Measurements of transverse-momentum dependent effects in semi-inclusive DIS at COMPASS

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MINISTRY OF EDUCATION, YOUTH AND SPORTS

CHARLES UNIVERSITY
Faculty of mathematics and physics

COMPASS

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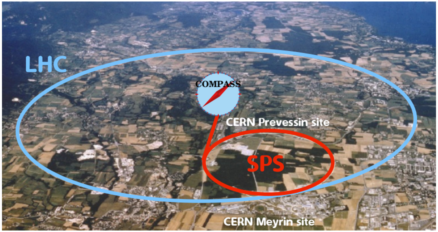
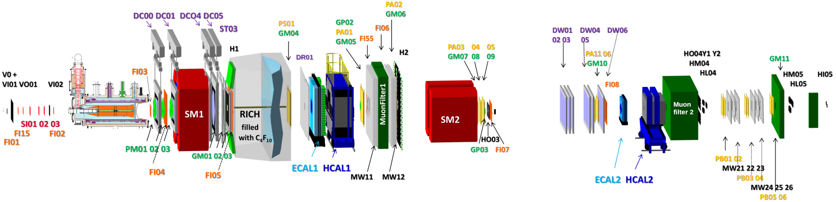
Large research infrastructure grant CERN-CZ from Czech MEYS, and Charles university grant PRIMUS/22/SCI/017.



- Multi-purpose fixed-target setup.
- M2 beamline of CERN's SPS North Area.
- 24 institutes, 13 countries.
- Nearly 200 physicists (2022).
- Taking data 2002–2022 (20 years!)
- Now analysis phase
- Collaboration active, new groups joining.



2022 setup with $^6\mathrm{LiD}^{\uparrow}$ target.

COMPASS: Physics programme

- SIDIS with 160 GeV (200 GeV) μ^+ beam and
  2002–2011 $\overrightarrow{p}$ or $\overrightarrow{d}$ (NH_3 or ^6LiD) targets,
  2002–2022 $p^\uparrow$ or $d^\uparrow$ (NH_3 or ^6LiD) targets,
  2016–2017 unpolarised liquid H_2 target.
  → this talk.

- Hadron spectroscopy and chiral dynamics with hadron beams and nuclear targets
  → New paper on strange meson spectroscopy
  [COMPASS, arXiv: 2504.09470 [hep-ex] (4/2025)].

- Drell–Yan with 190 GeV π^- beam and $p^\uparrow$ (NH_3) and unpolarised Al and W targets.
  → M. Niemiec, Wed. 18:23 (poster) [Indico],
  → Cross-section [V. Andrieux, DIS2024, Grenoble].

- Hard exclusive processes sensitive to GPDs with 160 GeV/c $\mu^\pm$ beam and liquid H_2 target
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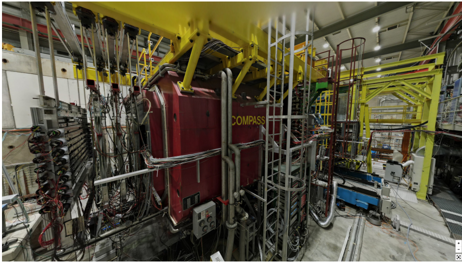

Polarised target refrigerator and MW cavity.

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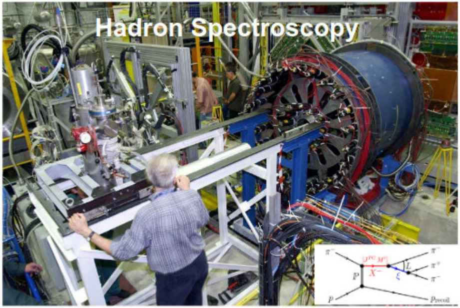

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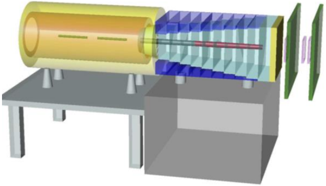

Polarised $NH_3^\uparrow$ target and hadron absorber.

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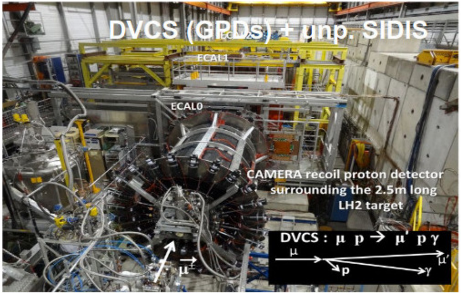
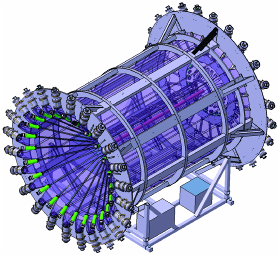
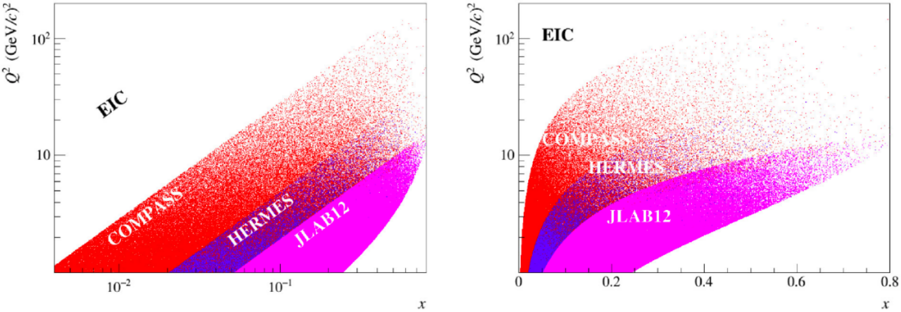




Recoil proton detector CAMERA.

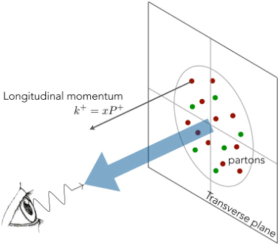
COMPASS: Kinematic coverage for DIS



Complementarity of deep-inelastic scattering experiments
in the coverage in standard variables x and Q^2.

- HERMES 1995–2007, $\sqrt{s} \approx 7.5$ GeV with 27.5 GeV/c $e^{\pm}$ beam and fixed gas targets.
- COMPASS 2002–2022, $\sqrt{s} \approx 17$ GeV with 160 GeV/c muon beam and fixed target.
- JLab12 2014–present, $\sqrt{s} \approx 5$ GeV with 12 GeV/c $e^{\pm}$ beams and fixed targets.
- EIC future, $\sqrt{s} \approx 100$ GeV with $e^{\pm}$ and ion beams.

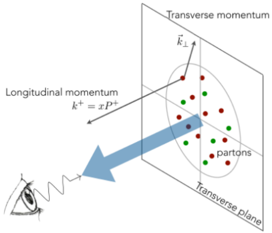
Transverse-momentum-dependent PDFs



Quark polarisation		Parent hadron polarization: Unpolarised	Longitudinal	Transverse
	Unpol.	$f_1(x, k_{\mathrm{T}}^2)$ (unpolarised)		
	Long.		$g_1(x, k_{\mathrm{T}}^2)$ (helicity)	
	Transverse			$h_1(x, k_{\mathrm{T}}^2)$ (transversity)

3 collinear parton distribution functions (PDFs).

Transverse-momentum-dependent PDFs



Quark polarisation	Parent hadron polarization: Unpolarised	Longitudinal	Transverse
Unpol.	$f_1(x, k_T^2)$ (unpolarised)		$f_{1T}^\perp(x, k_T^2)$ (Sivers)
Long.		$g_1(x, k_T^2)$ (helicity)	$g_{1T}(x, k_T^2)$ (Kotzinian–Mulders)
Transverse	$h_1^\perp(x, k_T^2)$ (Boer–Mulders)	$h_{1L}^\perp(x, k_T^2)$ (worm-gear)	$h_1(x, k_T^2)$ (transversity) $h_{1T}^\perp(x, k_T^2)$ (pretzelosity)

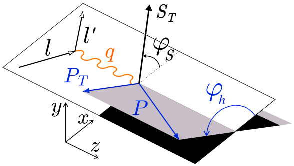
8 leading twist transverse momentum dependent (TMD) PDFs.

