



Nuclear Modification of Dijet at EIC

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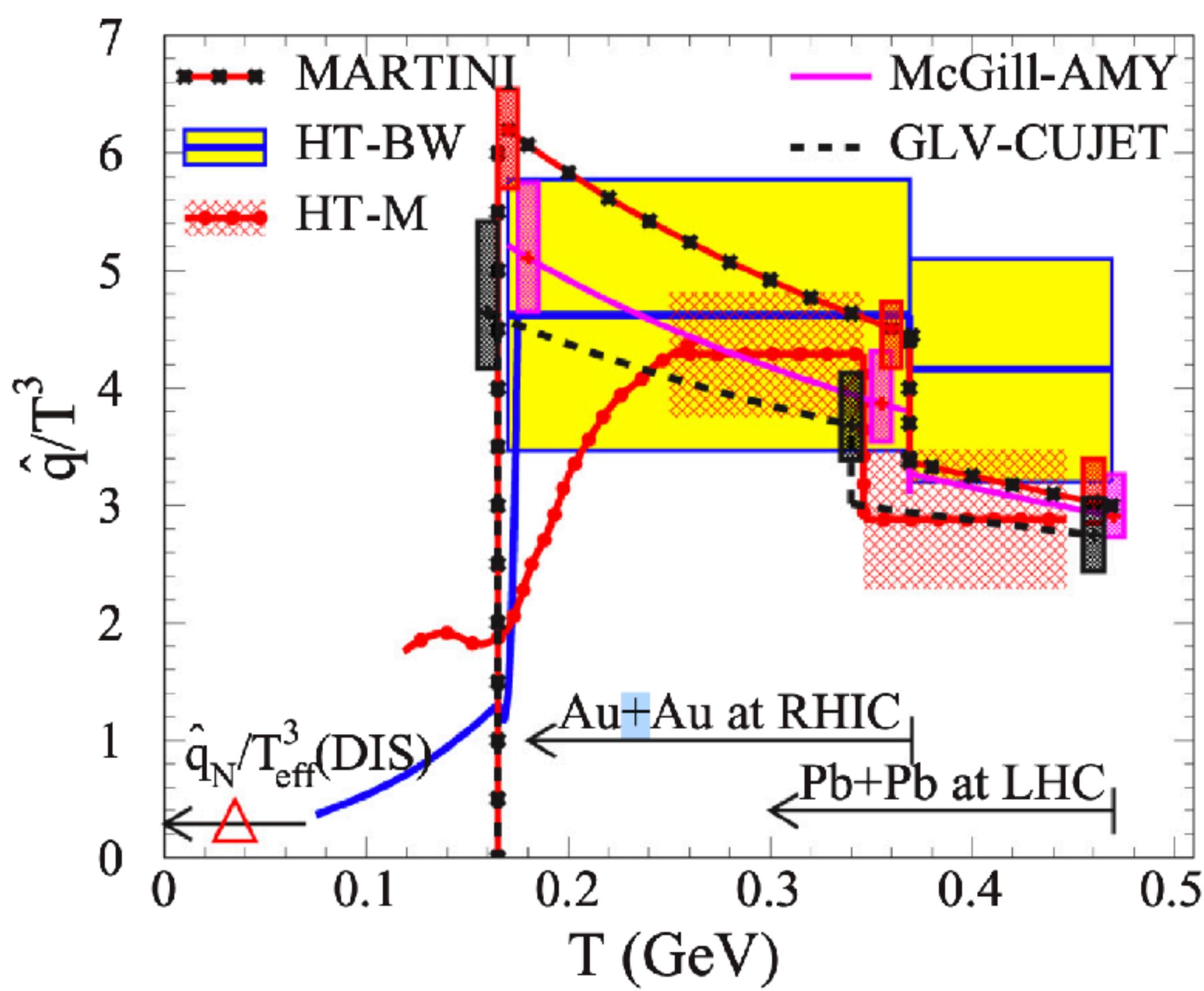
Collaborator : Xin-Nian Wang (LBL, CCNU)

Contents

- * Introduction
- * Dijet & TMD jet transport parameter $\hat{q}(k_\perp)$
- * Nuclear modification of dijet at EIC
- * Summary and discussion

QCD in Nuclear Matter

Jet transport coefficient \hat{q} T dependence



JET Collaboration, PRC 90, 014909

Heavy Ion Collision

$$\hat{q} \approx 1.2 \pm 0.3 \text{ GeV}^2/\text{fm} \quad \text{RHIC}$$

$$\hat{q} \approx 1.9 \pm 0.7 \text{ GeV}^2/\text{fm} \quad \text{LHC}$$

JET Collaboration, PRC 90, 014909

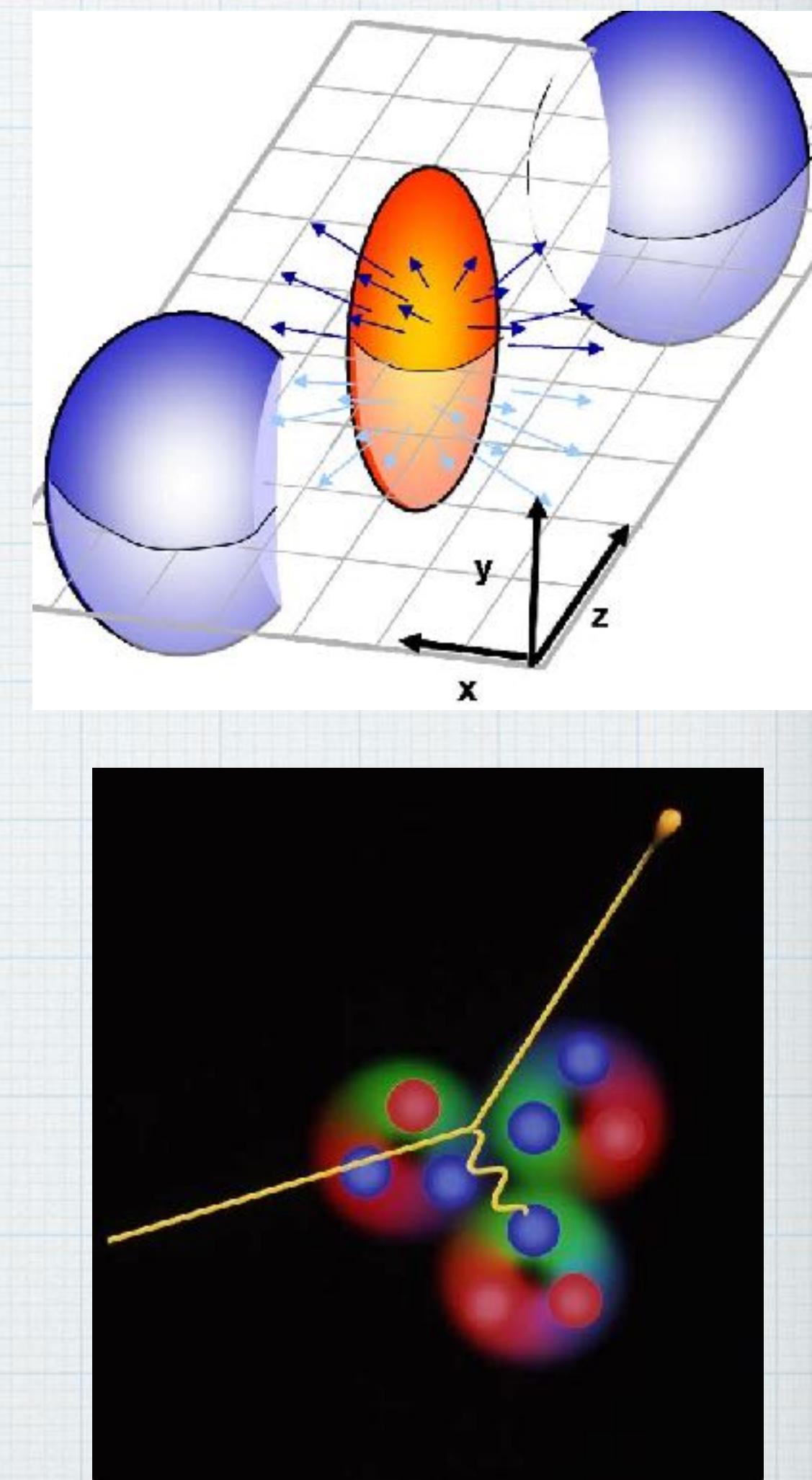
Electron Ion Collision

$$\hat{q} = 0.015 \text{ GeV}^2/\text{fm}$$

P. Ru et al, arXiv:2004.00027

NB Chang et al, PRC 89.3 (2014): 034911

E Wang, XN Wang, PRL 89.16 (2002): 162301



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Jet transport parameter in cold nuclei

