Transverse Momentum Effects in Unpolarized Semi-Inclusive DIS at COMPASS

Vendula Benešová on behalf of the COMPASS collaboration
Faculty of Mathematics and Physics
Charles University, Prague, Czechia

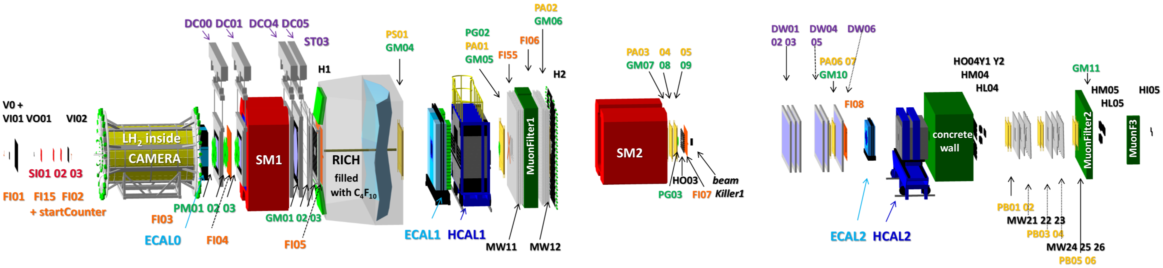
03. 09. 2025

Joint 21st International Workshop on Hadron Structure and Spectroscopy and
6th workshop on the QCD Structure of the Nucleon
Centro Carlos Santamaría, San Sebastian, Spain

PRIMUS

COMPASS experiment at CERN

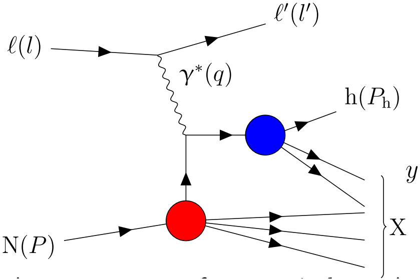
- COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) is a fixed target experiment at CERN
- 20 years of data measurement between 2002–2022 dedicated to spectroscopy and nucleon structure
- 2016–2017 setup: liquid hydrogen target, 160 GeV/c longitudinally polarized $\mu^{\pm}$ beam
  1. Deeply Virtual Compton Scattering (DVCS)
  2. Hard Exclusive Meson Production (HEMP)
  3. Semi-Inclusive Deeply Inelastic Scattering (SIDIS)

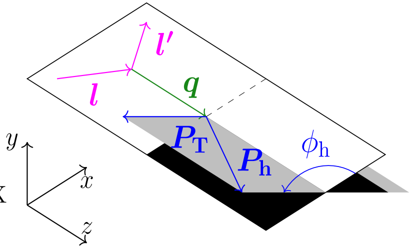


Unpolarised SIDIS

$$\ell(l)+\mathrm{N}(P) \rightarrow \ell'(l')+\mathrm{h}(P_\mathrm{h})+\mathrm{X}$$

- Hadron P_T originates from quark k_T and fragmentation $\rightarrow$ TMDs: TMD-PDFs $f^q(x, k_\mathrm{T}, Q^2)$ and TMD-FFs $D^{q\rightarrow h}(z, P_\perp, Q^2)$
- P_T and **azimuthal angle** ϕ_h are defined in γ^*-nucleon system (GNS):





$$x \equiv \frac{Q^2}{2P\cdot q}$$
$$Q^2 \equiv -(l-l')^2$$
$$y \equiv \frac{q\cdot P}{k\cdot P}$$
$$W^2 \equiv (q+P)^2$$
$$z \equiv \frac{P\cdot P_\mathrm{h}}{P\cdot q}$$

Unpolarized SIDIS – structure functions

- Unpolarized SIDIS cross-section: [A. Bacchetta et al., JHEP0702(2007)]

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

- Structure functions $F_{\mathrm{XU}}^{f(\phi_{\mathrm{h}})}(x, z, P_{\mathrm{T}}^2, Q^2)$ interpretation $\rightarrow$ weighted convolutions:

$$\mathscr{C}[wfD] = x\sum_q e_q^2 \int \mathrm{d}^2k_{\mathrm{T}}\mathrm{d}^2P_{\perp}\delta^{(2)}(zk_{\mathrm{T}} + P_{\perp} - P_{\mathrm{T}})w(k_{\mathrm{T}}, P_{\perp})f^q(x, k_{\mathrm{T}}, Q^2)D^{q\rightarrow h}(z, P_{\perp}, Q^2)$$

Unpolarized SIDIS – structure functions

- Structure functions $F_{XU}^{f(\phi_h)}(x, z, P_T^2, Q^2)$ interpretation $\rightarrow$ weighted convolutions:

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

- Leading twist description of unpolarized SIDIS:

TMD-PDFs $f^q(x, k_T, Q^2)$:
unpolarized f_1
Boer-Mulders $h_1^\perp$

TMD-FFs $D^{q\to h}(z, P_\perp, Q^2)$:
unpolarized D_1
Collins $H_1^\perp$

- Up to order $\frac{1}{Q}$:

$$F_{UU,T} = \mathscr{C}[f_1 D_1] \qquad F_{UU,L} = 0 \qquad F_{LU}^{\sin\phi_h} = 0 + ...$$

$$F_{UU}^{\cos 2\phi_h} = \mathscr{C}\left[\frac{2(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp) - (\boldsymbol{k}_T\cdot\boldsymbol{P}_\perp)}{zMM_h} h_1^\perp H_1^\perp\right] \qquad \leftarrow \hat{\boldsymbol{h}} = \frac{\boldsymbol{P}_T}{|\boldsymbol{P}_T|}$$

$$F_{UU}^{\cos\phi_h} = \frac{2M}{Q}\mathscr{C}\left[\underbrace{-\frac{(\hat{\boldsymbol{h}}\cdot\boldsymbol{k}_T)}{M} f_1 D_1}_{\text{Cahn effect}} + \underbrace{\frac{k_T^2(\hat{\boldsymbol{h}}\cdot\boldsymbol{P}_\perp)}{zM^2M_h} h_1^\perp H_1^\perp}_{\text{Boer-Mulders effect}} + ...\right] \qquad \leftarrow \text{W.W. type approximation}$$

