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Collins effect in pion-in-jet production in polarized *pp* and *ep* collisions

Carlo Flore
Università di Cagliari & INFN - Sezione di Cagliari

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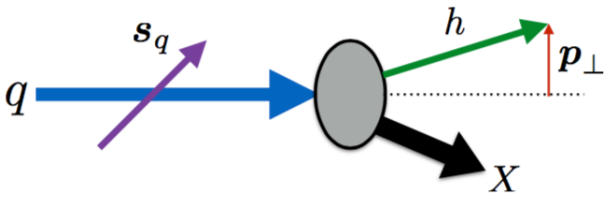
Bologna
May 5th, 2026

U. D'Alesio, CF, M. Zaccheddu,
Phys. Lett. B 871 (2025) 140024 & arXiv:2605:02890 [hep-ph]

Introduction - the Collins function



J.C. Collins, NPB 396:161-182 (1993)

$$D_{h/q^\uparrow}(z, \mathbf{p}_\perp) - D_{h/q^\uparrow}(z, -\mathbf{p}_\perp)$$
$$= \Delta^N D_{h/q^\uparrow}(z, p_\perp^2) \frac{(\hat{\mathbf{p}}_q \times \mathbf{p}_\perp) \cdot \mathbf{s}_q}{|\mathbf{p}_\perp|} \quad (TO - CA)$$
$$= -\frac{2|\mathbf{p}_\perp|}{z m_h} H_1^{\perp q}(z, p_\perp^2) \frac{(\hat{\mathbf{p}}_q \times \mathbf{p}_\perp) \cdot \mathbf{s}_q}{|\mathbf{p}_\perp|} \quad (Amsterdam)$$

- genuine TMD fragmentation function

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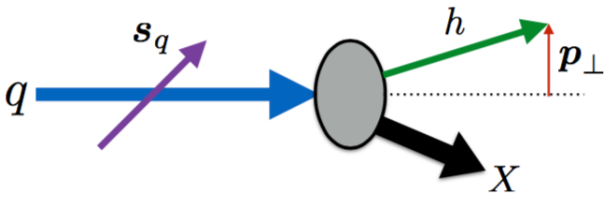

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- genuine TMD fragmentation function
- express correlation between quark transverse polarization and produced hadron $\mathbf{p}_\perp$

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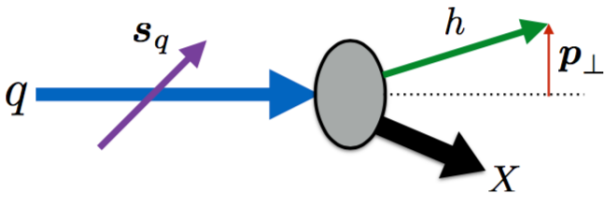

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- genuine TMD fragmentation function
- express correlation between quark transverse polarization and produced hadron $\mathbf{p}_\perp$
- extracted, together with TMD transversity h_1^q, in global fits of SIDIS azimuthal asymmetries:

$$A_{UT}^{\sin(\phi_h+\phi_S)} = \frac{2(1-y)}{1+(1-y)^2}\frac{F_{UT}^{\sin(\phi_h+\phi_S)}}{F_{UU,T}} \sim \frac{\mathcal{C}\left[h_1^q H_1^{\perp q}\right]}{\mathcal{C}\left[f_1^q D_1^q\right]}$$

and $e^+e^- \to h_1 h_2 X$ azimuthal asymmetries (double ratio):

$$\frac{R_0^U}{R_0{}^{L(C)}} = \frac{1+P_0^U\cos(2\phi_1)}{1+P_0^{L(C)}\cos(2\phi_1)} \simeq 1+\cos(2\phi_1)A_0^{UL(UC)} \sim \mathcal{C}\left[H_1^{\perp \bar{q}} H_1^{\perp q}\right]$$

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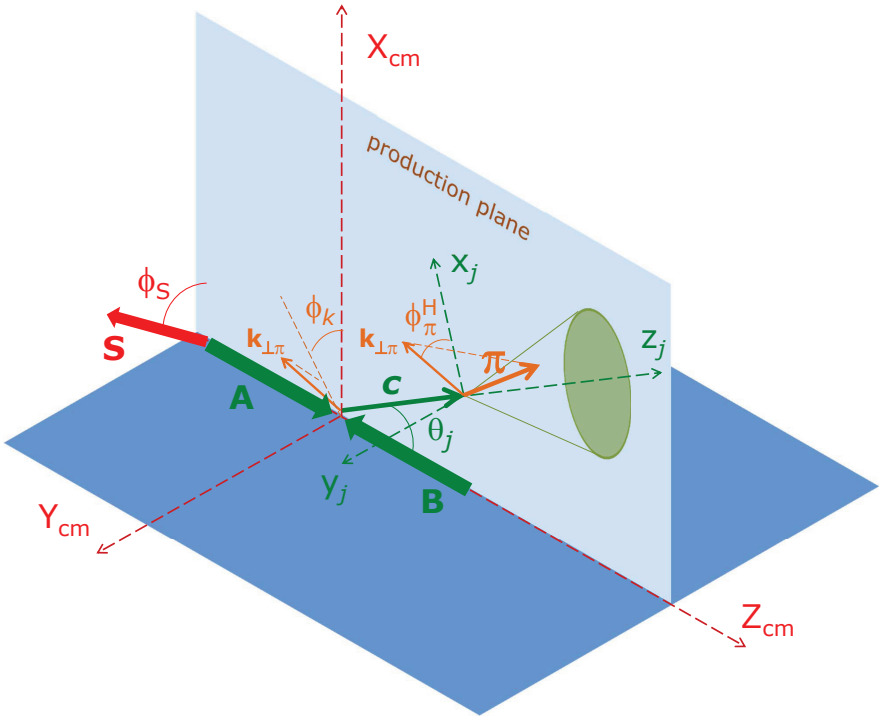
Introduction - hadron-in-jet production

U. D'Alesio, F. Murgia, C. Pisano, PRD 83 (2011) 034021 & PLB 773 (2017) 300
U. D'Alesio, CF, M. Zaccheddu, PLB 871 (2025) 140024 & in preparation



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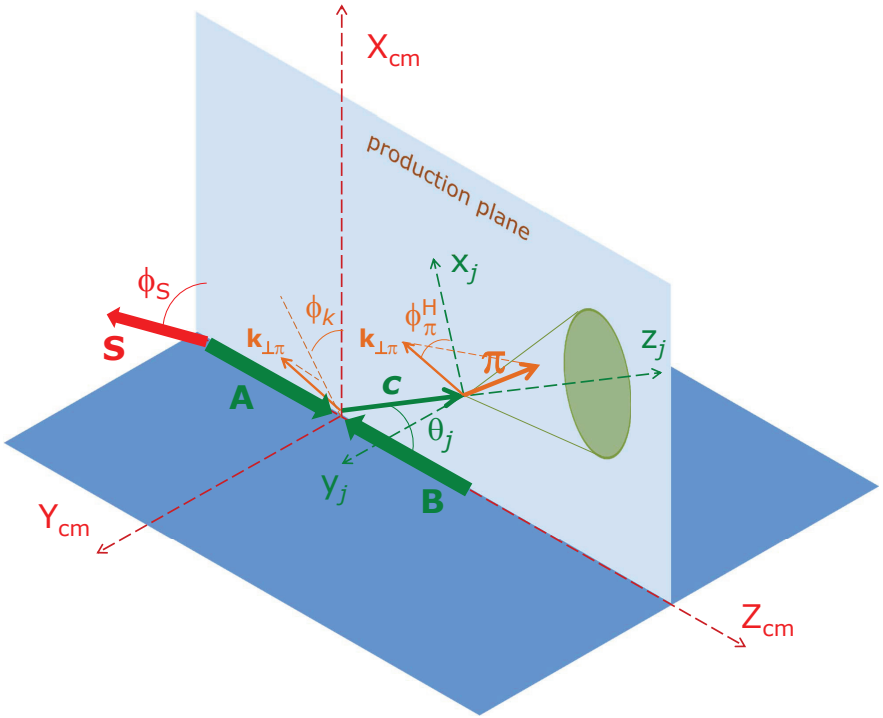

- a two scale process:
  - small $k_{\perp\pi}$
  - large p_{jT}

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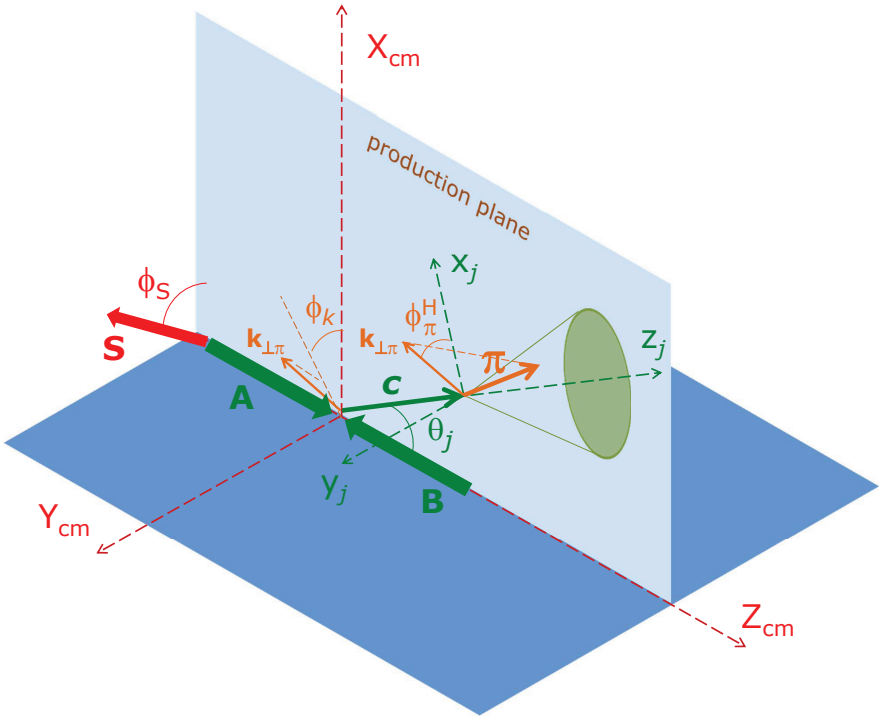

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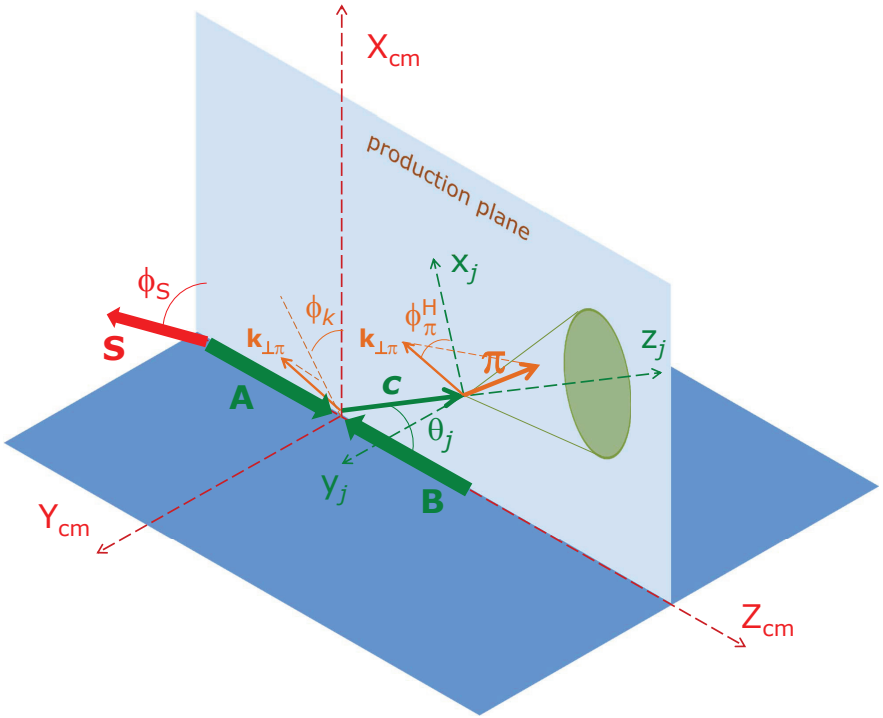