Cross-section for
- transversely polarised target ($\boldsymbol{S}_{\mathrm{T}}$) and
- longitudinally polarised beam ($\lambda \approx 0.8$ at COMPASS):

$$
\begin{aligned}
\frac{\mathrm{d}\sigma_{\mathrm{SIDIS}}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi_{\mathrm{S}}\,\mathrm{d}\phi_{\mathrm{h}}\,\mathrm{d}\boldsymbol{P}_{\mathrm{hT}}^2} &= \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right) \\
\times \Bigg\{ & \frac{2-2y+y^2}{2} F_{\mathrm{UU,T}} + (1-y) F_{\mathrm{UU,L}} + (2-y)\sqrt{1-y}\cos\phi_{\mathrm{h}} F_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}} \\
& + (1-y)\cos(2\phi_{\mathrm{h}}) F_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}} + \lambda y\sqrt{1-y}\sin\phi_{\mathrm{h}} F_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}} \\
& + |\boldsymbol{S}_{\mathrm{T}}| \Bigg[\sin(\phi_{\mathrm{h}}-\phi_{\mathrm{S}}) \left(\frac{2-2y+y^2}{2} F_{\mathrm{UT,T}}^{\sin(\phi_{\mathrm{h}}-\phi_{\mathrm{S}})} + (1-y) F_{\mathrm{UT,L}}^{\sin(\phi_{\mathrm{h}}-\phi_{\mathrm{S}})} \right) \\
& \quad + (1-y) \left(\sin(\phi_{\mathrm{h}}+\phi_{\mathrm{S}}) F_{\mathrm{UT}}^{\sin(\phi_{\mathrm{h}}+\phi_{\mathrm{S}})} + \sin(3\phi_{\mathrm{h}}-\phi_{\mathrm{S}}) F_{\mathrm{UT}}^{\sin(3\phi_{\mathrm{h}}-\phi_{\mathrm{S}})} \right) \Bigg] \\
& + \lambda |\boldsymbol{S}_{\mathrm{T}}| \Bigg[\frac{2y-y^2}{2} \cos(\phi_{\mathrm{h}}-\phi_{\mathrm{S}}) F_{\mathrm{LT}}^{\cos(\phi_{\mathrm{h}}-\phi_{\mathrm{S}})} + y\sqrt{1-y}\cos\phi_{\mathrm{S}} F_{\mathrm{LT}}^{\cos\phi_{\mathrm{S}}} \\
& \quad + y\sqrt{1-y}\cos(2\phi_{\mathrm{h}}-\phi_{\mathrm{S}}) F_{\mathrm{LT}}^{\cos(2\phi_{\mathrm{h}}-\phi_{\mathrm{S}})} \Bigg] \Bigg\},
\end{aligned}
$$

Transversely polarised target

Longitudinally polarised beam



Gamma–nuceon system.

TMD factorisation ($P_{\mathrm{T}}/z \ll Q$):

$$
F = \mathcal{C}[wfD] = x \sum_q e_q^2 \int \mathrm{d}^2\boldsymbol{k}_{\mathrm{T}}\,\mathrm{d}^2\boldsymbol{P}_{\perp}\,\delta^{(2)}(z\boldsymbol{k}_{\mathrm{T}} + \boldsymbol{P}_{\perp} - \boldsymbol{P}_{\mathrm{T}})
$$
$$
w(\boldsymbol{k}_{\mathrm{T}}, \boldsymbol{P}_{\perp})\, f^q(x, \boldsymbol{k}_{\mathrm{T}}, Q^2)\, D^{q\to h}(z, \boldsymbol{P}_{\perp}, Q^2)
$$

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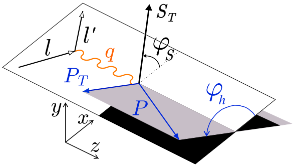
Cross-section for
- transversely polarised target ($\boldsymbol{S}_\mathrm{T}$) and
- longitudinally polarised beam ($\lambda \approx 0.8$ at COMPASS):

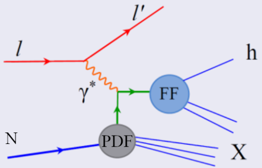
$$\frac{\mathrm{d}\sigma_\mathrm{SIDIS}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi_\mathrm{S}\,\mathrm{d}\phi_\mathrm{h}\,\mathrm{d}\boldsymbol{P}_\mathrm{hT}^2} = \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right) \times \Bigg\{ \frac{2-2y+y^2}{2} F_\mathrm{UU,T} + (1-y)F_\mathrm{UU,L} + (2-y)\sqrt{1-y}\cos\phi_\mathrm{h} F_\mathrm{UU}^{\cos\phi_\mathrm{h}}$$
$$+ (1-y)\cos(2\phi_\mathrm{h}) F_\mathrm{UU}^{\cos 2\phi_\mathrm{h}} + \lambda y\sqrt{1-y}\sin\phi_\mathrm{h} F_\mathrm{LU}^{\sin\phi_\mathrm{h}}$$
$$+ |\boldsymbol{S}_\mathrm{T}|\Bigg[\sin(\phi_\mathrm{h}-\phi_\mathrm{S})\left(\frac{2-2y+y^2}{2} F_\mathrm{UT,T}^{\sin(\phi_\mathrm{h}-\phi_\mathrm{S})} + (1-y) F_\mathrm{UT,L}^{\sin(\phi_\mathrm{h}-\phi_\mathrm{S})}\right)$$
$$+ (1-y)\left(\sin(\phi_\mathrm{h}+\phi_\mathrm{S}) F_\mathrm{UT}^{\sin(\phi_\mathrm{h}+\phi_\mathrm{S})} + \sin(3\phi_\mathrm{h}-\phi_\mathrm{S}) F_\mathrm{UT}^{\sin(3\phi_\mathrm{h}-\phi_\mathrm{S})}\right)\Bigg]$$
$$+ \lambda|\boldsymbol{S}_\mathrm{T}|\Bigg[\frac{2y-y^2}{2}\cos(\phi_\mathrm{h}-\phi_\mathrm{S}) F_\mathrm{LT}^{\cos(\phi_\mathrm{h}-\phi_\mathrm{S})} + y\sqrt{1-y}\cos\phi_\mathrm{S} F_\mathrm{LT}^{\cos\phi_\mathrm{S}}$$
$$+ y\sqrt{1-y}\cos(2\phi_\mathrm{h}-\phi_\mathrm{S}) F_\mathrm{LT}^{\cos(2\phi_\mathrm{h}-\phi_\mathrm{S})}\Bigg]\Bigg\},$$

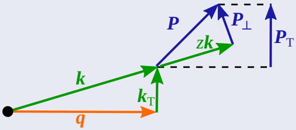
Transversely polarised target

Longitudinally polarised beam



Gamma–nuceon system.





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$$w(k_\mathrm{T}, P_\perp)\, f^q(x, k_\mathrm{T}, Q^2)\, D^{q\to h}(z, P_\perp, Q^2)$$

Structure functions in TMD factorisation

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Unpolarised-target part up to order $1/Q$, and denoting '...' terms vanishing in Wandzura–Wilczek-type approximation:

$$F_{\mathrm{UU,T}} = \mathcal{C}\left[f_1 D_1\right],$$

$$F_{\mathrm{UU,L}} = 0,$$

$$F_{\mathrm{UU}}^{\cos\phi_h} = \frac{2M}{Q}\mathcal{C}\left[\overbrace{-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathrm{T}}}{M} f_1 D_1}^{\text{Cahn effect}} \overbrace{-\frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp})k_{\mathrm{T}}^2}{M^2 M_{\mathrm{h}}} h_1^{\perp} H_1^{\perp}}^{\text{Boer–Mulders effect}} + \ldots\right]$$

$$F_{\mathrm{UU}}^{\cos 2\phi_h} = \mathcal{C}\left[\underbrace{-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathrm{T}})(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp}) - \boldsymbol{k}_{\mathrm{T}}\cdot\boldsymbol{P}_{\perp}}{M M_{\mathrm{h}}} h_1^{\perp} H_1^{\perp}}_{\text{Boer–Mulders effect}}\right]$$

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

- $\hat{\boldsymbol{h}} = \boldsymbol{P}_{\mathrm{T}}/P_{\mathrm{T}}$,
- $f_1(x, k_{\mathrm{T}}^2, Q^2)$

unpolarised TMD PDF,

- $h_1^{\perp}(x, k_{\mathrm{T}}^2, Q^2)$

Boer–Mulders function,

- $D_1(z, P_{\perp}^2, Q^2)$ unpolarised TMD FF,
- $H_1^{\perp}(z, P_{\perp}^2, Q^2)$ Collins FF.
- $h_1(x, k_{\mathrm{T}}^2, Q^2)$ transversity,
- $f_{1\mathrm{T}}^{\perp}(x, k_{\mathrm{T}}^2, Q^2)$ Sivers function.

