



NNLO QCD corrections to hadron production in DIS at finite transverse momentum

Shen Fang

Fudan University

QCD Evolution 2026

Madrid, Spain

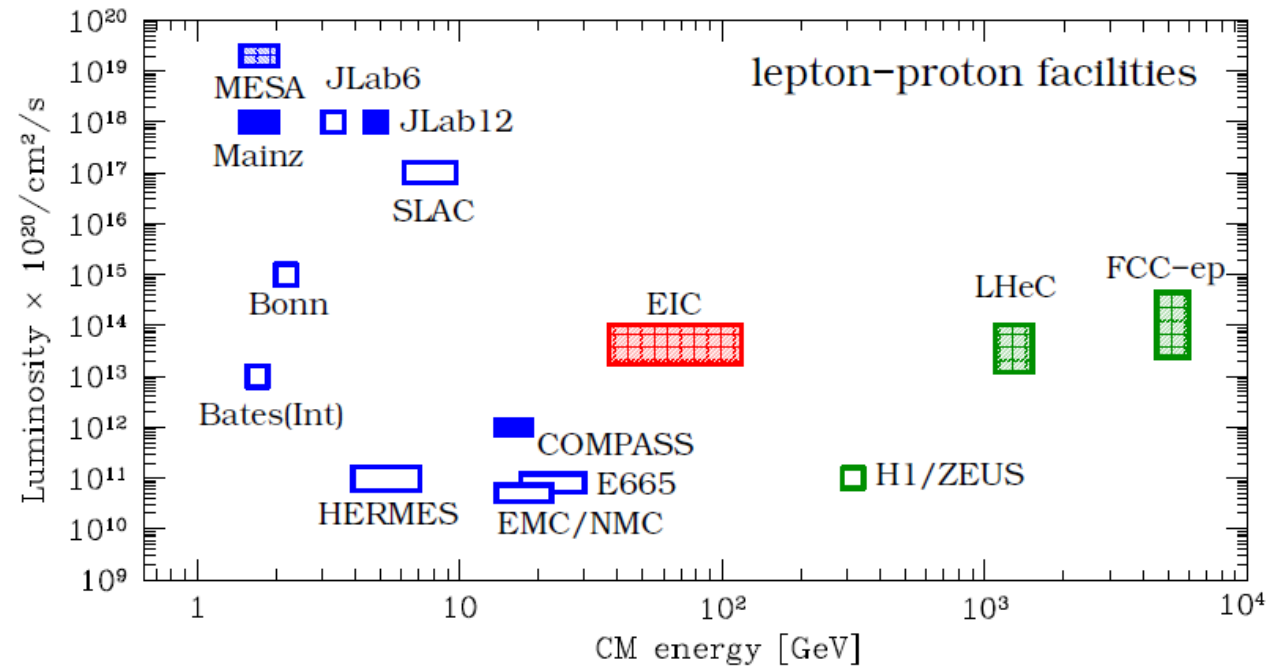
May 12, 2026

Collaborators: Liang Dong, Jun Gao, Hai Tao Li, Ding Yu Shao
& Yu Jiao Zhu

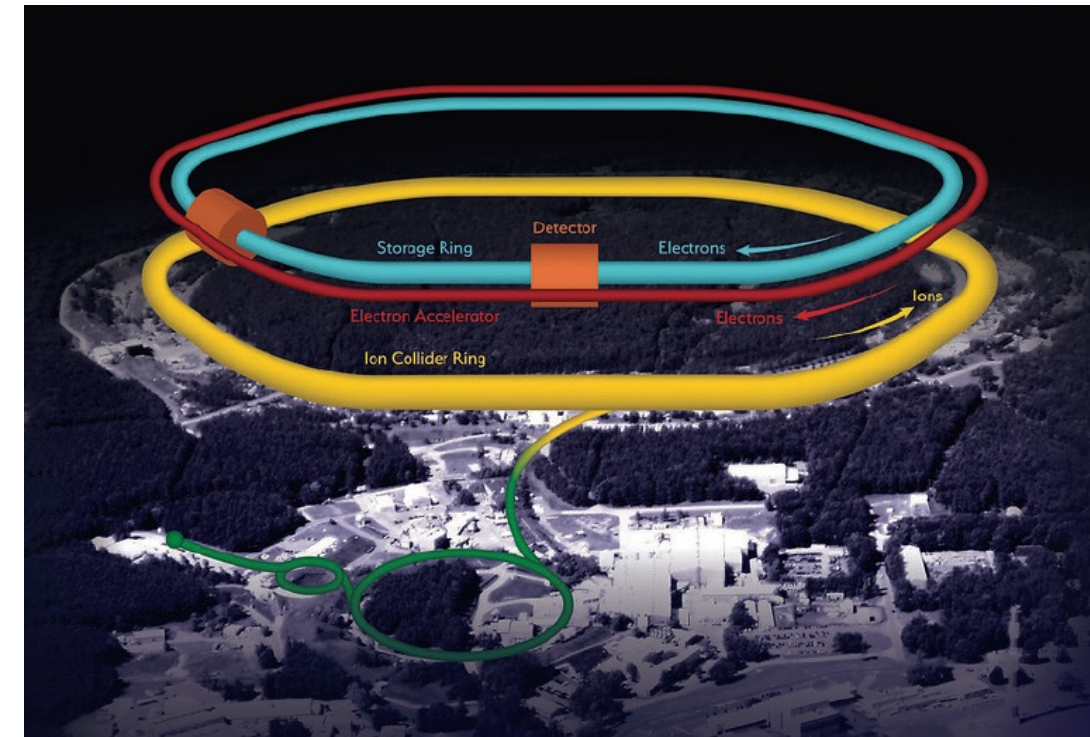
Reference: 2602.22972



Electron-ion collider (EIC)

