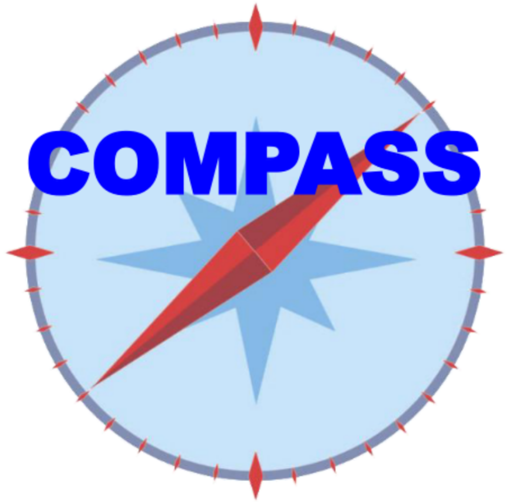
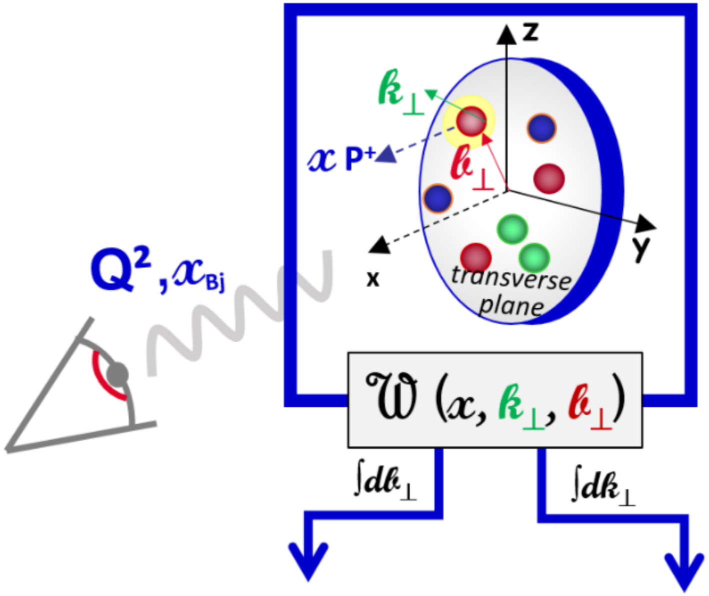
Studying GPDs and TMDs at COMPASS at CERN





Quantum tomography of the nucleon

Ji, PRL91 (2003)
Belitsky, Ji, Yuan, PRD69 (2004)
Lorcé et al, JHEP1105 (2011)

Nicole d'Hose
CEA – Université Paris-Saclay
for the COMPASS Collaboration

Transverse momentum

$f(x, k_\perp)$
8 TMDs

accessible in **SIDIS** *and* **Drell-Yan**

$\int dk_\perp$ → PDFs (x)

Transverse position

$q(x, b_\perp)$ $\int dx$ → Form Factors
8 GPDs

$\int db_\perp$ → PDFs (x)

accessible in **exclusive reactions**
DVCS: Deeply Virtual Compton Scattering
HEMP: Hard Exclusive Meson Production

QCD Evolution Workshop,
Orsay, May 22-26, 2023

université PARIS-SACLAY

Parallelism between GPDs and TMDs

Eight GPDs for quarks or gluons

Nucleon Polarization	Quark Polarization: Unpolarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	H		$2\widetilde{H}_T + E_T \equiv \overline{E}_T$
L		$\widetilde{H}$	$\widetilde{E}_T$
T	E	$\widetilde{E}$	$H_T, \widetilde{H}_T$

QCD approach proved for $|t| << Q^2$

Eight TMDs

Nucleon Polarization	Quark Polarization: U	L	T
U	f_1 unpolarized		$h_1^{\perp}$ Boer-Mulders
L		g_{1L} helicity	$h_{1L}^{\perp}$ longi-transversity (worm-gear)
T	$f_{1T}^{\perp}$ Sivers	g_{1T} trans-helicity (worm-gear)	h_1 transversity $h_{1T}^{\perp}$ pretzelosity

Nucleon spin   Quark spin

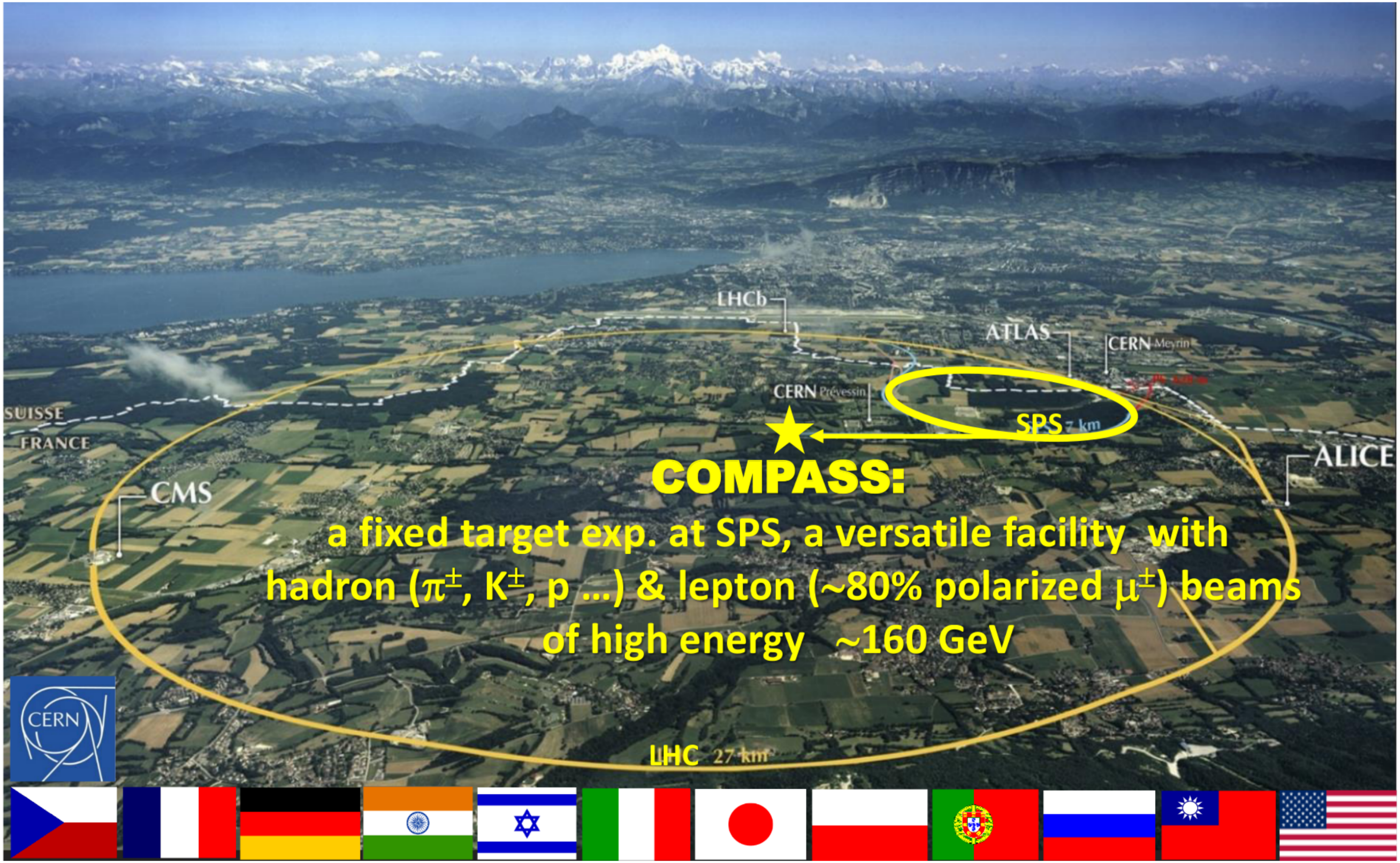
+ transverse momentum k_T

4 are Chiral-even, 4 are Chiral-odd

2 are T-odd

After integrating over k_T
only 3 survive: f_1, g_1, h_1

QCD approach proved for $k_T << \sqrt{Q^2}$


LHCb
ATLAS
CERN Meyrin
CERN Prévessin
SPS 7 km
SUISSE
FRANCE
ALICE
CMS
COMPASS:
a fixed target exp. at SPS, a versatile facility with
hadron ($\pi^{\pm}$, $K^{\pm}$, p ...) & lepton (~80% polarized $\mu^{\pm}$) beams
of high energy ~160 GeV
CERN
LHC 27 km

COMPASS: comprehensive experimental detector system & collaboration to study hadron structure using complementary tools:

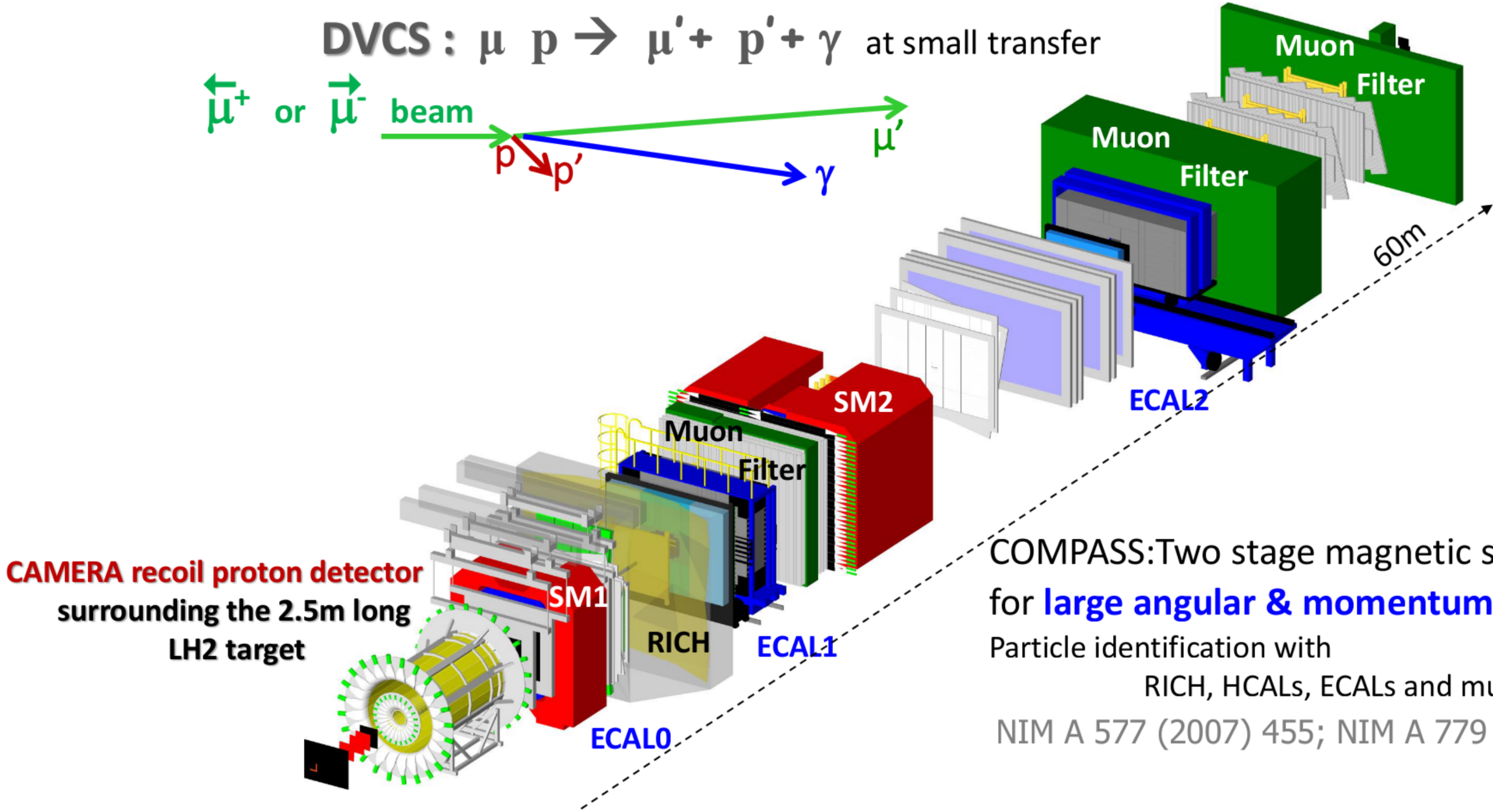
- ✓ Polarized Muon beam and L,T polarized and unpolarized target for DIS, SIDIS, DVCS, HEMP
- ✓ Hadron beam Scattering for hadron spectroscopy, Drell-Yan