Unpolarised SIDIS – azimuthal asymmetries

- Unpolarised SIDIS x-section:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}\phi_{\mathrm{h}}\mathrm{d}P_{\mathrm{T}}^2} = \sigma_0\left(1 + \varepsilon_1 A_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}}\cos\phi_{\mathrm{h}} + \varepsilon_2 A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}\cos 2\phi_{\mathrm{h}} + \lambda\varepsilon_3 A_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}}\sin\phi_{\mathrm{h}}\right)$$

- Azimuthal asymmetries $A_{\mathrm{XU}}^{f(\phi_{\mathrm{h}})}$ from a fit to the measured ϕ_{h} distributions
  - Asymmetries are directly connected to the structure functions:

$$A_{\mathrm{XU}}^{f(\phi_{\mathrm{h}})}(x, z, P_{\mathrm{T}}^2, Q^2) \equiv \frac{F_{\mathrm{XU}}^{f(\phi_{\mathrm{h}})}}{F_{\mathrm{UU}}} \qquad F_{\mathrm{XU}}^{f(\phi_{\mathrm{h}})} = \mathscr{C}[w\, f\, D]$$

$\rightarrow$ $A_{\mathrm{UU}}^{\cos\phi_{\mathrm{h}}}$: Cahn effect $\mathscr{C}[w f_1 D_1]$, $w < 0$

$\rightarrow$ $A_{\mathrm{UU}}^{\cos 2\phi_{\mathrm{h}}}$: Boer–Mulders effect $\mathscr{C}[w h_1^{\perp} H_1^{\perp}]$

$\rightarrow$ $A_{\mathrm{LU}}^{\sin\phi_{\mathrm{h}}}$: higher-order effects

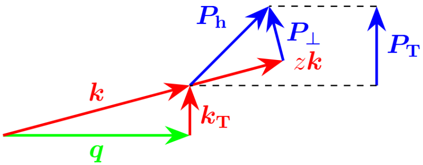
Unpolarised SIDIS – P_{T}^2-distributions

- Unpolarized SIDIS x-section integrated over ϕ_{h} (Gaussian model for transverse part of F_{UU}):

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x\mathrm{d}Q^2\mathrm{d}z\mathrm{d}P_{\mathrm{T}}^2} = \frac{2\pi^2\alpha^2}{xyQ^2}\frac{\left[1+(1-y)^2\right]}{y^2}F_{\mathrm{UU}} \propto \sum_q \exp\left(-\frac{P_{\mathrm{T}}^2}{\langle P_{\mathrm{T}}^2\rangle_q}\right)$$

- $\langle P_{\mathrm{T}}^2\rangle$ can be separated into contributions from fragmentation $\langle P_{\perp}^2\rangle$ and from intrinsic transverse momentum of quark $\langle k_{\mathrm{T}}^2\rangle$

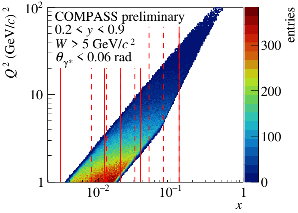
$$\langle P_{\mathrm{T}}^2\rangle = z^2\langle k_{\mathrm{T}}^2\rangle + \langle P_{\perp}^2\rangle\ .$$

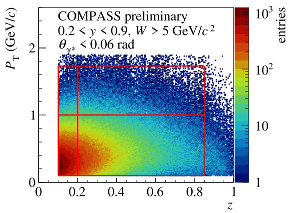


Data sample, kinematic range and binning

- Kinematical coverage:

$$0.2 < y < 0.9 \qquad 0.003 < x < 0.130$$
$$Q^2 > 1\ \mathrm{GeV}^2/c^2 \qquad \theta_\gamma < 60\ \mathrm{mrad}$$
$$0.2 < z < 0.85 \qquad W > 5\ \mathrm{GeV}/c^2$$
$$0.1\ \mathrm{GeV}/c < P_\mathrm{T} < 1.0\ \mathrm{GeV}/c$$





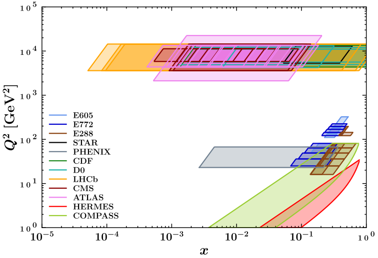
- Binnings:

for $A_{XU}^{f(\phi_\mathrm{h})}$:

- 1D x, z, P_T
- 2D $x : Q^2$
- 3D $P_\mathrm{T} : z : x$
- 4D $z : x : Q^2 : P_\mathrm{T}$

for P_T^2-distributions:

- 4D $z : x : Q^2 : P_\mathrm{T}^2$

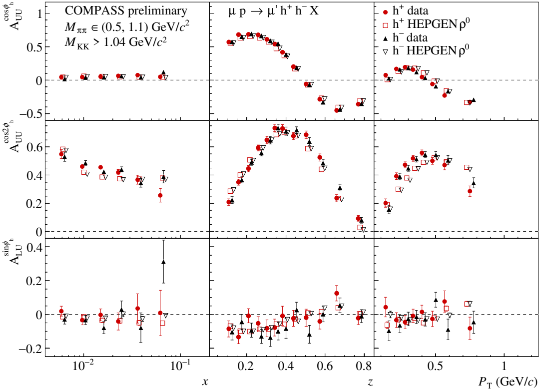


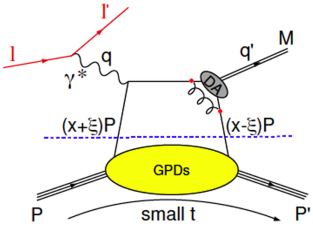
[JHEP 10 (2022) 127]