- * Use the suppression of leading hadron to extract \hat{q} in cold nuclei

NB Chang et al, PRC **89.3** (2014): 034911

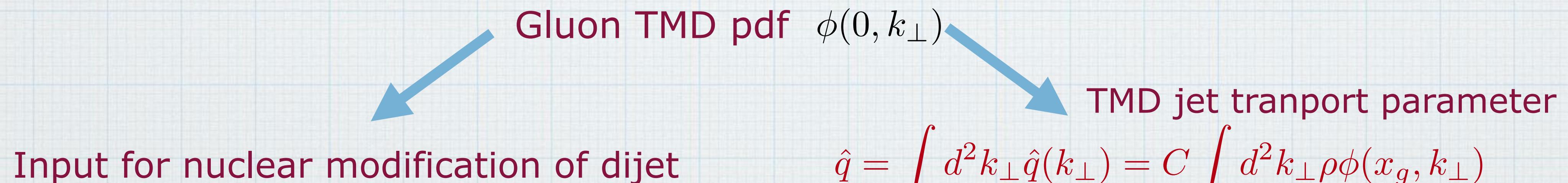
$$\hat{q} = 0.02 \text{ GeV}^2/\text{fm}$$

- * Use the pT broadening of final-state hadron to extract \hat{q} in cold nuclei

P. Ru et al, arXiv:2004.00027

$$\hat{q} = 0.015 \text{ GeV}^2/\text{fm} \quad \text{for DIS}$$

- * Our study: connection between nuclear modification of dijet and \hat{q}



$$\hat{q} = \int d^2 k_\perp \hat{q}(k_\perp) = C \int d^2 k_\perp \rho \phi(x_g, k_\perp)$$

J Casalderrey-Solana, XN Wang Phys. Rev. C **77**, 024902

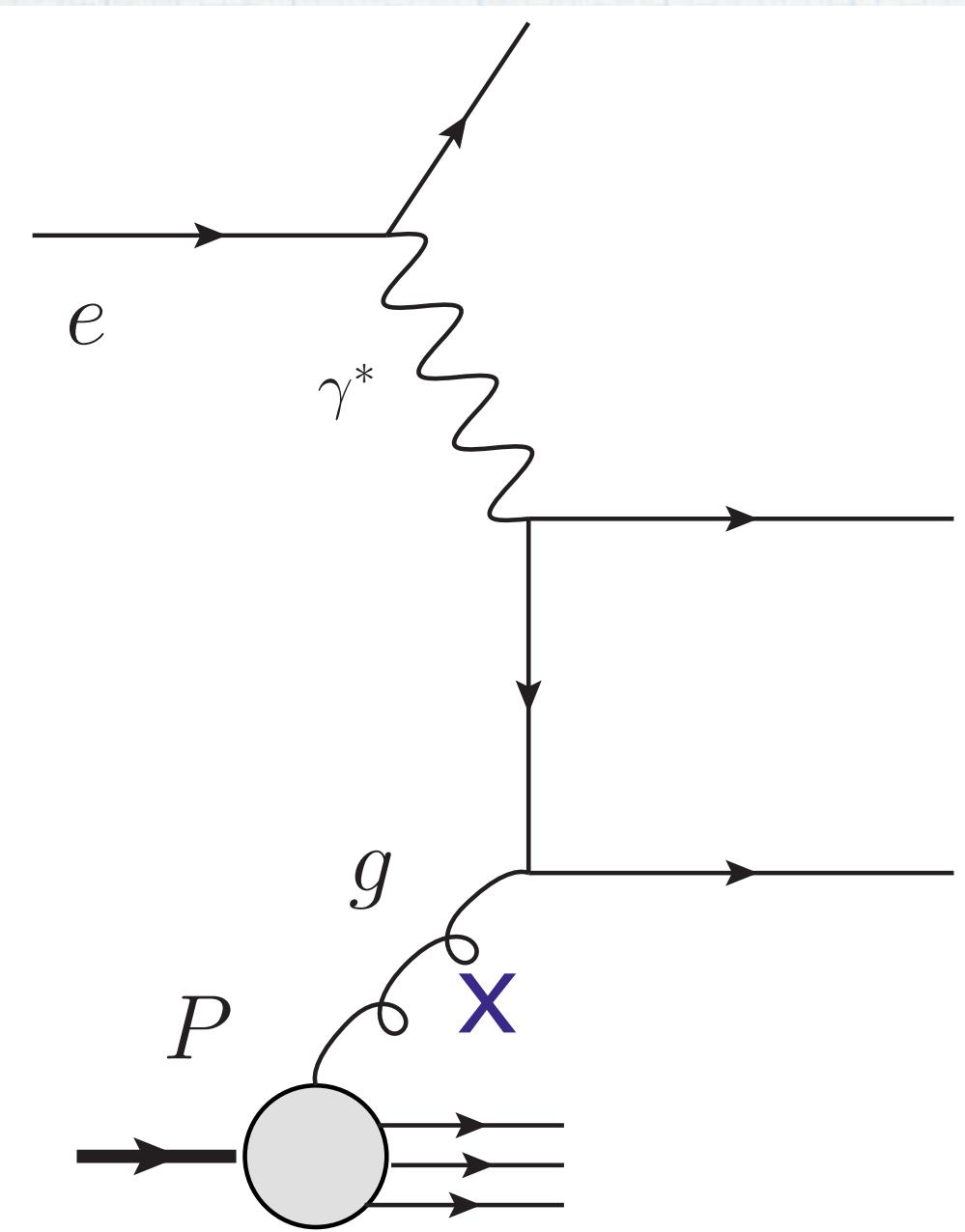
Dijet in e+A collisions

$$\text{Bjorken } x = \frac{Q^2}{2P * q}$$

Momentum fraction carried by parton from nucleon

Small Bjorken x

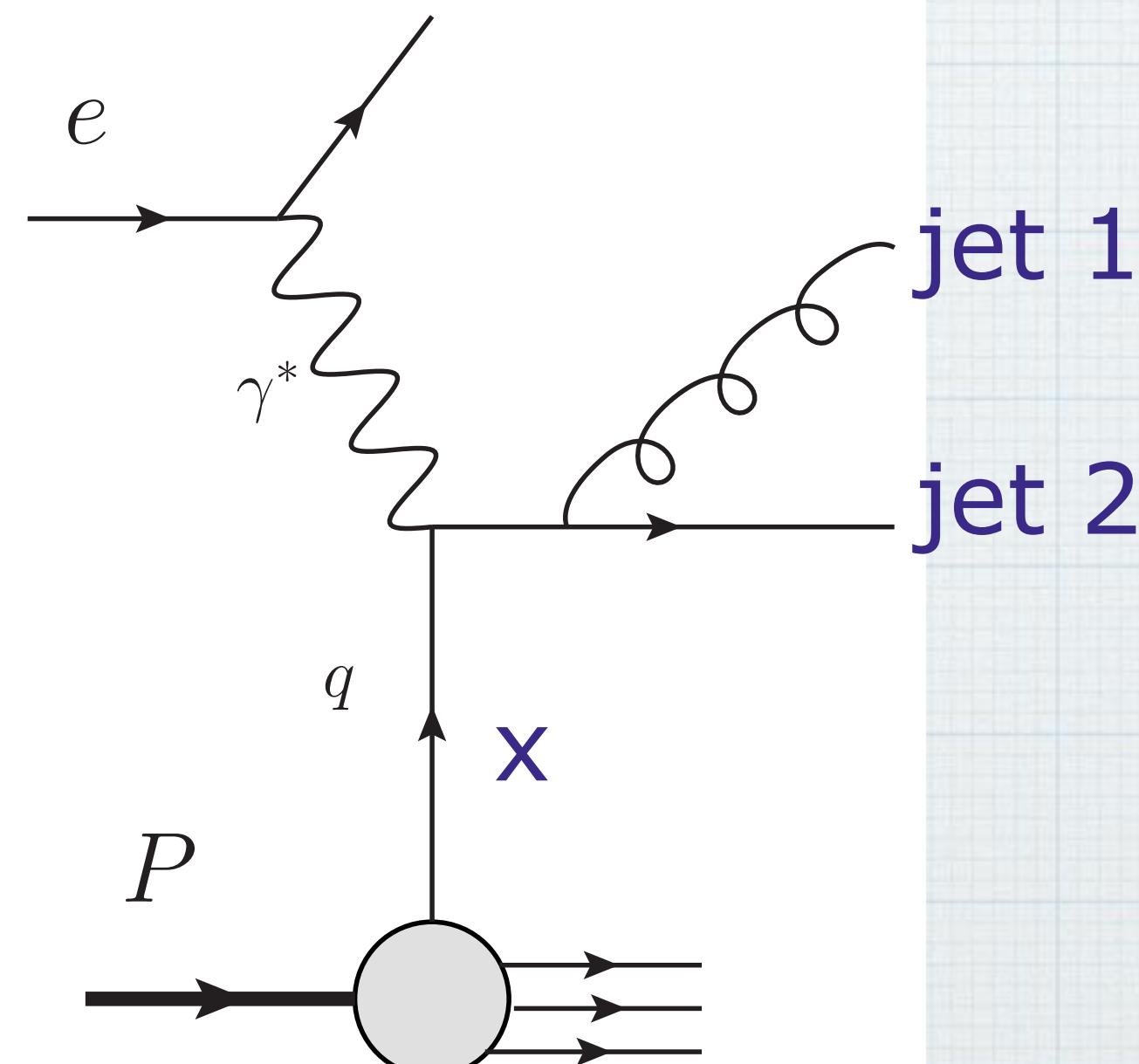
$g + \gamma^* \rightarrow q(\text{jet1}) + q(\text{jet2})$ dominates