Transversely-polarised target part at leading twist:

Collins effect: $F_{\mathrm{UT}}^{\sin(\phi_h+\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathrm{T}}}{M_h} h_1 H_1^{\perp}\right]$

Sivers effect: $F_{\mathrm{UT}}^{\sin(\phi_h-\phi_S)} = \mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp}}{M} f_{1\mathrm{T}}^{\perp} D_1\right]$

and many more...

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and many more...

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unpolarised TMD PDF,
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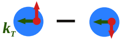

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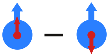
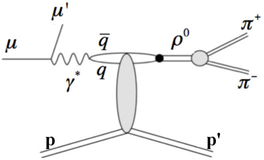


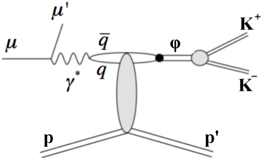
transversity,
- $f_{1\mathrm{T}}^{\perp}(x, k_{\mathrm{T}}^2, Q^2)$

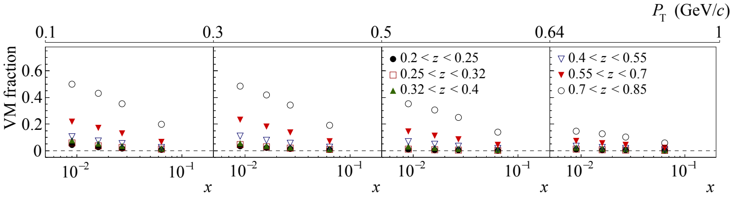
Sivers function.

Background from diffractive vector mesons (DVMs)

- Significant contributors: $\rho \to \pi^+\pi^-$ and $\phi \to K^+K^-$
- Strong x-, z- and P_T-dependence.
- Up to 50% of observed $h^\pm$ at low x, low P_T and high z
  $\to$ Important for multiplicities, cross sections.
- Strong azimuthal modulations for decay products
  $\to$ Important for (unpolarised) asymmetries too!
- Current COMPASS recipe (new H target results):
- Visible decays (both h reconstructed, $\approx 85\%$):
  $\to$ can be rejected in event selection.
- Non-visible decays (only one reconstructed, $\approx 15\%$):
  $\to$ can be simulated and subtracted by HEPGEN MC
  [A. Sandacz, P. Sznajder, arXiv:1207.0333]







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

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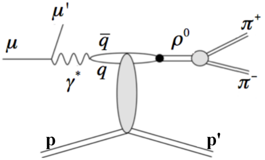
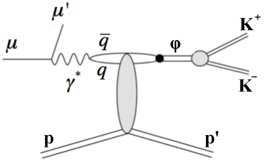
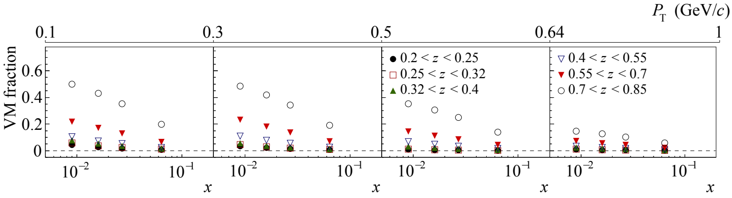


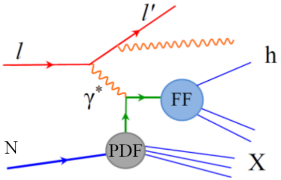




[COMPASS, Nucl.Phys.B 956 (2020) 115039]

TMD interpretation defined at tree level
→ QED radiative effects need to be accounted for:

- radiation of photons along the ℓ, ℓ' and γ^*,
  → changes in x, Q^2, tail from elastic scattering,
  → orientation of γ–nucleon system distorted.
- Our approach before 2024:
  - Only 'inclusive corrections',
  - based on TERAD (semi-analytical)
    [A.A. Akhundov *et al.*, Fortschr. Phys. 44 (1996) 373]
- New approach:
  - Based on DJANGOH Monte Carlo
    [K. Charchula, G.A. Schuler, H. Spiesberger, Comput. Phys. Commun. 81 (1994) 381–402]
  - Takes into account:
    → hadron phase space,
    → z-, P_{T}- and ϕ_h-dependences.

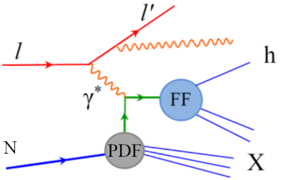


Example of a real photon emission.

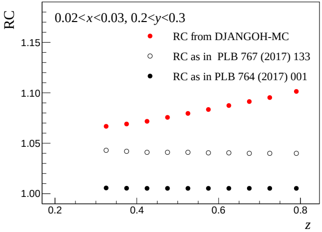
QED radiative corrections

TMD interpretation defined at tree level
→ QED radiative effects need to be accounted for:

- radiation of photons along the ℓ, ℓ' and γ^*,
  → changes in x, Q^2, tail from elastic scattering,
  → orientation of γ–nucleon system distorted.
- Our approach before 2024:
  - Only 'inclusive corrections',
  - based on TERAD (semi-analytical)
    [A.A. Akhundov *et al.*, Fortschr. Phys. 44 (1996) 373]
- New approach:
  - Based on DJANGOH Monte Carlo
    [K. Charchula, G.A. Schuler, H. Spiesberger, Comput. Phys. Commun. 81 (1994) 381–402]
  - Takes into account:
    → hadron phase space,
    → z-, P_{T}- and ϕ_h-dependences.



Example of a real photon emission.



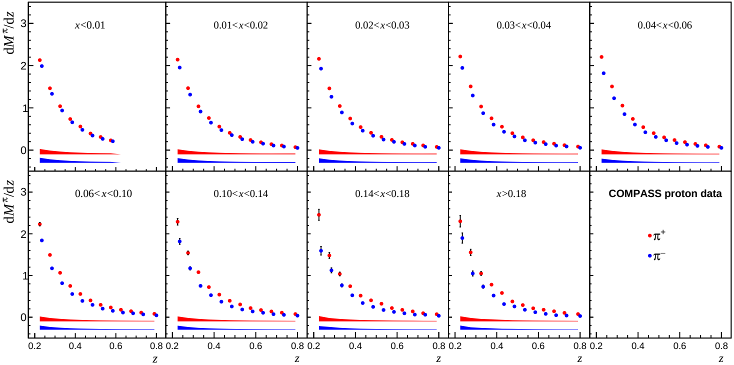
Comparison of the old and new RC for π^+ multiplicity in a bin in x and y, where $\mathrm{RC} = \frac{M^h_{\mathrm{rad.OFF}}}{M^h_{\mathrm{rad.ON}}}$.

Collinear hadron multiplicities

- Sensitive to fragmentation functions $D_1^{q\to h}(z,y)$, including $q/\bar{q}$ and flavour separation.

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

- Corrected for acceptance, diffractive VMs and for radiative effects.
- Previous results on isoscalar target:
  $h^\pm, \pi^\pm$ [COMPASS, Phys. Lett. B 764 (2017) 001], $K^\pm$ [COMPASS, Phys. Lett. B 767 (2017) 133].
- New results on H_2 target [COMPASS, Phys. Rev. D 112 (2025) 1, 012002]



Example: Multiplicity of charged pions in bins of x and z.