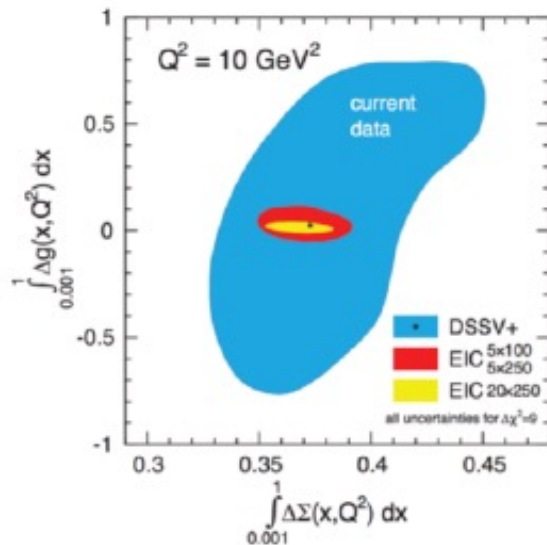


Abdul et al. '22

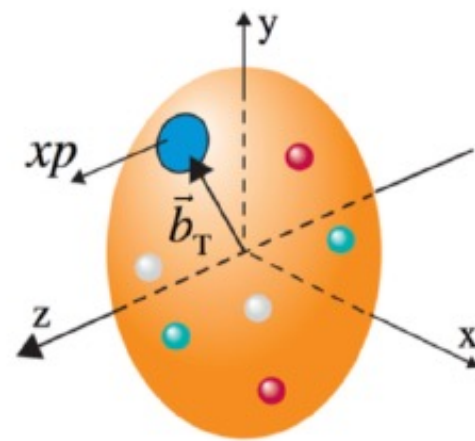


Abdul et al. '22

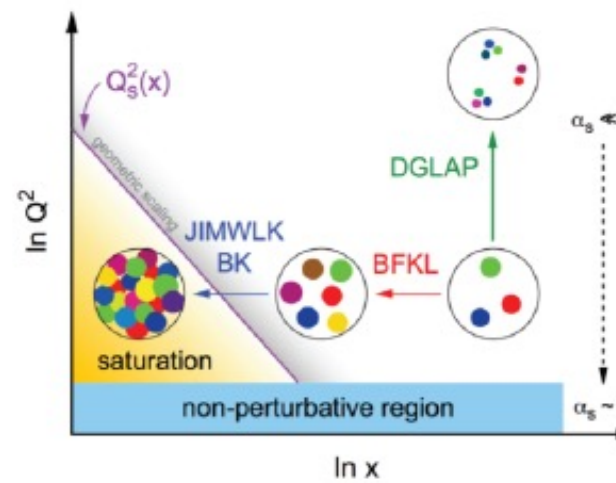
Proton spin



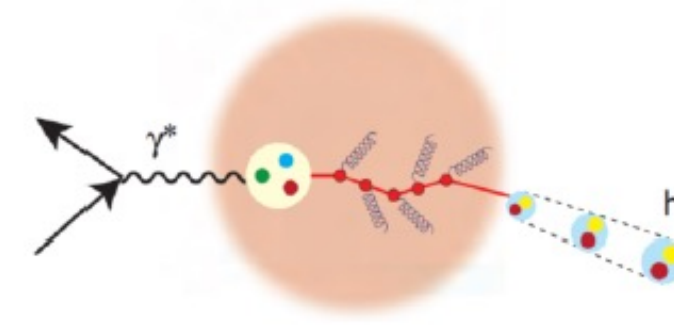
3D nucleon tomography



Gluon saturation

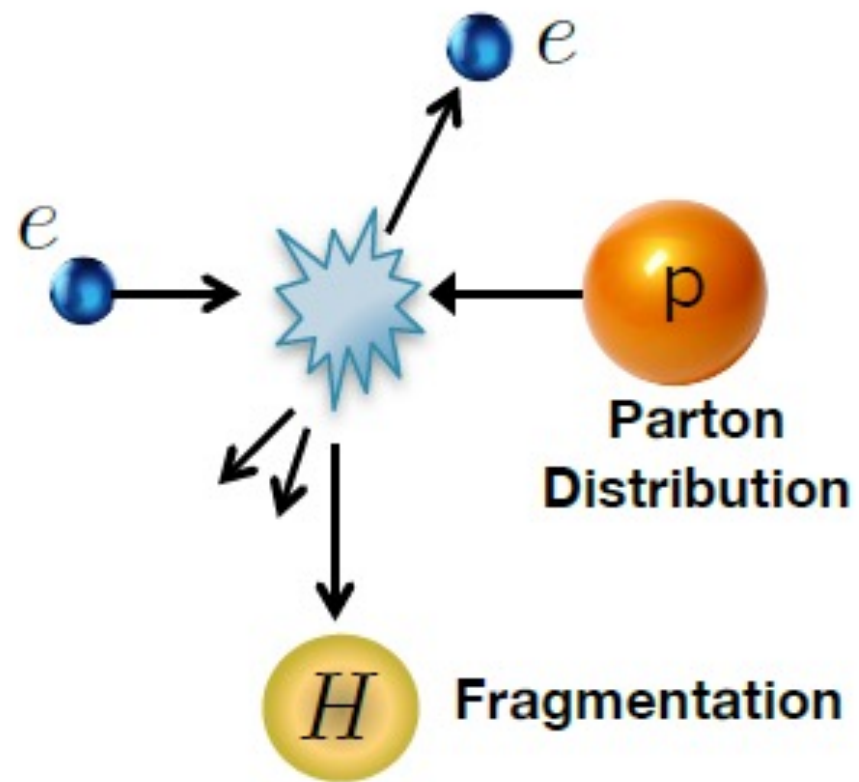


Hadronization in the nucleus

