Azimuthal angular asymmetries in diffractive di-jet production

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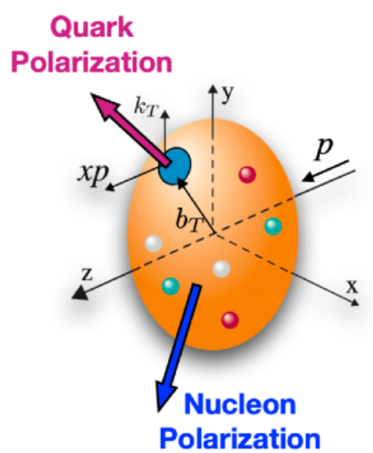
Heavy Ion Physics in the EIC Era   Seattle   Aug 13 2024

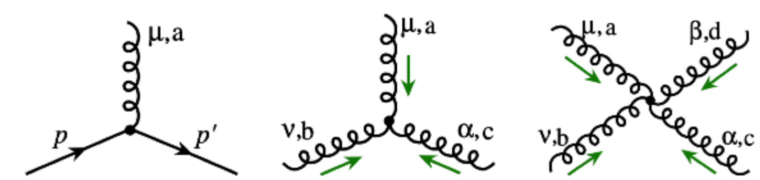
QCD and 3D imaging of nucleon

Transverse momentum distributions (TMDs) encode the quantum correlations between hadron polarization and the motion and polarization of quarks and gluons inside it.



Imaging a hadron would provide insights on QCD

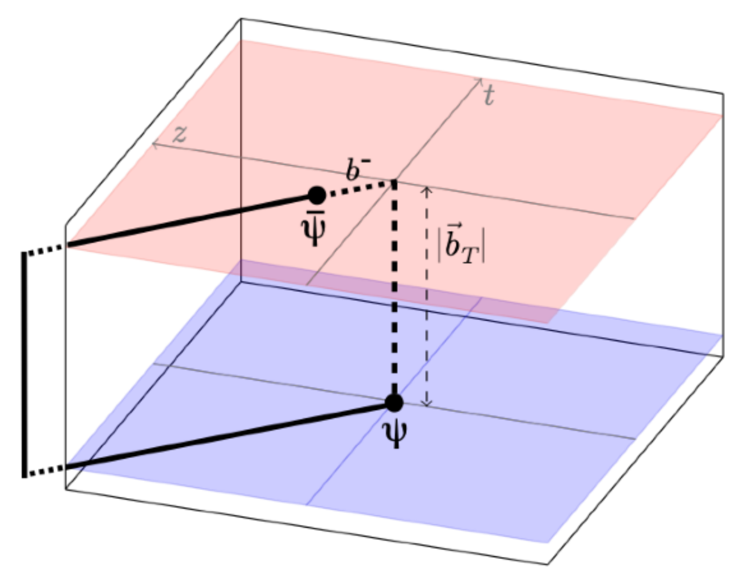
$$-\frac{1}{4}G^2_{\mu\nu,a}[A] + \sum_f \overline{\psi}_f \left(iD_\mu[A]\gamma^\mu - m_f\right)\psi_f$$



- **Both longitudinal and transverse motion**
- **Large Lorentz boost in longitudinal direction, but not in transverse momentum**
- **Correlation between hadron spin with parton(quark, gluon) orbital angular momentum**

$$\tilde{f}^{[\Gamma]0(\mathrm{u})}_{i/p_S}(x, \mathbf{b}_T, \epsilon, \tau, xP^+) =$$

$$\int \frac{\mathrm{d}b^-}{2\pi} e^{-ib^-(xP^+)} \left\langle p(P,S) \right| \left[\bar{\psi}^i(b^\mu) W_\sqsubset(b^\mu, 0) \frac{\Gamma}{2} \psi^i(0)\right]_\tau \left| p(P,S) \right\rangle$$



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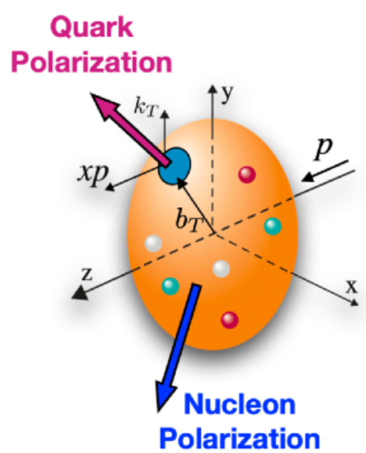

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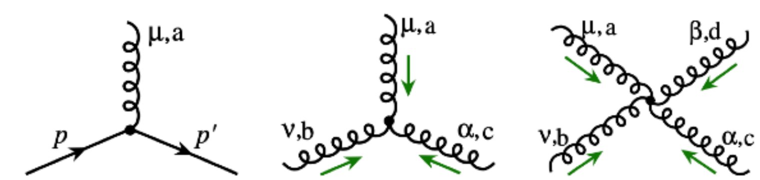

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$$f_{i/p_S}^{[\gamma^+]}(x,\mathbf{k}_T,\mu,\zeta) = f_1(x,k_T) - \frac{\epsilon_T^{\rho\sigma}k_{T\rho}S_{T\sigma}}{M}\kappa\, f_{1T}^{\perp}(x,k_T)\,,$$

$$f_{i/p_S}^{[\gamma^+\gamma_5]}(x,\mathbf{k}_T,\mu,\zeta) = S_L\, g_1(x,k_T) - \frac{k_T\cdot S_T}{M}g_{1T}^{\perp}(x,k_T)\,,$$

$$f_{i/p_S}^{[i\sigma^{\alpha+}\gamma_5]}(x,\mathbf{k}_T,\mu,\zeta) = S_T^\alpha h_1(x,k_T) + \frac{S_L k_T^\alpha}{M}h_{1L}^{\perp}(x,k_T)$$

$$-\frac{\mathbf{k}_T^2}{M^2}\left(\frac{1}{2}g_T^{\alpha\rho} + \frac{k_T^\alpha k_T^\rho}{\mathbf{k}_T^2}\right)S_{T\rho}h_{1T}^{\perp}(x,k_T) - \frac{\epsilon_T^{\alpha\rho}k_{T\rho}}{M}\kappa\, h_1^{\perp}(x,k_T)$$

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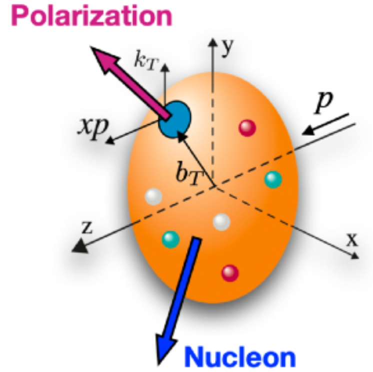

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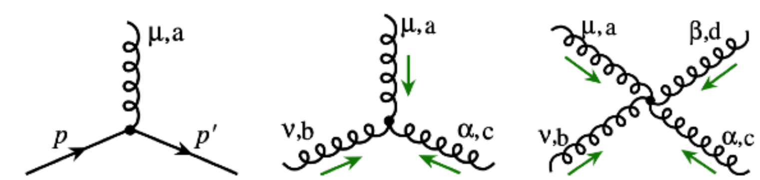

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TMDs		Quark Polarization: Unpolarized (U)	Longitudinally polarized (L)	Transversely polarized (T)
Nucleon Polarization	U	f_1 unpolarized		$h_1^\perp$ Boer-Mulders
	L		g_{1L} helicity	$h_{1L}^\perp$ longi-transversity
	T	$f_{1T}^\perp$ Sivers	g_{1T} trans-helicity	h_1 transversity $h_{1T}^\perp$ pretzelosity

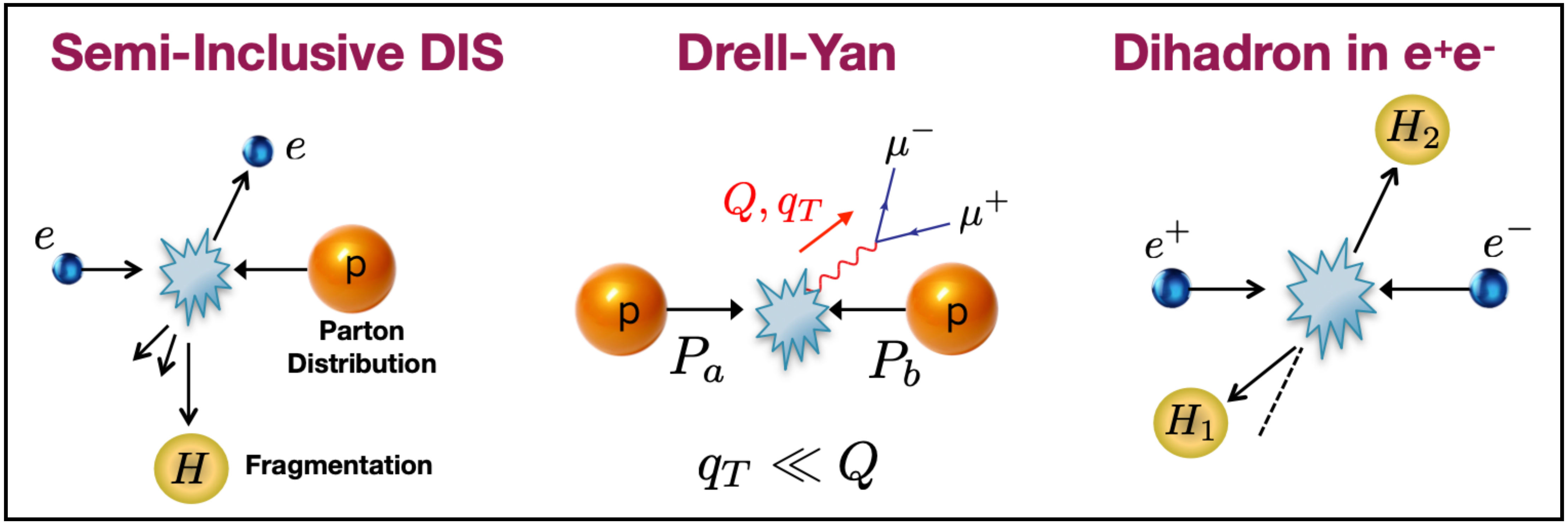
Nucleon spin — Quark spin

Figure 2.5: The leading-twist quark TMD distributions.

TMD handbook 2304.03302

Transverse momentum distributions of quarks

- Three classical processes used to probe quark TMDs



- Typical "two-scale" problem:

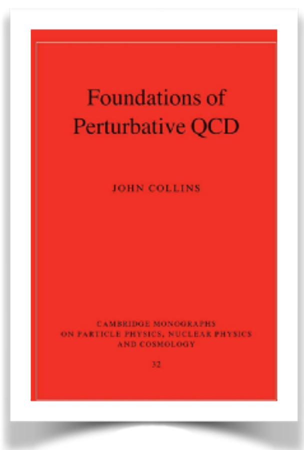
  transverse momentum of final particle (q_T) << scattering energy (Q)

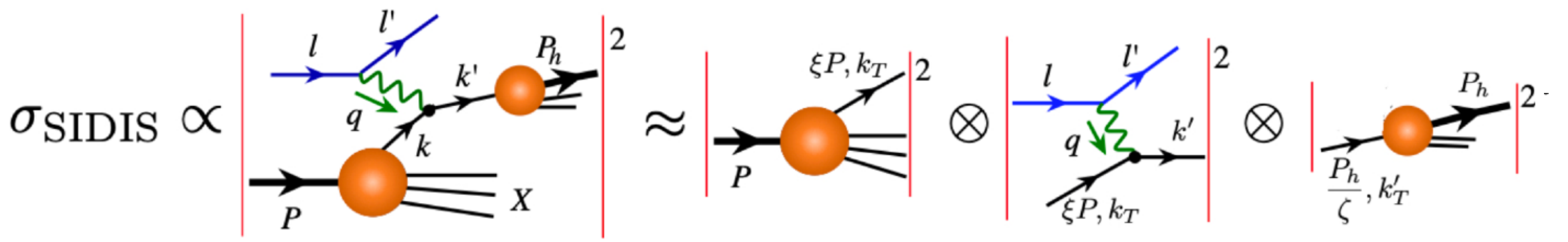
- Theory tools: factorization theorem; renormalization group evolution; effective field theory …

Theory Formalism in Semi-Inclusive DIS

$$e(\ell) + p\,(P, \mathbf{S}_\perp) \to e\,(\ell') + h\,(P_h) + X$$

TMD factorization theorems have been established at the leading power of q_T^2/Q^2





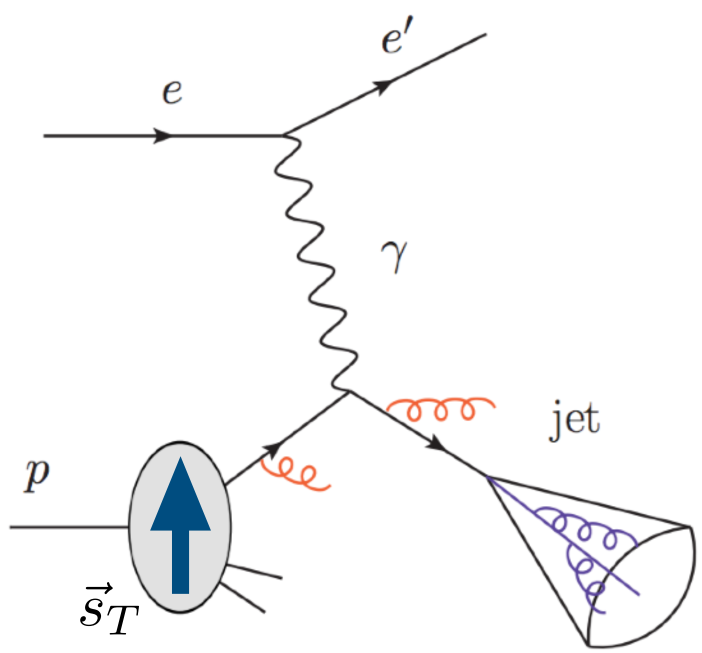
Theory framework: Collins-Soper-Sterman, Ji-Ma-Yuan, Soft-Collinear Effective Theory ……

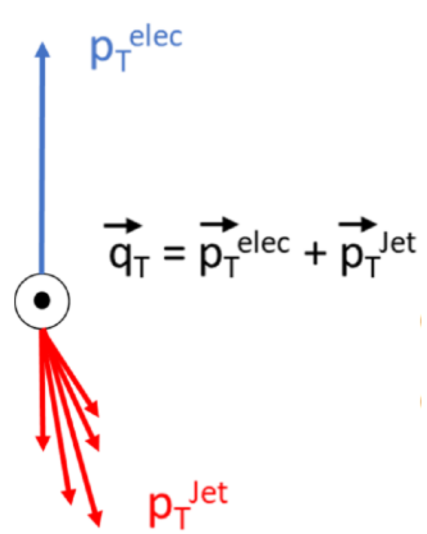
$$\frac{\mathrm{d}\sigma(ep \to ehX)}{\mathrm{d}Q\,\mathrm{d}x\,\mathrm{d}z\,\mathrm{d}\vec{q}_T} = H_{eq\to eq}(Q) F_q(\vec{q}_T, x) \otimes D_{q\to h}(\vec{q}_T, z)$$