jet 1
jet 2

Large Bjorken x

$q + \gamma^* \rightarrow q(\text{jet1}) + g(\text{jet2})$ dominates



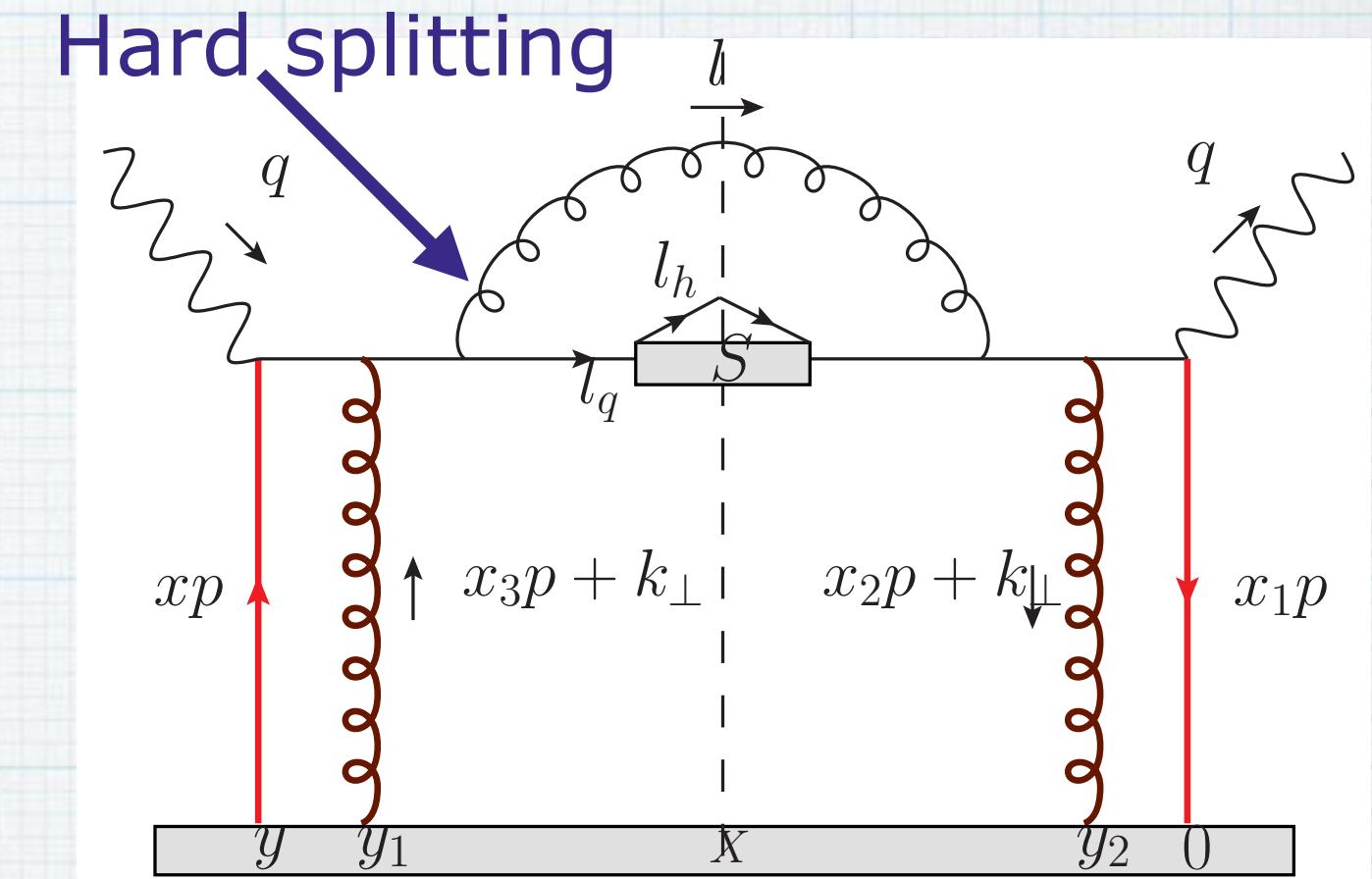
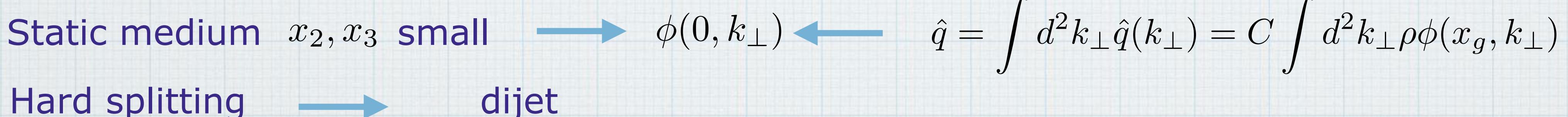
jet 1
jet 2

Dijet & TMD jet transport parameter

YY Zhang, GY Qin, XN Wang, PRD, 100(7), 074031 Radiated gluon spectrum

- * e+A scattering hardronic tensor (all diagrams)

$$\begin{aligned} \frac{dW^{static}}{dz} \sim & H_{(0)}^{\mu\nu} \otimes f_q^A(x) \otimes \frac{1 + (1 - z)^2}{z} \otimes \rho(y_1^-, \vec{y}_{1\perp}) \otimes \frac{\phi(0, \vec{k}_\perp)}{k_\perp^2} \\ & \otimes \left\{ C_F \left[\frac{1}{(\vec{l}_\perp - z\vec{k}_\perp)^2} - \frac{1}{l_\perp^2} \right] + \frac{1}{N_c} \left[\frac{\vec{l}_\perp \cdot (\vec{l}_\perp - z\vec{k}_\perp)}{l_\perp^2(\vec{l}_\perp - z\vec{k}_\perp)^2} - \frac{1}{l_\perp^2} \right] \times (1 - \cos[x_L p^+ y_1^-]) \right. \\ & \left. + C_A \left[\frac{2}{(\vec{l}_\perp - \vec{k}_\perp)^2} - \frac{\vec{l}_\perp \cdot (\vec{l}_\perp - \vec{k}_\perp)}{l_\perp^2(\vec{l}_\perp - \vec{k}_\perp)^2} - \frac{(\vec{l}_\perp - \vec{k}_\perp) \cdot (\vec{l}_\perp - z\vec{k}_\perp)}{(l_\perp - k_\perp)^2(\vec{l}_\perp - z\vec{k}_\perp)^2} \right] \times (1 - \cos[(x_L + \frac{x_D}{1-z}) p^+ y_1^-]) \right\}. \end{aligned}$$



Caculate the nuclear modification for dijet cross section, include initial quark v_\perp !