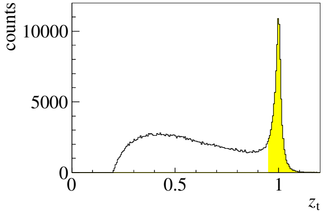
Key corrections in the analysis: Treatment of background from DVMs

- Background process: HEMP
- only non-negligible contributors: $\rho \to \pi^+\pi^-$ and $\phi \to K^+K^-$
- Diffractive vector mesons (DVM) inherit polarisation from γ^*

$\rightarrow$ large amplitudes of azimuthal modulations for decay products







[NPB 956 (2020) 115039]

Key corrections in the analysis: Treatment of background from DVMs

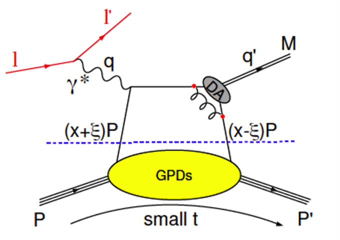
- Background process: HEMP
- only non-negligible contributors: $\rho \to \pi^+\pi^-$ and $\phi \to K^+K^-$
- Diffractive vector mesons (DVM) inherit polarisation from γ^*

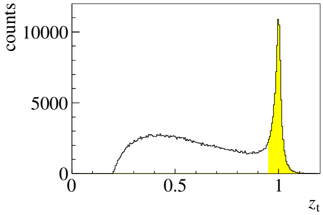
$\to$ large amplitudes of azimuthal modulations for decay products

- In case of hadrons from DVMs:
  - **visible hadron pairs**
    - both hadrons reconstructed
    - rejected using:

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

  - **invisible hadrons**
    - 1 hadron reconstructed
    - subtracted from ϕ_h distributions using HEPGEN MC





[NPB 956 (2020) 115039]

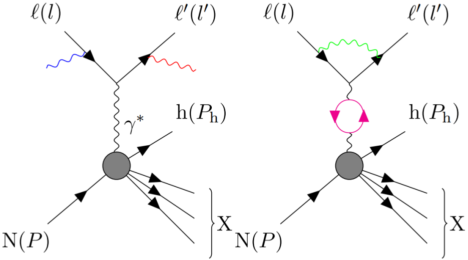
Key corrections in the analysis: Radiative correction

- Cross-section is defined at tree level → radiative corrections account for QED radiative effects (RE):

→ renormalisation of the vertices

→ radiation of photons along the μ, μ′ and virtual photon

→ corresponding changes in x, Q^2 and orientation of GNS



- impact of RE in hadronic variables (such as ϕ_h) not accessible analytically

→ simulations → DJANGOH generator
modified LEPTO generator with hadronisation in JETSET and SOPHIA
[K. Charchuła et al., DJANGOH]

- applied by multiplying ϕ_h distributions bin-by-bin by fraction η

$$\eta(\phi_\mathrm{h}) = \frac{N_h^{\text{RE-off}}(\phi_\mathrm{h})}{N_h^{\text{RE-on}}(\phi_\mathrm{h})}$$

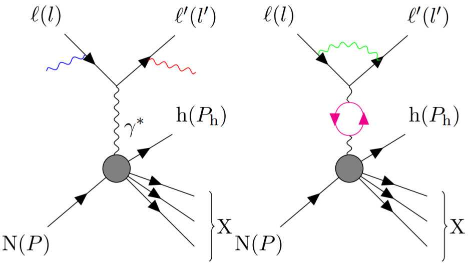
Key corrections in the analysis: Radiative correction

- Cross-section is defined at tree level → radiative corrections account for QED radiative effects (RE):

→ renormalisation of the vertices

→ radiation of photons along the μ, μ′ and virtual photon

→ corresponding changes in x, Q^2 and orientation of GNS



- impact of RE in hadronic variables (such as ϕ_h) not accessible analytically

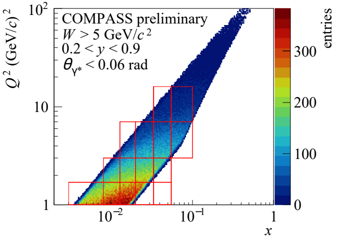
→ simulations → DJANGOH generator
modified LEPTO generator with hadronisation in JETSET and SOPHIA
[K. Charchuła et al., DJANGOH]

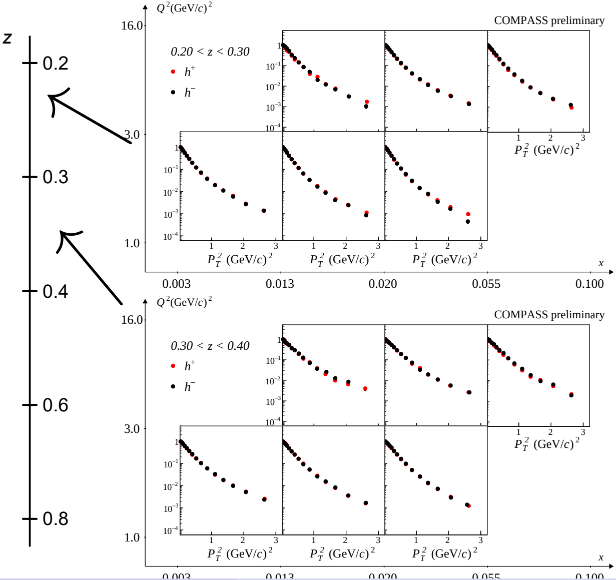
- applied by multiplying P_T^2 distributions bin-by-bin by fraction η

$$\boxed{\eta(P_\mathrm{T}^2) = \frac{N_\mathrm{h}^{\text{RE-off}}(P_\mathrm{T}^2)}{N_\mathrm{h}^{\text{RE-on}}(P_\mathrm{T}^2)}}$$

