

19–23 October 2026
Santiago de Compostela
(Spain)

PION-IN-JET COLLINS ASYMMETRIES FROM RHIC TO THE EIC: UNIVERSALITY TESTS AND CONSTRAINTS ON TRANSVERSITY

Umberto D'Alesio

C. Flore & M. Zaccheddu,

PLB 871 (2025) & PLB 878 (2026)

OUTLINE

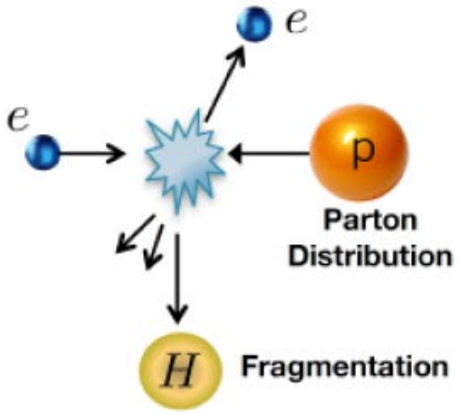
- Theoretical framework
- Hadron-in-jet: motivations
- *pp* collisions
  - ✓Formalism and phenomenology (STAR data@RHIC)
  - ✓Test of universality and TMD factorization
- ***ep*** collisions
  - ✓LO + quasireal photon exchange
  - ✓Predictions (@EIC)
  - ✓sensitivity to transversity (valence + sea)

Conclusions

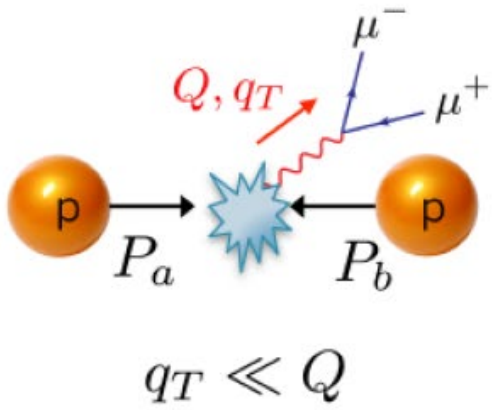


STANDARD TMD PROCESSES

Semi-Inclusive DIS

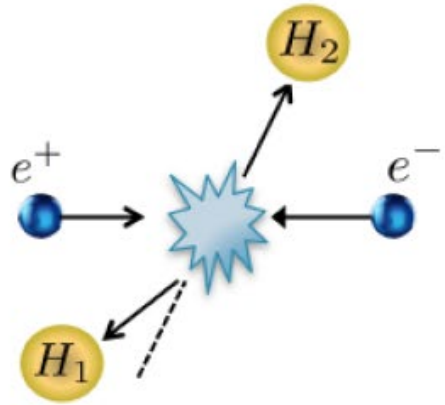


Drell-Yan



$q_T \ll Q$

Dihadron in e⁺e⁻

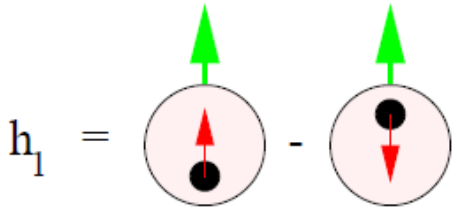


TMD factorization applies

Two-scale processes:

$Q^2 \gg p_T^2 \geq \Lambda_{QCD}^2$

TRANSVERSITY



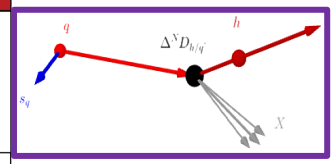
- chiral-odd quantity ⇒ needs a partner
- TMD framework (Collins effect in SIDIS); collinear QCD (two-hadrons with dihadron FF)
- Known mainly for valence quarks
- Related to tensor charge

$$\delta q = \int_0^1 \left[h_1^q(x) - h_1^{\bar{q}}(x) \right] dx \qquad g_T = \delta u - \delta d$$

Leading Quark TMDFFs — Hadron Spin — Quark Spin

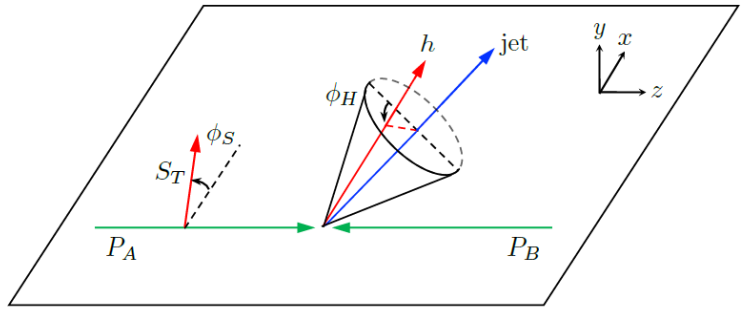
		Quark Polarization		
		Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
Unpolarized (or Spin 0) Hadrons		D_1 = Unpolarized		$H_1^\perp$ = Collins
Polarized Hadrons	L		G_1 = Helicity	$H_{1L}^\perp$ =
	T	$D_{1T}^\perp$ = Polarizing FF	$G_{1T}^\perp$ =	H_1 = Transversity; $H_{1T}^\perp$ =

TMD-FFS FOR SPIN ½ HADRONS



Collins FF

WHY HADRON-IN-JET?



- Complementary to SIDIS and e^+e^- processes
- two well-separated scales: $p_{jT} \gg p_{\perp h} = j_T$ [$\perp$ w.r.t. jet]

- Access to spin–momentum correlations in fragmentation
- Unique feature:
  - initial state → (use of) collinear (configuration)
  - fragmentation → TMD
- Independent test of TMD-FF universality and TMD factorization
  → Clean probe of transversity