Kinematics & Geometry

* Breit frame : initial quark $xP^\mu + \vec{v}_\perp \approx (\frac{Q}{2}, v_{\perp x}, v_{\perp y}, \frac{Q}{2}) = (\frac{Q}{\sqrt{2}}, 0, \vec{v}_\perp)$

$$Q^2 \gg v_\perp^2$$

quark after photon scattering

$$xP^\mu + \vec{v}_\perp + q^\mu \approx (\frac{Q}{2}, v_{\perp x}, v_{\perp y}, -\frac{Q}{2}) = (0, \frac{Q}{\sqrt{2}}, \vec{v}_\perp)$$

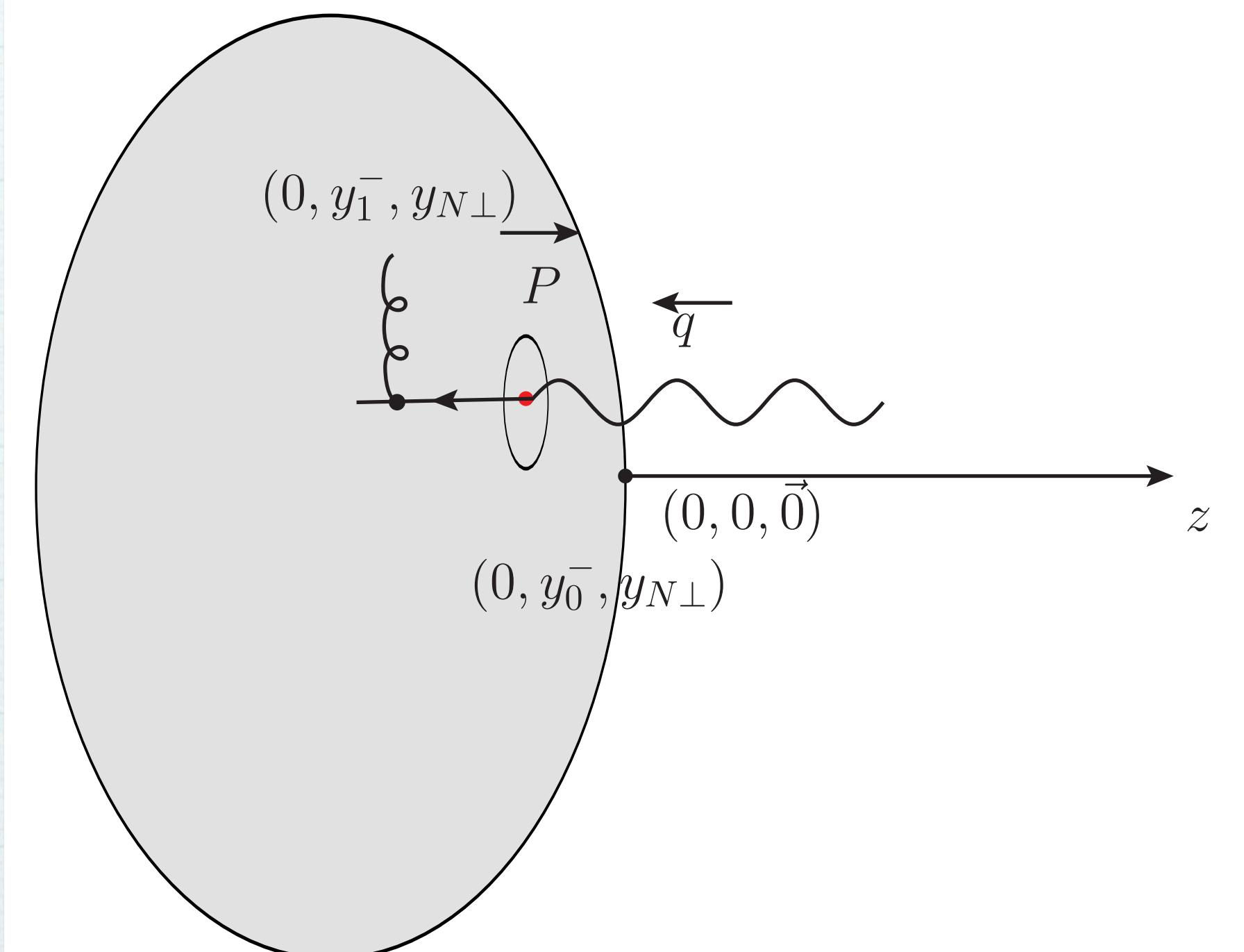
* Photon-quark scattering (first scattering) at

$$(0, y_0^-, \vec{y}_{N\perp})$$

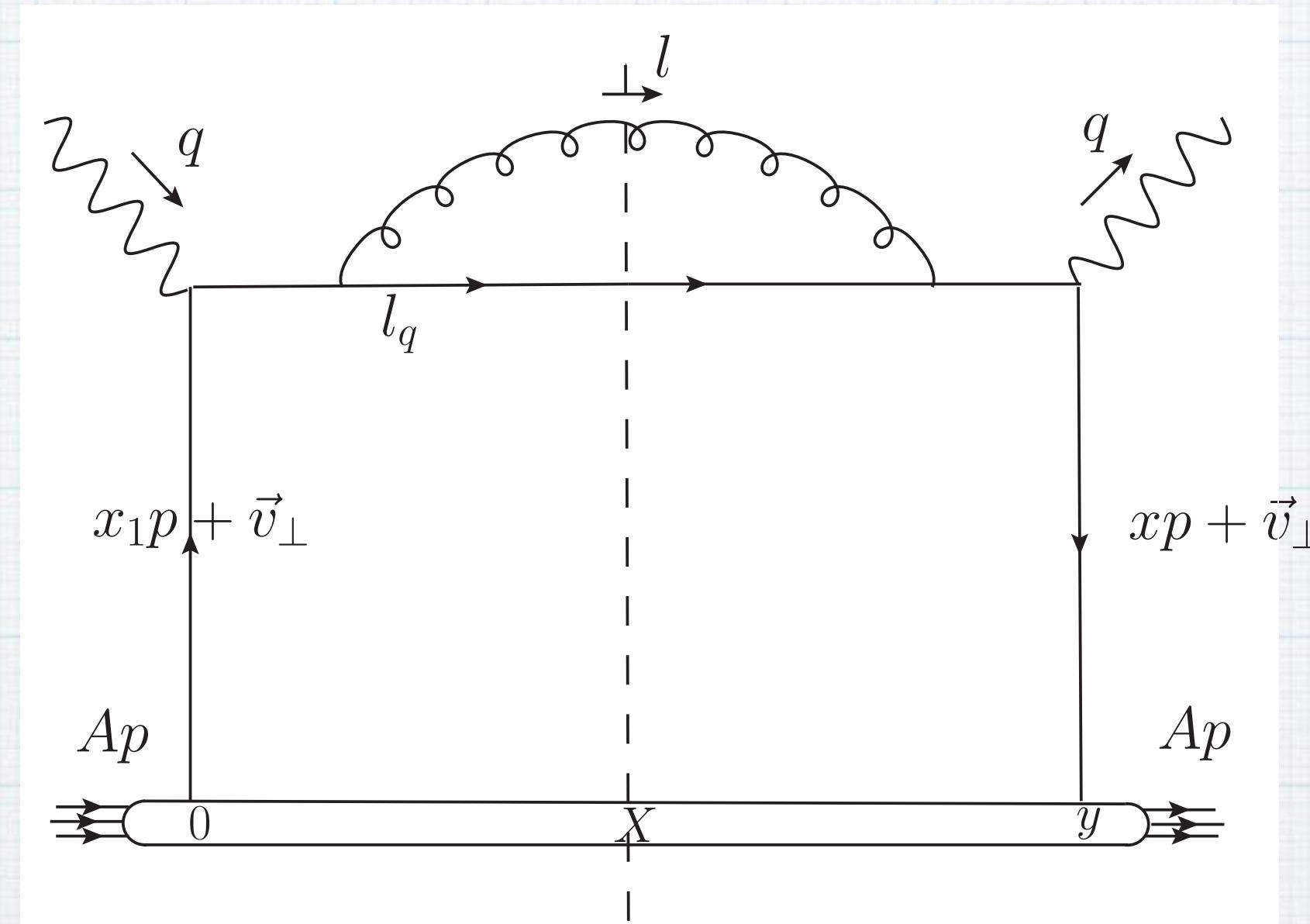
quark-nucleon scattering (second scattering) at

$$(0, y_1^-, \vec{y}_{N\perp})$$

(Eikonal approximation)



Dijet in e+A: Single scattering



$$\frac{d\hat{\sigma}_{e+A}}{dx dQ^2 dz d^2l_\perp d^2l_{q\perp}} = 2\pi\alpha_{\text{em}}^2 \sum_q e_q^2 [1 + (1 - \frac{Q^2}{xs})^2] \frac{\alpha_s}{2\pi} \frac{1+z^2}{1-z} \left\{ \frac{A}{\pi} f_q^N(x, \vec{l}_\perp + \vec{l}_{q\perp}) \frac{C_F}{[\vec{l}_\perp - (1-z)(\vec{l}_\perp + \vec{l}_{q\perp})]^2} \right\}$$

neglect nuclear modification to nPDF $f_q^A = A f_q^N$

Dijet in e+A : Double scattering

$$\frac{d\Delta\hat{\sigma}_{e+A}}{dx dQ^2 dz d^2 l_\perp d^2 l_{q\perp}} = 2\pi\alpha_{\text{em}}^2 \sum_q e_q^2 [1 + (1 - \frac{Q^2}{xs})^2] \frac{\alpha_s}{2\pi} \frac{1+z^2}{1-z} \frac{2\pi\alpha_s}{N_c} \int \frac{d^2 \vec{k}_\perp}{(2\pi)^2} \int dy_1^- A f_q^N(x, \vec{v}_\perp) \rho(y_1^-, \vec{0}) \frac{\phi(0, \vec{k}_\perp)}{k_\perp^2}$$