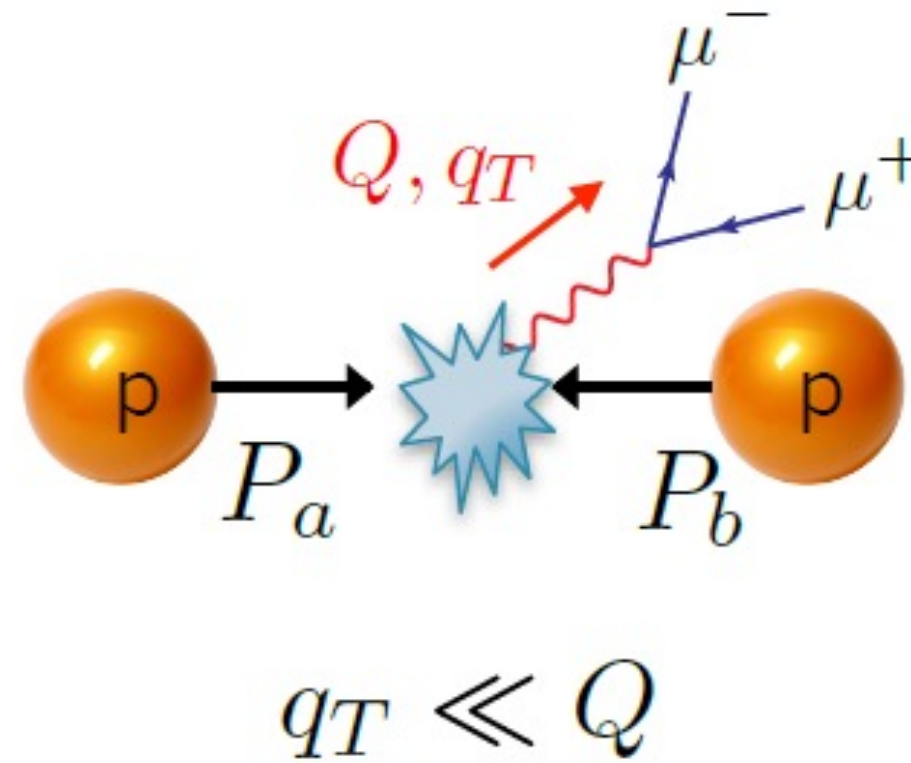


Nucleon tomography: a fundamental quest

Semi-Inclusive DIS



Drell-Yan

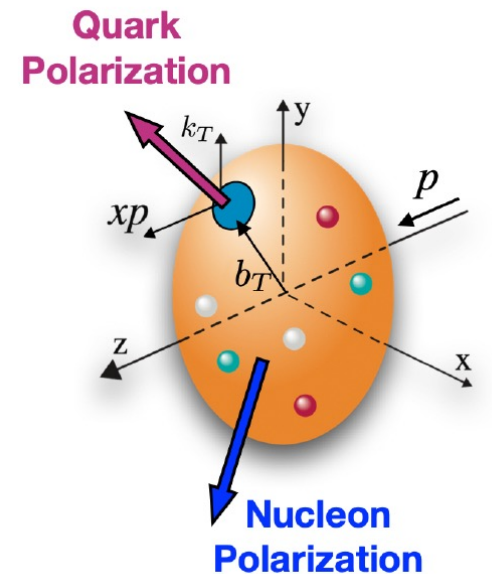


Proton structure: encoded in PDFs

$$\sigma = \sum_{a,b} \int_0^1 dx_1 dx_2 \hat{\sigma}_{ab}(Q, x_1, x_2, \mu_f) f_a(x_1, \mu_f) f_b(x_2, \mu_f) + \mathcal{O}(\Lambda_{\text{QCD}}/Q)$$

