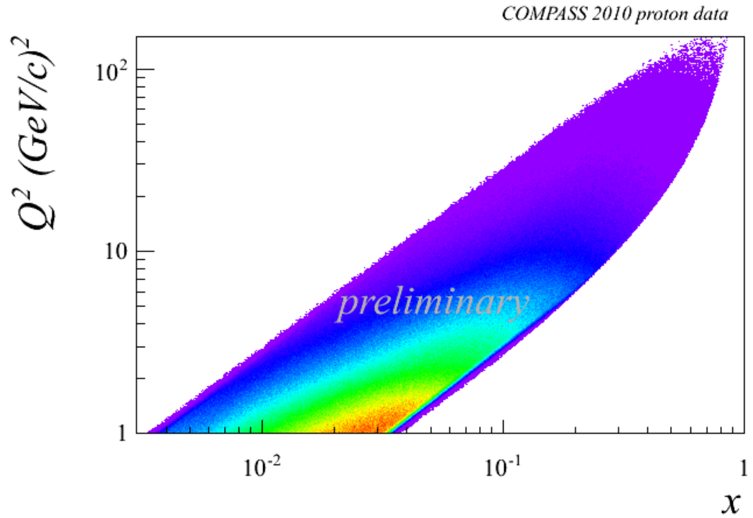


Kinematic distributions

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



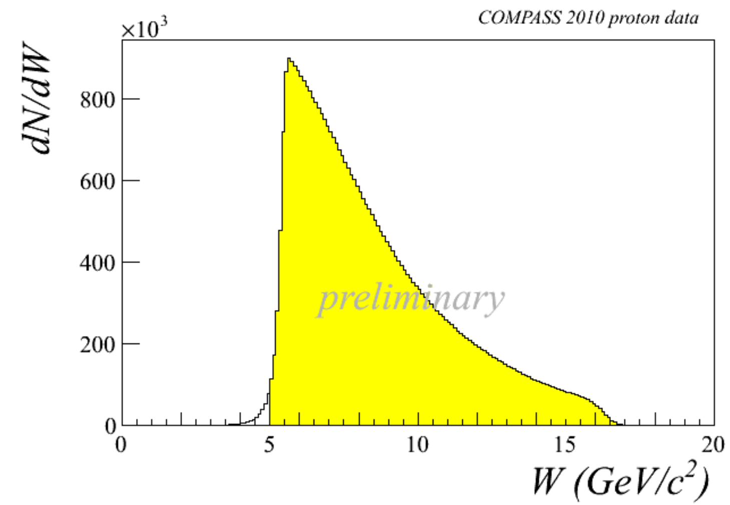


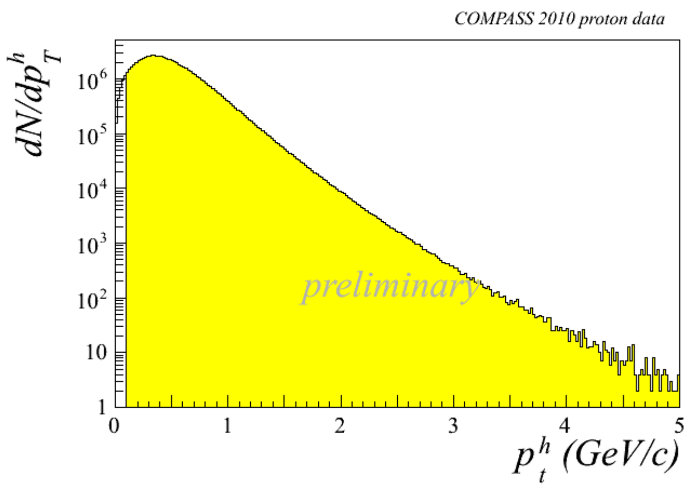


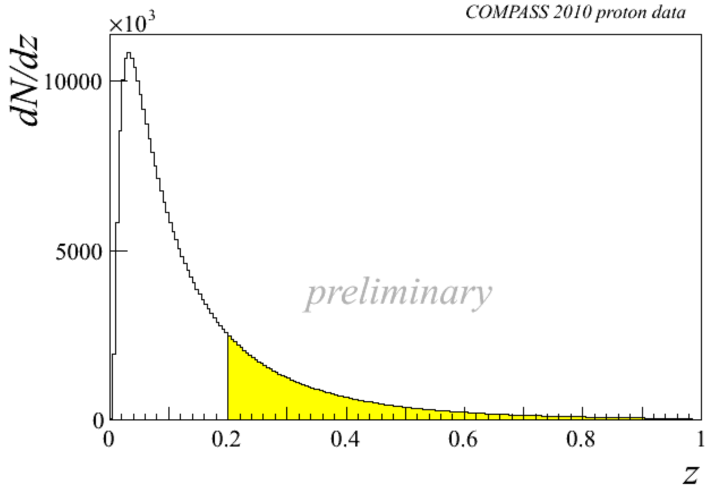
Kinematic distributions - 2

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

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







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 $\Delta g/g$

Measurements with the target transversely polarized:

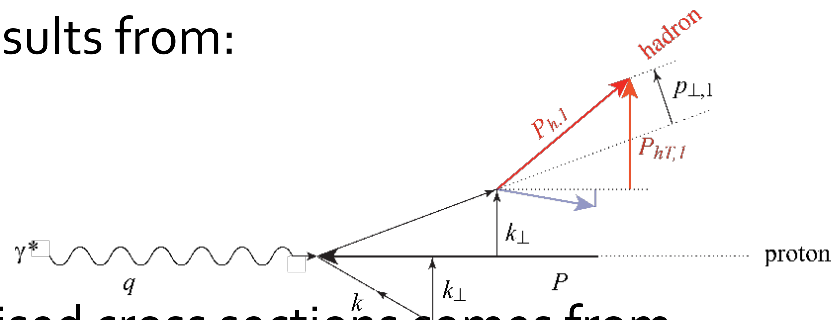
Year	Obs	
2005	$A^{h}_{Siv,d}, A^{h}_{Col,d}$	First ^{6}LiD data
2006	$A^{h}_{Siv,d}, A^{h}_{Col,d}$	Full ^{6}LiD statistics
2009	$A^{\pi^{\pm}, K^{\pm}, K^{0}_{S}}_{Siv,d}, A^{\pi^{\pm}, K^{\pm}, K^{0}_{S}}_{Col,d}$	Full ^{6}LiD statistics
2010	$A^{h}_{Siv,p}, A^{h}_{Col,p}$	2007 NH_3 data
2012	$A^{sin\phi_{RS}}_{UT,d}, A^{sin\phi_{RS}}_{UT,p}$	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 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	$dn^h/(dN^\mu dz\, dp_T^2)$	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_{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

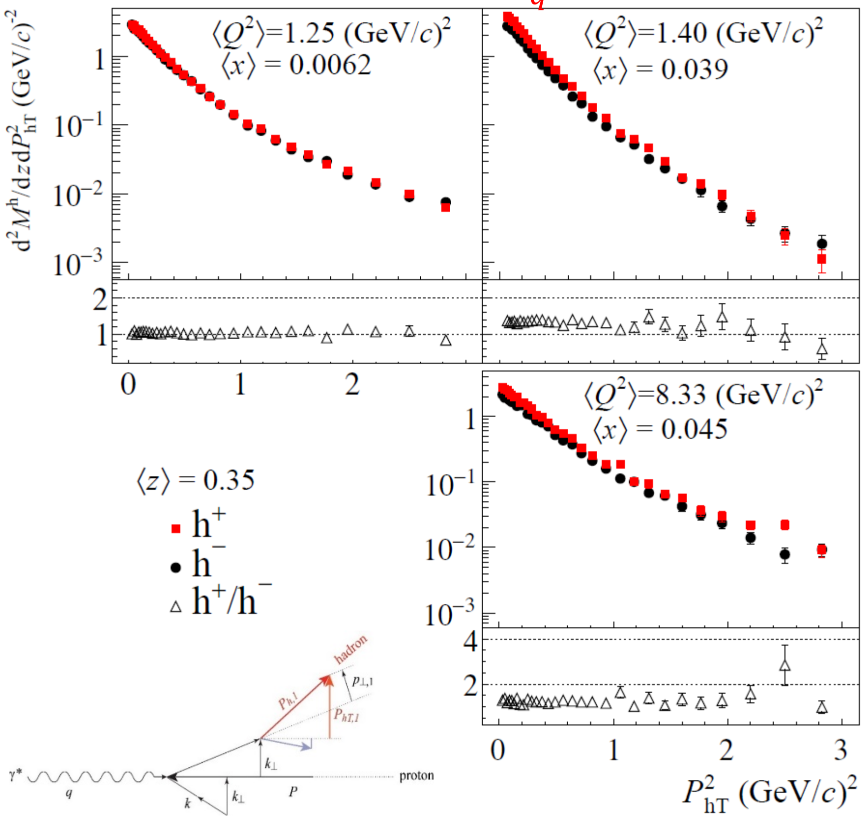
- Difficult measurements were one has to correct for the apparatus acceptance

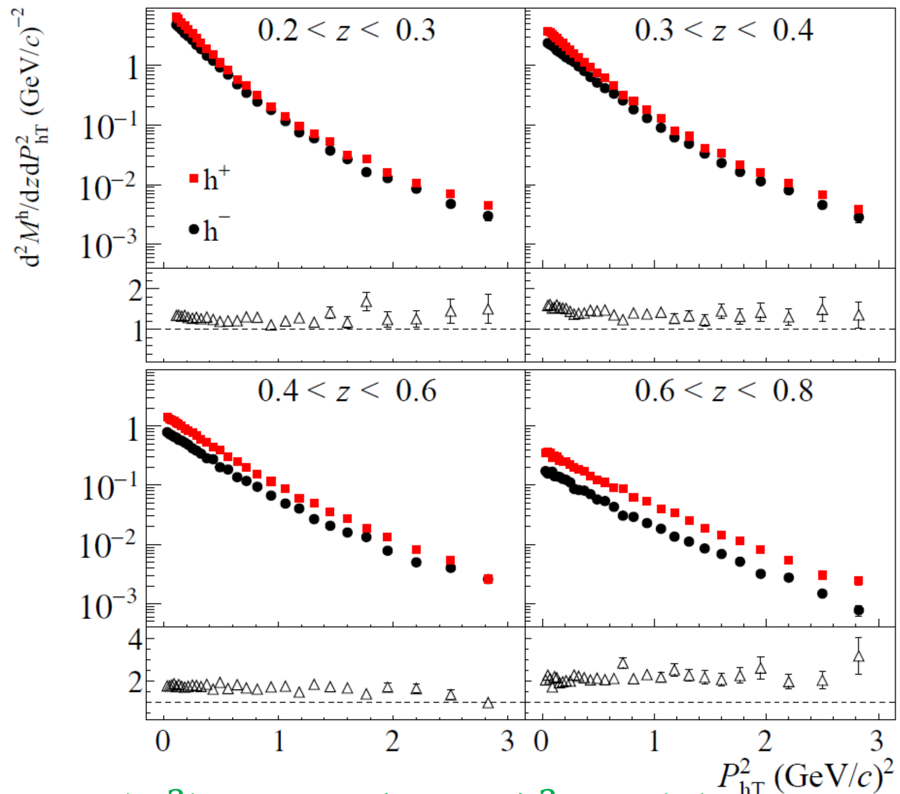
- COMPASS and HERMES have
  - results on ^6LiD $(\sim d)$ and preliminary on p from COMPASS
  - d and p from HERMESS

