Hadron Structure Studies at the COMPASS Experiment

The 3rd EIC Asia Workshop
National Cheng Kung University
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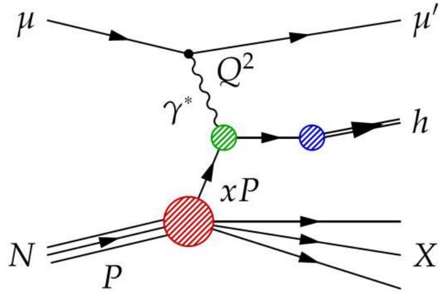
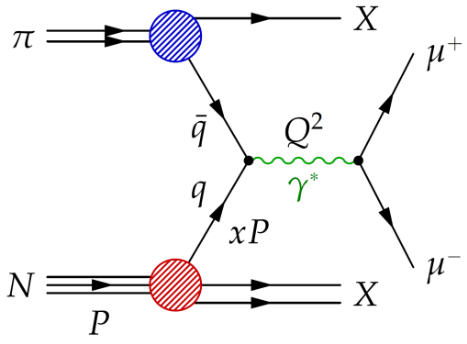
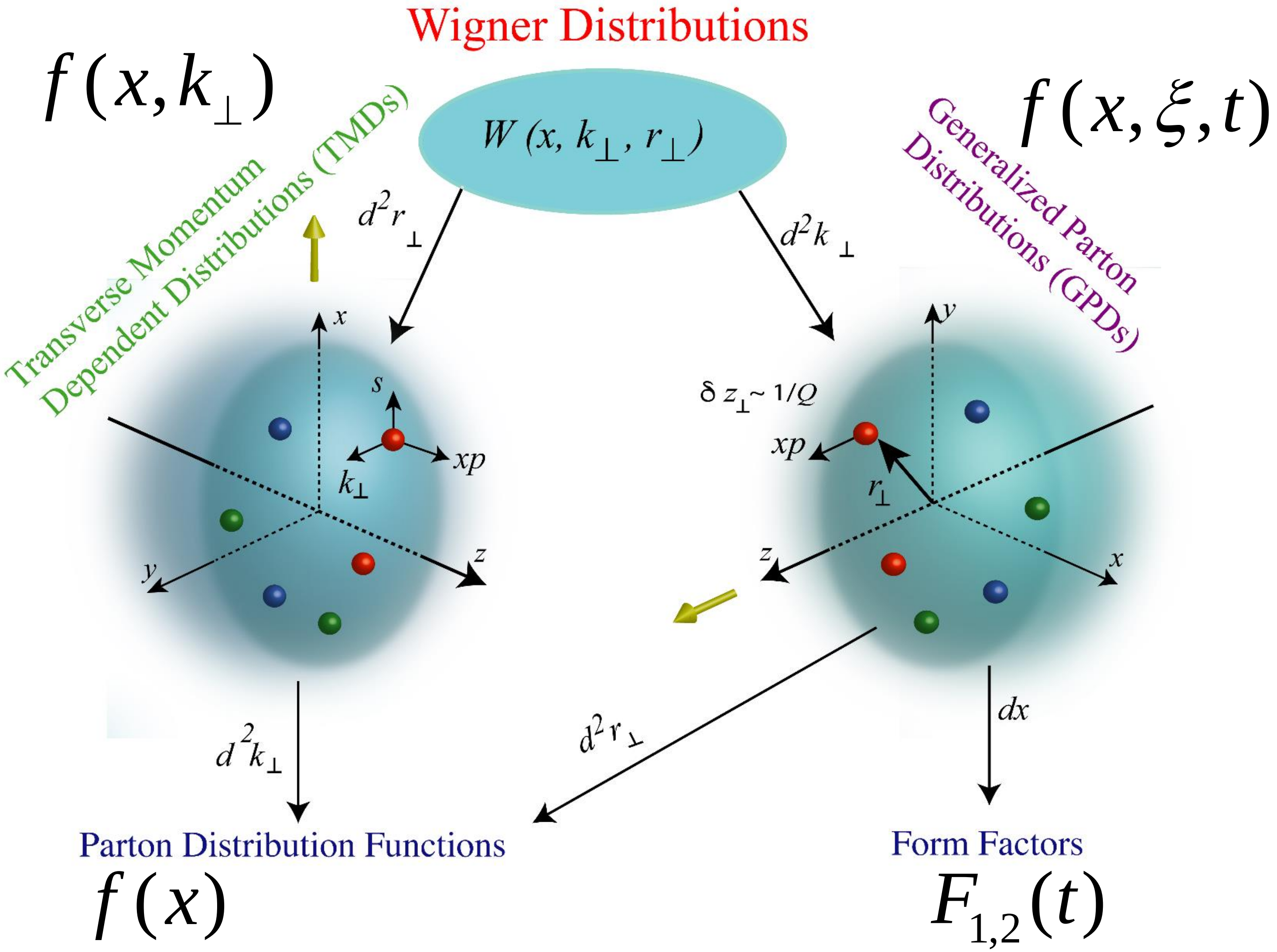
Multi-dimensional Partonic Structures

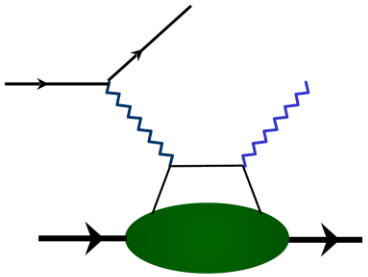


SIDIS

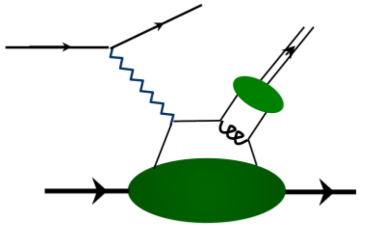


Drell-Yan





DVCS



HEMP

http://www.int.washington.edu/PROGRAMS/17-3/

Parellelism between TMDs and GPDs

Transverse momentum k_T not shown

Eight TMDs

Nucleon Spin — Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = − Boer-Mulders
L		g_1 = − Helicity	$h_{1L}^\perp$ = − Worm-gear
T	$f_{1T}^\perp$ = − Sivers	$g_{1T}^\perp$ = − Worm-gear	h_1 = − Transversity $h_{1T}^\perp$ = − Pretzelosity

Eight GPDs

Nucleon Spin — Quark Spin

Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	H		$\bar{E}_T = 2\tilde{H}_T + E_T$
L		$\tilde{H}$	E_T
T	E	$\tilde{E}$	$H_T, \tilde{H}_T$

4 chiral-even, 4 chiral-odd, 2 T-odd

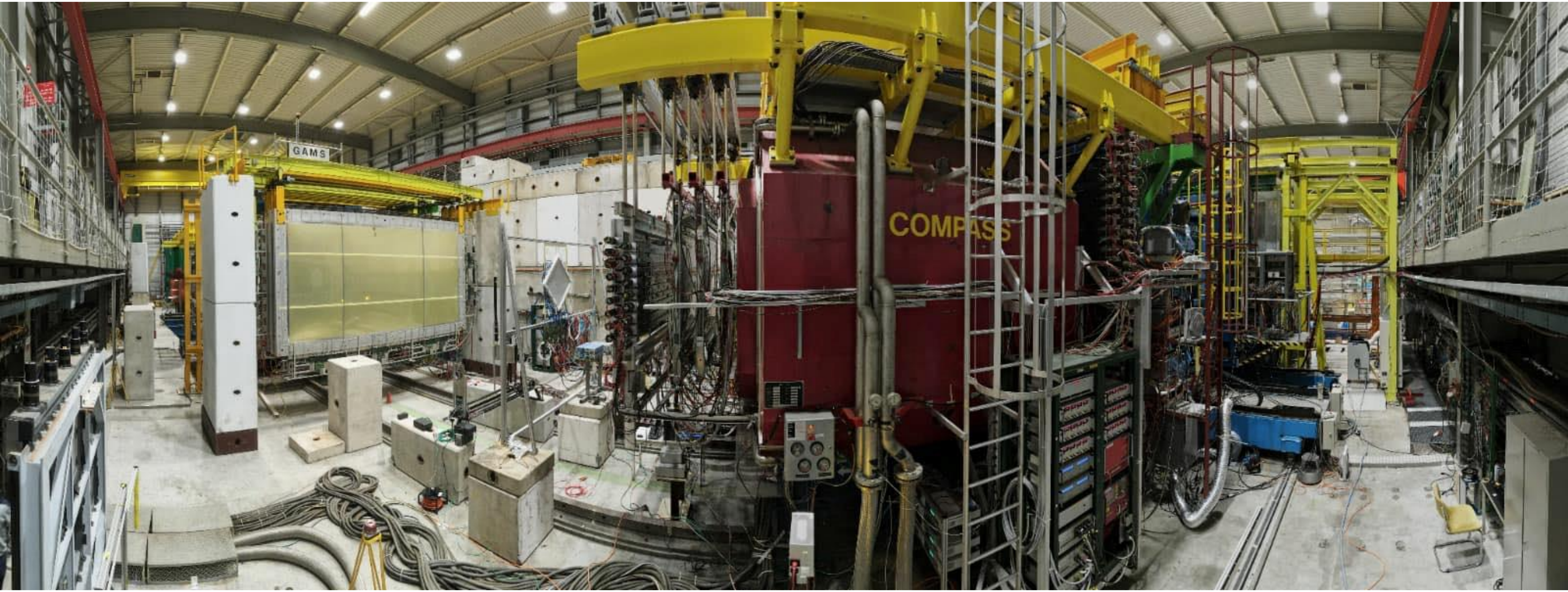
COMPASS Experiment

Versatile facility with hadron ($\pi^{\pm}$, $K^{\pm}$, p …) & lepton (polarized $\mu^{\pm}$) beams of energy 100 to 200 GeV

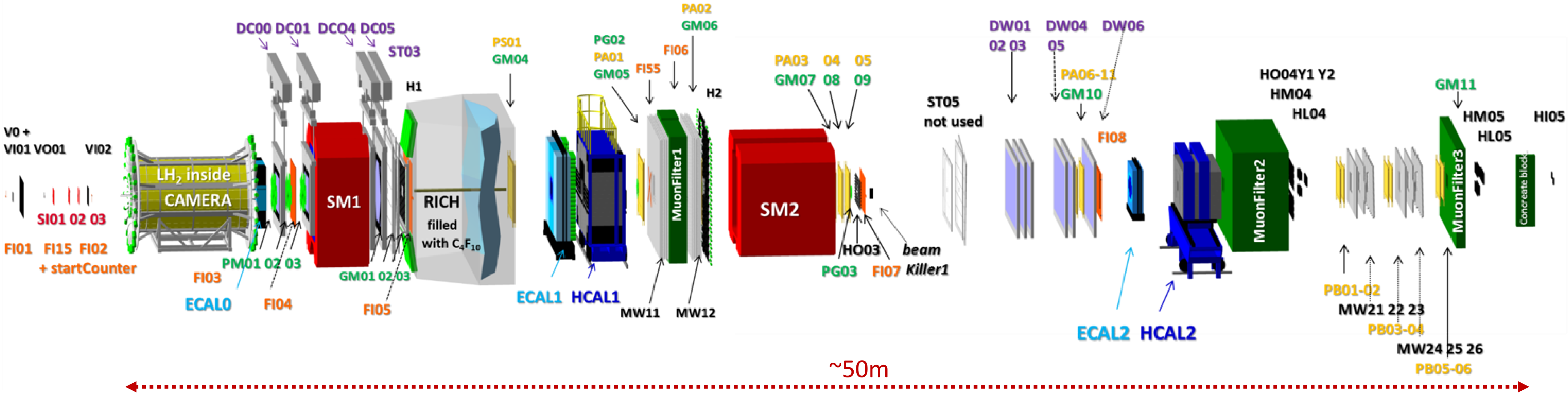
~220 physicists from 25 Institutes of 13 Countries

COmmon
Muon and
Proton
Apparatus for
Structure and
Spectroscopy

COMPASS Experimental Setup



COMPASS Experimental Setup



- ➢ Priamary beam – 400 GeV p from SPS
  - Impinging on Be production target
- ➢ 190 GeV secondary hadron beams
  - h^- beam: $97\%\ \pi^-, 2\%\ K^-, 1\%\ p$
  - h^+ beam: $75\%\ \pi^+, 24\%\ p, 1\%\ K^+$
- ➢ 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polzaized

Large-acceptance forward spectrometer

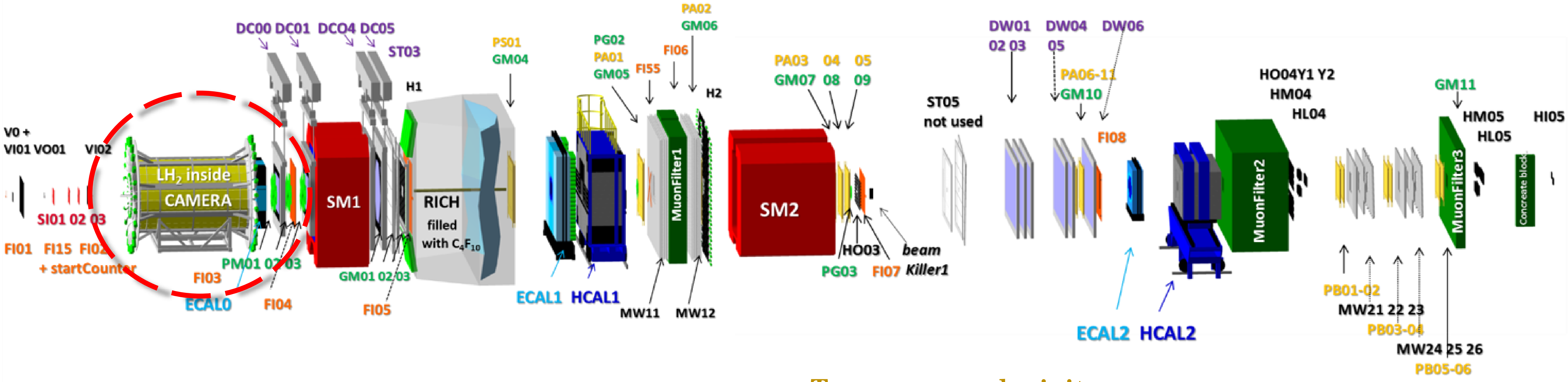
- Precise tracking (350 planes)
  SciFi, Silicon, MicroMegas, GEM, MWPC, DC, straw
- PID – CEDARs, RICH, calorimeters, Muon Walls

Various targets:

- Polarized soild-state NH_3 or ^6LiD
- Liquid H_2
- Solid-state nuclear targets

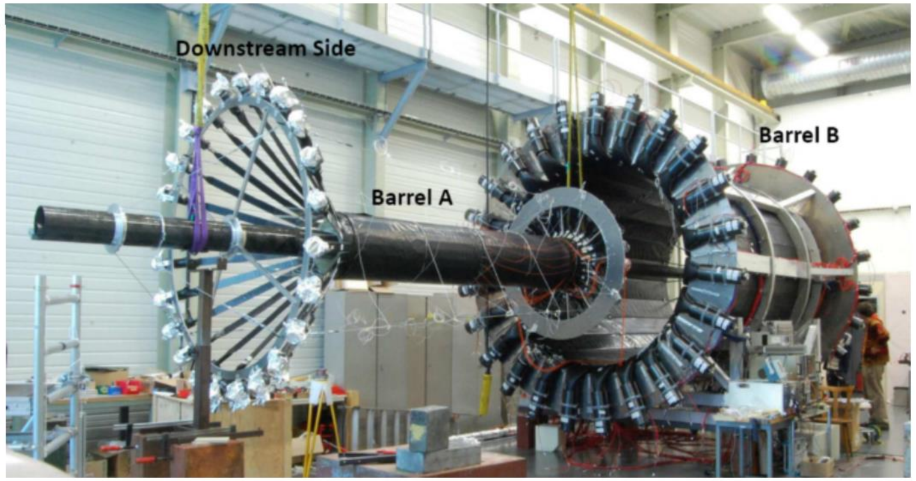
❖ NIM A 577 (2007) & NIM A 779 (2015) 69

COMPASS Setup for Exclusive Processes



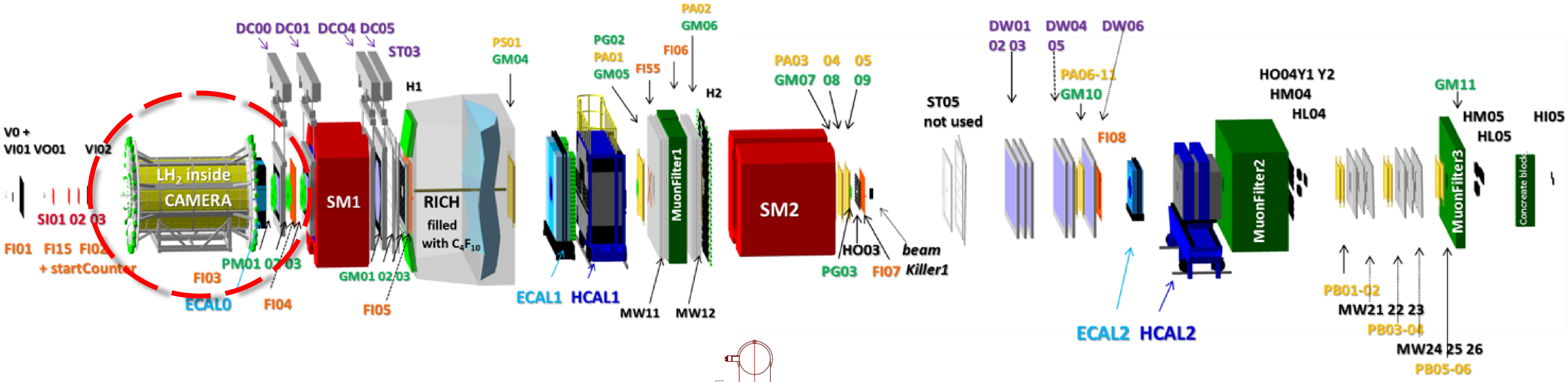
- Priamary beam – 400 GeV p from SPS
  - Impinging on Be production target
- 190 GeV secondary hadron beams
  - h^- beam: 97% π^-, 2% K^-, 1% p
  - h^+ beam: 75% π^+, 24% p, 1% K^+
- 160 GeV tertiary muon beams
  - $\mu^\pm$ longitudinally polzaized

To ensure exclusivity:



CAMERA recoil proton detector

COMPASS Setup for SIDIS



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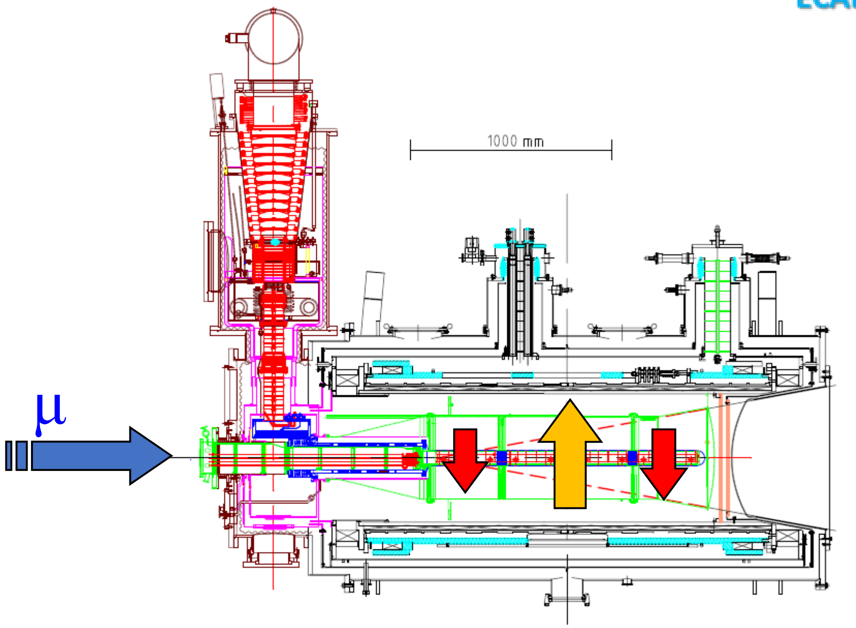
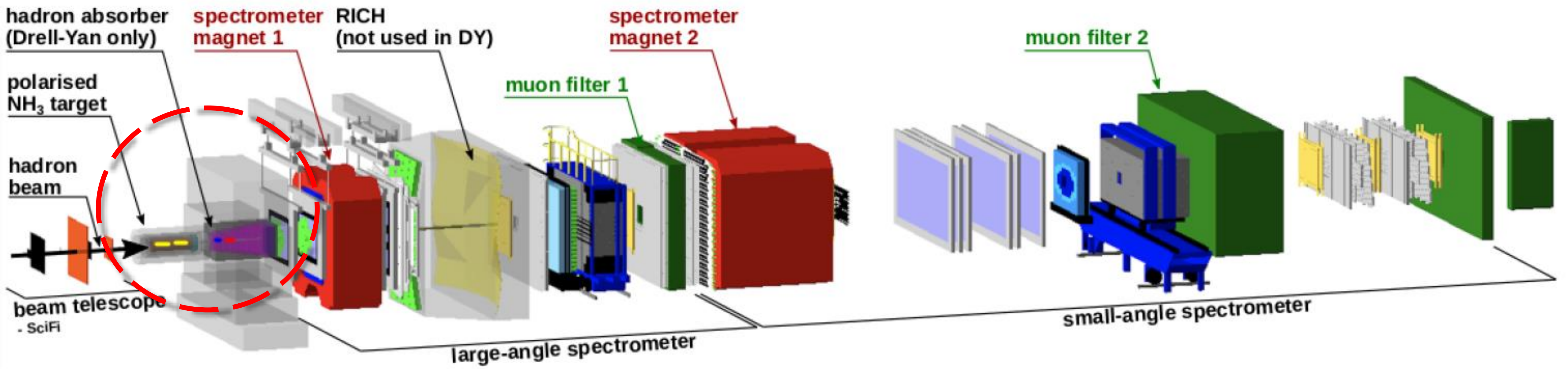


- Target polarized or unpolarized
  - ^{6}LiD ~50%
  - NH_3 ~85%
- 2 or 3 oppositely polarized cells
  - Polarization reversal by magnetic field rotation

COMPASS Setup for Drell-Yan



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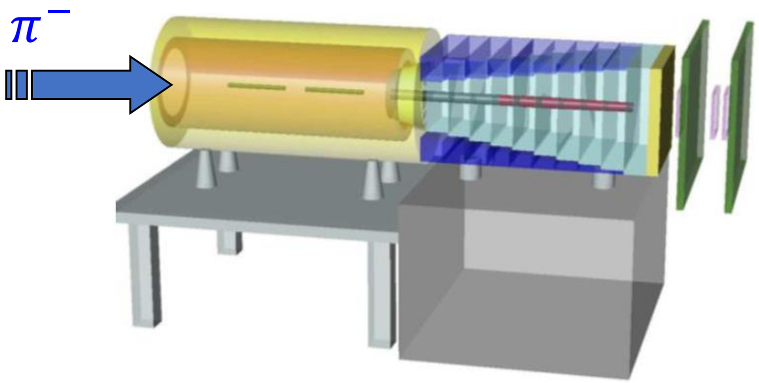
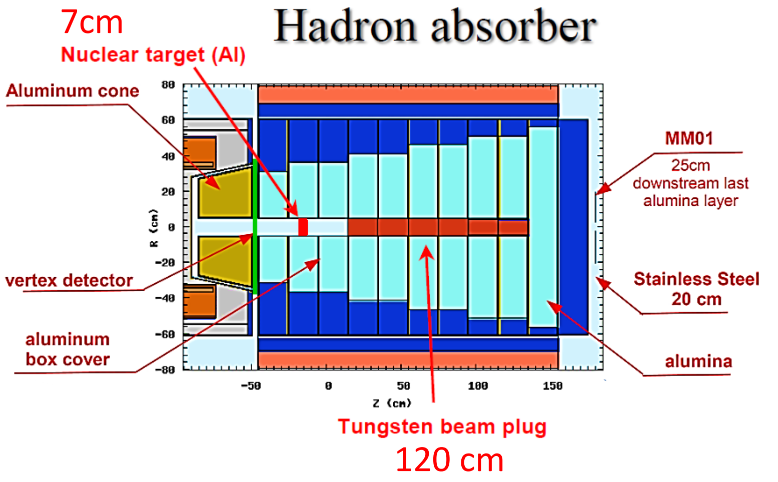




COMPASS Experiment

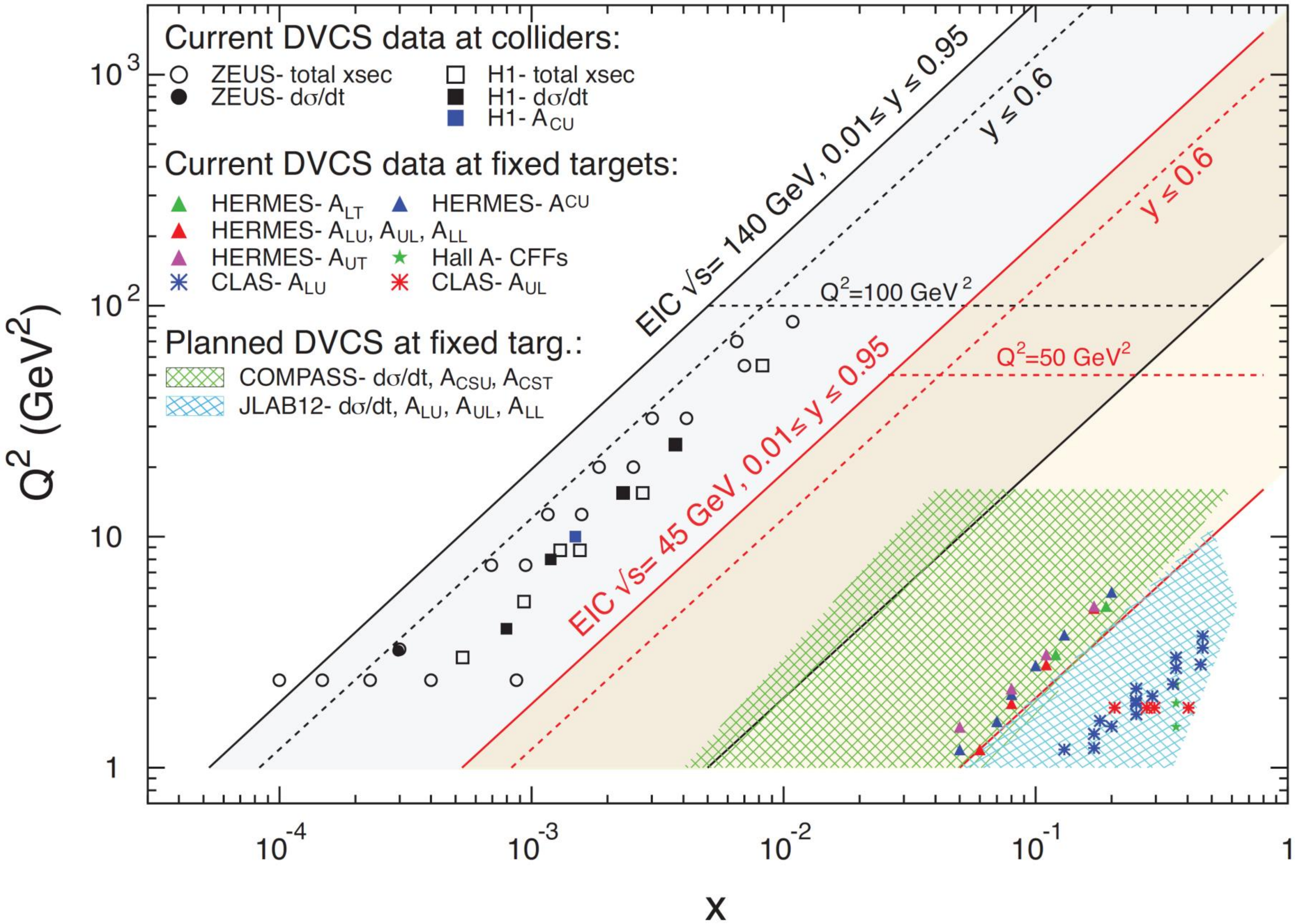
2002-2022 COMPASS data taking

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

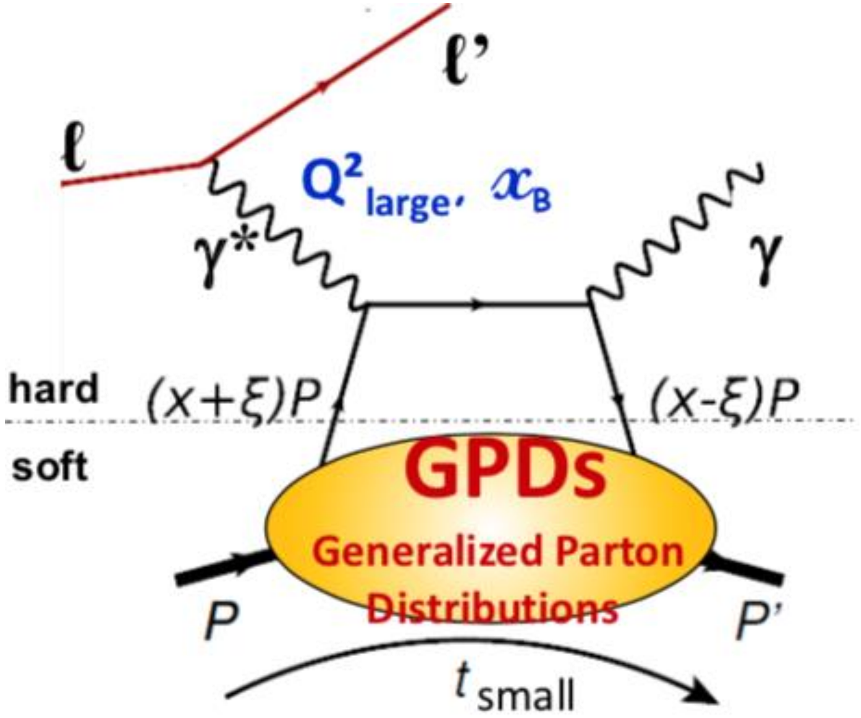
Study hadron structure with complmentary tools:

- **COMPASS holds the record for the longest-running CERN experiment**
- Unpolarized or L/T polarized targets
- Polarized muon beams for DIS, SIDIS, DVCS, DVMP
- Hadron beams for hadron spectroscopy and Drell-Yan

Lanscape – Global Programs of DVCS



DVCS



The variables measured in the experiment:

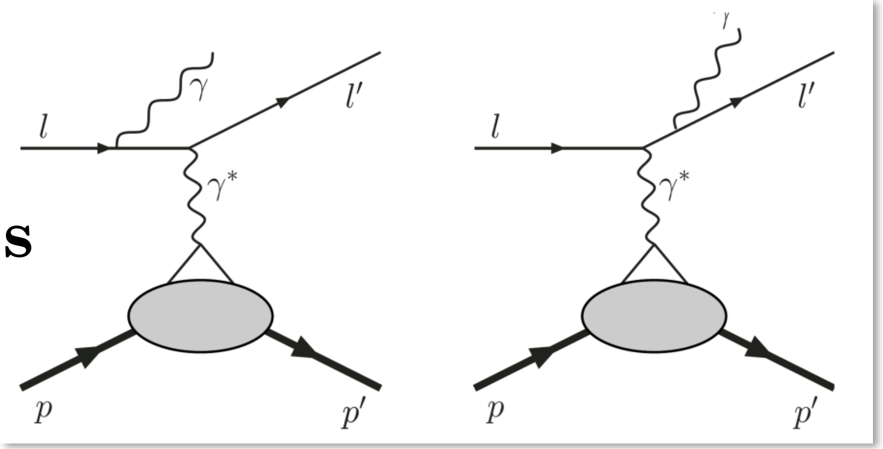
E_ℓ, Q^2, $x_{Bj} \sim 2\xi/(1+\xi)$,

t (or $\theta_{\gamma^*\gamma}$) and ϕ ($\ell\ell$' plane/$\gamma\gamma^*$ plane)

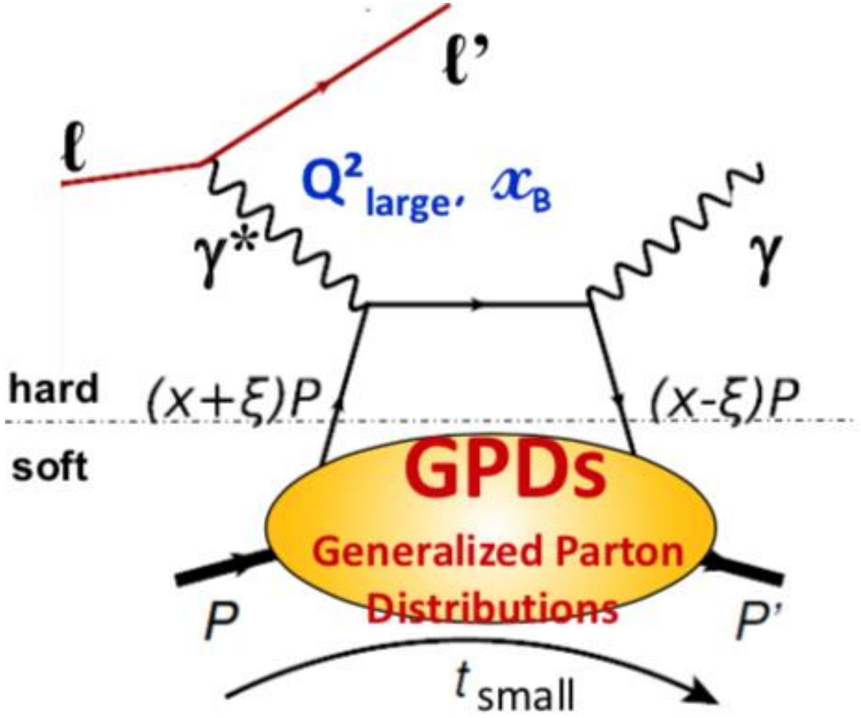
DVCS: $l + p \rightarrow l' + p' + \gamma$

To experimentally access the information about Generalized Parton Distributions (GPDs), DVCS is regarded as the golden channel and its interference with the well-understood Bethe-Heitler process gives access to more info.

BH Process



DVCS



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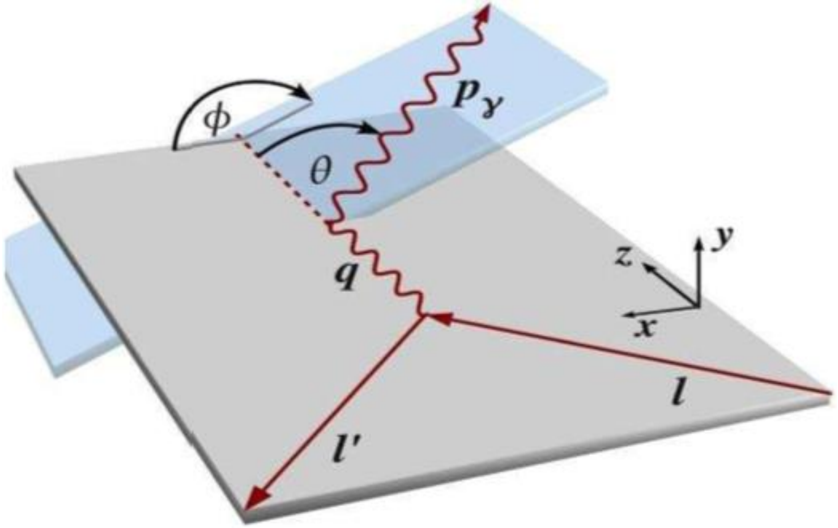

The variables measured in the experiment:

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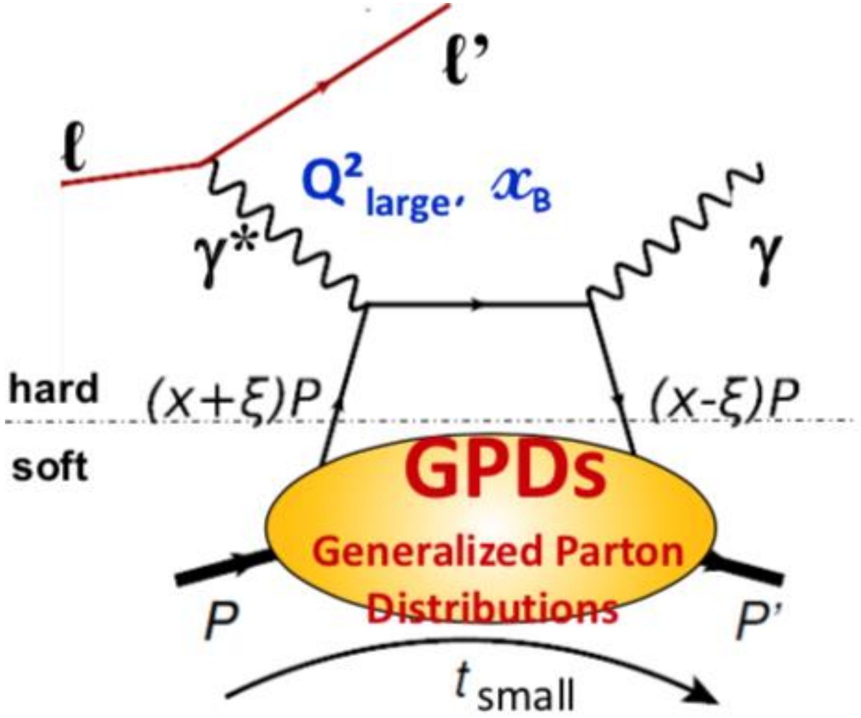
t (or $\theta_{\gamma^*\gamma}$) and ϕ (ℓℓ' plane/γγ* plane)

DVCS



- The GPDs depend on the following variables:

  x: average longitudinal momentum frac.