Some recent progresses on factorization theorem at the sub-leading power

See Jyotirmoy Roy's talk

QCD jets and 3D proton imaging at the EIC

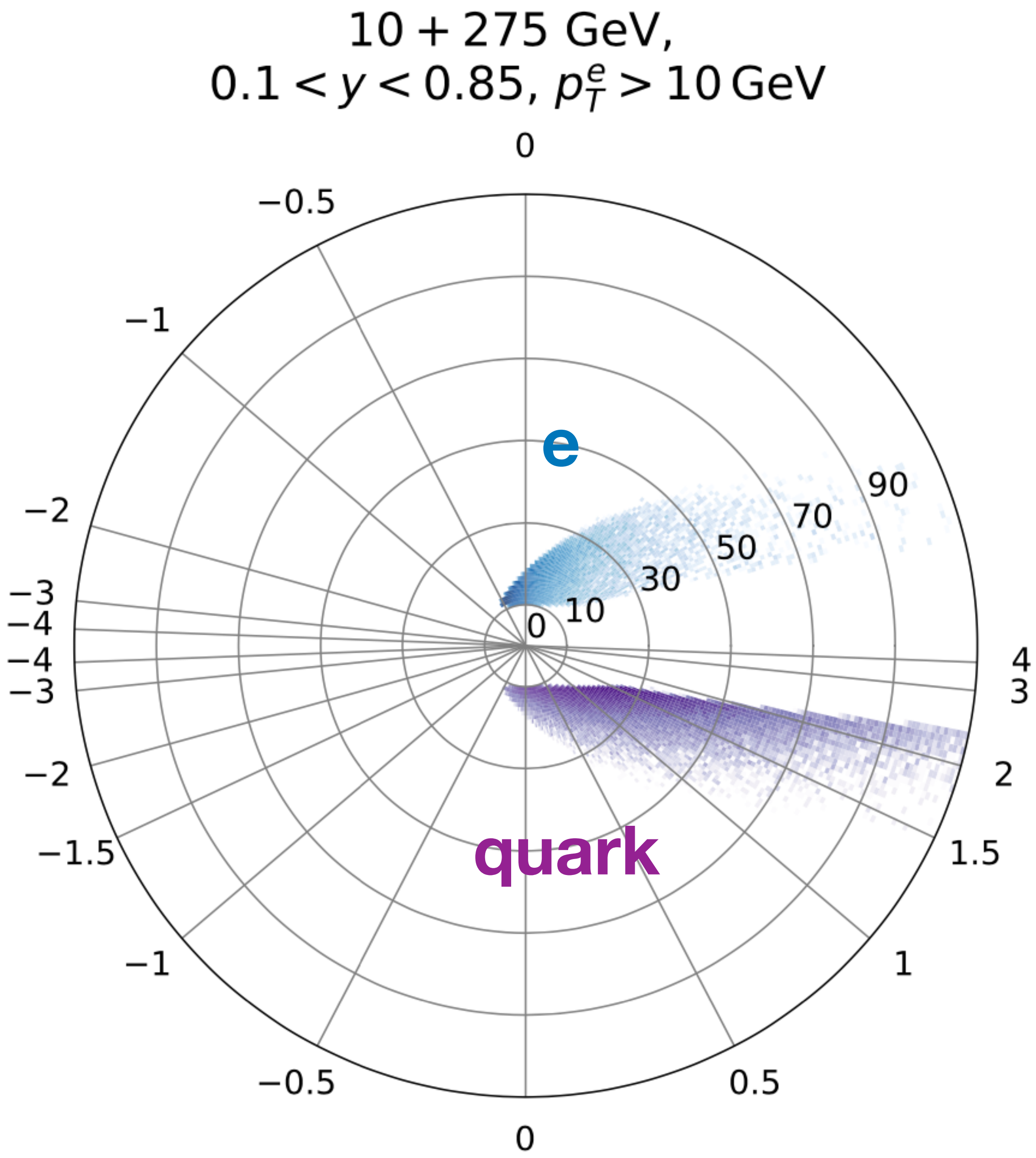


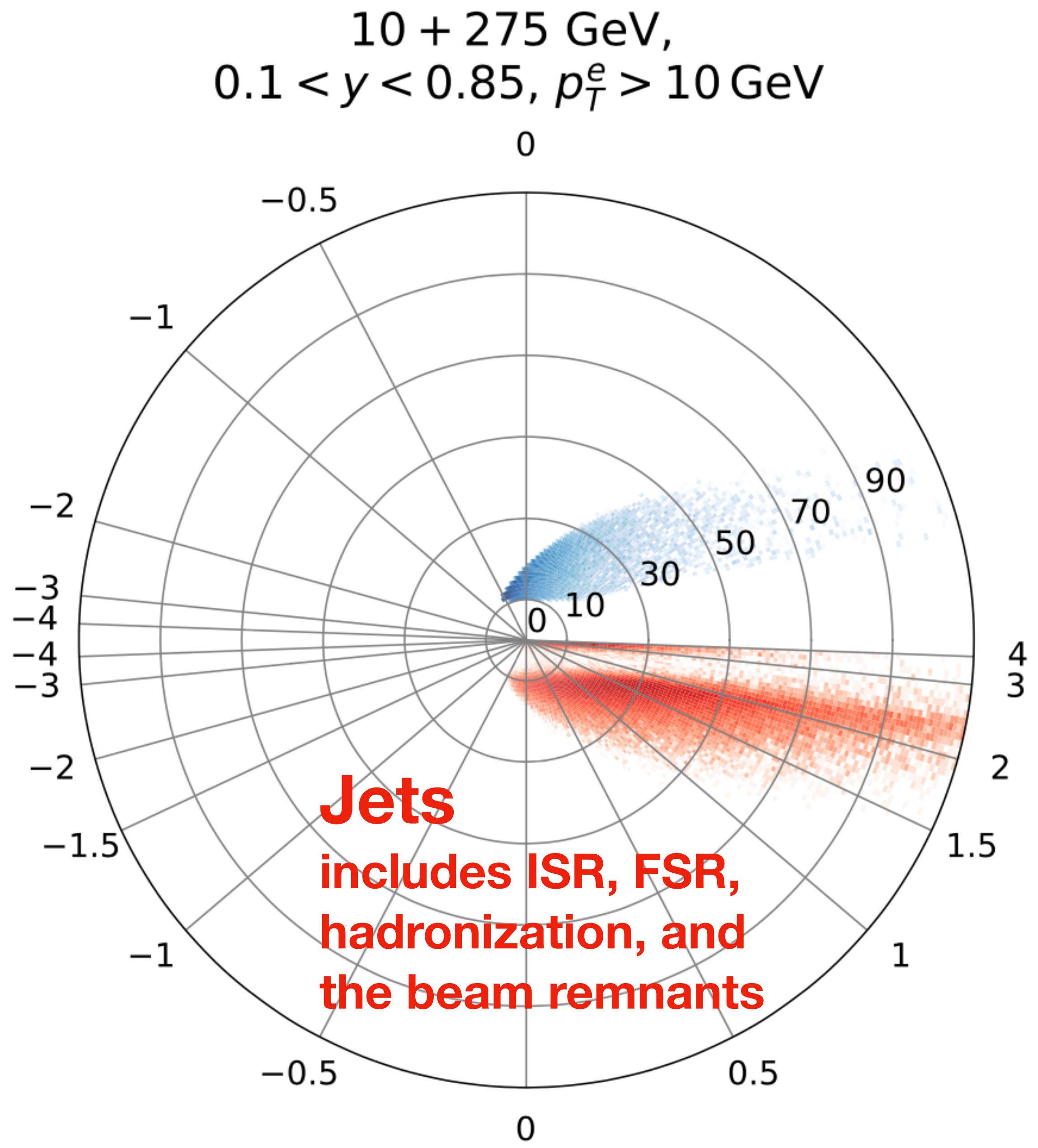


- **Recent investigations at both the RHIC and LHC have validated jets as effective tools for probing the spin structure of the nucleon.**
- **Jets are complementary to standard SIDIS extractions of TMDs**
- **Jet measurements allow independent constraints on TMD PDFs and FFs from a single measurement**
- **Azimuthal correlation between jet and lepton sensitive to TMD PDFs** (X. Liu, Ringer, Vogelsang, F. Yuan '19 PRL, ……)

Simulation results

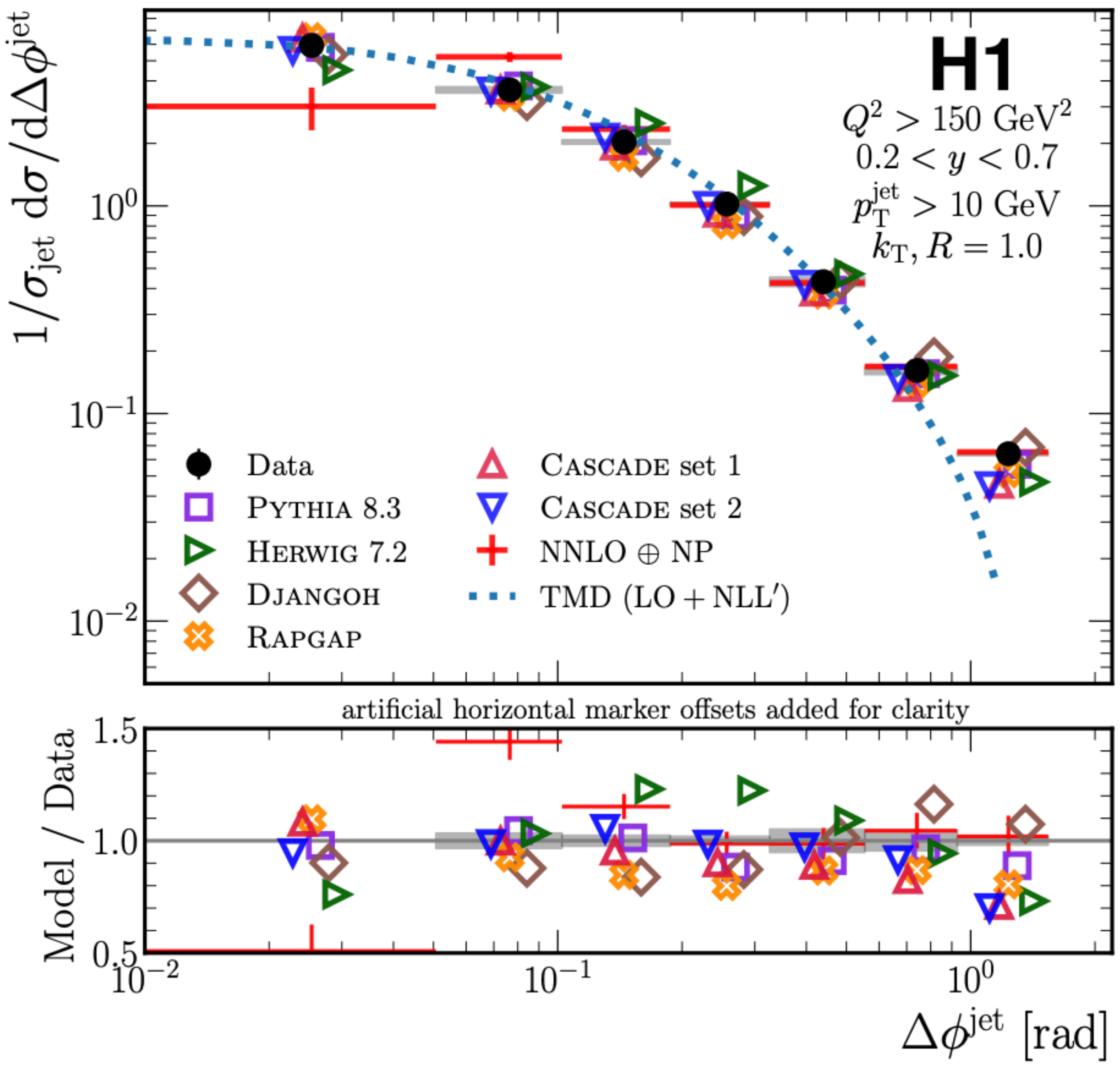
Arratia, Kang, Prokudin, Ringer '19



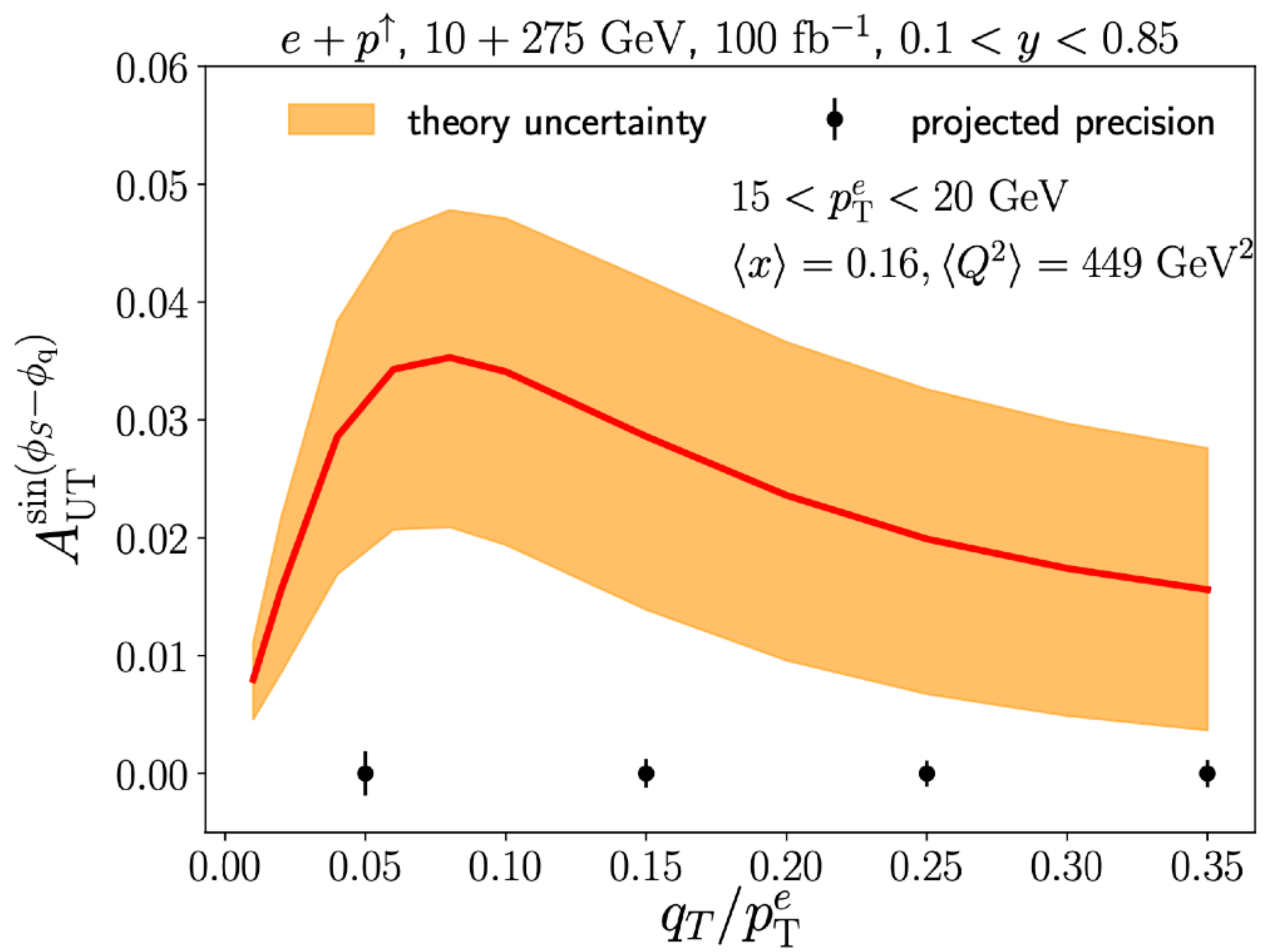


The jet distribution matches the struck-quark kinematics

Theory predictions and measurements in DIS



H1 collaboration, '22

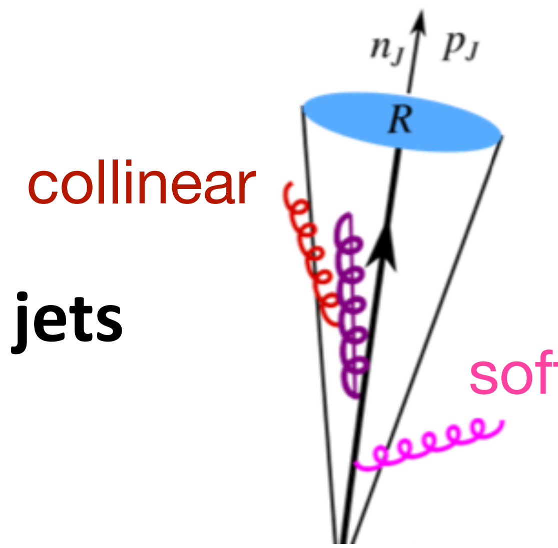


Arratia, Kang, Prokudin, Ringer '19

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:

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

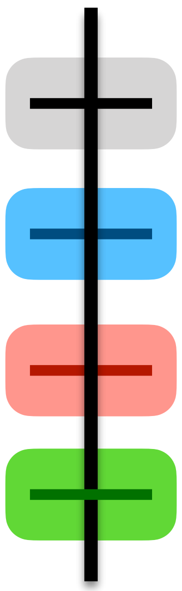
Perturbative Sudakov factor:

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

Jet radius and TMD joint resummation for boson-jet correlation

(Chien, DYS & Wu '19 JHEP)

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



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

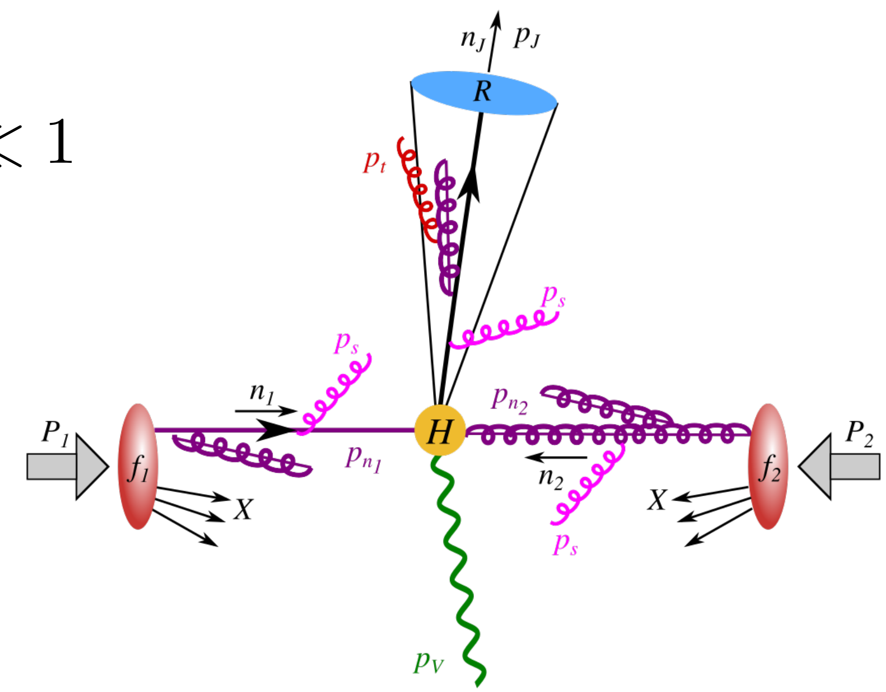
$p_{n_J} \sim p_T^J\,(R^2, 1, R)_{n_J \bar{n}_J}$

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

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

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

$$q_T \ll Q,\ R \ll 1$$



Construction of the theory formalism

- **Multiple scales in the problem**
- **Rely on effective field theory: SCET + Jet Effective Theory** (Becher, Neubert, Rothen, DYS '16 PRL)

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

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

New divergence in the ϕ-integral

The anomalous dimensions of the global soft function and collinear-soft function are given by

$$\gamma^{S_{\text{global}}} = \frac{\alpha_s C_F}{\pi}\left[2y_J + \ln\left(\frac{\mu^2}{\mu_b^2}\right) + \ln\left(4\cos^2\phi_x\right) - i\pi\,\text{sign}\left(\cos\phi_x\right)\right],$$
$$\gamma^{S_{\text{cs}}} = -\frac{\alpha_s C_F}{\pi}\left[\ln\left(\frac{\mu^2}{\mu_b^2 R^2}\right) + \ln\left(4\cos^2\phi_x\right) - i\pi\,\text{sign}\left(\cos\phi_x\right)\right],$$

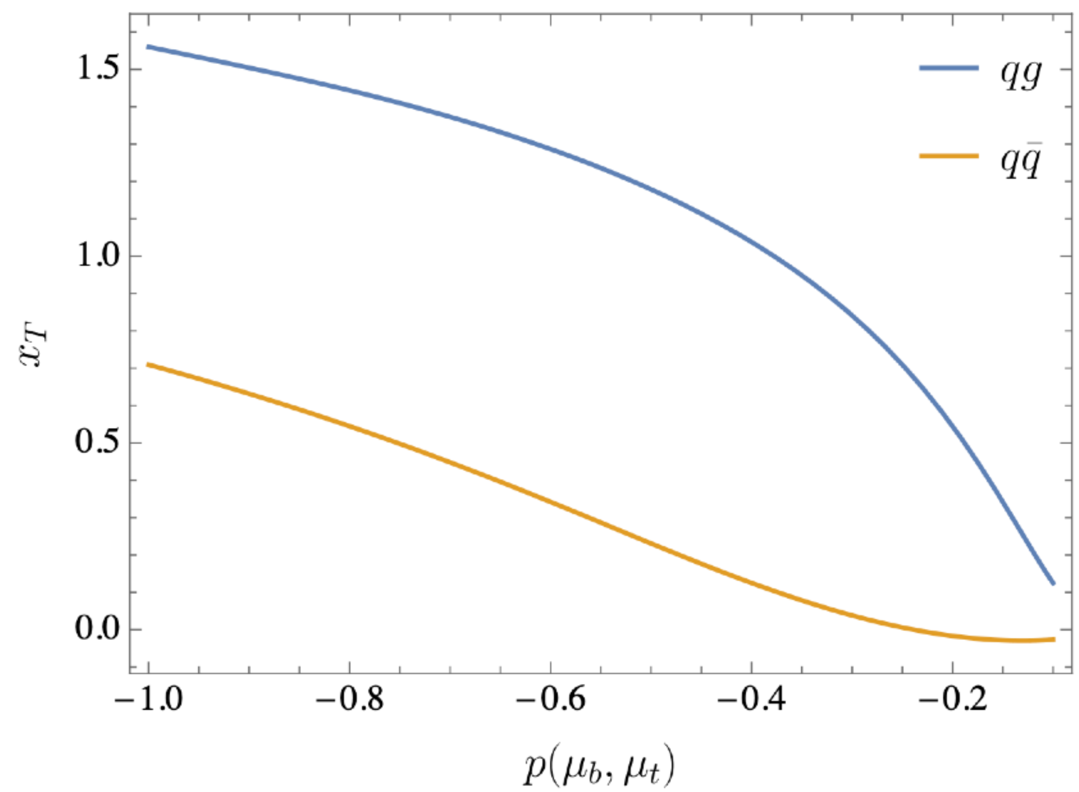
- **Scale separation introduced by the narrow cone approximation** $R \ll 1$
- **Both soft and collinear-soft functions are divergent as** $\phi_x = \pi/2$
- **ϕ dependent term in the RG solution between soft and collinear-soft scales reads**

$$\left|\cos\phi_x\right|^{p(\mu_b, R\mu_b)}$$

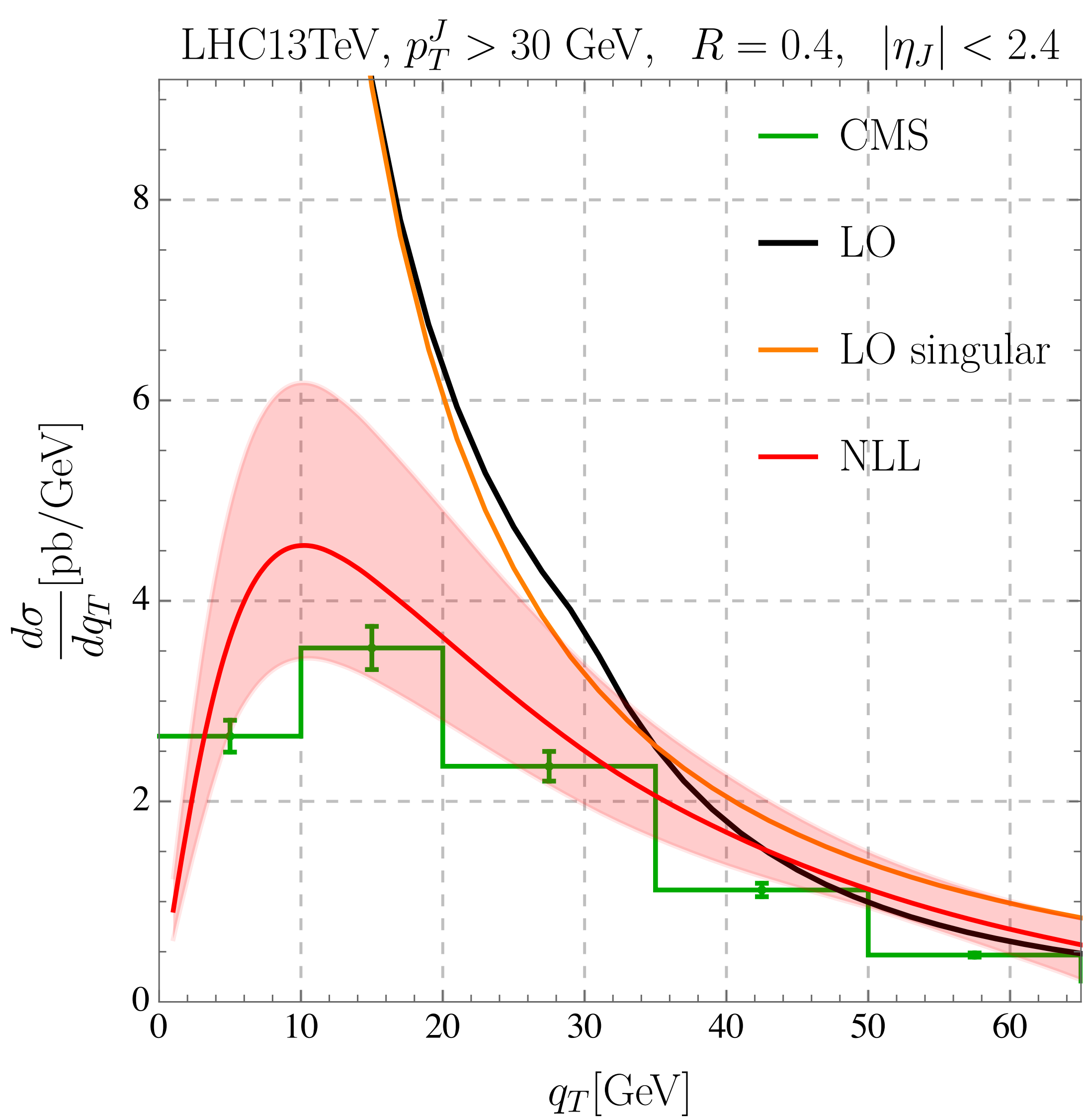
the ϕ-integral is convergent only if

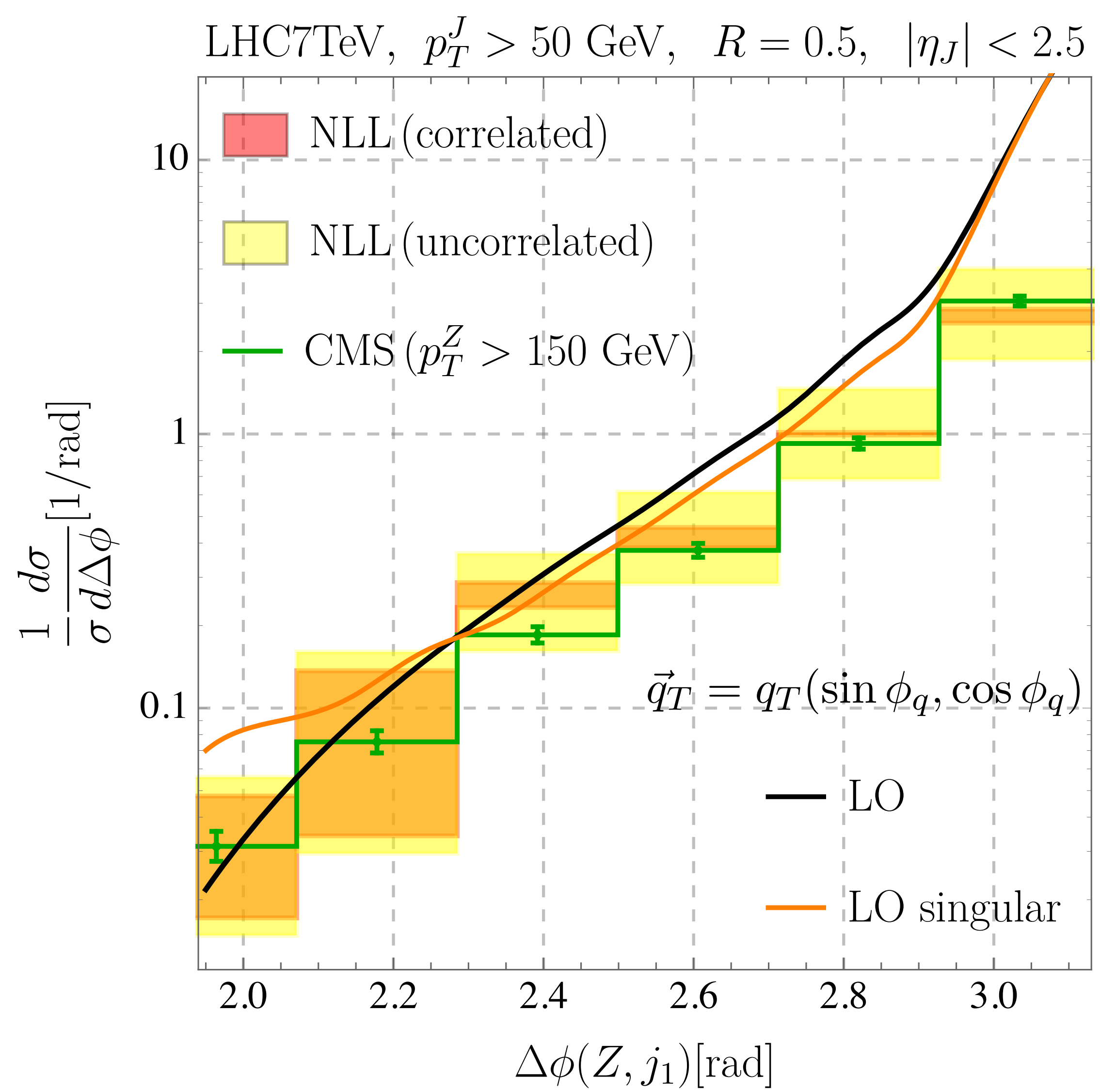
$$-1 < p(\mu_b,\mu_t) \equiv \frac{4C_k}{\beta_0}\log\frac{\alpha_s(\mu_b)}{\alpha_s(\mu_t)} \approx -\frac{2\alpha_s(\mu_t)}{\pi}\log\frac{1}{R}$$

One encounters such a divergence when the collinear-soft scale approaches to the non-perturbative region



