Anisotropy of Lepton-Jet Correlation in Inclusive and Diffractive DIS

In collaboration with Bowen Xiao, Yuanyuan Zhang: PRL.130, 151902(2023)
PRD. 109, 054004 (2024)

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DIS 2024

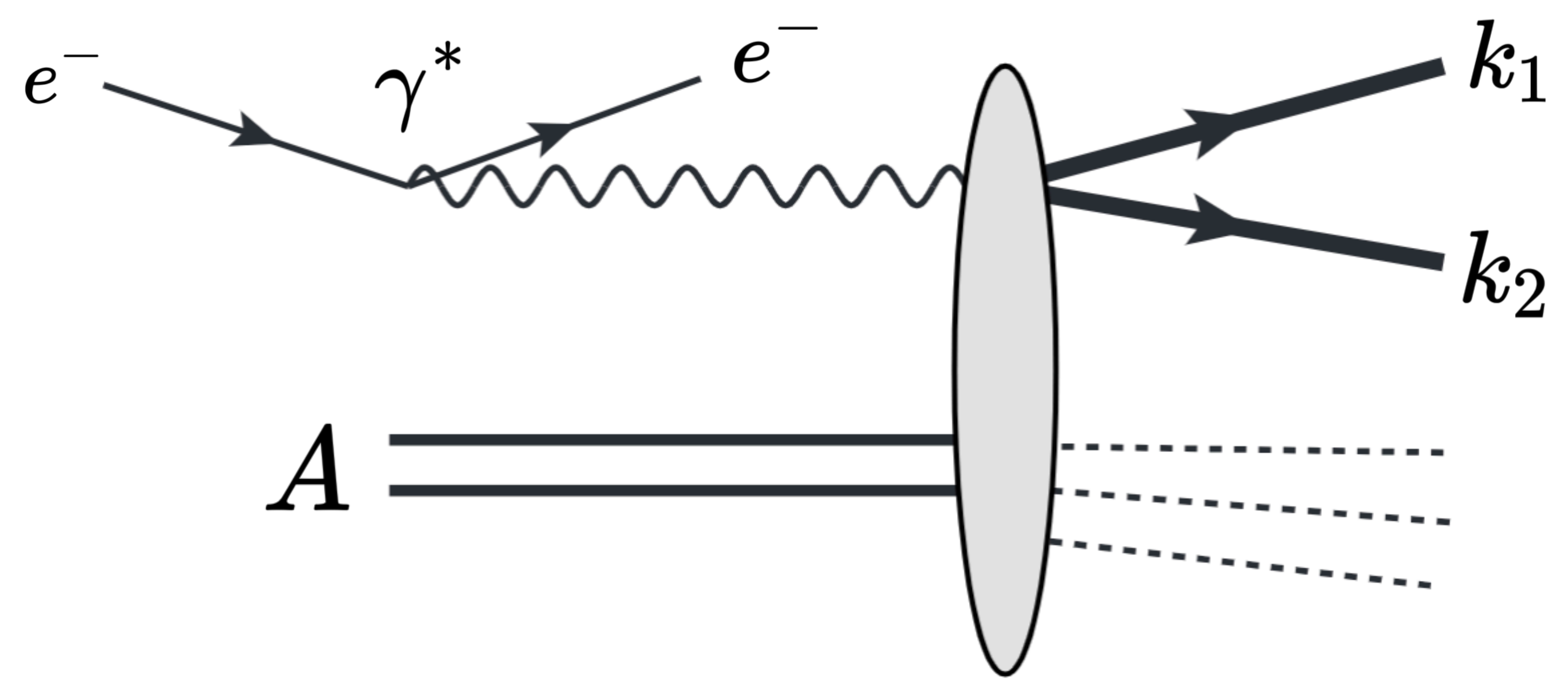
April 10th, 2024

HELSINKI INSTITUTE OF PHYSICS

UNIVERSITY OF JYVÄSKYLÄ

Centre of Excellence in Quark Matter

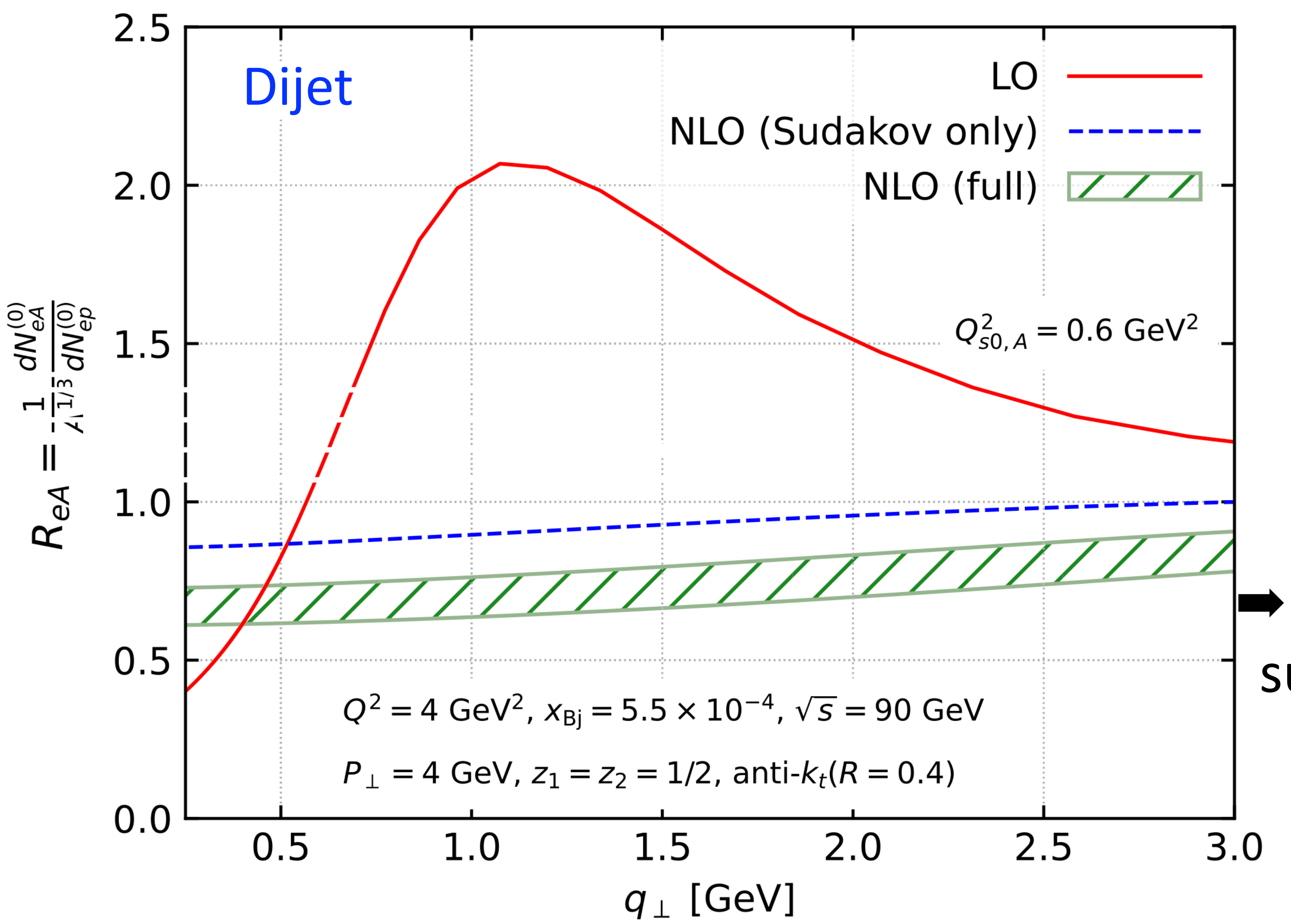
Two-particle correlation for saturation



- Tons of progress for the EIC !
  - Dihadron: e.g. Zheng-Aschenauer-Lee-Xiao, PRD89,074037(2014), Bergabo-Jaliilan-Marian PRD. 107, 054036 (2023) Iancu-Mulian JHEP07(2023)121
  - Dijet: e.g. Dominguez-Xiao-Yuan PRL106, 022301 (2011) Mäntysaari-Mueller-Salazar-Schenke PRL124,112301(2020) Caucal-Salazar-Schenke-Venugopalan JHEP11(2022)169
  - Photon-jet: e.g. Kolbé-Roy-Salazar-Schenke-Venugopalan JHEP01(2021)052

a recent review: Morreale-Salazar, Universe 7 (2021) 8, 312

- Back-to-back configuration
  - **Momentum imbalance** $\vec{q}_\perp = \vec{k}_{1\perp} + \vec{k}_{2\perp}$
  - Relative momentum $\vec{P}_\perp = (\vec{k}_{1\perp} - \vec{k}_{2\perp})/2$



➡Nuclear suppression

Caucal-Salazar-Schenke-Stebel-Venugopalan PRL 132, 081902 (2024)

- **Saturation momentum Q_s**

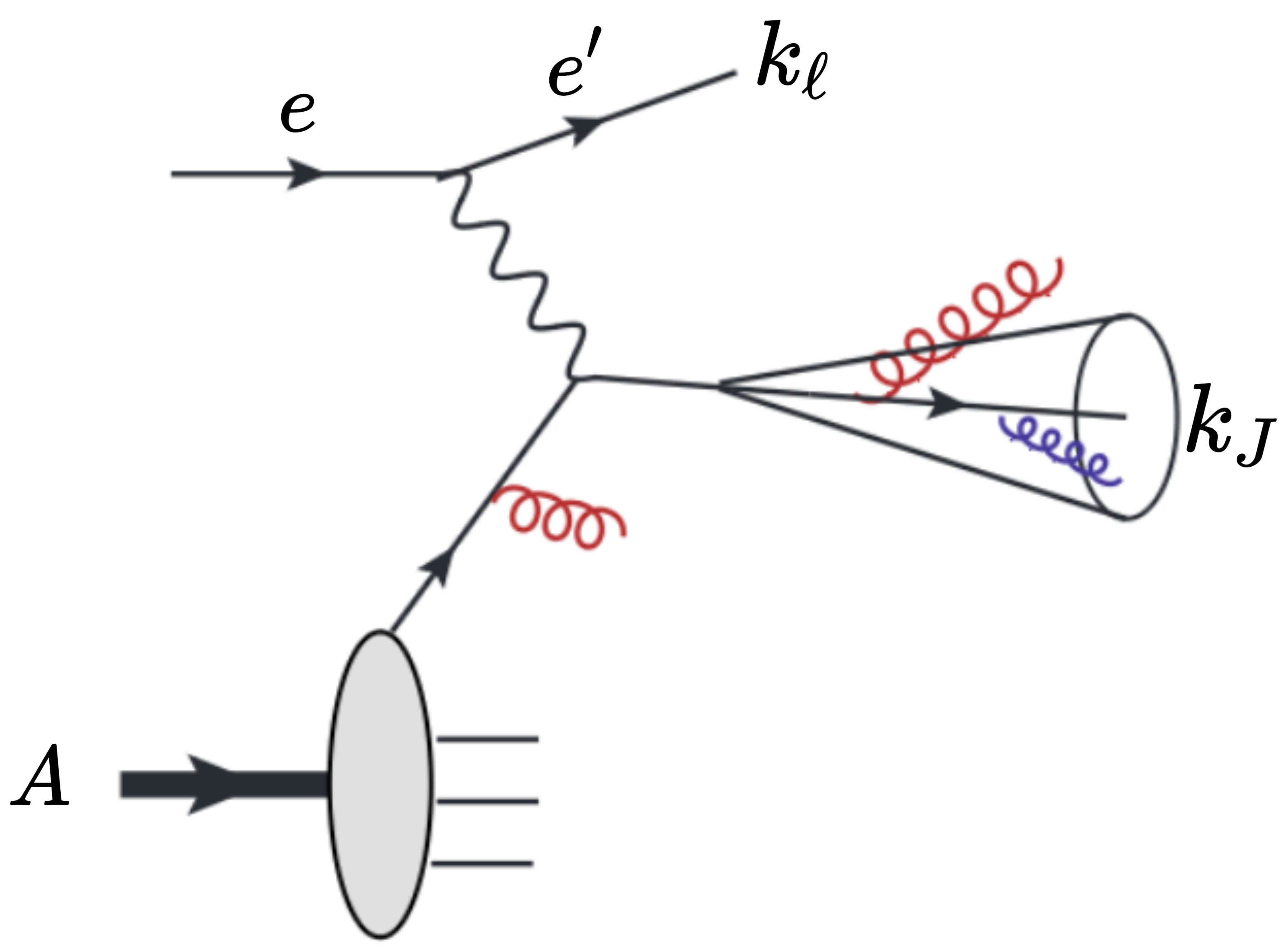
-Typical transverse momentum of small-x gluons

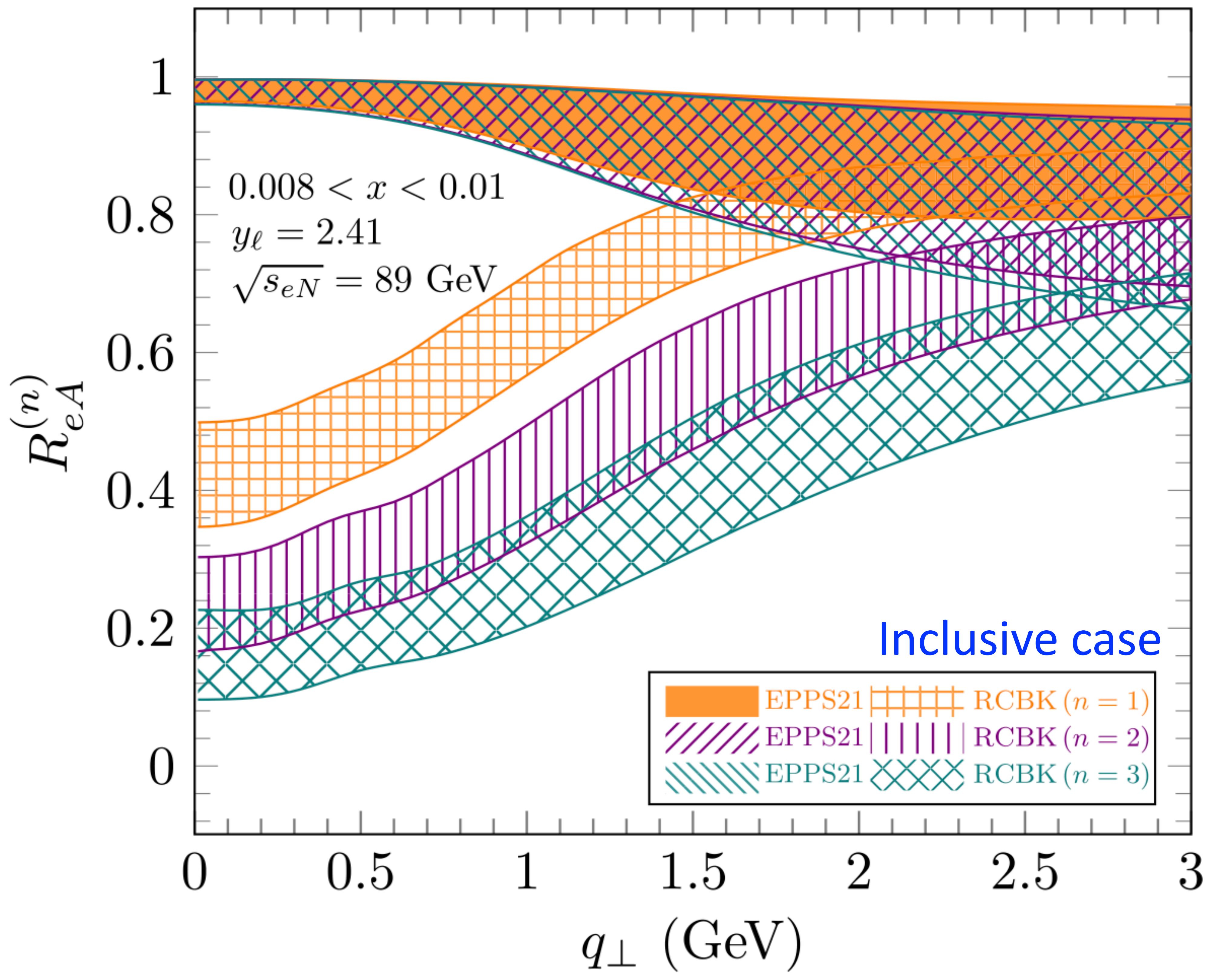
$$q_\perp \sim k_{g\perp} \lesssim Q_s$$

-Nuclear modification

$$Q_s^2 \propto A^{1/3} \Rightarrow R_{eA} = \frac{1}{A}\frac{d\sigma_{eA}}{d\sigma_{ep}} < 1$$

Lepton-jet correlation — a novel probe for saturation





$$R_{eA}^{(n)} = \frac{\langle \cos n\phi \rangle_{eA}}{\langle \cos n\phi \rangle_{ep}}$$

- **Anisotropy <cos(nϕ)>**
  - Sensitive to Q_s in both inclusive and diffractive DIS
  - Significant nuclear suppression.