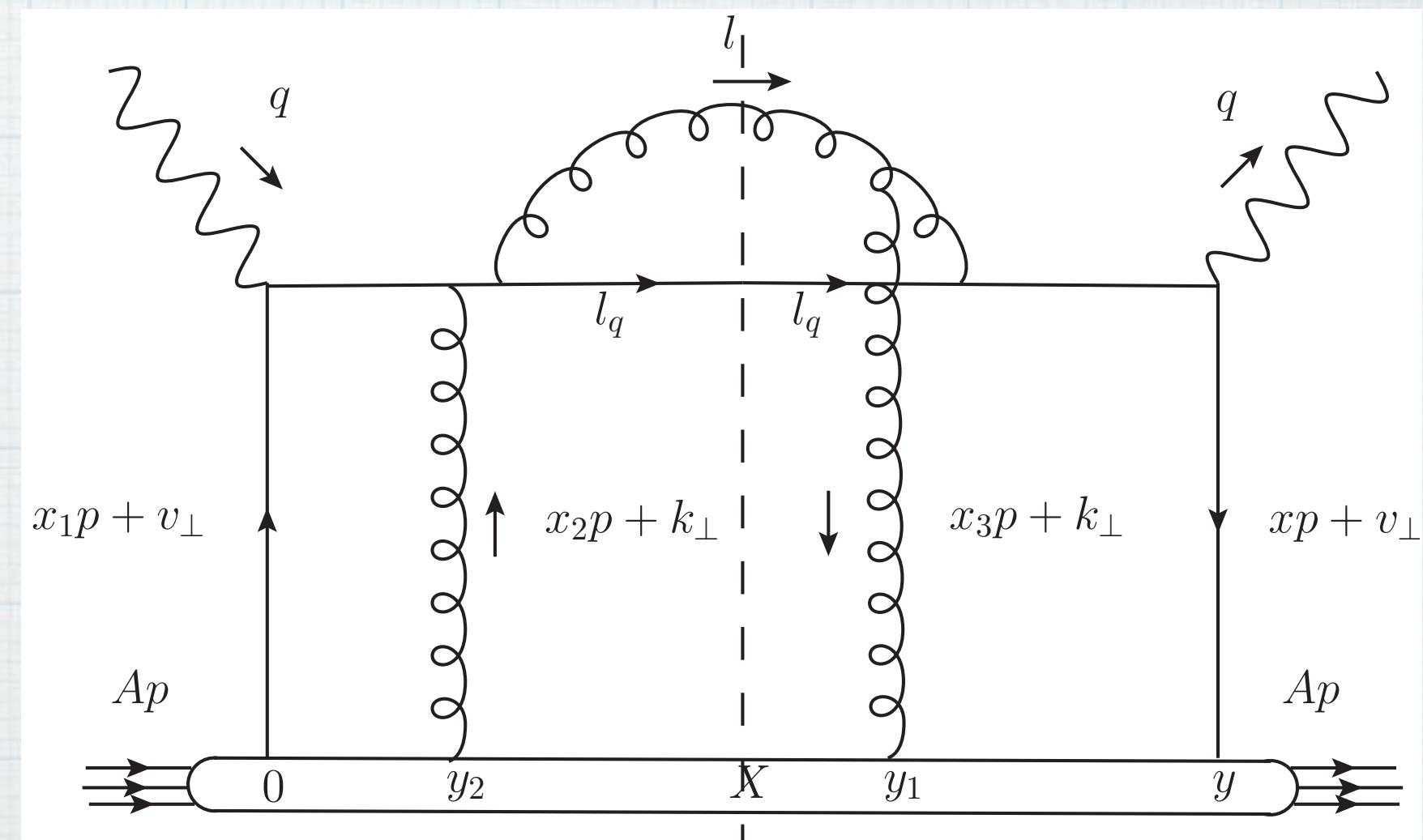
$$\left\{ C_F \left[\frac{1}{[\vec{l}_\perp - (1-z)(\vec{l}_\perp + \vec{l}_{q\perp})]^2} - \frac{1}{[\vec{l}_\perp - (1-z)\vec{v}_\perp]^2} \right] + \frac{1}{N_c} \left[\frac{[\vec{l}_\perp - (1-z)\vec{v}_\perp] \cdot [\vec{l}_\perp - (1-z)(\vec{l}_\perp + \vec{l}_{q\perp})]}{[\vec{l}_\perp - (1-z)\vec{v}_\perp]^2 [\vec{l}_\perp - (1-z)(\vec{l}_\perp + \vec{l}_{q\perp})]^2} \right. \right.$$

$$- \frac{1}{[\vec{l}_\perp - (1-z)\vec{v}_\perp]^2} \left. \times [1 - \cos(\frac{[\vec{l}_\perp - (1-z)\vec{v}_\perp]^2}{2q^- z(1-z)} \gamma y_1^-)] + C_A \left[\frac{2}{[\vec{l}_\perp - (1-z)\vec{v}_\perp - \vec{k}_\perp]^2} - \right. \right.$$

$$- \frac{[\vec{l}_\perp - (1-z)\vec{v}_\perp - \vec{k}_\perp] \cdot [\vec{l}_\perp - (1-z)(\vec{l}_\perp + \vec{l}_{q\perp})]}{[\vec{l}_\perp - (1-z)\vec{v}_\perp - \vec{k}_\perp]^2 [\vec{l}_\perp - (1-z)(\vec{l}_\perp + \vec{l}_{q\perp})]^2} - \frac{[\vec{l}_\perp - (1-z)\vec{v}_\perp] \cdot [\vec{l}_\perp - (1-z)\vec{v}_\perp - \vec{k}_\perp]}{[\vec{l}_\perp - (1-z)\vec{v}_\perp]^2 [\vec{l}_\perp - (1-z)\vec{v}_\perp - \vec{k}_\perp]^2} \left. \right]$$

$$\left. \times [1 - \cos(\frac{[\vec{l}_\perp - (1-z)\vec{v}_\perp - \vec{k}_\perp]^2}{2q^- z(1-z)} \gamma y_1^-)] \right\}$$

- integrate over $k_\perp, \varphi_2 \equiv \angle(k_\perp, l_{q\perp}), y_1^-$
- By $[\vec{l}_\perp - (1-z)\vec{v}_\perp] \Leftrightarrow \vec{l}_\perp \rightarrow$ hadronic tensor for quark without \vec{v}_\perp
- non-LPM term $C_F[\dots],$ LPM terms: q-LPM term $\frac{1}{N_c}[\dots][1 - \cos(a_1 * y_1^-)]$
g-LPM term $C_A[\dots][1 - \cos(a_2 * y_1^-)]$



TMD pdf of quarks and gluons

TMD pdf : TMDlib package, set “PB-NLO-HERAI+II-2018-set1”

