COLLINS EFFECT FOR PION-IN-JET PRODUCTION IN HADRON-HADRON AND LEPTON-HADRON COLLISIONS

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PLB 2025 &

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INFN CAGLIARI

Fondazione di Sardegna

HR EXCELLENCE IN RESEARCH

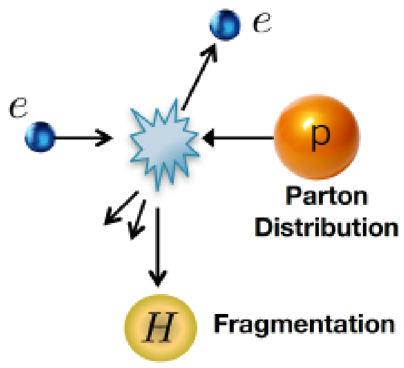
OUTLINE

- Hadron-in-jet in pp collisions
  - ✓ Motivations
- Pion-in-jet production in pp collisions: Collins asymmetry
  - ✓ Formalism
  - ✓ Predictions and comparison with STAR measurements
  - ✓ Test of universality and TMD factorization
- Pion-in-jet production in ℓp (ep) collisions: Collins asymmetry
  - ✓ LO + quasireal photon exchange
  - ✓ Predictions for EIC kinematics

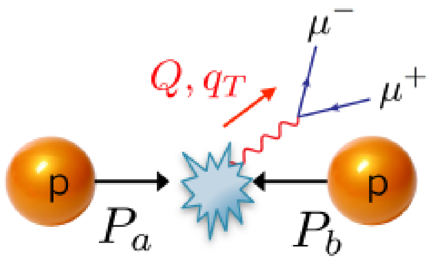
Conclusions

"STANDARD" TMD PROCESSES

Semi-Inclusive DIS

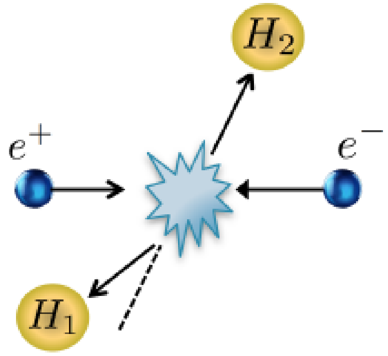


Drell-Yan

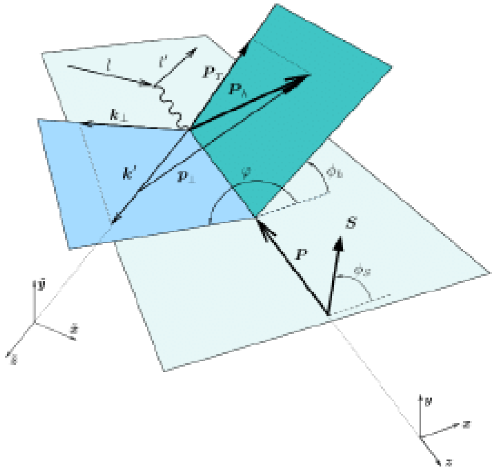


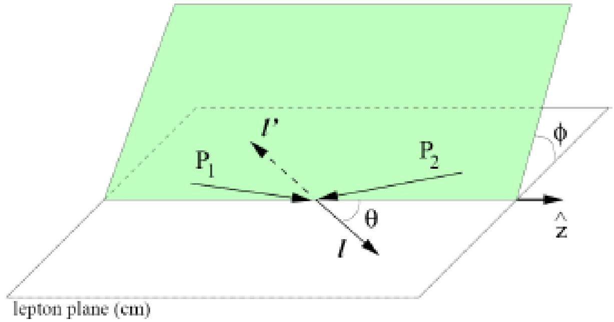
$q_T \ll Q$

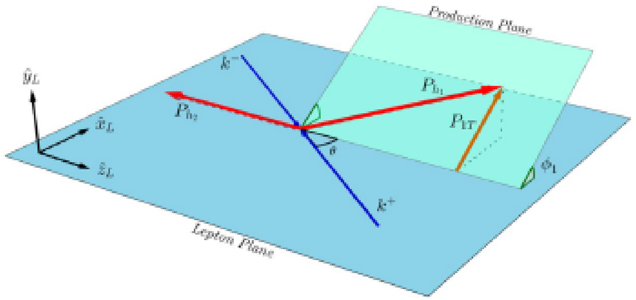
Dihadron in e+e-



Two-scale processes:
$Q^2 \gg p_T^2 \geq \Lambda^2_{QCD}$

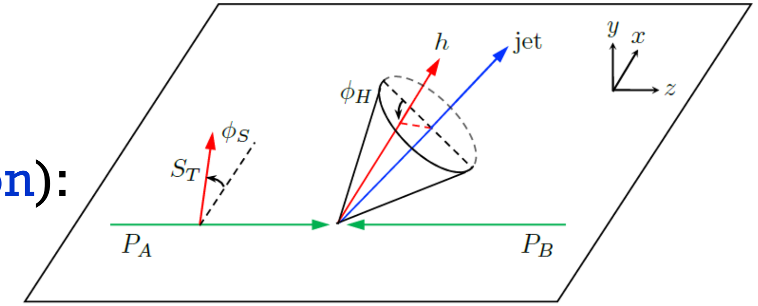






$p^\uparrow p \to \text{jet} + h + X$

Motivations



- Complementary to SIDIS and e^+e^- processes (TMD factorization):

- 2 well-separated scales: $p_{jT} \gg p_{\perp h} = j_T$ [⊥ w.r.t. jet]

- TMD effects **only** in the fragmentation mechanism: **collinear initial state**
- Test of TMD factorization and universality of TMD-FFs
- Existing studies show *consistent* results

[Yuan 2008; UD, Murgia, Pisano '11, '17; Kang et al. '17] with/without TMD evolution

- TMD-Jet-FFs *[Kang et al. '20, '21, '23]*

- STAR data: ***pp200*** *PRD* (2022), ***pp510*** *PRL* (2025)

Hadron-in-jet Physics: Modern Landscape

Selected/illustrative works

QCD Framework (SCET / FJF)

Kaufmann et al., JHEP 02 (2020)
Kang, Lee, Zhao, PLB 809 (2020)
Wang et al., PRD 103 (2021)
Kang et al., JHEP 03 (2024)

Global Analyses & Universality & Bridges

Gao et al., PRD 110 (2024) global FF fit incl. LHC jet data
Bacchetta et al., PRD 108 (2023) analogies h-jet and DiFFs
D'Alesio et al., global phenomenology (pp ↔ ep)
D'Alesio et al., EIC projections (2026)

Spin & TMD Observables

Arratia et al., PRD 102 (2020)
Kang et al., PLB 774 (2017)
D'Alesio et al., PLB 773 (2017)
Gutierrez-Reyes et al., PRL 121 (2018)

Experiment (RHIC & LHC)

[polarized] STAR, PLB 780 (2018)
[polarized] STAR, PRD 106 (2022)
[polarized] STAR, PRL 135 (2025)
[unpolarized] LHCb, PRL 123 (2019)
[unpolarized] LHCb, PRD 108 (2023)
[unpolarized] ALICE/ATLAS, jet fragmentation (2019–2021)

Very active field

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

- **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^-)

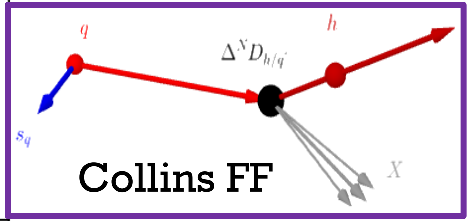
- At high energies: effects suppressed as $E_j/\sqrt{s}$: backward jet not relevant *[Boer '10]* …

TMD-FFS FOR SPIN ½ HADRONS

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	$H_{1L}^\perp$ = −
Polarized Hadrons	T	$D_{1T}^\perp$ = − Polarizing FF	$G_{1T}^\perp$ = −	H_1 = − Transversity; $H_{1T}^\perp$ = −



