

Energy correlators resolving proton spin

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第八届全国重味物理与量子色动力学研讨会

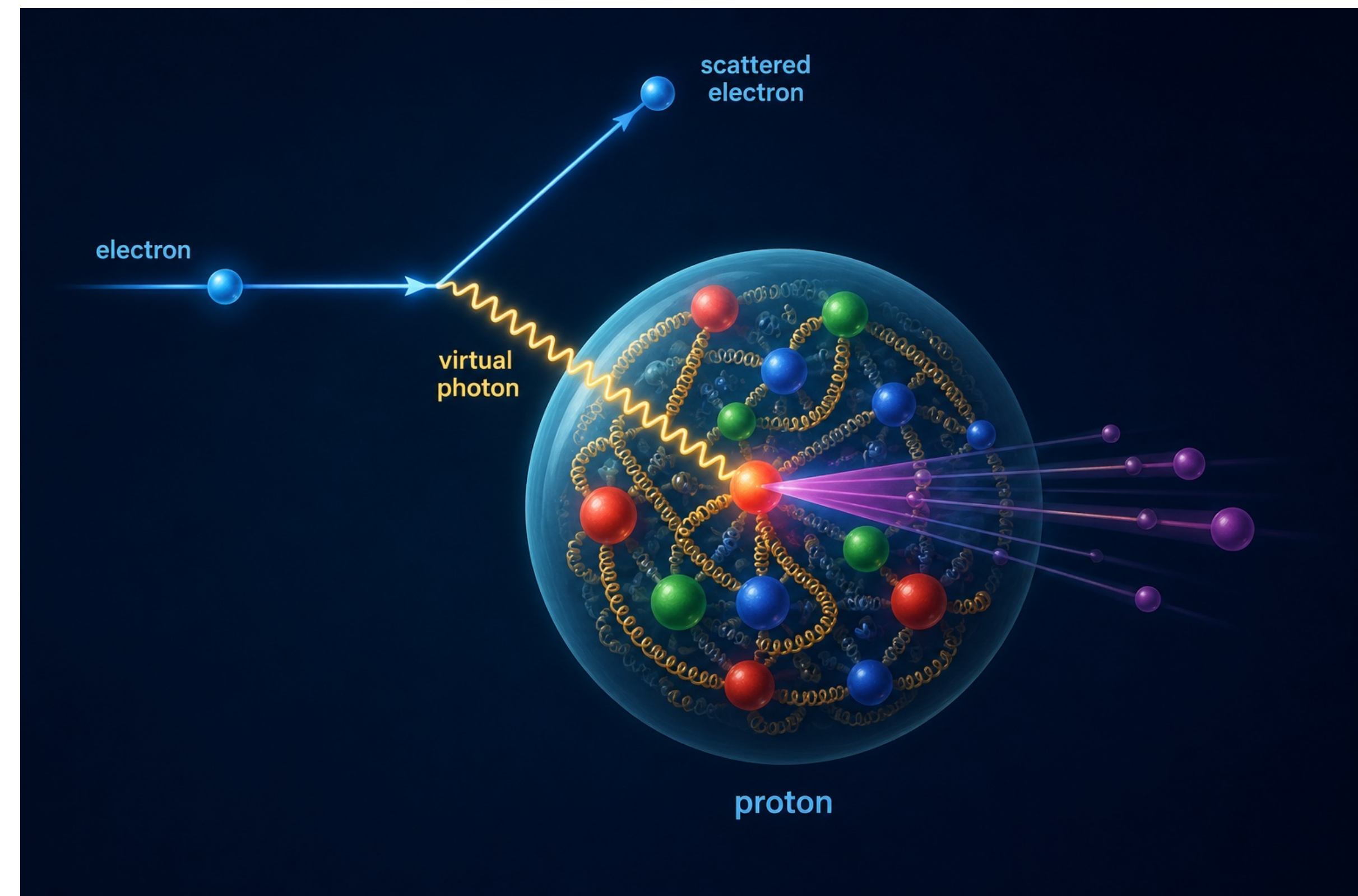
4月27日，重庆

Introduction

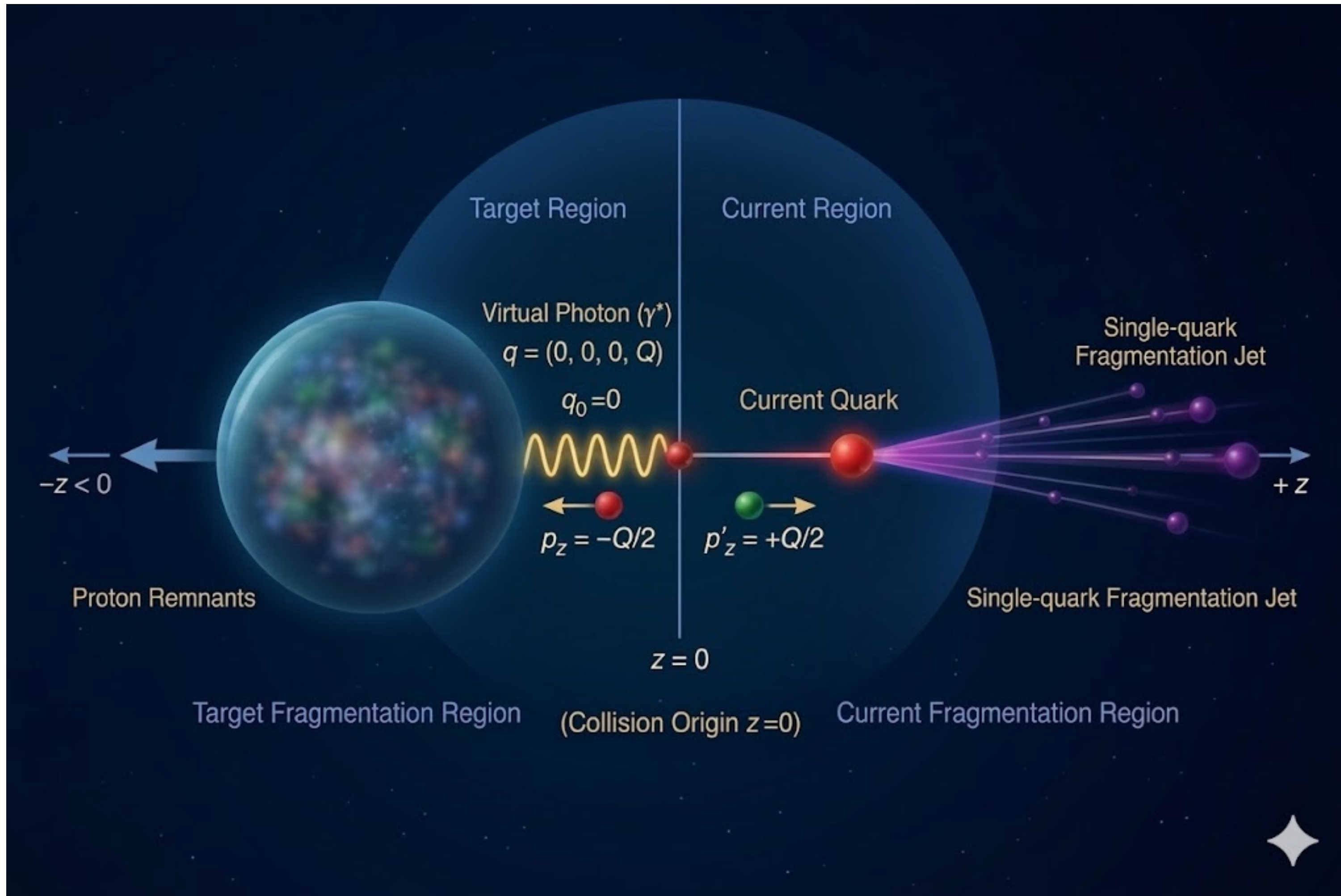
$$l + N \rightarrow l + h + X$$

$$\frac{d\sigma^{lp \rightarrow l' h X}}{dx_B dQ^2 dz_h} \propto \sum_q e_q^2 f_{q/p}(x_B, \mu_F) D_{h/q}(z_h, \mu_F)$$

- ❑ Studying the collinear PDFs of nucleon
- ❑ Probing the 3D Nucleon Structure
- ❑ Unraveling Spin-Orbit Correlations
- ❑ Understanding Hadronization Dynamics
- ❑ Advancing Precision pQCD & Factorization



Introduction



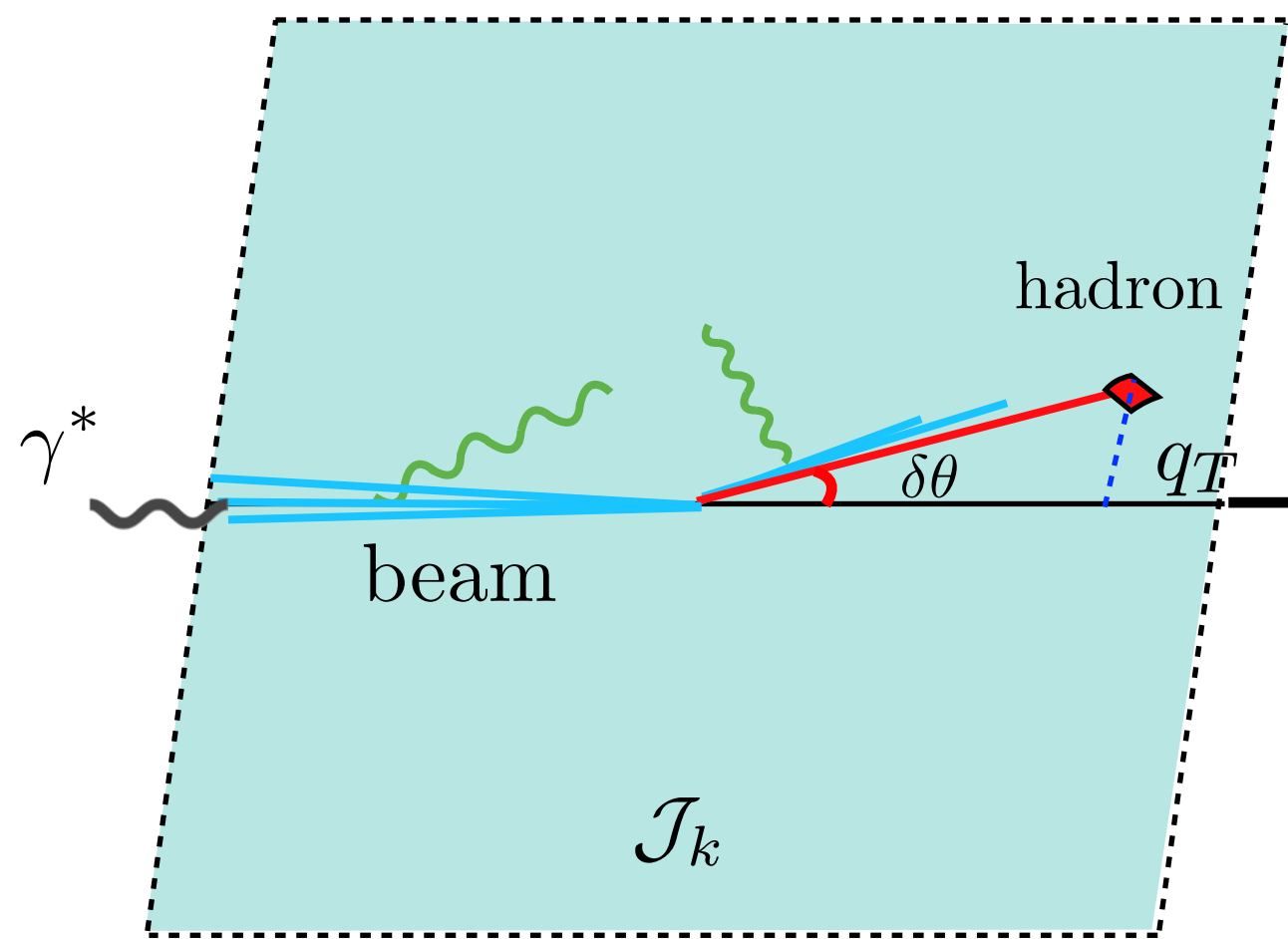
In the current region, for hadron with small p_T ,

$$\begin{aligned} \frac{d\sigma}{dx dQ^2 dz d^2q_\perp} &= H(Q^2; \mu) \sum_q e_q^2 \\ &\times \int \frac{d^2b_\perp}{(2\pi)^2} e^{iq_\perp \cdot b_\perp} \tilde{f}_{q/P}(x, b_\perp; \mu, \zeta) \\ &\times \tilde{D}_{i/q}(z, b_\perp; \mu, \zeta) S(b_\perp; \mu) \\ &+ O(M/Q) \end{aligned}$$

See Ding Yu Shao's talk

DIS with q_T subtraction

new method for calculating fully differential SIDIS cross sections

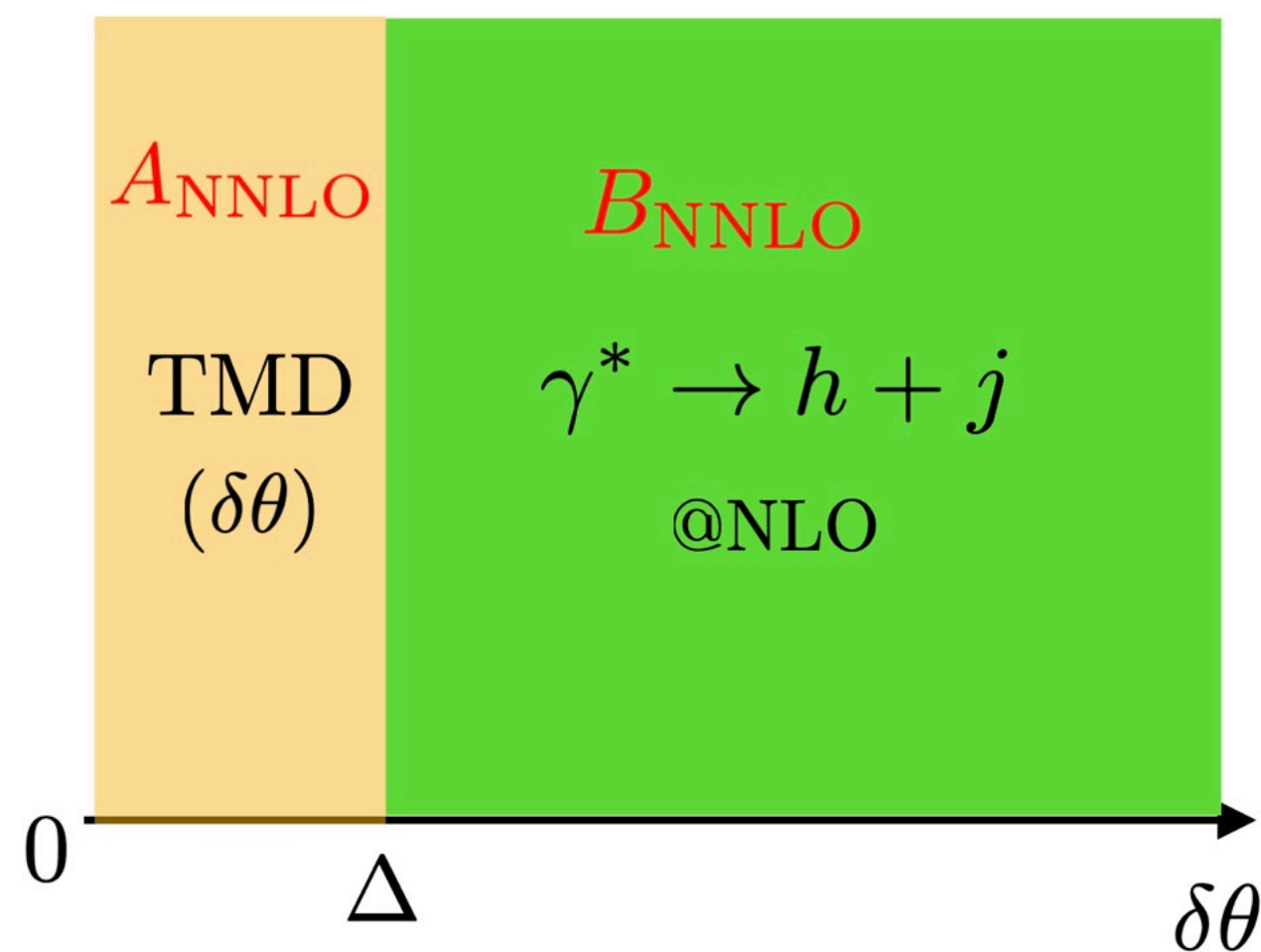


proton
 $\vec{q}_\perp = -\vec{P}_{\perp,h}/z$

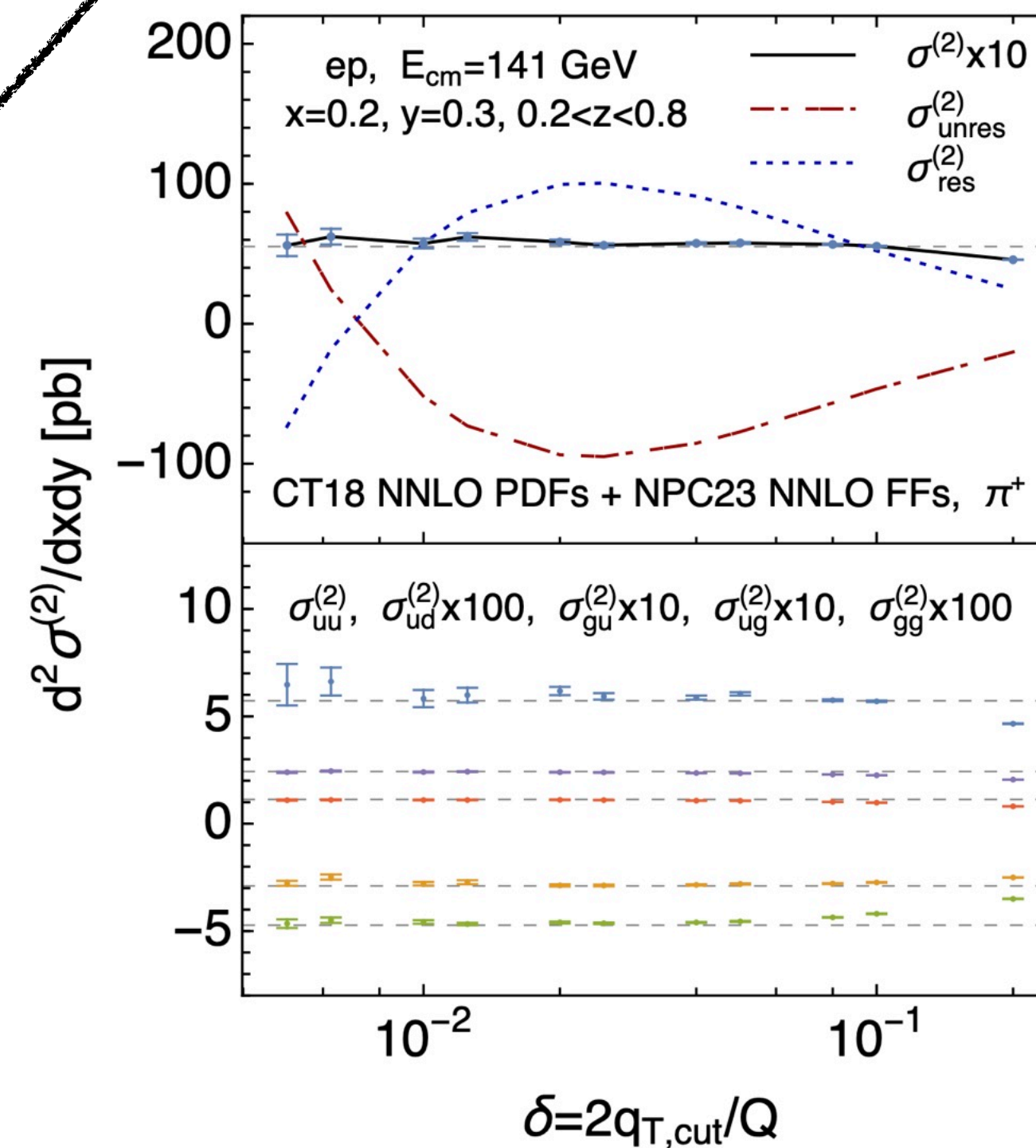
$$\frac{d\sigma}{d\mathcal{O}} = \int_{q_{T,cut}}^{q_{T,max}} dq_T \frac{d\sigma}{dq_T d\mathcal{O}} + \int_0^{q_{T,cut}} dq_T \frac{d\sigma}{dq_T d\mathcal{O}}$$