- a two scale process:
  - small $k_{\perp\pi}$
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- TMD effects only in the final state
- differential cross section:

$$\frac{E_j\, d\sigma^{p(S,\phi_S)p\to \text{jet}\,\pi(\phi_\pi^H)\,X}}{d^3\boldsymbol{p}_j\, dz\, d^2\boldsymbol{p}_{\perp\pi}\, d\phi_S} \equiv d\sigma(\phi_S, \phi_\pi^H)$$

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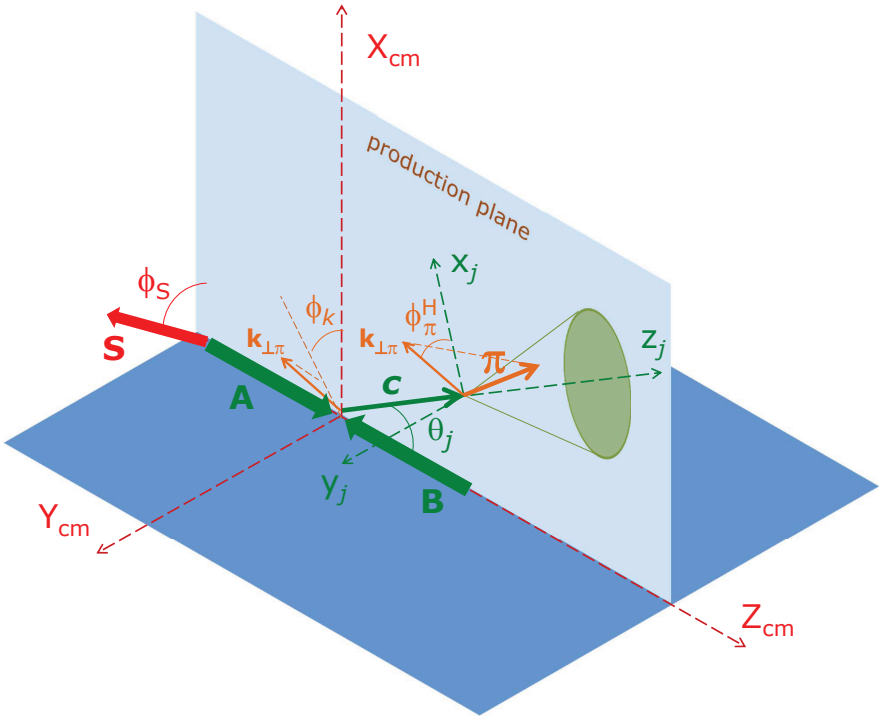

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- Collins azimuthal asymmetry:

$$A_N^{\sin(\phi_S-\phi_\pi^H)}(\boldsymbol{p}_j, z, p_{\perp\pi}) = 2\,\frac{\int d\phi_S\, d\phi_\pi^H\, \sin(\phi_S-\phi_\pi^H)\,[\,d\sigma(\phi_s,\phi_\pi^H) - d\sigma(\phi_s+\pi,\phi_\pi^H)\,]}{\int d\phi_S\, d\phi_\pi^H\,[\,d\sigma(\phi_s,\phi_\pi^H) + d\sigma(\phi_s+\pi,\phi_\pi^H)\,]}$$

$$N[A_N^{\sin(\phi_S-\phi_\pi^H)}] \sim \sum_{a,b,c,d} h_1^a(x_a) \otimes f_1^b(x_b) \otimes \Delta\hat{\sigma}^{ab\to cd} \otimes H_1^{\perp\, c}(z, \boldsymbol{p}_{\perp\pi}^2)$$

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Parametrizations

M. Boglione, U. D'Alesio, CF, J.O. Gonzalez-Hernandez, F. Murgia, A. Prokudin, PLB 854 (2024) 138712

- transversity (at $Q_0^2 = 0.81\ \text{GeV}^2$):

$$h_1^q(x, Q_0^2) = \mathcal{N}_q^T(x)\frac{1}{2}\left[f_{q/p}(x, Q_0^2) + g_{1L}^q(x, Q_0^2)\right]$$

where

$$\mathcal{N}_q^T(x) = N_q^T x^\alpha (1-x)^\beta \frac{(\alpha+\beta)^{\alpha+\beta}}{\alpha^\alpha \beta^\beta}, \quad (q = u_v, d_v)$$

- h_1^q fulfils the Soffer Bound, applied a posteriori

U. D'Alesio, CF, A. Prokudin, PLB 803 (2020) 135347

- Collins FF:

$$H_1^{\perp q}(z, p_\perp^2) = \mathcal{N}_q^C(z)\frac{z m_h}{M_C}\sqrt{2e}\, e^{-p_\perp^2/M_C^2} D_{h/q}(z, p_\perp^2), \ (q = \text{fav}, \text{unf})$$

$$\mathcal{N}_{\text{fav}}^C(z) = N_{\text{fav}}^C z^\gamma, \qquad \mathcal{N}_{\text{unf}}^C(z) = N_{\text{unf}}^C$$

- hard scale of the process: p_{jT}

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Pion-in-jet at STAR (I)

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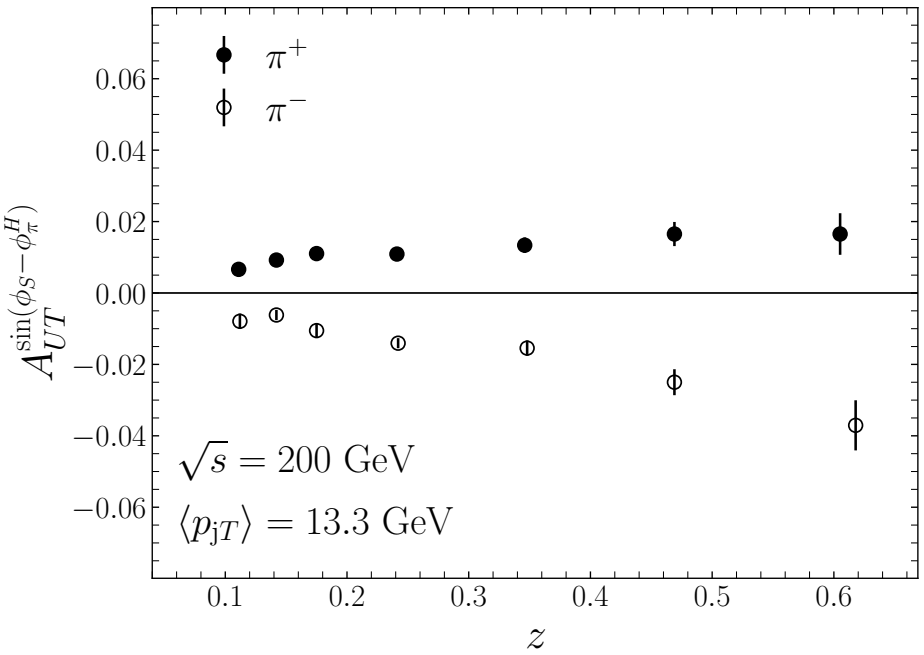

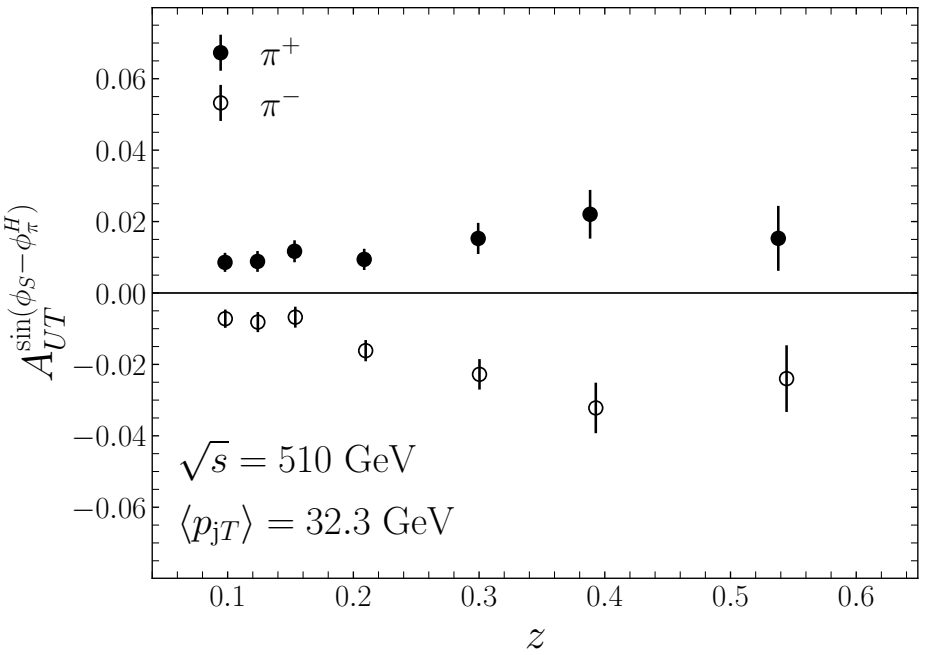

- STAR data at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 510$ GeV

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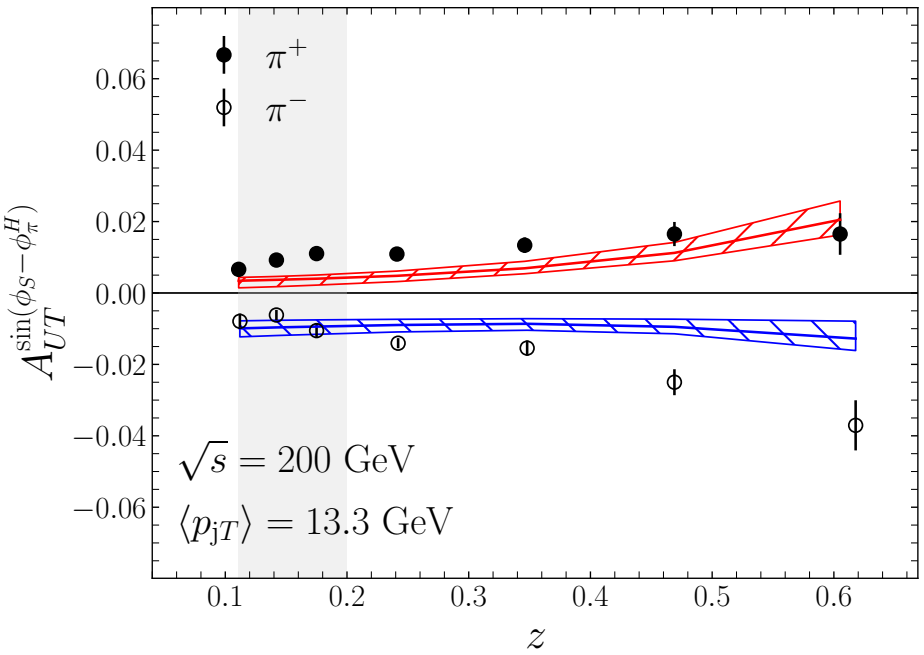