Numerical results

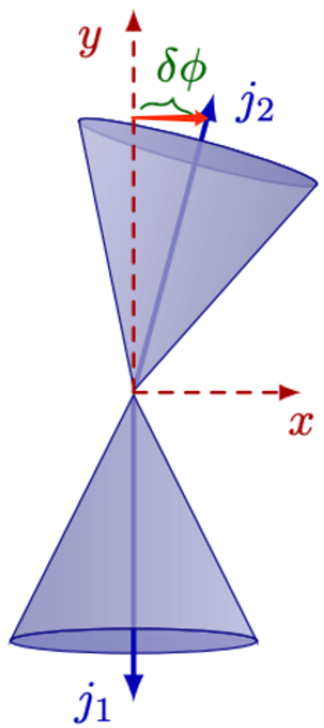




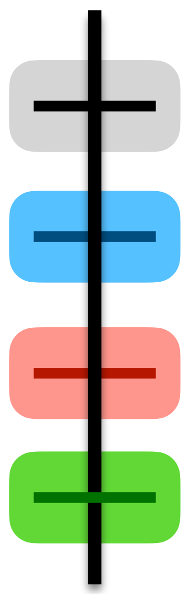
- **NLL resummation is consistent with the LHC data (q_T & ΔΦ)**
- **ΔΦ distribution for dijet production can be a clean probe of *factorization violation***
  (Collins & Qiu '07, Rogers & Mulders '10, ……)
- **NLL result has 20-30% scale uncertainties. Higher-order is necessary.**

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

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



Indirect



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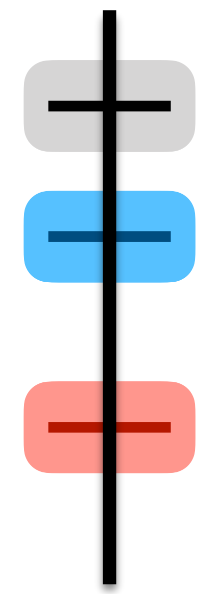

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$p_{c_i}^\mu \sim p_T\,(\delta\phi^2, 1, \delta\phi)_{n_i \bar{n}_i}$

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

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

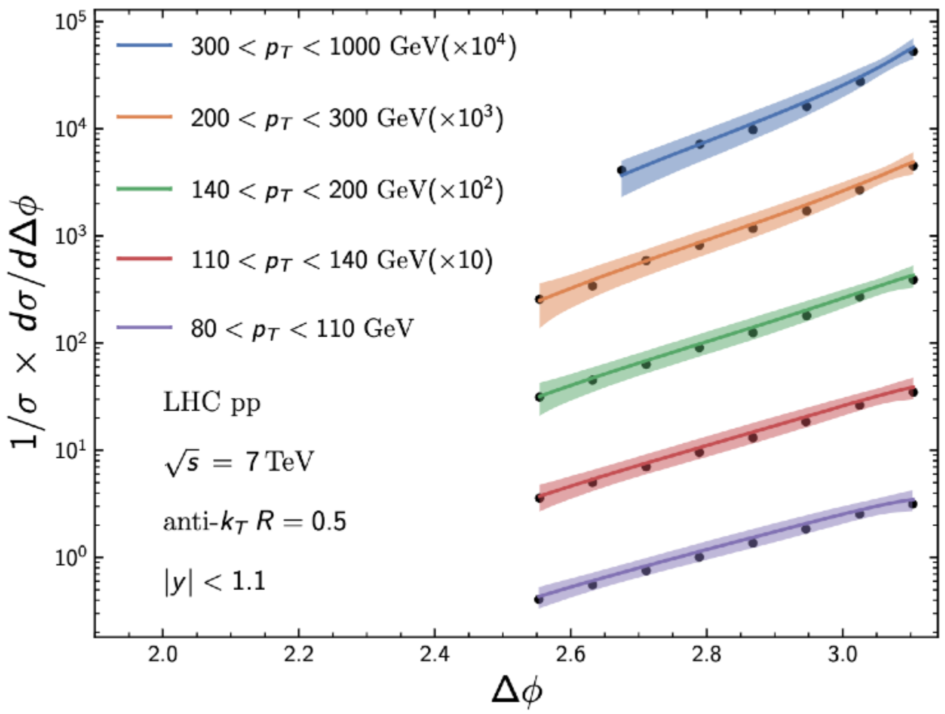
The factorization formula

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

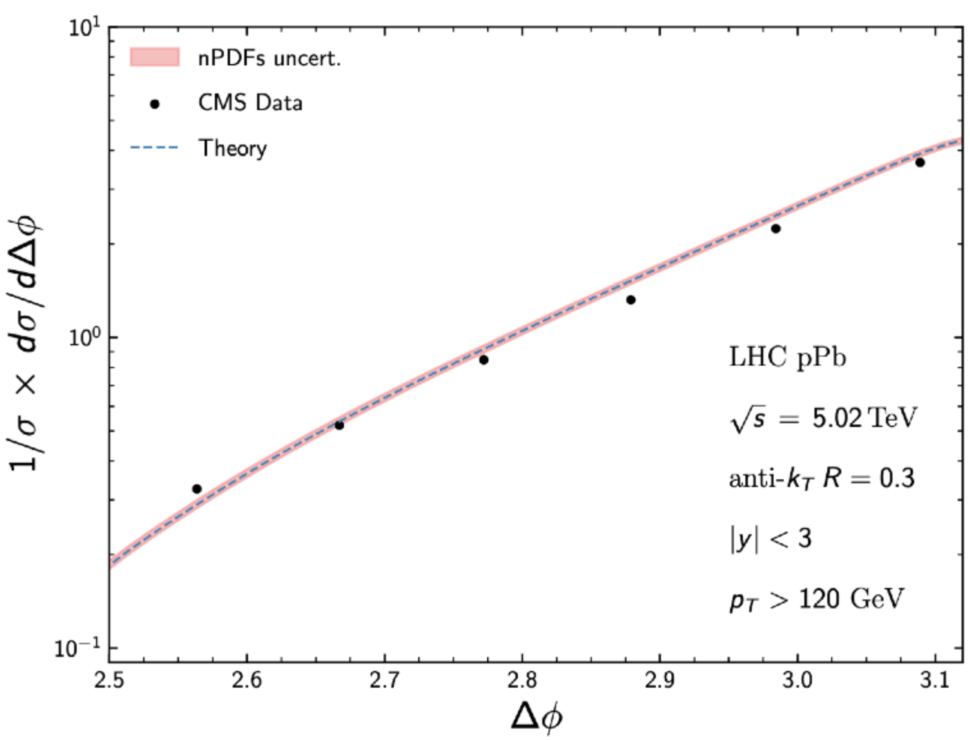
$$\mathcal{C}_x\left[f_{a/p}^{\mathrm{unsub}}\, f_{b/p}^{\mathrm{unsub}}\, \boldsymbol{S}_{ab\to cd,IJ}^{\mathrm{unsub}}\, S_c^{\mathrm{cs}}\, S_d^{\mathrm{cs}}\right] = \int \mathrm{d}k_{ax}\,\mathrm{d}k_{bx}\,\mathrm{d}k_{cx}\,\mathrm{d}k_{dx}\,\mathrm{d}\lambda_x\, \boldsymbol{S}_{ab\to cd,IJ}^{\mathrm{unsub}}(\lambda_x,\mu,\nu)$$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

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 N4LL accuracy**
  - **Better angular resolution?**
  - **Reduce contamination from UE?**
- **One possible solution:**
  - **Recoil-free jet definition**

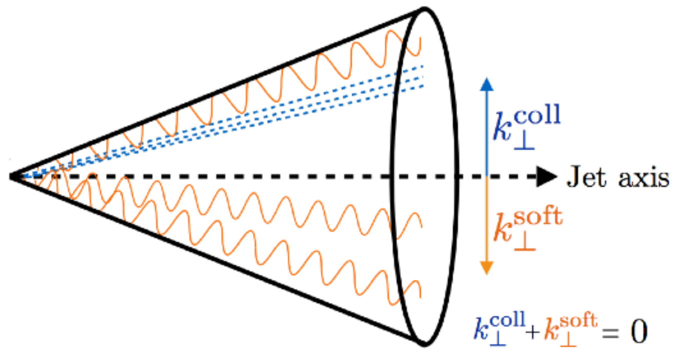
  E.g. anti-k$_T$ clustering algorithm + p_T^n -weighted recombination scheme

Recoil-free jet and all-order structure

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

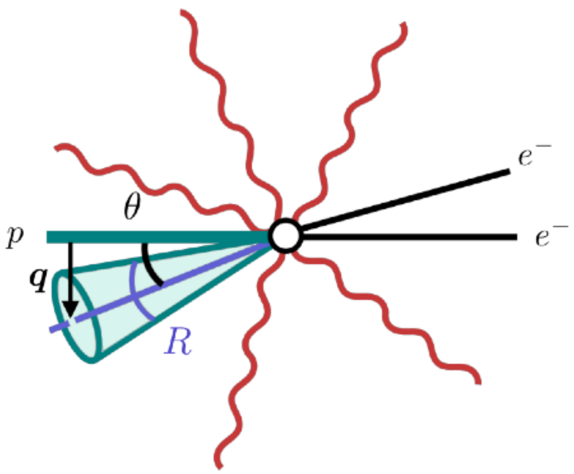
$$p_{t,r} = p_{t,i} + p_{t,j}\,,$$
$$\phi_r = (w_i\phi_i + w_j\phi_j)/(w_i + w_j)$$
$$y_r = (w_i y_i + w_j y_j)/(w_i + w_j)$$

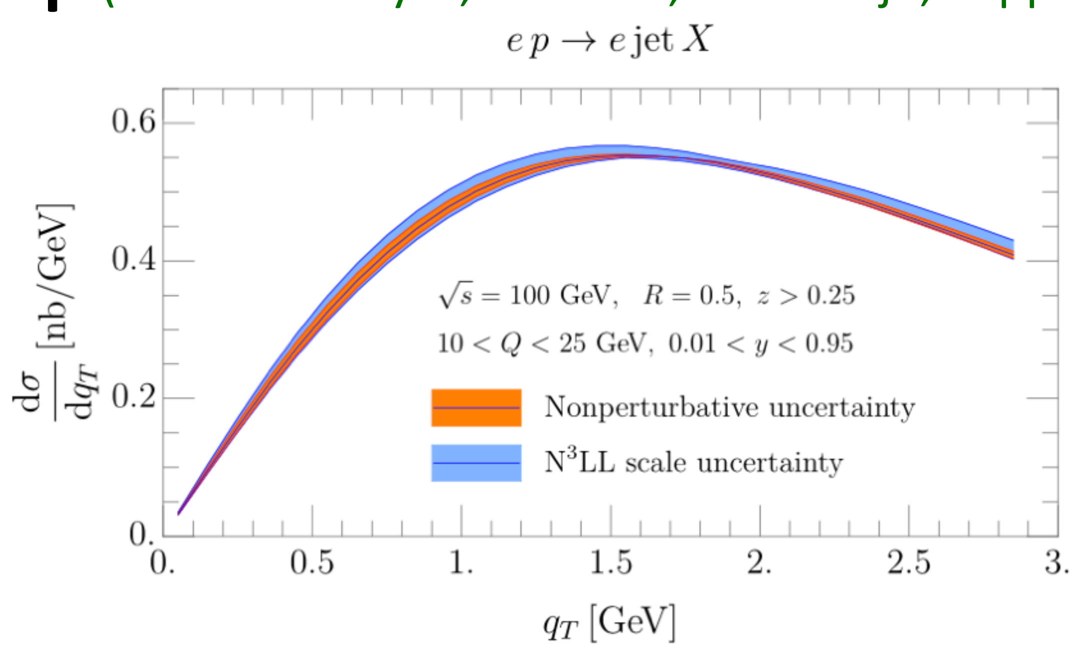
$$w_i = p_t^n$$



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

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



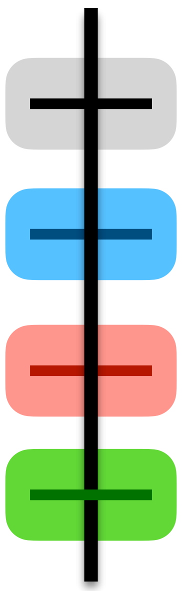


- **NNLL resummation for $\delta\phi$ @ pp** (Chien, Rahn, DYS, Waalewijn & Wu '22 JHEP + Schrignder '21 PLB)
- **NNLL resummation for $\delta\phi$ @ ep & eA** (Fang, Ke, DYS, Terry '23 JHEP)

Recoil-free azimuthal angle for boson-jet correlation

(Chien, Rahn, DYS, Waalewijn & Wu ’22 JHEP + Schrigdner ’21 PLB)

Indirect



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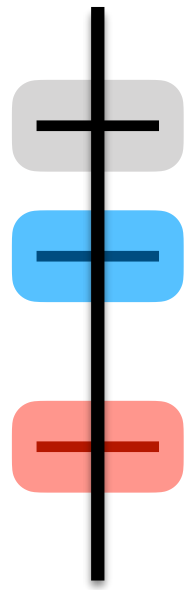
Direct



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

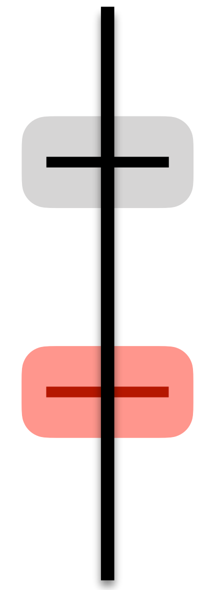
$p_{n_J} \sim p_T^J\,(R^2,1,R)_{n_J\bar{n}_J}$