F Hautmann, et al., The European Physical Journal C, 74(12), 3220

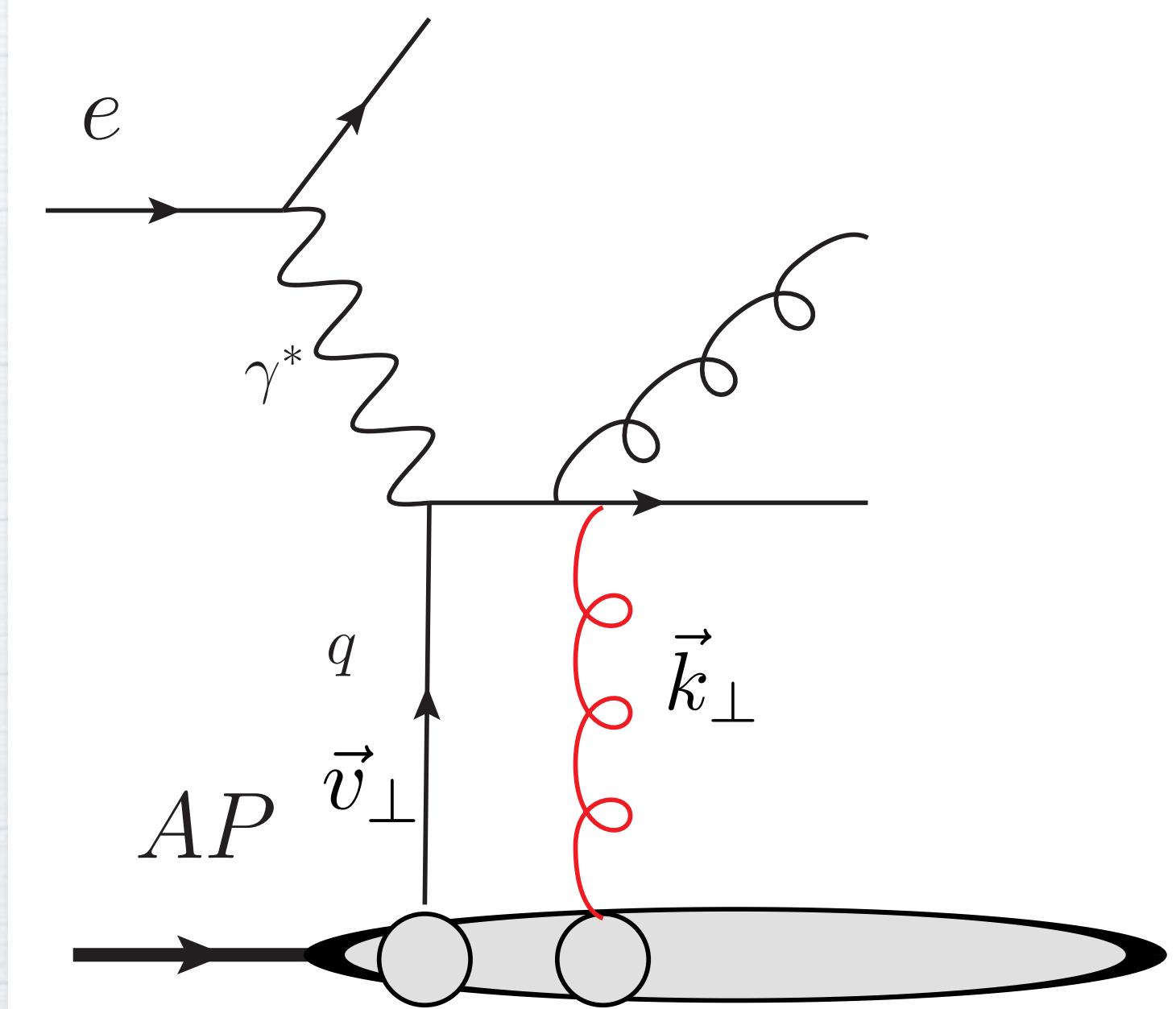
$$f(x, v_\perp) \quad \phi(x_g \approx 0, k_\perp)$$

- The quark and gluon TMD pdf drop quickly as $\vec{v}_\perp, \vec{k}_\perp$ increase

→ $Q^2 \gg k_\perp^2, v_\perp^2$

- “Small-x” gluon TMD pdf $\phi(x_g \approx 0, k_\perp, \mu = k_\perp)$

$$x_g \approx \frac{k_\perp^2}{Q^2} * x$$



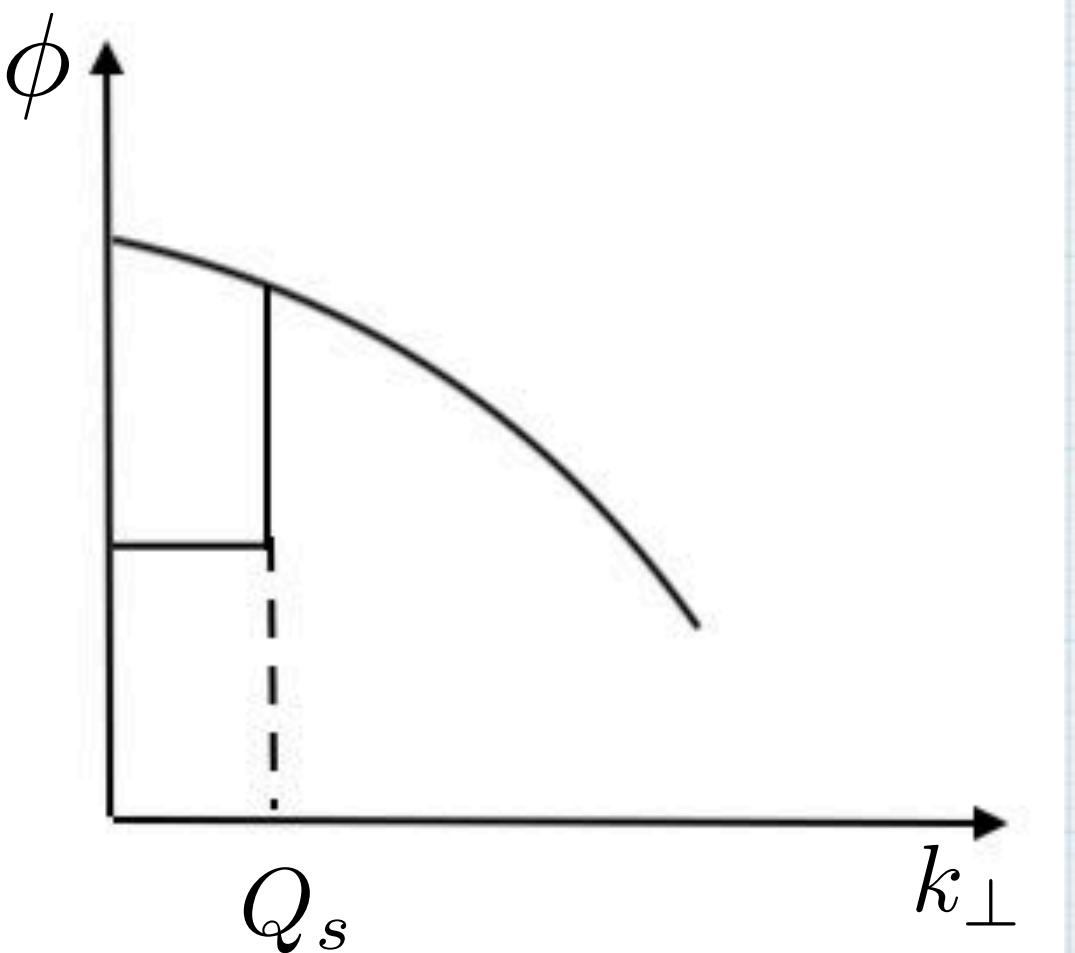
Gluon saturation & qhat

- * Saturation scale : the pT broadening of gluon in nuclei. Determined self-consistently

$$Q_s^2 = \int dy^- \hat{q}(y) = \frac{C_2(G)}{N_c^2 - 1} \int dy^- \rho(y^-, \vec{0}) \int d^2 k_\perp \alpha_s \phi(x_g = \frac{k_\perp^2}{Q^2} x, k_\perp)$$

In the integration over k_\perp : $k_\perp < Q_s$, $\phi = s_0 * \phi(x_g = \frac{Q_s^2}{Q^2} x, Q_s)$

- * Jet transport coefficient :



$$\hat{q}(y) = s_1 * \frac{C_2(Q)}{N_c^2 - 1} \rho(y^-, \vec{0}) \int d^2 k_\perp \alpha_s \phi(x_g = \frac{k_\perp^2}{Q^2} x, \vec{k}_\perp)$$

Fit with the $\hat{q} = 0.015 \text{ GeV}^2/\text{fm}$ from paper P. Ru et al, arXiv:2004.00027
we get the overall suppression factor s1

We have parameters s_0, s_1 for $\phi(x_g = \frac{k_\perp^2}{Q^2} x, k_\perp)$ and Q_s !

Nuclear modified dijet : A dependence

$$\frac{d\Delta\hat{\sigma}_{e+A}}{dx dQ^2 dz d^2l_\perp d^2l_{q\perp}} / \frac{d\hat{\sigma}_{e+A}}{dx dQ^2 dz d^2l_\perp d^2l_{q\perp}}$$