$$A^{\uparrow}(p_A)\, B(p_B) \to \mathrm{jet}(p_{\mathrm{j}}) + \pi(p_\pi) + X$$

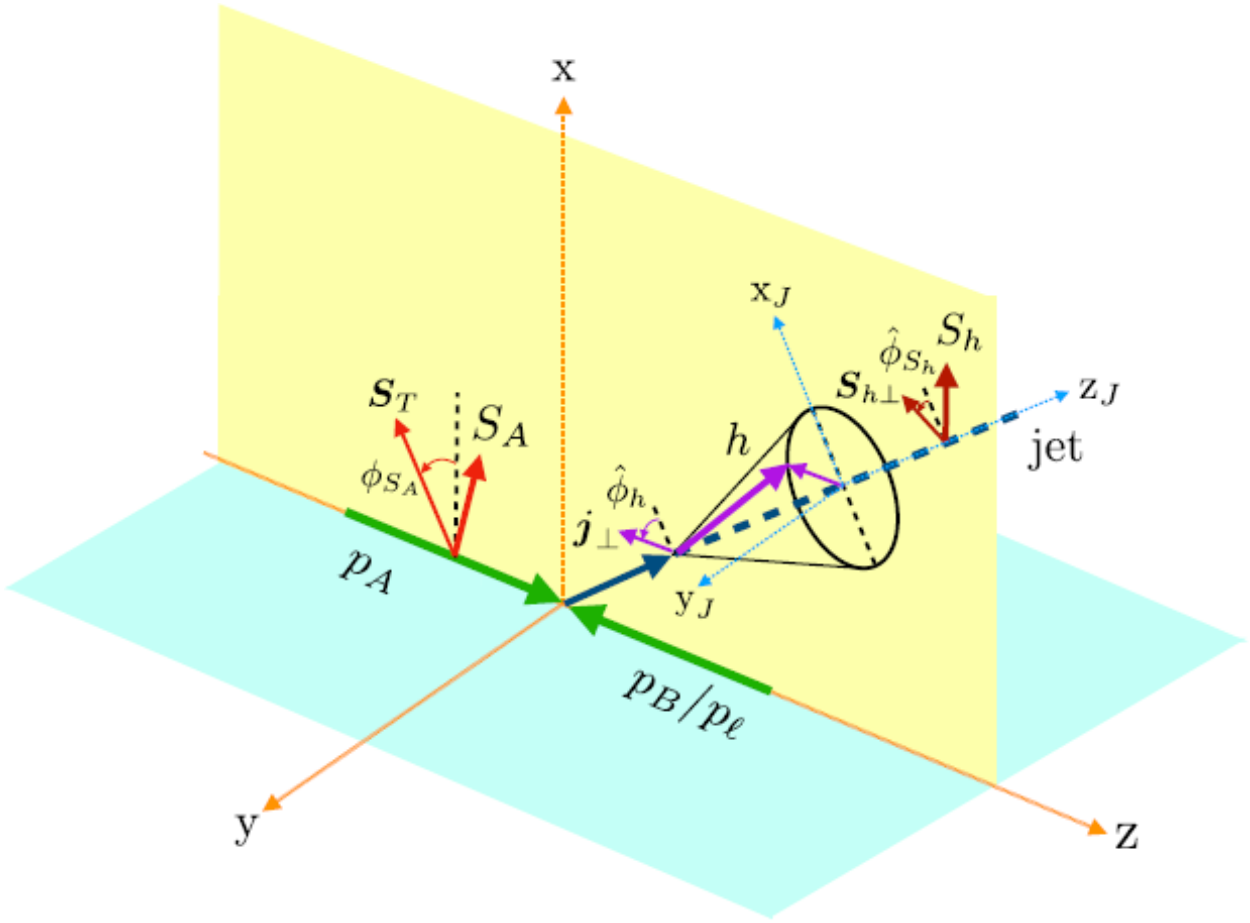


Figure from Kang, Lee, Zhao 2020

Existing studies:
Yuan 2008;

UD, Murgia, Pisano 2011, 2017;
Kang et al. 2017
with/without TMD evolution
(*consistent* results)

COLLINS ASYMMETRY

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

$qq \to qq, \quad qg \to qg, \quad qg \to gq, \quad gq \to qg,$

$gq \to gq \quad gg \to q\bar{q}, \quad q\bar{q} \to gg, \quad gg \to gg,$

$$A_N^{\sin(\phi_S-\phi_\pi^H)}(\boldsymbol{p}_j, z, p_{\perp\pi})$$

$$=2\,\frac{\int d\phi_S\, d\phi_\pi^H\, \sin(\phi_S-\phi_\pi^H)\,[\,d\sigma(\phi_S,\phi_\pi^H)-d\sigma(\phi_S+\pi,\phi_\pi^H)\,]}{\int d\phi_S\, d\phi_\pi^H\,[\,d\sigma(\phi_S,\phi_\pi^H)+d\sigma(\phi_S+\pi,\phi_\pi^H)\,]}$$

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

Collinear initial state



PARAMETRIZATIONS

FIT to SIDIS and e^+e^- data

Boglione, UD, Flore, Gonzalez-Hernandez, Murgia, Prokudin, PLB2024

$h_1^q(x)$ Transversity: only valence - Soffer bound *a posteriori*

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

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

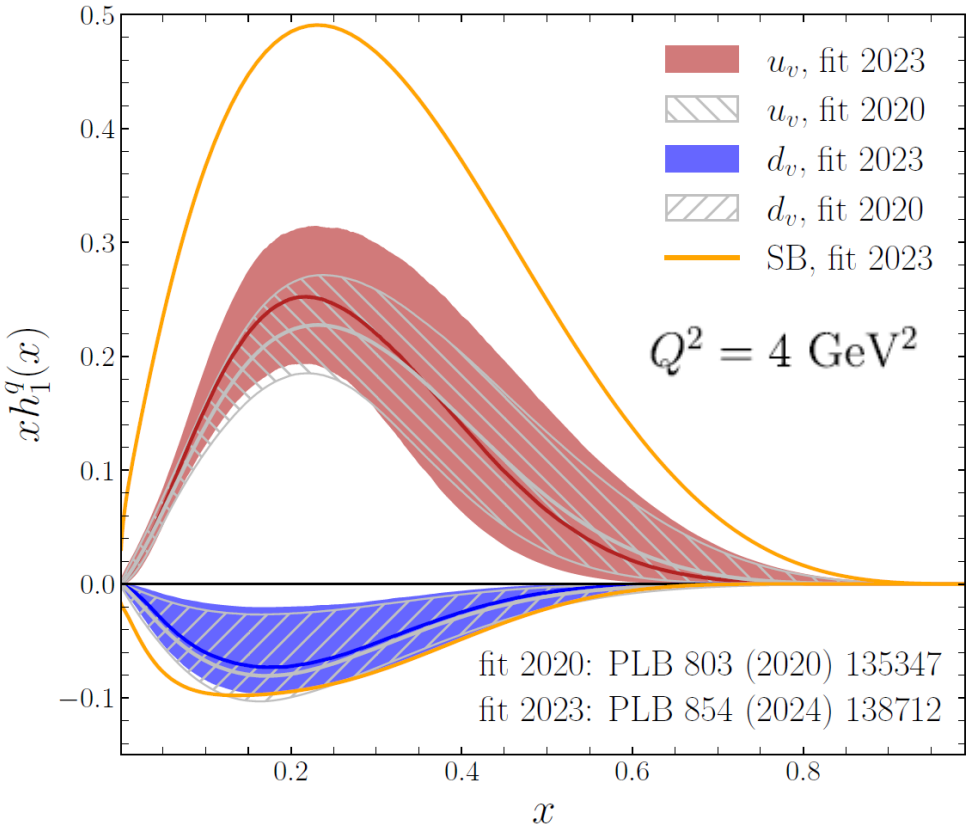
$$D_{h/q}(z, p_\perp^2) = D_{h/q}(z)\, \frac{e^{-p_\perp^2/\langle p_\perp^2 \rangle}}{\pi \langle p_\perp^2 \rangle}$$

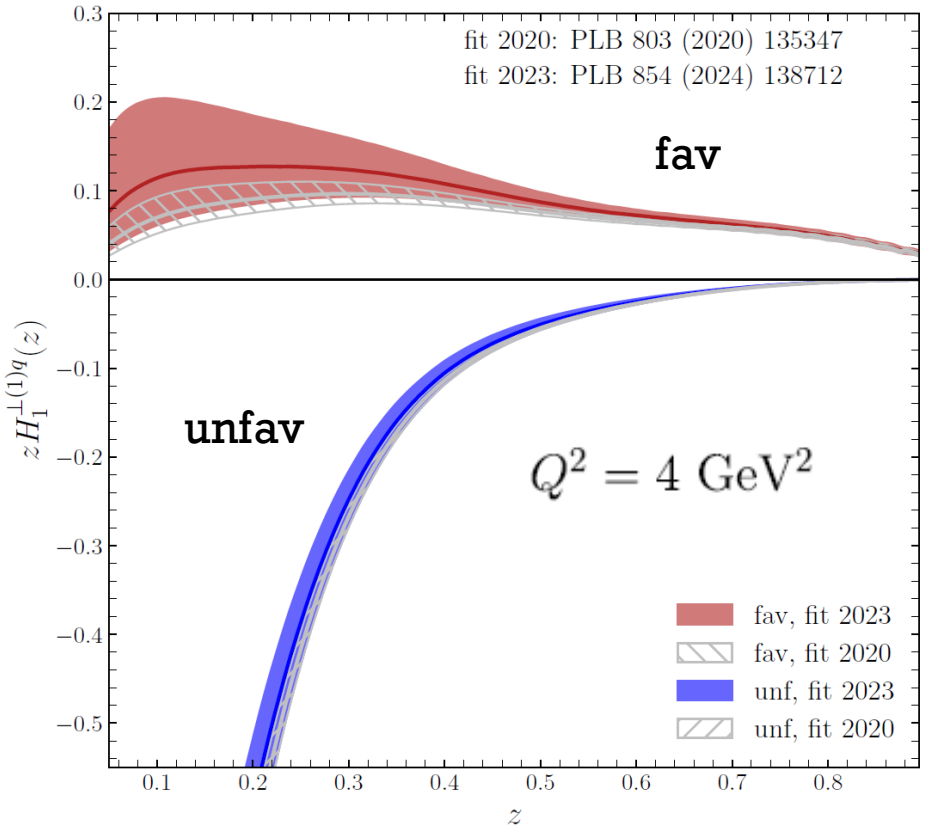
Gaussian



TRANSVERSITY AND COLLINS FFS

From SIDIS and e^+e^- data





PLB 2020 UD, Flore, Prokudin

PLB 2024 Boglione, UD, Flore, Gonzalez-Hernandez, Murgia, Prokudin

PREDICTIONS VS STAR DATA

UD, Flore, Zaccheddu, PLB 871 (2025)