TMD factorization

all components ready up to three loops

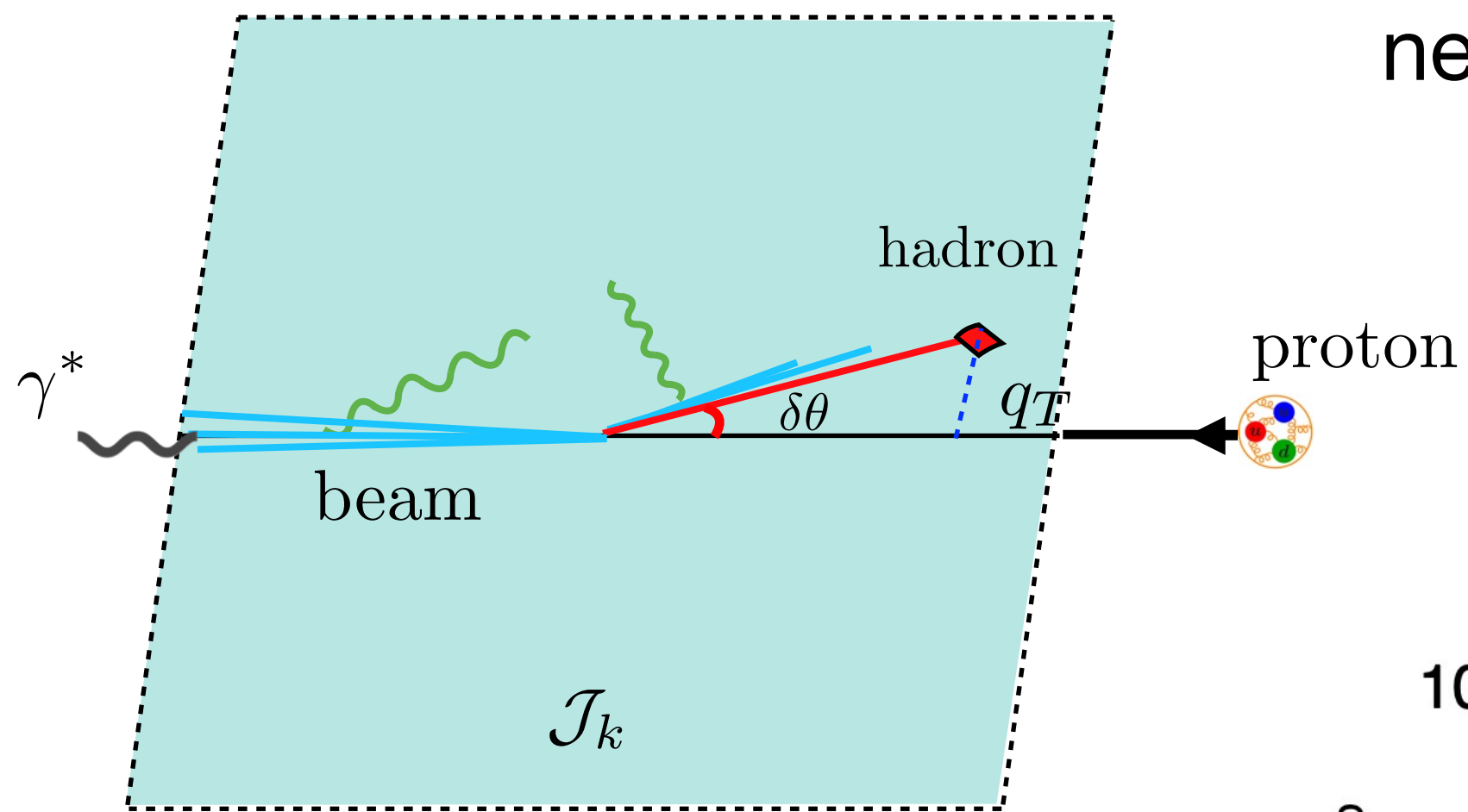


fixed order calculation of h+jet production

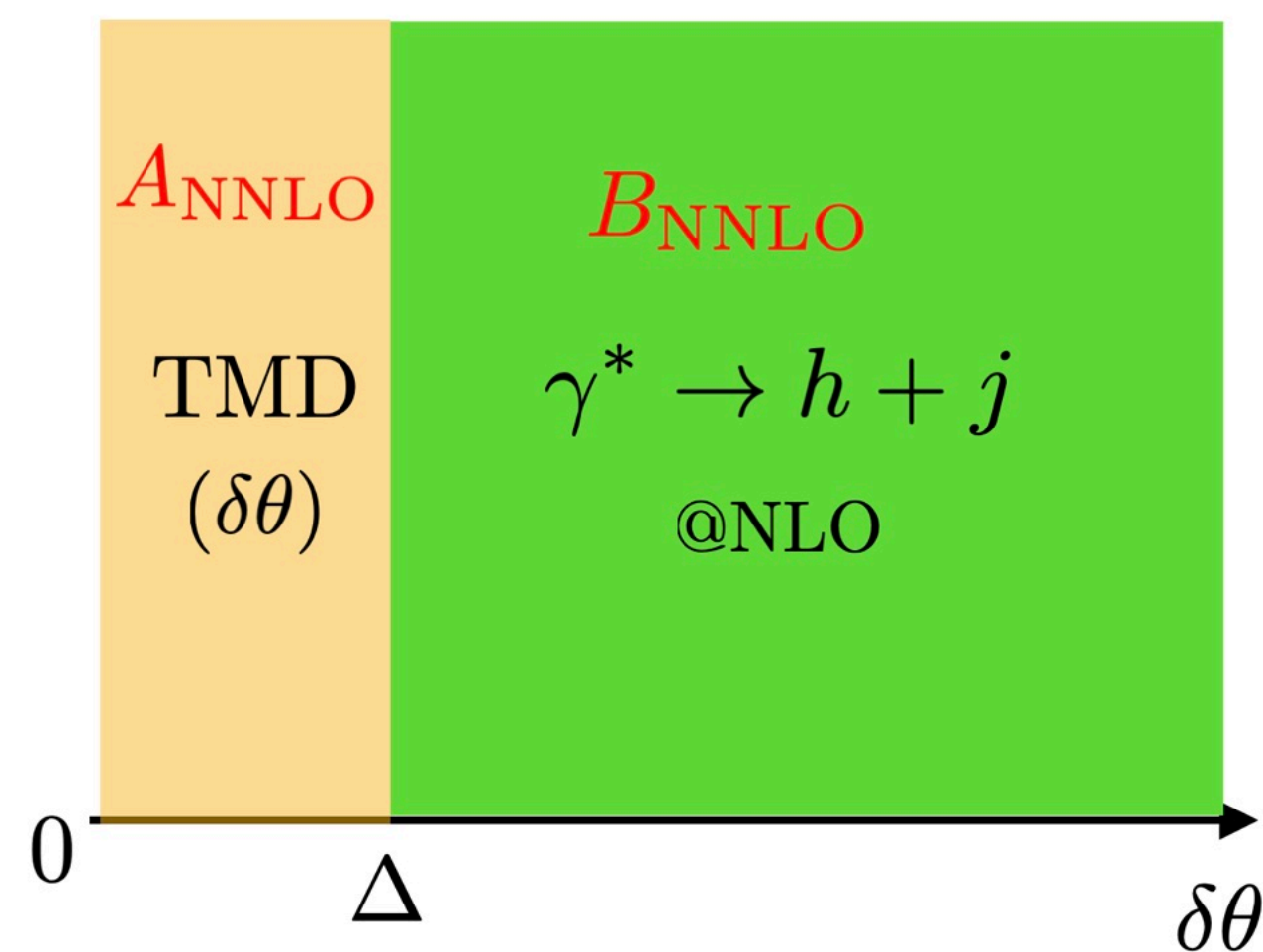


DIS with qT subtraction

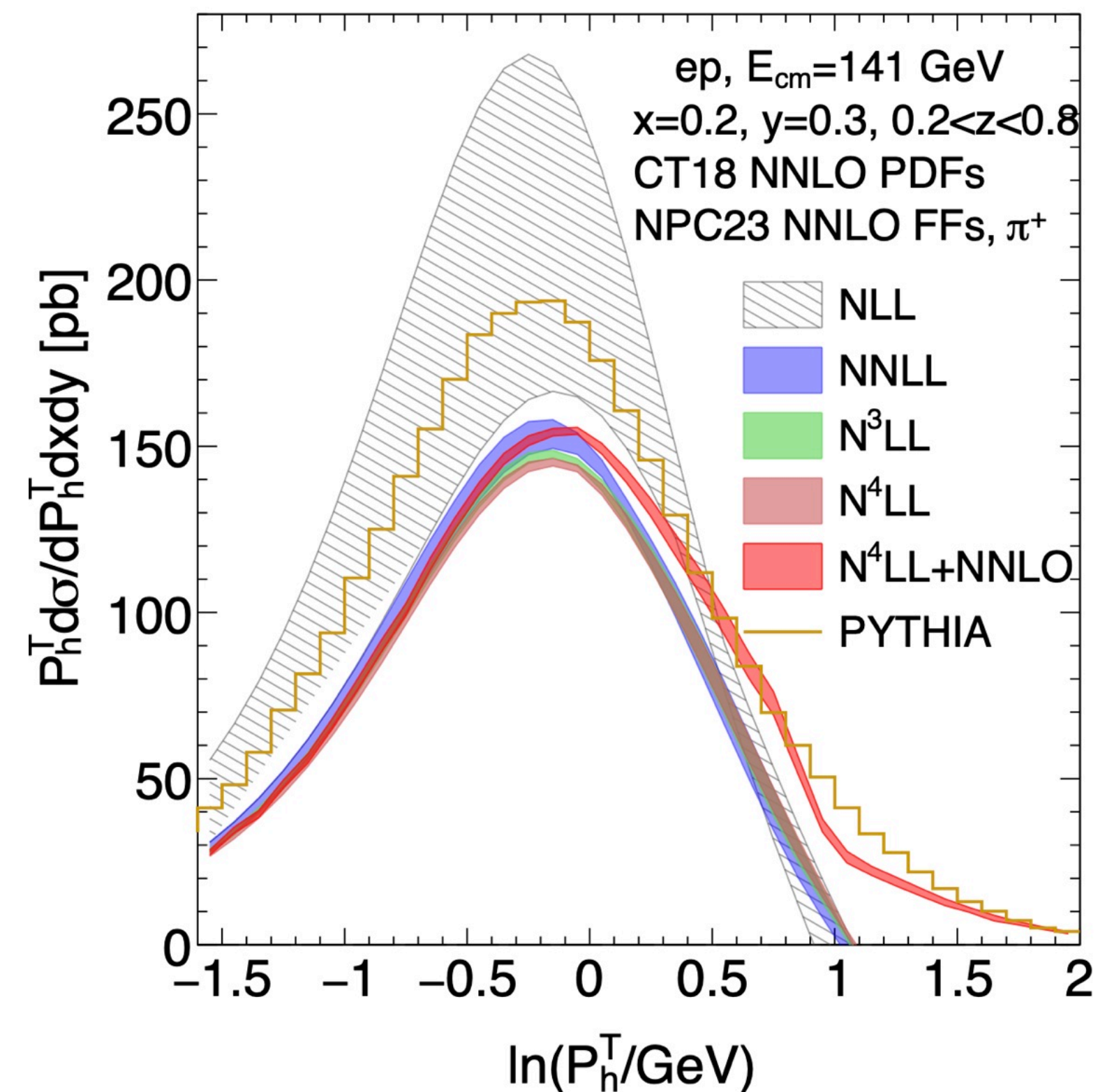
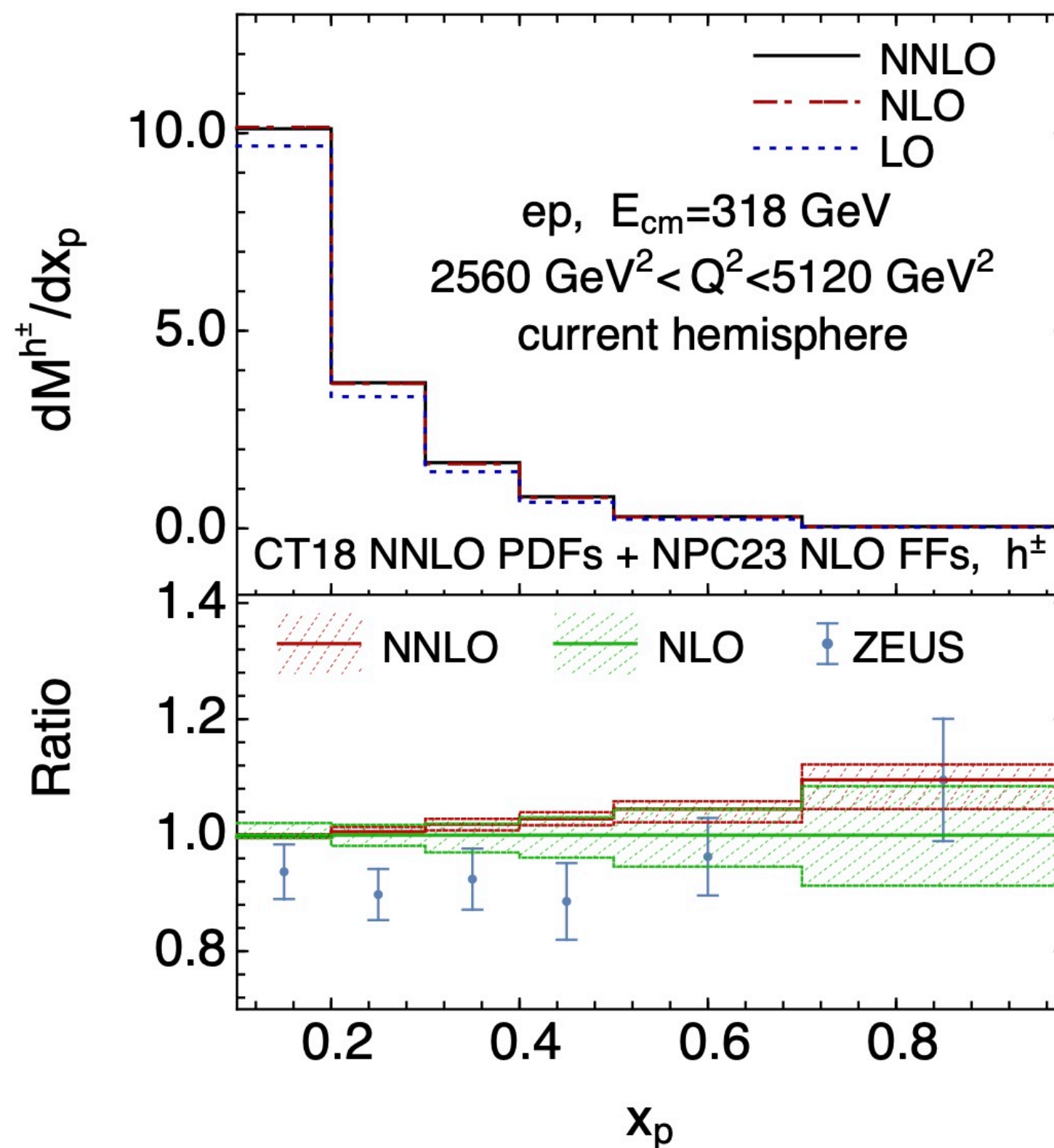
new method for calculating fully differential SIDIS cross sections



$$\frac{d\sigma}{d\mathcal{O}} = \int_{q_{T,\text{cut}}}^{q_{T,\text{max}}} dq_T \frac{d\sigma}{dq_T d\mathcal{O}} + \int_0^{q_{T,\text{cut}}} dq_T \frac{d\sigma}{dq_T d\mathcal{O}}$$