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

Positive vs Negative charged hadrons (^{6}LiD)

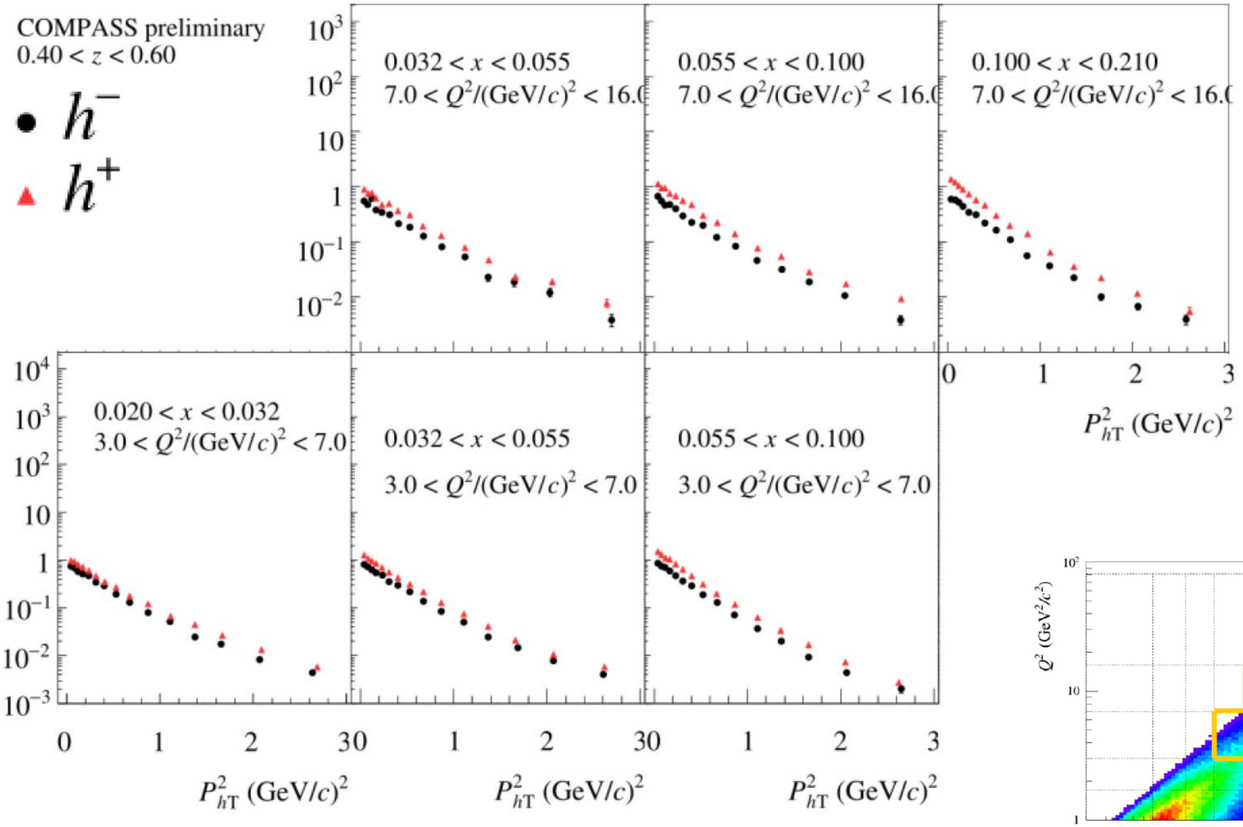
$$F_{UU}^{h}(x,z,P_{hT}^{2};\,Q^{2}) = x\sum_{q} e_q^2 \int d^2\vec{k}_\perp d^2\vec{p}_\perp \delta(\vec{p}_\perp + z\vec{k}_\perp - \vec{P}_{hT})\; f_1^q(x,k_\perp^2;Q^2) D_1^{q\to h}(z,p_\perp^2;Q^2)$$

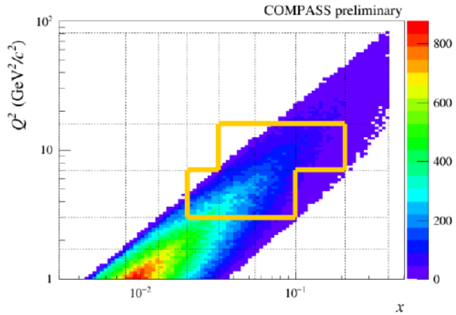




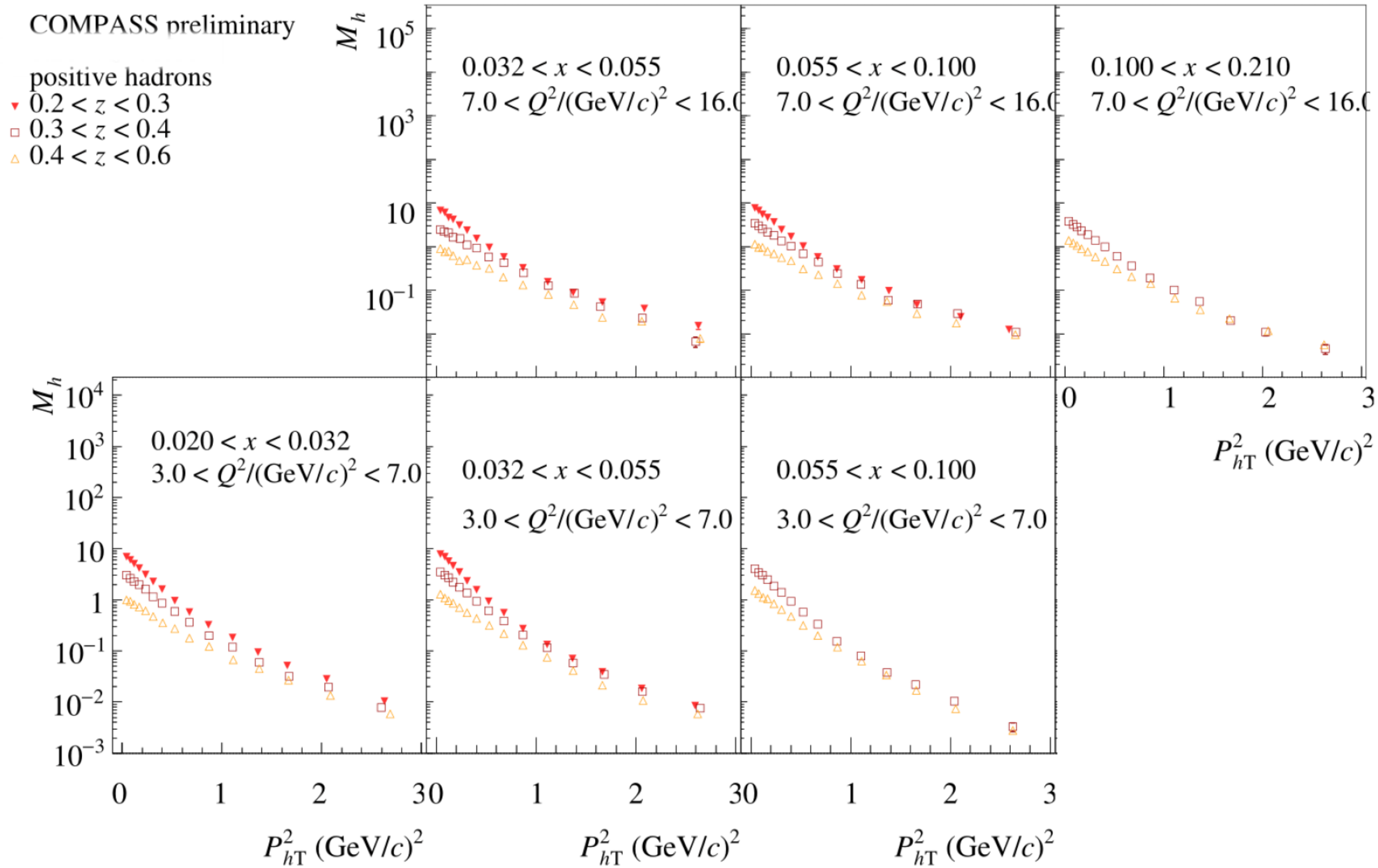
$\langle Q^2\rangle = 9.78\ (\mathrm{eV}\ \ /c)^2$ and $\langle x\rangle = 0.149$

Positive vs Negative charged hadrons (p)

