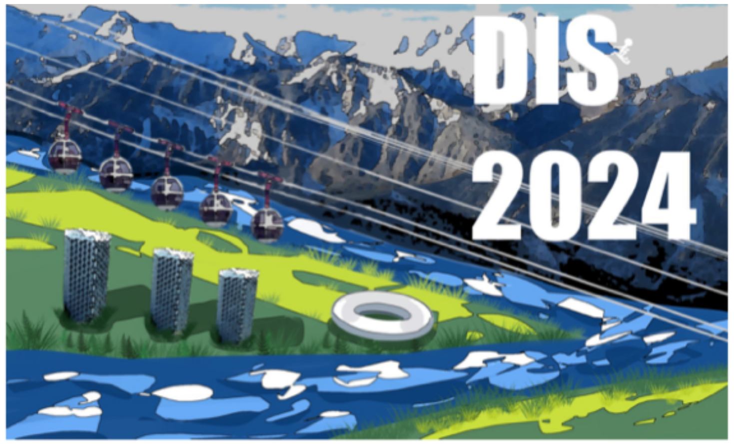

Precision three-dimensional imaging of nuclei using recoil-free jets

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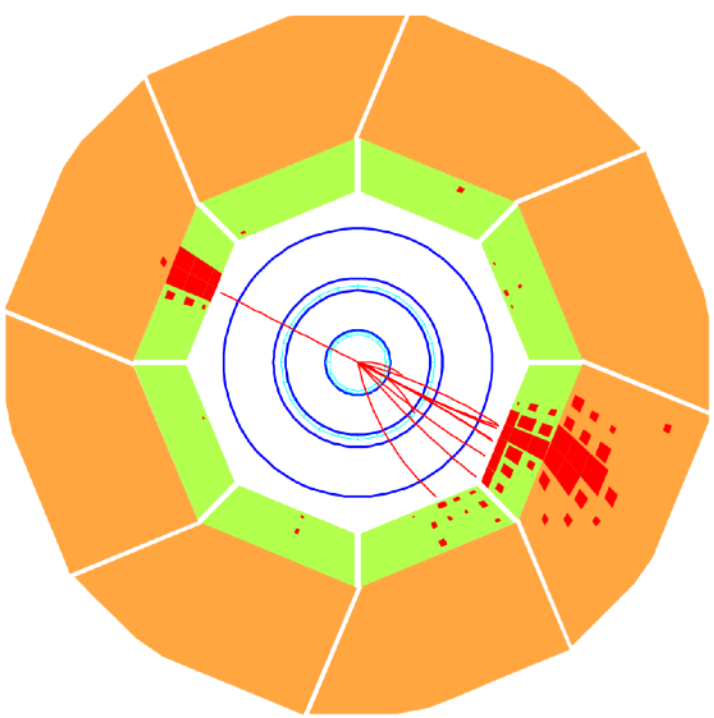
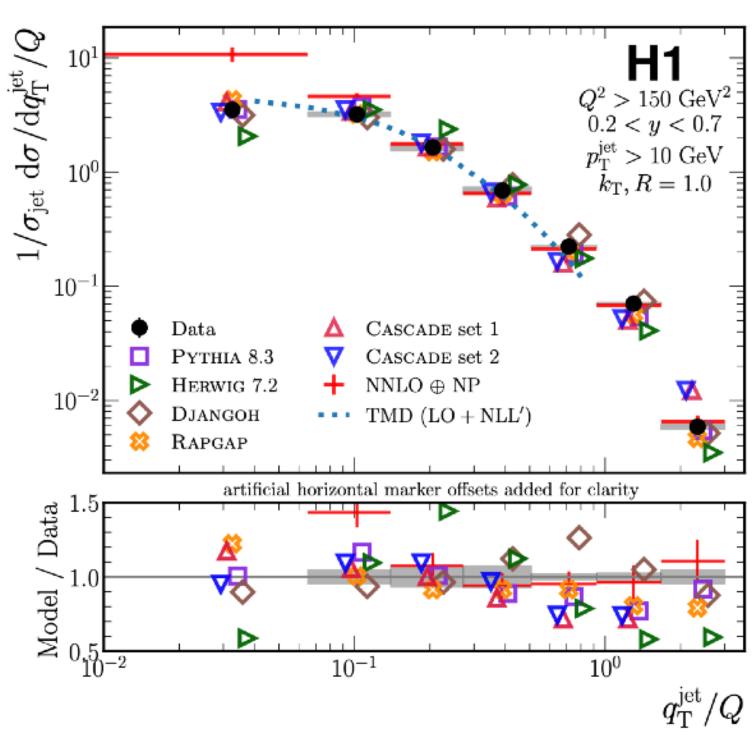
Fudan University

