Measurements of transverse momentum dependent effects in SIDIS at COMPASS

European nuclear physics conference 2025
21-26 Sept 2025, Moho, Caen, France

CHARLES UNIVERSITY
Faculty of mathematics and physics

COMPASS

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on behalf of the **COMPASS Collaboration**
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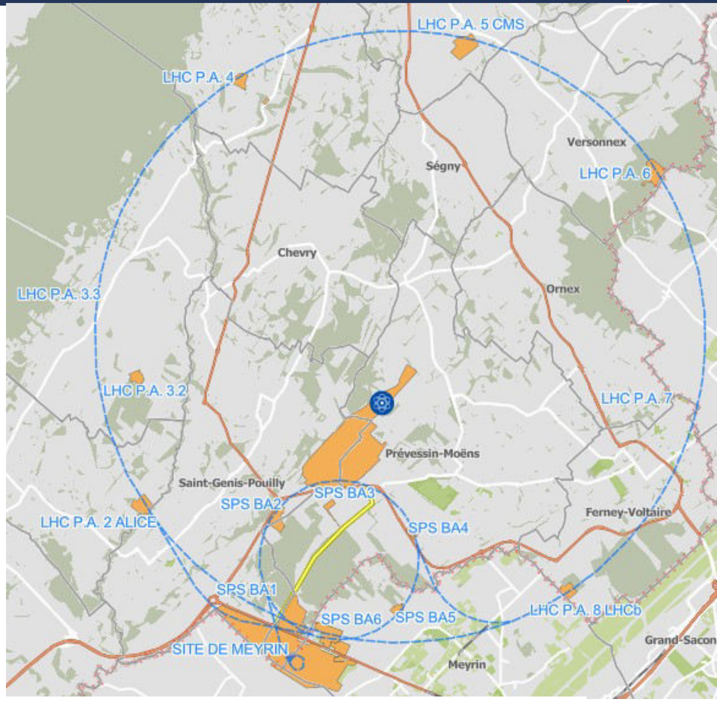
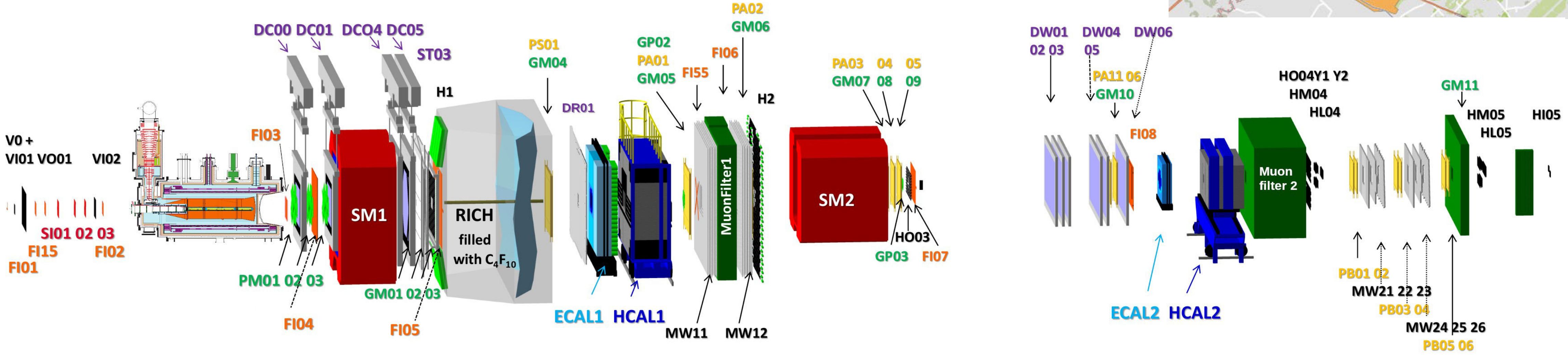
Supported by Charles university grant PRIMUS/22/SCI/017.

COMPASS collaboration



COmmon Muon Proton Apparatus
for Structure and Spectroscopy

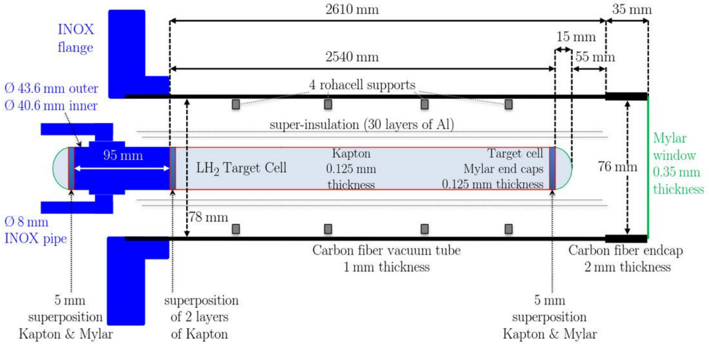
- **About 200 members** from **15** different **countries**
- Located in CERN North Area (SPS, M2 beam line)
- Measurements from 2002 to 2022
- Currently in analysis phase



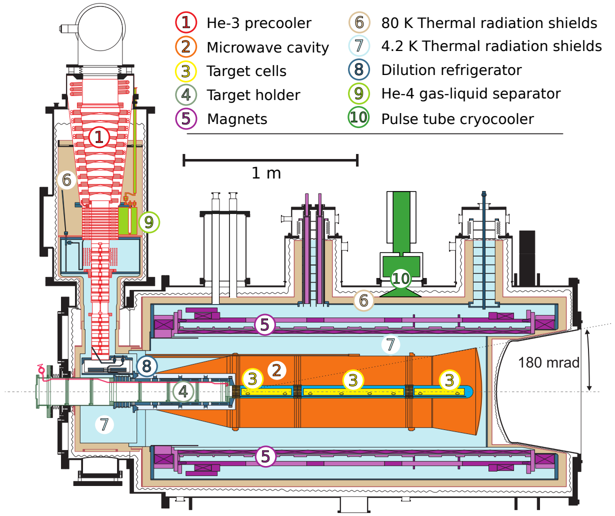
COMPASS collaboration

- Primary beam: 400 GeV/c p from CERN SPS
- Secondary beam: 190 GeV/c negative hadrons π^-(97%), K^-(2.5), $\overline{p}$ (0.5%)
- Tertiary beam: 160(200) GeV/c μ^+(μ^-)
- Fixed target

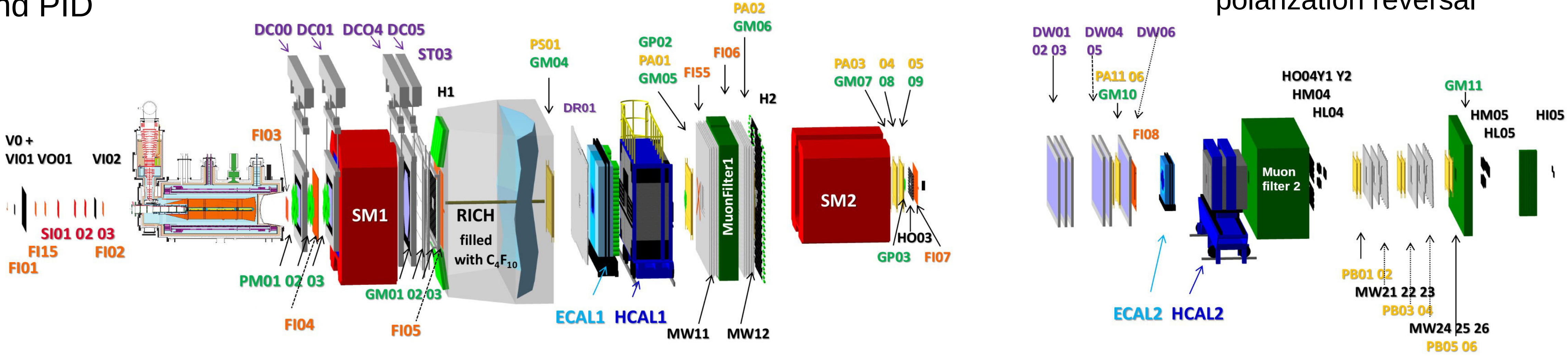
Apparatus:
- Large angle spectrometer and small angle spectrometer
- Two dipole analyzing magnets: SM1 and SM2
- Detector systems for precise tracking, calorimetry and PID



2016: unpolarized liquid H target

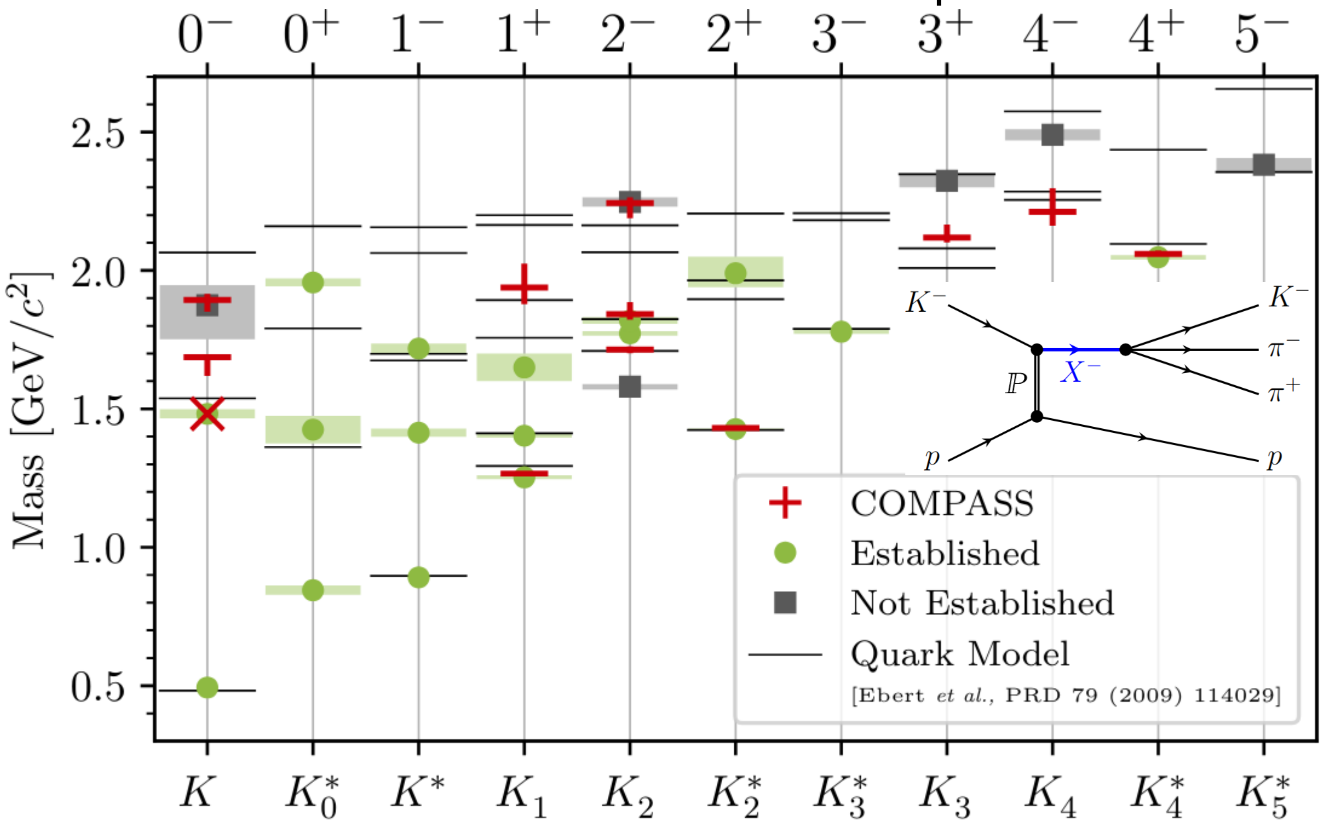


2022: ^{6}LiD target in 3 transversely polarized cells with periodic polarization reversal