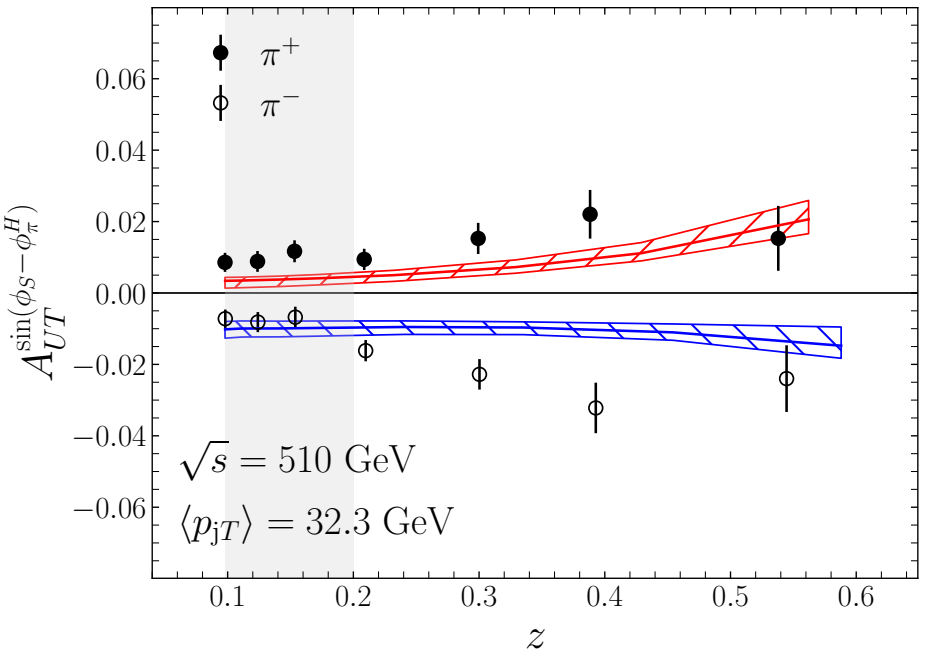

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- postdiction from updated fit of SIDIS and e^+e^- data

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- shaded area not covered in the kinematical coverage of SIDIS and and e^+e^- data

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Pion-in-jet at STAR (II)

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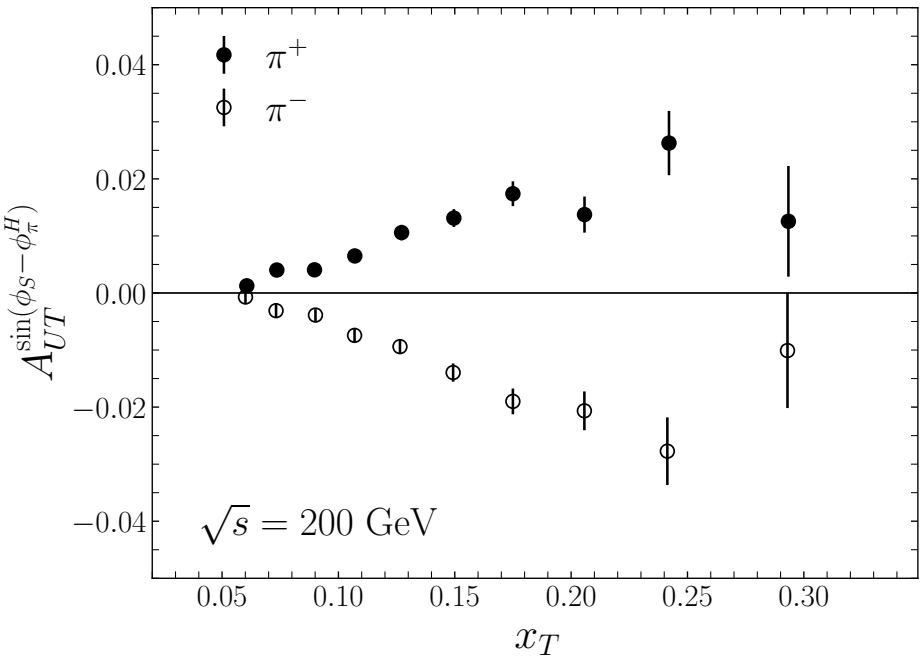

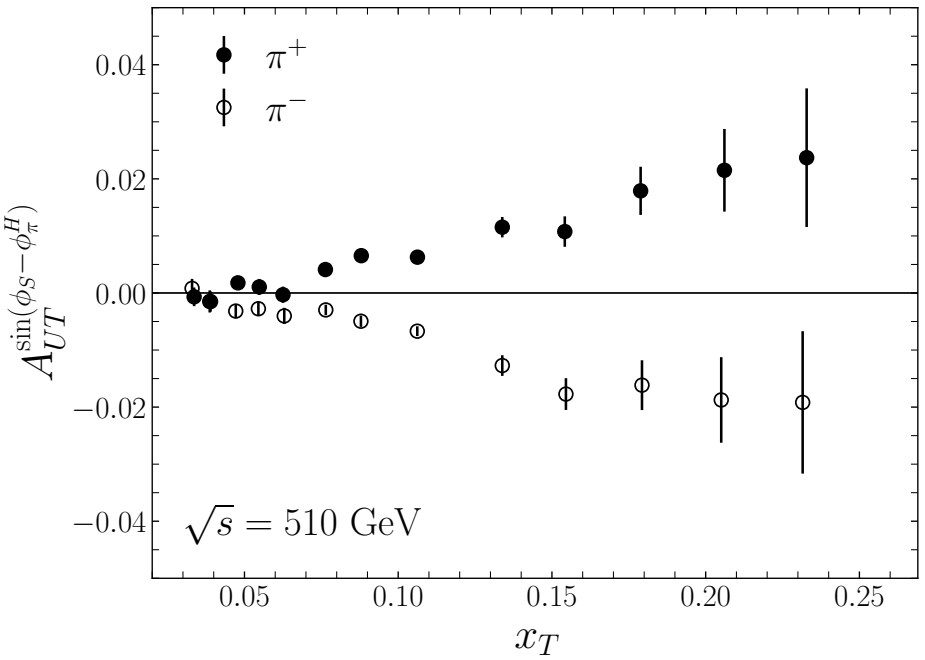

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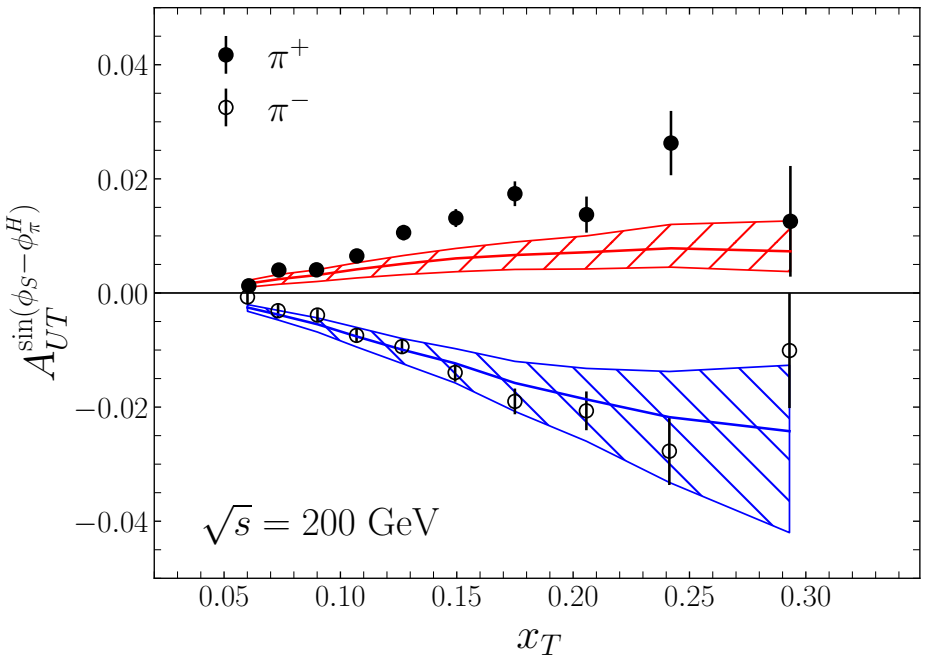

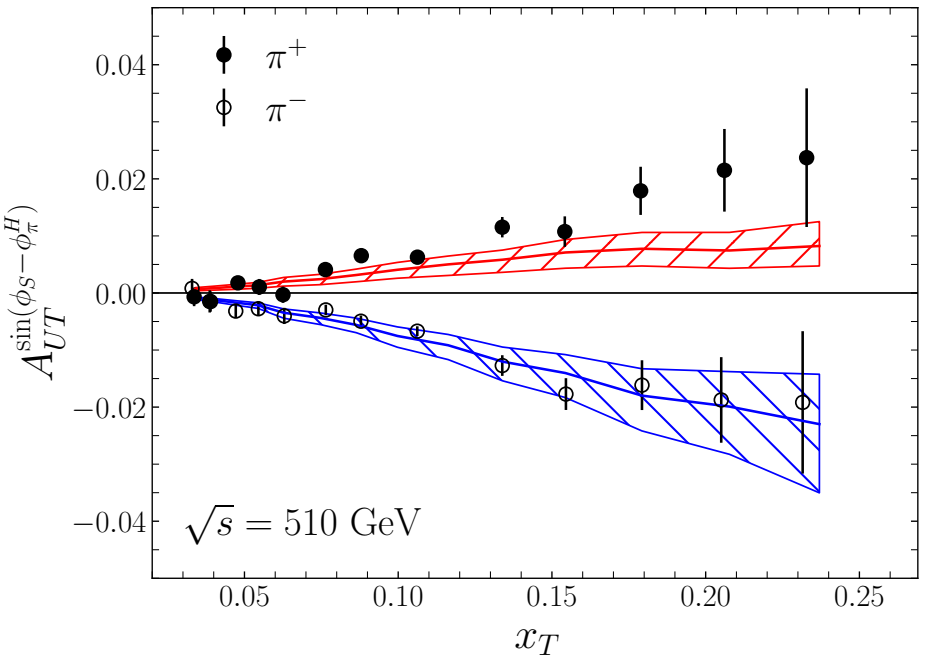

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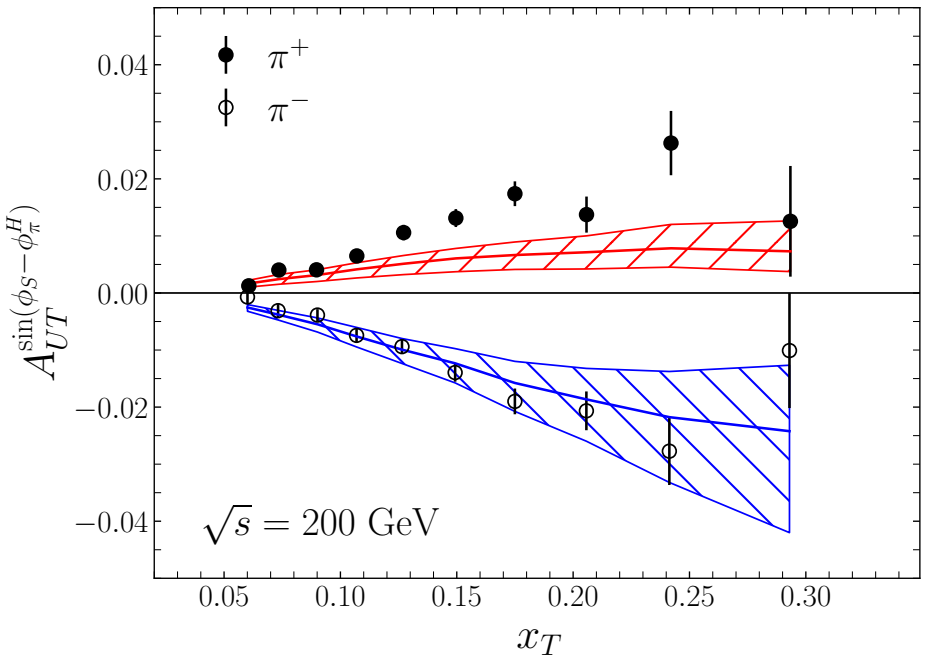