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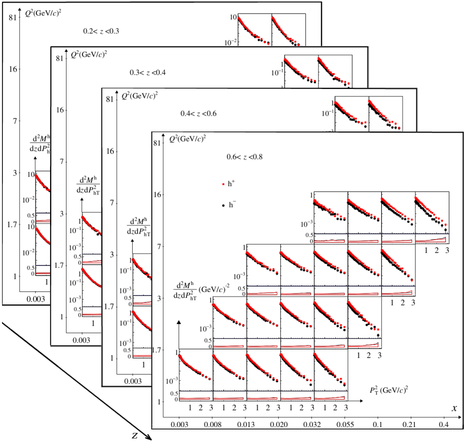
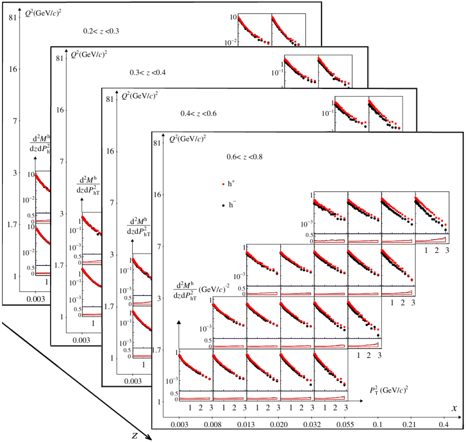
P_{T}-dependent multiplicities on isoscalar target



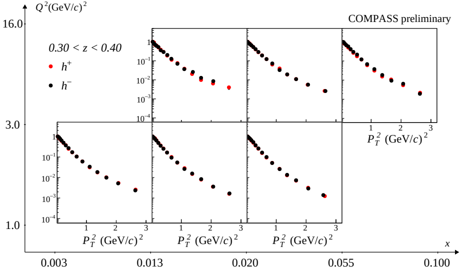
- Results in bins of $x, Q^2, z, P_{\mathrm{T}}^2$
- DVM contamination subtracted.
- Radiative corrections based on RADGEN.
- [Compass, Phys.Rev.D97 (2018)]

P_{T}-dependent multiplicities on isoscalar target



- Results in bins of $x, Q^2, z, P_{\mathrm{T}}^2$
- DVM contamination subtracted.
- Radiative corrections based on RADGEN.
- [COMPASS, Phys.Rev.D97 (2018)]

P_{T}-dependent distributions on H_2 target (2016 data)



Preliminary results, DVM contamination subtracted, no RC [A. Moretti, Proc. of ICNFP 2020].

Ongoing work:

- Expanding kinematic domain.
- New radiative corrections using DJANGOH. [V. Benešová, IWHSS–CPHI 2024, 30.9.–4.10. 2024, Yerevan, Armenia]

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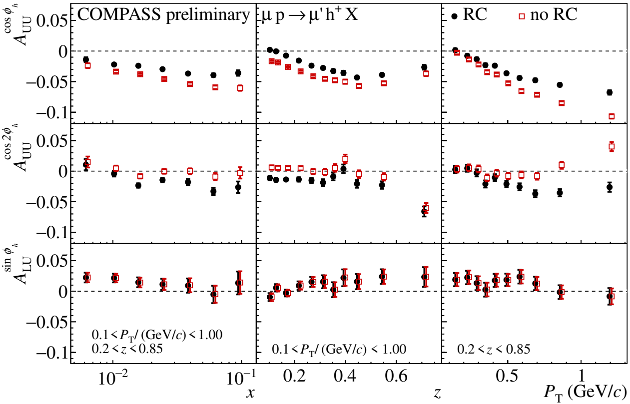
Results from isoscalar target (2004 data, no RC, no DVM corr.): [COMPASS, Nucl.Phys.B 886 (2014)]
Corrections for diffractive vector mesons: [COMPASS, Nucl.Phys.B 956 (2020)]
New preliminary results on H_2 target (2016 data): [V. Benešová, PoS DIS2024 (2025), 223]

- Both DVM and RC based on DJANGOH (→ new, important!).
- 1D and multi-D results in preparation for publication.



The impact of DJANGOH radiative corrections on h^+.

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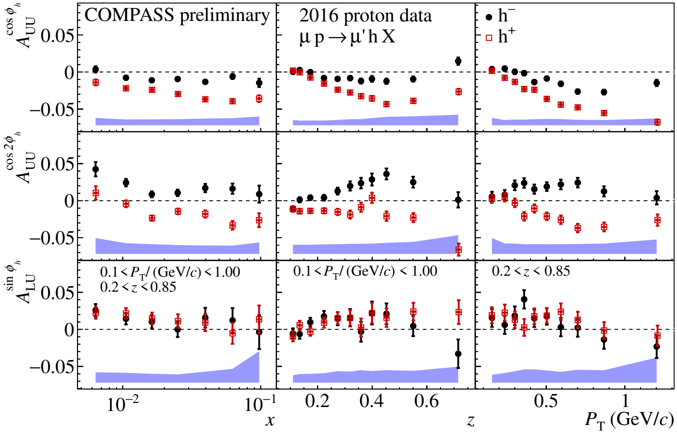


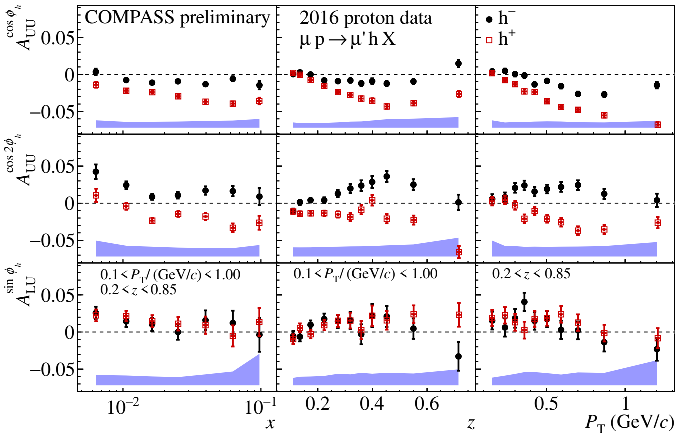
[V. Benešová, PoS DIS2024 (2025), 223]

Unpolarised-target part up to order $1/Q$ and in Wandzura–Wilczek-type approximation:

$$A_{\mathrm{XX}}^{f(\phi_h)} = \frac{F_{\mathrm{XX}}^{f(\phi_h)}}{F_{\mathrm{UU,T}}} = \frac{F_{\mathrm{XX}}^{f(\phi_h)}}{\mathcal{C}\,[f_1 D_1]}$$

$$F_{\mathrm{UU}}^{\cos\phi_h} = \frac{2M}{Q}\,\mathcal{C}\left[-\overbrace{\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}}}{M} f_1 D_1}^{\text{Cahn effect}} - \overbrace{\frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp})k_{\mathrm{T}}^2}{M^2 M_{\mathrm{h}}} h_1^{\perp} H_1^{\perp}}^{\text{Boer–Mulders effect}} + \ldots \right]$$

Unpolarised and beam-spin asymmetries



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

Unpolarised-target part up to order $1/Q$ and in Wandzura–Wilczek-type approximation:

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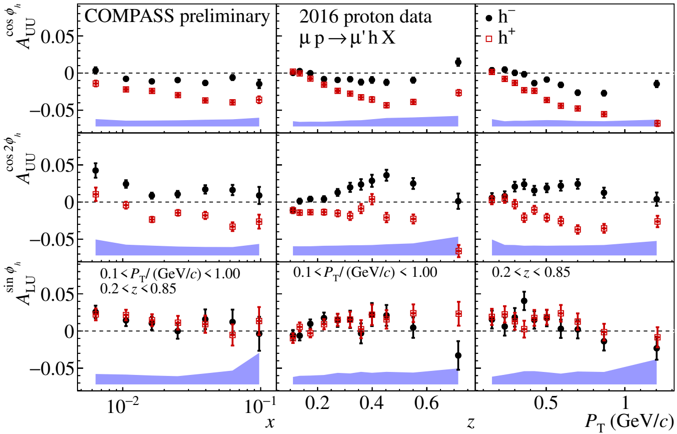
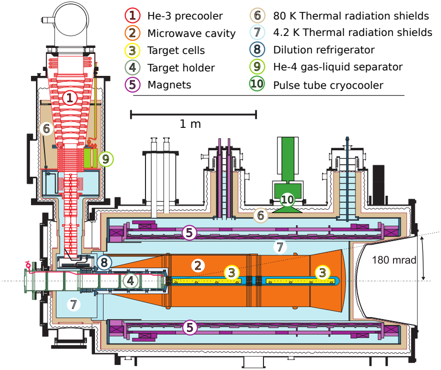


[V. Benešová, PoS DIS2024 (2025), 223]

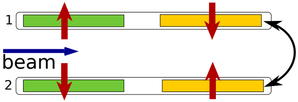
Unpolarised-target part up to order $1/Q$ and in Wandzura–Wilczek-type approximation:

$$A_{\mathrm{XX}}^{f(\phi_h)} = \frac{F_{\mathrm{XX}}^{f(\phi_h)}}{F_{\mathrm{UU,T}}} = \frac{F_{\mathrm{XX}}^{f(\phi_h)}}{\mathcal{C}\left[f_1 D_1\right]} \qquad F_{\mathrm{LU}}^{\sin\phi_h} = \frac{2M}{Q}\mathcal{C}\left[\text{pure twist-3 qgq terms}\right]$$



Polarised target system (2015).