T-odd, chiral-odd

KINEMATIC CONFIGURATION

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

$$a\,b \to c\,d$$

ab collinear

$c \equiv \mathrm{jet}$ LO

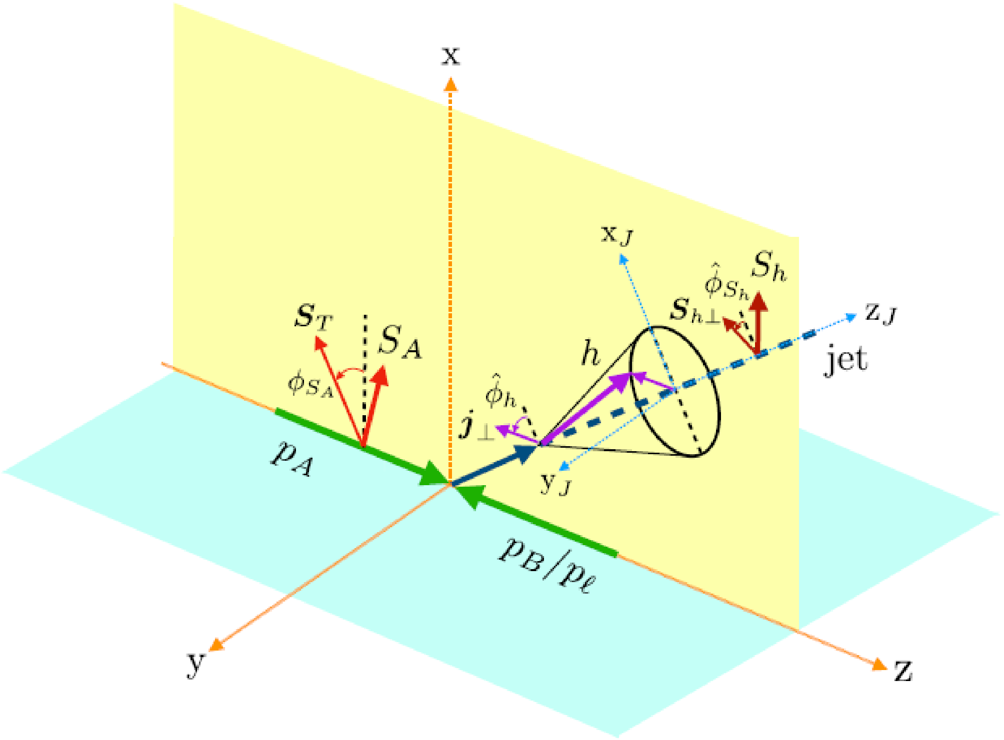


Figure from Kang, Lee, Zhao 2020

$$p_c^\mu \equiv p_{\mathrm{j}}^\mu = p_{\mathrm{j}T}(\cosh\eta_{\mathrm{j}}, 1, 0, \sinh\eta_{\mathrm{j}})$$

AZIMUTHAL STRUCTURE

$$\frac{E_{\rm j}\, d\sigma^{p(S,\phi_S)p\to {\rm jet}\,\pi(\phi_\pi^H)\,X}}{d^3\boldsymbol{p}_{\rm j}\, dz\, d^2\boldsymbol{p}_{\perp\pi}\; d\phi_S}$$

UD, Murgia, Pisano 2011

$$d\sigma(\phi_{S_A}, \phi_\pi^H) - d\sigma(\phi_{S_A} + \pi, \phi_\pi^H) \sim d\Delta\sigma_0 \sin\phi_{S_A}$$
$$+ d\Delta\sigma_1^- \sin(\phi_{S_A} - \phi_\pi^H) + d\Delta\sigma_1^+ \sin(\phi_{S_A} + \phi_\pi^H)$$
$$+ d\Delta\sigma_2^- \sin(\phi_{S_A} - 2\phi_\pi^H) + d\Delta\sigma_2^+ \sin(\phi_{S_A} + 2\phi_\pi^H),$$

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

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

Collins effect

COLLINS ASYMMETRY

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

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

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

Collinear initial state

PARAMETRIZATIONS

FIT to SIDIS and e^+e^- data

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

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

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

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

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

RESULTS
PREDICTIONS

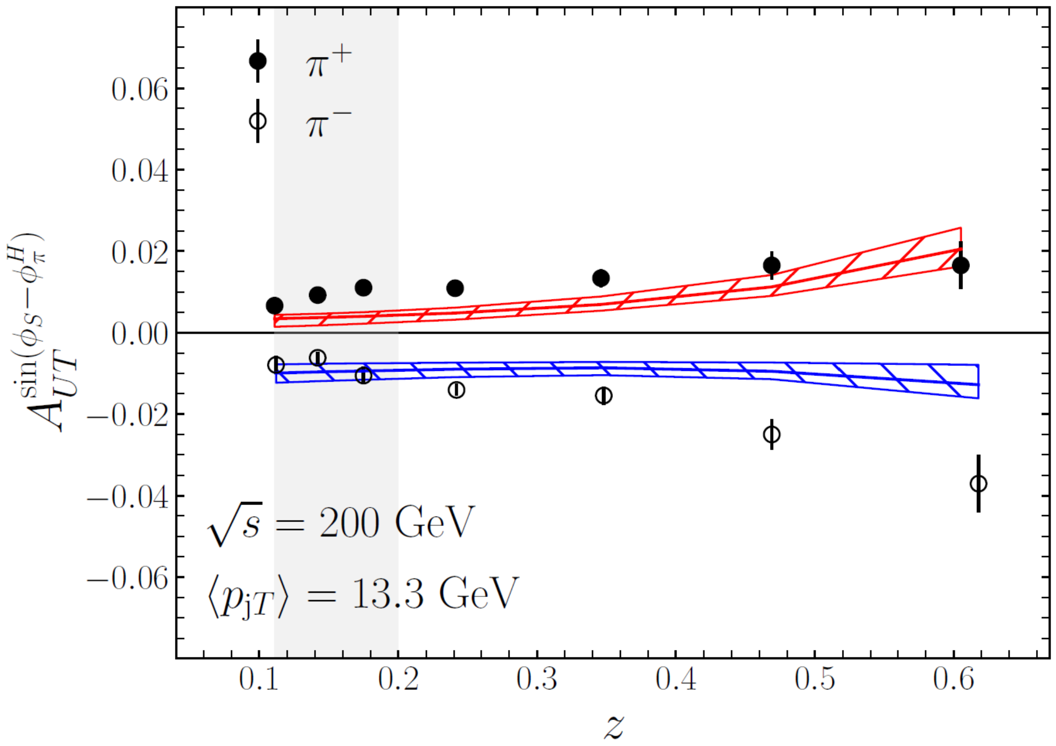
UD, C. Flore, M. Zaccheddu, PLB 2025

STAR KINEMATICS

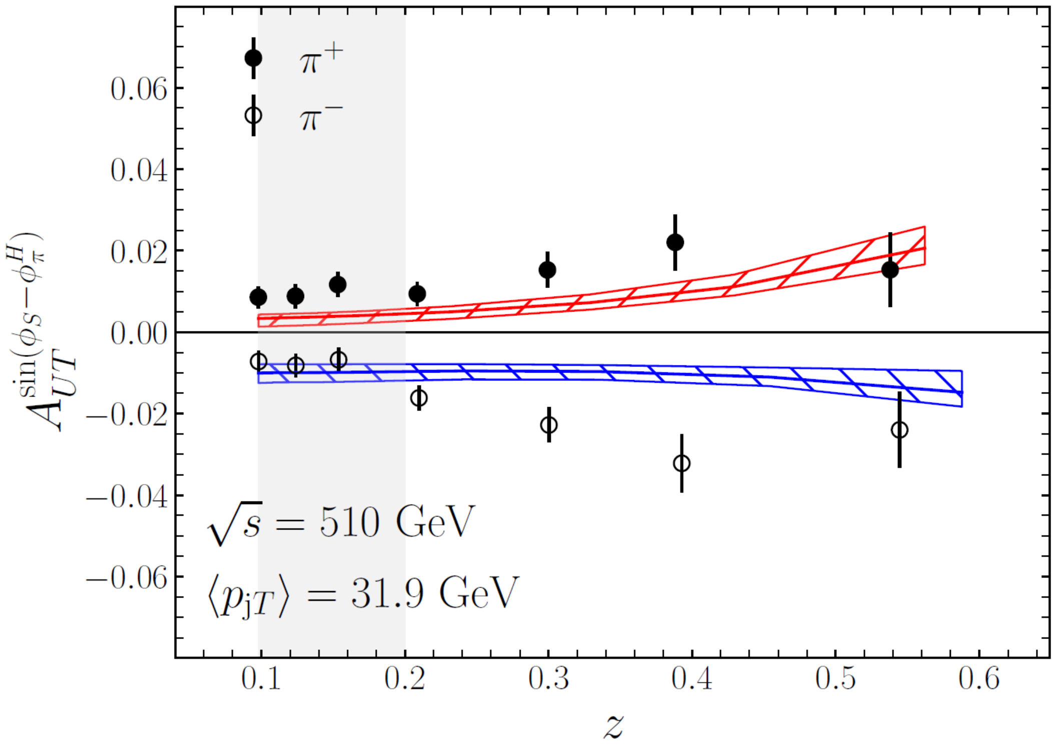
Variable	Values/ranges	Description
$\sqrt{s}$	200 500 GeV	Center-of-mass energy
p_{jT}	[6–30] [8–60] GeV	Jet transverse momentum
η_j	≤0.9	Jet pseudorapidity
x_T	$2\, p_{jT} / \sqrt{s}$	Scaling variable
j_T	[0.1–1.25] [0.1-1.5] GeV	Pion transverse momentum relative to the jet axis
z	[0.1–0.8]	Longitudinal momentum fraction carried by the pion
R	[0.05–0.6]	Jet cone radius