Leading-order analysis = **proof of concept**

- Check that the mechanism works
- Test consistency with data

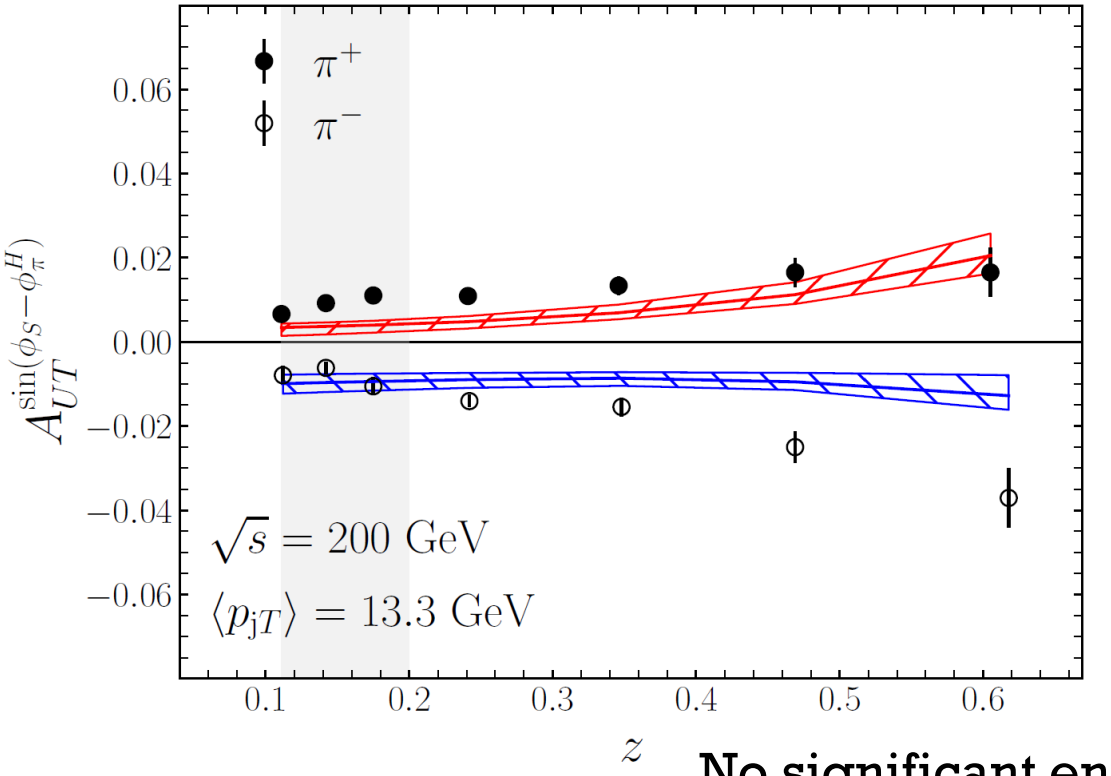
→ baseline for more refined studies (in progress)

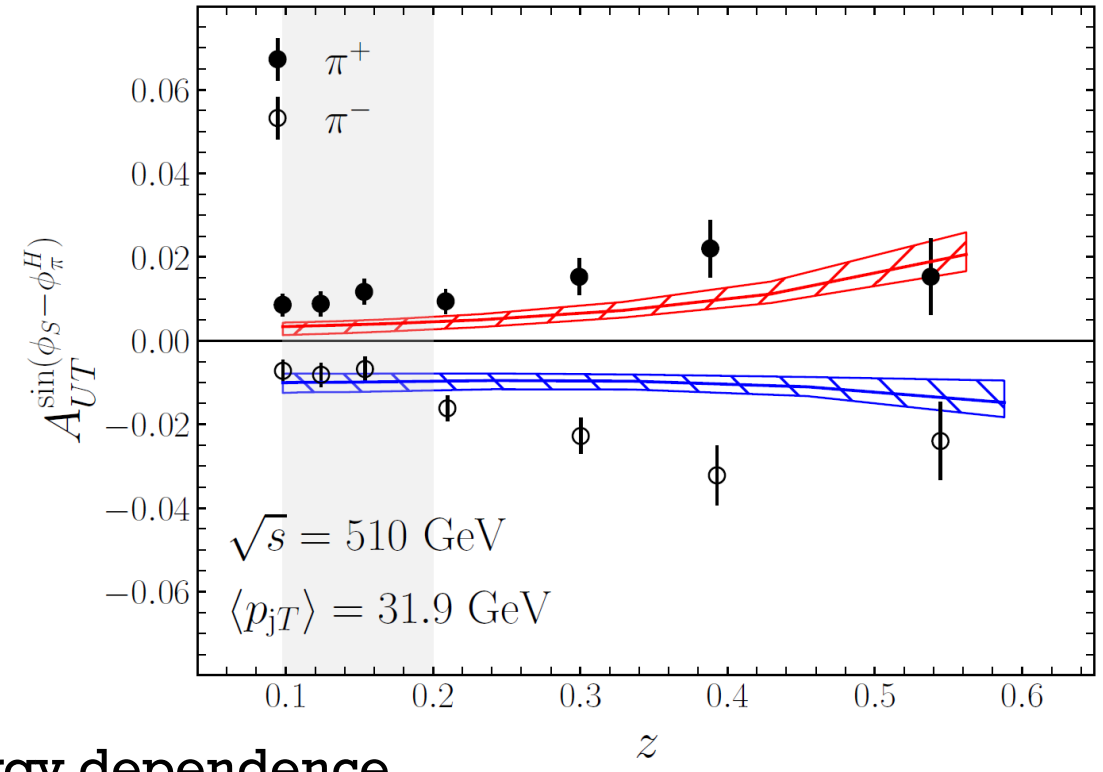
Framework tested directly against STAR data



