Nuclear Modification of Dijet at EIC

Yuan-Yuan Zhang (CCNU)

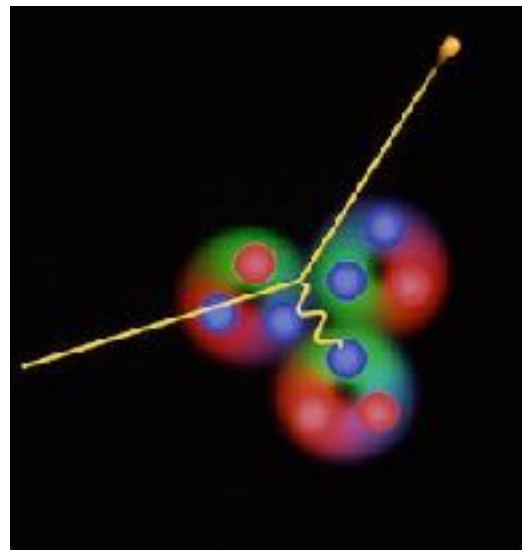
Collaborator : Xin-Nian Wang (LBL)

Contents

- Introduction: Jet Transport Cofficient $\hat{q}$ in cold nuclei
- Single Scattering Dijet & Double Scattering Dijet Cross Section
- Nuclear Modification of Dijet in e+A ($\Delta\phi, |y_{l_q} - y_l|, R_A$ dependence)
- Summary

$\hat{q}$ in QGP and Cold Nuclei
-average pT transfer squared per unit length

Electron Ion Collision

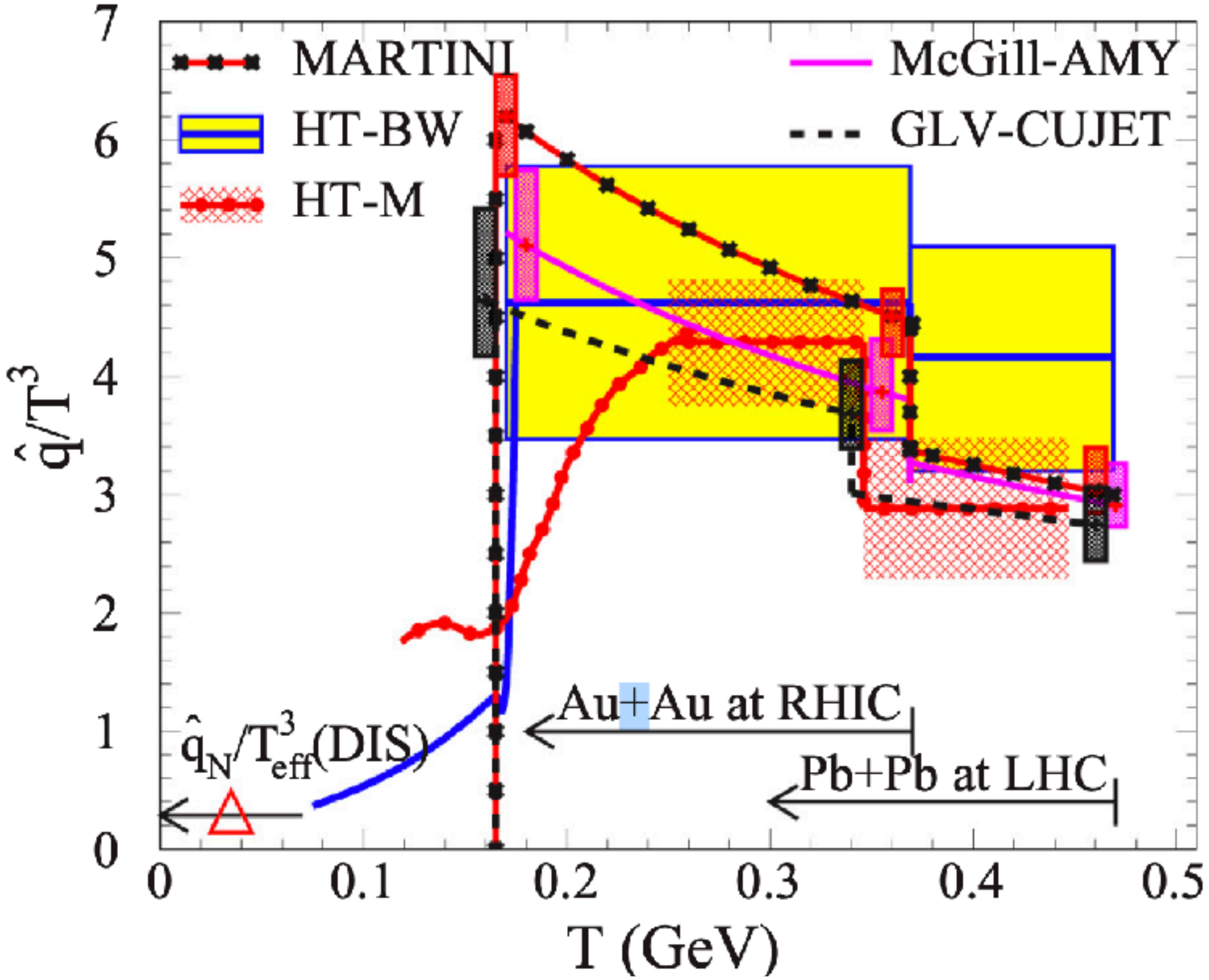


$\hat{q} \approx 0.015$ GeV$^2/fm$

P. Ru et al, arXiv:2004.00027

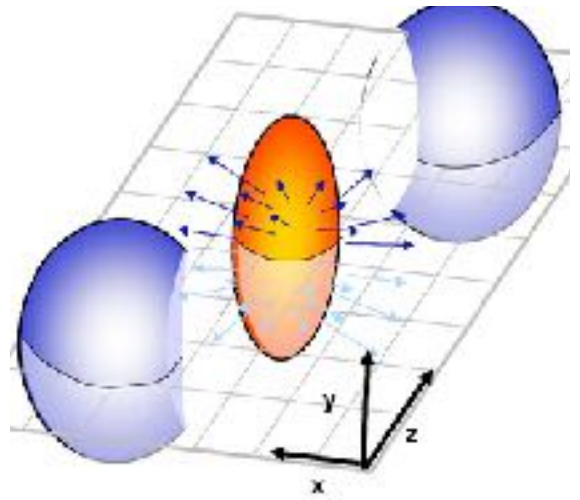
NB Chang et al, PRC **89.3** (2014): 034911

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



JET Collaboration, PRC **90**, 014909

Heavy Ion Collision



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

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

JET Collaboration, PRC **90**, 014909

Existing efforts on $\hat{q}$ in cold nuclei

High Twist Approach

- Use the pT broadening of final-state hadron (DIS) to extract $\hat{q}$

  $\hat{q} \approx 0.015$ GeV$^2/fm$ P. Ru et al, arXiv:2004.00027

- Use the the suppression of leading hadron (DIS) to extract $\hat{q}$

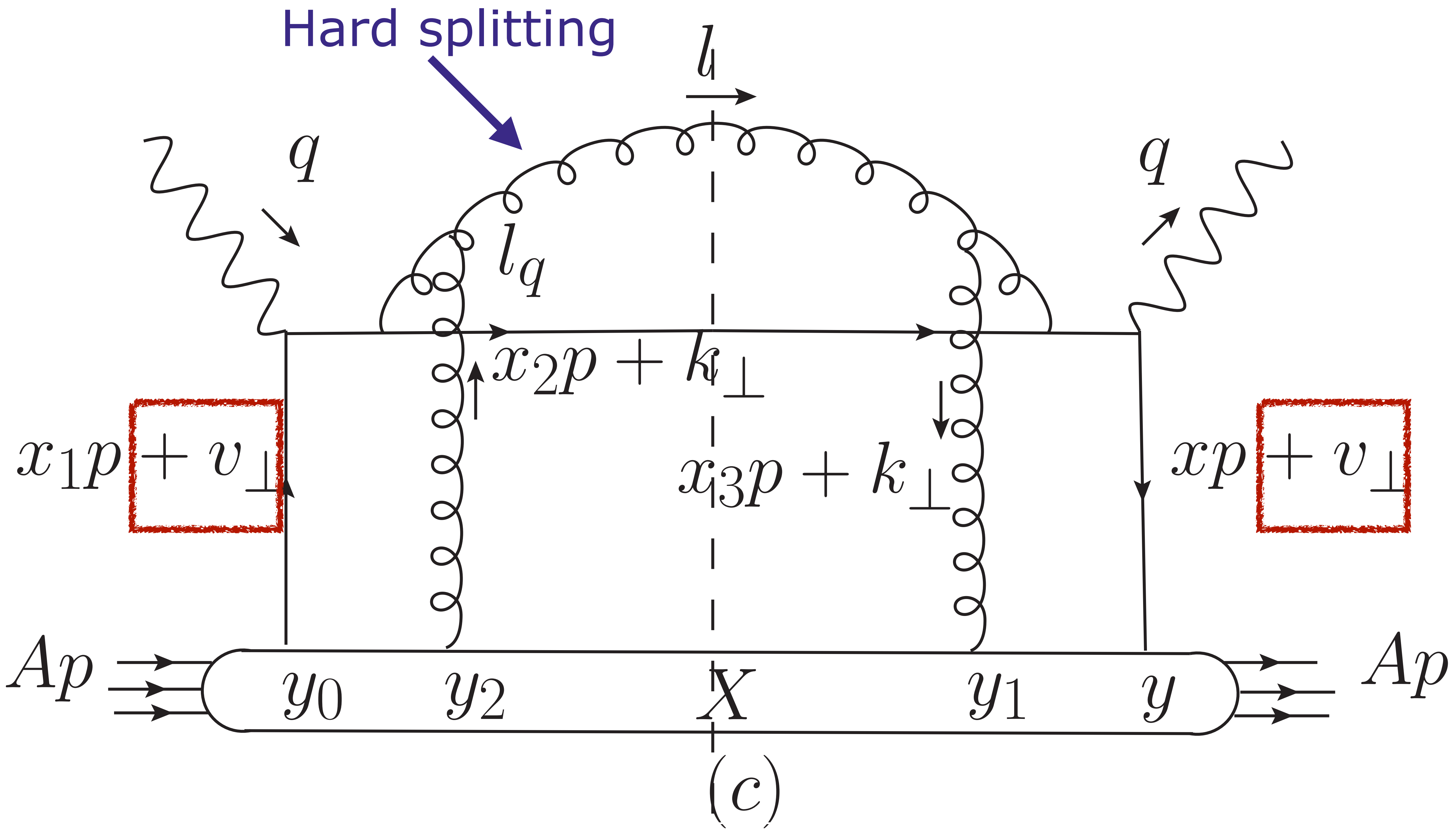
  $\hat{q} \approx 0.02$ GeV$^2/fm$ NB Chang et al, PRC **89.3** (2014): 034911

Generalized High Twist Approach Zhang, Y. Y., Qin, G. Y., & Wang, X. N. (2019). *PRD*, *100*(7), 074031.