ASYMMETRIES VS *z*

PREDICTIONS/DATA



STAR 200 GeV

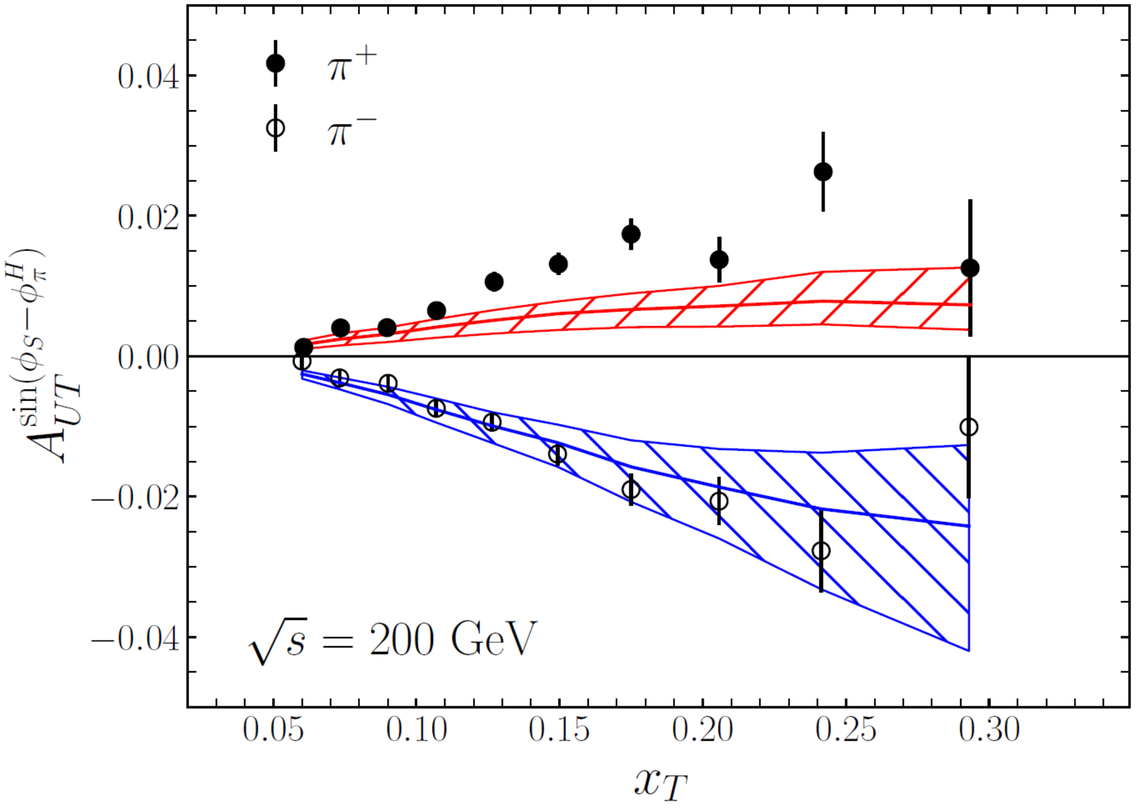


STAR 510 GeV

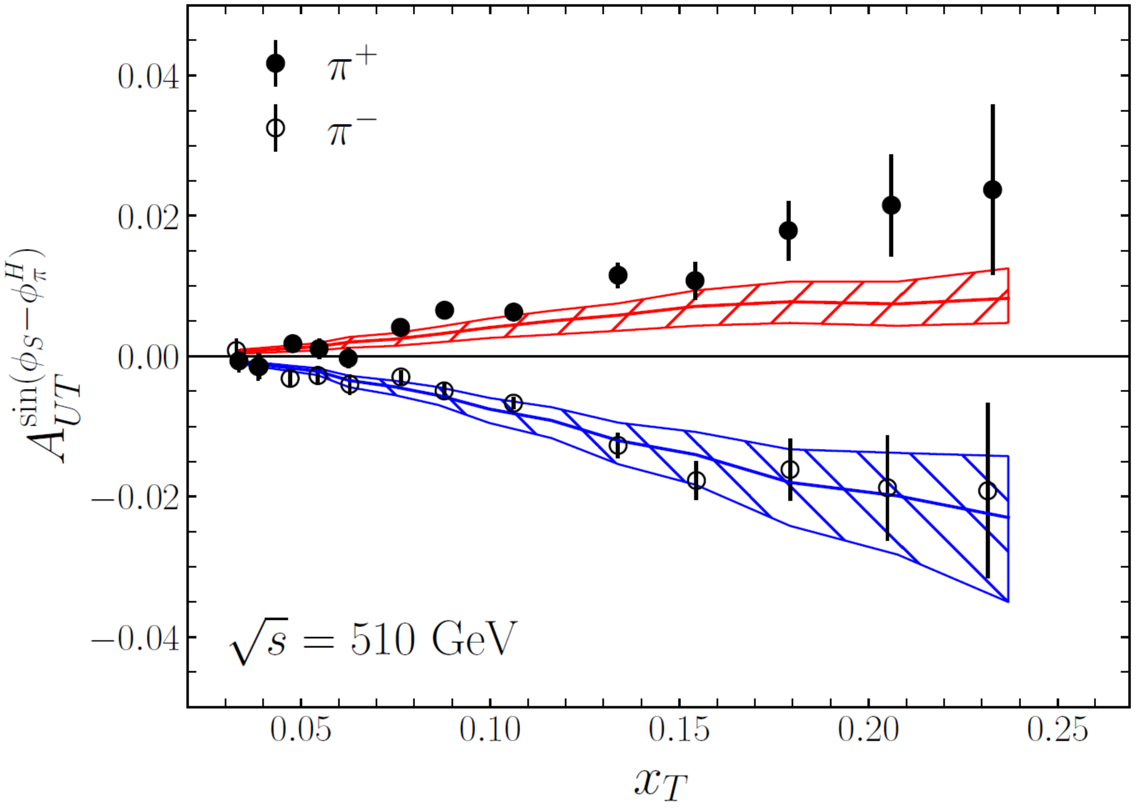
Central value: median of the compressed 10^6 MC sets; uncertainties at 2σ (CL).