⇒

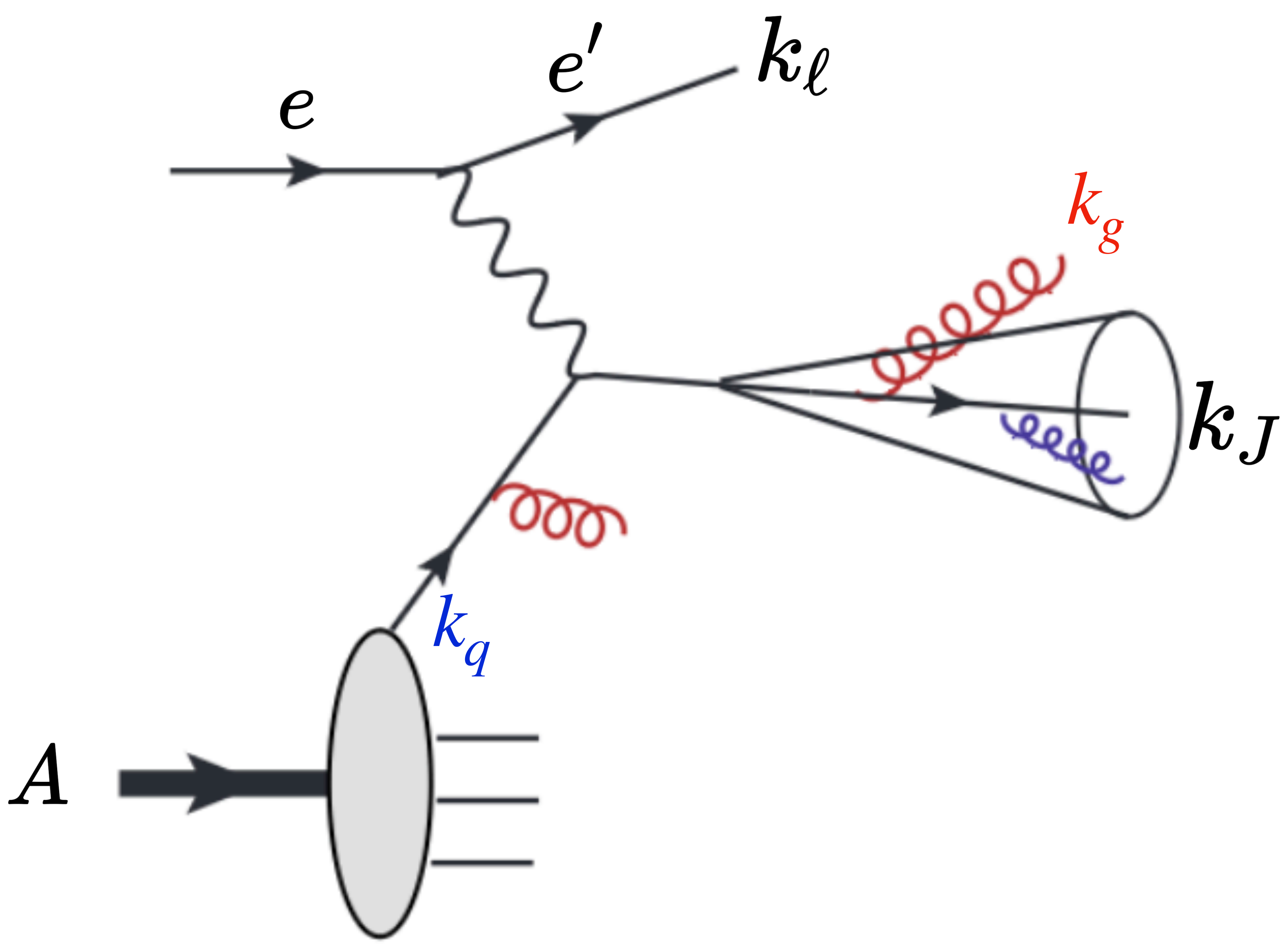
✦Properties

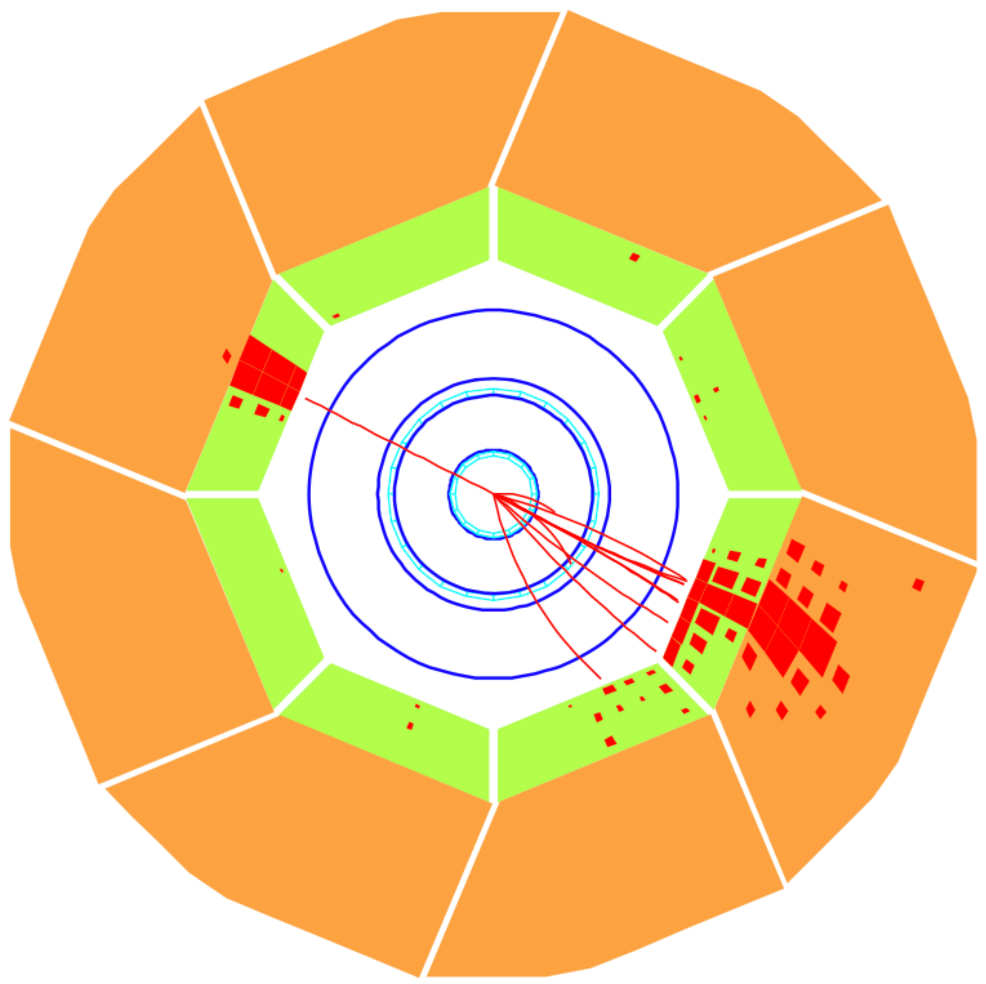
✦Mechanism

✦Numerics

Lepton-jet correlation

Liu-Ringer-Vogelsang-Yuan PRL22,192003 (2019); PRD102,094022 (2020)





H1 PRL 128, 132002 (2022)

- Golden channel to study quark TMDs

➡see more in WG5 talk by Dingyu Shao

$$\frac{d^5\sigma(\ell p \to \ell' J)}{dy_\ell d^2k_{\ell\perp} d^2q_\perp} = H(Q) \int d^2k_{q\perp} d^2k_{g\perp} x f_q(x, k_{q\perp}) S_J(k_{g\perp}) \times \delta^{(2)}(q_\perp - k_{q\perp} + k_{g\perp}).$$

-Clear, no fragmentation functions

-Simple kinematics, easy to measure

- Directly defined in the lab frame(or e-A c.m. frame)

- Final lepton and jet: back to back

-Electron as tag (precisely measured, no QCD correction)

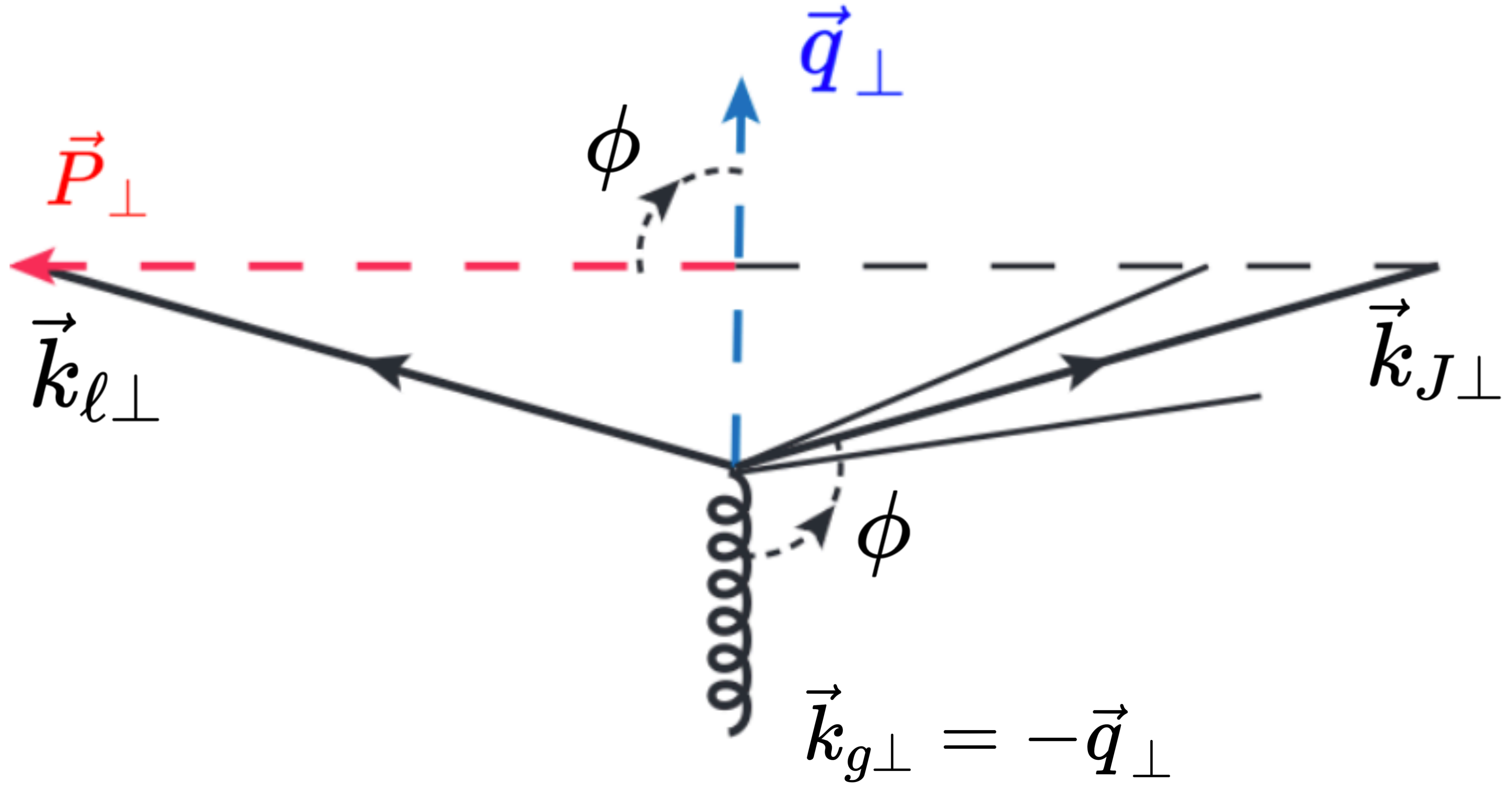
-Jet as a hard probe ($k_{J\perp} \sim k_{\ell\perp} \gg q_\perp$)

★ $q_\perp = k_{\ell\perp} + k_{J\perp}$ comes from Initial quark $k_{q\perp}$

Soft gluon radiations $k_{g\perp}$

Azimuthal angle anisotropy

Hatta-Xiao-Yuan-Zhou, PRD104,054037 (2021)



- Anisotropy:

$$\langle \cos n\phi \rangle = \frac{\sigma_n}{\sigma_0}$$

✦ Reveal the directional preference of $\vec{q}_\perp$

✦Generated by **Final-state soft-gluon radiations**

➡prefer the jet-cone direction, due to collinear enhancement

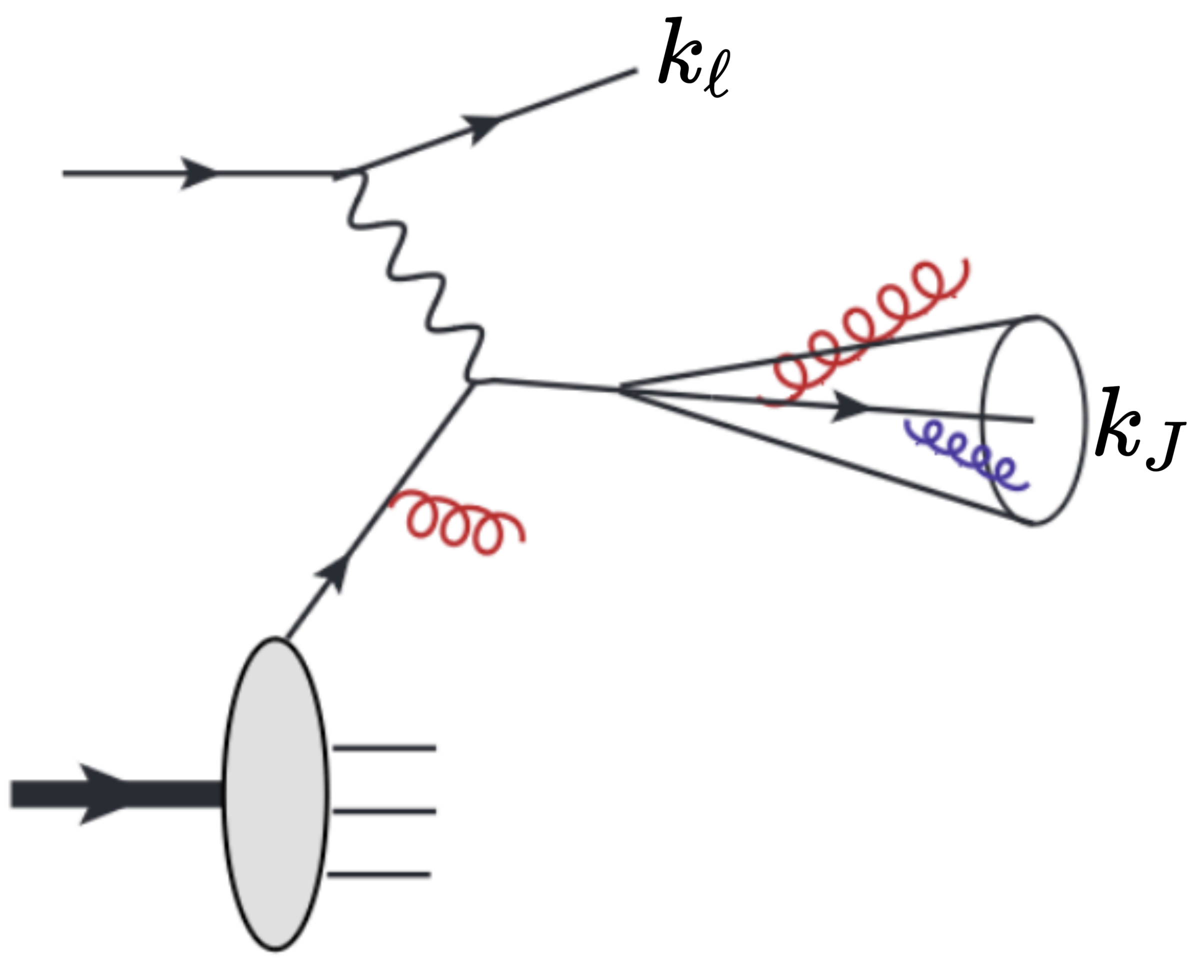
- ϕ is the azimuthal angle between:

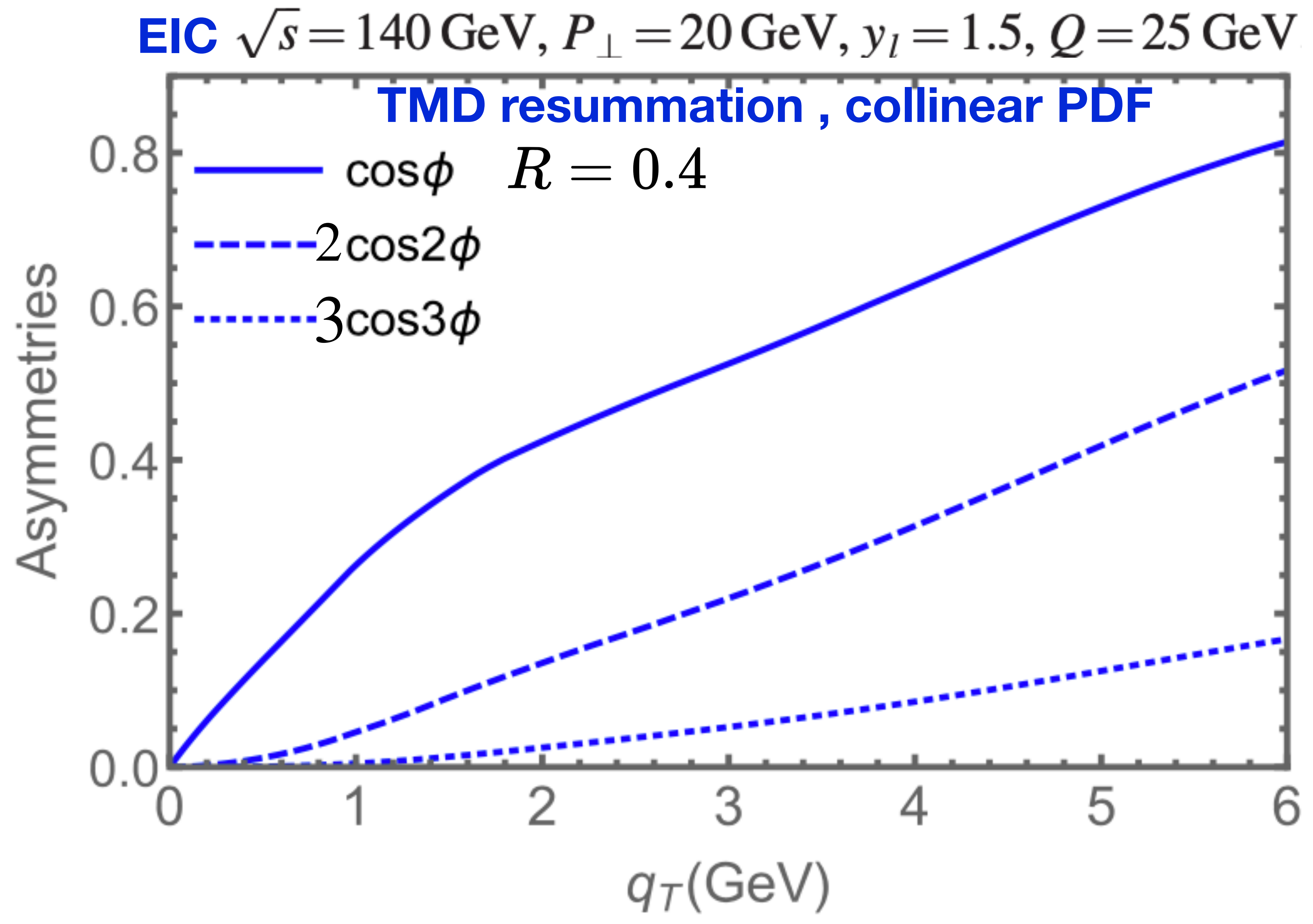
$$\vec{q}_\perp = \vec{k}_{\ell\perp} + \vec{k}_{J\perp}$$

$$\vec{P}_\perp = (\vec{k}_{\ell\perp} - \vec{k}_{J\perp})/2$$

- Harmonic expansion:

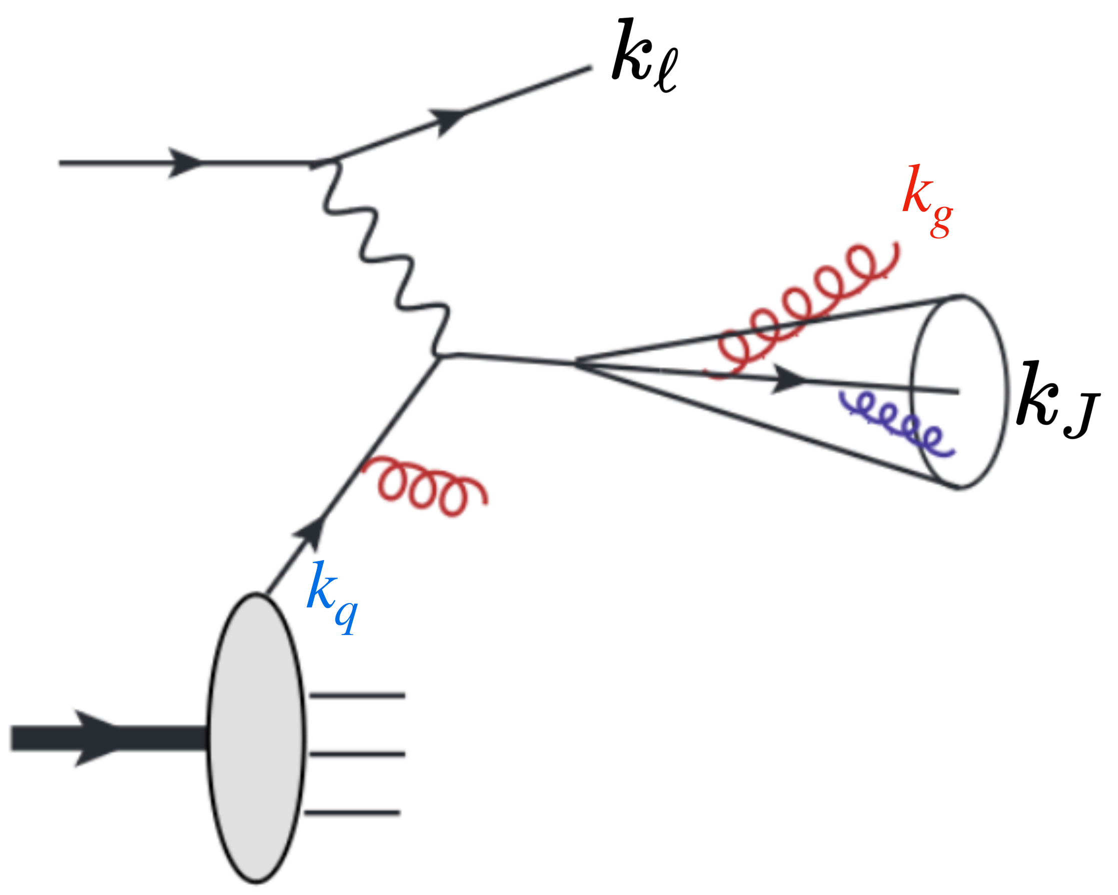
$$\frac{d\sigma}{dy_\ell d^2P_\perp d^2q_\perp} = \sigma_0 + 2\sum_{n=1}^{\infty} \sigma_n \cos(n\phi)$$





Sizable! Dominated by cos(ϕ)-modulaiton

Azimuthal angle anisotropy



- $q_\perp$ of LJC comes from (1) Initial quark $k_{q\perp}$ -> Can it produce an anisotropy?
  (2) Final-state soft gluon radiations $k_{g\perp}$

Observables / $\vec{q}_\perp$	Dijet: $\cos 2\phi$	lepton-jet $\cos n\phi$
Intrinsic transverse momentum (Unpolarzied target)	✓ linearly polarized gluon e.g. Boer-Brodsky-Mulders-Pisano 2011 Metz-Zhou 2011	× unpolarized initial quark
Radiation Hatta-Xiao-Yuan-Zhou 2021	✓ soft gluon	✓ soft gluon

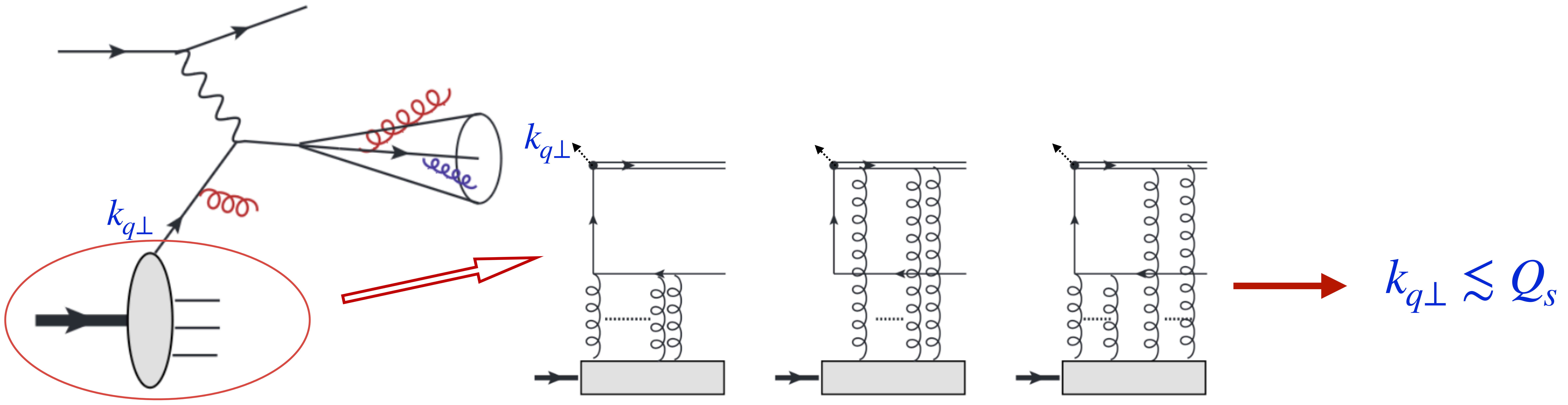
➡ No angular preference!

➡ Large probability in the jet direction

This unique property of the lepton-jet anisotropy -> Search for parton saturation!

Lepton-jet anisotropy: a novel indicator of parton saturation

✦At small x, the initial quark kT is from multiple scatterings of small-x gluons and their radiations



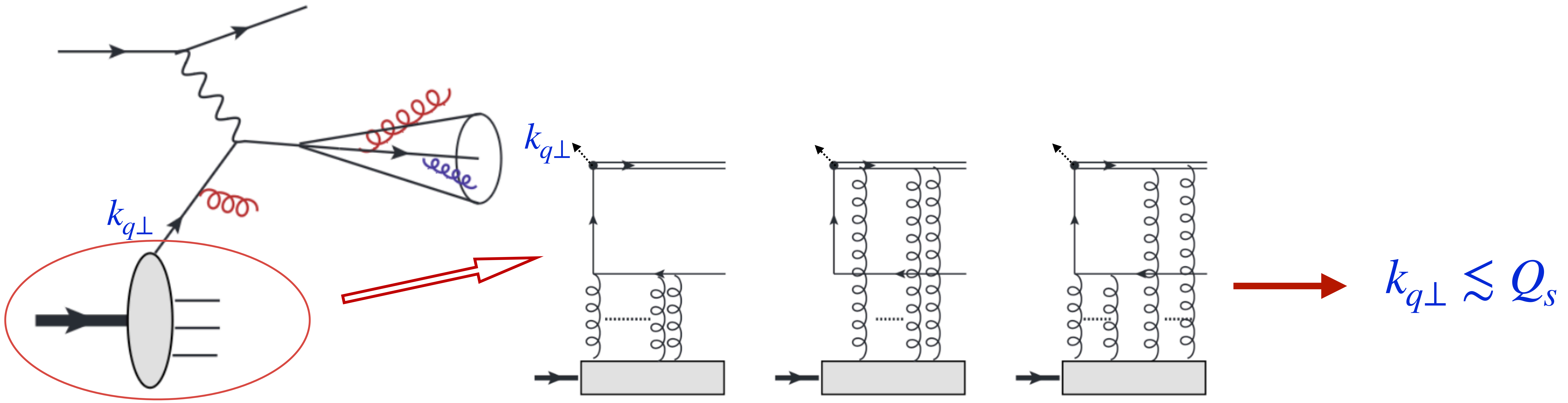
✦ For a given $q_\perp$, larger Q_s , **“less room” left for final-state gluons to produce anisotropy**

➡Saturation effects wash out the anisotropy, especially in the region $q_\perp \lesssim Q_s$.

➡Suppression of the anisotropy from ep to eA. $Q_s^2 \propto A^{1/3}$

Lepton-jet anisotropy: a novel indicator of parton saturation

✦At small x, the initial quark kT is from multiple scatterings of small-x gluons and their radiations

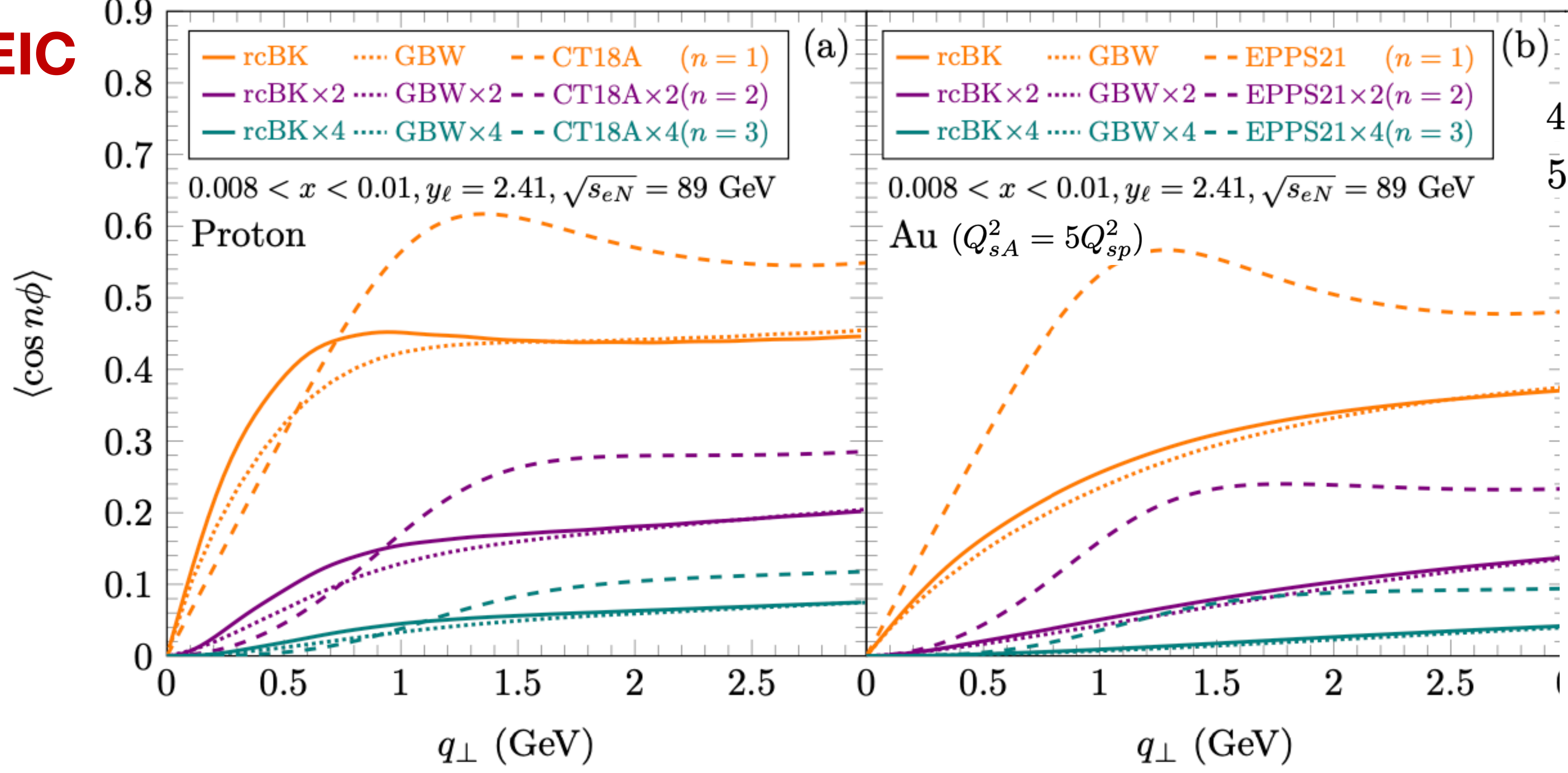


➡Small-x TMD quark distribution:

McLerran-Venugopalan, PRD 59,094002 (1999)
Mueller NPB 558, 285-303 (1999)
Xiao-Yuan-Zhou, NPB 921,104-126 (2017)

$$x f_q(x, r_\perp) = \frac{N_c S_\perp}{8\pi^4} \int d\epsilon_f^2 d^2 y_\perp \frac{(\vec{r}_\perp + \vec{y}_\perp) \cdot \vec{y}_\perp}{|\vec{r}_\perp + \vec{y}_\perp| \, |\vec{y}_\perp|}$$
$$\times \epsilon_f^2 K_1(\epsilon_f |\vec{r}_\perp + \vec{y}_\perp|) K_1(\epsilon_f |\vec{y}_\perp|)$$
$$\times [1 + \mathcal{S}_x(r_\perp) - \mathcal{S}_x(r_\perp + y_\perp) - \mathcal{S}_x(y_\perp)]$$

Prediction for the EIC



4 GeV< $P_\perp$ <4.4 GeV,
5.6 GeV< Q <5.9 GeV
R=0.4

- Resummation formula

$$\langle \cos n\phi \rangle = \frac{\sigma_{\rm LO} \int r_\perp dr_\perp J_n\left(q_\perp r_\perp\right) \frac{\alpha_s C_F c_n(R)}{n\pi} e^{-{\rm Sud}(r_\perp, R)} \sum_q e_q^2 x f_q(x, r_\perp)}{\sigma_{\rm LO} \int r_\perp dr_\perp J_0\left(q_\perp r_\perp\right) e^{-{\rm Sud}(r_\perp, R)} \sum_q e_q^2 x f_q(x, r_\perp)} .$$