- Large-acceptance superconducting magnet.
- Dilution refrigerator to reach below 100 mK.
- Dynamic nuclear polarisation with microwaves.
- NMR for polarisation measurement.



Measurement method

- 2 (3) target cells,
- alternating polarisation
- → azimuthal acceptance is cancelled.

DVM and radiative effects

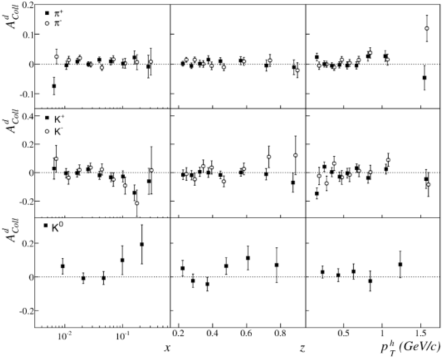
- not sensitive to polarisation,
- DVMs: small effect,
- RC taken into account in the dilution factor (TERAD-based).

1st COMPASS measurement of transverse spin asymmetries:

- $d^{\uparrow}$ in ^{6}LiD target, data taking 2002–2004.
- Both Collins and Sivers asymmetries compatible with zero (unlike HERMES on $p^{\uparrow}$).

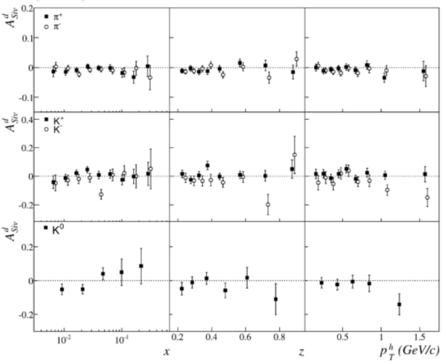
Collins asymmetry

$$A_{UT}^{\sin(\phi_h+\phi_S)} = \frac{F_{UT}^{\sin(\phi_h+\phi_S)}}{F_{UU}} = \frac{\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}}}{M_h} h_1 H_1^{\perp}\right]}{\mathcal{C}\left[f_1 D_1\right]}$$

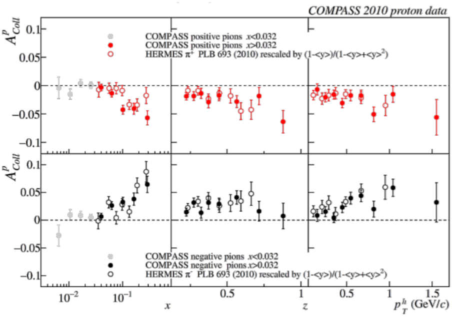


Sivers asymmetry

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{F_{UT}^{\sin(\phi_h-\phi_S)}}{F_{UU}} = \frac{\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_{\perp}}{M} f_{1T}^{\perp} D_1\right]}{\mathcal{C}\left[f_1 D_1\right]}$$



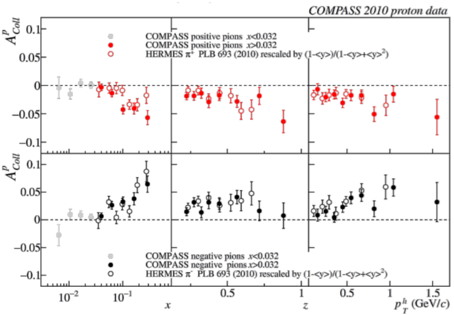
[COMPASS, Phys. Lett. B 673 (2009) 127]



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

- $p^{\uparrow}$ in NH_3 target, data taking 2007–2010.
- Collins asymmetries non-zero.
- Compatible with HERMES.
- Number of global extractions,
- d-quark not well constrained.
- Deuteron is necessary, only COMPASS measured on $d^{\uparrow}$.

Transverse-spin asymmetries: Transversity and Collins effect



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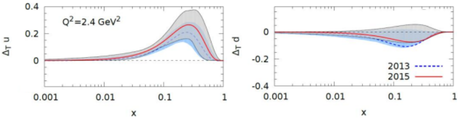
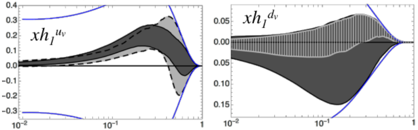
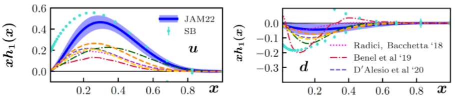


[Anselmino et al., Phys. Rev. D 92 (2015)]



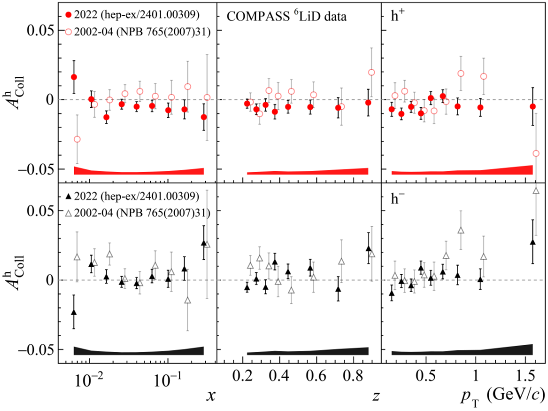
[M. Radici, A. Bacchetta, Phys. Rev. Lett. 120 (2018)]



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

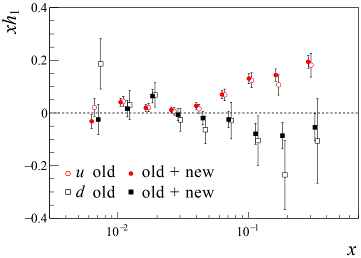
Transverse-spin asymmetries: New Collins on deuteron

Charles University



Collins asymmetries on d$^\uparrow$: old and new (2022) data.

$$A_{UT}^{\sin(\phi_h+\phi_S)} = \frac{\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M_h} h_1 H_1^\perp\right]}{\mathcal{C}\left[f_1 D_1\right]}$$



Point-by-point extraction to show the expected impact.

Looking forward to global fits!

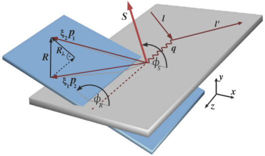
See the new paper [COMPASS, Phys. Rev. Lett. 133 (2024) 10, 101903]

Transverse-spin asymmetries: Dihadrons

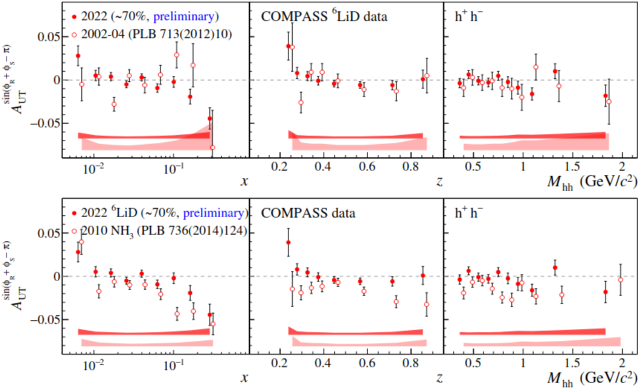
Collinear way to access transversity (no TMD factorisation) [M. Radici *et al.*, Phys. Rev. D 65 (2002)]

$$\frac{\mathrm{d}^7\sigma}{\mathrm{d}\cos\theta\,\mathrm{d}M_{\mathrm{hh}}\,\mathrm{d}\phi_{\mathrm{R}}\,\mathrm{d}z\,\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}\phi_{\mathrm{S}}} = \frac{\alpha^2}{2\pi Q^2 y}\Bigg(\Big(1-y+\frac{y^2}{2}\Big)\sum_q e_q^2\; f_1^q(x)\; D_{1,q}(z, M_{\mathrm{hh}}^2, \cos\theta) + S_\perp(1-y)\sum_q e_q^2 \frac{|\mathbf{p}_1-\mathbf{p}_2|}{2M_{\mathrm{hh}}}\sin\theta\;\sin\phi_{RS}\; \underbrace{h_1^q(x)}_{\text{transversity PDF}}\; \underbrace{H_{1,q}^{\sphericalangle}(z, M_{\mathrm{hh}}^2, \cos\theta)}_{\text{dihadron FF (interference FF)}}\Bigg)$$

COMPASS proton results are available [COMPASS, Phys. Lett. B 736 (2014)]



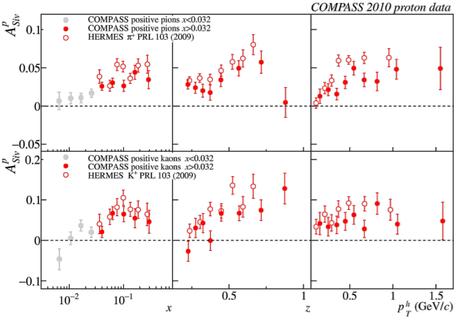
Definition of the angles in the gamma–nucleon system.



