Measurement of azimuthal modulations in SIDIS off proton target at COMPASS

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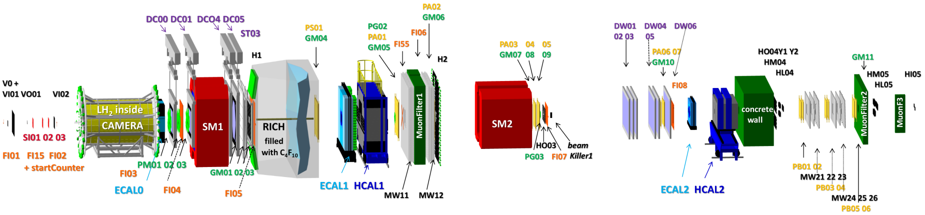
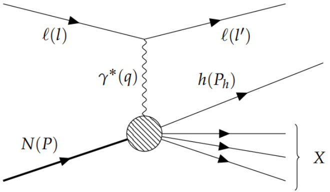
COMPASS experiment at CERN

- 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)

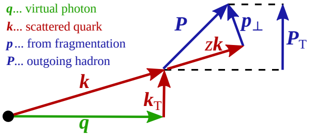


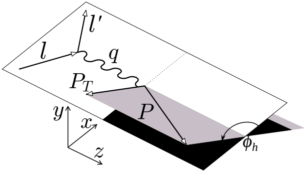
Unpolarized SIDIS

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



- Hadron P_T originates from quark k_T and fragmentation → TMDs
- P_T and **azimuthal angle** ϕ_h are defined in γ^*-nucleon system (GNS):





Unpolarized SIDIS – structure functions

- Unpolarized SIDIS cross-section [A. Bacchetta et al., JHEP 0702 (2007)]

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}\phi_h P_\mathrm{T}^2} = \frac{2\pi\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}(1+\frac{\gamma^2}{2x})\Big[F_{\mathrm{UU,T}} + \varepsilon F_{\mathrm{UU,L}} + \sqrt{2\varepsilon(1+\varepsilon)}F_{\mathrm{UU}}^{\cos\phi_h}\cos\phi_h + \varepsilon F_{\mathrm{UU}}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\sqrt{2\varepsilon(1+\varepsilon)}F_{\mathrm{LU}}^{\sin\phi_h}\sin\phi_h\Big]$$

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

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

- leading twist description of unpolarized SIDIS:

2 TMD-PDFs $f^q(x, k_\mathrm{T}, Q^2)$:

- unpolarized f_1
- Boer-Mulders $h_1^\perp$

2 TMD-FFs $D^{q\rightarrow h}(z, P_\perp, Q^2)$:

- unpolarized D_1
- Collins $H_1^\perp$

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

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

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

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

Unpolarized SIDIS – azimuthal asymmetries

- Unpolarized SIDIS cross-section:

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}x\mathrm{d}y\mathrm{d}z\mathrm{d}\phi_h\mathrm{d}P_\mathrm{T}} = p_0(1 + \varepsilon_1 A_\mathrm{UU}^{\cos\phi_h}\cos\phi_h + \varepsilon_2 A_\mathrm{UU}^{\cos 2\phi_h}\cos 2\phi_h + \lambda\varepsilon_3 A_\mathrm{LU}^{\sin\phi_h}\sin\phi_h)$$

- Azimuthal asymmetries are obtained by fitting the cross-section on the measured ϕ_h distributions
- Asymmetries are directly connected to the structure functions:

$$A_\mathrm{XU}^{f(\phi_h)}(x, z, P_\mathrm{T}^2, Q^2) \equiv \frac{F_\mathrm{XU}^{f(\phi_h)}}{F_\mathrm{UU}} \qquad F_\mathrm{UU} = F_\mathrm{UU,T} + F_\mathrm{UU,L}$$

→ $A_\mathrm{UU}^{\cos\phi_h}$: Cahn effect – negative modulation expected

→ $A_\mathrm{UU}^{\cos 2\phi_h}$: Boer–Mulders effect

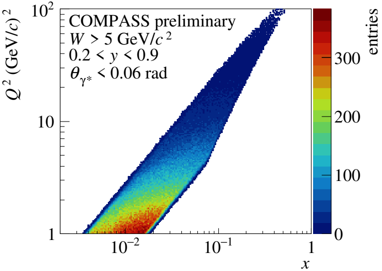
→ $A_\mathrm{LU}^{\sin\phi_h}$: higher-twist effects

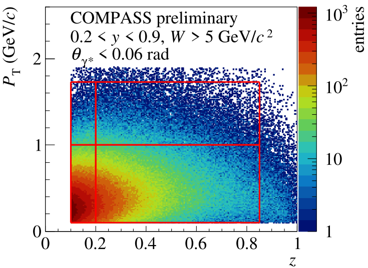
Data sample, kinematic range and binning

- Results of 2016 unpolarized SIDIS previously presented [DIS 2022] [SPIN 2023]
- **New**: 2x larger data sample, radiative corrections in z, x and P_{T} bins
- Reasonable acceptance → kinematical coverage:

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

→ enlarged in z down to 0.1 and P_{T} up to 1.73 to include more bins

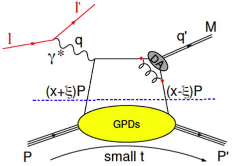




Background treatment

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

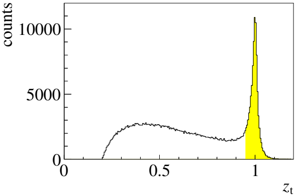
→ large amplitudes of azimuthal modulations for decay products



- In case of hadrons from EVMs:
  - **visible hadron pairs**
    - both hadrons reconstructed
    - rejected using '**EVM cut**':

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

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

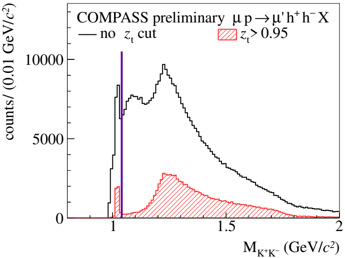


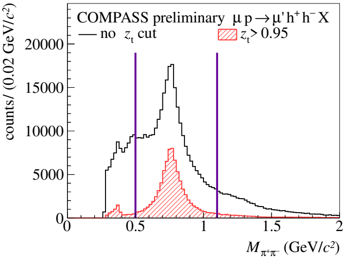
[NPB 956 (2020) 115039]

Visible hadron pairs: looking for EVM

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

$$\rho \to \pi^+\pi^- : M_{K^+K^-} \in [1.04, \infty] \ \mathrm{GeV}/c^2$$
$$\text{and } M_{\pi^+\pi^-} \in [0.5, 1.1] \ \mathrm{GeV}/c^2$$
$$\phi \to K^+K^- : M_{K^+K^-} \in [0, 1.04] \ \mathrm{GeV}/c^2$$

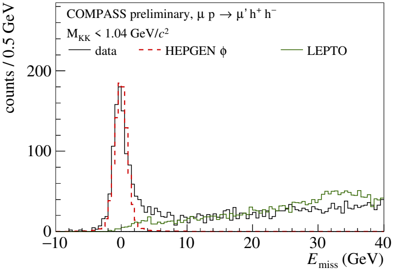


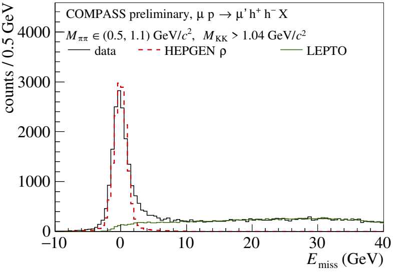


Subtraction of invisible hadrons from EVM decays

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

$$E_{\text{miss}} = \frac{M_X^2 - M_p^2}{2M_p} \qquad M_X^2 = (p + q - P_{h^+} - P_{h^-})^2$$

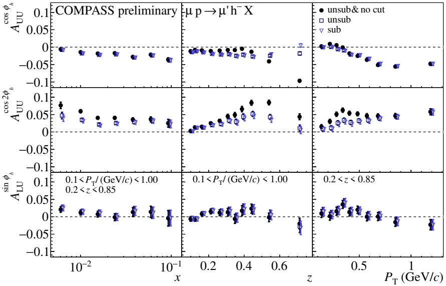




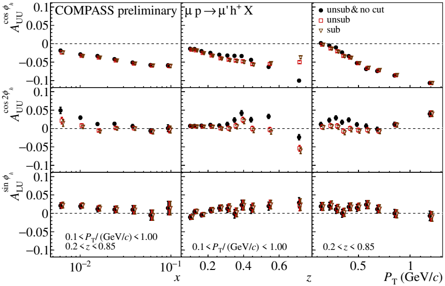
Effect of EVM cut and subtraction

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

negative hadrons

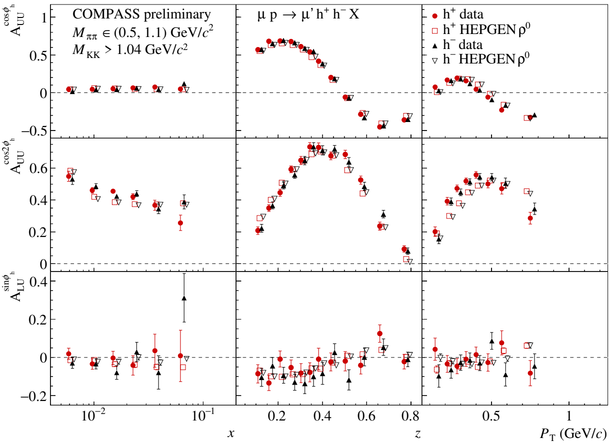


positive hadrons



Azimuthal asymmetries of visible hadron pairs in data and HEPGEN

- HEPGEN nicely describes modulations in measured data thanks to SDMEs being plugged in [EPJC (2023) 83 924]