Results for P_{T}^2-distributions

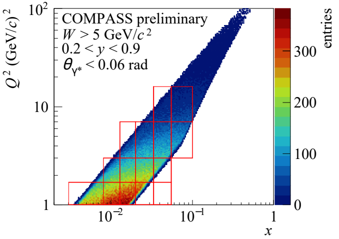
- Normalisation to the first P_{T}^2 bin
- Background from DVMs excluded
- Ongoing work on:
  - applying RC
  - extending the data sample
  - refining the binning in x and Q^2

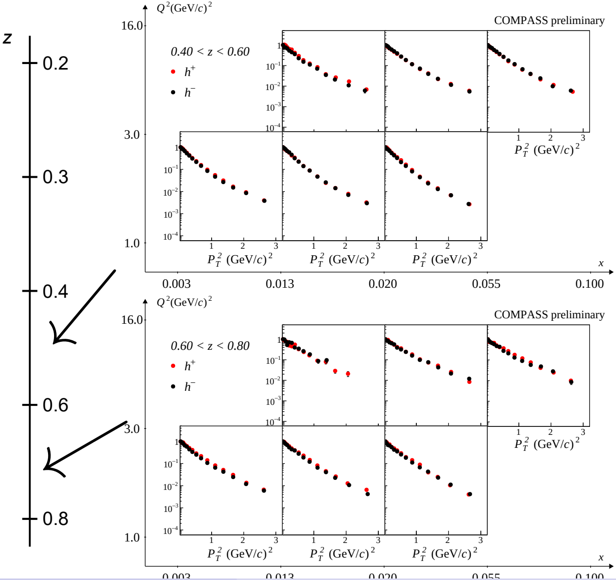




Results for P_{T}^2-distributions

- Normalisation to the first P_{T}^2 bin
- Background from DVMs excluded
- Ongoing work on:
  - applying RC
  - extending the data sample
  - refining the binning in x and Q^2



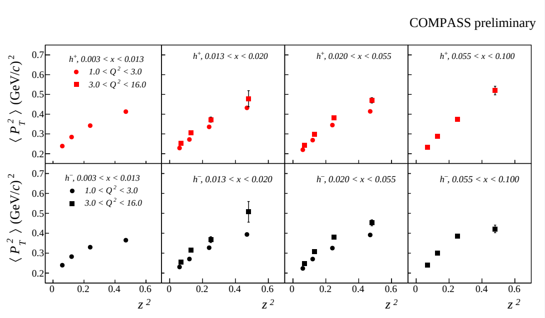


Results for P_{T}^2-distributions

- Norm
- Backg
- Ongo
  - a

Up to 3 GeV$^2/c^2$: double exponential fit

$$\sigma(P_{\mathrm{T}}^2) = \sum_{i=1}^{2} A_i \exp\left(-\frac{P_{\mathrm{T}}^2}{a_i}\right) \qquad \langle P_{\mathrm{T}}^2 \rangle = \frac{A_1 a_1^2 + A_2 a_2^2}{A_1 a_1 + A_2 a_2}$$



$\langle P_{\mathrm{T}}^2 \rangle$ rising with z^2

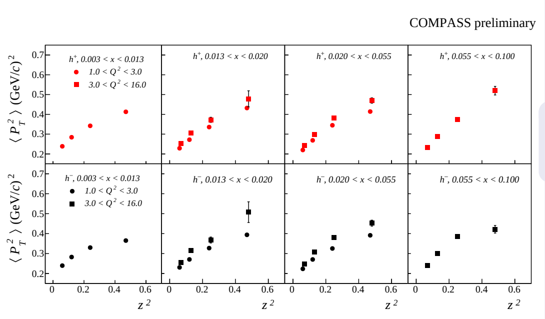
Results for P_{T}^2-distributions

- Norm
- Backg
- Ongo
  - a

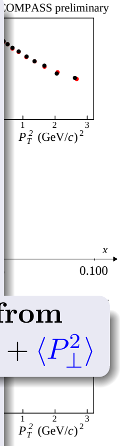
Up to 3 GeV$^2/c^2$: double exponential fit

$$\sigma(P_{\mathrm{T}}^2) = \sum_{i=1}^{2} A_i \exp\left(-\frac{P_{\mathrm{T}}^2}{a_i}\right) \qquad \langle P_{\mathrm{T}}^2 \rangle = \frac{A_1 a_1^2 + A_2 a_2^2}{A_1 a_1 + A_2 a_2}$$

$\langle P_{\mathrm{T}}^2 \rangle$ rising with z^2



deviation from $\langle P_{\mathrm{T}}^2 \rangle = z^2 \langle k_{\mathrm{T}}^2 \rangle + \langle P_{\perp}^2 \rangle$

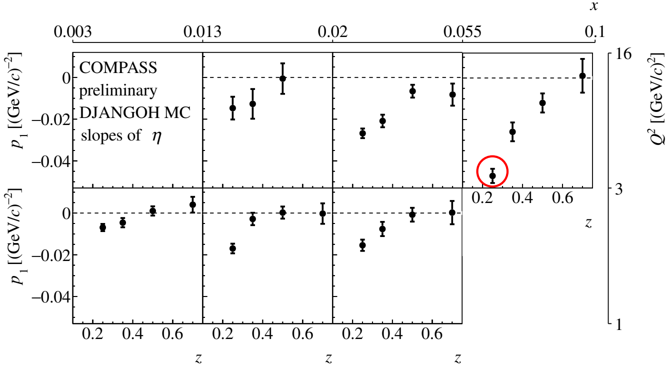


Effect of RC on P_T^2 distributions

- Slopes of η of charged hadrons in $x : Q^2 : z$ dependence

$\rightarrow$ largest correction (slope) in:

$$z \in [0.2, 0.3],\ x \in [0.055, 0.1],\ Q^2 \in [3, 16]\ \mathrm{GeV}^2/c^2$$



- More about RC for P_T^2 distributions [IWHSS-CPHI 2024]