  ξ: longitudinal momentum diff.

  t: four momentum transfer
  (correlated to $b_\perp$ via Fourier transform)

  Q^2: virtuality of γ^*

Sensible to 4 GPDs, with LH_2 target and small x_B coverage
→ focuses on **H** at COMPASS

CFF, GPD

REAL part **Imaginary part**

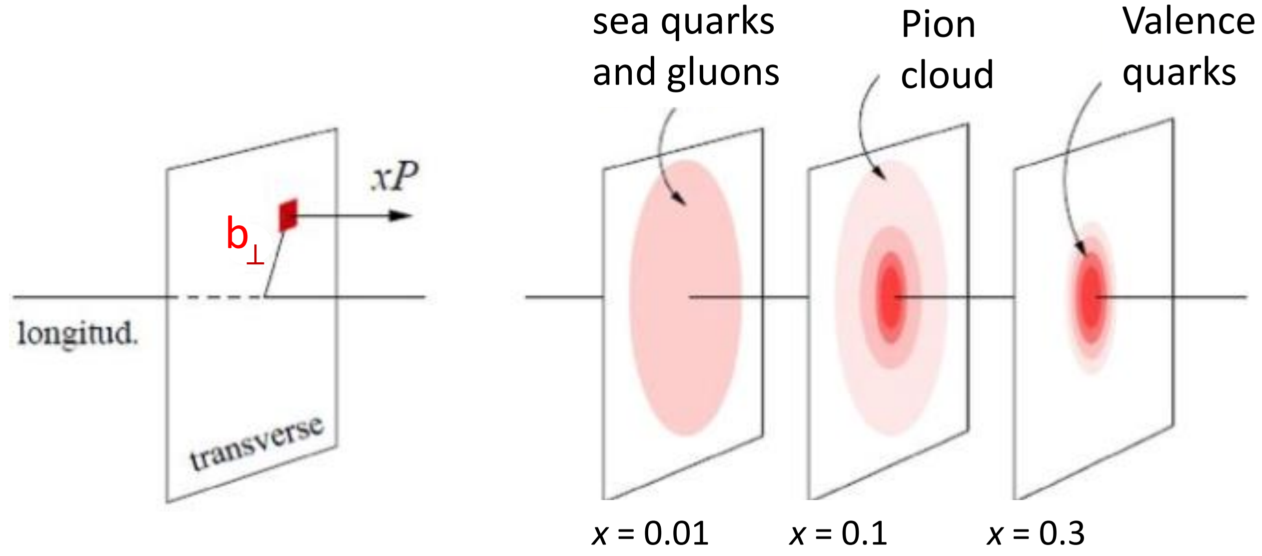
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\,\mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

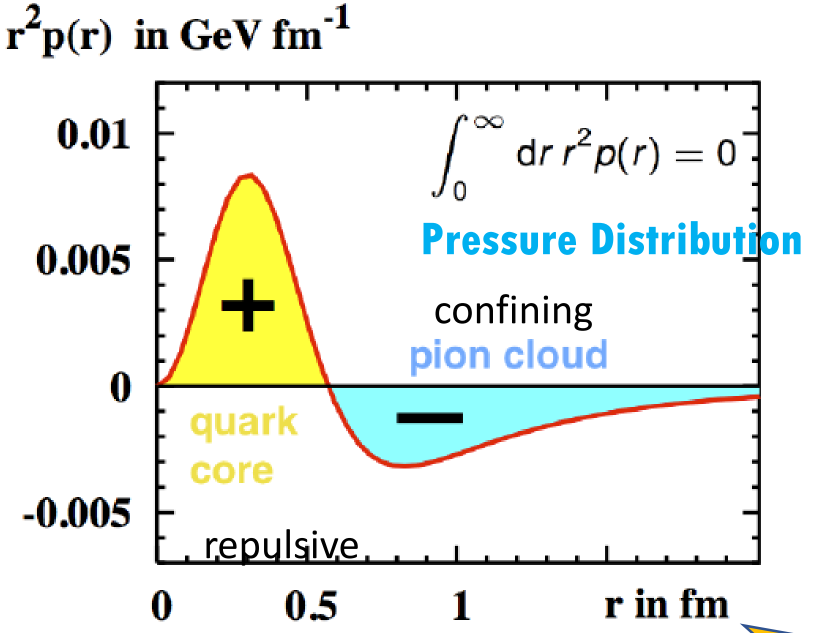
$$\mathcal{R}e\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx \frac{\mathcal{I}m\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

Transverse Imaging and Pressure Distribution

M. Polyakov, P. Schweitzer, Int.J.Mod.Phys. A33 (2018)

Mapping in the transverse plane





FT of H(x, ξ=0,t)

CFF GPD

REAL part Imaginary part

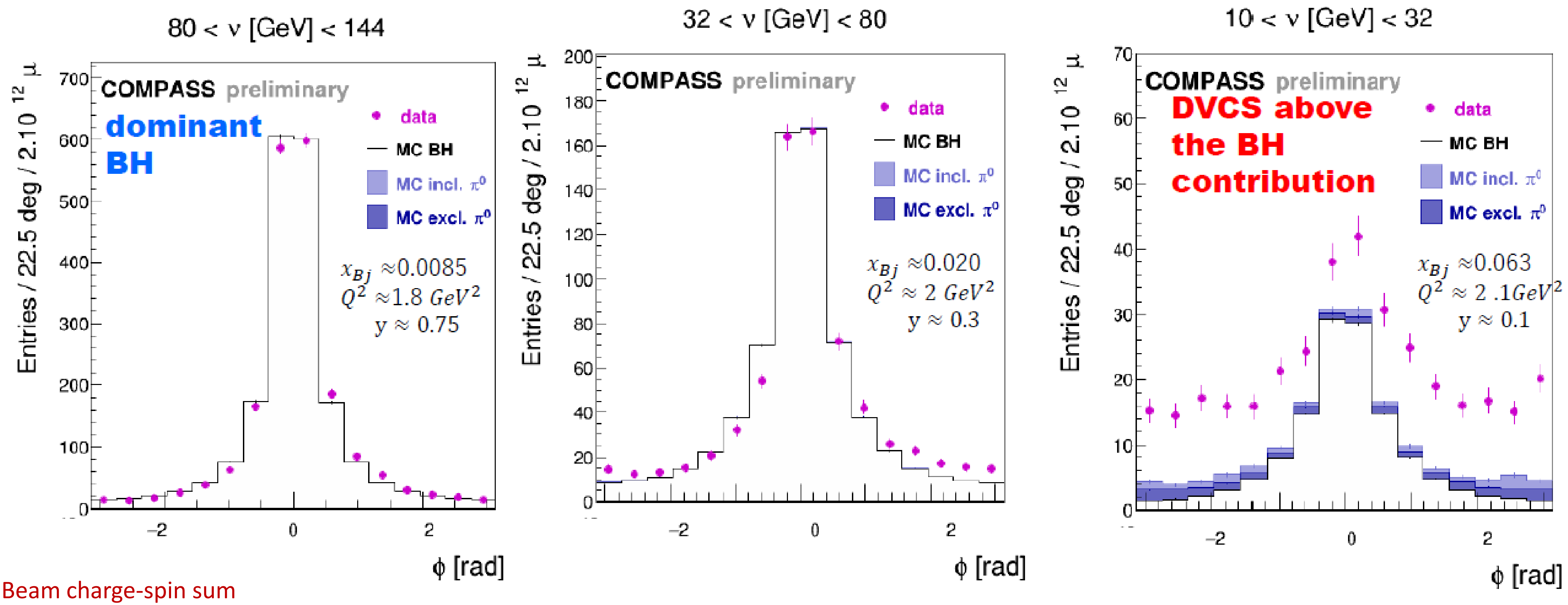
$$\mathcal{H}(\xi,t) = \int_{-1}^{+1} dx\, \frac{\mathbf{H}(x,\xi,t)}{x-\xi+i\varepsilon} + \ldots = \mathcal{P}\int_{-1}^{+1} dx\, \frac{\mathbf{H}(x,\xi,t)}{x-\xi} - i\pi\, \mathbf{H}(x=\pm\xi,\xi,t) + \ldots$$

$$Re\,\mathcal{H}(\xi,t) = \mathcal{P}\int dx\, \frac{Im\,\mathcal{H}(x,t)}{x-\xi} + \Delta(t)$$

$d_1(t)$

D-term

COMPASS 2016 Preliminary Results



- Beam charge-spin sum

$$S_{CS,U}(\phi) \equiv d\sigma(\mu^{+\leftarrow}) + d\sigma(\mu^{-\rightarrow}) = 2[\,d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + \mathrm{Im}\,I\,]$$

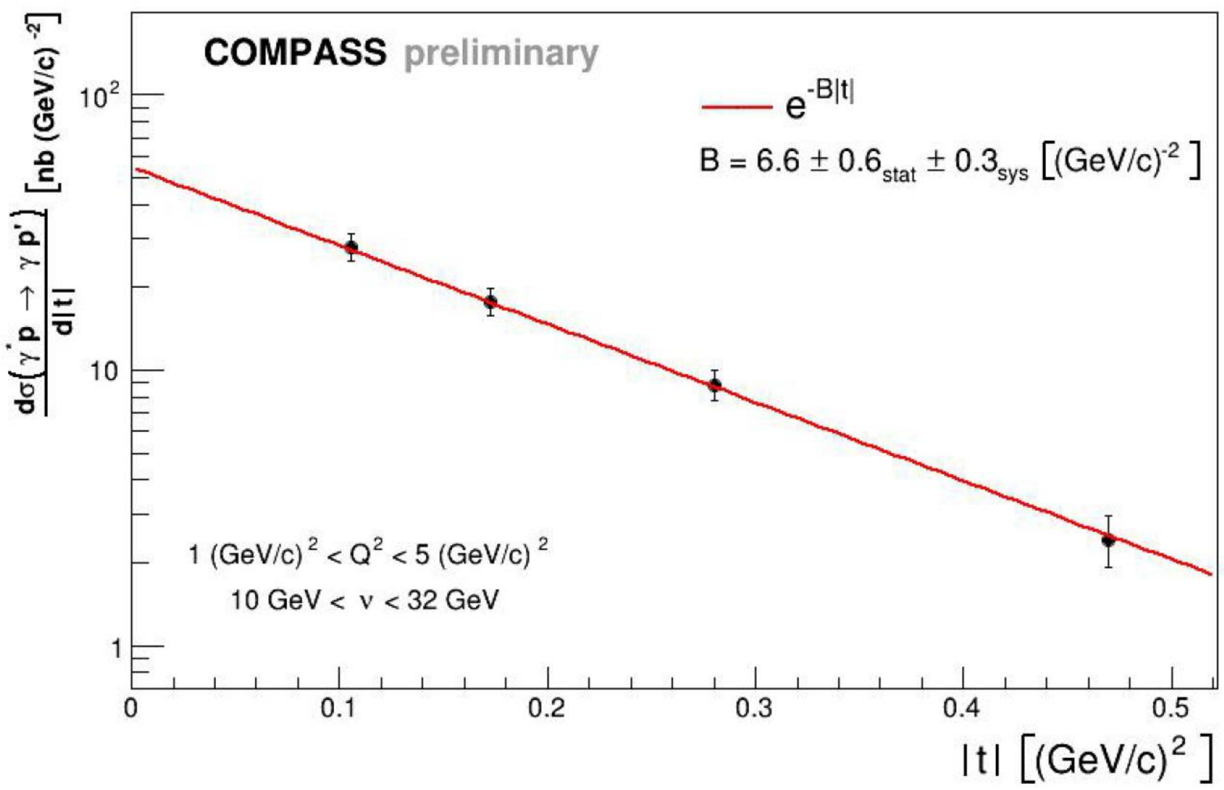
$$= 2[\,d\sigma^{BH} + c_0^{DVCS} + c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi + s_1^I \sin\phi + s_2^I \sin 2\phi\,]$$

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

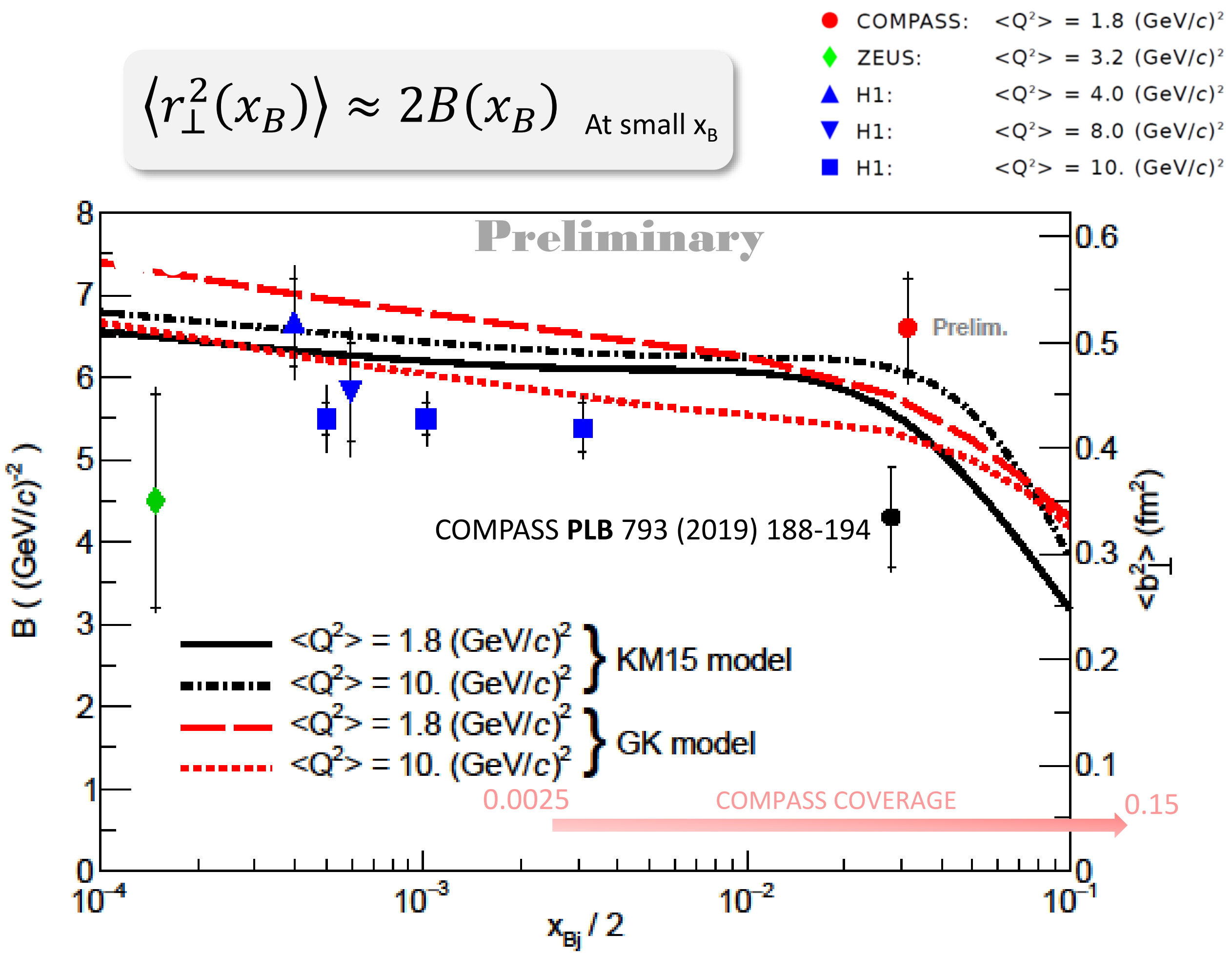
small x_{Bj} — model dependent

Tranverse extension of partons – 2016 data

$d\sigma^{DVCS}/d|t| \propto e^{-B|t|}$



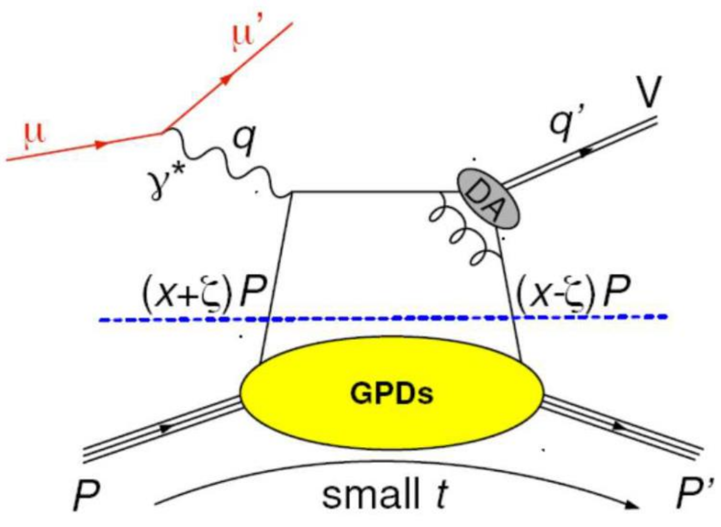
$\langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$ At small x_B



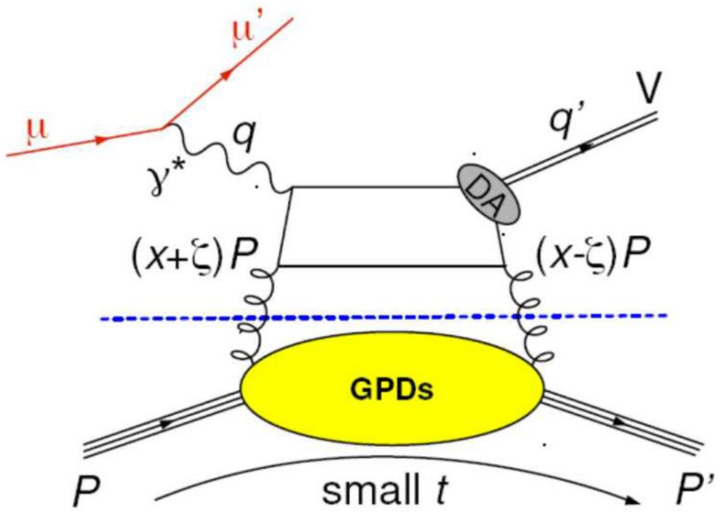
➢ The transverse-size evolution as a function of x_{Bj} → Expect at least 3 x_{Bj} bins from 2016-17 data

GPDs in Hard Exclusive Meson Production

quark contribution



gluon contribution



4 chiral-even GPDs: helicity of parton unchanged

$H^q(x, \xi, t)$	$E^q(x, \xi, t)$	→ **Vector Meson**
$\tilde{H}^q(x, \xi, t)$	$\tilde{E}^q(x, \xi, t)$	→ **Pseudo-Scalar Meson**

+ 4 chiral-odd or transversity GPDs: helicity of parton changed

(not possible in DVCS)

$H^q_T(x, \xi, t)$ $E^q_T(x, \xi, t)$

$\tilde{H}^q_T(x, \xi, t)$ $\tilde{E}^q_T(x, \xi, t)$

$$\overline{E}^q_T = 2\,\tilde{H}^q_T + E^q_T$$

- Universality of GPDs, quark flavor filter
- Ability to probe the chiral-odd GPDs.
- Additional non-perturbative term from meson wave function
- In addition to nuclear structure, provide insights into reaction mechanism

Exclusive π^0 Production on Unpolarized Proton

$\mu\, p \rightarrow \mu\, \pi^0\, p$

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

ϵ : degree of longitudinal polarization

$$\frac{d\sigma_L}{dt} = \frac{4\pi\alpha}{k'}\frac{1}{Q^6}\left\{(1-\xi^2)\left|\langle\tilde{H}\rangle\right|^2 - 2\xi^2\mathrm{Re}\left[\langle\tilde{H}\rangle^*\langle\tilde{E}\rangle\right] - \frac{t'}{4m^2}\xi^2\left|\langle\tilde{E}\rangle\right|^2\right\}$$