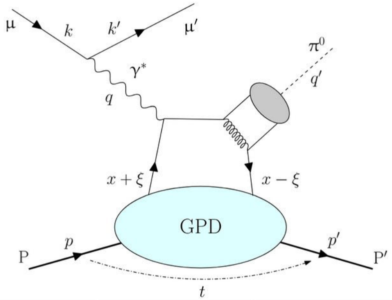


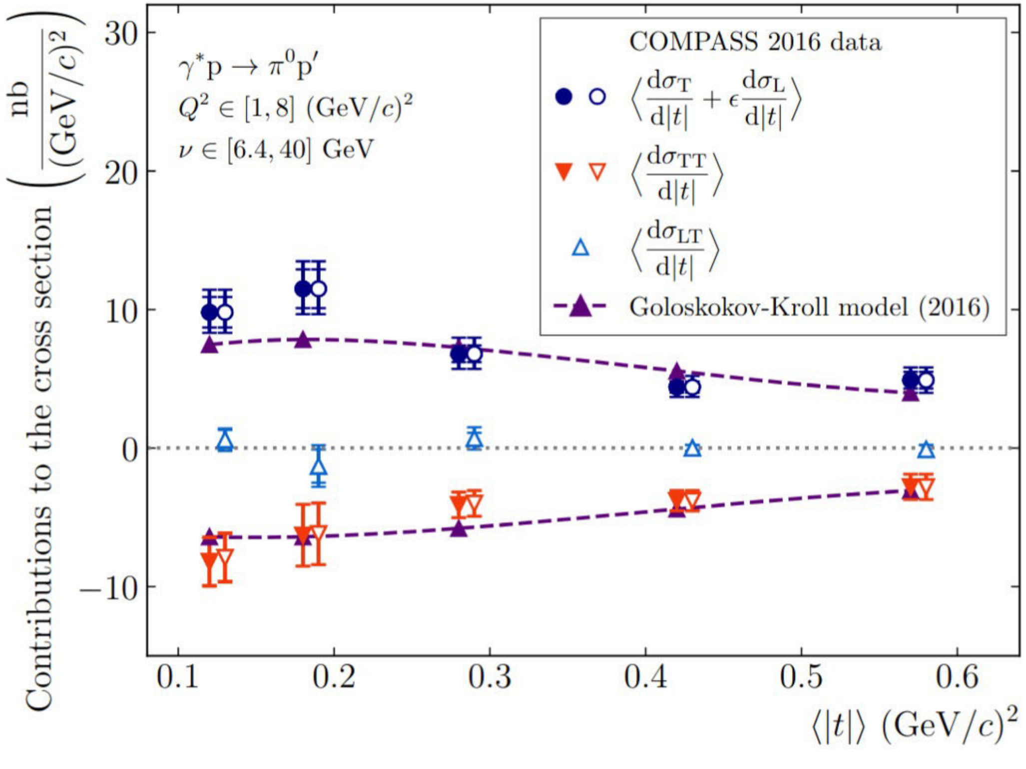
COMPASS experiment

Wide physics programme:
- Hadron spectroscopy
- Chiral dynamics
- Generalized parton distribution functions (GPDs)
- Nuclear structure: SIDIS and Drell-Yan processes



[COMPASS, arXiv: 2504.09470 [hep-ex]]

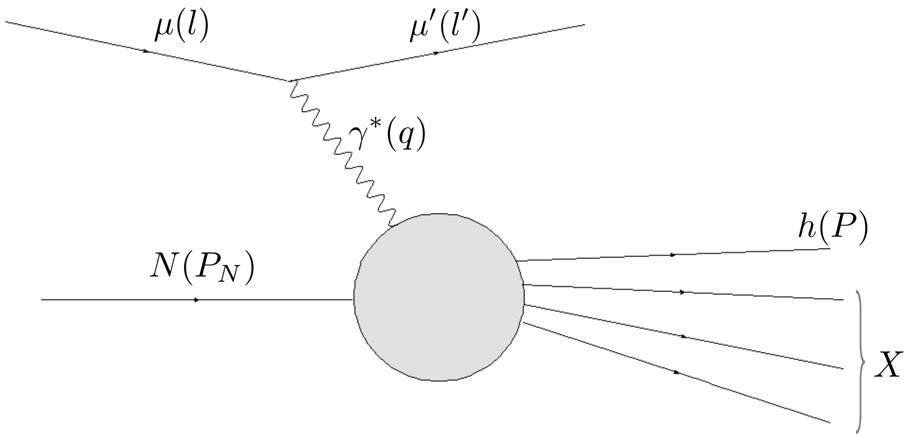




[Compass, arXiv: 2412.19923 [hep-ex], accepted by Phys. Lett. B]

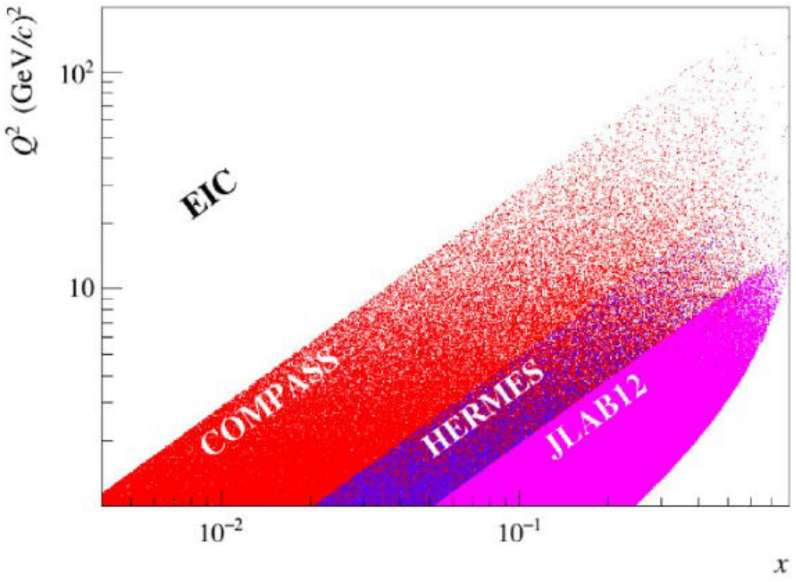
SIDIS

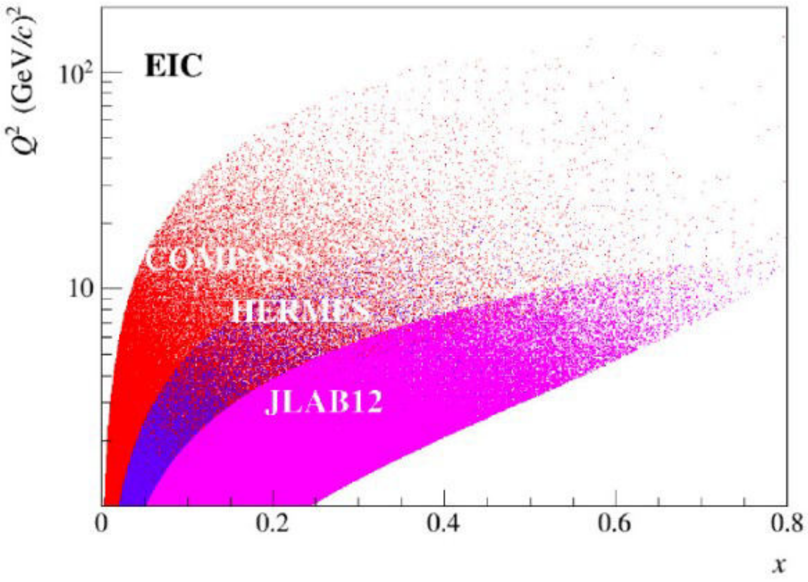
Semi-Inclusive Deep Inelastic Scattering (SIDIS):



$$\mu(l) + N(P_N) \longrightarrow \mu'(l') + h(P) + X$$

- Photon virtuality $Q^2 = -q^2 = -(l-l')^2$
- Bjorken variable $x = \frac{Q^2}{2P_N \cdot q}$
- $z = \frac{P_N \cdot P}{P_N \cdot q}$
- Inelasticity $y = \frac{q \cdot P_N}{l \cdot P_N}$





SIDIS

Single hadron production cross section for beam with longitudinal polarization λ and target polarization S_L, S_T :

$$\frac{d\sigma}{dx\,dy\,dz\,dP_T^2\,d\phi_h\,d\phi_s} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right](F_{UU,T}+\epsilon F_{UU,L})$$
$$\Big\{1+\sqrt{2\epsilon(1+\epsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon A_{UU}^{\cos(2\phi_h)}\cos(2\phi_h)+\lambda\sqrt{2\epsilon(1-\epsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$
$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\epsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]$$
$$+S_L\lambda\left[\sqrt{1-\epsilon^2}A_{LL}+\sqrt{2\epsilon(1-\epsilon)}A_{LL}^{\cos(\phi_h)}\cos(\phi_h)\right]$$
$$+S_T\left[A_{UT}^{\sin(\phi_h-\phi_s)}\sin(\phi_h-\phi_s)+\epsilon A_{UT}^{\sin(\phi_h+\phi_s)}\sin(\phi_h+\phi_s)+\epsilon A_{UT}^{\sin(3\phi_h-\phi_s)}\sin(3\phi_h-\phi_s)+\sqrt{2\epsilon(1+\epsilon)}A_{UT}^{\sin(\phi_s)}\sin(\phi_s)+\sqrt{2\epsilon(1+\epsilon)}A_{UT}^{\sin(2\phi_h-\phi_s)}\sin(2\phi_h-\phi_s)\right]$$
$$+S_T\lambda\left[\sqrt{1-\epsilon^2}A_{LT}^{\cos(\phi_h-\phi_s)}\cos(\phi_h-\phi_s)+\sqrt{2\epsilon(1-\epsilon)}A_{LT}^{\cos\phi_s}\cos\phi_s+\sqrt{2\epsilon(1-\epsilon)}A_{LT}^{\cos(2\phi_h-\phi_s)}\cos(2\phi_h-\phi_s)\right]\Big\}$$

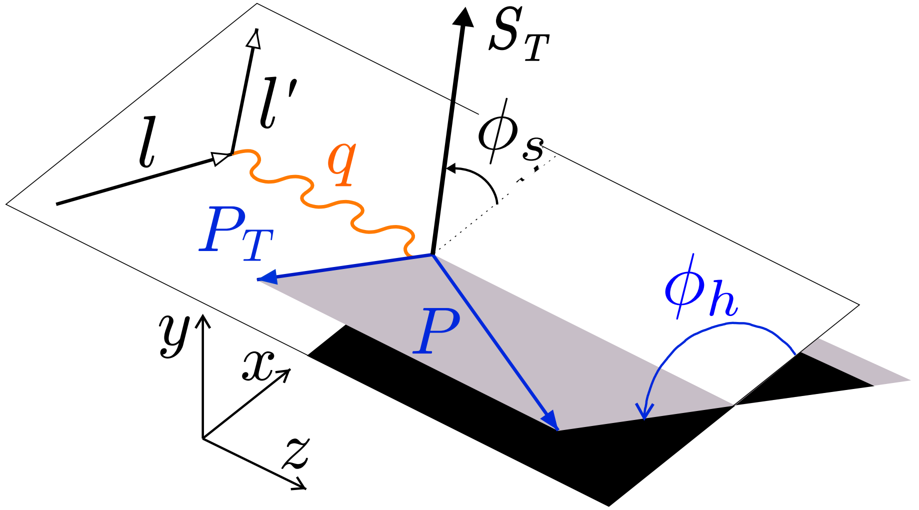
$$\gamma = 2\frac{M_X}{Q} \quad \epsilon = \frac{1-y-\frac{1}{4}\gamma^2y^2}{1-y+\frac{1}{2}y^2+\frac{1}{4}\gamma^2y^2}$$

Amplitudes A_{XY}, ***azimuthal asymmetries***

- Beam polarization X
- Target polarization Y
- Azimuthal modulation on angles φ_s, φ_h

Ratios of ***structure functions*** to $F_{U,U}$

$$A_{XY}^{f(\phi_h,\phi_s)}(x,z,P_T^2,Q^2) \equiv \frac{F_{XY}^{f(\phi_h,\phi_s)}}{F_{UU}}$$

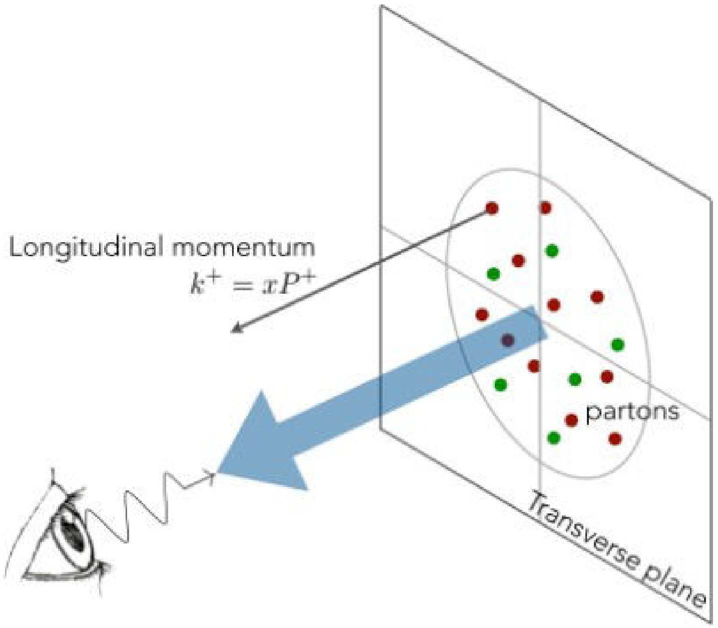


Structure functions: collinear formalism

DIS regime:
Integrating over hadron transverse momentum

$$F_{UU,T} = x \sum_q e_q^2 f_1^q(x) D_1^q(z) \qquad F_{UU,L} = 0 \qquad F_{LL} = x \sum_q e_q^2 g_1^q(x) D_1^q(z)$$

- ***Parton distribution functions*** (PDFs)
- ***Fragmentation functions*** (FFs)