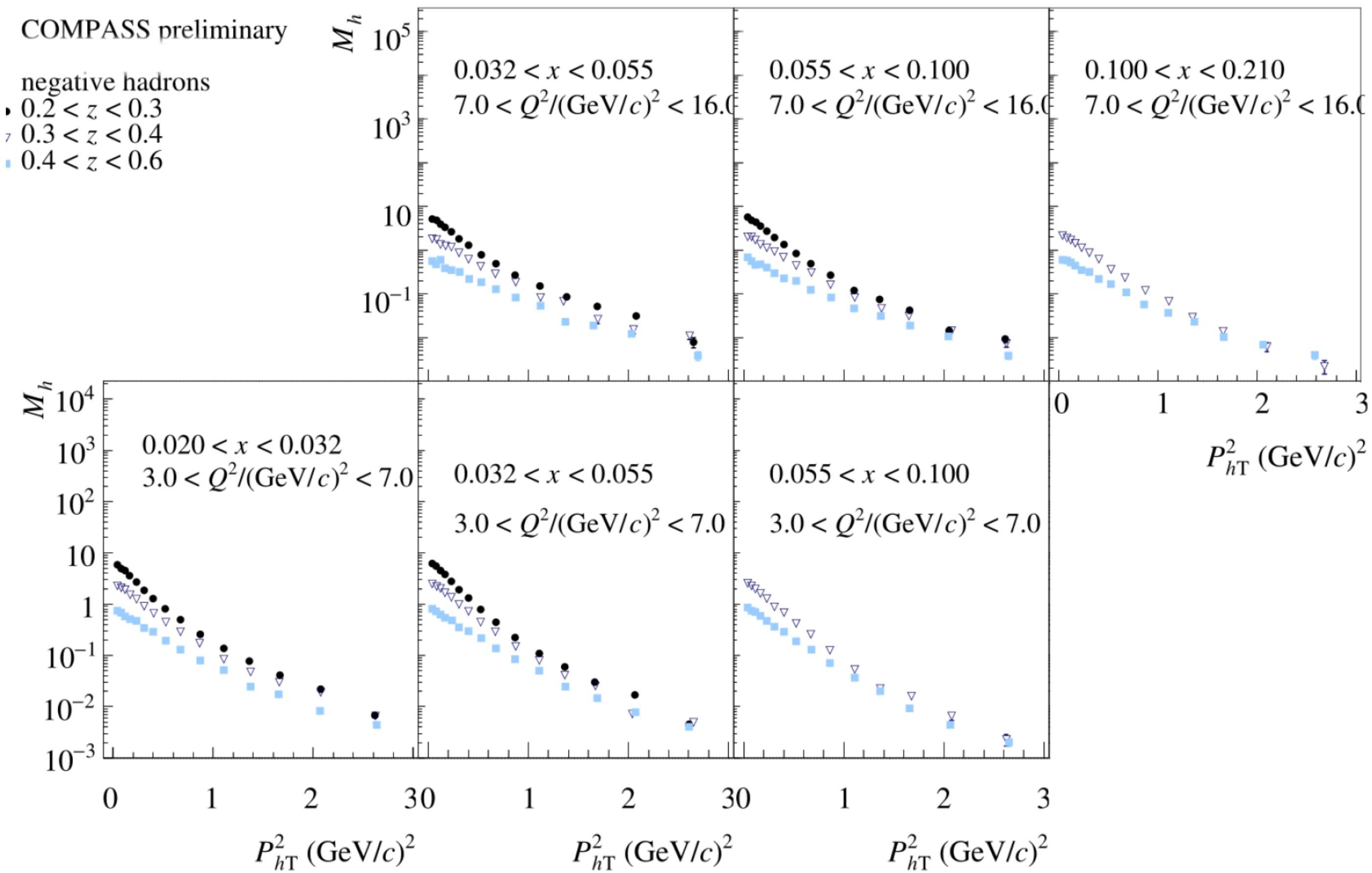




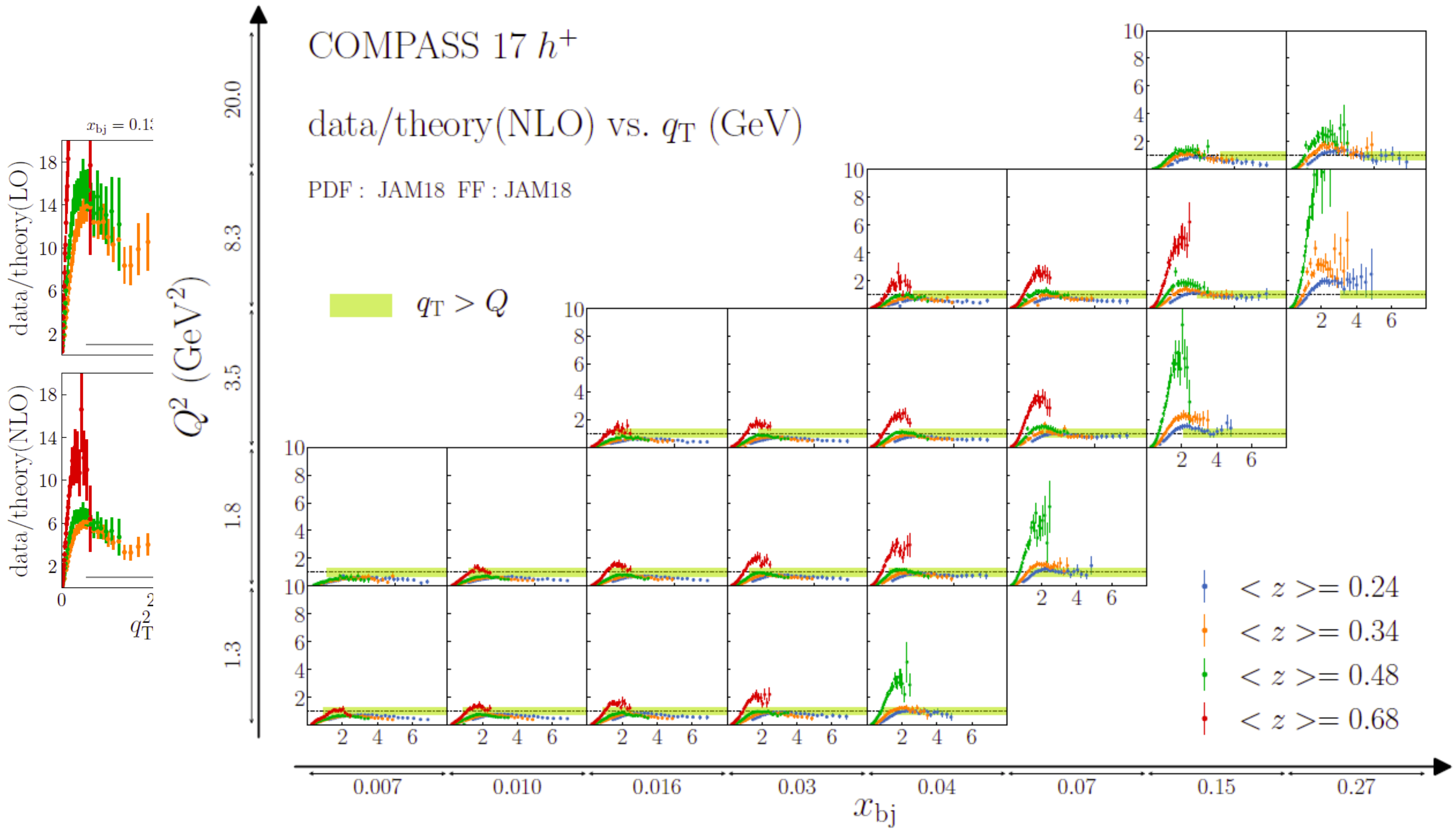
Positive charged hadrons (p)



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:

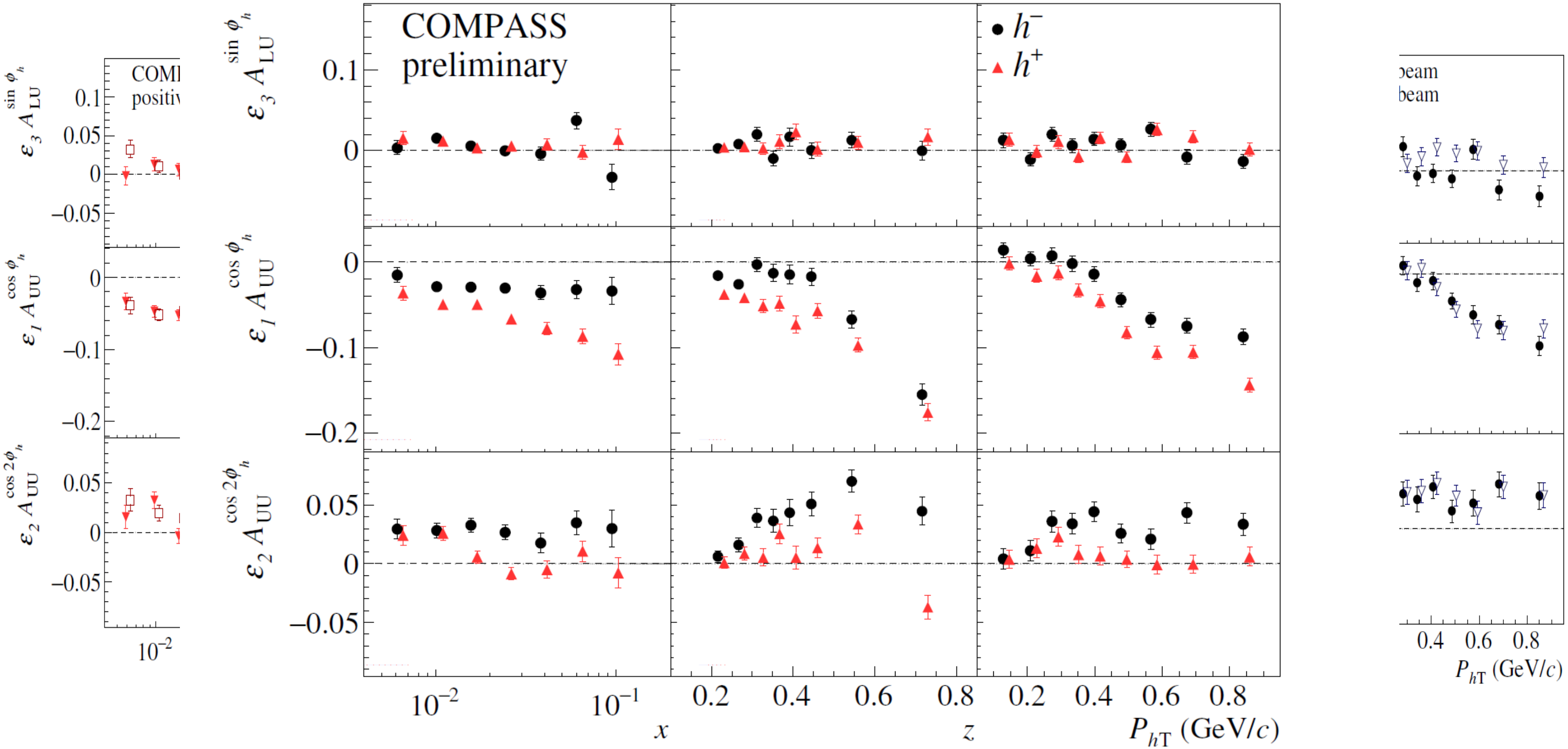
$$F_{UU}^{\cos\phi_h} = -\frac{2M}{Q} C\left[\frac{\hat{h}\cdot\vec{k}_\perp}{M} f_1 D_1 - \frac{p_\perp k_\perp}{M}\frac{\vec{P}_{hT} - z\left(\hat{h}\cdot\vec{k}_\perp\right)}{zM_h M} h_1^\perp H_1^\perp\right] + \text{twists} > 3$$

