Unpolarised Semi-Inclusive DIS at COMPASS

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On behalf of the COMPASS collaboration

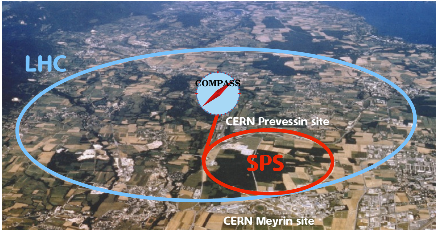
26. 9. 2023,
25th International Spin Symposium (SPIN 2023)
Duke University, Durham, North Carolina, USA

CHARLES UNIVERSITY
Faculty of mathematics
and physics

PRIMUS

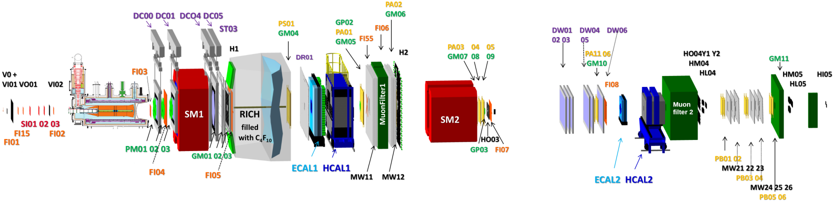
COMPASS

COMPASS:



- M2 beamline of CERN's SPS.
- 24 institutes, 13 countries.

- SIDIS with 160 GeV (200 GeV) μ^+ beam and longitudinally/transversely-polarised proton (NH_3) or deuteron (^{6}LiD) target
  A. Martin (Wed, TMDs),
  G. Reicherz (Wed, Polarised targets),
  B Parsamyan (Thu, plenary)
- Hadron spectroscopy with hadron beams and nuclear targets.
- Drell–Yan with 190 GeV π^- beam and $p^\uparrow$ (NH_3), Al, W targets.
  V. Andrieux (Wed, TMDs),
  A. Vijayakumar (poster).
- Hard exclusive processes and SIDIS with 160 GeV/c $\mu^\pm$ beam and liquid H_2 target.
  This talk and DVCS/DVMP on Mon in GPDs.



2022 setup with ^{6}LiD$^\uparrow$ target: Experiments concluded, now in analysis phase.

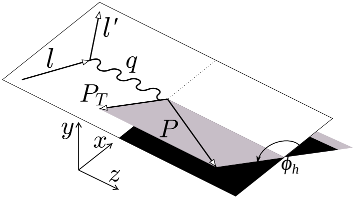
Hadron production DIS

The cross section for producing a hadron h in DIS on unpolarised target $\ell\mathrm{N} \rightarrow \ell'\mathrm{hX}$:
[A. Bacchetta *et al.*, JHEP 0702 (2007)]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\,\mathrm{d}y\,\mathrm{d}z\,\mathrm{d}\phi_\mathrm{h}\,\mathrm{d}P_\mathrm{T}^2} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{2xM^2}{Q^2}\right)\Big(F_{\mathrm{UU,T}} + \varepsilon F_{\mathrm{UU,L}} + \sqrt{2\varepsilon(1+\varepsilon)}F_{\mathrm{UU}}^{\cos\phi_\mathrm{h}}\cos\phi_\mathrm{h} + \varepsilon F_{\mathrm{UU}}^{\cos 2\phi_\mathrm{h}}\cos 2\phi_\mathrm{h} + \lambda\sqrt{2\varepsilon(1-\varepsilon)}F_{\mathrm{LU}}^{\sin\phi_\mathrm{h}}\sin\phi_\mathrm{h}\Big)$$

$$= \sigma_0\left(1 + \varepsilon_1 A_{\mathrm{UU}}^{\cos\phi_\mathrm{h}}\cos\phi_\mathrm{h} + \varepsilon_2 A_{\mathrm{UU}}^{\cos 2\phi_\mathrm{h}}\cos 2\phi_\mathrm{h} + \lambda\varepsilon_3 A_{\mathrm{LU}}^{\sin\phi_\mathrm{h}}\sin\phi_\mathrm{h}\right)$$

- where x, y, Q^2 are usual DIS variables,
- λ is the beam polarisation (≈ 0.8 at COMPASS),
- z is the fraction of γ^* energy carried by h.
- P_T is the transverse momentum of h in the γN frame, ϕ_h is its azimuthal angle.
- $F_{\mathrm{XU}}^{f(\phi_\mathrm{h})}(x, z, P_\mathrm{T}^2, Q^2)$ are structure functions.
- $A_{\mathrm{XU}}^{f(\phi_\mathrm{h})}(x, z, P_\mathrm{T}^2, Q^2)$ are commonly called azimuthal asymmetries.