Leading twist expected to be dominant

But measured as ≈ only a few % of $\frac{d\sigma_T}{dt}$

The other contributions arise from the coupling between chiral-odd (quark helicity flip) GPDs to the twist-3 pion amplitude

$$\frac{d\sigma_T}{dt} = \frac{4\pi\alpha}{2k'}\frac{\mu_\pi^2}{Q^8}\left[(1-\xi^2)\left|\langle H_T\rangle\right|^2 - \frac{t'}{8m^2}\left|\langle \bar{E}_T\rangle\right|^2\right]$$

$$\frac{\sigma_{LT}}{dt} = \frac{4\pi\alpha}{\sqrt{2}k'}\frac{\mu_\pi}{Q^7}\xi\sqrt{1-\xi^2}\frac{\sqrt{-t'}}{2m}\mathrm{Re}\left[\langle H_T\rangle^*\langle\tilde{E}\rangle\right]$$

$$\frac{\sigma_{TT}}{dt} = \frac{4\pi\alpha}{k'}\frac{\mu_\pi^2}{Q^8}\frac{t'}{16m^2}\left|\langle \bar{E}_T\rangle\right|^2$$

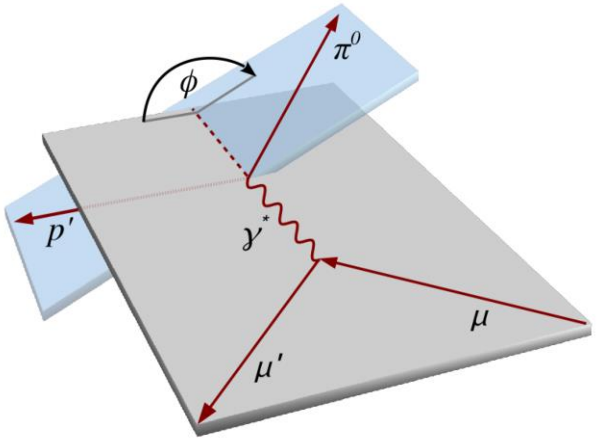
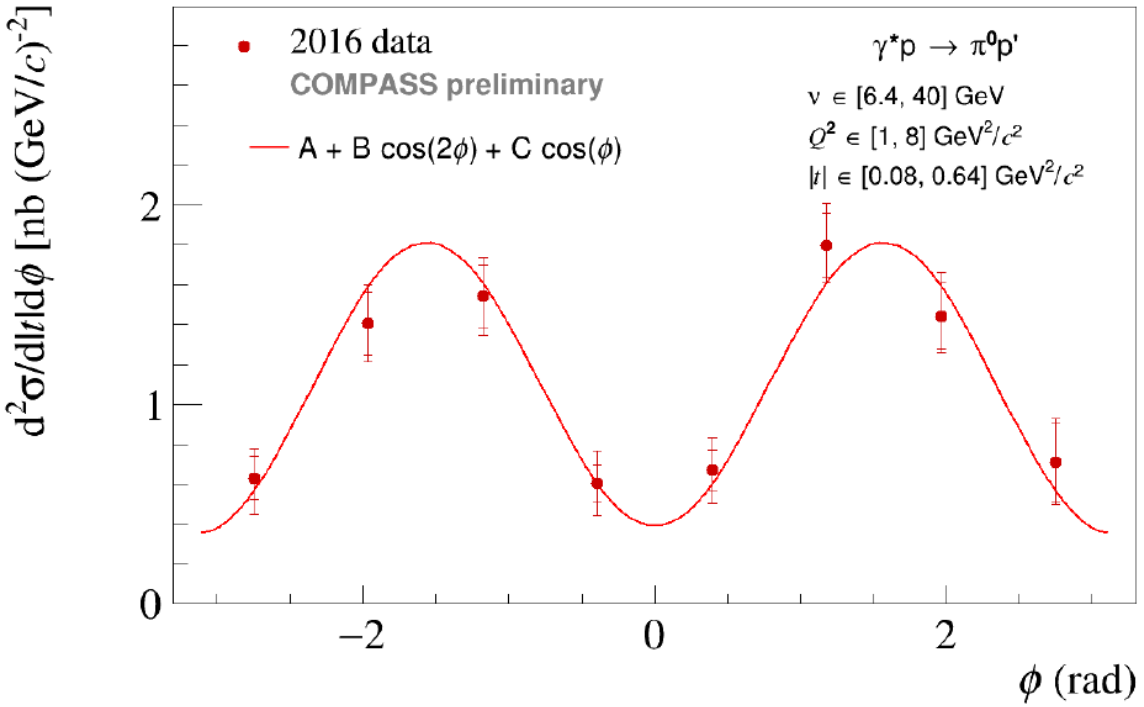
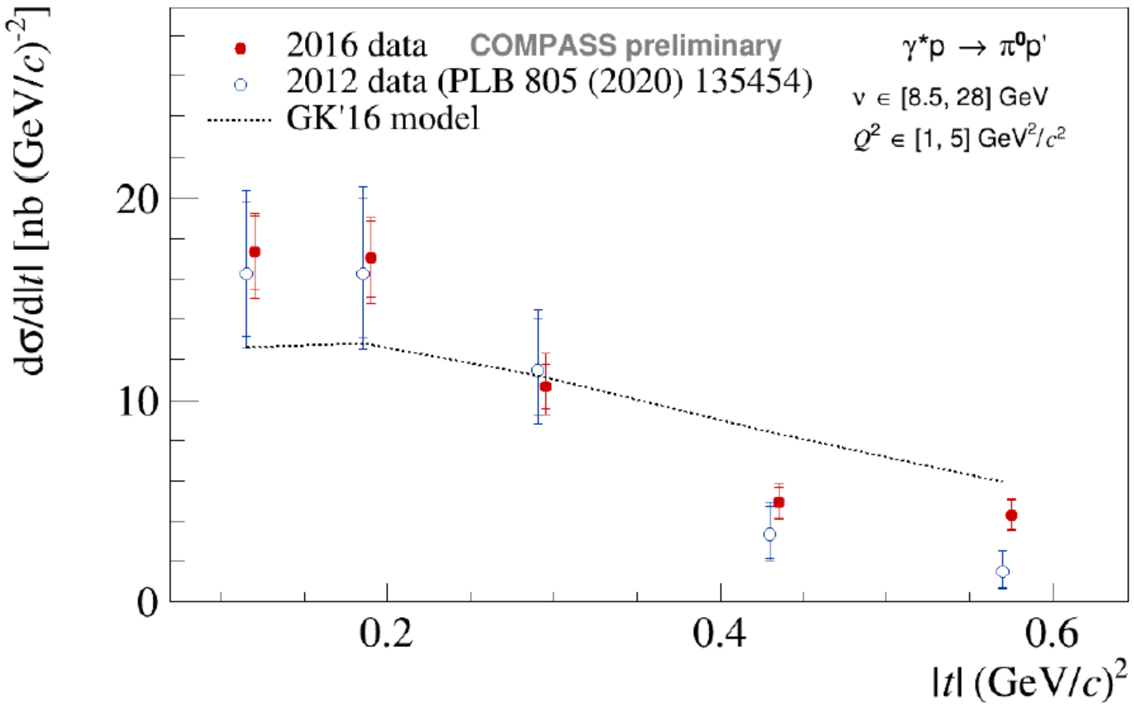


Fig: M.G. Alexeev et al. *Phys.Lett.B* 805 (2020)

2016 Exclusive π^0 Prod. on Unpolarized Proton

➢ New 2016 data release: statistics about 2.3 times larger than the published 2012 pilot run.





$$\left\langle \frac{\sigma_T}{|t|} + \epsilon \frac{\sigma_L}{|t|} \right\rangle = (6.9 \pm 0.3_{\text{stat}} \pm 0.8_{\text{syst}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$$

$$\left\langle \frac{\sigma_{TT}}{|t|} \right\rangle = (-4.5 \pm 0.5_{\text{stat}} \pm 0.2_{\text{syst}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$$

$$\left\langle \frac{\sigma_{LT}}{|t|} \right\rangle = (0.06 \pm 0.2_{\text{stat}} \pm 0.1_{\text{syst}}) \frac{\text{nb}}{(\text{GeV}/c)^2}$$

➢ Inputs for constraining phenomenological models
➢ The whole collected 2016/2017 statistics ~ 9 times larger than the 2012 data

SIDIS Cross Section and TMDs at Leading Twist

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

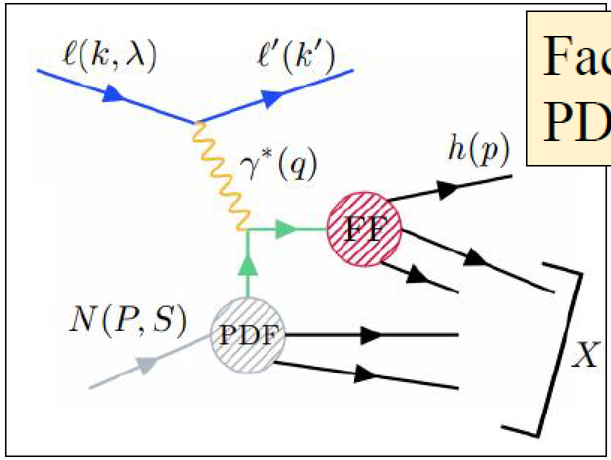
$$\times \begin{cases} 1+\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\varepsilon A_{UU}^{\cos 2\phi_h}\cos 2\phi_h\right] \\ +\lambda\sqrt{2\varepsilon(1-\varepsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h \\ +S_L\left[\sqrt{2\varepsilon(1+\varepsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\varepsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right] \\ +S_L\lambda\left[\sqrt{1-\varepsilon^2}A_{LL}+\sqrt{2\varepsilon(1-\varepsilon)}A_{LL}^{\cos\phi_h}\cos\phi_h\right] \\ +S_T\left[\begin{array}{l} A_{UT}^{\sin(\phi_h-\phi_S)}\sin(\phi_h-\phi_S) \\ +\varepsilon A_{UT}^{\sin(\phi_h+\phi_S)}\sin(\phi_h+\phi_S) \\ +\varepsilon A_{UT}^{\sin(3\phi_h-\phi_S)}\sin(3\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin\phi_S}\sin\phi_S \\ +\sqrt{2\varepsilon(1+\varepsilon)}A_{UT}^{\sin(2\phi_h-\phi_S)}\sin(2\phi_h-\phi_S)\end{array}\right] \\ +S_T\lambda\left[\begin{array}{l} \sqrt{(1-\varepsilon^2)}A_{LT}^{\cos(\phi_h-\phi_S)}\cos(\phi_h-\phi_S) \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos\phi_S}\cos\phi_S \\ +\sqrt{2\varepsilon(1-\varepsilon)}A_{LT}^{\cos(2\phi_h-\phi_S)}\cos(2\phi_h-\phi_S)\end{array}\right] \end{cases}$$

Unpol target: ← Cahn & Boer-Mulders

Long pol target: ↖ Worm-gear L

Trans pol target: ← Sivers effect; ← Collins effect; ← Pretzelosity; ← Worm-gear T

λ Beam polarization



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

$x = Q^2/2m\nu$
$z = E_h/\nu$
p_T^h correlated to k_T

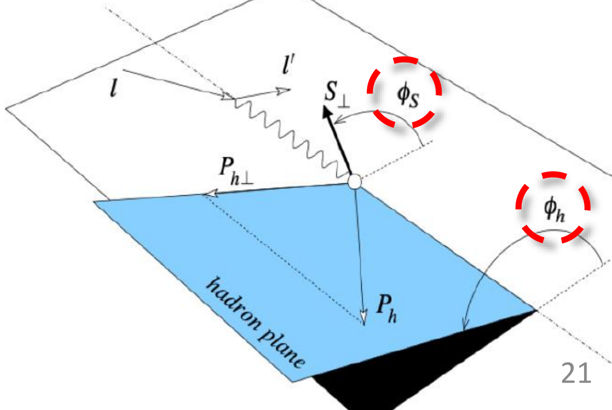
➢ Measure the azimuthal modulations in experiment

$$A_{UT}(\phi) = \frac{1}{f S_T}\frac{N^{\uparrow}(\phi)-N^{\downarrow}(\phi)}{N^{\uparrow}(\phi)+N^{\downarrow}(\phi)}$$

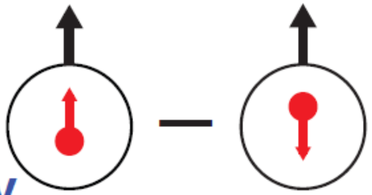
1st: beam, 2nd: target

U: Unpolarized
T: Transversly
L: Logitudinally

More complicated in reality



COMPASS 2010 – Trans. Pol. Target

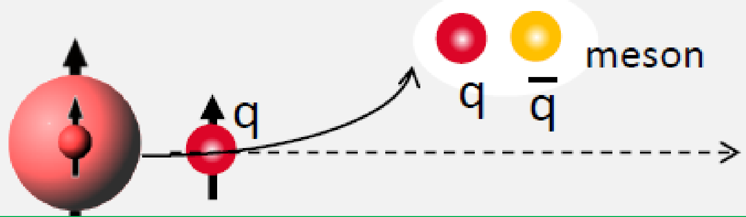
h_1 =


Transversity

- Difference of quarks with spin parallel or anti-parallel to the transverse spin of the nucleon
- Describes the spin-spin correlation of a transversely polarized parton in a transversely polarized hadron.

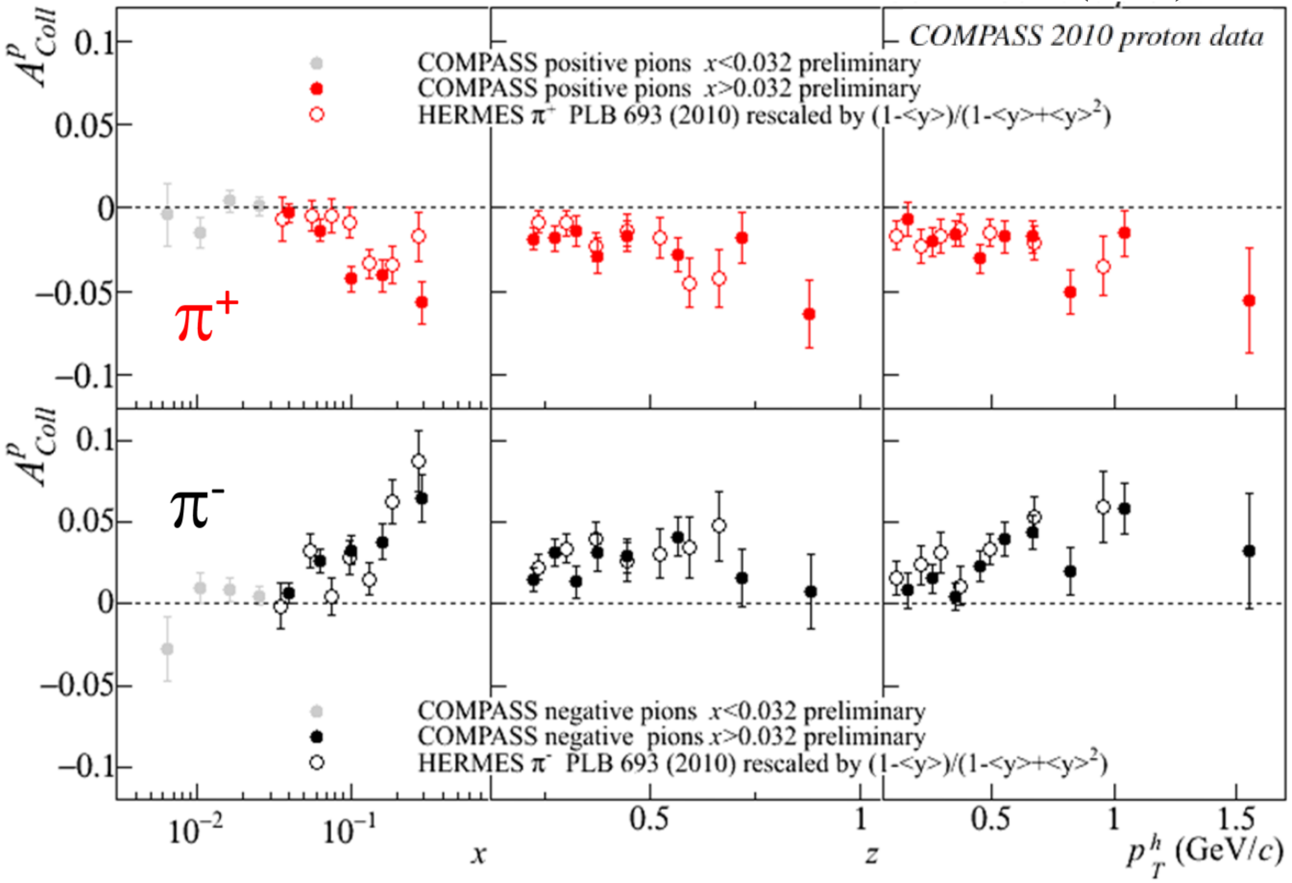
Collins Asymmetry

Transversity chiral-odd PDF × Collins odd FF



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

COMPASS PLB 774 (2015) 250



Significant asymmetry of opposite sign for π^+ & π^-

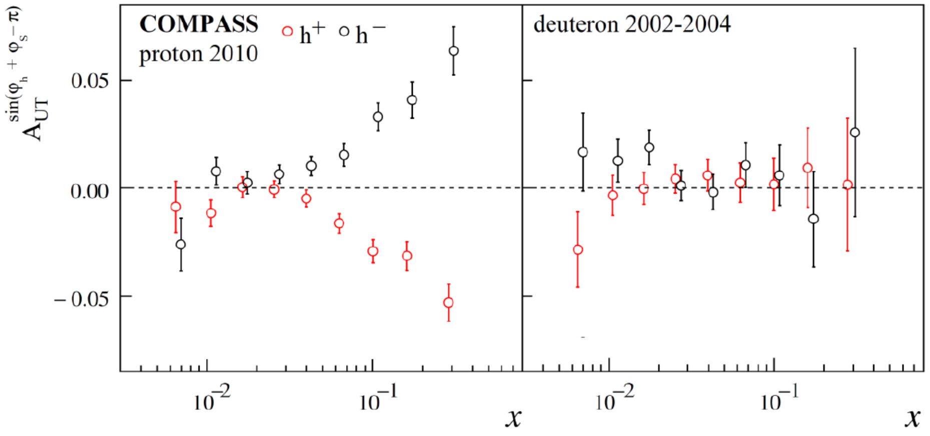
- Agreement between COMPASS & HERMEST for x > 0.032
- COMPASS Q^2 domain larger by a factor of 2 to 3
  → Absence of Q^2 evolution?