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

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

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

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



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

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

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

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

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

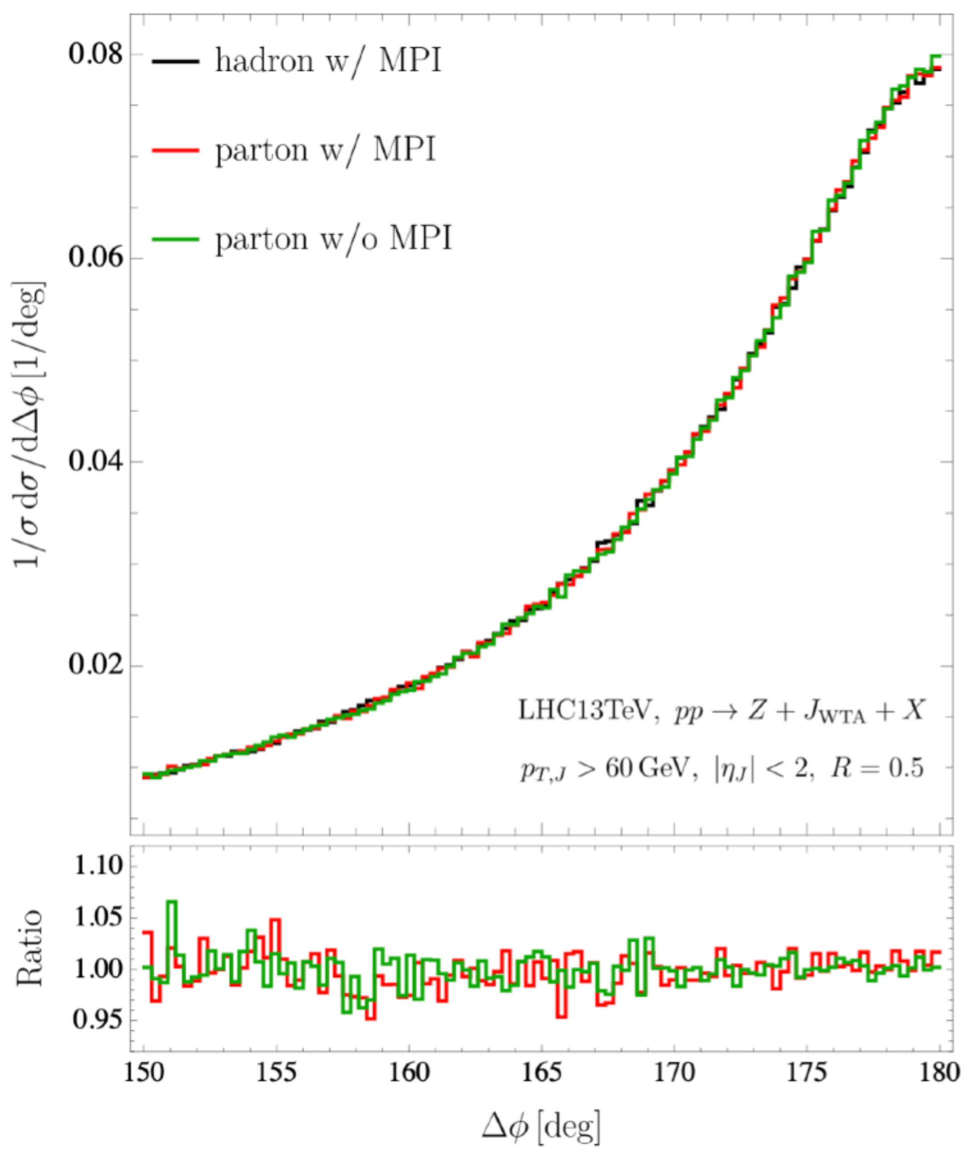
Fourier transformation in 1-dim

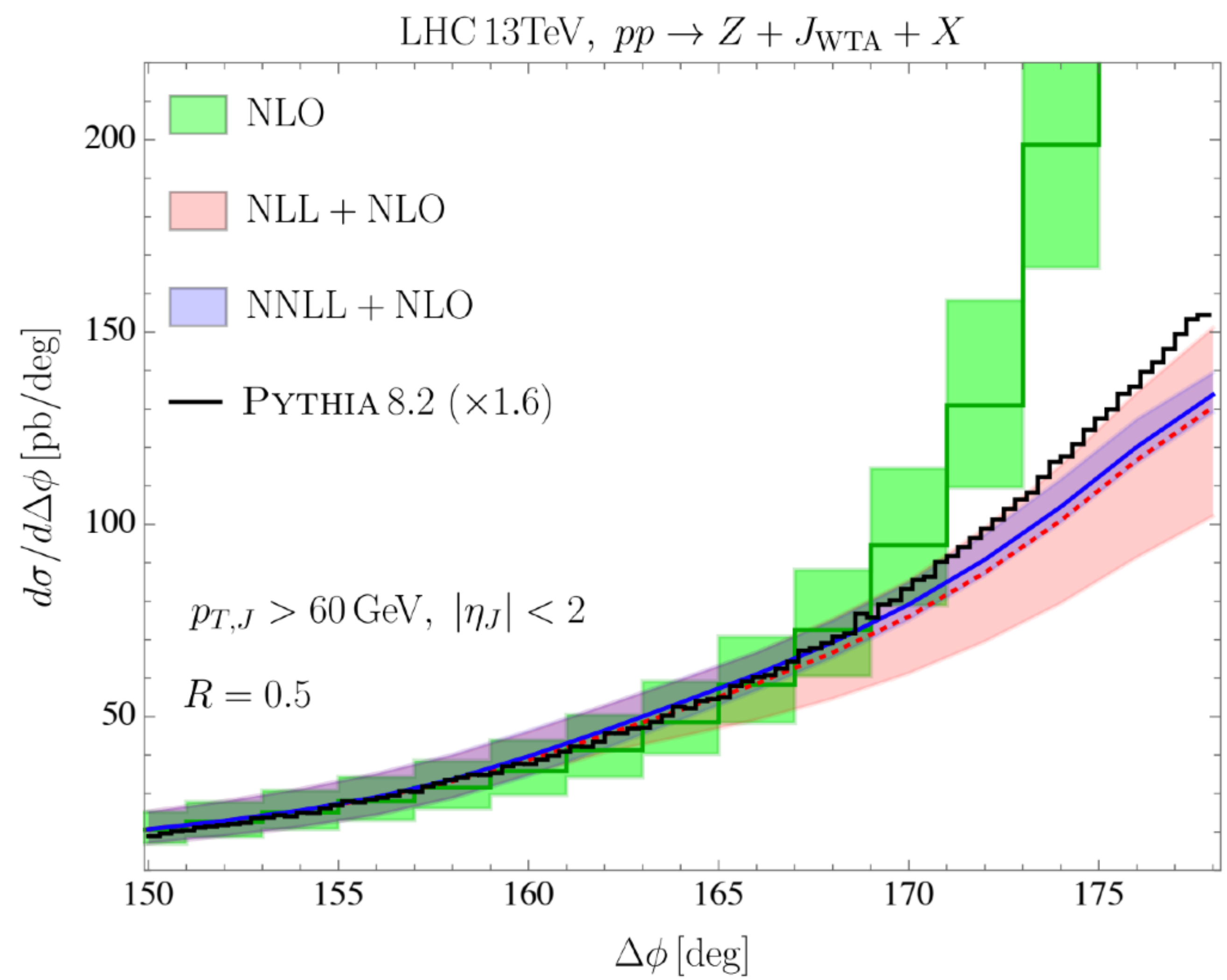
Soft function can be obtained by boosted invariance

(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**

Linearly-polarized gluon jets

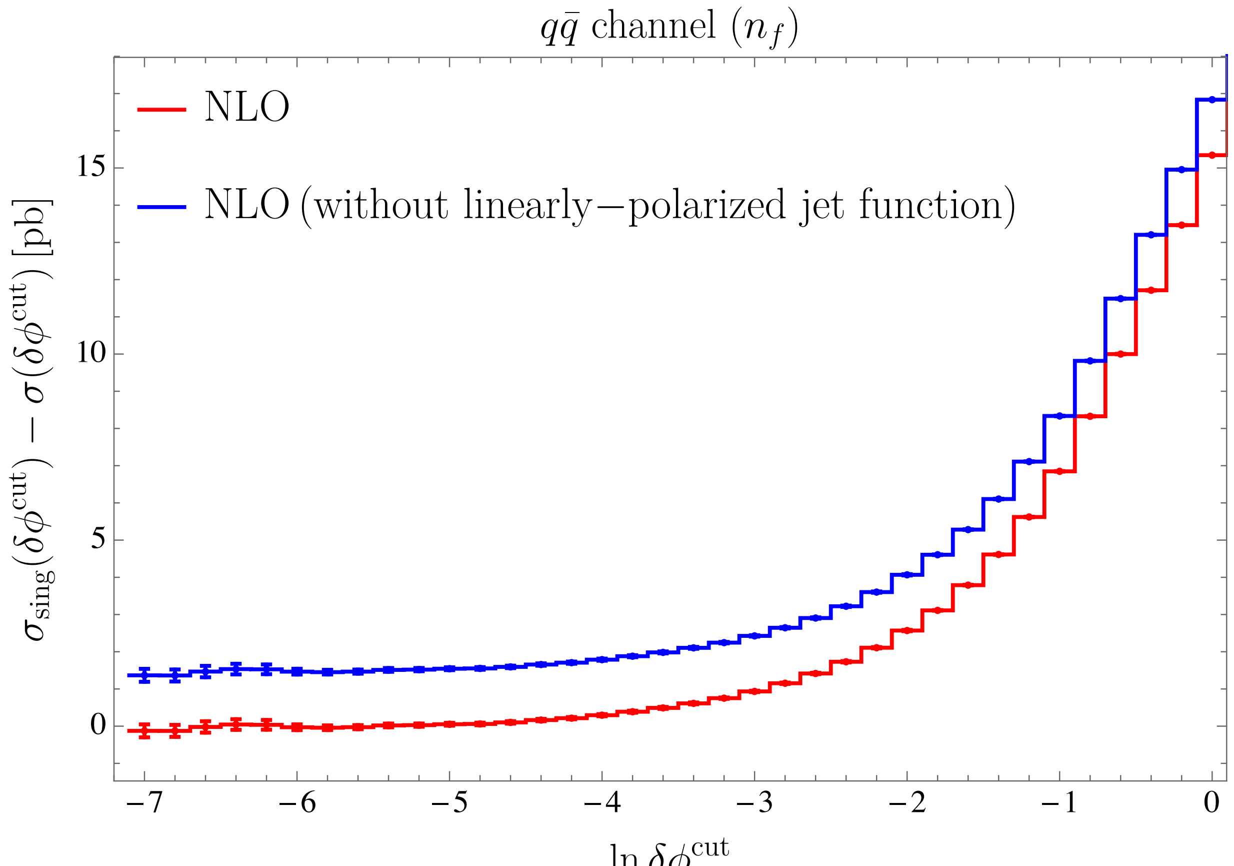
The linearly-polarized jet function describes the effect of a spin-superposition of the gluon initiating the jet

$$J_g^L(\vec{b}_\perp,\mu,\nu) = \left[\frac{1}{d-3}\left(\frac{g_\perp^{\mu\nu}}{d-2}+\frac{b_\perp^\mu b_\perp^\nu}{\vec{b}_\perp^2}\right)\right]\frac{2(2\pi)^{d-1}\omega}{N_c^2-1}\langle 0|\delta(\omega-\bar{n}\cdot\mathcal{P})\delta^{d-2}(\mathcal{P}_\perp)\mathcal{B}^a_{n\perp\mu}(0)e^{i\vec{b}_\perp\cdot\hat{\vec{k}}_\perp}\mathcal{B}^a_{n\perp\nu}(0)|0\rangle$$

The first non-vanishing order is one loop

$$J_g^{L(1)}(\vec{b}_\perp,\mu,\nu) = -\frac{1}{3}C_A+\frac{2}{3}T_F n_f$$

We provide evidence for contributions from linearly-polarized gluon jet functions using MCFM

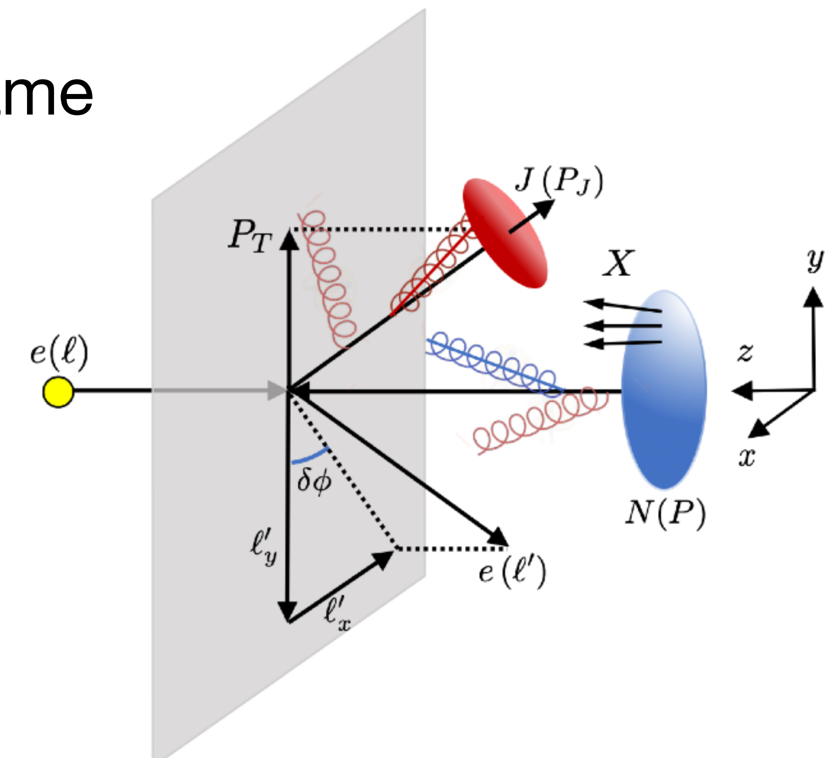


Recoil-free azimuthal angle for electron-jet correlation

Fang, Ke, DYS, Terry ’23 JHEP

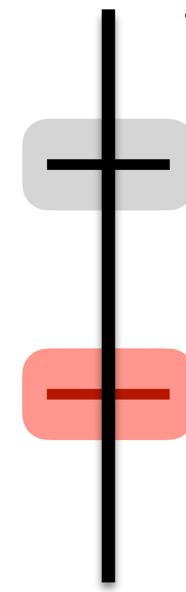
$$e(\ell) + N(P) \to e(\ell') + J(P_J) + X$$

Lab frame



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

Chien, Rahn, DYS, Waalewijn & Wu ’22 JHEP + Schrignder ’21 PLB



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

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

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

Similar to Transverse-EEC in back to back

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

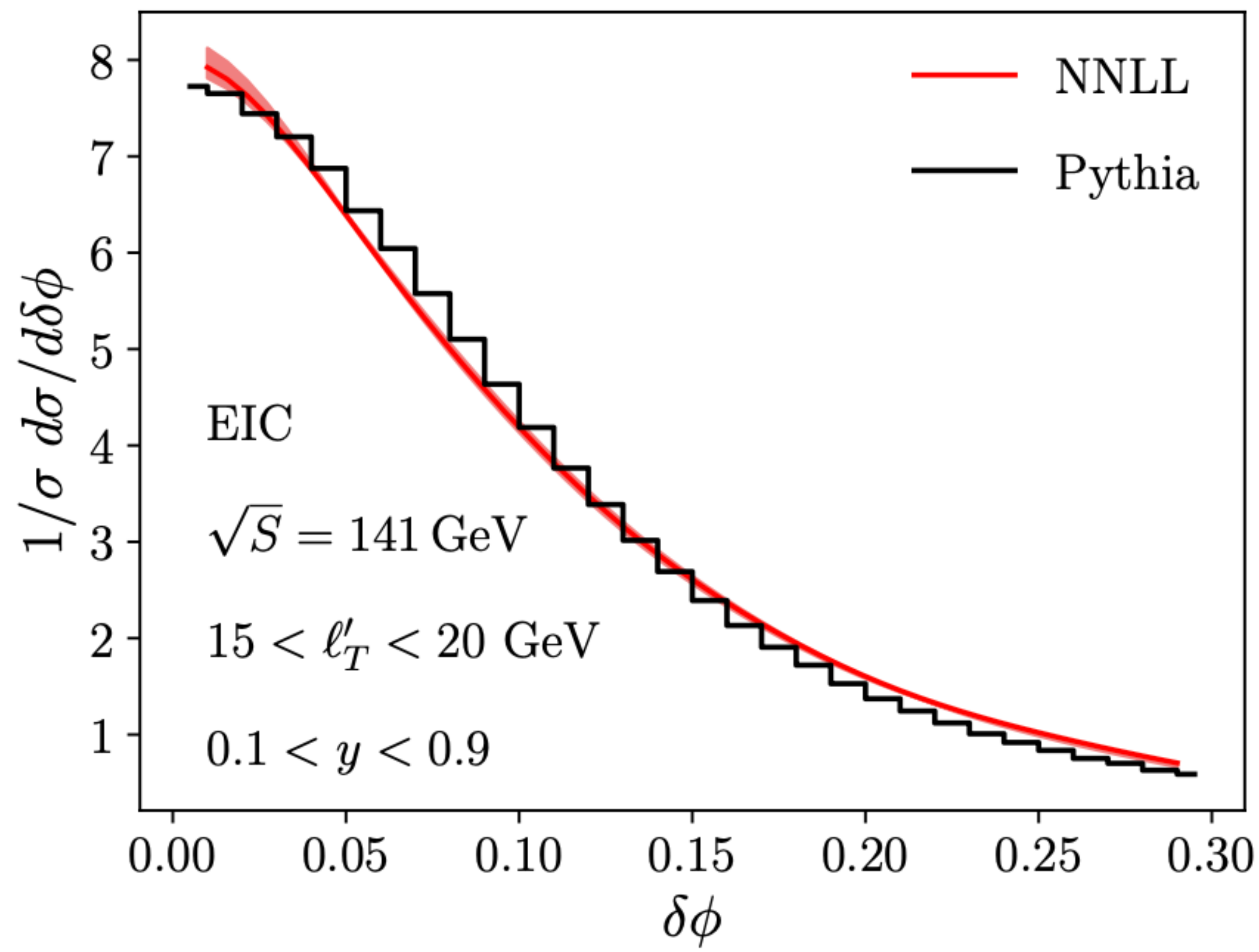
$$b_* = b/\sqrt{1+b^2/b^2_{\rm max}} \qquad \mu_{b_*} = 2e^{-\gamma_E}/b_*$$