SIDIS in the γ–nucleon frame.

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$$+ \sqrt{2\varepsilon(1+\varepsilon)}F_{\mathrm{UU}}^{\cos\phi_\mathrm{h}}\cos\phi_\mathrm{h} + \varepsilon F_{\mathrm{UU}}^{\cos 2\phi_\mathrm{h}}\cos 2\phi_\mathrm{h} + \lambda\sqrt{2\varepsilon(1-\varepsilon)}F_{\mathrm{LU}}^{\sin\phi_\mathrm{h}}\sin\phi_\mathrm{h}\Big)$$

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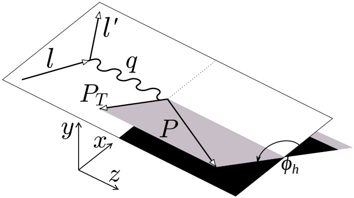


SIDIS in the γ–nucleon frame.

Hadron production DIS

The structure functions in terms of TMD PDFs and TMD FFs, up to order $1/Q$:

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

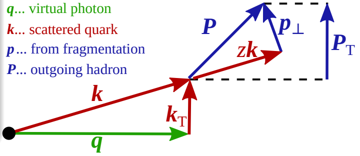
$$F_{\mathrm{UU,L}} = 0,$$

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

$$F_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}} = \mathcal{C}\left[-\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}})(\hat{\boldsymbol{h}}\cdot\boldsymbol{p}_{\perp}) - \boldsymbol{k}_{\mathbf{T}}\cdot\boldsymbol{p}_{\perp}}{M M_{\mathrm{h}}} h_1^{\perp} H_1^{\perp}\right]$$

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

- $f_1(x, k_{\mathrm{T}}^2, Q^2)$ 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 function.
- $\hat{\boldsymbol{h}} = \boldsymbol{P}_{\mathbf{T}}/P_{\mathrm{T}}$,
- $\mathcal{C}$ = sum over flavours and convolution over $\boldsymbol{p}_{\perp}, \boldsymbol{k}_{\mathbf{T}}$,
- $\ldots$ = twist-three terms.



$\boldsymbol{q}$... virtual photon
$\boldsymbol{k}$... scattered quark
$\boldsymbol{p}$... from fragmentation
$\boldsymbol{P}$... outgoing hadron

Momentum vectors
$\boldsymbol{P}_{\mathbf{T}} = z\boldsymbol{k}_{\mathbf{T}} + \boldsymbol{p}_{\perp}$

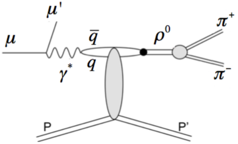
Summary of the observables

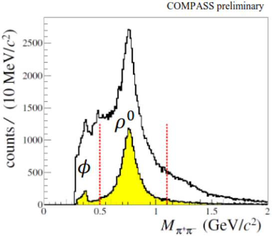
- Collinear hadron multiplicities $\propto f_1(x)D_1(z)$
  - Input for collinear fragmentation functions $D_1(z)$.
  - Definition:

$$\frac{\mathrm{d}M^h(x,y,z)}{\mathrm{d}z} = \frac{1}{N^{\mathrm{DIS}}_{\mathrm{events}}(x,y)} \frac{\mathrm{d}N^{\mathrm{DIS}}_h(x,y,z)}{\mathrm{d}z}$$

- P_T-dependent distributions (or multiplicities) of hadrons $\propto F_{\mathrm{UU,T}} = \mathcal{C}[f_1(x,k_\mathrm{T}^2)D_1(z,p_\perp^2)]$.
  - Input for TMD fragmentation functions.
  - Sensitive to k_T.
- Azimuthal asymmetries of hadrons
  - $A_{\mathrm{UU}}^{\cos\phi_\mathrm{h}}$ – sensitive to k_T via Cahn effect, and other terms,
  - $A_{\mathrm{UU}}^{\cos 2\phi_\mathrm{h}}$ – main contribution from Boer–Mulders function.
  - $A_{\mathrm{LU}}^{\sin\phi_\mathrm{h}}$ – sensitive to higher-twist effects.
- Azimuthal asymmetries of hadron pairs
  - $A_{\mathrm{UU}}^{\cos 2\phi_\mathrm{hh}}$, $A_{\mathrm{UU}}^{\cos(\phi_\mathrm{hh}+\phi_\mathrm{R})}$, $A_{\mathrm{UU}}^{\cos\phi_\mathrm{R}}$ – all sensitive to Boer–Mulders function and $2h$-fragmentation functions.
- Multiplicity of hadron pairs.

