Radiative correction for unpolarized SIDIS at COMPASS

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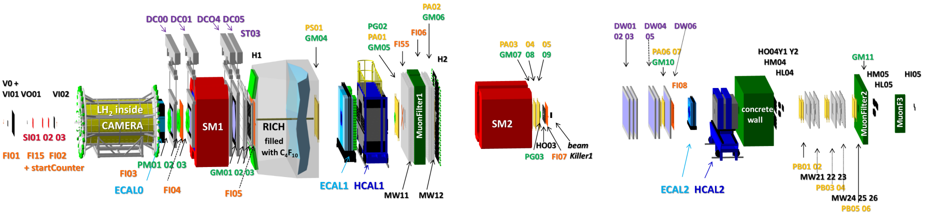
PRIMUS

COMPASS

COMPASS experiment at CERN

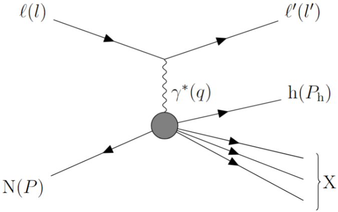
- COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) is a fixed target experiment at CERN
- 20 years of data measurement between 2002–2022 dedicated to spectroscopy and nucleon structure
- 2016–2017 setup: liquid hydrogen target, 160 GeV/c longitudinally polarized $\mu^{\pm}$ beam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



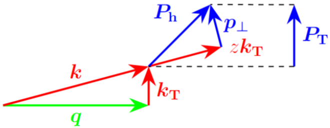
Unpolarized SIDIS

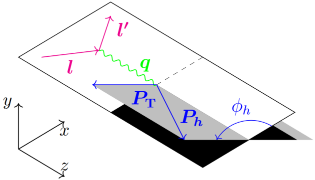
- SIDIS:

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



- 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., JHEP0702(2007)]

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

  - P_T^2 distributions at twist 2: $F_{UU} = F_{UU,T} + \varepsilon F_{UU,L} \approx F_{UU,T}$

$$\frac{d\sigma}{dx\,dQ^2\,dz\,dP_T^2} = \frac{2\pi^2\alpha^2}{xyQ^2}\frac{\left[1+(1-y)^2\right]}{y^2}F_{UU}$$

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

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

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- Leading twist description of unpolarized SIDIS:

TMD-PDFs $f^q(x,k_{\mathrm{T}},Q^2)$:
- 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 $\frac{1}{Q}$:

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

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

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

Unpolarized SIDIS – azimuthal asymmetries

- Unpolarized SIDIS cross-section:

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

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

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

→ $A_{\mathrm{UU}}^{\cos\phi_h}$: Cahn effect with negative weight

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

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

Data sample, kinematic range and binning

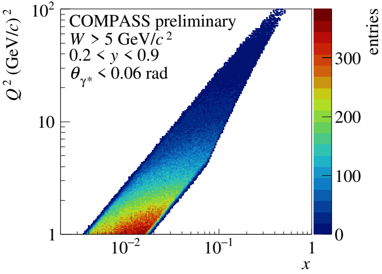
- Results of 2016 unpolarized SIDIS presented previously:
  - [DIS 2022]
  - [SPIN 2023]
  - [DIS 2024]
- Kinematical coverage:

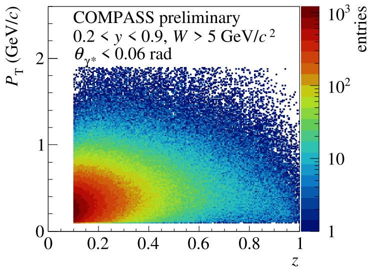
$0.2 < y < 0.9$ $\quad$ $0.003 < x < 0.130$

$Q^2 > 1\ \mathrm{GeV}^2/c^2$ $\quad$ $\theta_\gamma < 60$ mrad

$0.2 < z < 0.85$ $\quad$ $W > 5\ \mathrm{GeV}/c^2$

$0.1\ \mathrm{GeV}/c < P_\mathrm{T} < 1.0\ \mathrm{GeV}/c$





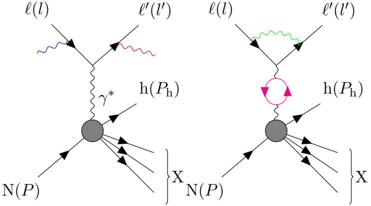
Radiative corrections

- 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



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

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

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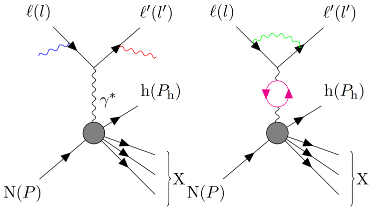

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- DJANGOH: modified LEPTO generator with hadronization in JETSET and SOPHIA [K. Charchuła et al., DJANGOH]