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

Transverse-spin asymmetries: Sivers effect

$$A_{UT}^{\sin(\phi_h - \phi_S)} = \frac{\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp}{M} f_{1T}^{\perp} D_1\right]}{\mathcal{C}\left[f_1 D_1\right]}$$

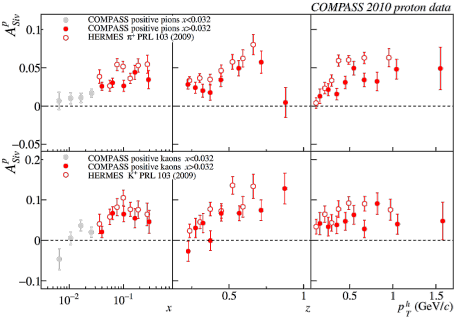


[COMPASS, Phys. Lett. B 774 (2015) 250]

- $p^{\uparrow}$ in NH_3 target, data taking 2007–2010.
- Nonzero, smaller than HERMES.
- Number of global extractions.
- Again, unique role of COMPASS in providing deuteron data.

Transverse-spin asymmetries: Sivers effect

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp}{M} f_{1T}^{\perp} D_1\right]}{\mathcal{C}\left[f_1 D_1\right]}$$



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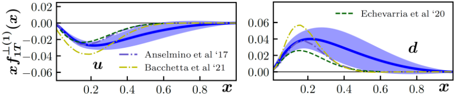
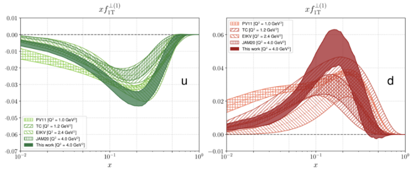
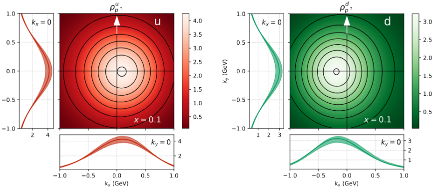


[JAM, Phys. Rev. D 106 (2022)]

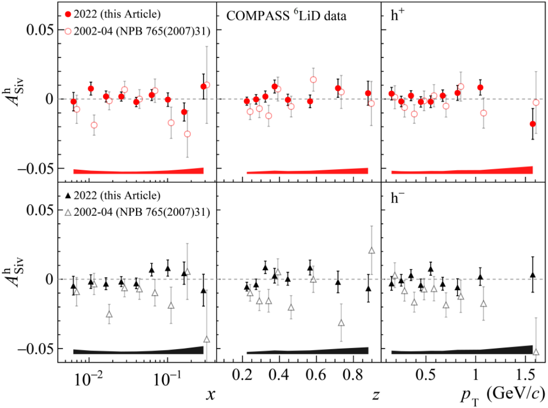


Distortion in the transverse plane of the TMD quark distribution in a $p^\uparrow$

$$\Phi^{[\gamma^+]}_{q/p^\uparrow}(x,k_x,k_y) = f_1^q(x,k_T^2) - \frac{k_x}{M} f_{1T}^{\perp q}(x,k_T^2) \qquad [Q^2 = 4\ \mathrm{GeV}^2]$$

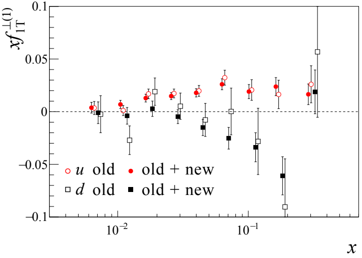


[A. Bacchetta *et al.*, Phys. Lett. B 827 (2022)]



Sivers asymmetries on d$^{\uparrow}$: old and new (2022) data.

$$A_{UT}^{\sin(\phi_h-\phi_S)} = \frac{\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp}{M} f_{1T}^{\perp} D_1\right]}{\mathcal{C}\left[f_1 D_1\right]}$$



Point-by-point extraction to show the expected impact.

Looking forward to global fits!

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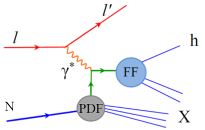
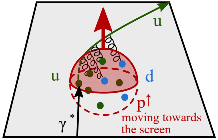


Pion production in DIS off $p^{\uparrow}$



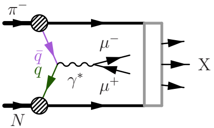
Sivers effect in SIDIS
[M. Burkardt, Nucl. Phys. A735 (2004)].

A change of sign predicted for Sivers and Boer–Mulders TMD PDFs due to gauge link structure:

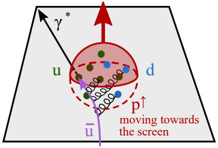
$$f_{1T}^{\perp q}\big|_{\mathrm{SIDIS}} = -f_{1T}^{\perp q}\big|_{\mathrm{DY}}$$

$$h_1^{\perp q}\big|_{\mathrm{SIDIS}} = -h_1^{\perp q}\big|_{\mathrm{DY}}$$

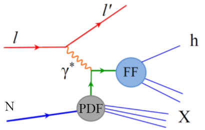
[J. Collins, Phys.Lett. B536 (2002) 43]



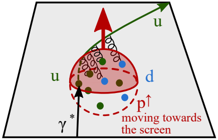
Pion–$p^{\uparrow}$ Drell–Yan



Sivers effect in Drell–Yan drawn in the same manner.



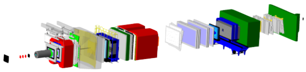
Pion production in DIS off p$^\uparrow$



Sivers effect in SIDIS

[M. Burkardt, Nucl. Phys. A735 (2004)].

COMPASS 2007 + 2010 data



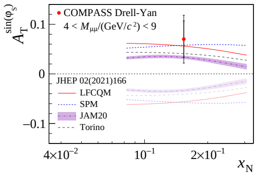
Very close Q^2 range to COMPASS Drell–Yan, the same apparatus.

A change of sign predicted for Sivers and Boer–Mulders TMD PDFs due to gauge link structure:

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

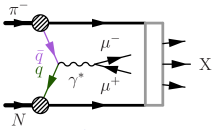
$$h_1^{\perp q}|_{\text{SIDIS}} = -h_1^{\perp q}|_{\text{DY}}$$

[J. Collins, Phys.Lett. B536 (2002) 43]

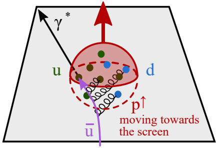


Data favour the change.

[COMPASS, Phys. Rev. Lett. 133 (2024) 7, 071902]

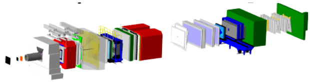


Pion–p$^\uparrow$ Drell–Yan



Sivers effect in Drell–Yan drawn in the same manner.

COMPASS 2015 + 2018 data



Weighted asymmetry approach: M. Niemiec, Wed. 18:23 (poster)

[Indico].

Conclusion

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- COMPASS entered analysis phase, but still very active.
- Plenty of results to come!
- Recent results in semi-inclusive DIS:
  - Multiplicities of $h^{\pm}$, $\pi^{\pm}$, $K^{\pm}$ on H_2 with new RC [COMPASS, Phys. Rev. D 112 (2025) 1, 012002]
  - Sivers and Collins asymmetries on $d^{\uparrow}$ [COMPASS, Phys. Rev. Lett. 133 (2024) 10, 101903],
- Ongoing work in semi-inclusive DIS:
  - Unpolarised asymmetries on H_2 with new RC [V. Benešová, PoS DIS2024 (2025), 223]
  - P_T-dependent distributions on H_2 with new RC.
  - Transversity-induced dihadron asymmetry [A. Asatryan, PoS DIS2024 (2025), 236]
  - Other transverse spin asymmetries on $d^{\uparrow}$.
  - Multi-dimensional analyses of $d^{\uparrow}$ data...
- Other selected highlights:
  - Strange meson spectroscopy [COMPASS, arXiv: 2504.09470 [hep-ex] (4/2025)].
  - Drell–Yan weighted asymmetries [M. Niemiec, Wed. 18:23 (poster)].
  - Drell–Yan multi-D cross-section [V. Andrieux, DIS2024, Grenoble, France, 4/2024].
  - Hard exclusive π^0 muoproduction [COMPASS, arXiv: 2412.19923 [hep-ex] (12/2024)]

Thank you for your attention!