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

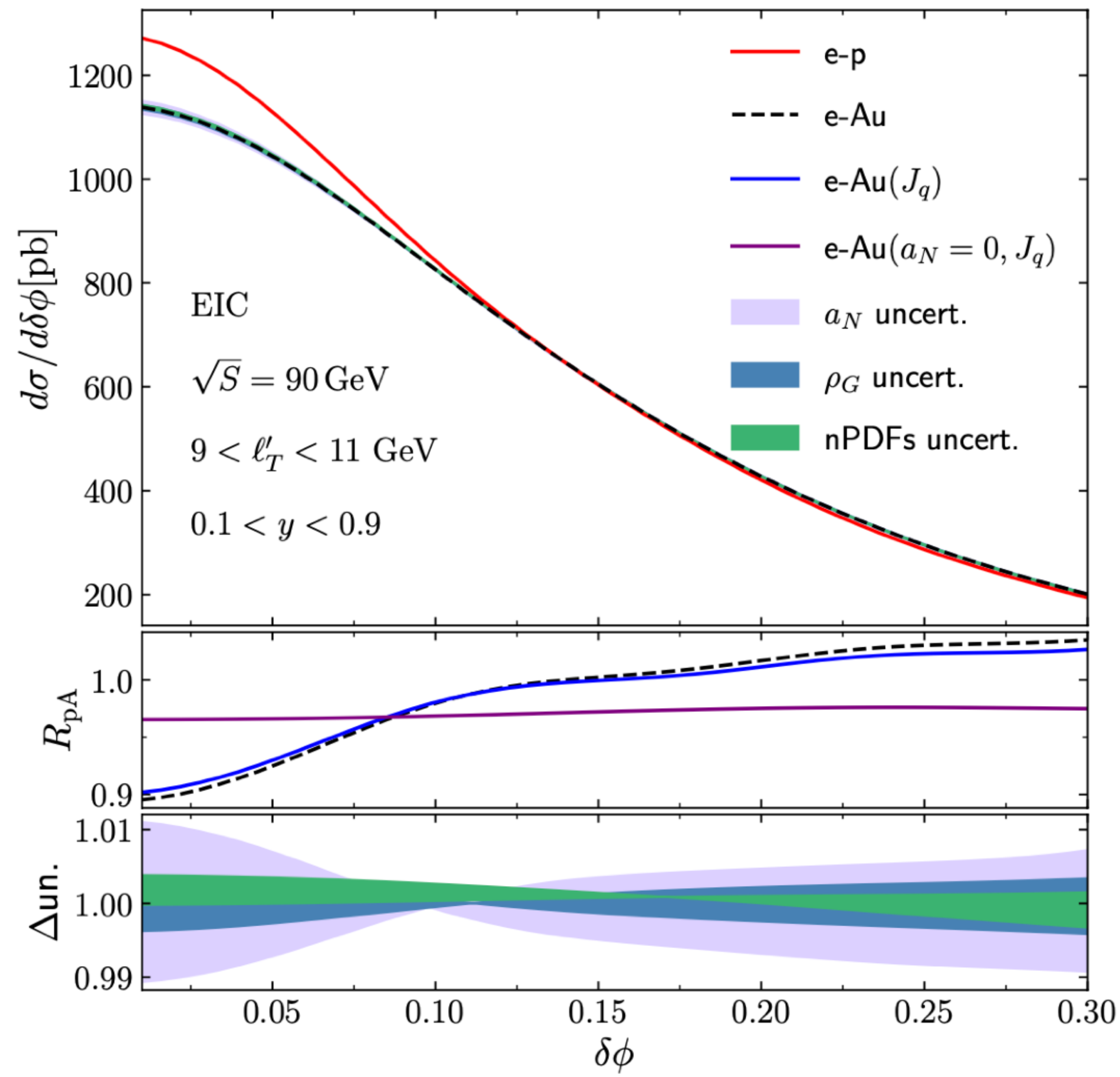
(Gyulassy, Levai, & Vitev '02)

ρ_G : density of the medium

ξ : the screening mass

L: the length of the medium

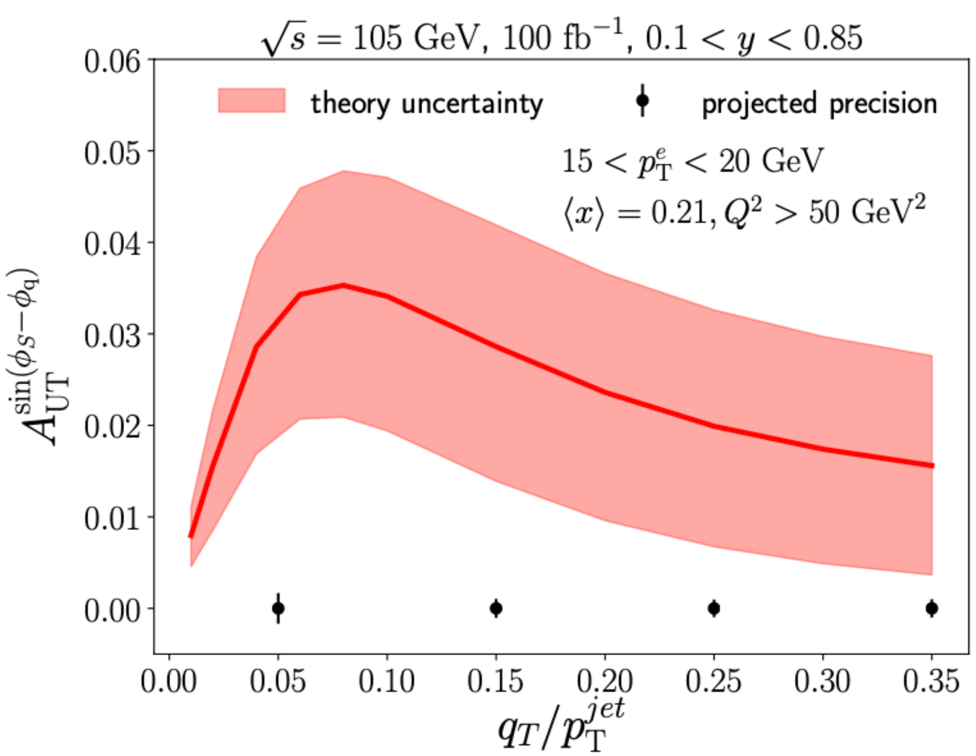
Parameter values are taken from a recent comparison between SCET$_G$ in e-A from the HERMES Ke and Vitev '23



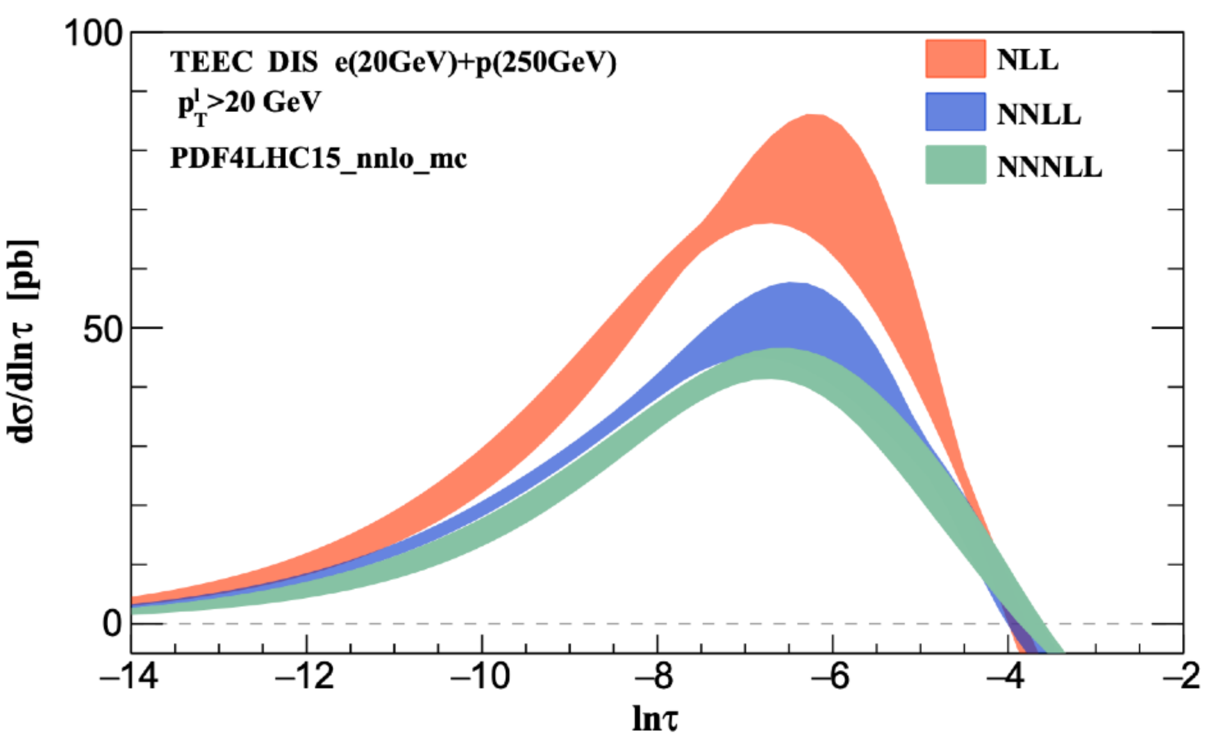
The process is primarily sensitive to the initial state's broadening effects, thereby serving as a clean probe of nTMD PDF

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



Li, Vitev, & Zhu '20, Li, Makris, Vitev '21

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

Fang, Gao, Li, DYS 2408.XXXXX

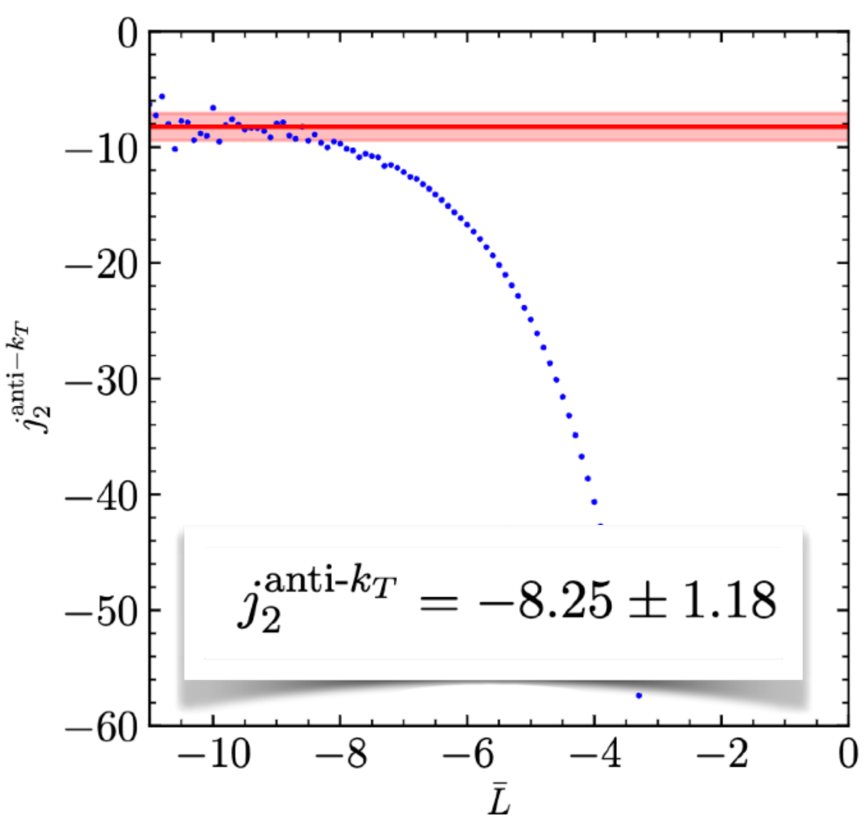
- **All ingredients are known at N³LL+ $\mathcal{O}(\alpha_s^2)$, except the two loop jet function j_2 .**
  - **It was extracted numerically from the Event2** (Gutierrez-Reyes, Scimemi, Waalewijn, Zoppi '19)
  - **A preliminary numerical results are also calculated from SoftSERVE** (Brune SCET2023)
- **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:

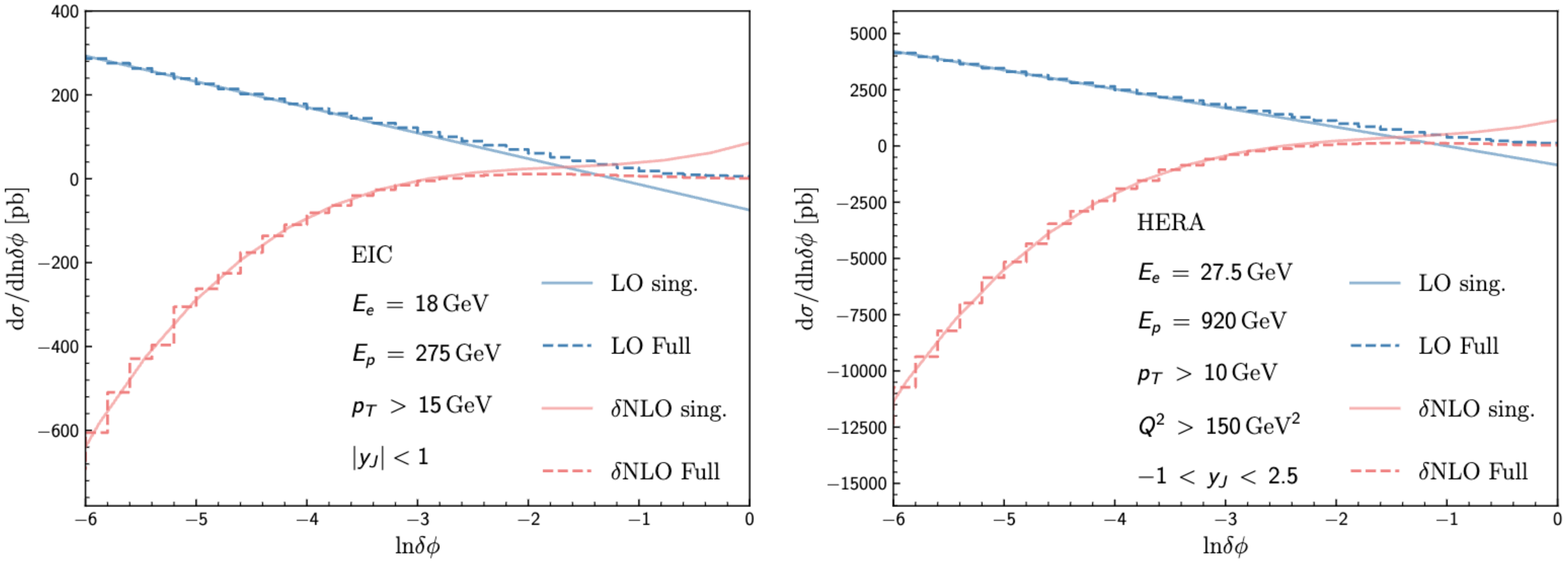
$$B = C_F^2 \left[\frac{\bar{L}^4}{2} + 3\bar{L}^3 + \bar{L}^2\left(\frac{11}{2} - \frac{\pi^2}{3} + 6\ln 2\right) + \bar{L}\left(\frac{9}{4} + 18\ln 2 - 4\,\zeta_3\right) - \frac{189}{16} + 5\,\pi^2 - \frac{173\,\pi^4}{720} + 27\ln 2 - \frac{9}{2}\pi^2\ln 2 + 9\ln^2 2 - 3\,\zeta_3\right] + C_F C_A\left[\frac{11\bar{L}^3}{9}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