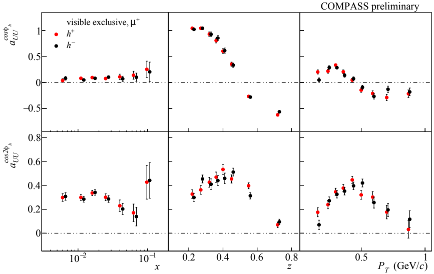
Background from exclusive vector mesons





Invariant mass distribution in the data, before and after cutting in missing energy

- Diffractive production of vector mesons (VMs) contributes to the hadron sample.
- $\rho^0 \to \pi^+\pi^-$, $\phi \to K^+K^-$
- At low Q^2, low P_T and high z.
- The VMs inherit the polarisation of the γ^* → large azimuthal modulations of the decay $h^\pm$.



Azimuthal modulations for $h^\pm$ from exclusive $\mu p \to \mu' p' h^+ h^-$ (exclusivity: $z_{h+} + z_{h-} > 0.95$)

Solution:
- Reject visible pairs in selection,
- subtract non-visible using HEPGEN MC.

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

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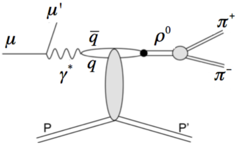

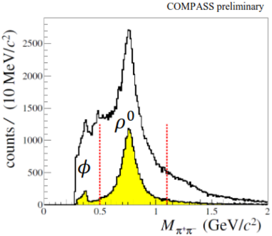

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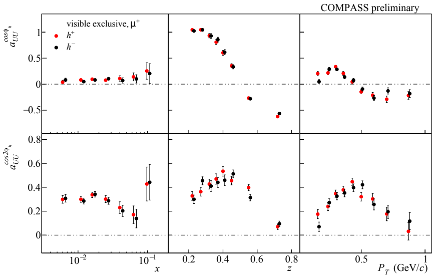

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Radiative corrections

- The PDFs, FFs, TMDs are defined at tree (Born) level.
- In reality: renormalisation of the vertices, radiation of photons along the lepton (μ, μ') and virtual photon momenta → change of Q^2, x and orientation of the GNS.
- Radiative corrections: $\mathrm{RC} = \frac{N_{\mathrm{rad.OFF}}}{N_{\mathrm{rad.ON}}}$, which multiply the measured quantity.
- In COMPASS analyses before 2019:
  Inclusive DIS corrections, based on TERAD program, trials with RADGEN.
- New: DJANGOH MC with radiative effects [DJANGO6]
  - Hard scattering in LEPTO → correction → hadronisation in JETSET/SOPHIA (low W).
  - Allows to extract correction for hadron production.
- Challenge:
  - RC at a given Q^2 depends on all lower Q^2 (including elastic scattering).
  - LEPTO uses PDFs as input, PDFs are not defined below $Q^2 = 1\ (\mathrm{GeV}/c)^2$
  - Solution: tuning of LEPTO parameters to get inclusive correction close to TERAD.
  - Such events have no or only low-energy hadrons → the hadron correction is not affected.
  - Long-term solution: using a generator that treats correctly both low and high Q^2.
- Finally, DJANGOH has been integrated into COMPASS MC chain.

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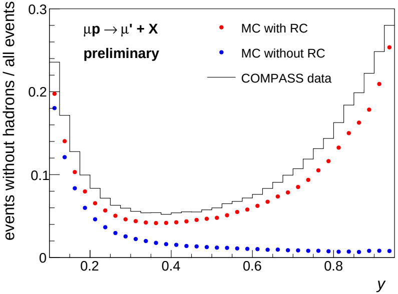
Validation of DJANGOH on real data



- The fraction of events with just μ' in the final state (no h or low-energy h not seen by the spectrometer)
- At high $y = \frac{E_\mu - E'_\mu}{E_\mu}$ few such events expected, naively.
- Radiative γ carry away part of the energy → events shifted to higher y.
- Qualitative agreement.

