陽子-原子核衝突実験で探るパートンエネルギー損失

- An overview of parton energy loss in nuclear media -

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Heavy Ion Pub, 広島大学, 12/23/2025

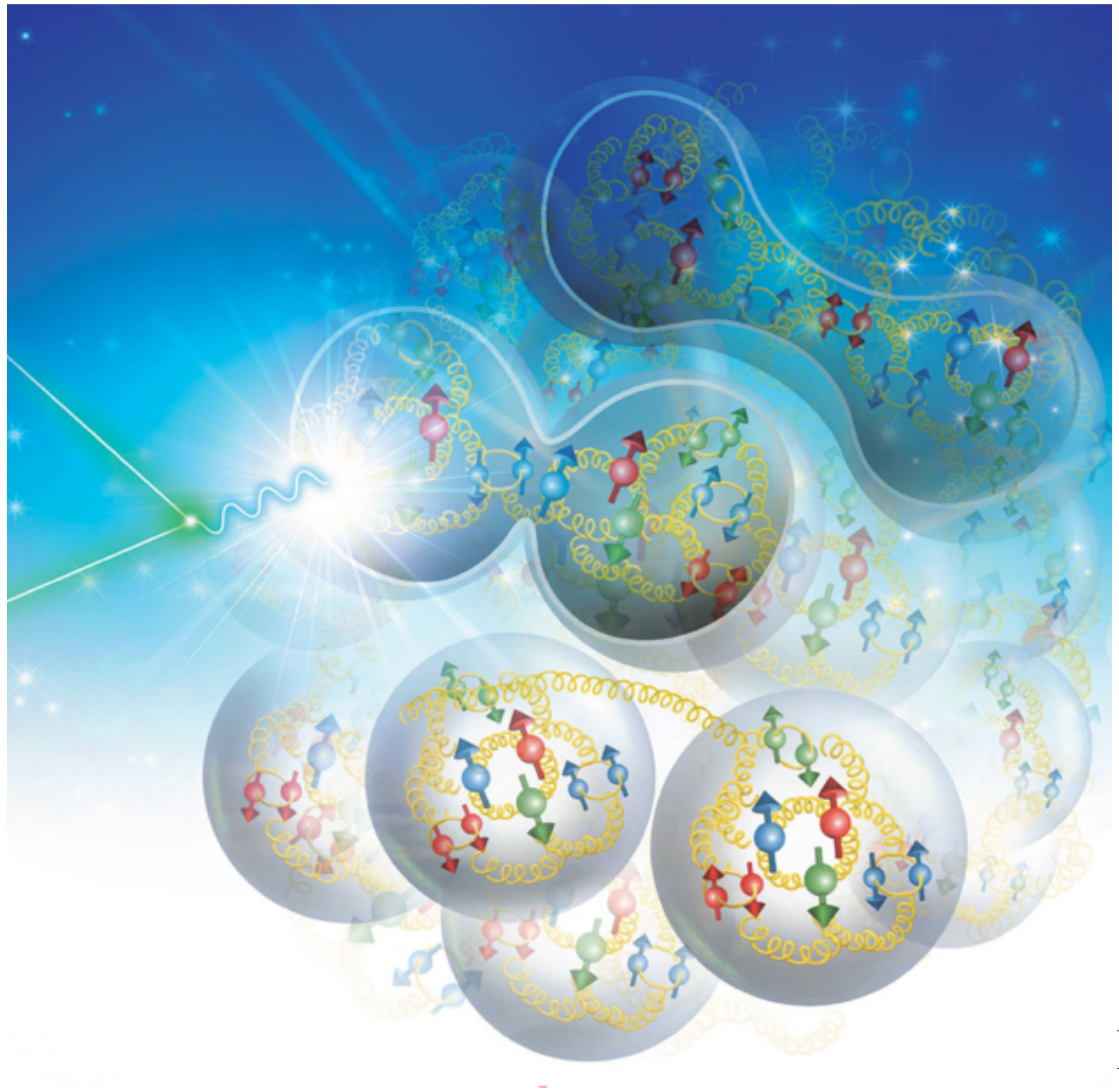
Outline

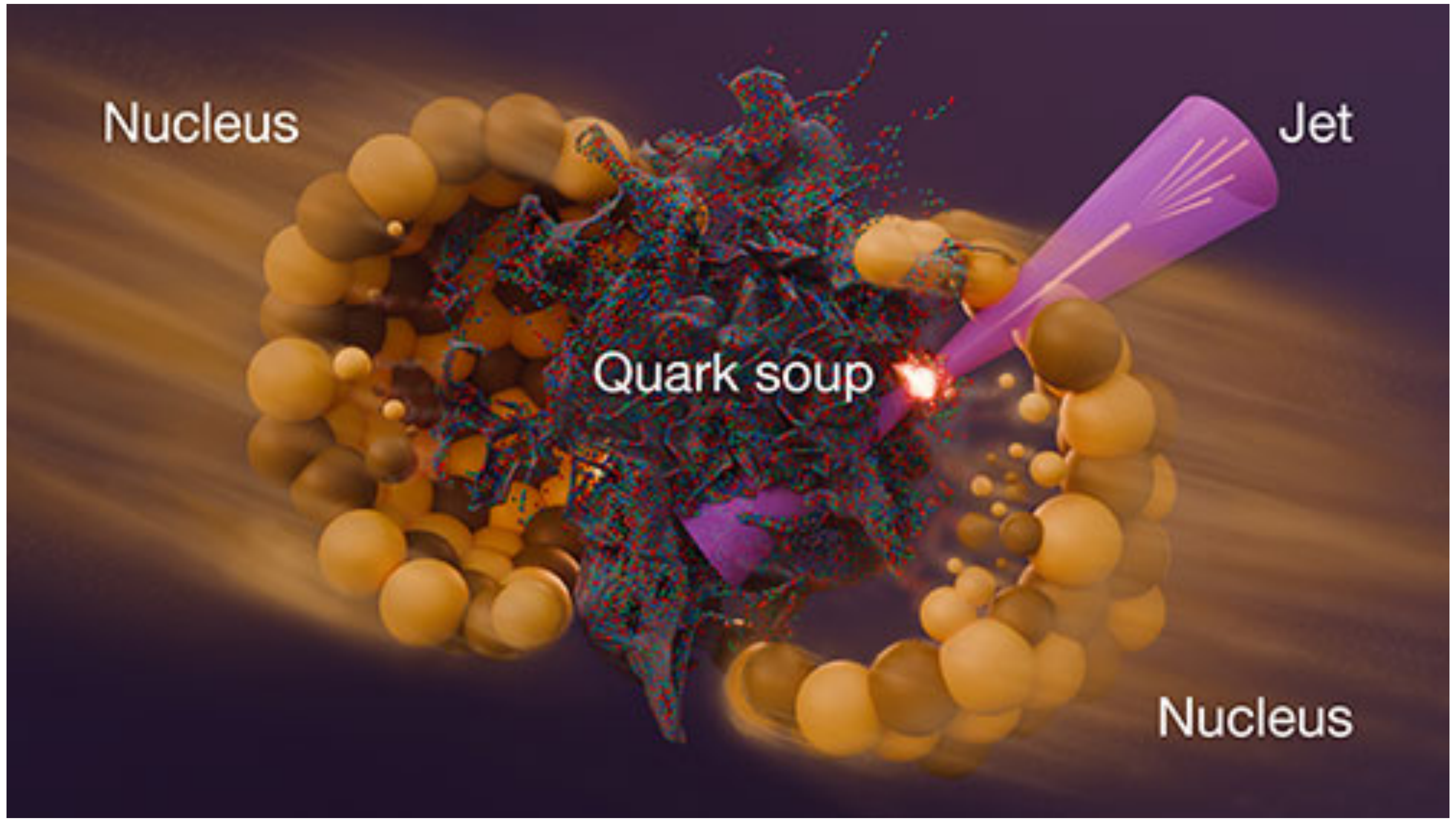
1. Background
2. LPM E-loss
3. FCEL E-loss
4. Perspectives

TOHOKU UNIVERSITY

Probing the strong force by studying partons in medium

When a high-energy parton (quark or gluon) traverses a cold nuclear medium (like in proton-nucleus or lepton-nucleus scattering) or a hot QCD matter (in nucleus-nucleus scattering), it interacts with the surrounding environments, which act as **femto-scale labs** for studying parton propagation, interaction, and hadronization.



