Precision Predictions for Three-Dimensional Nucleon Tomography

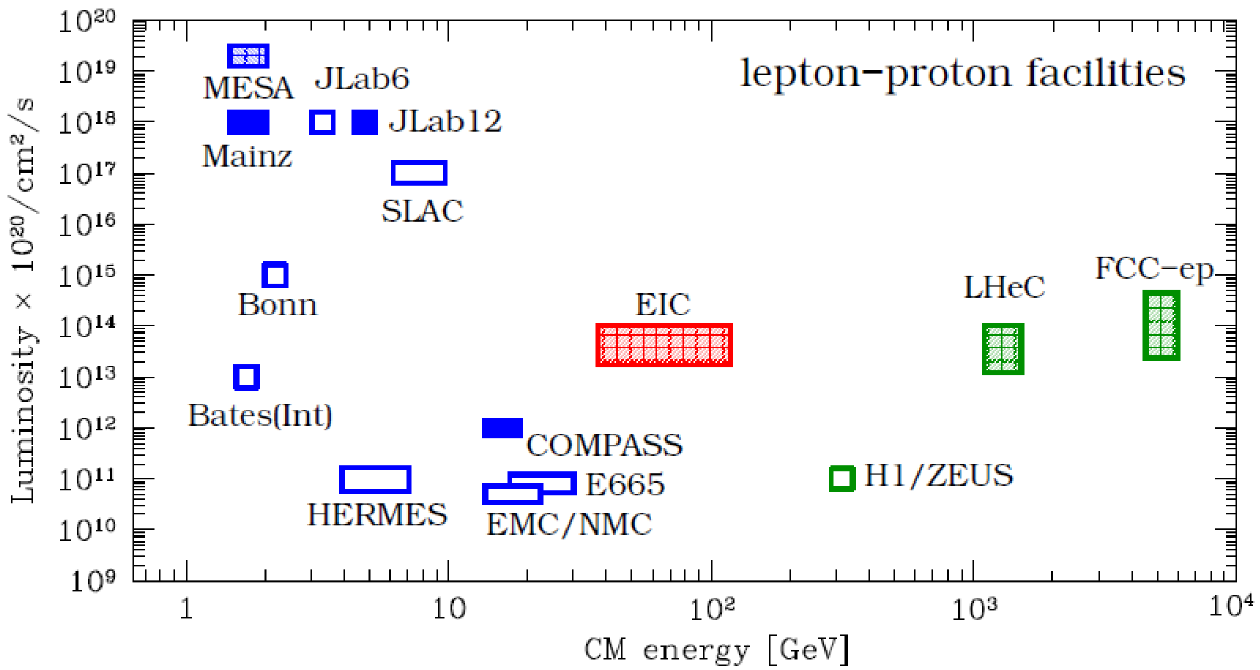
Shen Fang (方申)
Fudan University

The 26th international symposium on spin physics (SPIN2025)
Qingdao Sep 23, 2025

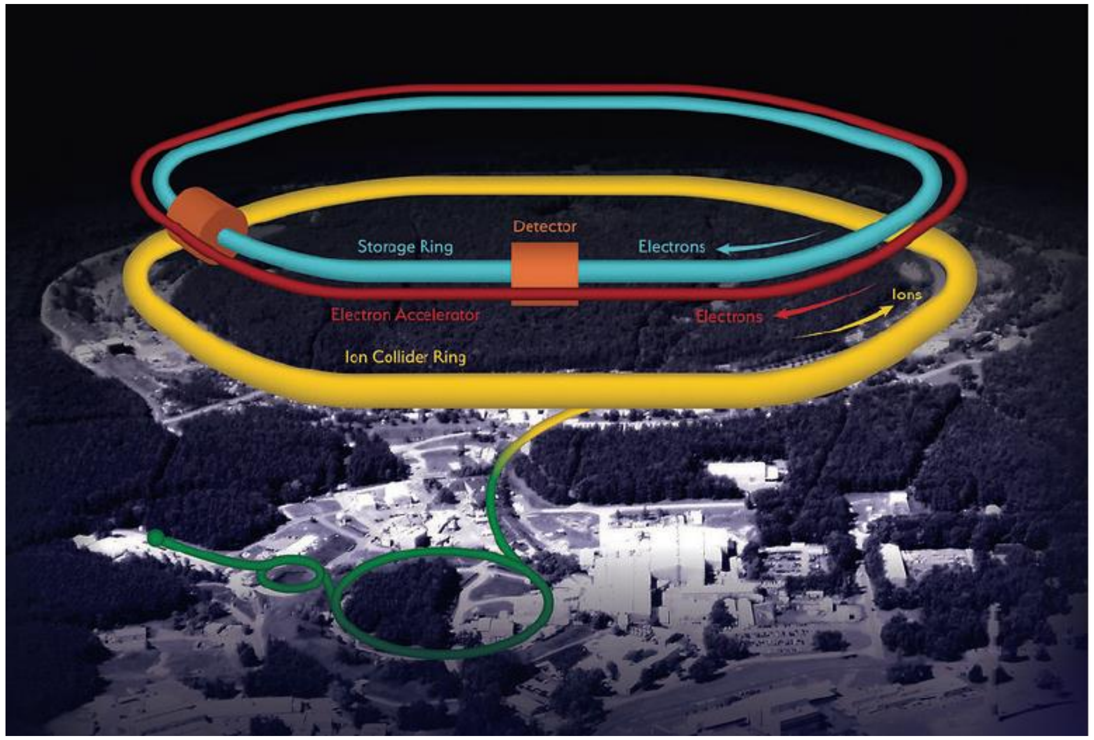
Collaborators: Dingyu Shao, Weiyao Ke, John Terry, Meisen Gao, Haitao Li, Zhongbo Kang

Reference: JHEP05(2024)066, JHEP01(2025)029

Electron-ion collider (EIC)