2002-2022 COMPASS data taking

2002-2004	DIS & SIDIS, μ^+-**d**, 160 GeV, **L** & **T polarized target**
2005	*CERN accelerator shutdown, increase of COMPASS acceptance*
2006	DIS & SIDIS, μ^+-**d**, 160 GeV, **L polarized target**
2007	DIS & SIDIS, μ^+ -**p**, 160 GeV, **L** & **T polarized target**
2008-2009	Hadron spectroscopy & Primakoff reaction, **π/K/p** beam
2010	SIDIS, μ^+ -**p**, 160 GeV, **T polarized target**
2011	DIS & SIDIS, μ^+ -**p**, 200 GeV, **L polarized target**
2012	Primakoff reaction, **π/K/p** beam
2012 pilot run	DVCS/HEMP/SIDIS, μ^+ **&** μ^- -**p**, 160 GeV, **unpolarized target**
2013	*CERN accelerator shutdown, LS1*
2014-2015	Drell-Yan, π- -**p**, **T polarized target**
2016-2017	DVCS/HEMP/SIDIS, μ^+ **&** μ^- -**p**, 160 GeV, **unpolarized target**
2018	Drell-Yan, π- -**p**, **T polarized target**
2019-2020	*CERN accelerator shutdown, LS2*
2021-2022	SIDIS, μ^+-**d**, 160 GeV, **T polarized target**

Measurement of exclusive cross sections at COMPASS

DVCS : μ p → μ′+ p′+ γ at small transfer



COMPASS:Two stage magnetic spectrometer

for **large angular & momentum acceptance**

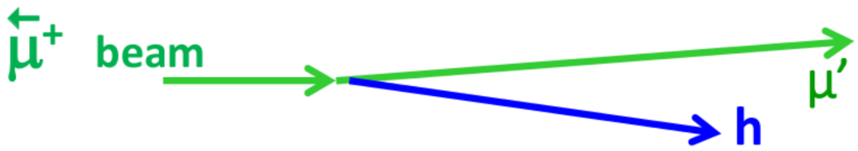
Particle identification with

RICH, HCALs, ECALs and muon filters

NIM A 577 (2007) 455; NIM A 779 (2015) 69

Measurement of SIDIS at COMPASS

SIDIS : $\mu\ p \rightarrow \mu' + h + X$

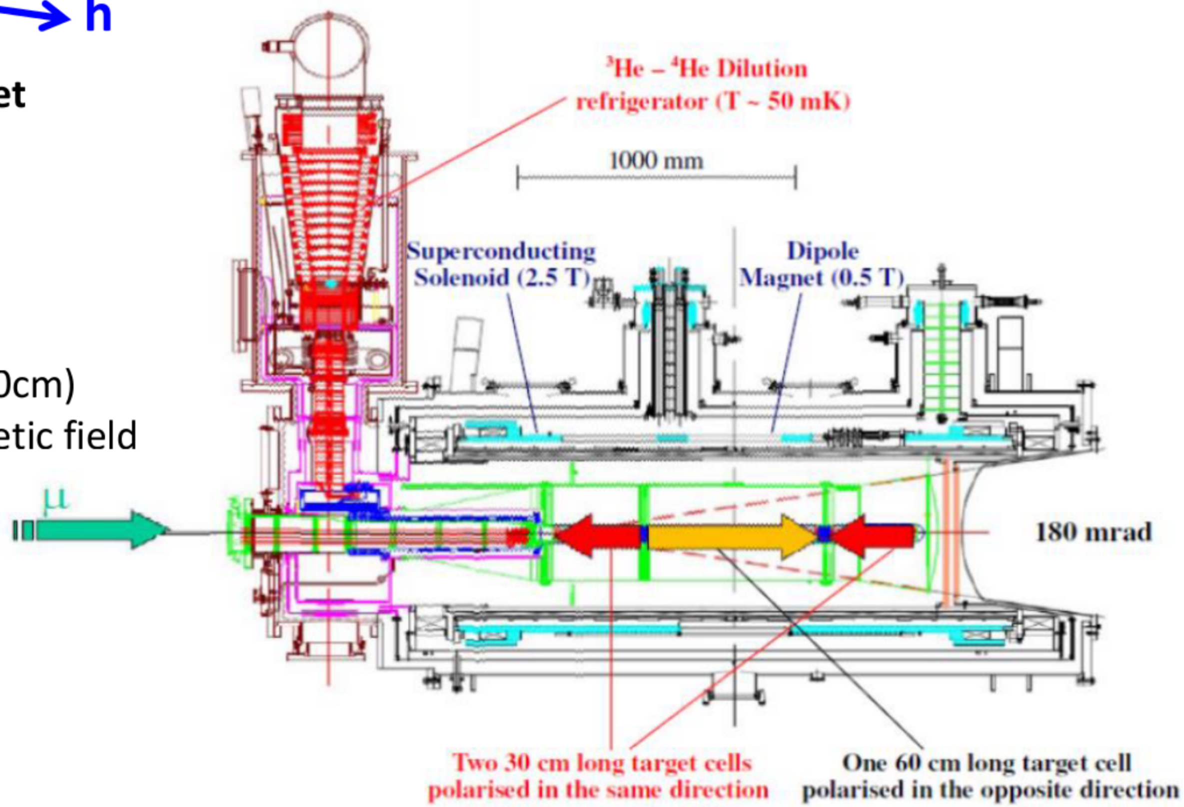


Unpol. Or Polarized target

^{6}LiD ~50%

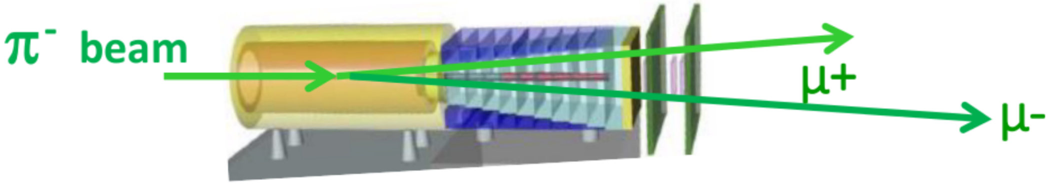
NH_3 ~85%

2 or 3 oppositely polarized cells (30-60-30cm)
Polarization reversal by rotation of magnetic field



Measurement of DY at COMPASS

DY : $\pi \; p \rightarrow \mu^+ + \mu^- + X$

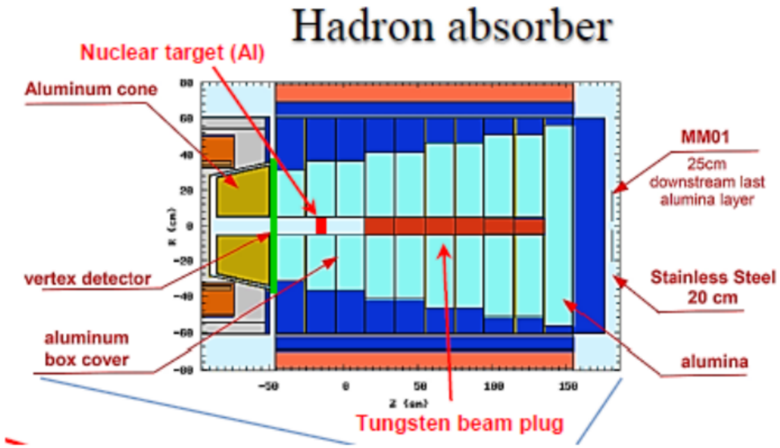


Polarized target

NH_3 ~85%

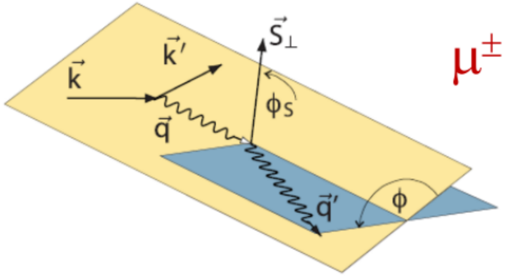
2 oppositely polarized cells (each of 55cm)
Polarization reversal by rotation of magnetic field

+

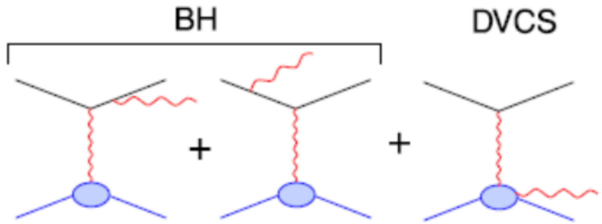


Al target (7cm) + W beam plug (120cm)

COMPASS 2016 DVCS+BH cross section on proton at E_μ=160 GeV

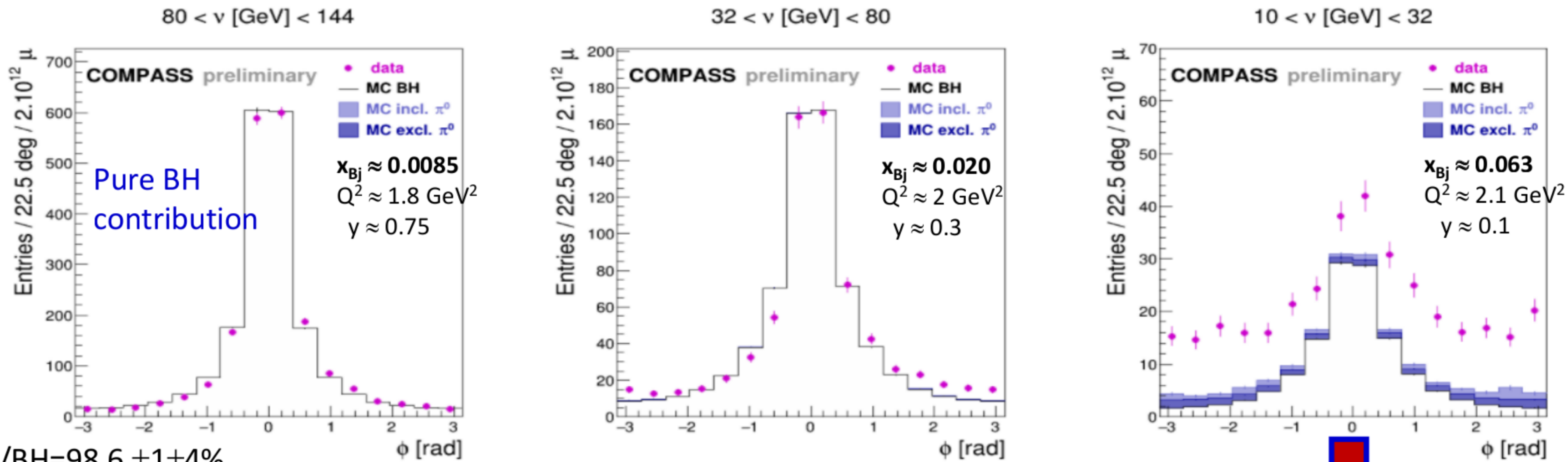


$\mu^\pm p \rightarrow \mu^\pm \gamma p$



$\Sigma = d\sigma\,(\overleftarrow{\mu^+}) + d\sigma\,(\overrightarrow{\mu^-})$

$d\sigma \;\alpha\; |T^{BH}|^2$ + Interference Term + $|T^{DVCS}|^2$



Data/BH=98.6 ±1±4%

DVCS above the BH contrib.