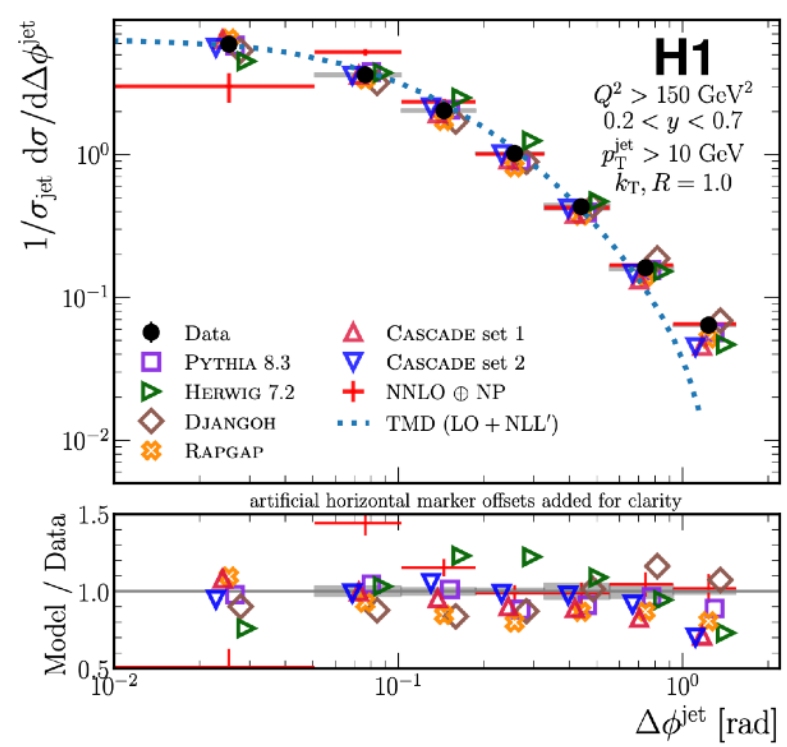
DIS2023 Grenoble Apr 10, 2023

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

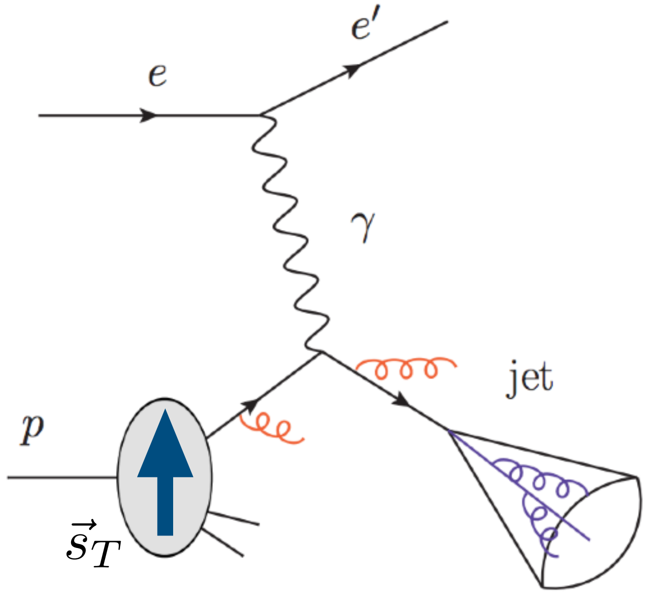


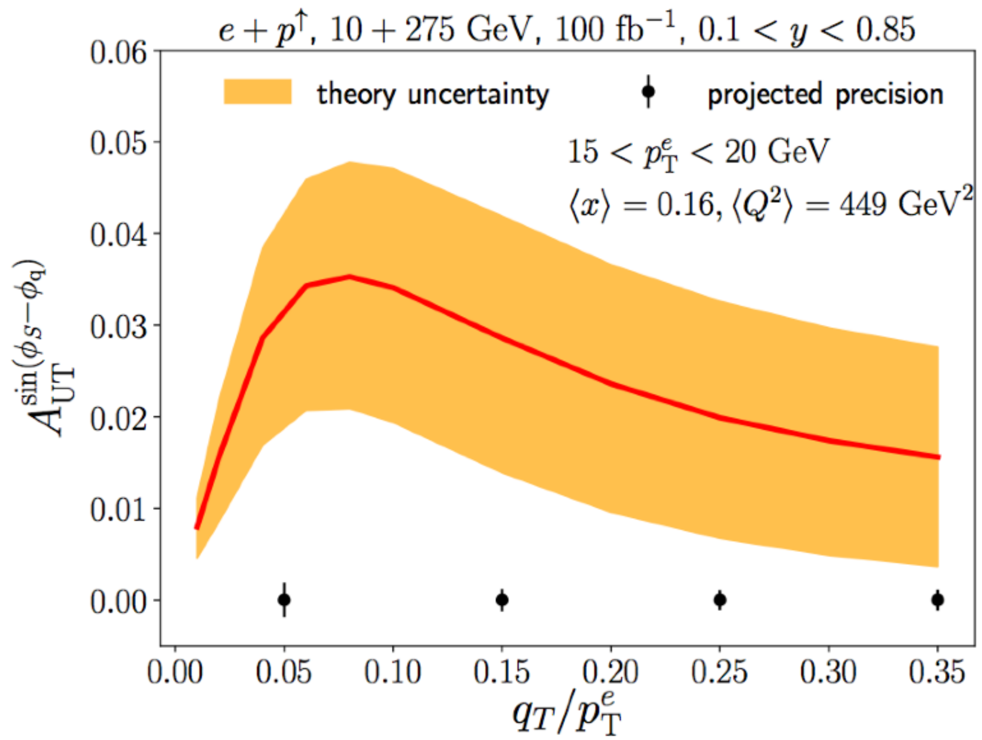




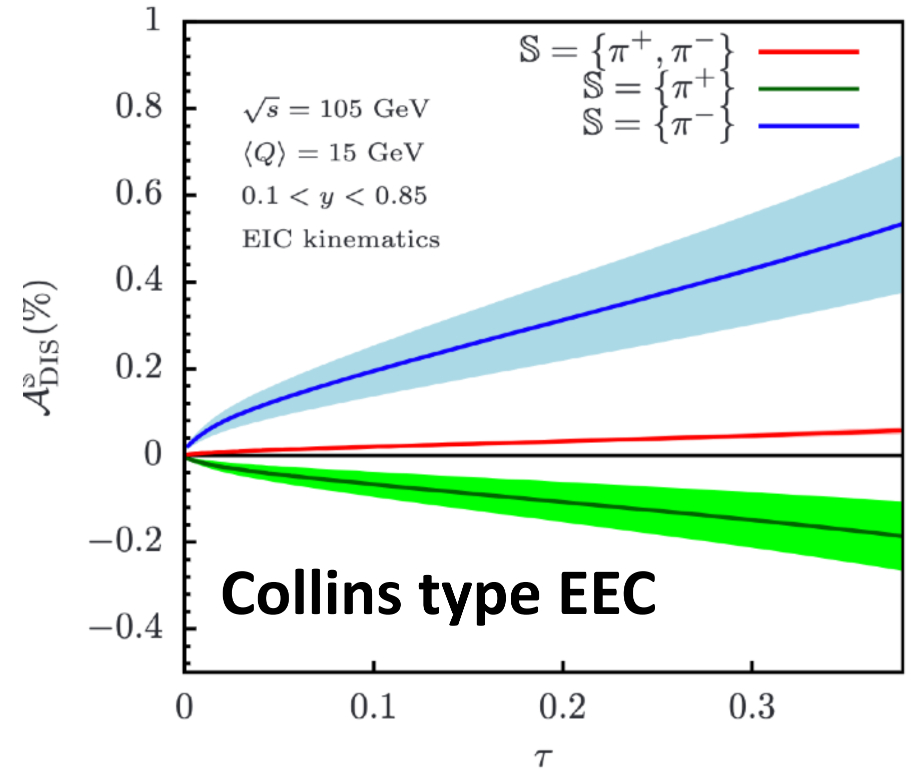
H1 collaboration 2108.12376

Jets and 3D imaging

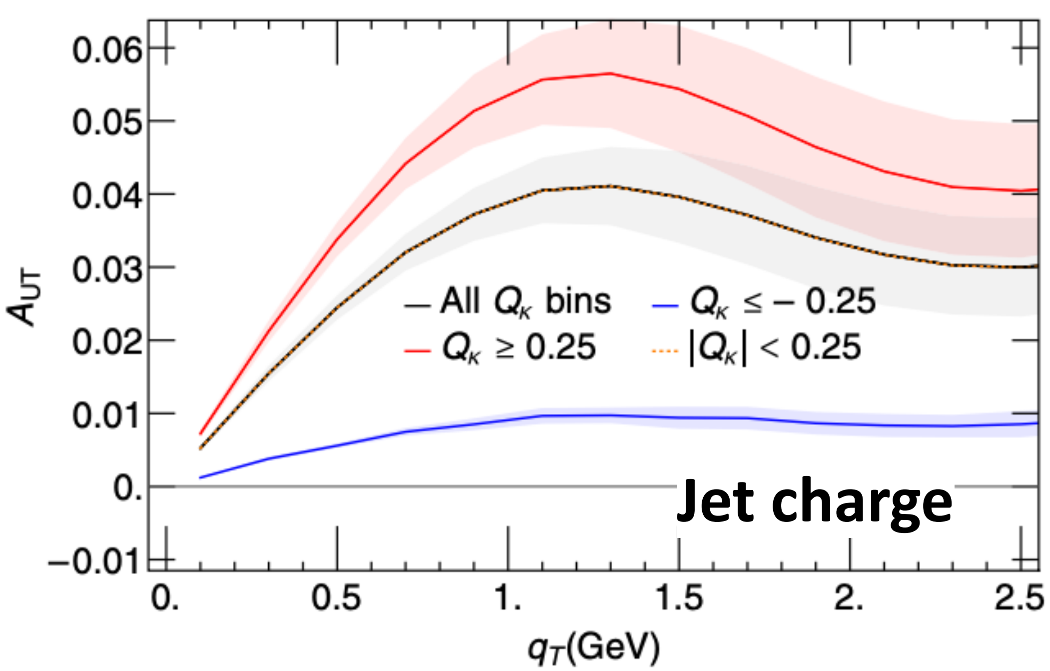




Arratia, Kang, Prokudin, Ringer ’19
Liu, Ringer, Vogelsang, Yuan ’19



Kang, Lee, DYS, Zhao ’23



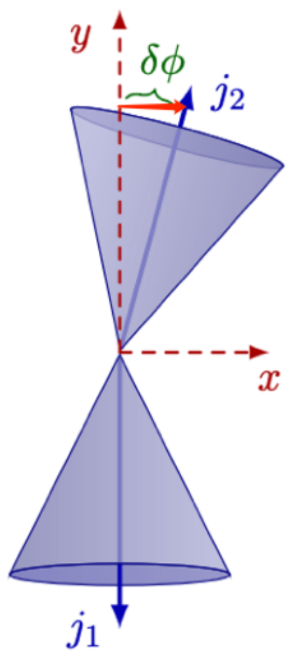
Kang, Liu, Mantry, DYS ’20
See Xiaoxuan Chu’ talk

- Jets are complementary to standard SIDIS extractions of TMDs
- 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 decorrelation of dijet in pp, pA, AA-UPC