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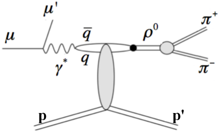
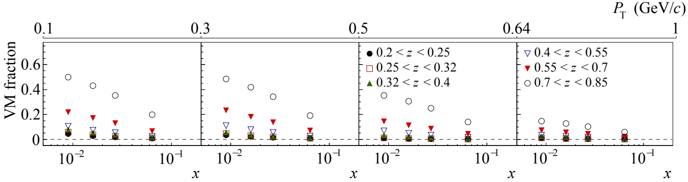
Thank you for your attention!

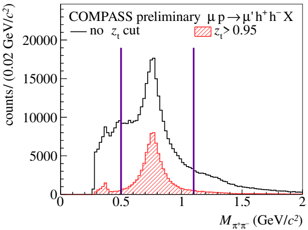
Backup: Background from diffractive vector mesons

Significant contributors: $\rho \to \pi^+\pi^-$ and $\phi \to K^+K^-$



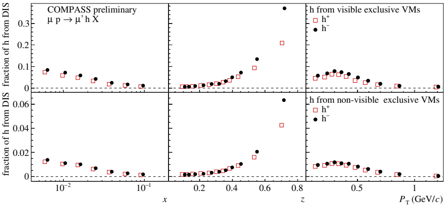


[COMPASS, Nucl.Phys.B 956 (2020) 115039]

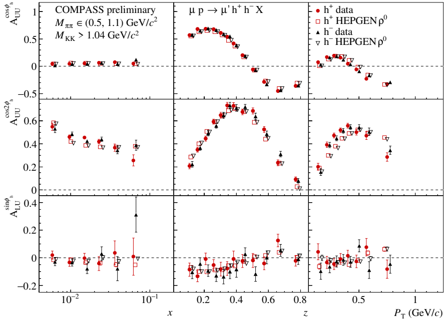


- Strong x-, z- and P_T-dependence.
- Up to 50% of observed $h^{\pm}$ at low x, low P_T and high z
  → Important for multiplicities, cross sections.
- Strong azimuthal modulations for decay products
  → Important for (unpolarised) asymmetries too!
- Visible decays (both h reconstructed):
  → can be rejected in event selection.
- Non-visible decays (only one reconstructed):
  → can be simulated and subtracted by HEPGEN MC
  [A. Sandacz, P. Sznajder, arXiv:1207.0333]

Backup: Background from diffractive vector mesons



Visible and non-visible contamination in bins of 1D asymmetries.



Modulations can be reasonably reproduced by HEPGEN MC.

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

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COMPASS

TMD interpretation defined at tree level
→ QED radiative effects need to be accounted for:

- radiation of photons along the ℓ, ℓ' and γ^*,
  → changes in x, Q^2, tail from elastic scattering,
  → orientation of γ–nucleon system distorted.
- Our approach before 2024:
  - Only 'inclusive corrections',
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    [A.A. Akhundov *et al.*, Fortschr. Phys. 44 (1996) 373]

New approach based on DJANGOH (DJANGO6) MC:

- [K. Charchula, G.A. Schuler, H. Spiesberger, Comput. Phys. Commun. 81 (1994) 381–402]
- Updated recently
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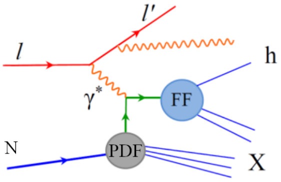
- Hadron phase space, z-, P_{T}- and ϕ_h-dependences taken into account



Example of a real photon emission.

Backup: QED radiative corrections

Charles University

COMPASS

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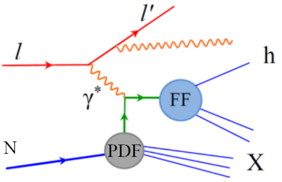

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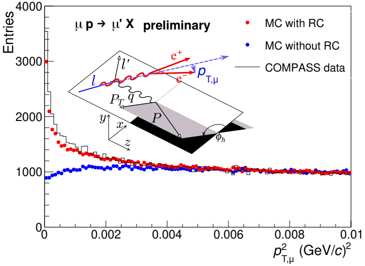

Example: DJANGOH reproduces e$^{\pm}$ from radiative γ in COMPASS data.

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COMPASS

- The multiplicities are corrected for acceptance, diffractive VMs and for radiative effects.

$$\frac{\mathrm{d}M^h(x,y,z)}{\mathrm{d}z} = \frac{\mathrm{d}M^h_{\mathrm{raw}}(x,y,z)}{\mathrm{d}z}\,\frac{C_{\mathrm{VM}}(x,y,z)\mathrm{RC}(x,y,z)}{a(x,y,z)} = \frac{F_{\mathrm{UU}}(x,y,z)}{F_2(x,y)}$$

$$\mathrm{RC} = \frac{M^h_{\mathrm{rad.OFF}}}{M^h_{\mathrm{rad.ON}}} = \frac{N^{\mathrm{DIS}}_{h,\mathrm{rad.OFF}}}{N^{\mathrm{DIS}}_{\mathrm{events,rad.OFF}}} \Big/ \frac{N^{\mathrm{DIS}}_{h,\mathrm{rad.ON}}}{N^{\mathrm{DIS}}_{\mathrm{events,rad.ON}}}$$

- Sensitive to fragmentation functions $D_q^h(z,Q^2)$, including $q/\bar{q}$ and flavour separation.
- Previous results – TERAD corrections:
  - No explicit z-dependence.
  - [Phys. Lett. B 764 (2017) 001] ($h^\pm, \pi^\pm$).
  - [Phys. Lett. B 767 (2017) 133] ($K^\pm$),
- New RC from DJANGOH:
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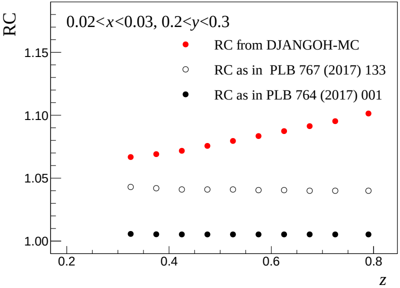
  - New paper: [COMPASS, Phys. Rev. D 112 (2025) 1, 012002]
- Diference up to 15% in certain bins.
- Publication of the new corrections for the old d results is foreseen.



Example: comparison of the old and new RC for π^+ in a given bin in x and y.

Backup: Collinear hadron multiplicities

- The multiplicities are corrected for acceptance, diffractive VMs and for radiative effects.

$$\frac{\mathrm{d}M^h(x,y,z)}{\mathrm{d}z} = \frac{\mathrm{d}M^h_{\mathrm{raw}}(x,y,z)}{\mathrm{d}z}\,\frac{C_{\mathrm{VM}}(x,y,z)\mathrm{RC}(x,y,z)}{a(x,y,z)} = \frac{F_{UU}(x,y,z)}{F_2(x,y)}$$

$$\mathrm{RC} = \frac{M^h_{\mathrm{rad.OFF}}}{M^h_{\mathrm{rad.ON}}} = \frac{N^{\mathrm{DIS}}_{h,\mathrm{rad.OFF}}}{N^{\mathrm{DIS}}_{\mathrm{events,rad.OFF}}} \Bigg/ \frac{N^{\mathrm{DIS}}_{h,\mathrm{rad.ON}}}{N^{\mathrm{DIS}}_{\mathrm{events,rad.ON}}}$$

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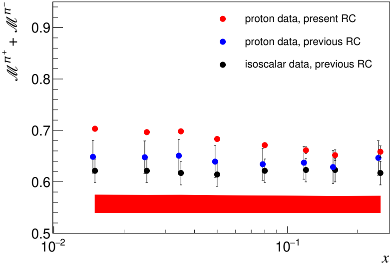

Comparison of COMPASS pion multiplicities.