ASYMMETRIES VS x_T

PREDICTIONS/DATA



200 GeV

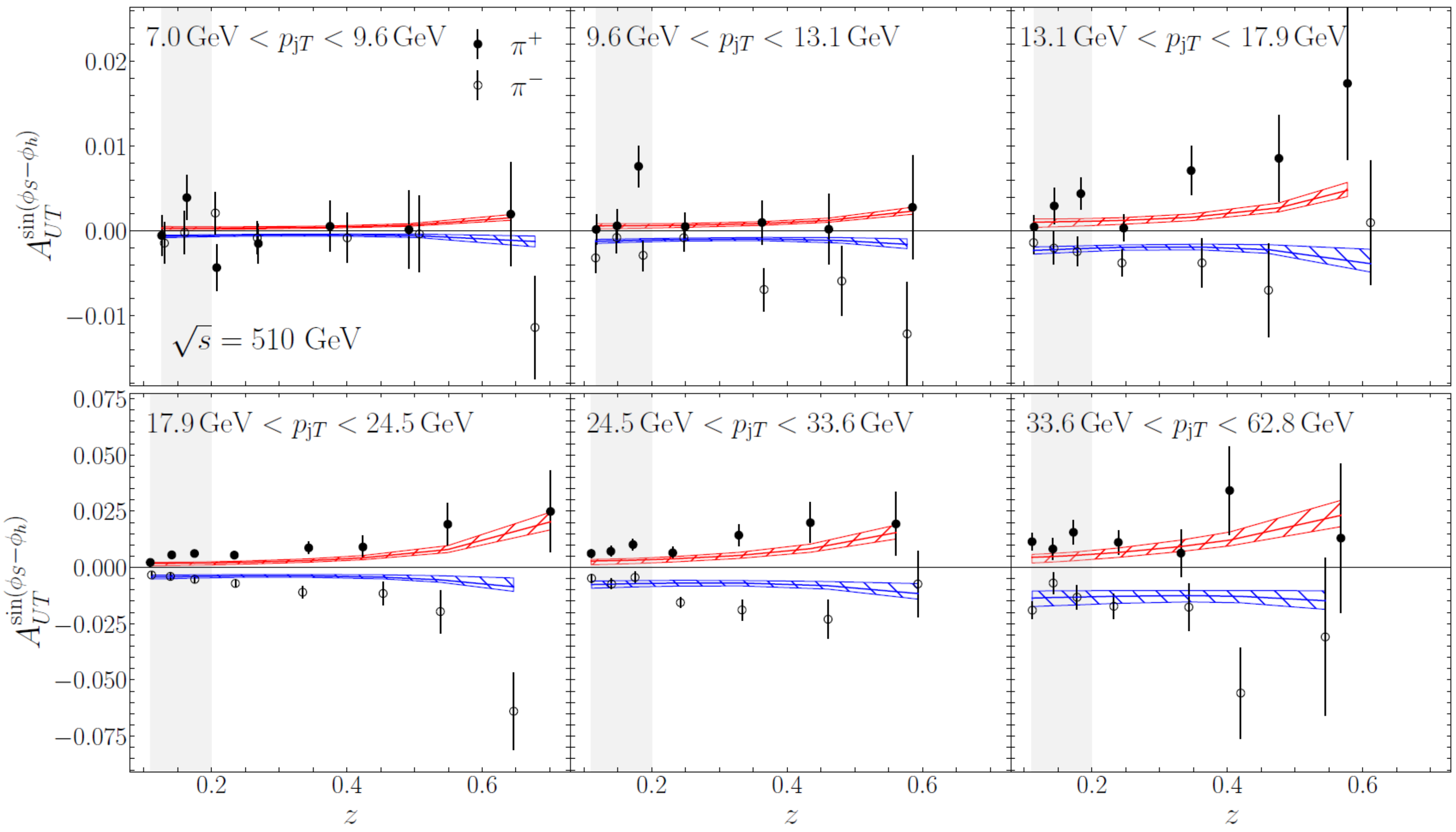


510 GeV

ASYMMETRIES VS z BINNED IN p_{jT}

PREDICTIONS/DATA

STAR
510 GeV



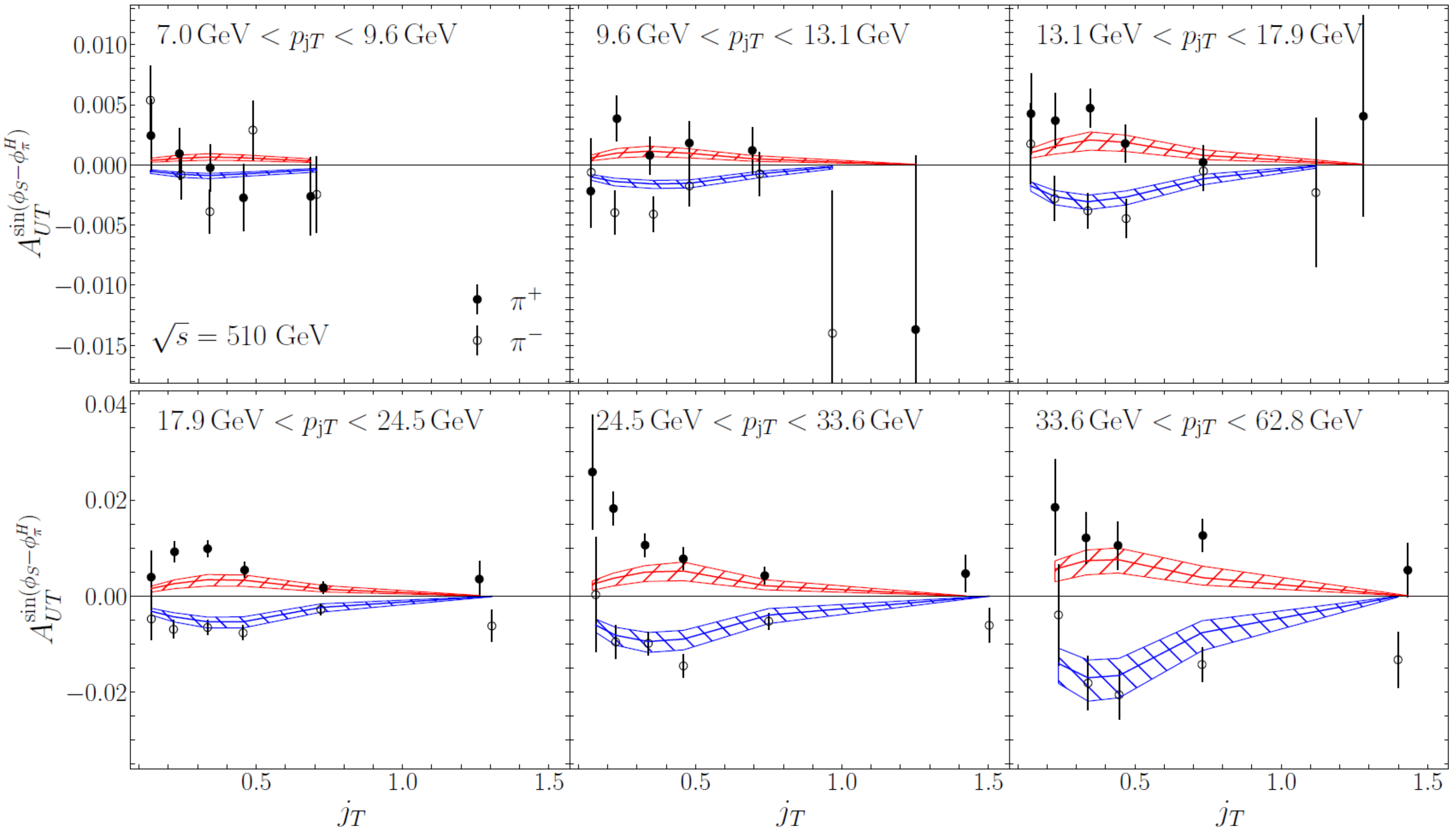
REMARKS I

- No significant energy dependence; good agreement data-theory
- No evidence of TMD-factorization breaking and mild evolution effect
- Discrepancies at moderate/large z: limits in Collins FF parametrization; reliable for $z > 0.2$
- Fixed x_T,probes transversity at $x > x_T$,(beyond SIDIS) access to large x.
- Combined/global fit, including this dataset, essential

ASYMMETRIES VS j_T BINNED IN p_{jT}

PREDICTIONS/DATA

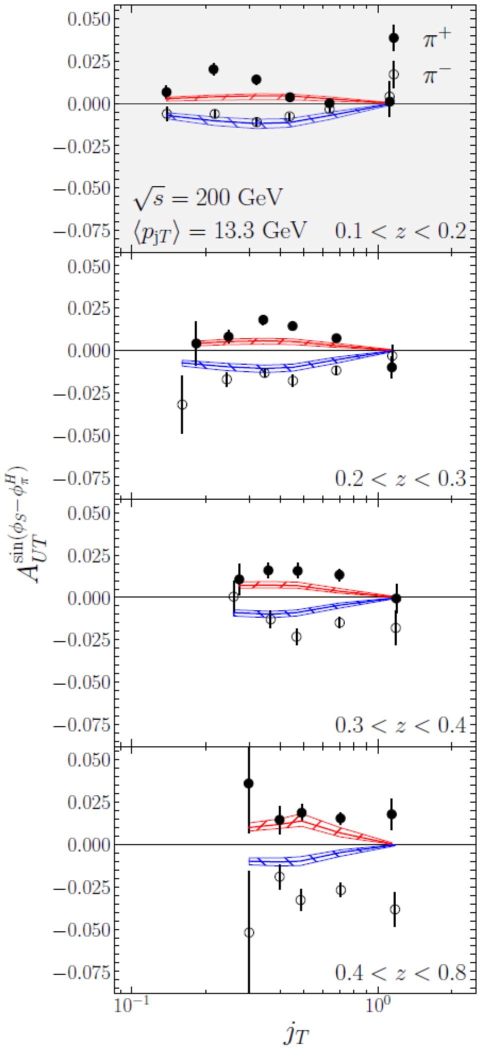
STAR
510 GeV

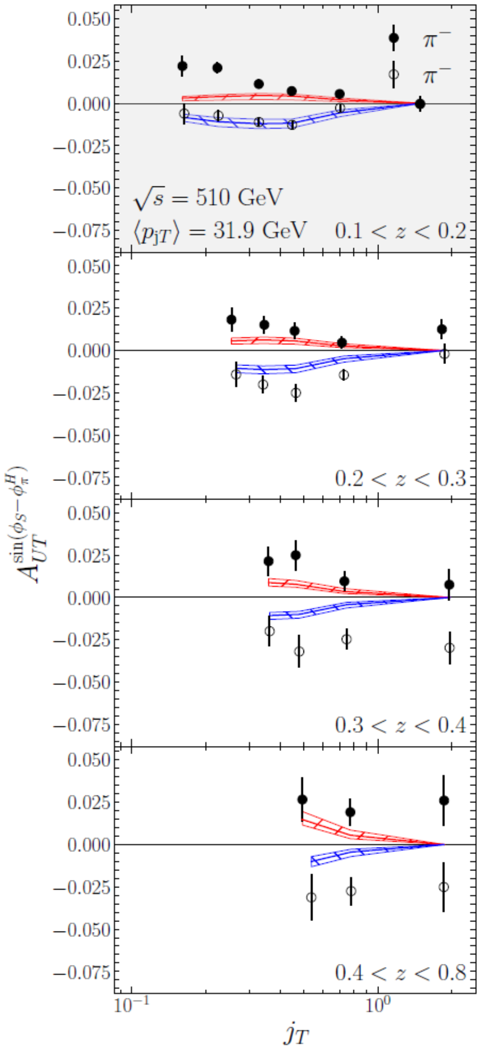


ASYMMETRIES VS j_T BINNED IN z

PREDICTIONS/DATA

STAR
200 GeV





STAR
510 GeV

REMARKS II

- Overall good agreement
- Sensitive distributions ⟶ probe intrinsic transverse momentum and its z correlation.
- Over-simplified Gaussian j_T modeling → needs more flexible (flavor/z dependent parametrization, especially at large z.
- Mild-scale dependence in j_T.
- Need for improved jet-fragmentation modeling (and/or j_T model).
- Importance of a combined fit

