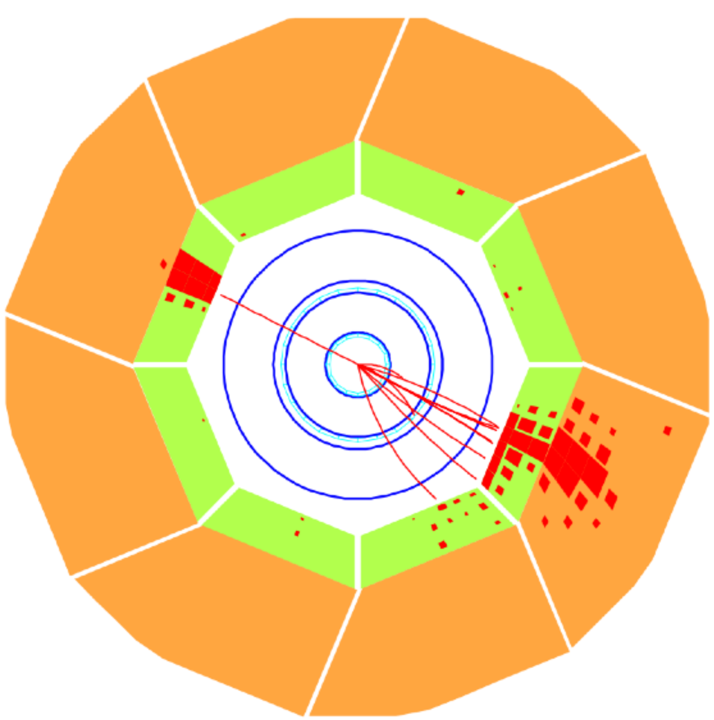
Precision three-dimensional imaging of nuclei using recoil-free jets

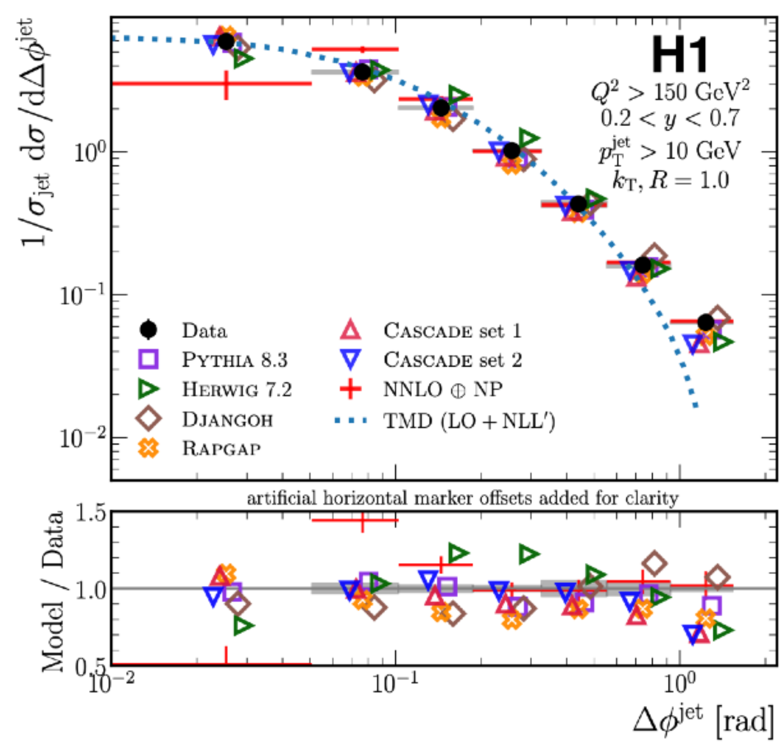
Ding-Yu Shao
Fudan University

The 4th EIC-Asia Workshop   Fudan University   Jul 1, 2024

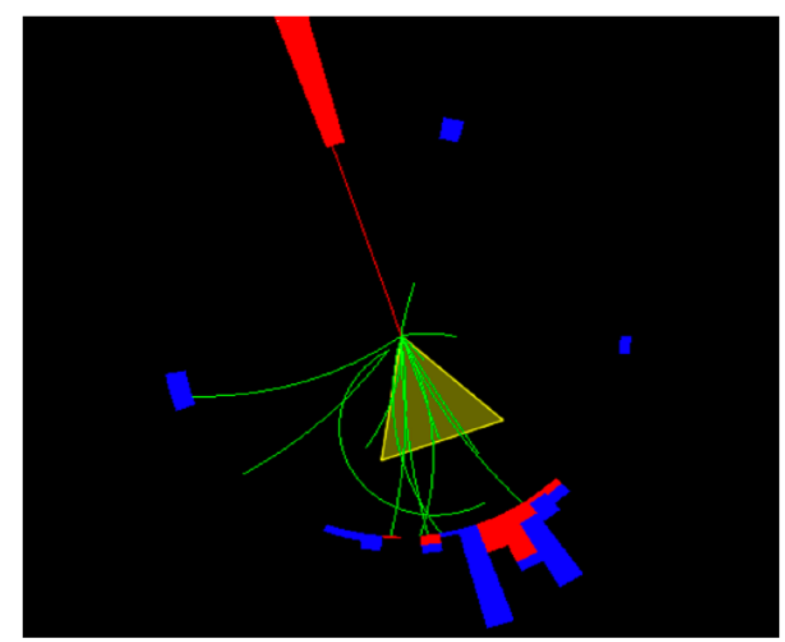
Introduction

- **In past DIS experiments, scientists mainly focused on jet behaviors in the Breit frame—the frame of the virtual photon and the nucleon.**
- **Recently, there has been many interests in studying observables in the lab frame of the incoming lepton and nucleus**
  - **Event shape** Kang, Mantry, Qiu '12; Kang, Lee, Stewart '13; Li, Vitev, Zhu, '20
  - **Jet production** Liu, Ringer, Vogelsang, Yuan '19; Arratia, Kang, Prokudin, Ringer '19
  - **Hadron production** Gao, Michel, Stewart, Sun '22