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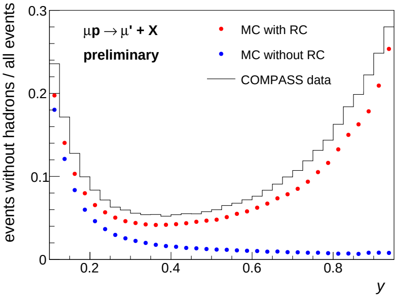

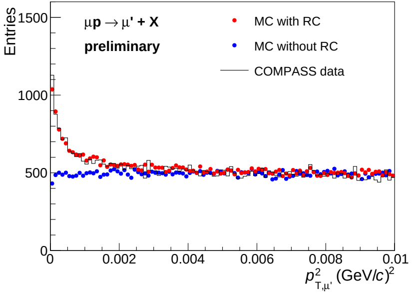

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- Transverse momentum with respect to μ' of hadron candidates.
- Peak from e^+e^- converted from the radiative γ is reproduced.
- Events with at least 3 hadron candidates were selected to demonstrate the effects are visible in events with hadrons.
- Good agreement.

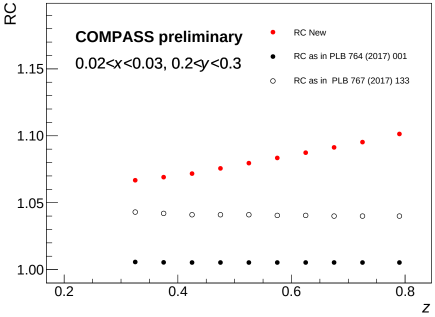
New RC for collinear multiplicities

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

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

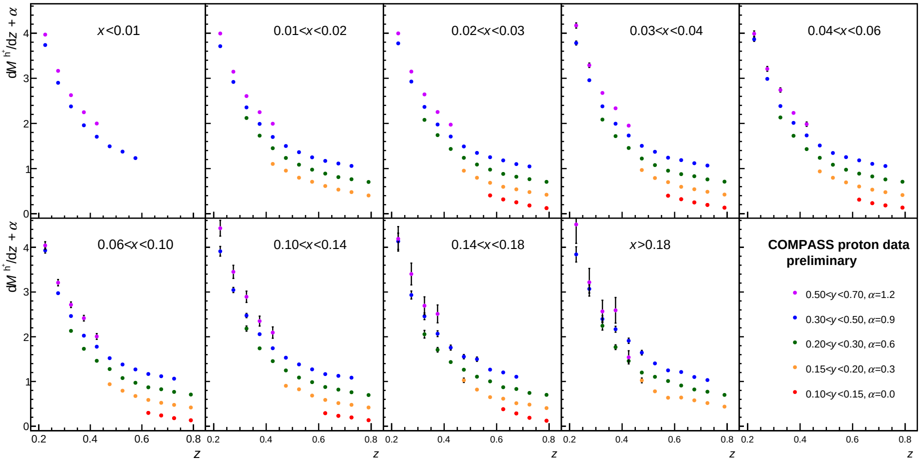
$$\mathrm{RC} = \frac{M^h_{\mathrm{rad.OFF}}}{M^h_{\mathrm{rad.ON}}} = \frac{N^{\mathrm{DIS}}_{h,\mathrm{rad.OFF}}}{N^{\mathrm{DIS}}_{\mathrm{events,rad.OFF}}} \Bigg/ \frac{N^{\mathrm{DIS}}_{h,\mathrm{rad.ON}}}{N^{\mathrm{DIS}}_{\mathrm{events,rad.ON}}}$$

- Corrections in previous COMPASS results:
  - based on TERAD inclusive correction,
  - therefore no explicit z-dependence.
  - [PLB 764 (2017) 001] $(h^{\pm}, \pi^{\pm})$.
  - [PLB 767 (2017) 133] $(\mathrm{K}^{\pm})$,
- New RC from DJANGOH:
  - Rise in z, as the DIS events shifted to higher y by radiative effects have fewer high-z hadrons.
- Diference up to 15% in certain bins.
- New RC used for new results on p target.
- Publication of the new corrections for the old d results is foreseen.