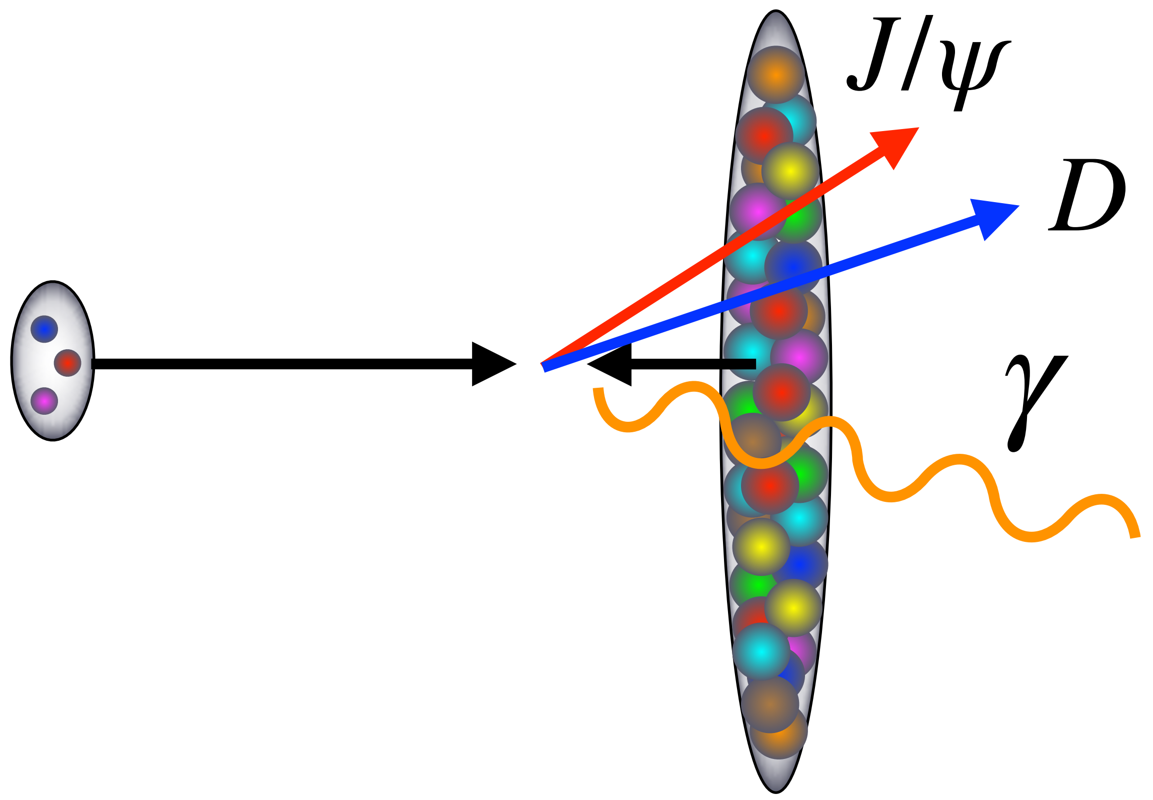


Figures by BNL

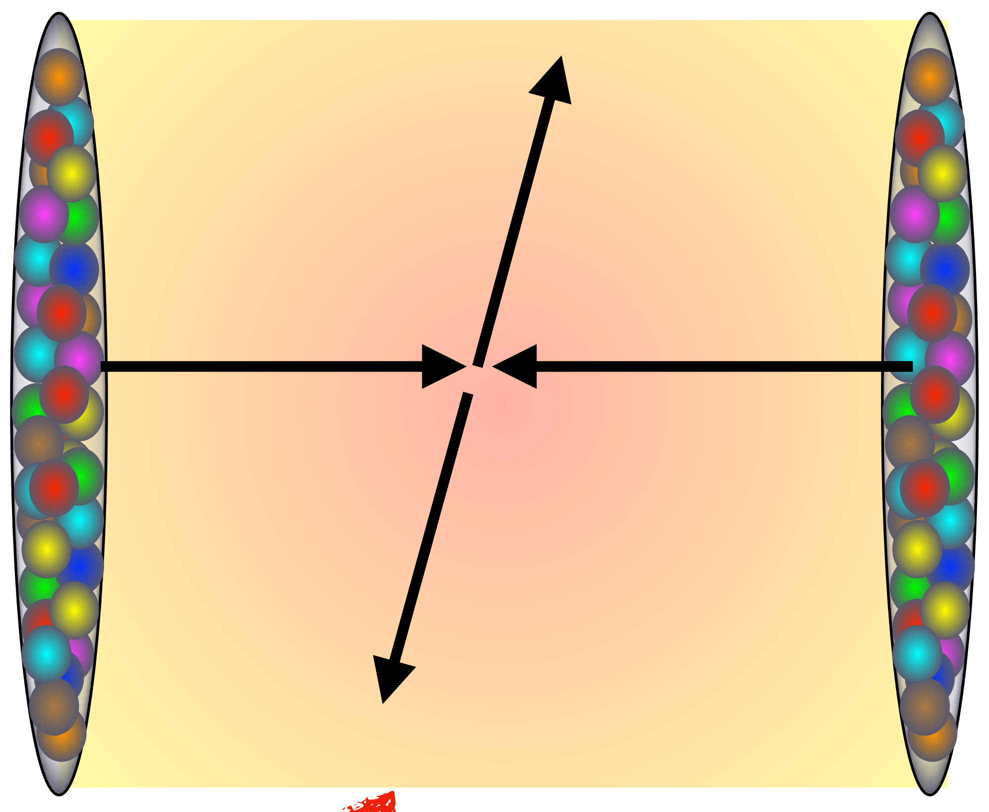
Cold Nuclear Matter Effects

High-energy proton-nucleus (pA) collisions enable the study of cold nuclear matter (CNM) effects.

Smaller system



Large system



- ✓ Nuclear parton distribution functions (initial)
- ✓ Gluon saturation effect (initial)
- ✓ Energy loss effect (initial & final)
- ✓ Comover (final)
- ✓ Nuclear absorption (final)

CNM effects can be observed in large systems but pose a challenge for theory…

Parton energy-loss in cold QCD matter

Unlike the "hot" medium of a Quark-Gluon Plasma (QGP), **cold QCD matter** consists of static nucleons in a nucleus, providing a cleaner environment to study parton's propagation and hadronization.