MC: BH contribution evaluated for the integrated luminosity
$\pi°$ background contribution from SIDIS (LEPTO) + exclusive production (HEPGEN)

COMPASS 2016 DVCS cross section on proton for 10 < υ < 32 GeV

At COMPASS using polarized positive and negative muon beams:

At NLO and twist-3

$$\Sigma \equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2[d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Im}\, I]$$

$$= 2[d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS} \cos\phi + c_2^{DVCS} \cos 2\phi + s_1^I \sin\phi + s_2^I \sin 2\phi\,]$$

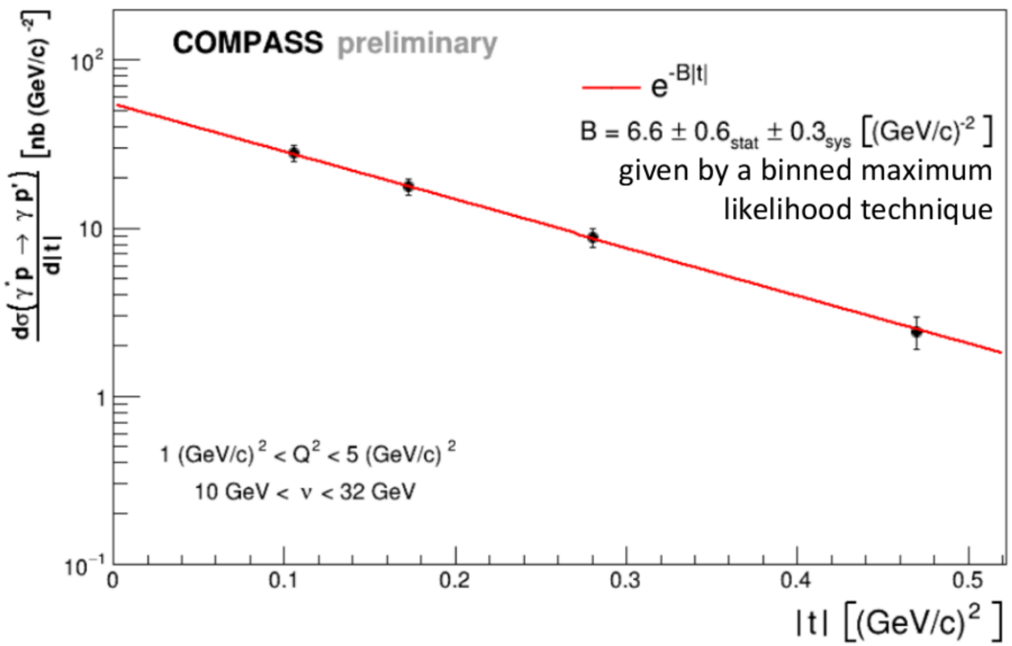
calculable
can be subtracted

All the other terms are cancelled in the integration over ϕ

$$\frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt} = \int_{-\pi}^{\pi} d\phi\, (d\sigma - d\sigma^{BH}) \propto c_0^{DVCS}$$

$$\frac{d\sigma^{\gamma^* p}}{dt} = \frac{1}{\Gamma(Q^2, \nu, E_\mu)} \frac{d^3\sigma_T^{\mu p}}{dQ^2 d\nu dt}$$

Flux for transverse
virtual photons



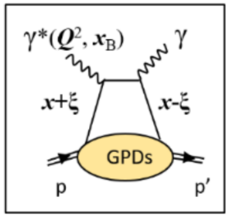
COMPASS 2012-16 Transverse extention of partons in sea quark range

$$d\sigma^{DVCS}/dt = e^{-B|t|} = c_0^{DVCS} \propto (Im\mathcal{H})^2$$

$$c_0^{DVCS} \propto 4(\mathcal{H}\mathcal{H}^* + \tilde{\mathcal{H}}\tilde{\mathcal{H}}^*) + \frac{t}{M^2}\mathcal{E}\mathcal{E}^*$$

In the COMPASS kinematics, $x_B \approx 0.06$, dominance of $Im\mathcal{H}$
97% (GK model) 94% (KM model)

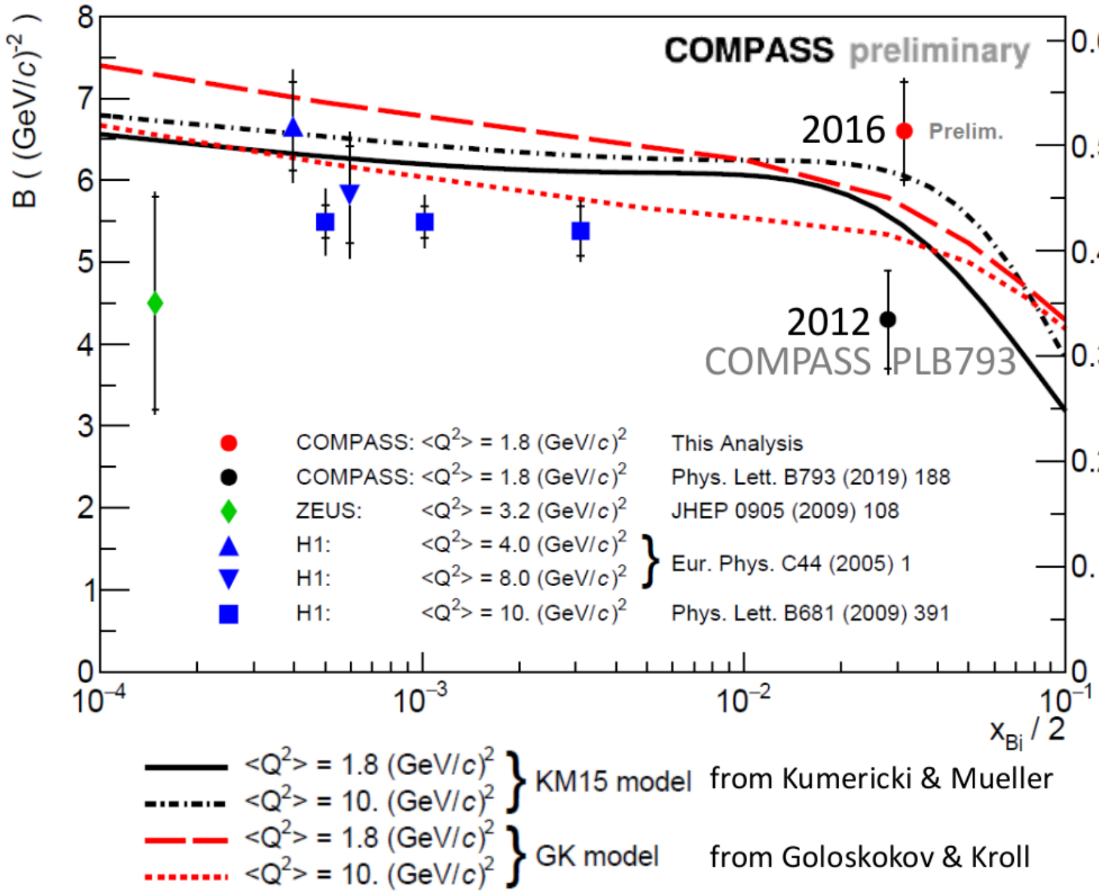
$Im\mathcal{H}$ = H (x=ξ, ξ, t)
x = ξ ≈ $x_B/2$ close to 0



$$q(x, \mathbf{b}_\perp) = \int \frac{d^2\mathbf{\Delta}_\perp}{(2\pi)^2} e^{-i\mathbf{b}_\perp \cdot \mathbf{\Delta}_\perp} H_-^q(x, 0, -\mathbf{\Delta}_\perp{}^2).$$

$$\langle b_\perp^2 \rangle_x^f = \frac{\int d^2 b_\perp b_\perp^2 q_f(x, b_\perp)}{\int d^2 b_\perp q_f(x, b_\perp)} = -4\frac{\partial}{\partial t} \log H^f(x, \xi = 0, t)\Big|_{t=0}$$

$$\langle b_\perp^2(x) \rangle \approx 2B(\xi)$$



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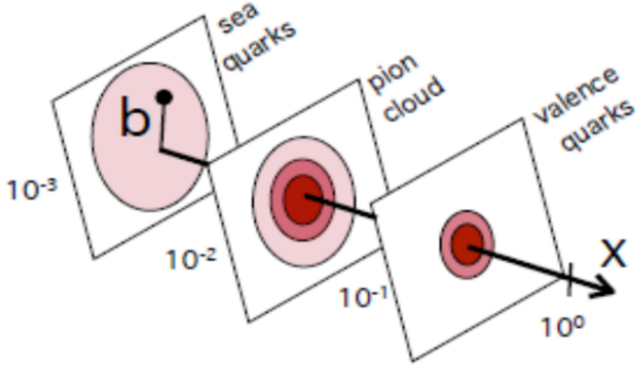
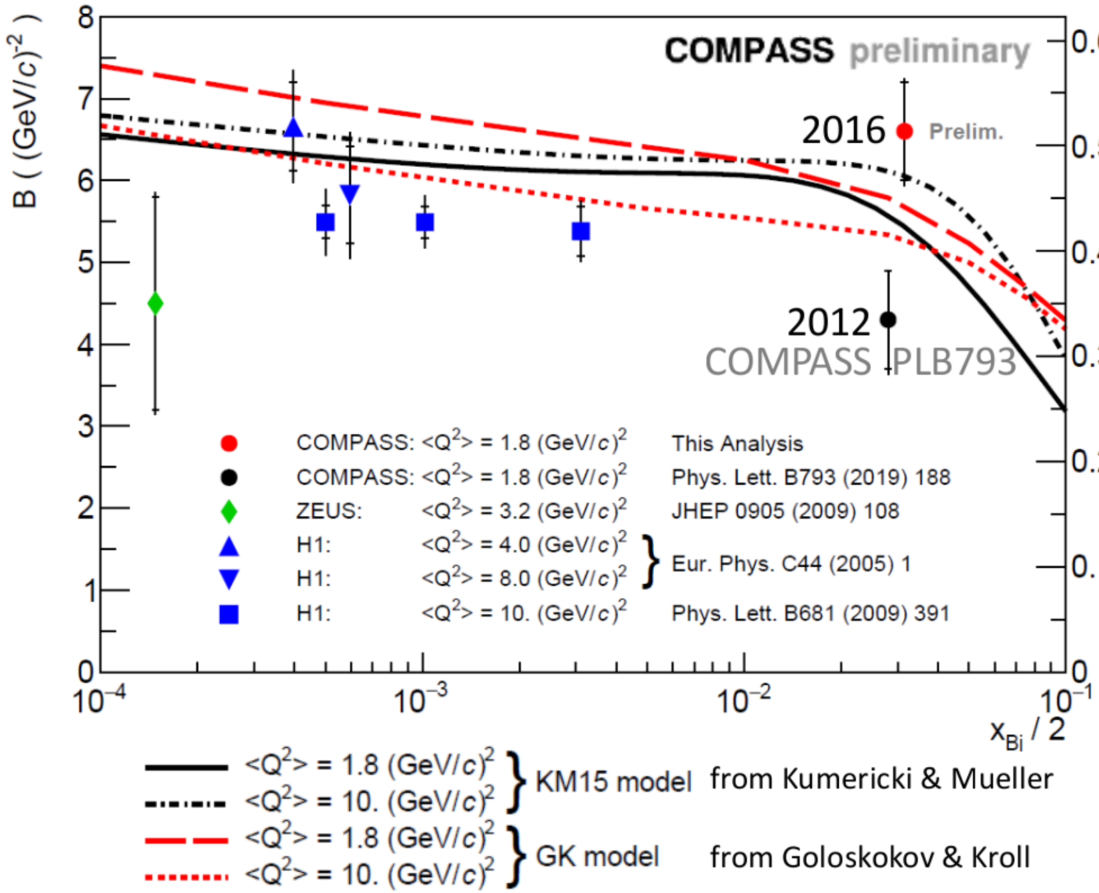


2012 statistics = Ref
2016 analysed statistics = 2.3 × Ref
2016+2017 expected statistics = 10 × Ref



3σ difference between 2012 and 2016 data

- more advanced analysis with 2016 data
- π^0 contamination with different thresholds
- binning with 3 variables (t,Q^2,ν) or 4 variables (t,ϕ,Q^2,ν)

COMPASS 2012-16 Exclusive π^0 production on unpolarized proton

$\mu^{\pm} p \rightarrow \mu^{\pm} \pi^0 p$

$F\pi^0 = 2/3 F^u + 1/3 F^d$

$$\frac{d^2\sigma}{dt\,d\phi_\pi} = \frac{1}{2\pi}\left[\left(\epsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt}\right) + \epsilon\cos 2\phi_\pi \frac{d\sigma_{TT}}{dt} + \sqrt{2\epsilon(1+\epsilon)}\cos\phi_\pi \frac{d\sigma_{LT}}{dt}\right]$$

COMPASS
Q^2=2.0 GeV^2
x_B=0.093
$|t|\sim$ 0.26 GeV^2
ε close to 1

$$\frac{d\sigma_L}{dt} \propto \left|\langle\tilde{H}\rangle\right|^2 - \frac{t'}{4m^2}\left|\langle\tilde{E}\rangle\right|^2$$

$$\frac{d\sigma_T}{dt} \propto |\langle H_T\rangle|^2 - \frac{t'}{8m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

$$\frac{\sigma_{TT}}{dt} \propto \frac{t'}{16m^2}\left|\langle\bar{E}_T\rangle\right|^2$$

$$\frac{\sigma_{LT}}{dt} \propto \frac{\sqrt{-t'}}{2m}\,\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\left\langle\frac{d\sigma_T}{d|t|} + \epsilon\frac{d\sigma_L}{d|t|}\right\rangle = (8.2 \pm 0.9_{\text{stat}}\,{}^{+\,1.2}_{-\,1.2}|_{\text{sys}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