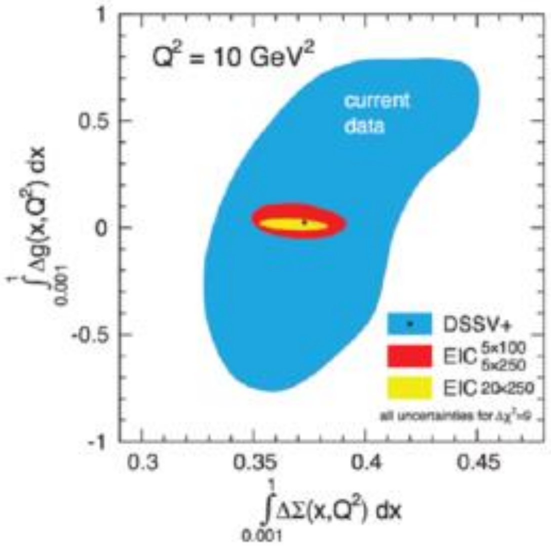


Abdul et al. '22

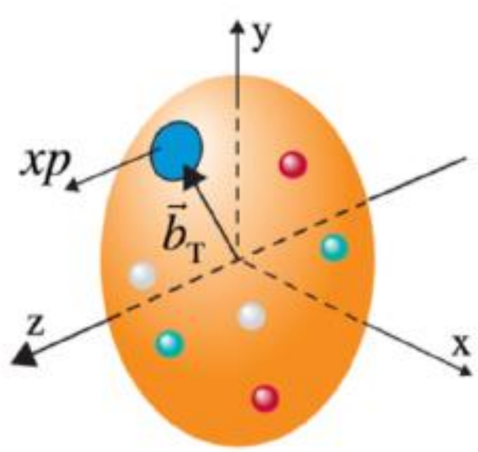


Abdul et al. '22

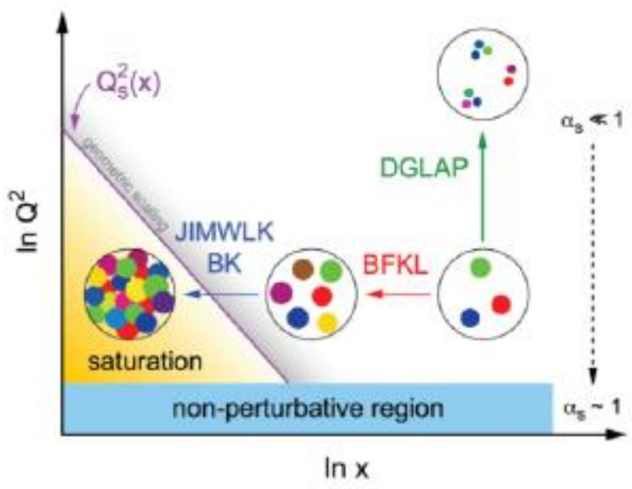
Proton spin



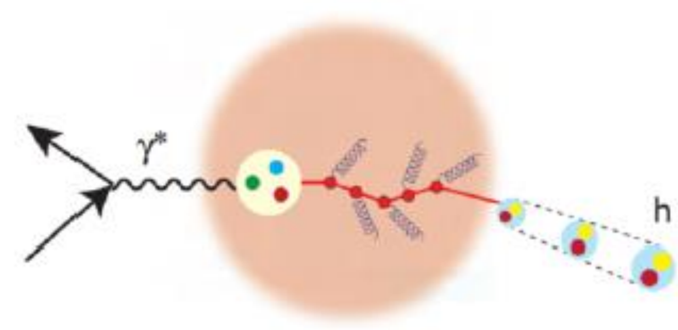
3D nucleon tomography



Gluon saturation



Hadronization in the nucleus

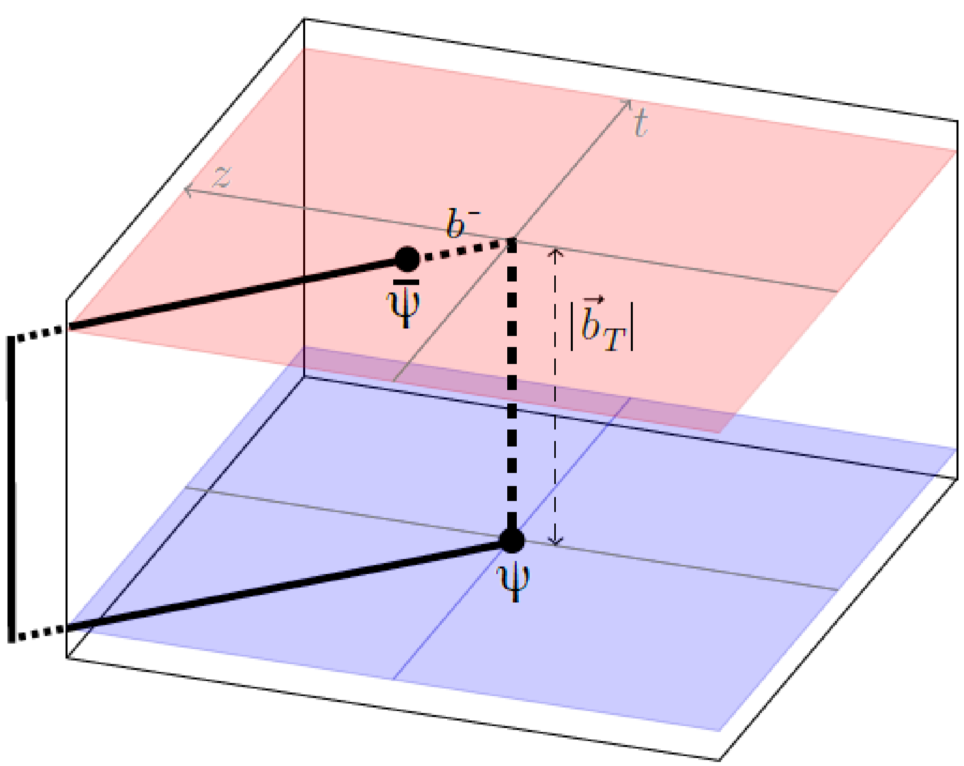


3D imaging of the nucleons

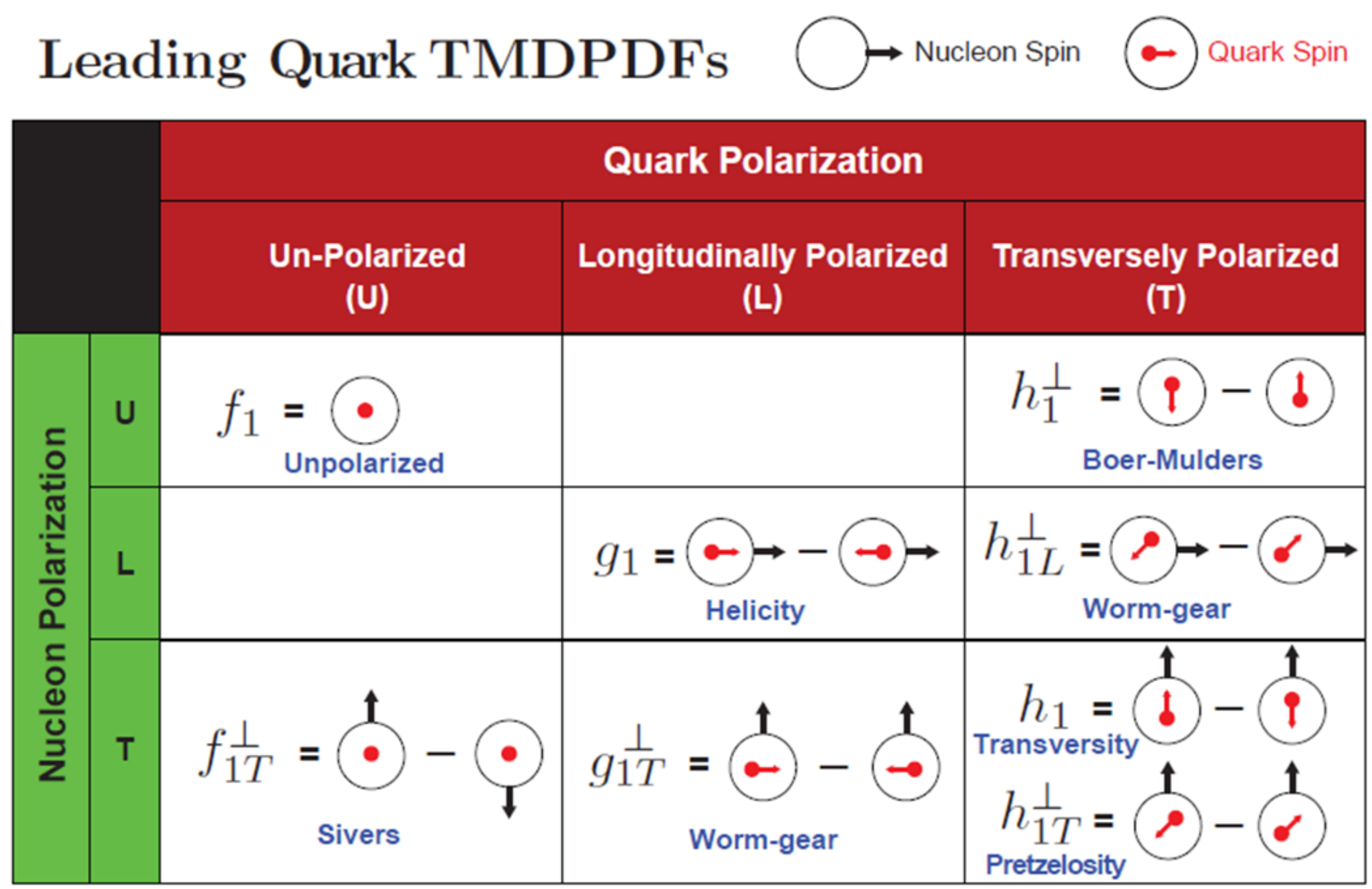
- **Both longitudinal and transverse motion**
- **Correlation between nucleon spin with parton(quark, gluon) orbital angular momentum**