Effect of RC on P_{T}^2 distributions

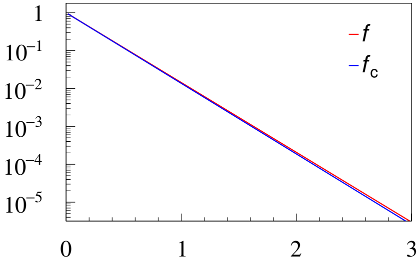
- Slopes of η of charged hadrons in $x : Q^2 : z$ dependence

$\rightarrow$ largest correction (slope) in:

$$\boxed{z \in [0.2, 0.3],\ x \in [0.055, 0.1],\ Q^2 \in [3, 16]\ \mathrm{GeV}^2/c^2}$$

- Assume exponential shape of the P_{T}^2 distributions before the correction:

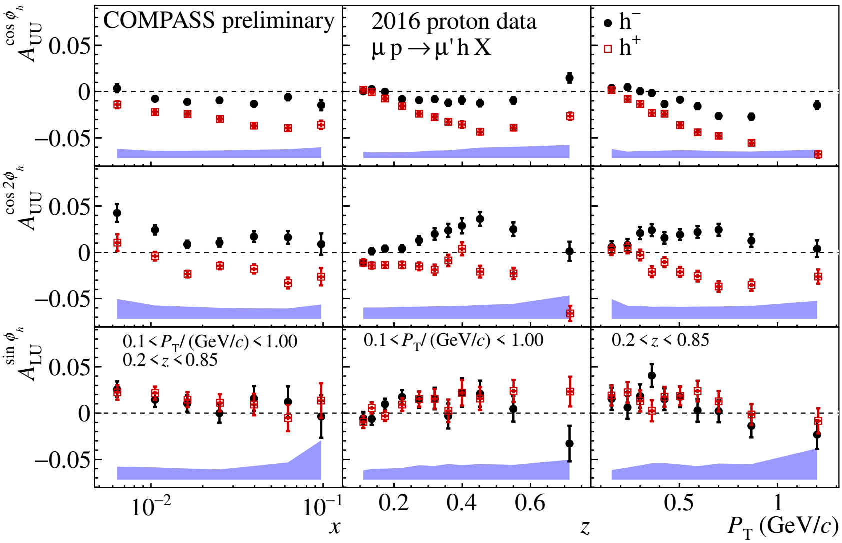
$$f(P_{\mathrm{T}}^2) = A \exp\left(-\frac{P_{\mathrm{T}}^2}{\langle P_{\mathrm{T}}^2 \rangle}\right) \quad \rightarrow \quad f_{\mathrm{c}}(P_{\mathrm{T}}^2) = A(1 + p_1 P_{\mathrm{T}}^2) \exp\left(-\frac{P_{\mathrm{T}}^2}{\langle P_{\mathrm{T}}^2 \rangle}\right)$$