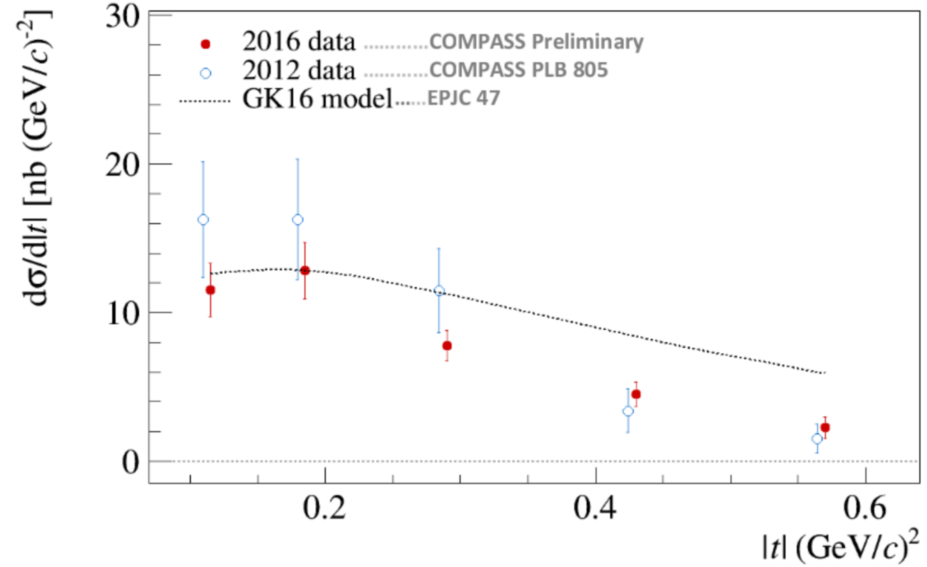
$$\left\langle\frac{d\sigma_{TT}}{d|t|}\right\rangle = (-6.1 \pm 1.3_{\text{stat}}\,{}^{+\,0.7}_{-\,0.7}|_{\text{sys}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

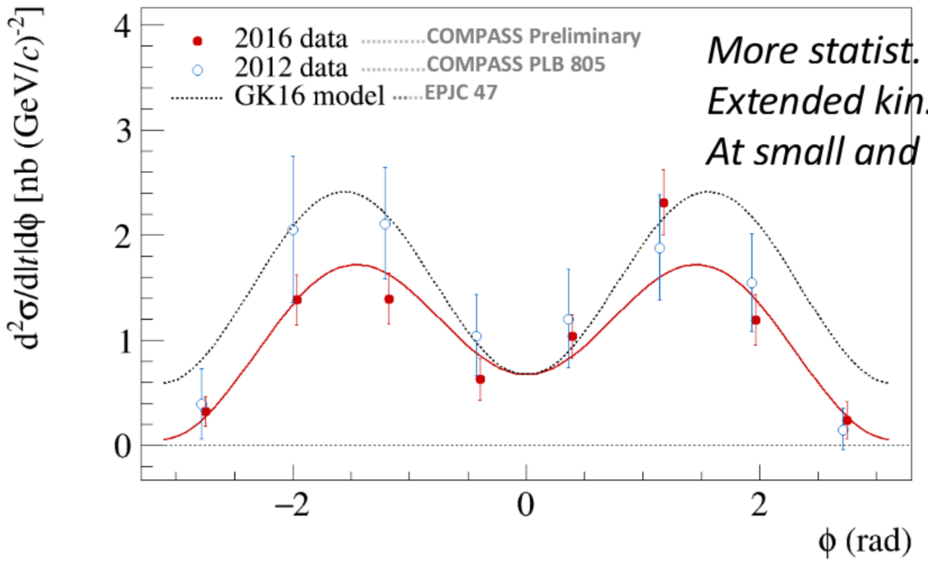
$$\left\langle\frac{d\sigma_{LT}}{d|t|}\right\rangle = (1.5 \pm 0.5_{\text{stat}}\,{}^{+\,0.3}_{-\,0.2}|_{\text{sys}})\frac{\text{nb}}{(\text{GeV}/c)^2}$$

PLB 805 (2020)

σ_{TT} large - impact of $\bar{E}_T$

σ_{LT} small but significantly positive as at CLAS





More statist. will come
Extended kin. domain
At small and large x_B

Data: **COMPASS,** PLB 805 (2020) Models: **GK** Kroll Goloskokov EPJC47 (2011) Also **GGL**: Golstein Gonzalez Liuti PRD91 (2015)

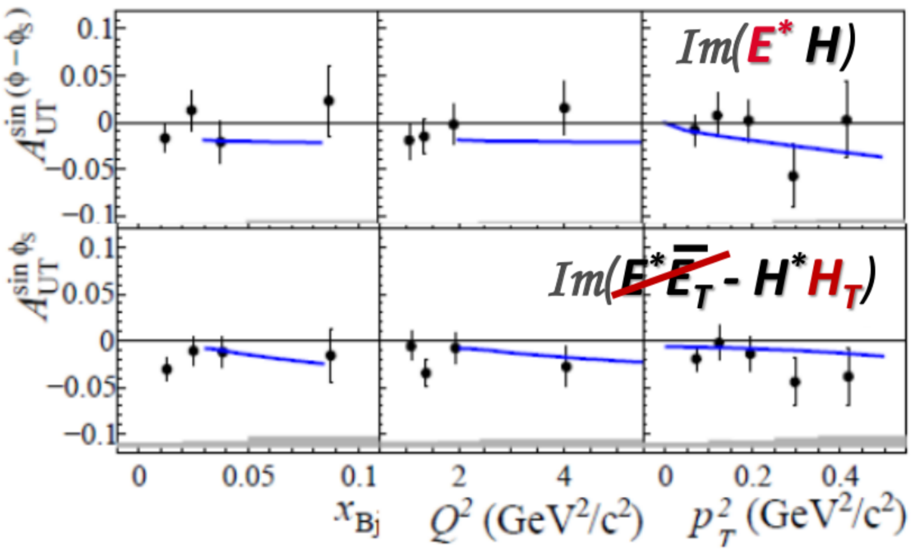
COMPASS 2010 2007 HEMP with transversely polarized NH_3 (p) target without RPD

Gparity: G(π)=-1; G(ρ)=+1; G(ω)=-1

Vector mesons: $\rho^0 \to \pi^+\pi^-$

$$E_{\rho^0} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u + \frac{1}{3}E^d + \frac{3}{4}\frac{E_g}{x}\right)$$

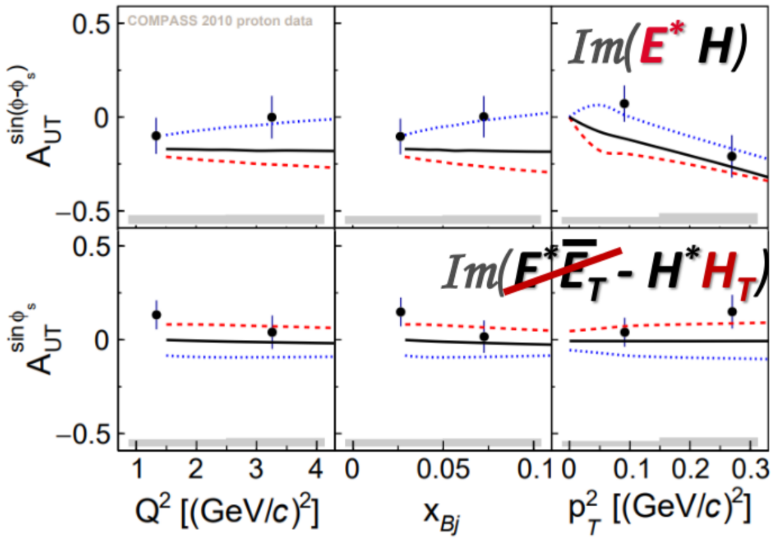
COMPASS, NPB 865 (2012), PLB731 (2014)



$\omega \to \pi^+\pi^-\pi^0$

$$E_{\omega} = \frac{1}{\sqrt{2}}\left(\frac{2}{3}E^u - \frac{1}{3}E^d + \frac{1}{4}\frac{E_g}{x}\right)$$

COMPASS, NPB 915 (2017)

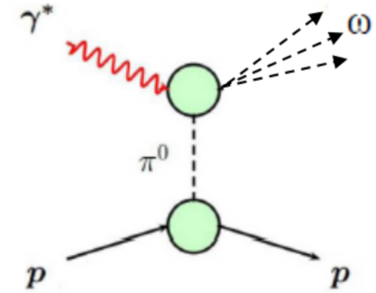


E^u and E^d of opposite sign

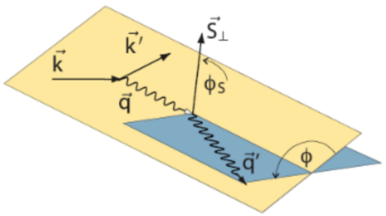
ω is more promising (see the larger scale) but there is the inherent pion pole contribution

$\Gamma(\omega \to \pi^0\gamma) = 9\times\Gamma(\rho^0 \to \pi^0\gamma)$

Same for πω FF but sign unknown



- positive πω form factor
- no pion pole
- negative πω form factor

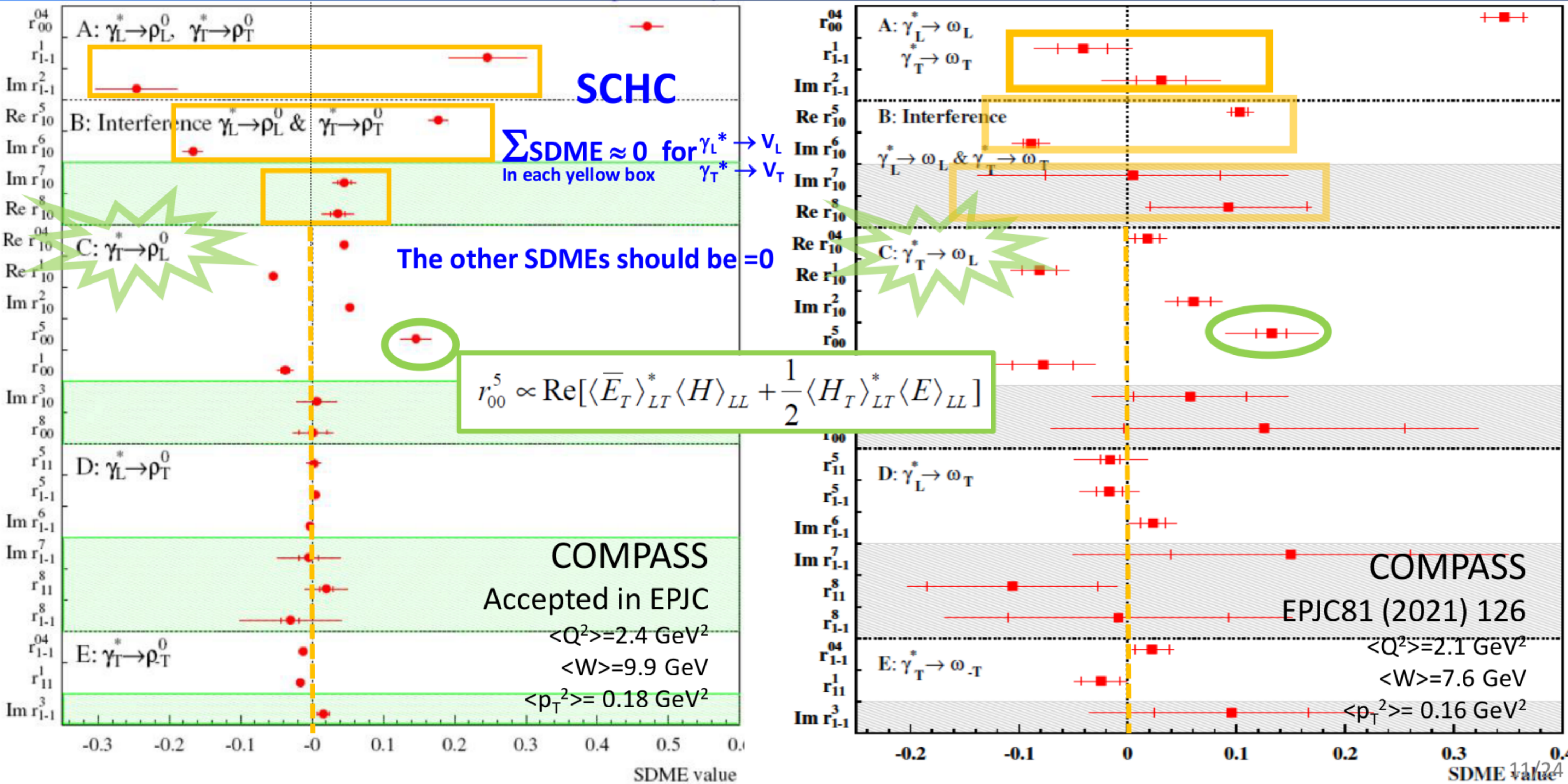


GK Goloskokov, Kroll, EPJC42,50,53,59,65,74 GPD model constrained by HEMP at small x_B

longitudinal $\gamma_L^*\, p \to M\, p$ and transv. polar. $\gamma_T^*\, p \to M\, p$

quark and gluon contributions (GPDs **H, E, H_T, E_T**) and beyond leading twist

COMPASS 2012 Exclusive ρ^0 and ω production on unpolarized proton



SIDIS cross section and TMDs at twist-2

$$\frac{d\sigma}{dxdydzdp_T^2 d\phi_h d\phi_S} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right]\left(F_{UU,T}+\varepsilon F_{UU,L}\right)$$