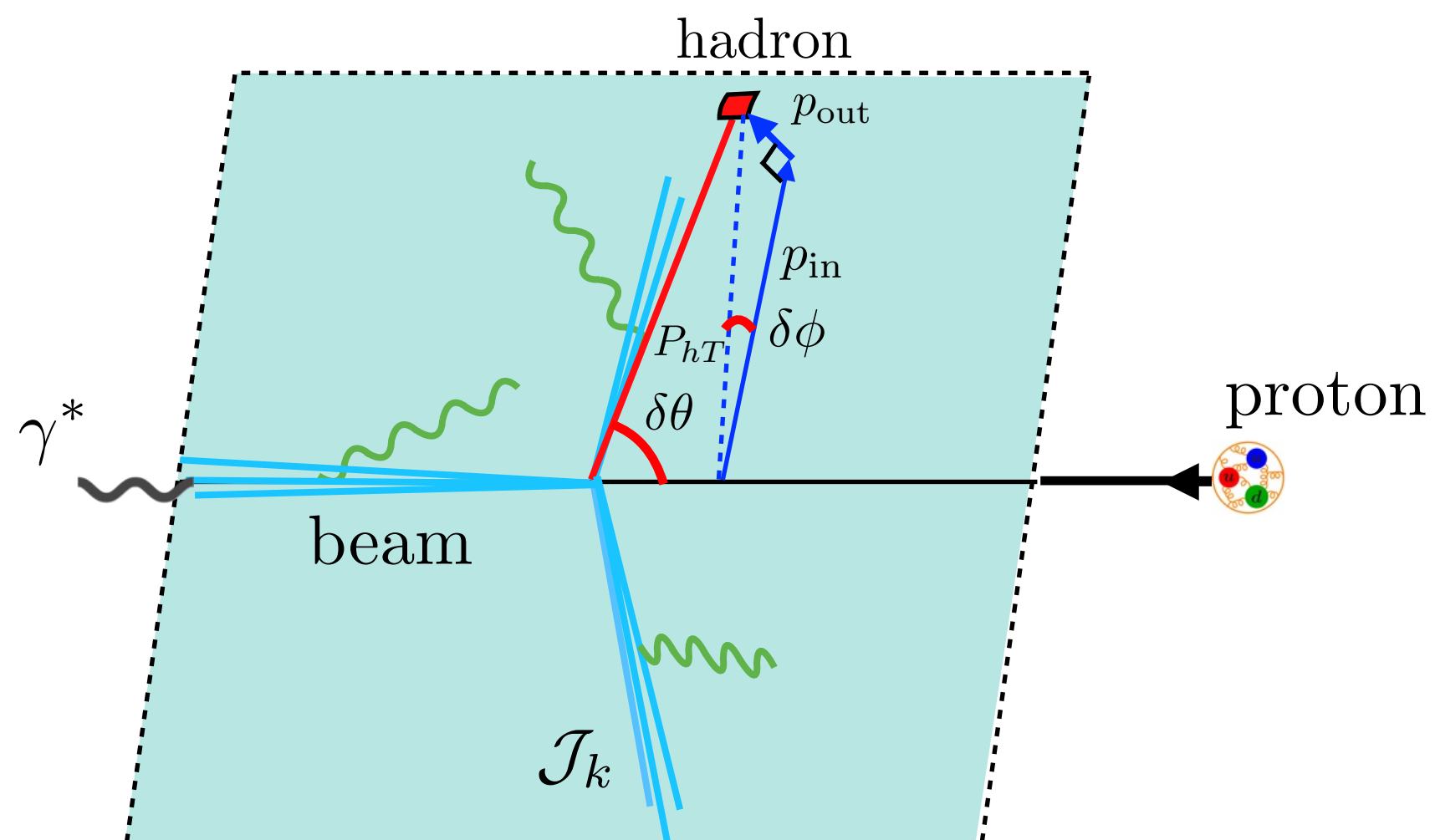


See Jun Gao's talk



Gao, HTL, Zhu, Zhu, arXiv:2602.06364

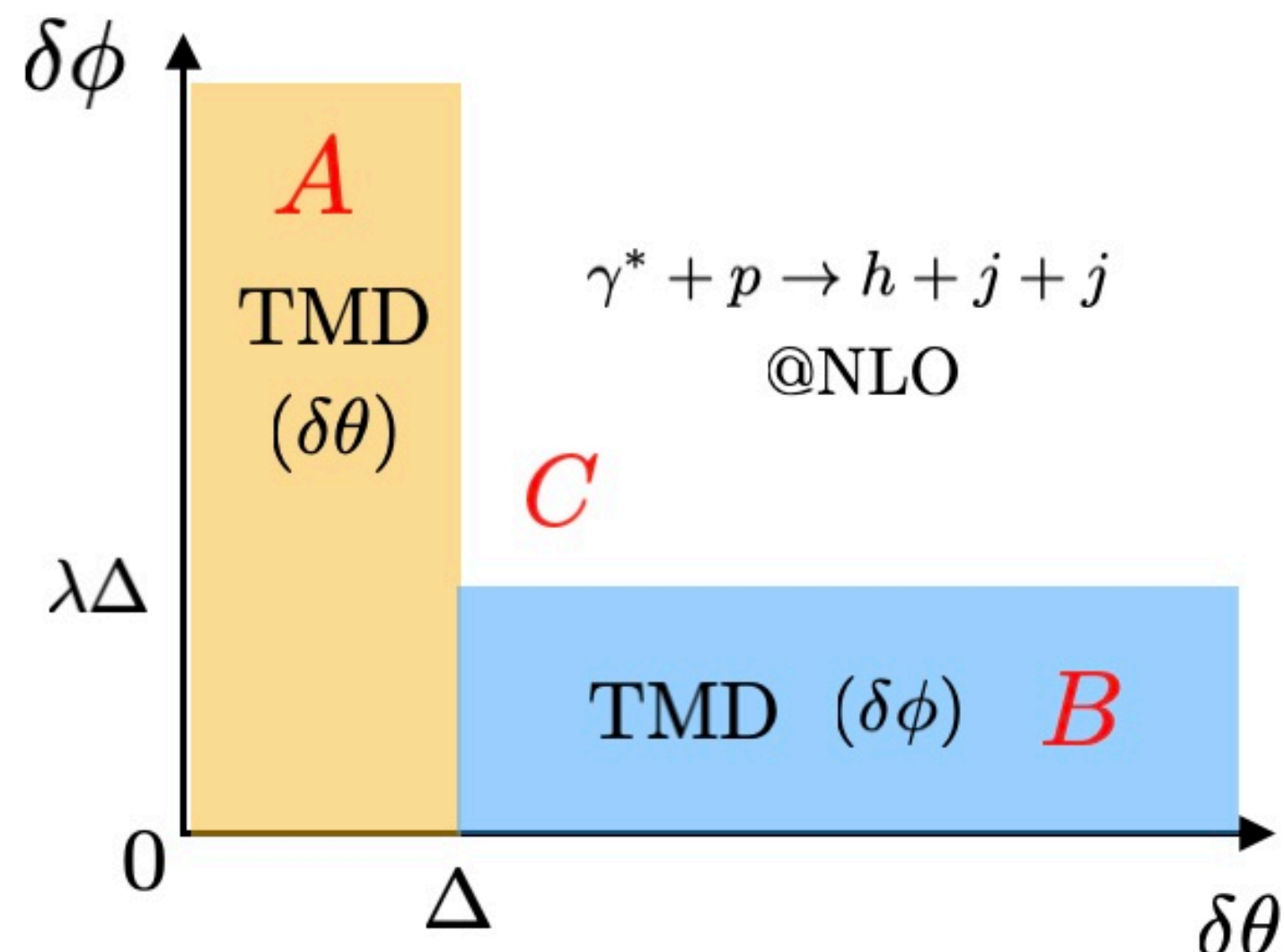
DIS with qT subtraction



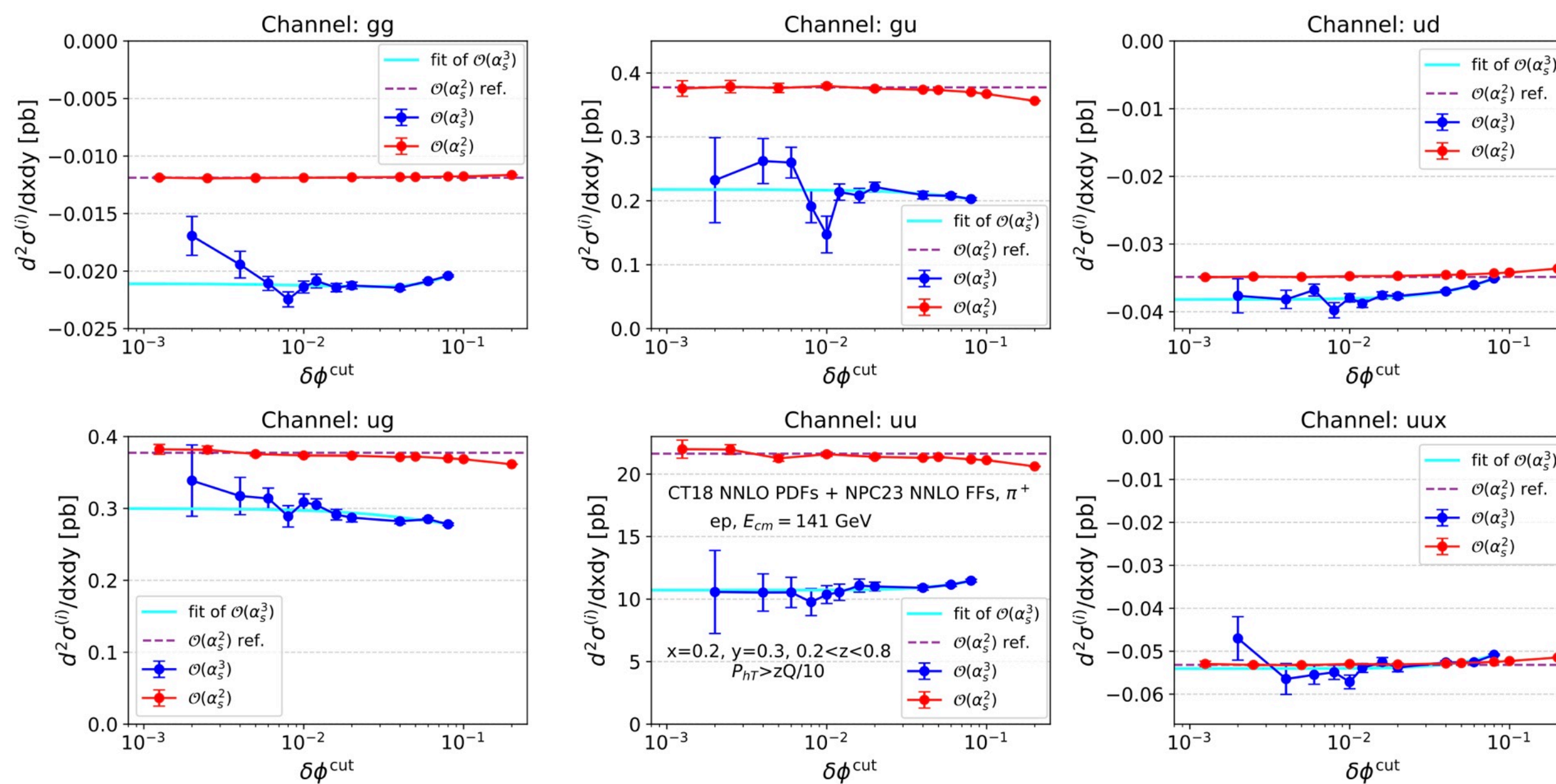
$$\frac{d\sigma}{d\mathcal{O}} = \underbrace{\int_0^\Delta d\delta\theta \frac{d\sigma^A}{d\delta\theta d\mathcal{O}}}_A +$$

$$\int_\Delta^{\delta\theta^{\max}} d\delta\theta \times \left(\underbrace{\int_0^{\lambda\Delta} d\delta\phi \frac{d\sigma^B}{d\delta\theta d\delta\phi d\mathcal{O}}}_B + \underbrace{\int_{\lambda\Delta}^{\delta\phi^{\max}} d\delta\phi \frac{d\sigma^C}{d\delta\theta d\delta\phi d\mathcal{O}}}_C \right)$$

See Ding Yu Shao's talk

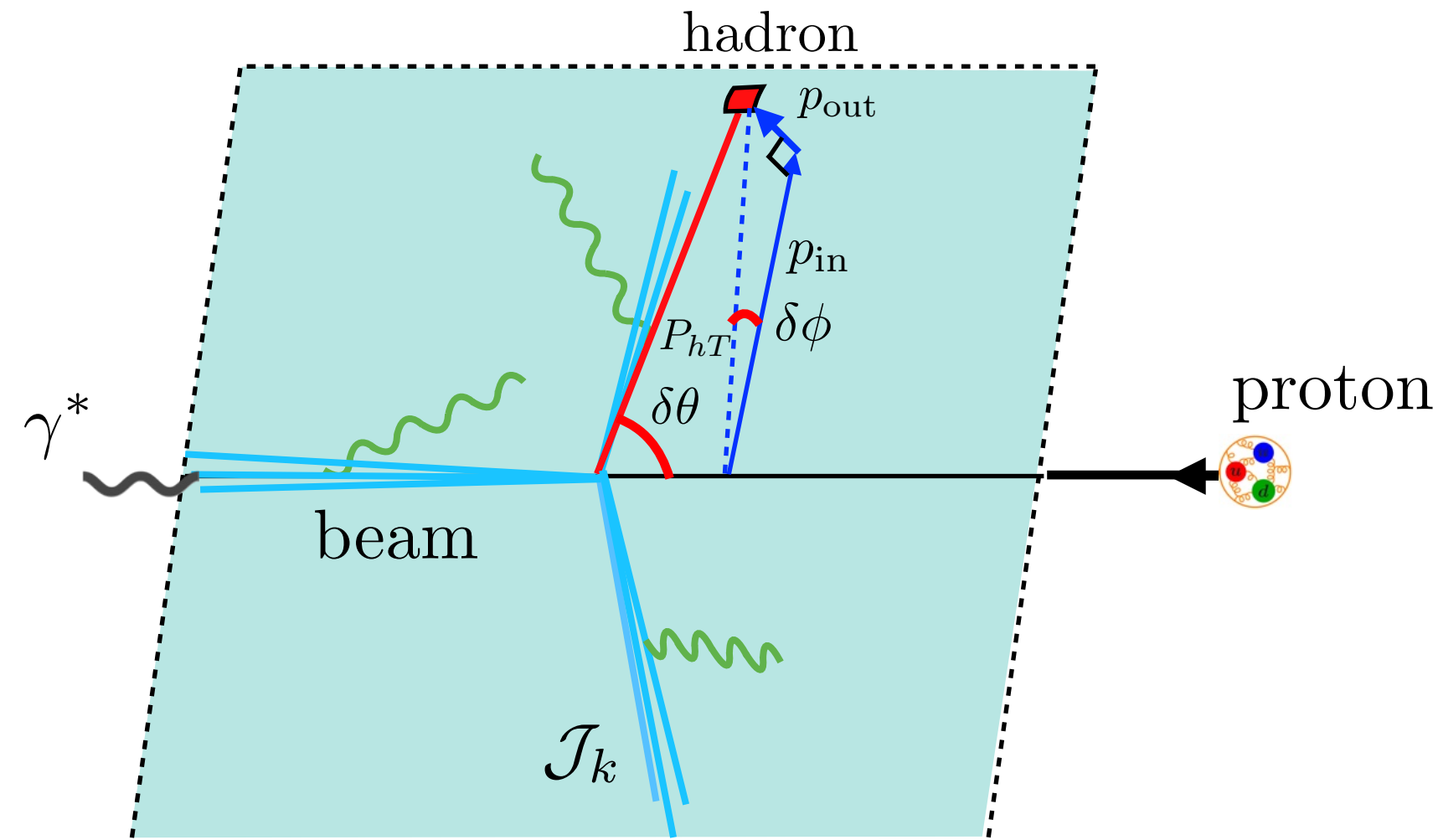


SIDIS @ N³NLO



Dong, Fang, Gao, HTL, Shao, Zhu, Zhu,
arXiv:2602.22972, arXiv:2603.29673

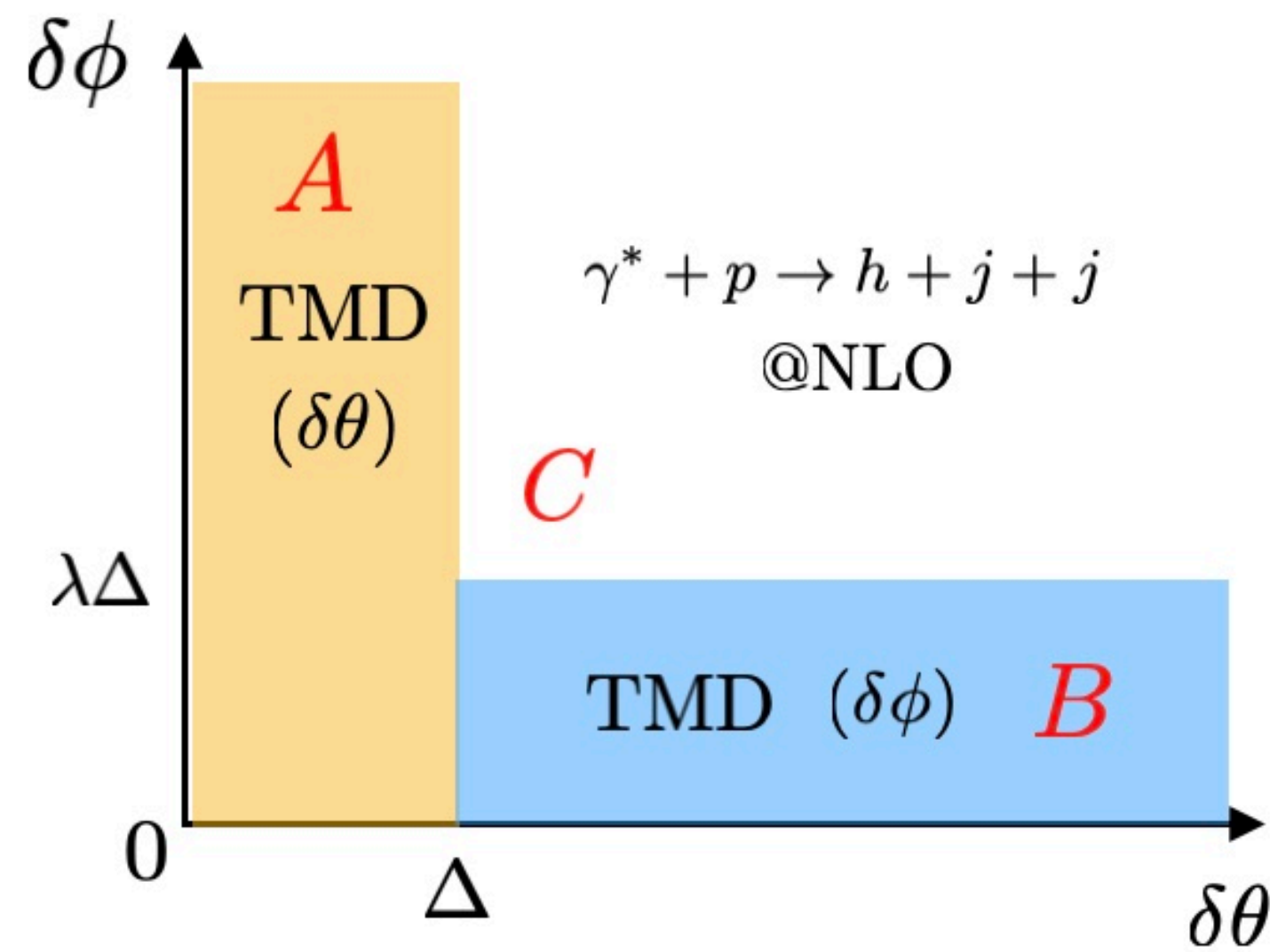
DIS with qT subtraction



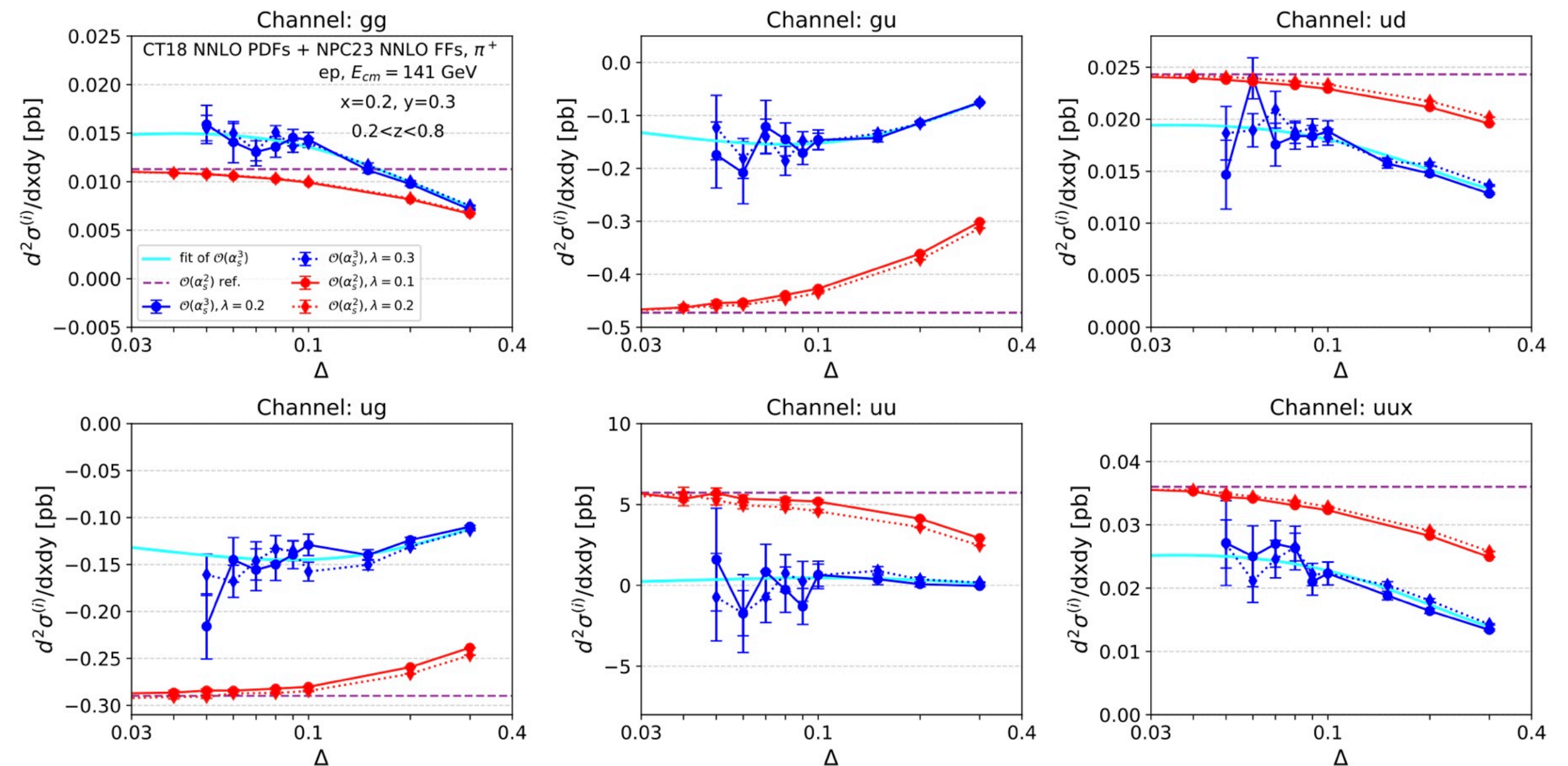
$$\frac{d\sigma}{d\mathcal{O}} = \underbrace{\int_0^\Delta d\delta\theta \frac{d\sigma^A}{d\delta\theta d\mathcal{O}}}_A +$$

$$\int_\Delta^{\delta\theta^{\max}} d\delta\theta \times \left(\underbrace{\int_0^{\lambda\Delta} d\delta\phi \frac{d\sigma^B}{d\delta\theta d\delta\phi d\mathcal{O}}}_B + \underbrace{\int_{\lambda\Delta}^{\delta\phi^{\max}} d\delta\phi \frac{d\sigma^C}{d\delta\theta d\delta\phi d\mathcal{O}}}_C \right)$$