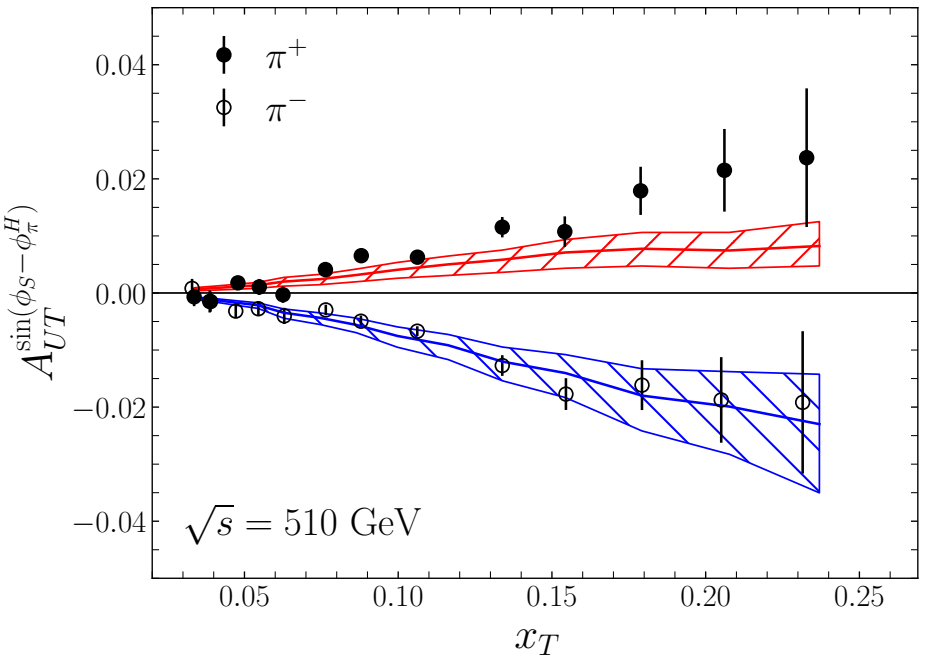

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- good overall agreement with STAR data

[also for j_T-dependence and binned data ⇒ backup slides]

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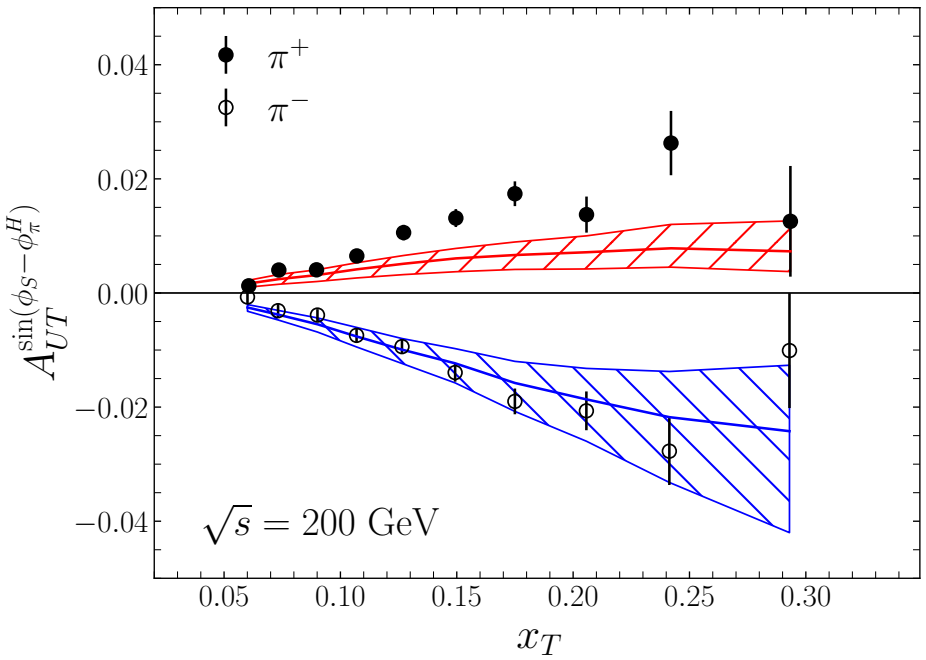

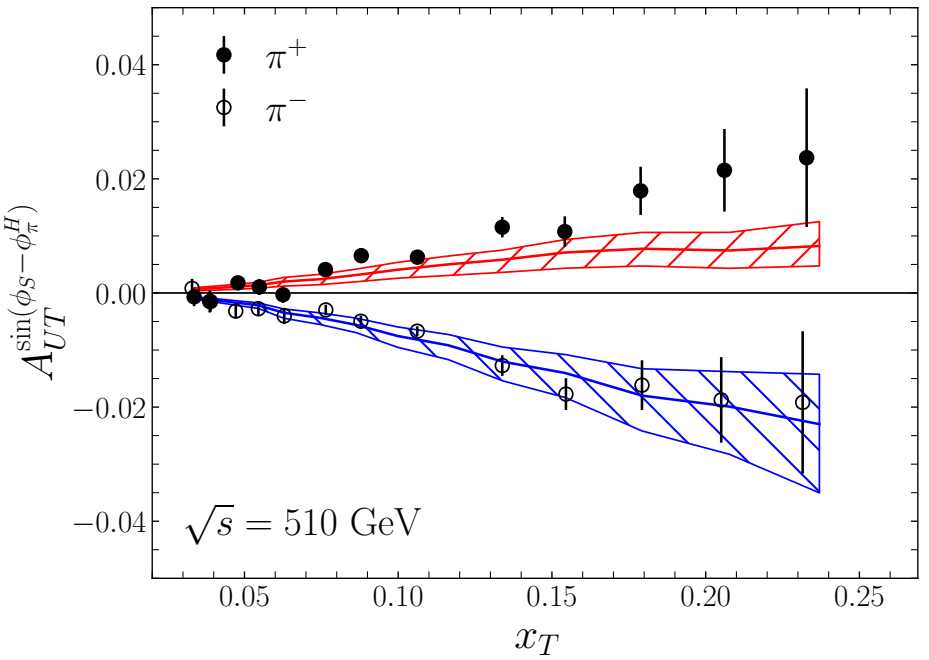

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- support for universality of the Collins function and for TMD factorization for this process

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Pion-in-jet at the EIC

U. D'Alesio, CF, M. Zaccheddu, arXiv:2605.02890 [hep-ph]

- $\ell N^{\uparrow} \to \text{jet}\, h\, X$ is a simpler process w.r.t. $p^{\uparrow} p \to \text{jet}\, h\, X$ but also complementary
- at LO, it involves only $q\ell \to q\ell$ partonic scattering $\Rightarrow$ no gluon contribution

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- cross section:

$$d\sigma(\phi_S, \phi_h^H) = d\sigma_{\text{LO}}(\phi_S, \phi_h^H)$$

with

$$2\, d\sigma_{\text{LO}}^{\text{unp}}(\phi_h^H) \sim \sum_q f_{q/N}(x) \otimes d\hat{\sigma}_{q\ell\to q\ell} \otimes D_{h/q}(z, p_{\perp h}^2)\,,$$

$$d\Delta\sigma_{\text{LO}} \sim \sin(\phi_S - \phi_h^H) \sum_q h_1^q(x) \otimes d\Delta\hat{\sigma}_{q\ell\to q\ell} \otimes H_1^{\perp q}(z, p_{\perp h}^2)$$

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- cross section dominated by $Q^2 \sim 0$
  $\Rightarrow$ equivalent photon/ Weizsäcker-Williams approximation

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$$d\sigma(\phi_S, \phi_h^H) = d\sigma_{\text{LO}}(\phi_S, \phi_h^H) + d\sigma_{\text{WW}}(\phi_S, \phi_h^H)$$

with

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- cross section dominated by $Q^2 \sim 0$
  $\Rightarrow$ equivalent photon/ Weizsäcker-Williams approximation

$$d\sigma_{\text{WW}}(\ell N \to \text{jet}\, h\, X) = \int dy\, f_{\gamma/\ell}(y)\, d\sigma(\gamma N \to \text{jet}\, h\, X)$$

where

$$f_{\gamma/\ell}(y) = \frac{\alpha}{2\pi}\left[\frac{1+(1-y)^2}{y}\ln\frac{Q^2_{\text{max}}}{Q^2_{\text{min}}(y)} + 2m_\ell^2 y\left(\frac{1}{Q^2_{\text{max}}} - \frac{1}{Q^2_{\text{min}}(y)}\right)\right]$$

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Pion-in-jet at the EIC - WW contribution

U. D'Alesio, CF, M. Zaccheddu, arXiv:2605.02890 [hep-ph]

- unpolarized cross section receives new contributions:

$$2d\sigma^{\text{unp}}_{\text{WW}}(\phi_h^H) = \sum_{a,c,d} \int dy \frac{dx}{16\pi^2 \hat{s}} \delta(\hat{s}+\hat{t}+\hat{u})\, 2\Sigma^{\text{unp}}_{a\gamma\to cd}$$

where

$$2\Sigma^{\text{unp}}_{q\gamma\to qg} = f_{\gamma/\ell}(y)\, f_{q/N}(x)\, (|\hat{M}_1|^2 + |\hat{M}_2|^2)_{q\gamma}\, D_{h/q}(z, p_{\perp h}^2)$$
$$2\Sigma^{\text{unp}}_{q\gamma\to gq} = f_{\gamma/\ell}(y)\, f_{q/N}(x)\, (|\hat{M}_1|^2 + |\hat{M}_3|^2)_{q\gamma}\, D_{h/g}(z, p_{\perp h}^2)$$
$$2\Sigma^{\text{unp}}_{g\gamma\to q\bar{q}} = f_{\gamma/\ell}(y)\, f_{g/N}(x)\, (|\hat{M}_2|^2 + |\hat{M}_3|^2)_{g\gamma}\, D_{h/q}(z, p_{\perp h}^2)$$

[M_i's taken from U. D'Alesio, CF, F. Murgia, PRD 95 (2017) 094002]

- at the numerator, only quark-induced channel

$$d\Delta\sigma_{\text{WW}} \sim \sin(\phi_S - \phi_h^H) \sum_q f_{\gamma/\ell}(y) \otimes h_1^q(x) \otimes d\Delta\sigma_{q\gamma} \otimes H_1^{\perp q}(z, p_{\perp h}^2)$$

[All other spin transfers are zero and no h_1^g exists for a spin- 1/2 target]