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

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

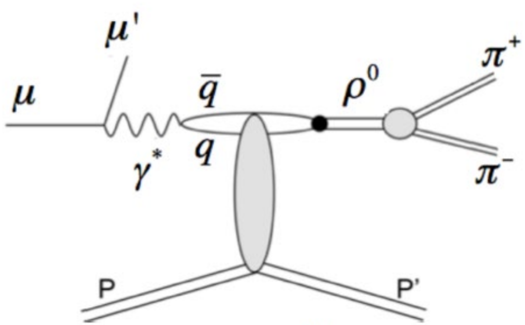
$$F_{\text{Cahn}}^{\cos 2\phi_h} \approx \frac{2}{Q^2} C\left[\left\{2\left(\hat{h}\cdot\vec{k}_\perp\right)^2 - k_\perp^2\right\} f_1 D_1\right]$$

Azimuthal modulations on p

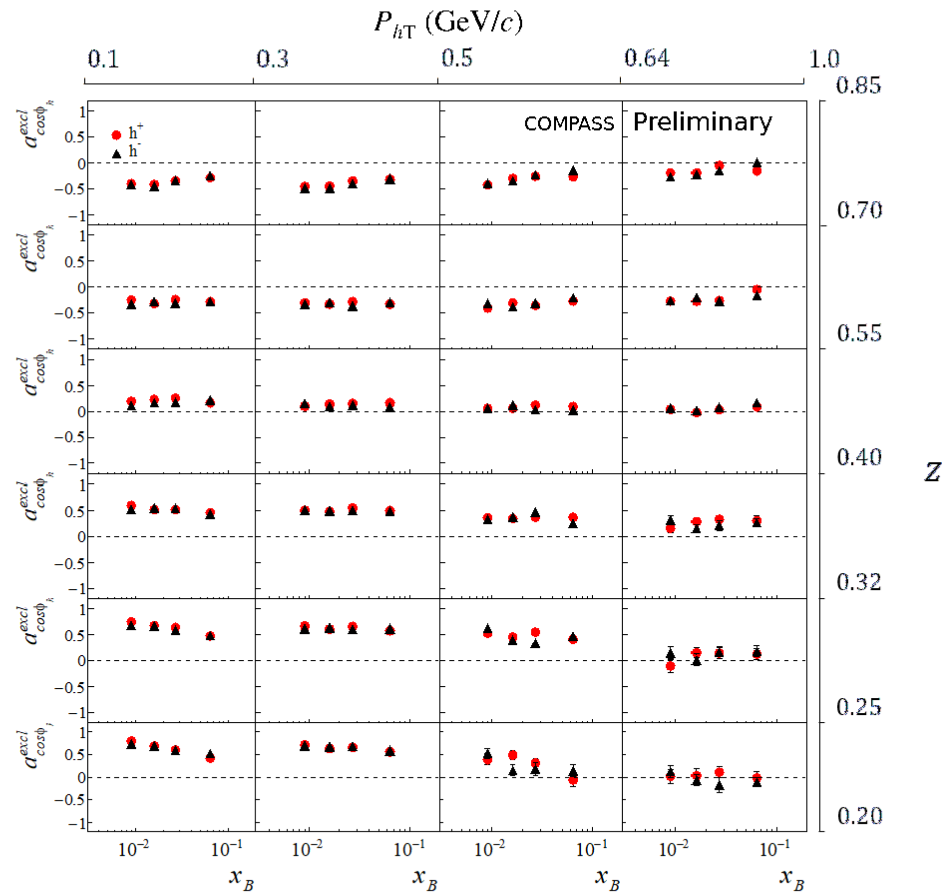


Contribution of diffractive VMs

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

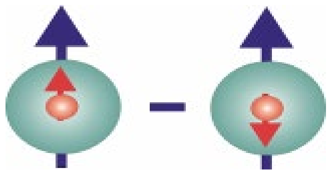


The diffractive ρ^0 production and decay.



Transversity PDF

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



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

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……………… $2|h_1^q| \leq f_1^q + g_1^q$ *Soffer, PRL 74 (1995)*
- first moments: tensor charge……… $\delta q(Q^2) = \int_0^1 dx[h_1^q(x) - h_1^{\bar{q}}(x)]$
- 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"

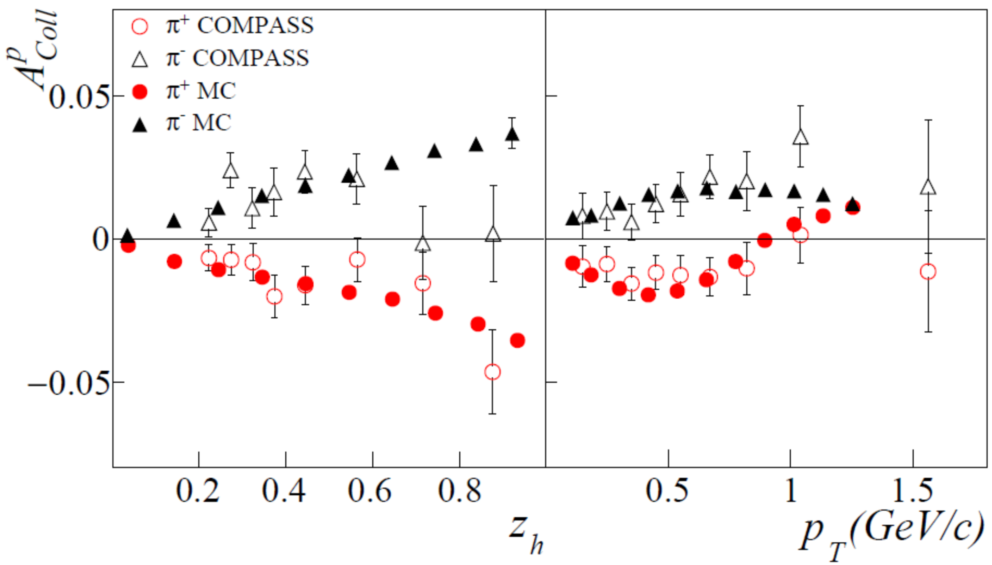
$\ell N^{\uparrow} \rightarrow \ell' \text{ h X}$ — **"Collins" asymmetry**
"Collins" Fragmentation Function

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

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

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

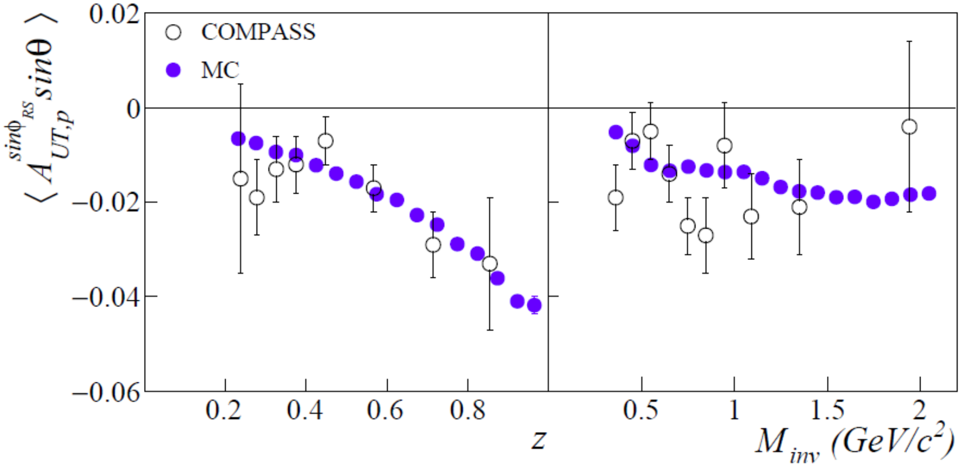
Albi Kerbizi @ DSPIN17 http://theor.jinr.ru/~spin/2017/
Phys. Rev. D 97, 074010 (2018)/**arXiv:1802.00962**

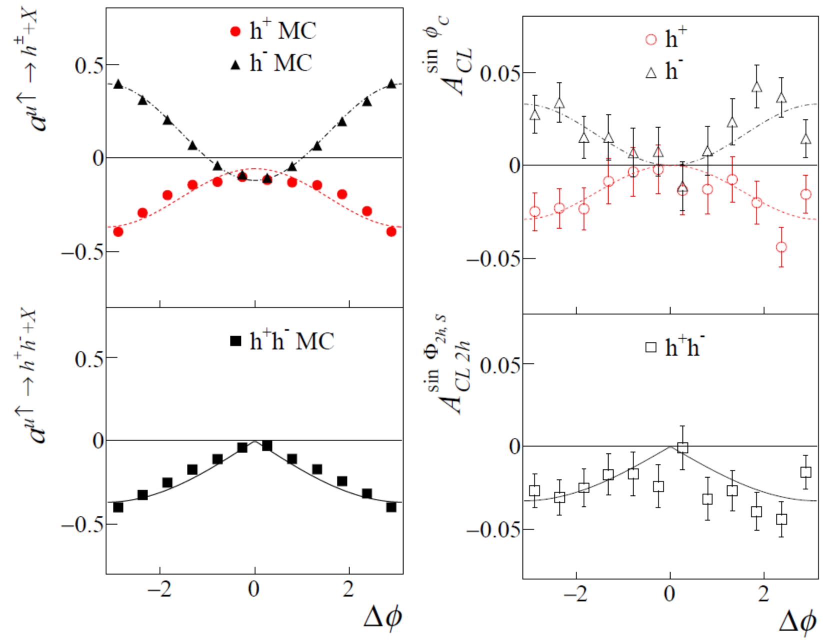


- The curves are fits of the Monte Carlo data, scaled by $\lambda \sim \langle h_1^u / f_1^u \rangle \sim 0.055$
- Agreement with the measured Collins asymmetry is quite satisfactory