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

UD, C. Flore & M. Zaccheddu, arXiv:2605.02890 [hep-ph] to appear in PLB

COLLINS ASYMMETRY

$$\frac{E_{\rm j}\, d\sigma^{\ell\, p(S,\phi_S)\to {\rm jet}\,\pi(\phi_\pi^H)\, X}}{d^3\boldsymbol{p}_{\rm j} dz d^2\boldsymbol{p}_{\perp\pi} d\phi_S}\,.$$

$$A_{UT}^{\sin(\phi_S-\phi_h^H)}(\boldsymbol{p}_{\rm j}, z, p_{\perp\pi})$$

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

Formally identical, but less channels involved w.r.t the *pp* case

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

LO $\quad q\ell \to q\ell$

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

$$d\Delta\hat{\sigma}^{q\ell\to q\ell} = -e_q^2\,\frac{\hat{s}\hat{u}}{\hat{t}^2}$$

$$x = \frac{x_T e^{\eta_\mathrm{j}}}{2 - x_T e^{-\eta_\mathrm{j}}}$$

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

Large $p_{\mathrm{j}T}$ implies large Q^2
(at not large positive η_j)

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

Final lepton is not observed → **also collinear…**
quasireal photon exchange [WW approximation]

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

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

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

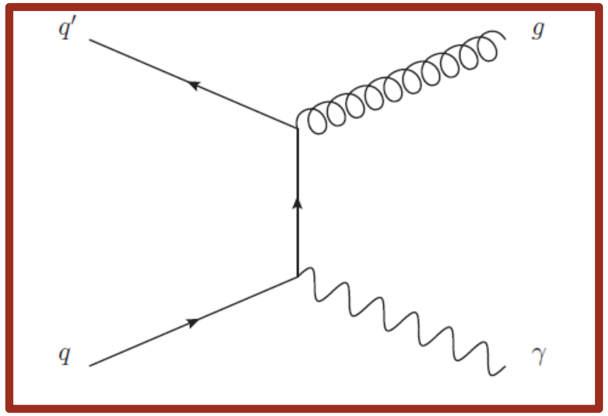
$$f_{\gamma/\ell}(y) = \frac{\alpha_{\rm em}}{2\pi}\left[\frac{1+(1-y)^2}{y}\ln\frac{Q^2_{\rm max}}{Q^2_{\rm min}(y)} + 2m_\ell^2 y\left(\frac{1}{Q^2_{\rm max}} - \frac{1}{Q^2_{\rm min}(y)}\right)\right]$$

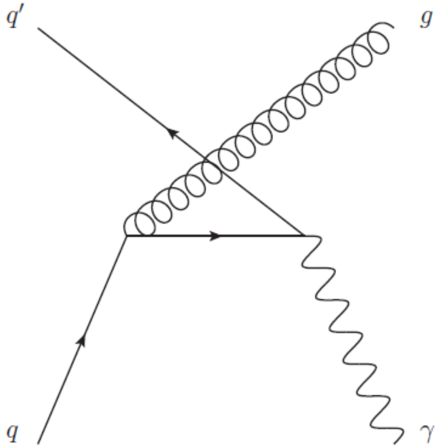
B. A. Kniehl, G. Kramer, M. Spira, Z. Phys. C 1997

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

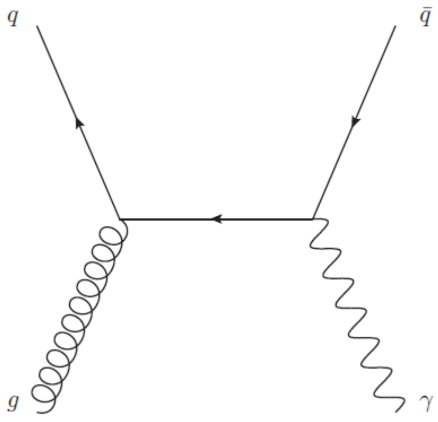
Channels

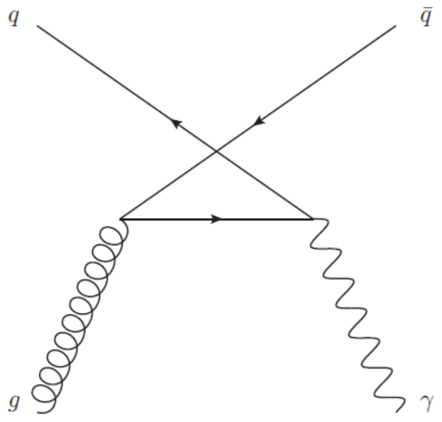
$$q\gamma \to qg$$





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





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

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

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

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

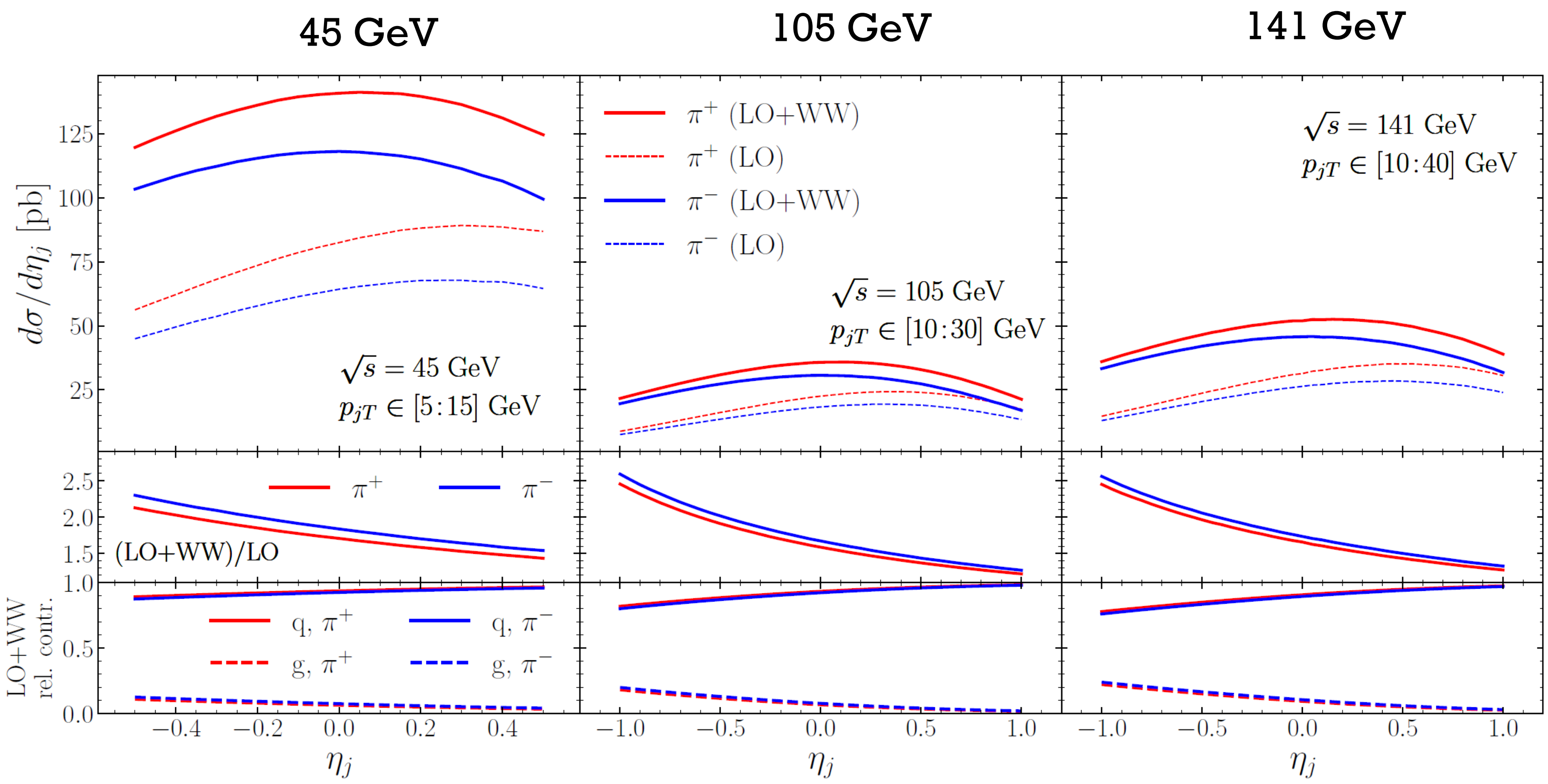
$$f_{\gamma/\ell}(y)\otimes h_1^q(x)\otimes d\Delta\hat{\sigma}^{q\gamma\to qg}\otimes H_1^{\perp q}(z,j_T)$$

$$d\Delta\hat{\sigma}^{q\gamma\to qg} = \frac{8}{3}e_q^2$$

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.