Primary medium effects

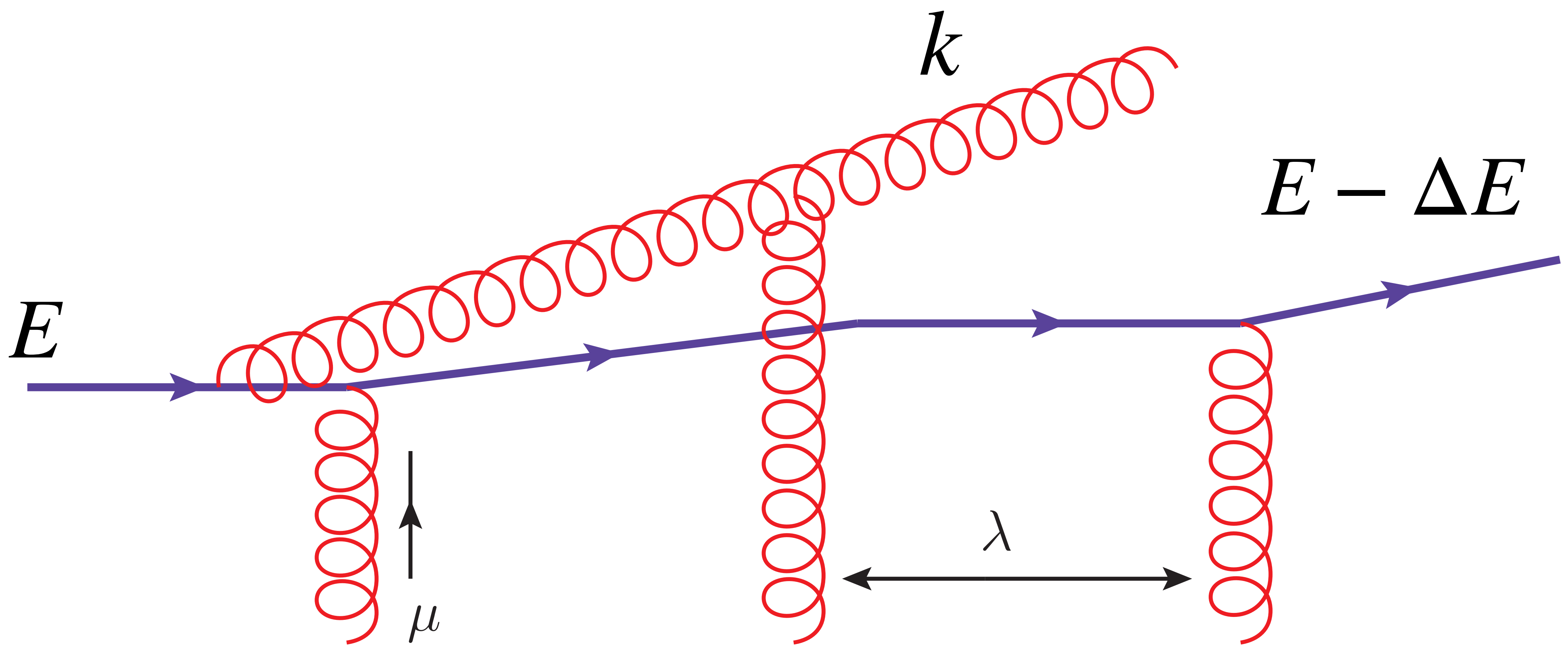
1. **Energy Loss:** Emission of soft gluons due to multiple scatterings in the target.
2. **Transverse Momentum Broadening:** Partons acquire a "kick" (Δp_T) as they travel.
3. **Hadron or Jet Quenching:** A reduction in the yield of high-energy hadrons compared to a vacuum (pp).

We can use these effects to tomographically study the properties of nuclear matter.

Transport coefficient

J. D. Bjorken, FERMILAB-PUB-82-059-THY (1982)
M. Gyulassy and X. N. Wang, NPB420, 583-614 (1994)

E-loss happens via scattering with medium or induced gluon radiation:



$\hat{q}_{\rm cold} = \mathcal{O}(0.01 - 0.1\ \mathrm{GeV^2/fm})$

$\hat{q}_{\rm hot} = \mathcal{O}(1\ \mathrm{GeV^2/fm})$

E-loss is characterized by transport (diffusion) coefficient $\hat{q} = \mu^2/\lambda$:

- ✓ λ: parton's mean-free path in the medium.
- ✓ μ: typical momentum transferred from 1 soft scattering.
- ✓ $\langle k_\perp^2 \rangle \sim \hat{q}\, t_f$ with $t_f \sim k^+/k_\perp^2$: transverse momentum broadening in the medium.

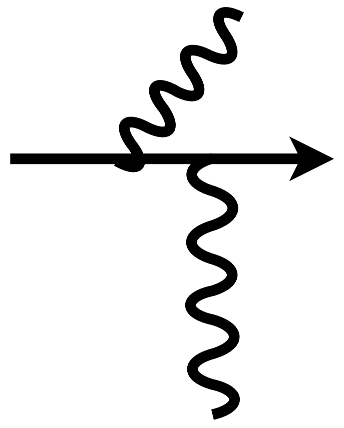
* Formation time t_f: The distance it takes for the parton and gluon to separate enough to be distinct particles.

Distinct E-loss regimes

See, [Peigne, Smilga, Phys. Usp. 52, 659 (2009)]

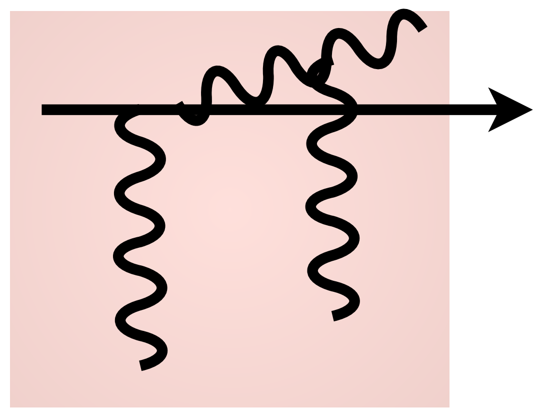
➡ **Bethe-Heitler regime:** $t_f \ll \lambda$

- Each scattering center acts as an independent source of radiation.



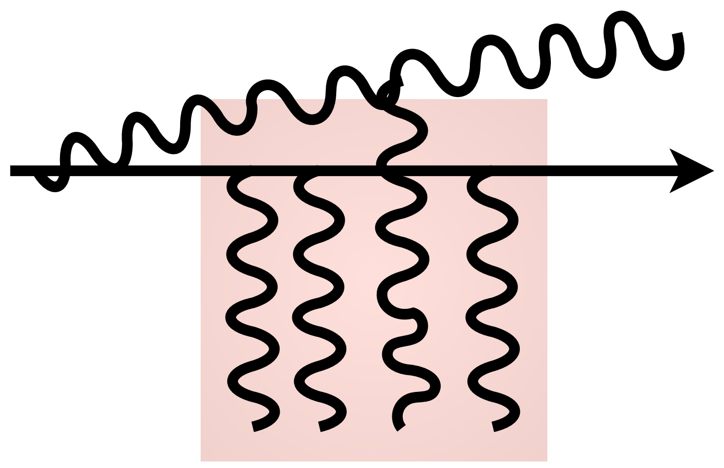
➡ **Landau-Pomeranchuk-Migdal (LPM) regime:** $\lambda \ll t_f \ll L$

- An energetic parton is suddenly produced in the medium.
- A group of t_f/λ scattering centers acts as a single radiator



➡ **Fully coherent (Long formation time or Factorization) regime:** $L \ll t_f$

- An energetic parton crosses the medium.
- All scattering centers act as a source of radiation (fully coherent over medium)



This talk will focus on LPM and FCEL.

LPM (+ nPDFs)

LPM E-loss

Baier-Dokshitzer-Mueller-Peigné-Schiff and Zakharov (BDMPS-Z) framework describes radiative energy loss where successive scatterings interfere destructively.

Parametric dependence of LPM E-loss

Baier, Dokshitzer, Mueller, Peigne, Schiff, NPB484, 265 (1997), Zakharov, JETP Lett.63, 952 (1996), Wang and Guo, NPA696, 788-832 (2001), Gyulassy, Levai and Vitev, NPB 571, 197 (2000) …

$$\Delta E_{\rm LPM}^{\rm BDMPS} = \langle \epsilon \rangle = \int d\epsilon \epsilon \mathscr{P}(\epsilon) \sim \alpha_s \hat{q} L^2$$

✓ Important for hadron production in nuclear DIS (SIDIS), Drell-Yan, and jet in QGP.

✓ The fractional E-loss: $\Delta E/E \to 0$ as $E \to \infty$.