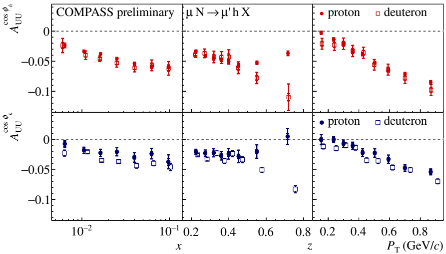


Comparison of results on proton and deuteron target

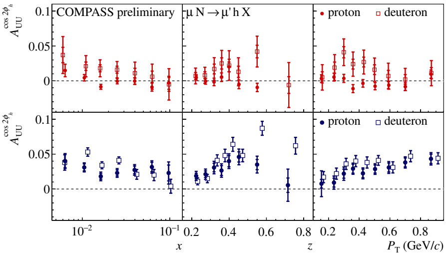
- Results on deuteron target
  - preliminary in P_{T}, z and x binning
  - in $P_{\mathrm{T}} : z : x$ binning [NPB 956 (2020) 115039]
- Differences in results on proton (u quark dominant) and deuteron (isoscalar) target

→ possible quark flavour dependence of structure functions

$A_{\mathrm{UU}}^{\cos\phi_h}$



$A_{\mathrm{UU}}^{\cos 2\phi_h}$



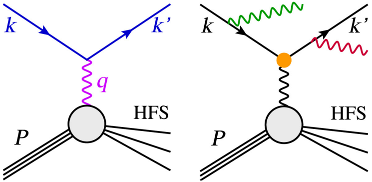
Radiative corrections

- 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



[M. Arratia et al., kinematics of DIS]

- impact of RE in hadronic variables (such as ϕ_h) accessed only through simulations
- DJANGOH: modified LEPTO generator with hadronization in JETSET and SOPHIA [K. Charchuła et al., DJANGOH]

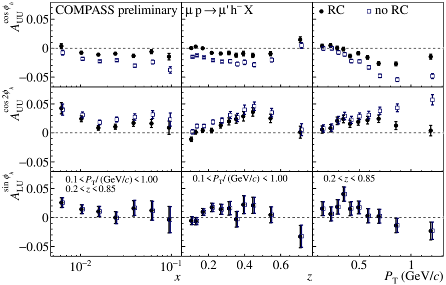
- applied by dividing fraction RC from ϕ_h distributions bin-by-bin

$$RC(\phi_h) = \frac{N_h^{\text{RE-on}}}{N_h^{\text{RE-off}}}$$

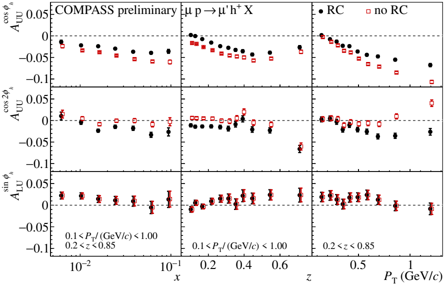
Effect of radiative corrections on results

- The effect on azimuthal asymmetries grows with P_{T}, x and goes down with z
- No effect is observed, or expected for $A_{\mathrm{LU}}^{\sin\phi_h}$

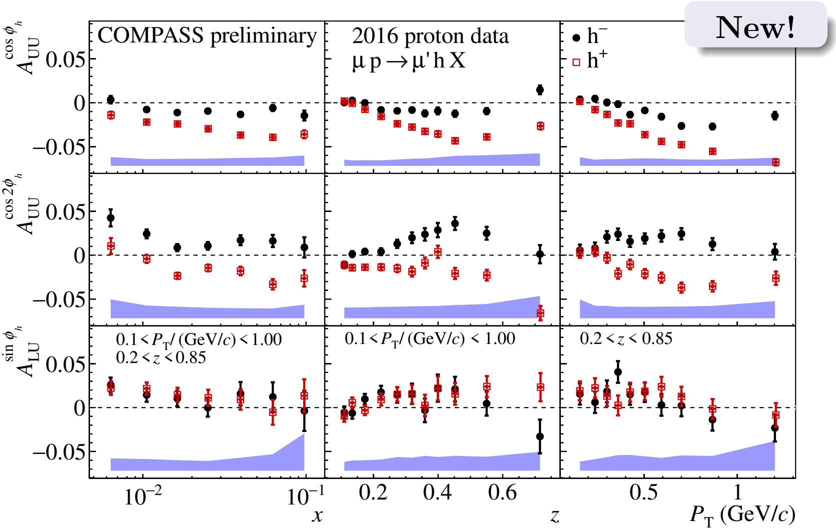
negative hadrons



positive hadrons



Final results corrected on radiative effects



- systematic uncertainty is denoted as a band at the bottom (common for $h^{\pm}$)

Summary and conclusions

- **2016 unpolarized SIDIS on proton target**
  - New preliminary results of azimuthal asymmetries corrected on RE in 1D binning of z, x and P_{T}

  → significant effect of the radiative corrections

  → significant effect of excluding background from EVMs
  - Ongoing work on radiative corrections in $P_{\mathrm{T}} : z : x$ and $x : Q^2$ binning

  ⇒ Paper drafting to be started soon

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Thank you for your attention!