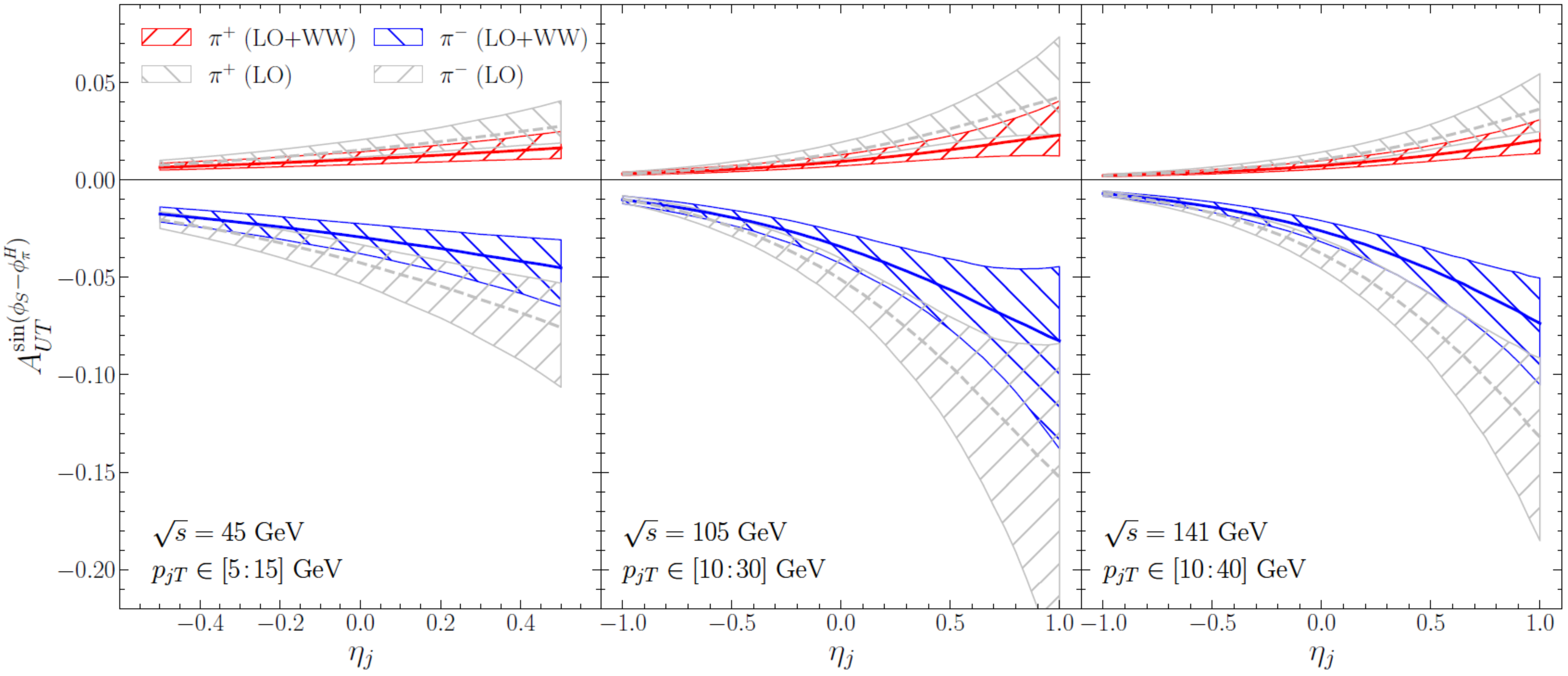
(LO+WW)/LO around 2-1.5

Quark dominance!!!

backward region: gluon-initiated channels, entering only via the WW term, play *some* role

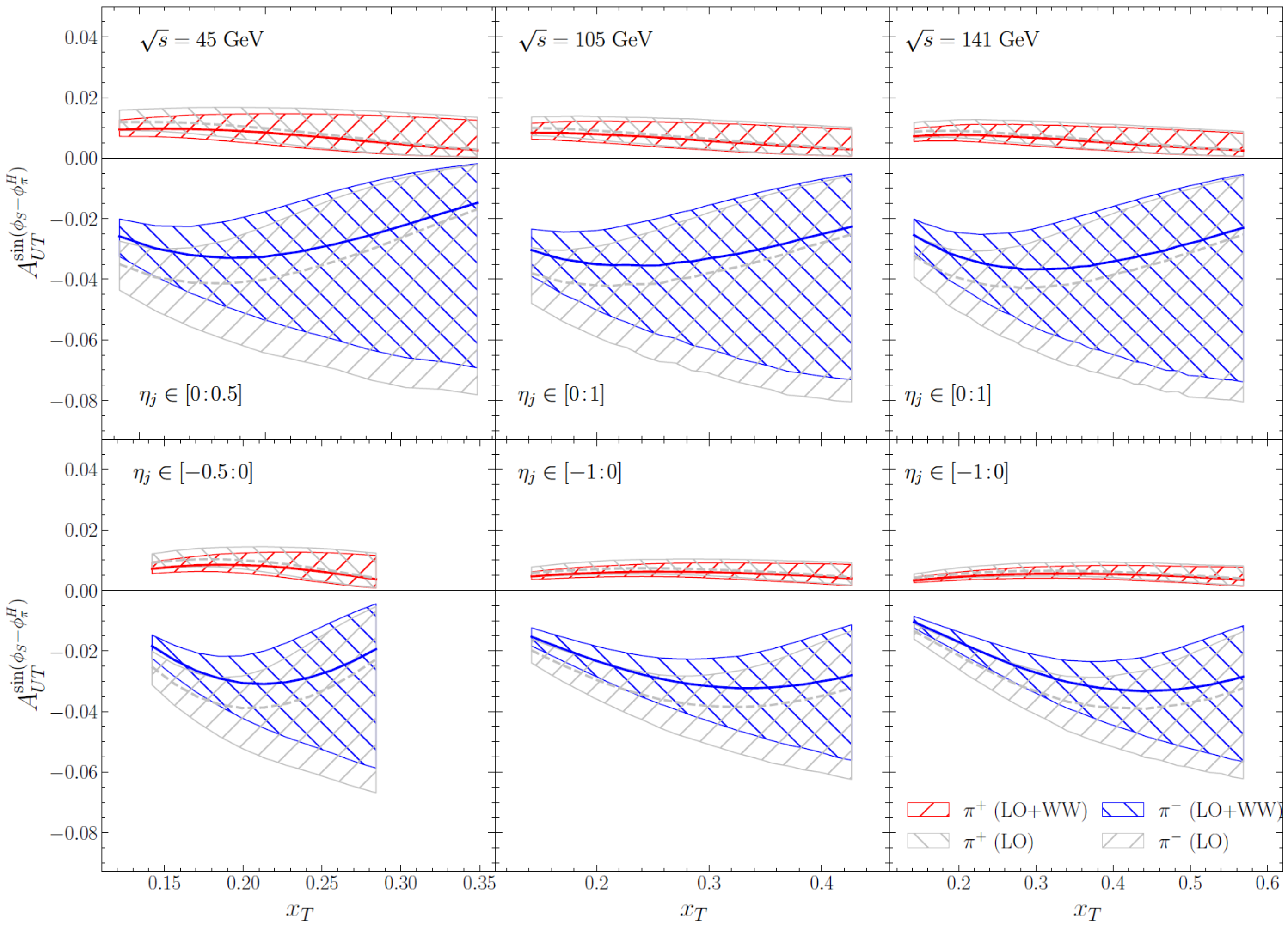
AZIMUTHAL ASYMMETRIES VS η_J

45 GeV 105 GeV 141 GeV



AZIMUTHAL ASYMMETRIES VS x_T

45 GeV 105 GeV 141 GeV



[LO+WW] results

- π^+ lower values

  π^- larger values, in size:

- Larger unfavored Collins FF (integrated over low z) × u-quark transversity ⇒ stronger effect in π^-
- Expectations testable at EIC