- Relax $l_\perp, l_{q\perp} \gg k_\perp$, no $k_\perp$ /twist expansion
- medium-induced radiation spectra contain medium gluon TMD pdf $\phi(x_G, k_\perp)$ or TMD $\hat{q}(k_\perp)$

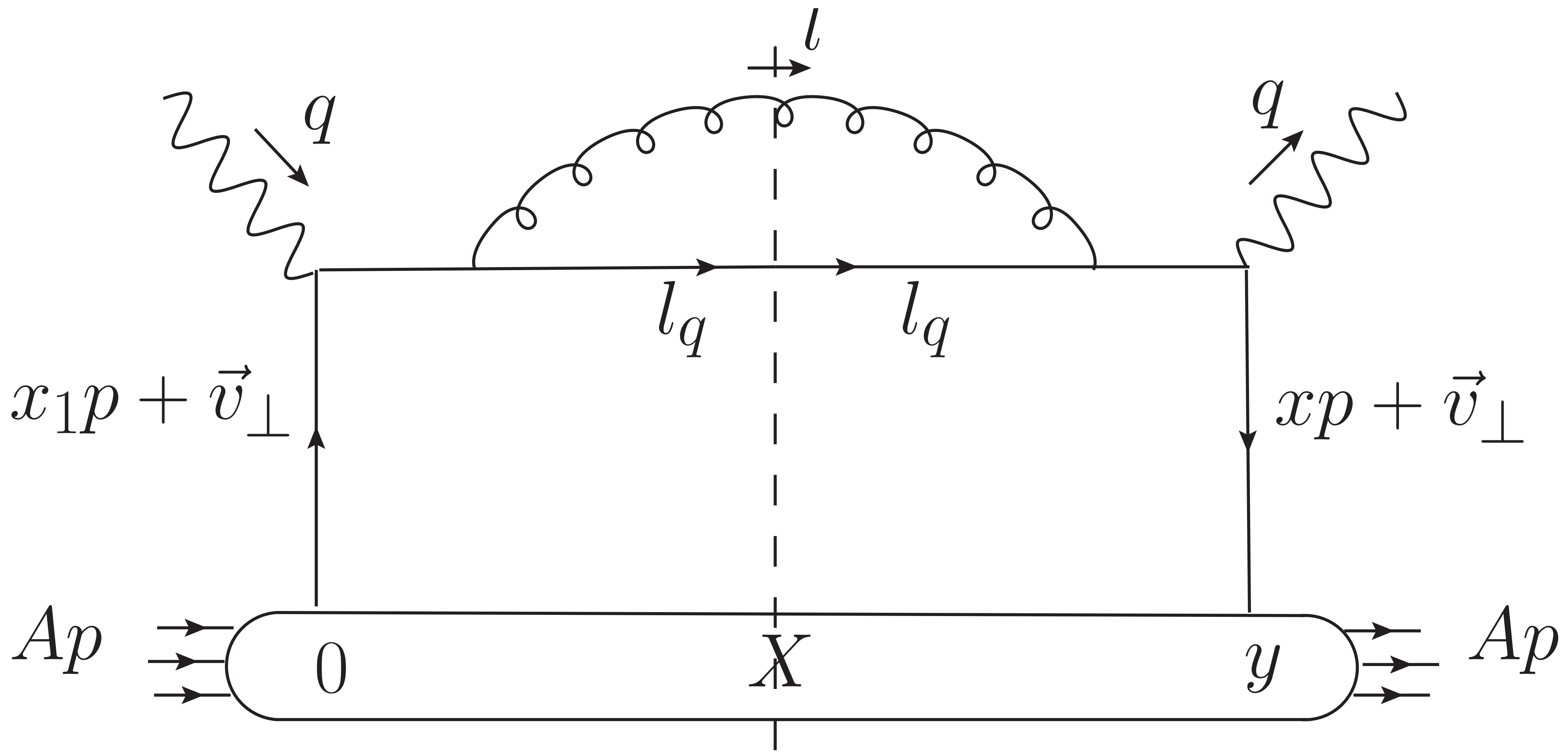
$$\hat{q} = \int d^2k_\perp \hat{q}\left(k_\perp\right) = C \int d^2k_\perp \rho\phi\left(x_g, k_\perp\right)$$

Dijet to probe gluon TMD pdf or TMD $\hat{q}(k_\perp)$



- Generalized High Twist Approach deals with hard splitting
- Second scattering directly probe gluon TMD pdf
- Further include initial quark transverse momentum $v_\perp$

Dijet in e+A: Single scattering



nuclear modification

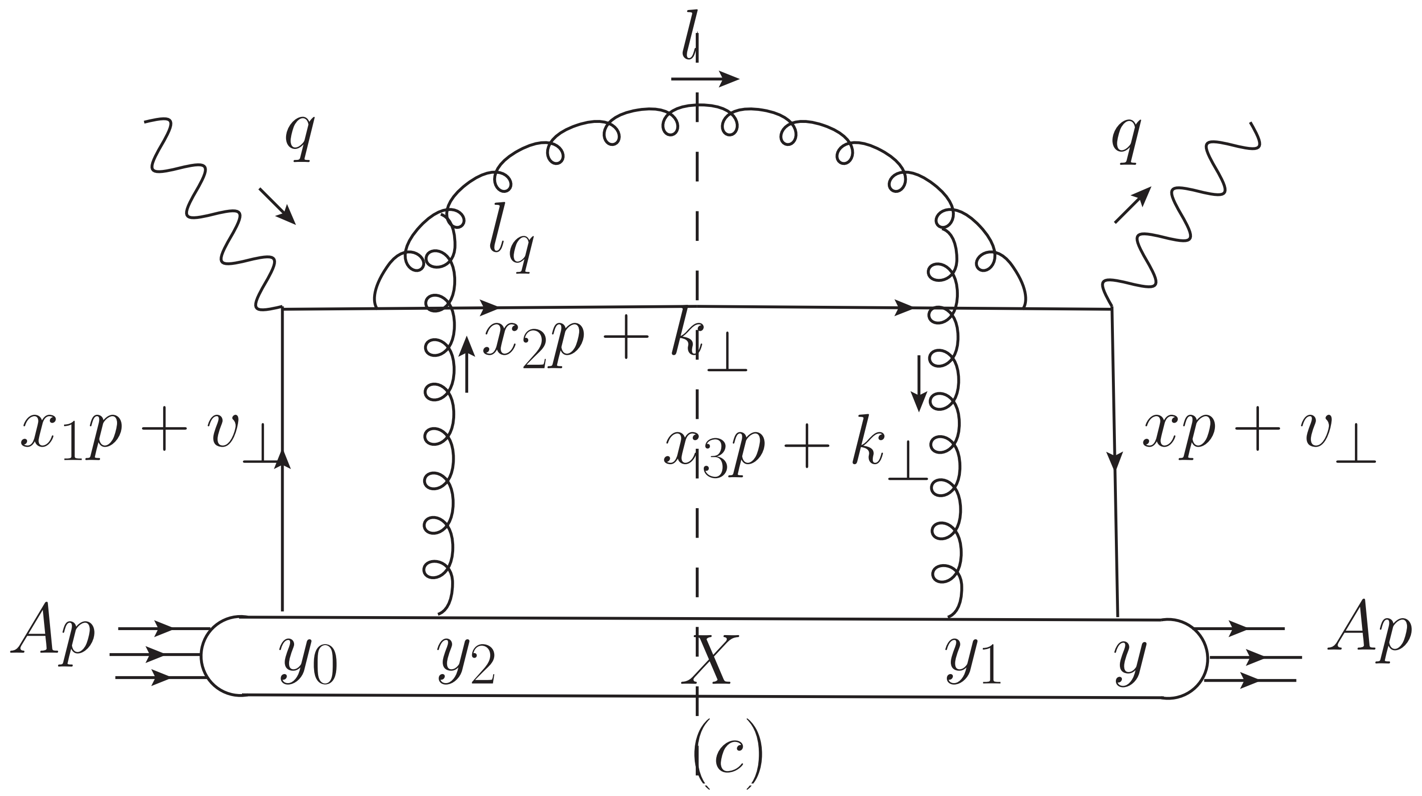
$$\frac{d\hat{\sigma}^S_{eA}}{dx_B dQ^2 dz d^2 l_\perp d^2 l_{q\perp}} = \frac{2\pi\alpha_{em}^2}{Q^4} \sum_q e_q^2 [1 + (1 - \frac{Q^2}{x_B s})^2] \frac{\alpha_s}{2\pi} \frac{1+z^2}{1-z} \frac{C_F}{\pi} \frac{q_A(x_B, \vec{v}_\perp)}{[\vec{l}_\perp - (1-z)\vec{v}_\perp]^2}$$

- multiple soft interaction (eikonalized as gauge link) → quark pT broadening

  pT broadening embedded in effective $q_N(x, \vec{v}_\perp, \vec{b}_\perp)$, gaussian broadening with width

  $\Delta_F(\vec{b}_\perp) = \int dy_0^- \hat{q}_F(y_0^-, \vec{b}_\perp)$ depend on $\hat{q}$ Liang, Z. T., Wang, X. N., & Zhou, J. (2008). *PRD*, *77*(12), 125010.

Dijet in e+A : Double scattering



Under two-parton correlation factorization

$$T^A_{qg} = \rho_A(y_0^-) \otimes \rho_A(y_1^-) \otimes q_N(x_B, \vec{v}_\perp) \otimes \phi_N(x_G, \vec{k}_\perp)$$

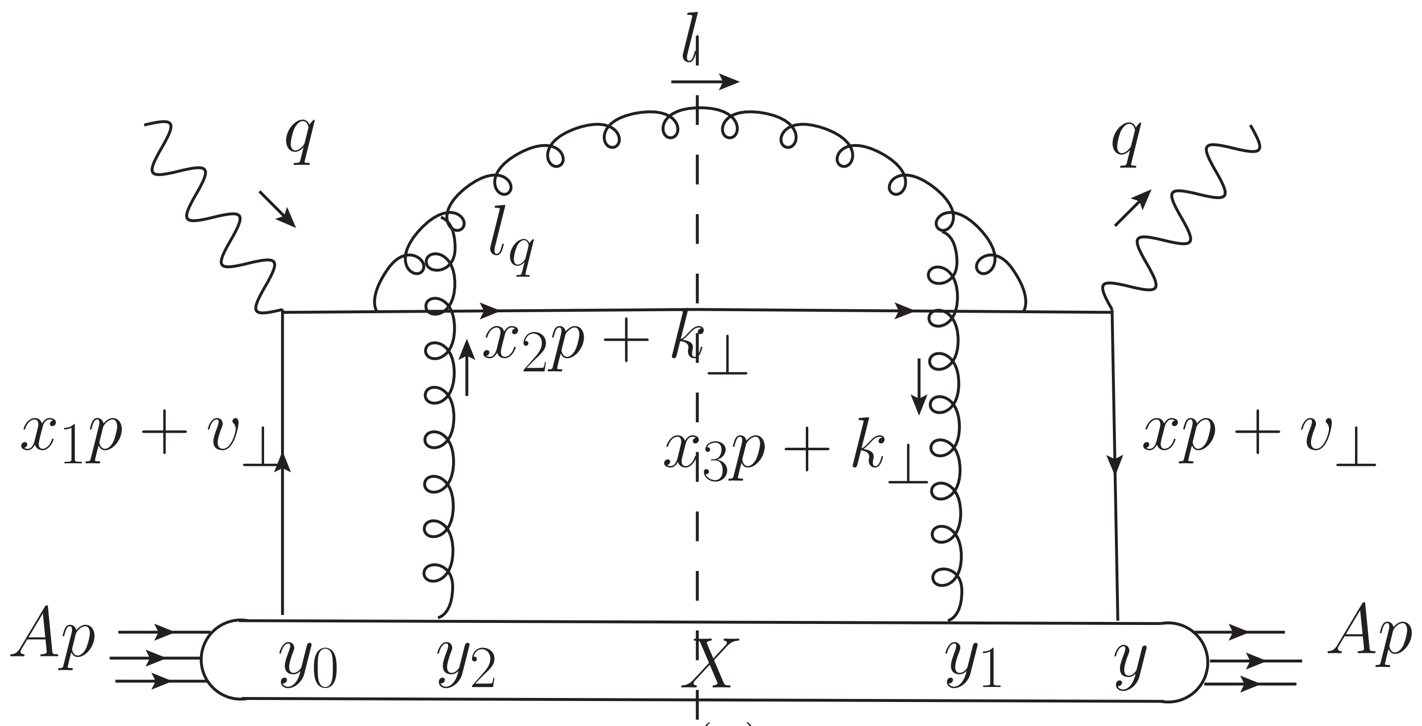
- $x_G = \dfrac{k_\perp^2}{2p^+q^-}$ smaller than x_B
- harder than gauge link gluons

$$\frac{d\hat{\sigma}^D_{eA}}{dx_B dQ^2 dz d^2l_\perp d^2l_{q\perp}} = \frac{2\pi\alpha_{em}^2}{Q^4}\sum_q e_q^2[1+(1-\frac{Q^2}{x_B s})^2]\frac{\alpha_s}{2\pi}\frac{1+z^2}{1-z}\frac{2\pi\alpha_s}{N_c}\int\frac{d^2k_\perp}{(2\pi)^2}\int d^2b_\perp dy_0^- dy_1^-$$

$$\rho_A(y_0^-, \vec{b}_\perp)\rho_A(y_1^-, \vec{b}_\perp)q_N(x_B, \vec{v}_\perp, \vec{b}_\perp)\frac{\phi_N(x_G, \vec{k}_\perp)}{k_\perp^2}\left[\mathcal{N}_g^{\text{nonLPM}} + \mathcal{N}_g^{\text{qLPM}} + \mathcal{N}_g^{\text{gLPM}}\right]$$