✦Saturation framework:

- Small-x quark TMDs with dipole amplitude

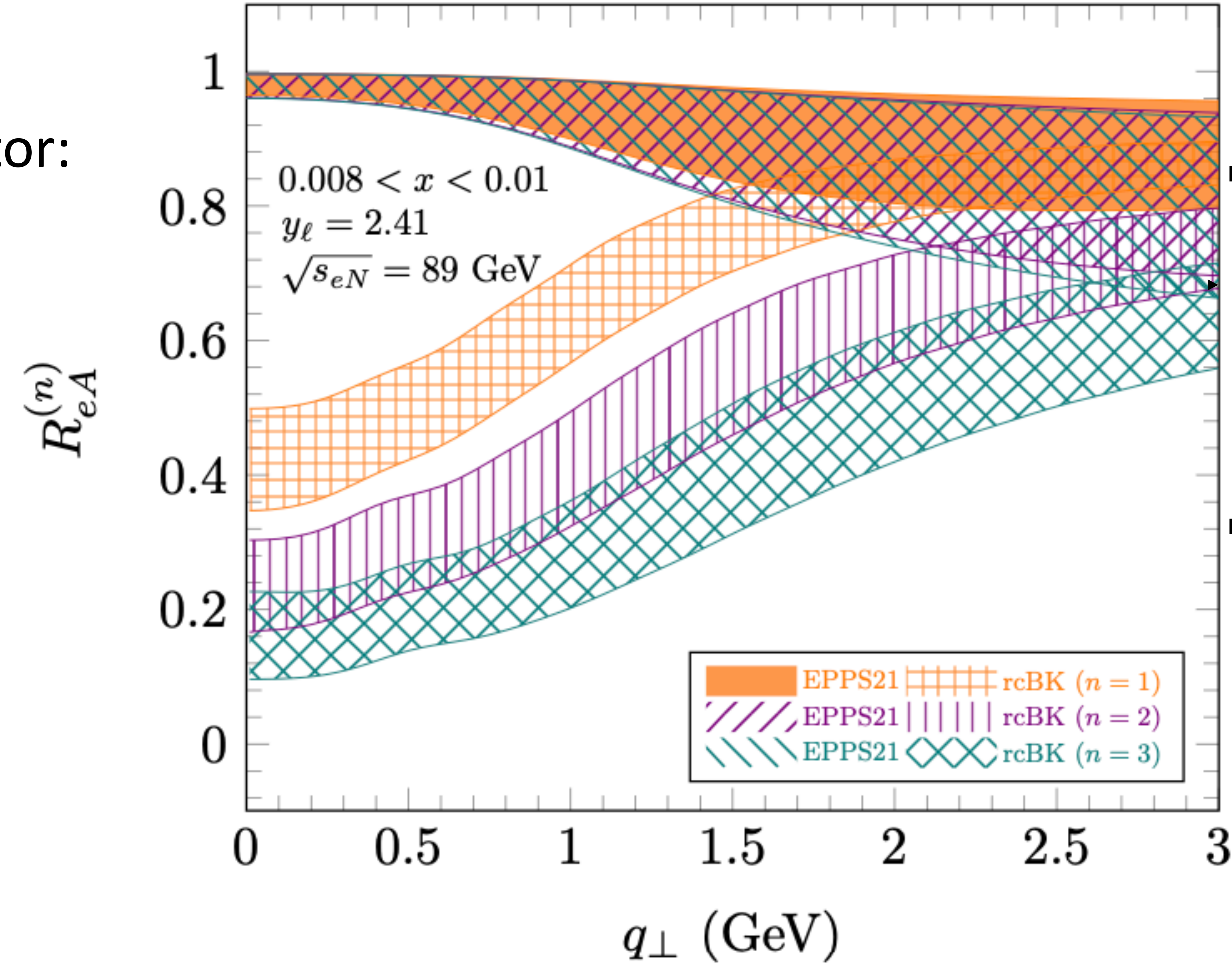
✦Non-saturation framework: Hatta-Xiao-Yuan-Zhou, 2021

- Collinear quark PDF, proton(CT18A), Gold(EPPS21)

Prediction for the EIC

✦Nuclear modification factor:

$$R_{eA}^{(n)} = \frac{\langle \cos n\phi \rangle_{eA}}{\langle \cos n\phi \rangle_{ep}}$$



➡Collinear framework:

- Uncertainty from the PDFs

➡Saturation framework

$3Q_{sp}^2 < Q_{sA}^2 < 5Q_{sp}^2$

✦Saturation-framework: the anisotropies have a sizable decrease from ep to eA

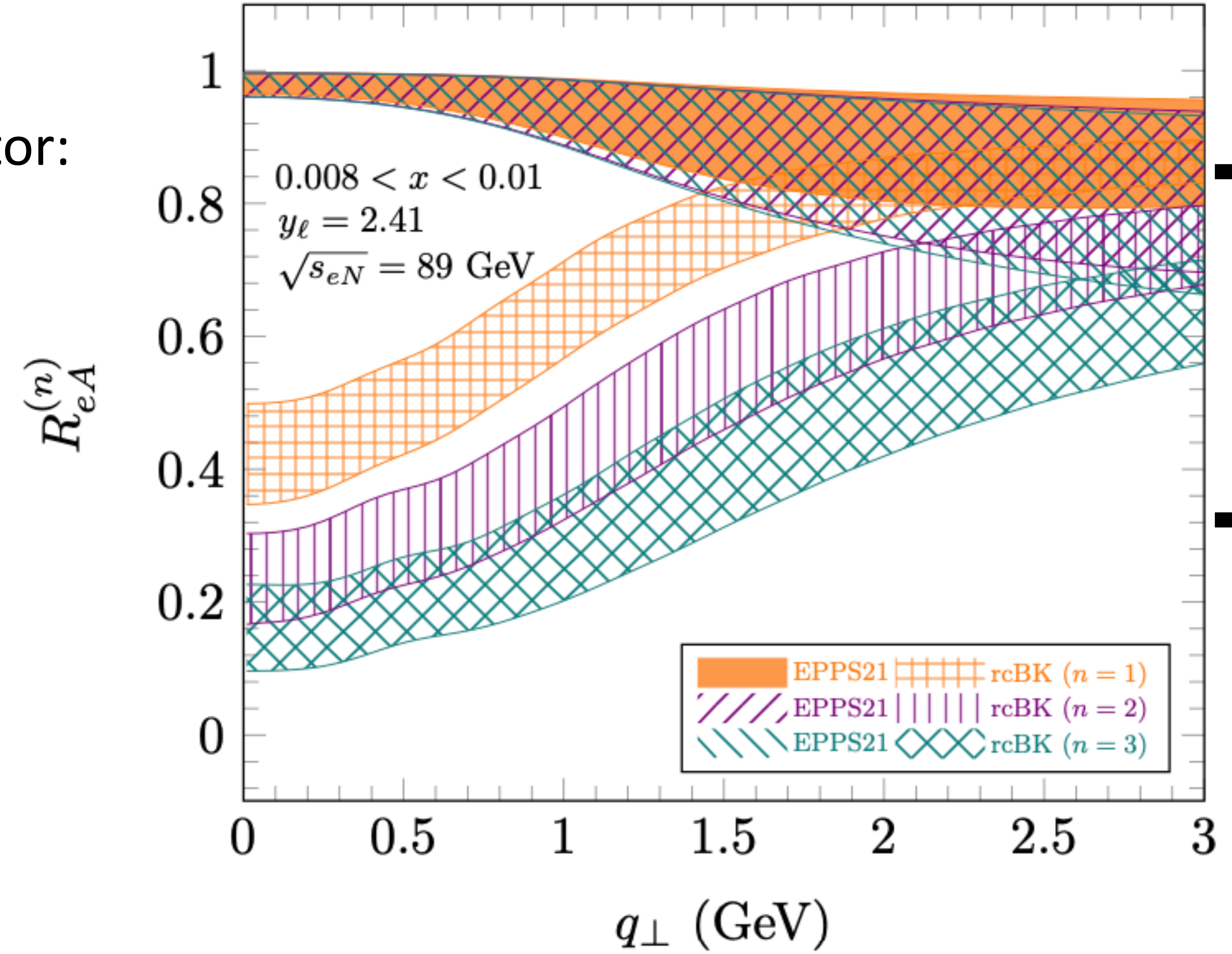
Sensitive to the saturation effects.

Significant at small $q_\perp$

Prediction for the EIC

✦Nuclear modification factor:

$$R_{eA}^{(n)} = \frac{\langle \cos n\phi \rangle_{eA}}{\langle \cos n\phi \rangle_{ep}}$$



➡Collinear framework:

‣ Uncertainty from the PDFs

➡Saturation framework

$3Q_{sp}^2 < Q_{sA}^2 < 5Q_{sp}^2$

✦Collinear framework: nearly no nuclear suppression at small-$q_\perp$

-No intrinsic kT ; Nuclear effects cancel by construction of anisotropy

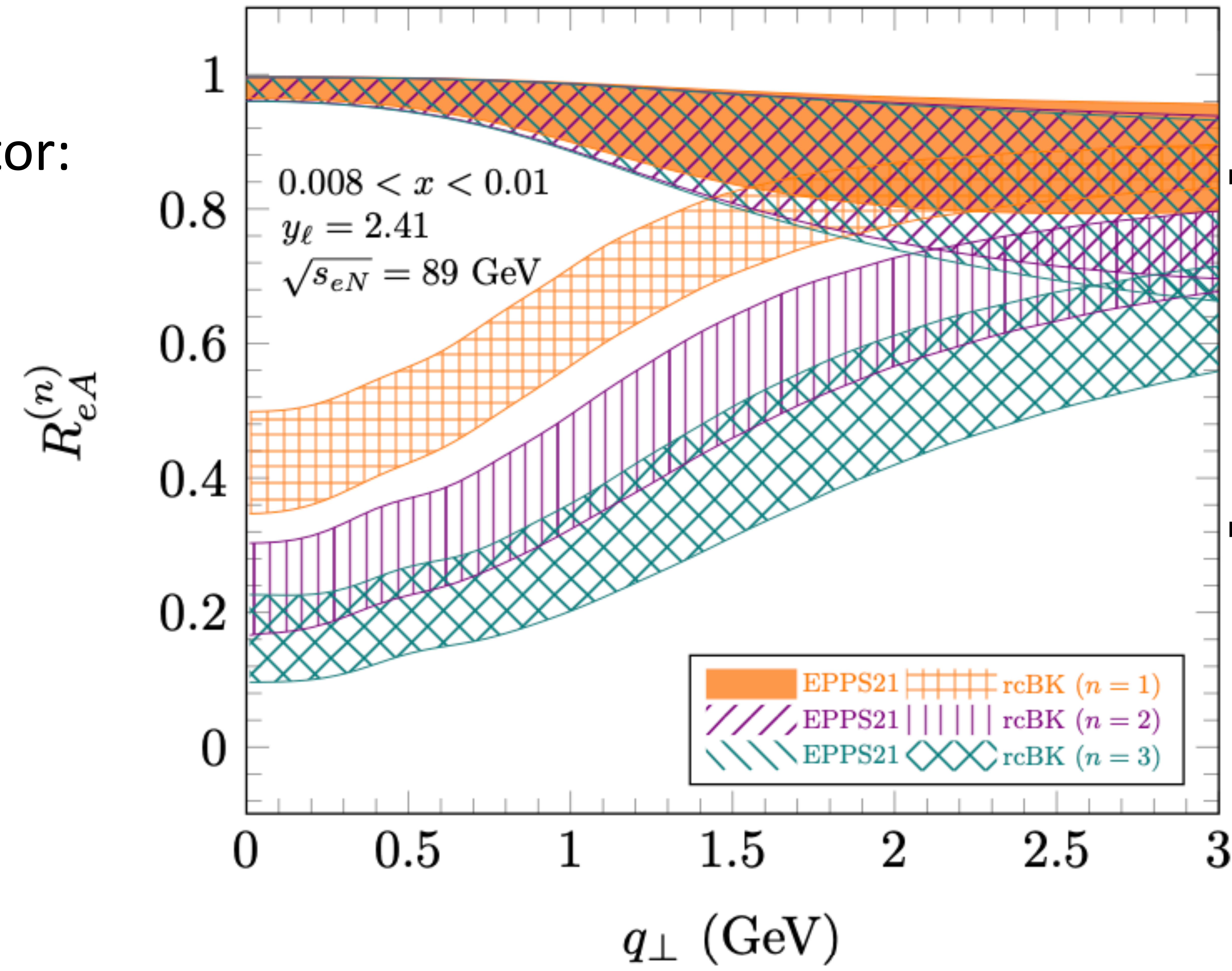
e.g., $f_q^A(x) \approx R_q^A(x) f_q^p(x)$

$$\langle \cos n\phi \rangle_A = \frac{\sigma_{n,A}}{\sigma_{0,A}} \approx \frac{R_q^A \sigma_{n,p}}{R_q^A \sigma_{0,p}} \approx \langle \cos n\phi \rangle_p \Longrightarrow R_{eA}^{(n)} \approx 1$$

Prediction for the EIC

✦Nuclear modification factor:

$$R_{eA}^{(n)} = \frac{\langle \cos n\phi \rangle_{eA}}{\langle \cos n\phi \rangle_{ep}}$$



➡Collinear framework:

- Uncertainty from the PDFs

➡Saturation framework

$3Q_{sp}^2 < Q_{sA}^2 < 5Q_{sp}^2$

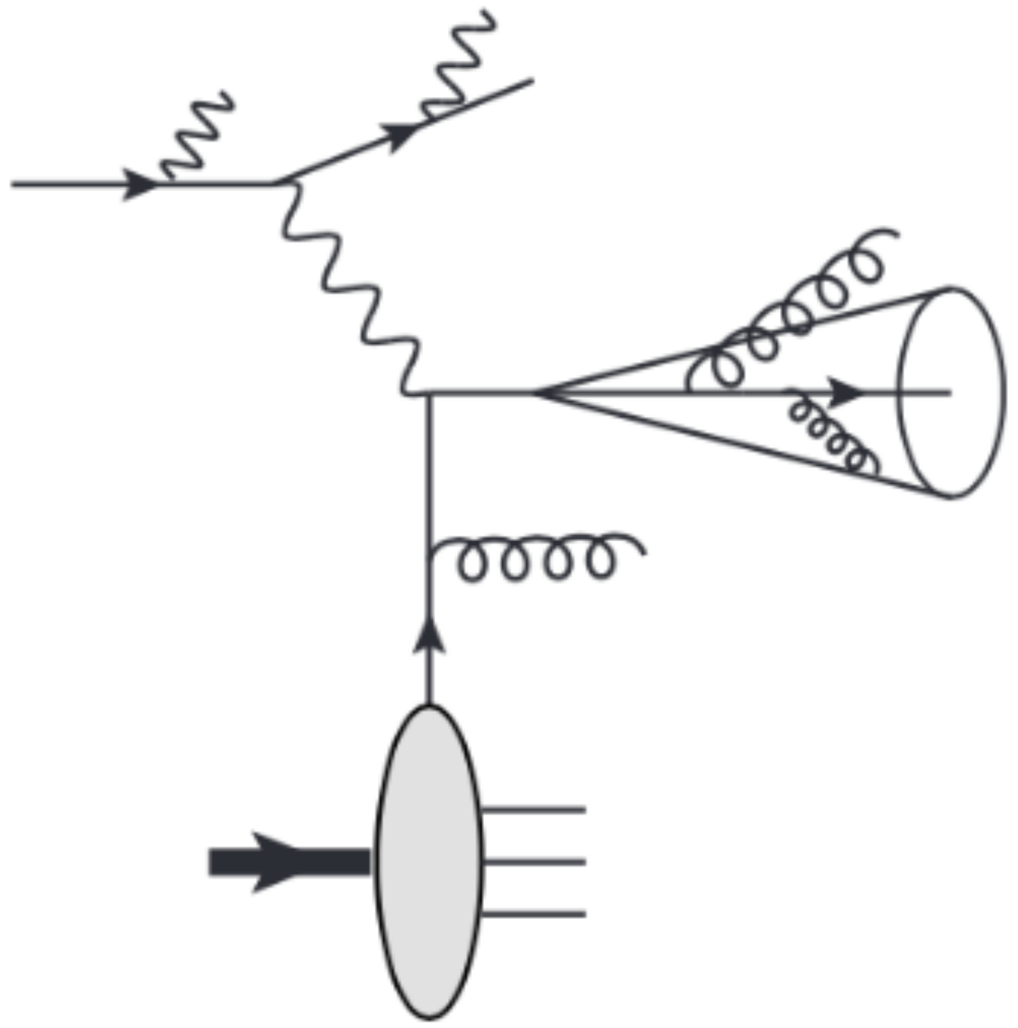
✦Striking difference between saturation framework and collinear framework at small $q_\perp$