- **small effect**
- size compatible with the statistical error

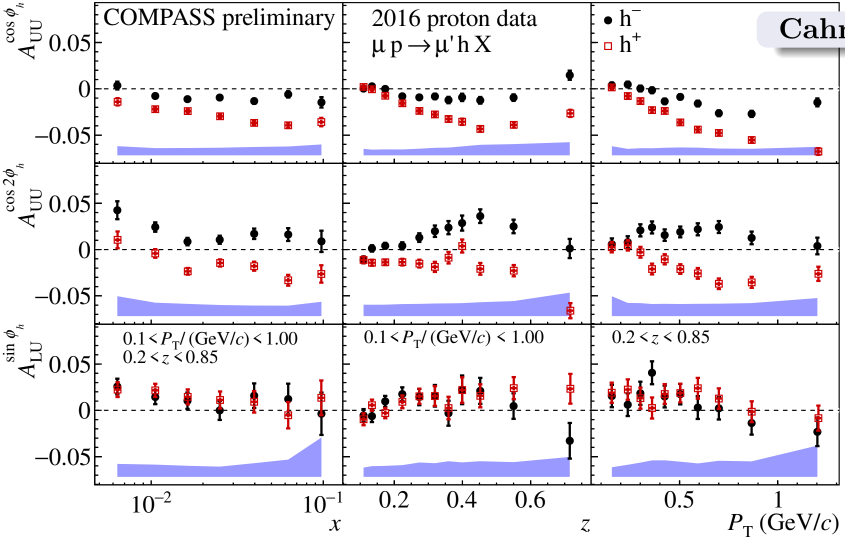
$\rightarrow$ RC cannot be neglected

Results for $A_{\mathrm{XU}}^{f(\phi_\mathrm{h})}$

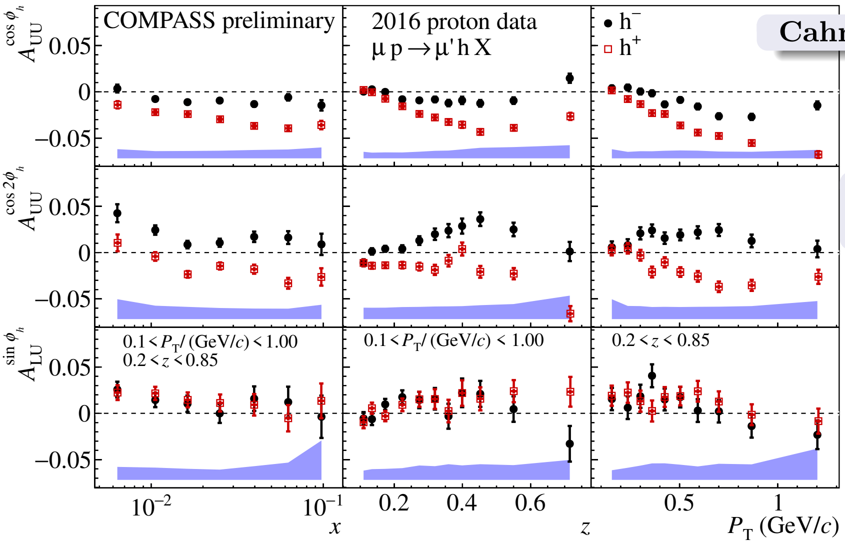


Results for $A_{\mathrm{XU}}^{f(\phi_{\mathrm{h}})}$

Cahn effect



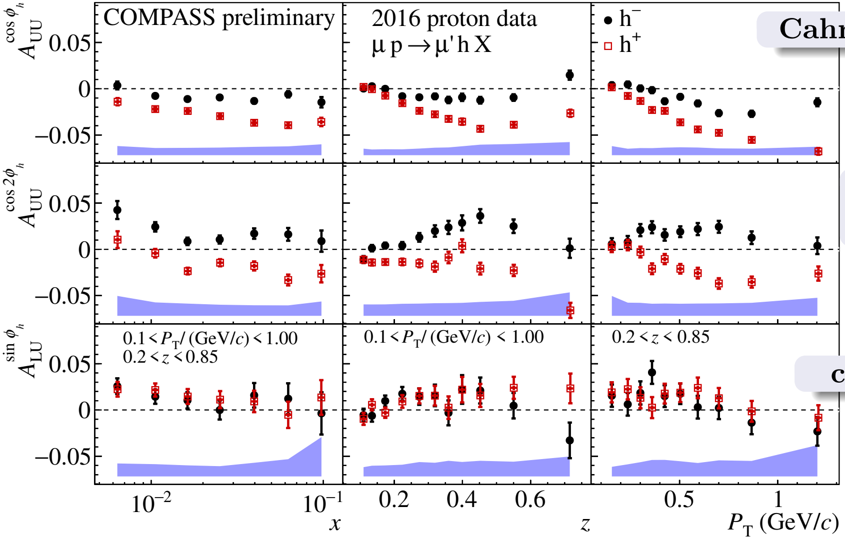
Results for $A_{\mathrm{XU}}^{f(\phi_\mathrm{h})}$



Cahn effect

mirror symmetry

Results for $A_{XU}^{f(\phi_h)}$

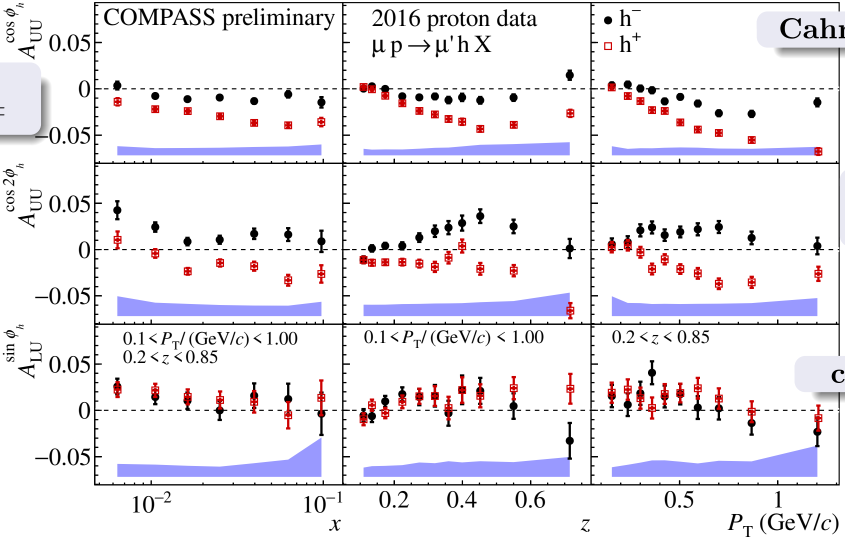


Cahn effect

mirror symmetry

close to 0

Results for $A_{\mathrm{XU}}^{f(\phi_\mathrm{h})}$



Cahn effect

different results $h^{\pm}$

mirror symmetry

close to 0

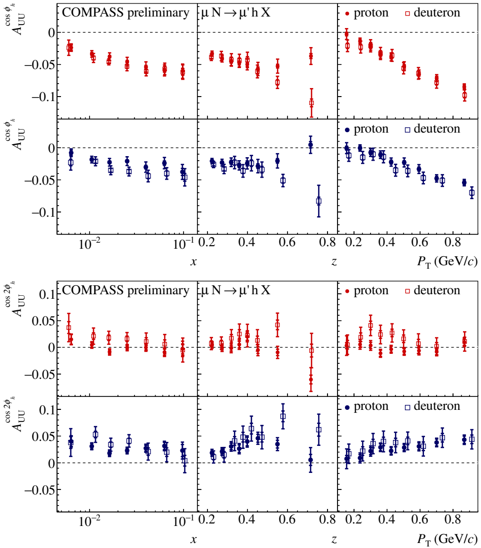
Proton-deuteron comparison

- Comparison of COMPASS unpolarised asymmetries on deuteron [NPB 956 (2020) 115039] and 2016 results on proton

- Insight into flavour dependence
- No radiative corrections applied

→ large difference at high z

→ TMD-FFs of up and down quark?



2016 unpolarised SIDIS on proton target

- Results of **azimuthal asymmetries** for $\mathrm{h}^{\pm}$

$\rightarrow$ ongoing work on multi-D

$\rightarrow$ publication coming soon

- Results of $P_{\mathbf{T}}^2$ **distributions** for $\mathrm{h}^{\pm}$

$\rightarrow$ ongoing work on expanding the data sample

$\rightarrow$ ongoing work on refining the $z : Q^2 : x : P_{\mathrm{T}}^2$ binning

Summary of the results and conclusions

2016 unpolarised SIDIS on proton target

- Results of **azimuthal asymmetries** for $h^{\pm}$

$\rightarrow$ ongoing work on multi-D
$\rightarrow$ publication coming soon

- Results of $P_{\mathbf{T}}^2$ **distributions** for $h^{\pm}$

$\rightarrow$ ongoing work on expanding the data sample
$\rightarrow$ ongoing work on refining the $z : Q^2 : x : P_{\mathrm{T}}^2$ binning

- Significant influence of the treatment of backgrounds from exclusive events and radiative corrections

Summary of the results and conclusions

2016 unpolarised SIDIS on proton target

- Results of **azimuthal asymmetries** for $h^{\pm}$

$\rightarrow$ ongoing work on multi-D
$\rightarrow$ publication coming soon

- Results of P_{T}^2 **distributions** for $h^{\pm}$

$\rightarrow$ ongoing work on expanding the data sample
$\rightarrow$ ongoing work on refining the $z : Q^2 : x : P_{\mathrm{T}}^2$ binning

- Significant influence of the treatment of backgrounds from exclusive events and radiative corrections

Thank you for your attention!