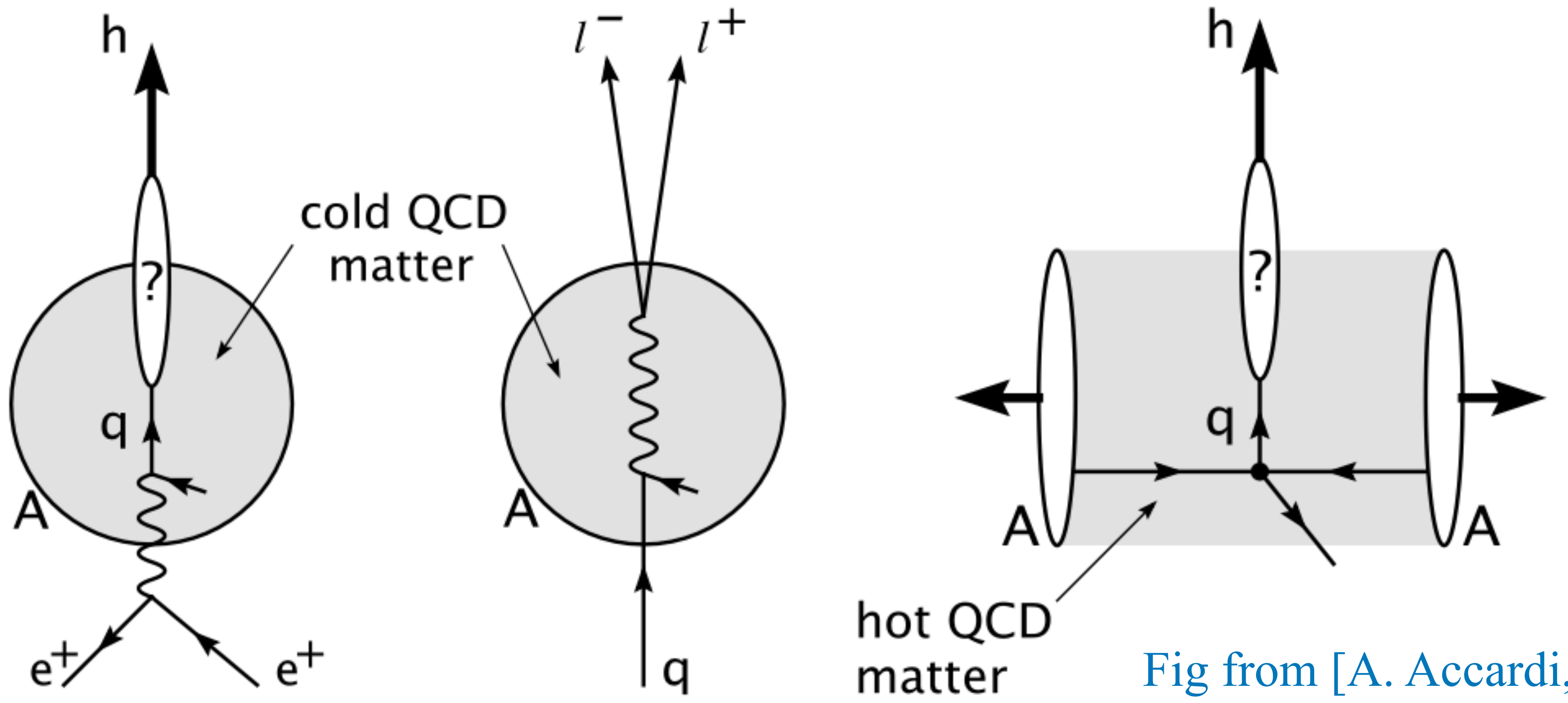
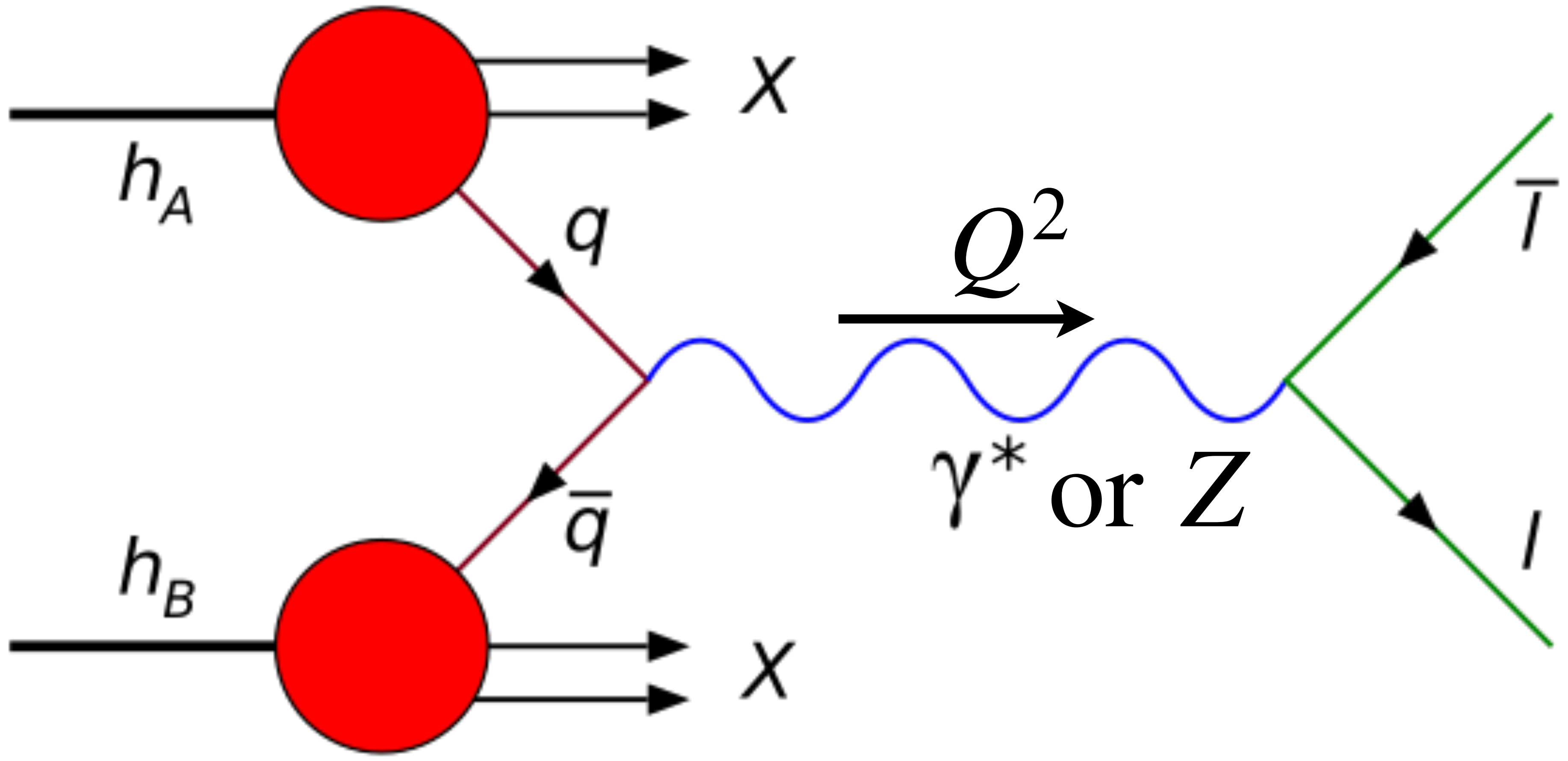


Fig from [A. Accardi, F. Arleo, W.~K. Brooks, D. D'Enterria and V. Muccifora, Riv. Nuovo Cim. 32, no.9-10, 439-554 (2009)]

Probing LPM effect: The Drell-Yan Process

$$x_{A,B} = e^{\pm y}\sqrt{\frac{Q^2}{s}}$$

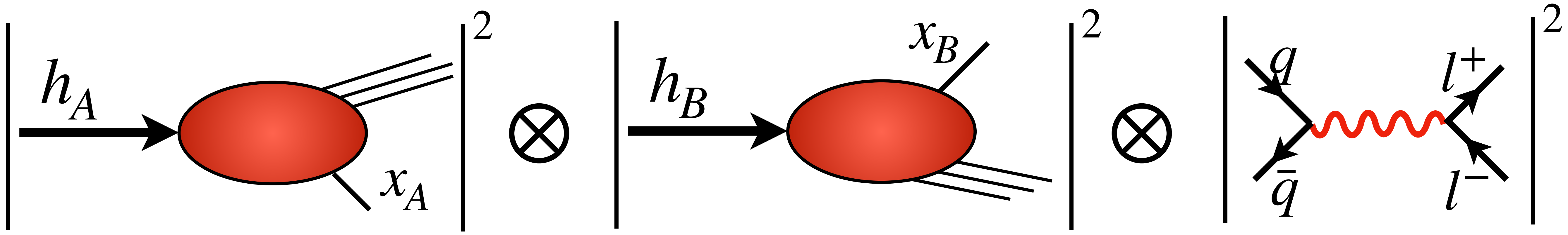
y: rapidity of the vitural photon in CM frame



A laboratory for sea quarks

❖ **Factorization (Approximation) valid at $Q^2 \gg \Lambda^2_{\mathrm{QCD}}$:**

$d\sigma_{DY} \approx$



Nonperturbative Parton Distribution Functions (PDFs)　**Probe (perturbatively calculable)**

❖ **Color-Neutral Final State:** Because the final lepton pair carries no color charge, it cannot radiate gluons.