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

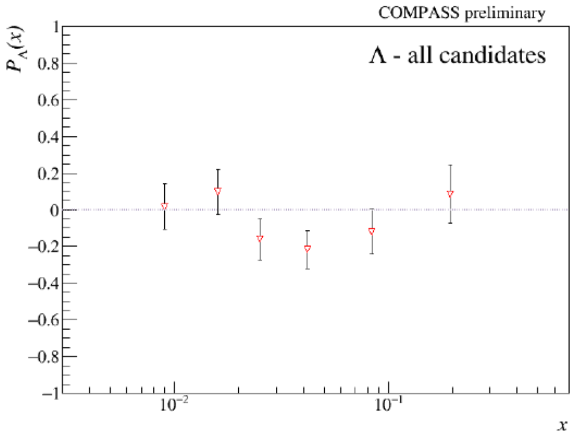
$$A_{UT}^{\sin(\phi_R+\phi_S-\pi)} = \frac{\sum_q e_q^2 h_1^q(x) H_{q\to h_1 h_2}^{\measuredangle}\left(z, \mathcal{M}_{h_1 h_2}^2\right)}{\sum_q e_q^2 q(x) D_q^{h_1 h_2}\left(z, \mathcal{M}_{h_1 h_2}^2\right)}$$

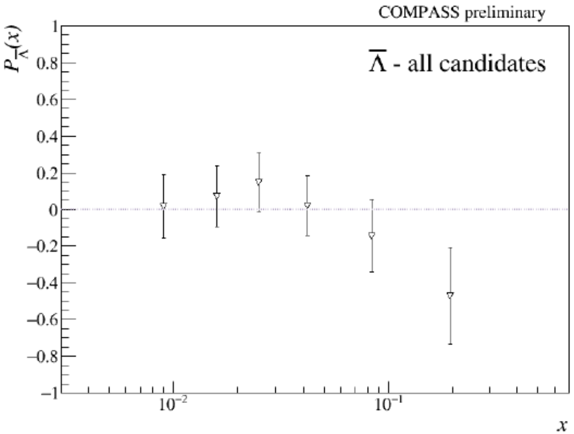




$$a_P^{u\uparrow\to h^+h^-X} = \langle \sin(\phi_R+\phi_S-\pi)\rangle$$ and $\vec{R} = \frac{z_2\vec{P}_{h1}-z_1\vec{P}_{h2}}{z_1+z_2}$ and as before $\lambda \sim \langle h_1^u/f_1^u\rangle \sim 0.055$

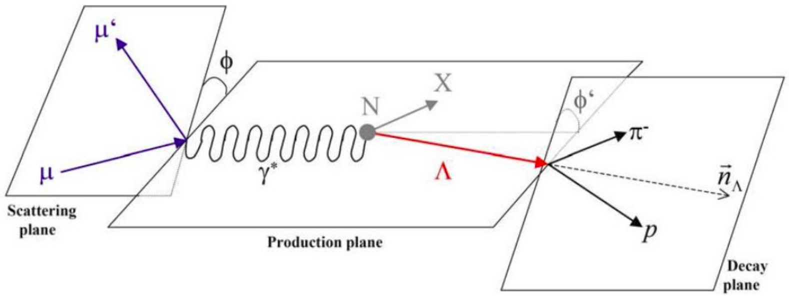
Λ transverse spin transfer from COMPASS





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

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



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 $A_{Siv}^{\pi^-} = 0$

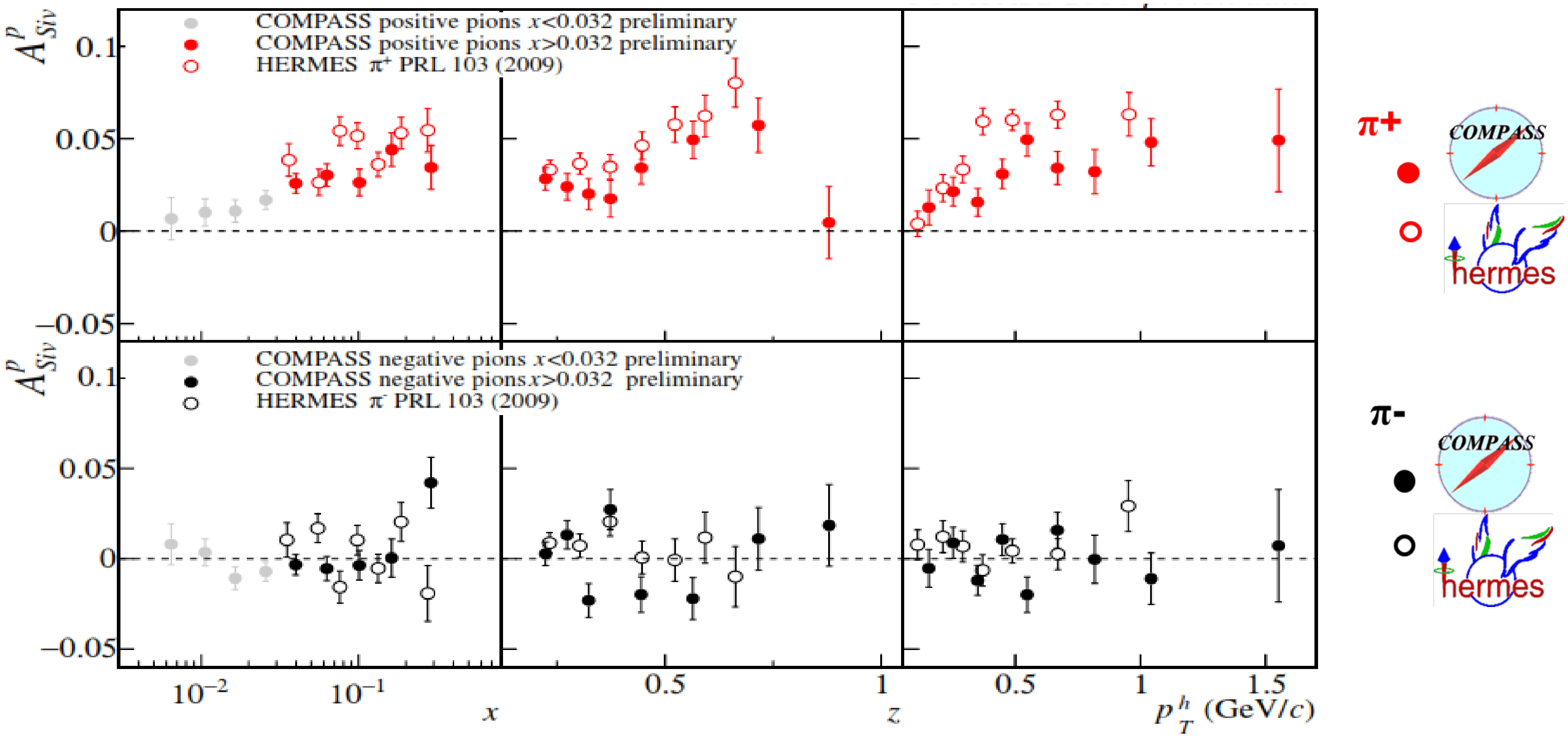
Sivers Asymmetry

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

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



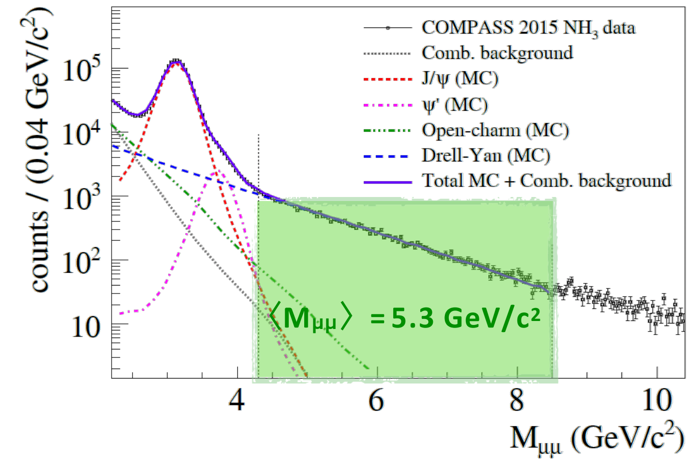
Drell-Yan measurements at COMPASS

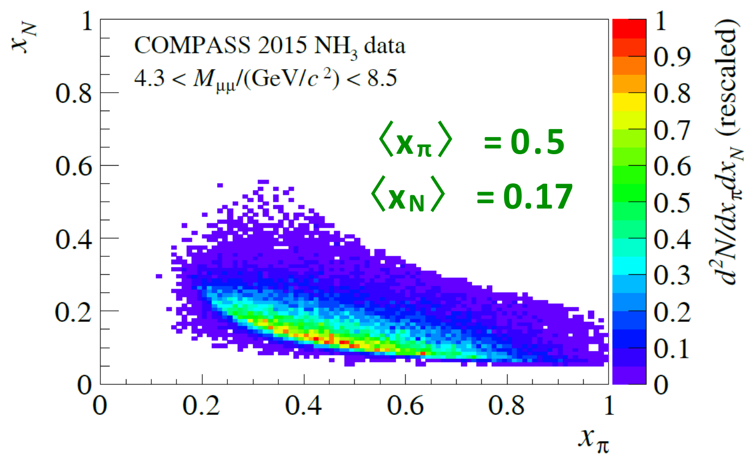
I. $1 < M_{\mu\mu}/(GeV/c^2) < 2$, "Low mass"
- Large background contamination