$$\tilde{f}^{[\Gamma]0(\mathrm{u})}_{i/ps}(x,\mathbf{b}_T,\epsilon,\tau,xP^+) = \int \frac{\mathrm{d}b^-}{2\pi} e^{-ib^-(xP^+)} \Big\langle p(P,S) \Big| \Big[\bar{\psi}^i(b^\mu) W_{\sqsubset}(b^\mu,0) \frac{\Gamma}{2} \psi^i(0) \Big]_\tau \Big| p(P,S) \Big\rangle$$

- **Dirac structures** $\Gamma \in \{ \gamma^+ , \gamma^+\gamma_5 , i\sigma^{\alpha+}\gamma_5 \}$



Boussarie et al. ’23

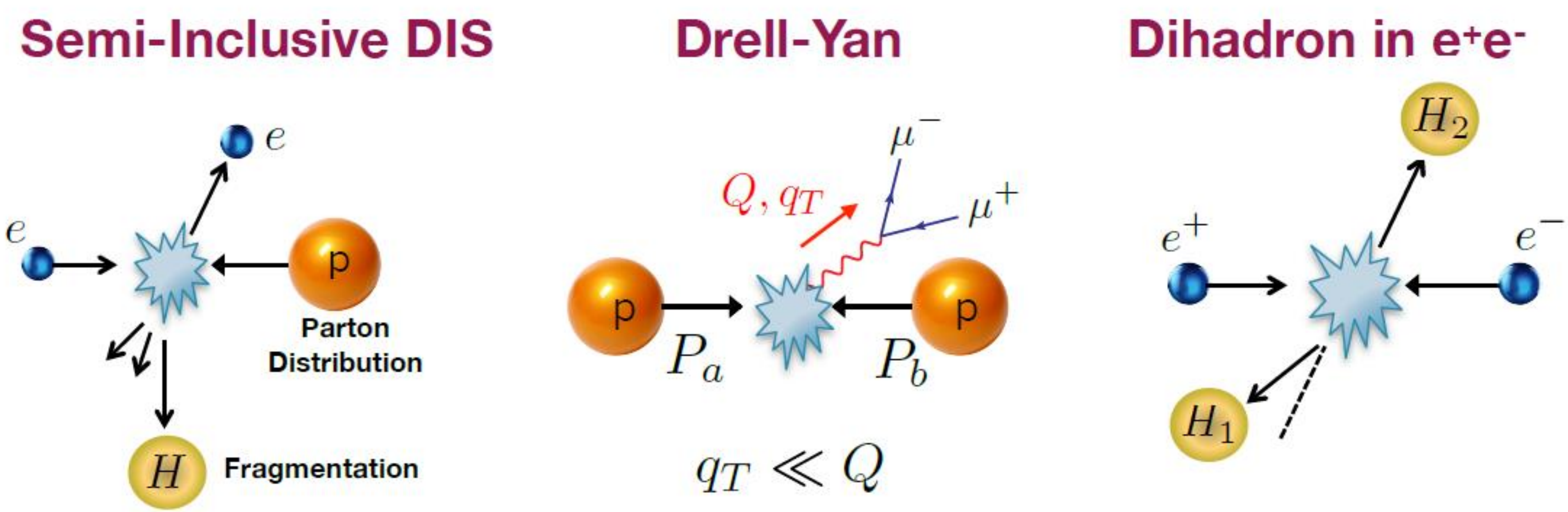


Nucleon Polarization	Quark Polarization: Un-Polarized (U)	Longitudinally Polarized (L)	Transversely Polarized (T)
U	f_1 = Unpolarized		$h_1^\perp$ = Boer-Mulders
L		g_1 = Helicity	$h_{1L}^\perp$ = Worm-gear
T	$f_{1T}^\perp$ = Sivers	$g_{1T}^\perp$ = Worm-gear	h_1 = Transversity; $h_{1T}^\perp$ = Pretzelosity

Transverse momentum distributions of quarks

- **Three classical processes used to probe quark TMDs:**

Boussarie et al. ’23



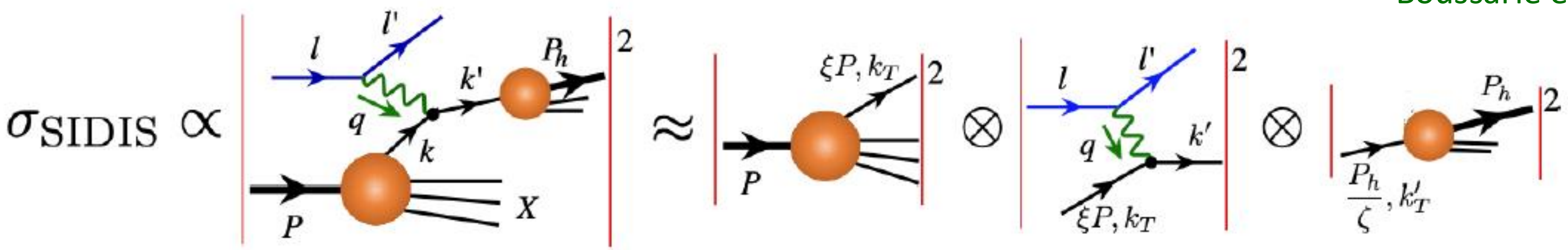
- **Typical multi-scale problems**
- **Theory tools: TMD factorization**

Collins, Soper & Sterman 1985
Florian & Grazzini ’01

Semi-inclusive deep inelastic scattering

Factorized SIDIS cross section in the parton model:

Boussarie et al. ’23

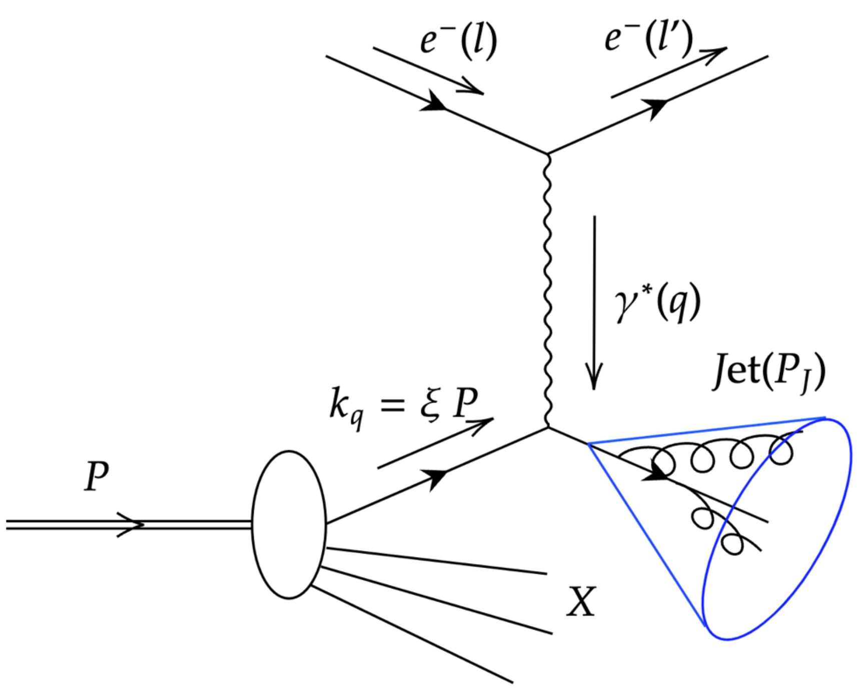


Jets

Liu, Ringer, Vogelsang & Yuan ’18

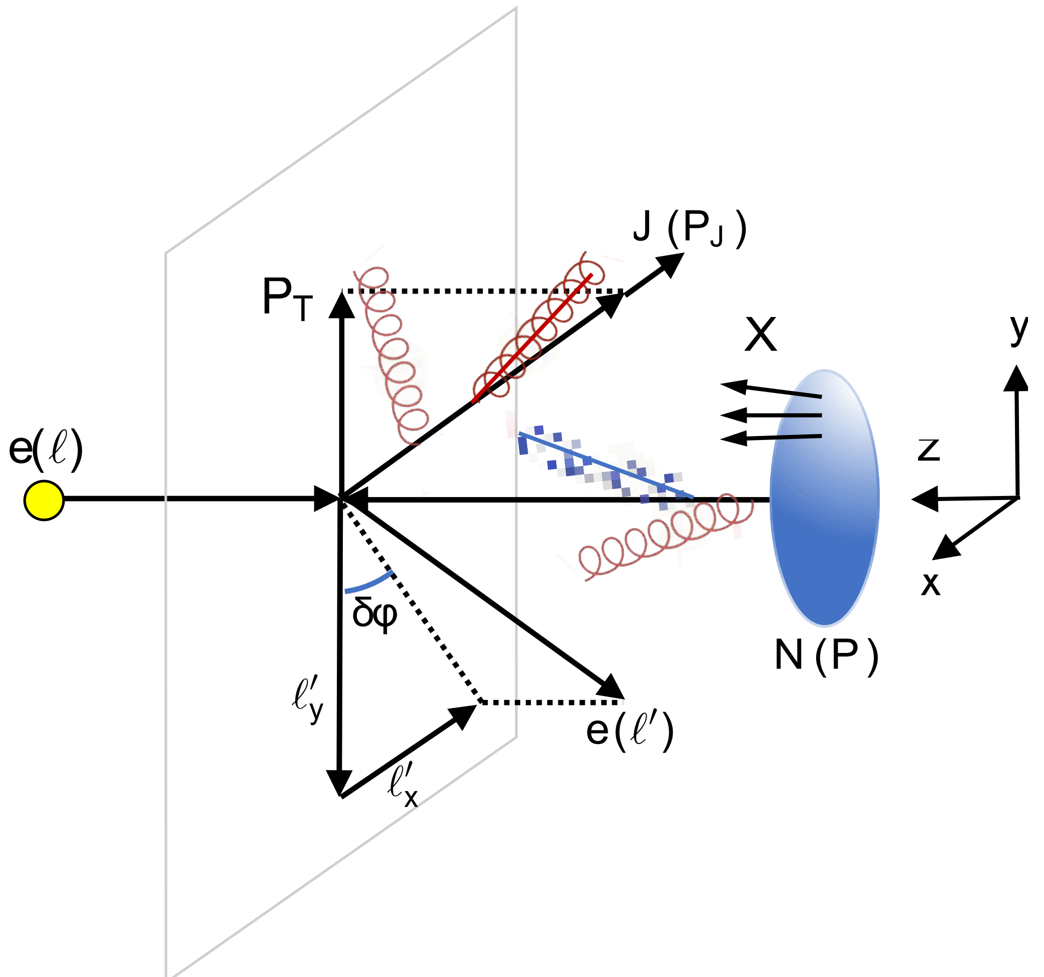
Winner-Take-All jets/ Recoil-free jets

Bertolini, Chan & Thaler ’14



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

QCD factorization



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

- **Factorization formula :**

$$\frac{d\sigma}{d^2\ell'_T\, dy\, dq_x} = \frac{\sigma_0}{1-y} H\,(Q,\mu)\,\mathcal{C}\,[B\,\mathcal{J}\,S]\ ,$$

$$\mathcal{C}\,[B\,\mathcal{J}\,S] = \sum_q e_q^2 \int \frac{db}{2\pi} \cos(b\, q_x) B_{q/N}\,(x_B, b, \mu, \zeta_B/\nu^2)$$

$$\mathcal{J}_q\,(b, \mu, \zeta_{\mathcal{J}}/\nu^2)\ S\,(b, n\cdot n_J, \mu, \nu)\ .$$