ASYMMETRIES VS z

PREDICTIONS/DATA





No significant energy dependence

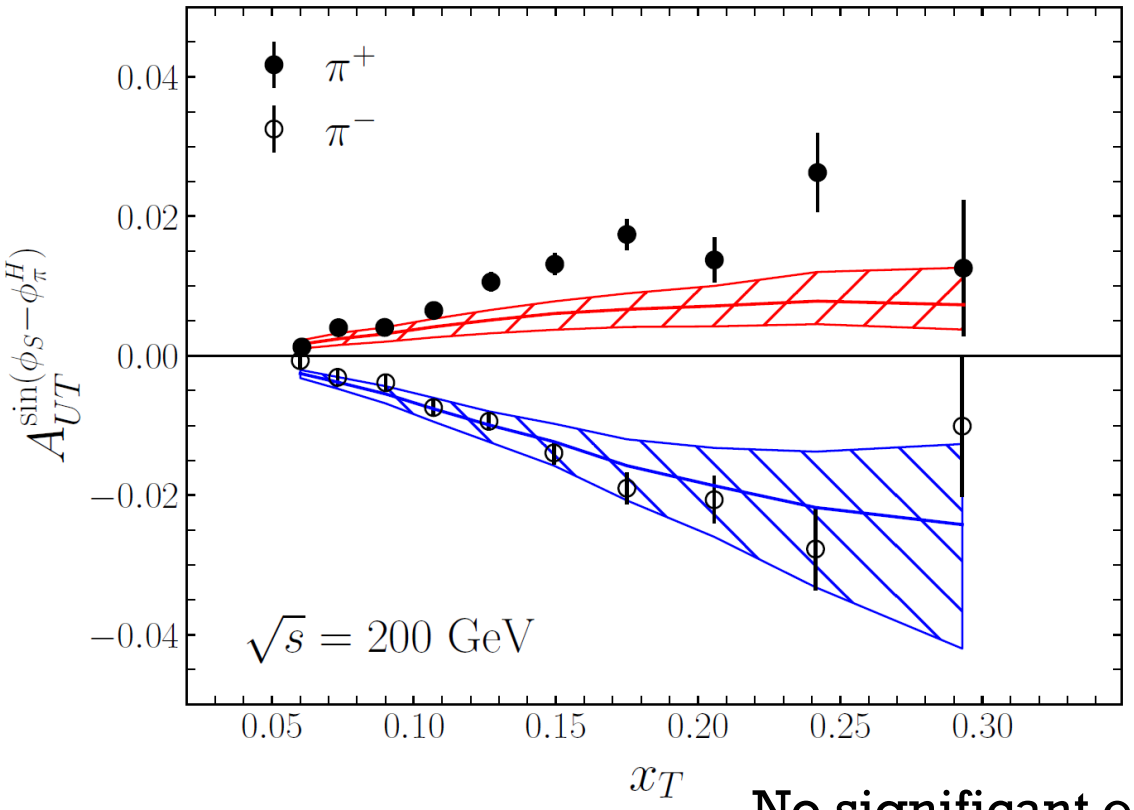
STAR 200 GeV

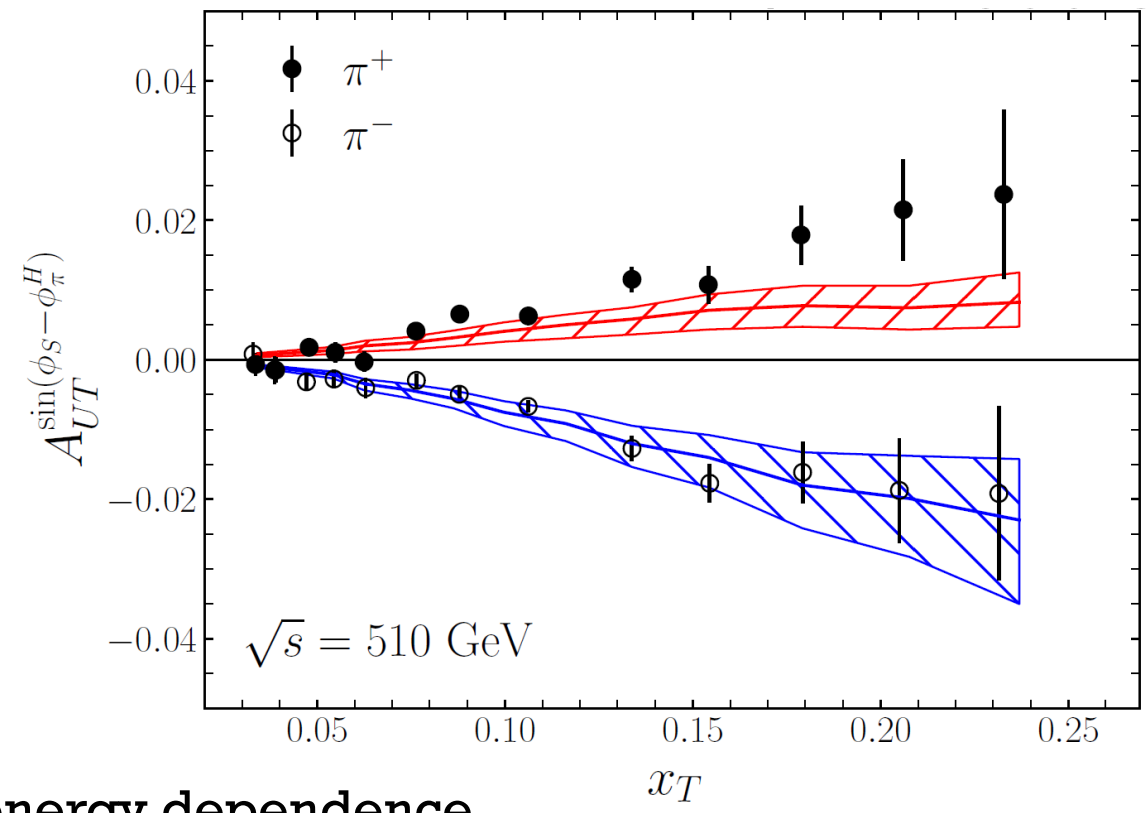
STAR 510 GeV

ASYMMETRIES VS x_T

PREDICTIONS/DATA

$$x_T = 2\,p_{jT}/\sqrt{s}$$





No significant energy dependence

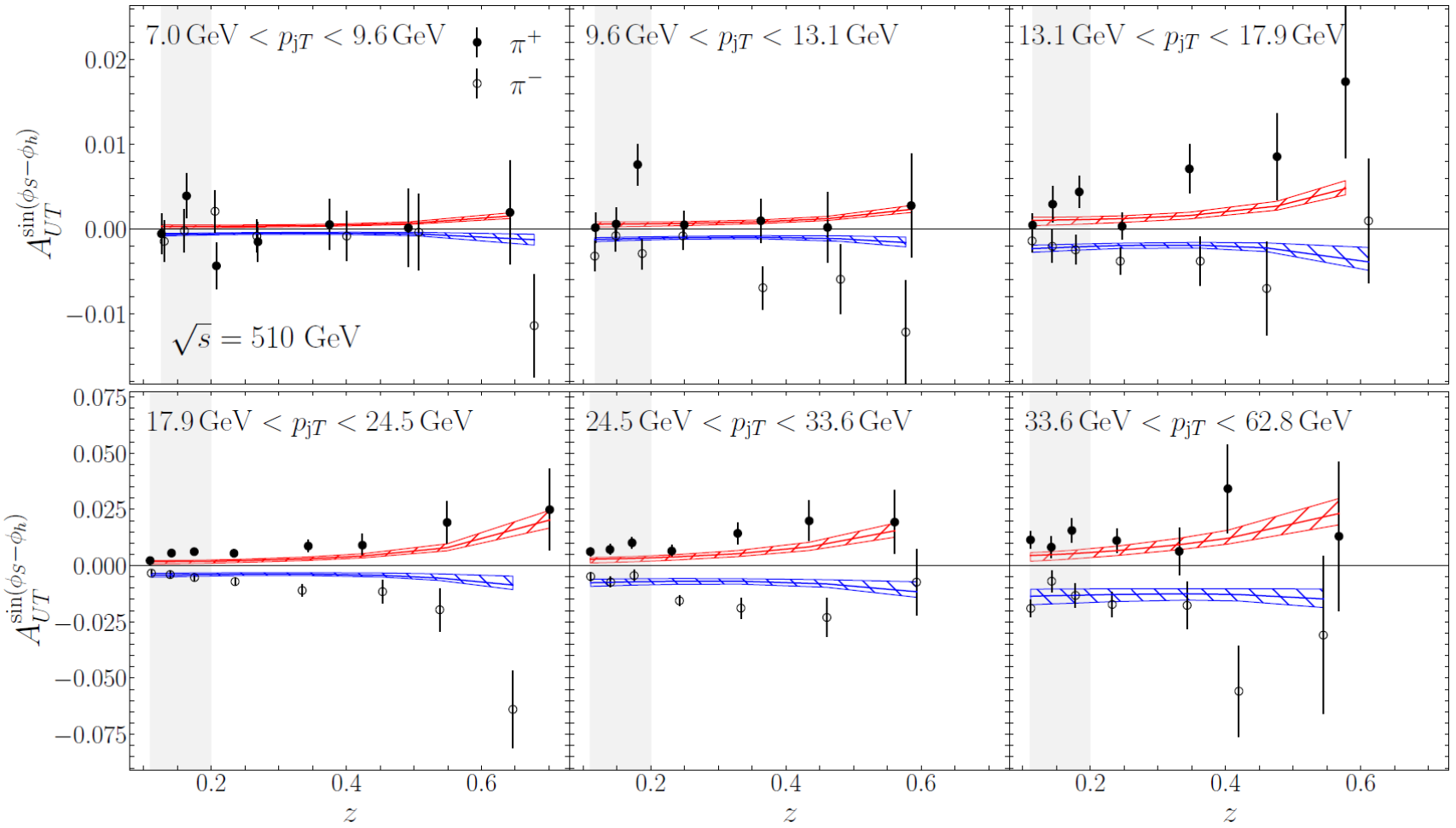
STAR 200 GeV

STAR 510 GeV

ASYMMETRIES VS z BINNED IN p_{jT}

PREDICTIONS/DATA

STAR
510 GeV



REMARKS

- Good agreement data-theory [despite LO]
- No TMD-factorization breaking and mild evolution effect
- Discrepancies: limits in Collins FF parametrization
- Fixed x_T probes transversity at $x > x_T$,(beyond SIDIS) access to large x



$$\ell(p_\ell)\, p^{\uparrow}(P) \rightarrow \mathrm{jet}(p_\mathrm{j})\, \pi(p_\pi) + X$$