See Ding Yu Shao's talk

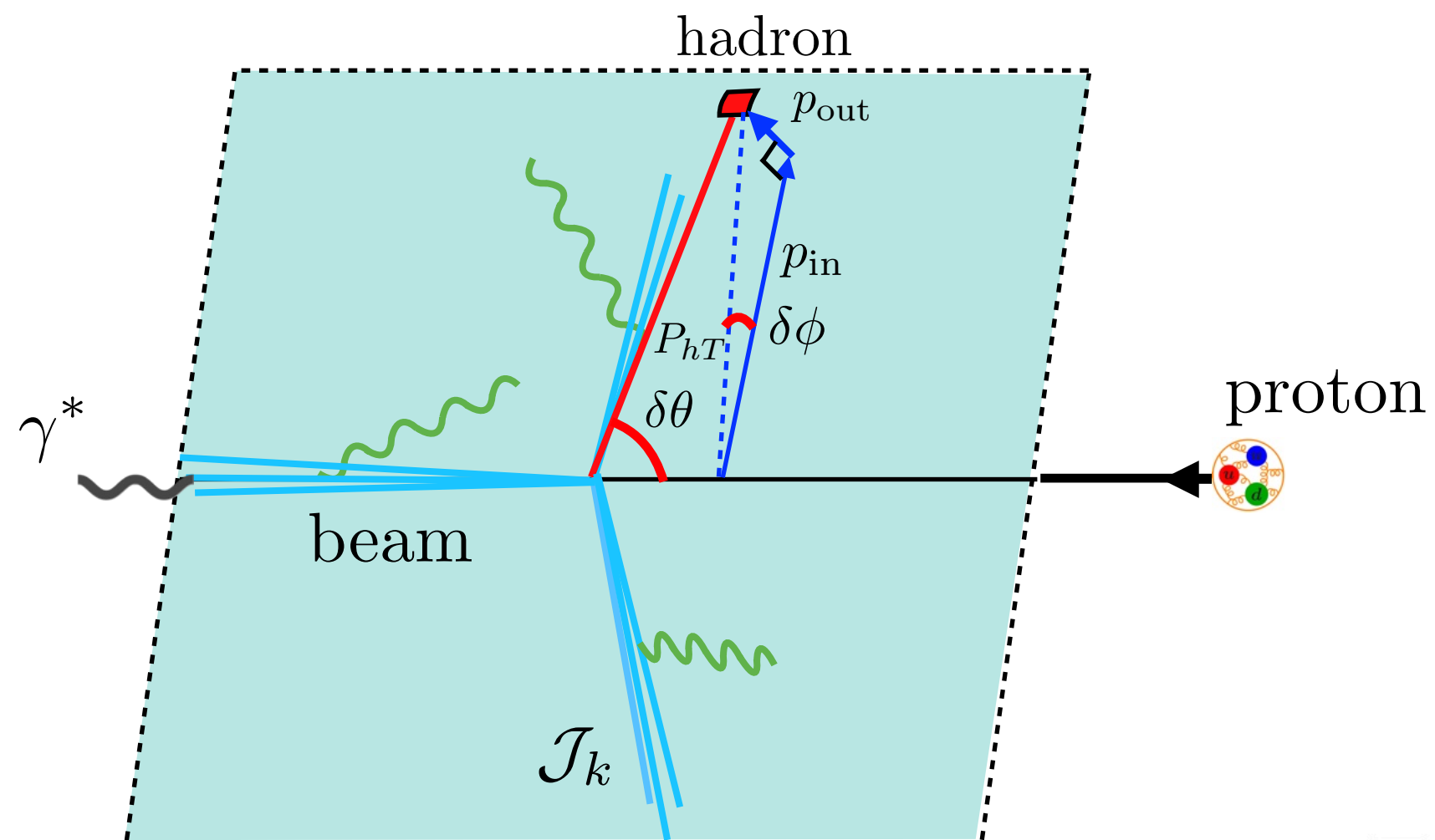


SIDIS @ N³NLO



Dong, Fang, Gao, HTL, Shao, Zhu, Zhu,
arXiv:2602.22972, arXiv:2603.29673

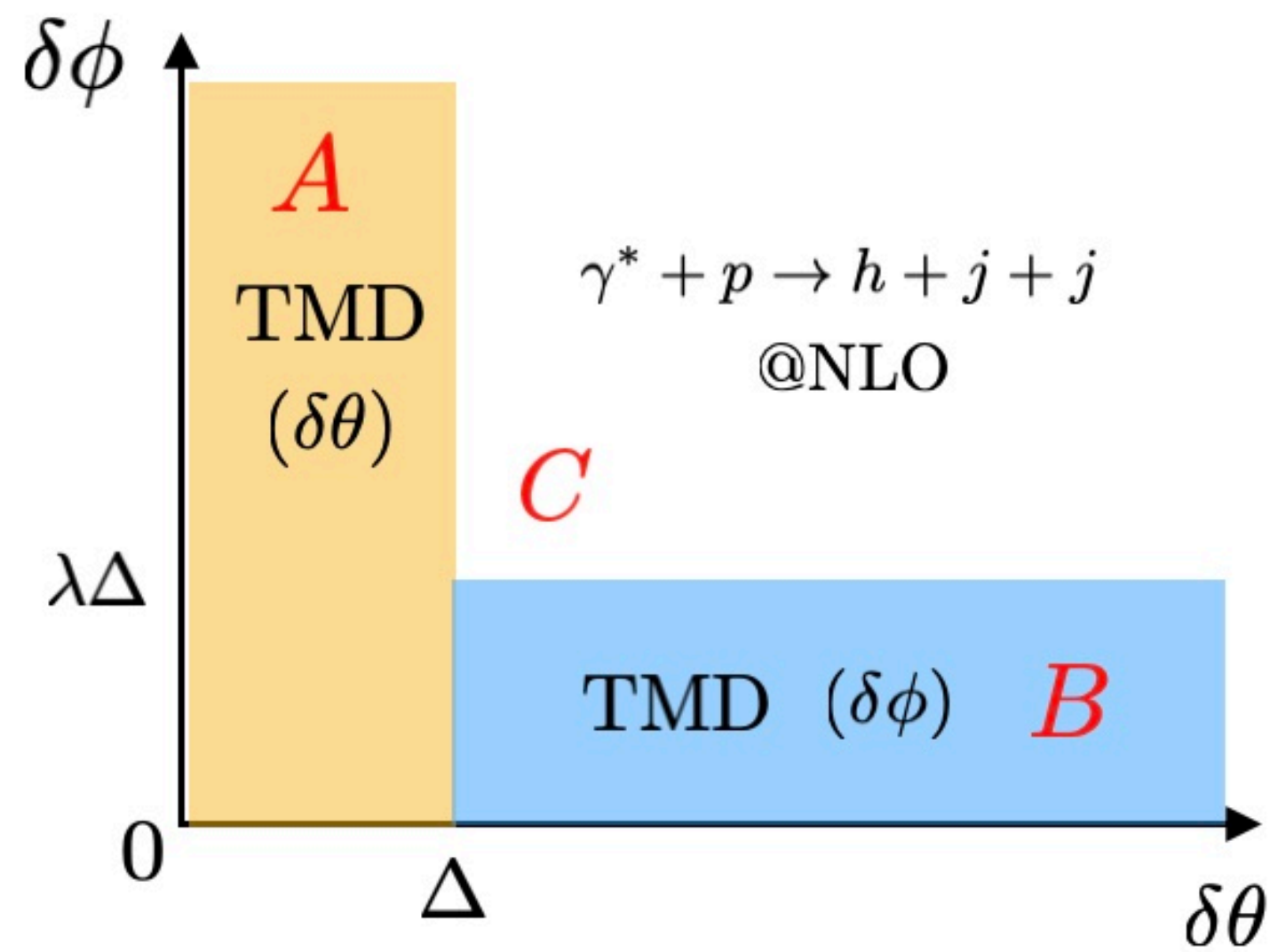
DIS with qT subtraction



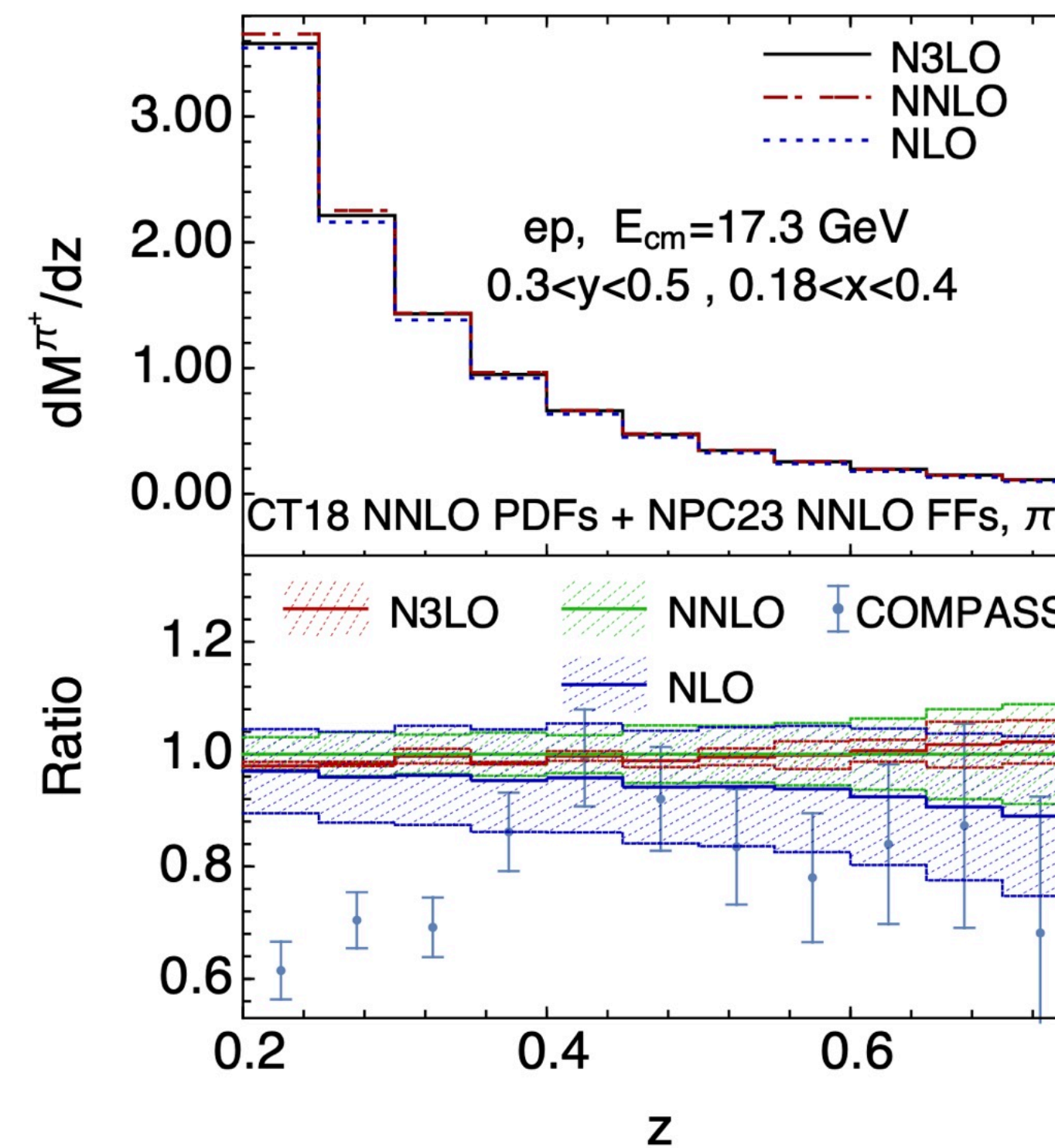
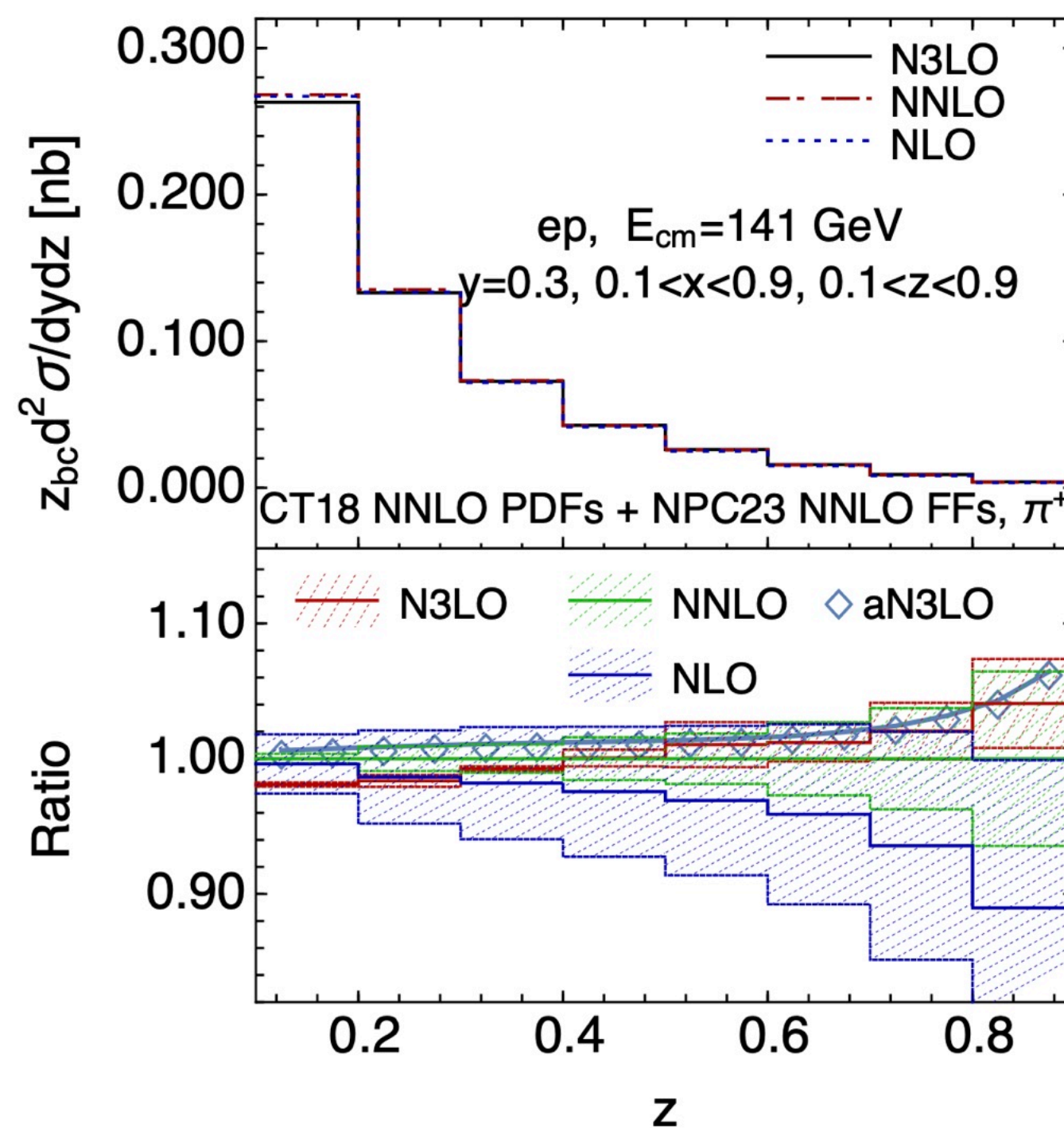
$$\frac{d\sigma}{d\mathcal{O}} = \underbrace{\int_0^\Delta d\delta\theta \frac{d\sigma^A}{d\delta\theta d\mathcal{O}}}_A +$$

$$\int_\Delta^{\delta\theta^{\max}} d\delta\theta \times \left(\underbrace{\int_0^{\lambda\Delta} d\delta\phi \frac{d\sigma^B}{d\delta\theta d\delta\phi d\mathcal{O}}}_B + \underbrace{\int_{\lambda\Delta}^{\delta\phi^{\max}} d\delta\phi \frac{d\sigma^C}{d\delta\theta d\delta\phi d\mathcal{O}}}_C \right)$$

See Ding Yu Shao's talk



SIDIS @ N³NLO

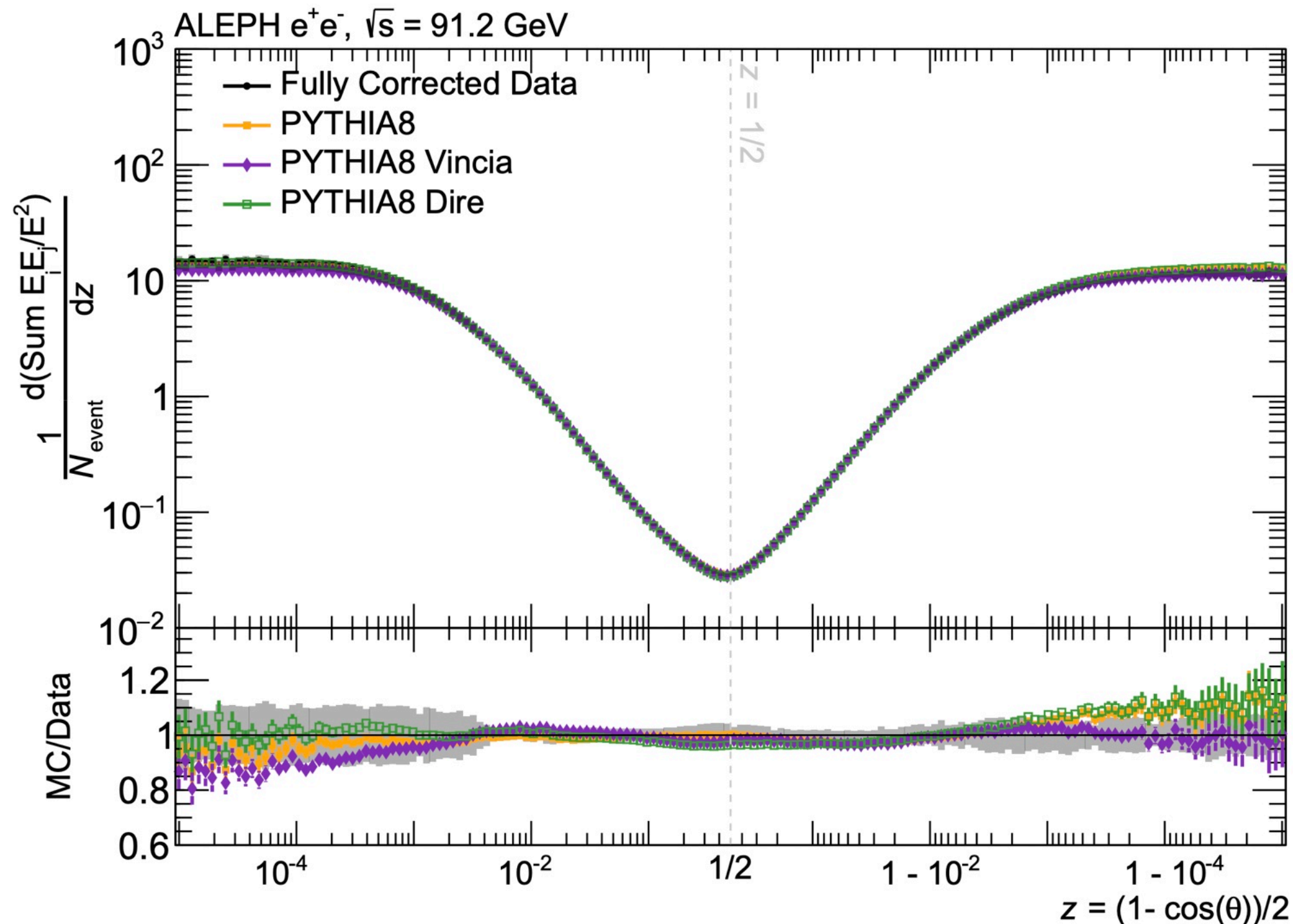


EEC in DIS

EEC a uniquely infrared-safe, multi-scale observable that bridges perturbative and non-perturbative QCD

$$EEC = \sum_{a,b} \int d\sigma_{V \rightarrow a+b+X} \frac{2E_a E_b}{Q^2 \sigma_{\text{tot}}} \delta(\cos(\theta_{ab}) - \cos(\chi))$$

$$TEEC = \sum_{a,b} \int d\sigma_{pp \rightarrow a+b+X} \frac{2E_{T,a} E_{T,b}}{|\sum_i E_{T,i}|^2} \delta(\cos \phi_{ab} - \cos \phi)$$