Collinear PDFs

Quark polarisation \ Nucleon polarisation	U	L	T
U	$f_1^q(x)$ Number density		
L		$g_1^q(x)$ Helicity	
T			$h_1^q(x)$ Transversity

nucleon spin

quark spin

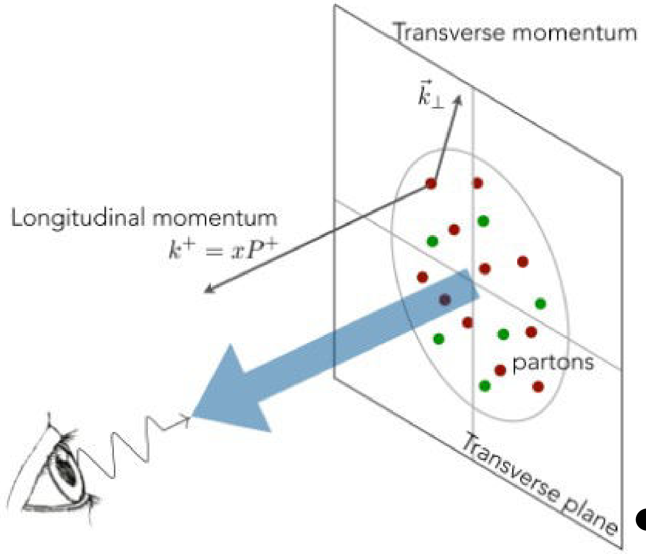
Structure functions: TMD formalism

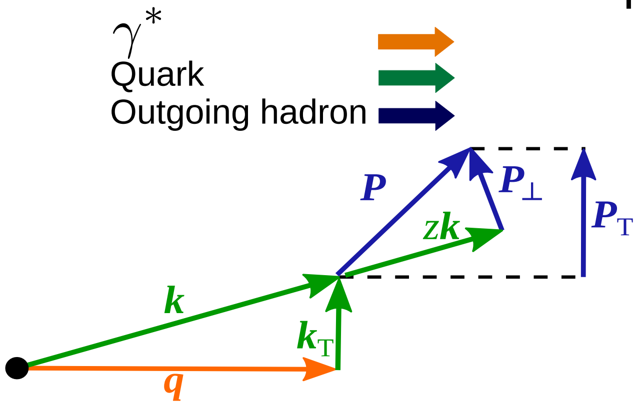
DIS regime:

$q_T << Q$ → ***Transverse momentum dependent*** (TMD) factorisation

$$F = \mathcal{C}[\omega f D] = x \sum_q e_q^2 \int d^2k_T d^2P_\perp \delta^{(2)}(zk_T + P_\perp - P_T) w(k_T, P_\perp) f^q(x, k_T, Q^2) D^{q \to h}(z, P_\perp, Q^2)$$

Transverse momentum dependent (TMD) PDFs and FFs





TMD PDFs

nucleon spin

quark spin

quark k_T

Nucleon polarisation

Quark polarisation	U	L	T
U	$f_1^q(x, k_T^2)$ Number density		$f_{1T}^{\perp q}(x, k_T^2)$ Sivers
L		$g_1^q(x, k_T^2)$ Helicity	$g_{1T}^q(x, k_T^2)$ Kotzinian−Mulders
T	$h_1^{\perp q}(x, k_T^2)$ Boer−Mulders	$h_{1L}^{\perp q}(x, k_T^2)$ Worm−gear	$h_1^q(x, k_T^2)$ Transversity $h_{1T}^{\perp q}(x, k_T^2)$ Pretzelosity

Unpolarized asymmetries

Three asymmetries related to the unpolarized target

$$\frac{d\sigma}{dxdydzdP_T^2d\phi_hd\phi_s} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right](F_{UU,T}+\epsilon F_{UU,L})$$

$$\Big\{1+\sqrt{2\epsilon(1+\epsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon A_{UU}^{\cos(2\phi_h)}\cos(2\phi_h)+\lambda\sqrt{2\epsilon(1-\epsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$

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

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

$$+S_T\left[A_{UT}^{\sin(\phi_h-\phi_s)}\sin(\phi_h-\phi_s)+\epsilon A_{UT}^{\sin(\phi_h+\phi_s)}\sin(\phi_h+\phi_s)+\epsilon A_{UT}^{\sin(3\phi_h-\phi_s)}\sin(3\phi_h-\phi_s)+\sqrt{2\epsilon(1+\epsilon)}A_{UT}^{\sin(\phi_s)}\sin(\phi_s)+\sqrt{2\epsilon(1+\epsilon)}A_{UT}^{\sin(2\phi_h-\phi_s)}\sin(2\phi_h-\phi_s)\right]$$

$$+S_T\lambda\left[\sqrt{1-\epsilon^2}A_{LT}^{\cos(\phi_h-\phi_s)}\cos(\phi_h-\phi_s)+\sqrt{2\epsilon(1-\epsilon)}A_{LT}^{\cos\phi_s}\cos\phi_s+\sqrt{2\epsilon(1-\epsilon)}A_{LT}^{\cos(2\phi_h-\phi_s)}\cos(2\phi_h-\phi_s)\right]\Big\}$$

At order 1/Q using Wandzura-Wilczek type approximation the structure functions at twist 3 are simplified to:

$$F_{UU,T}=\mathcal{C}\left[f_1D_1\right] \qquad F_{UU,L}=0$$

$$F_{UU}^{\cos\phi_h}=\frac{2M}{Q}\mathcal{C}\left[-\overbrace{\frac{\hat{h}\cdot k_T}{M}f_1D_1}^{\text{Cahn effect}}-\overbrace{\frac{(\hat{h}\cdot P_\perp)k_T^2}{M^2M_h}h_1^\perp H_1^\perp}^{\text{Boer-Mulders effect}}+\dots\right]$$

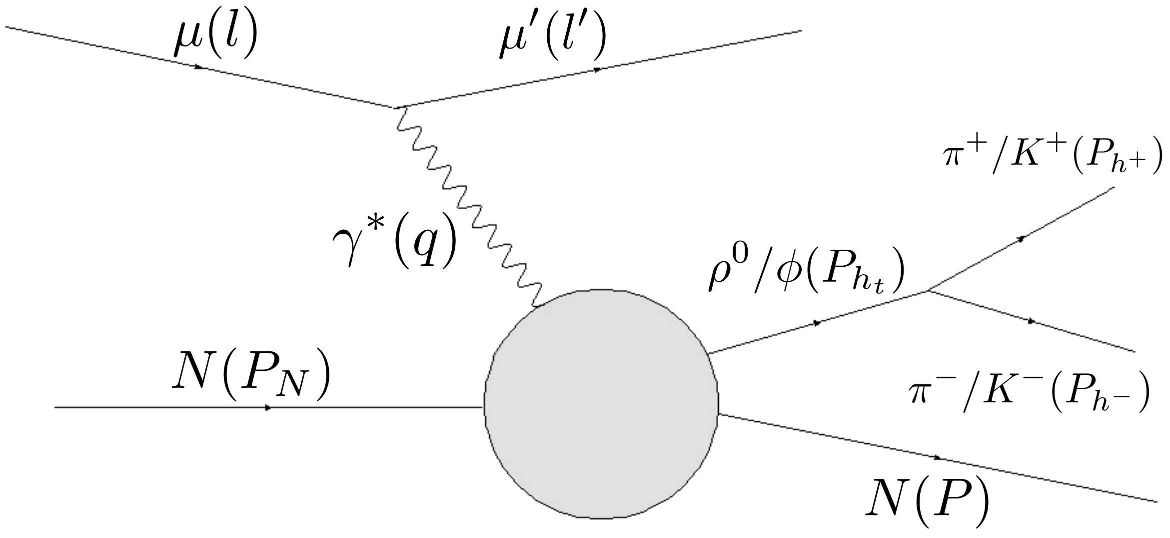
$$F_{UU}^{\cos 2\phi_h}=\mathcal{C}\left[-\overbrace{\frac{2(\hat{h}\cdot k_T)(\hat{h}\cdot P_\perp)-k_T\cdot P_\perp}{MM_h}h_1^\perp H_1^\perp}^{\text{Boer-Mulders effect}}\right]$$

$$F_{LU}^{\sin\phi_h}=\frac{2M}{Q}\mathcal{C}\left[\dots\right]$$

DVM background

Background from ***Diffractive Vector Mesons***

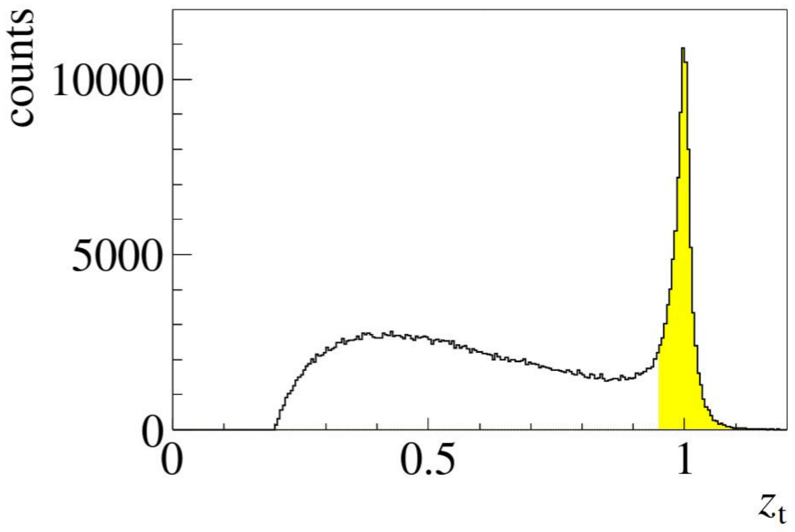
$$\rho \to \pi^+ \; \pi^- \qquad\qquad \phi \to k^+ \; k^-$$



- Both hadrons of the pair reconstructed: rejected imposing

$$z_t = z_{h^+} + z_{h^-} < 0.95$$

[Nucl. Phys. B 956 (2020) 115039]



- Only one hadron of the pair reconstructed: subtracted using a HEPGEN MC

[A. Sandacz, P. Sznajder, arXiv:1207.0333]

Radiative corrections

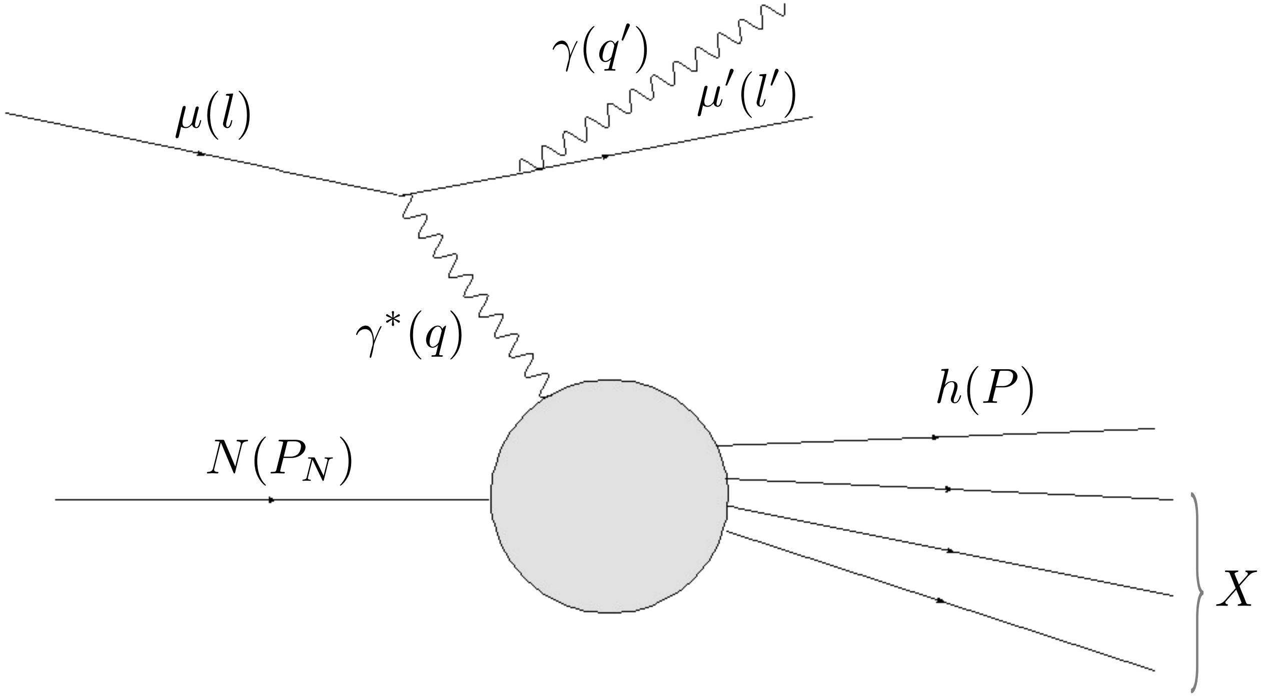
Real photon emission causes a shift in kinematics → Radiative corrections

- Till 2024:
  Inclusive correction based on TERAD.

  [A.A. Akhundov et al., Fortschr. Phys. 44 (1996) 373]

- New approach:
  Based on DJANGOH MC, corrects φ_h and P_T distributions.