Extraction of Transversity PDF

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

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

Favored: $u \to \pi^+, d \to \pi^-$
Unfavored: $u \to \pi^-, d \to \pi^+$



Entensive analyses and global fits: using data from HERMES (p), COMASS (p & d), Belle (e^+e^-)

$$H_1^{\perp,fav} \approx -H_1^{\perp,unf}$$

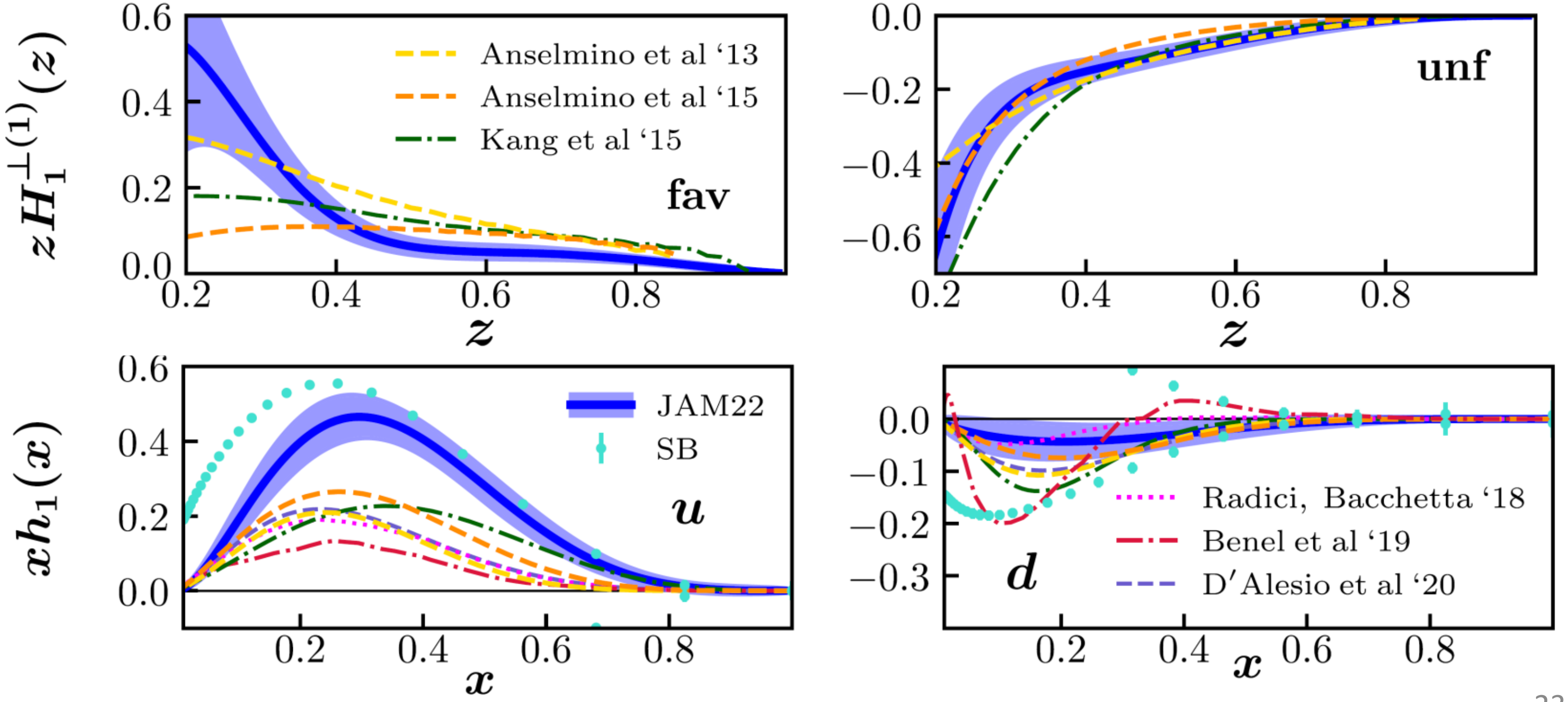
$$\langle \sin(\varphi+\varphi_s) \rangle_{UT}^{\pi^+} \sim 4(h_1^u - h_1^d) H_1^{\perp,fav}$$

$$\langle \sin(\varphi+\varphi_s) \rangle_{UT}^{\pi^-} \sim -4(h_1^u - h_1^d) H_1^{\perp,fav}$$

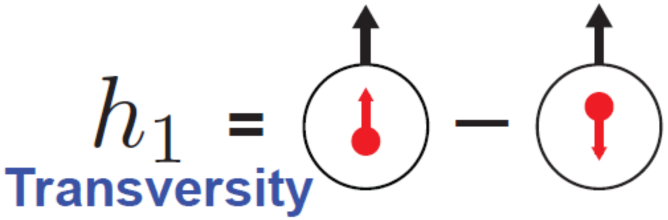
- COMPASS Collins asymmetries on the deutron compatiable with zero
- Cancellation between u & d quark → u- and d-quark transversity PDFs have opposite sign.

- d-quark transversity PDF relatively poor determined due to the lack of neutron (deuteron) data

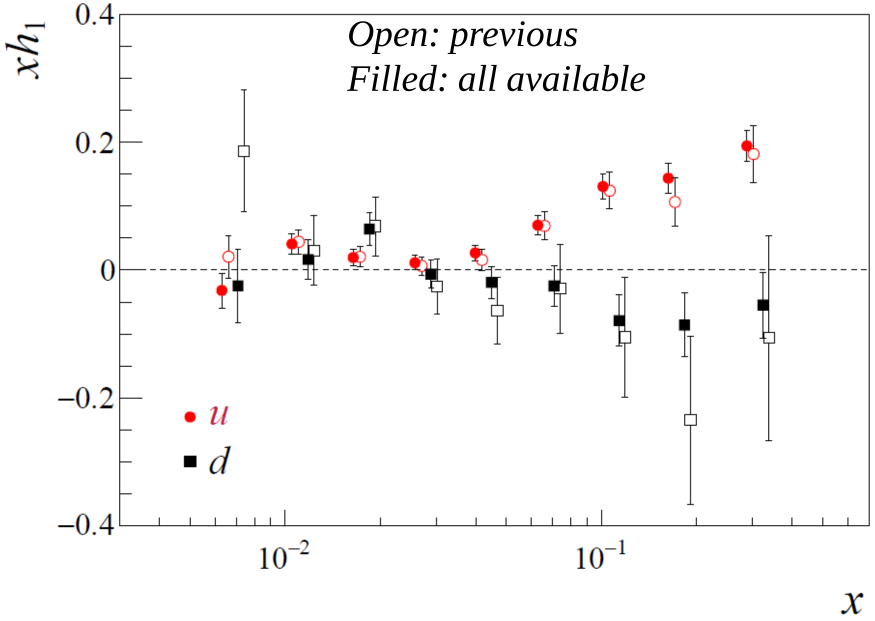
JAM Collaboration, PRD 106 (2022) 034014



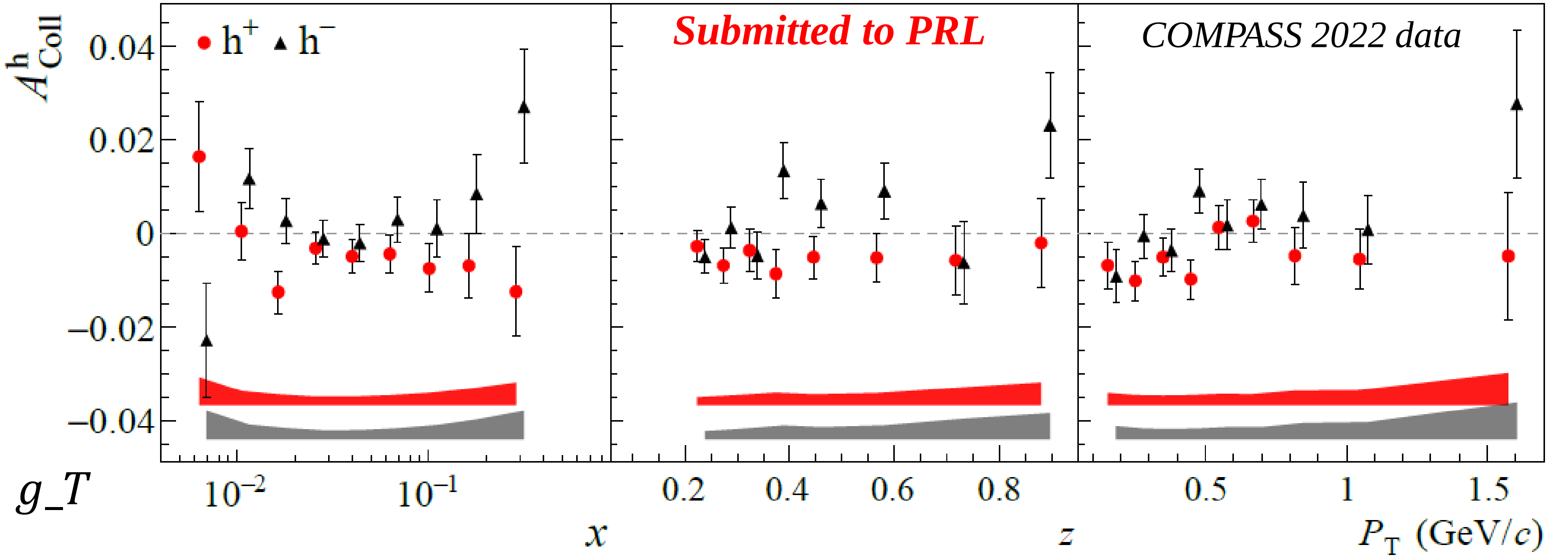
COMPASS 2022 – Trans. Pol. Deuteon



- Important input for Transversity PDF
- Uncertainty reduced in all p and 2022 d data, especially for the d-quark h_1



Arxiv:2401.00309



g_T

Tensor charge: $\delta q(Q^2) = \int_0^1 dx[h_1^q(x,Q^2) - h_1^{\bar{q}}(x,Q^2)]$ & $q_T = \delta u - \delta d$

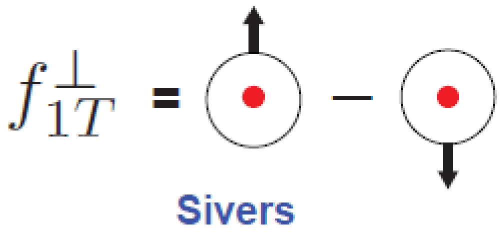
Isovector combination

- Interesting quantity not only related to QCD phenomenology, but also for ab initio studies and BSM physics.

data	$\delta u = \int_{0.008}^{0.210} dx\, h_1^{u_v}(x)$	$\delta d = \int_{0.008}^{0.210} dx\, h_1^{d_v}(x)$	$g_T = \delta u - \delta d$
previous [25, 28, 29]	0.187 ± 0.030	-0.178 ± 0.097	0.365 ± 0.078
previous [25, 28, 29] and present	0.214 ± 0.020	-0.070 ± 0.043	0.284 ± 0.045

- Complementary masurements at JLab and future EIC

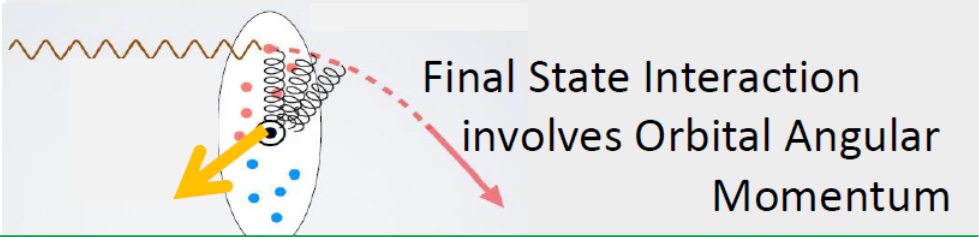
COMPASS 2010 – Trans. Pol. Target



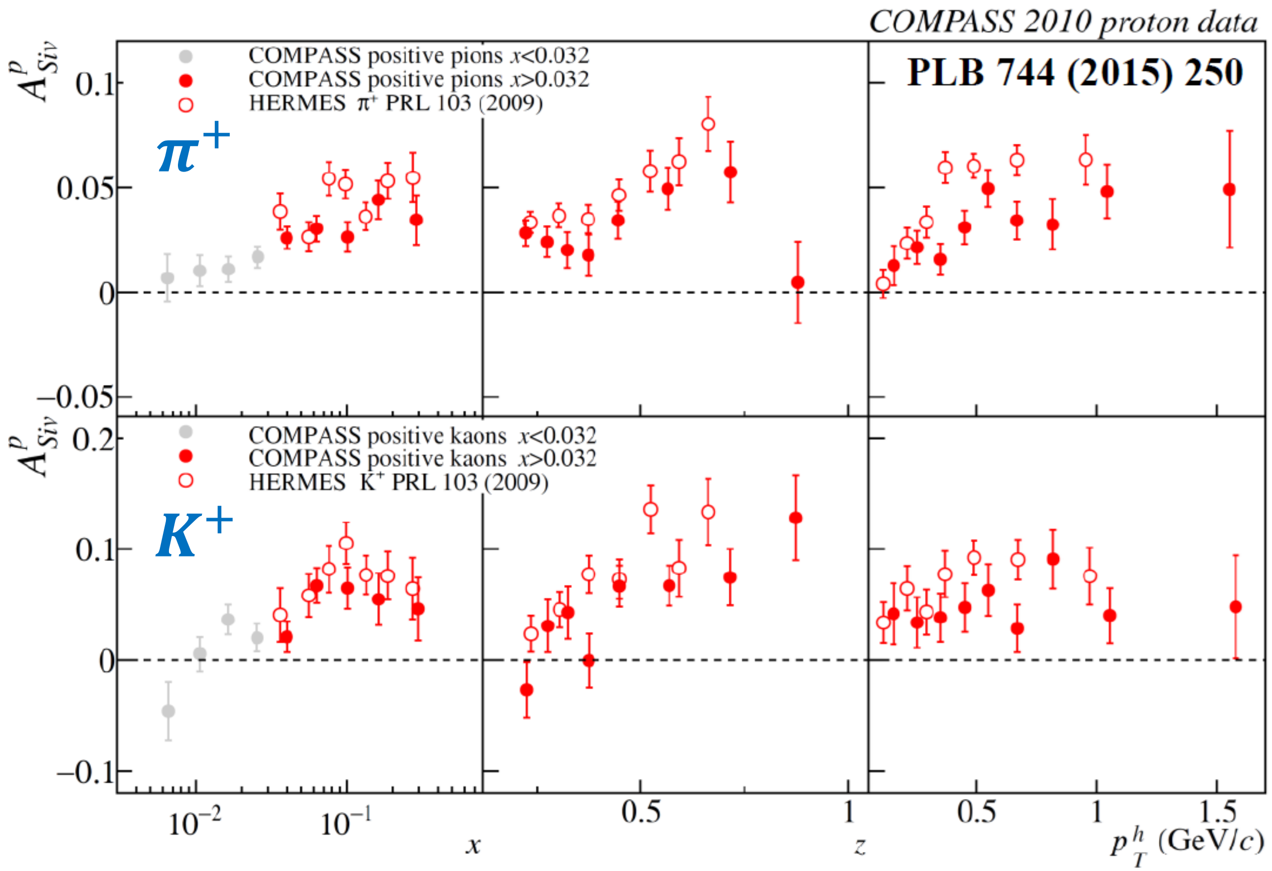
- Correlates the quark transverse momentum k_T and the transverse spin of the nucleon
- Describes the strength of the distortion in transverse momentum space relative to the symmetric unpolarized distribution f_1

Sivers Asymmetry

Sivers Chiral-even but T-odd

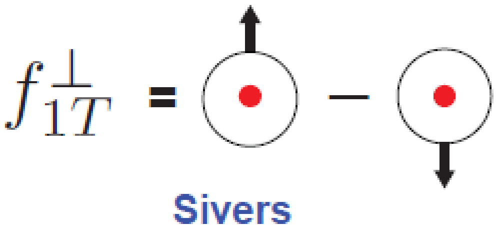


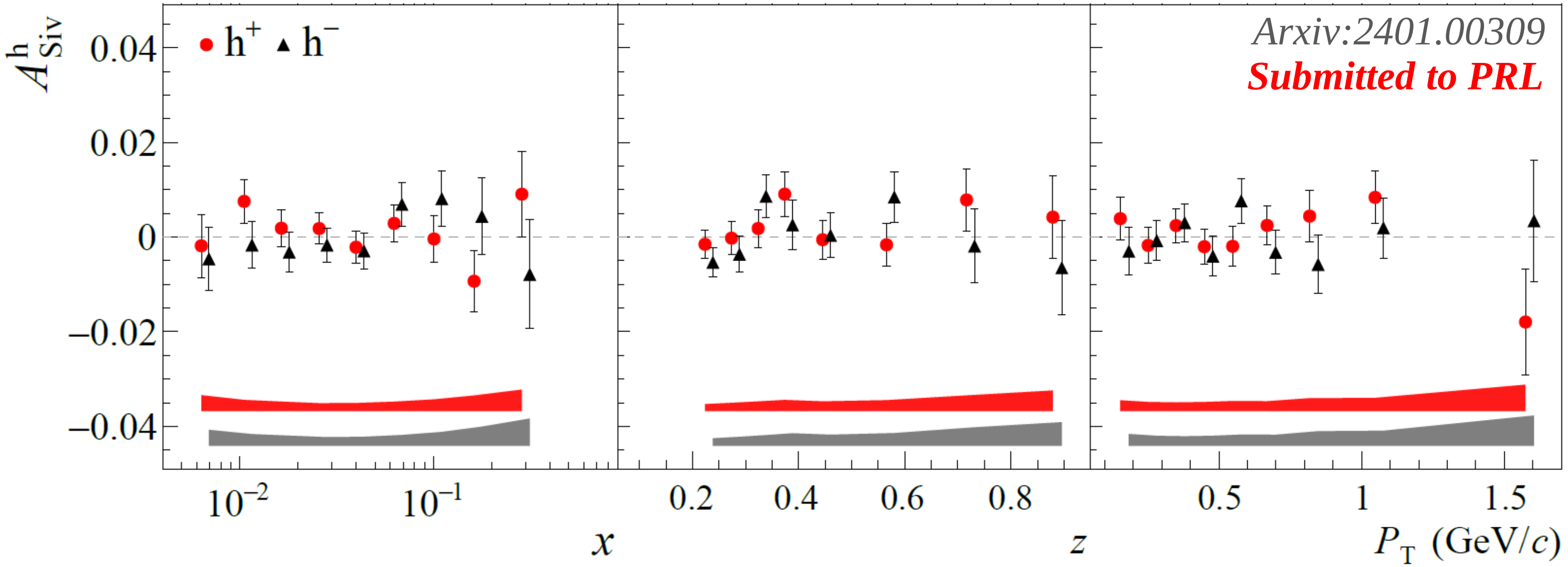
$$A_{Siv} \approx \frac{\sum_q e_q^2 \, f_{1T}^{\perp q}(x) \otimes D_{1q}^h(z, p_T^h)}{\sum_q e_q^2 \, f_1^q(x) \otimes D_{1q}^h(z, p_T^h)}$$



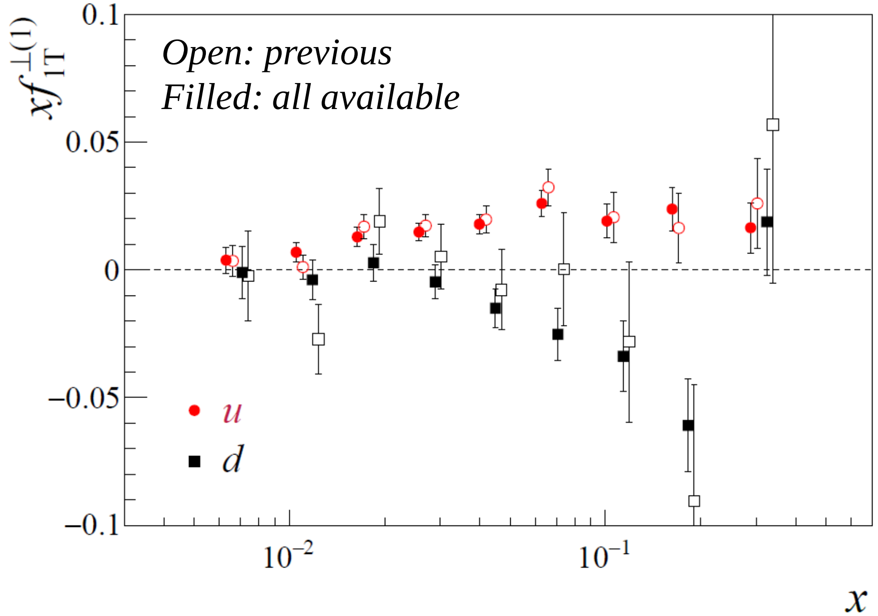
- ➢ Sivers effect smaller at COMPASS than at HERMES. TMD evolution?
- ➢ Kaon amplitudes larger than pion, unexpected if u-quark scattering dominates. Role of sea quarks?