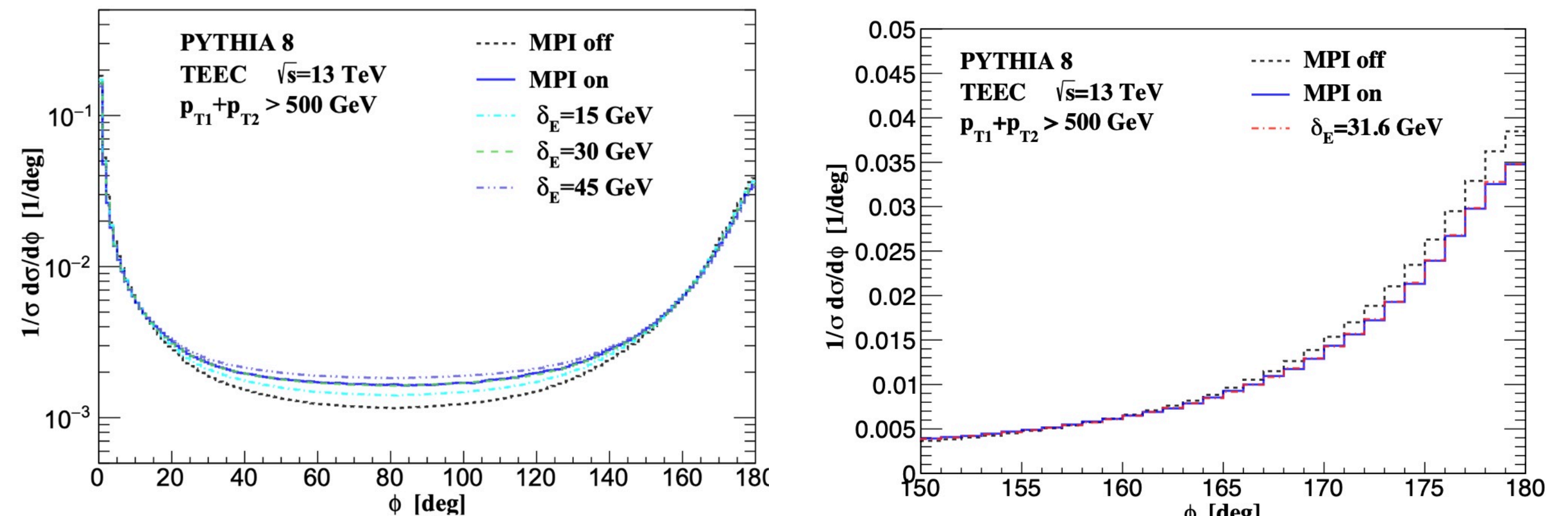


2025 HB - Finalization of Result

Bossi et al arXiv:2505.11828,

for EEC see Huaxing Zhu, Xiaohui Liu and Haolin Wang's talk

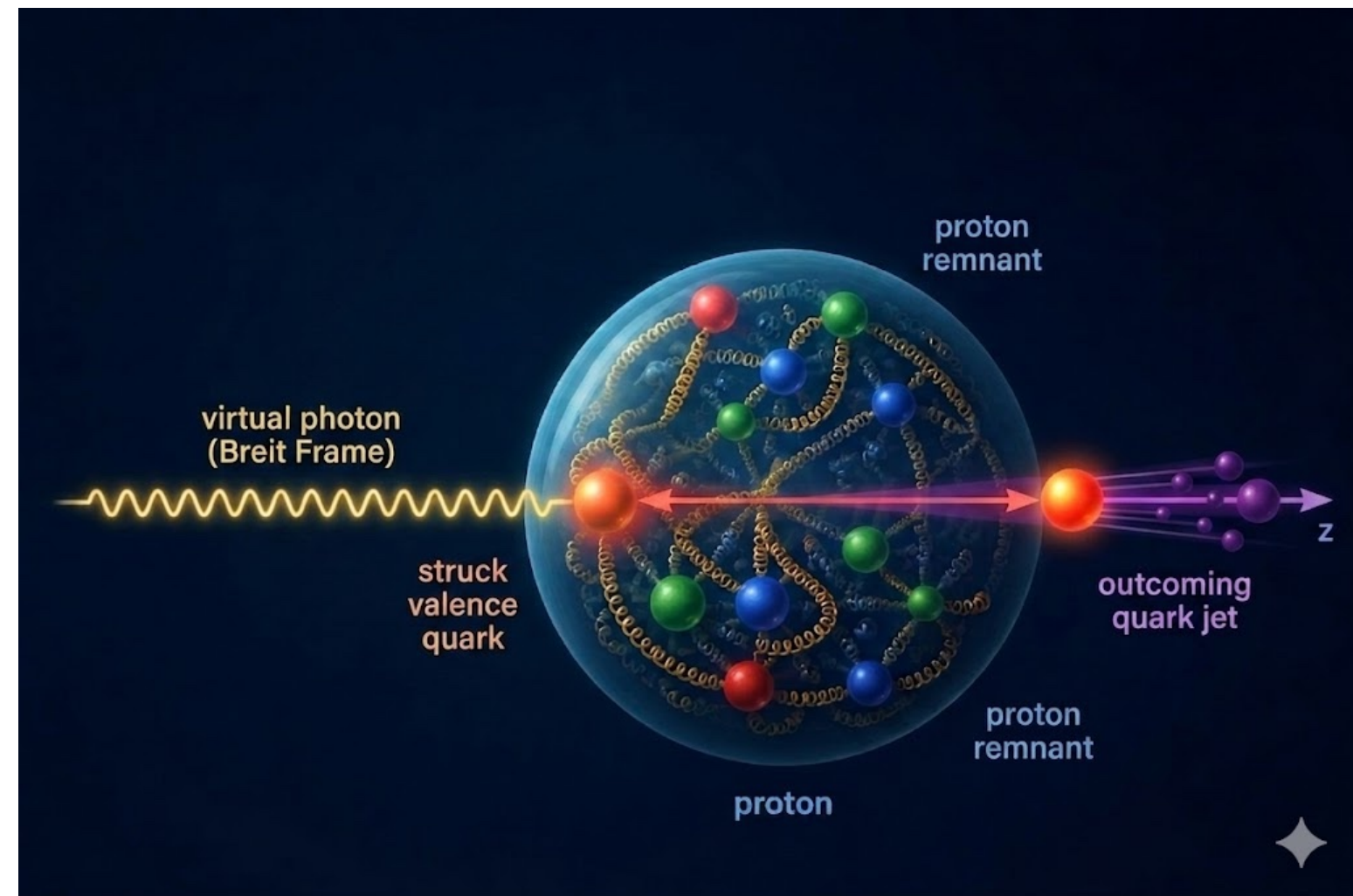
test on sensitivity of TEEC to underlying events



$$\frac{1}{\sigma_{\text{MPI}}} \frac{d\sigma_{\text{MPI}}}{d\phi} = \frac{Q}{Q + 2\delta_E} \left(\frac{1}{\sigma} \frac{d\sigma}{d\phi} + \frac{2}{\pi} \frac{\delta_E}{Q} \right)$$

Gao, HTL, Mout, Zhu, PRL, 2019, JHEP, 2024

EEC in DIS



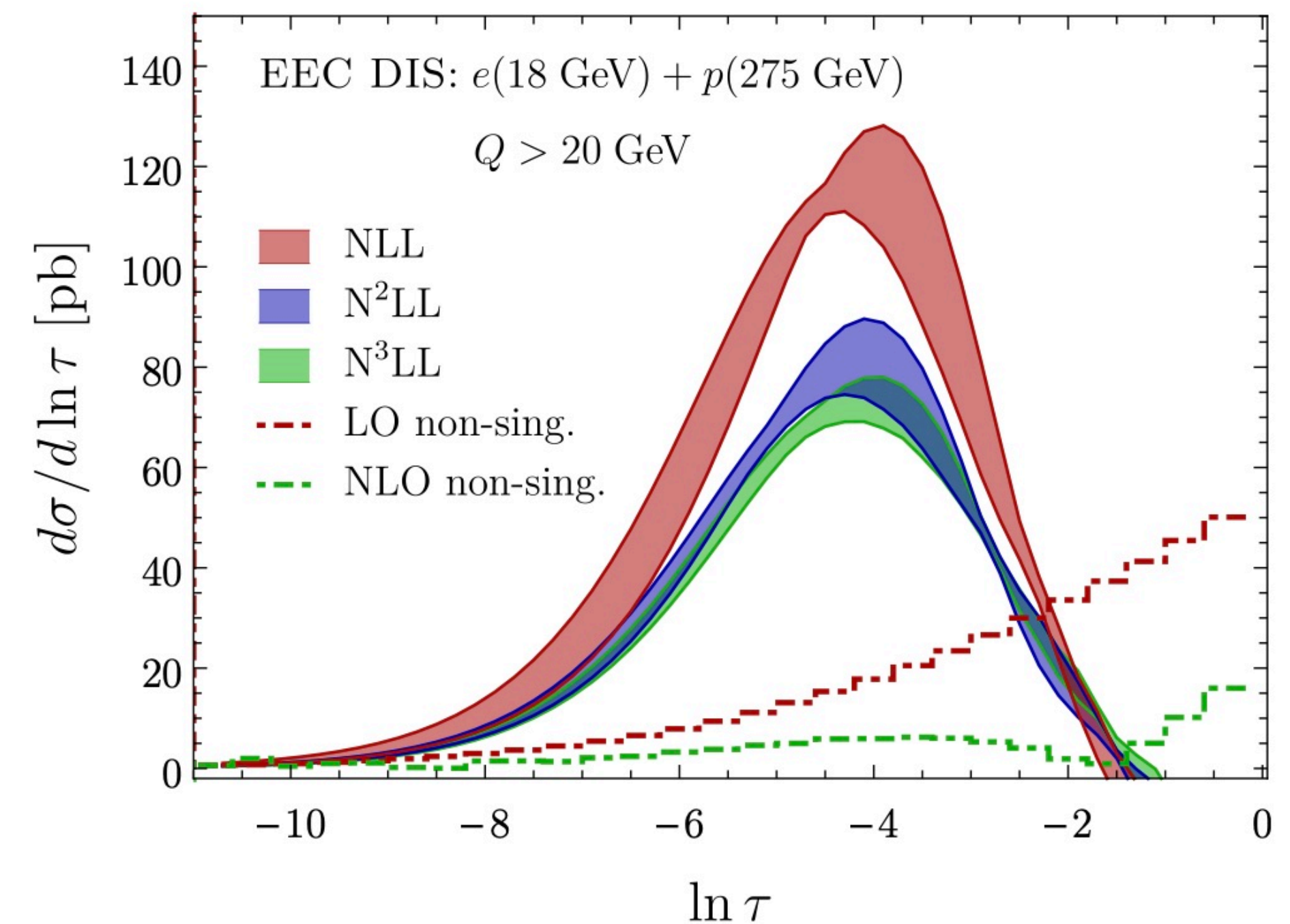
We proposed a definition of EEC in DIS:
correlation between initial proton and final state hadron

$$\text{EEC} = \sum_a \int d\sigma_{lp \rightarrow l+a+X} \left(\frac{p \cdot p_a}{\sum_i p \cdot p_i} \right) \delta(\cos \chi - \cos \theta_{ap})$$

Li, Makris, Vitev, PRD 2021

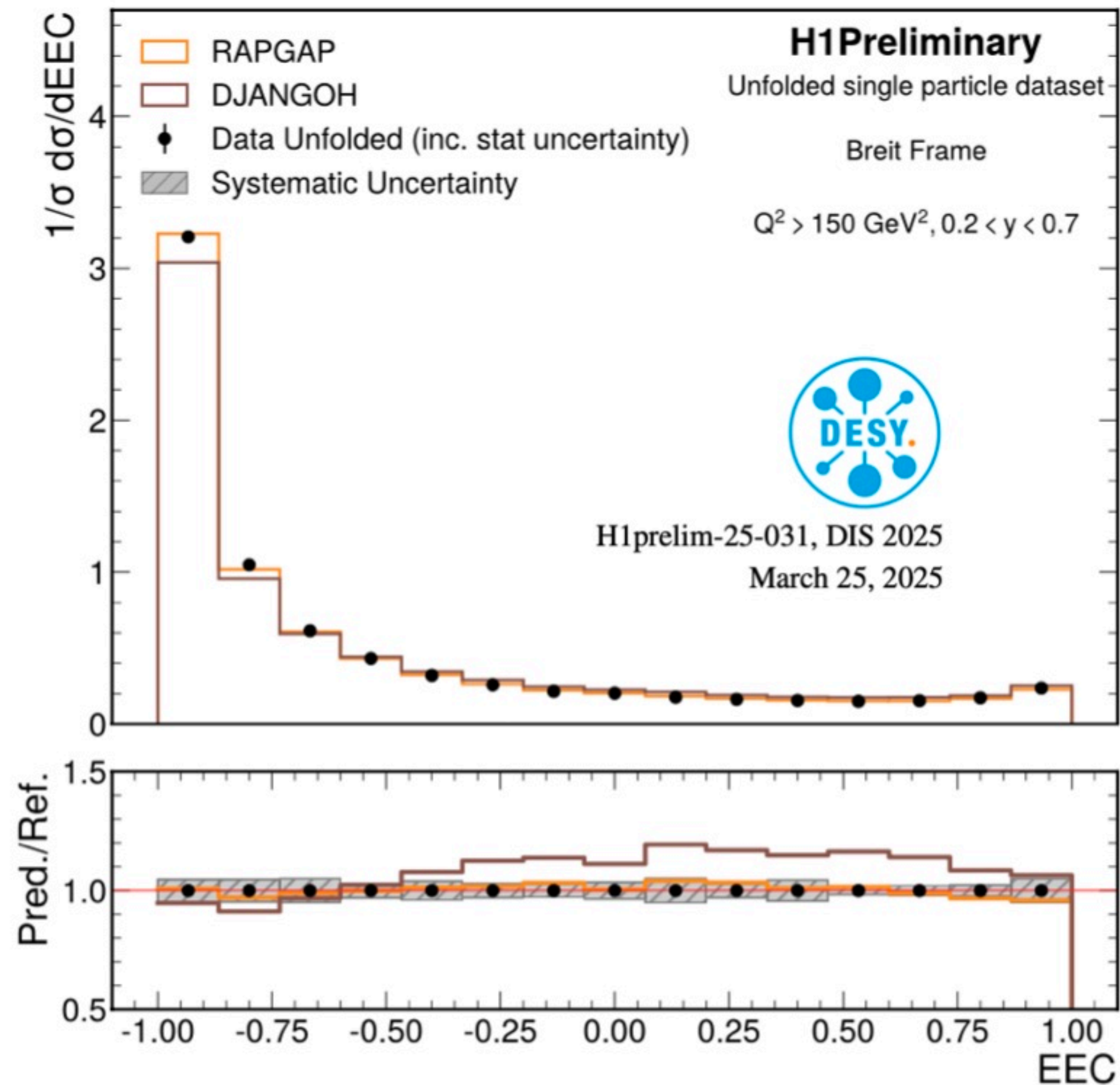
infrared-safe, well-defined: similar to EEC definition in e^+e^- collisions

- weight function is Lorentz Invariant
- radiation close to the beam direction is suppressed
- soft radiation/hadronization effect is suppressed
- beam remnants are suppressed