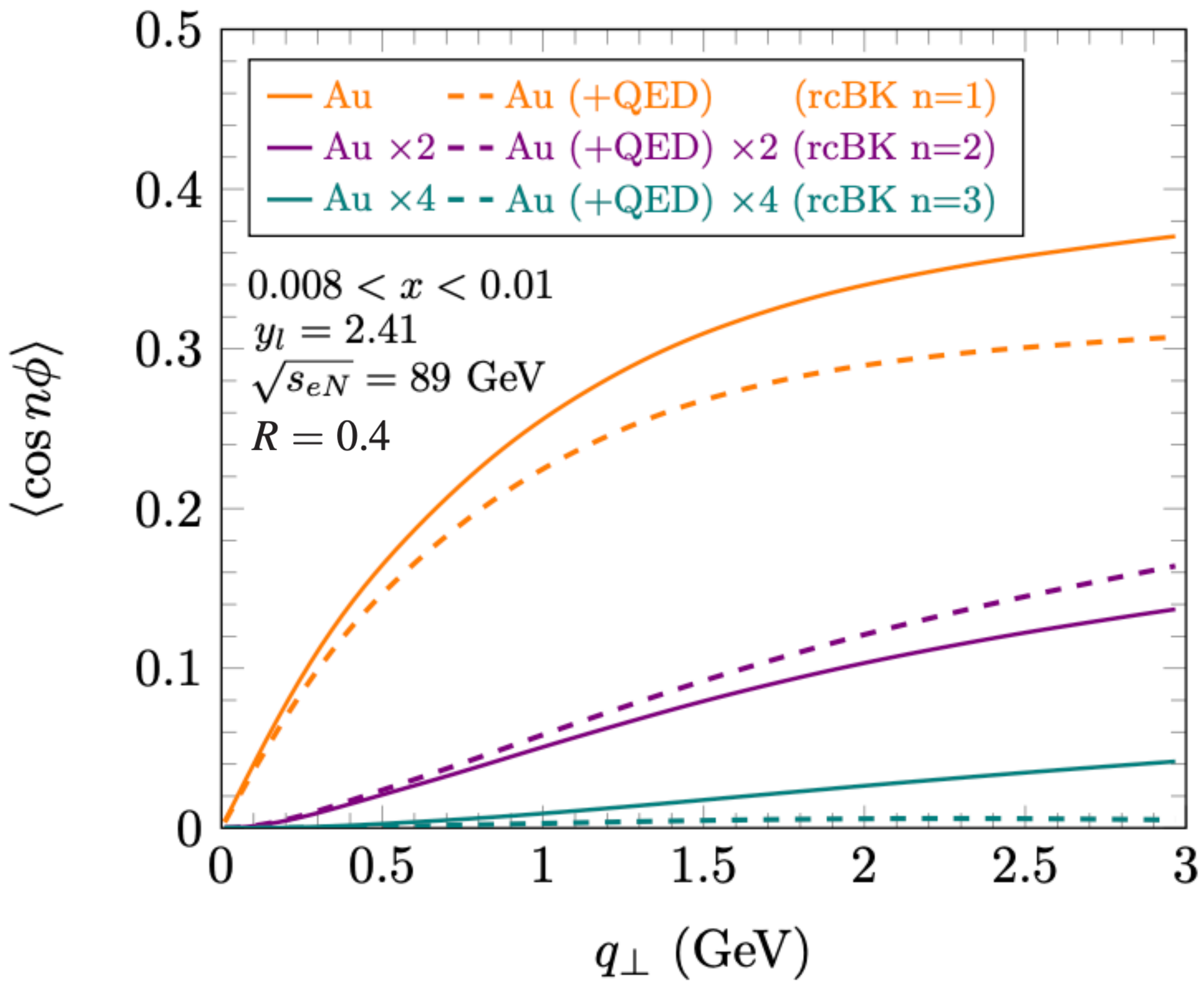
-Power to discriminate competing mechanisms

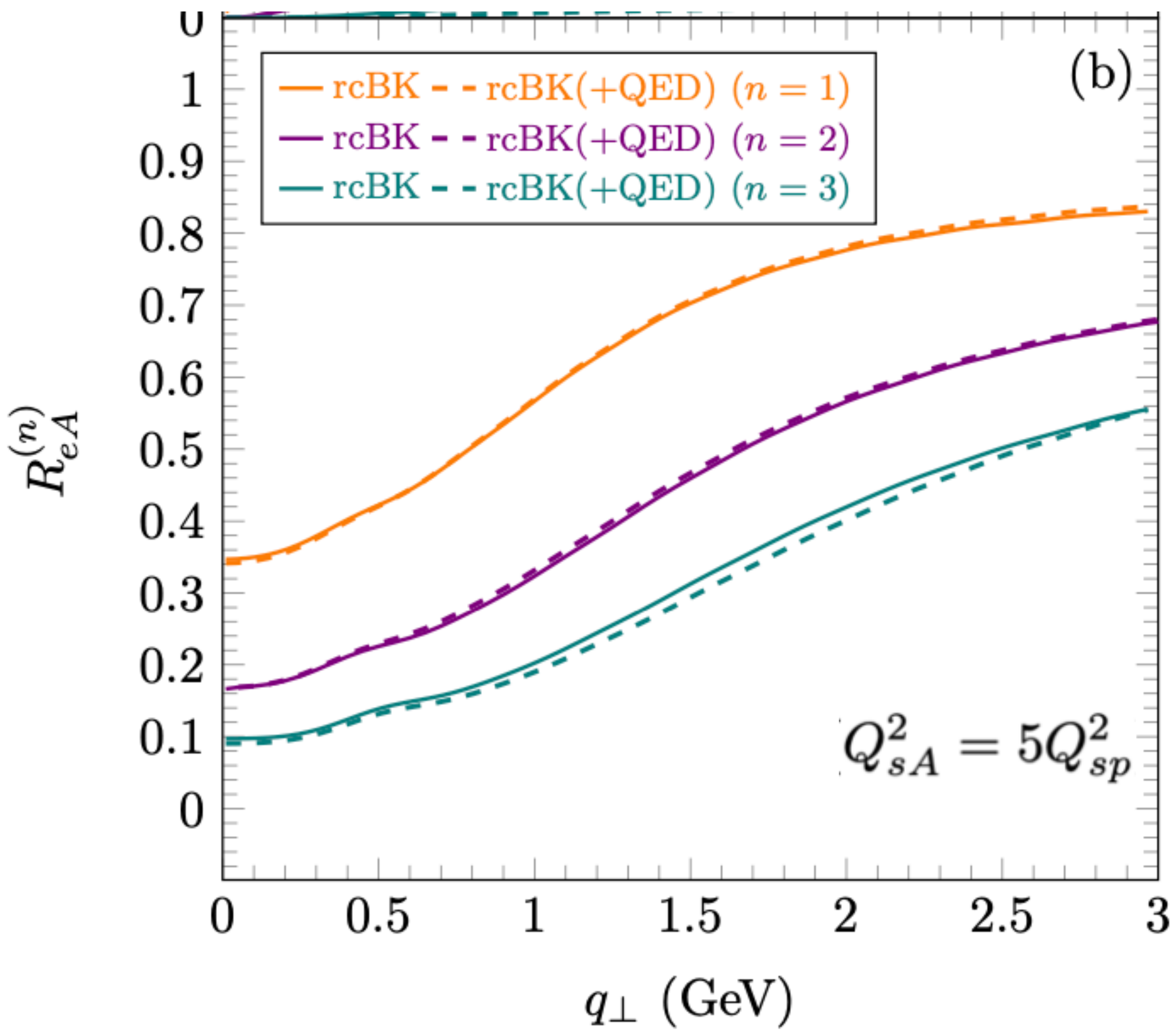
-Can pinpoint the signature of saturation at the EIC

Prediction for the EIC

✦QED correction



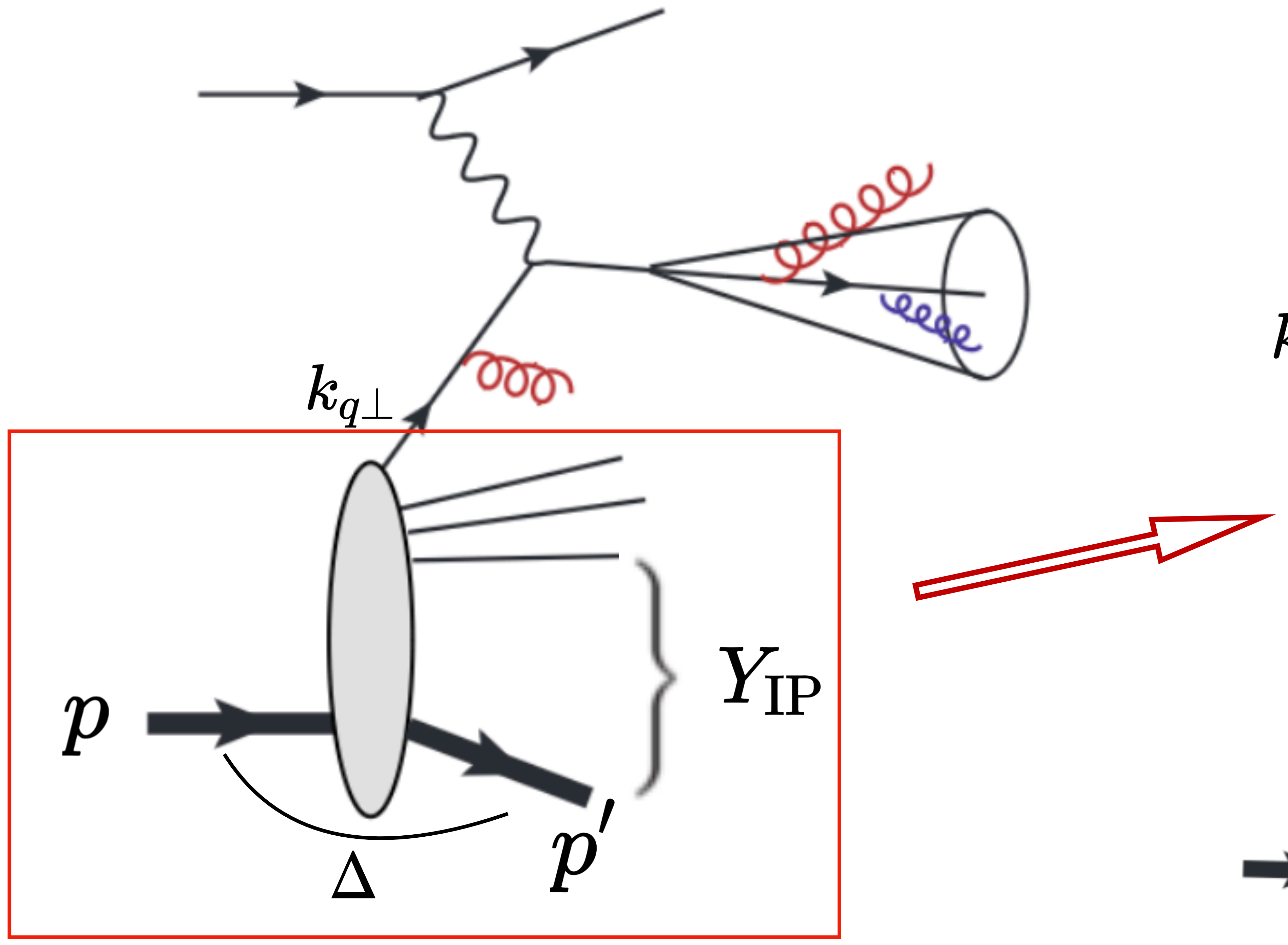


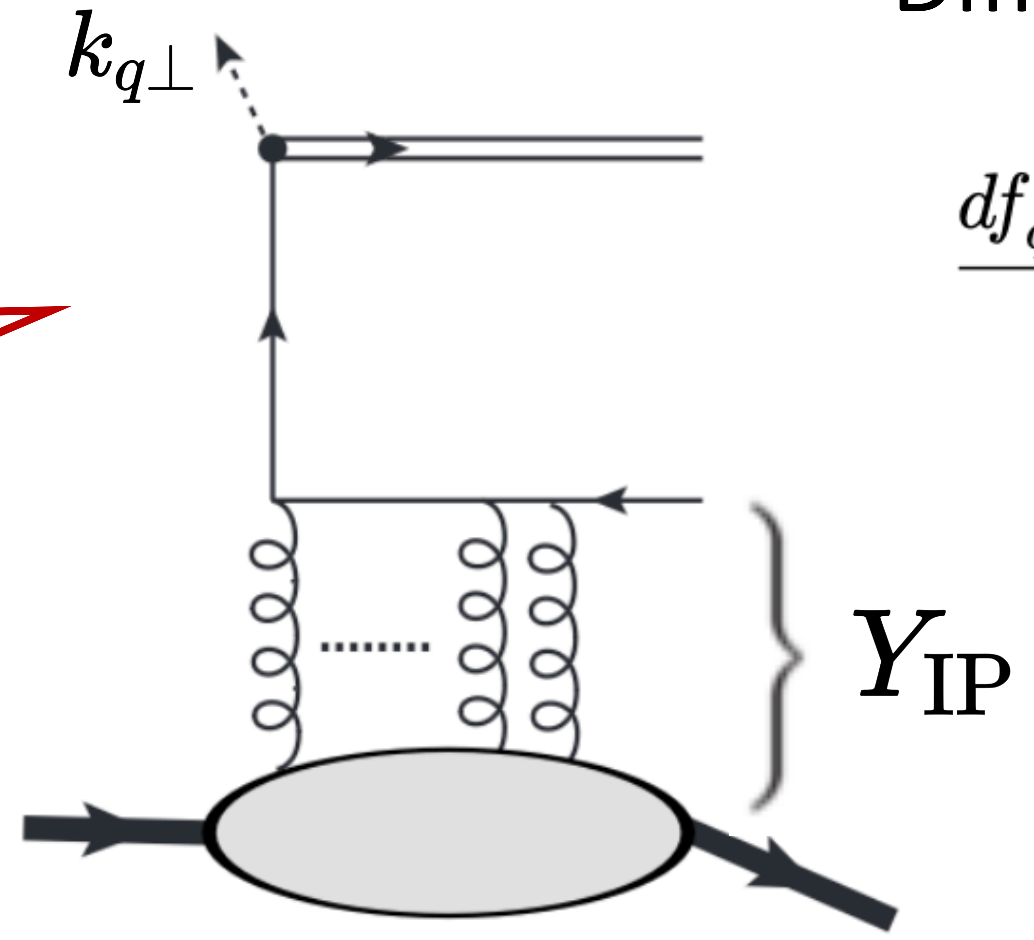


➡Corrections to $\langle \cos n\phi \rangle$ are apparent : reduce odd harmonics & increase even harmonics.

➡Corrections to $R_{eA}^{(n)}$ are negligible, due to cancellation in the ratios . $R_{eA}^{(n)} = \frac{\langle \cos n\phi \rangle_{eA}}{\langle \cos n\phi \rangle_{ep}}$

Lepton-jet correlation in Diffractive DIS





- Diffractive quark TMDs($\sim$dipole^2)

$$\frac{df_q^D(\beta, k_\perp, t; x_{\rm IP})}{dY_{\rm IP}dt} = \frac{N_c\beta}{2\pi}\int d^2k_{1\perp}d^2k_{2\perp}\mathcal{F}_{x_{\rm IP}}(k_{1\perp},\Delta_\perp) \times \mathcal{F}_{x_{\rm IP}}(k_{2\perp},\Delta_\perp)\mathcal{T}_q(k_\perp,k_{1\perp},k_{2\perp})$$

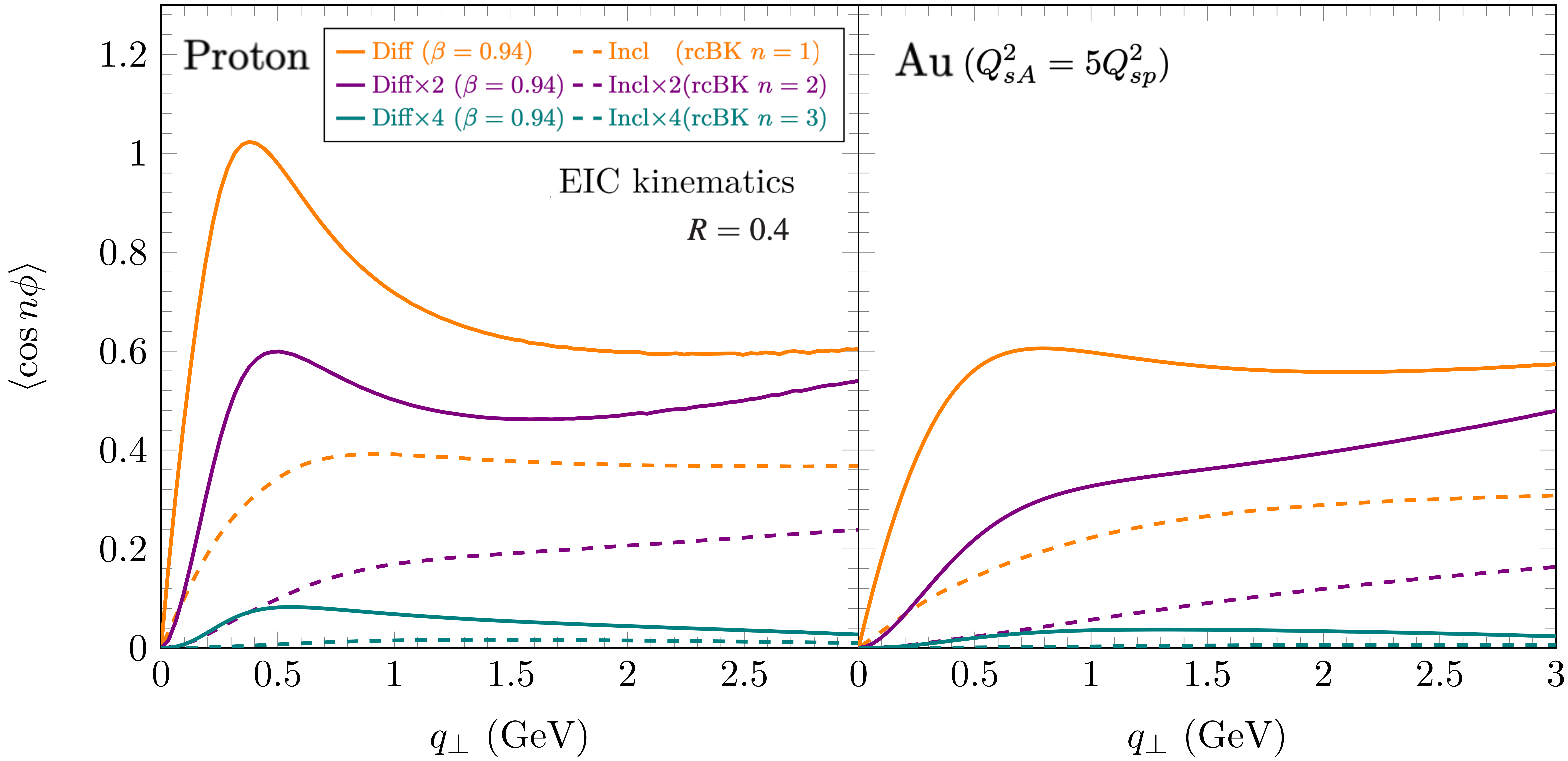
Hatta et al PRD 106, 094015 (2022)
Iancu et al PRL128,202001 (2022)