❖ **The Signature:** Any suppression of DY yields in a nucleus compared to a proton could be due to the incoming quark losing energy before it hits an antiquark from the target.

Implementing LPM effect

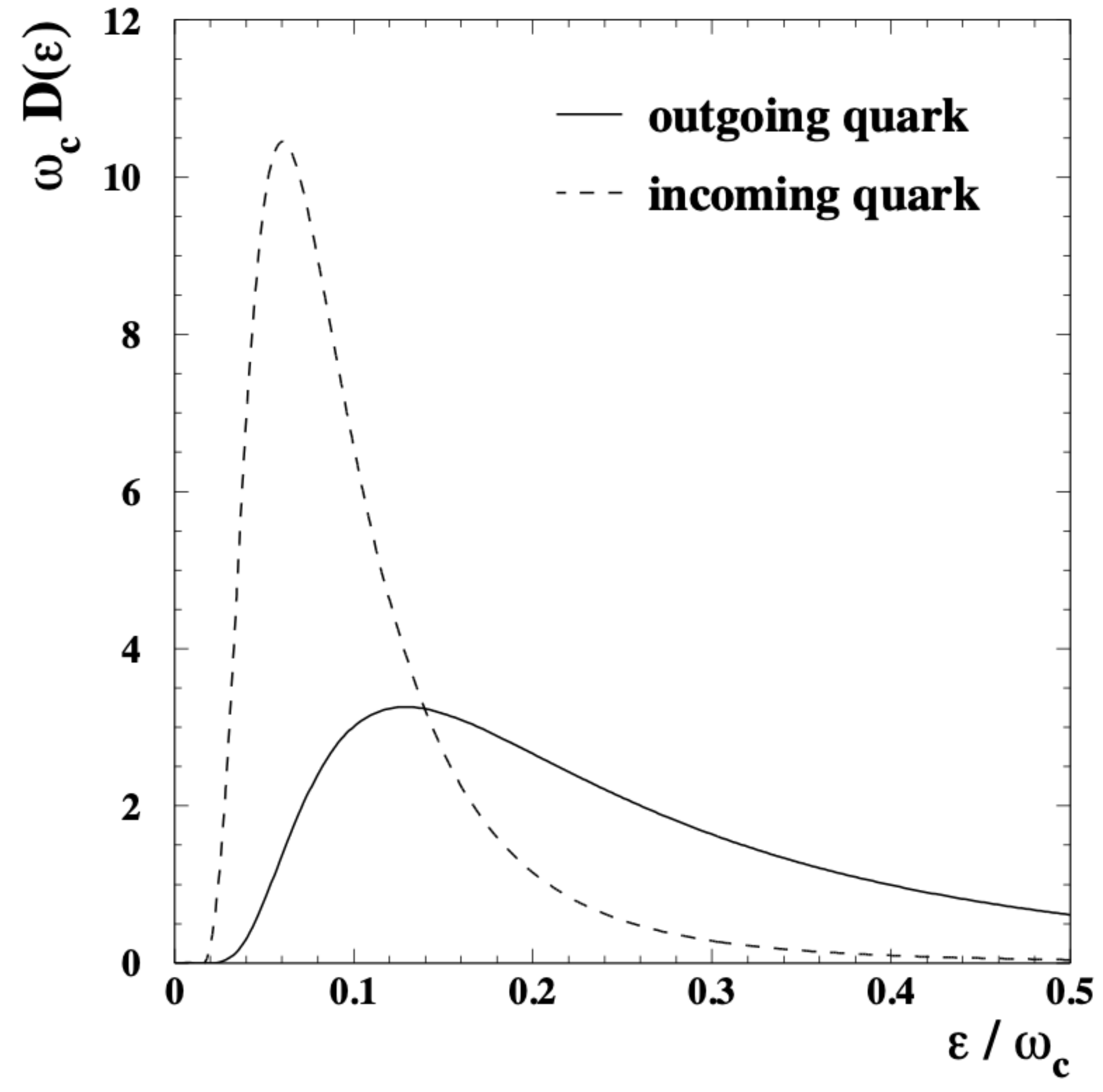
Partons from the hadron projectile suffer multiple scattering in the target nucleus.

$$\frac{d\sigma_{hA}}{dx_F dM} = \sum_{ij=q,\bar{q},g} \int dx_1 \int dx_2 \int d\epsilon\, \mathscr{P}(\epsilon) f_{i/h}\left(x_1 + \frac{\epsilon}{E_{\rm beam}}\right) f_{j/A}(x_2) \frac{d\hat{\sigma}_{ij}(x_1, x_2)}{dx_F dM}$$

Probability distribution (**quenching weight**) derived in Poisson approximation

Baier, Dokshitzer, Mueller, Schiff, JHEP09, 033 (2001)

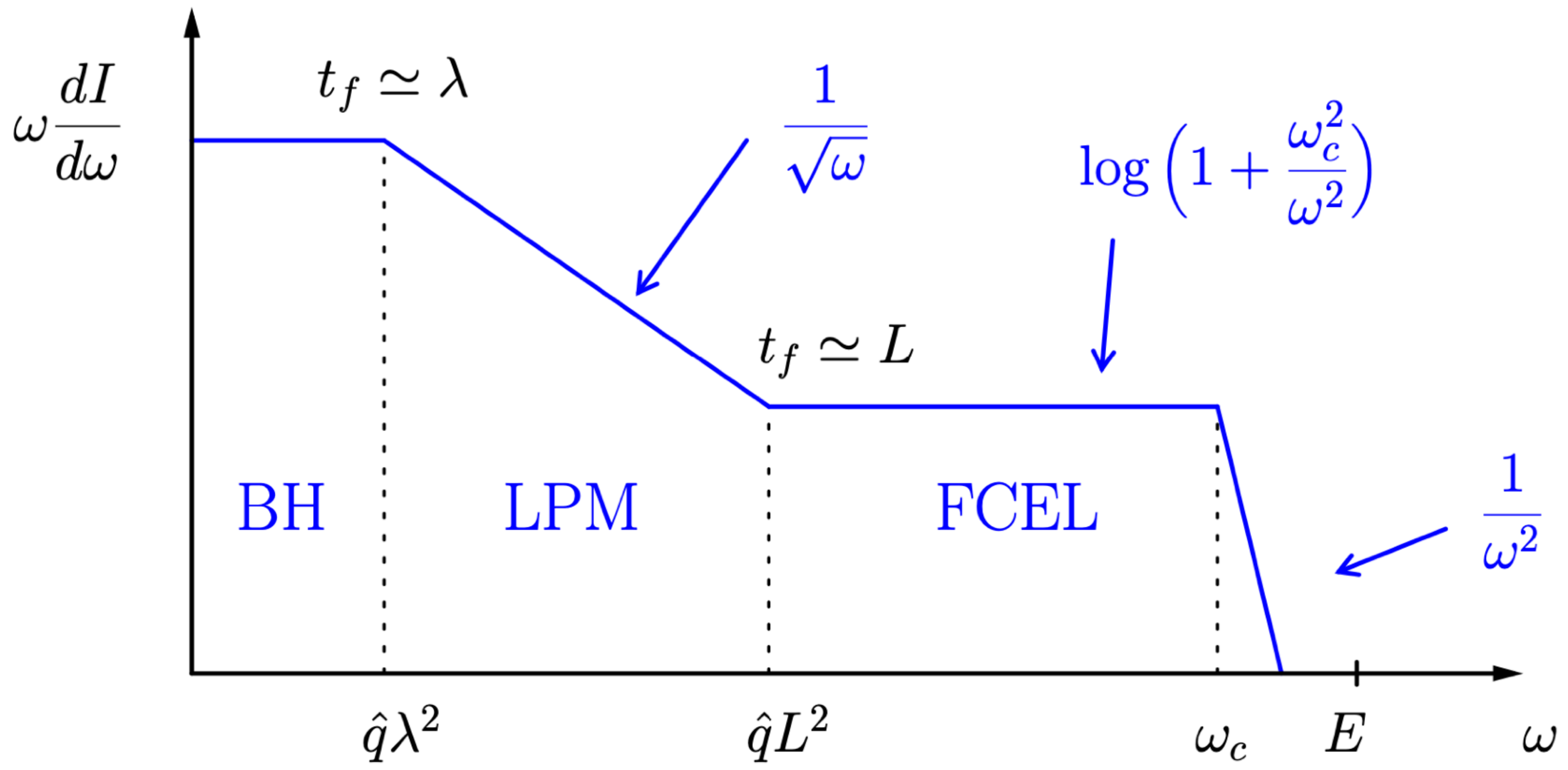
$$\mathscr{P}(\epsilon) = \sum_n^{\infty} \frac{1}{n!} \left[\Pi_{i=1}^n \int d\omega_i \frac{dI}{d\omega}\right] \delta(\epsilon - \sum_i \omega_i) \exp\left[-\int_0^{+\infty} d\omega \frac{dI}{d\omega}\right]$$