  [COMPASS, Phys. Rev. D 112 (2025) 1, 012002]

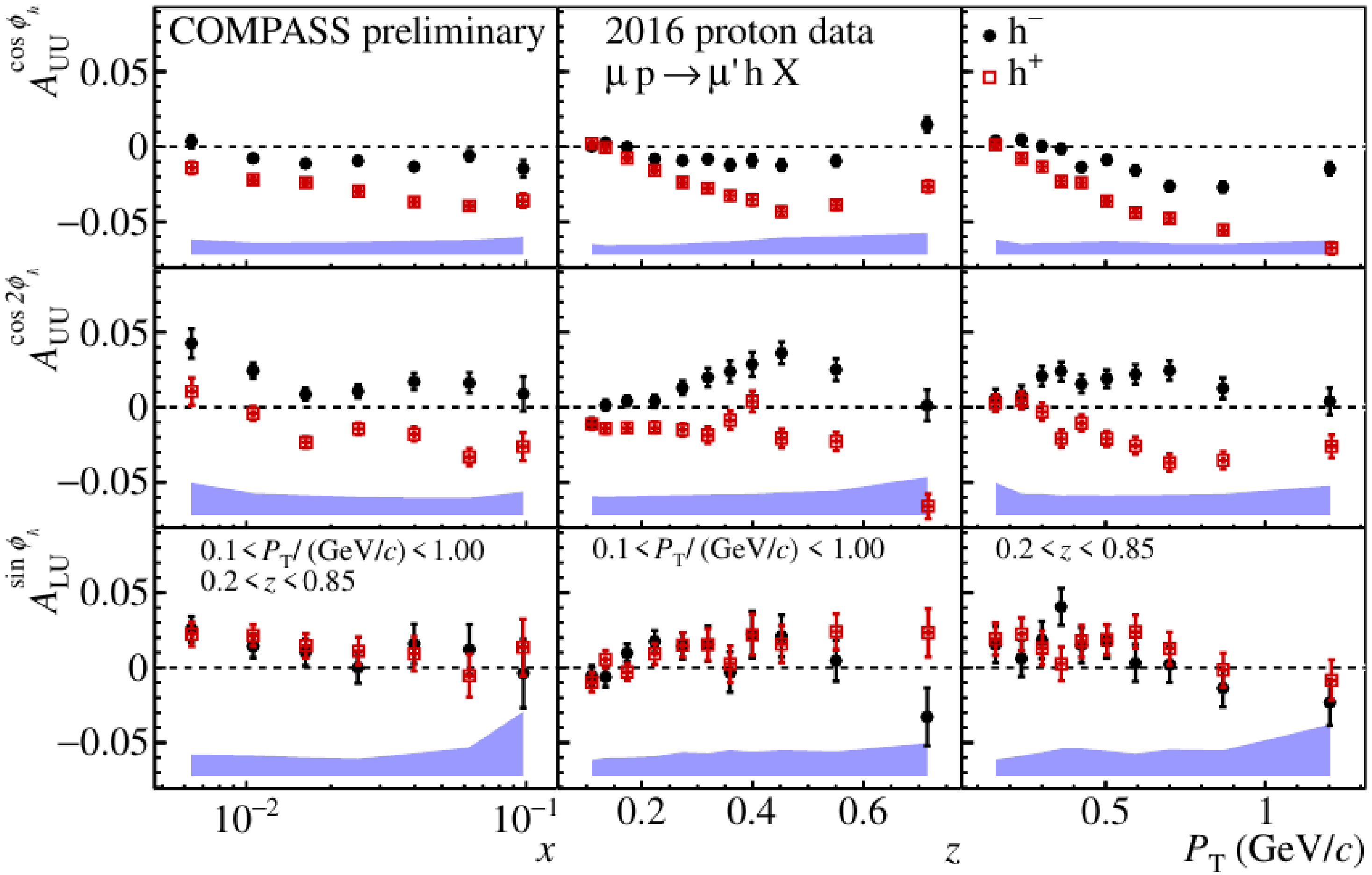


Unpolarized asymmetries

- Previously studied on isoscalar target [COMPASS, Nucl.Phys.B 886 (2014)]
- Ongoing work on 2016 data [V. Benesová, PoS DIS2024 (2025), 223]

$A_{UU}^{\cos\phi_h}$ and $A_{UU}^{\cos 2\phi_h}$ significantly different from 0 with difference between h$^+$ h$^-$

Suggests presence of Boer-Mulders effect



Collinear hadron multiplicities

At Leading Order:

$$\frac{dM^h(x,y,z)}{dz} = \frac{F_{UU}(x,y,z)}{F_2(x,y)} \propto \sum_q e_q^2 f_1^q(x,Q^2) D_1^{q\to h}(z,Q^2)$$

Previously extracted by COMPASS for $h^\pm$, $\pi^\pm$ and $K^\pm$ with isoscalar target

[COMPASS, Phys. Lett. B 764 (2017) 001]

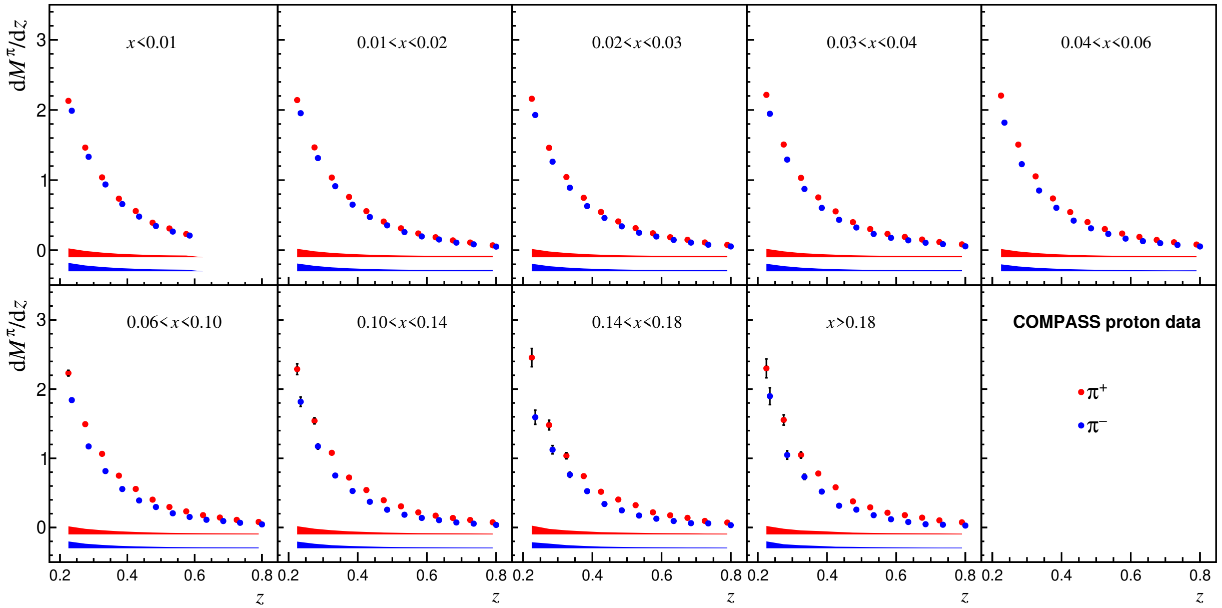
[COMPASS, Phys. Lett. B 767 (2017) 133]

Useful statistics for phenomenology studies

Experiment	Ref.	N_{dat} ($h=\pi$)	χ^2/N_{dat} NLO ($h=\pi$)	χ^2/N_{dat} NNLO ($h=\pi$)	N_{dat} ($h=K$)	χ^2/N_{dat} NLO ($h=K$)	χ^2/N_{dat} NNLO ($h=K$)
HERMES h^- d	[38]	2	0.41	0.32	2	0.18	0.13
HERMES h^+ p	[38]	2	0.01	0.02	2	0.05	0.04
HERMES h^- d	[38]	2	0.17	0.11	2	0.58	0.48
HERMES h^+ p	[38]	2	0.35	0.32	2	0.56	0.43
COMPASS h^-	[25,37]	157	0.48	0.55	156	0.74	0.59
COMPASS h^+	[25,37]	157	0.62	0.72	156	0.76	0.67
Total SIDIS		322	0.47	0.52	320	0.64	0.54
Global data set		**699**	**0.68**	**0.76**	**659**	**0.62**	**0.55**

[MAP, Phys.Lett.B 834 (2022) 137456]

New COMPASS results from 2016 proton target data



[COMPASS, Phys. Rev. D 112 (2025) 1, 012002]

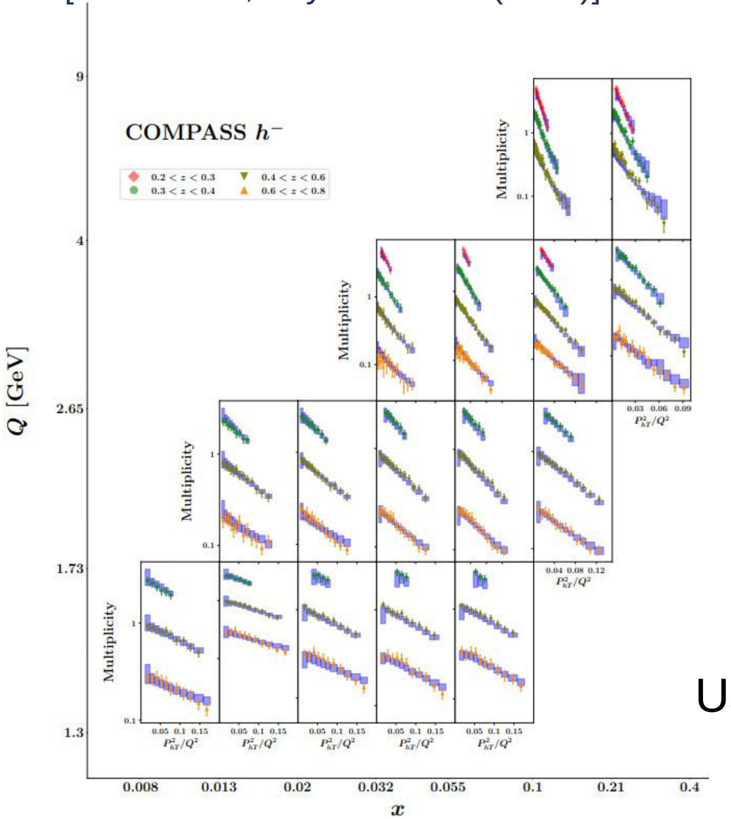
TMD hadron multiplicities

With TMD dependence

$$\frac{dM^h(x,z,P_T,Q^2)}{dz} = \frac{F_{UU}(x,z,P_T,Q^2)}{F_2(x,y)} \propto \mathcal{C}[f_1(x,k_T^2,Q^2)D_1(z,P_\perp^2,Q^2)]$$

Previously on isoscalar target

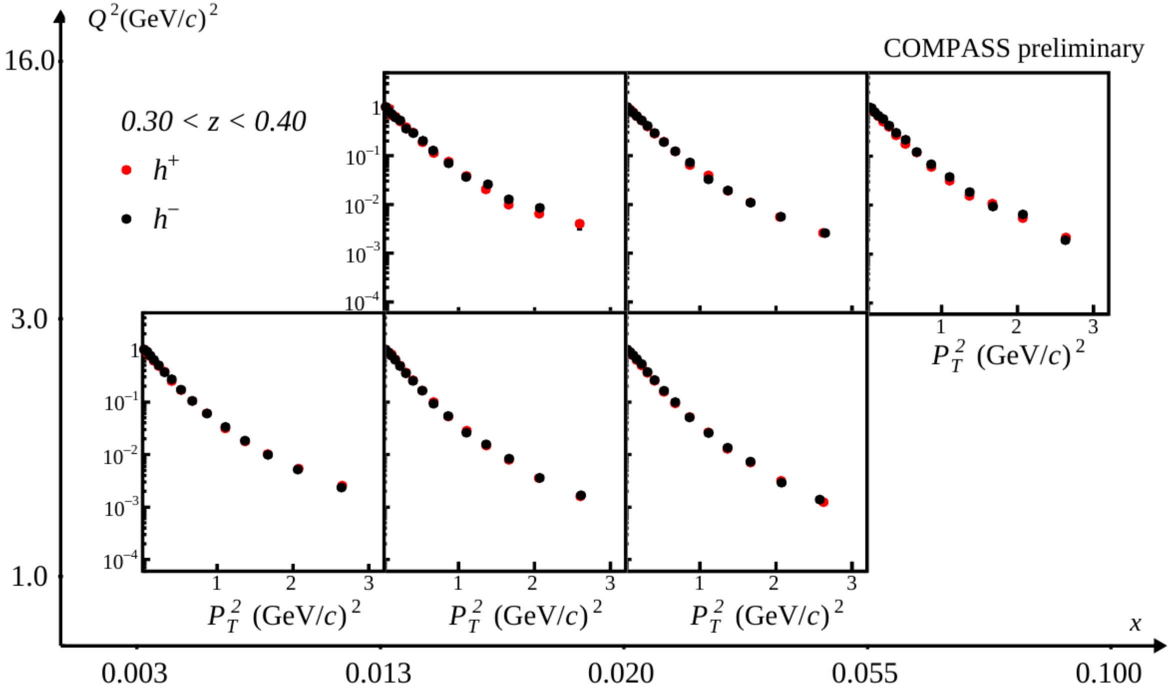
[COMPASS, Phys.Rev.D97 (2018)]