COMPASS 2022 – Trans. Pol. Deuteon



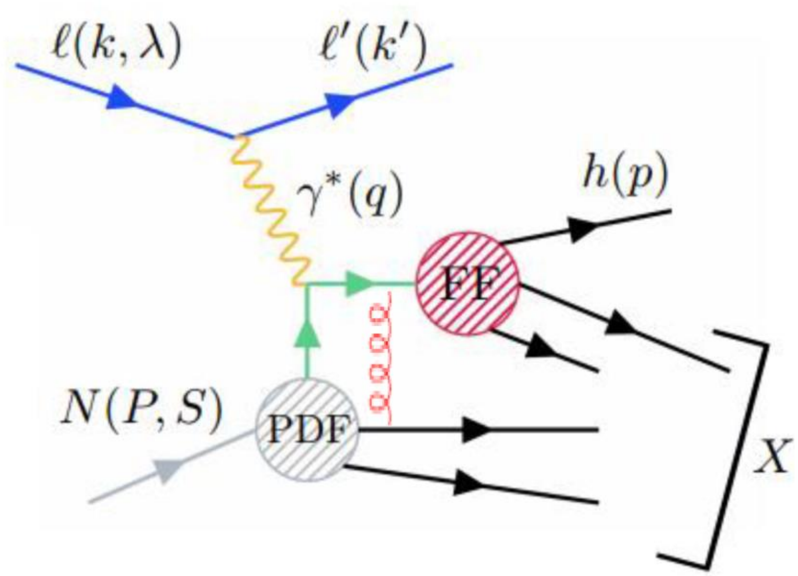


- Sivers asymmetries, weighted with the hadron transverse momentum P_T, provide direct measurement of TMD k_T^2 moments without assumptions on K_T shape.
- Different signs in u- and d-quark Sivers functions, uncertainty significantly reduced in d-quark case
- Crucial input for Sivers PDF for the d-quark

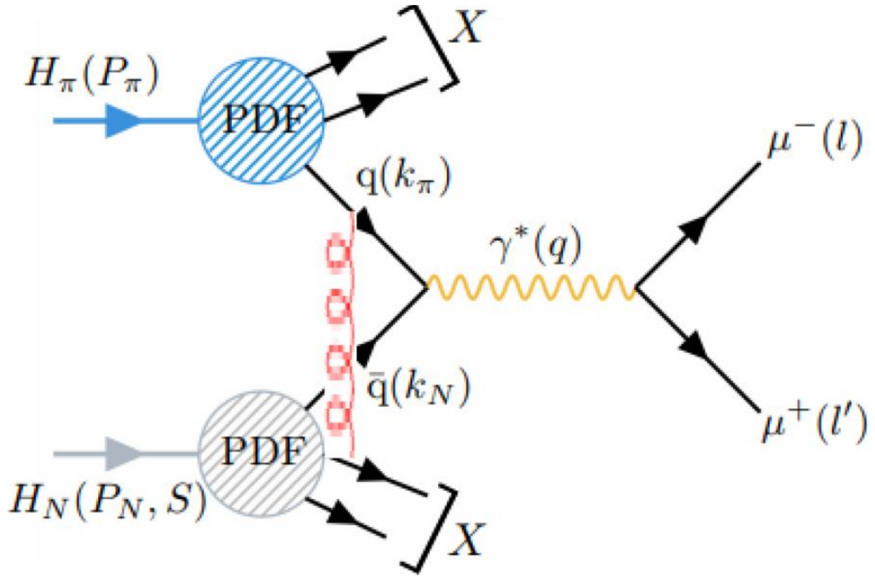


SIDIS & Drell-Yan

SIDIS: $l + p^{\uparrow} \rightarrow l' + h^{\pm} + X$



Drell-Yan: $\pi + p^{\uparrow} \rightarrow \mu^{+} + \mu^{-} + X$



SIDIS: TMD ⊗ FF^{h}

TMDs involve final state interaction

DY: TMD^{Beam} ⊗ TMD^{Target}

TMDs involve initial state interaction

TMD universality, expect same magnitude but different signs for naïve T-odd TMD PDFs in SIDIS and DY

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

SIDIS and Single-polarised Drell-Yan

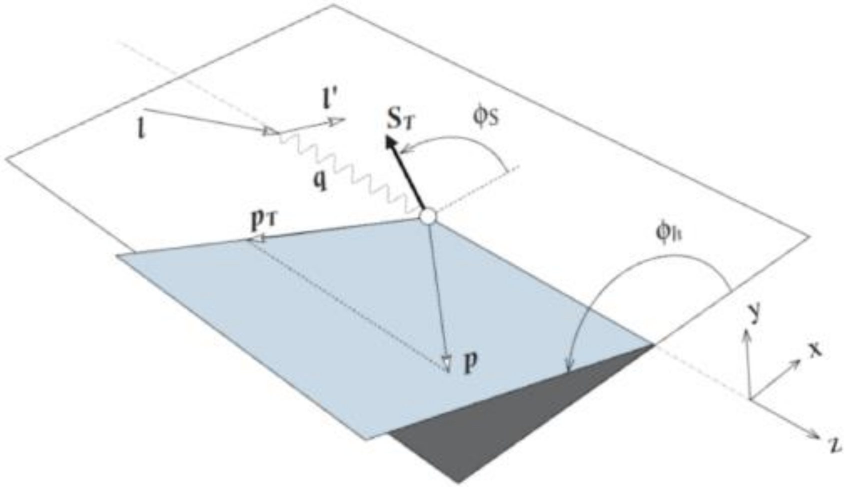
SIDIS

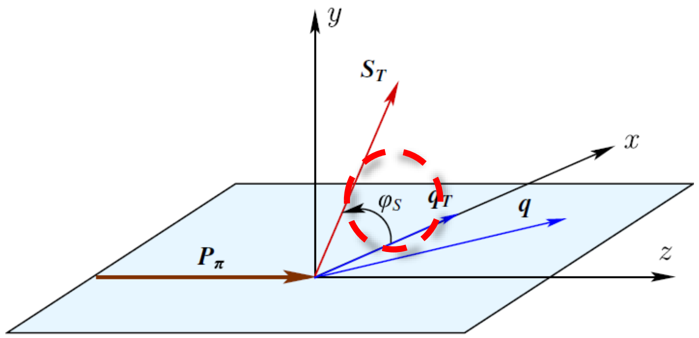
$$\frac{d\sigma^{LO}}{dxdydzdp_T^2\,d\phi_h\,d\phi_S} \propto \left(F_{UU,T} + \varepsilon F_{UU,L}\right) \times \left\{ \begin{array}{l} 1 + \varepsilon A_{UU}^{\cos 2\phi_h} \cos 2\phi_h \\ + S_L\,\varepsilon A_{UL}^{\sin 2\phi_h} \sin 2\phi_h + S_L \lambda \sqrt{1-\varepsilon^2}\,A_{LL} \\ + S_T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

Drell-Yan

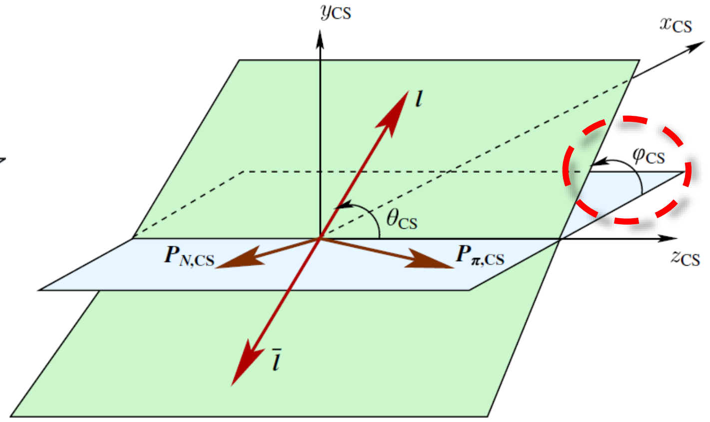
$$\frac{d\sigma^{LO}}{dq^4\,d\Omega} \propto F_U^1 \left(1+\cos^2\theta_{CS}\right) \times \left\{ \begin{array}{l} 1 + D_{[\sin^2\theta_{CS}]} A_U^{\cos 2\varphi_{CS}} \cos 2\varphi_{CS} \\ + S_L \sin^2\theta_{CS} A_L^{\sin 2\varphi_{CS}} \sin 2\varphi_{CS} \\ + S_T \left[\begin{array}{l} A_T^{\sin\varphi_S}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

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





Target rest frame



Collins-Soper frame

SIDIS and Single-polarised Drell-Yan

SIDIS

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

Drell-Yan

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

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

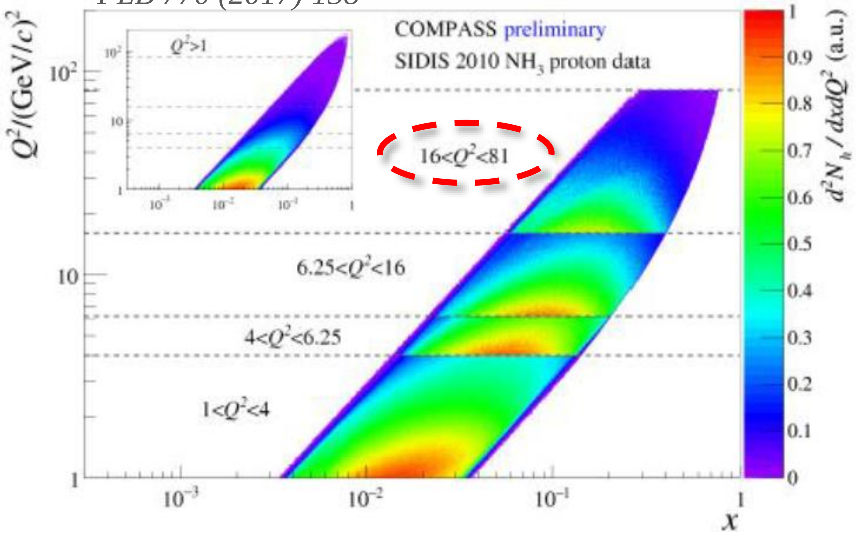
SIDIS		Drell-Yan
$A_{UU}^{\cos 2\phi_h} \propto h_1^{\perp q} \otimes H_{1q}^{\perp h} + ..$	**Boer-Mulders**	$A_U^{\cos 2\varphi_{CS}} \propto h_{1,\pi}^{\perp q} \otimes h_{1,p}^{\perp q}$
$A_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp q} \otimes D_{1q}^h$	**Sivers**	$A_T^{\sin\varphi_S} \propto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

Uniqueness in Testing TMD Universality

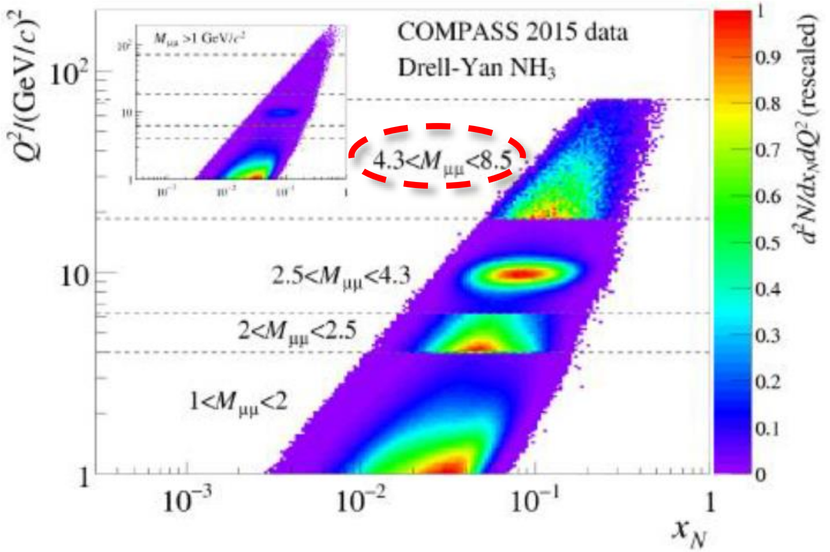
- SIDIS with transversely polarized proton
  → COMPASS 2007, 2010

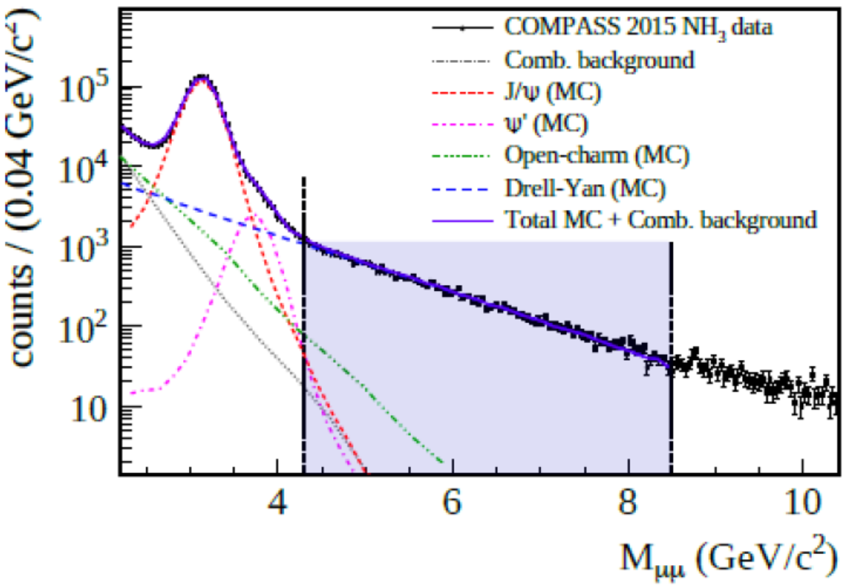
- Pion-induced transversely polarized Drell-Yan
  → COMPASS 2015, 2018

PLB 770 (2017) 138



PRL 119 (2017) 112002





SIDIS: $16 < Q^2/(GeV/c)^2 < 81$ ⟷ Drell-Yan: $4.3 < M_{\mu\mu}/(GeV/c^2) < 8.5$

- Q^2-evolution effect minimized with similar (x, Q^2) coverage in comparing the TMDs extracted from DIDIS and Drell-Yan

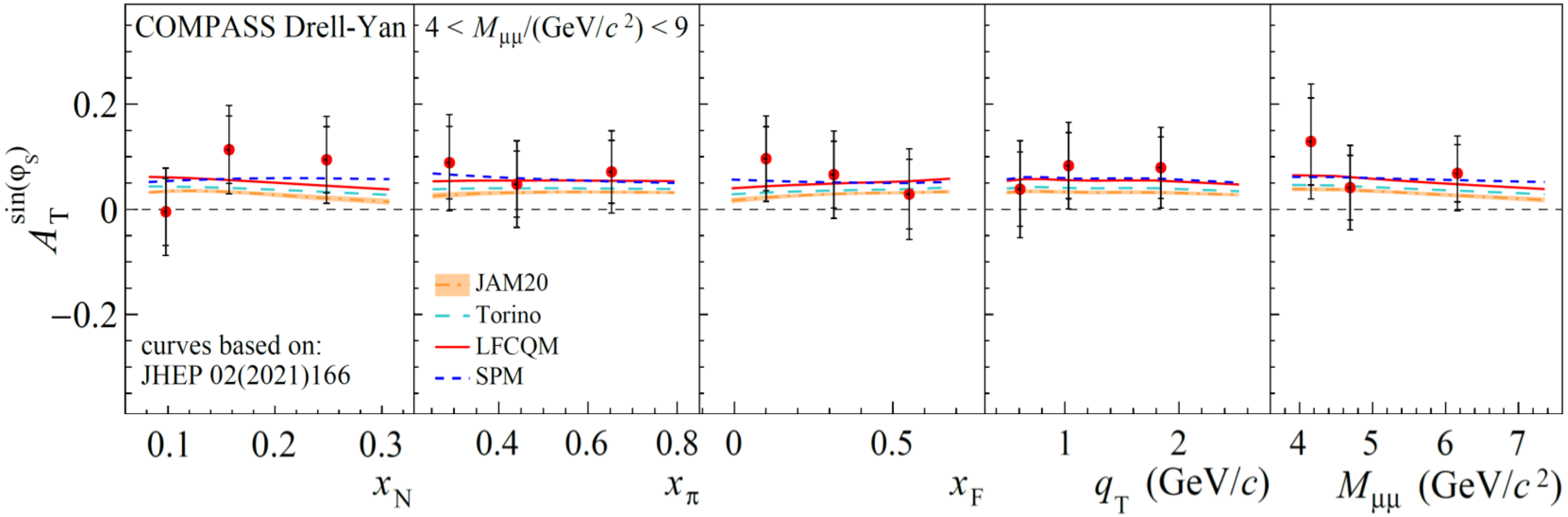
Sivers in Drell-Yan and SIDIS

Arxiv:2312.17379

Drell-Yan

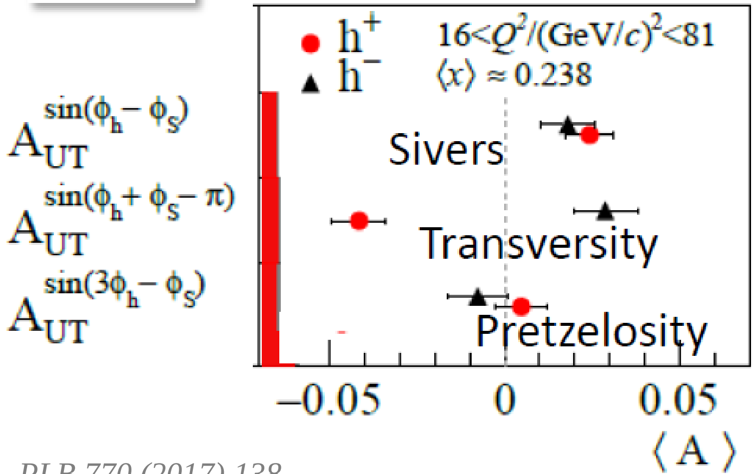
- First ever polarized DY in 2015
- Final result:
  2015 & 2018 data combined