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

New RC for collinear multiplicities



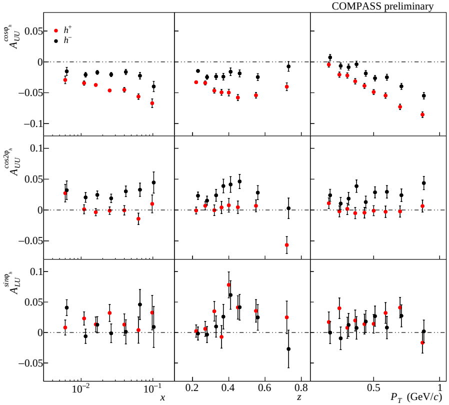
New results for charged hadron multiplicities in DIS off liquid hydrogen (LH) target.
To be presented in more detail at MENU 2023 in October together with $\pi^{\pm}$ and $K^{\pm}$.

New RC for azimuthal asymmetries

- DJANGOH MC allows us to study the impact of radiative effects on the azimuthal distributions of hadrons for the first time.

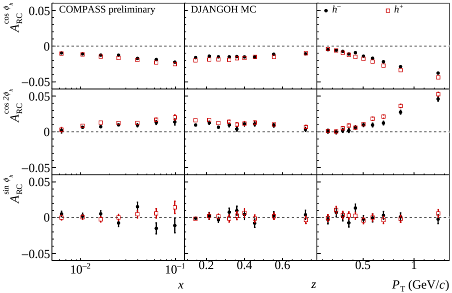
- $N^h_{\mathrm{raw}}(x, z, P_{\mathrm{T}}, \phi_{\mathrm{h}})$ will be multiplied by

$$\mathrm{RC}(x, z, P_{\mathrm{T}}, \phi_{\mathrm{h}}) = \frac{N^h_{\mathrm{rad.OFF}}(x, z, P_{\mathrm{T}}, \phi_{\mathrm{h}})}{N^h_{\mathrm{rad.ON}}(x, z, P_{\mathrm{T}}, \phi_{\mathrm{h}})}.$$



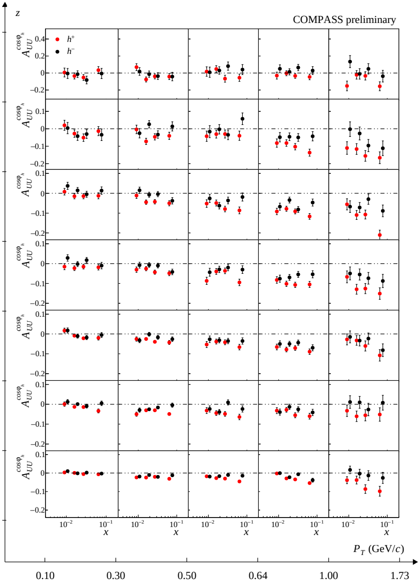
Azimuthal asymmetries for hadrons on LH target (preliminary [A. Moretti, Proc. of ICNFP 2020])

- Analysis of 2016 data with the RC is being finalised (≈ 2× larger smaple).
- To show the impact, we fitted the $\frac{1}{\mathrm{RC}}(\phi_{\mathrm{h}})$ by the same function as the azimuthal distributions of $h^{\pm}$.

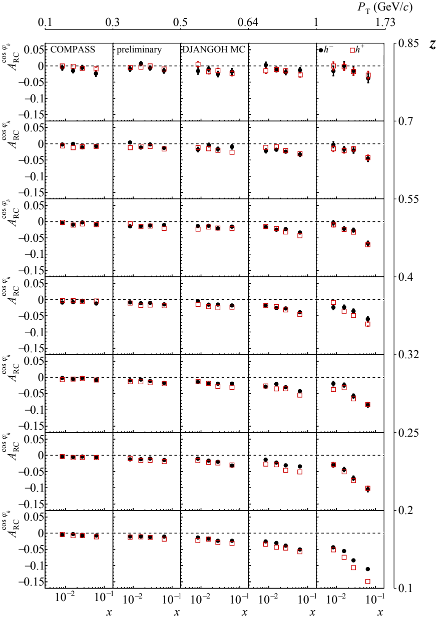


New: Azimuthal amplitudes of 1/RC.
(effectively, these amplitudes are to be subtracted from the measured asymmetries)

New RC for azimuthal asymmetries



$\cos\phi_\mathrm{h}$ asymmetry for hadrons on LH target (preliminary, [A. Moretti, Proc. of ICNFP 2020]).