Used for global fits on TMDs

[MAP, JHEP 08 (2024) 232]

New preliminary results (proton data)



[A. Moretti, Proc. of ICNFP 2020]

Collins and Sivers asymmetries

$$\frac{d\sigma}{dxdydzdP_T^2d\phi_h d\phi_s} = \left[\frac{\alpha}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\left(1+\frac{\gamma^2}{2x}\right)\right](F_{UU,T}+\epsilon F_{UU,L})$$
$$\Big\{1+\sqrt{2\epsilon(1+\epsilon)}A_{UU}^{\cos\phi_h}\cos\phi_h+\epsilon A_{UU}^{\cos(2\phi_h)}\cos(2\phi_h)+\lambda\sqrt{2\epsilon(1-\epsilon)}A_{LU}^{\sin\phi_h}\sin\phi_h$$
$$+S_L\left[\sqrt{2\epsilon(1+\epsilon)}A_{UL}^{\sin\phi_h}\sin\phi_h+\epsilon A_{UL}^{\sin 2\phi_h}\sin 2\phi_h\right]$$
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$$+S_T\left[A_{UT}^{\sin(\phi_h-\phi_s)}\sin(\phi_h-\phi_s)+\epsilon A_{UT}^{\sin(\phi_h+\phi_s)}\sin(\phi_h+\phi_s)+\epsilon A_{UT}^{\sin(3\phi_h-\phi_s)}\sin(3\phi_h-\phi_s)+\sqrt{2\epsilon(1+\epsilon)}A_{UT}^{\sin(\phi_s)}\sin(\phi_s)+\sqrt{2\epsilon(1+\epsilon)}A_{UT}^{\sin(2\phi_h-\phi_s)}\sin(2\phi_h-\phi_s)\right]$$
$$+S_T\lambda\left[\sqrt{1-\epsilon^2}A_{LT}^{\cos(\phi_h-\phi_s)}\cos(\phi_h-\phi_s)+\sqrt{2\epsilon(1-\epsilon)}A_{LT}^{\cos\phi_s}\cos\phi_s+\sqrt{2\epsilon(1-\epsilon)}A_{LT}^{\cos(2\phi_h-\phi_s)}\cos(2\phi_h-\phi_s)\right]\Big\}$$

Collins and Sivers asymmetries dependent on transversity and Sivers TMD PDFs, correspondingly

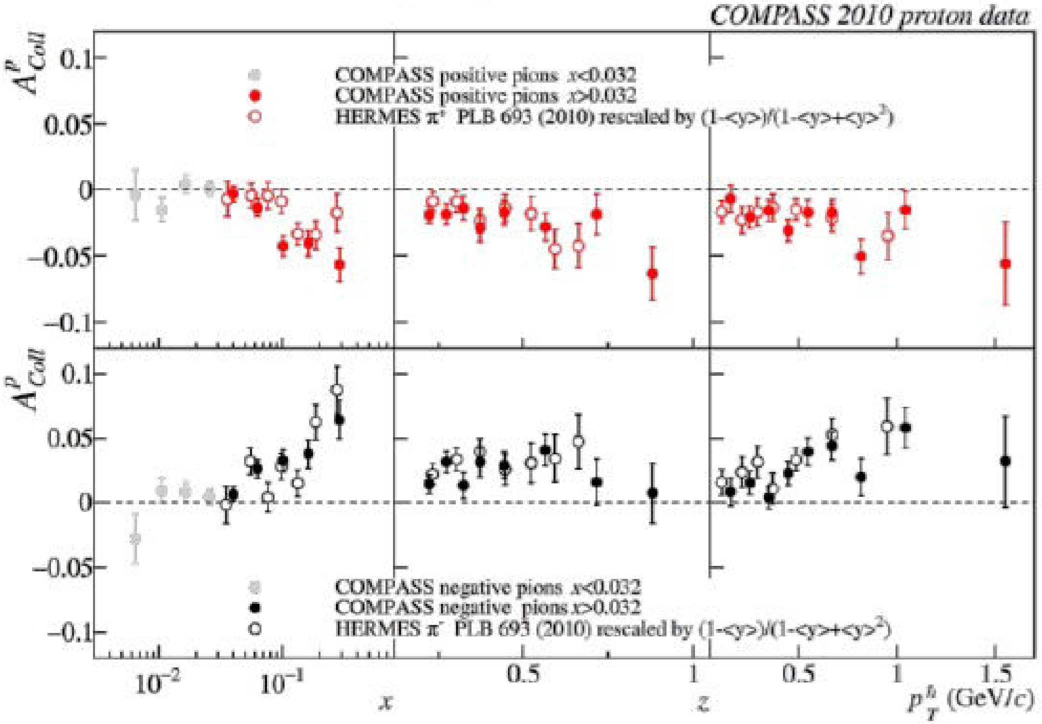
$$A_{UT}^{\sin(\phi_h+\phi_s)} = \frac{\mathcal{C}\left[-\frac{\tilde{h}\cdot k_T}{M_h}h_1 H_1^\perp\right]}{\mathcal{C}\left[f_1 D_1\right]}$$

$$A_{UT}^{\sin(\phi_h-\phi_s)} = \frac{\mathcal{C}\left[-\frac{\tilde{h}\cdot P_\perp}{M}f_{1T}^\perp D_1\right]}{\mathcal{C}\left[f_1 D_1\right]}$$

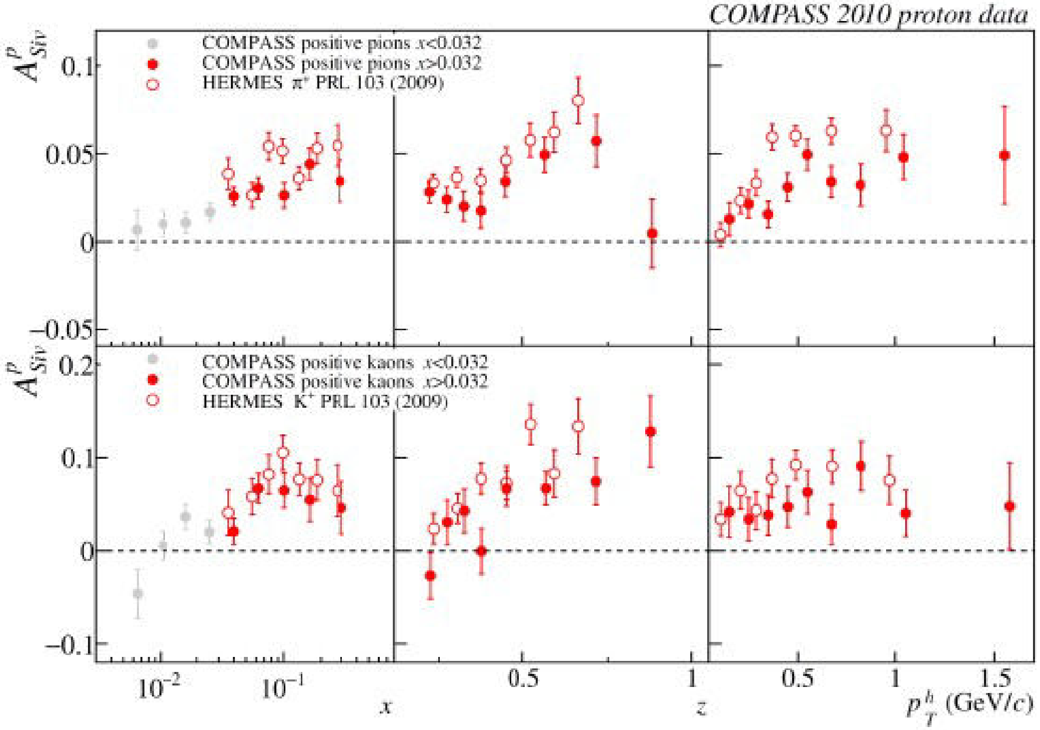
Transverse spin asymmetries on proton

- SIDIS on NH_3 target in 2007,2010
- First measurements by HERMES, lower beam energy and Q^2
- Non zero effect for Collins and Sivers asymmetries on p↑
- First evidences confirming TMD approach in QCD

Compatible results for Collins asymmetry



Smaller Sivers asymmetry at COMPASS

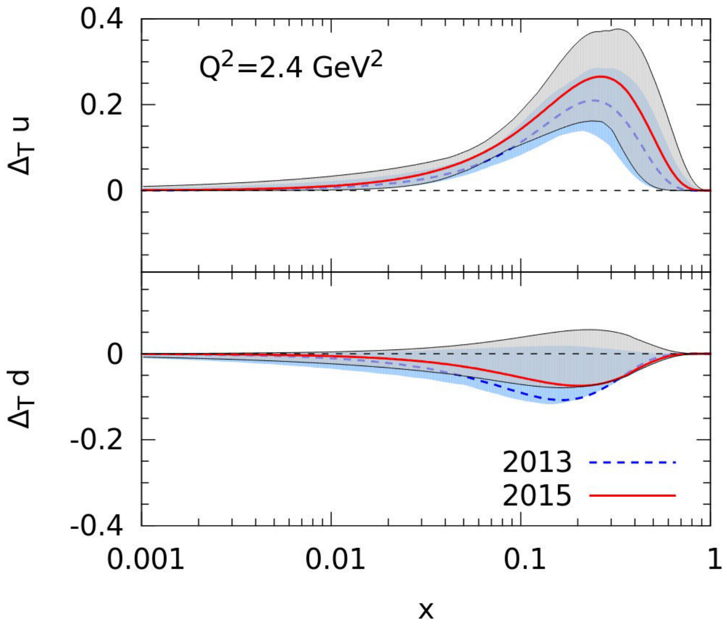


[COMPASS, Phys. Lett. B 774 (2015) 250]

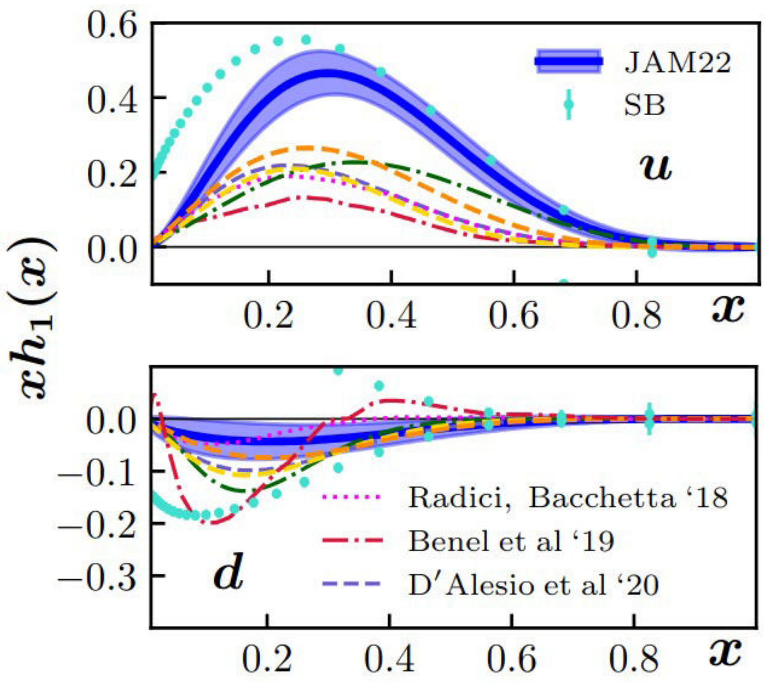
TMD PDF global fits

- Fits on data from HERMES, JLab and COMPASS (NH_3 target in 2007,2010 and ^{6}LiD target from 2002-2004, unique deuteron data)
- Insufficient deuteron statistics to constrain d quark distributions → new deuteron measurement

Transversity TMD PDF

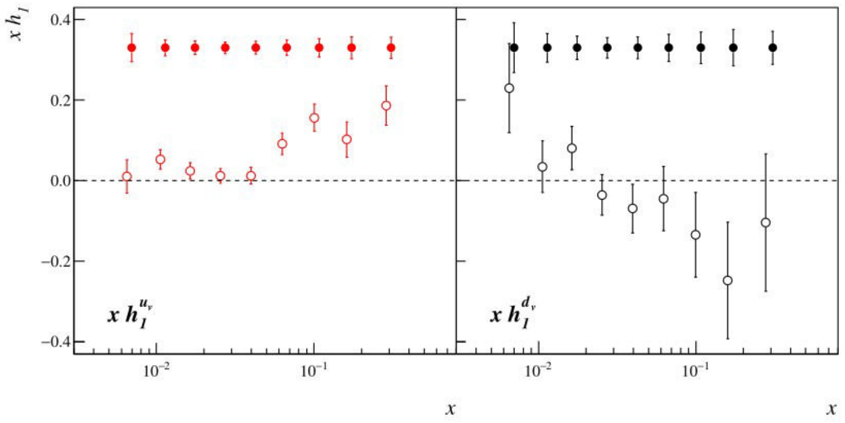


[Anselmino et al., Phys. Rev. D 92 (2015)]