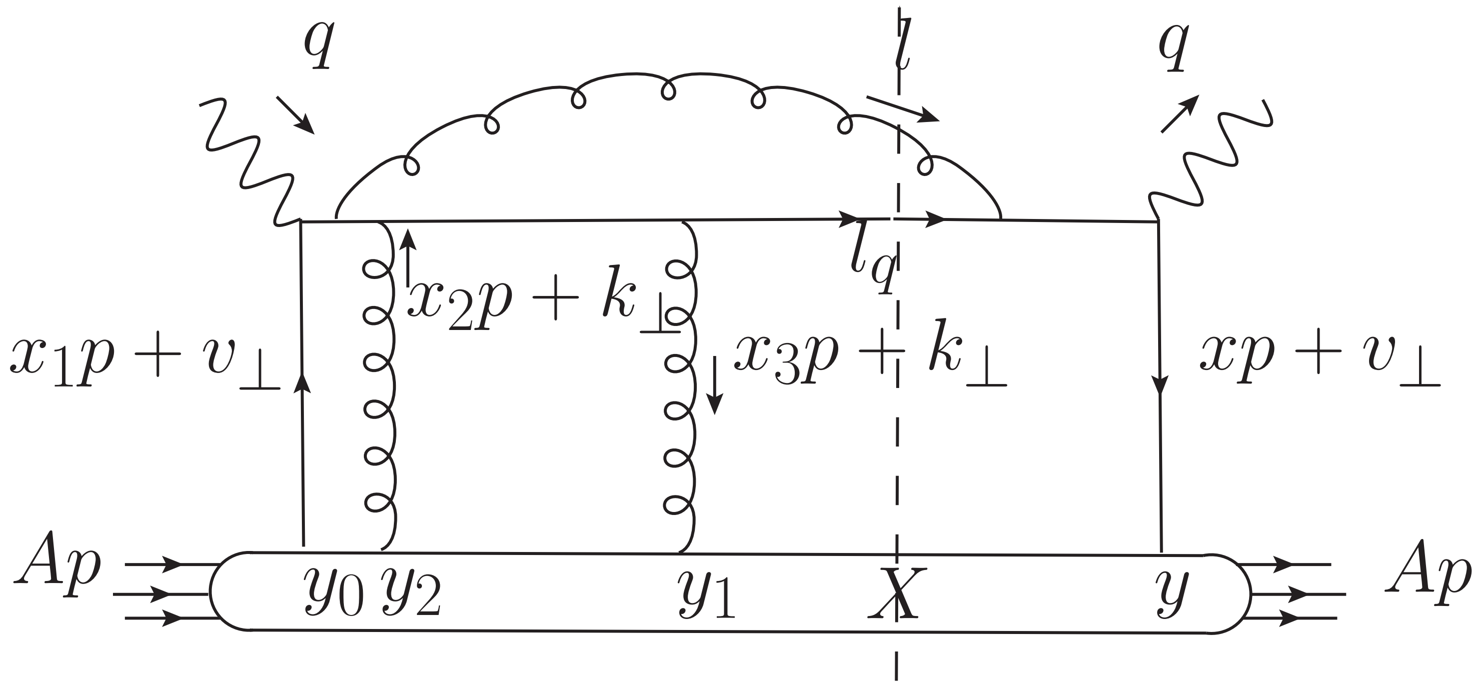
- intial quark $q_N(x, \vec{v}_\perp, \vec{b}_\perp)$ contain pT broadening, depend on $\hat{q}$ indirectly
- depend on $\phi(x_G, k_\perp) \sim \hat{q}(k_\perp)$ directly

Double scattering: different diagrams



(c)

Central cut diagrams: 9



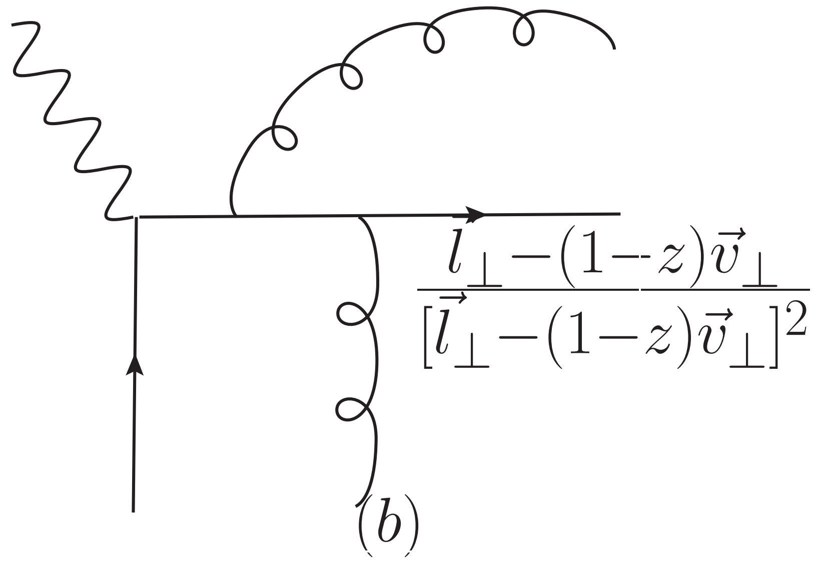
Right/left cut diagrams: 7*2

Different contribution in double scattering

Contribution divided by how gluon radiated, understand from central cut diagrams

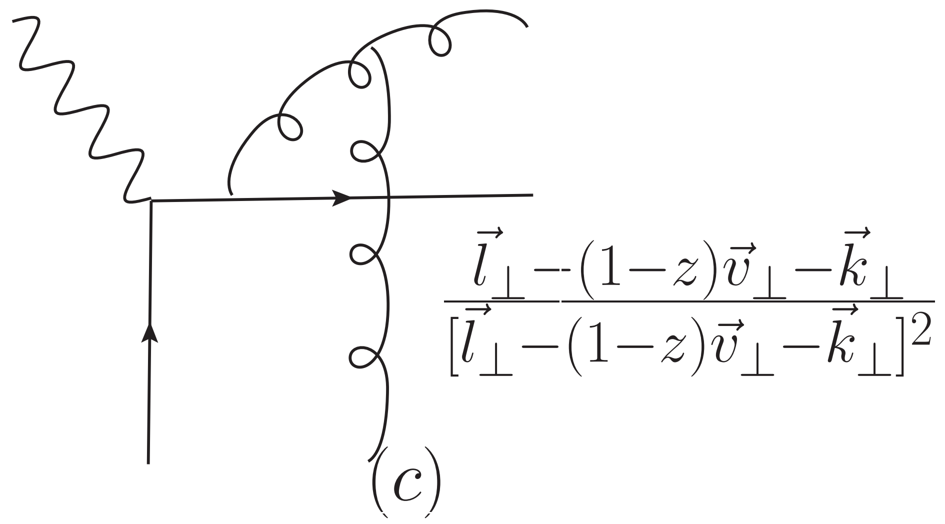
$$\mathcal{N}_g^{\text{qLPM}} = \frac{1}{N_c}(\cdots)\left[1-\cos\left(\frac{y_1^- - y_0^-}{\tau_{gf}}\right)\right]$$

$$\tau_{qf} = \frac{2q^- z(1-z)}{[\vec{l}_\perp - (1-z)\vec{v}_\perp]^2}$$



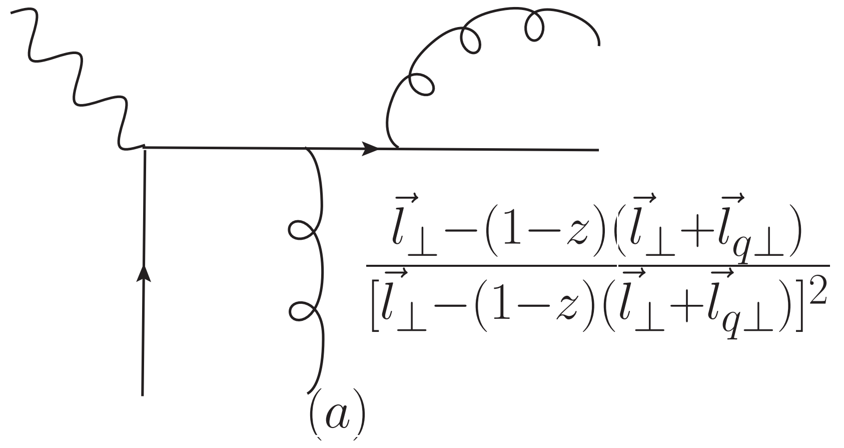
$$\mathcal{N}_g^{\text{gLPM}} = C_A(\cdots)\left[1-\cos\left(\frac{y_1^- - y_0^-}{\tau_{gf}}\right)\right]$$

$$\tau_{gf} = \frac{2q^- z(1-z)}{[\vec{l}_\perp - (1-z)\vec{v}_\perp - \vec{k}_\perp]^2}$$



$$\mathcal{N}_g^{\text{nonLPM}} = C_F(\cdots)$$

no LPM interference



A simple model for gluon saturation in $\phi(x_G, k_\perp) \sim \hat{q}(k_\perp)$