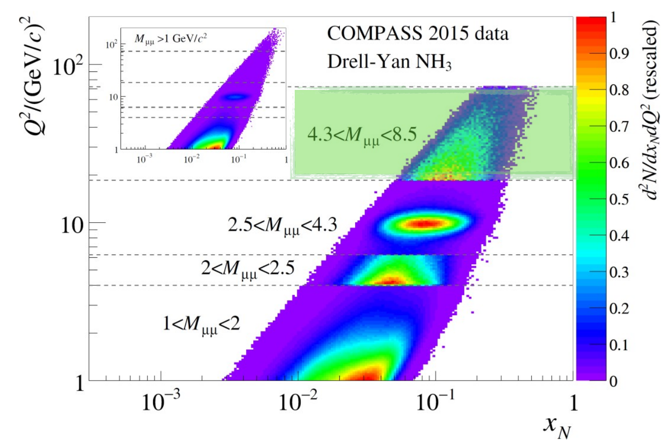
II. $2 < M_{\mu\mu}/(GeV/c^2) < 2.5$, "Intermediate mass"
- High DY cross section.
- Still low DY-signal/background ratio

III. $2.5 < M_{\mu\mu}/(GeV/c^2) < 4.3$, "Charmonia mass"
- Strong J/ψ signal: J/ψ physics.
- Good signal/background.

IV. $4.3 < M_{\mu\mu}/(GeV/c^2) < 8.5$, "High mass" background <4%
- Valence quark region ➔Largest asymmetries!
- Low DY cross-section







Transverse Spin Asymmetry in Drell-Yan

190 GeV/c π^- beam, transversely polarized NH_3 target

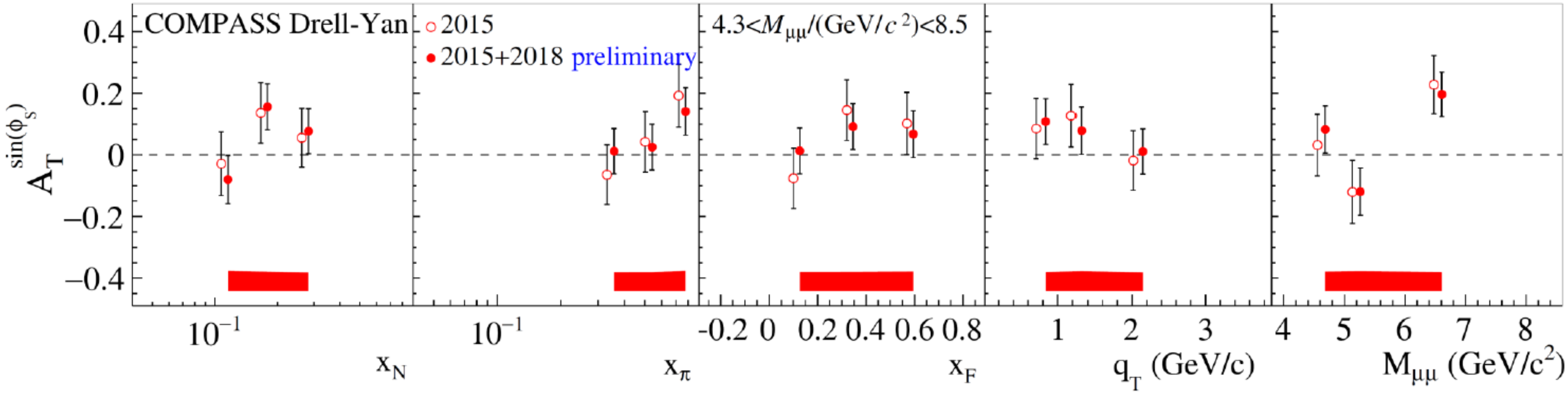
$$f_{1T,\mathrm{DY}}^{\perp} = -f_{1T,\mathrm{SIDIS}}^{\perp}$$

$$\frac{d\sigma}{dq^4 d\Omega} \propto 1 + \ldots + S_T \left[A_T^{\sin\varphi_S} \sin\varphi_S + \ldots \right]$$

Sivers DY TSA

$$A_T^{\sin\varphi_S} \propto f_{1,\pi}^{q} \otimes f_{1T,p}^{\perp q}$$

COMPASS 2015 (*PRL 119, 112002 (2017)*) + 2018 (~50%)



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

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

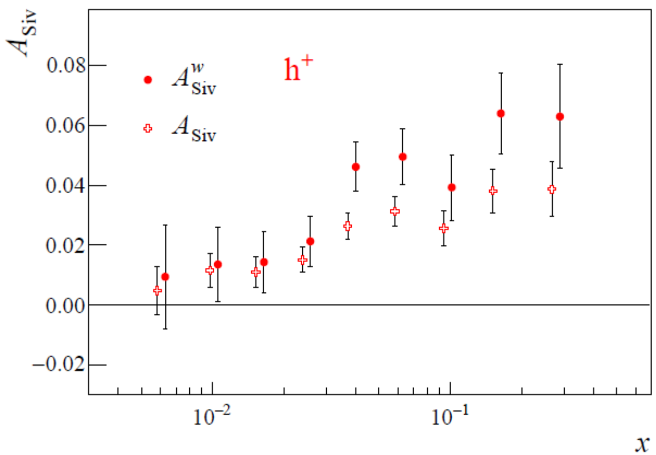
with $f_{1T}^{\perp(1)q}(x) = \int d^2\vec{k}_T \frac{k_T^2}{2M^2} f_{1T}^{\perp q}(x,k_T^2)$

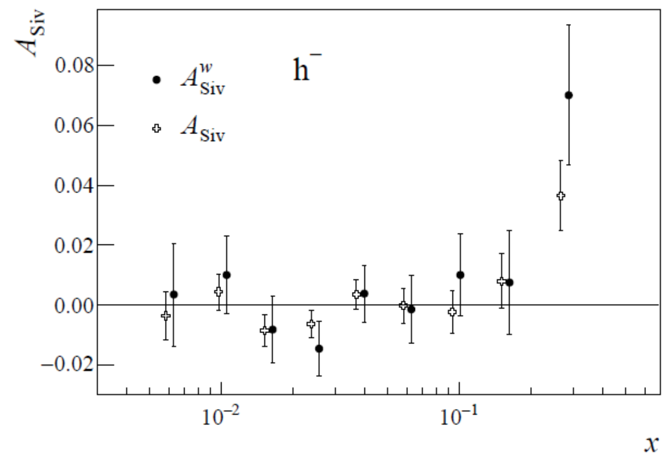
The weighted Sivers asymmetry

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

$w = P_T/zM$

standard cuts
z>0.2





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

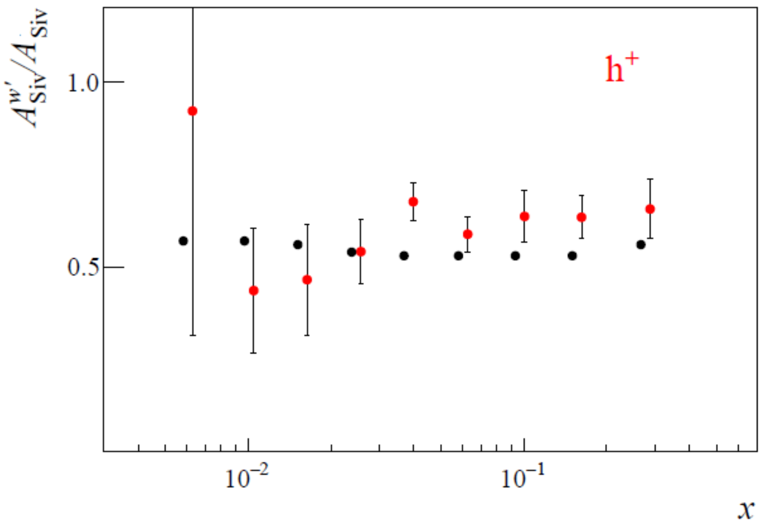
both $f_{1T}^{\perp(1)u}$ and $f_{1T}^{\perp(1)d}$
contribute