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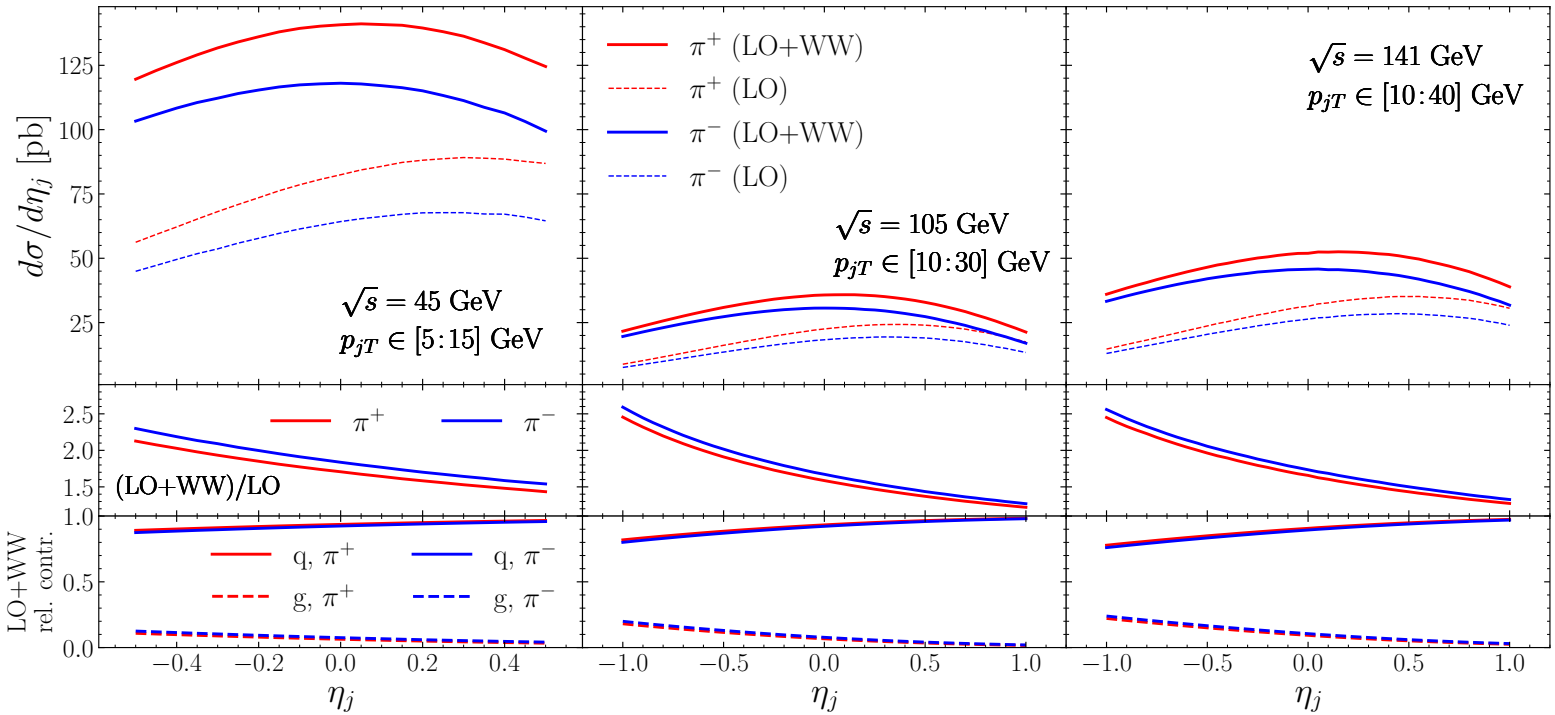
Pion-in-jet at the EIC - role of WW contribution

U. D'Alesio, CF, M. Zaccheddu, arXiv:2605.02890 [hep-ph]



- WW term heavily contributes to the cross section
  $\Rightarrow$ about $\times 2$ in the backward and $\times 1.5$ in the forward regions
- gluon-induced channels contribute mostly in the backward region
- quark-induced contribution still the dominant one
  $\sim$ 80-90% of the LO+WW cross section

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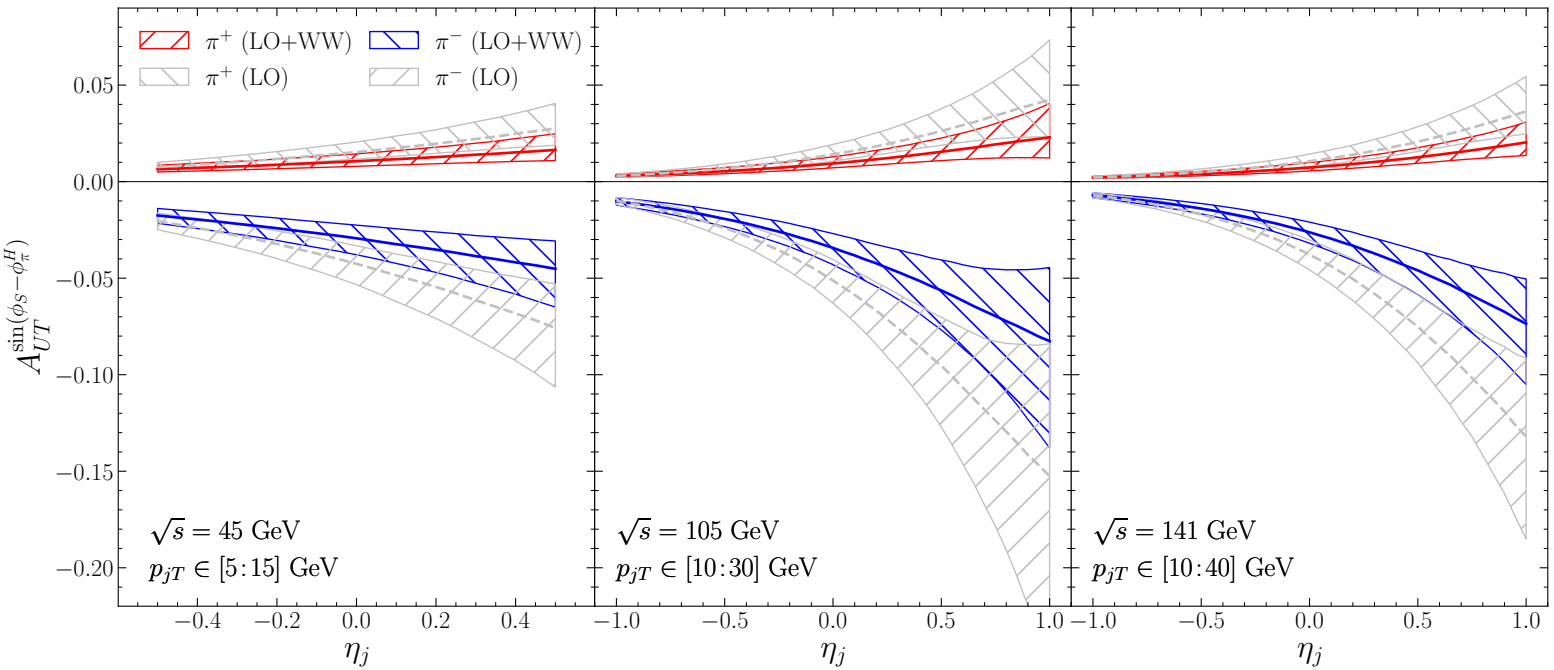
Pion-in-jet at the EIC - predictions (I)

U. D'Alesio, CF, M. Zaccheddu, arXiv:2605.02890 [hep-ph]



- median as central value, asymmetric bands at 2σ CL
- asymmetry decrease with inclusion of WW term, larger at forward rapidity:
  - (i) integrating over z, contribution from $H_1^{\perp\,\mathrm{fav}}$ partially suppressed w.r.t. the one of $H_1^{\perp\,\mathrm{unf}}$
  - (ii) larger values of x at forward rapidity $\Rightarrow h_1^{u_v}$ contribution more relevant

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Pion-in-jet at the EIC - predictions (II)

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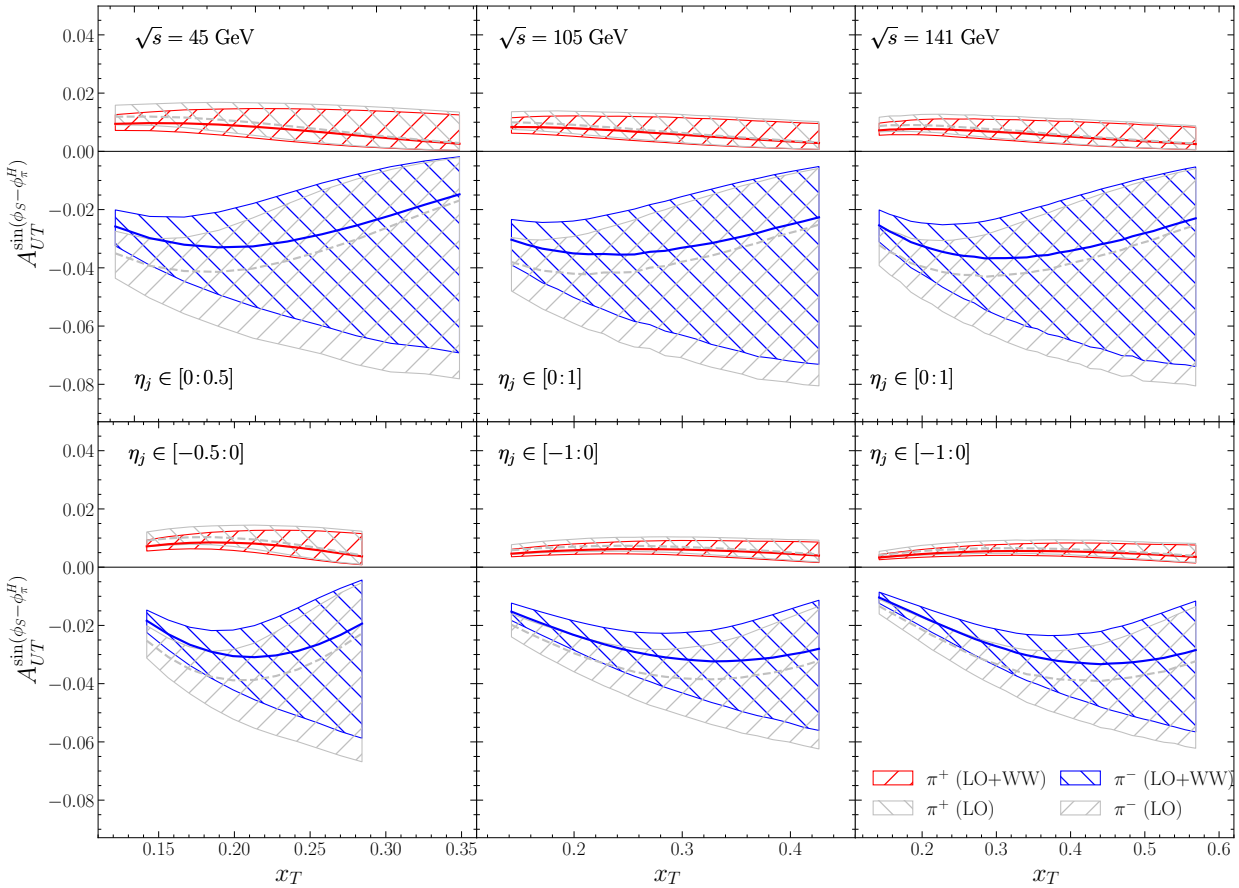

- same decrease at backward rapidity
- asymmetry at $\sim$ 1% for π^+, larger for π^- within larger uncertainties