$\times \Big\{$

Unpol target

$$1+\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h\right] + \lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

← Cahn & Boer-Mulders

Long pol target

$$+\,S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]$$

↖ Worm-gear L

$$+\,S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right]$$

Trans pol target

$$+\,S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\,\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\,\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\,\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\,\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S) \end{array}\right]$$

← Sivers effect

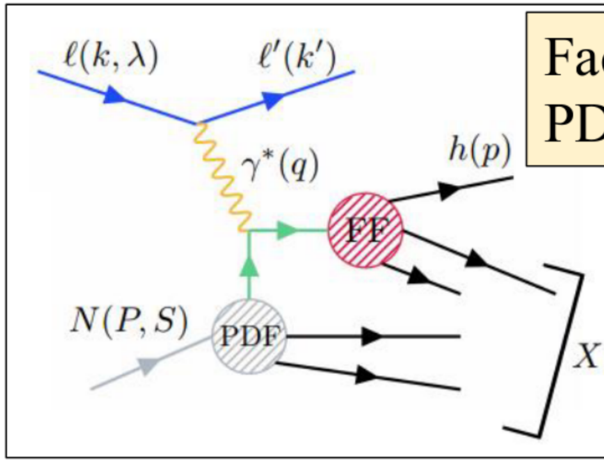
← Collins effect

← Pretzelosity

$$+\,S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\,\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ +\,\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S) \end{array}\right]\Big\}$$

← Worm-gear T

λ Beam polarization



Factorisation
$\mathrm{PDF}(x,k_T)\otimes\mathrm{FF}(p_T{}^h,z)$

$x = Q2/2m\,\upsilon$
$y = \upsilon/k$
$z = E_h/\upsilon$
$p_T{}^h$ linked to k_T

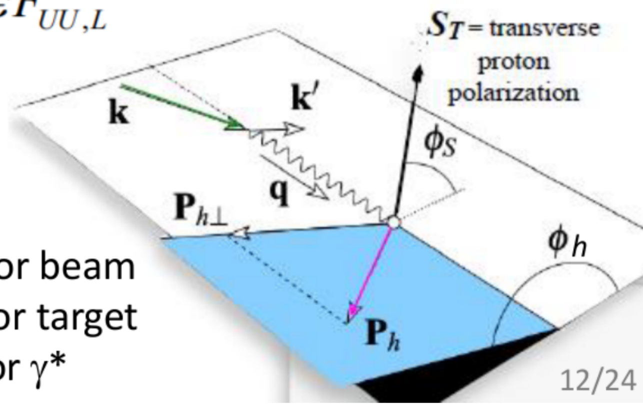
Each modulation measured at COMPASS, for ex:

Transv. Polar. SIDIS: ℓ p↑ → ℓ h± X

$$A_{U(L),T}^{w(\varphi_h,\varphi_s)} = \frac{F_{U(L),T}^{w(\varphi_h,\varphi_s)}}{F_{UU,T}+\varepsilon F_{UU,L}}$$

U Unpolarized
L Long pol
T Transversely pol

2 (or 3) indices 1st for beam
2nd for target
3rd for γ^*

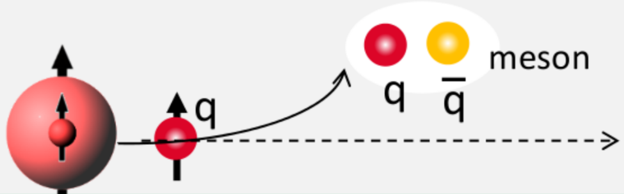


COMPASS 2010 Transverse T: Collins Asym= Transversity ⊗ Collins FF

The transversity h_1 or $\Delta_T q$

Measures the diff. of density of quarks with spin // and anti// to the transverse spin of the nucleon

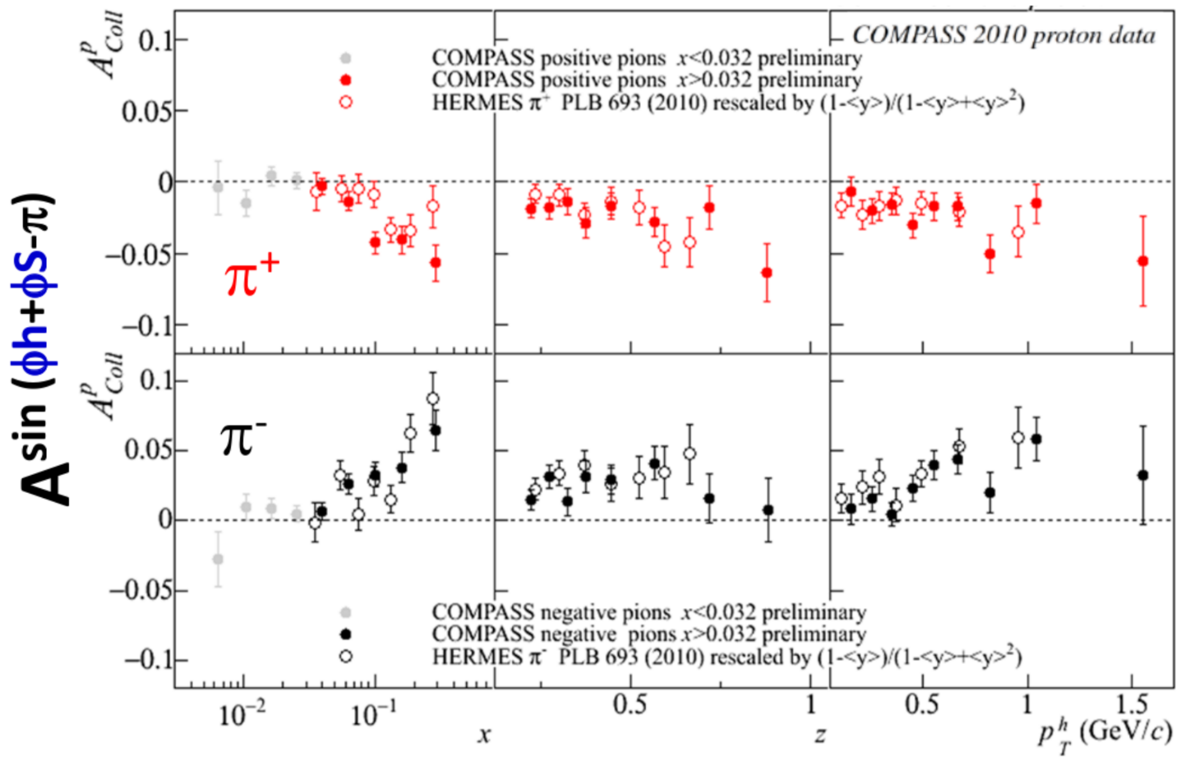
Transversity chiral-odd PDF × Collins odd FF



$$A_{Coll} \approx \frac{\sum_q e_q^2 \, h_1^q(x) \otimes H_{1q}^{\perp h}(z, p_T^h)}{\sum_q e_q^2 \, f_1^q(x) \otimes D_{1q}^h(z, p_T^h)}$$

Transversity describes the spin-spin correlation of a transversely polarized parton in a transversely polarized hadron.

COMPASS:PLB 692 (2010), PLB 717 (2012), PLB 744 (2015)



Large effect of opposite sign for π^+ and π^-

Good agreement between COMPASS and HERMES for x > 0.032

Not obvious as the COMPASS Q^2 domain is larger by a factor of about 2or 3

COMPASS 2010 and others extraction of Transversity PDF

$$A_{\rm Coll}^{p,\pi^+} \sim e_u^2 h_1^u H_1^{\perp,\rm fav} + e_d^2 h_1^d H_1^{\perp,\rm unf}$$

$$A_{\rm Coll}^{p,\pi^-} \sim e_u^2 h_1^u H_1^{\perp,\rm unf} + e_d^2 h_1^d H_1^{\perp,\rm fav}$$

$$H_{1,\rm fav}^{\perp} \simeq -H_{1,\rm dis}^{\perp}$$

$$\langle \sin(\phi+\phi_S)\rangle_{UT}^{\pi^+} \sim \left(4h_1^u - h_1^d\right) H_{1,\rm fav}^{\perp} > 0$$

$$\langle \sin(\phi+\phi_S)\rangle_{UT}^{\pi^-} \sim -\left(4h_1^u - h_1^d\right) H_{1,\rm fav}^{\perp} < 0$$

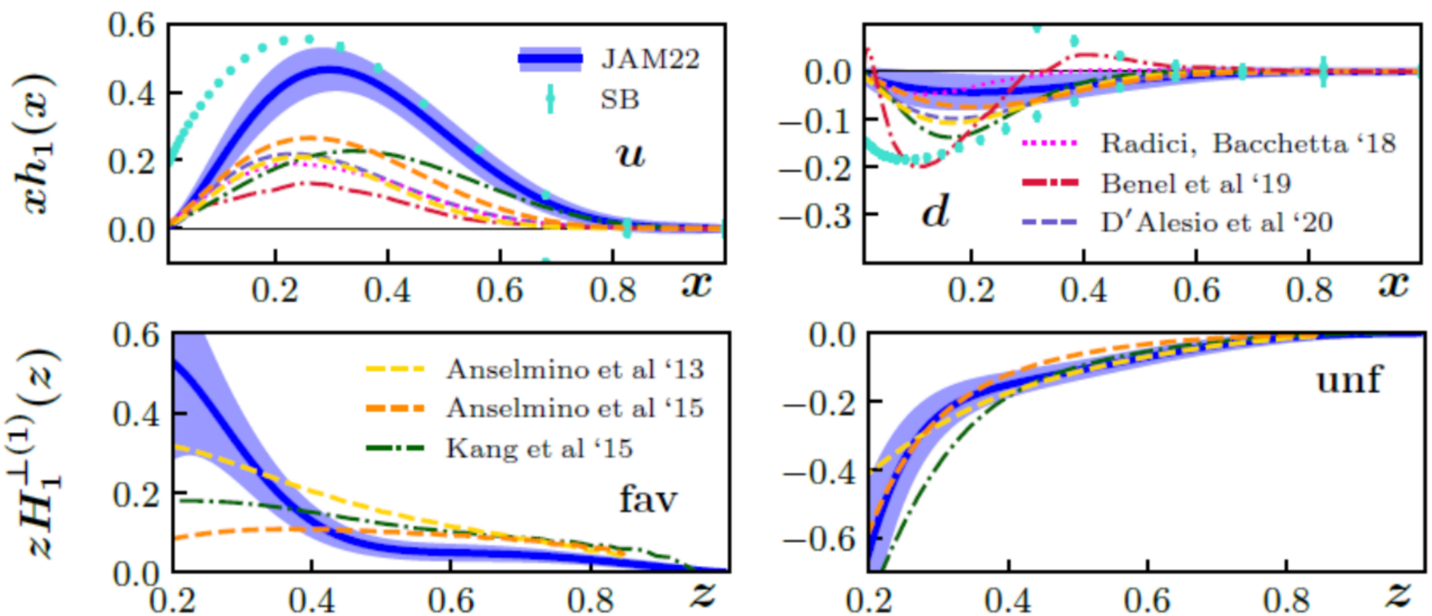
COMPASS Collins asymmetries on the deuteron compatible with zero
➔ u- and d-quark cancellations

Clearly, u- and d-quark transversity PDFs have opposite sign

d-quark transversity PDF much worse determined than u-quark one because of the scarcity of deuteron (neutron) data
➔ motivation for the 2022 run

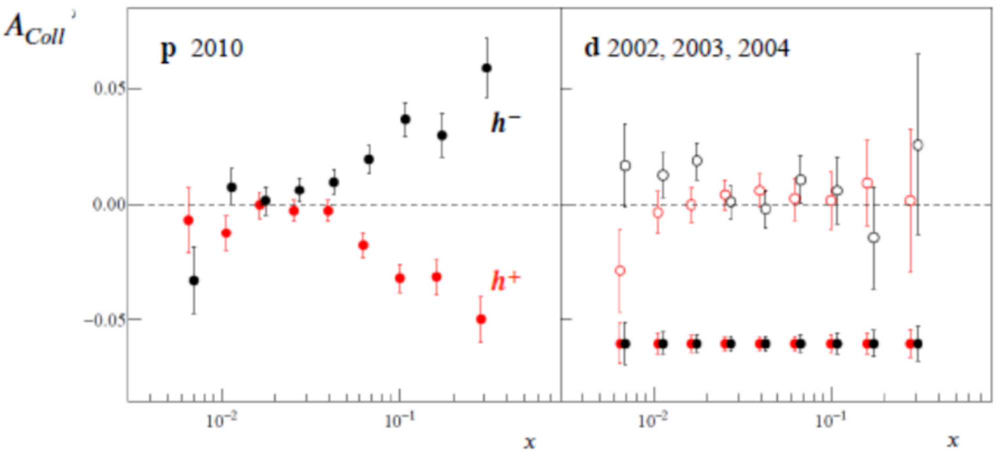
Global fit using data from
HERMES p, COMPASS p and d, Belle e+e- (for FF)
Bacchetta et al., JHEP1303 (2013), Kang et al., PRD93 (2016), Anselmino at al., PRD87 (2013), PRD92 (2015), and JAM Coll.