➡see more in the talk by Sigtryggur Hauksson

$$x_{IP} = \frac{\Delta^+}{P^+}, \quad \beta = \frac{x}{x_{IP}}$$

- Coherent diffraction: recoiled target & rapidity gap
  - Final-state soft gluons& hard scatterings remain unchanged
  - Resummation formula for <cos $n\phi$> : replace inclusive TMDs with diffractive TMDs
- $\Delta_\perp$ -dependence -> Target shape in the impact parameter $b_\perp$-space

Forward limit: $\Delta_\perp = 0$



$\sqrt{s_{eN}} = 89$ GeV, $y_l = 2.41$

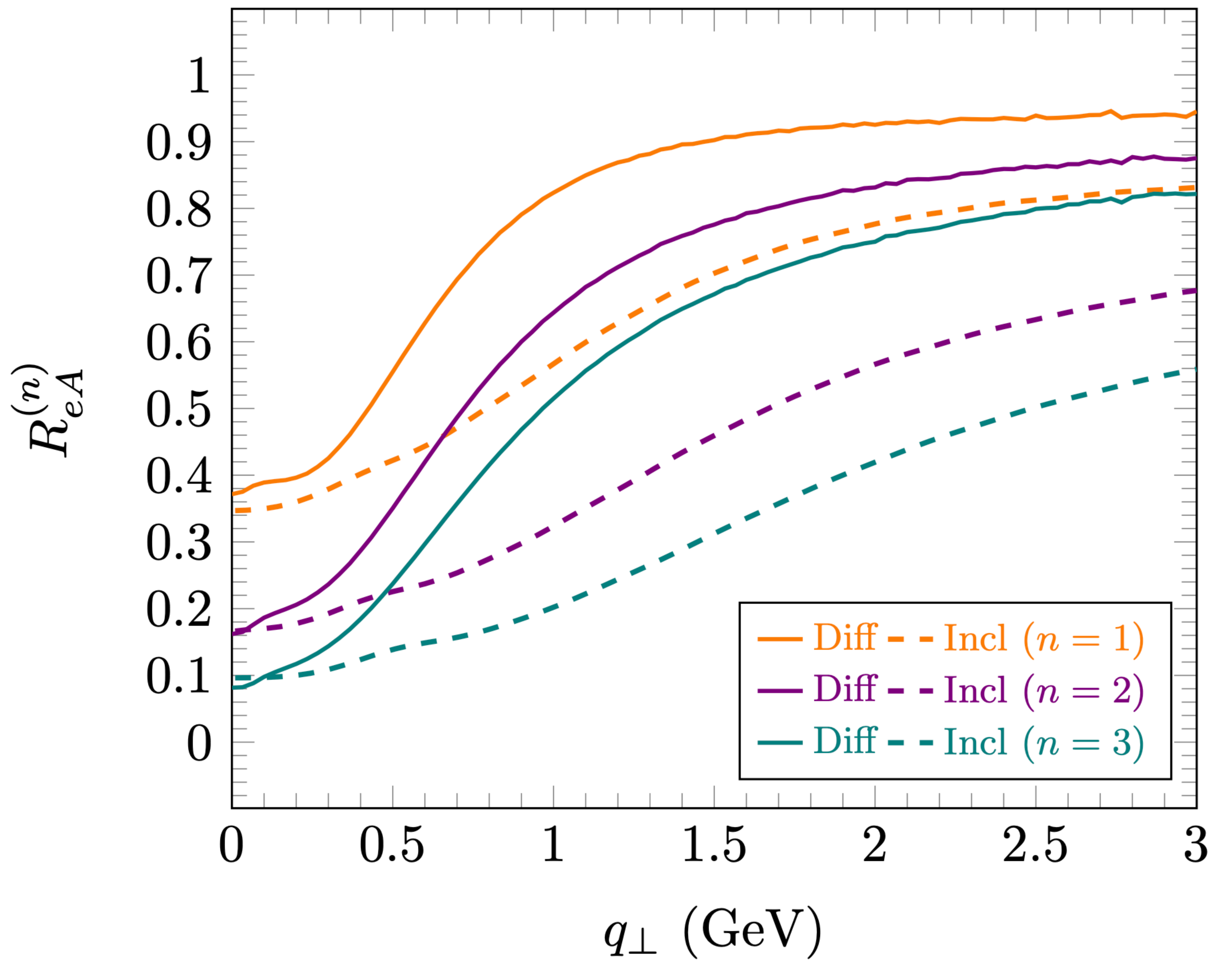
$0.008 < x < 0.0094$

QED corrections included

✦**Diffractive anisotropies($\Delta_\perp = 0, \beta = 0.94$)are much larger than inclusive ones.**

diff: $k_{q\perp} \lesssim (1-\beta)^{1/2} Q_s \approx 0.24 Q_s$

Forward limit: $\Delta_\perp = 0$



$\sqrt{s_{eN}} = 89$ GeV, $y_l = 2.41$

$0.008 < x < 0.0094$

QED corrections included

✦**Diffractive $R_{eA}^{(n)}$ exhibit a significant nuclear suppression, similar to the inclusive case**

➡**Sensitive to Q_s**

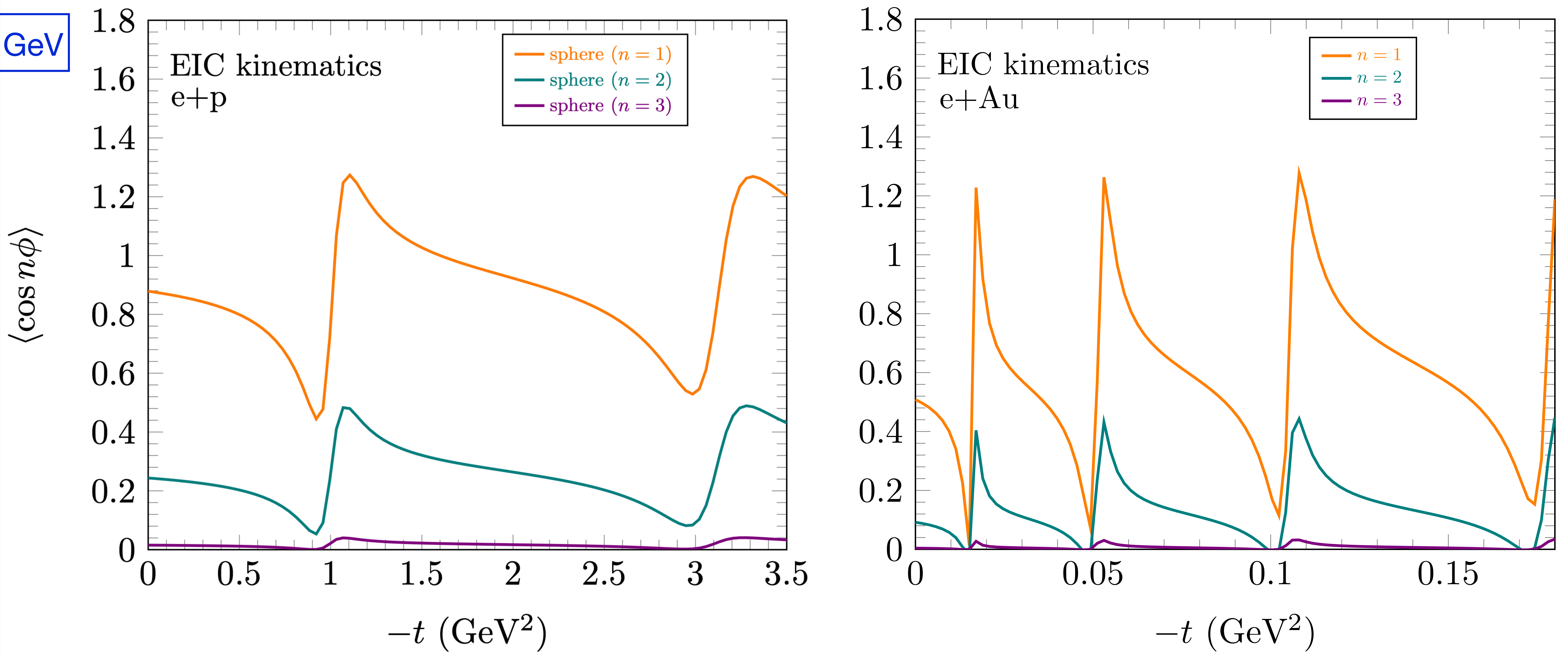
$\Delta_\perp$-distribution

Toy model: uniform sphere

$$\mathcal{S}_x(r_\perp, b_\perp) = e^{-\frac{r_\perp^2 Q_{s,p}^2(x,b_\perp)}{4}} \qquad Q_{s,p}^2(x,b_\perp) = c_s\sqrt{1-\frac{b_\perp^2}{r_p^2}} .$$

$$\int d^2b_\perp Q_{s,p}^2(x,b_\perp) = \pi r_p^2 Q_{s,p}^2(x) .$$

$q_\perp = 0.5$ GeV



★Pulse shape—diffractive partern

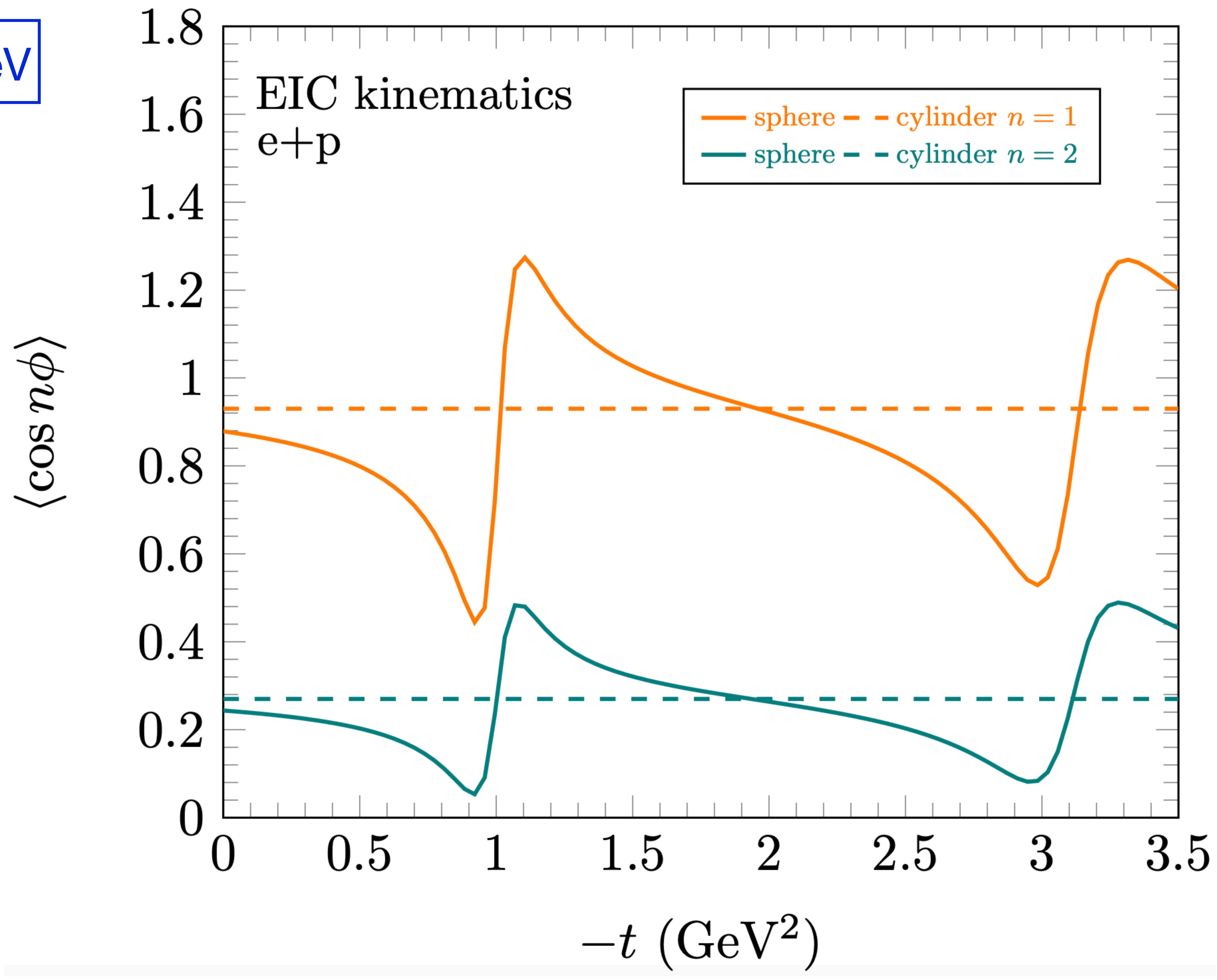
- Positions $\sim$ zeros of $J_1(r_p\Delta_\perp)$—fourier transform of a circular
- e.g. proton $r_p\Delta_\perp = 3.8, 7.0, 10.2, \ldots$.