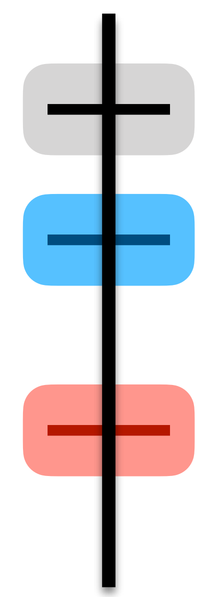
(Zhang, Dai, DYS, ’22, Gao, Kang, DYS, Terry, Zhang ‘23)

$$N_1 + N_2 \to j + j + X$$



$$\delta\phi \ll 1$$
$$R \ll 1$$

QCD modes contributing to the back-to-back dijet cross section



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

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

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

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

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

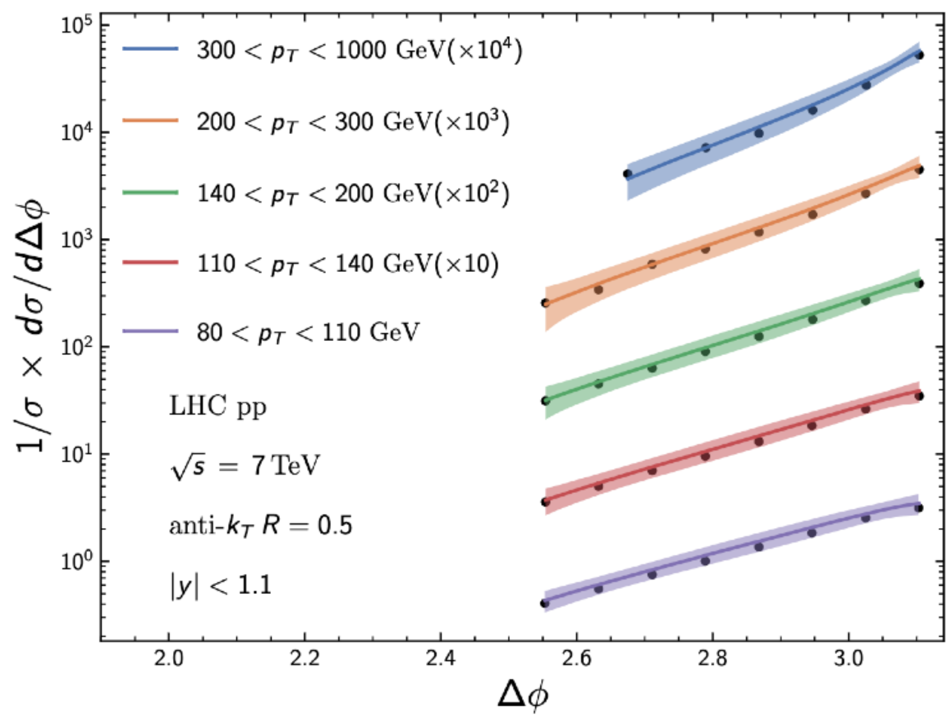
Construction of the theory formalism

- **Multiple scales in the problem**
- **Rely on effective field theory: Soft-Collinear Effective Theory (SCET)**