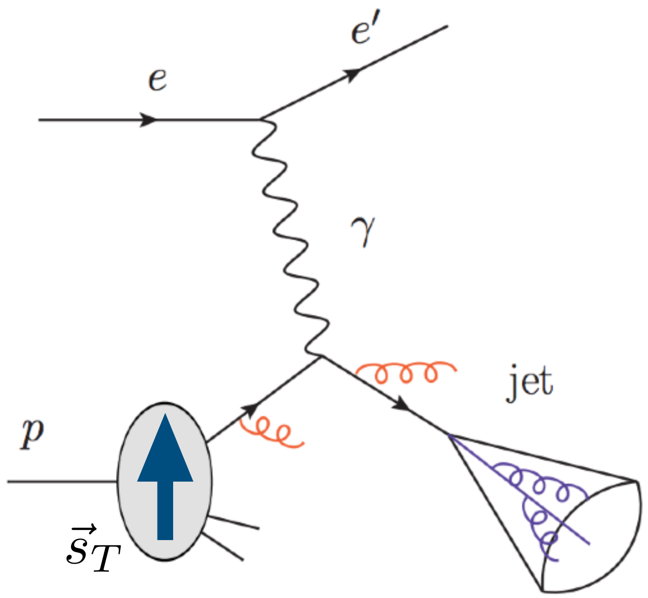


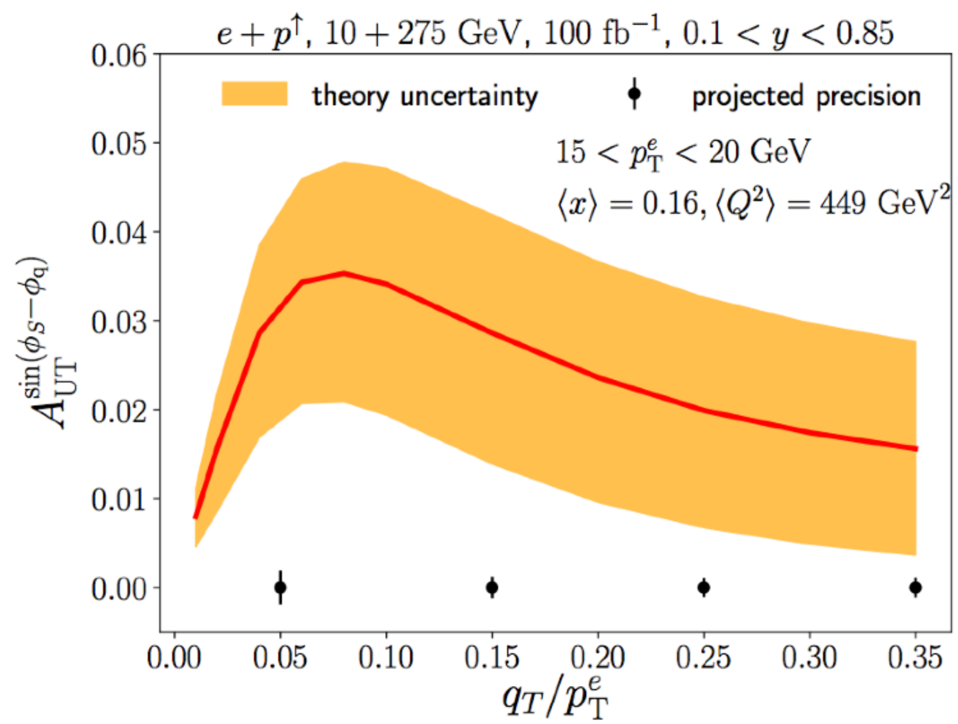
H1 2108.12376



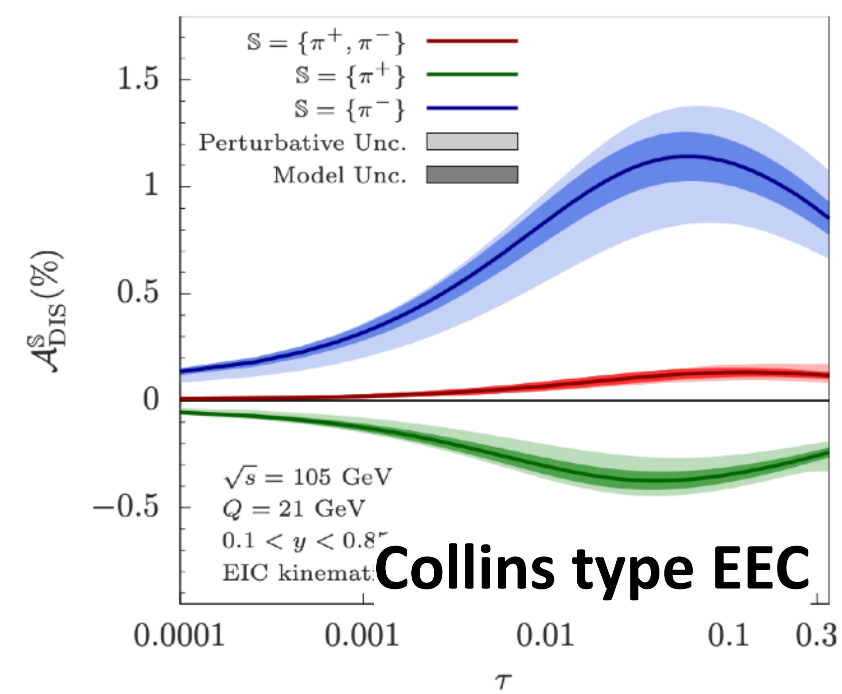
EIC Yellow Report

Jets and 3D imaging

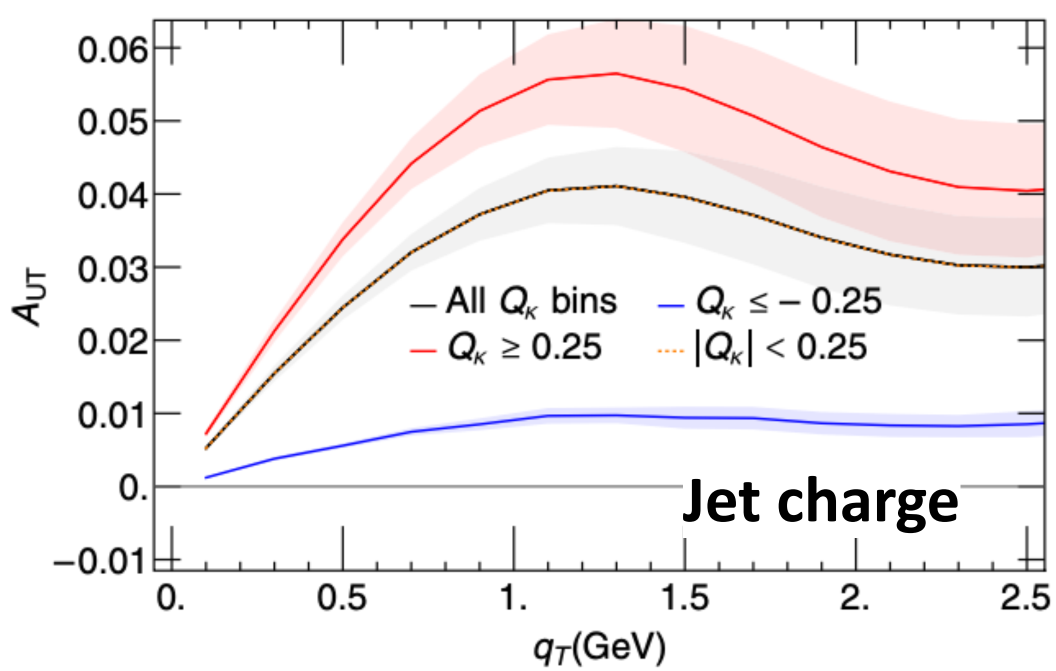




Arratia, Kang, Prokudin, Ringer ’19
Liu, Ringer, Vogelsang, Yuan ’19



Kang, Lee, DYS, Zhao ’23 JHEP



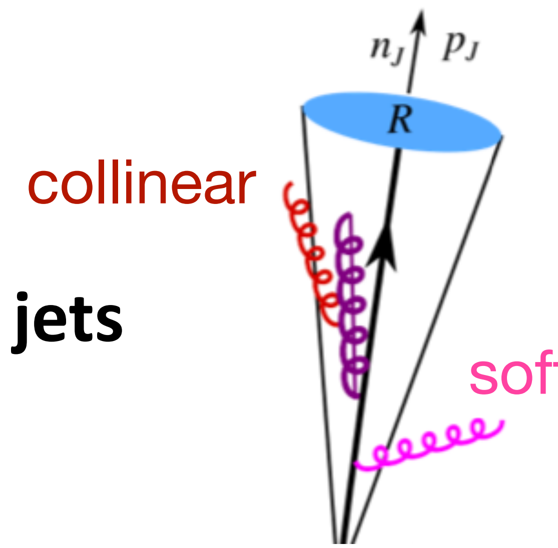
Kang, Liu, Mantry, DYS ’20 PRL

- Jets are complementary to standard SIDIS extractions of TMDs See Zhongbo’s talk
- Jet measurements allow independent constraints on TMD PDFs and FFs from a single measurement
- Azimuthal correlation between jet and lepton sensitive to TMD PDFs

Azimuthal correlations of QCD jets

- **All-order resummation of azimuthal correlation of QCD jets was first studied by** (Banfi, Dasgupta & Delenda '08)

$$q_T = \Big| \sum_{i \notin \text{ jets}} \vec{k}_{T,i} \Big| + \mathcal{O}\left(k_T^2\right)$$



  - **sum over all soft and collinear partons not combined with jets**
  - **caused by particle flow outside the jet regions**
  - **non-global observables** (Dasgupta & Salam '01)

- **CSS framework (indirect formalism, construct azimuthal angle from q_T)**
  - **dijet** (Sun, Yuan & Yuan '14 & '15)

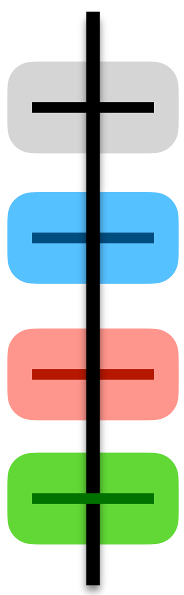
Resummation formula: $$\frac{d\sigma}{d\Delta\phi} = x_a f_a(x_a, \mu_b) x_b f_b(x_b, \mu_b) \frac{1}{\pi} \frac{d\sigma_{ab\to cd}}{d\hat{t}} b\, J_0(|\vec{q}_\perp| b) e^{-S(Q,b)}$$

Perturbative Sudakov factor: $$S_P(Q,b) = \sum_{q,g} \int_{\mu_b^2}^{Q^2} \frac{d\mu^2}{\mu^2} \left[A \ln \frac{Q^2}{\mu^2} + B + D \ln \frac{1}{R^2} \right]$$

Jet radius and TMD joint resummation for boson-jet correlation in SCET

(Buffing, Kang, Lee, Liu ’18; Chien, DYS & Wu ’19 JHEP)

$$N_1(P_1) + N_2(P_2) \to \underbrace{\text{boson}(p_V) + \text{jet}(p_J)}_{q_T} + X$$



$p_h \sim Q(1,1,1)$

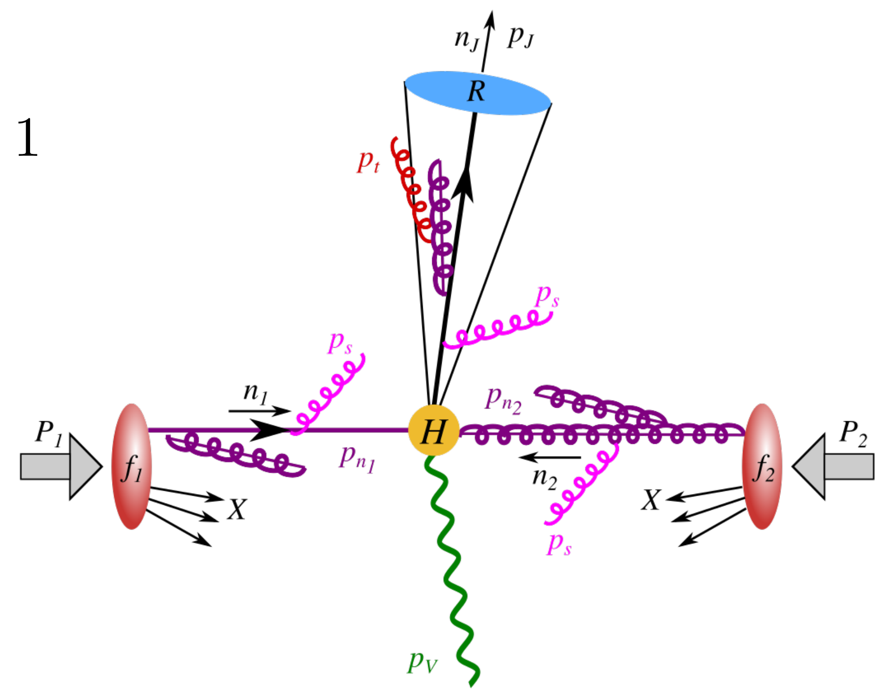
$p_{n_J} \sim p_T^J\,(R^2, 1, R)_{n_J \bar{n}_J}$

$p_{n_1} \sim (q_T^2/Q, Q, q_T)_{n_1 \bar{n}_1}$

$p_s \sim (q_T, q_T, q_T)$

$p_t \sim q_T\,(R^2, 1, R)_{n_J \bar{n}_J}$

$q_T \ll Q, R \ll 1$



Construction of the theory formalism

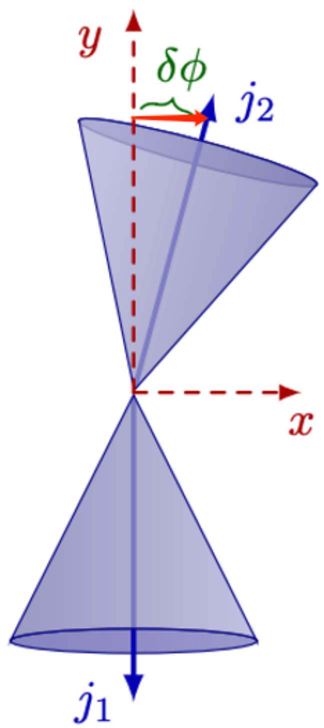
- **Multiple scales: *p_T, $p_T R$, q_T, $q_T R$***
- **Theory tools: SCET + multi-Wilson formalism** (Becher, Neubert, Rothen, DYS ’16 PRL)

$$\frac{d\sigma}{d^2q_T d^2p_T d\eta_J dy_V} = \sum_{ijk} \int \frac{d^2x_T}{(2\pi)^2} e^{i\vec{q}_T\cdot\vec{x}_T} \mathcal{S}_{ij\to Vk}(\vec{x}_T,\epsilon)\mathcal{B}_{i/N_1}(\xi_1,x_T,\epsilon)\mathcal{B}_{j/N_2}(\xi_2,x_T,\epsilon)$$

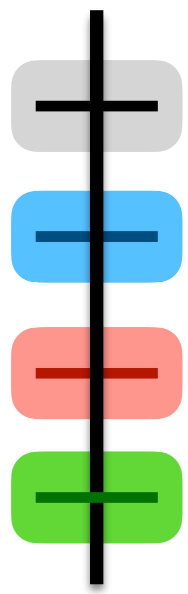
$$\times\,\mathcal{H}_{ij\to Vk}(\hat{s},\hat{t},m_V,\epsilon)\sum_{m=1}^{\infty}\langle \boldsymbol{\mathcal{J}}_m^k(\{\underline{n_J}\}, R\,p_J,\epsilon)\otimes \boldsymbol{\mathcal{U}}_m^k(\{\underline{n_J}\}, R\,\vec{x}_T,\epsilon)\rangle$$

Azimuthal decorrelation of QCD jets in pp, pA & UPC($\gamma\gamma$)

(Zhang, Dai, DYS, ’22 JHEP, Gao, Kang, DYS, Terry, Zhang ’23 JHEP)



Indirect



$p_h \sim Q(1,1,1)$

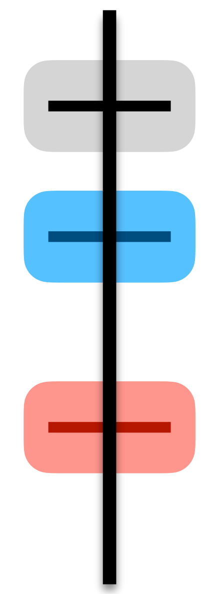
$p_{n_J} \sim p_T^J\,(R^2,1,R)_{n_J\bar{n}_J}$

$p_{n_1} \sim (q_T^2/Q, Q, q_T)_{n_1\bar{n}_1}$

$p_s \sim (q_T, q_T, q_T)$

$p_t \sim q_T\,(R^2,1,R)_{n_J\bar{n}_J}$

Direct



$p_h \sim Q(1,1,1)$

$p_{n_J} \sim p_T^J\,(R^2,1,R)_{n_J\bar{n}_J}$

$p^\mu_{c_i} \sim p_T\,(\delta\phi^2, 1, \delta\phi)_{n_i\bar{n}_i}$

$p^\mu_s \sim p_T\,(\delta\phi, \delta\phi, \delta\phi)$

$p^\mu_{cs_i} \sim \frac{p_T\,\delta\phi}{R}(R^2,1,R)_{n_i\bar{n}_i}$

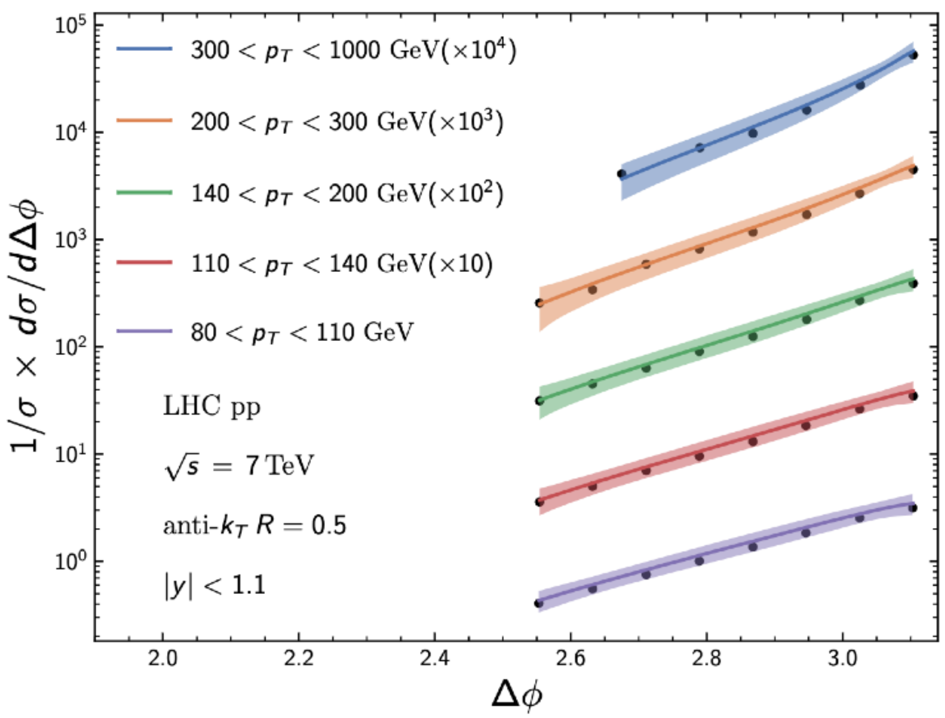
The factorization formula

$$\frac{\mathrm{d}^4\sigma_{\mathrm{pp}}}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}q_x} = \sum_{abcd} \frac{x_a x_b}{16\pi\hat{s}^2}\frac{1}{1+\delta_{cd}}\mathcal{C}_x\left[f^{\mathrm{unsub}}_{a/p}\,f^{\mathrm{unsub}}_{b/p}\,\boldsymbol{S}^{\mathrm{unsub}}_{ab\to cd,IJ}\,S^{\mathrm{cs}}_c\,S^{\mathrm{cs}}_d\right]\boldsymbol{H}_{ab\to cd,JI}(\hat{s},\hat{t},\mu)\,J_c(p_T R,\mu)\,J_d(p_T R,\mu)$$