- The multiplicities are corrected for acceptance, diffractive VMs and for radiative effects.

$$\frac{\mathrm{d}M^h(x,y,z)}{\mathrm{d}z} = \frac{\mathrm{d}M^h_{\mathrm{raw}}(x,y,z)}{\mathrm{d}z}\,\frac{C_{\mathrm{VM}}(x,y,z)\mathrm{RC}(x,y,z)}{a(x,y,z)} = \frac{F_{\mathrm{UU}}(x,y,z)}{F_2(x,y)}$$

$$\mathrm{RC} = \frac{M^h_{\mathrm{rad.OFF}}}{M^h_{\mathrm{rad.ON}}} = \frac{N^{\mathrm{DIS}}_{h,\mathrm{rad.OFF}}}{N^{\mathrm{DIS}}_{\mathrm{events,rad.OFF}}} \Bigg/ \frac{N^{\mathrm{DIS}}_{h,\mathrm{rad.ON}}}{N^{\mathrm{DIS}}_{\mathrm{events,rad.ON}}}$$

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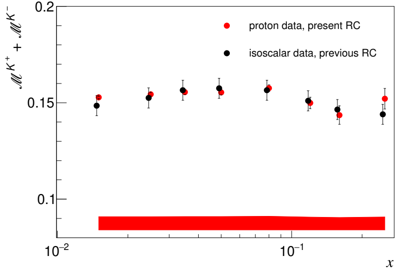
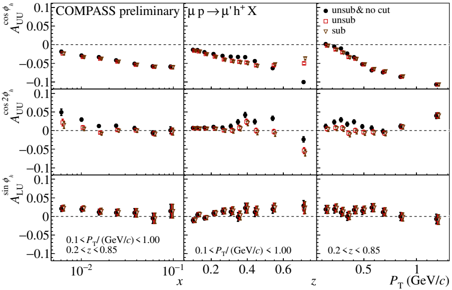


Comparison of COMPASS kaon multiplicities.

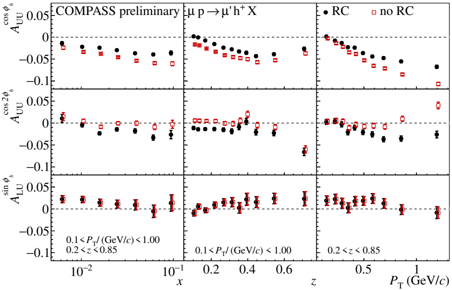
Backup: Unpolarised and beam-spin asymmetries

Results from isoscalar target (2004 data): [COMPASS, Nucl.Phys.B 886 (2014)]
Corrections for diffractive vector mesons: [COMPASS, Nucl.Phys.B 956 (2020)]

New preliminary results on H_2 target (2016 data): [V. Benešová, PoS DIS2024 (2025), 223]



Impact of DVM rejection and subtraction.



Impact of DJANGOH radiative corrections.

Ongoing work, 1D and multi-D results in preparation for publication.
Feasibility studies for π^0 reconstruction and $\pi^\pm/K^\pm$ identification with RICH.

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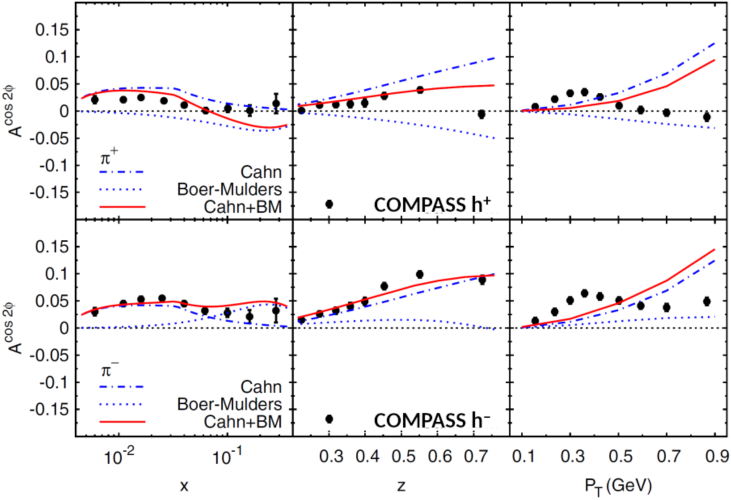
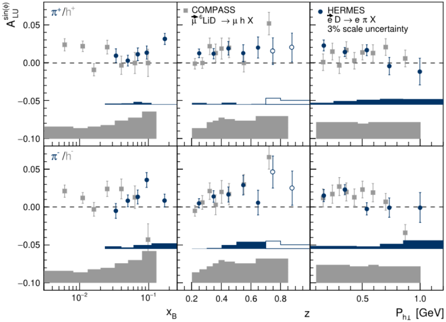
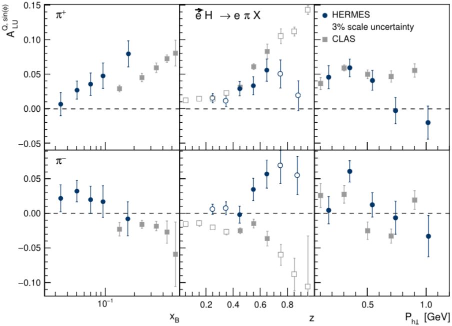


COMPASS $A_{UU}^{\cos 2\phi_h}$ for $h^{\pm}$ on isoscalar target (no RC, no DVM corr.)
[COMPASS, Nucl.Phys.B886 (2014) 1046–1077],
fitted [V. Barone *et al.*, Phys.Rev.D91 (2015) 074019].



Beam-spin asymmetry at HERMES and COMPASS.



Beam-spin asymmetry at HERMES and CLAS.

[HERMES, Phys.Lett.B 797 (2019) 134886]

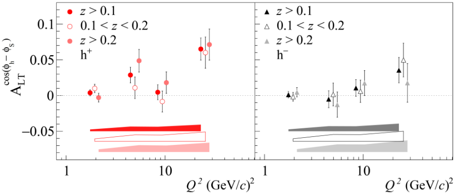
Other transverse spin asymmetries

$$
\begin{aligned}
\frac{\mathrm{d}\sigma_{\mathrm{SIDIS}}}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi_S\,\mathrm{d}\phi_h\,\mathrm{d}\boldsymbol{P}_{hT}^2} &= \frac{\alpha^2}{xyQ^2}\left(1+\frac{\gamma^2}{2x}\right) \\
\times \Bigg\{ & \frac{2-2y+y^2}{2} F_{UU,T} + (1-y) F_{UU,L} + (2-y)\sqrt{1-y}\cos\phi_h F_{UU}^{\cos\phi_h} \\
& + (1-y)\cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda y\sqrt{1-y}\sin\phi_h F_{LU}^{\sin\phi_h} \\
& + |\boldsymbol{S}_T| \Bigg[\sin(\phi_h-\phi_S)\left(\frac{2-2y+y^2}{2} F_{UT,T}^{\sin(\phi_h-\phi_S)} + (1-y) F_{UT,L}^{\sin(\phi_h-\phi_S)}\right) \\
& \quad + (1-y)\left(\sin(\phi_h+\phi_S) F_{UT}^{\sin(\phi_h+\phi_S)} + \sin(3\phi_h-\phi_S) F_{UT}^{\sin(3\phi_h-\phi_S)}\right)\Bigg] \\
& + \lambda|\boldsymbol{S}_T| \Bigg[\frac{2y-y^2}{2}\cos(\phi_h-\phi_S) F_{LT}^{\cos(\phi_h-\phi_S)} + y\sqrt{1-y}\cos\phi_S F_{LT}^{\cos\phi_S} \\
& \quad + y\sqrt{1-y}\cos(2\phi_h-\phi_S) F_{LT}^{\cos(2\phi_h-\phi_S)} \Bigg] \Bigg\},
\end{aligned}
$$

Transversely polarised target

Longitudinally polarised beam

E.g. Kotzinian–Mulders asymmetry:



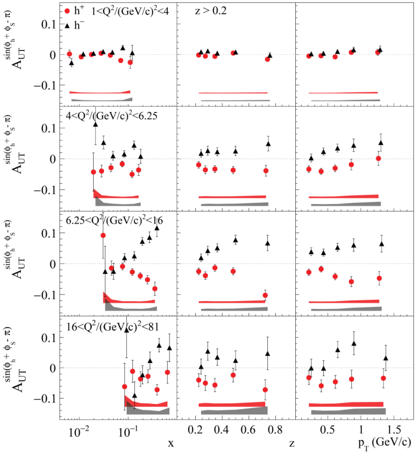
Asymmetry on p↑

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

$$A_{LT}^{\sin(\phi_h-\phi_S)} = \frac{\mathcal{C}\left[\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T}{M} g_{1T} D_1\right]}{\mathcal{C}\left[f_1 D_1\right]}$$

Multi-dimensional studies

E.g. Q^2 dependence of Collins asymmetry:



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

Unpolarised measurements, J/ψ production...