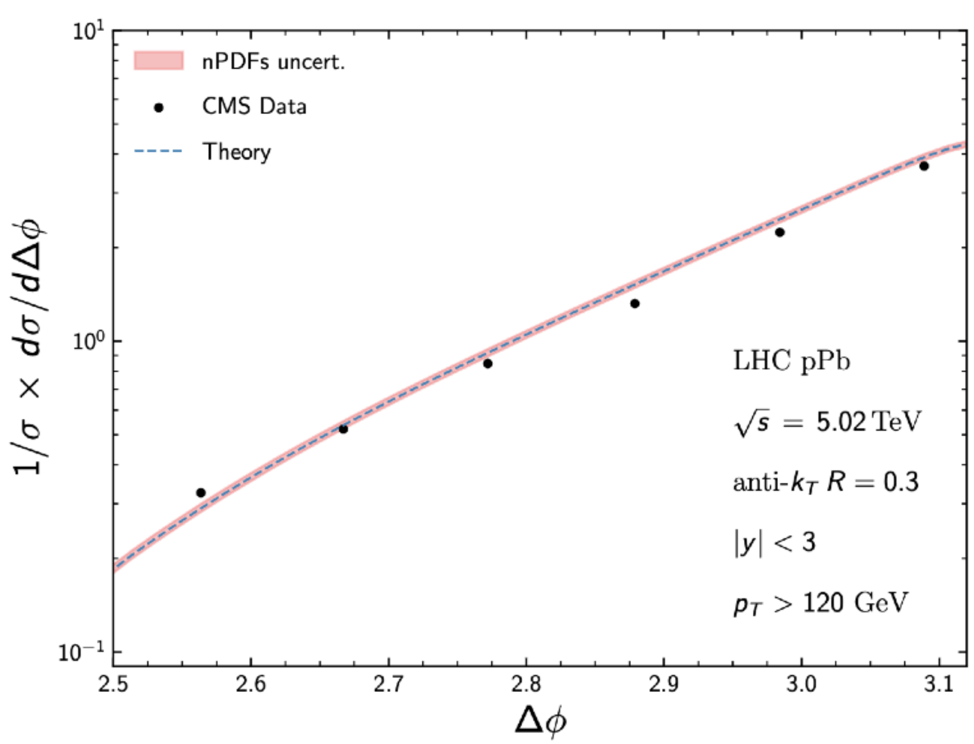
$$\frac{\mathrm{d}^4\sigma_{\mathrm{pp}}}{\mathrm{d}y_c\,\mathrm{d}y_d\,\mathrm{d}p_T^2\,\mathrm{d}q_x} = \sum_{abcd} \frac{x_a x_b}{16\pi \hat{s}^2} \frac{1}{1+\delta_{cd}} \mathcal{C}_x \left[f_{a/p}^{\mathrm{unsub}}\, f_{b/p}^{\mathrm{unsub}}\, \boldsymbol{S}_{ab\to cd, IJ}^{\mathrm{unsub}}\, S_c^{\mathrm{cs}}\,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

Numerical results in pp, pA

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



(also see Sun, Yuan, Yuan '14)



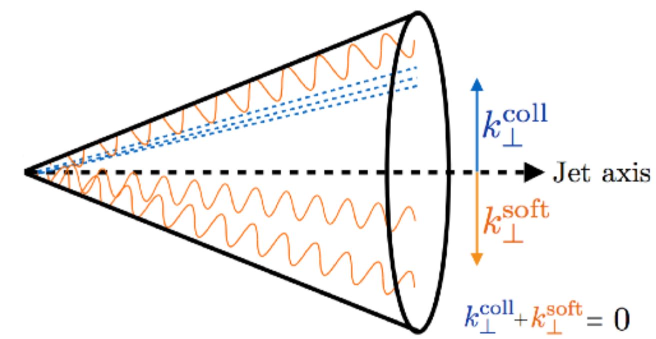
Nuclear modified TMD PDFs

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

- **NLL resummation result is consistent with LHC data**
- **Open questions:**
  - **Higher resummation accuracy? SIDIS is known at N⁴LL**
  - **Better angular resolution?**
  - **Reduce contamination from UE?**
- **One possible solution:**
  - **Recoil-free jet definition**

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

Jet TMDs and all-order structure



- **Large logarithms in jet TMDs** (Banfi, Dasgupta & Delenda '08)

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

  - **sum over all soft and collinear partons not combined with hard jets**
  - **deviation from q_T=0 are only caused by particle flow outside the jet regions**
  - **non-global observables** (Dasgupta & Salam '01)
- **Recoil absent for the p_T^n-weighted recombination scheme** (Banfi, Dasgupta & Delenda '08)

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

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

- **NNNLL 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 + Schrignder '21)
- **NNLL resummation for $\delta\phi$ @ ep & eA** (Fang, Ke, DYS, Terry '23)