TMDs: 3D tomography of nucleon structure

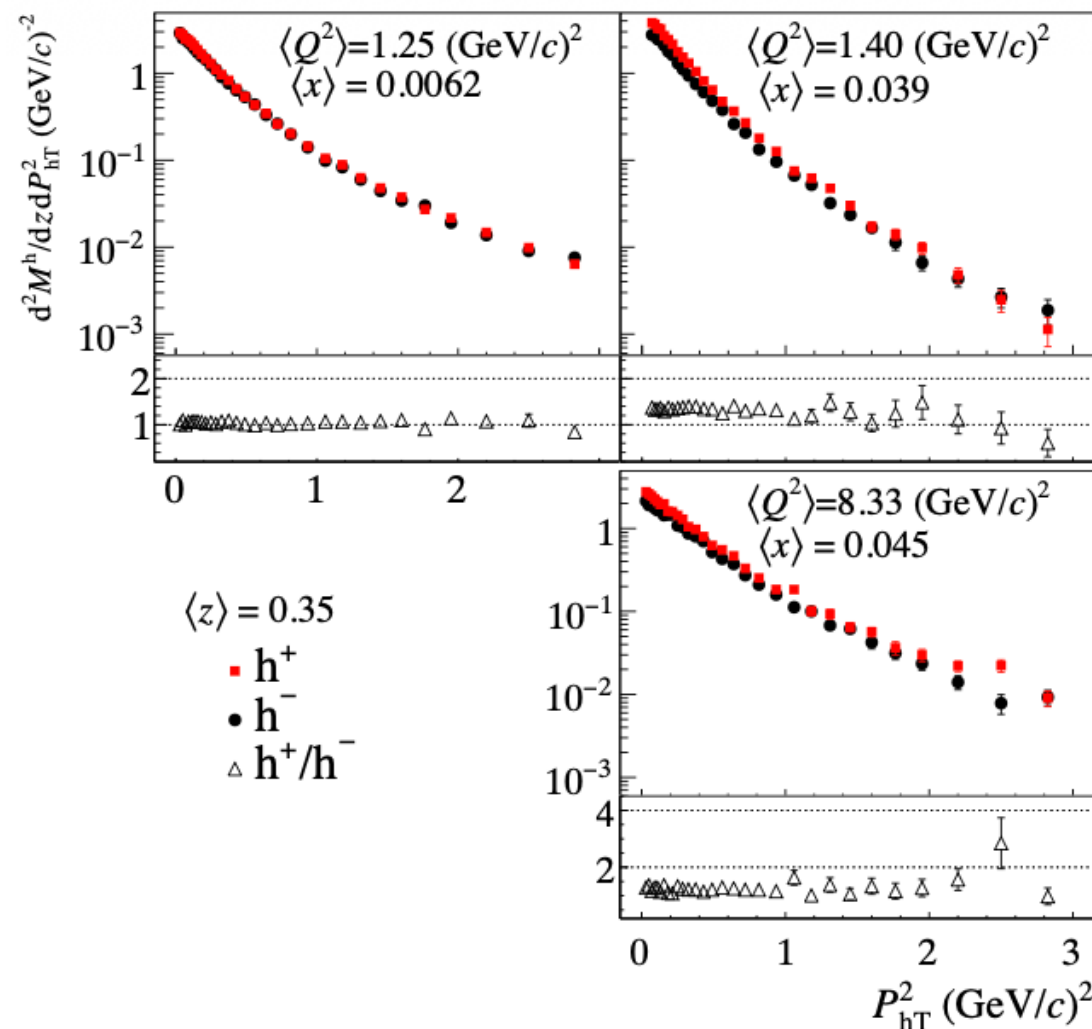
- **TMD PDF:** $\tilde{f}_{i/ps}^{[\Gamma]0(u)}(x, \mathbf{b}_T, \epsilon, \tau, xP^+) = \int \frac{db^-}{2\pi} e^{-ib^-(xP^+)} \left\langle p(P, S) \left| \left[\bar{\psi}^i(b^\mu) W_\square(b^\mu, 0) \frac{\Gamma}{2} \psi^i(0) \right]_\tau \right| p(P, S) \right\rangle$
- **TMD FF:** $\tilde{\Delta}_{h/i}^{[\Gamma]0(u)}(z, \mathbf{b}_T, \epsilon, \tau, P^+/z) = \frac{1}{4N_c z} \text{Tr} \int \frac{db^-}{2\pi} \sum_X e^{ib^-(P^+/z)} \Gamma_{\alpha\alpha'}^+$
 $\times \left\langle 0 \left| \left[(W_\square \psi_i^{0\alpha})(b) \right]_\tau \right| h(P, S), X \right\rangle \left\langle h(P, S), X \left| \left[(\bar{\psi}_i^{0\alpha'} W_\square)(0) \right]_\tau \right| 0 \right\rangle.$
- **Drell-Yan:** Camarda, Cieri, Ferrera '23; Moos, Scimemi, Vladimirov, Zurita '23; Billis, Michel, Tackmann 24'
 - **small q_T : N⁴LL**
 - **large q_T : N²LO V+jet** Gehrmann-De Ridder et al. '16, 18; Boughezal et al. '15, 16; Campbell, Ellis, Williams '17
- **SIDIS:** Moos, Scimemi, Vladimirov, Zurita '25
 - **small q_T : N⁴LL**
 - **large q_T : N²LO h+jet** Dong, SF, Gao, Li, Shao, Zhu '26
 - **matched q_T : N⁴LL+ $\mathcal{O}(\alpha_s^2)$** Gao, Li, Zhu, Zhu '26