Ratio of nuclear modification/ dijet e+A

Consider the integration over y_1^-

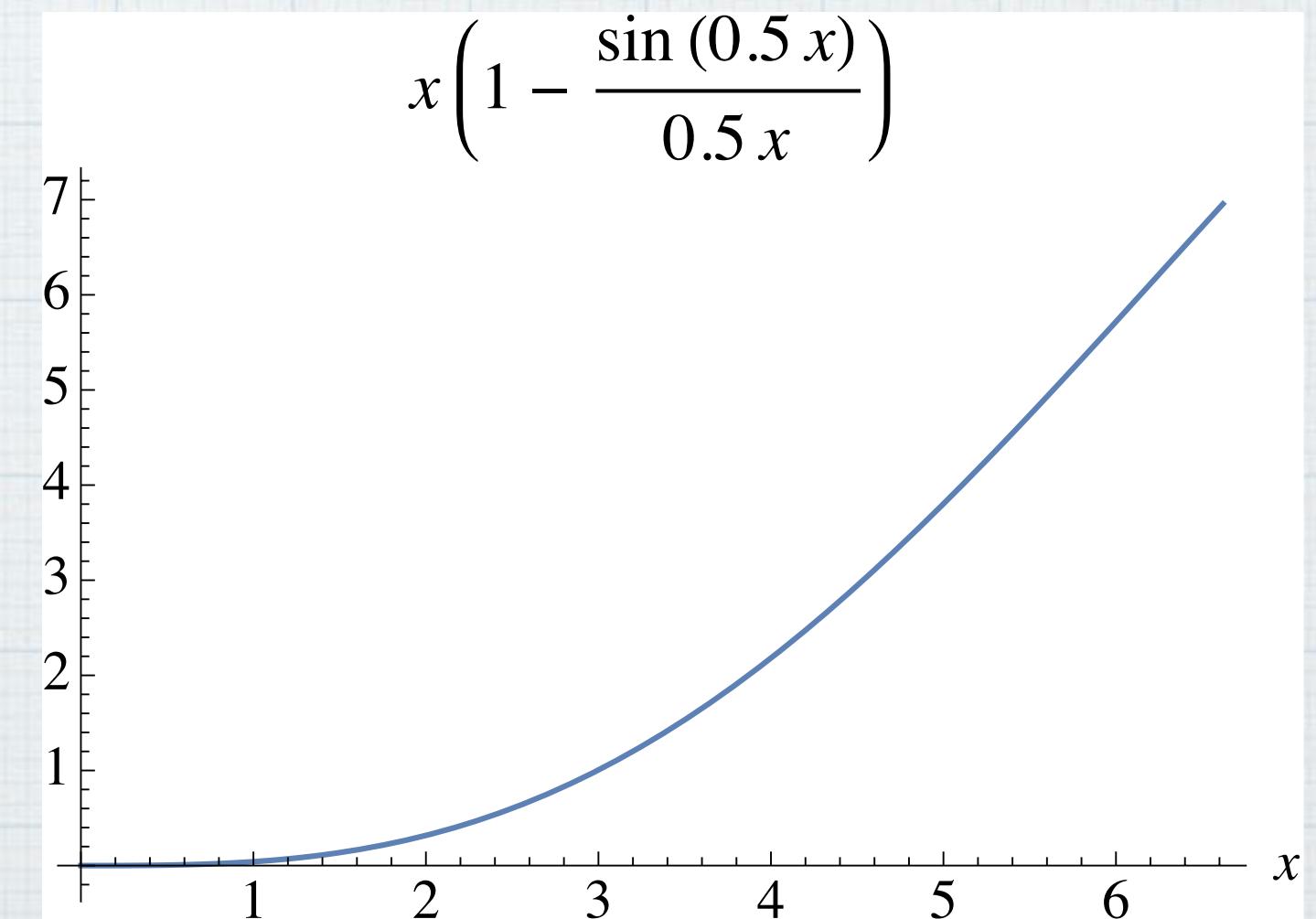
1. Non-LPM term ($C_F[\dots]$)

$$\int_0^{\sqrt{2}R_A/\gamma} dy_1^- = \sqrt{2}R_A/\gamma \sim A^{1/3}$$

2. LPM terms (q-LPM $\frac{1}{N_c}[\dots][1 - \cos(a_1 * y_1^-)]$, g-LPM $C_A[\dots][1 - \cos(a_2 * y_1^-)]$)

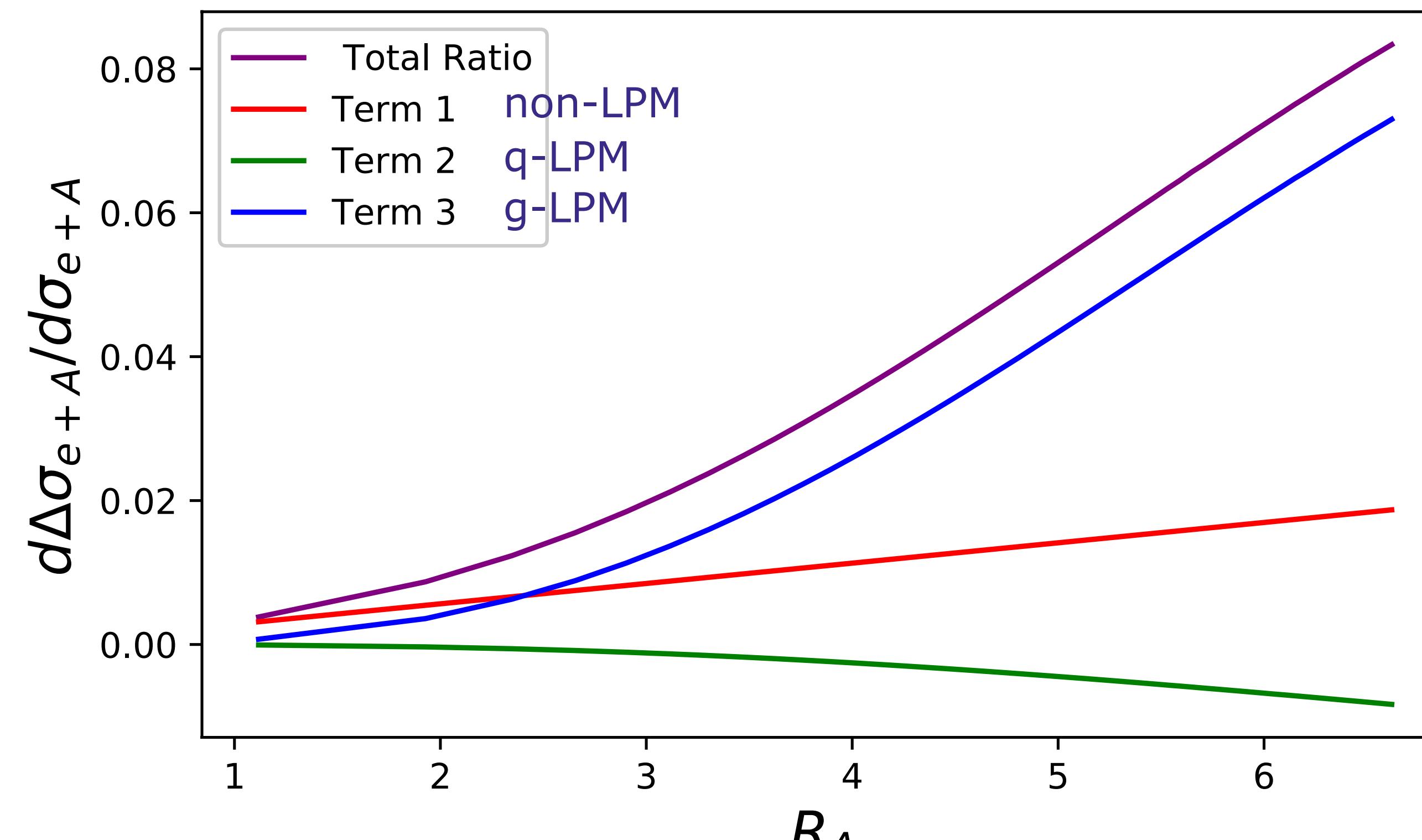
$$a_1 = \frac{[\vec{l}_\perp - (1-z)v_\perp]^2}{2q^-z(1-z)}\gamma \quad a_2 = \frac{[\vec{l}_\perp - (1-z)v_\perp - \vec{k}_\perp]^2}{2q^-z(1-z)}\gamma$$

$$\begin{aligned} & \int_0^{\sqrt{2}R_A/\gamma} dy_1^- [1 - \cos(a * y_1^-)] \\ &= \frac{\sqrt{2}R_A}{\gamma} \left[1 - \frac{\sin(a * \frac{\sqrt{2}R_A}{\gamma})}{a * \frac{\sqrt{2}R_A}{\gamma}} \right] \end{aligned}$$



Nuclear modified dijet : A dependence

$$x = 0.4 \quad z = 0.2 \quad Q^2 = 10000 \text{ GeV}^2 \quad l_\perp = l_{q\perp} = 2.8 \text{ GeV} \quad \varphi_1 = 1$$
$$\frac{d\Delta\sigma_{e+A}/d\sigma_{e+A}}$$



non-linear
linear
non-linear

LPM Terms bring the non-linear R_A dependence !