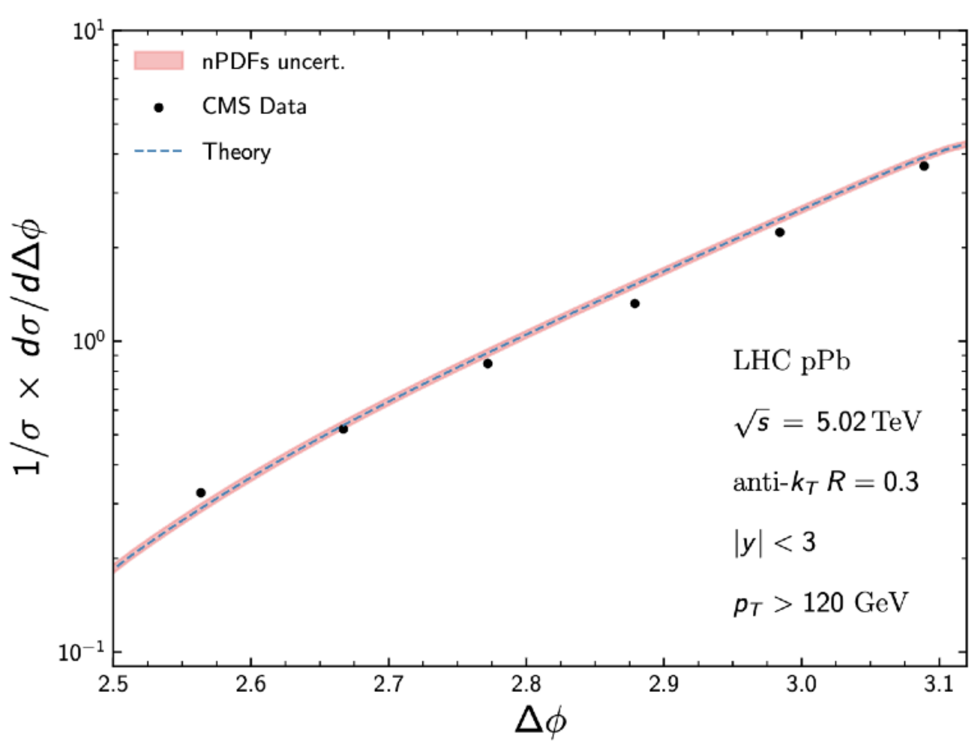
$$\mathcal{C}_x\left[f^{\mathrm{unsub}}_{a/p}\,f^{\mathrm{unsub}}_{b/p}\,\boldsymbol{S}^{\mathrm{unsub}}_{ab\to cd,IJ}\,S^{\mathrm{cs}}_c\,S^{\mathrm{cs}}_d\right] = \int \mathrm{d}k_{ax}\,\mathrm{d}k_{bx}\,\mathrm{d}k_{cx}\,\mathrm{d}k_{dx}\,\mathrm{d}\lambda_x\,\boldsymbol{S}^{\mathrm{unsub}}_{ab\to cd,IJ}(\lambda_x,\mu,\nu)$$
$$\times\, f^{\mathrm{unsub}}_{a/p}(x_a,k_{ax},\mu,\zeta_a/\nu^2)\,f^{\mathrm{unsub}}_{b/p}(x_b,k_{bx},\mu,\zeta_b/\nu^2)\,S^{\mathrm{cs}}_c(k_{cx},R,\mu,\nu)\,S^{\mathrm{cs}}_d(k_{dx},R,\mu,\nu)$$
$$\times\,\delta\left(q_x - k_{ax} - k_{bx} - k_{cx} - k_{dx} - \lambda_x\right)\,.$$

Numerical results in pp, pA

(Zhang, Dai, DYS, '22 JHEP, Gao, Kang, DYS, Terry, Zhang '23 JHEP)



(also see Sun, Yuan, Yuan '14)



Nuclear modified TMD PDFs

(Alrashed, Anderle, Kang, Terry & Xing, '22)

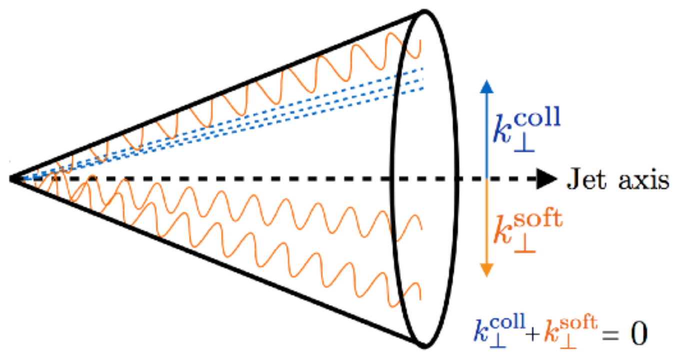
- **NLL resummation result is consistent with LHC data**
- **Open questions:**
  - **Higher resummation accuracy? SIDIS is known at N3LL' accuracy**
  - **Better angular resolution?**
  - **Reduce contamination from UE?**
- **One possible solution:**
  - **Recoil-free jet definition**

  E.g. anti-k_T clustering algorithm + p_T^n-weighted recombination scheme

Recoil-free jet and all-order structure

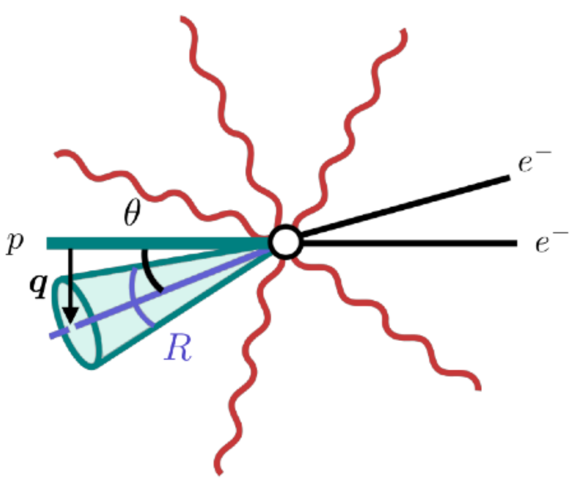
- **Recoil absent for the p_T^n-weighted recombination scheme** (Banfi, Dasgupta & Delenda '08)

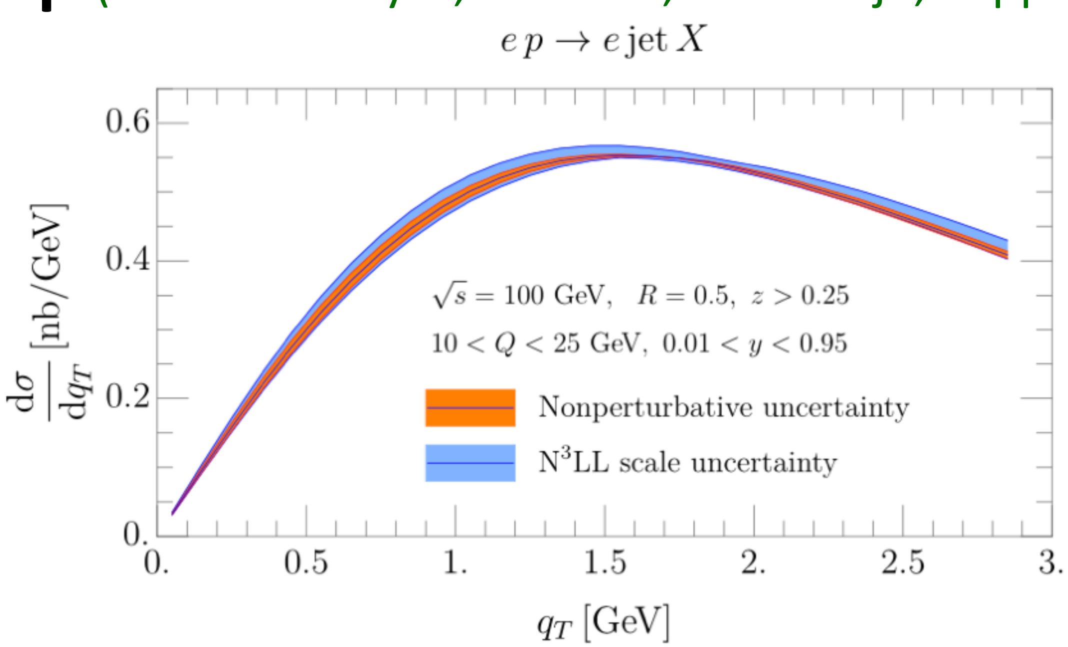
$$p_{t,r} = p_{t,i} + p_{t,j}\,,$$
$$\phi_r = (w_i\phi_i + w_j\phi_j)/(w_i + w_j) \qquad w_i = p_t^n$$
$$y_r = (w_i y_i + w_j y_j)/(w_i + w_j)$$



$n \to \infty$ **Winner-take-all scheme** (Bertolini, Chan, Thaler '13)

- **N3LL resummation for jet q_T @ ee and ep** (Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi '18 '19)



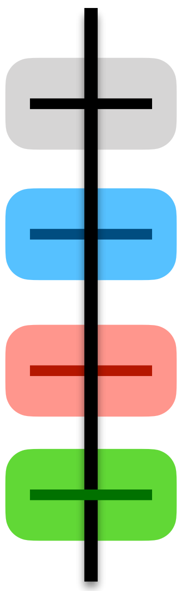


- **NNLL resummation for $\delta\phi$ @ pp** (Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB)
- **NNLL resummation for $\delta\phi$ @ ep & eA** (Fang, Ke, DYS, Terry '23 JHEP)

Recoil-free azimuthal angle for boson-jet correlation

(Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrigndêr '21 PLB)

Indirect



$p_h \sim Q(1,1,1)$

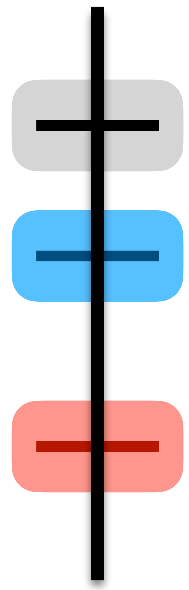
$p_{n_J} \sim p_T^J\,(R^2, 1, R)_{n_J \bar{n}_J}$

$p_{n_1} \sim (q_T^2/Q, Q, q_T)_{n_1 \bar{n}_1}$

$p_s \sim (q_T, q_T, q_T)$

$p_t \sim q_T\,(R^2, 1, R)_{n_J \bar{n}_J}$

Direct



$p_h \sim Q(1,1,1)$

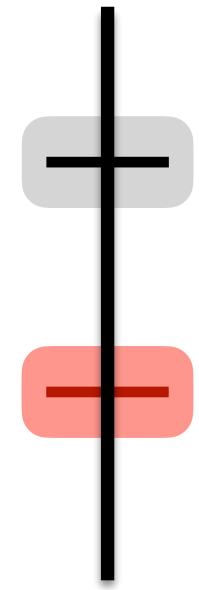
$p_{n_J} \sim p_T^J\,(R^2, 1, R)_{n_J \bar{n}_J}$