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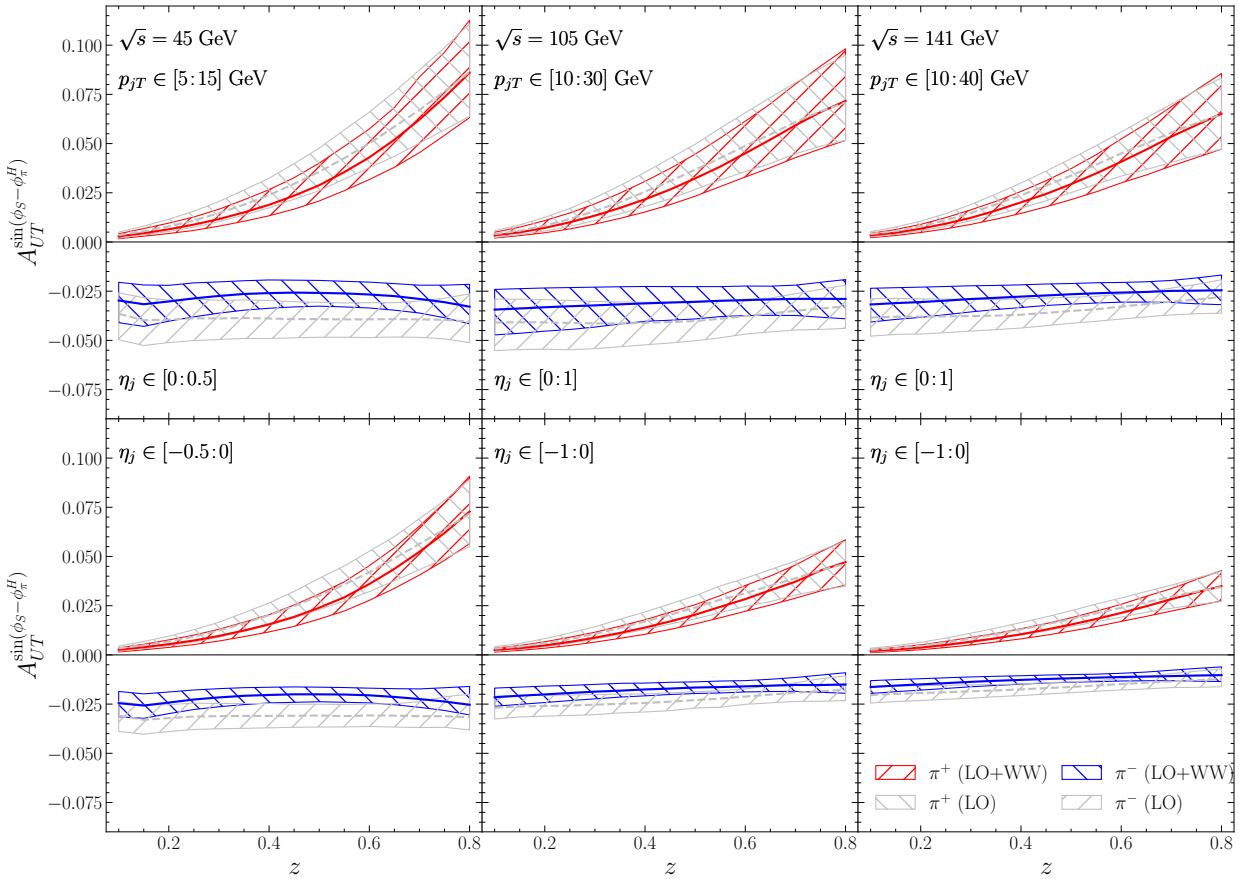
Pion-in-jet at the EIC - predictions (III)

U. D'Alesio, CF, M. Zaccheddu, arXiv:2605.02890 [hep-ph]



- larger asymmetries for π^+, up to 8%
- asymmetries larger than in the *pp* case $\Leftrightarrow$ gluons play a negligible role here
- sizeable asymmetries also w.r.t. j_T (backup slides)

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Conclusions and outlook

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Conclusions and outlook

- Support for universality of Collins function for hadron-in-jet production

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- good description of *pp* data from STAR

  data allow to improve and extend TMDs knowledge at large *x*

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  - further test of TMD factorization

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Thank you

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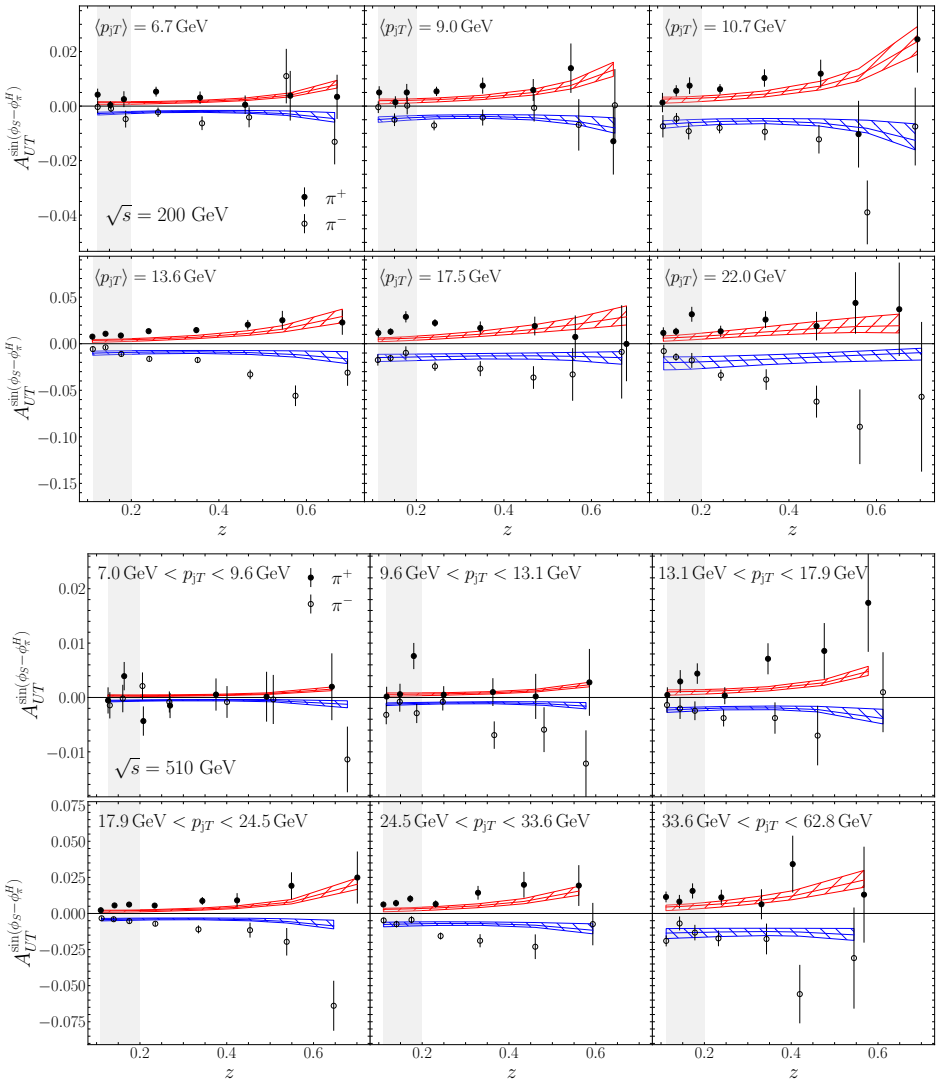
Backup

Pion-in-jet at STAR - binned data

U. D'Alesio, CF, M. Zaccheddu, PLB 871 (2025) 140024



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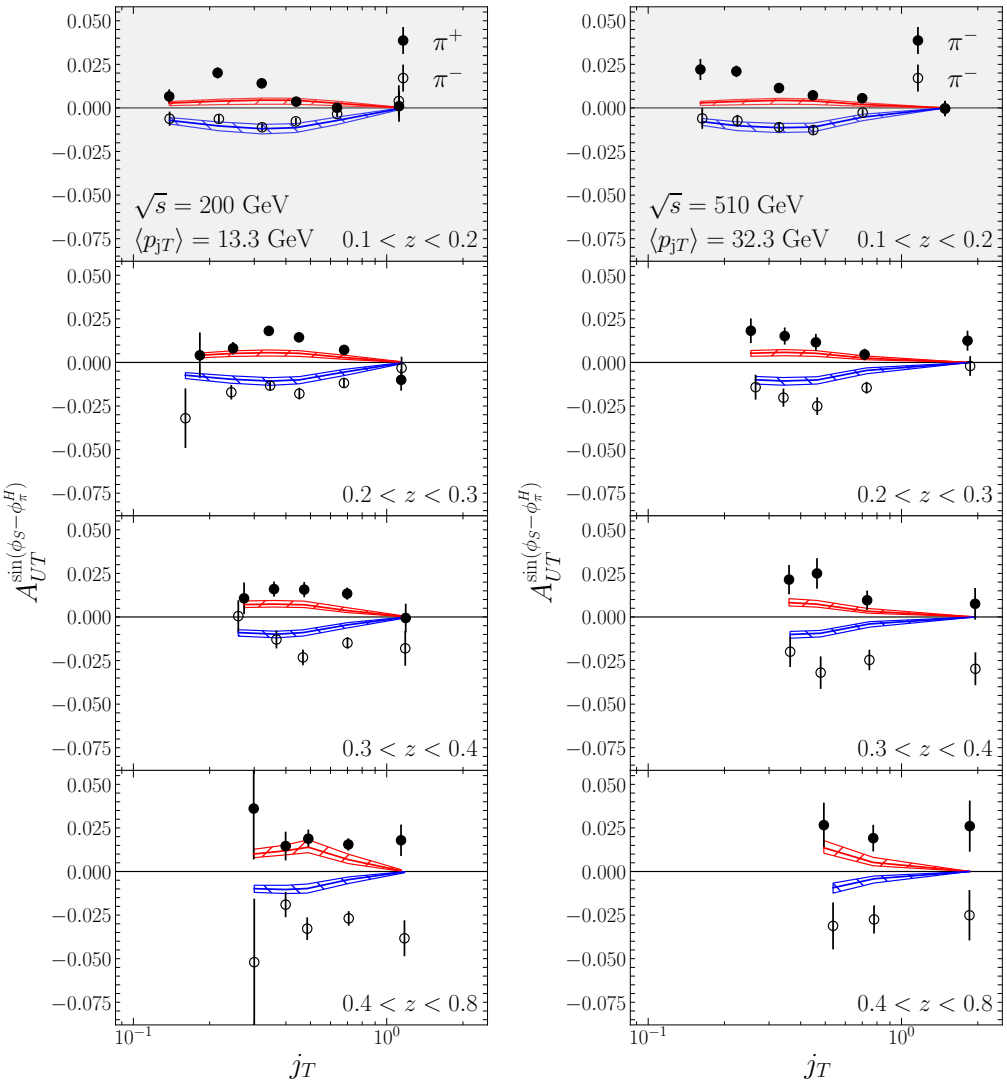
Pion-in-jet at STAR - j_T