Simple model to include saturation

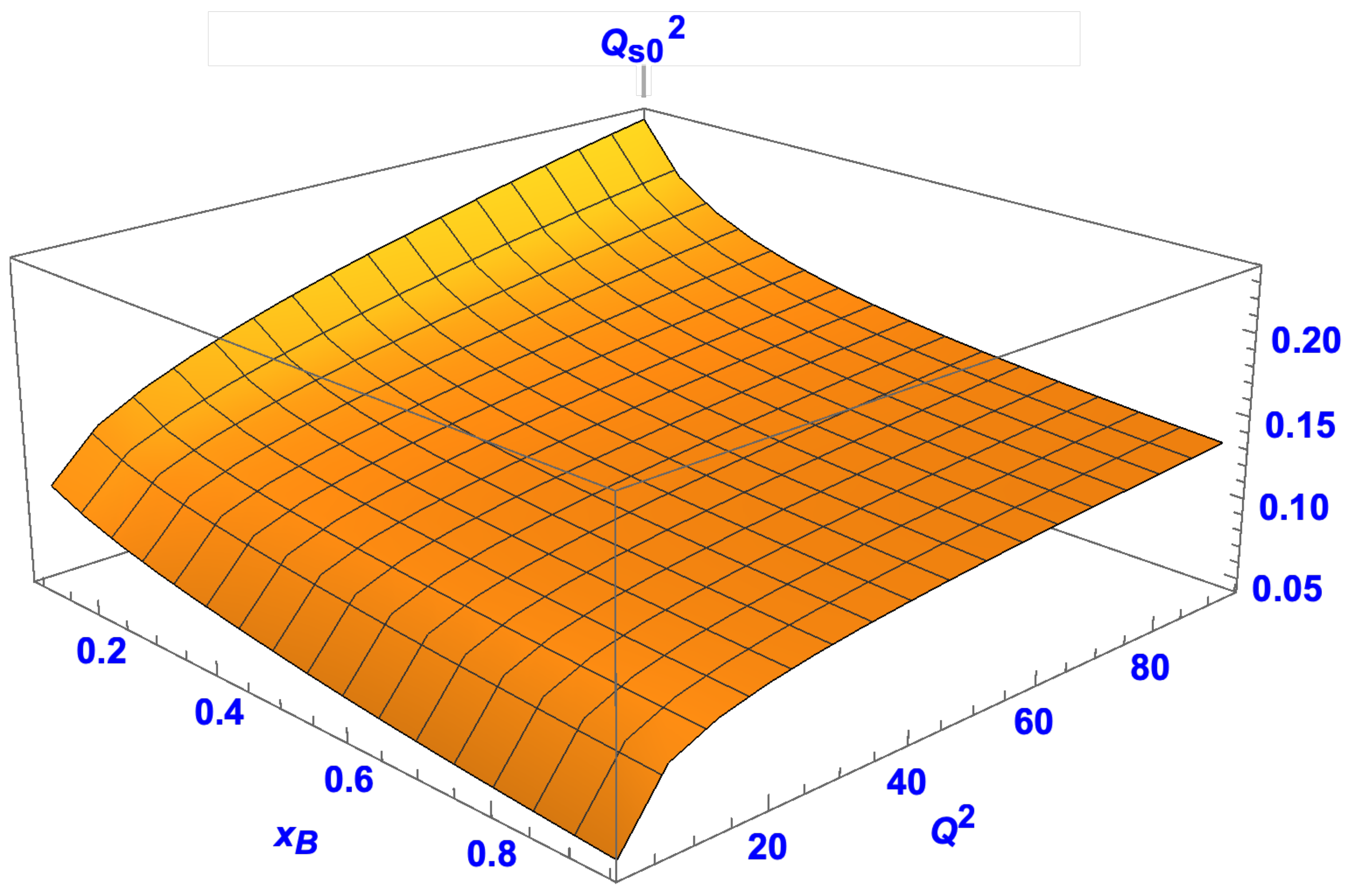
$$\phi_N(x_G, k_\perp, \mu^2) = \begin{cases} \phi_N^0 \text{ at } Q_s, & k_\perp < Q_s; \\ \phi_N^0(\mu^2 = k_\perp^2), & k_\perp > Q_s, \end{cases}$$

TMDlib Package

F Hautmann et al., EPJC 74 (2014), 3220

Calculate saturation scale self-consistently

$$Q_s^2(x_B, Q^2, b_\perp) = C \int dy_0^- \rho(y_0^-, b_\perp) \int \frac{d^2k_\perp}{(2\pi)^2} \alpha_s(\mu) \phi_N(x_G, k_\perp, \mu^2)$$



Scale in $\alpha_s(\mu)$ and $\phi_N(x_G, k_\perp, \mu^2)$ is $\mu^2 = k_\perp^2$

$\hat{q}_F$ from our simple saturation model

From definition of saturation scale, relation between quark qhat & gluon qhat

$$Q_s^2 = \int dy_0^- \hat{q}_A(y_0^-, b_\perp, k_\perp), \hat{q}_F = \frac{4}{9}\hat{q}_A$$

For kinematics: $x_B = 0.1 - 0.4, Q^2 = 2 - 6$ GeV^2

Our simple model give $\hat{q}_F^0 \approx 0.014 - 0.025$ GeV^2/fm

pT broadening of final-state hadron method give $\hat{q}_F^0 \approx 0.015$ GeV^2/fm

P. Ru et al, arXiv:2004.00027

Suppression of leading hadron method give $\hat{q}_F^0 \approx 0.02 - 0.03$ GeV^2/fm

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

Nuclear Modification Ratio

Ratio of dijet cross section in e+A and e+p

$$R_{eA}^{S(D)}(l_\perp, l_{q\perp}, \Delta\phi, z) = \frac{d\hat{\bar{\sigma}}_{eA}^{S(D)}}{d\mathscr{P}} / A \frac{d\hat{\bar{\sigma}}_{ep}}{d\mathscr{P}} \qquad d\mathscr{P} \equiv dx_B dQ^2 dz d^2 l_\perp d^2 l_{q\perp}$$

Don’t distinguish quark jet from gluon jet

$$\hat{\bar{\sigma}} \equiv \hat{\sigma}(l_\perp, l_{q\perp}, \Delta\phi, z) + \hat{\sigma}(l_{q\perp}, l_\perp, \Delta\phi, 1 - z)$$

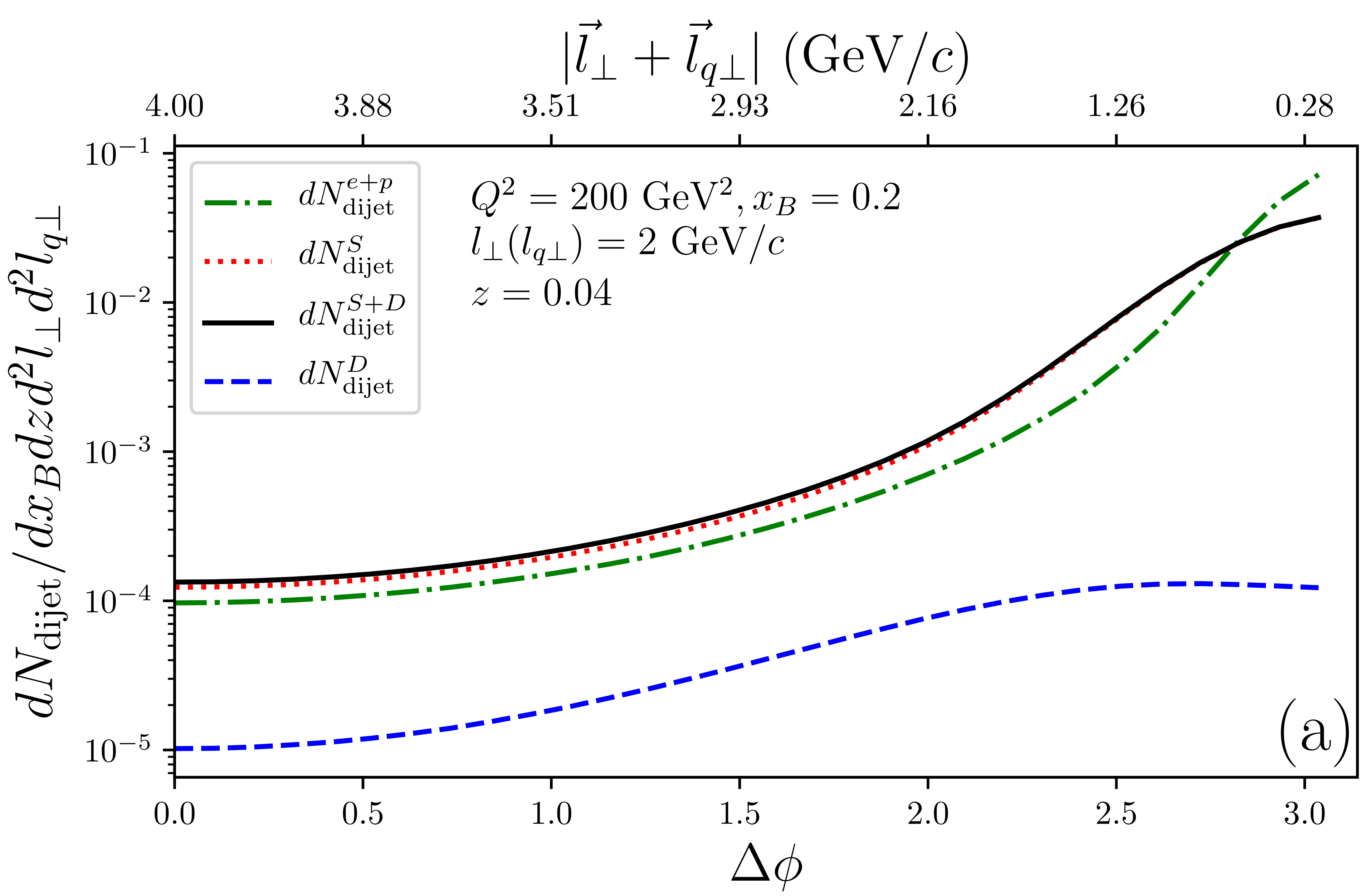
Kinematics for calculation:

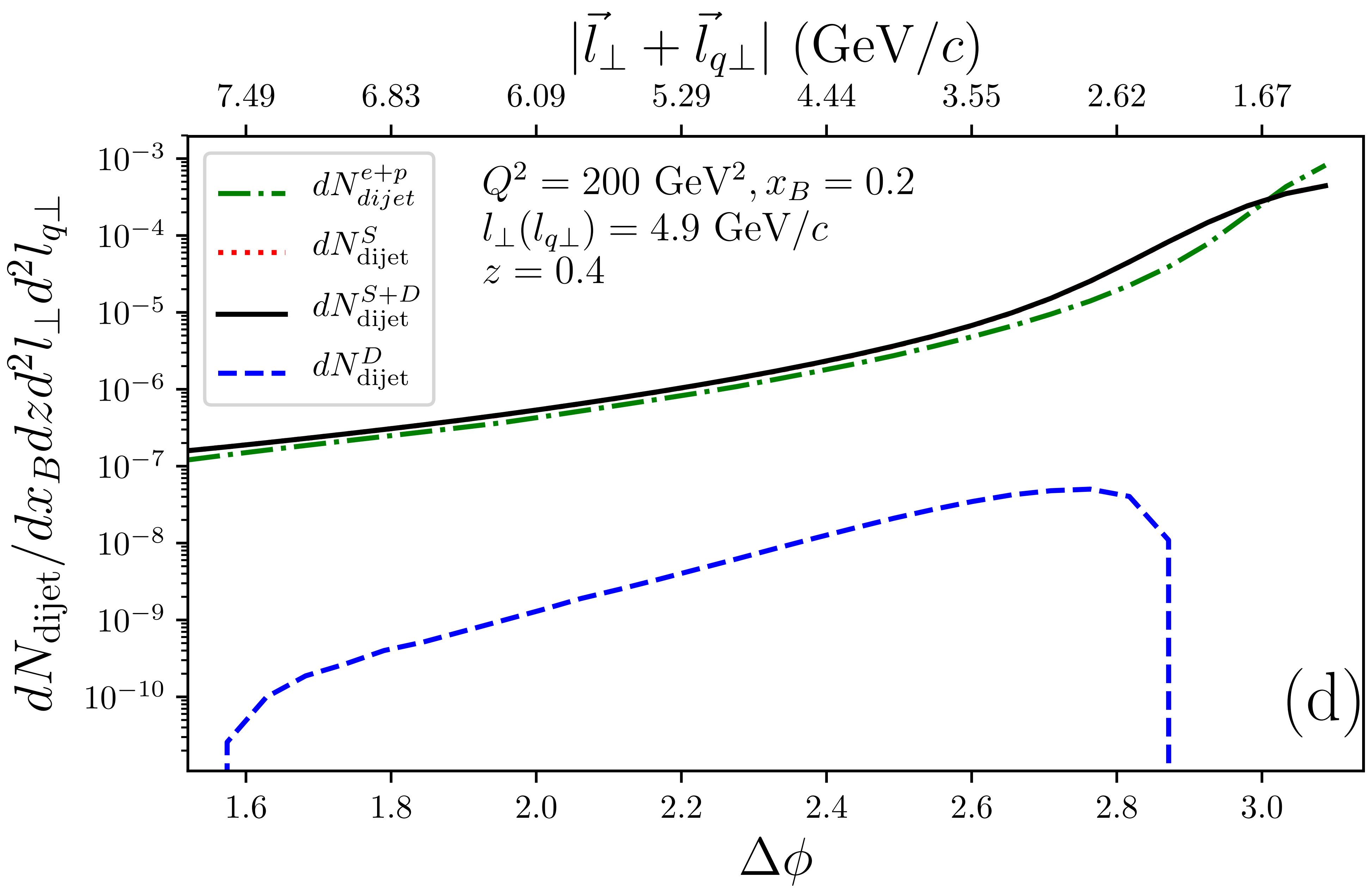
$E_e = 10$ GeV, $E_N = 100$ GeV, $x_B = 0.2,\ Q^2 = 200$ GeV^2, $A = 208$