JAM Coll., PRD 106, 034014 (2022)



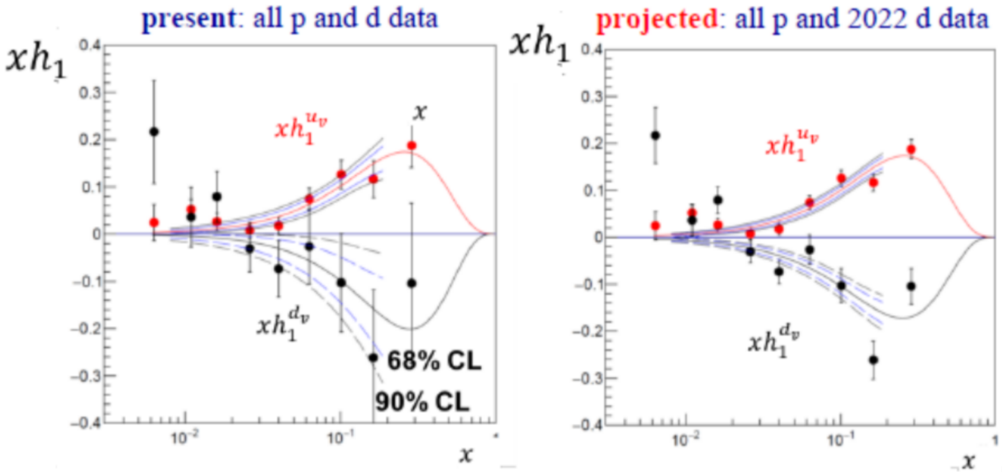
COMPASS 2022 new data with Transverse T→ impact on Transversity

provide valuable input for the determination of the Transversity PDF and the isovector nucleon tensor charge $g_T = \delta u - \delta d$,



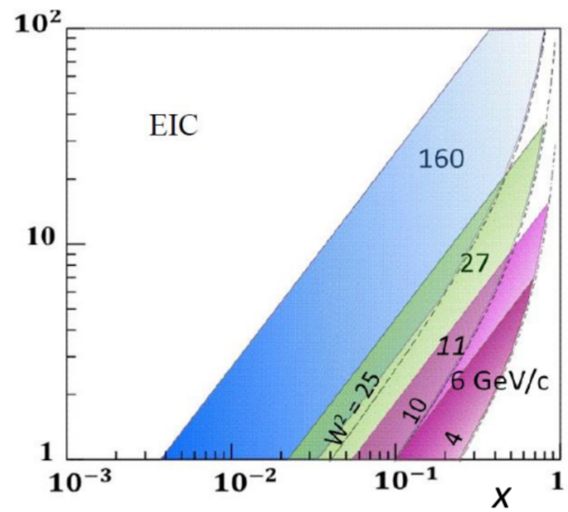
The quark tensor charges: $\delta q(Q^2) = \int_0^1 dx[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)]$

Ω_x: 0.008 ÷ 0.210	$\delta_u = \int_{\Omega_x} dx h_1^{u_v}(x)$	$\delta_d = \int_{\Omega_x} dx h_1^{d_v}(x)$	$g_T = \delta_u - \delta_d$
present	0.201 ± 0.032	- 0.189 ± 0.108	0.390±0.087
projected	0.201 ± 0.019	- 0.189 ± 0.040	0.390±0.044



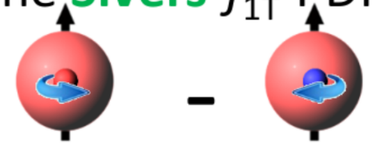
The work will not be over with the COMPASS measurements. Precise measurements are needed, in particular at larger *x*.

Complementary measurements at Jlab 12 and 20+ would allow for a more precise measurement of the tensor charge and, in the farther future, the EIC.



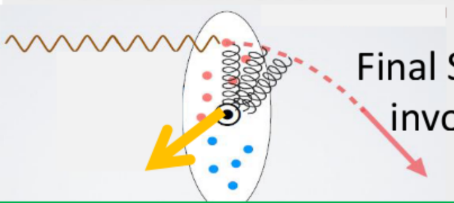
COMPASS 2010 Transverse T: Sivers Asym= Sivers ⊗ D_1 FF

The Sivers $f_{1T}^{\perp}$ PDF



correlates the quark k_T and the nucleon transv . spin

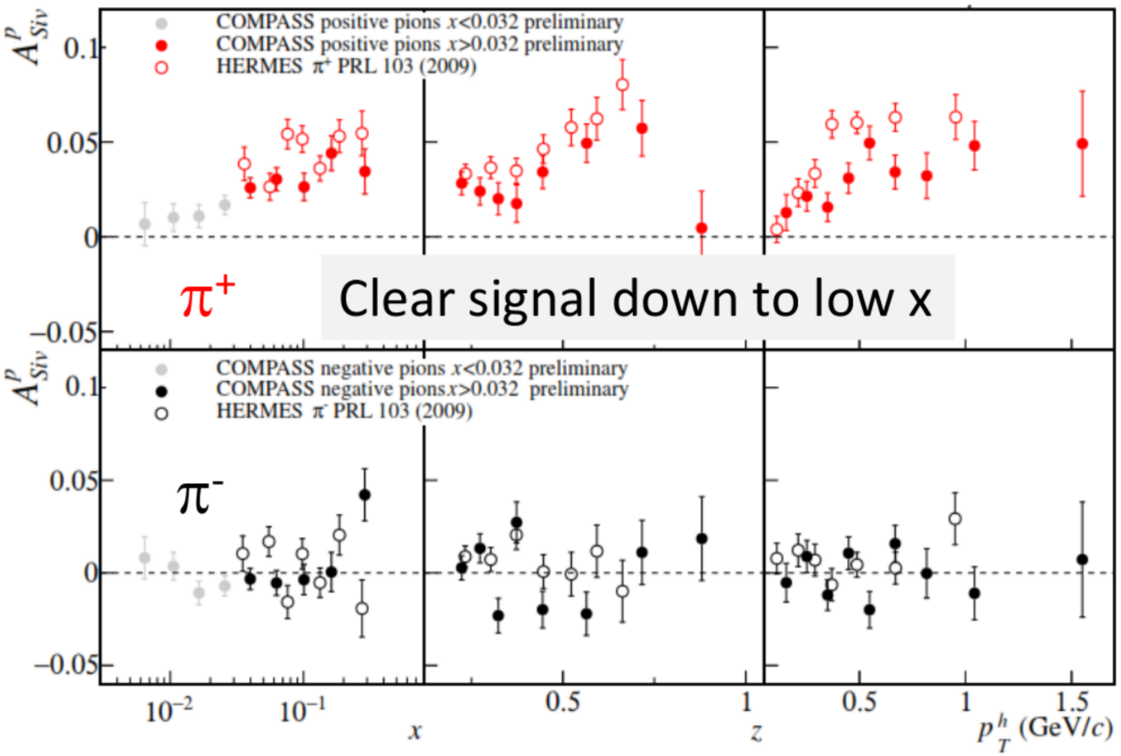
Sivers Chiral-even but T-odd



$$A_{Siv} \approx \frac{\sum_q e_q^2 \, f_{1T}^{\perp q}(x) \otimes D_{1q}^h(z, p_T^h)}{\sum_q e_q^2 \, f_1^q(x) \otimes D_{1q}^h(z, p_T^h)}$$

Sivers function describes strength of distortion in transverse momentum space from the symmetric unpolarized distribution f_1

COMPASS:PLB 692 (2010), PLB 717 (2012), PLB 744 (2015)



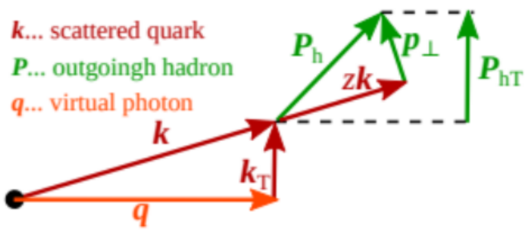
agreement between COMPASS and HERMES for x > 0.032 but clear indication that the strengh ↘ when Q^2 ↗
TMD evolution?

COMPASS 2010 + 22 + others extraction of Sivers PDF

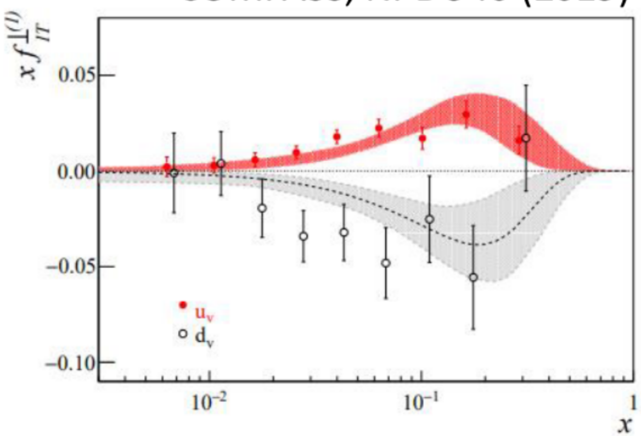
The **Sivers** asymmetries, when **weighted** with the hadron transverse momentum P_T provide direct information on the Sivers function (to overcome the convolution over intrinsic k_T without any ansatz.)

$$A_{\mathrm{Siv}}(x,z,P_T) = \frac{\sum_q e_q^2 x \mathscr{C}\left[\frac{P_T \cdot k_T}{M P_T} f_{1T}^{\perp q}(x,k_T^2) D_1^q(z,p_\perp^2)\right]}{\sum_q e_q^2 x \mathscr{C}\left[f_1^q(x,k_T^2) D_1^q(z,p_\perp^2)\right]}$$

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

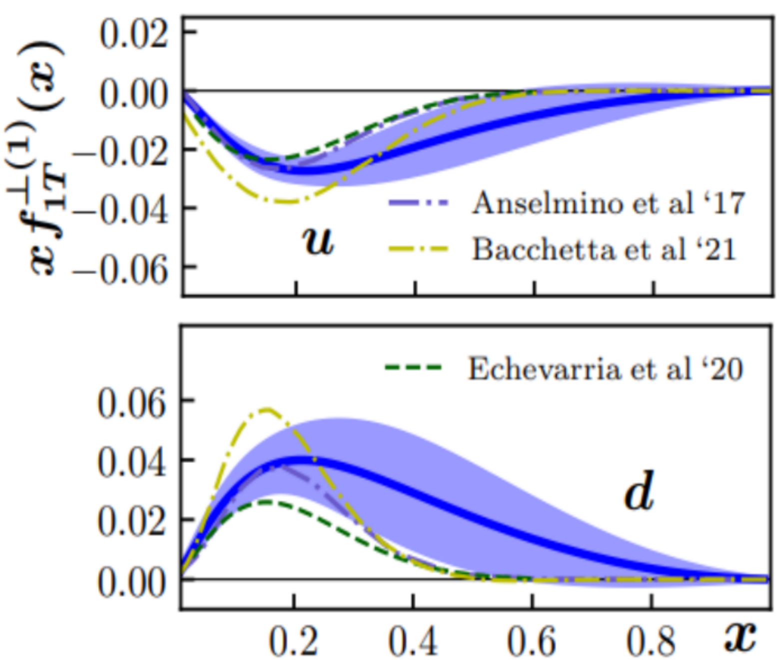


COMPASS, NPB 940 (2019)



Global fit using data from
HERMES p, COMPASS p and d

JAM Coll., PRD 106, 034014 (2022)



Impact of the COMPASS 2022 run on the Sivers PDF for the d quark
promising - a first look at the quality of 10% of the new data has been presented at DIS2023

COMPASS 2016 Unpolarized T: Cahn effect & Boer-Mulders ⊗ Collins FF

The **Boer-Mulders function** describes the strength of the spin-orbit correlation between quark spin $\boldsymbol{S_T}$ and intrinsic transv. mom. $\boldsymbol{k_T}$.