UD, Flore & Zaccheddu, PLB 878 (2026)



$$\ell(p_\ell)\, p^{\uparrow}(P) \to \mathrm{jet}(p_\mathrm{j})\, \pi(p_\pi) + X$$

Cleaner environment: *ep* (EIC)

LO $q\ell \to q\ell$ quark dominance

$$h_1^q(x) \otimes d\Delta\hat{\sigma}^{q\ell\to q\ell} \otimes H_1^{\perp q}(z, j_T)$$

$$\hat{t} = -Q^2 = -x\sqrt{s}\, p_{\mathrm{j}T}\, e^{-\eta_\mathrm{j}}$$

Large p_{jT} implies large Q^2
(at not large positive η_j)

lepton in the final state: appearance of a third scale, different treatment, spoiling the similarity with *pp*



$$\ell(p_\ell)\, p^{\uparrow}(P) \to \mathrm{jet}(p_\mathrm{j})\, \pi(p_\pi) + X$$

Final lepton is not observed → also collinear…(NLO)
quasireal photon exchange [Weizsäcker–Williams approximation]

$$d\sigma(\phi_S, \phi_\pi^H) = d\sigma_{\mathrm{LO}}(\phi_S, \phi_\pi^H) + d\sigma_{\mathrm{WW}}(\phi_S, \phi_\pi^H)$$

$$d\sigma_{\mathrm{WW}}(\ell p \to \mathrm{jet}\, \pi\, X) = \int dy\, f_{\gamma/\ell}(y)\, d\sigma(\gamma p \to \mathrm{jet}\, \pi\, X)$$

lepton as a source of quasi-real photons
$\ell \to \ell\gamma$ final lepton almost collinear

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

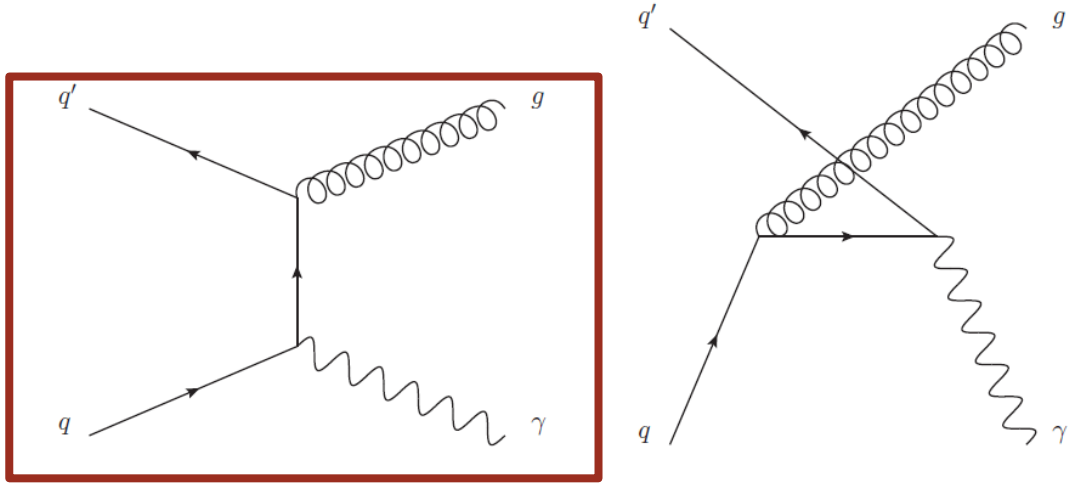
B. A. Kniehl, G. Kramer, M. Spira, Z. Phys. C 1997

$$Q^2_{\mathrm{min}}(y) = m_\ell^2 y^2/(1-y) \qquad Q^2_{\mathrm{max}} = 1\mathrm{GeV}^2$$



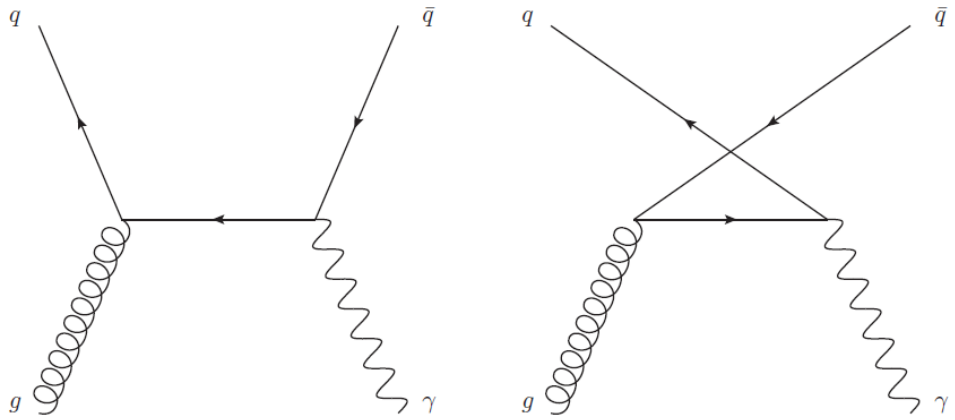
Partonic channels

$$q\gamma \to qg$$



$$d\hat{\sigma}^{q\gamma\to qg} = -\frac{4}{3}e_q^2\frac{\hat{s}^2+\hat{u}^2}{\hat{s}\hat{u}}$$

$$g\gamma \to q\bar{q}$$



$$d\hat{\sigma}^{g\gamma\to q\bar{q}} = e_q^2\frac{\hat{t}^2+\hat{u}^2}{\hat{t}\hat{u}}$$

$\hat{u}$ dependence (absent in the LO term)

Numerator: only one channel $q\gamma \to qg$

$$f_{\gamma/\ell}(y) \otimes h_1^q(x) \otimes d\Delta\hat{\sigma}^{q\gamma\to qg} \otimes H_1^{\perp q}(z, j_T)$$