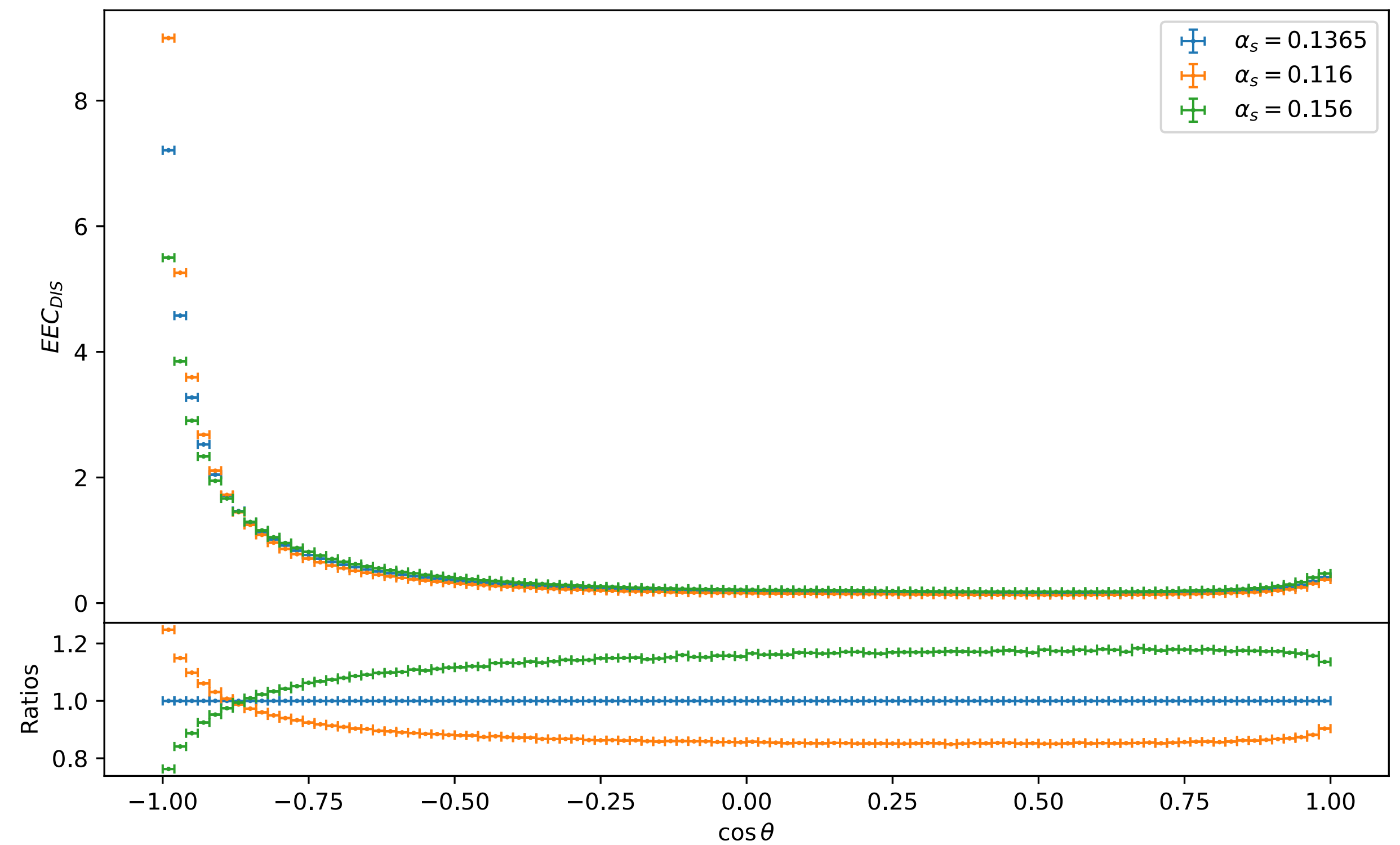


EEC in DIS

Proposed EEC in DIS measured by H1



sensitivity to the strong coupling constant



Chen, He, HTL, in preparation 2026

EEC in DIS

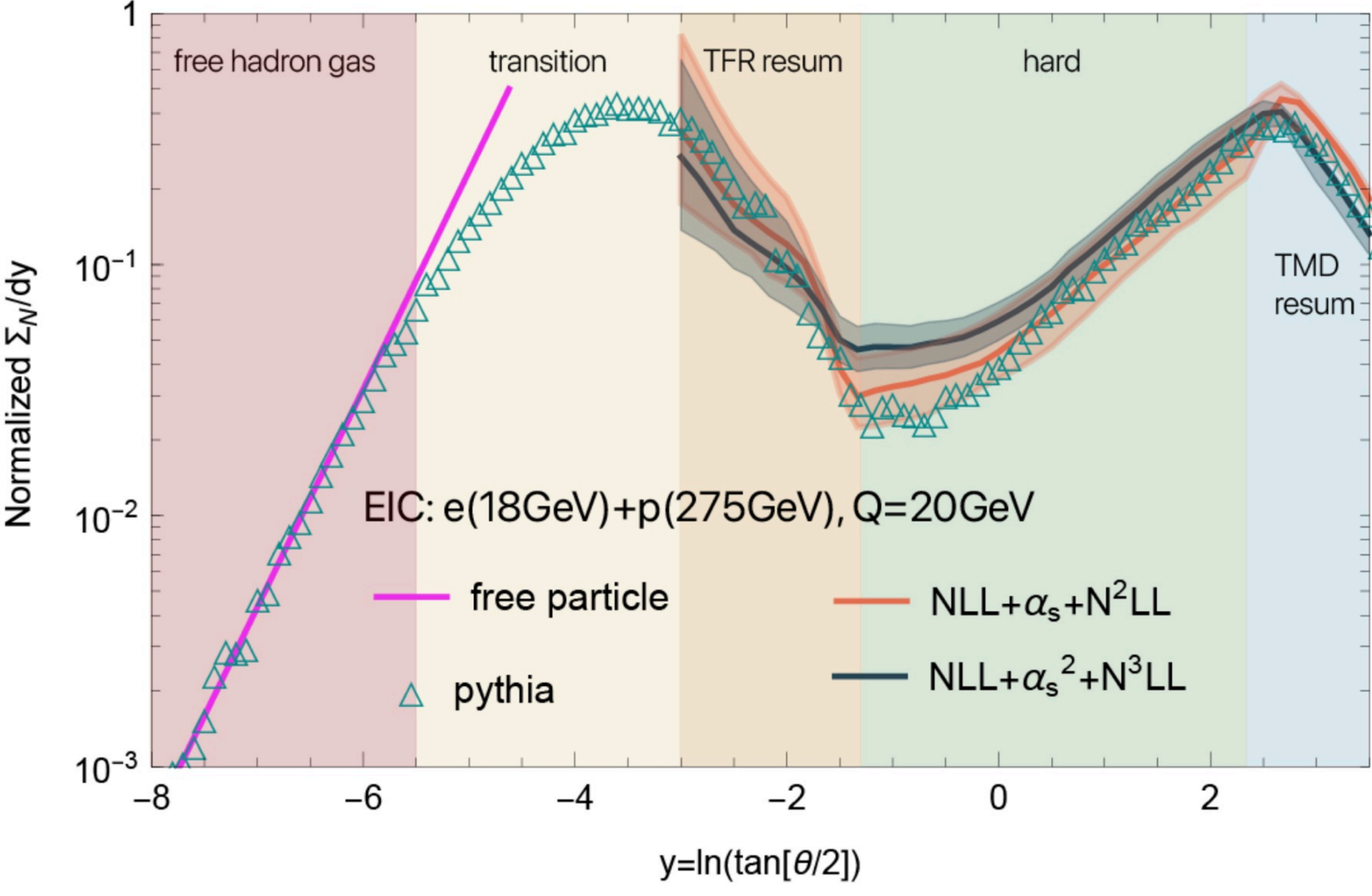
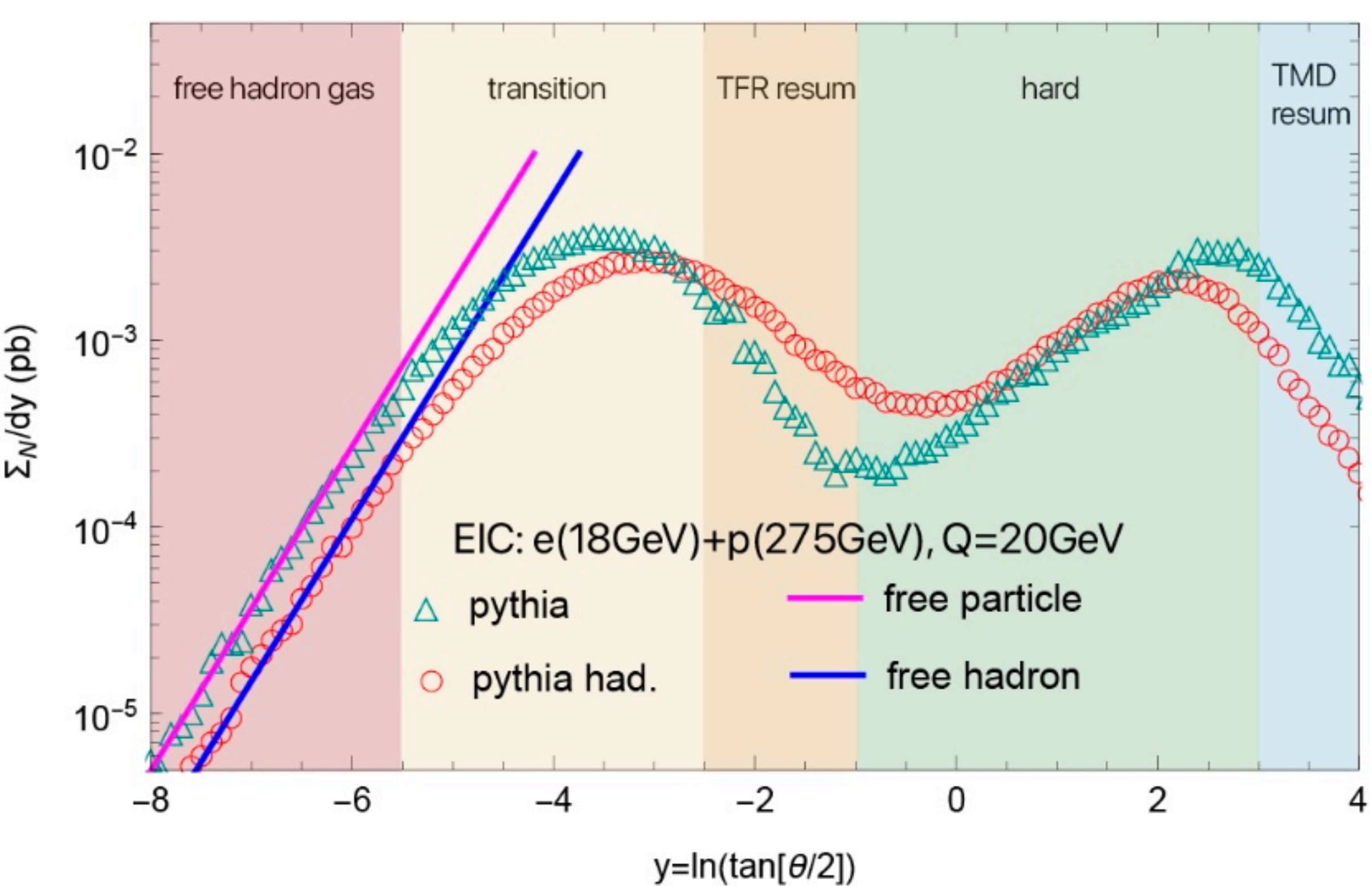
NEEC in DIS

Nucleon Energy Correlators

$$\Sigma_N(Q^2, \theta^2) = \sum_i \int d\sigma(x_B, Q^2, p_i) x_B^{N-1} \frac{\bar{n} \cdot p_i}{P} \delta(\theta^2 - \theta_i^2)$$

Liu, Zhu, PRL 2023

Cao, Liu, Zhu, PRD 2024



EEC in Polarized DIS

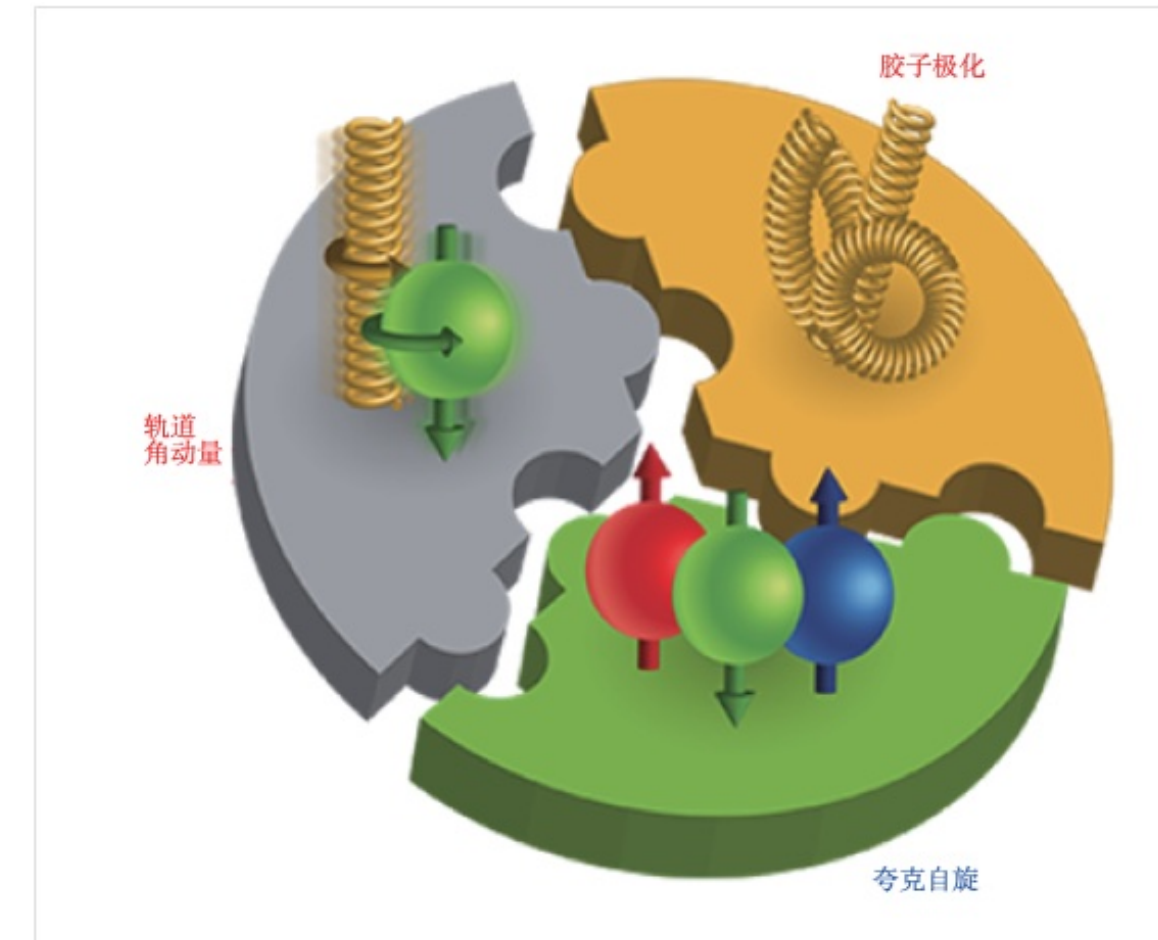
○ Unraveling the Proton Spin Puzzle

see Jian Zhou's talk

Ji's sum rule for proton spin

$$\frac{1}{2} = \frac{1}{2} \Delta\Sigma + L_q + J_g$$

Helicity dependent PDFs: JAM, NNPDF, BDSSV, MAP et al



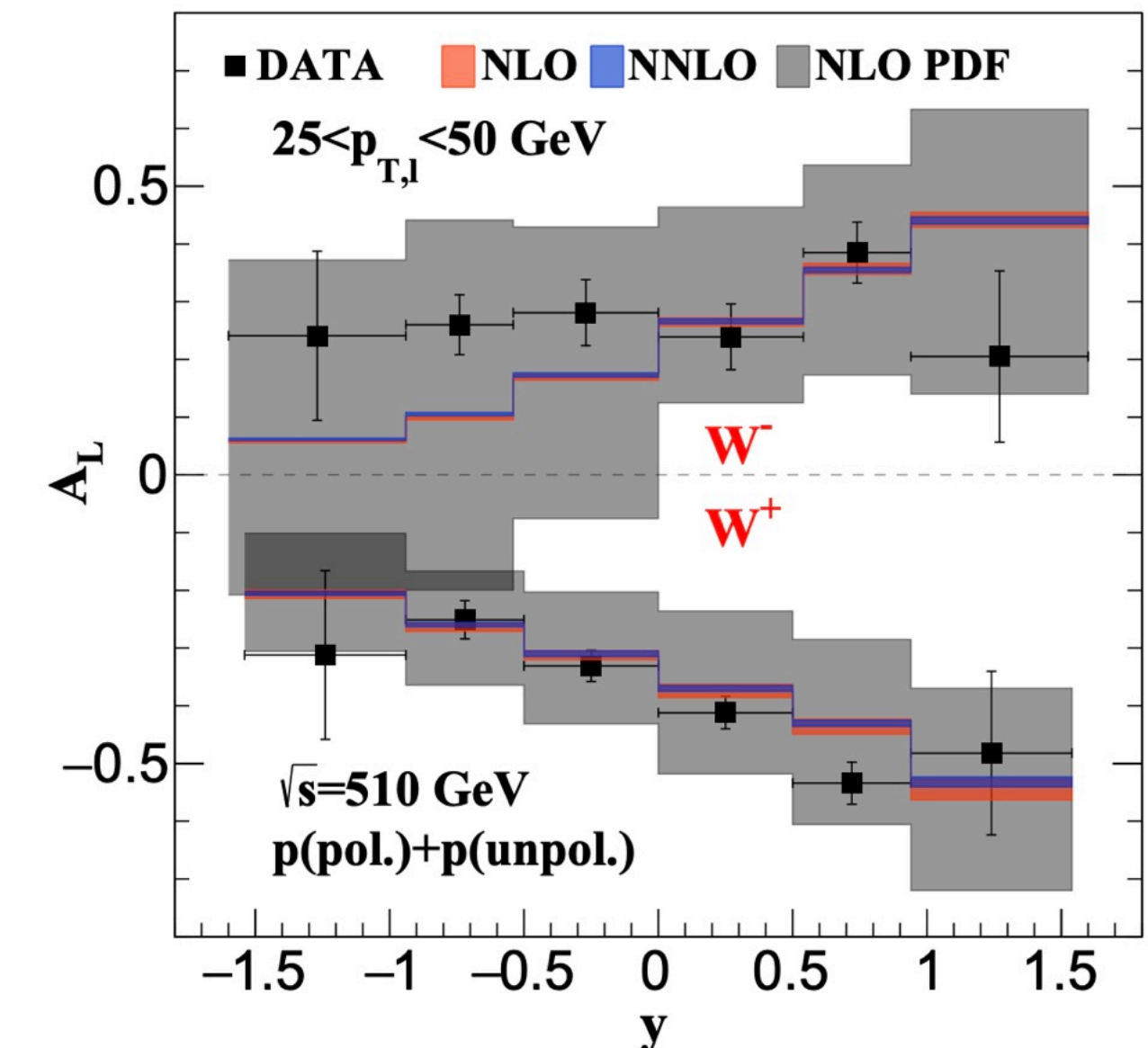
○ Advancing Precision pQCD & Factorization

$$\Delta\mathcal{B}_{i/N}^{\text{bare}}(x, b_{\perp}) = \sum_i \int_x^1 \frac{d\xi}{\xi} \Delta\mathcal{I}_{ij}^{\text{bare}}(\xi, b_{\perp}) \Delta\phi_{j/N}^{\text{bare}}(x/\xi) + \mathcal{O}(\Lambda_{\text{QCD}} b_{\perp})$$

Matching of helicity TMDs, Zhu, JHEP 2026

○ Novel Observables for 3D Structure such as EEC

Gao, HTL, Zhu, PRD 2026



Boughezal, HTL, Petriello, PLB 2021 12/16

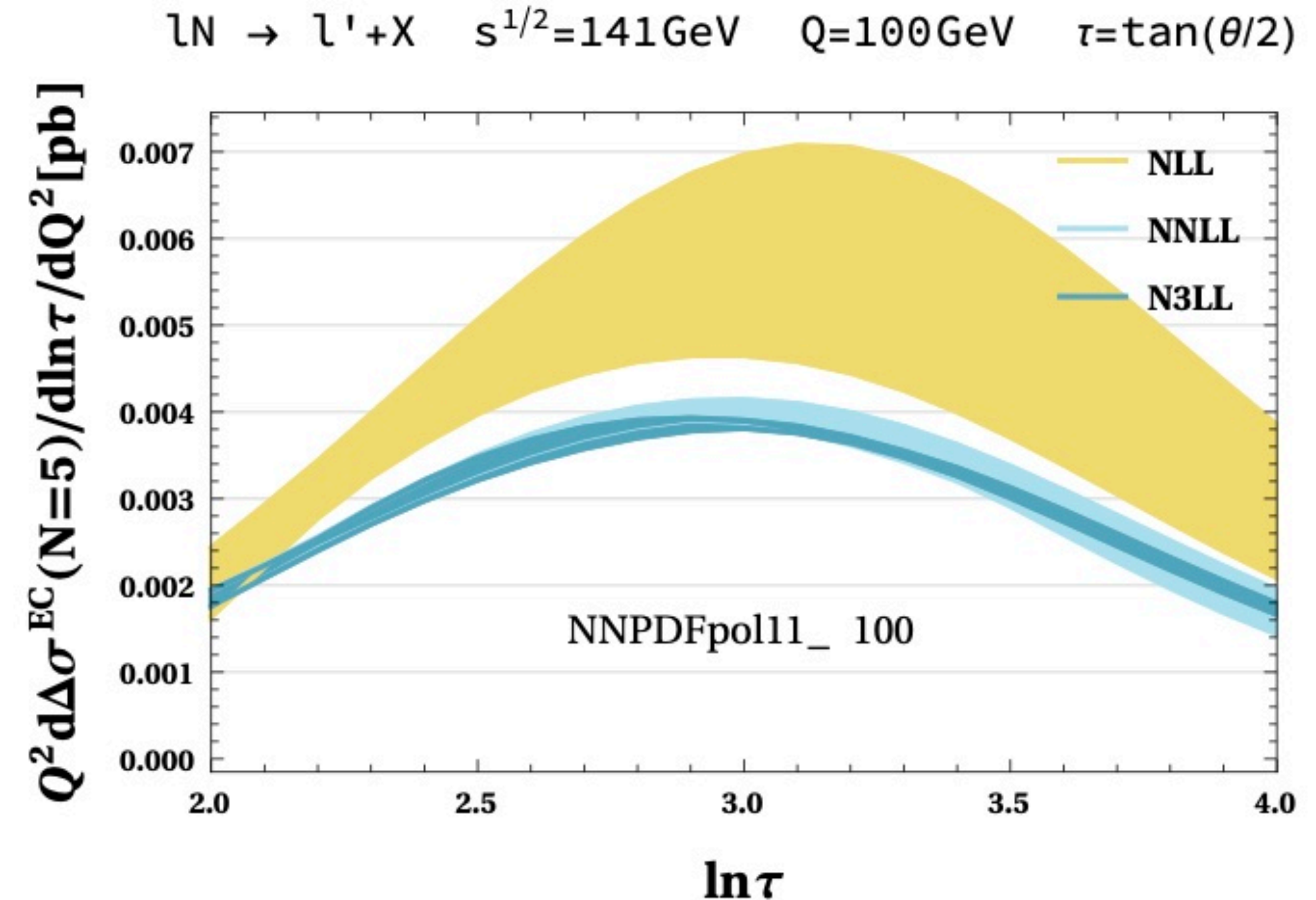
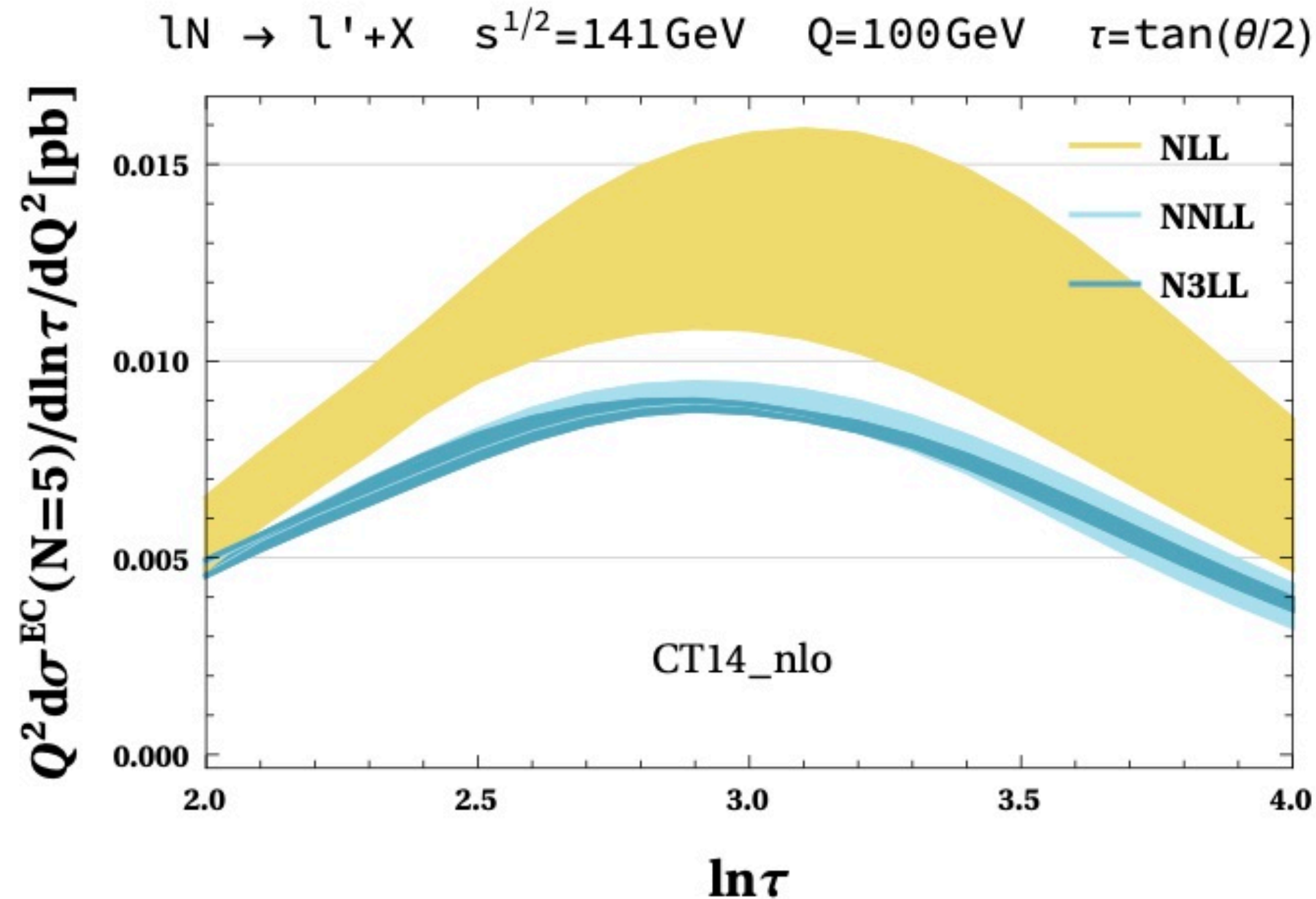
EEC in Polarized DIS