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

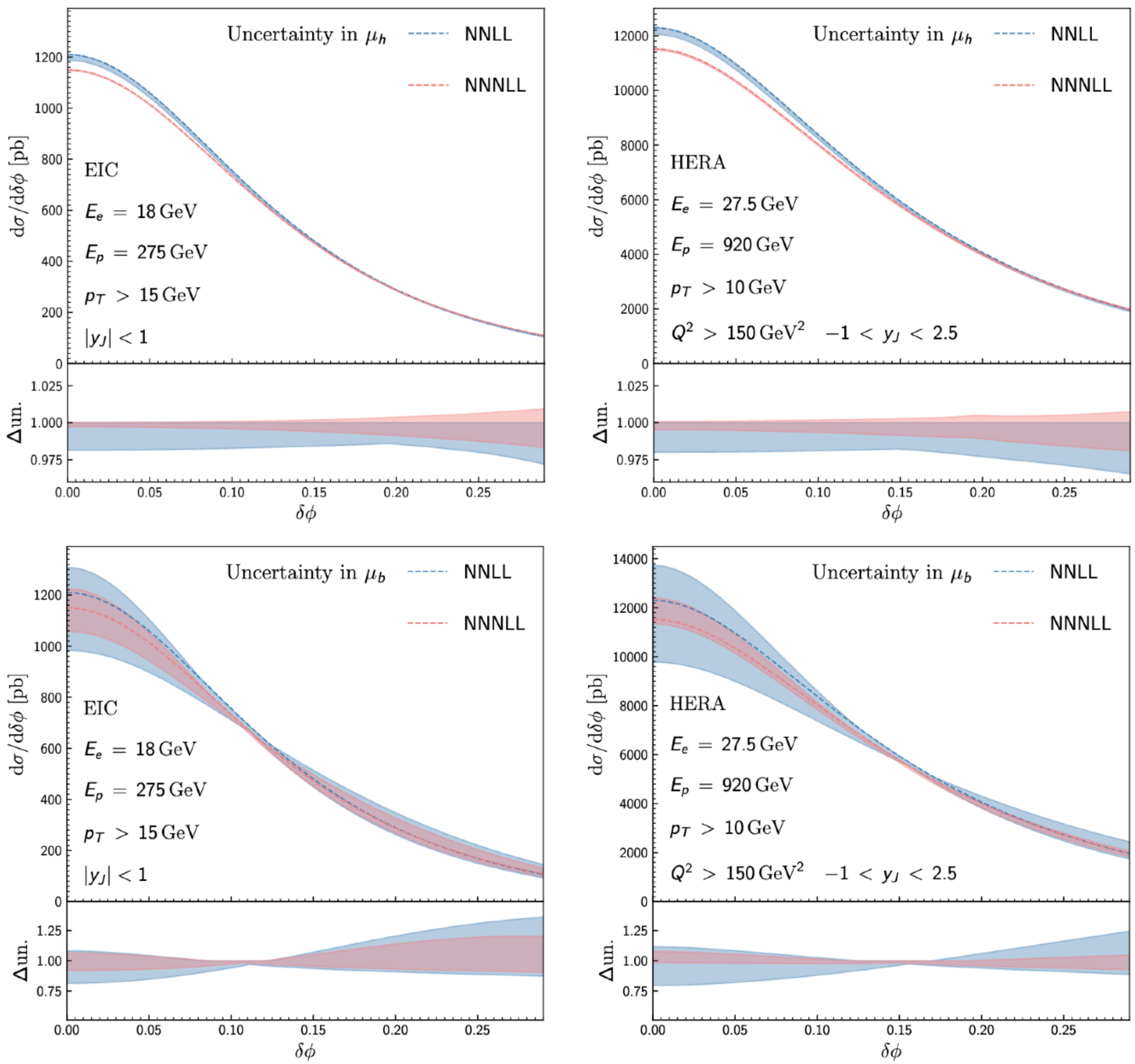
Fang, Gao, Li, DYS 2408.XXXXX

- **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 2408.XXXXX



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

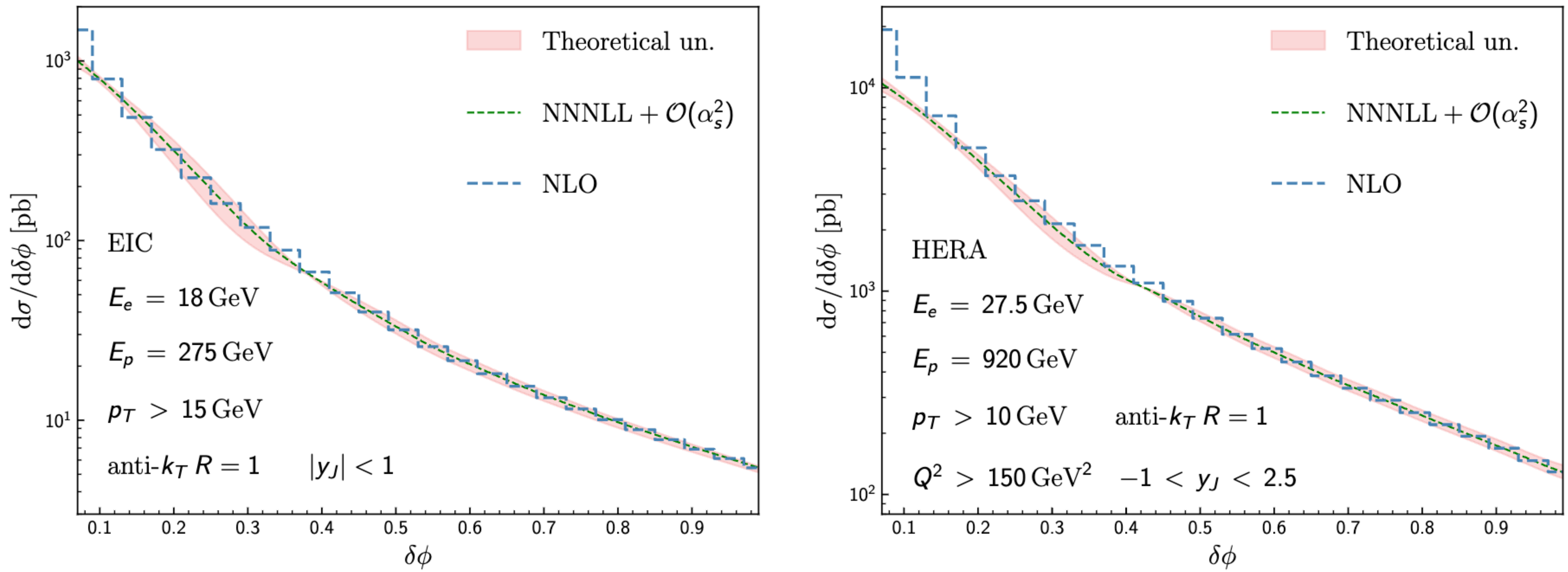
$N^3LL + \mathcal{O}(\alpha_s^2)$ predictions on lepton jet azimuthal correlation in DIS

Fang, Gao, Li, DYS 2408.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**

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

$$d\sigma(\text{NNNLL} + \mathcal{O}(\alpha_s^2)) = [1 - t(\delta\phi)]d\sigma_{\rm add}\,(\text{NNNLL} + \mathcal{O}(\alpha_s^2)) + t(\delta\phi)d\sigma(\text{NLO})$$

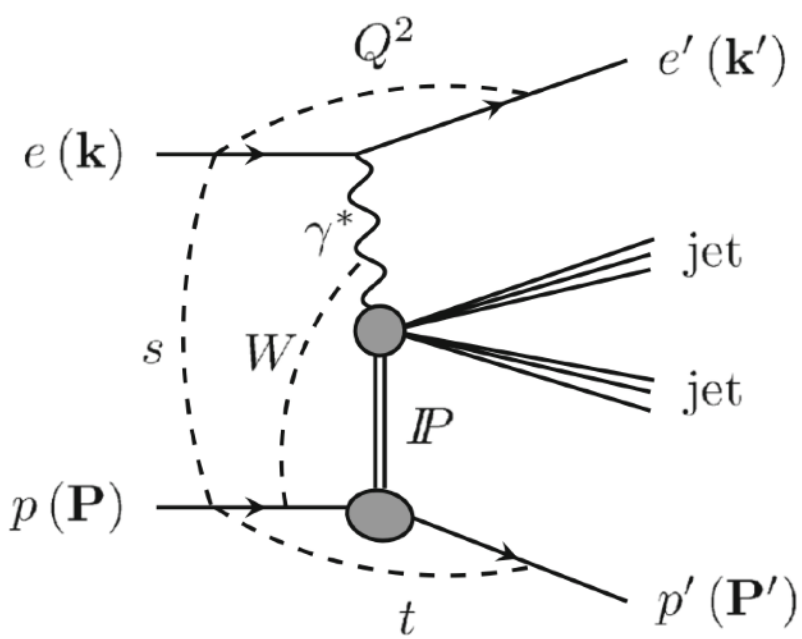


Azimuthal angular asymmetries in diffractive di-jet production

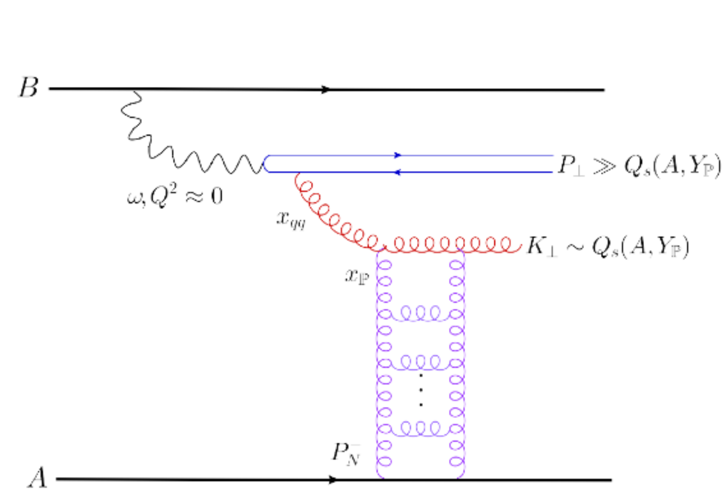
DYS, Y. Shi, C. Zhang, J, Zhou, Y. Zhou ’24 JHEP + ’24 in progress

Diffractive dijets photo-production

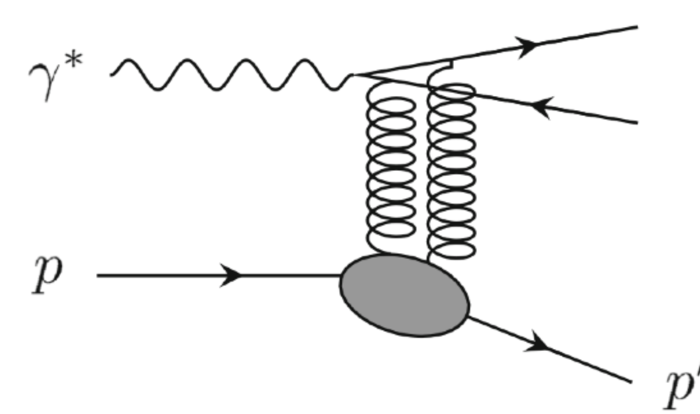
- **Diffractive di-jet production provide rich information on nucleon internal structure.**



diffractive production of (2+1) jets



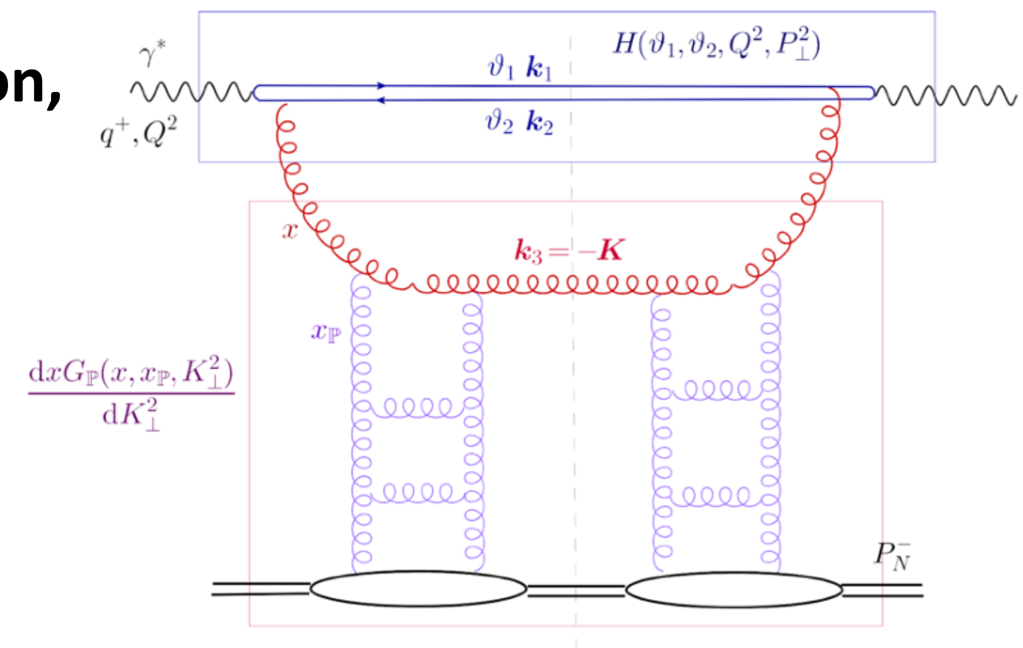
diffractive production of exclusive dijets



- **In cases of diffractive tri-jet production, where a semi-hard gluon is emitted towards the target direction and remains undetected, the experimental signature of this process becomes indistinguishable from that of exclusive di-jet production.**
- **Recent studies have shown that the cross section for coherent tri-jet photo-production significantly surpasses that of exclusive di-jet production** Iancu, Mueller & Triantafyllopoulos '21
- **The production of color octet hard quark-anti-quark dijets enables the emission of soft gluons from the initial state. This mechanism significantly influences the total transverse momentum $q_\perp$ distribution of the dijet.**

Diffractive dijets photo-production

- **The CGC calculation of diffractive di-jet photo-production, accompanied by a semi-hard gluon emission, has been studied in** Iancu, Mueller & Triantafyllopoulos ’21; Iancu, Mueller, Triantafyllopoulos, & S. Y. Wei ’23



$$\gamma(x_\gamma p) + A \rightarrow q(k_1) + \bar{q}(k_2) + g(l) + A$$

- **The Born cross section for semi-inclusive diffractive back-to-back dijet production is expressed as**

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}^2\boldsymbol{P}_\perp\mathrm{d}^2\boldsymbol{q}_\perp} = \sigma_0 x_\gamma f_\gamma(x_\gamma) \int \frac{\mathrm{d}x_{\mathbb{P}}}{x_{\mathbb{P}}} x_g G_{\mathbb{P}}(x_g, x_{\mathbb{P}}, q_\perp)$$