$p_{c_i}^\mu \sim p_T\,(\delta\phi^2, 1, \delta\phi)_{n_i \bar{n}_i}$

$p_s^\mu \sim p_T\,(\delta\phi, \delta\phi, \delta\phi)$

$p_{cs_i}^\mu \sim \frac{p_T\,\delta\phi}{R}(R^2, 1, R)_{n_i \bar{n}_i}$

Direct (recoil free) $\delta\phi \ll \mathcal{O}(1)$



$p_h \sim Q(1,1,1)$

$p_{c_i}^\mu \sim p_T\,(\delta\phi^2, 1, \delta\phi)_{n_i \bar{n}_i}$

$p_s^\mu \sim p_T\,(\delta\phi, \delta\phi, \delta\phi)$

Following the standard steps in SCET2 we obtain the following factorization formula

$$\frac{d\sigma}{dp_{x,V}\,dp_{T,J}\,dy_V\,d\eta_J} = \int \frac{db_x}{2\pi}\, e^{ip_{x,V} b_x} \sum_{i,j,k} B_i(x_a, b_x) B_j(x_b, b_x) S_{ijk}(b_x, \eta_J) H_{ij\to Vk}(p_{T,V}, y_V - \eta_J) J_k(b_x)$$

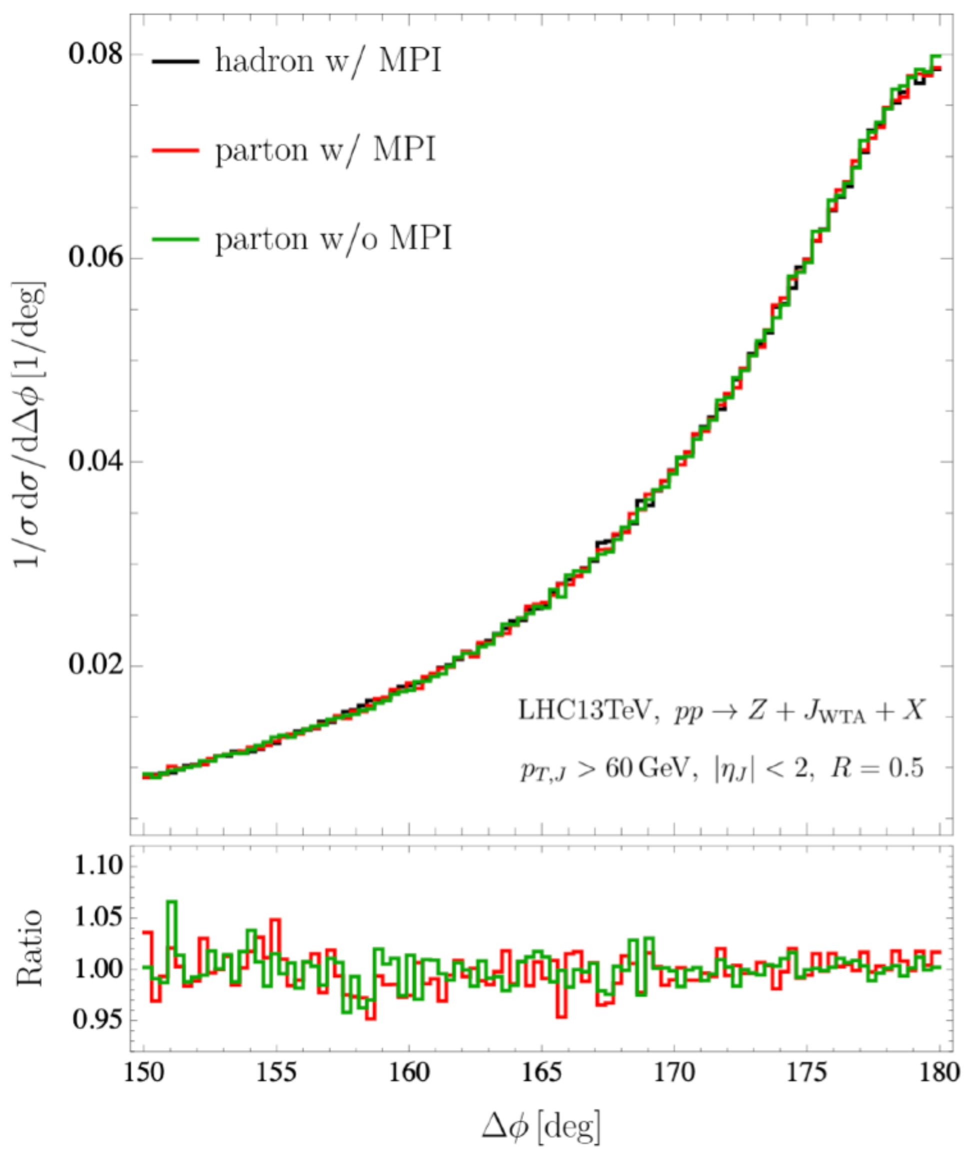
Fourier transformation in 1-dim

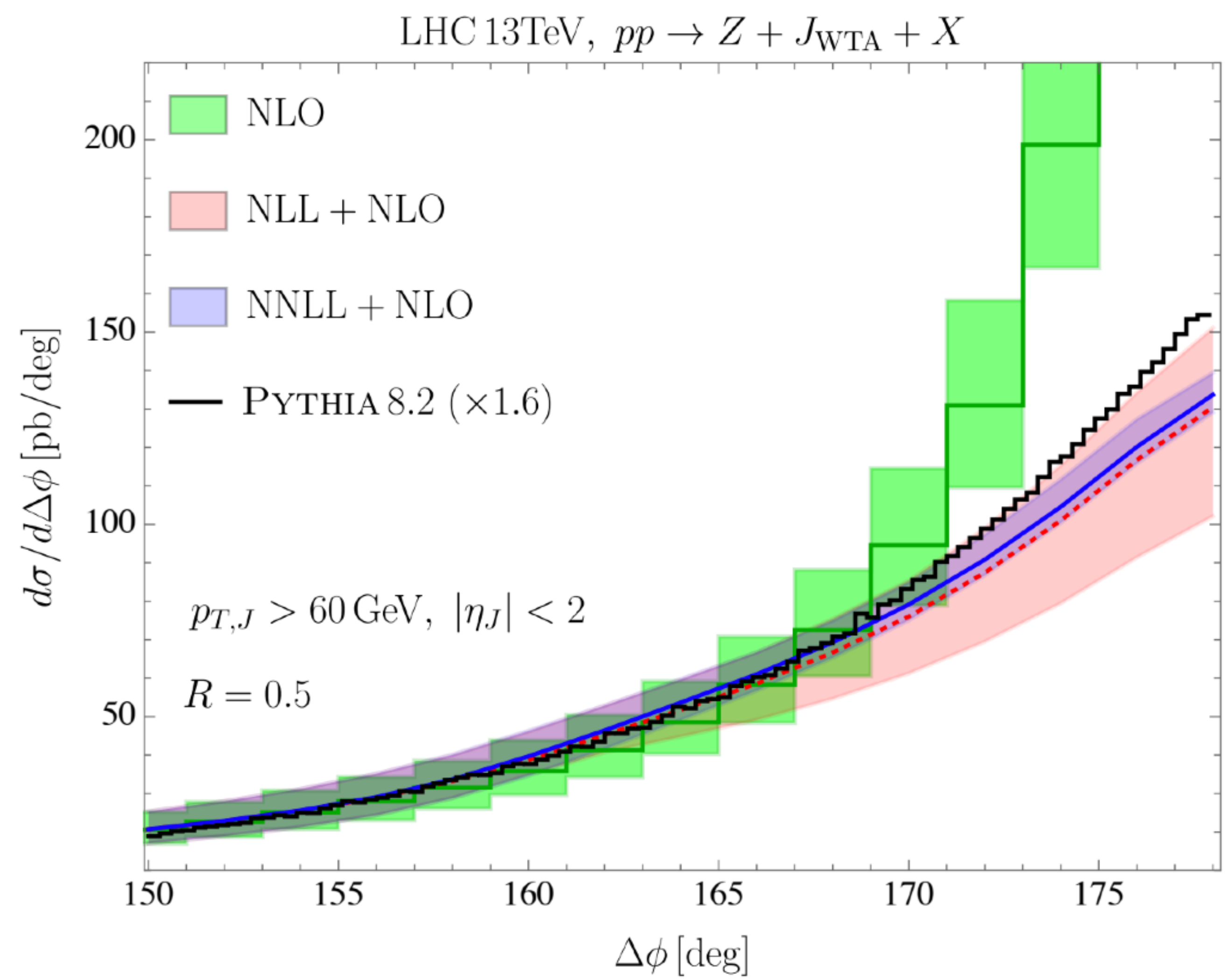
Soft function can be obtained by boosted invariance

(also see Gao, Li, Moult, Zhu '19,...)

Numerical results

(Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB)





- **first NNLL resummation including full jet dynamics (anti-k_T algorithm + WTA)**
- **non-perturbative effects (hadronization and MPI) are mild**

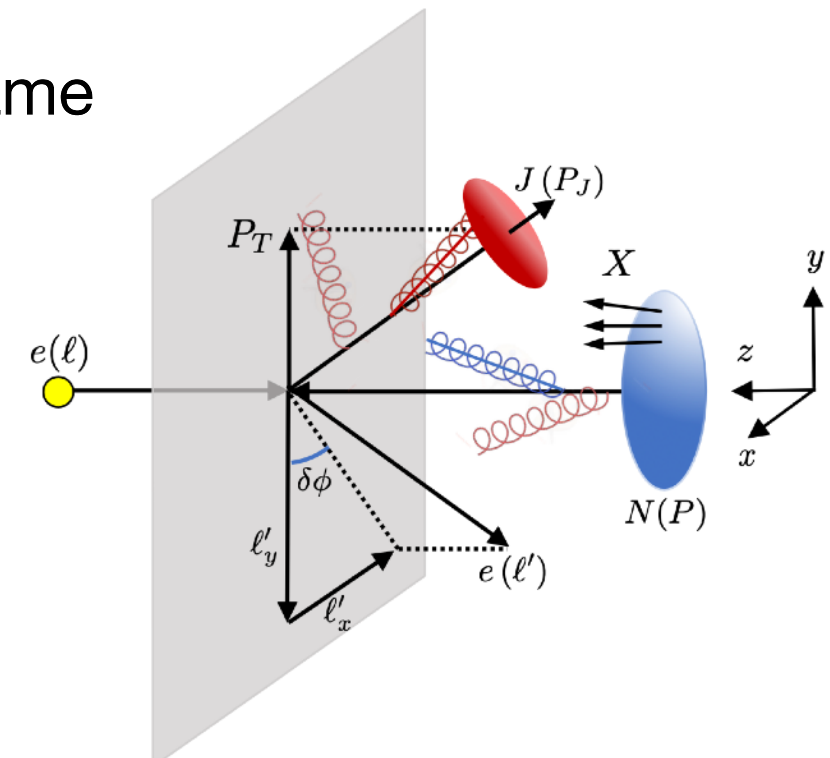
Recoil-free azimuthal angle for electron-jet correlation

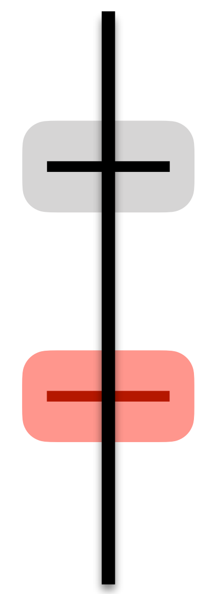
Fang, Ke, DYS, Terry '23 JHEP

$$e(\ell) + N(P) \to e(\ell') + J(P_J) + X$$

Standard TMD in back to back limit: $Q >> q_T \sim l_T\,\delta\phi$

Lab frame





$p_h \sim Q(1,1,1)$

$p_{c_i}^{\mu} \sim l_T\,(\delta\phi^2, 1, \delta\phi)_{n_i \bar{n}_i}$

$p_s^{\mu} \sim l_T(\delta\phi, \delta\phi, \delta\phi)$

Following the standard steps in SCET and CSS, we obtain the following resummation formula

$$\frac{d\sigma}{d^2\ell'_T\,dy\,d\delta\phi} = \frac{\sigma_0\,\ell'_T}{1-y} H(Q,\mu) \int_0^{\infty} \frac{db}{\pi} \cos\left(b\ell'_T\delta\phi\right) \sum_q e_q^2\, f_{q/N}(x_B, b, \mu, \zeta_f)\, J_q(b, \mu, \zeta_J)$$