Factorized formula in polarized DIS

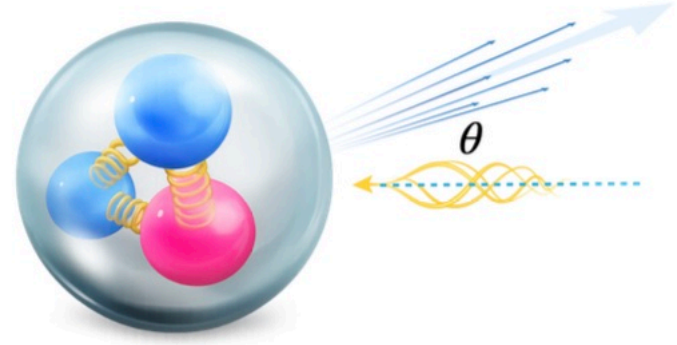
Gao, HTL, Zhu, PRD 2026

$$xyz \frac{d\sigma_{\ell+N \rightarrow \ell'+h+X}}{d^2\vec{q}_\perp dx dy dz} \simeq \sum_f H_f(Q^2, \mu) \int \frac{d^2\vec{b}_\perp}{(2\pi)^2} e^{-i\vec{b}_\perp \cdot \vec{q}_\perp} \mathcal{S}_{n\bar{n}}(b_\perp, \mu, \nu) z \mathcal{F}_{h/f} \left(z, \frac{b_\perp}{z}, E_{\bar{n}}, \mu, \nu \right) \\ \times \left(\sigma_0^U \times x \mathcal{B}_{f/N}(x, b_\perp, E_n, \mu, \nu) + \lambda_\ell S_\parallel \times \sigma_0^L \times x \Delta \mathcal{B}_{f/N}(x, b_\perp, E_n, \mu, \nu) \right),$$

$$\tau = \tan(\theta/2)$$



EEC in Polarized DIS

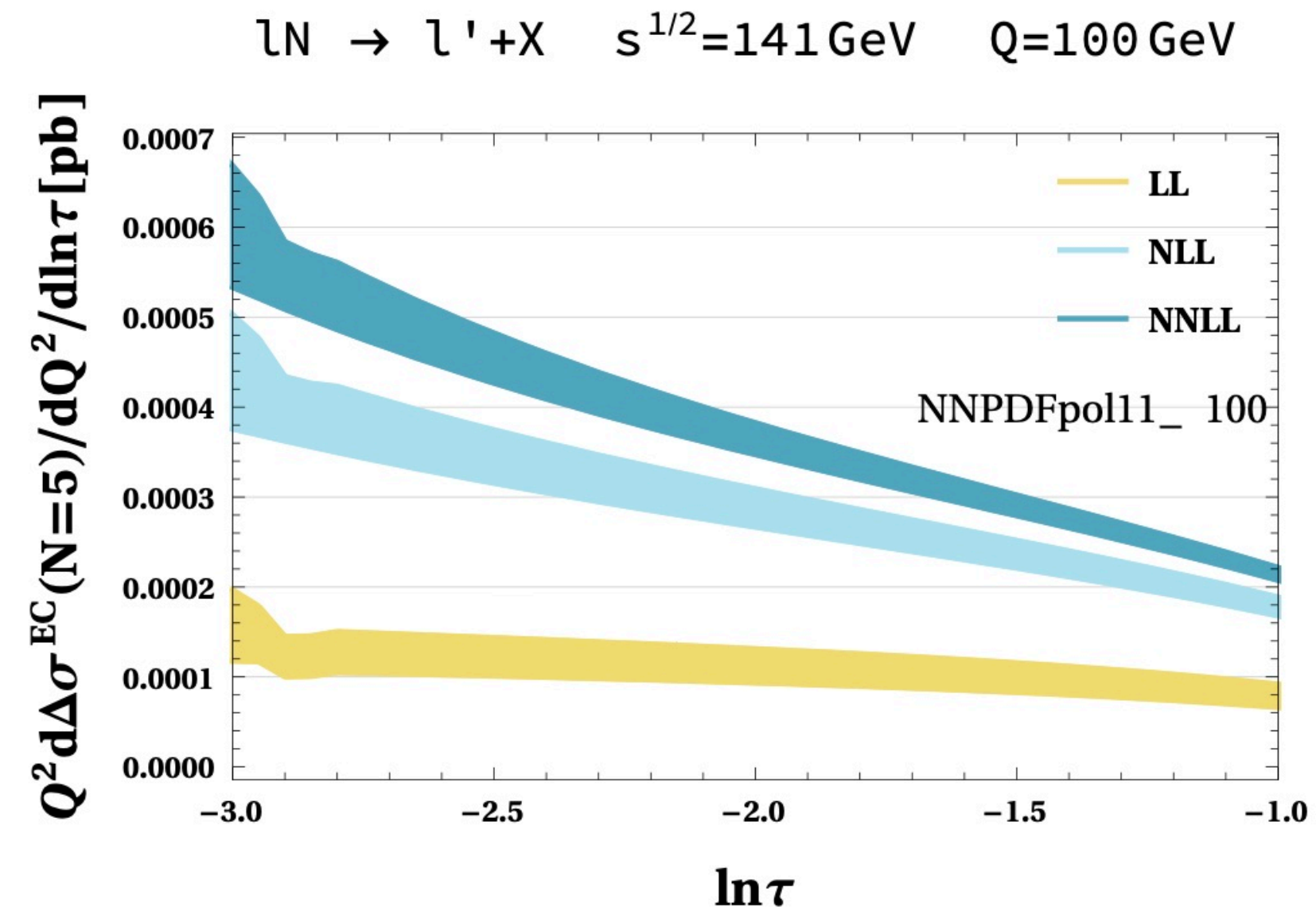
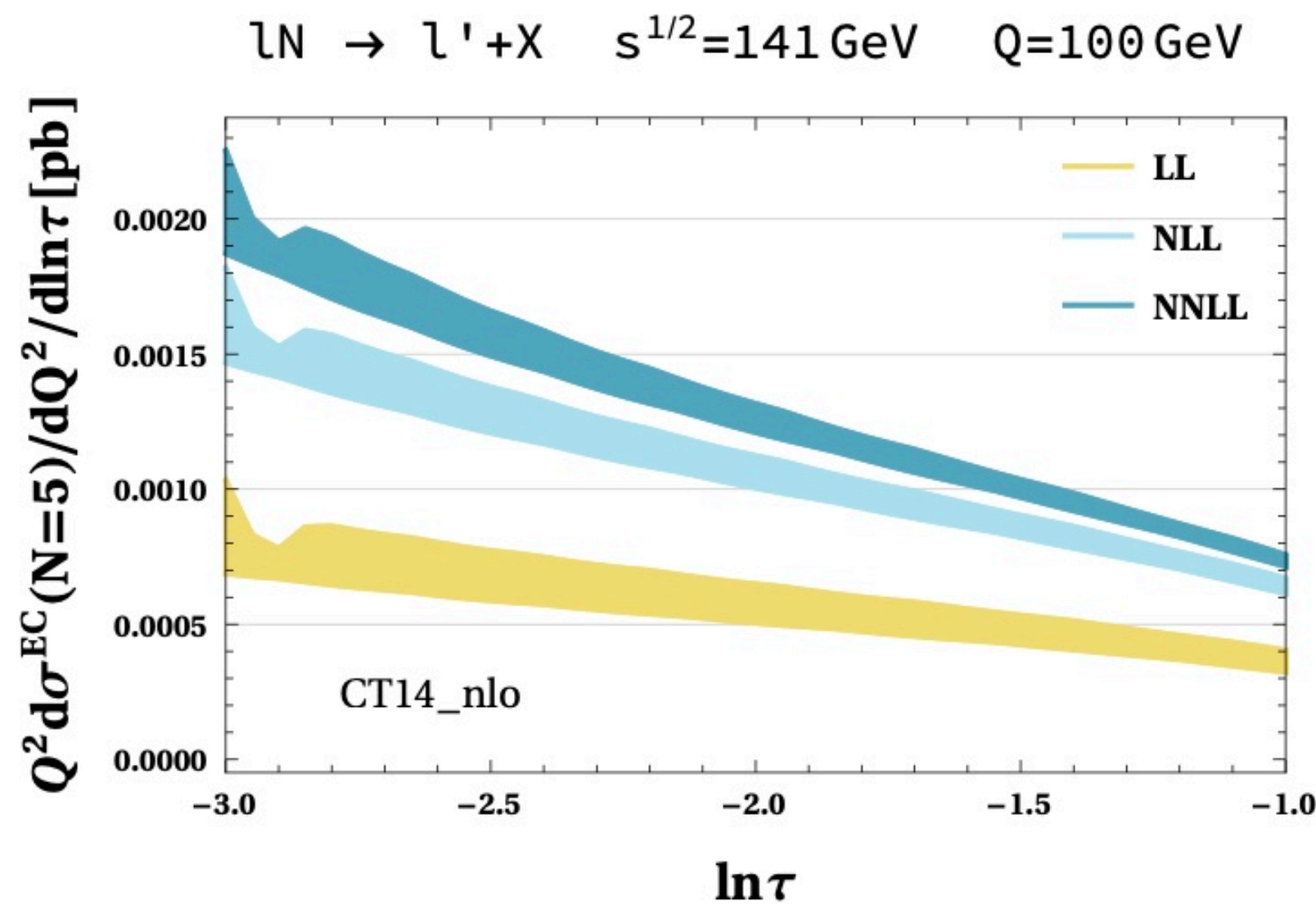


in the target region

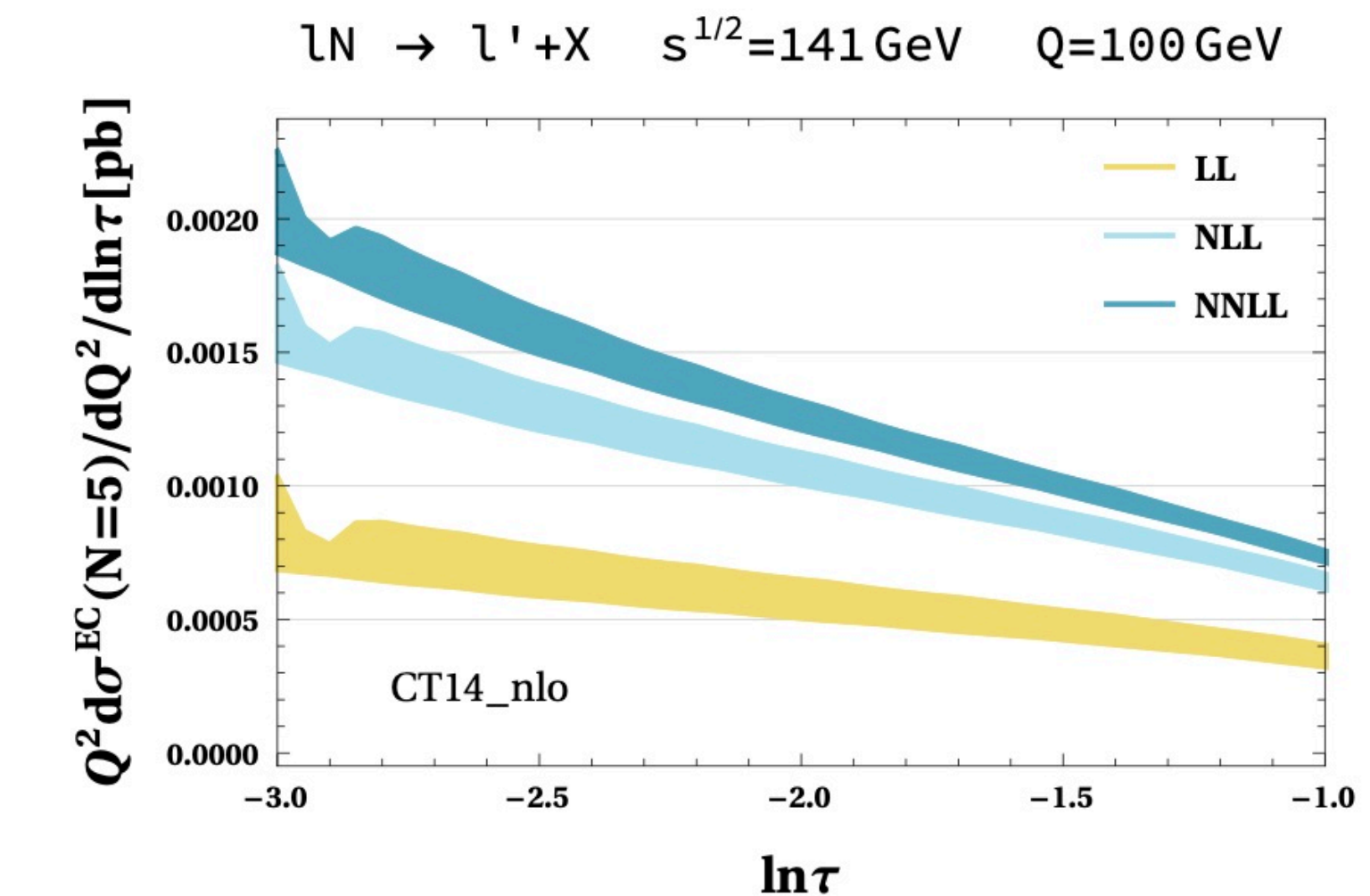
Gao, HTL, Zhu, PRD 2026

$$\mathcal{F}_{i/N}^{\text{EC}} \left(z, \ln \frac{E_a \sin \theta}{\mu}, \mu \right) = f_i(z, \mu) - \int_z^1 \frac{d\xi}{\xi} \times \mathcal{I}_{ij} \left(\frac{z}{\xi}, \ln \frac{E_a \sin \theta}{\mu}, \alpha_s(\mu) \right) \xi f_j(\xi, \mu) + \mathcal{O} \left(\frac{\Lambda_{\text{QCD}}}{q_T} \right)$$