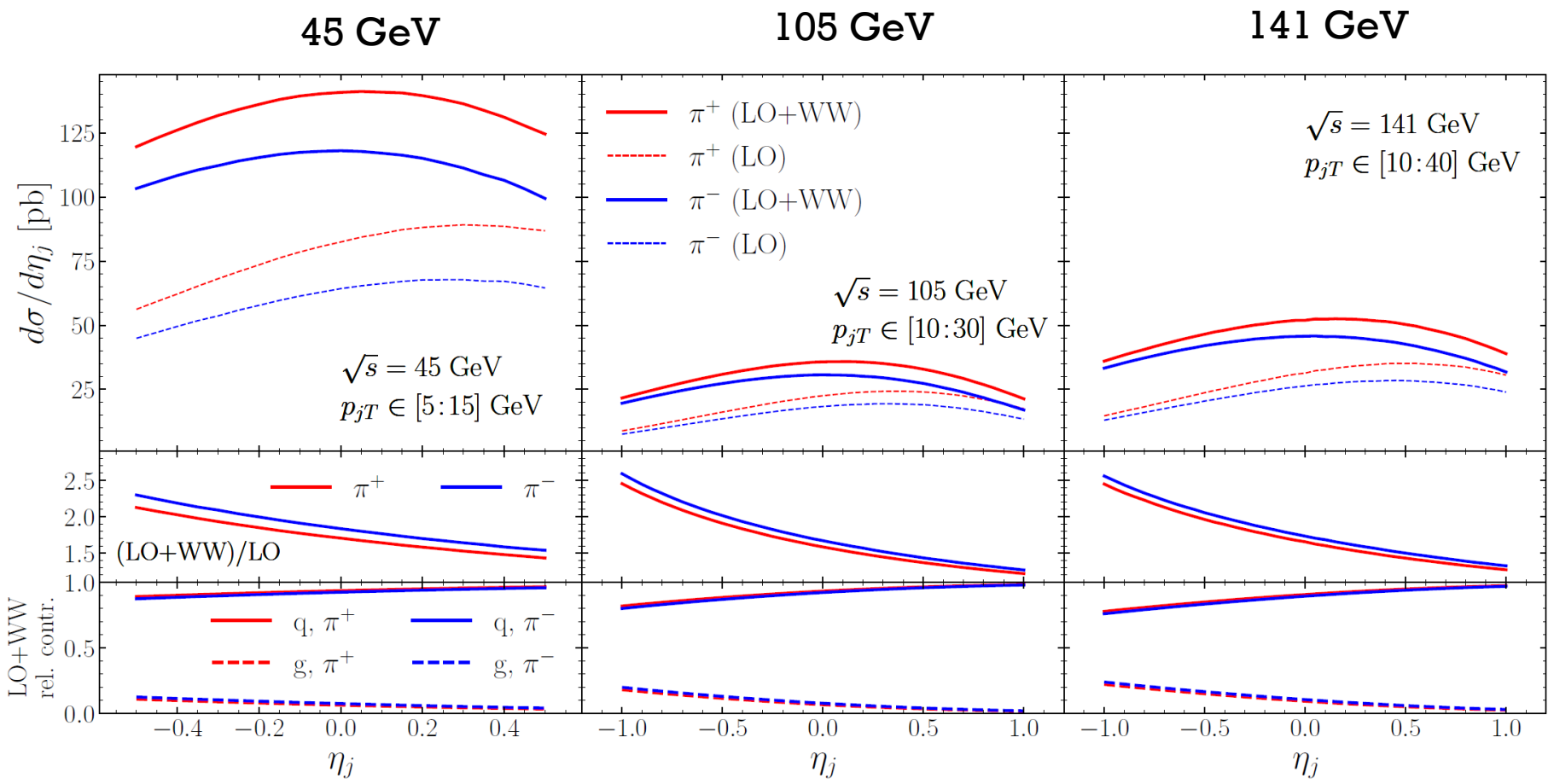


EIC KINEMATICS

Variable	Values/ranges				Description
$\sqrt{s}$	45	105	141	GeV	Center-of-mass energy
p_{jT}	[5–15]	[10–30]	[10–40]	GeV	Jet transverse momentum
$\lvert\eta_j\rvert$	≤ 0.5	≤ 1	≤ 1		Jet pseudorapidity
x_T	$2\ p_{jT} / \sqrt{s}$				Scaling variable
j_T	[0.1–1.5] GeV				Pion transverse momentum relative to the jet axis
z	[0.1–0.8]				Longitudinal momentum fraction carried by the pion
R	[0.05–0.6]				Jet cone radius



UNPOLARIZED CROSS SECTIONS VS η_J



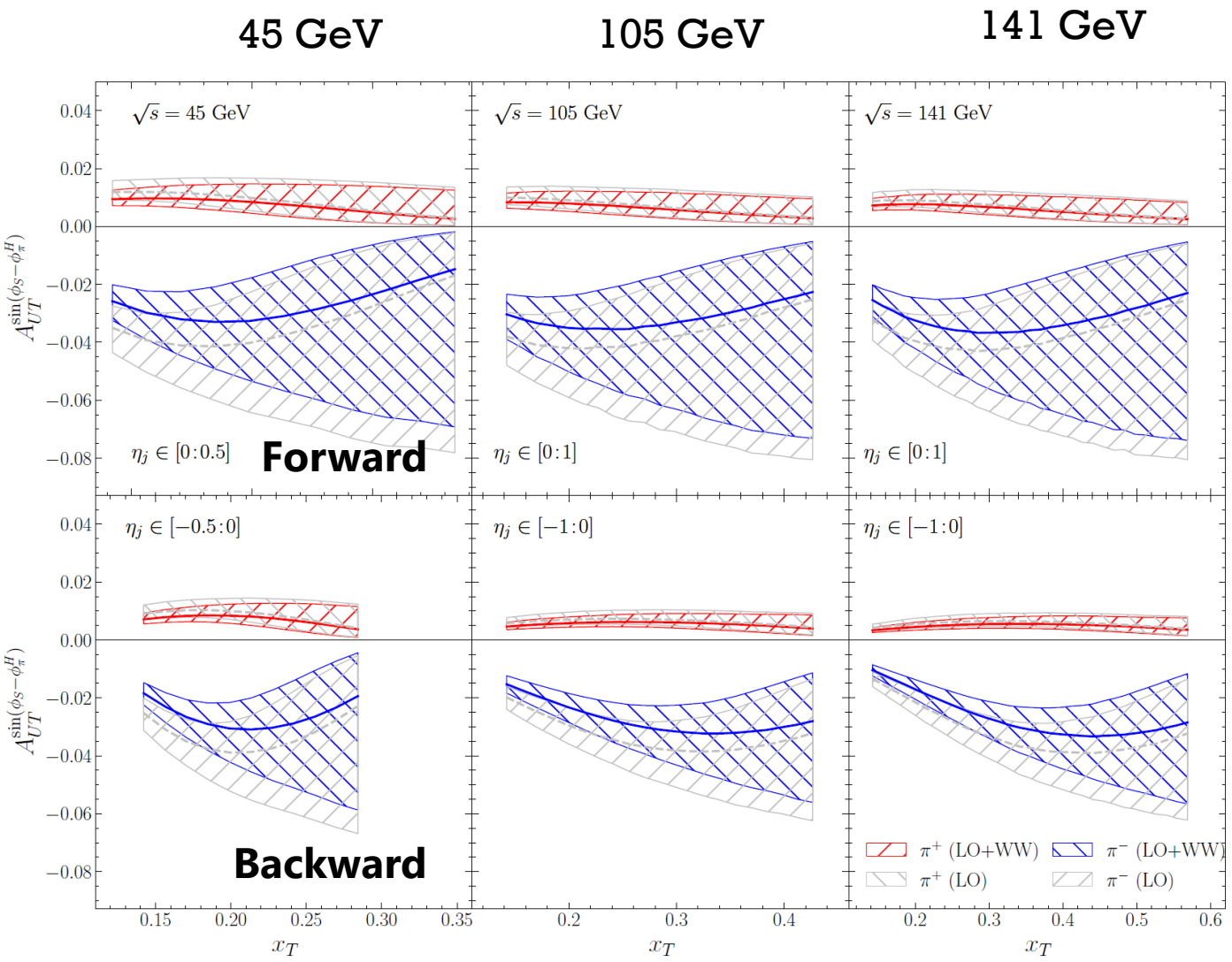
Sizeable WW contr.

(LO+WW)/LO around 2-1.5

Quark dominance!!!

backward region: small gluon contribution (WW only)

AZIMUTHAL ASYMMETRIES VS x_T



[LO+WW] results

- π^+ / π^- lower/larger values

- Driven by the behavior of FFs (integrated over z)
- Expectations testable at EIC

- Small x_T & backward region:

Access to $x < 0.1$

transversity for sea quarks

REMARKS

❑ **Quark-dominated observable**

- gluons play a minor role in the denominator (even including WW)
- numerator ∝ transversity (no gluon contribution)

👉 clean access to h_1 - large negative rapidities ⇒ sea-quarks!