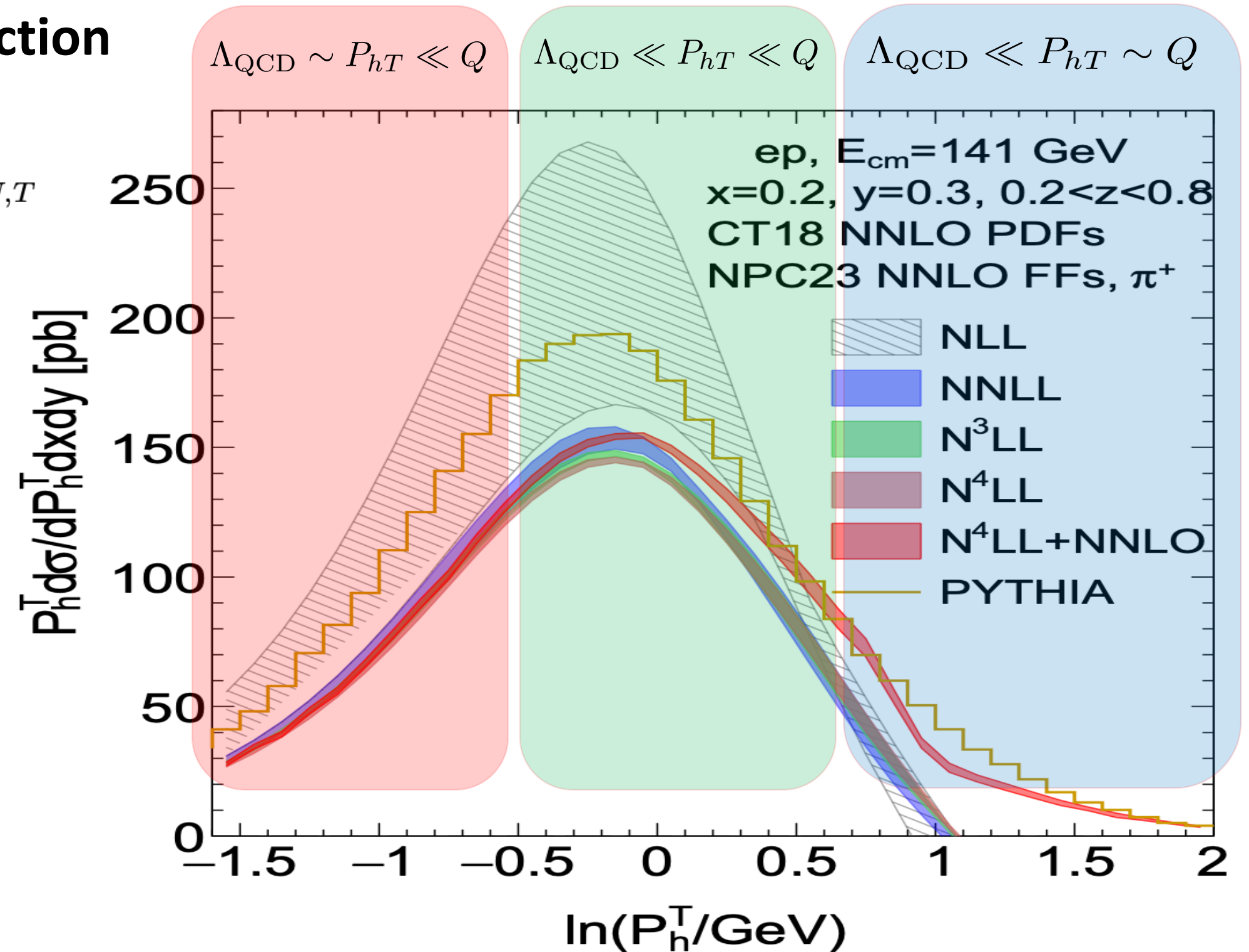
Quark TMDs in e-p collisions

One of the most fundamental measurements in SIDIS related to TMDs is the study of the unpolarized P_{hT} differential cross section

$$\frac{d\sigma}{dx dy dz dP_{hT}^T} = P_h^T \frac{8\pi^2 \alpha_{em}^2}{x y Q^2} \left(1 - y + \frac{1}{2}y^2\right) F_{UU,T}$$



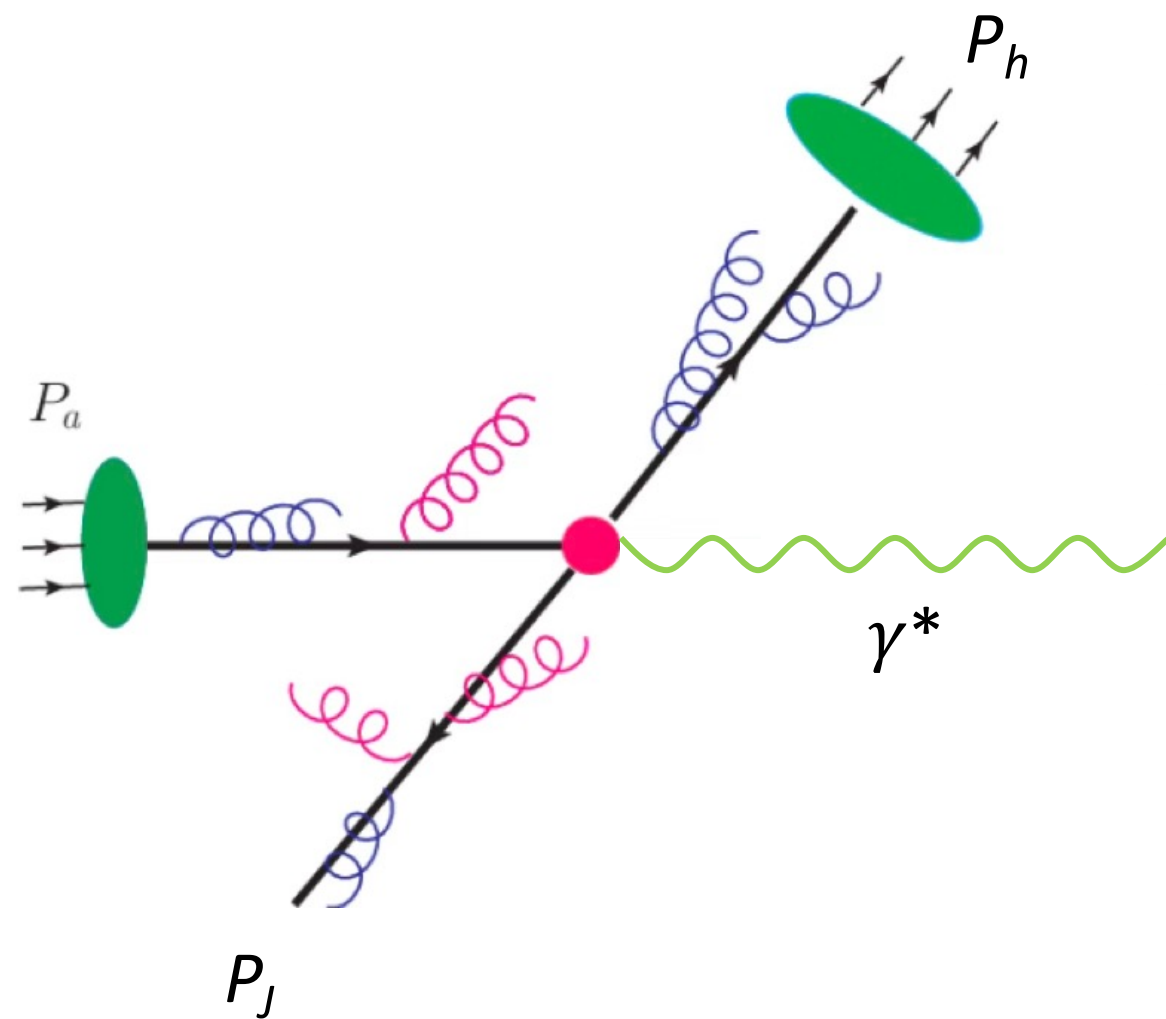
COMPASS '17



Gao, Li, Zhu, Zhu '26

NNLO QCD corrections for P_{hT} distribution

Hadron + jets @ NNLO



- A key challenge is handling infrared (IR) divergences, which must cancel between real and virtual configurations.