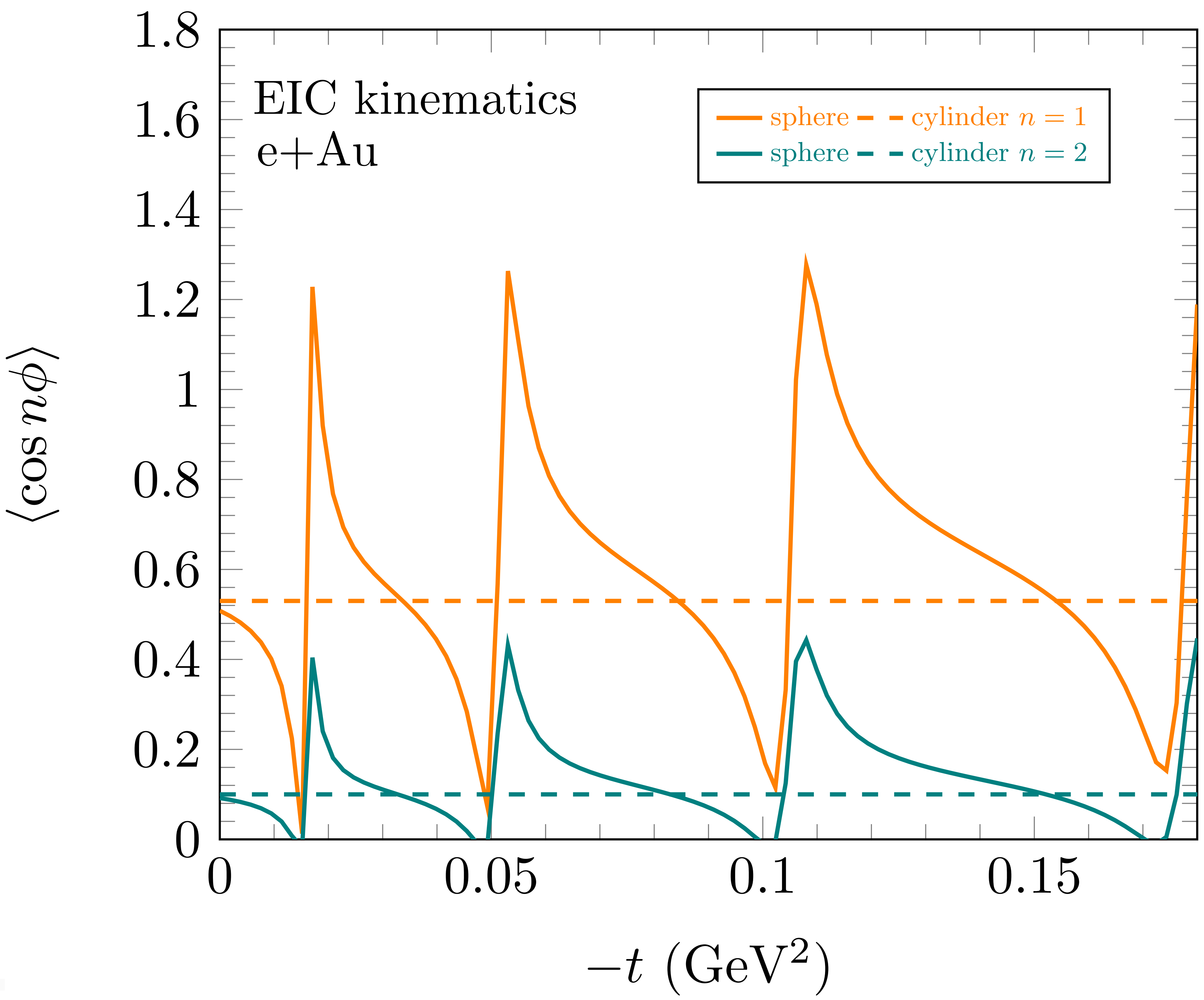
Akin to Caldwell-Kowalski 2010

- **Positions&shape change drastically from ep to eA-> Sensitive to the A-dependence of geometry**

$\Delta_\perp$-distribution   Toy model: sphere v.s. cylinder

$q_\perp = 0.5$ GeV





★ **Potential to probe the geometry of targets**

- Cylinder-like target : $d\sigma$ has t-dependence as $J_1(r_p\Delta_\perp)/\Delta_\perp$, completely cancels in $\langle \cos n\phi \rangle = \dfrac{\sigma_n}{\sigma_0}$

Summary

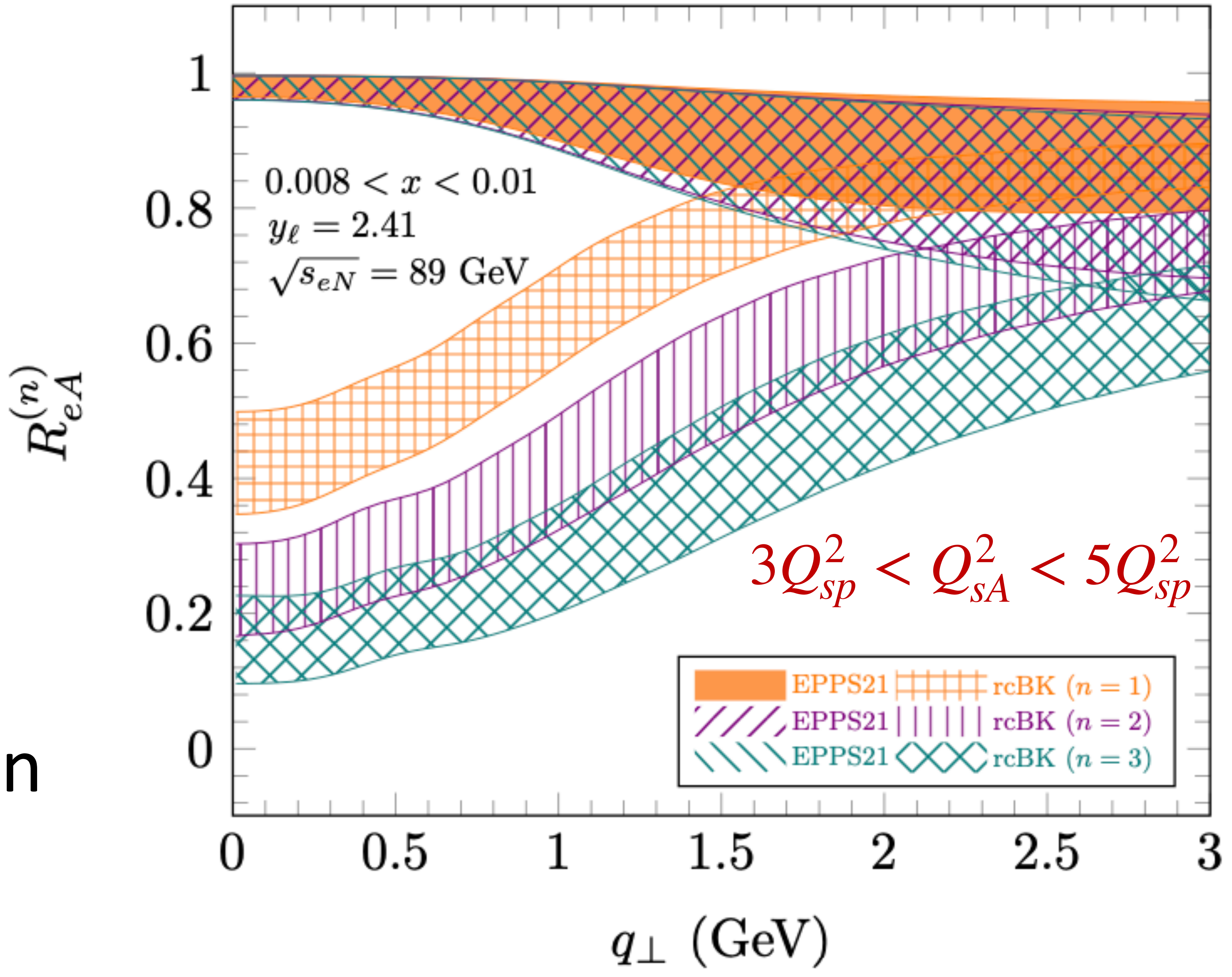
✦Lepton-jet correlation at small x in inclusive and diffractive DIS

✓Sensitivity of the anisotropy to the saturation effects.

✓Power to discriminate underlying mechanisms

✓ t-dependent anisotropy→ proton&nuclear shape

✦Great potential in searching for compelling evidences of gluon saturation at the EIC.

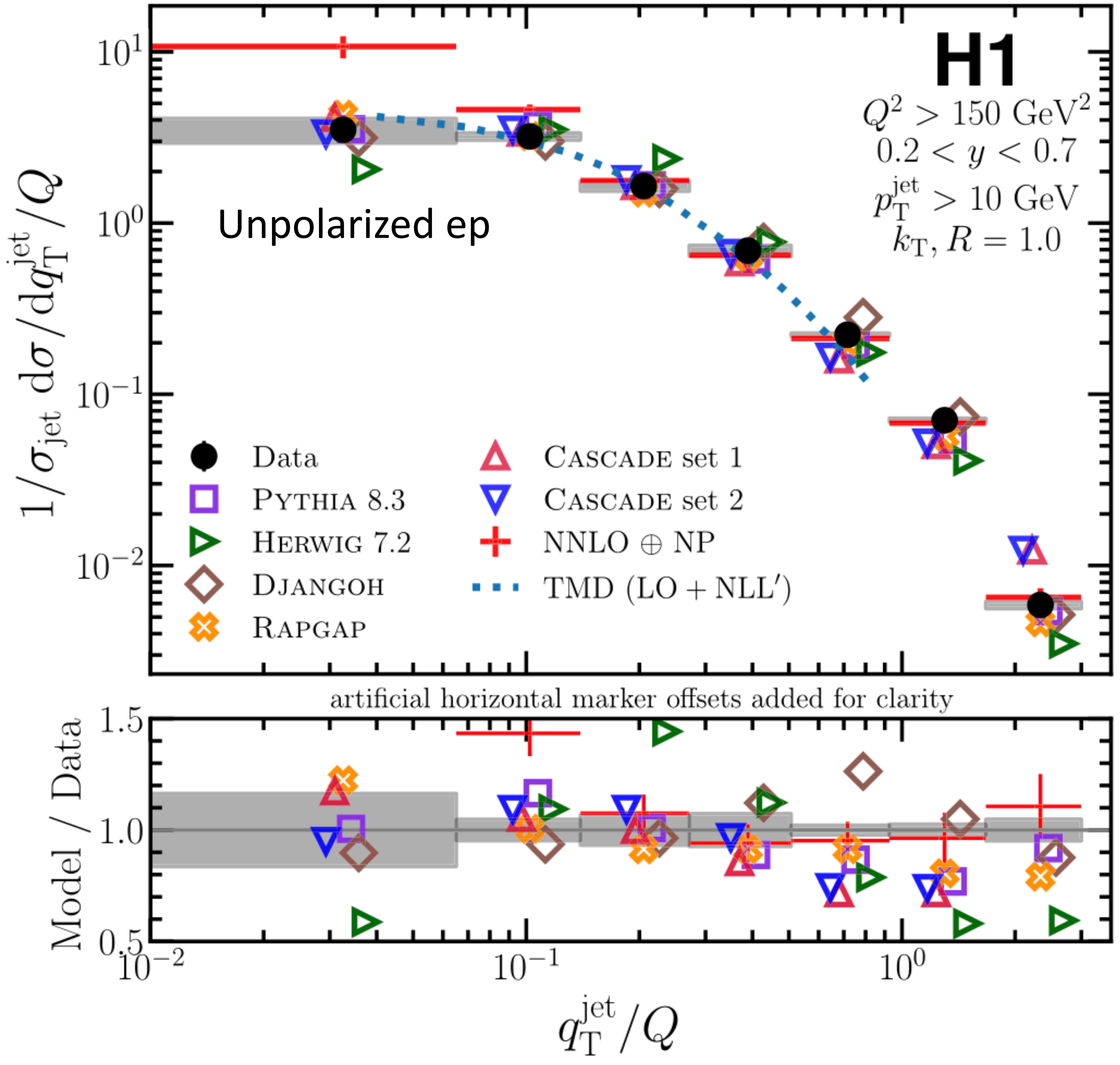


Outlook

- Improve the prediction, especially the diffractive case.
- Incoherent diffaction
- SSA of lepton-jet at small-x ➡Sivers functions & spin-dependent odderon
- H1 measurement of lepton-jet anisotropy ➡see DIS2023 talk by Fernando Acosta
- From jet to energy flow or transverse energy flow ➡see later talk by Jani Penttala

Measurement of LJC at HERA(H1)

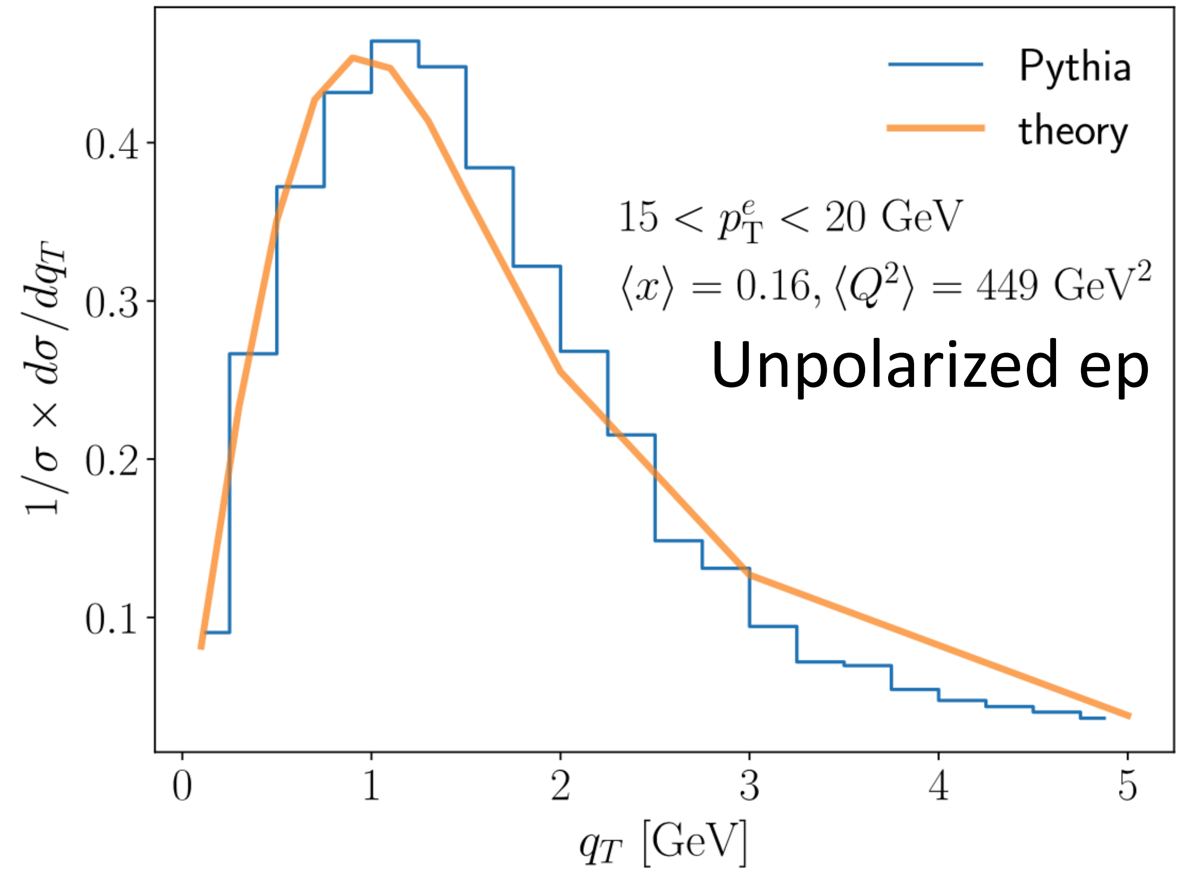
H1 PRL 128,132002(2022)



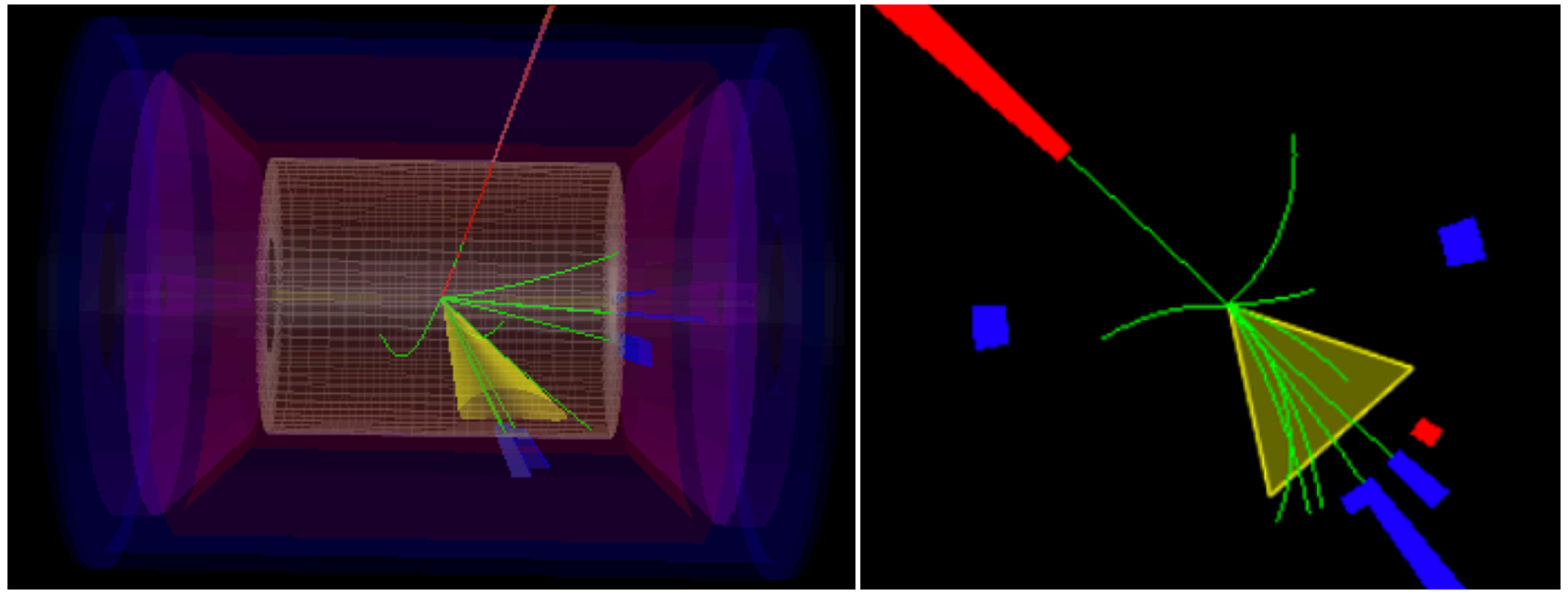
Simulation studies at the EIC

Arratia-Song-Ringer-Jacak PRC101,065204(2020)

Arratia-Kang-Prokudin-Ringer PRD102,074015 (2020)



"The expected performance of a hermetic EIC detector with reasonable parameters is sufficient to perform these measurement"