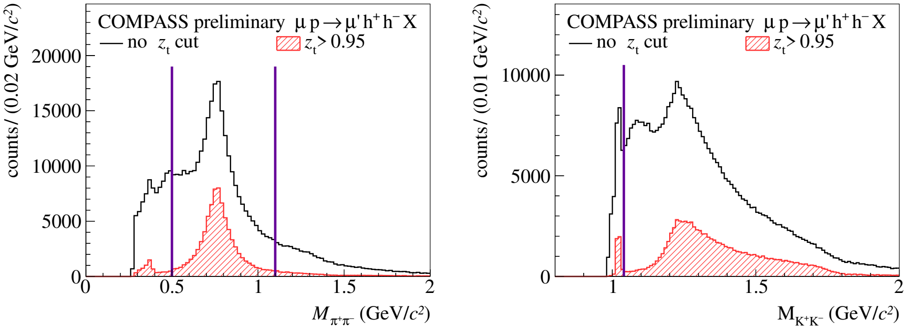
Backup

Visible hadron pairs: looking for hadrons from DVMs

- ρ and ϕ mesons are visible in invariant mass distributions of the **visible hadron pairs**:

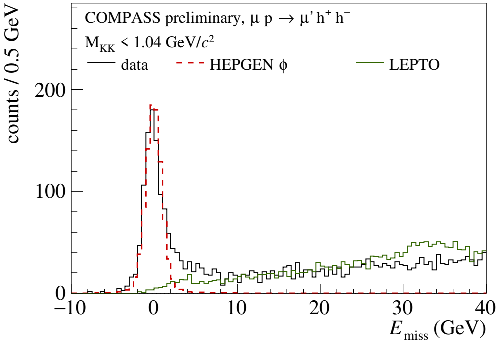
$$\rho \to \pi^+\pi^- : M_{K^+K^-} \in [1.04, \infty]\ \mathrm{GeV}/c^2$$
$$\text{and } M_{\pi^+\pi^-} \in [0.5, 1.1]\ \mathrm{GeV}/c^2$$

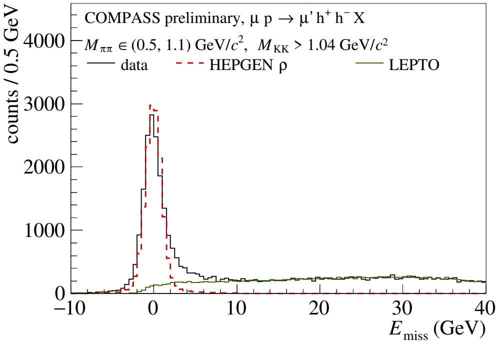
$$\phi \to K^+K^- : M_{K^+K^-} \in [0, 1.04]\ \mathrm{GeV}/c^2$$



- Normalization of HEPGEN ρ and HEPGEN ϕ is estimated using E_{miss} distributions of **visible hadron pairs**

$$E_{\mathrm{miss}} = \frac{M_{\mathrm{X}}^2 - M_{\mathrm{p}}^2}{2M_{\mathrm{p}}} \qquad M_{\mathrm{X}}^2 = (p + q - P_{\mathrm{h}^+} - P_{\mathrm{h}^-})^2$$

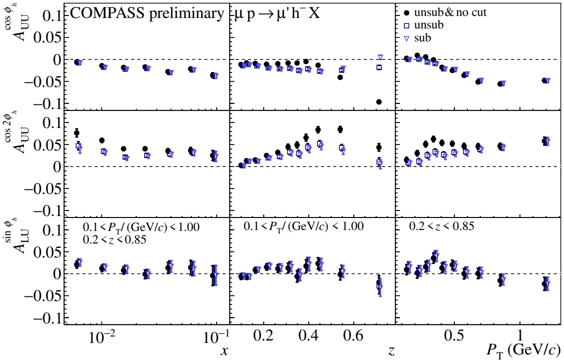




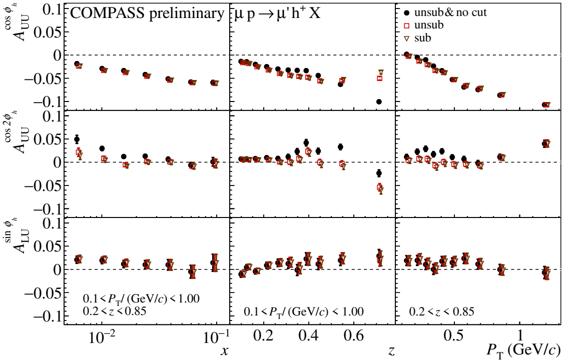
Effect of DVM cut and subtraction in 1D

- Background of hadrons from DVM decays has significant impact on the results
- High z, low x and low P_{T} regions are affected the most