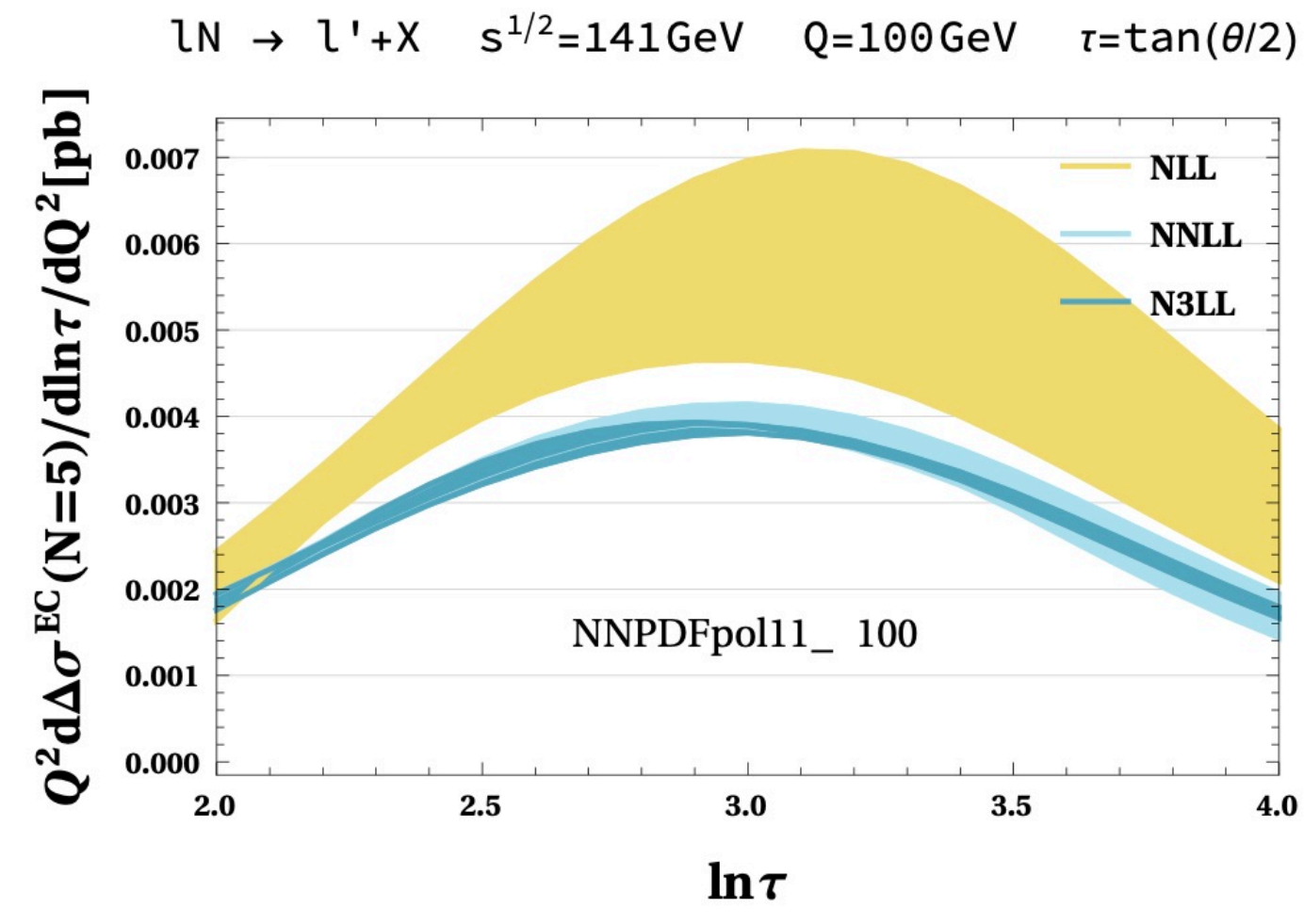
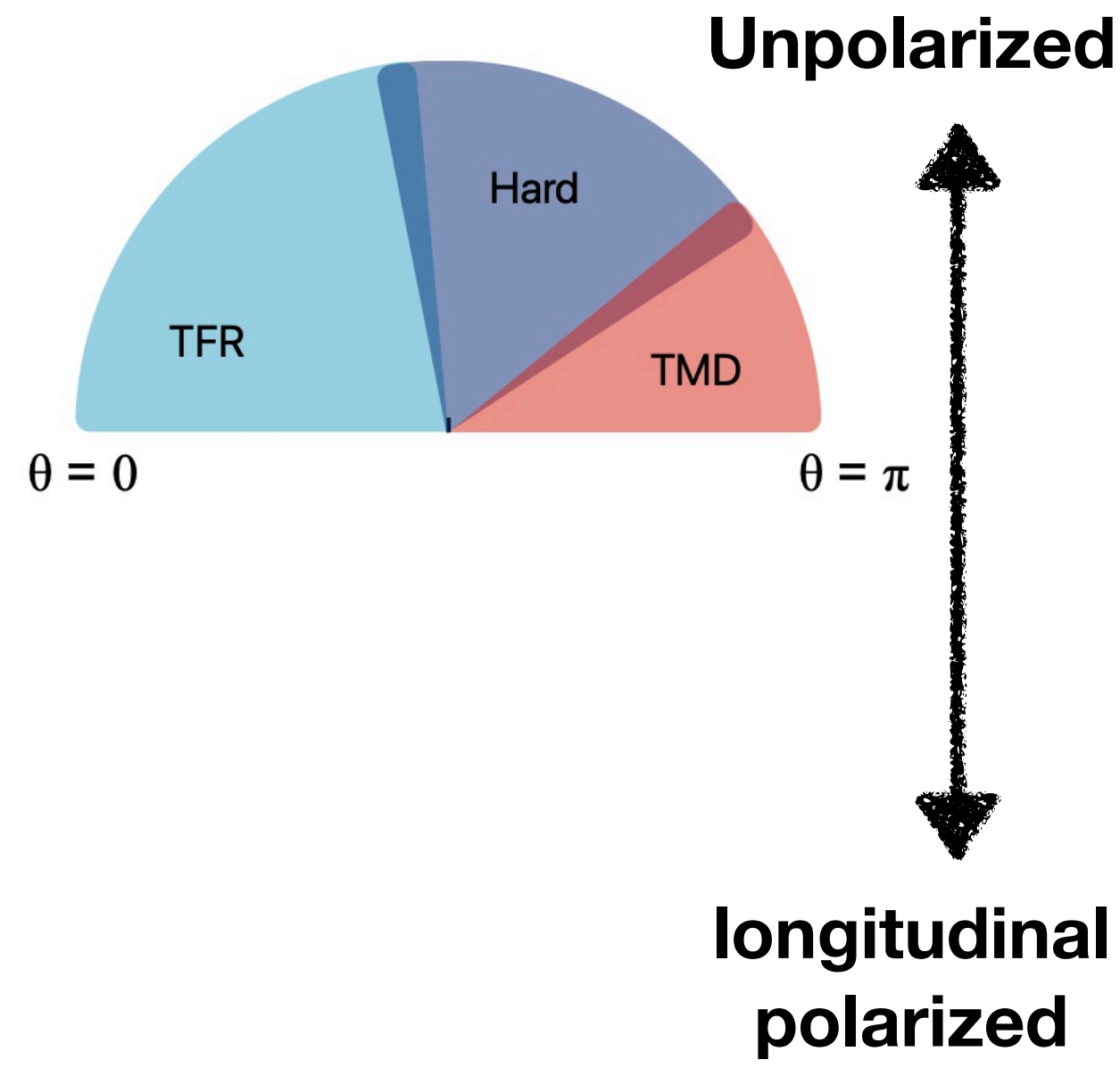
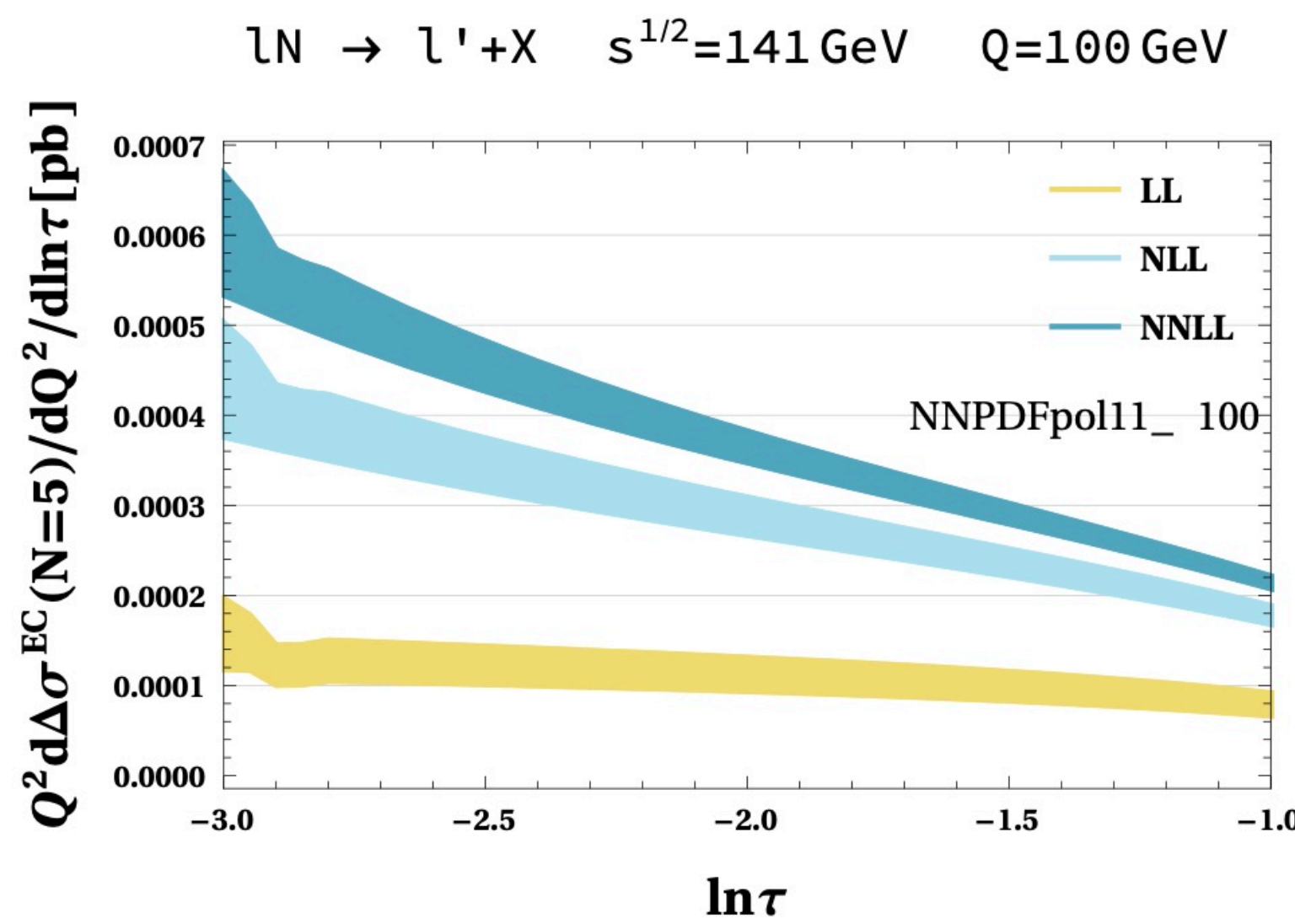
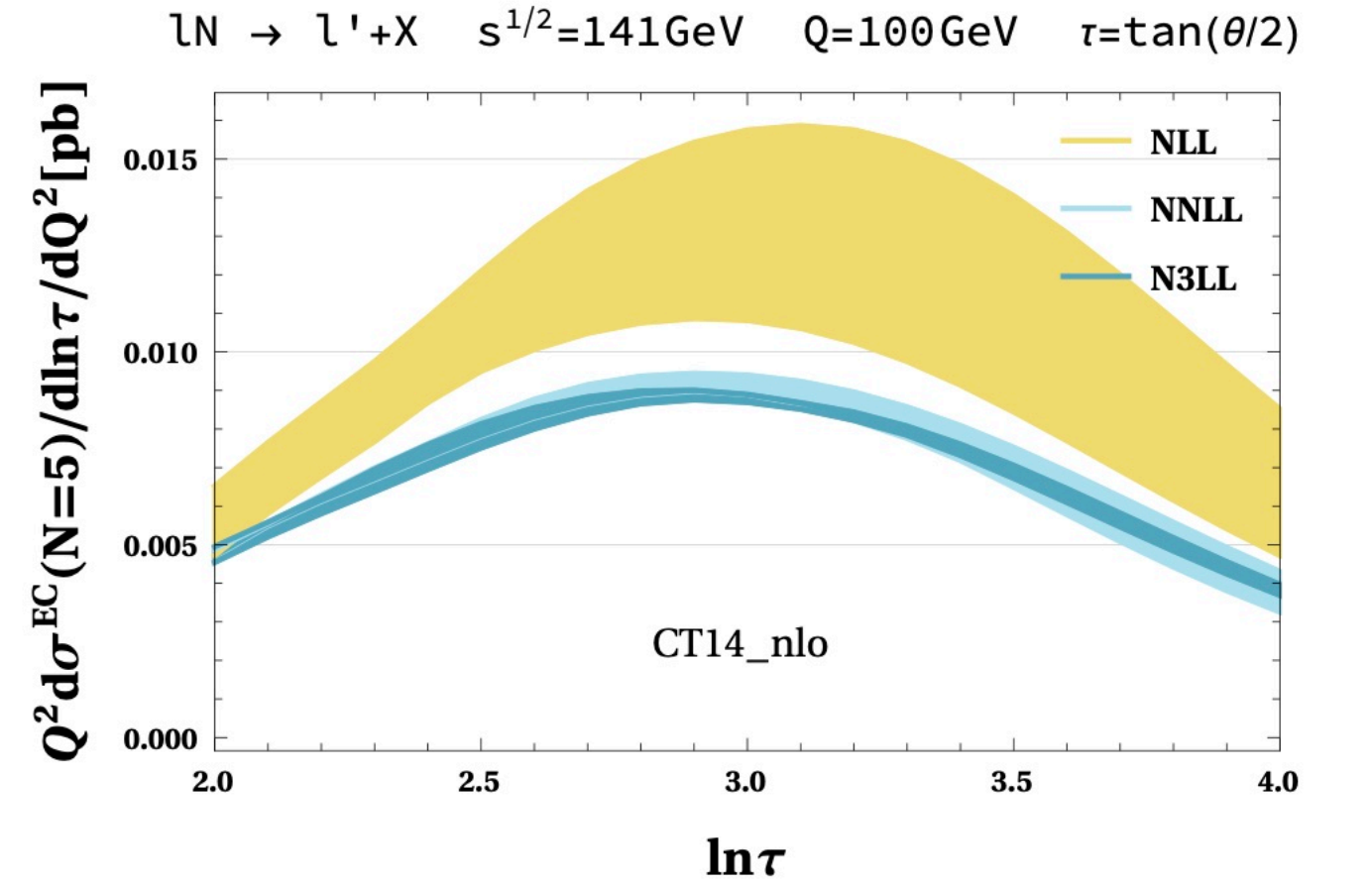
$$\frac{d\mathcal{I}_{ij}}{d \ln \mu^2} \left(z, \ln \frac{E_a \sin \theta}{\mu} \right) = \int_z^1 \frac{d\xi}{\xi} \left[P_{ik}(\xi) \mathcal{I}_{kj} \left(\frac{z}{\xi}, \ln \frac{E_a \sin \theta}{\xi \mu} \right) - \mathcal{I}_{ik} \left(\frac{z}{\xi}, \ln \frac{E_a \sin \theta}{\mu} \right) \xi P_{kj}(\xi) \right].$$



EEC in Polarized DIS

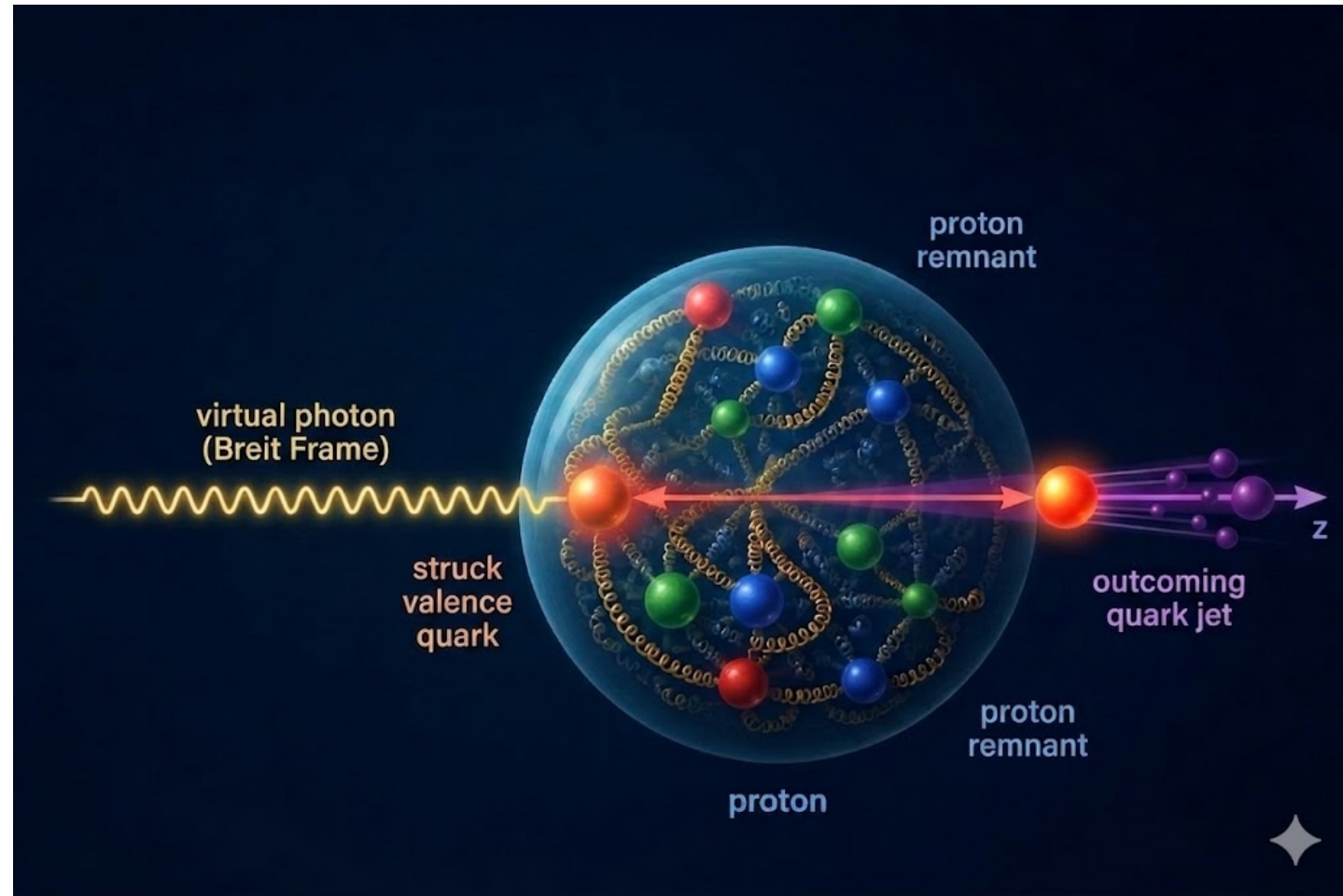


Target Region \longleftrightarrow Current Region

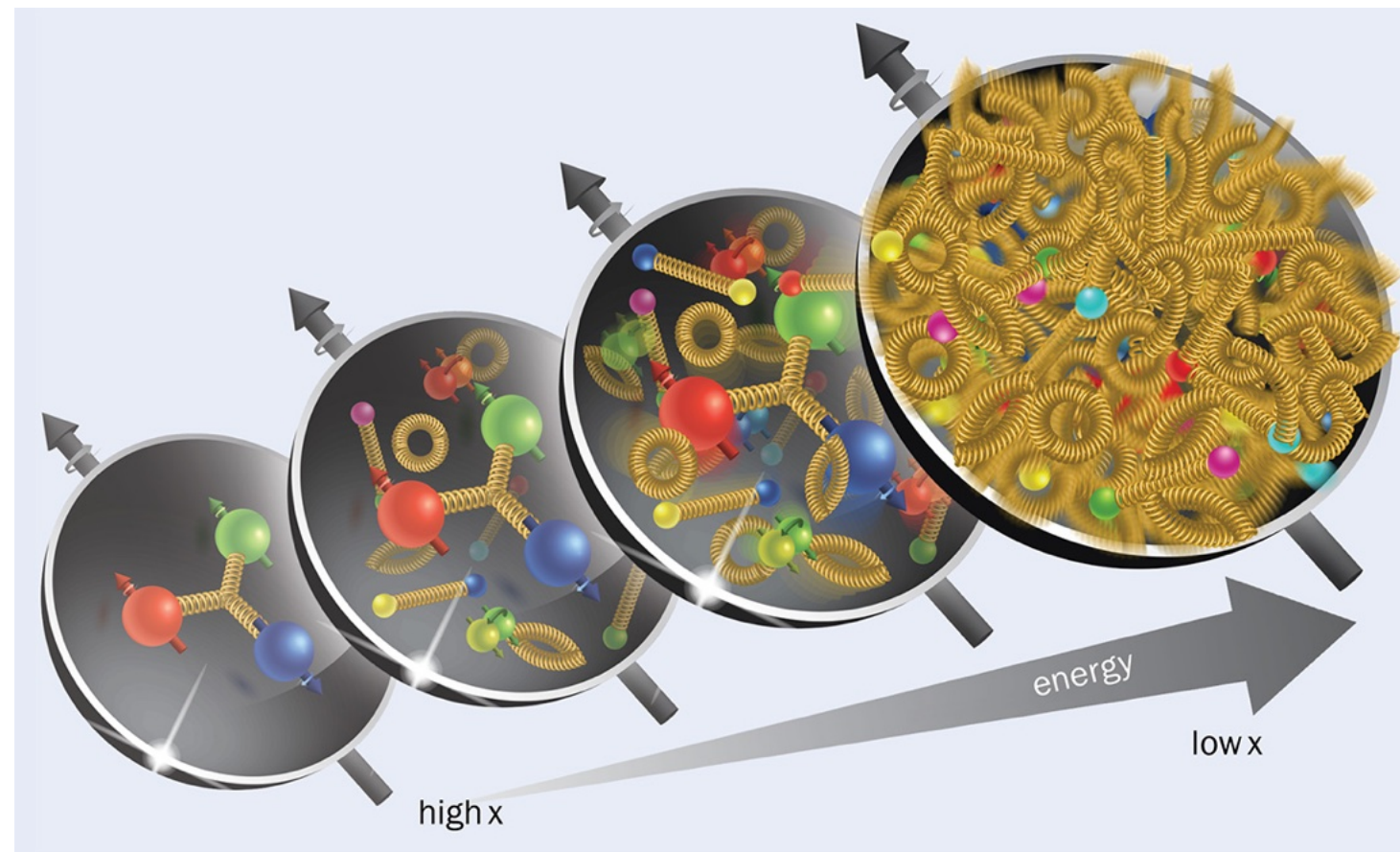


polarized distribution in both limits are validated with NLO results

Summary



- A new method to calculate fixed order results with hadron final state, obtained the NNLO and N3LO fully differential SIDIS cross section.
- The Breit-frame DIS energy-energy correlator (EEC) is a novel, theoretically clean observable that directly probes collinear and transverse-momentum
- All-Angle Description: from target (NLL) to current region (N3LL) EEC
- Polarized Extension: from target (NNLL) to current region (N3LL) EEC



Thank you!