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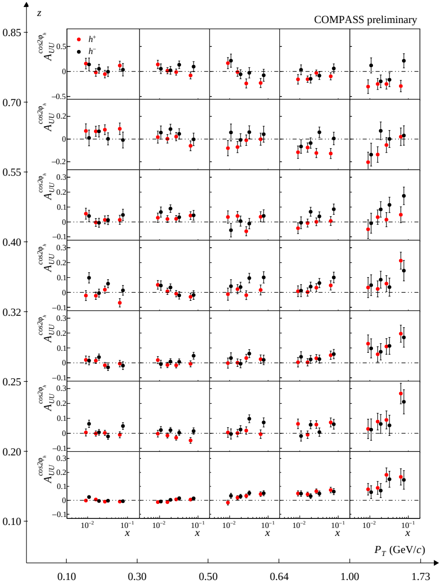
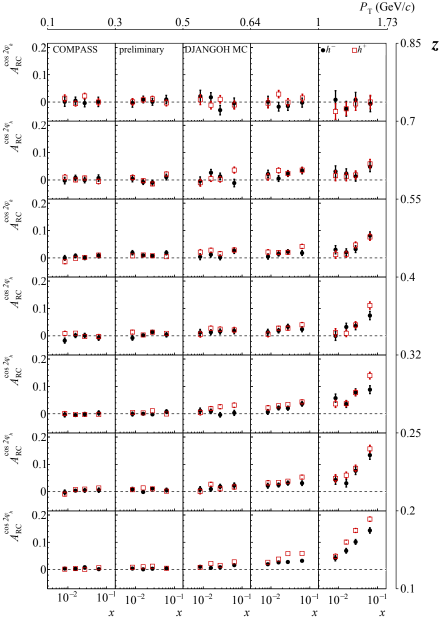


$\cos 2\phi_h$ asymmetry for hadrons on LH target (preliminary, [A. Moretti, Proc. of ICNFP 2020]).



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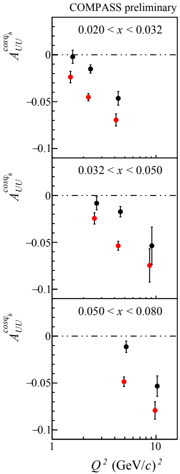
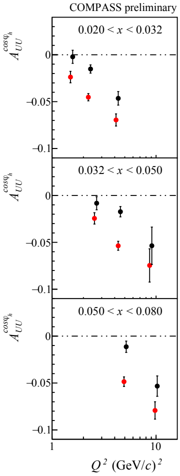
New RC for azimuthal asymmetries



[A. Moretti, Proc. of DIS 2021]

- Cahn effect was expected to be the dominant contribution to $A_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}}$, as
$$F_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}} = \frac{2M}{Q}\mathcal{C}\left[-\frac{\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_{\mathbf{T}}}{M} f_1 D_1 + \dots\right]$$
- Assuming no flavour dependence,
$$A_{\mathrm{UU,Cahn}}^{\cos\phi_{\mathrm{h}}} = -\frac{2zP_{\mathrm{T}}\langle k_{\mathrm{T}}^2\rangle}{Q\langle P_{\mathrm{T}}^2\rangle}.$$
- Despite that, the asymmetry grows with Q^2.
- Can be the radiative effects responsible?
- ...probably not, or not fully.

New RC for azimuthal asymmetries



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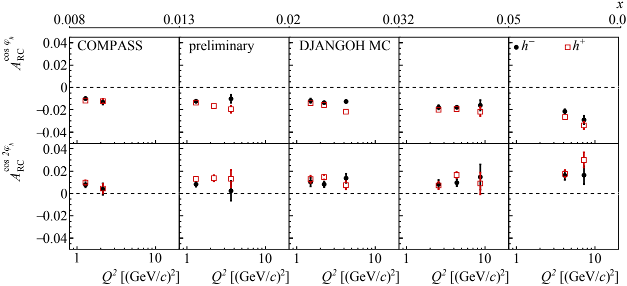
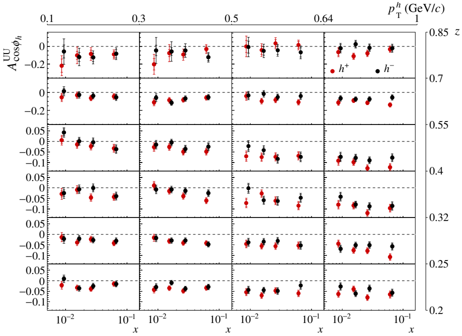


Azimuthal amplitudes of 1/RC.