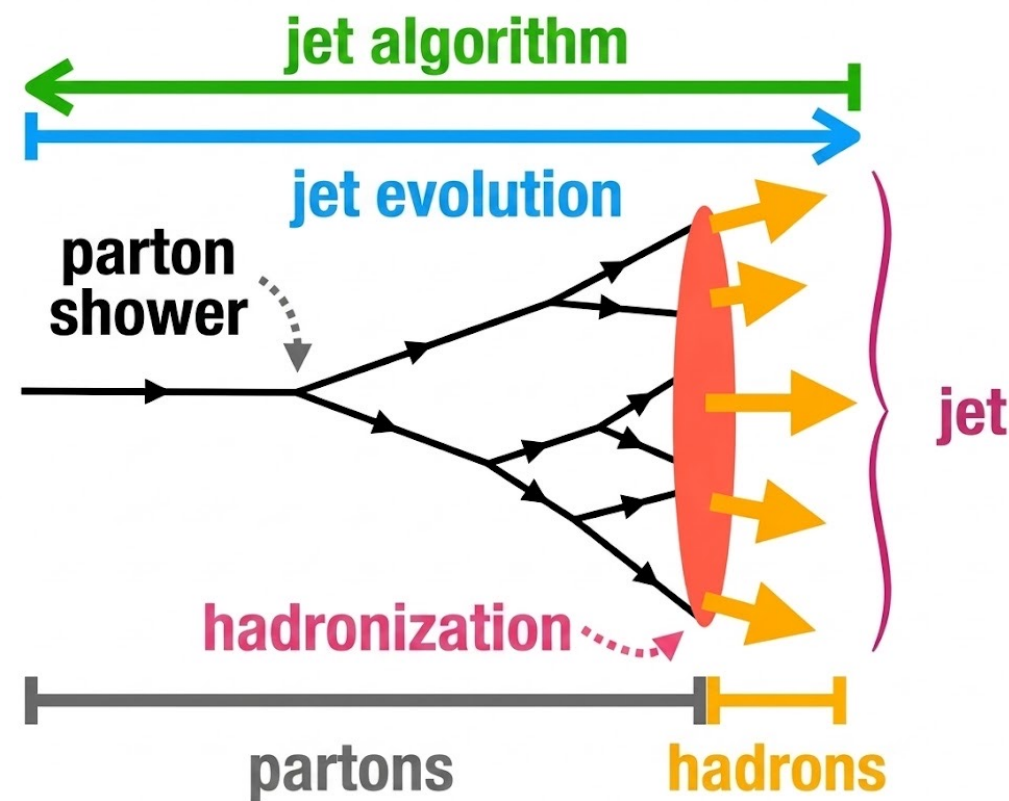
$$\sigma_{\text{tot}} = \left| \begin{array}{c} e^+e^- \rightarrow q\bar{q} \\ \text{tree} + \text{loop} \end{array} \right|^2 + \left| \begin{array}{c} e^+e^- \rightarrow q\bar{q}g \\ \text{tree} + \text{loop} \end{array} \right|^2$$

- **FMNLO** for hadron production at NLO Liu, Shen, Zhou, Gao '23
- **Transverse momentum (q_T) subtraction** for hadron production at NNLO Gao, Li, Zhu, Zhu '26
- q_T subtraction works well for colorless or colored (but massive) system
 - **N³LO Higgs** Cieri, Chen, Gehrmann, Glover, Huss '18; Billis Dehnadi, Ebert, Michel, Tackmann '21
 - **N³LO Drell-Yan** Chen, Gehrmann, Glover, Huss, Yang, Zhu '23
 - **N³LO di-photon** Czakon, Eschment, Generet, Poncelet '26
- **For processes with standard inclusive jets, q_T is unsuitable because $q_T = 0$ for radiation emitted inside jets.**