- **Observables:**

$$y = 1 - P\cdot\ell'/P\cdot l \qquad q_x = \ell'_T\delta\phi$$

- **EFT parameters:**

$$\delta\phi \ll 1$$

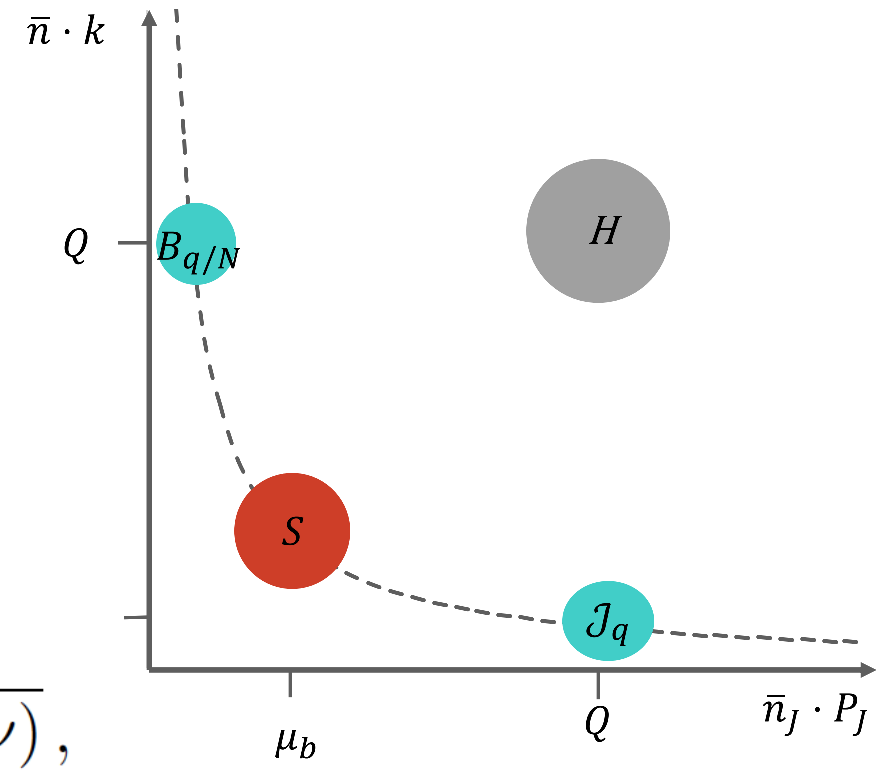
- **EFT modes :**

$$\begin{aligned}
\textbf{hard}:&\ \ p_h^\mu \sim \ell'_T(1,1,1),\\
n\textbf{-collinear}:&\ \ p_c^\mu \sim \ell'_T\,(\delta\phi^2, 1, \delta\phi),\\
\textbf{soft}:&\ \ p_s^\mu \sim \ell'_T\,(\delta\phi, \delta\phi, \delta\phi),\\
n_J\textbf{-collinear}:&\ \ p_J^\mu \sim \ell'_T\,(\delta\phi^2, 1, \delta\phi)_J\ ,
\end{aligned}$$

RG evolution

Hierarchy Problem:

$$\mu_b = \frac{2e^{-\gamma_E}}{b} \ll Q \qquad L = \ln\frac{Q^2}{\mu_b^2} \gg 1$$



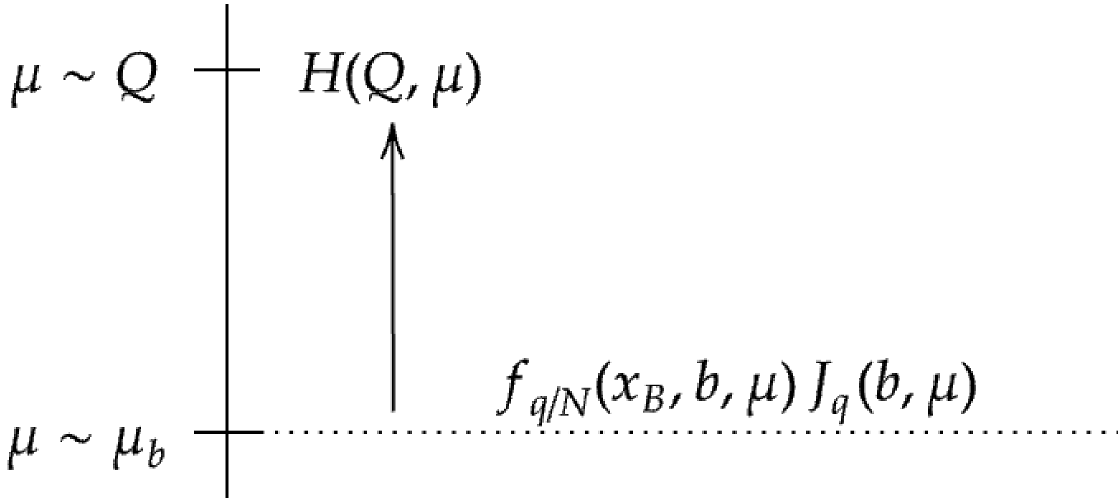
Standard CSS formalism: Collins '13

$$f_{q/N}(x_B, b, \mu, \zeta_f) = B_{q/N}(x_B, b, \mu, \zeta_B/\nu^2)\,\sqrt{S_{n\bar{n}}(b,\mu,\nu)}\,,$$

$$J_q(b,\mu,\zeta_J) = \mathcal{J}_q(b,\mu,\zeta_{\mathcal{J}}/\nu^2)\,\frac{S(b, n\cdot n_J, \mu, \nu)}{\sqrt{S_{n\bar{n}}(b,\mu,\nu)}}\,,$$

Scale independence:

$$\frac{\mathrm{d}}{\mathrm{d}\ \ln\mu}\ln\ \sigma_{\text{phsy}}(Q,\mu_b,\mu) = 0$$



Predictions in e-A

SF, Ke, Shao, Terry '23

non-perturbative model

$$U_{\rm NP}^f(x,b,A,Q_0,Q) = \exp\left[-g_1^A b^2 - \frac{g_2}{2}\ln\frac{Q}{Q_0}\ln\frac{b}{b_*}\right],$$

Sun, Isaacson, Yuan & Yuan '14

We apply modified nuclear 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 $\mathrm{SCET_G}$

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

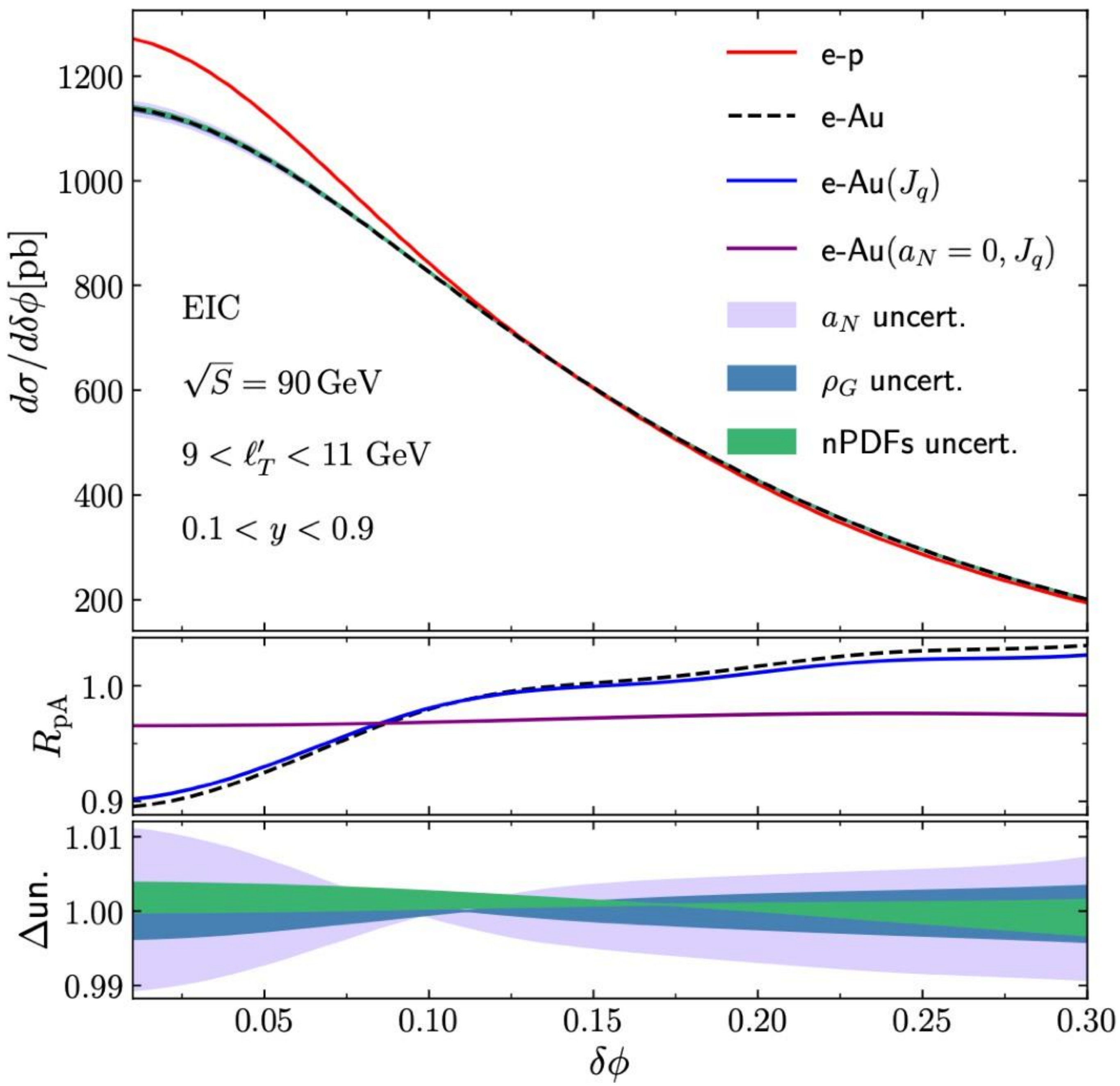
Opacity parameter $\chi = \frac{\rho_G L}{\xi^2}\alpha_s(\mu_{b_*})C_F$