Other unpolarised azimuthal asymmetries

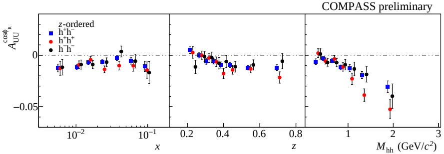
$h^{\pm}$ asymmetries on d (isoscalar) target



$\cos\phi_h$ asymmetry on isoscalar target, with DVM contamination subtracted [COMPASS, Nucl.Phys.B 956 (2020)].

Results before subtraction: [COMPASS, Nucl.Phys.B 886 (2014)].

$2h^{\pm}$ asymmetries on LH target

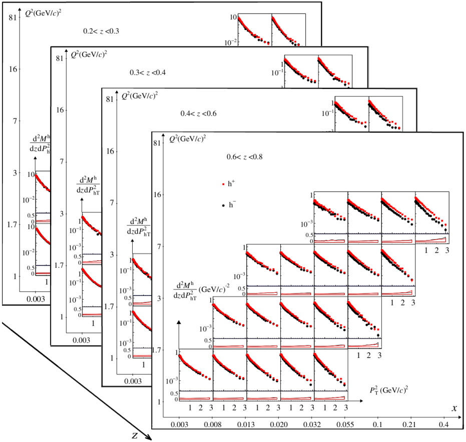


Example: $\cos\phi_R$ modulation for hadron pairs, [A. Moretti, Transversity 2022]

Both without radiative corrections.

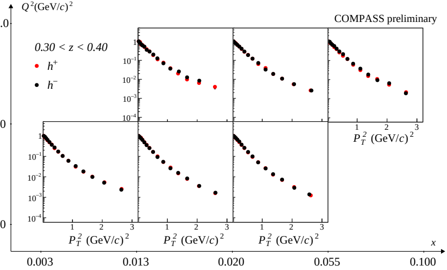
P_{T}-dependent distributions

P_{T}^2-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 → to be compared with DJANGOH.

P_{T}^2-dependent distributions on LH target



- Results in bins of $x, Q^2, z, P_{\mathrm{T}}^2$.
- Restrited kinematic domain – to be expanded.
- Normalised to the lowest-P_{T} point.
- DVM contamination subtracted.
- No radiative corrections – to be evaluated using DJANGOH.
- [A. Moretti, Proc. of ICNFP 2020]

Conclusion

- Unpolarised SIDIS on deuteron (isoscalar) target – a wealth of published results:
  - Collinear multiplicities of $h^{\pm}$, $\pi^{\pm}$ $\mathrm{K}^{\pm}$ K^{-}/K^{+} and $\bar{\mathrm{p}}/\mathrm{p}$
    [PLB 764 (2017) 001] [PLB 767 (2017) 133] [PLB 786 (2018) 390] [PLB 807 (2020) 135600]
  - P_{T}^{2}-dependent multiplicities [COMPASS, Phys.Rev.D97 (2018)]
  - Azimuthal asymmetries [COMPASS, Nucl.Phys.B 886 (2014)] [COMPASS, Nucl.Phys.B 956 (2020)]
- The multiplicities on deuteron target were corrected for radiative effects using TERAD or RADGEN.
- Preliminary results on LH target (using part of 2016–2017 data)
  - Collinear multiplicities: new results, to be presented at MENU in two weeks.
  - P_{T}^{2}-dependent distributions – [A. Moretti, Proc. of ICNFP 2020]
  - Azimuthal asymmetries [A. Moretti, Proc. of ICNFP 2020] [A. Moretti, Proc. of DIS 2021]
  - Dihadron azimuthal asymmetries [A. Moretti, Transversity 2022]
- New radiative corrections based on DJANGOH.
  - Simulate the effect of QED radiation on hadrons,
  - Used for the new multiplicities,
  - to be calculated also for the deuteron target,
  - to be used for the azimuthal asymmetries for the first time, with the corrections being significant.

Conclusion

- Unpolarised SIDIS on deuteron (isoscalar) target – a wealth of published results:
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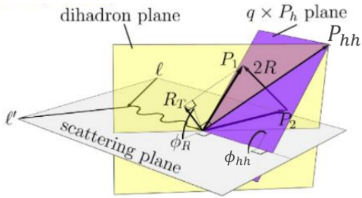
Thank you for your attention!