F. Arleo, JHEP11, 044 (2002)

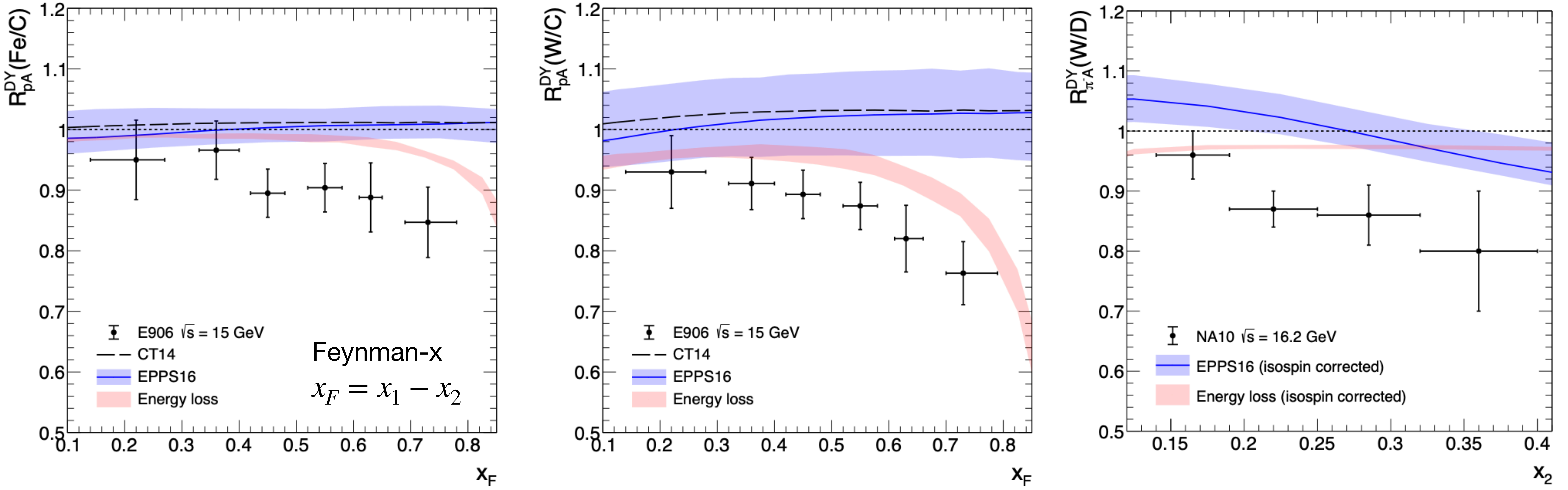
The $k_\perp$-integraed gluon radiation spectrum controls the quenching weight.

$$dI = \frac{d\sigma_{\rm rad}}{d\sigma_{\rm el}} = \frac{\sum |M_{\rm rad}|^2}{\sum |M_{\rm el}|^2} \frac{dk^+ dk_\perp^2}{2k^+(2\pi)^3}$$



Experimental Evidence of LPM E-loss

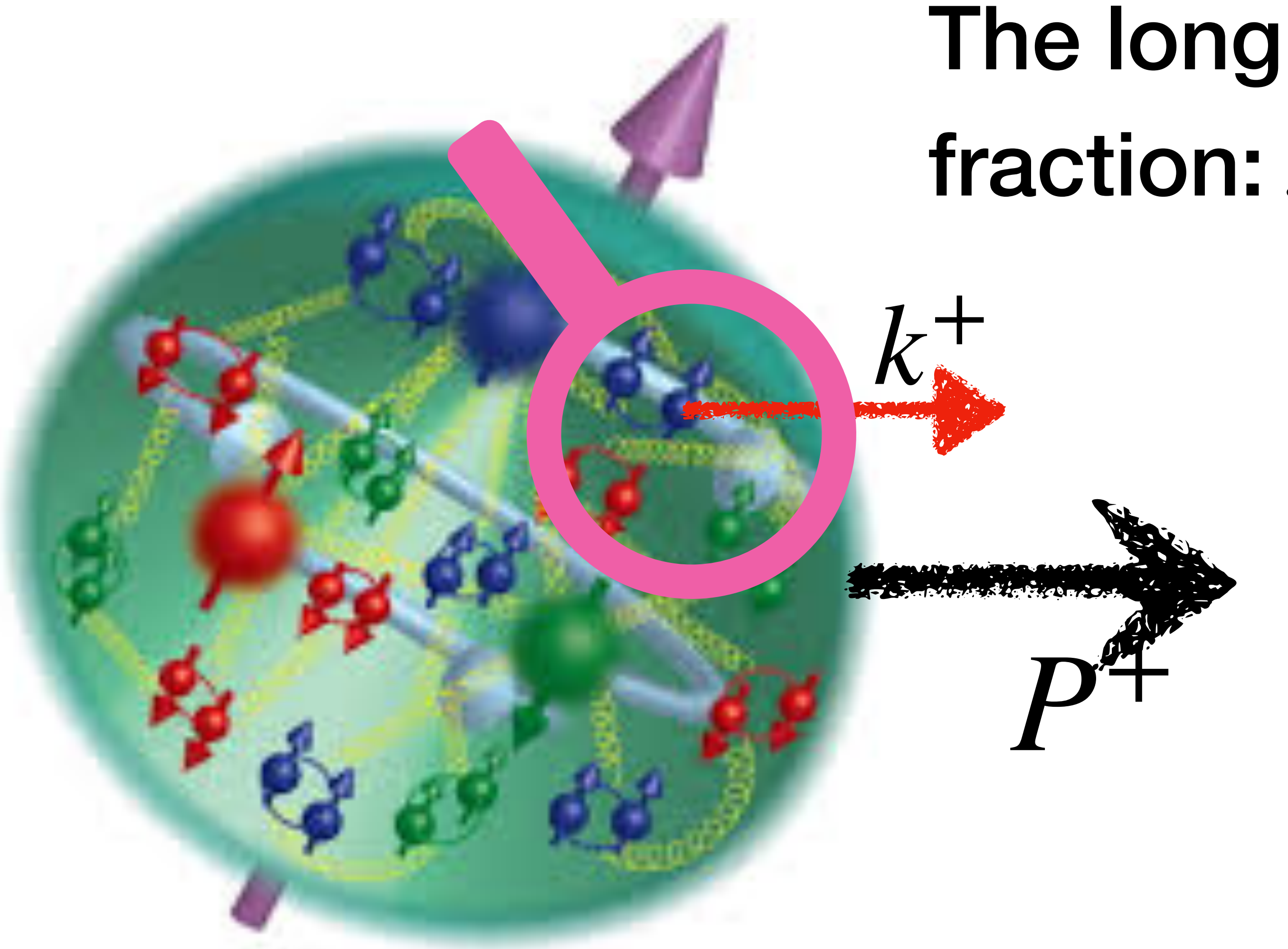
F. Arleo, C. J. Naïm and S. Platchkov, JHEP01, 129 (2019)



❖ Nuclear PDFs (nPDFs) alone cannot explain the suppression data; they predict a ratio close to unity in this specific kinematic range.