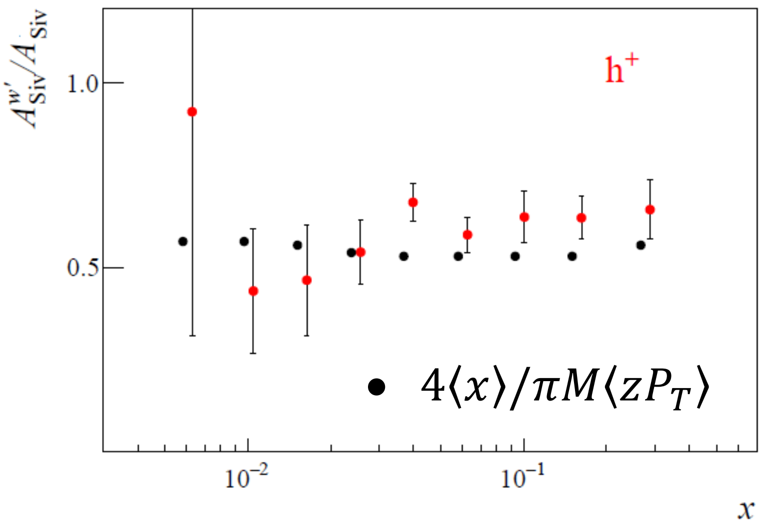
The weighted Sivers asymmetry

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

$w = P_T/zM$

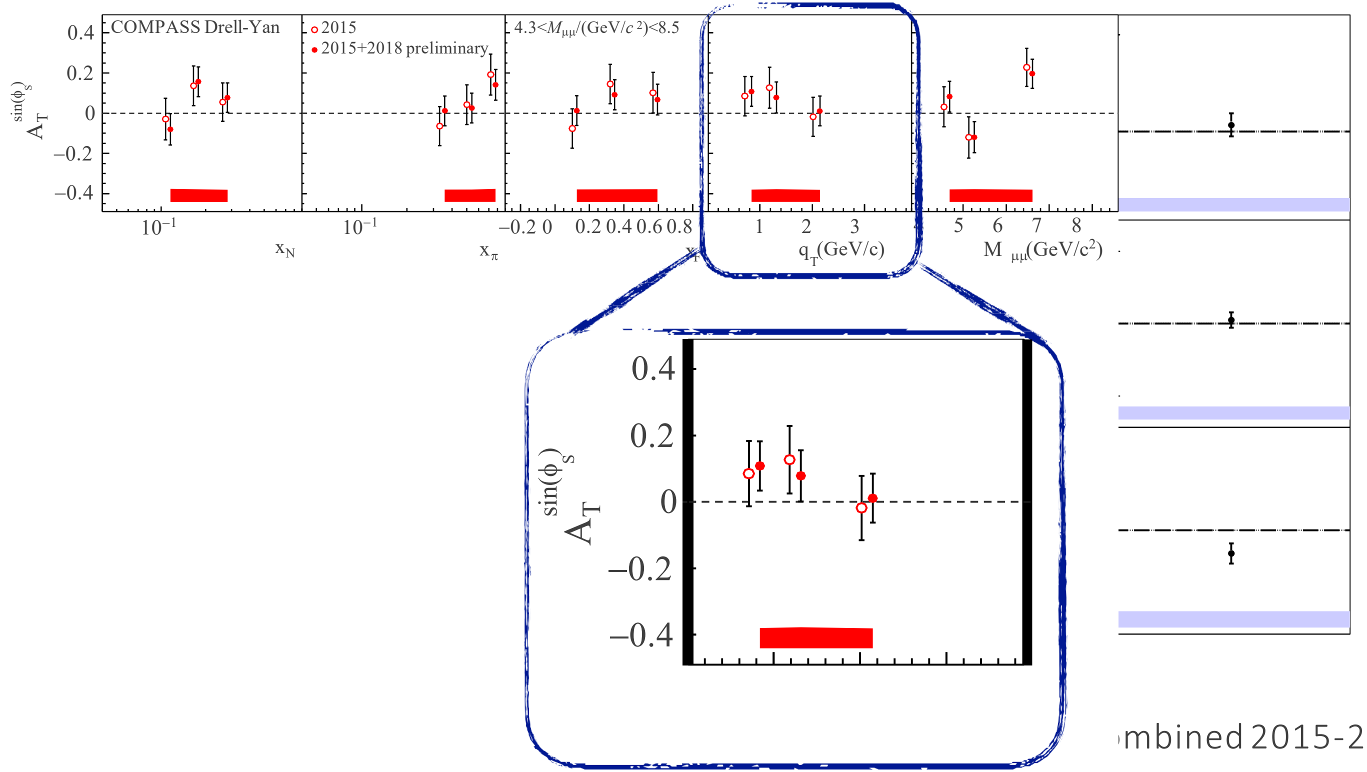
standard cuts
z>0.2





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

q_T weighted asymmetries: 2015+2018

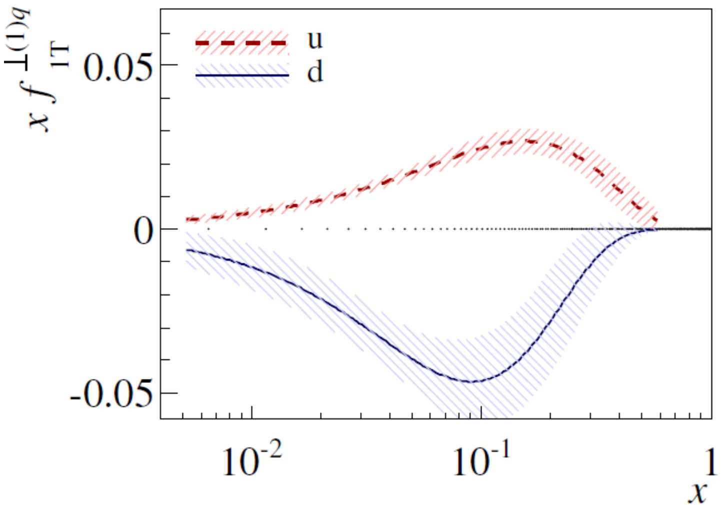


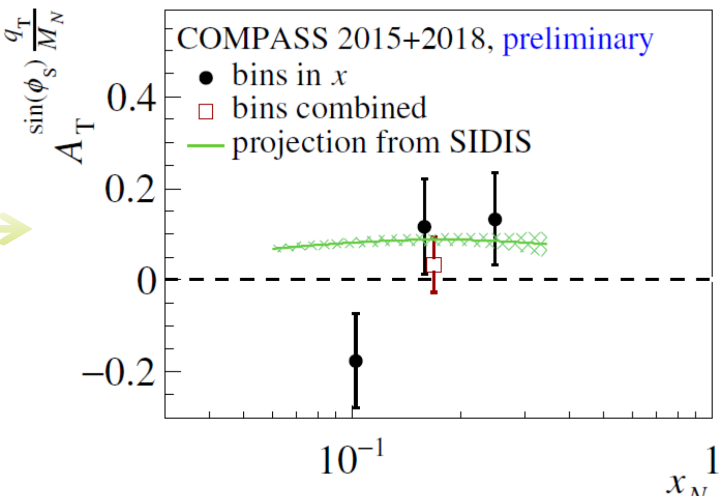
- ...mbined 2015-2018 ...sed.
- Additional uncertainties of about 5% from the polarization and 8% from dilution factor calculation have to be added to the systematic errors.

Weighted asymmetries: from SIDIS to DY

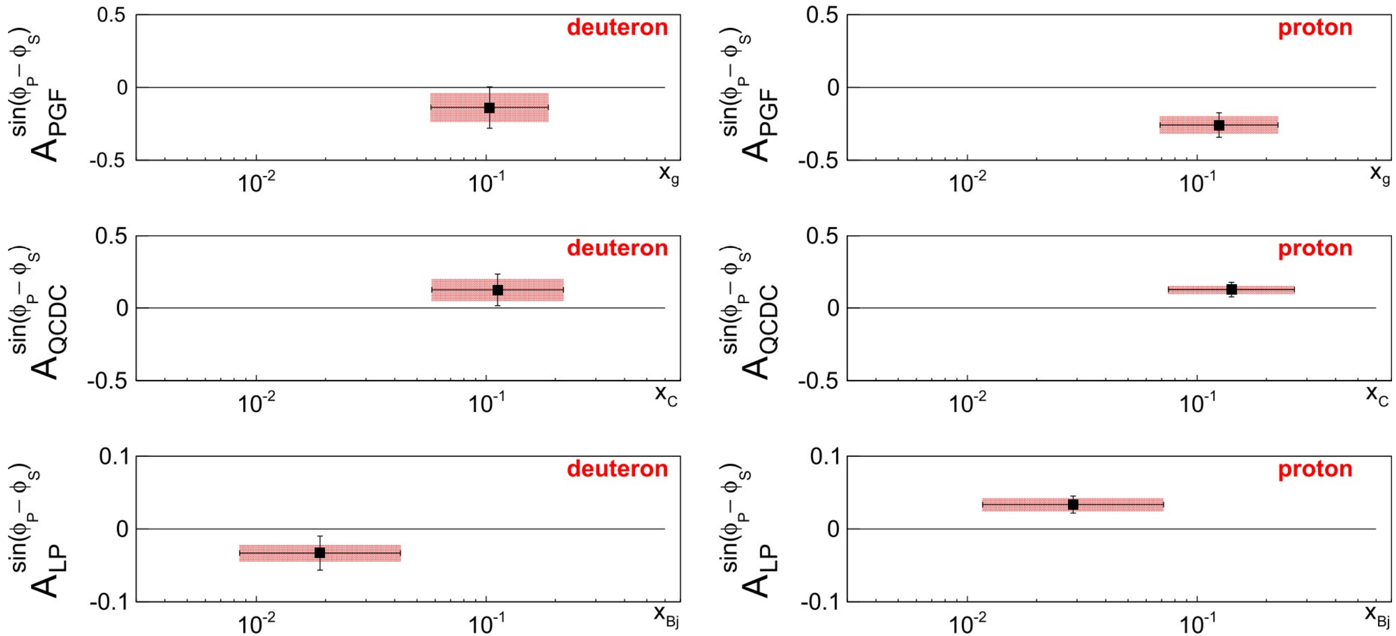
1st $k_\perp^2$-moment of the Sivers function from SIDIS data at $Q^2_{SIDIS}(x)$

Assuming:
- u-dominance
$$A_T^{\sin(\phi_S)\frac{q_T}{M_N}} \sim \frac{f_{1T}^{\perp(1)u}}{f_1^u}$$
- Same Q^2 for SIDIS and DY
- Sine change $f_{1T}^{\perp(1)u}\Big|_{DY} = f_{1T}^{\perp(1)u}\Big|_{DIS}$





Sivers Asymmetry for Gluon from SIDIS



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

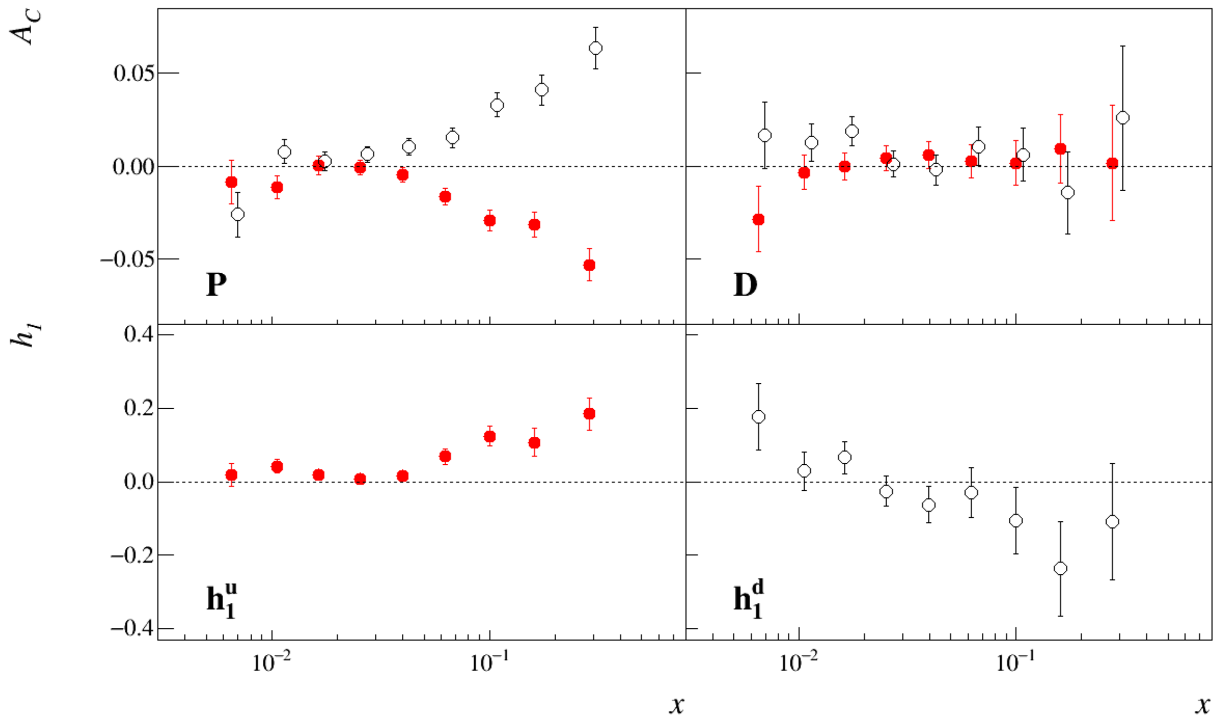
$$A_{PGF}^{Siv,p} = -0.26 \pm 0.09(\text{stat.}) \pm 0.06(\text{syst.})$$
$$\langle x_g \rangle = 0.15$$