[JAM, Phys. Rev. D 106 (2022)]

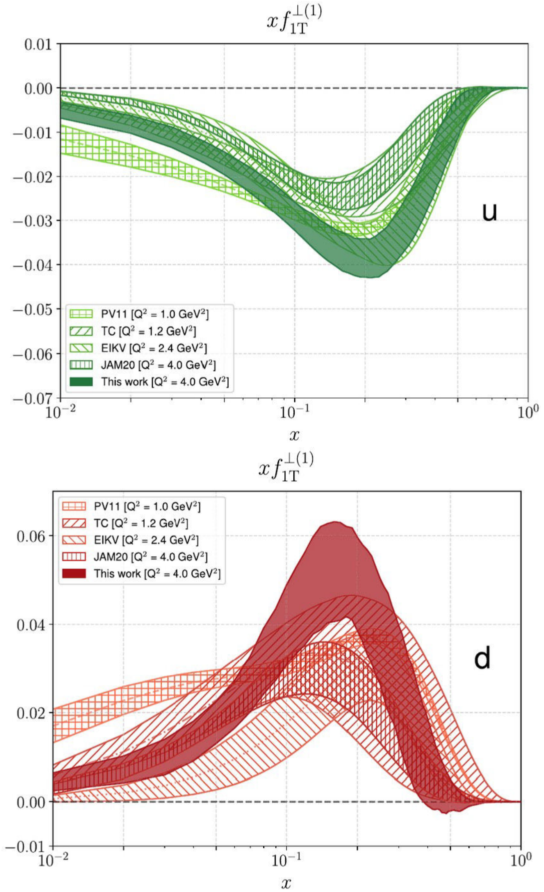
Estimated projections



[CERN–SPSC–2017–034]

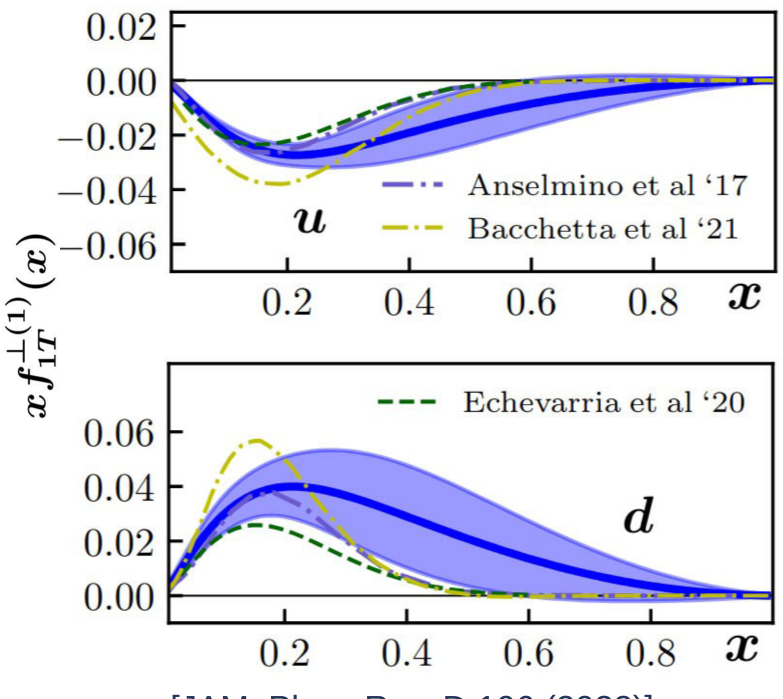
TMD PDF fits

- Global fits on data from HERMES, JLab, Belle and COMPASS (NH_3 target in 2007,2010 and ^{6}LiD target from 2002-2004, unique deuteron data)
- Insufficient deuteron statistics to constrain d quark distributions → new deuteron measurement



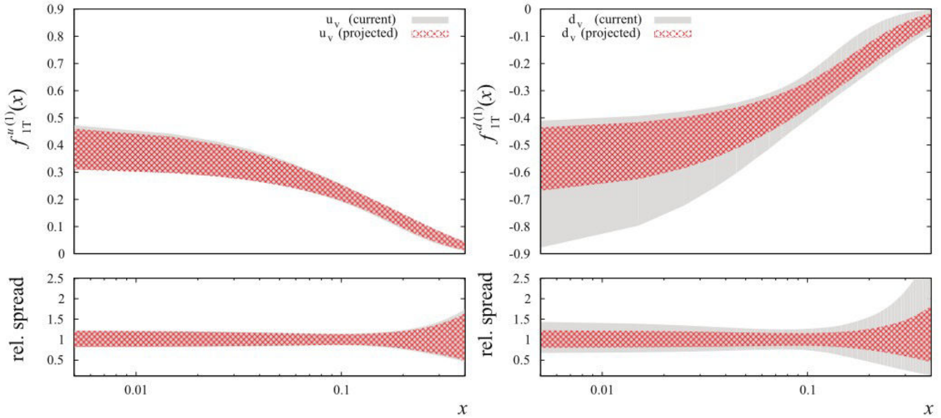
[A. Bacchetta et al., Phys. Lett. B 827 (2022)]

First moment of Sivers PDF



[JAM, Phys. Rev. D 106 (2022)]

Estimated projections



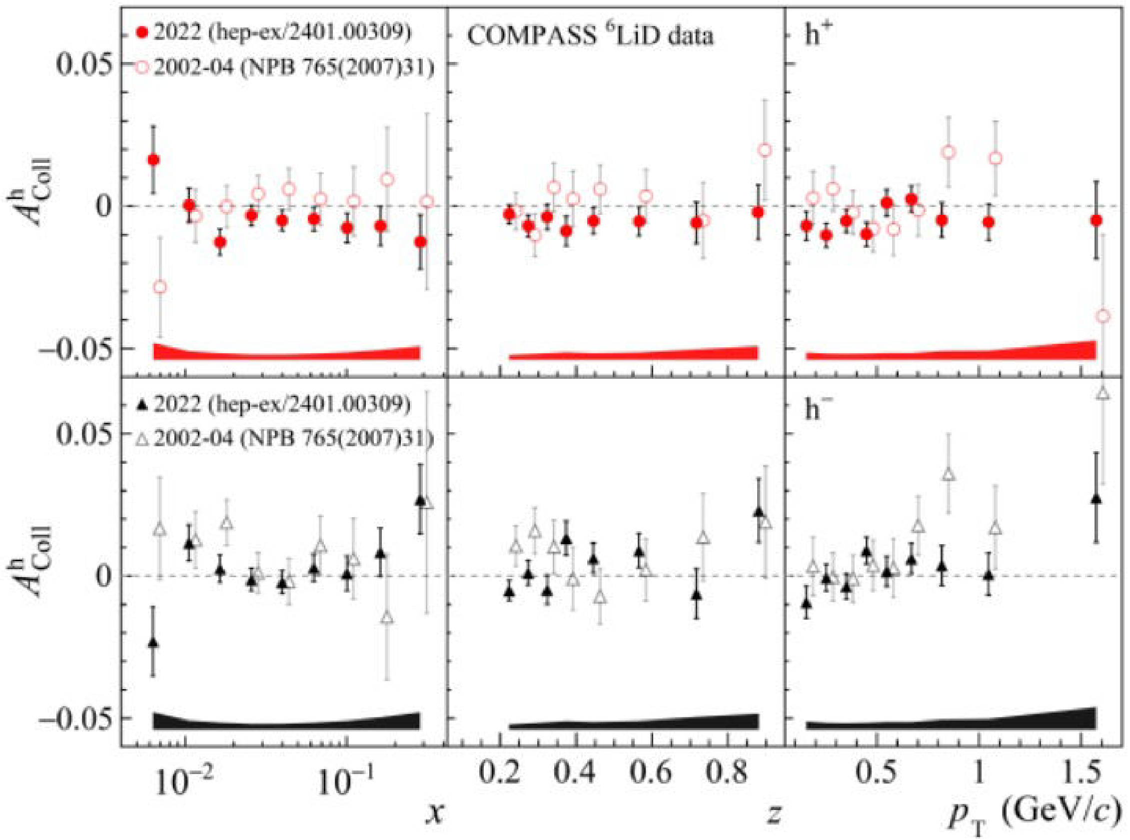
[CERN–SPSC–2017–034]

Transverse deuteron spin asymmetries

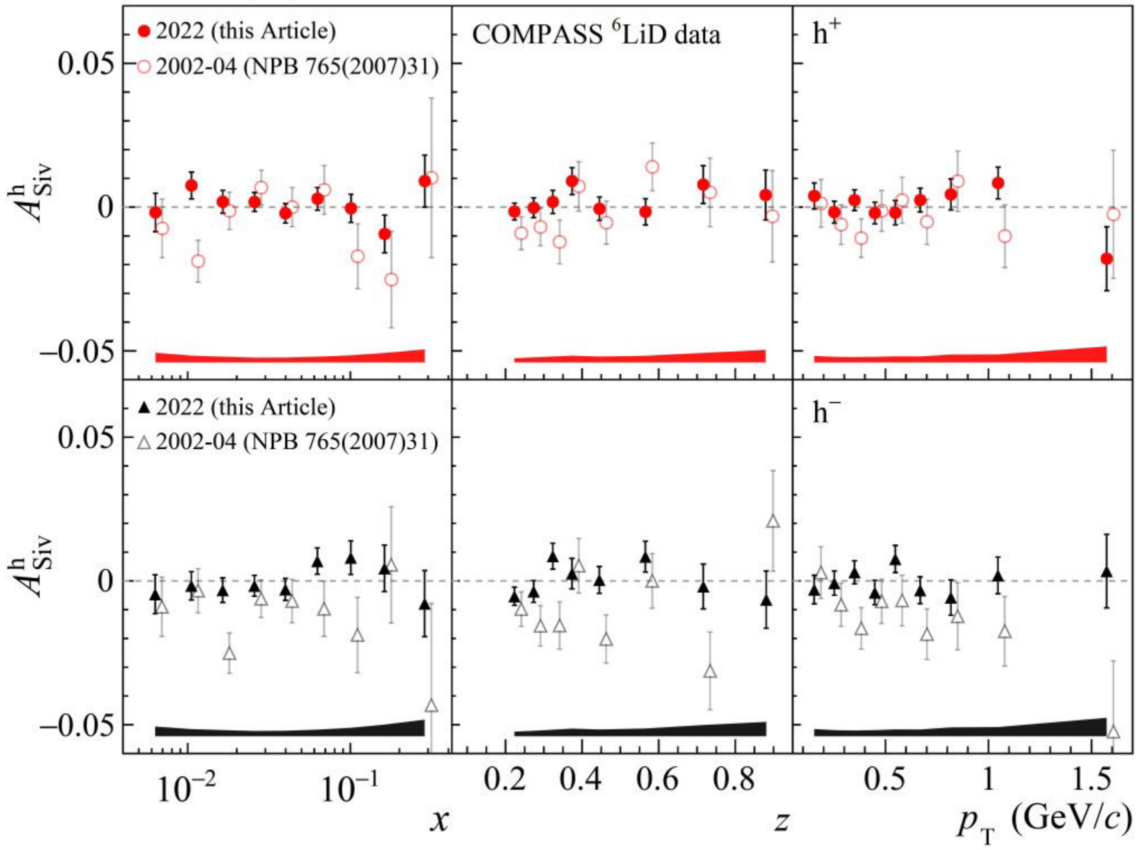
SIDIS scattering on ^{6}LiD target in 2002-2004 and 2022 → deuteron asymmetries

- Consistent results, smaller uncertainties in 2022
- Collins: hint of signal at large x with opposite dependence on h^+ and h^-
- Sivers: compatible with zero

2009 paper: [COMPASS, Phys. Lett. B 673 (2009) 127]
New paper [COMPASS, Phys. Rev. Lett. 133 (2024) 10, 101903]