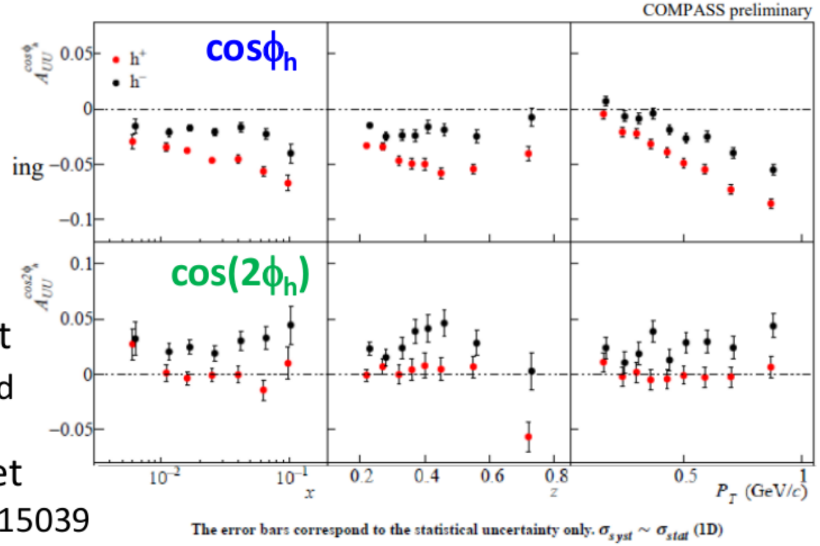
Contributes to **cosϕ_h** and **cos(2ϕ_h)**

Strong kinematic dependences & interesting differences between positive and negative hadrons, as observed in previous measurements (COMPASS d, HERMES) (u-quark dominance, opposite signs of Collins FF into h+ and h-)

Cahn effect additional contribution to **cosϕ_h** only - modulation purely due to the presence of intrinsic transverse momenta of unpolarized quarks in the unpolarized nucleon. No such modulation in the collinear case. NLO effect.

Azimuthal asymmetries – 1D (x or z or p_T)

Strong dependence on $\boldsymbol{p_T}$,
Compatible with 0 at high z.
Complementary access to **$\boldsymbol{k_T}$ quark intrinsic transverse momentum**



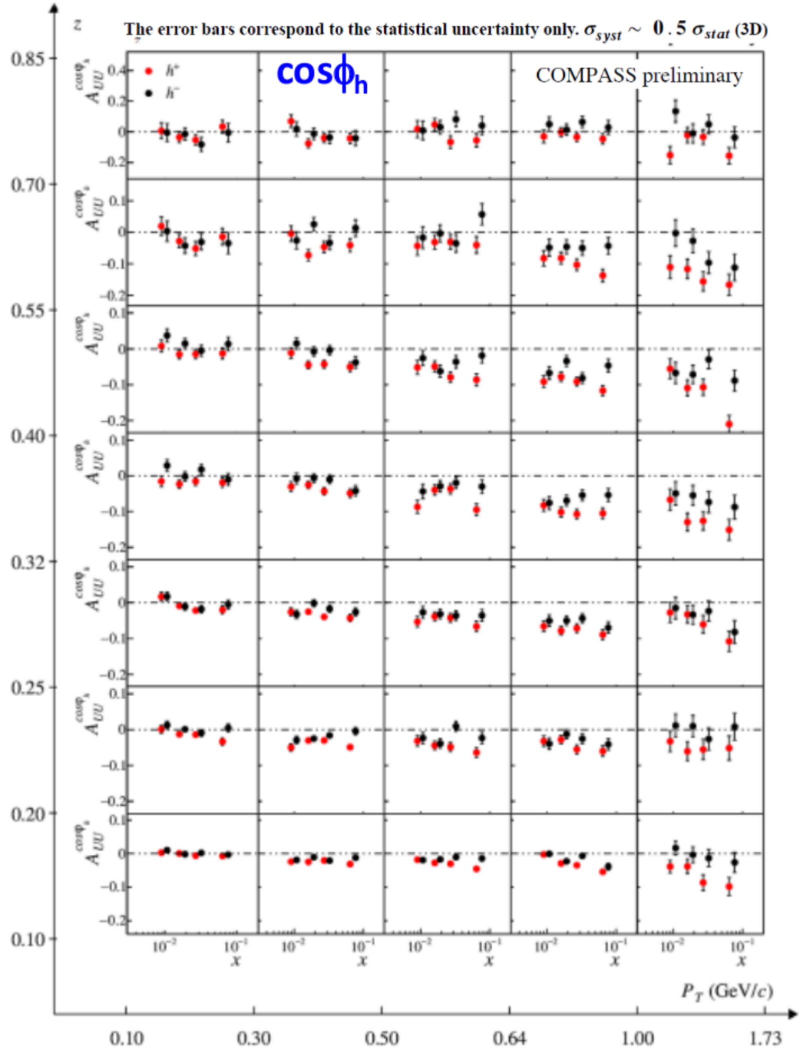
On proton target

Exclusive hadron contribution subtracted

On deuteron target

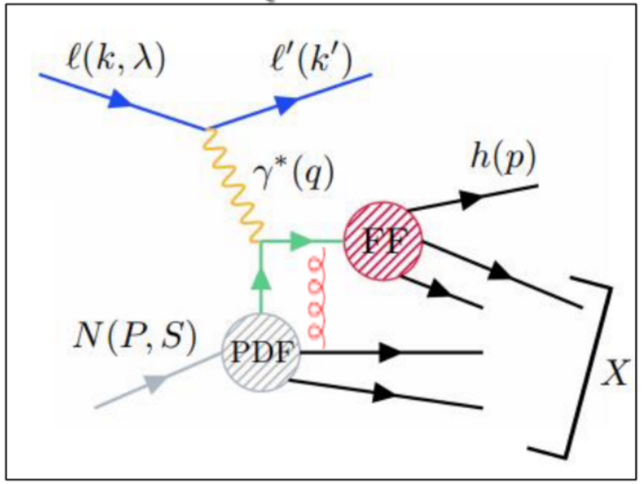
NPB 886 (2014) 1046, NPB 956 (2020) 115039

Azimuthal asymmetries – 3D (x, z, p_T)



COMPASS unique set up to perform both SIDIS and Drell-Yan

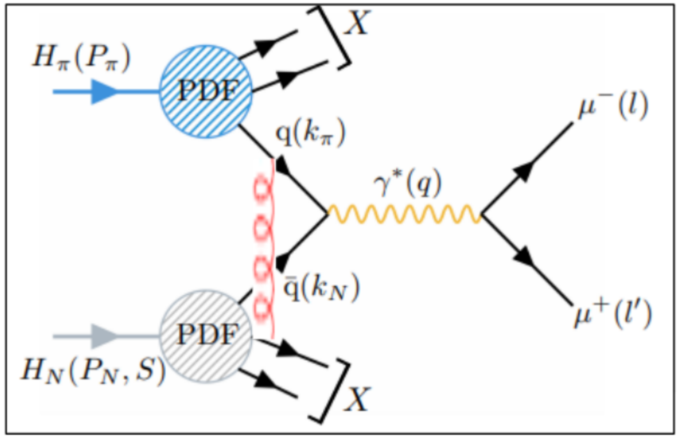
SIDIS: ℓ p↑ → ℓ h± X



SIDIS: convolution TMD ⊗ FF^h

TMDs involve Final State Interaction

Drell-Yan (DY): π p↑ → μ⁺ μ⁻ X



DY: convolution TMD^{beam} ⊗ TMD^{target}

TMDs involve Initial State Interaction

TMD PDFs are universal but Sign Flip for naive T-odd TMD PDFs

Boer-Mulders

$$h_{1,p}^{\perp q}|_{DY} = -h_{1,p}^{\perp q}|_{SIDIS}$$

Sivers

$$f_{1T,p}^{\perp q}|_{DY} = -f_{1T,p}^{\perp q}|_{SIDIS}$$

→ Crucial test of TMD framework in QCD

SIDIS and single-polarized Drell-Yan cross section at twist-2

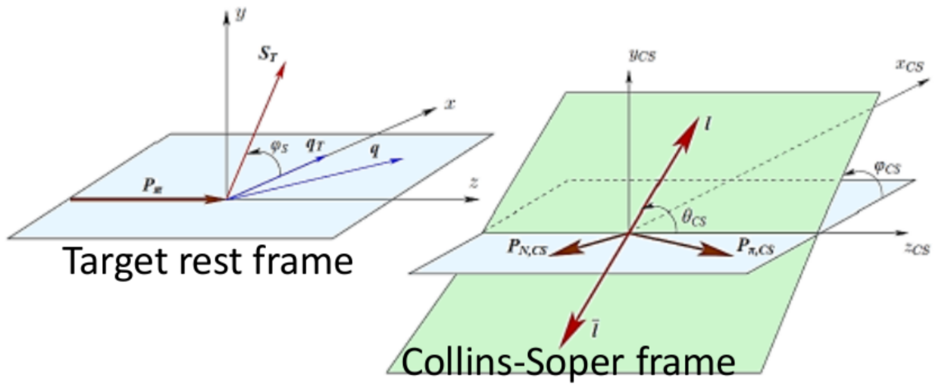
SIDIS

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h - \phi_S)} \sin(\phi_h - \phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h + \phi_S)} \sin(\phi_h + \phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h - \phi_S)} \sin(3\phi_h - \phi_S) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h - \phi_S)} \cos(\phi_h - \phi_S) \right] \end{array} \right\}$$

DY

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1 + \cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS} - \varphi_S)} \sin(2\varphi_{CS} - \varphi_S) \\ + A_T^{\sin(2\varphi_{CS} + \varphi_S)} \sin(2\varphi_{CS} + \varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1 + \cos^2\theta_{CS}\right)$



SIDIS and single-polarized Drell-Yan cross section at twist-2

SIDIS

$$\frac{d\sigma^{LO}}{dxdydzdp_T^2 d\phi_h d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L\, \varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2} A_{LL} \\ + S_T \left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)} \sin(\phi_h-\phi_S) \\ + \varepsilon A_{UT}^{\sin(\phi_h+\phi_S)} \sin(\phi_h+\phi_S) \\ + \varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)} \sin(3\phi_h-\phi_S) \end{array} \right] \\ + S_T \lambda \left[\sqrt{(1-\varepsilon^2)} A_{LT}^{\cos(\phi_h-\phi_S)} \cos(\phi_h-\phi_S) \right] \end{array} \right\}$$

DY

$$\frac{d\sigma^{LO}}{dq^4 d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S} \sin\varphi_S \\ + D_{[\sin^2\theta_{CS}]} \left(\begin{array}{l} A_T^{\sin(2\varphi_{CS}-\varphi_S)} \sin(2\varphi_{CS}-\varphi_S) \\ + A_T^{\sin(2\varphi_{CS}+\varphi_S)} \sin(2\varphi_{CS}+\varphi_S) \end{array} \right) \end{array} \right] \end{array} \right\}$$

where $D_{[\sin^2\theta_{CS}]} = \sin^2\theta_{CS} / \left(1+\cos^2\theta_{CS}\right)$

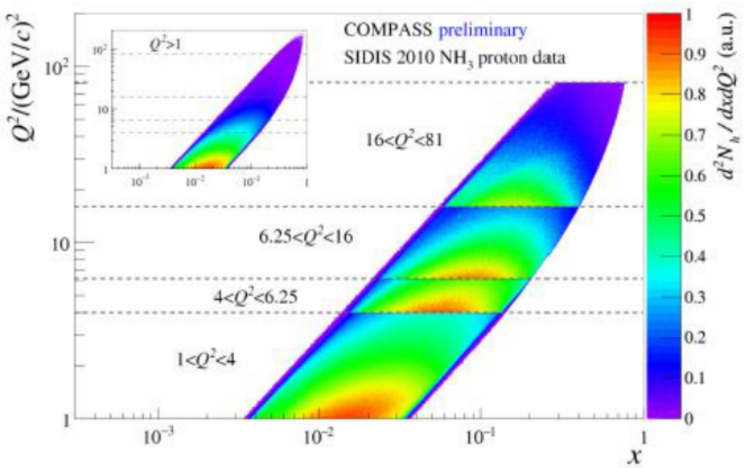
SIDIS		DY
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + ..$	Boer-Mulders	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$	Sivers	$A_T^{\sin\varphi_S} \propto f_{1,\pi}^q \otimes f_{1T,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1^q \otimes H_{1q}^{\perp h}$	Transversity	$A_T^{\sin(2\varphi_{CS}-\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^q$
$A_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp q} \otimes H_{1q}^{\perp h}$	Pretzelosity	$A_T^{\sin(2\varphi_{CS}+\varphi_S)} \propto h_{1,\pi}^{\perp q} \otimes h_{1T,p}^{\perp q}$