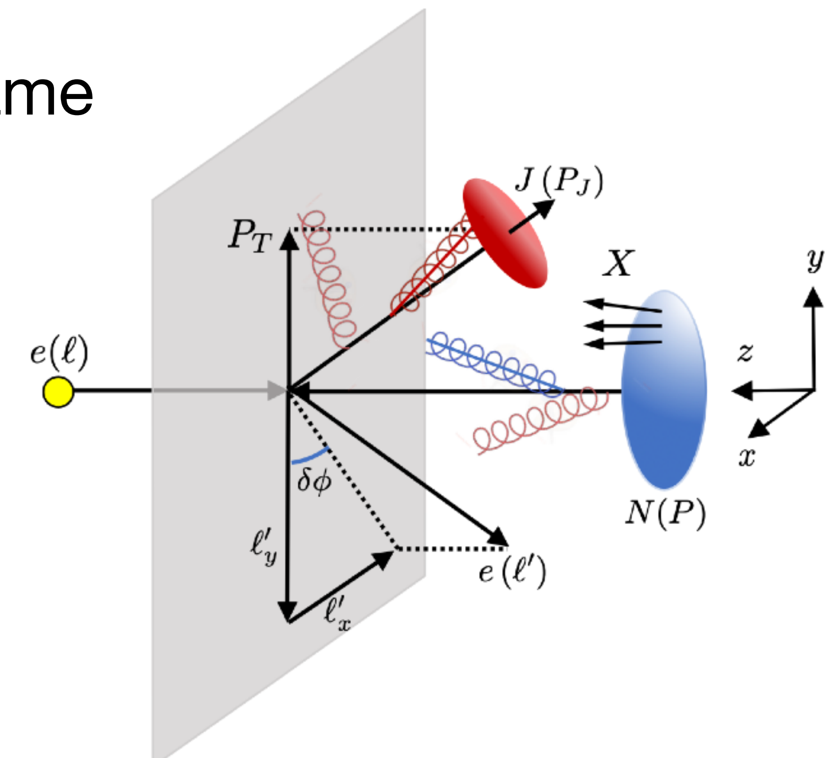
See Bin Wu's talk, WG4, Wed 10am

Recoil-free azimuthal angle for electron-jet correlation

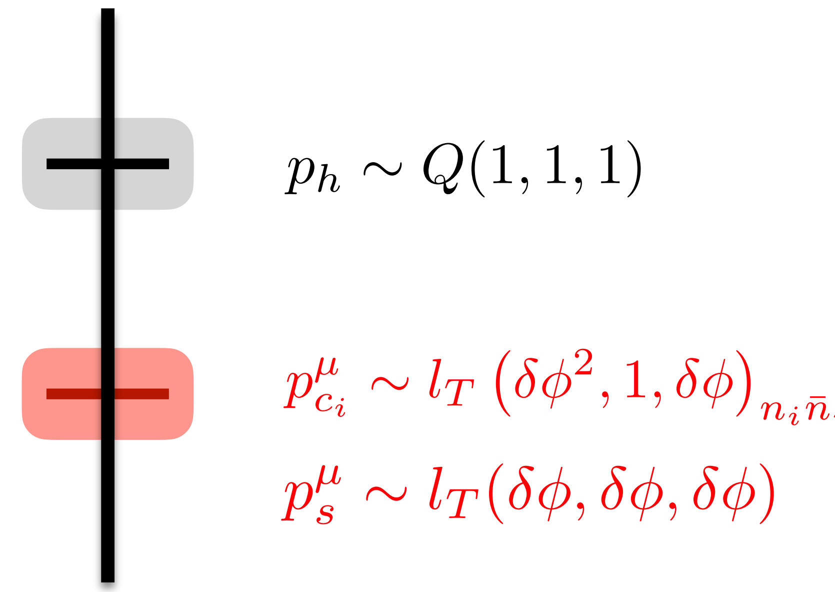
Fang, Ke, DYS, Terry '23

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

Lab frame



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



Effects of jet algorithm are suppressed, first appear at two loop

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

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

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

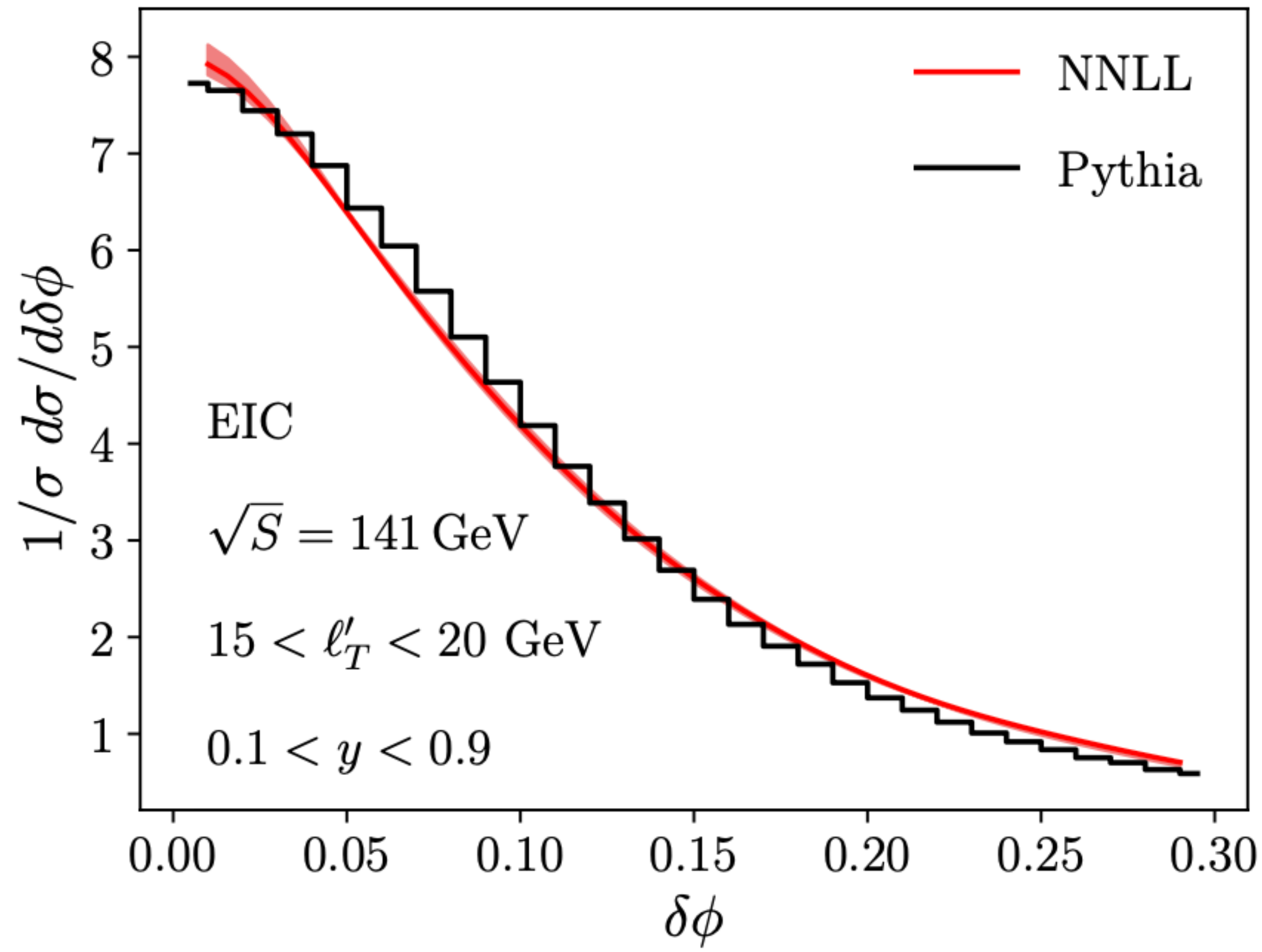
$$b_* = b/\sqrt{1 + b^2/b^2_{\rm max}} \qquad \mu_{b_*} = 2e^{-\gamma_E}/b_*$$