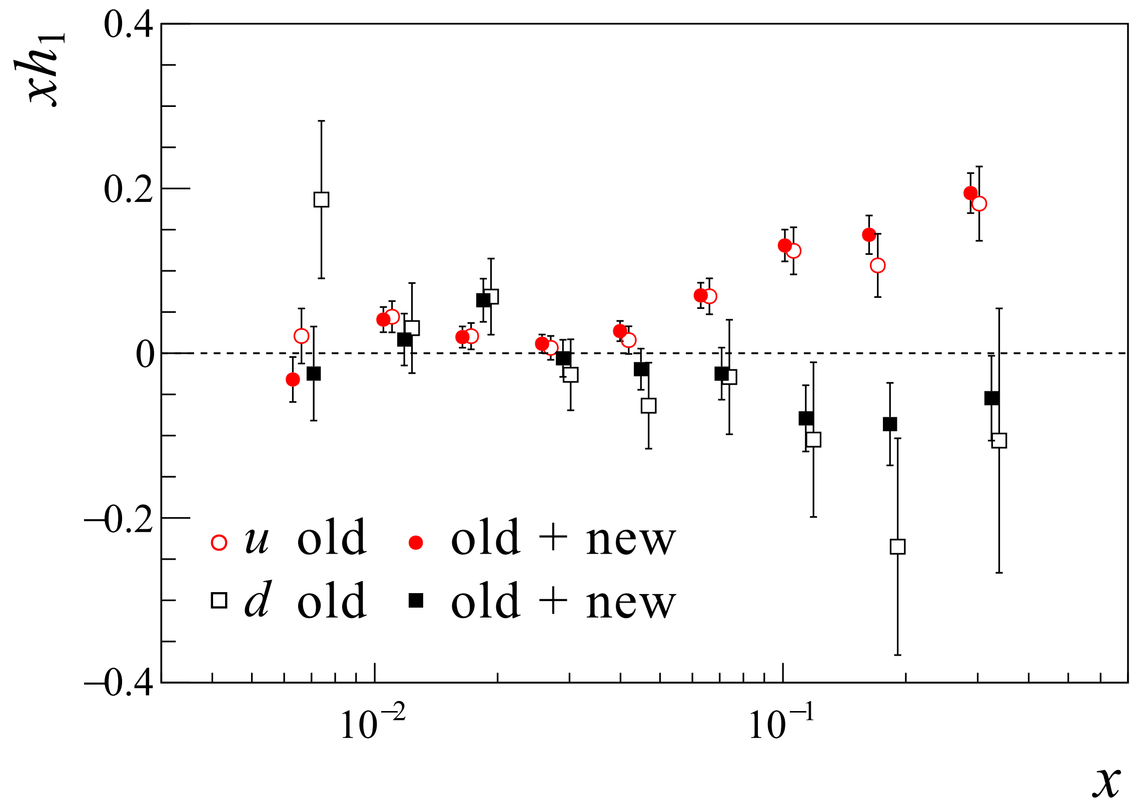
Collins Asymmetry

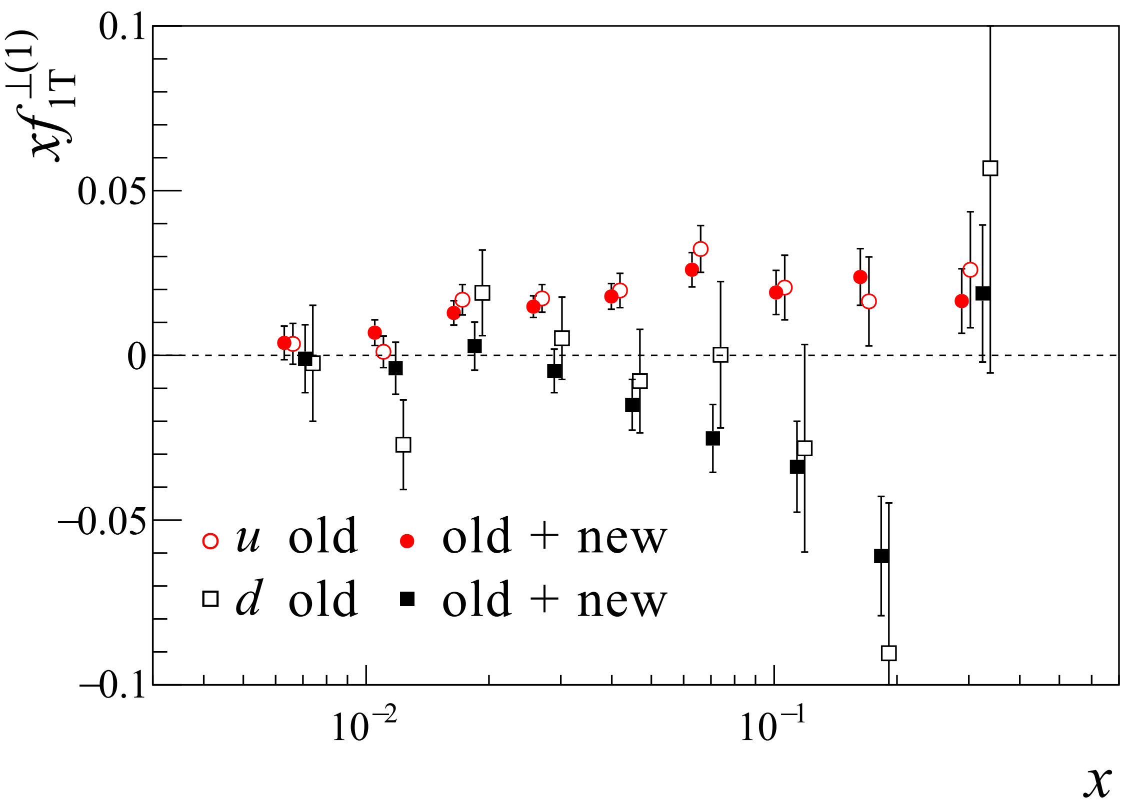


Sivers Asymmetry

Transverse spin asymmetries: u and d quarks

Extraction of transversity and Sivers TMDs for up and down quarks through p and d asymmetries, at leading twist





[COMPASS, Phys. Rev. Lett. 133 (2024) 10, 101903]

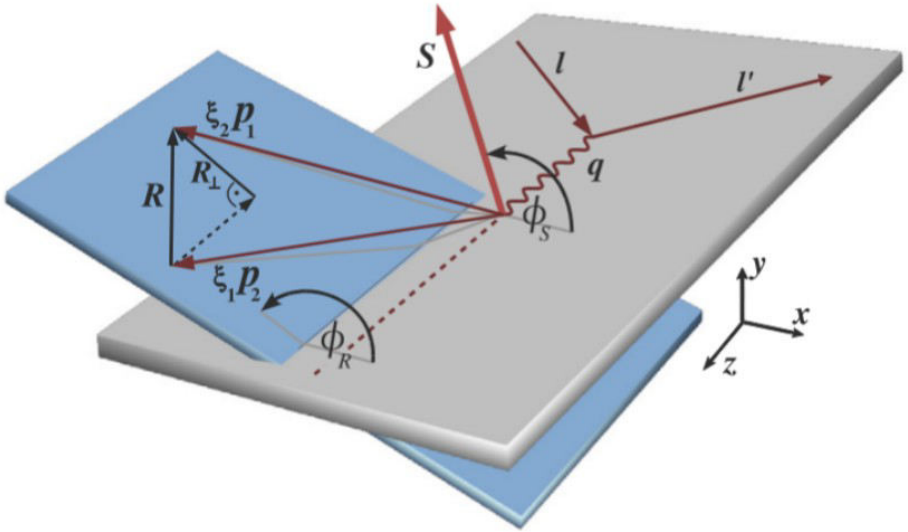
Dihadron transverse spin asymmetry

Through dihadron production transversity PDF can be extracted in a collinear way [M. Radici et al., Phys. Rev. D 65 (2002)]

$$\mu(l) + N(P) \longrightarrow \mu'(l') + h_1(P_{h1}) + h_2(P_{h2}) + X$$

Cross section dependent on transversity PDF and a dihadron FF:

$$\frac{d^7\sigma}{d\cos\theta dM_{hh} d\phi_R dz dx dy d\phi_s} = \frac{\alpha^2}{2\phi Q^2 y}\left((1-y+\frac{y^2}{2})\sum_q e_q^2 f_1^q(x) D_{1q}(z, M_{hh}^2, \cos\theta) + S_\perp (1-y) \underbrace{\sum_q e_q^2 \frac{|P_{h1}-P_{h2}|}{2M_{hh}} \sin\theta\, h_1^q(x) H_{1q}^{\sphericalangle}(z, M_{hh}^2, \cos\theta)}_{A_{UT}^{\sin(\phi_R+\phi_s-\pi)}} \sin(\phi_R+\phi_S-\pi) \right)$$



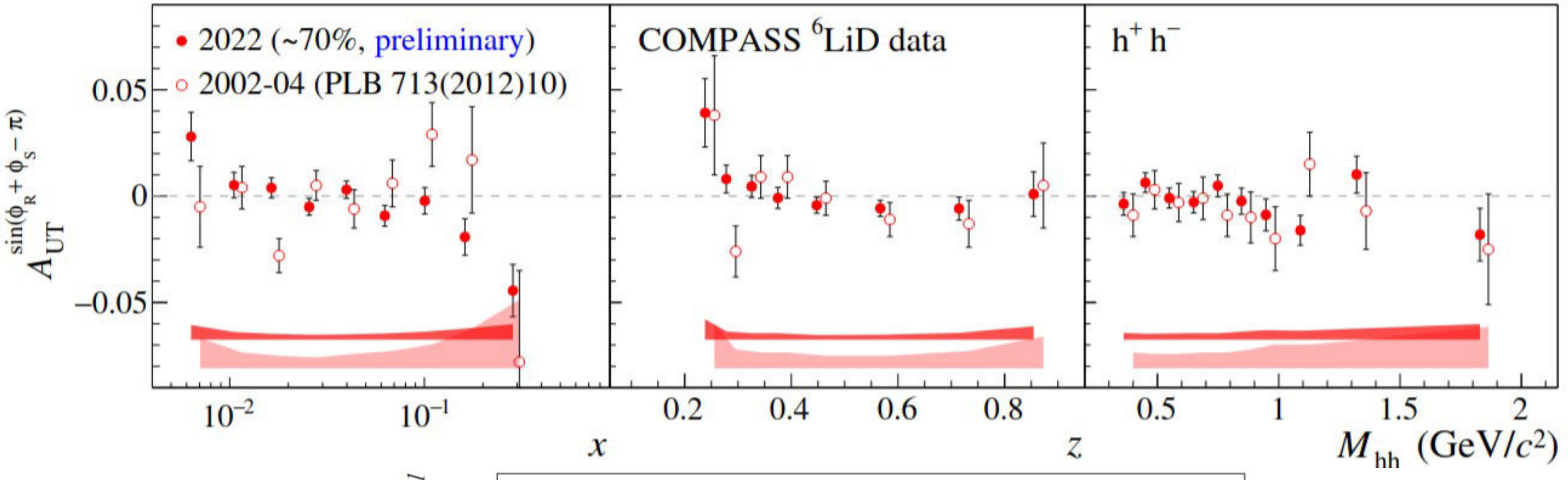
Dihadron transverse spin asymmetry

New 2022 extraction on deuteron

Comparison with previous measurement of 2002-2004

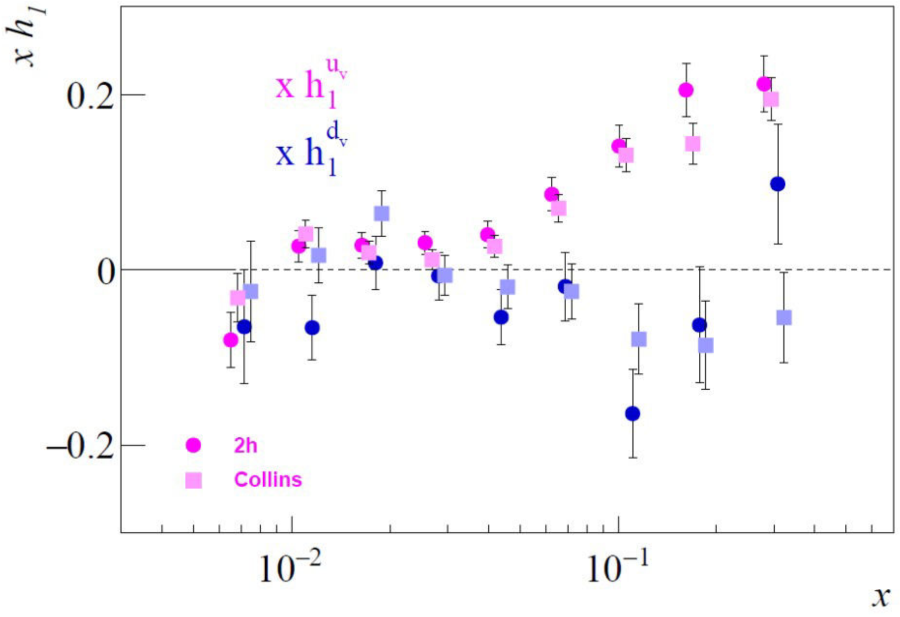
[COMPASS, Phys. Lett. B 713(2012)10]

[A. Asatryan, PoS DIS2024 (2025), 236]



Comparison of transversity PDF from COLLINS extractions

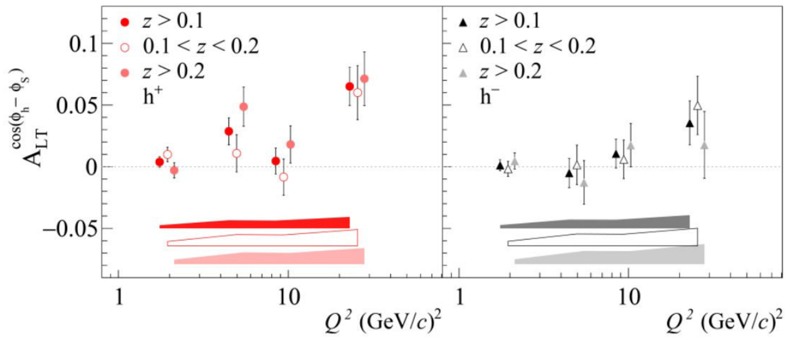
[A. Martin, IWHSS and QCD-N (2025)]