- Small x_T & backward region: low-x values, < 0.1 : access to

  transversity for sea quarks

$$x_{\min} = \frac{x_T e^{\eta_j}}{2 - x_T e^{-\eta_j}}$$

REMARKS

❑ **Quark-dominated observable**

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

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

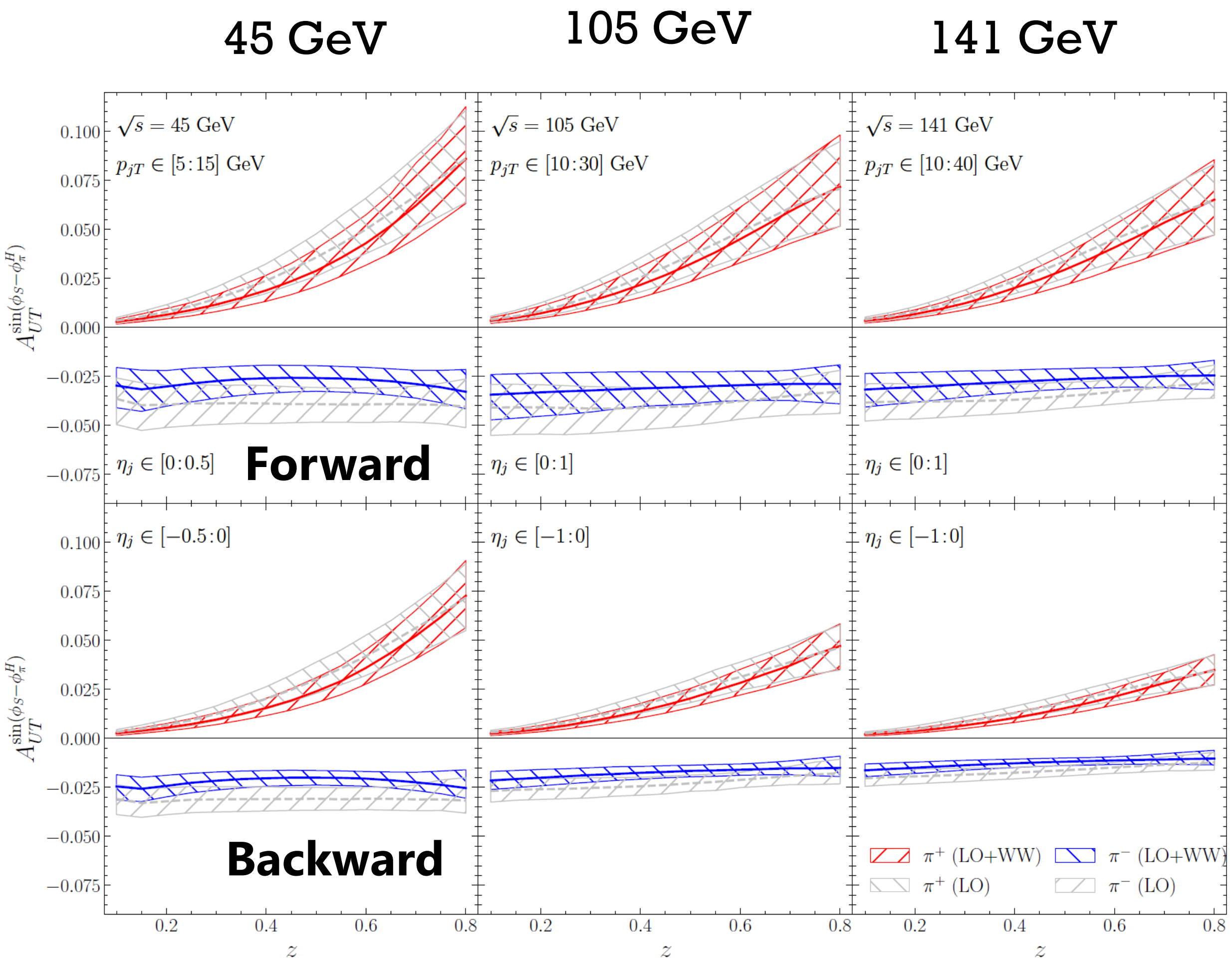
❑ **Implications**

- expect sizeable asymmetries
- enhanced sensitivity to transversity

❑ **Contrast: *pp* asymmetries**

- denominator gluon dominated ⇒ suppressed asymmetries

AZIMUTHAL ASYMMETRIES VS z



Forward: quark dominated (also backward at low energy)
Higher energies: gluons contrib. ⇒ forward–backward differences

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

Large z:
- Collins FFs follow unpolarized FFs
- unfavored strongly suppressed

u-quark dominance (charge factor)
- transversity h_1^u 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

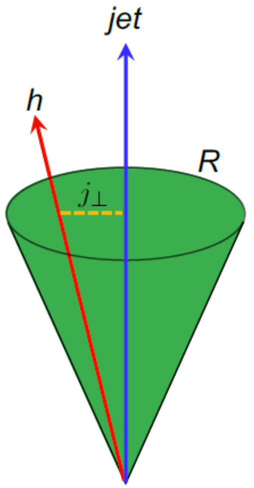
- **h-in-jet azimuthal asymmetries in *pp***
  → test of TMD-FF universality & TMD factorization
- **TMD mechanism only in fragmentation**
  → clean access, two-scale process
- **Phenomenology**
  → good agreement (Collins asymmetries)
  → also spontaneous transverse Λ polarization
- **EIC potential (*ep*)**
  → sizeable, measurable asymmetries
  → sensitivity to valence & sea transversity
  → flavor separation of Collins FFs
- **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

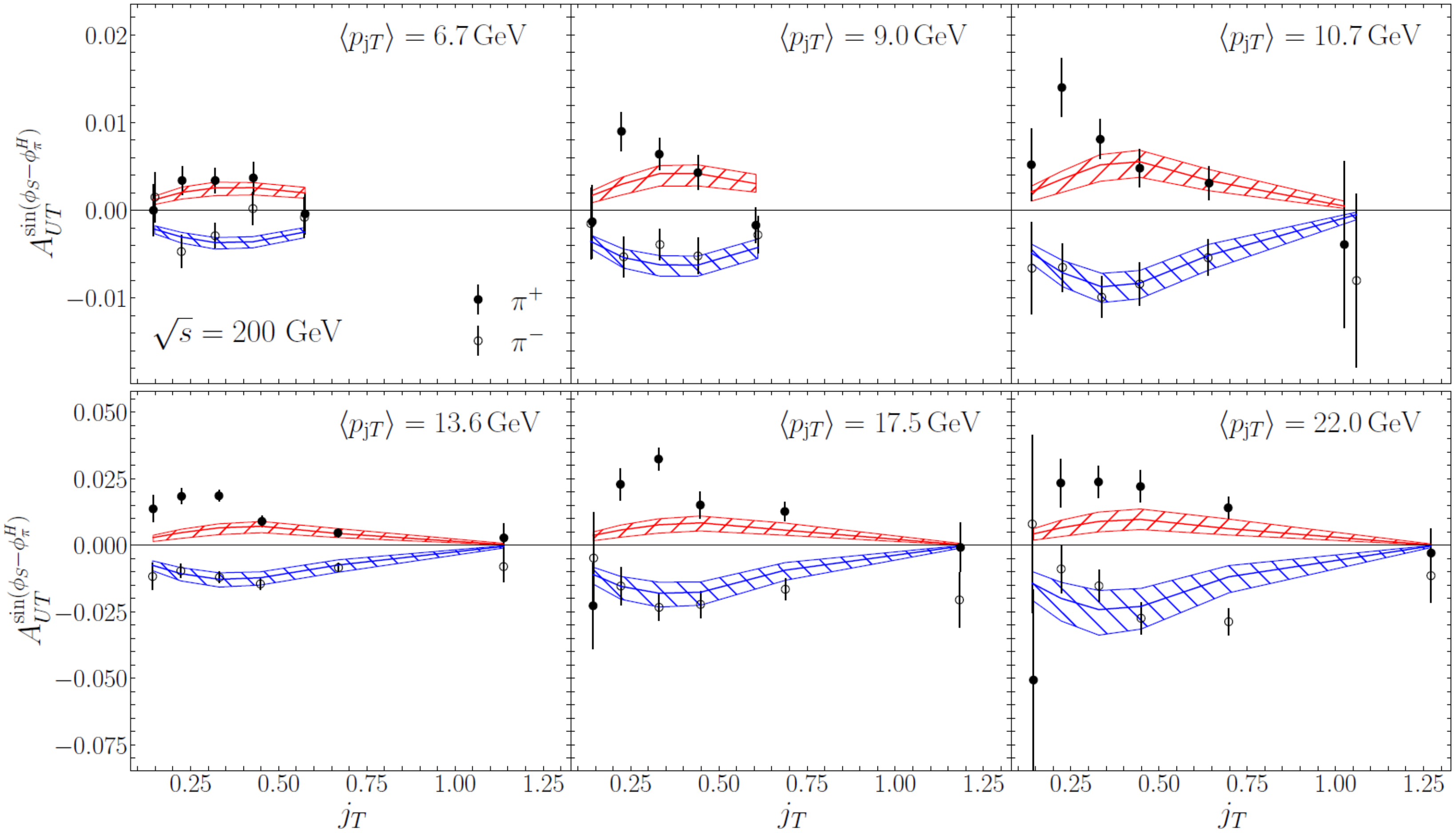
We adopt as an indicator the Welch's t-statistic, defined as