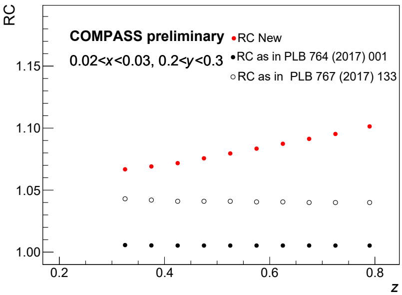
- applied by multiplying P_T^2 distributions bin-by-bin by fraction η

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

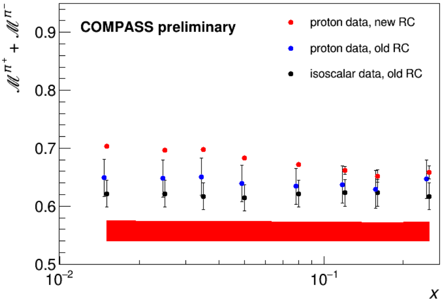
Old radiative corrections at COMPASS

- **Inclusive correction** based on TERAD in previous COMPASS results on multiplicities of charged hadrons
  - Multiplicities of $\pi^{\pm}$ [Phys.Lett.B 764 (2017)]
  - Multiplicities of $K^{\pm}$ [Phys.Lett.B 767 (2017)]

→ No dependence on hadronic variables (ϕ_h, z, P_T) included in TERAD



$RC \equiv \eta$

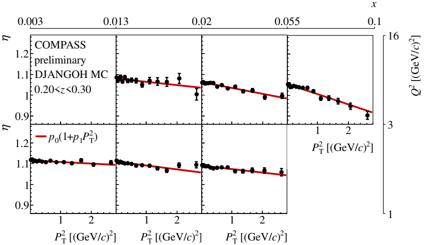


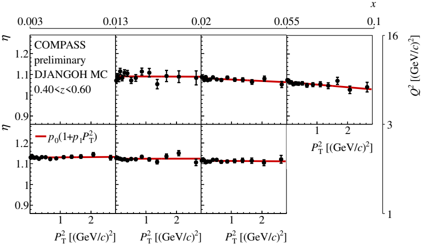
RC for P_T^2 distributions

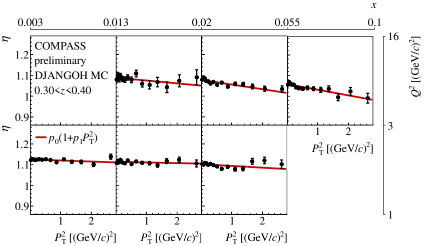
New!

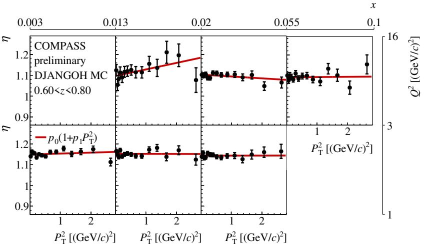
- Distributions of η of charged hadrons in $x : Q^2 : z : P_T^2$ dependence

$\rightarrow$ linear P_T^2 dependence with mostly negative slopes









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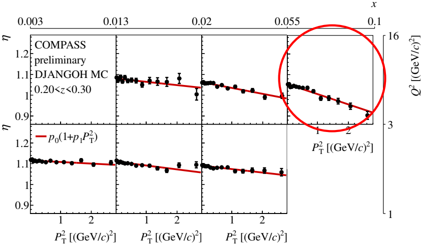
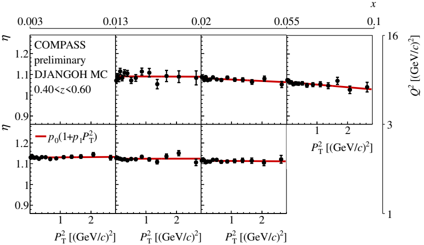
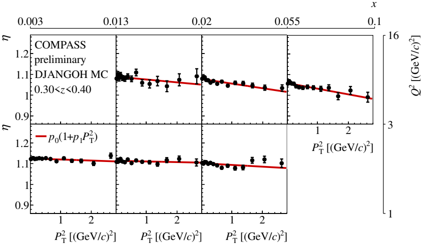
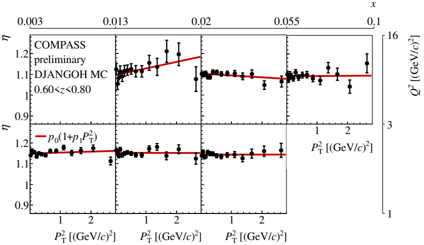