Kinematic constraints from approximations, experiments

Dijet Spectrum

$$\frac{d\sigma_{eA}^{S(D)}}{dx_B dQ^2 dz d^2l_\perp d^2l_{q\perp}} \equiv A \frac{d\sigma_{ep}^0}{dQ^2} \frac{dN_{\mathrm{dijet}}^{S(D)}}{dx_B dz d^2l_\perp d^2l_{q\perp}}$$



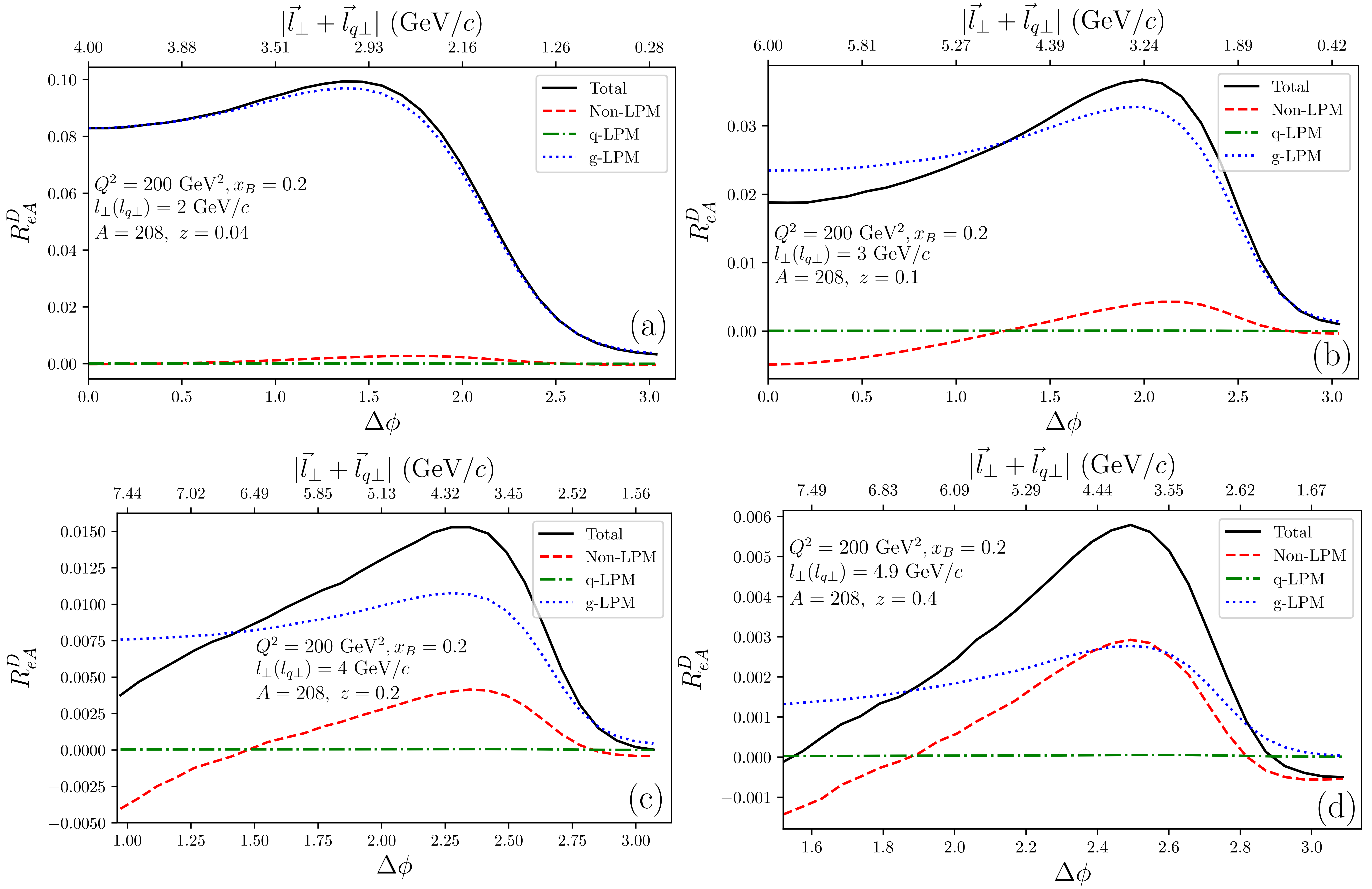


- Dijet spectra from e+p and e+A scattering peak at $\Delta\phi = \pi$
- Double scattering dijet Xsection small, can be negative due to non-LPM term

Azimuthal angle $\Delta\phi$ dependence : R_{eA}^{D}

$|\vec{l}_{\perp} + \vec{l}_{q\perp}| = 2l_{\perp}^2(1+\cos\Delta\phi)$

for $l_{\perp} = l_{q\perp}$



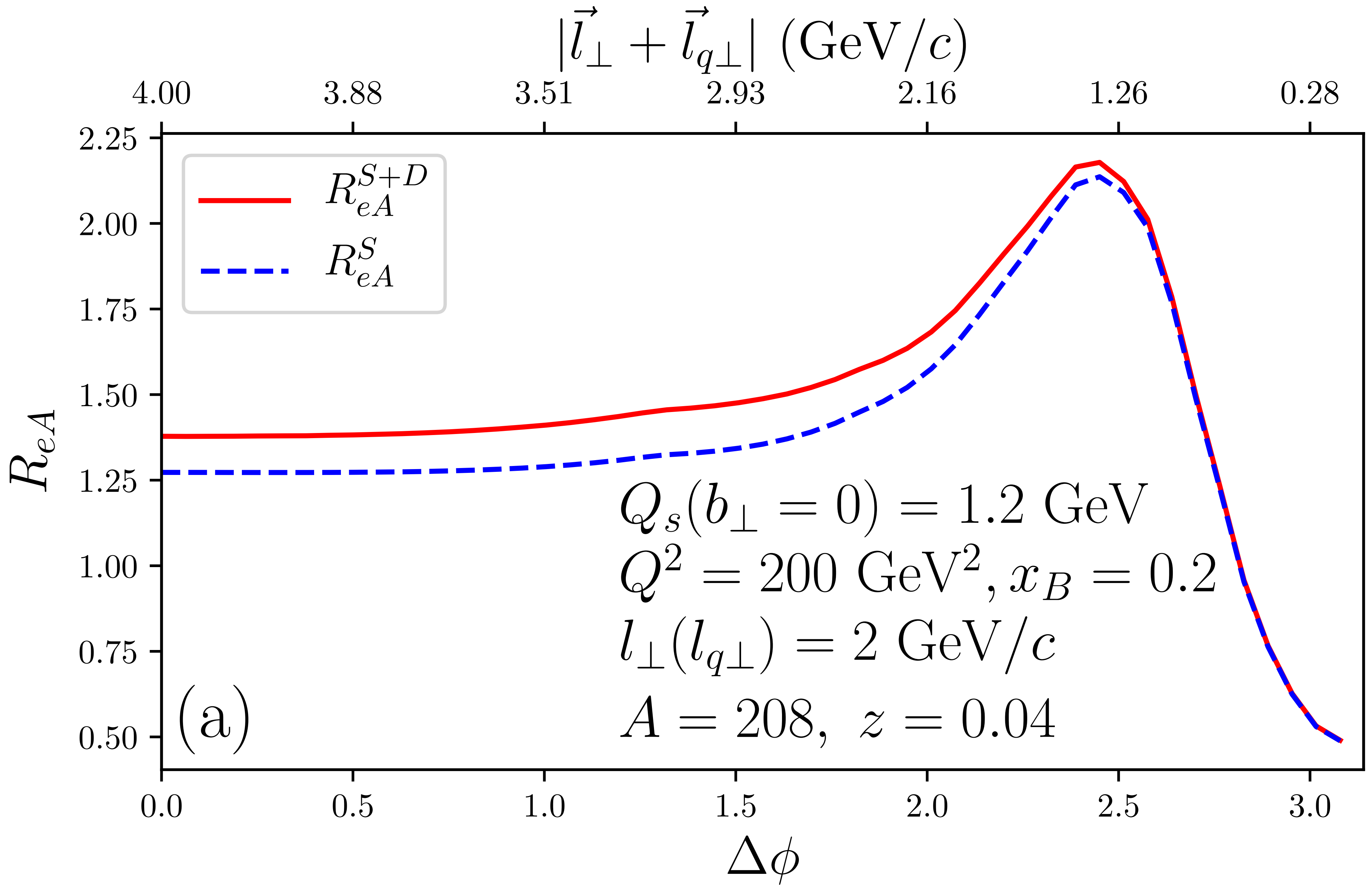
nonLPM: finite(relative contribution increase with z increase)

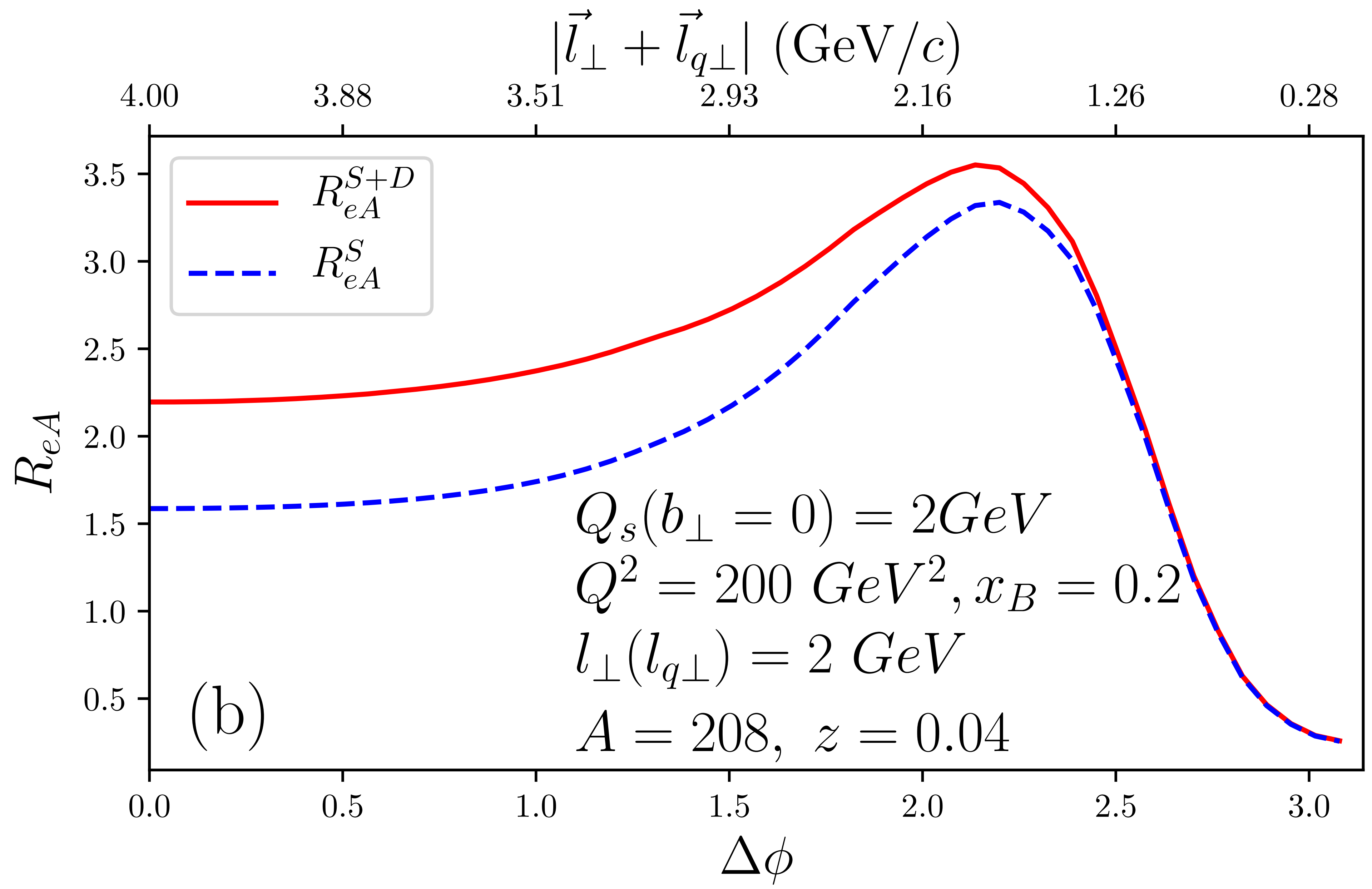
qLPM: negligible(suppress by color and LPM factor)

gLPM: dominant

- R_{eA}^{D} magnitude decrease with increase of $l_{\perp}(l_{q\perp})$, double scattering contribution power suppressed by $l_{\perp}(l_{q\perp})$