Winner-take-all q_T subtraction for jets

Fu, Rahn, Shao, Waalewijn, Wu '25: see Rong-Jun's talk

- **Winner-take-all recombination scheme** Bertolini, Chan, Thaler '13



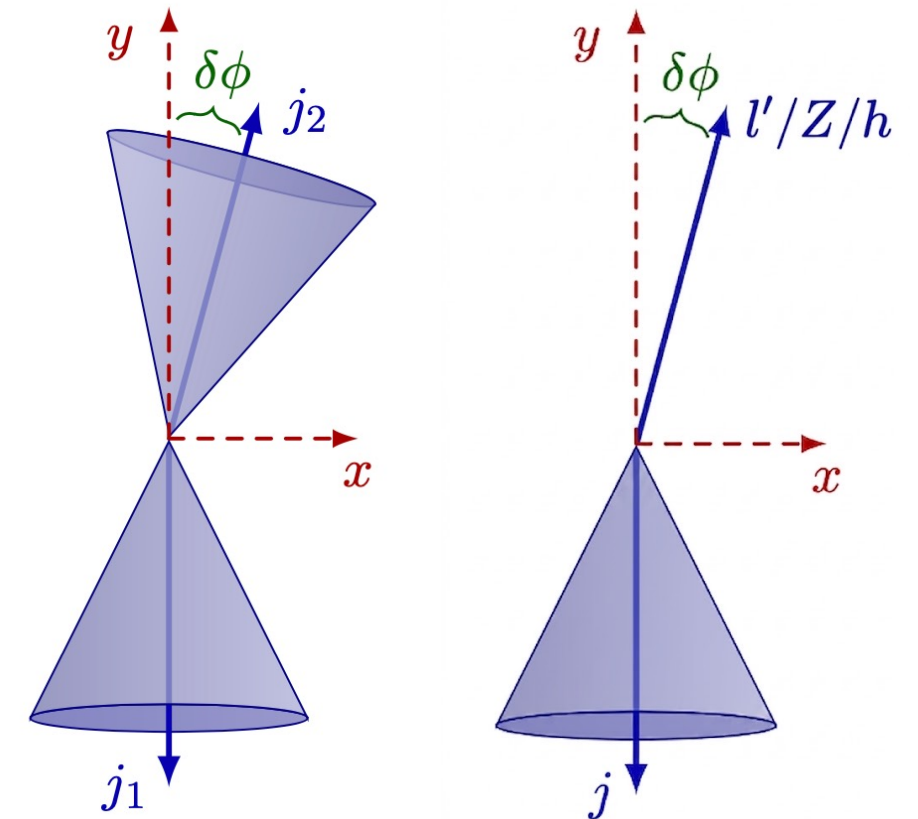
Winner-take-all recombination scheme

$$p_{t,r} = p_{t,i} + p_{t,j}$$

$$\phi_r = (w_i \phi_i + w_j \phi_j) / (w_i + w_j)$$

$$y_r = (w_i y_i + w_j y_j) / (w_i + w_j)$$

$$w_i = (p_{t,i})^n \quad n \rightarrow \infty$$



- **Factorization theorem is significantly simplified** Chien, Rahn, Shao, Waalewijn & Wu '22 + Schrignder '21
 - NNLL resummation for $\delta\phi$ @ ep & eA SF, Ke, Shao, Terry '24
 - N³LL + $\mathcal{O}(\alpha_s^2)$ resummation for $\delta\phi$ @ ep SF, Gao, Li, Shao '25

Winner-take-all q_T subtraction for jets

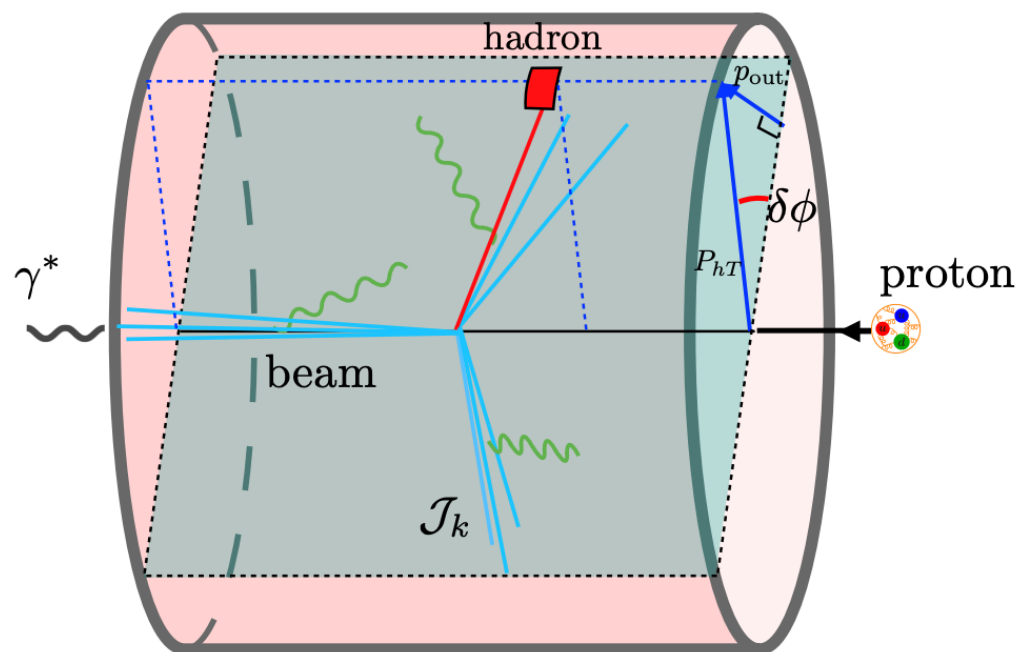
Fu, Rahn, Shao, Waalewijn, Wu '25: see Rong-Jun's talk

- We propose two ways of extending q_T subtraction to processes with jets
 - **The key ingredient is the use of a recoil-free WTA jet axis!**
- Azimuthal decorrelation: $\delta\phi$ or q_x
 - Suitable for processes that are **planar at LO**: $pp \rightarrow 2$ jets, $\gamma^* p \rightarrow 2$ jets, $e^+ e^- \rightarrow 3$ jets, etc.
 - Standard TMD PDFs, FFs and soft functions: known at N³LO Luo, Yang, Zhu, Zhu '19; Ebert, Mistlberger, Vita '20; Zhu '26; Li, Zhu '17...
 - TMD jet functions: partially known at NNLO Reyes, Scimemi, Waalewijn, Zoppi '19; Bell, Brune, Das, Wald '23; SF, Gao, Li, Shao '24
- Total transverse momentum q_T
 - Suitable for **LO non-planar processes**, such as $pp \rightarrow V/H + 2$ jets, $pp \rightarrow 3$ jets, etc.
 - Soft function is new: Outside the jet (b_T), Inside the jet (b_x)

NNLO QCD corrections for P_{hT} distribution

Dong, SF, Gao, Shao, Li, Zhu '26

- We present the **first** complete calculation of hadron production in DIS at finite transverse momentum to NNLO



- subtraction method:**

$$\frac{d\sigma}{d\mathcal{O}} = \int_0^{\delta\phi^{\text{cut}}} d\delta\phi \frac{d\sigma}{d\delta\phi d\mathcal{O}} + \int_{\delta\phi^{\text{cut}}}^{\delta\phi^{\text{max}}} d\delta\phi \frac{d\sigma}{d\delta\phi d\mathcal{O}}$$