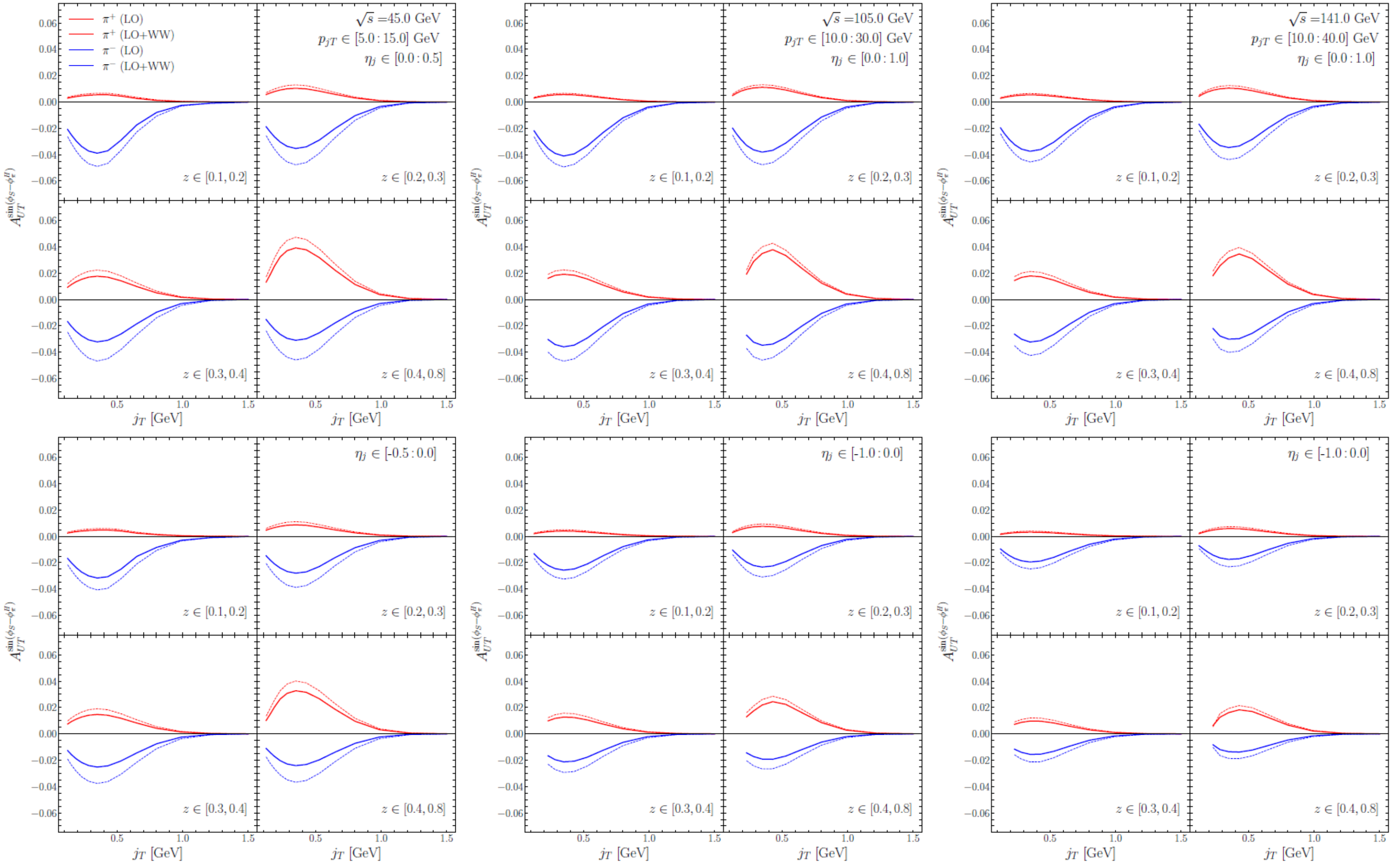
$$t = \frac{\mu_{\boldsymbol{a}} - \mu_{\boldsymbol{a}'}}{\sqrt{\frac{\sigma_a^2}{N_{\text{set}}^a} + \frac{\sigma_{a'}^2}{N_{\text{set}}^{a'}}}},$$

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.

PREDICTIONS VS. j_T BINNED IN p_{jT}

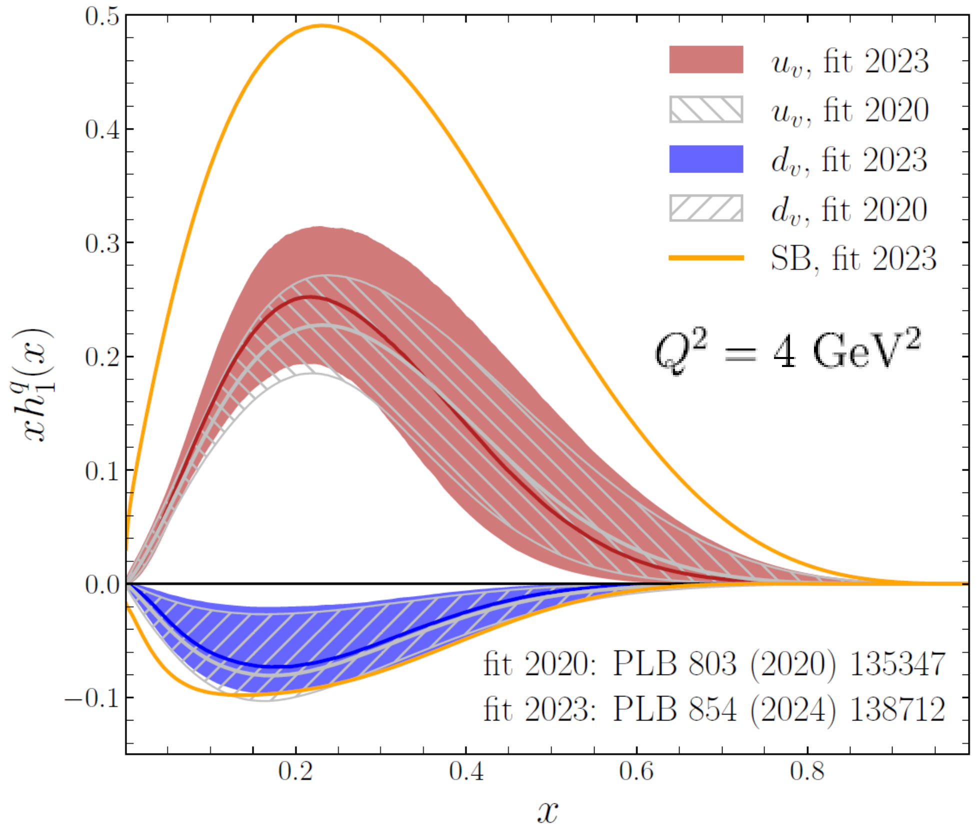
STAR
200 GeV

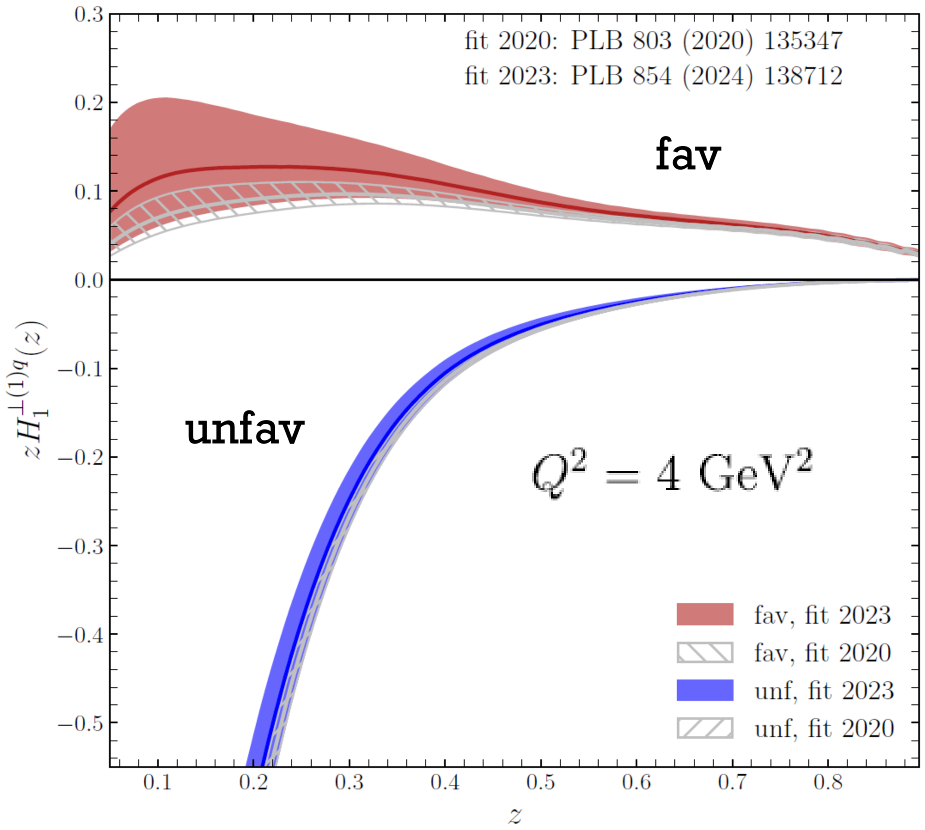




Azimuthal asymmetries in lepton-proton collisions as a function of j_T at fixed z bins

TRANSVERSITY AND COLLINS FFS





PLB 2020 UD, Flore, Prokudin

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

Proper use of the Soffer bound in a fit

$$|h_1^q(x, Q^2)| \leq \frac{1}{2}\left[f_{q/p}(x, Q^2) + g_{1L}^q(x, Q^2)\right]$$