❑ **Implications**

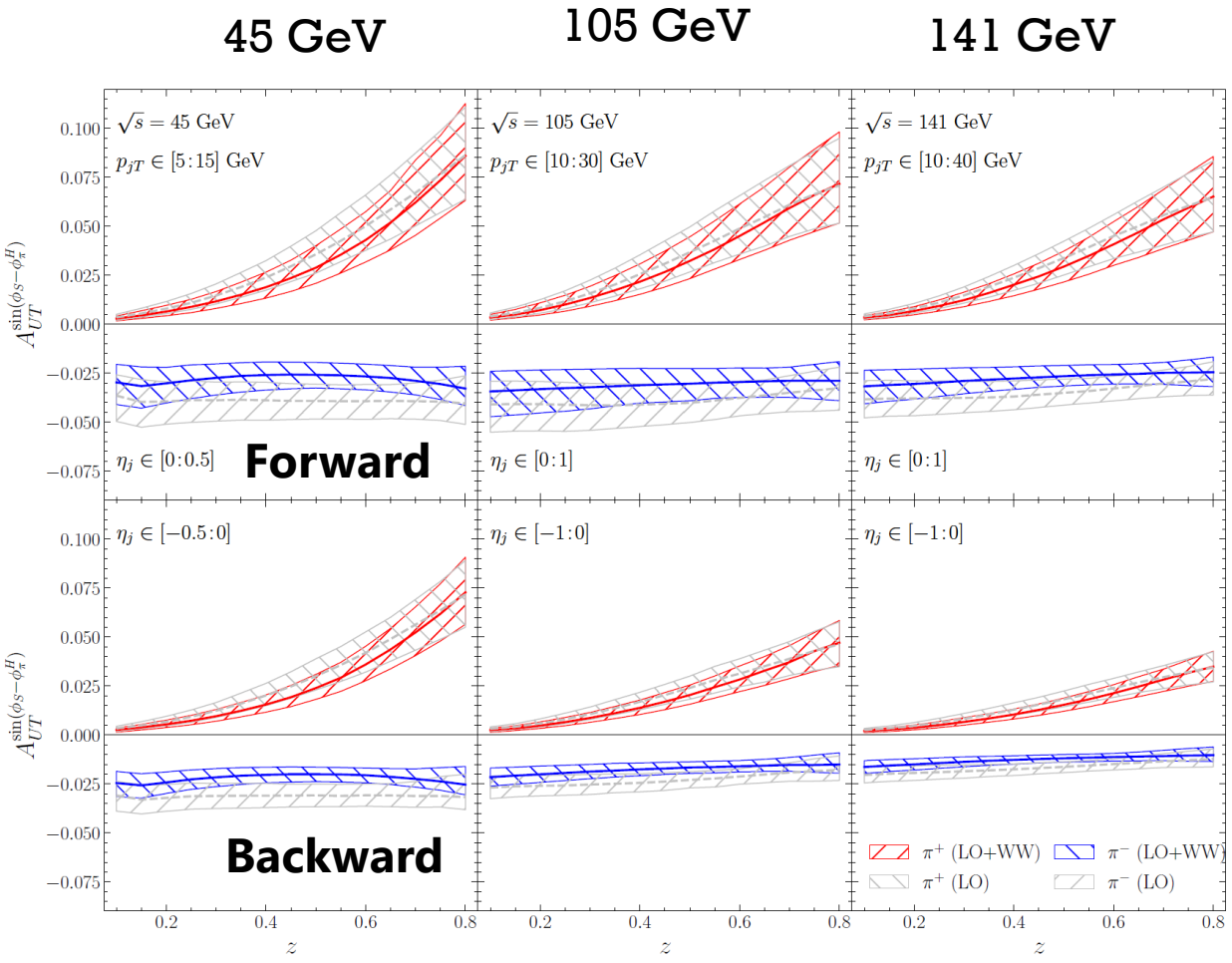
- expect sizeable asymmetries
- enhanced sensitivity to transversity

❑ **Contrast: *pp* asymmetries**

- denominator gluon dominated ⇒ suppressed asymmetries



AZIMUTHAL ASYMMETRIES VS z



Large z

$$\mathcal{N}^C_{\rm fav}(z) = N^C_{\rm fav} z^\gamma, \qquad \mathcal{N}^C_{\rm unf}(z) = N^C_{\rm unf}$$

- Collins FFs *follow* unpolarized FFs
- unfavored strongly suppressed

u-quark dominance (charge factor)

- u-transversity drives the observable

Charge separation

– π^+ h_1^u × fav Collins → both large ⇒ dominant contribution
– π^- one suppressed factor (unfav./transversity) ⇒ reduced effect

Low z

- favored Collins suppressed ⇒ π^+ asymmetry strongly reduced

Comparison with *pp*

- denominator gluon dominated
- no u-quark dominance ⇒ **much smaller asymmetries (~2%)**

Expectations *testable* at the EIC

CONCLUSIONS

- ***hadron*-in-jet azimuthal asymmetries**

→ **clean probe, two-scale process**

→ **test of TMD-FF universality & TMD factorization**

- ***pp* phenomenology (RHIC)**
  → good agreement data-theory, universality, no factorization breaking
  → similar results for spontaneous transverse Λ polarization
- ***ep* (EIC potential)**

→ **sizeable asymmetries**
  → sensitivity to valence & sea transversity
  → golden channel

- **Open theoretical issues**
  → factorization breaking? TMD vs models
  → beyond LO: jet fragmentation, jet-TMD-FF, TMD FFs

THANKS for the ATTENTION

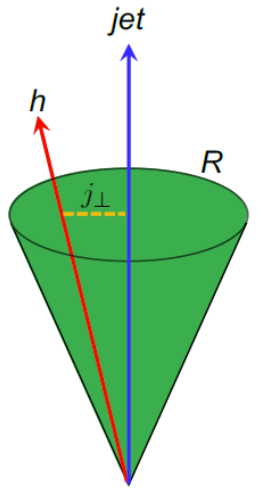


BACK-UP SLIDES



THE SEMI-INCLUSIVE TMD FRAGMENTING JET FUNCTION

$$\frac{d\sigma^{pp\to(\text{jet }h)X}}{dp_T d\eta dz_h d^2\boldsymbol{j}_\perp} = \sum_{a,b,c} f_a(x_a,\mu)\otimes f_b(x_b,\mu)\otimes H^c_{ab}(x_a,x_b,\eta,p_T/z,\mu)\otimes \mathcal{G}^h_c(z,z_h,\omega_J R,\boldsymbol{j}_\perp,\mu)$$



$$\mathcal{G}^h_c(z,z_h,\omega_J R,\boldsymbol{j}_\perp,\mu) = \mathcal{C}_{c\to i}(z,\omega_J R,\mu)\int \frac{d^2\boldsymbol{b}}{(2\pi)^2} e^{i\,\boldsymbol{j}_\perp\cdot\boldsymbol{b}/z_h}\hat{\mathcal{D}}_{h/i}(z_h,\boldsymbol{b};\mu_J)$$

$$\mathcal{G}^h_c(z,z_h,\omega_J R,\boldsymbol{j}_\perp,\mu) = \mathcal{C}_{c\to i}(z,\omega_J R,\mu)\,\hat{\mathcal{D}}_{h/i}(z_h,\boldsymbol{j}_\perp;\mu_J)$$

$$\mu_J \sim \omega_J \tan(R/2) \to p_T R$$

$$\hat{\mathcal{D}}_{h/i}(z_h,\boldsymbol{j}_\perp;\mu_J) = \int \frac{d^2\boldsymbol{b}}{(2\pi)^2} e^{i\,\boldsymbol{j}_\perp\cdot\boldsymbol{b}/z_h}\hat{\mathcal{D}}_{h/i}(z_h,\boldsymbol{b};\mu_J)$$ TMD FF

$$\Lambda_{\rm QCD} \lesssim j_\perp \ll p_T R$$ TMD factorization

Kang, Liu, Ringer, Xing, JHEP 1711 (2017) 068



UNCERTAINTY BANDS

Compression procedure

We adopt as an indicator the Welch's t-statistic, defined as

$$t = \frac{\mu_a - \mu_{a'}}{\sqrt{\frac{\sigma_a^2}{N_{\text{set}}^a} + \frac{\sigma_{a'}^2}{N_{\text{set}}^{a'}}}},$$

which quantifies the difference of the arithmetical means of two samples with unequal variances and sizes. One has to verify that $|t|$ is such that the corresponding p-values are $\gtrsim 0.1$. Provided this condition holds, one can conclude that the sampled distribution and the original distribution are statistically equivalent. Notice that we sample directly in the parameter space.



$$p^{\uparrow} p \rightarrow \text{jet} + h + X$$

- **Factorization scale and jet-cone radius R:**

- proper initial scale $\mu = p_{\mathrm{jT}} R$

- Evolution up to $\mu = p_{\mathrm{jT}}$: resummation of single logs in jet param.