Nuclear modified dijet : Azimuthal angle

- * The peak of angle distribution move to left, with final dijet pT $l_\perp(l_{q\perp})$ decrease

Three peaks give same

$$|\vec{l}_\perp + \vec{l}_{q\perp}| = \sqrt{l_\perp^2 + l_{q\perp}^2 + 2l_\perp l_{q\perp} \cos(\varphi_1)} \approx Q_s$$

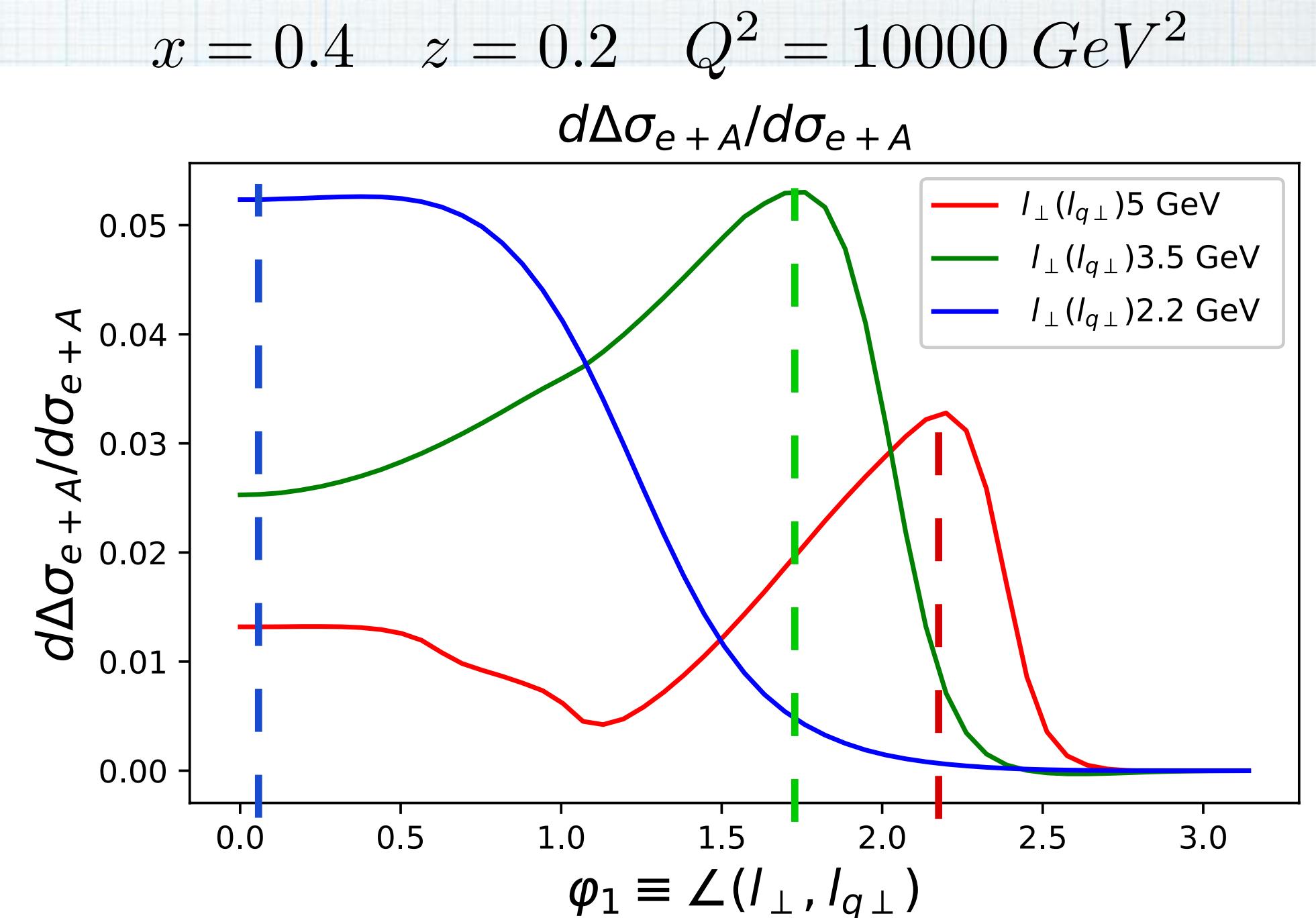
Transverse momentum conservation

$$\vec{l}_\perp + \vec{l}_{q\perp} = \vec{v}_\perp + \vec{k}_\perp$$

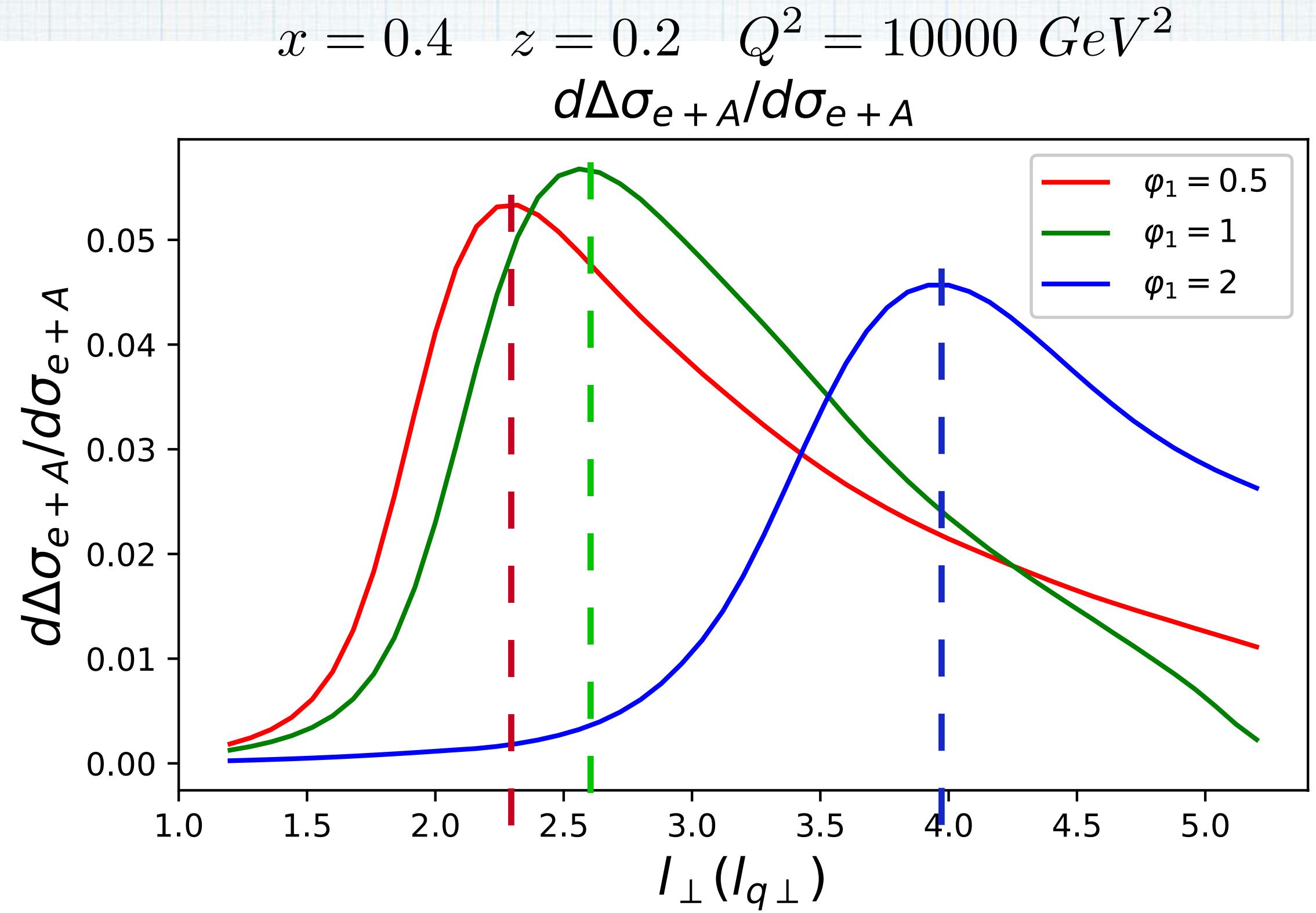
The $\frac{d\Delta\sigma_{e+A}}{d\sigma_{e+A}}$ contain $f(x, v_\perp) * \phi(0, k_\perp)$

{ quark TMD pdf $f(x, v_\perp)$, gluon TMD pdf $\phi(0, k_\perp)$ drop quickly for large v_\perp, k_\perp
gluon TMD pdf suppressed for $k_\perp < Q_s$

$|\vec{v}_\perp + \vec{k}_\perp|$ small but $\gtrsim Q_s$ gives largest $f(x, v_\perp) * \phi(0, k_\perp)$ \rightarrow largest $\frac{d\Delta\sigma_{e+A}}{d\sigma_{e+A}}$



Nuclear modified dijet : jet pT



- * The peak of jet pT distribution also move to left, as azimuthal angle φ_1 between dijet decrease

$$|\vec{l}_\perp + \vec{l}_{q\perp}| = \sqrt{l_\perp^2 + l_{q\perp}^2 + 2l_\perp l_{q\perp} \cos(\varphi_1)} \approx Q_s$$

Outlook

- Derive the nuclear modification to dijet in e+A collision
- Gluon TMD pdf and TMD \hat{q}
- The non-linear R_A dependence due to LPM effect
- The structure of azimuthal angle/pT distribution related to saturation scale Q_s

Further work

- Consider the pT broadening of quark and radiated gluon
- Understand the overall suppression s_1 of gluon TMD pdf constrained by \hat{q}

Thanks for your attention!