Further potential of 2022 data

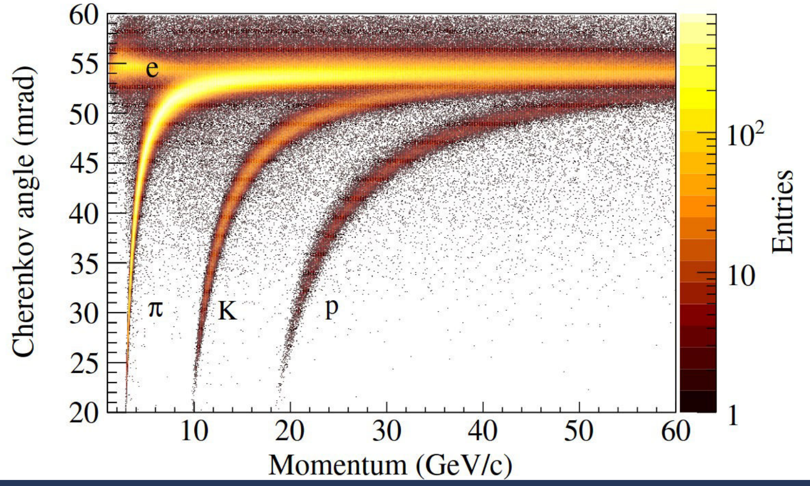
Many other studies planned:

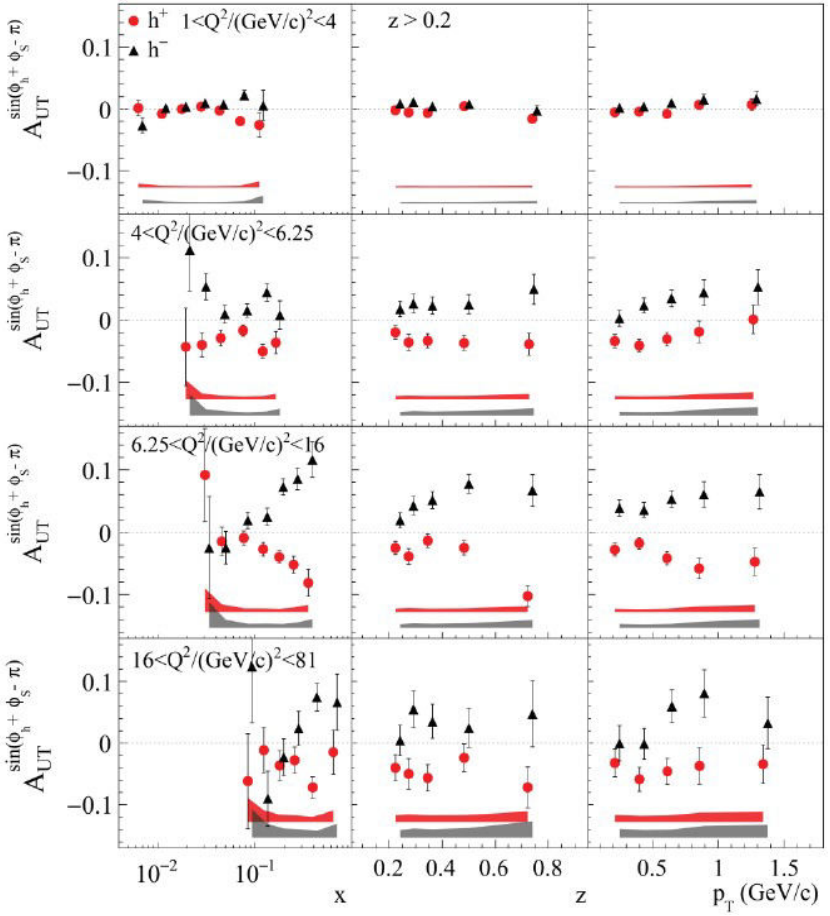
- Inclusion of hadron identification using RICH
- Other unpolarized and transverse spin asymmetry measurements
- Multi dimensional dependence of asymmetries and multiplicities
- J/ψ asymmetries and high P_T hadrons (sensistive to gluon TMDs)
- Λ polarisation and polarisation transfer
- P_T weighted transverse spin asymmetries
- Many other measurements ongoing/planned



Kotzinian–Mulders asymmetry from proton↑

[COMPASS, Phys. Lett. B 770 (2017) 138]





Q^2 dependence of Collins asymmetry:

[COMPASS, Phys. Lett. B 770 (2017) 138]

Conclusion

Many new results:

From 2016, unpolarized target

- Collinear multiplicitites [Nucl. Phys. B 956 (2020) 115039]
- TMD multiplicities
- Azimuthal asymmetries
- P_T distributions

From 2022, transversely polarized deuteron target

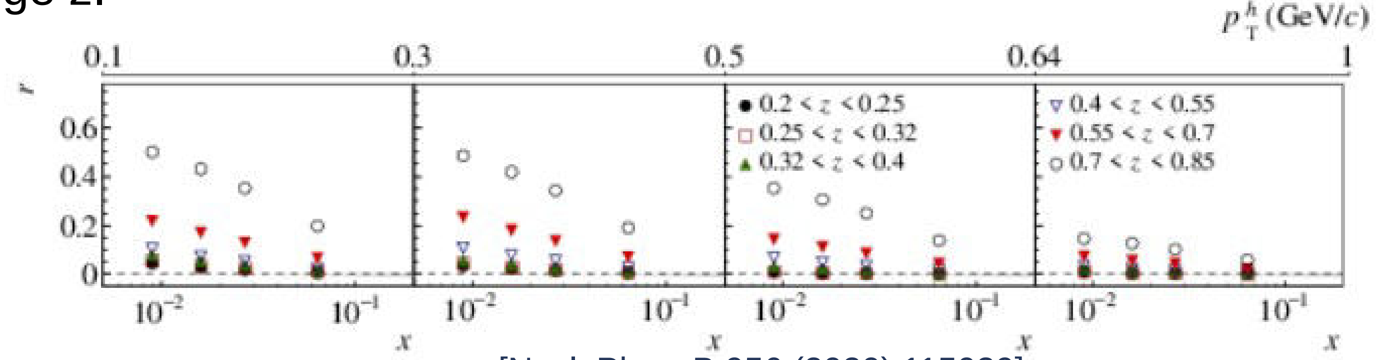
- Collins and Sivers asymmetries for charged hadrons [COMPASS, Phys. Rev. Lett. 133 (2024) 10, 101903]
- Dihadron transverse spin asymmetries
- Many other ongoing measurements

Backup

DVM background

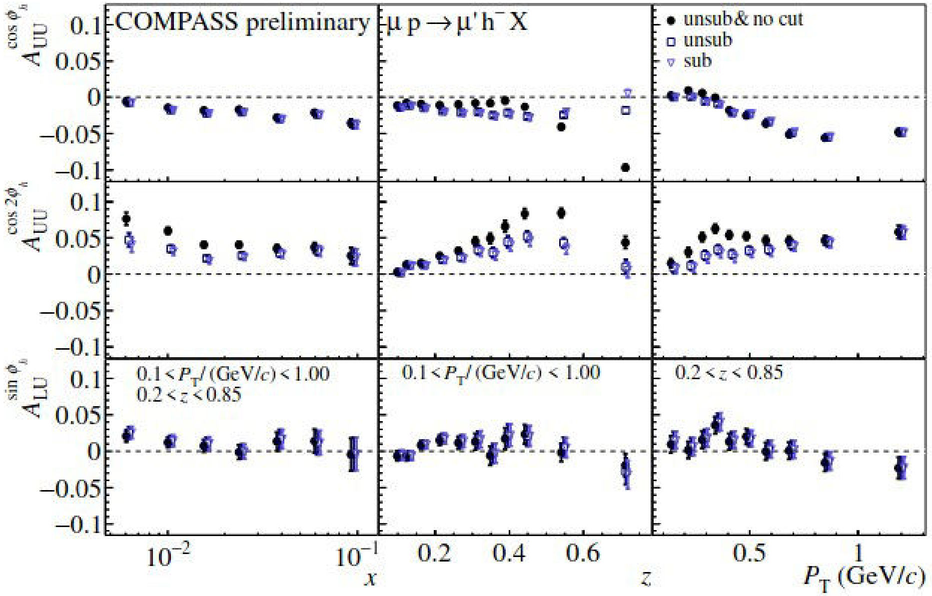
Significant effect of DVM at small x and P_T and at large z.

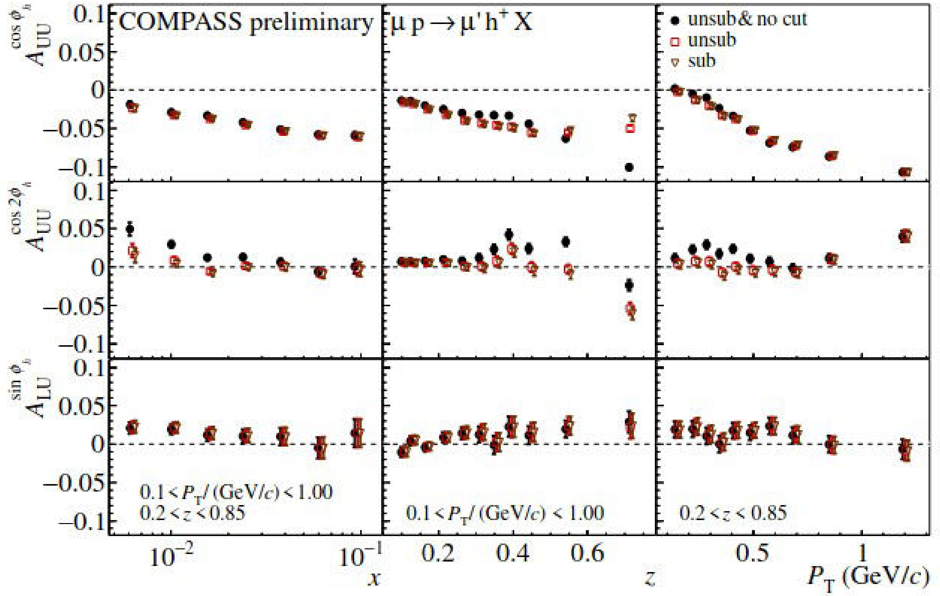
- Ratio of vector mesons in relation to x, in bins of z at a set P_T



[Nucl. Phys. B 956 (2020) 115039]

- Difference in asymmetry extraction before and after DVM correction for h^+ and h^-





[V. Benesová, PoS DIS2024 (2025), 223]

Transversity extraction

From the proton and the deuteron Collins asymmetries the u and d quark transversity functions are extracted as

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

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

$$xh_1^{\bar{u}} = \frac{1}{15}\frac{1}{\tilde{\alpha}_P^h(1-\tilde{\alpha}^2)}\left[(1-4\tilde{\alpha})xf_p^+ A_p^+ + (4-\tilde{\alpha})xf_p^- A_p^- - xf_d^+ A_d^+ + \tilde{\alpha}xf_d^- A_d^-)\right]$$

$$xh_1^{\bar{d}} = \frac{1}{15}\frac{1}{\tilde{\alpha}_P^h(1-\tilde{\alpha}^2)}\left[(4\tilde{\alpha}-1)xf_p^+ A_p^+ - (4-\tilde{\alpha})xf_p^- A_p^- - 4\tilde{\alpha}xf_d^+ A_d^+ + 4xf_d^- A_d^-)\right]$$

where the two alpha terms are constants and f are functions of PDFs.

[Phys. Rev. D 91, 014034 (2015)]

Sivers extraction

From the proton and the deuteron Sivers asymmetries the u and d quark sivers functions are extracted as

$$xf_{1T}^{\perp(1)u} = \frac{1}{5G\rho(1-\beta^{(1)})}\left[(xf_p^+A_p^+ - xf_p^-A_p^-) + \frac{1}{3}(xf_d^+A_d^+ - xf_d^-A_d^-)\right]$$

$$xf_{1T}^{\perp(1)d} = \frac{1}{5G\rho(1-\beta^{(1)})}\left[\frac{4}{3}(xf_d^+A_d^+ - xf_d^-A_d^-) - (xf_p^+A_p^+ - xf_p^-A_p^-)\right]$$

$$xf_{1T}^{\perp(1)\bar{u}} - xf_{1T}^{\perp(1)\bar{d}} = \frac{1}{15G\rho(1-\beta^{(1)2})}\Big[2(1-4\beta^{(1)})xf_p^+A_p^+ + 2(4-\beta^{(1)})xf_p^-A_p^- - (1-4\beta^{(1)})xf_d^+A_d^+ - (4-\beta^{(1)})xf_d^-A_d^-\Big]$$

where G, ρ and β are constants and f are functions of PDFs.

[Phys. Rev. D 95, 094024 (2017)]