- unresolved part:**

$$e + p \rightarrow e + h + j + X \quad \text{at NNLO}$$

- factorization formula:**

$$\begin{aligned} \frac{d\sigma_{\text{LP}}}{dx dy dz d^2\vec{P}_{hT} dp_{\text{out}}} &= \int \frac{db}{2\pi} e^{ip_{\text{out}}b/\zeta} \\ &\times \sum_{ijk} \int d\xi H_{ei \rightarrow ejk}(Q, \xi, \zeta) \\ &\times \mathcal{B}_{i/p}(\xi, b) \mathcal{D}_{h/j}(\zeta, b) \mathcal{J}_k(b) S_{ijk}(b) \end{aligned}$$

- back-to-back limit:**

$$\delta\phi = \frac{p_{\text{out}}}{P_{hT}}$$

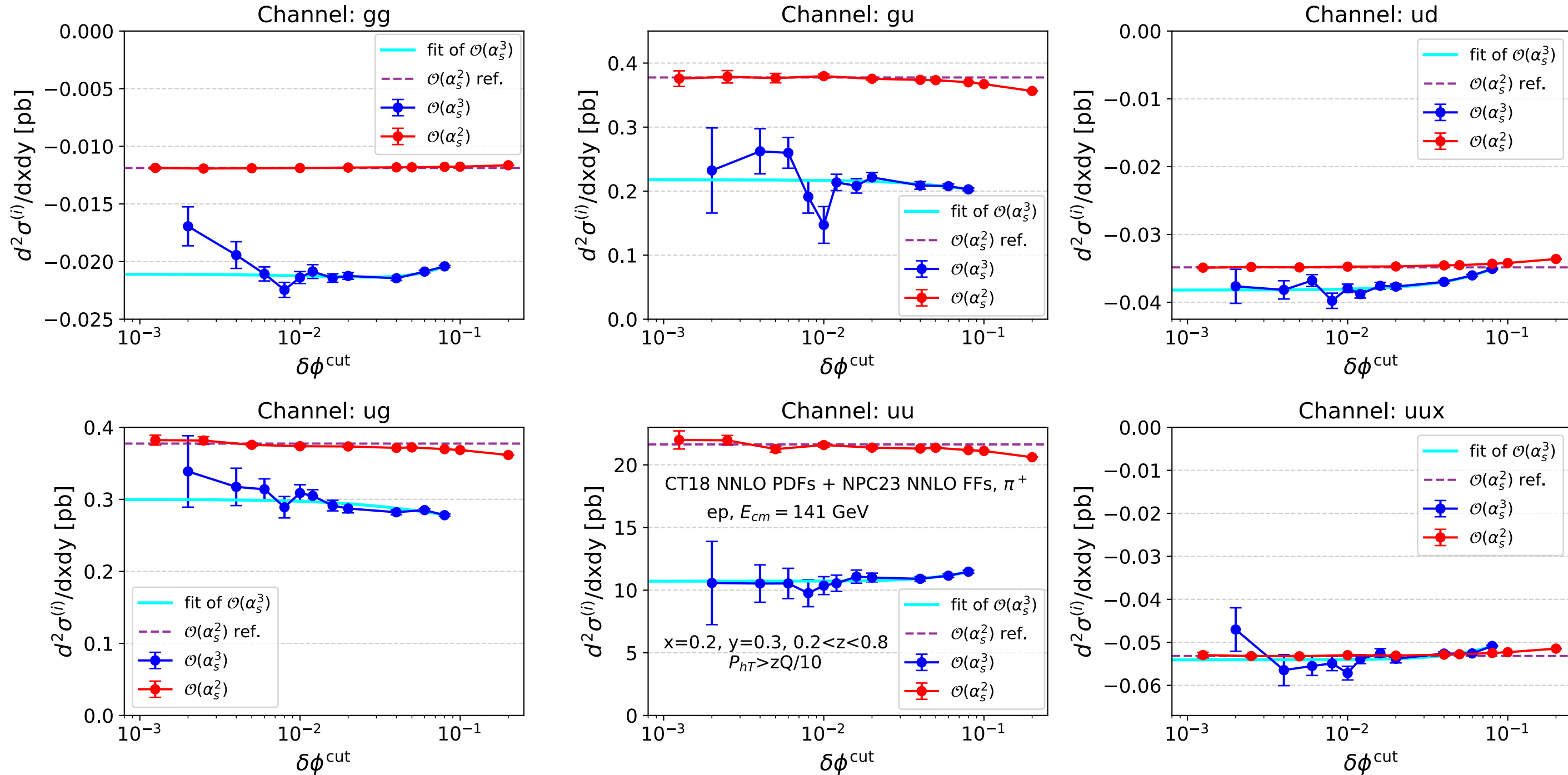
- resolved part:**

$$e + p \rightarrow e + h + 2j + X \quad \text{at NLO}$$

- First N³LO SIDIS** Dong, SF, Gao, Shao, Li, Zhu, Zhu 2603.29673, see Hai-Tao's talk

Numerical results

Dong, SF, Gao, Shao, Li, Zhu '26



- Both NLO and NNLO results converge to a constant platform.

Summary

- **We developed a systematic routine of subtraction/slicing methods for identified hadron production, and presented the first complete NNLO QCD corrections to single inclusive hadron production in DIS at finite transverse momentum.**
- **With the advancements on ingredients of both non-perturbative and perturbative QCD, we are on the way of building a precision framework for fully differential N³LO and N⁴LL+ $\mathcal{O}(\alpha_s^3)$ predictions of SIDIS at the future EIC.**

Thank you!