U. D'Alesio, CF, M. Zaccheddu, PLB 871 (2025) 140024



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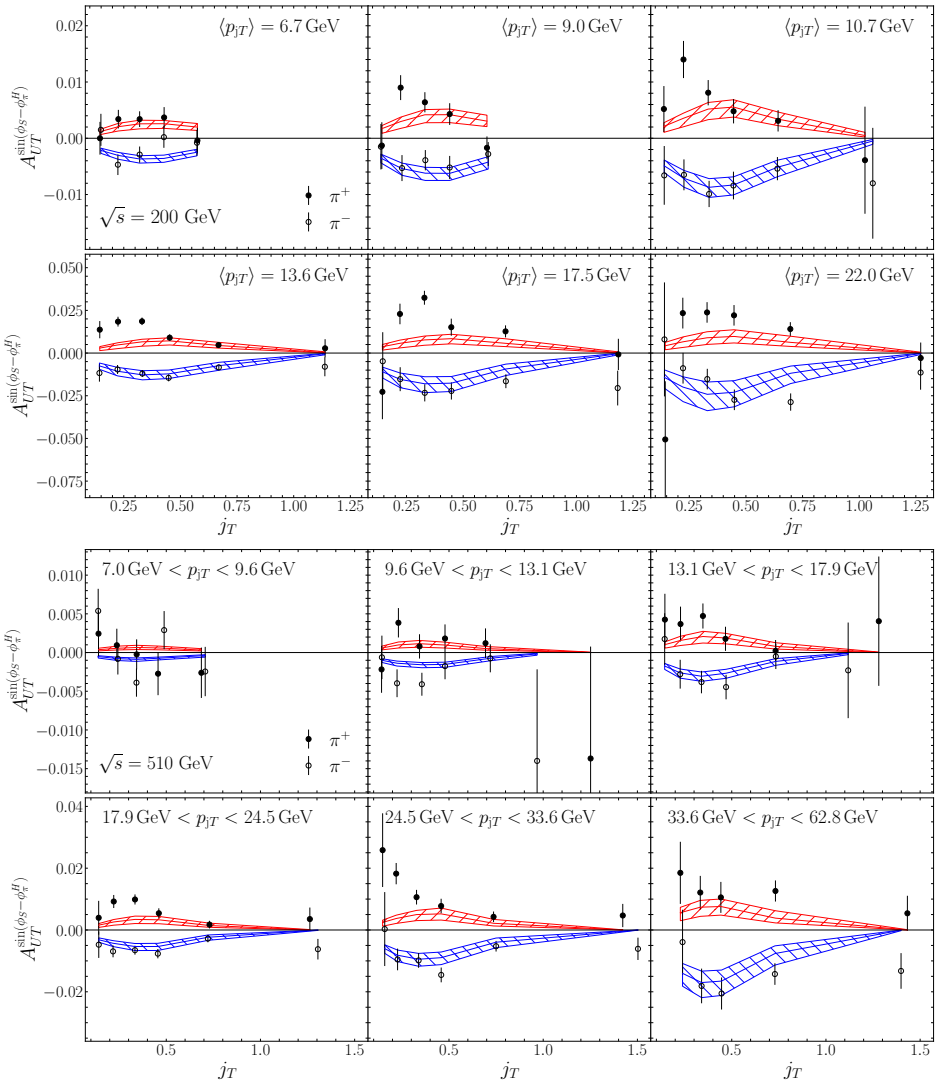

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Pion-in-jet at STAR - reweighted - GPM

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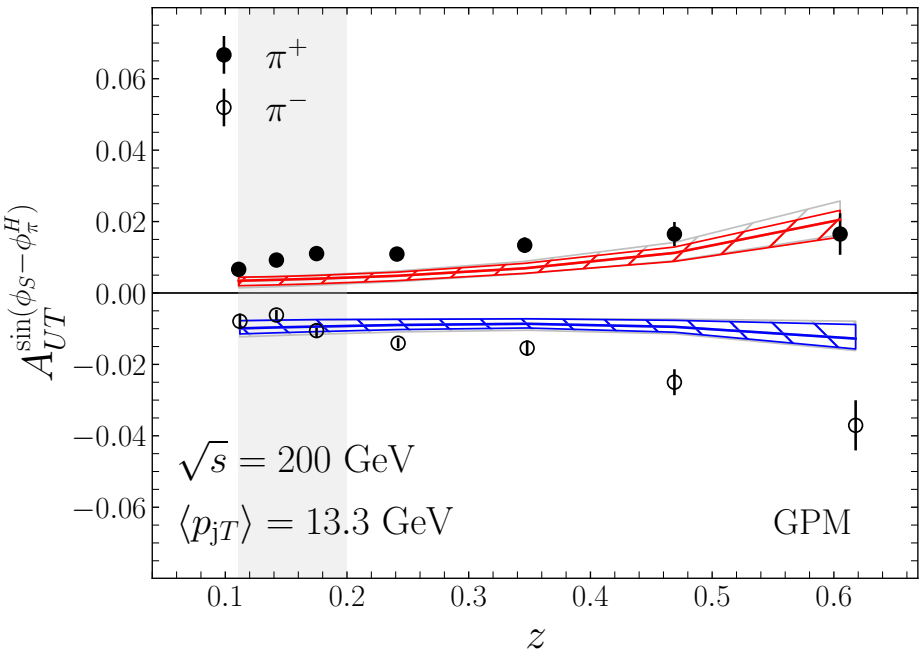

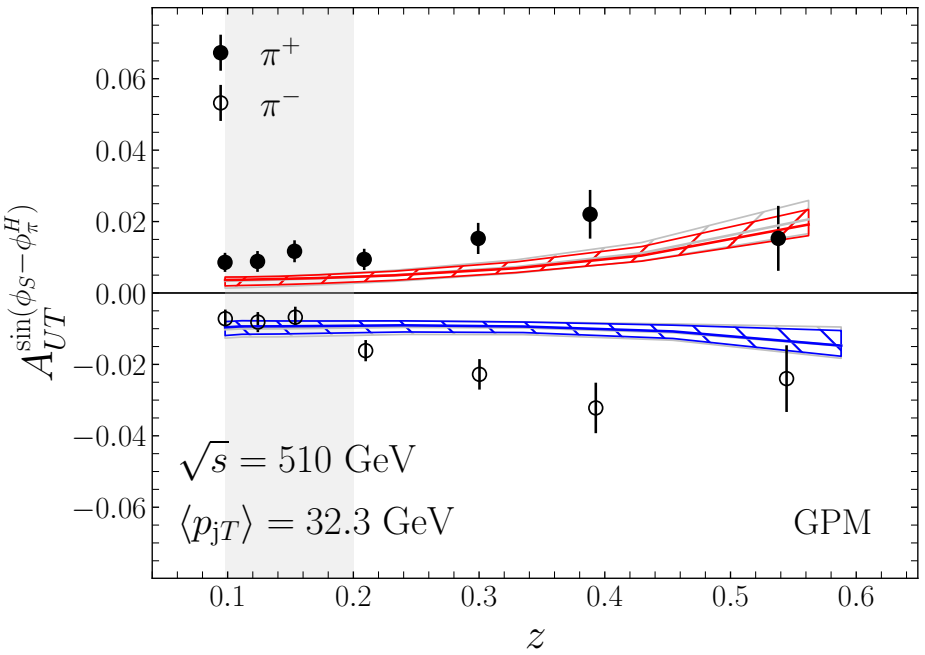

- STAR data at $\sqrt{s} = 200$ GeV and $\sqrt{s} = 510$ GeV
- priors from updated fit of SIDIS and e^+e^- data
- posteriors from simultaneous reweighting on A_N data

M. Boglione, U. D'Alesio, CF, J.O. Gonzalez-Hernandez, F. Murgia, A. Prokudin, PLB 854 (2024) 138712

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Pion-in-jet at STAR - reweighted - CGI

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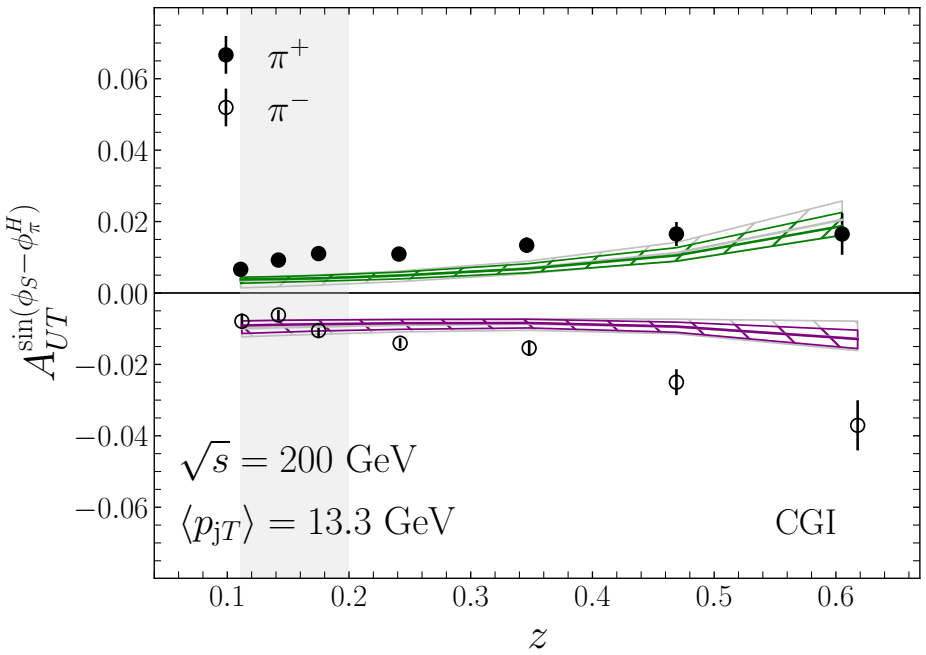

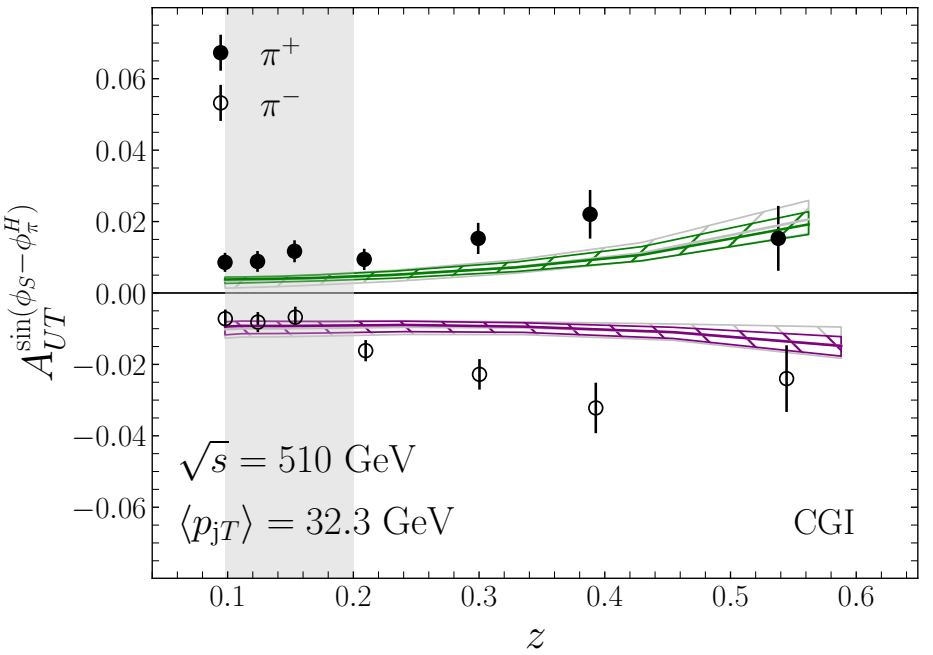

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- reweighted predictions well describe STAR data at both $\sqrt{s}$