- At LO (no dependence on R) $\mu = p_{\mathrm{jT}}$ Kang et al '17

- **Backward going jet** Boer, Bomhof, Hwang, Mulders '07

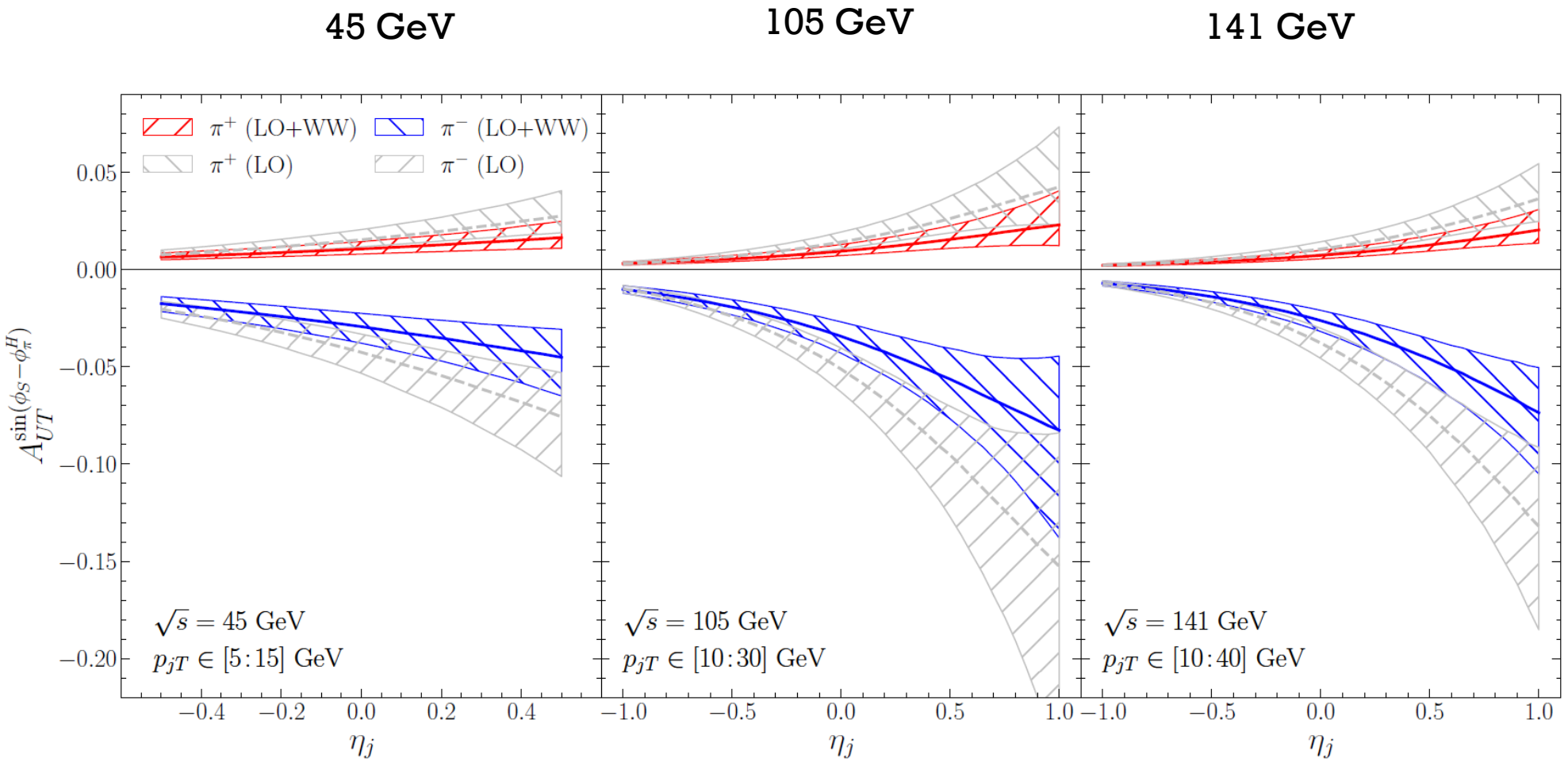
- To be used to determine the partonic cm frame ($\neq pp$ cm frame, depending on x_1, x_2)

- z and $p_\perp$ are not Lorentz invariant in TMD-FF (pp vs e^+e^-)

- At high energies: effects suppressed as $E_j/\sqrt{s}$: backward jet not relevant *[Boer '10]* …



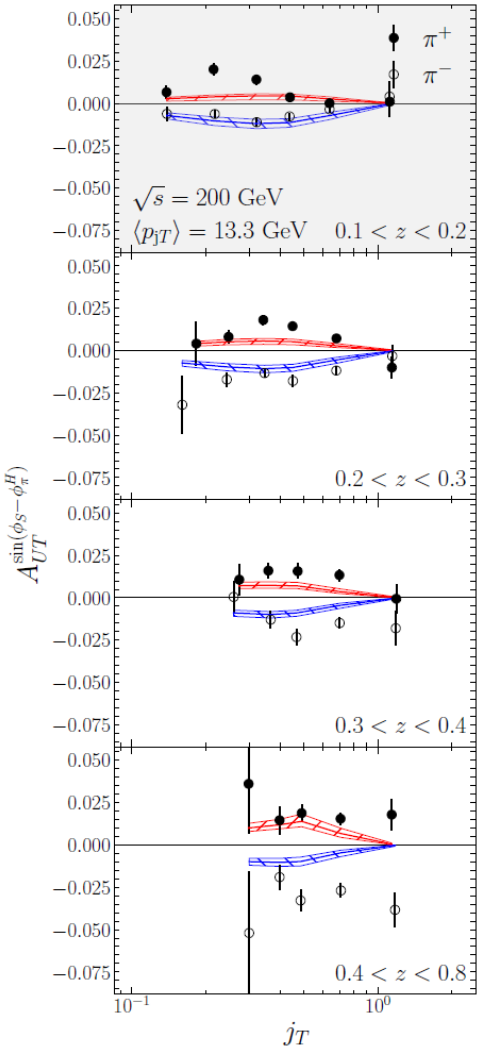
AZIMUTHAL ASYMMETRIES VS η_J

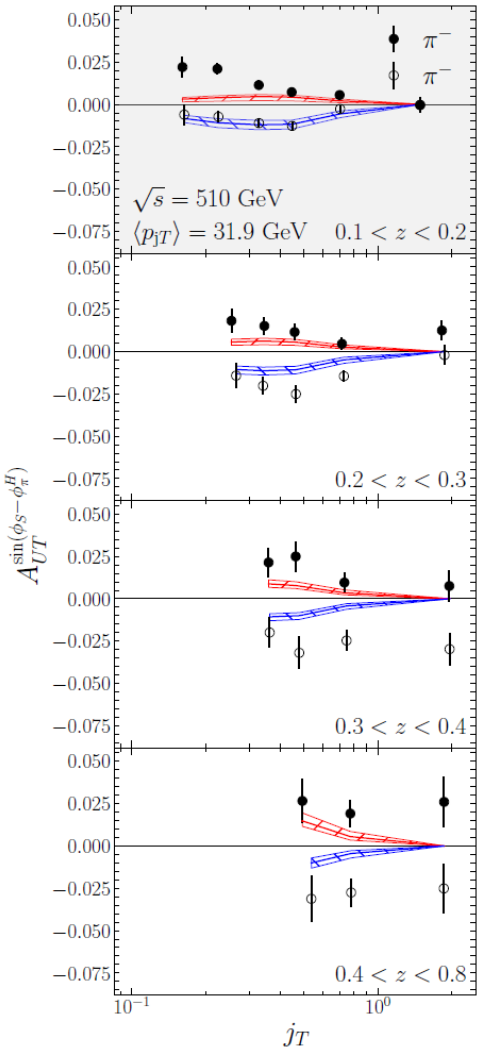


ASYMMETRIES VS j_T BINNED IN z

PREDICTIONS/DATA

STAR
200 GeV





STAR
510 GeV