Azimuthal angle $\Delta\phi$ dependence : R_{eA}^{S} & R_{eA}^{S+D}





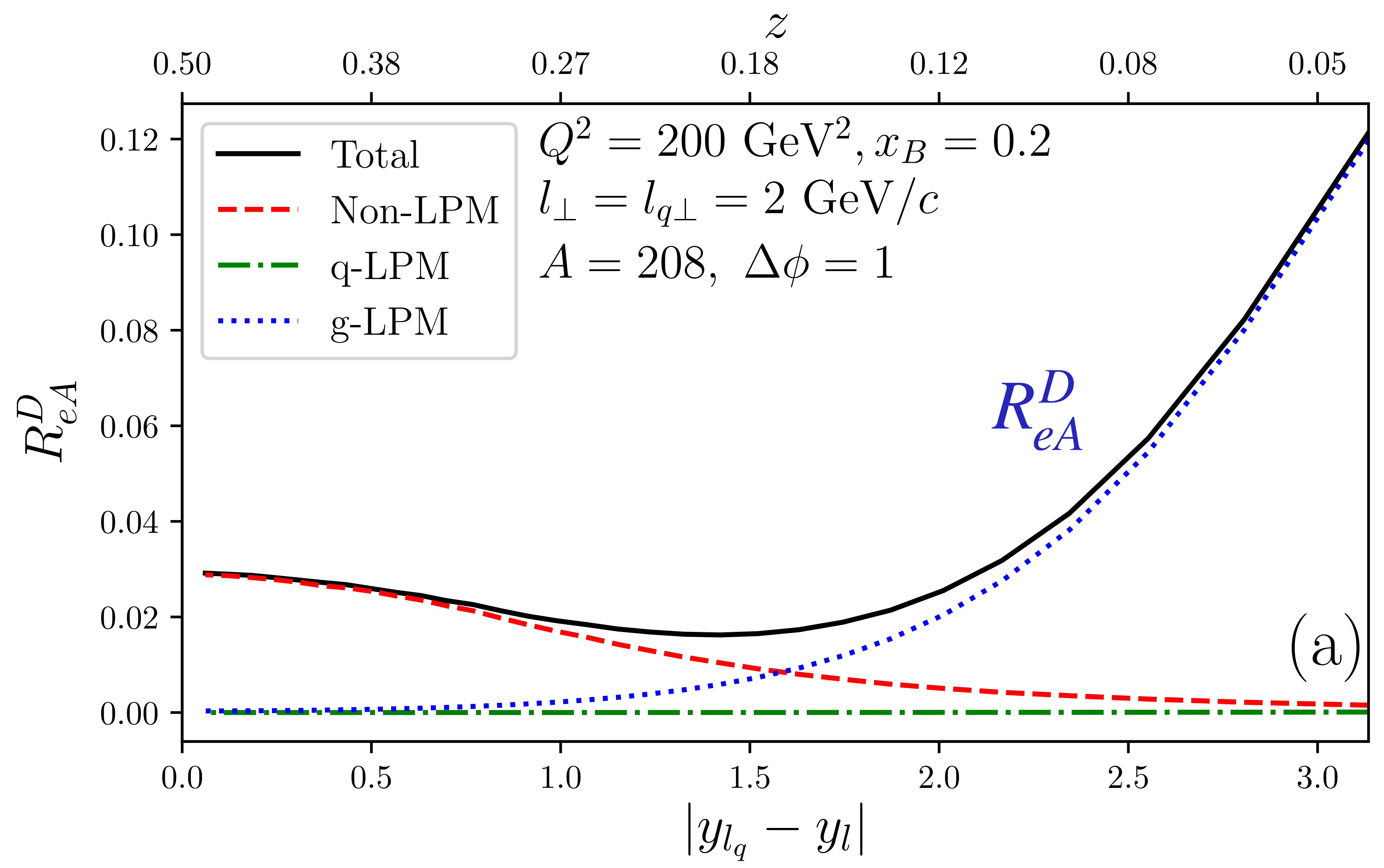
$Q_s = 1.2$ GeV

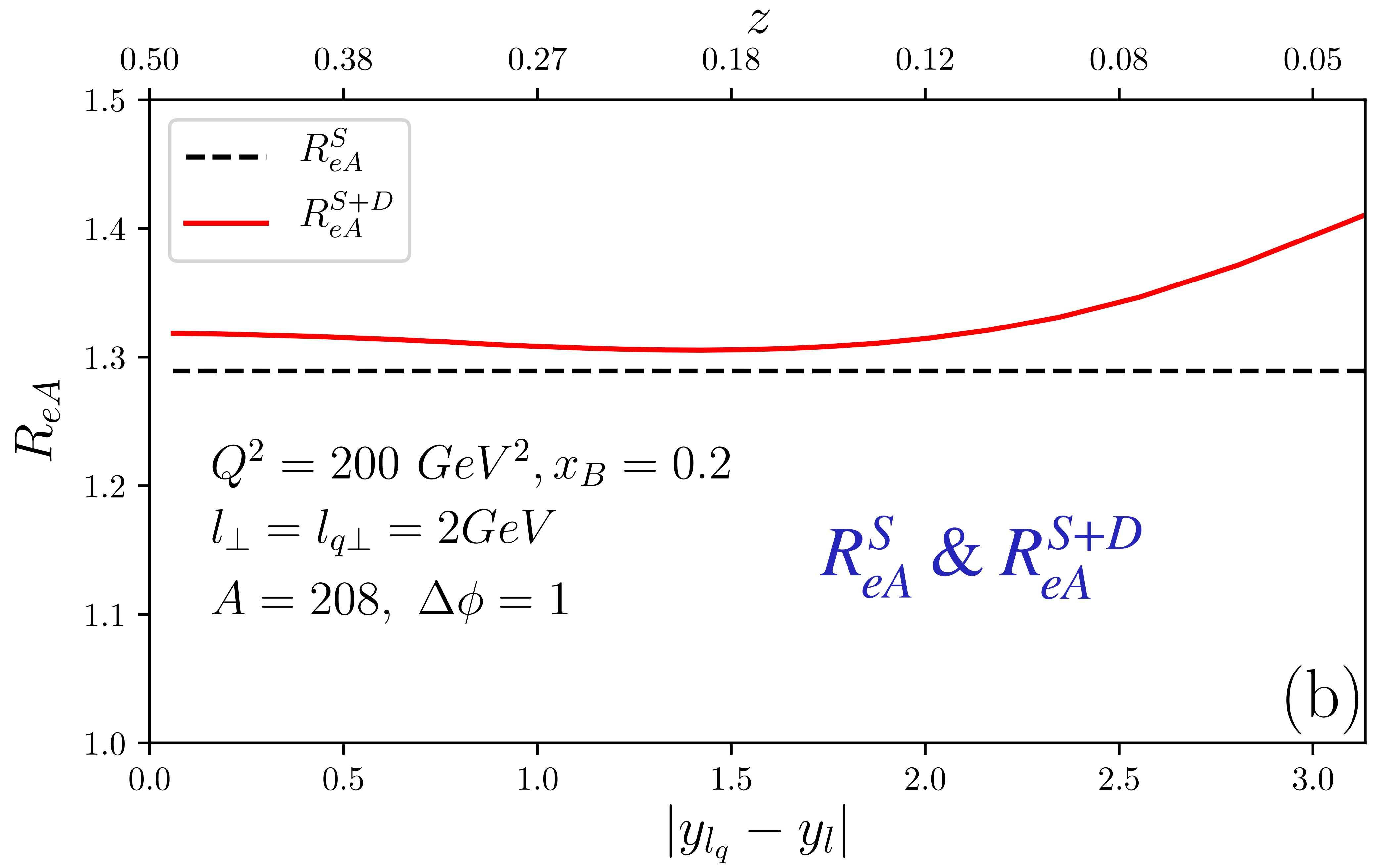
$Q_s = 2$ GeV

- Single scattering dominates in dijet Xsection, R_{eA}^{S} dominate in R_{eA}^{S+D}
- Q_s artificially increase, peak in R_{eA}^{S} moves, R_{eA}^{D} contribution increase

Rapidity gap $|y_{l_q} - y_l|$ dependence

$y_{l_q} - y_l = \ln(\frac{z}{1-z})$ for $l_\perp = l_{q\perp}$

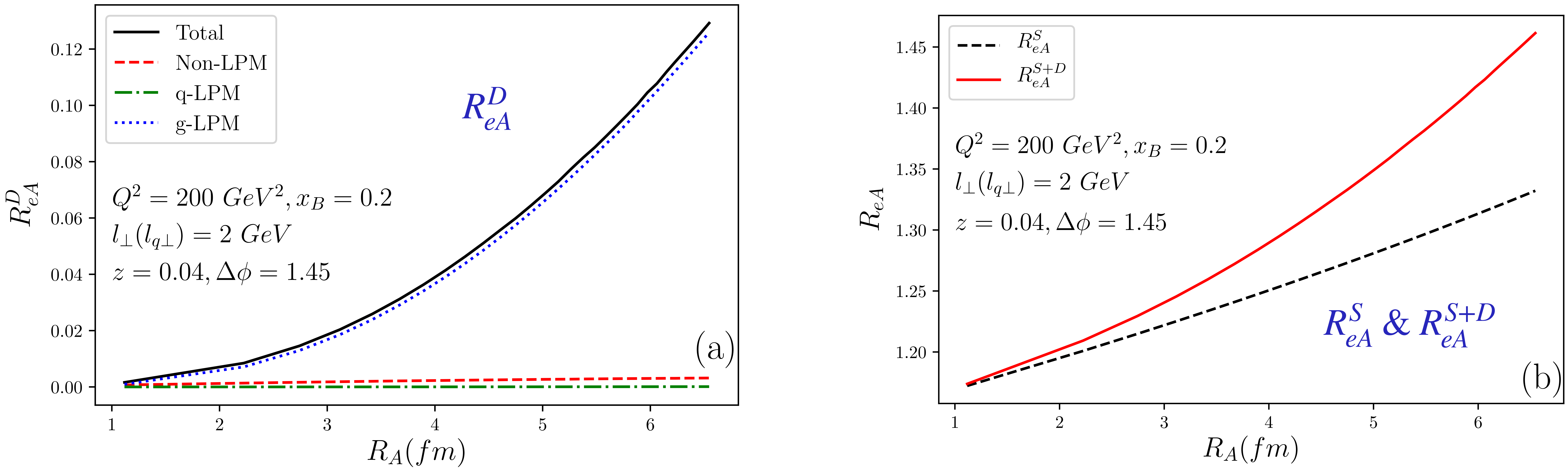




- R^S_{eA} only due to quark pT broadening, independent of rapidity gap $|y_{l_q} - y_l|$
- R^D_{eA} dominant - gLPM term with LPM suppression factor $1 - \cos\frac{y_1^- - y_0^-}{\tau_{gf}}$