COMPASS unique conditions to test TMD universality

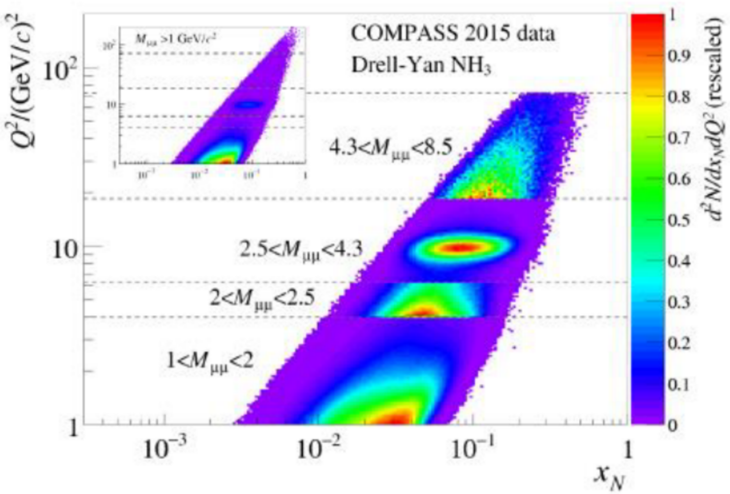
SIDIS on transversely polarized proton
COMPASS 2007, 2010

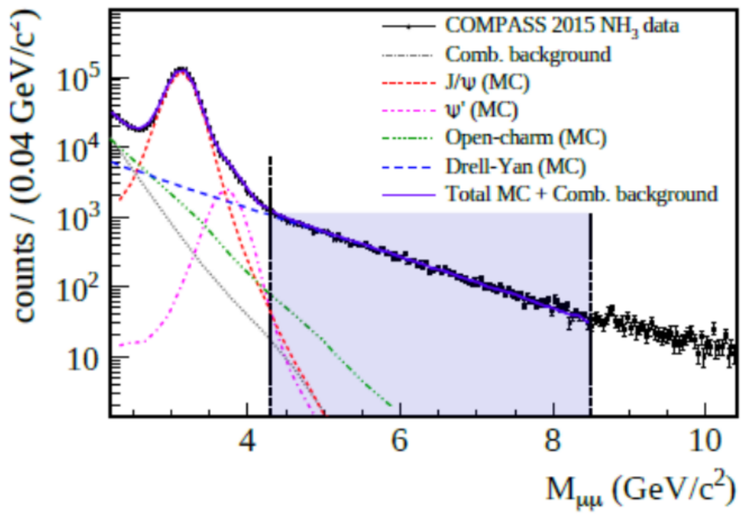
Pion-induced transversely polarized Drell-Yan
COMPASS 2015, 2018

PLB 770 (2017) 138



PRL 119 (2017) 112002





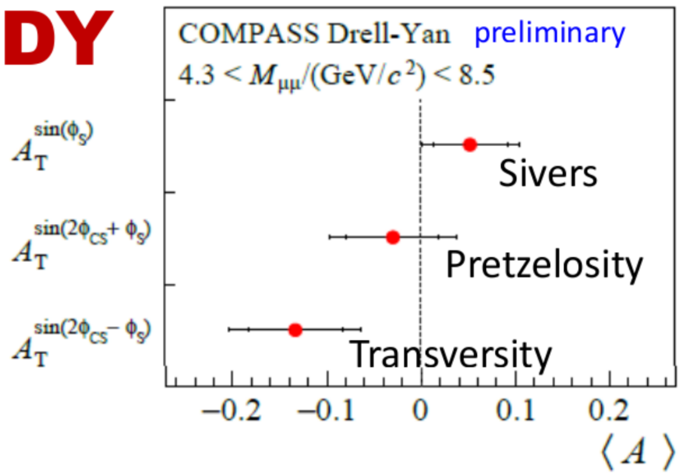
Safe Drell-Yan domain: $4.3 < M_{\mu\mu}/(\mathrm{GeV}/c^2) < 8.5$

Corresponding SIDIS domain: $16<Q^2/(\mathrm{GeV}/c)^2<81$

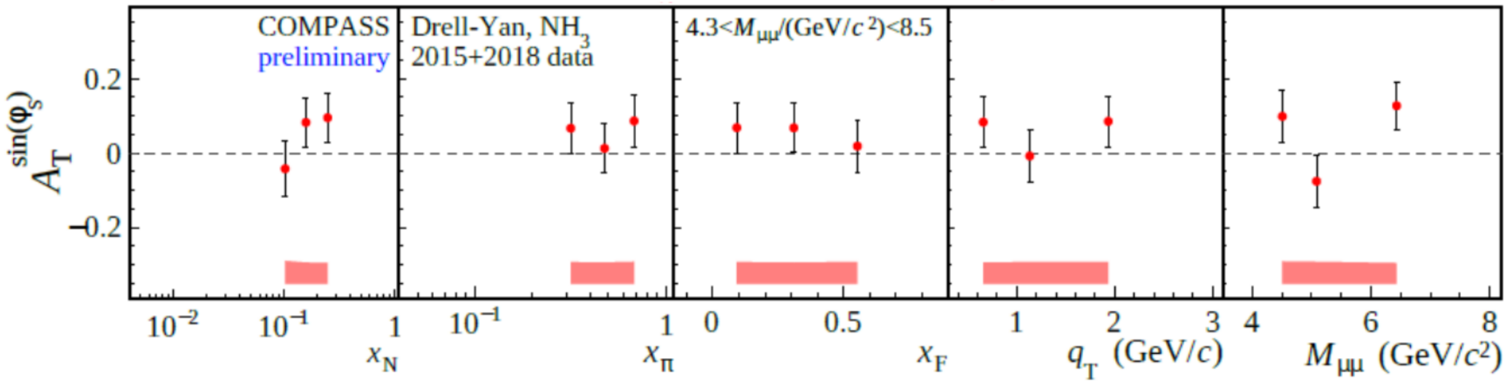
Similar (x,Q^2) coverage to minimize the Q^2 evolution effects
to compare TMDs in SIDIS and DY

COMPASS results in Drell-Yan and SIDIS

DY

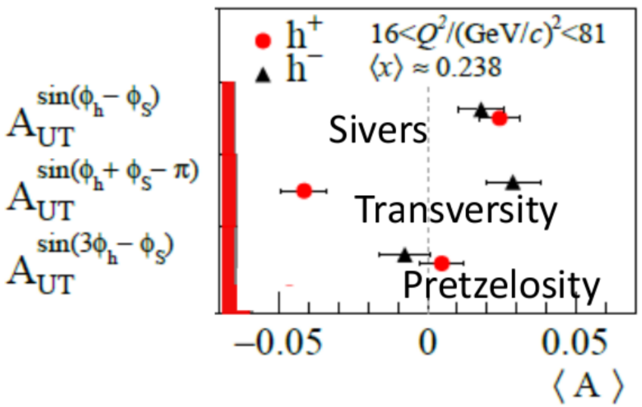


Sivers in DY: $A^{\sin(\phi_S)} \propto f_{1,\pi} \otimes f_{1T,p}^{\perp}$

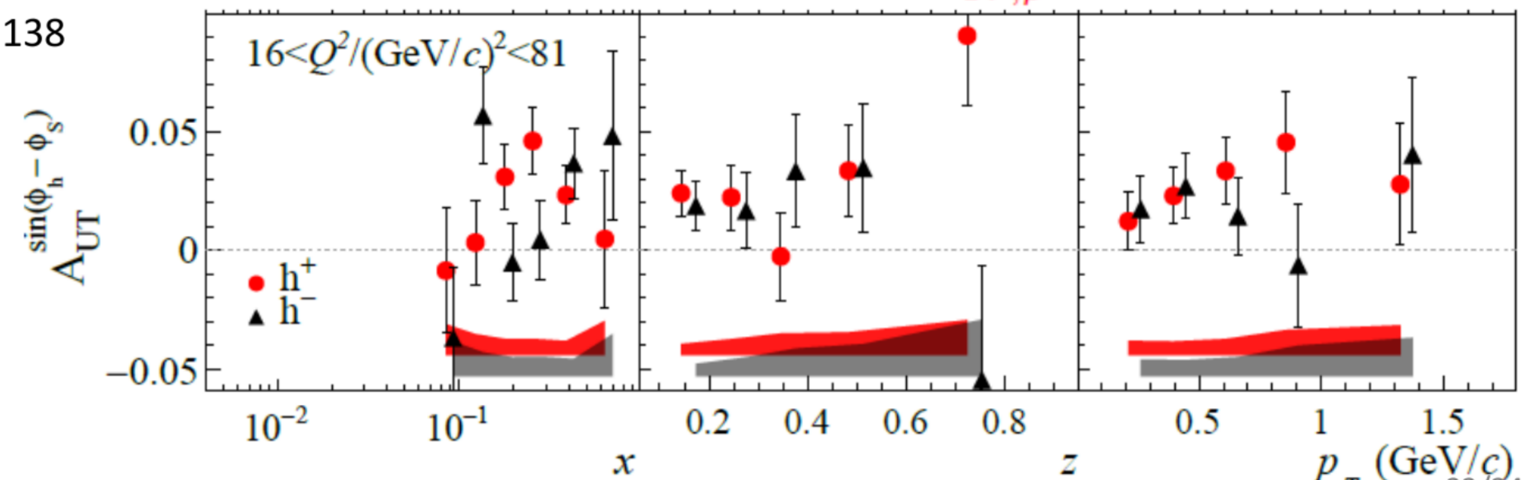


SIDIS

COMPASS SIDIS PLB 770 (2017) 138



Sivers in SIDIS: $A^{\sin(\phi_h-\phi_S)} \propto f_{1T,p}^{\perp} \otimes D_1^h$

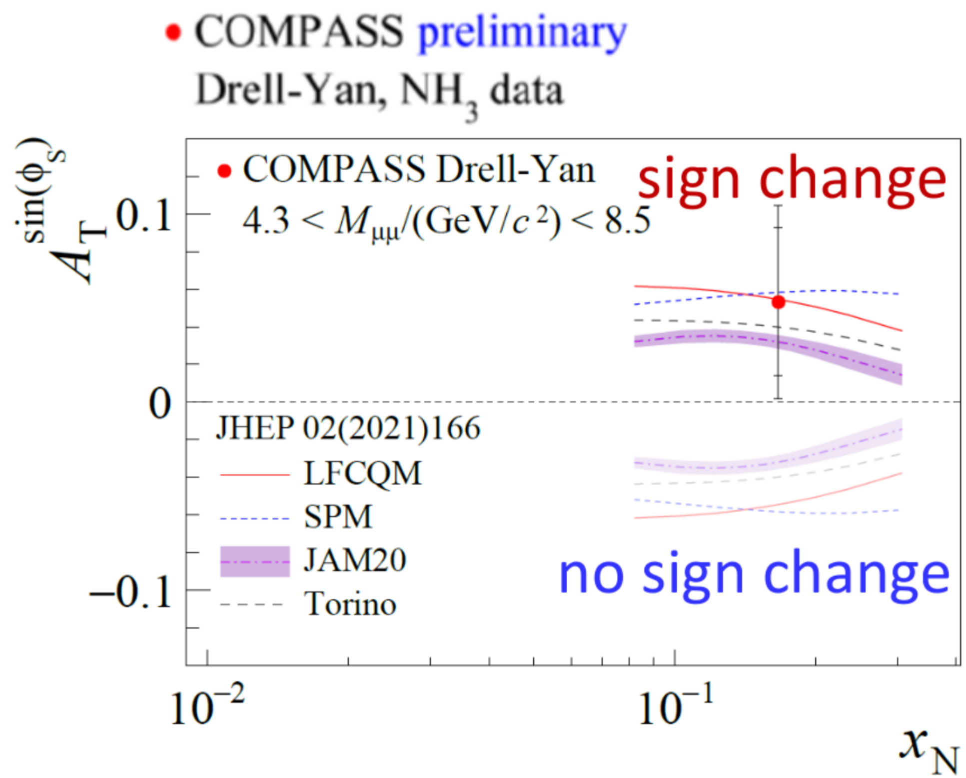


COMPASS first ever polarized Drell-Yan to test the Sivers sign change

PRL 119 (2017) 112002 + preliminary results with 2015+2018 data

The average Sivers asymmetry integrated over the entire kinematic range is found to be above zero at about one standard deviation of total uncertainty.

$$\langle A_T^{\sin \varphi_S} \rangle = 0.053 \pm 0.039(stat.) \pm 0.033(sys.)$$



conclusions

Only a selection of COMPASS results

Exclusive reactions for GPD studies: difficult experiments, limited in statistics
work in progress

SIDIS and first ever polarized DY measurements Drell-Yan:
rich in statistics to perform multi-dimensional analysis
studies of multiplicities, p_T dependence (x,z,Q^2)
studies of universality, factorization, evolution

Still more results will come