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

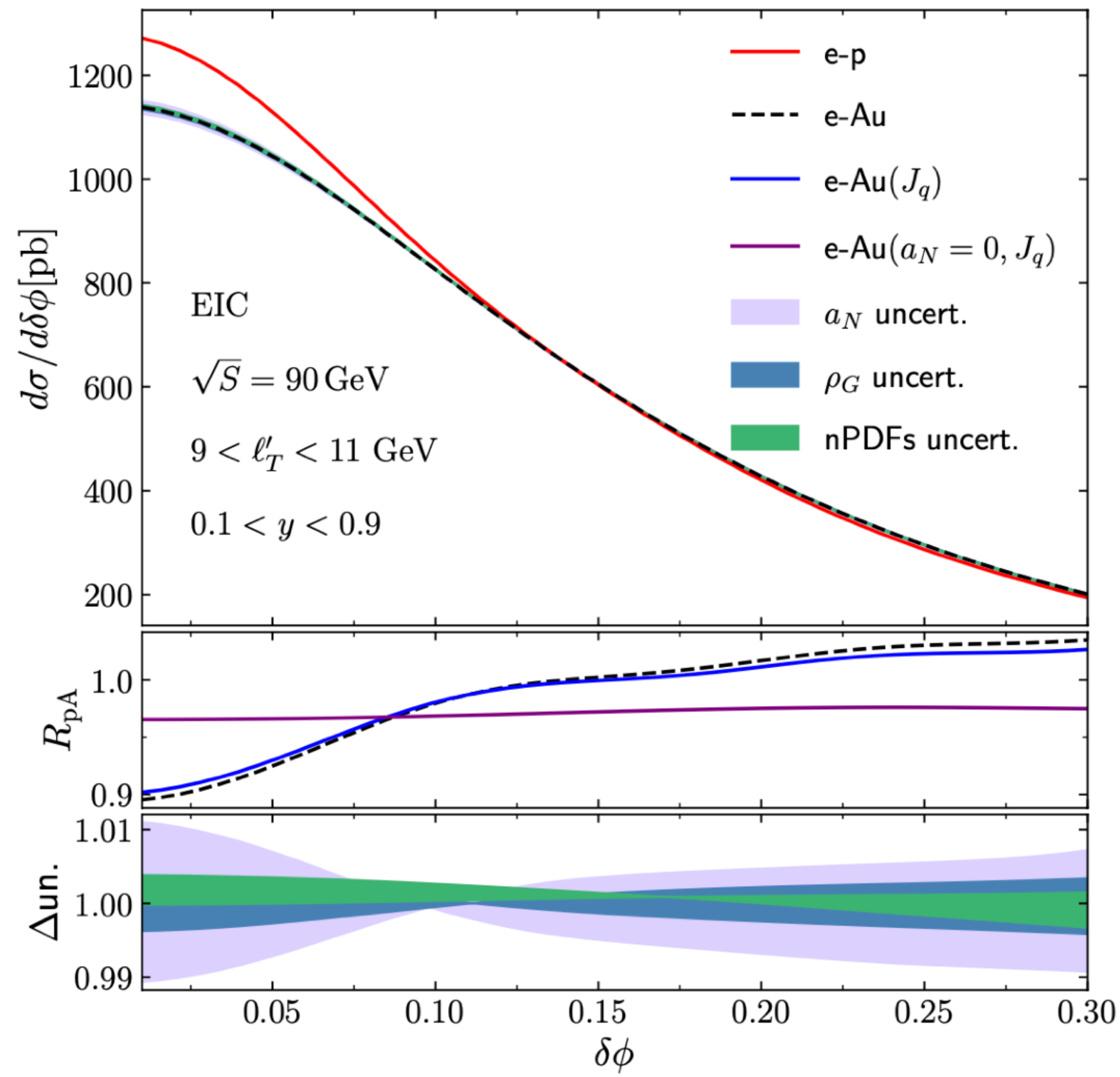
(Gyulassy, Levai, & Vitev '02)