Hard factor — Fourier transformation in 1-dim — TMD PDF — Jet function

Predictions in e-p

Fang, Ke, DYS, Terry '23

TMD PDF (CSS treatment)

$$f_{q/N}(x_B, b, \mu, \zeta_f) = [C \otimes f]_{q/N}(x_B, b, \mu_f, \zeta_{fi})\, U^f_{\rm NP}(x_B, b, A, Q_0, \zeta_f) \times \exp\left[\int_{\mu_f}^{\mu} \frac{d\mu'}{\mu'} \gamma^f_\mu(\mu', \zeta_f)\right] \left(\frac{\zeta_f}{\zeta_{fi}}\right)^{\frac{1}{2}\gamma^f_\zeta(b,\mu_f)},$$

Jet function

$$J_q(b, \mu, \zeta_J) = J_q(b, \mu_J, \zeta_{Ji})\, U^J_{\rm NP}(b, A, Q_0, \zeta_J) \times \exp\left[\int_{\mu_J}^{\mu} \frac{d\mu'}{\mu'} \gamma^J_\mu(\mu', \zeta_J)\right] \left(\frac{\zeta_J}{\zeta_{Ji}}\right)^{\frac{1}{2}\gamma^J_\zeta(b,\mu_J)}$$

scale choice

$$\mu_H = Q\,, \qquad \mu_f = \mu_J = \sqrt{\zeta_{fi}} = \sqrt{\zeta_{Ji}} = \mu_b = 2e^{-\gamma_E}/b$$

b*-prescription to avoid Landau pole

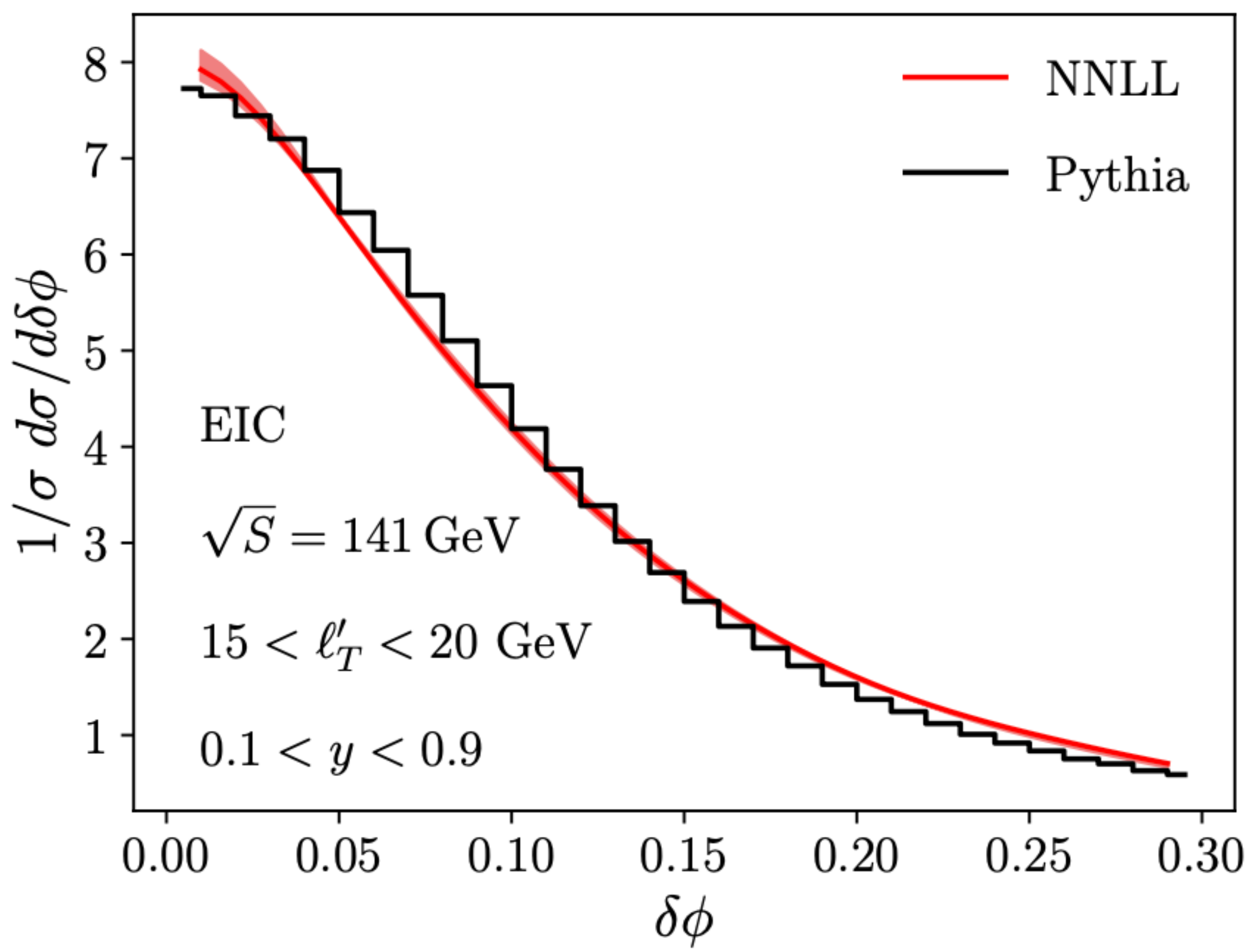
$$b_* = b/\sqrt{1 + b^2/b^2_{\rm max}} \qquad \mu_{b_*} = 2e^{-\gamma_E}/b_*$$

non-perturbative model

$$U^f_{\rm NP} = \exp\left[-g^f_1 b^2 - \frac{g_2}{2} \ln\frac{Q}{Q_0} \ln\frac{b}{b_*}\right]$$

$$U^J_{\rm NP} = \exp\left[-\frac{g_2}{2} \ln\frac{Q}{Q_0} \ln\frac{b}{b_*}\right]$$

Sun, Isaacson, Yuan, Yuan '14



μ_H varies between Q/2 and 2Q. μ_b is fixed

Predictions in e-A

Fang, Ke, DYS, Terry '23

We apply nuclear modified TMD PDFs

$$g_1^A = g_1^f + a_N(A^{1/3} - 1) \quad a_N = 0.016 \pm 0.003 \text{ GeV}^2$$

Collinear dynamics (nPDF) using EPPS16

(Alrashed, Anderle, Kang, Terry & Xing, '22)

We include LO momentum broadening of the jet within SCET$_G$

$$J_q^A(b,\mu,\zeta_J) = J_q(b,\mu,\zeta_J)e^{\chi[\xi b K_1(\xi b)-1]}$$

Opacity parameter $\chi = \frac{\rho_G L}{\xi^2}\alpha_s(\mu_{b_*})C_F$

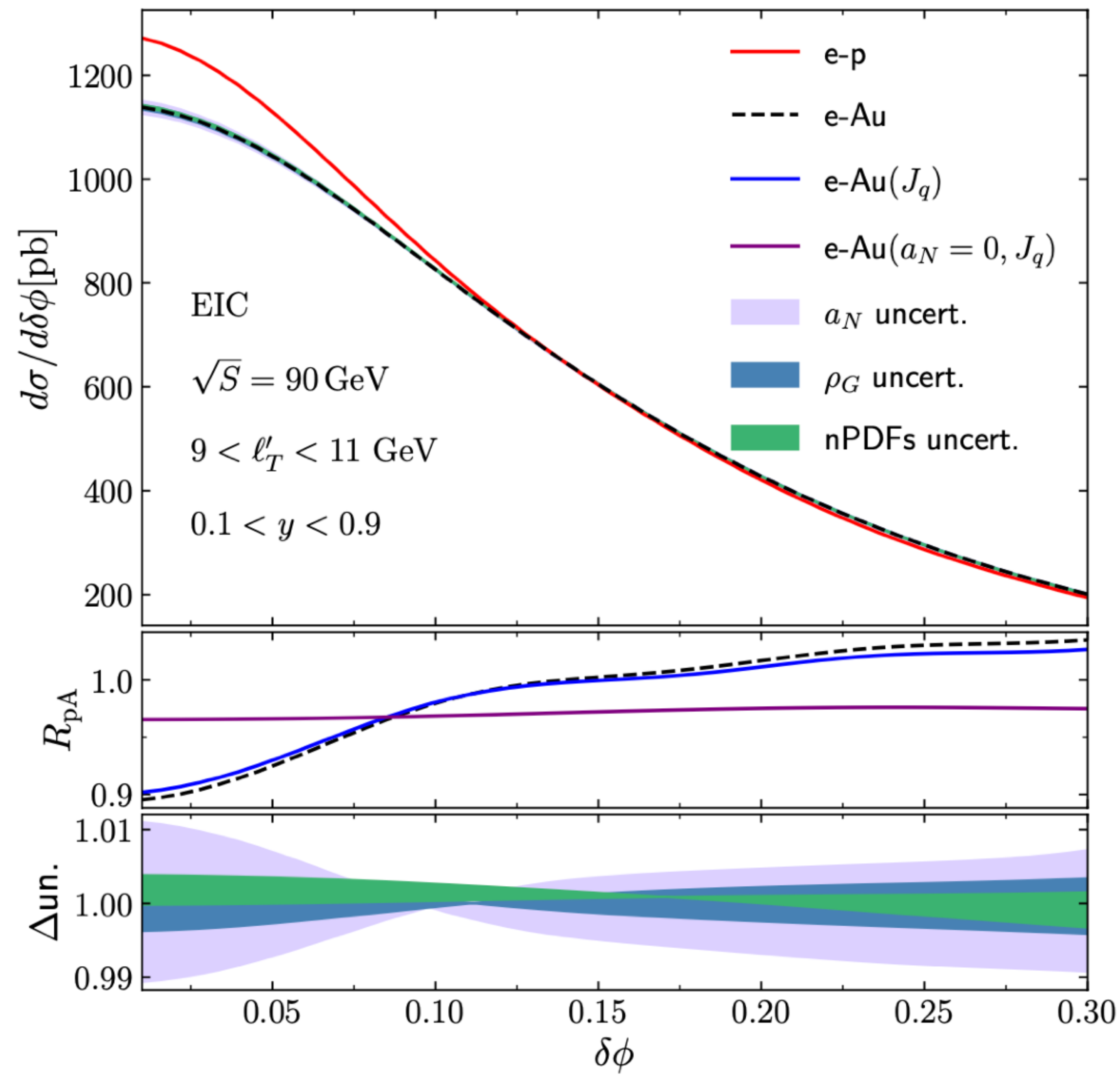
(Gyulassy, Levai, & Vitev '02)

ρ_G : density of the medium

ξ : the screening mass

L: the length of the medium

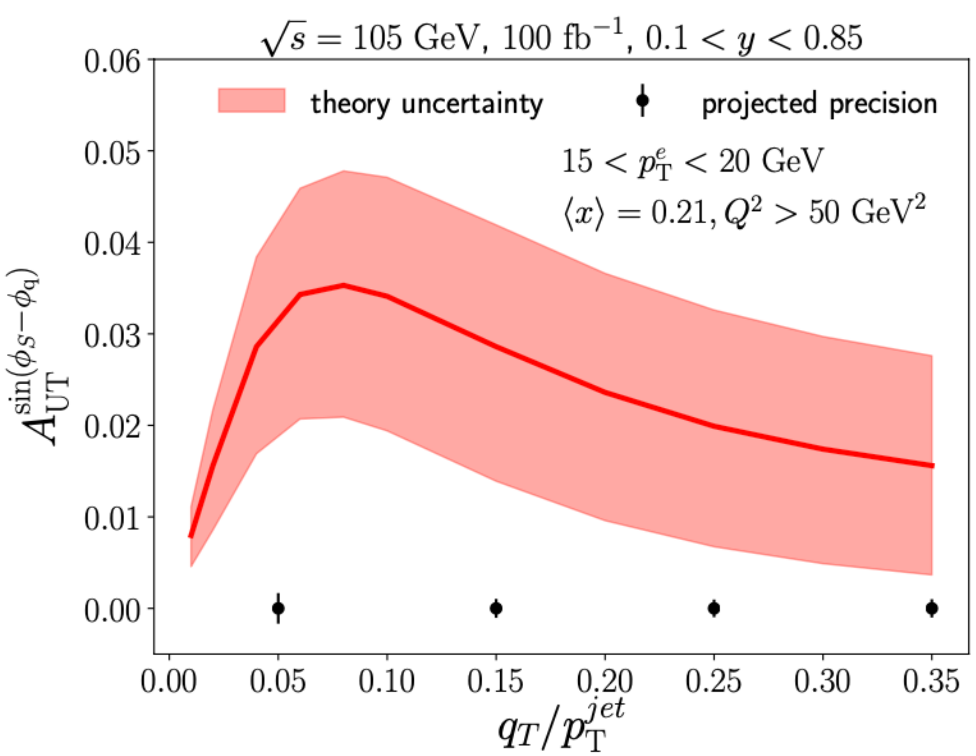
Parameter values are taken from a recent comparison between SCET$_G$ in e-A from the HERMES Ke and Vitev '23