  $|y_{l_q} - y_l| \uparrow, z \downarrow, \tau_{gf} \downarrow$, when $2R_A/\tau_{gf} \geq 2\pi$ LPM suppression disappear, increased incoherent contribution

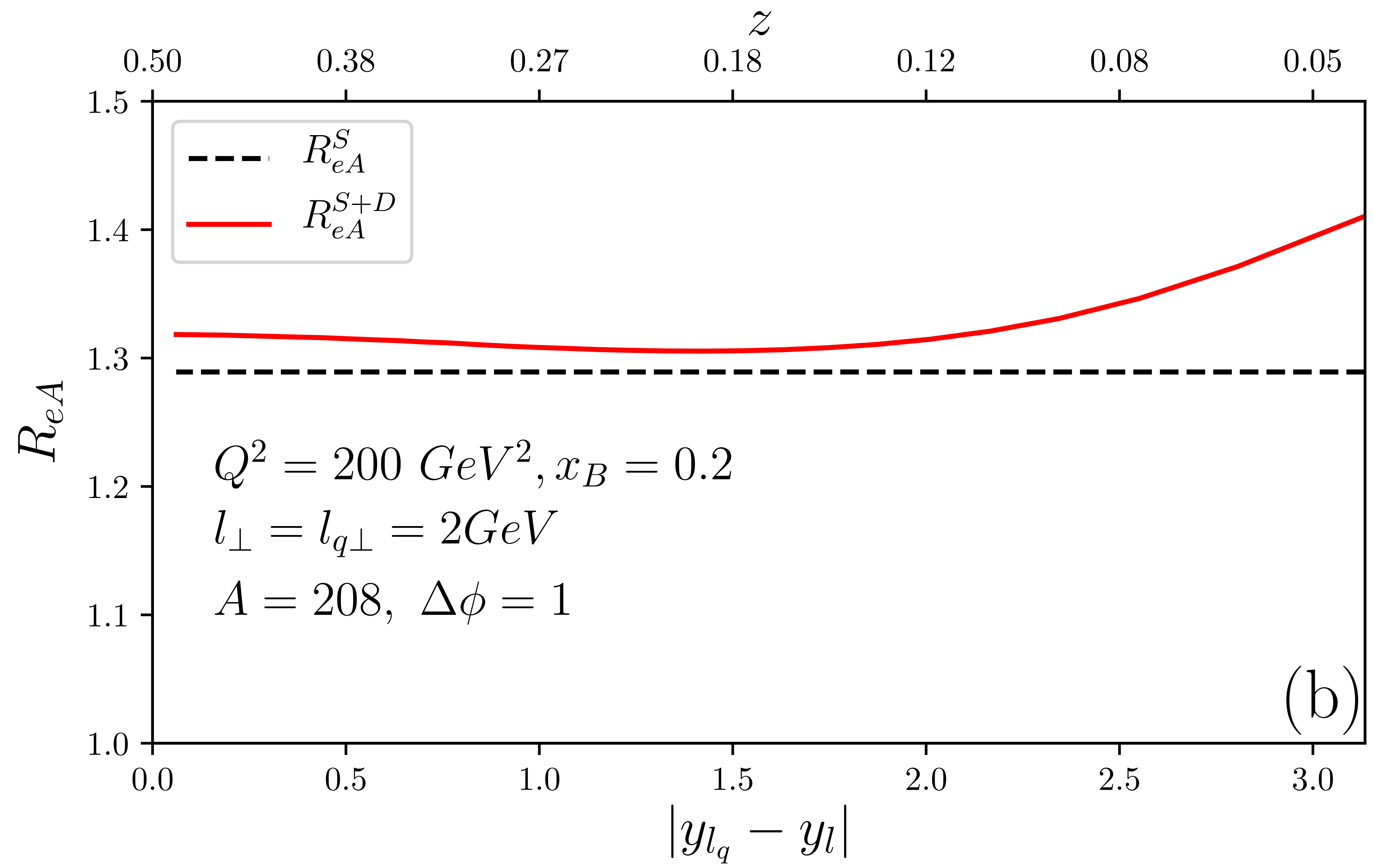
Nuclear size R_A dependence

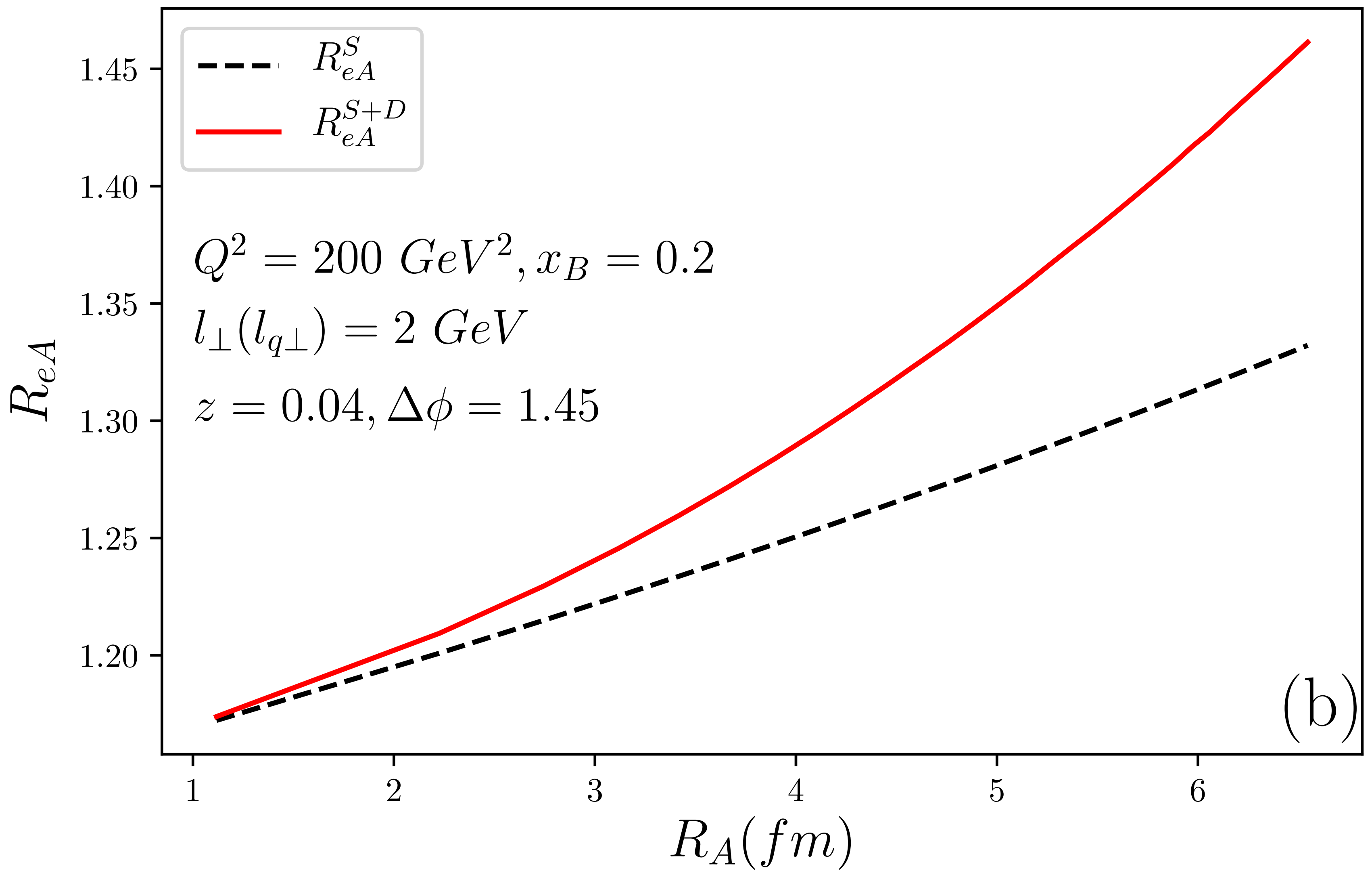


- R_{eA}^D nonLPM $\propto \frac{1}{A}\int d^2b_\perp dy_0^- \rho_A(y_0^-, b_\perp)\int dy_1^- \rho_A(y_1^-, b_\perp) \sim \frac{9R_A}{16\pi r_0^3}$
- R_{eA}^D : qLPM , gLPM $\propto \int_0^{R_A} dy_1^- \rho_A(y_1^-, 0_\perp)[1 - \cos\frac{y_1^-}{\tau_f}] = \frac{3}{4\pi r_0^3} R_A(1 - \frac{\sin(R_A/\tau_f)}{R_A/\tau_f})$
- R_{eA}^S linear in R_A

Non-linear R_A dependence

Summary



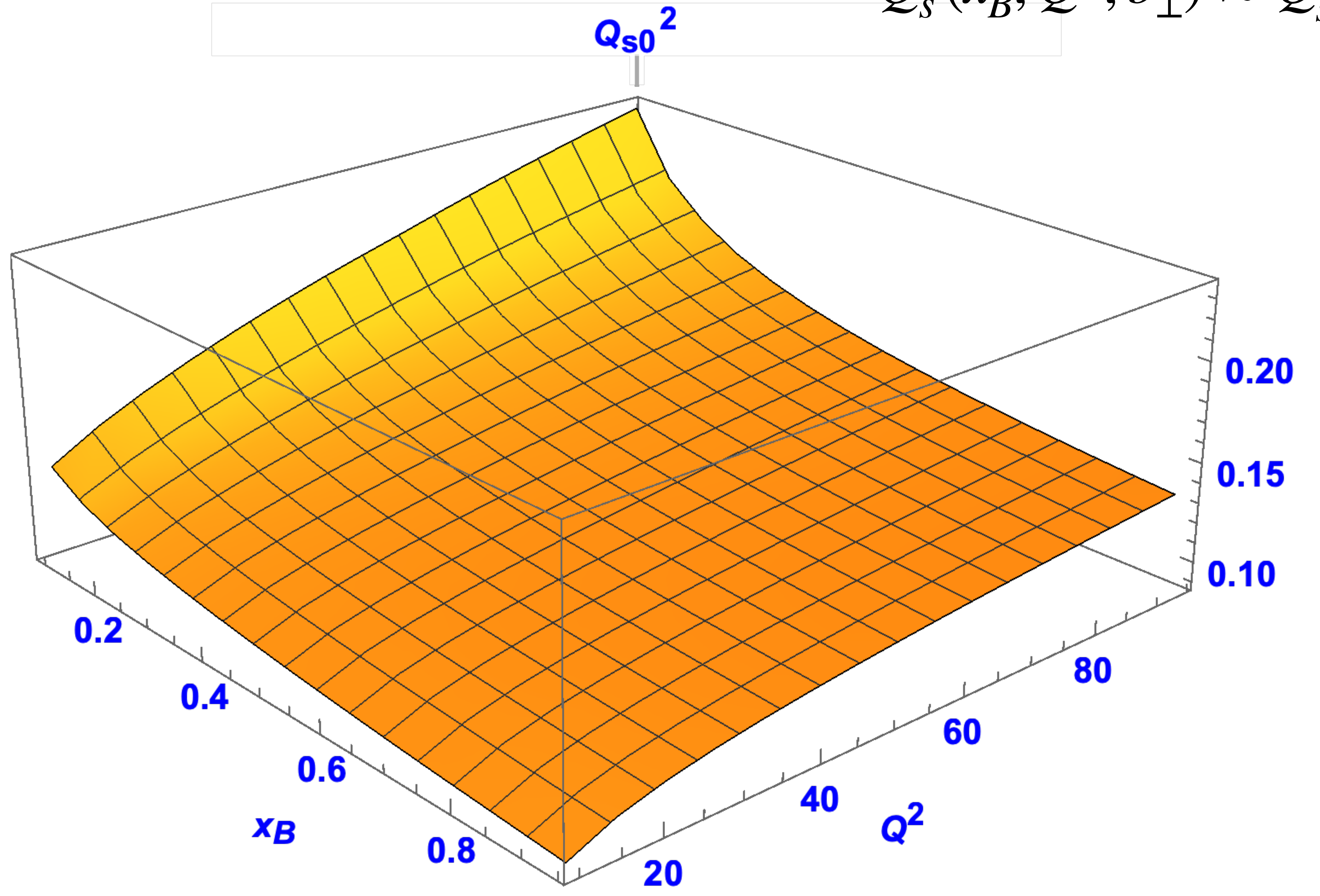


- Use dijet correlation in e+A to probe gluon TMD pdf $\phi(x_G, k_\perp)$ or TMD $\hat{q}(k_\perp)$
- Nuclear modification in single and double scattering depend on $\phi(x_G, k_\perp)$
- LPM effect and gluon saturation embedded in $\phi(x_G, k_\perp)$ bring unique features in $\Delta\phi, |y_{l_q} - y_l|, R_A$ dependence of nuclear modification ratio