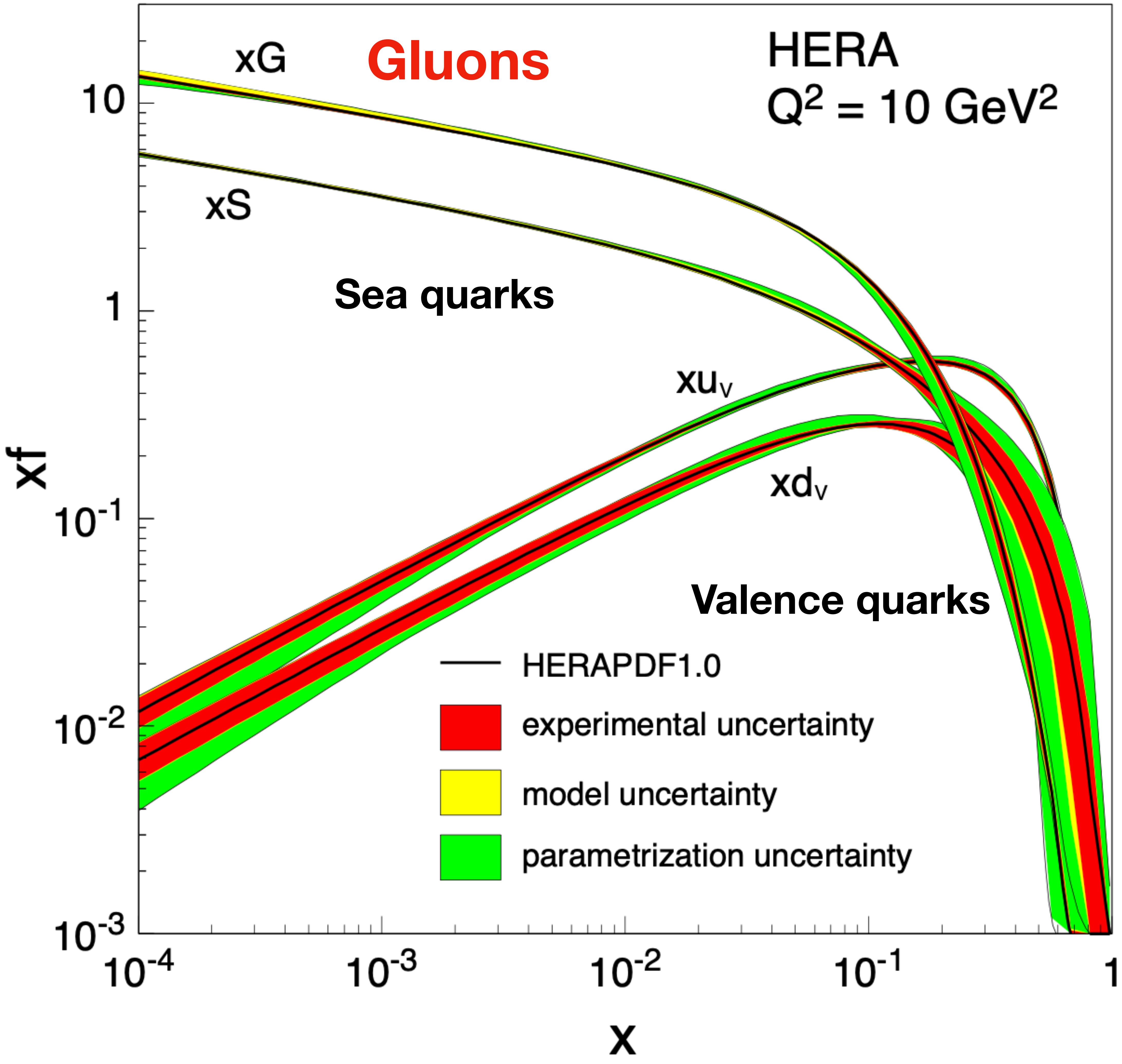
❖ Preliminary data suggest the existence of initial-state quark energy loss as modeled by the BDMPS (LPM) framework.

Review: Parton Distribution Functions (PDFs)



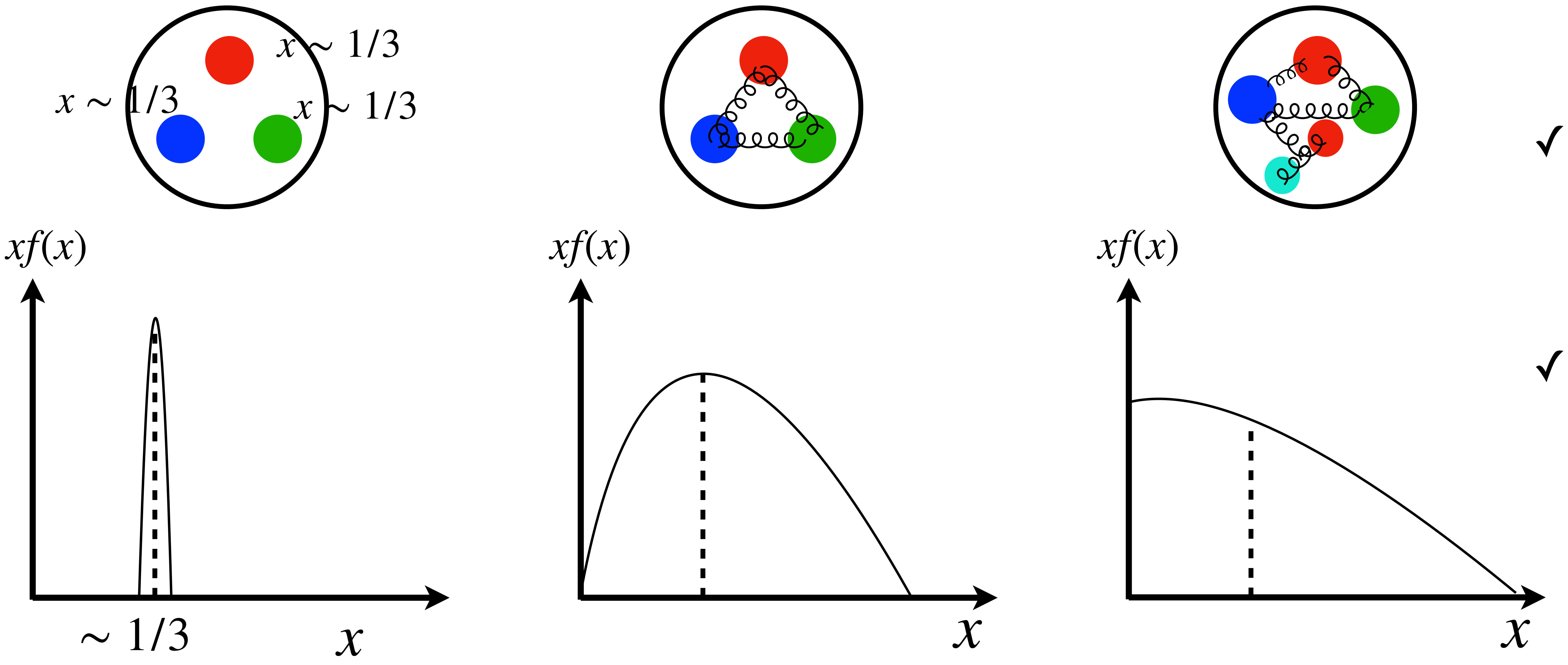
The longitudinal momentu fraction: $x = k^+/P^+$

The probability distribution for finding a parton with a given momentum fraction x when observing the inside of the proton at a certain resolution Q : $f_{i/p}(x, Q^2)$



Universality: The proton PDFs extracted from lepton-hadron scattering experiments can be applied to other scattering processes, such as hadron-hadron collisions.