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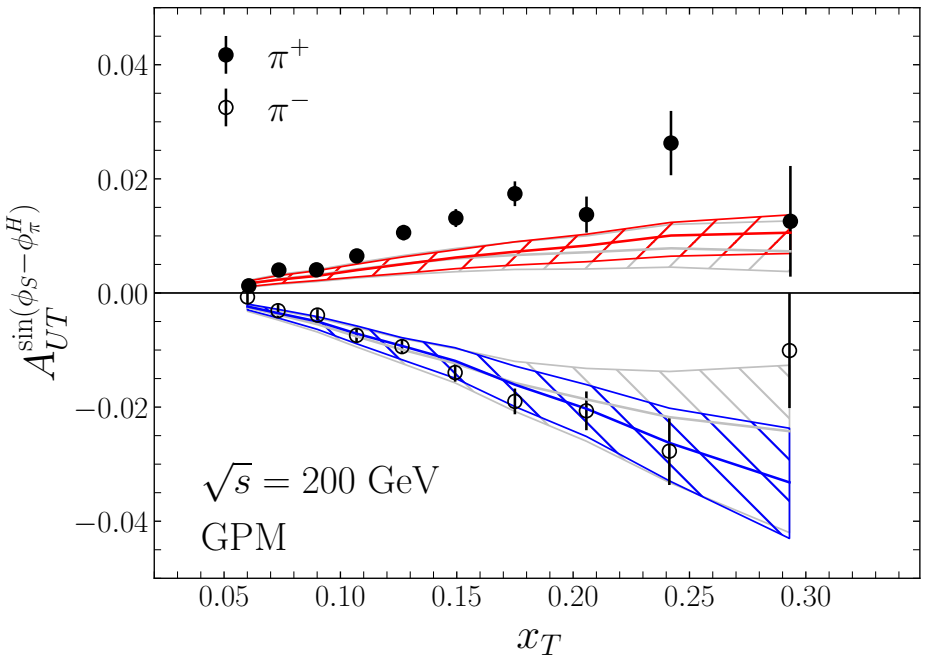

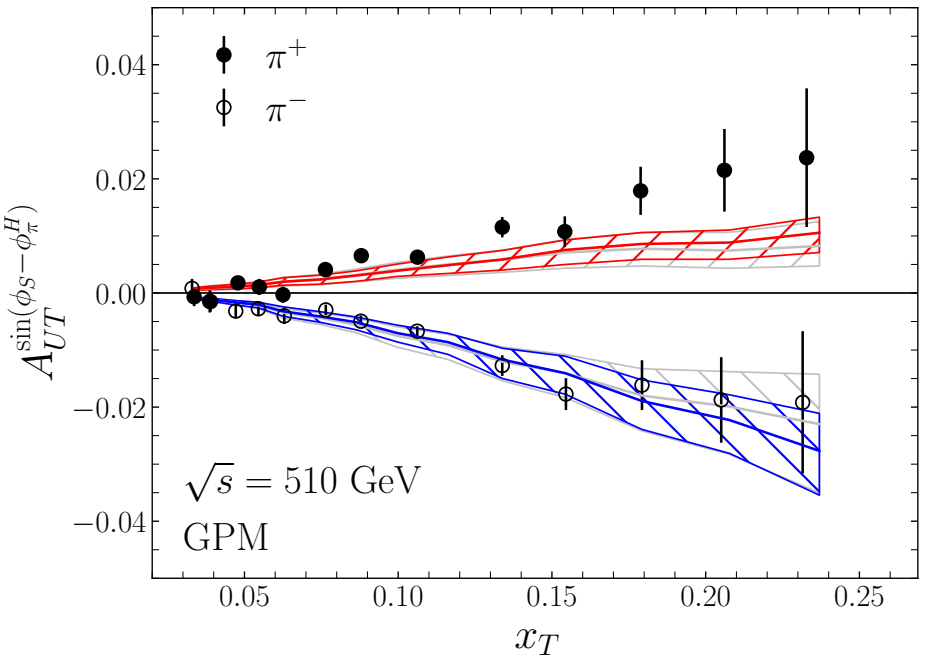

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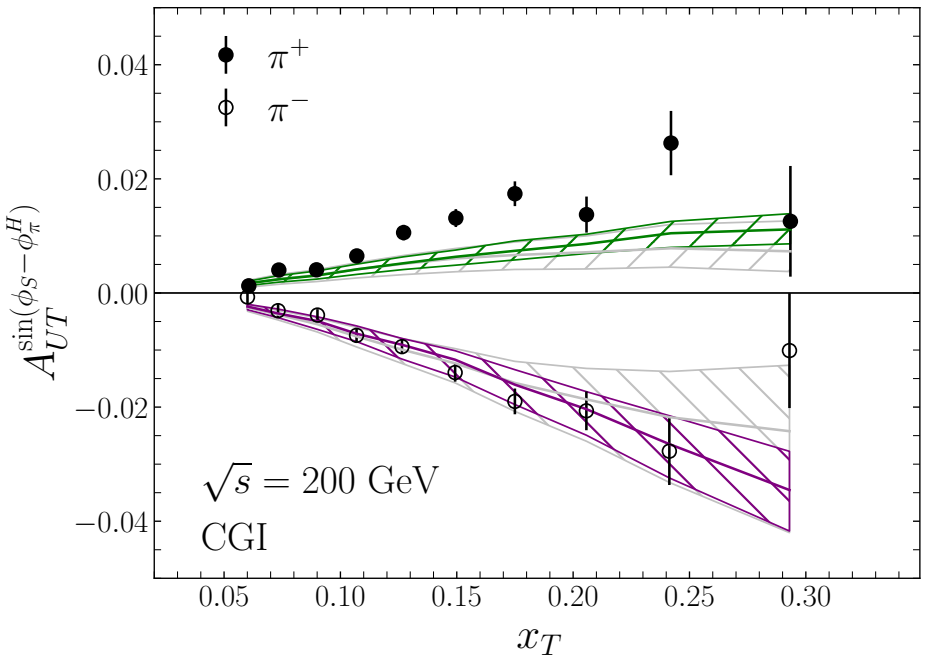

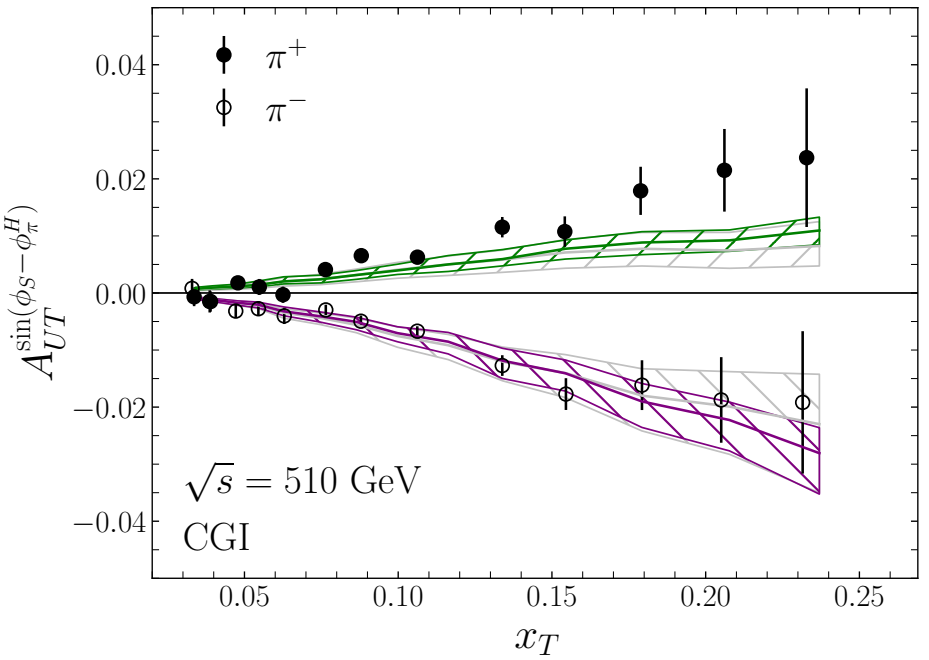

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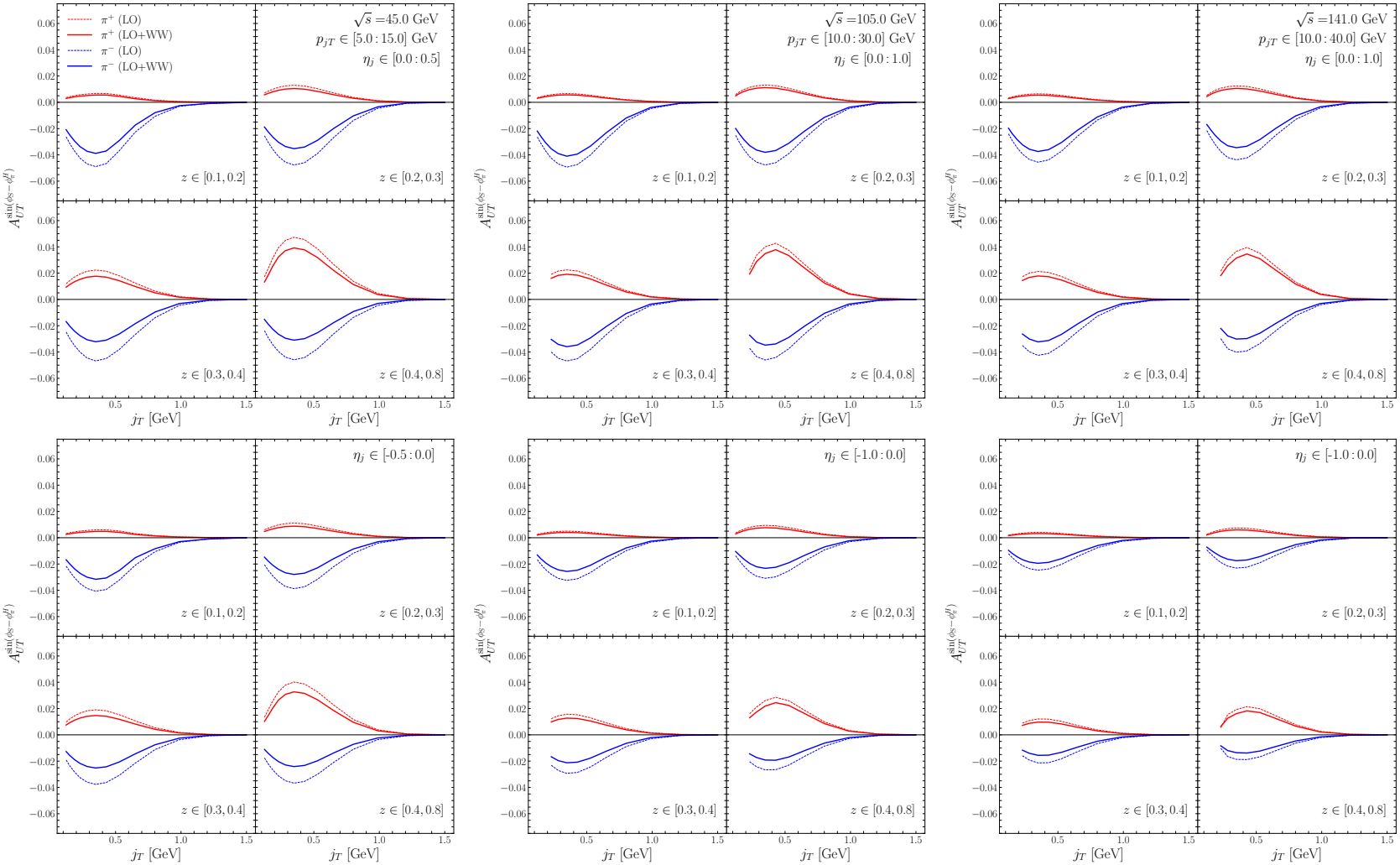

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