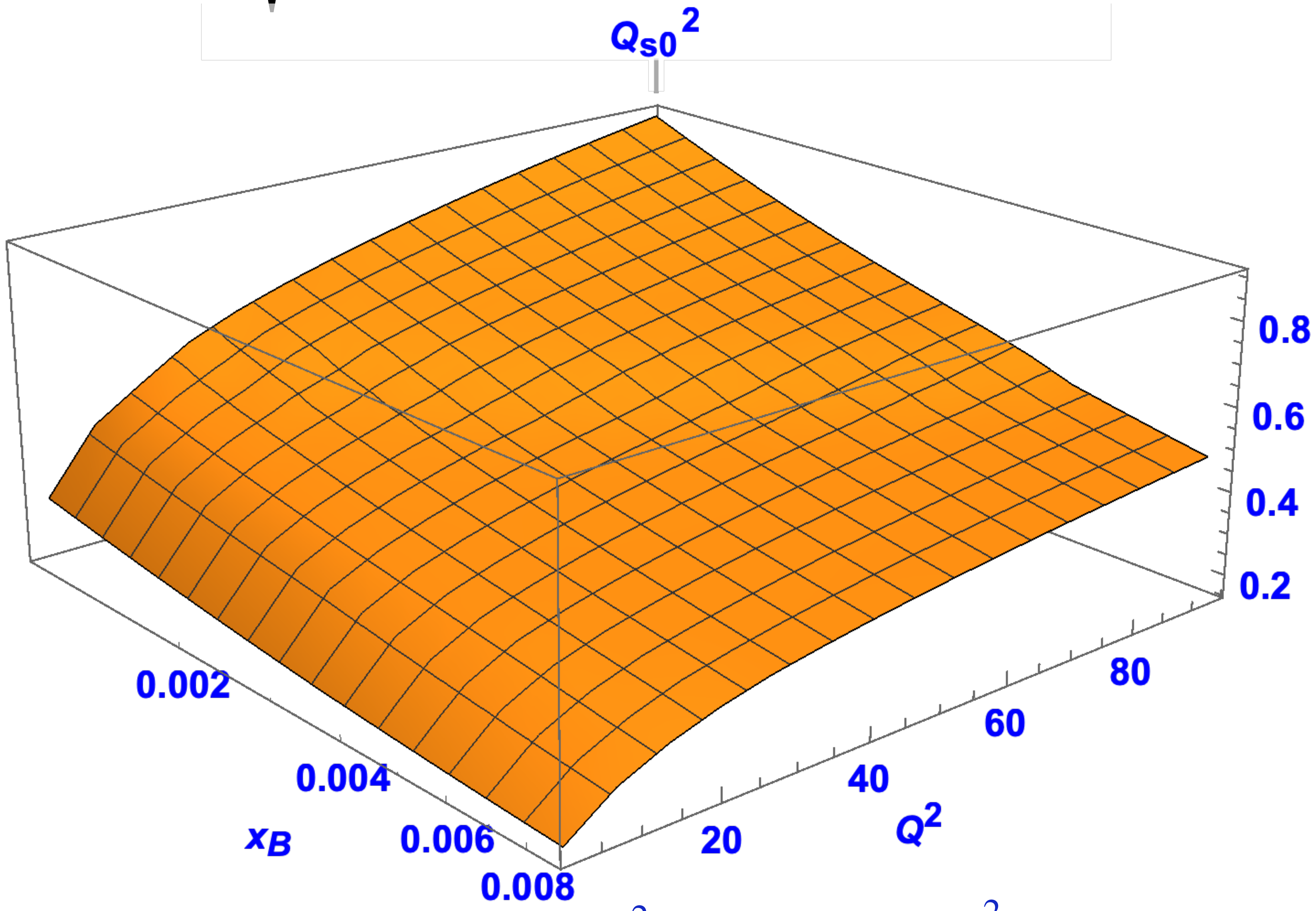
Thanks for your attention!

Backup: Saturation scale Q_s^2

$$Q_s^2(x_B, Q^2, b_\perp) \approx Q_{s0}^2(x_B, Q^2) A^{1/3} \sqrt{1 - \frac{b_\perp^2}{R_A^2}}$$



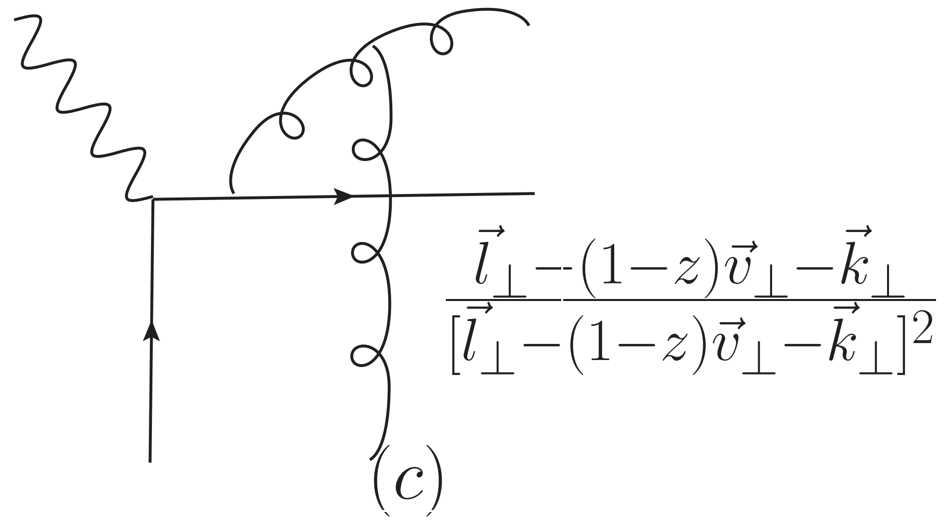
$x_B = 0.1 - 1,\ Q^2 = 2 - 100$ GeV^2



$x_B = 0.001 - 0.01,\ Q^2 = 2 - 100$ GeV^2

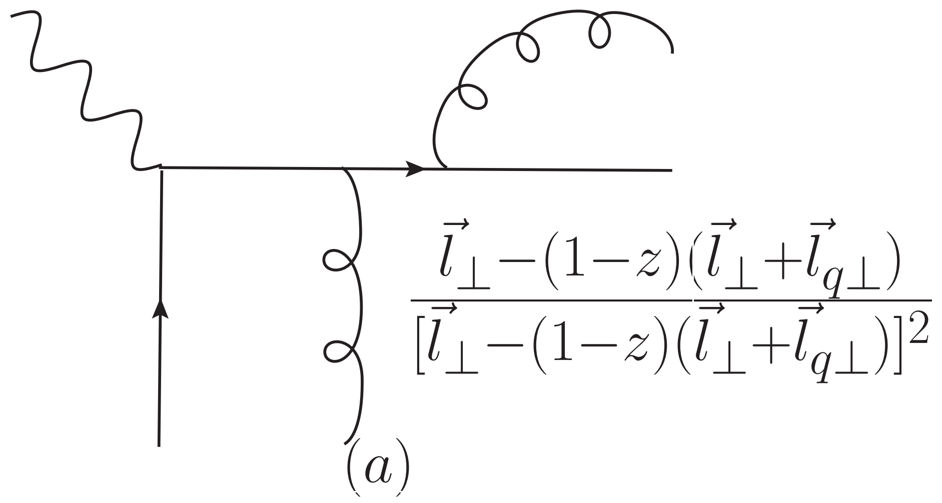
can reach 1 GeV^2 at $x_B = 0.001, Q^2 = 100$ GeV^2

Divergences in double scattering



$$\vec{l}_\perp-(1-z)\vec{v}_\perp-\vec{k}_\perp=0$$

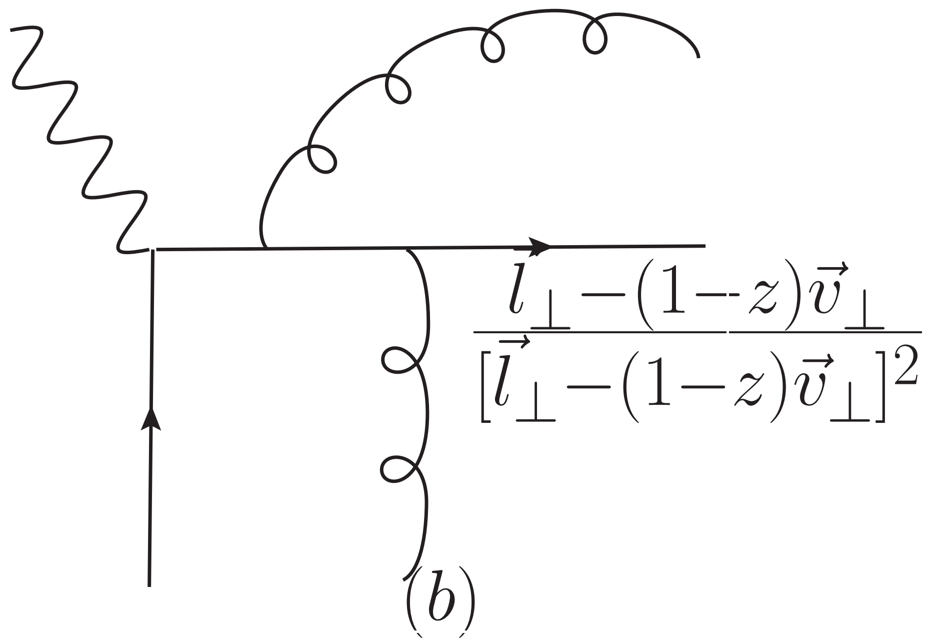
Regularized by LPM factor in gLPM



$$\vec{l}_\perp-(1-z)(\vec{l}_\perp+\vec{l}_{q\perp})=0$$

$$\vec{l}_\perp//\vec{l}_{q\perp}$$

Regularized by dijet seperation



$$\vec{l}_\perp-(1-z)\vec{v}_\perp=0$$

Absorb into renormalized TMD
q-g correlation function

$\vec{l}_\perp-(1-z)\vec{v}_\perp<\mu_f^2$, factorization scale μ_f