Gyulassy, Levai & Vitev '02

ρ_G : density of the medium

ξ : the screening mass

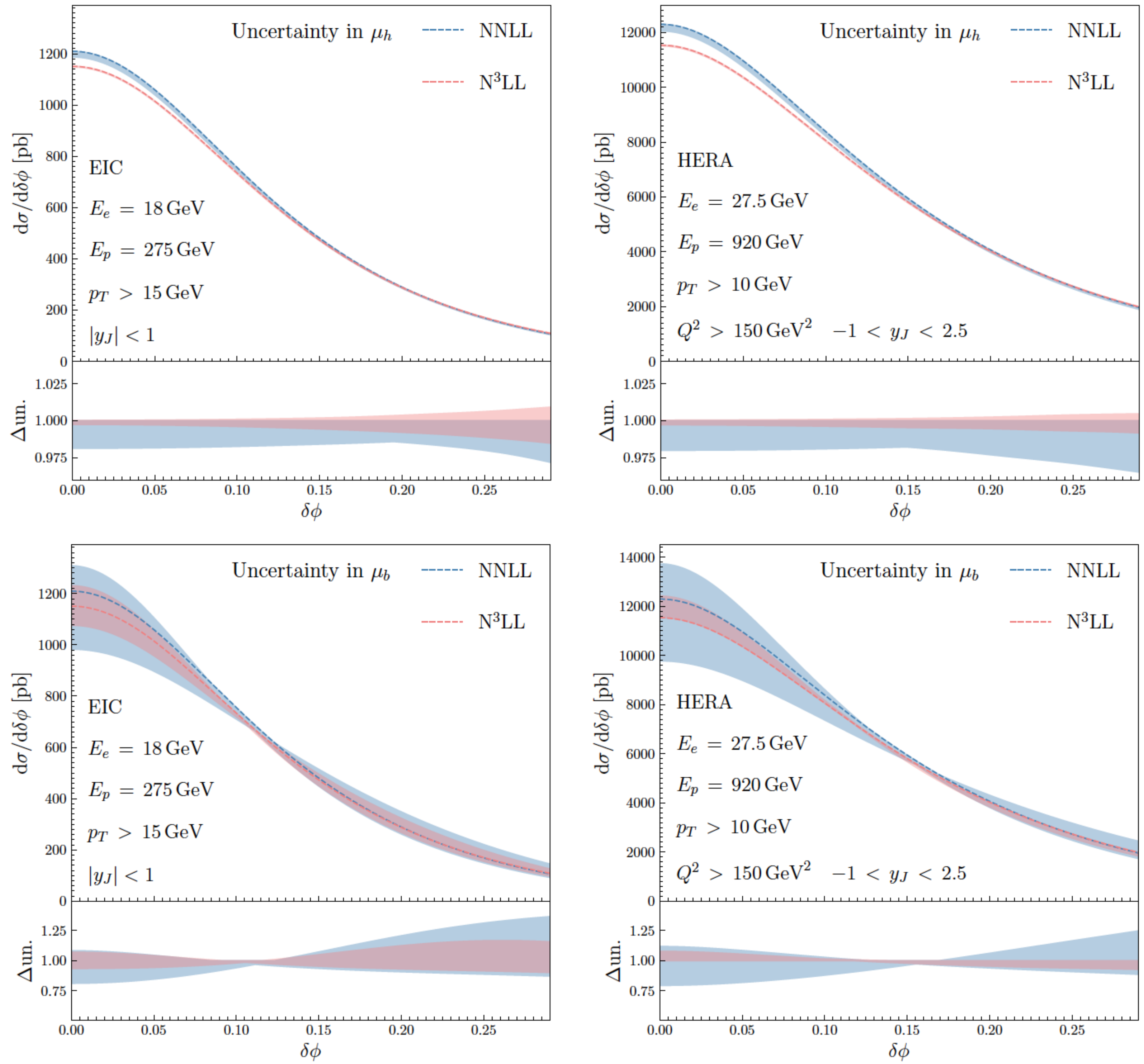
L: the length of the medium



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

Comparison of resummation results at NNLL and N^{3}LL

SF, Gao, Li, Shao 24'