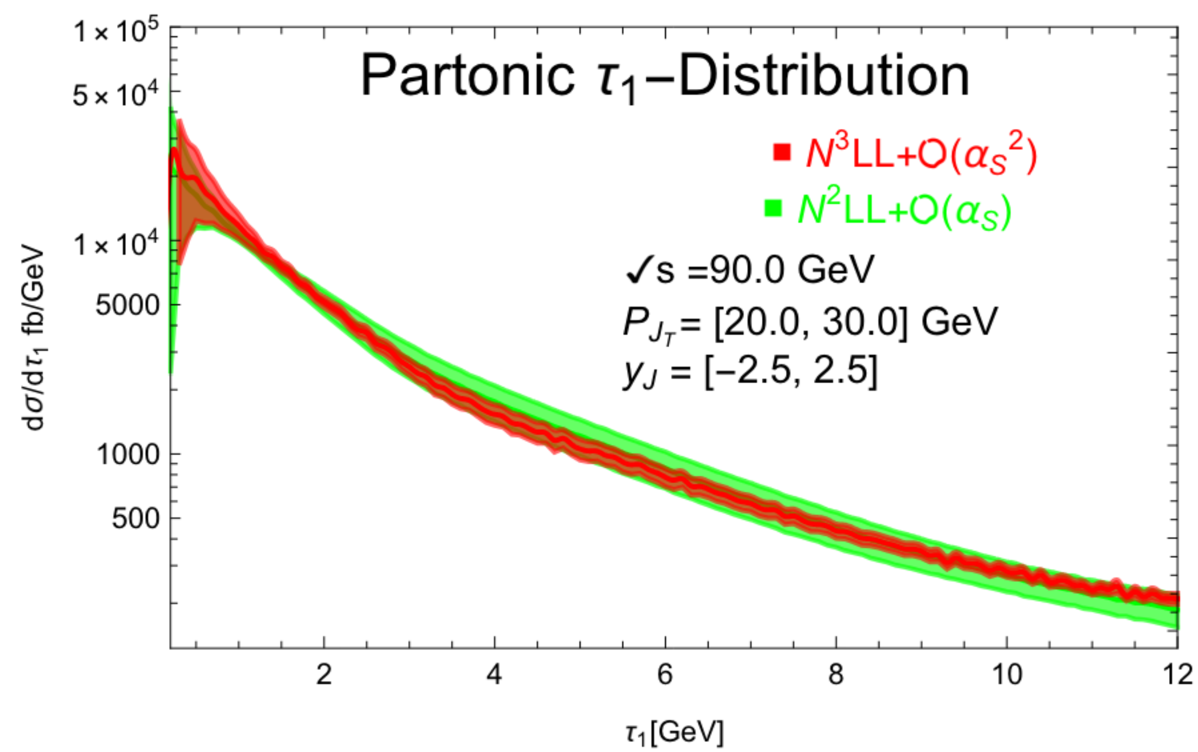
The process is primarily sensitive to the initial state's broadening effects, thereby serving as a clean probe of nTMD PDF

Precision calculation for jets in DIS

- **Precision calculations in DIS are essential for enhancing our understanding of partonic interactions and the internal structure of nucleons.**
- **The high-order calculation has reached N3LO accuracy for jet production in DIS** Currie, Gehrmann, Glover, Huss, Niehues, & Vogt '18
- **Several global event shape distributions in DIS are know at N3LL + $\mathcal{O}(\alpha_s^2)$**
  - **thrust** Kang, Lee, & Stewart '15
  - **(transverse) energy energy correlator** Li, Vitev, & Zhu '20, Li, Makris, Vitev '21
  - **1-jettiness** Cao, Kang, Liu & Mantry '23



Arratia, Kang, Prokudin, Ringer '19



Cao, Kang, Liu & Mantry '23

N^{3}LL + $\mathcal{O}(\alpha_s^2)$ predictions on lepton jet azimuthal correlation in DIS

Fang, Gao, Li, DYS 2407.XXXXX

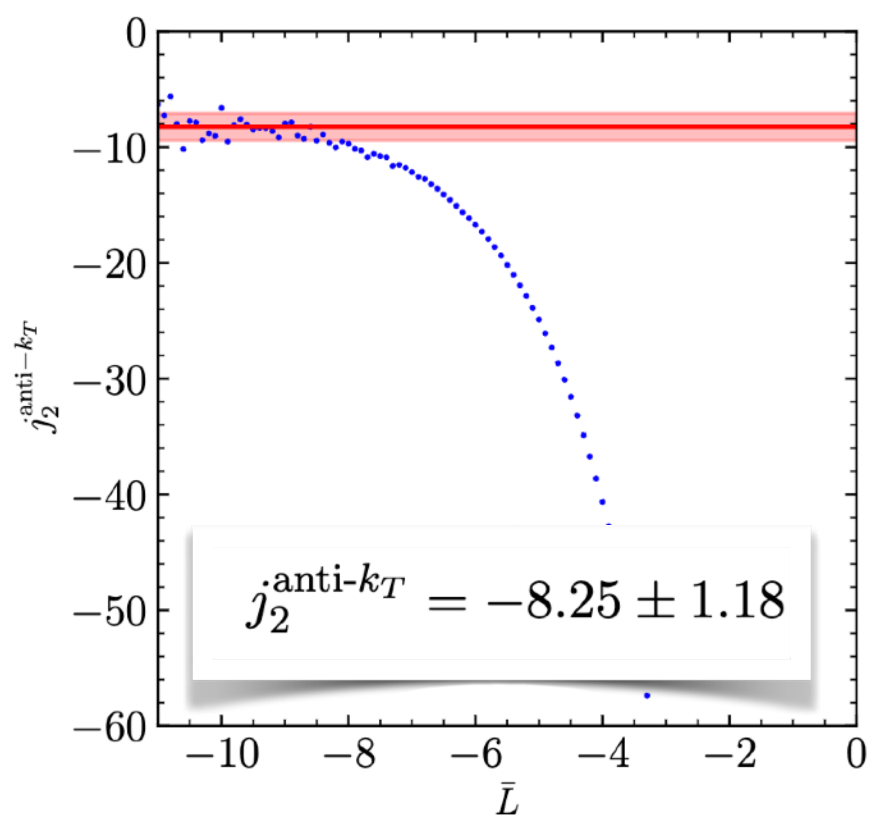
- **All ingredients are known at N^{3}LL+ $\mathcal{O}(\alpha_s^2)$, except the two loop jet function j_2 .**
  - **It was extracted numerically from the Event2** (Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi '19)
  - **A preliminary numerical results are also calculated from SoftSERVE** (Brune SCET2023)
- **We study dijet production in e+e-, and compare two-loop singular cross section and $\mathcal{O}(\alpha_s^2)$ predictions from NLOJET++ generator to extract j2**

$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_T} = \bar{\sigma}_0\, H(Q,\mu_h) q_T \int_0^\infty b_T\, \mathrm{d}b_T J_0(q_T b_T) J_q(b_T,\mu_h,\zeta_f) J_{\bar{q}}(b_T,\mu_h,\zeta_f)$$

Integrated cross section: $\sigma_L(Q_T) \equiv \int_0^{Q_T} \mathrm{d}q_T \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}$

Two-loop coefficient:

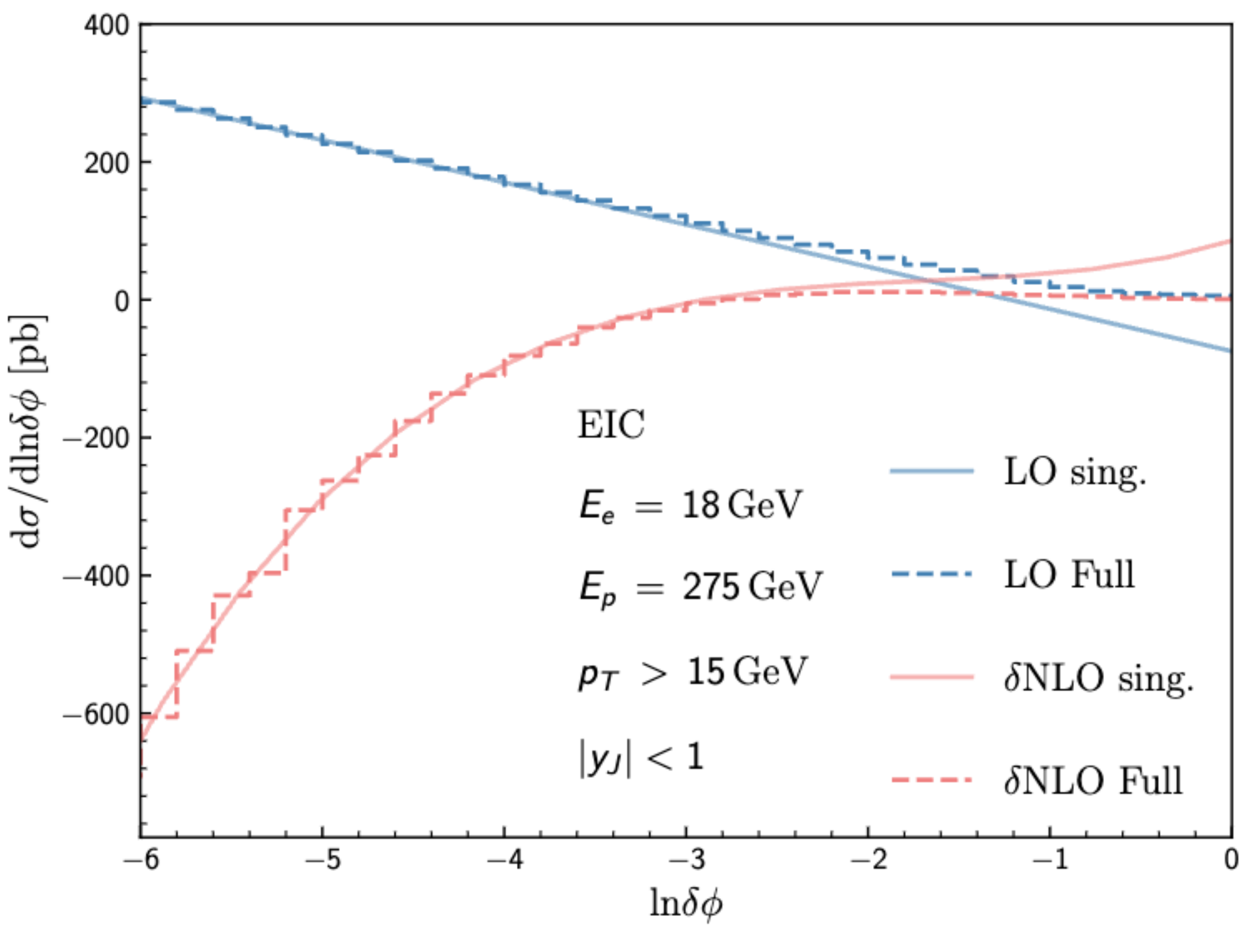
$$B = C_F^2\left[\frac{\bar{L}^4}{2} + 3\bar{L}^3 + \bar{L}^2\left(\frac{11}{2} - \frac{\pi^2}{3} + 6\ln 2\right) + \bar{L}\left(\frac{9}{4} + 18\ln 2 - 4\,\zeta_3\right) - \frac{189}{16} + 5\,\pi^2 - \frac{173\,\pi^4}{720} + 27\ln 2 - \frac{9}{2}\pi^2\ln 2 + 9\ln^2 2 - 3\,\zeta_3\right] + C_F C_A\left[\frac{11\bar{L}^3}{9} + \bar{L}^2\left(-\frac{35}{36} + \frac{\pi^2}{6}\right) + \bar{L}\left(-\frac{57}{4} + \frac{11\pi^2}{18} + 11\ln 2 + 6\,\zeta_3\right) - \frac{51157}{1296} + \frac{1061\pi^2}{216} - \frac{2\pi^4}{45} + \frac{401\zeta_3}{18}\right] + C_F T_F n_f\left[-\frac{4\bar{L}^3}{9} + \frac{\bar{L}^2}{9} + \bar{L}\left(5 - \frac{2\pi^2}{9} - 4\ln 2\right) + \frac{4085}{324} - \frac{91\pi^2}{54} - \frac{14\zeta_3}{9}\right] + \frac{j_2}{2}\,,$$