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

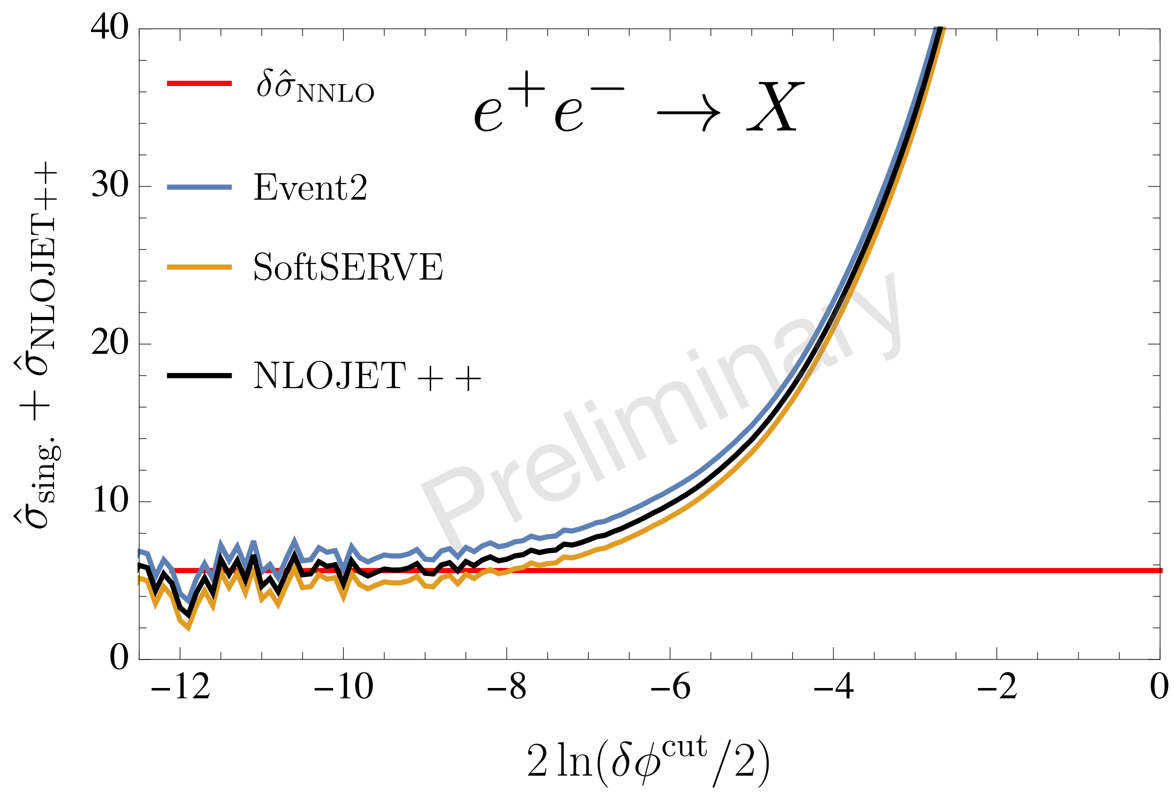


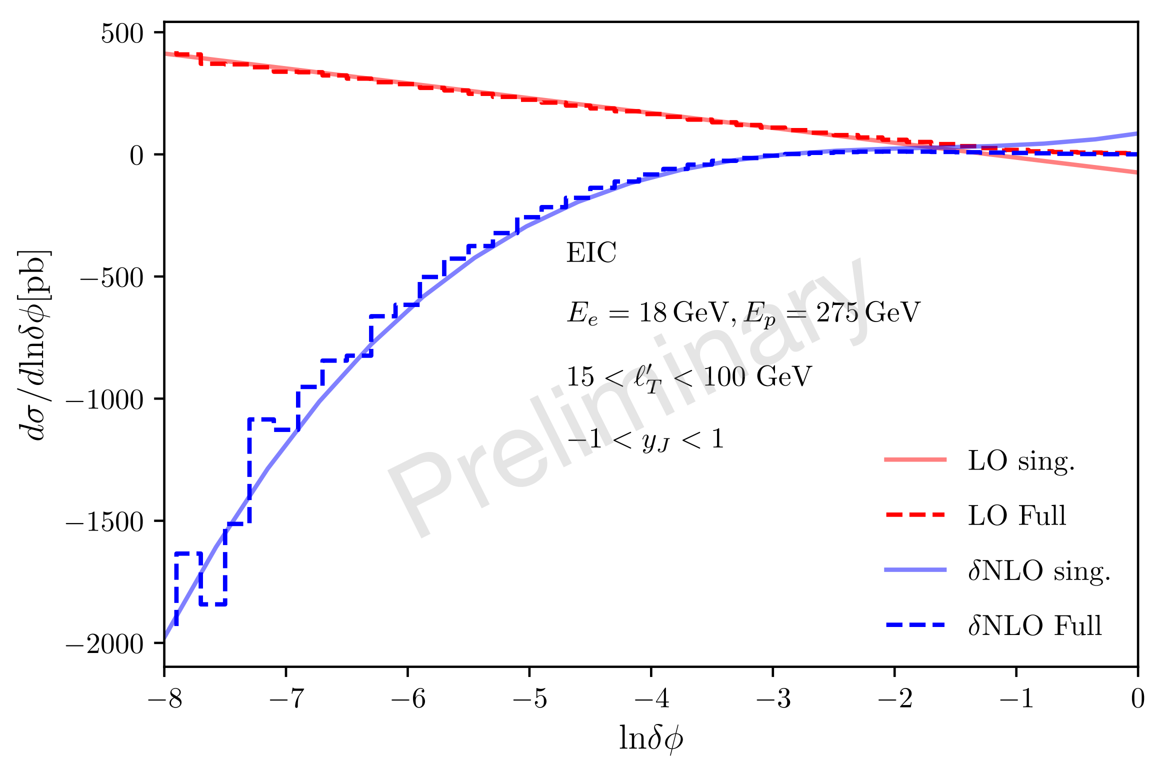
The process is primarily sensitive to the initial state's broadening effects, thereby serving as a clean probe of nTMD PDF

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

Fang, Gao, Li, DYS work in progress

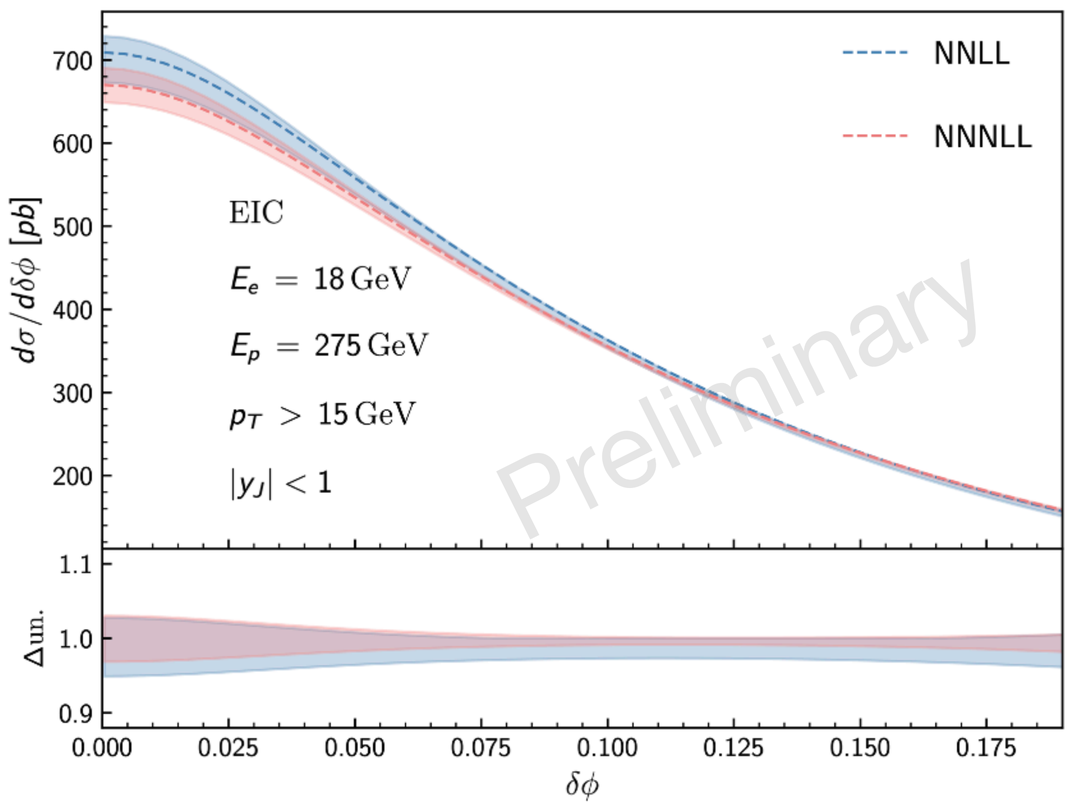
- **All perturbative and non-perturbative ingredients are known at N³LL+ $\mathcal{O}(\alpha_s^2)$, with the exception of the two loop jet function j_2 .**
- **The non-log constant was extracted numerically from the Event2 generator** (Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi '19)
- **A preliminary numerical results are also calculated from SoftSERVE** (Brune SCET2023)
- **We apply NLOJET++ event generator to extract j_2, and find it is consistent with previous results within uncertainties**
- **We also compare the resummation expanded singular contribution with the full prediction from NLOJET++ up to $\mathcal{O}(\alpha_s^2)$. Good agreement is observed.**