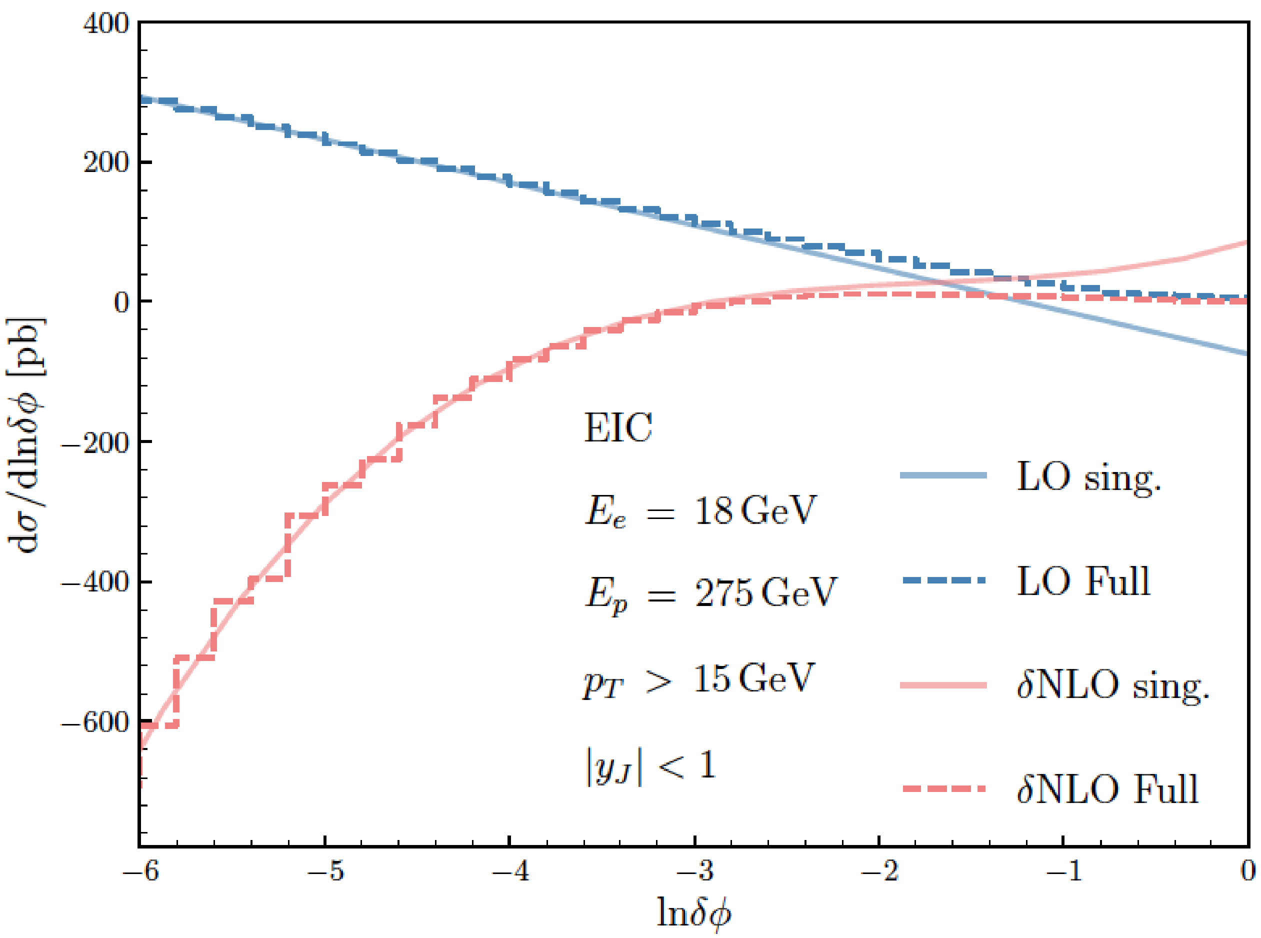
- **The uncertainty bands are narrower at N^{3}LL (red) compared to NNLL (blue)**
- **At N3LL the dominant scale uncertainties are from μ_b variation**

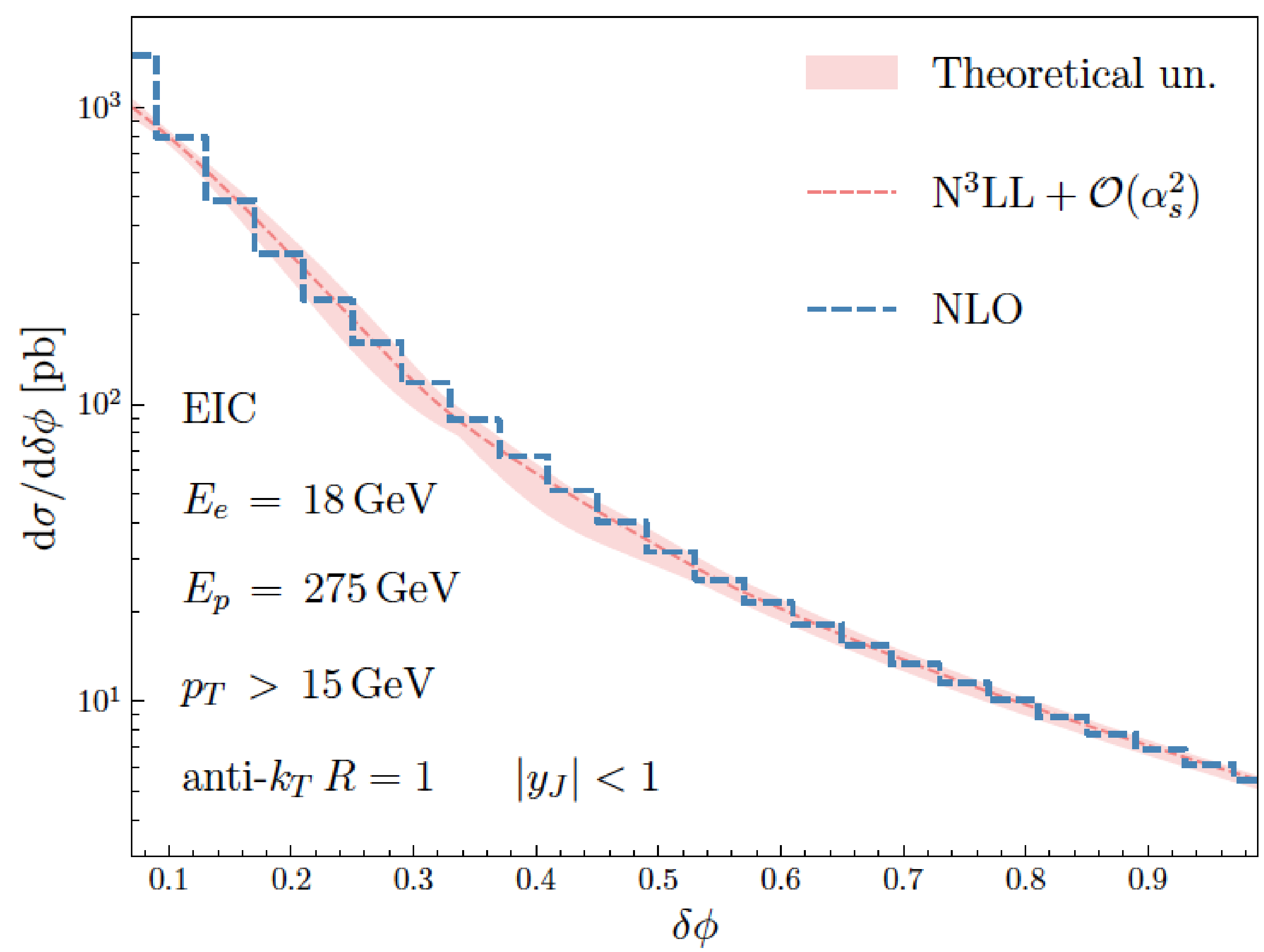
$\mathrm{N^3LL} + \mathcal{O}(\alpha_s^2)$ predictions on lepton-jet azimuthal correlation

SF, Gao, Li, Shao '24

- **In the back-to-back limit ($\delta\phi \to 0$) the singular contributions in DIS are consistent with the fixed-order results from NLOJET++ up to $\mathcal{O}(\alpha_s^2)$**
- **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**