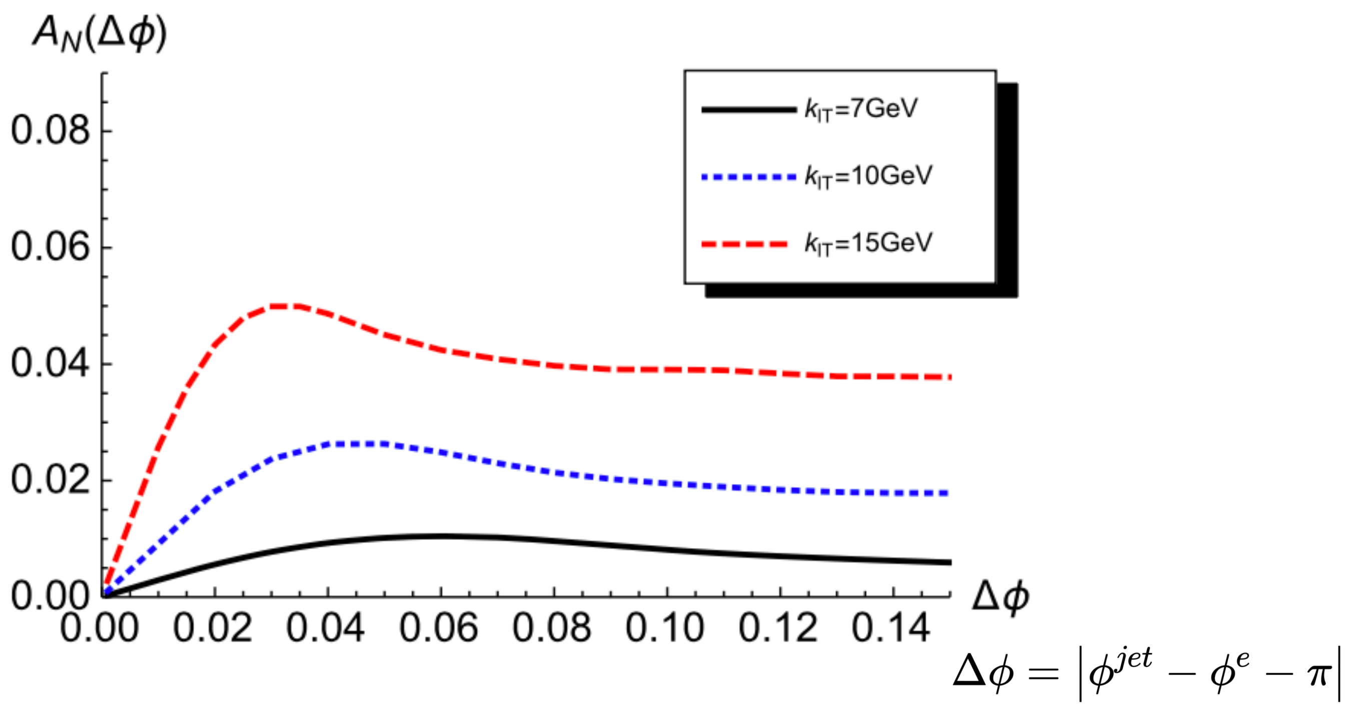


- H1 datas agree with TMD calculation(with different set) in a wide kinematics.

- Indicate the feasibility of LJC measurement at the EIC.

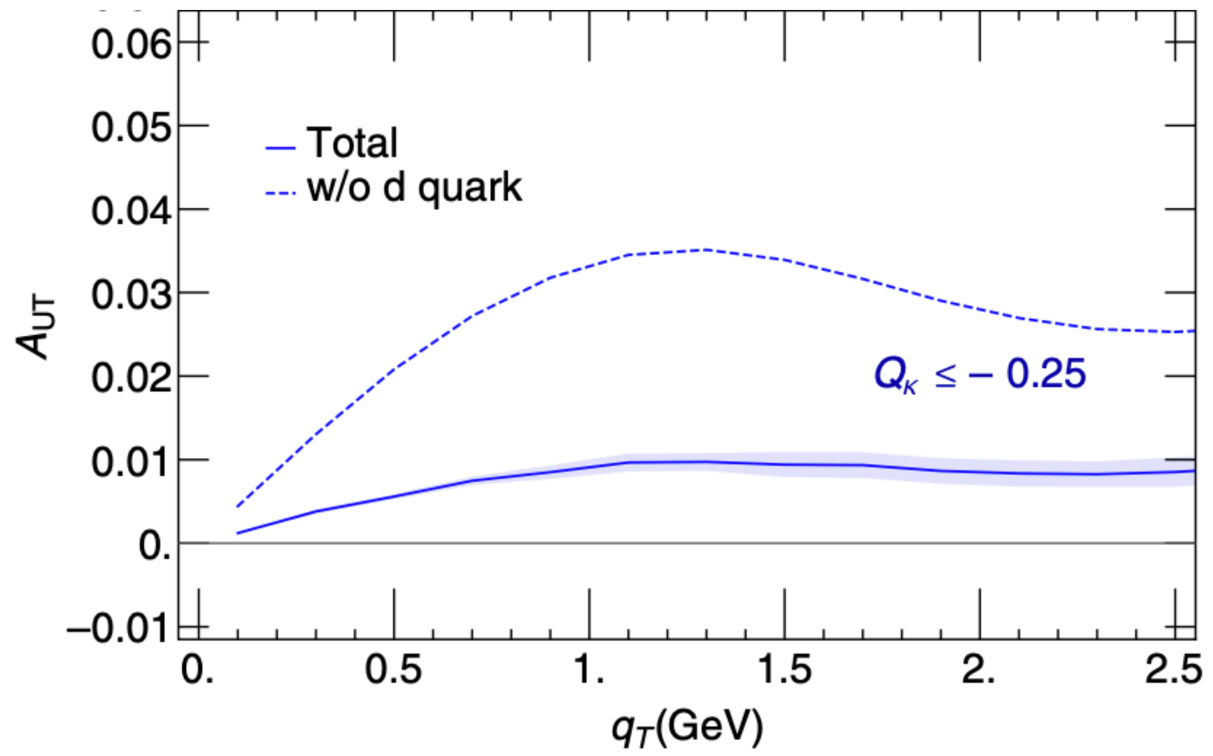
Azimuthal angle asymmetries from proton transverse spin

- Sivers asymmetry $A_{UT}^{\sin(\phi_s-\phi_q)}$ Liu-Ringer-Vogelsan-Yuan PRL22,192003 (2019); PRD102,094022 (2020)
  - ➡ Sivers function: unpolarized quark in an transversely polarized proton

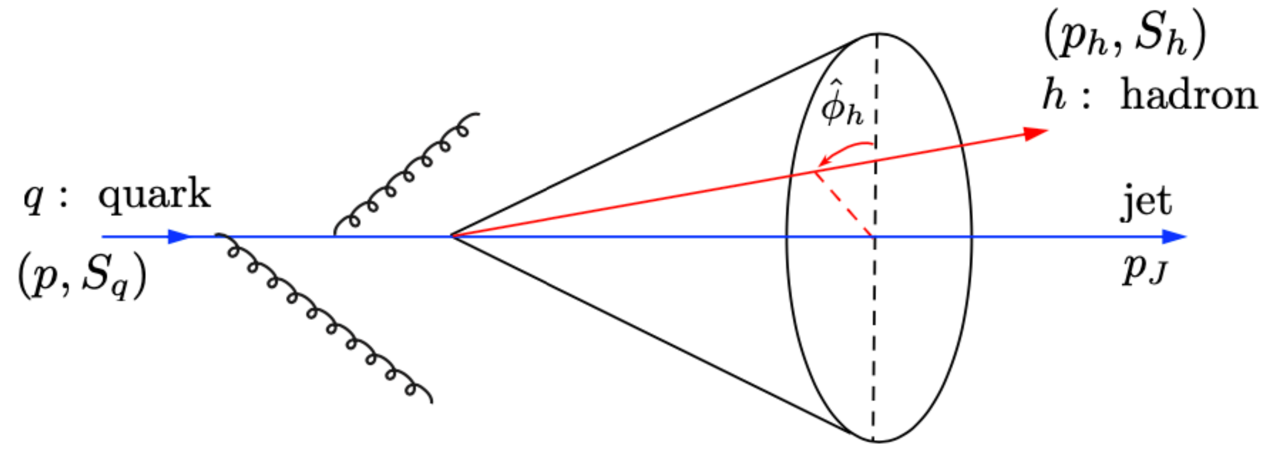


  - ‣ Jet charge: novel tool to unveil the favor structure $Q_\kappa \equiv \sum_{h\in \text{jet}} z_h^\kappa Q_h,$

Kang-Liu-Mantry-Shao PRL 125, 242003(2020)

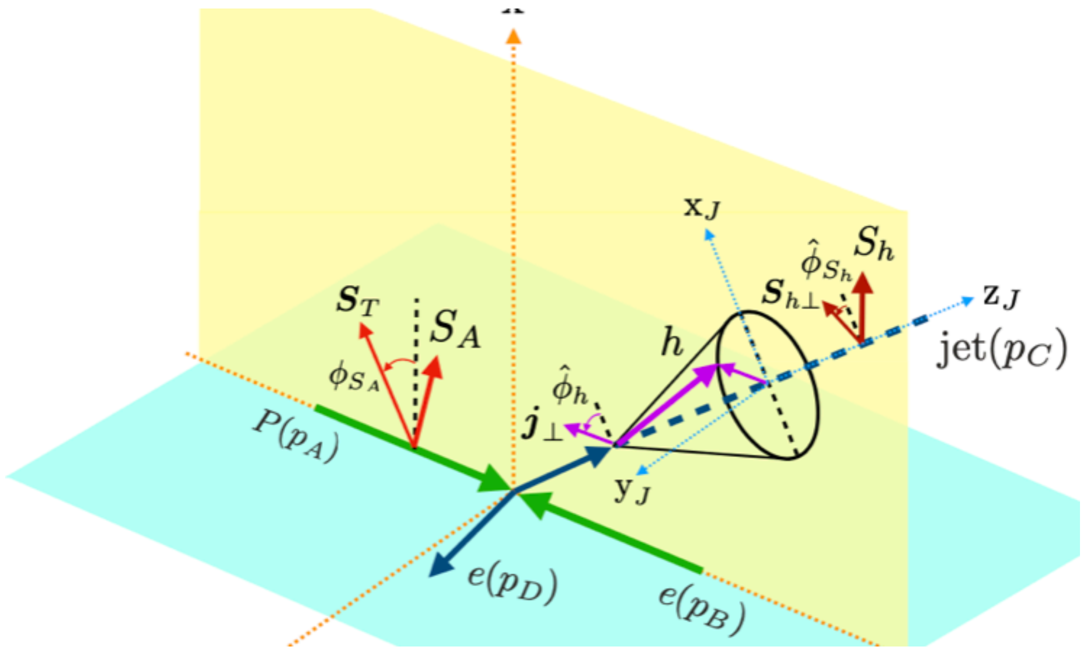


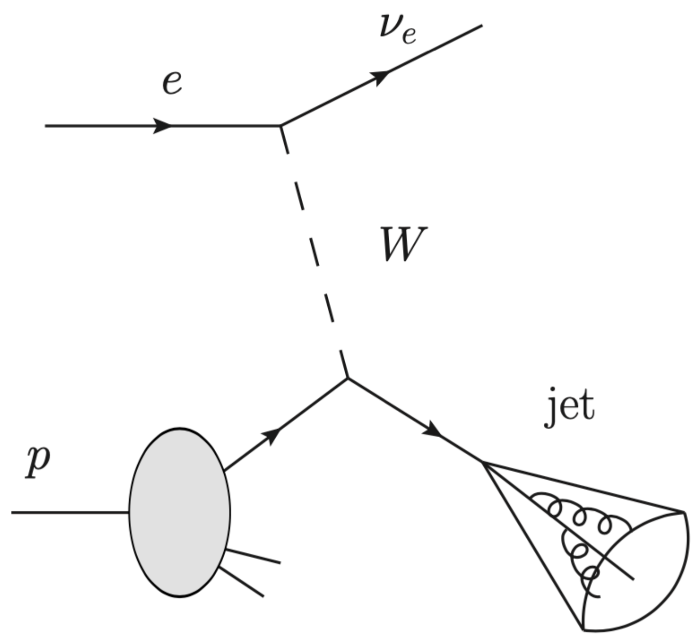
- Collins asymmetry: $A_{UT}^{\sin(\phi_s-\phi_h)}$ Arratia-Kang-Prokudin-Ringer PRD102,074015 (2020) Kang-Lee-Shao-Zhao JHEP 11 (2021) 005
  - ‣ jet fragmentation



See a review in Sec.9, TMD Handbook 2304.03302

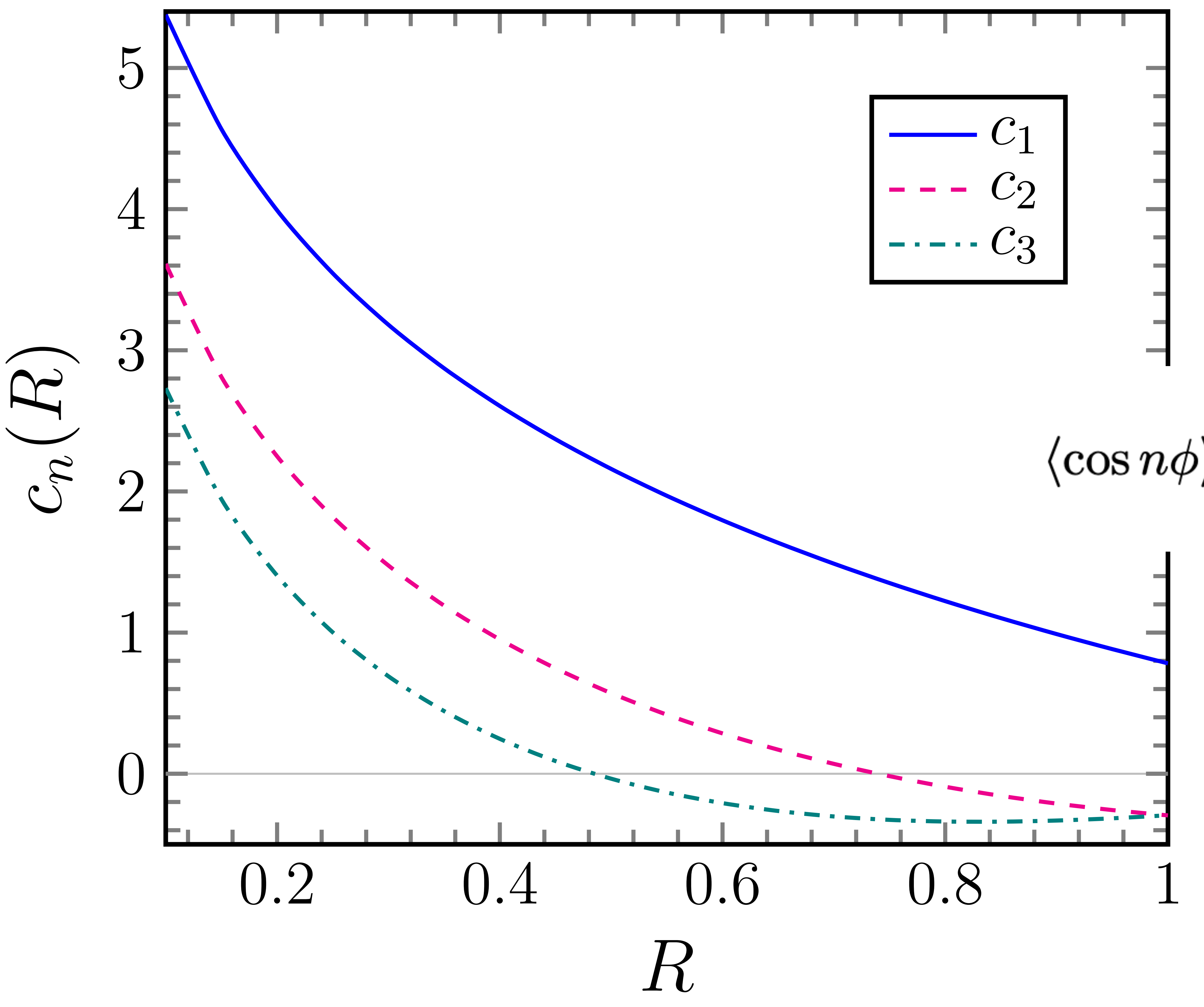
  - ➡ Collin fragmentaion function: unpolarized hadron from transversely polarized quark





- Spin asymmetries in Neutrino-jet correlation:

Arratia-Kang-Paul-Prokudin-Ringer-Zhao 2212.02432



$$\langle \cos n\phi \rangle = \frac{\sigma_{\rm LO} \int r_\perp dr_\perp J_n(q_\perp r_\perp) \frac{\alpha_s C_F c_n(R)}{n\pi} e^{-{\rm Sud}(r_\perp, R)} \sum_q e_q^2 x f_q(x, r_\perp)}{\sigma_{\rm LO} \int r_\perp dr_\perp J_0(q_\perp r_\perp) e^{-{\rm Sud}(r_\perp, R)} \sum_q e_q^2 x f_q(x, r_\perp)} .$$

✦The hierarchy of anisotropy on n is inherited from the Fourier coefficients $c_n(R)$;

✦$c_n(R)$ decreases as R becomes larger; For larger jet cone, more gluons are likely included in the jet and have less probability to radiate outside the jet cone.

✦R-dependence largely cancel in the $R_{eA}^{(n)}$