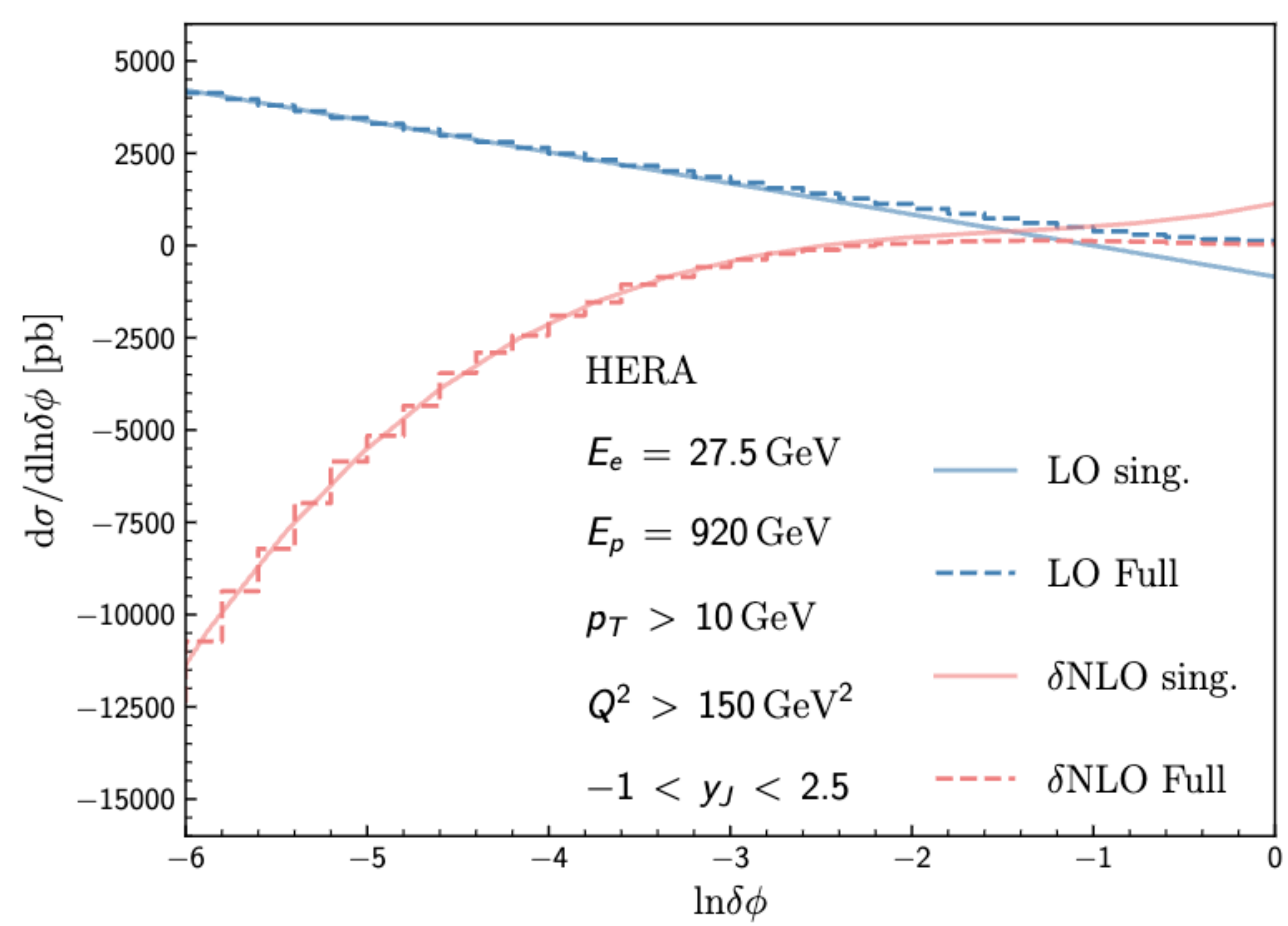


N3LL + $\mathcal{O}(\alpha_s^2)$ predictions on lepton jet azimuthal correlation in DIS

Fang, Gao, Li, DYS 2407.XXXXX

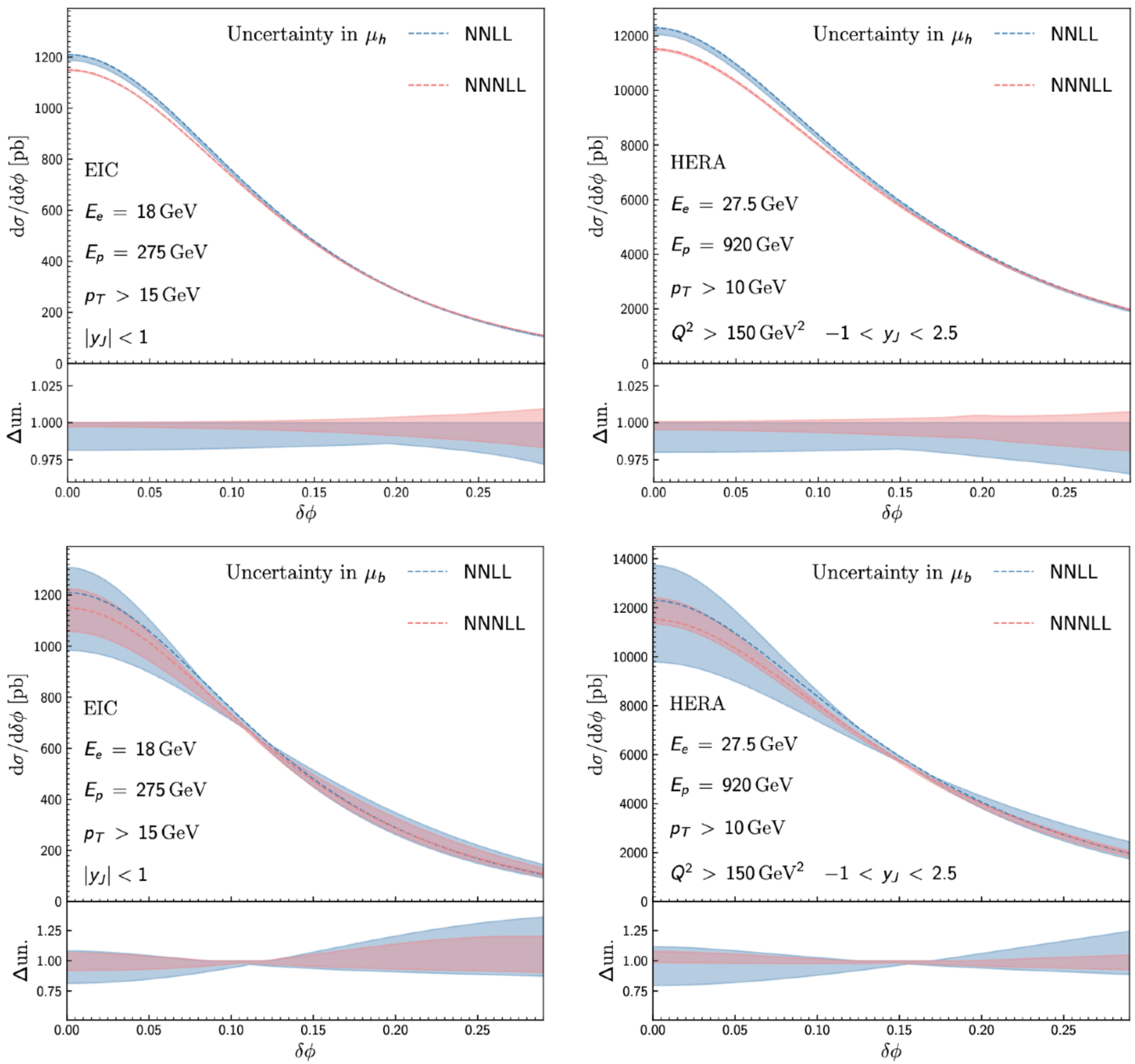
- We also compare the resummation expanded singular contribution in DIS with the full prediction from NLOJET++ up to $\mathcal{O}(\alpha_s^2)$.
- Good agreement in the back-to-back limit ($\delta\phi$ —> 0) is observed.
- Matching corrections (Y term) are important in the large $\delta\phi$ region





Comparison of resummation results at N2LL and N3LL

Fang, Gao, Li, DYS 2407.XXXXX



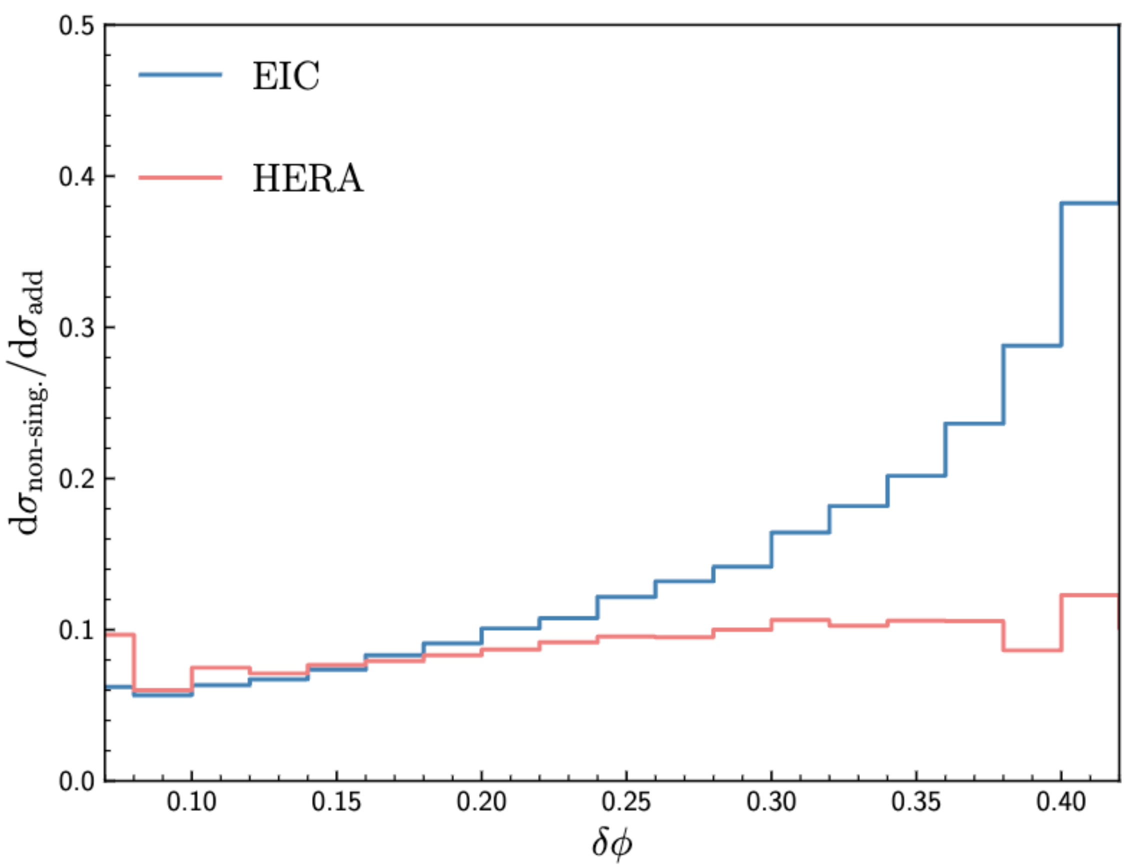
- **The uncertainty bands are narrower at N3LL (red) compared to NNLL (blue)**
- **At N3LL the dominant scale uncertainties are from μ_b variation**