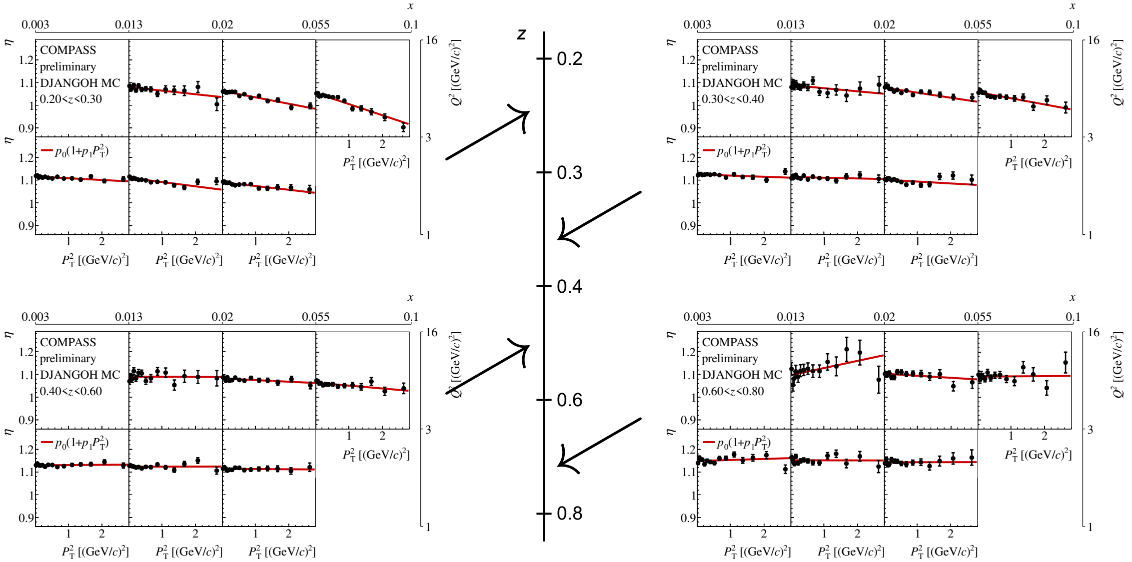
negative hadrons



positive hadrons



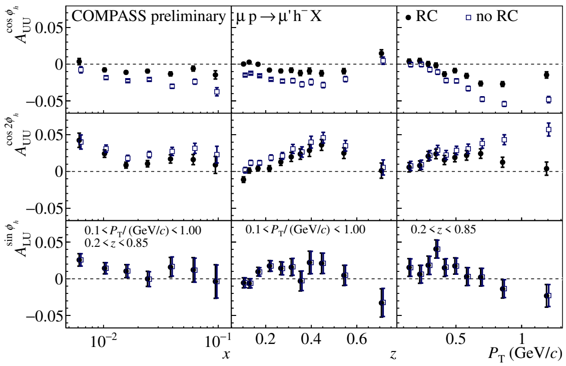
RC for P_T^2 distributions



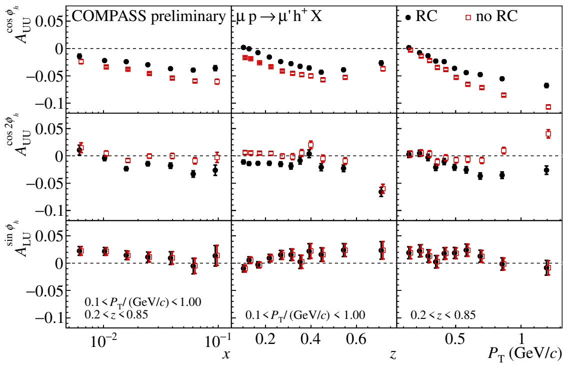
Effect of RC on measured azimuthal asymmetries in 1D binning

- The effect on azimuthal asymmetries grows with P_T, x and goes down with z
- No effect is observed (nor expected) for $A_{\mathrm{LU}}^{\sin\phi_\mathrm{h}}$

h^-

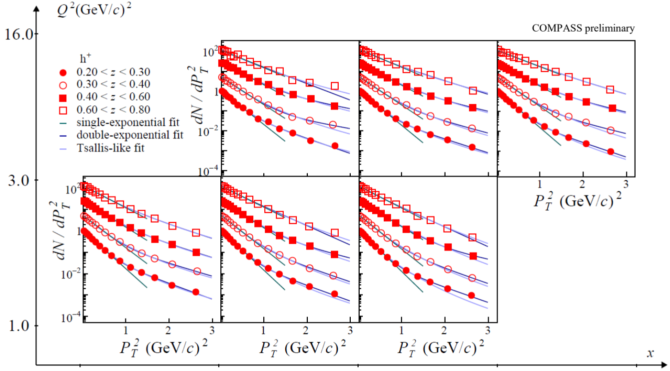


h^+



Comparison of different fitting functions

single-exponential	**double-exponential**	**Tsallis-like distribution**
$\sigma(P_{\mathrm{T}}^2) = A\exp\left(-\frac{P_{\mathrm{T}}^2}{\langle P_{\mathrm{T}}^2\rangle}\right)$	$\sigma(P_{\mathrm{T}}^2) = \sum_{i=1}^{2} A_i \exp\left(-\frac{P_{\mathrm{T}}^2}{a_i}\right)$	$\sigma(P_{\mathrm{T}}^2) = c_1(1 + c_2\langle P_{\mathrm{T}}^2\rangle)^{-c_3}$



Comparison of different fitting functions

single-exponential

$$\sigma(P_{\mathrm{T}}^2) = A\exp\left(-\frac{P_{\mathrm{T}}^2}{\langle P_{\mathrm{T}}^2\rangle}\right)$$

double-exponential

$$\sigma(P_{\mathrm{T}}^2) = \sum_{i=1}^{2} A_i \exp\left(-\frac{P_{\mathrm{T}}^2}{a_i}\right)$$

$$\langle P_{\mathrm{T}}^2\rangle = \frac{A_1 a_1^2 + A_2 a_2^2}{A_1 a_1 + A_2 a_2}$$

Tsallis-like distribution

$$\sigma(P_{\mathrm{T}}^2) = c_1(1 + c_2\langle P_{\mathrm{T}}^2\rangle)^{-c_3}$$

$$\langle P_{\mathrm{T}}^2\rangle = \frac{1}{c_2(c_3-2)}$$