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

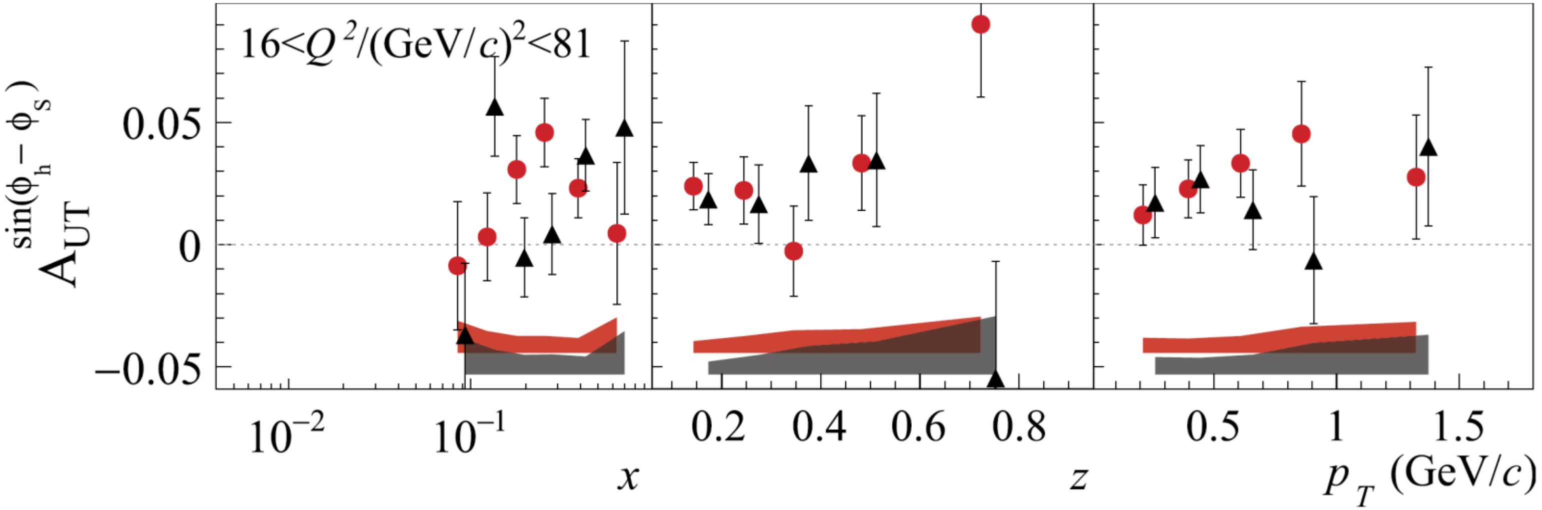


SIDIS

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



PLB 770 (2017) 138

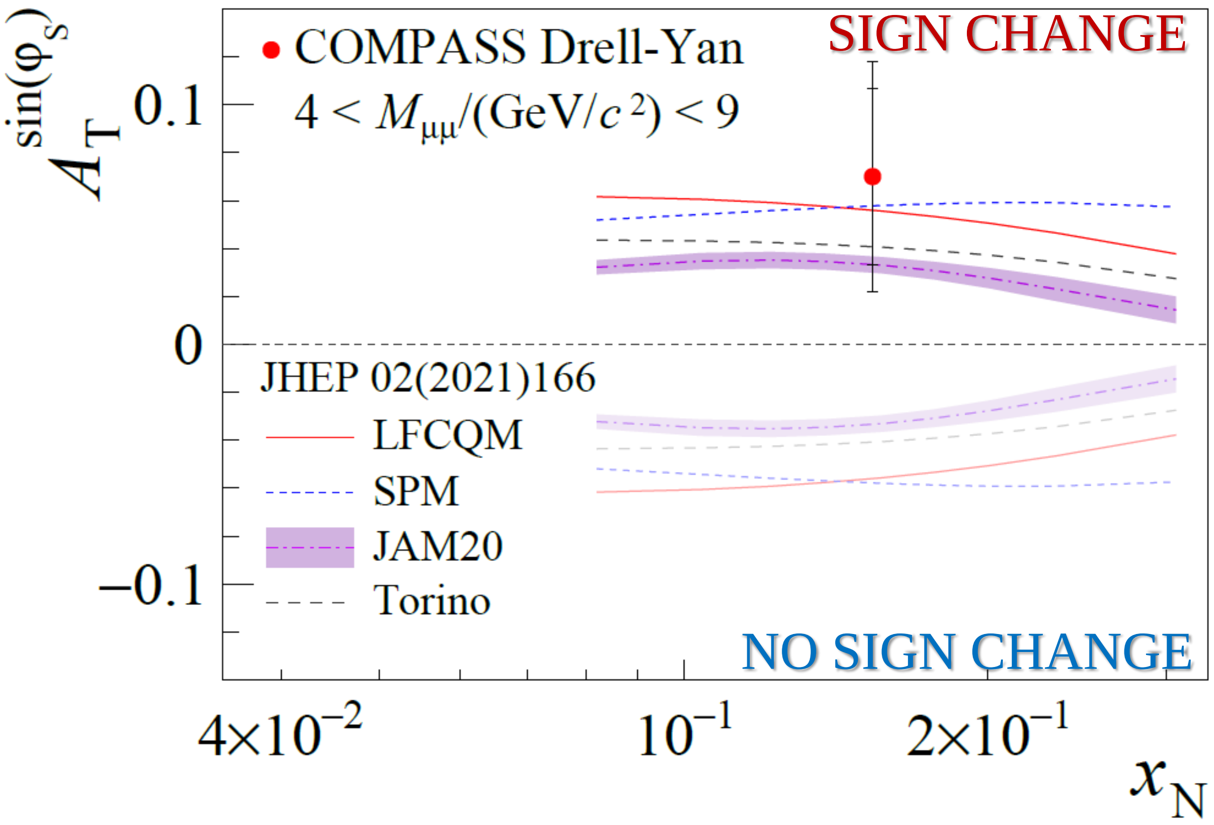


Final Result on TSA in Drell-Yan

Arxiv:2312.17379
Submitted to PRL

COMPASS pion induced DY 2015 + 2018

Sivers TSA



$$\left\langle A_T^{\sin\varphi_s}\right\rangle = 0.070 \pm 0.037(stat.) \pm 0.031(sys.)$$

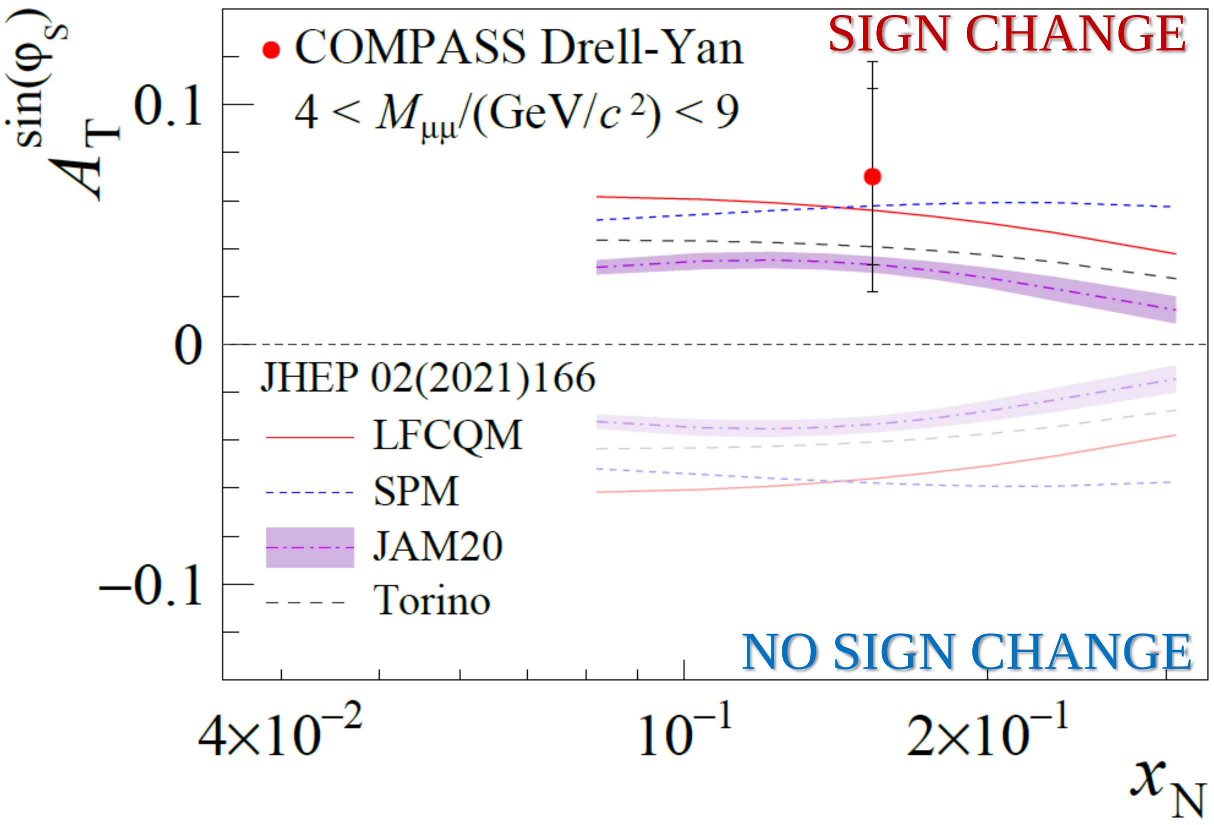
- Average Sivers asymmetry integrated over the entire kinematic range found to be above zero at about 1.5 σ of the total uncertainty.
- Confirm the fundamental QCD prediction of a sign change of naïve time-reversal-odd TMD PDFs when comparing Drell-Yan and SIDIS.

Final Result on TSA in Drell-Yan

Arxiv:2312.17379
Submitted to PRL

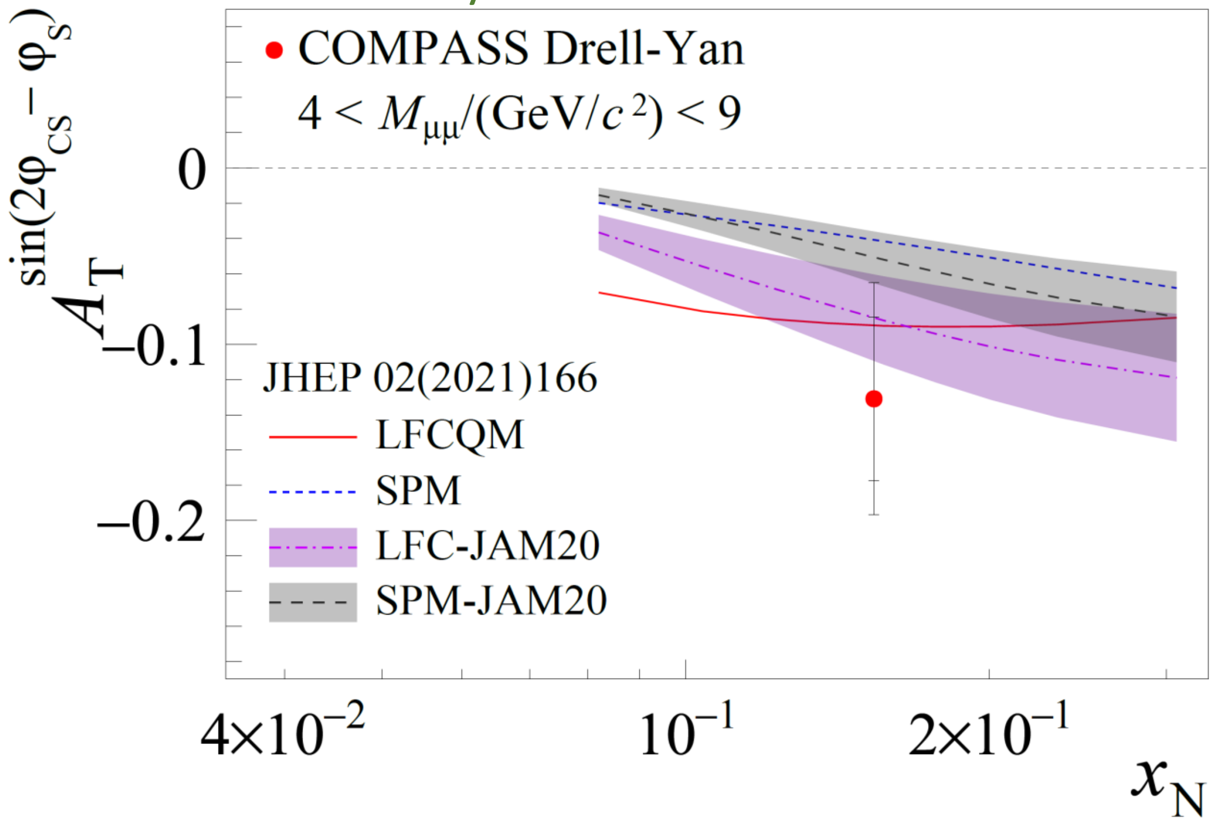
COMPASS pion induced DY 2015 + 2018

Sivers TSA



$$\left\langle A_T^{\sin\varphi_S} \right\rangle = 0.070 \pm 0.037(stat.) \pm 0.031(sys.)$$

Transversity TSA

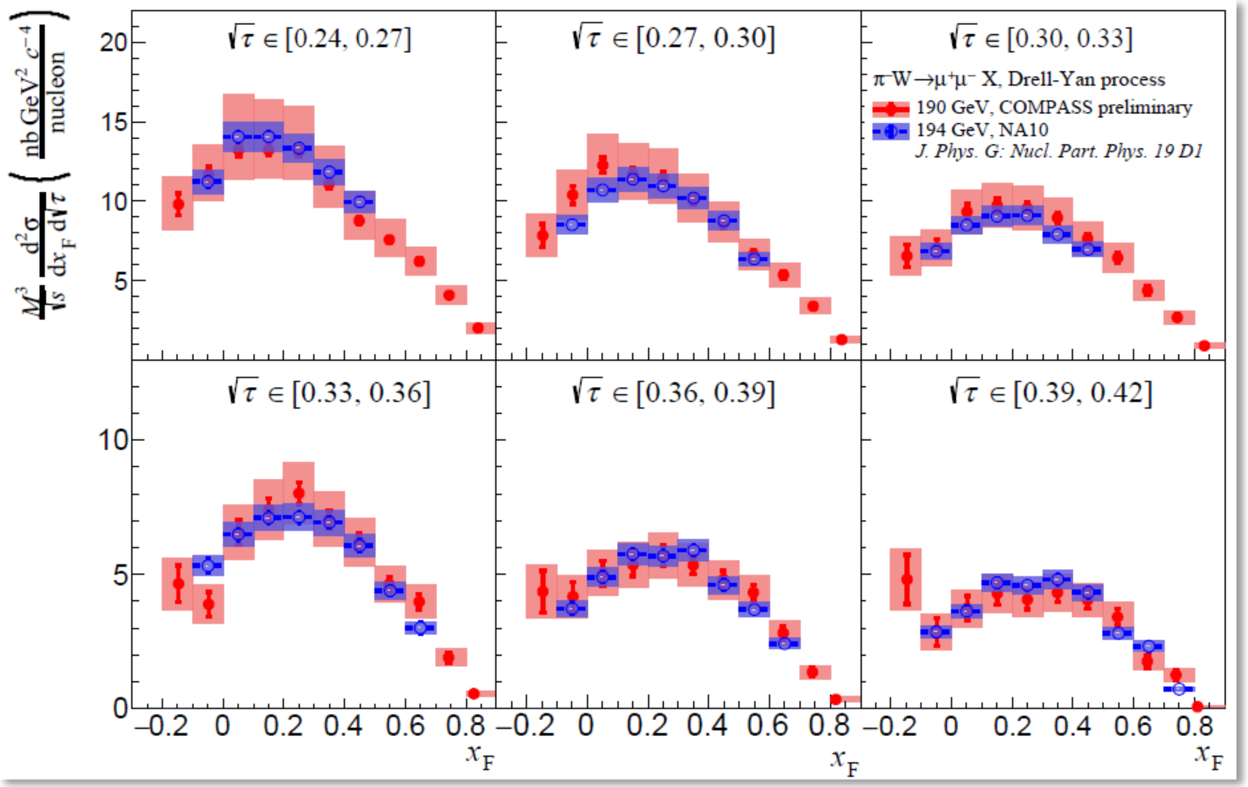


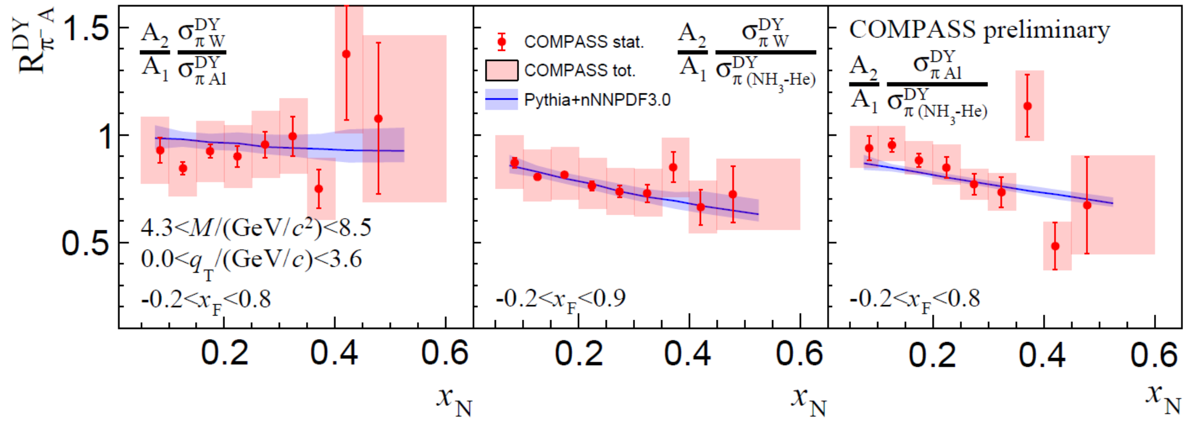
$$\left\langle A_T^{\sin(2\varphi_{CS}-\varphi_S)} \right\rangle = -0.131 \pm 0.046(stat.) \pm 0.047(sys.)$$

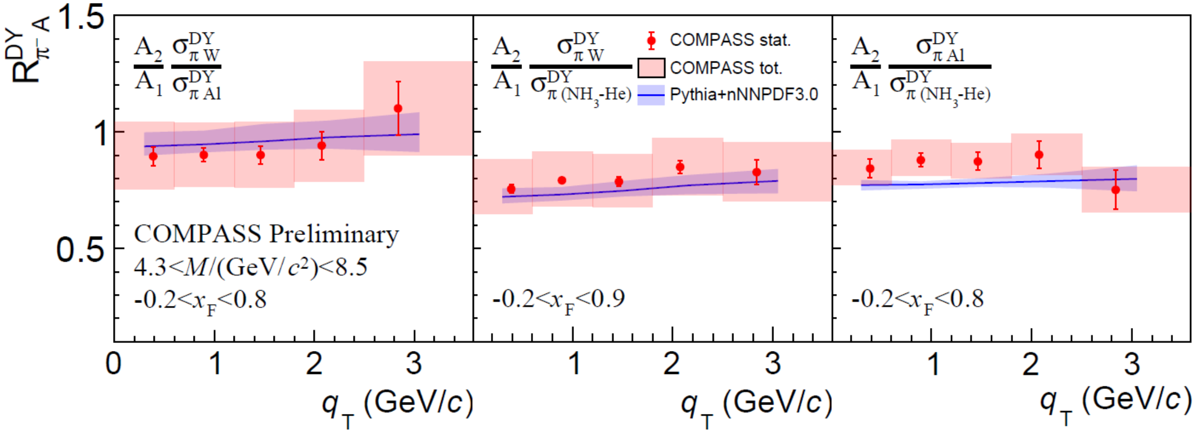
- Universality of transversity TMD PDFs
- Constraint on pion Boer-Mulders