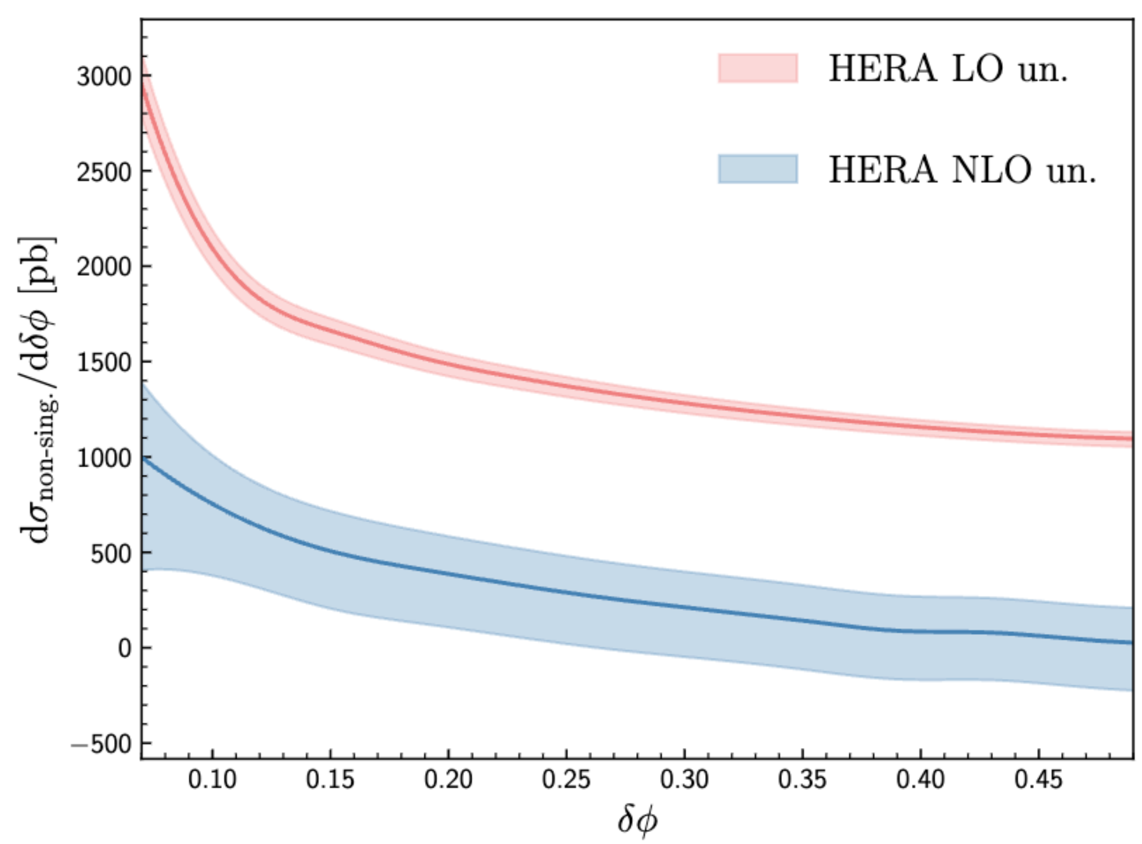
N³LL + $\mathcal{O}(\alpha_s^2)$ predictions on lepton jet azimuthal correlation in DIS

Fang, Gao, Li, DYS 2407.XXXXX

- **In the large $\delta\phi$ region the resummation formula receives significant matching corrections**
- **It is necessary to switch off the resummation and instead employ fixed-order calculations**

$$\mathrm{d}\sigma_{\mathrm{add}}\left(\mathrm{NNNLL}+\mathcal{O}(\alpha_s^2)\right) \equiv \mathrm{d}\sigma(\mathrm{NNNLL}) + \underbrace{\mathrm{d}\sigma(\mathrm{NLO}) - \mathrm{d}\sigma(\mathrm{NLO\ singular})}_{\mathrm{d}\sigma(\mathrm{NLO\ non\text{-}singular})}$$



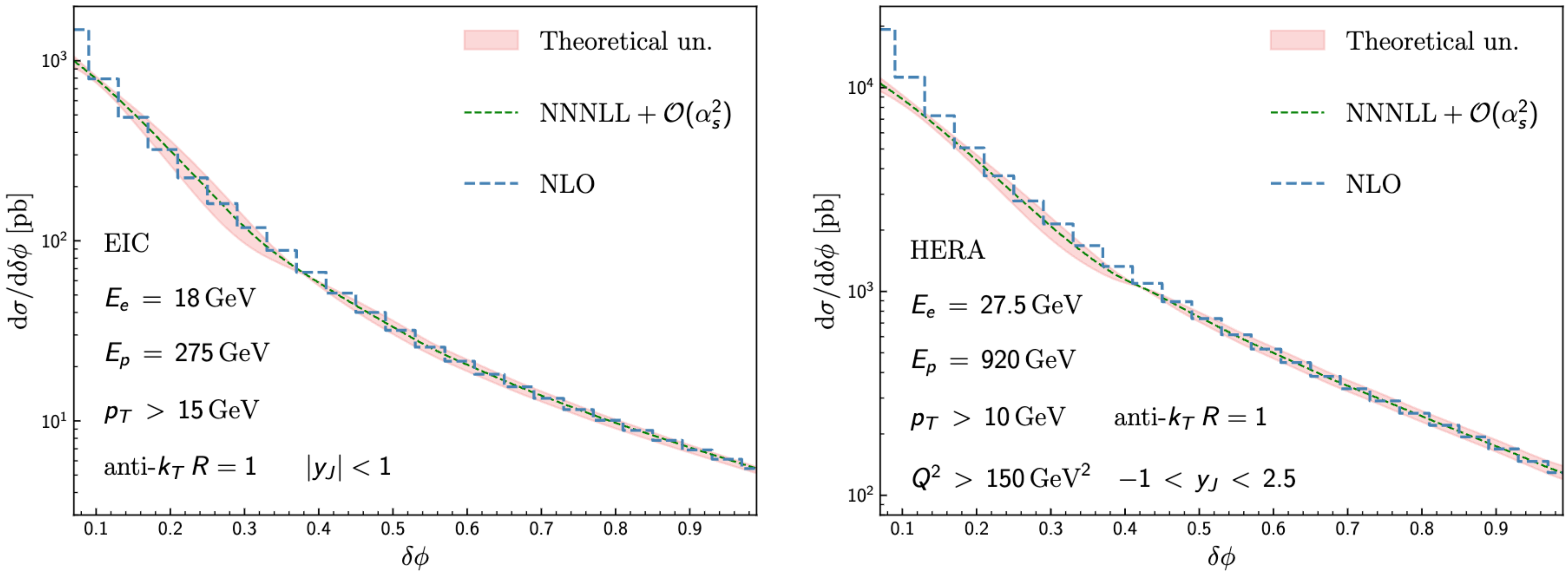


N³LL + $\mathcal{O}(\alpha_s^2)$ predictions on lepton jet azimuthal correlation in DIS

Fang, Gao, Li, DYS 2407.XXXXX

- **In the large $\delta\phi$ region the resummation formula receives significant matching corrections**
- **It is necessary to switch off the resummation and instead employ fixed-order calculations**

$$\mathrm{d}\sigma_{\mathrm{add}}\left(\mathrm{NNNLL}+\mathcal{O}(\alpha_s^2)\right) \equiv \mathrm{d}\sigma(\mathrm{NNNLL}) + \underbrace{\mathrm{d}\sigma(\mathrm{NLO}) - \mathrm{d}\sigma(\mathrm{NLO\ singular})}_{\mathrm{d}\sigma(\mathrm{NLO\ non\text{-}singular})}$$



Summary

- We have studied on the lepton-jet correlation in both e-p and e-A collisions. Utilizing SCET, we derived a factorization theorem for back-to-back lepton-jet configurations.
- In e-A collisions, we discussed the utility of our approach in disentangling intrinsic non-perturbative contributions from nTMDs and dynamical medium effects in nuclear environments. We find the process is primarily sensitive to the initial state's broadening effects.
- TMD resummation accuracy has been improved to N3LL + $\mathcal{O}(\alpha_s^2)$ accuracy in e-p collisions. It is good to have the measurement at the HERA to make a comparison.
- Our work sets the groundwork for future experiments at the EIC, offering a robust framework for measuring nTMDs.

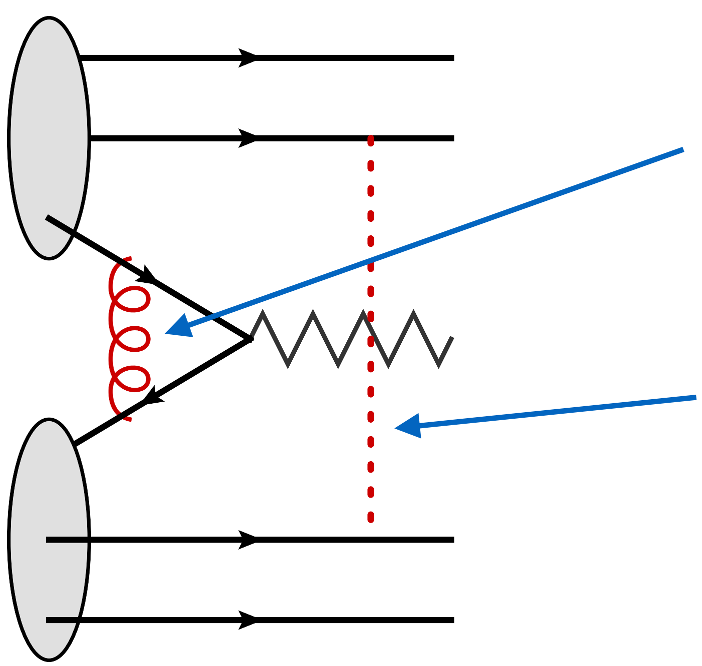
Thank you

Backup

Quite nontrivial that the low-energy matrix element factorizes into a product

$$\langle P(p_1)|O_a(x_1)|P(p_1)\rangle \, \langle P(p_2)|O_b(x_2)|P(p_2)\rangle$$

One should be worried about long-distance interactions mediated by soft gluons

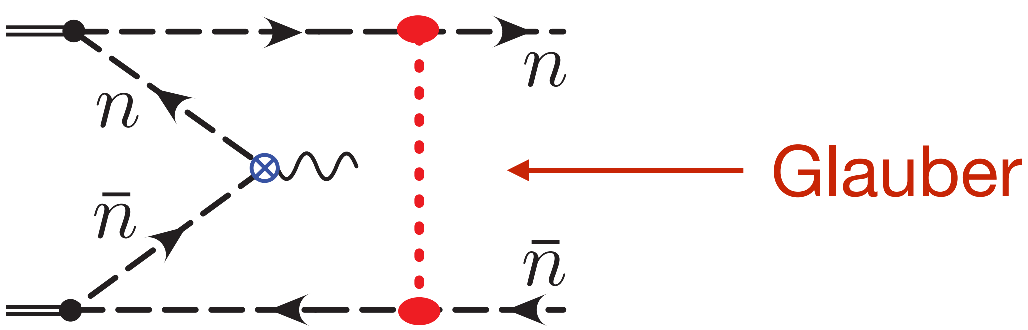


standard soft gluon

Glauber gluon

$$p^\mu \approx p_\perp^\mu$$

All proton collisions include forward component (proton remnants)



Absence of factorization-violation due to Glauber gluons is important element of factorization proof for Drell-Yan process. Bodwin ’85; Collins, Soper, Sterman ’85 ’88 …

e.g. Transverse momentum dependent (TMD) factorization is violated in di-jet production

Collins, Qiu `07; Collins `07, Vogelsang, Yuan `07; Rogers, Mulders `10, …

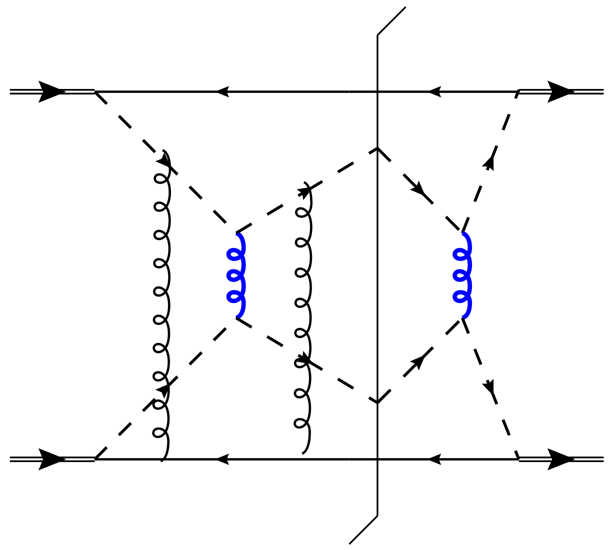


FIG. 8 (color online). The exchange of two extra gluons, as in this graph, will tend to give nonfactorization in unpolarized cross sections.

We remark that, because the TMD factorization breaking effects are due to the Glauber region where all components of gluon momentum are small, the interactions responsible for breaking TMD factorization are associated with large distance scales.

Rogers, Mulders `10