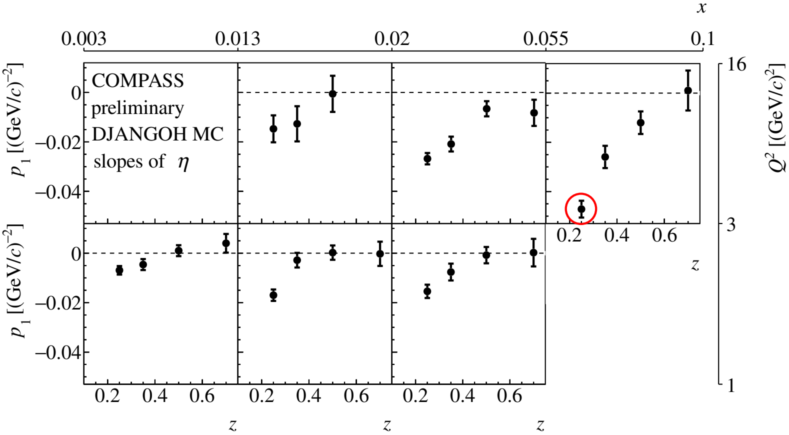
Effect of RC on P_T^2 distributions

New!

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

→ largest correction (slope) in:

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



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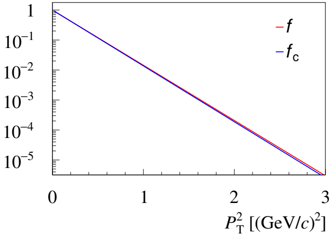
- Assume exponential shape of the P_T^2 distributions before the correction:

$$f(P_T^2) = A \exp\left(-\frac{P_T^2}{\langle P_T^2 \rangle}\right) \quad \rightarrow \quad f_c(P_T^2) = A(1 + p_1 P_T^2) \exp\left(-\frac{P_T^2}{\langle P_T^2 \rangle}\right)$$



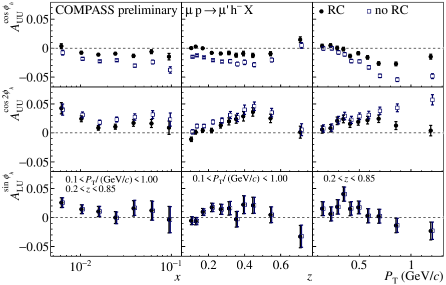
- **small effect**
- size compatible to the statistical error

$\rightarrow$ RC cannot be neglected

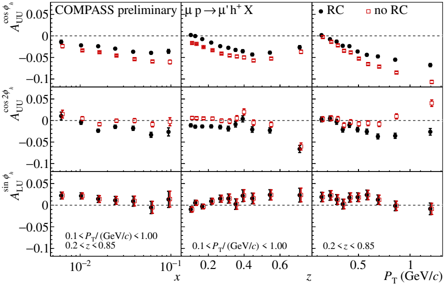
Effect of RC on azimuthal asymmetries

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

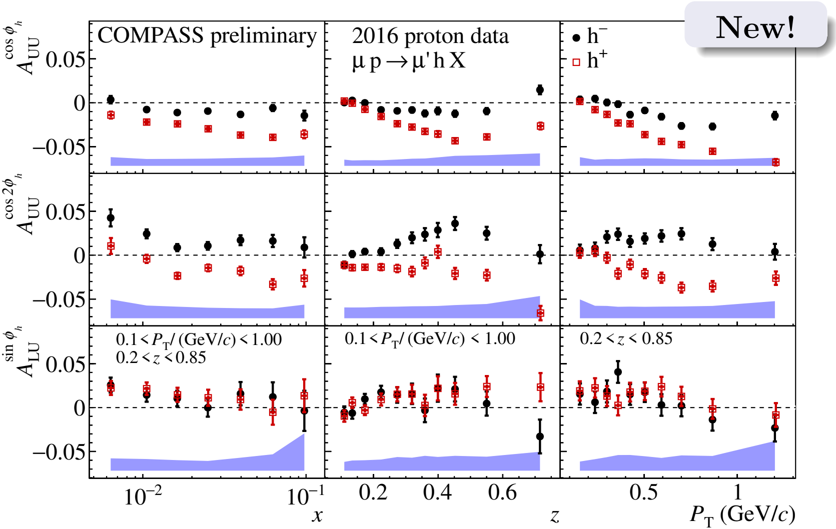
negative hadrons



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

azimuthal asymmetries

- New preliminary results of azimuthal asymmetries corrected on RE in 1D binning of z, x and P_{T}

$\rightarrow$ significant effect of the radiative corrections

- Ongoing work on applying RC on measured azimuthal asymmetries in 2D and 3D binnings

P_{T}^2 distributions

- RE on P_{T}^2 distributions are small, but larger than σ_{stat}
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$\Rightarrow$ **Paper drafting to be started soon**

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Thank you for your attention!

Supported by: Charles University grant PRIMUS/22/SCI/017