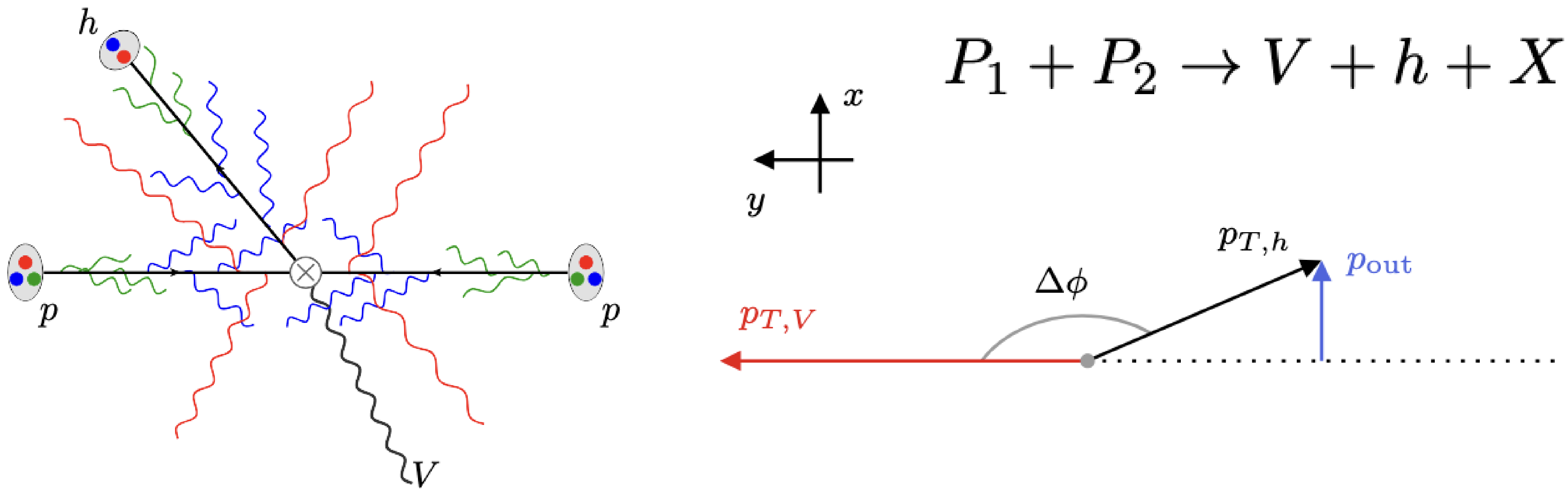
$$\mathrm{d}\sigma_{\mathrm{add}}\,(\mathrm{NNNLL} + \mathcal{O}(\alpha_s^2)) \equiv \mathrm{d}\sigma(\mathrm{NNNLL}) + \underbrace{\mathrm{d}\sigma(\mathrm{NLO}) - \mathrm{d}\sigma(\mathrm{NLO\ singular})}_{\mathrm{d}\sigma(\mathrm{NLO\ non\text{-}singular})}$$

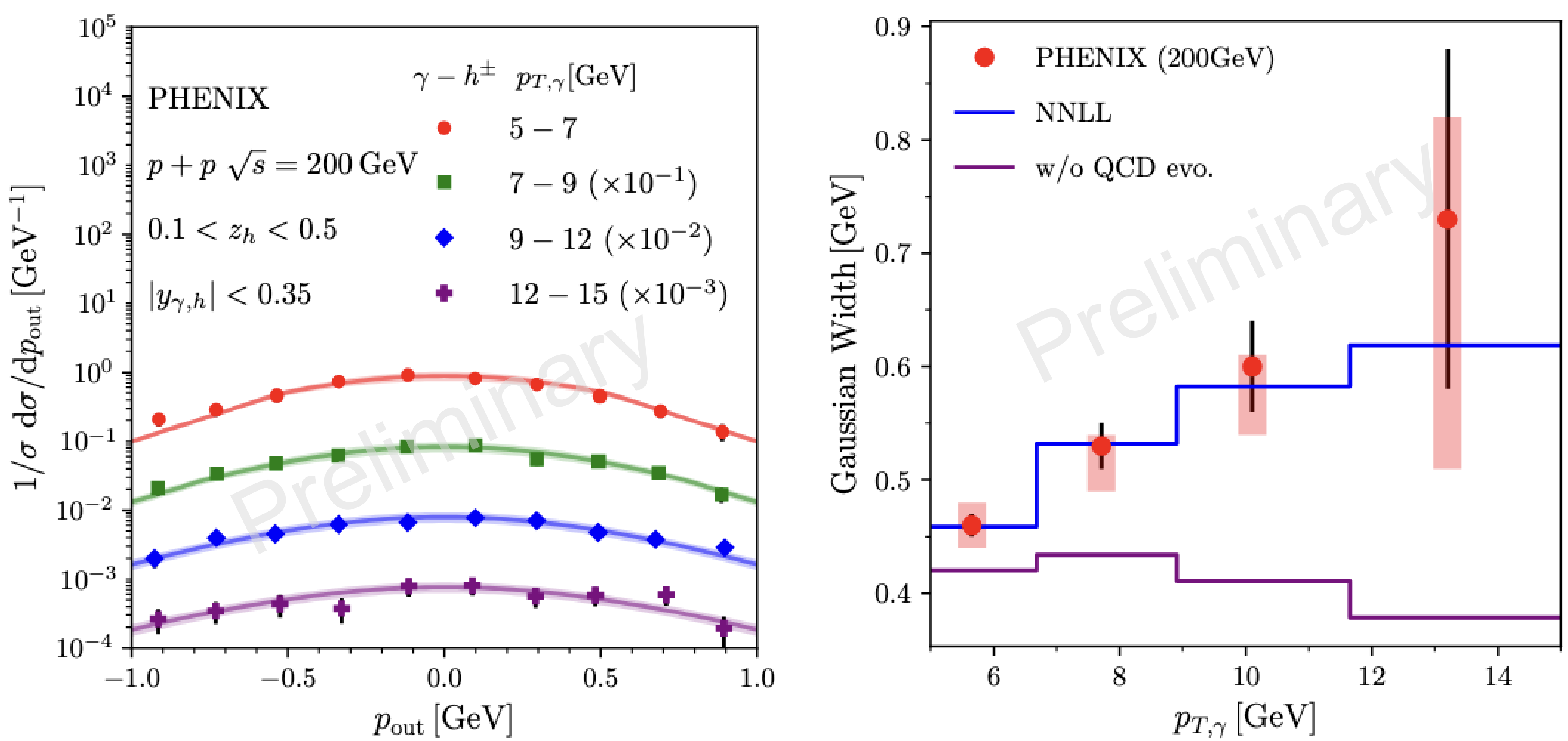




NNLL predictions on photon-hadron azimuthal correlation

SF, Gao, Kang, Shao 2510.XXXXX





- **The Gaussian widths (blue) are consistent with PHENIX results (red)**
- **Perturbative evolution also contributes to the Gaussian widths**

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 N^3LL + $\mathcal{O}(\alpha_s^2)$ accuracy in e-p collisions. It is good to have the measurement at the HERA to make a comparison.**
- **In pp collisions, we find perturbative QCD dynamics contribute substantially to the TMD broadening effects.**
- **Our work sets the groundwork for spin-independent TMD effects in e-A and p-p collisions, offering a robust framework for measuring nTMDs.**

Thank you