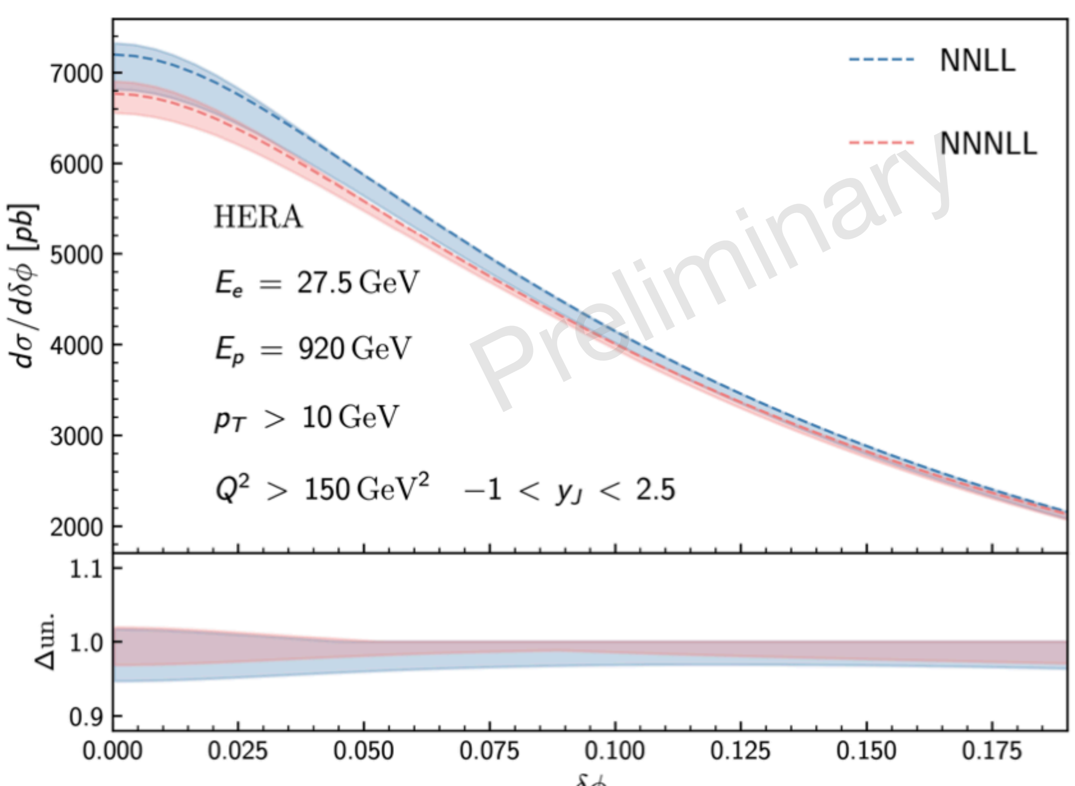




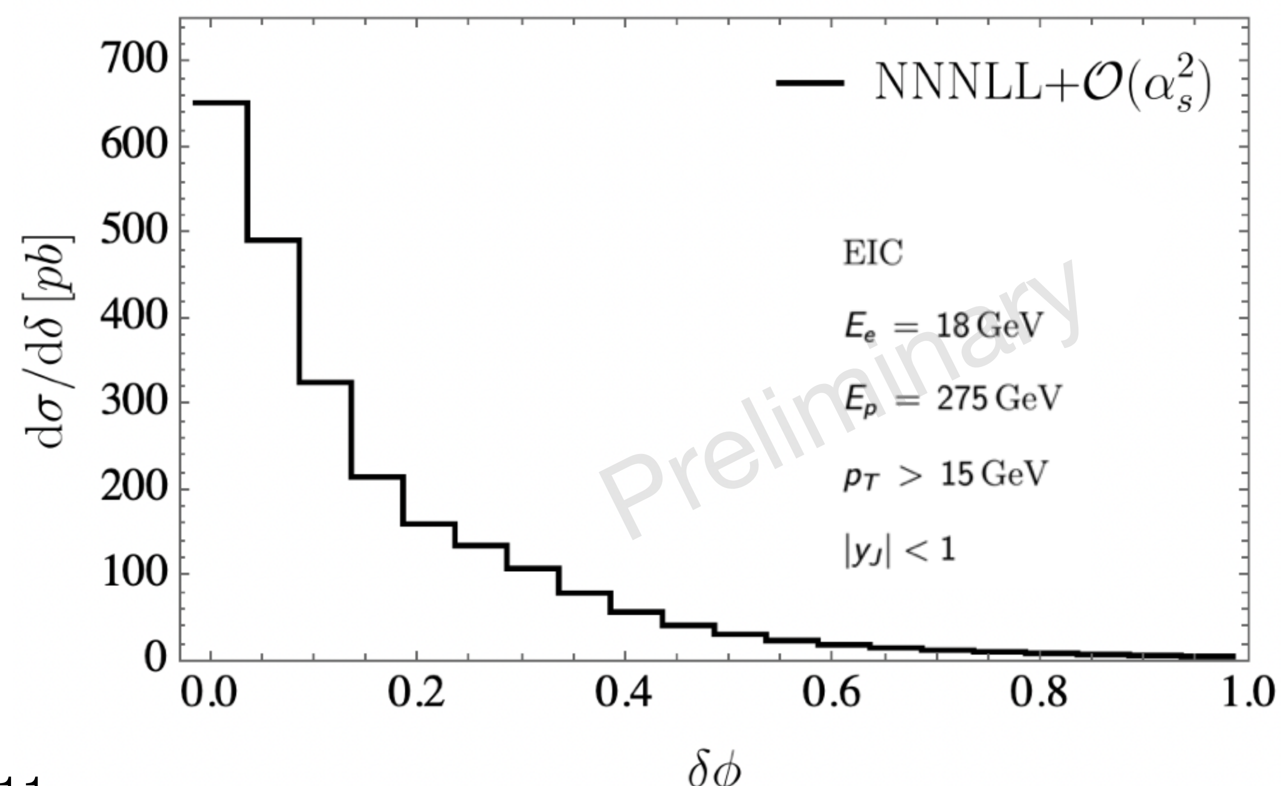
NNNLL predictions in e-p

Fang, Gao, Li, DYS work in progress





- **Good perturbative convergence is observed**
- **The theory uncertainties are reduced from NNLL to NNNLL**



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 NNNLL + $\mathcal{O}(\alpha_s^2)$ 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