Pion Structure and More

Figure: Vincent Andrieux, 25th Spin Symposium





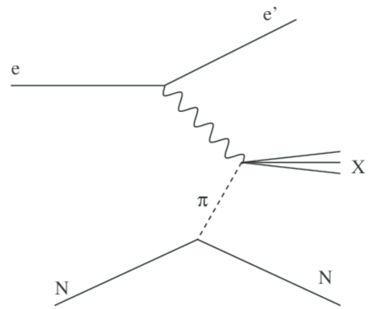


- Inputs for pion PDF study
- Cold nuclear matter effect

Summary

- 3-D partonic structure provides further insights into nucleon properties
- A limited selection of COMPASS results has been presented
  - GPDs though DVCS & HEMP → working on 2016-2017
  - TMDs through SIDIS & Drell-Yan → new 2022 data release
- **COMPASS has entered its analysis phase, expect more results soon!**

- **EIC will further extend the measurements covered by COMPASS**
  - **Wide phase space coverage**
  - **GPD & TMD study with various processes**
  - **Meson structure via Sullivan process**
  - **Cold nuclear matter effect**



Backup Slides

COMPASS 2016 – Unpol. Target

➢ Cahn effect & Boer-Mulders ⊗ Collins FF

➢ Boer-Mulders: contributing to $\cos\varphi_h$ and $\cos 2\varphi_h$

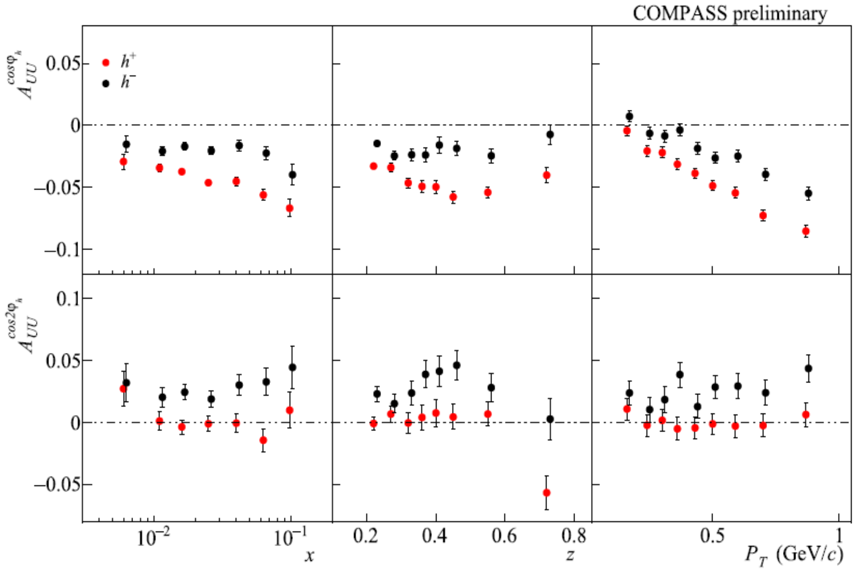
Describes the strength of the spin-orbit correlation between the quark spin s_T and the intrinsic transverse momentum k_T

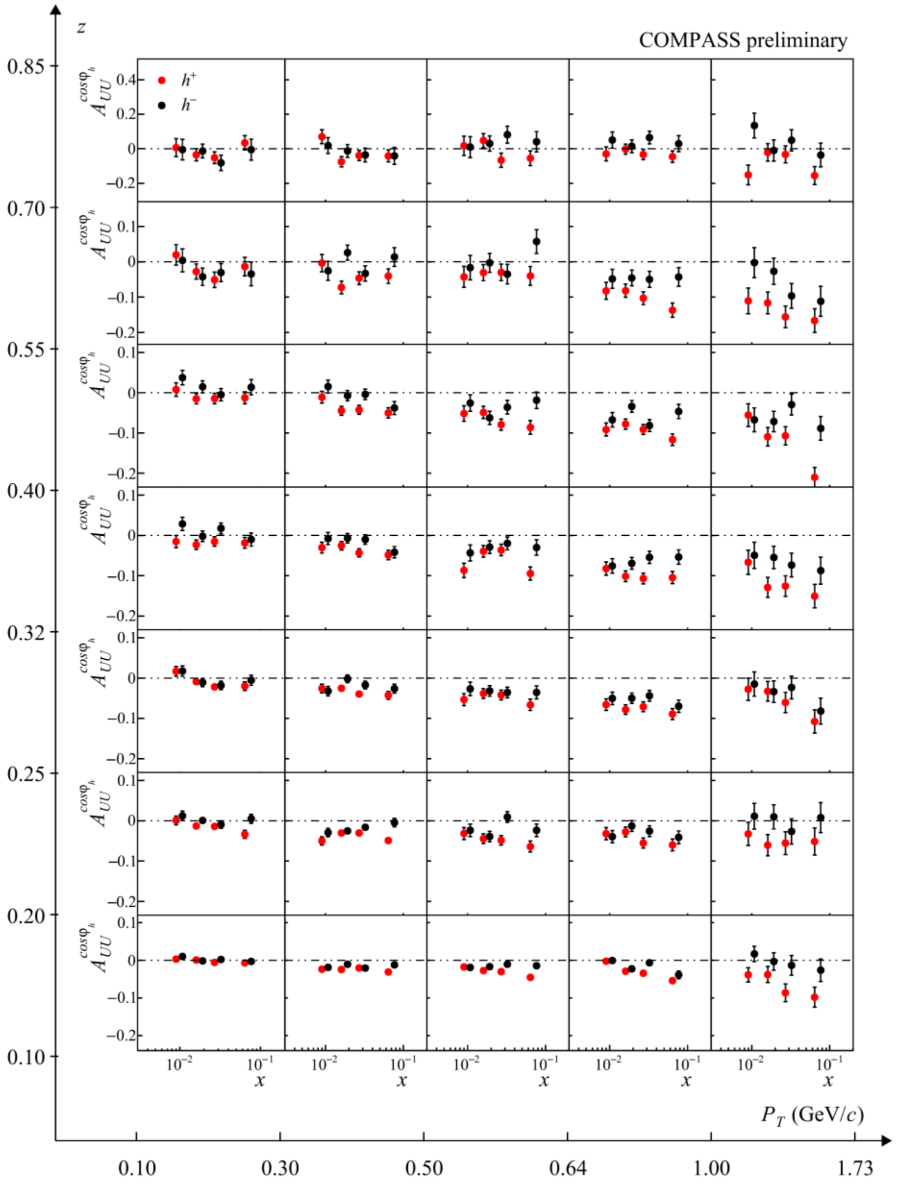
- Still Unknown
- Complex kinematic dependences & interesting differences between positive and negative hadrons from previous observations

➢ Cahn effect: contributing to $\cos\varphi_h$

Azimuthal modulation induced due to the presence of non-zero intrinsic transverse momentum k_T of unpolarized quarks in the unpolarized nucleon.

- Strong P_T dependence
- Complementary access to k_T
- On-going analysis with proton data
- More to come with 2022 deuteron data





2012 Exclusive ω Prod. on Unpolarized Proton

SCHC ($\lambda_\gamma = \lambda_V$)
(S-Channel Helicity Conservation)

SCHC implies:

- $r^1_{1-1} + \mathrm{Im}\, r^2_{1-1} = 0$

  = - 0.010 ± 0.032 ± 0.047 OK

- $\mathrm{Re}\, r^5_{10} + \mathrm{Im}^6_{10} = 0$

  = 0.014 ± 0.011 ± 0.013 OK

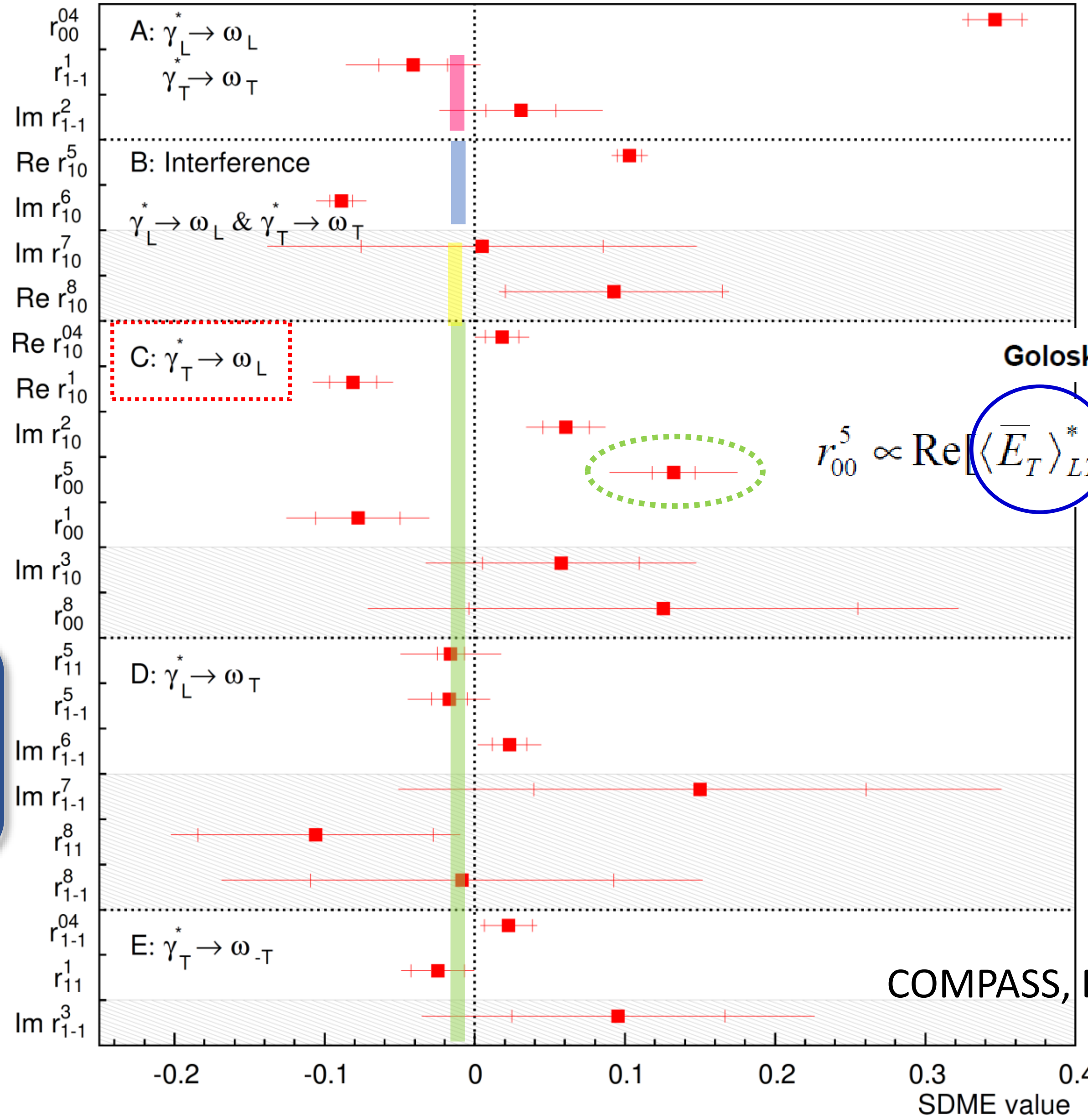
- $\mathrm{Im}\, r^7_{10} - \mathrm{Re}\, r^8_{10} = 0$

  = - 0.088 ± 0.110 ± 0.196 OK

- all elements of classes C, D, E should be 0

for $\gamma^*_L \to \omega_T$ and $\gamma^*_T \to \omega_{-T}$ OK within errors

NOT OBSERVED for transitions $\gamma^*_T \to \omega_L$



Goloskokov and Kroll, EPJC 74 (2014) 2725

$$r^5_{00} \propto \mathrm{Re}[\langle \overline{E}_T \rangle^*_{LT} \langle H \rangle_{LL} + \frac{1}{2} \langle H_T \rangle^*_{LT} \langle E \rangle_{LL}]$$

Exclusive ρ^0, ω production with trans. pol. target

COMPASS, NPB865 (2012) 1-20
COMPASS, PLB731 (2014) 19
COMPASS, NPB915 (2017) 454-475

COMPASS, **Eur.Phys.J.C** 81 (2021) 126

COMPASS++ / AMBER

A new QCD facility
at the M2 beam line of the CERN SPS

- Unique beam line with polarised $\mu^{\pm}$ and high-intensity **Pion** beam
- Possible high-intensity **antiproton** and **Kaon** beams, provided by RF-separation technique
- With upgraded apparatus

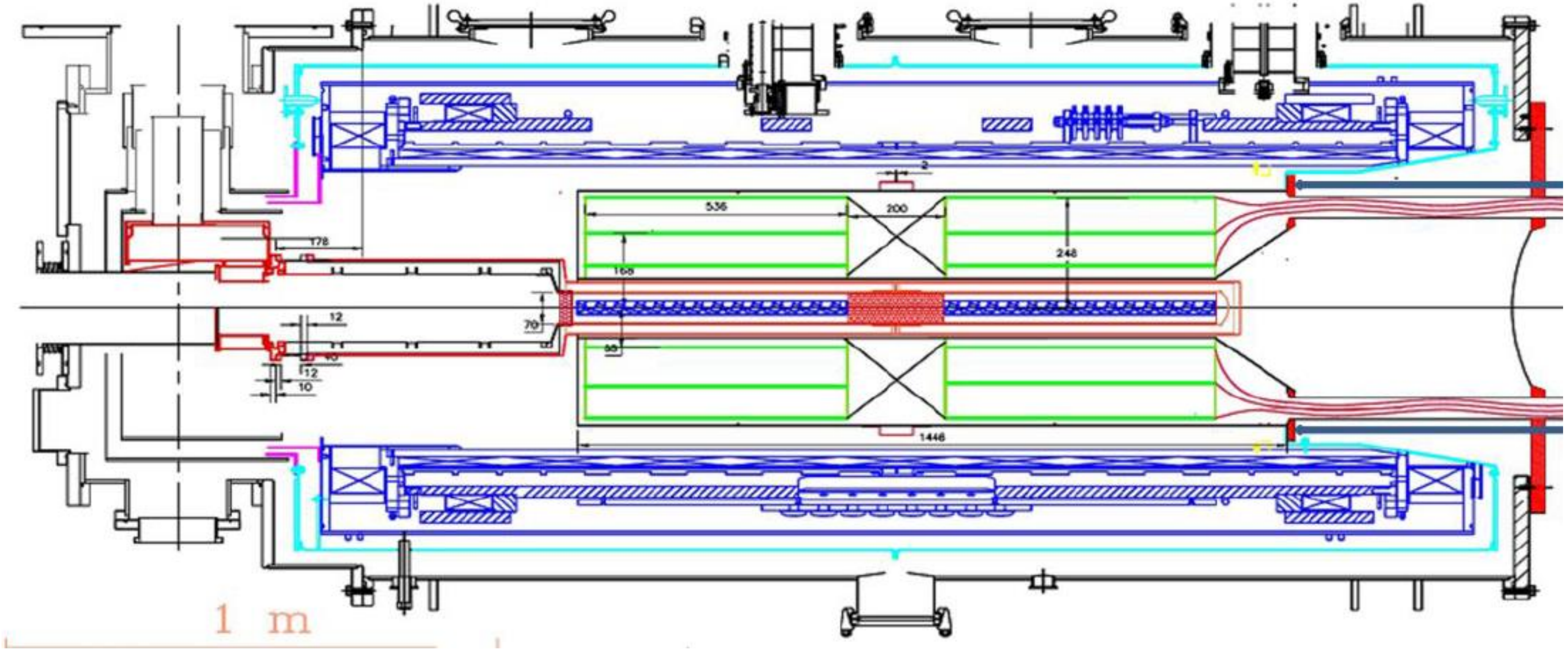
Proposed physics goals

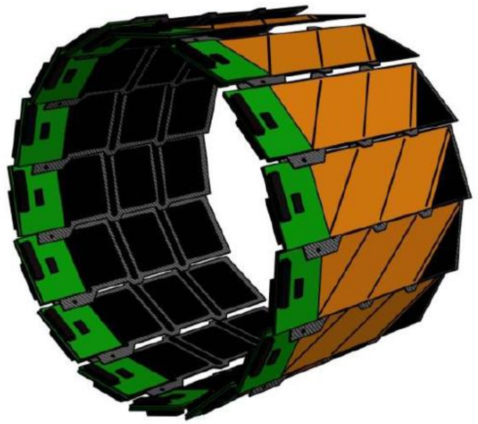
Proton Radius
Meson PDF – gluon PDF
Proton spin structure
3D imaging (TMDs and GPDs)
Hadron spectroscopy
Anti-matter cross section

Program	Physics Goals	Beam Energy [GeV]	Beam Intensity [s^{-1}]	Trigger Rate [kHz]	Beam Type	Target	Earliest start time, duration	Hardware Additions
μp elastic scattering	Precision proton-radius measurement	100	$4 \cdot 10^6$	100	$\mu^{\pm}$	high-pressure H2	2022 1 year	active TPC, SciFi trigger, silicon veto,
Hard exclusive reactions	GPD E	160	$2 \cdot 10^7$	10	$\mu^{\pm}$	$NH_3^{\uparrow}$	2022 2 years	recoil silicon, modified PT magnet
Input for Dark Matter Search	$\bar{p}$ production cross section	20-280	$5 \cdot 10^5$	25	p	LH2, LHe	2022 1 month	LHe target
$\bar{p}$-induced Spectroscopy	Heavy quark exotics	12, 20	$5 \cdot 10^7$	25	$\bar{p}$	LH2	2022 2 years	target spectr.: tracking, calorimetry
Drell-Yan	Pion PDFs	190	$7 \cdot 10^7$	25	$\pi^{\pm}$	C/W	2022 1-2 years	
Drell-Yan (RF)	Kaon PDFs & Nucleon TMDs	$\sim$100	10^8	25-50	$K^{\pm}, \bar{p}$	$NH_3^{\uparrow}$, C/W	2026 2-3 years	"active absorber", vertex det.
Primakoff (RF)	Kaon polarisability & pion life time	$\sim$100	$5 \cdot 10^6$	> 10	K^-	Ni	non-exclusive 2026 1 year	
Prompt Photons (RF)	Meson gluon PDFs	≥ 100	$5 \cdot 10^6$	10-100	$K^{\pm}$ $\pi^{\pm}$	LH2, Ni	non-exclusive 2026 1-2 years	hodoscope
K-induced Spectroscopy (RF)	High-precision strange-meson spectrum	50-100	$5 \cdot 10^6$	25	K^-	LH2	2026 1 year	recoil TOF, forward PID
Vector mesons (RF)	Spin Density Matrix Elements	50-100	$5 \cdot 10^6$	10-100	$K^{\pm}, \pi^{\pm}$	from H to Pb	2026 1 year	

Possible RPD for COMPASS++/AMBER

A recoil proton detector (RPD) is mandatory to ensure the exclusivity. A Silicon detector is included *between* the target surrounded by the modified MW cavity *and* the polarizing magnet





A technology developed at JINR for NICA for the BM@N experiment

No possibility for ToF ➔ PID of p/π with dE/dx
Momentum and trajectory measurments
$|t|_{min} \sim 0.1$ GeV