Backup

- [A. Bianconi *et al.*, Phys.Rev.D 62 (2000)], [A. Bacchetta & M. Radici, Phys.Rev.D 69 (2004)]
- Hadrons with masses M_1, M_2 and $z_1 > z_2$.
- $\boldsymbol{P_{\mathrm{hh}}} = \boldsymbol{P_1} + \boldsymbol{P_2}$,
- $\boldsymbol{R} = \frac{z_2 \boldsymbol{P_1} - z_1 \boldsymbol{P_2}}{z_1 + z_2}$
- Accessing the same PDFs as in the 1h case.
- Fragmentation functions: 2h-unpolarised FF D_1 2h-Collins FF $H_1^{\perp}$, interference FF $H_1^{\sphericalangle}$.



In particular, possibilities to access Boer–Mulders TMD PDF $h_1^{\perp}$:

$$\cos 2\phi_{\mathrm{hh}} \text{ amplitude: } \varepsilon_2 A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{hh}}} = \varepsilon_2 \frac{\mathcal{C}\left[\frac{w_1(p_\perp, k_\mathrm{T})}{M(M_1+M_2)} h_1^{\perp} H_1^{\perp}\right]}{\mathcal{C}[f_1 D_1]}$$

$$\cos(\phi_{\mathrm{hh}} + \phi_{\mathrm{R}}) \text{ amplitude: } \varepsilon_2 |\boldsymbol{R_T}| A_{\mathrm{UU}}^{\cos(\phi_{\mathrm{hh}}+\phi_{\mathrm{R}})} = \varepsilon_2 |\boldsymbol{R_T}| \frac{\mathcal{C}\left[\frac{w_2(p_\perp, k_\mathrm{T})}{M(M_1+M_2)} h_1^{\perp} H_1^{\sphericalangle}\right]}{\mathcal{C}[f_1 D_1]}$$

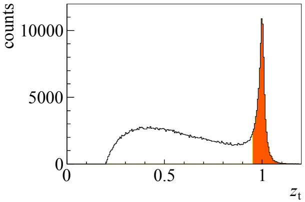
$$\cos \phi_{\mathrm{R}} \text{ amplitude: } \varepsilon_1 \frac{|\boldsymbol{R_T}|}{Q} A_{\mathrm{UU}}^{\cos \phi_{\mathrm{R}}} = \varepsilon_1 \frac{|\boldsymbol{R_T}|}{Q} \frac{\mathcal{C}\left[\frac{1}{z} f_1 \tilde{D}^{\sphericalangle} + \frac{xM}{M_{\mathrm{hh}}} \tilde{h} H_1^{\sphericalangle} + \frac{k_\mathrm{T}^2}{M M_{\mathrm{hh}}} h_1^{\perp} H_1^{\sphericalangle}\right]}{\mathcal{C}[f_1 D_1]}$$

Cahn effect is also expected in $\cos \phi_{\mathrm{hh}}$ modulation: $\varepsilon_1 A_{\mathrm{UU}}^{\cos \phi_{\mathrm{hh}}}$

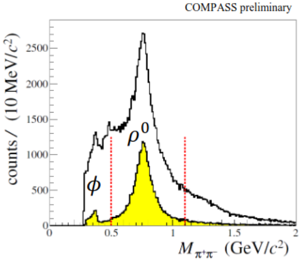
Backup: Background from exclusive VMs

Background treatment in latest analyses:

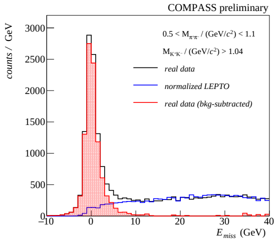
- Visible exclusive pairs: are excluded from the event selection ($\mu p \rightarrow \mu' p' h^+ h^-$ $z_{h+} + z_{h-} > 0.95$)
- Non-visible pairs (only 1 hadron reconstructed): subtracted using HEPGEN MC [A. Sandacz & P. Sznajder, arXiv:1207.0333].
- The MC describes also the azimuthal dependences thanks to SDMEs being plugged in.
- HEPGEN ρ^0 and ϕ are scaled to the data using E_{miss} distribution for pairs in ρ^0 and ϕ invariant mass range.



$z_t = z_{h+} + z_{h-}$



Invariant mass distribution in the data, before and after cutting in missing energy



E_{miss} distribution in the data and scaled HEPGEN and LEPTO MC.