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

WHAT WILL COME NEXT

2021 Deuteron run

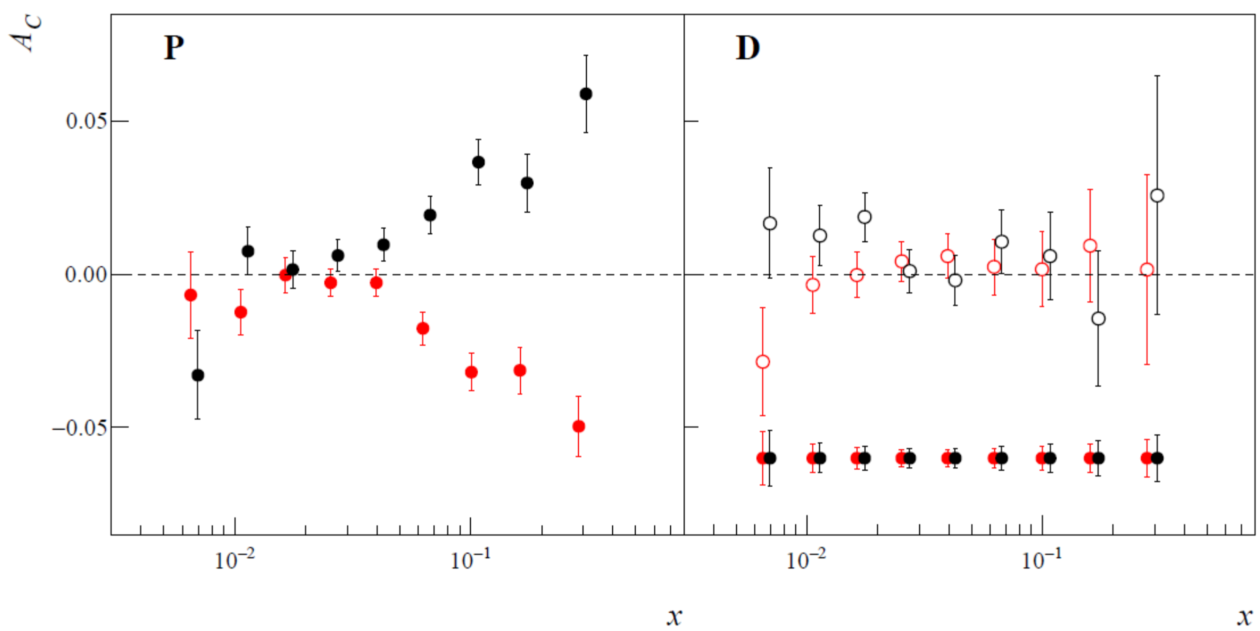
- Benchmark: h_1 extraction from Collins asymmetries



Transversity extracted as in PRD 91(2015) 014034

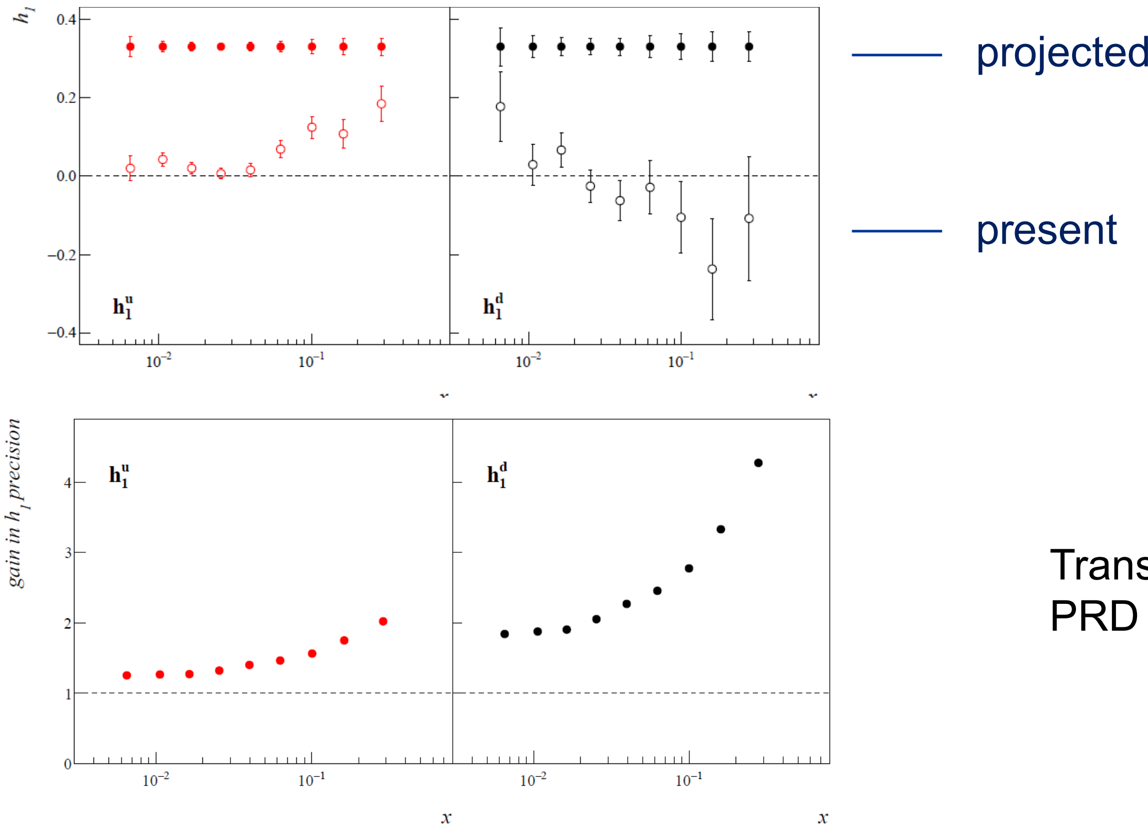
2021 Deuteron Run

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



New deuteron data

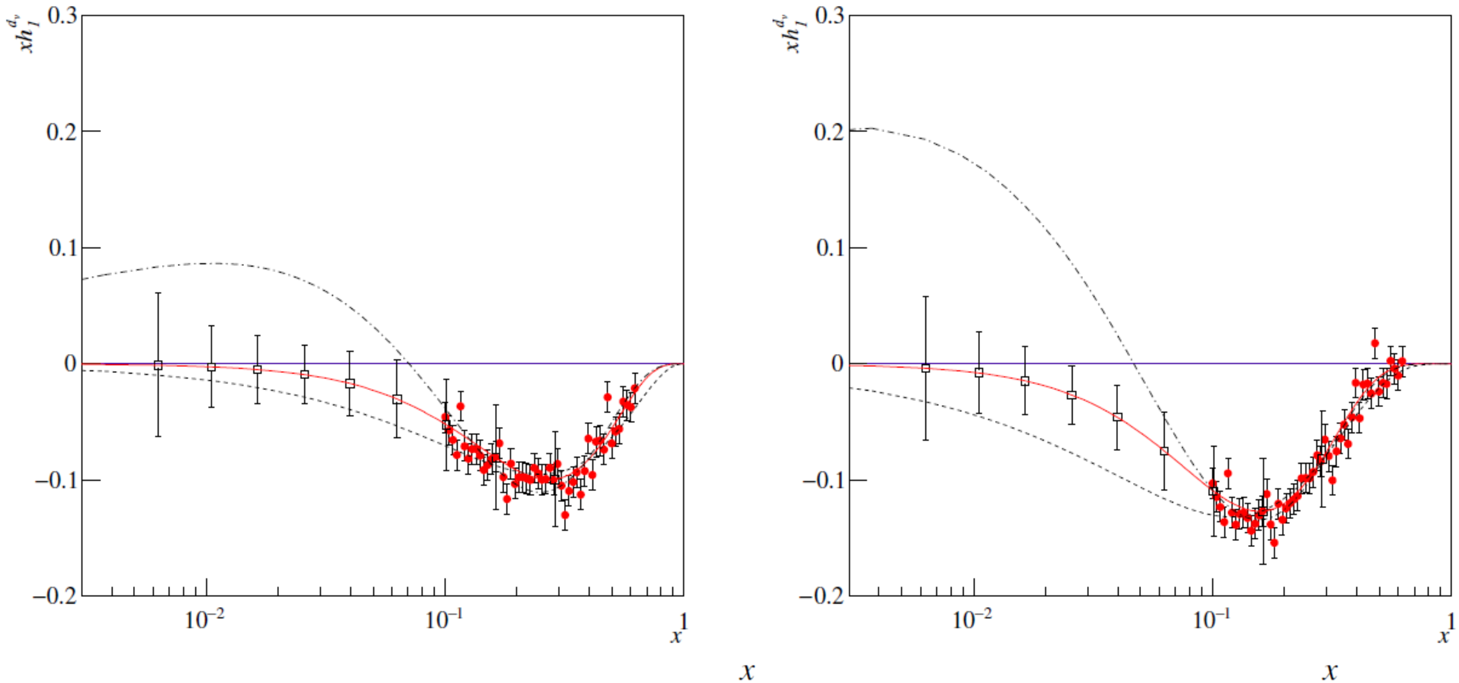
- 1 full year (same as 2010). We also gain from $\frac{f_p P_{pT}}{f_D P_{DT}} = \frac{0.155 \times 0.8}{0.40 \times 0.5} = 0.6$



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