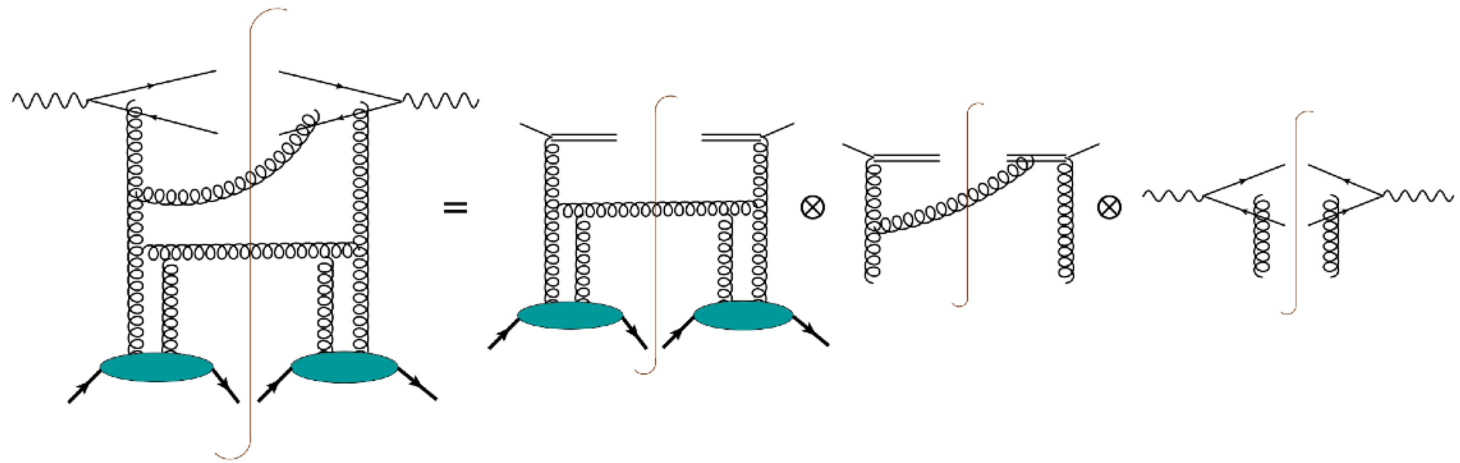
- **Within the CGC formalism, the gluon distribution of the pomeron is related to the gluon-gluon dipole scattering amplitude**

$$x_g G_{\mathbb{P}}(x_g, x_{\mathbb{P}}, q_\perp) = \frac{S_\perp(N_c^2-1)}{8\pi^4(1-x)} \left[\frac{xq_\perp^2}{1-x} \int r_\perp \mathrm{d}r_\perp J_2(q_\perp r_\perp) K_2\left(\sqrt{\frac{xq_\perp^2 r_\perp^2}{1-x}}\right) \mathcal{T}_g(x_{\mathbb{P}}, r_\perp) \right]^2$$

dipole amplitude

Factorizaton and resummation

- **By treating the gluon DTMD as if it were an ordinary TMD, we assume that the standard TMD factorization framework can be used in the back-to-back region**
  Hatta, Xiao & Yuan '22



$$\frac{d\sigma}{dy_1\, dy_2\, d^2\boldsymbol{P}_\perp\, d^2\boldsymbol{q}_\perp} = \sigma_0 x_\gamma f_\gamma(x_\gamma) H_{\gamma^* g}(P_\perp, R, \mu) \int d^2\boldsymbol{k}_\perp d^2\boldsymbol{\lambda}_\perp \delta^{(2)}(\boldsymbol{q}_\perp - \boldsymbol{k}_\perp - \boldsymbol{\lambda}_\perp)$$
$$\times S(\boldsymbol{\lambda}_\perp, R, \mu) \int \frac{dx_{\mathbb{P}}}{x_{\mathbb{P}}} x_g G_{\mathbb{P}}^{\text{unsub}}(x_g, x_{\mathbb{P}}, k_\perp, \mu).$$

- **We refactorize the gluon DTMD as the matching coefficients and the integrated pomeron gluon function**

DGLAP evolution of the pomeron gluon DPDF ?

Glauber SCET Rothstein, Stewart, `16

$$G_{\mathbb{P}}(x_g, x_{\mathbb{P}}, k_\perp, \mu, \zeta) = \int_{x_g}^1 \frac{dz}{z} I_{g\leftarrow g}(z, k_\perp, \mu, \zeta) G_{\mathbb{P}}(x_g/z, x_{\mathbb{P}}, \mu) + G_{\mathbb{P}}(x_g, x_{\mathbb{P}}, k_\perp)$$

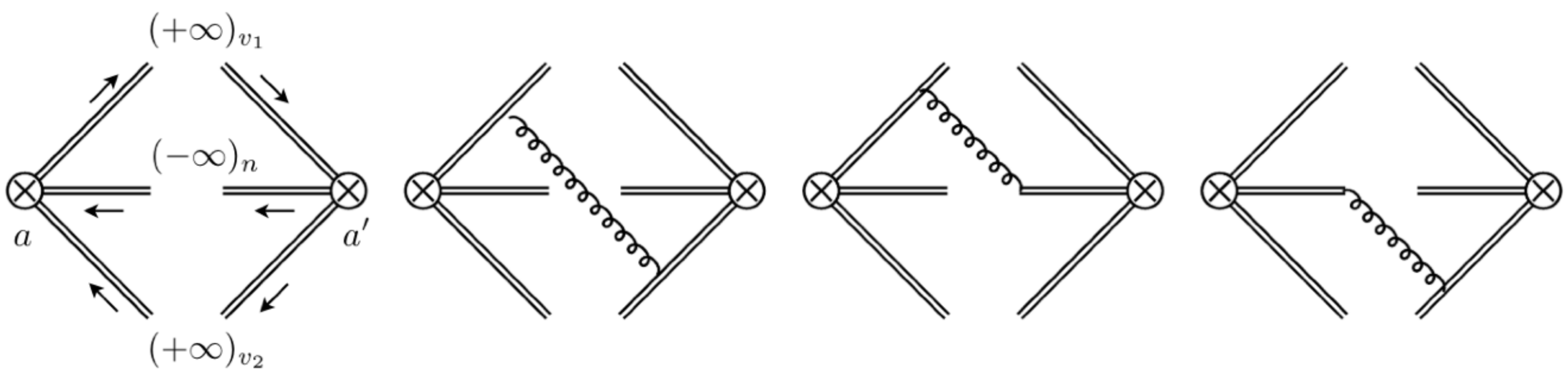
additional static source term in the modified DGLAP equation
Iancu, Mueller, Triantafyllopoulos, & Wei '23

Factorization and resummation

- **Resummation formula**

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y_1\,\mathrm{d}y_2\,\mathrm{d}^2\boldsymbol{P}_\perp\,\mathrm{d}^2\boldsymbol{q}_\perp} = \sigma_0 x_\gamma f_\gamma(x_\gamma)\int \frac{\mathrm{d}^2\boldsymbol{b}_\perp}{(2\pi)^2} e^{i\boldsymbol{q}_\perp\cdot\boldsymbol{b}_\perp} e^{-\mathrm{Sud}_{\mathrm{pert}}(b_\perp)}\tilde{S}^{\mathrm{rem}}(\boldsymbol{b}_\perp,\mu_b)$$
$$\times\int \mathrm{d}^2\boldsymbol{k}_\perp e^{-i\boldsymbol{b}_\perp\cdot\boldsymbol{k}_\perp}\int\frac{\mathrm{d}x_{\mathbb{P}}}{x_{\mathbb{P}}} x_g G_{\mathbb{P}}(x_g, x_{\mathbb{P}}, k_\perp),$$

- **NLO azimuthal angle-dependent soft function**

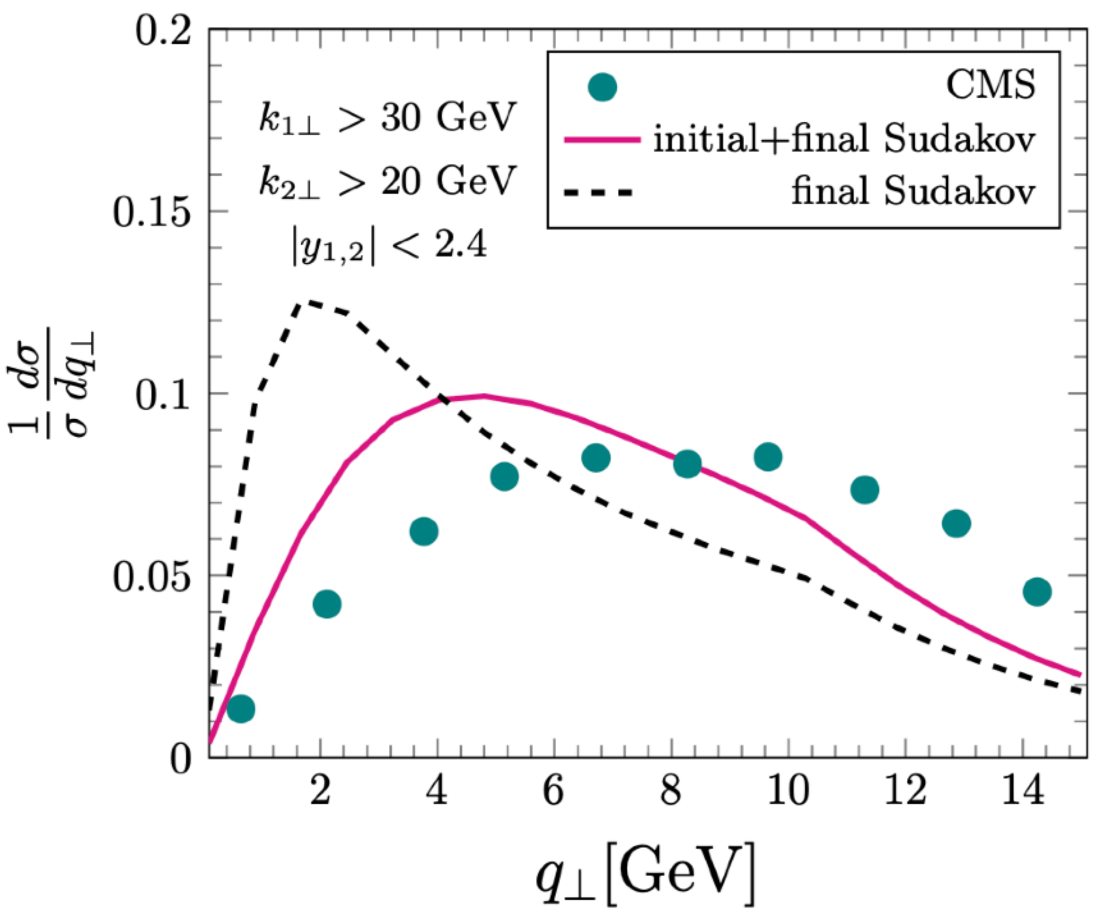


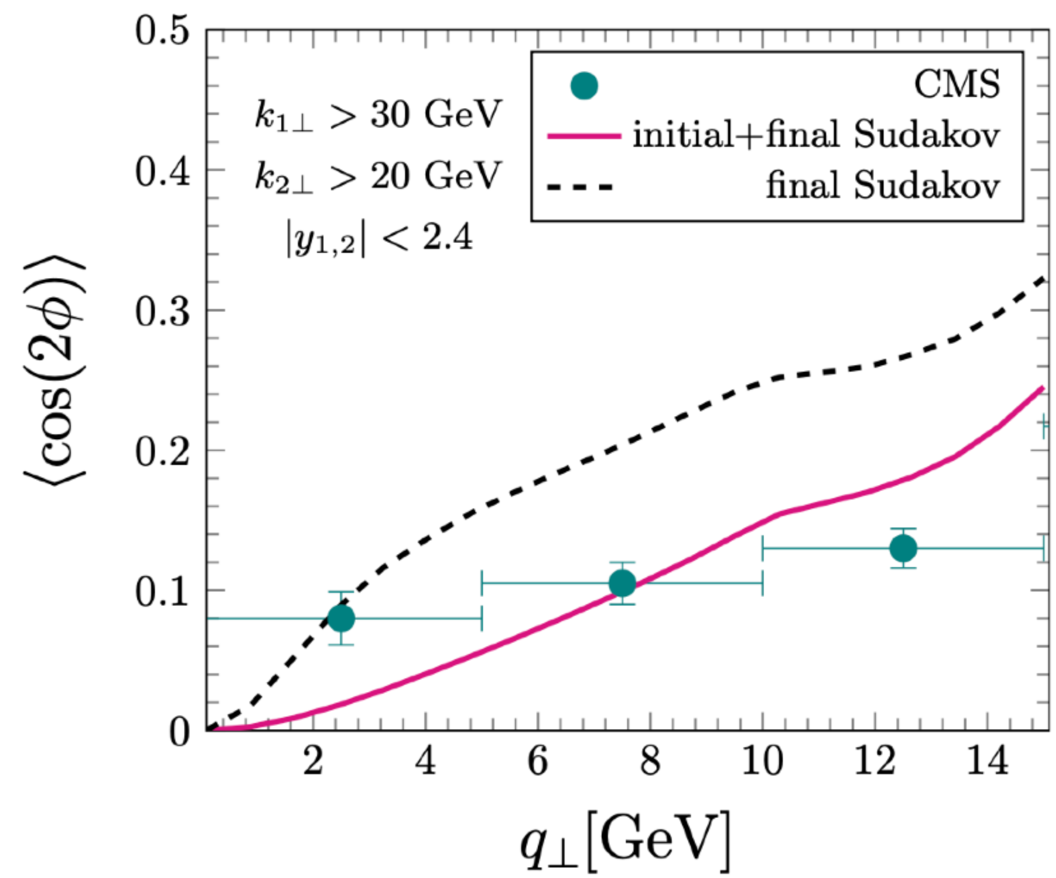
$$\tilde{S}^{\mathrm{NLO}}_{\phi_b-\mathrm{dep}}(\boldsymbol{b}_\perp, R, \mu_b) = \frac{\alpha_s(\mu_b)}{\pi}\Bigg\{C_F\left(-\ln\frac{4}{R^2}\ln c_\phi^2 - \frac{1}{2}\ln^2 c_\phi^2\right) + \frac{1}{2N_c}\Bigg[-\frac{1}{2}\ln^2 c_\phi^2 + \ln c_\phi^2\ln x$$
$$-\ln c_\phi^2 \ln\left(1-\frac{x}{c_\phi^2}\right) + \ln x \log\left(1-\frac{x}{c_\phi^2}\right) + \mathrm{Li}_2\left(\frac{x}{c_\phi^2}\right)\Bigg]\Bigg\}$$

$$\boxed{c_\phi = \cos\phi_b}$$

Numerical results and measurements in UPCs

DYS, Y. Shi, C. Zhang, J, Zhou, Y. Zhou '24 JHEP





- **Incorporating the initial state gluon radiation offers a more accurate representation of the CMS data**
- **Difference remains.**

$$\langle\cos(2\phi)\rangle \equiv \frac{\int d\mathcal{P}.\mathcal{S}.\cos(2\phi)\frac{d\sigma}{dy_1 dy_2 d^2\boldsymbol{P}_\perp d^2\boldsymbol{q}_\perp}}{\int d\mathcal{P}.\mathcal{S}.\frac{d\sigma}{dy_1 dy_2 d^2\boldsymbol{P}_\perp d^2\boldsymbol{q}_\perp}}$$

The azimuthal asymmetry: Our result underestimates the asymmetry at low $q_\perp$ and overshoots it at high

Summary

- **We have studied 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.**
- **We study azimuthal angular asymmetry in diffractive di-jet production. The production of color octet dijets expands the color space, enabling the emission of soft gluons in the initial state.**
- **This mechanism significantly influences the total transverse momentum distribution.**
- **Our new results quantitatively capture the overall trends in the $q_\perp$ distribution and the asymmetry observed by the CMS Collaboration, a sizable discrepancy between the experimental data and theoretical calculations remains.**

Thank you