Valence and Sea partons



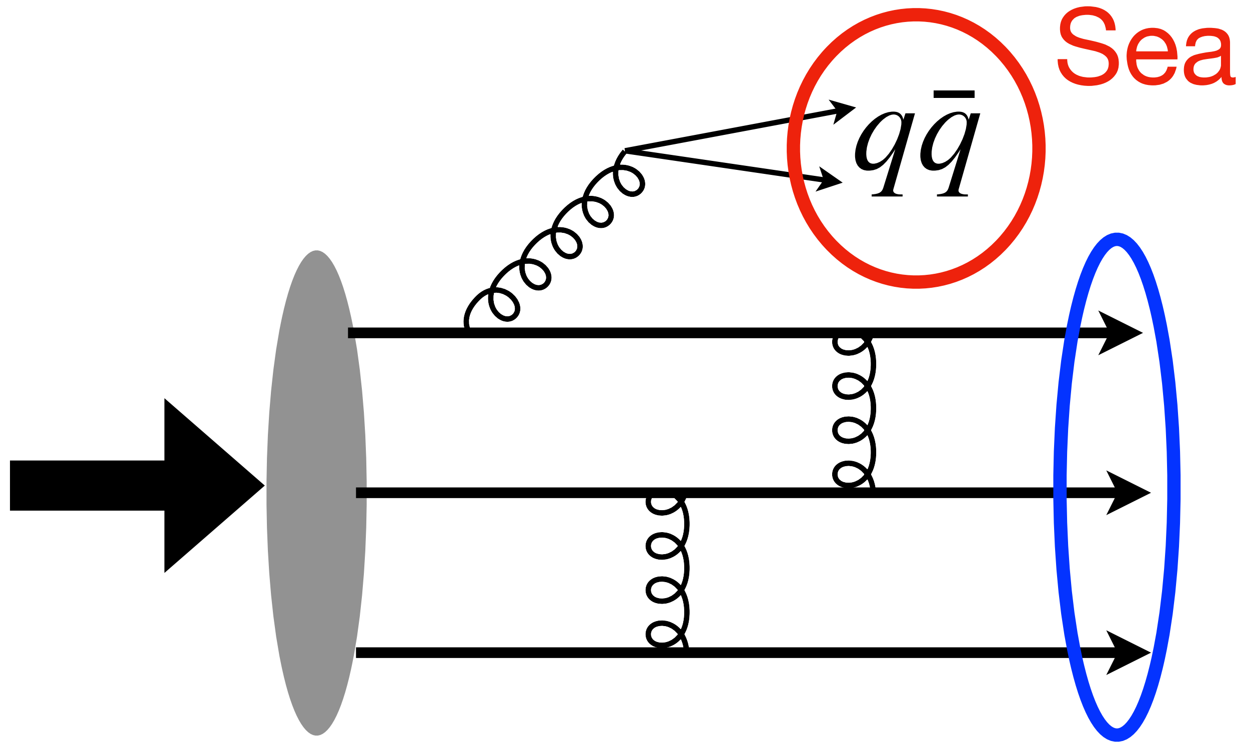
- ✓ Valence partons determine the quantum numbers of a hadron, such as electric charge and baryon number.
- ✓ Sea quarks with a small momentum fraction are produced through quantum fluctuations and radiation effects.

Valence parton   Sea parton

$$q(x) = q_v(x) + q_s(x)$$

Gluons and quarks are mixed through quantum evolution (radiation).

Sea parton has a short life time.

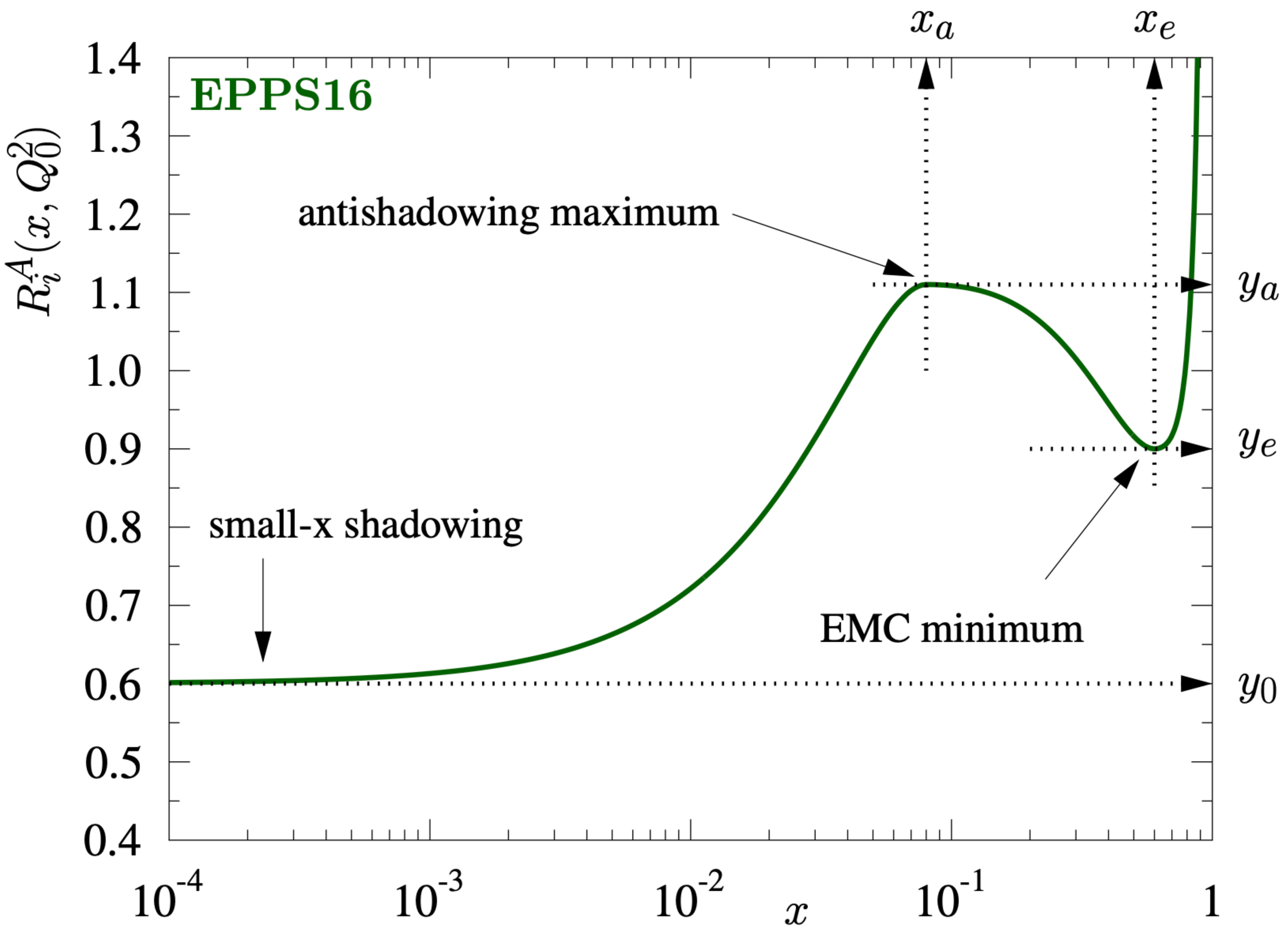


Valence Parton has a long lifetime due to Lorentz time dilation. They are effectively frozen during EM interactions in DIS.

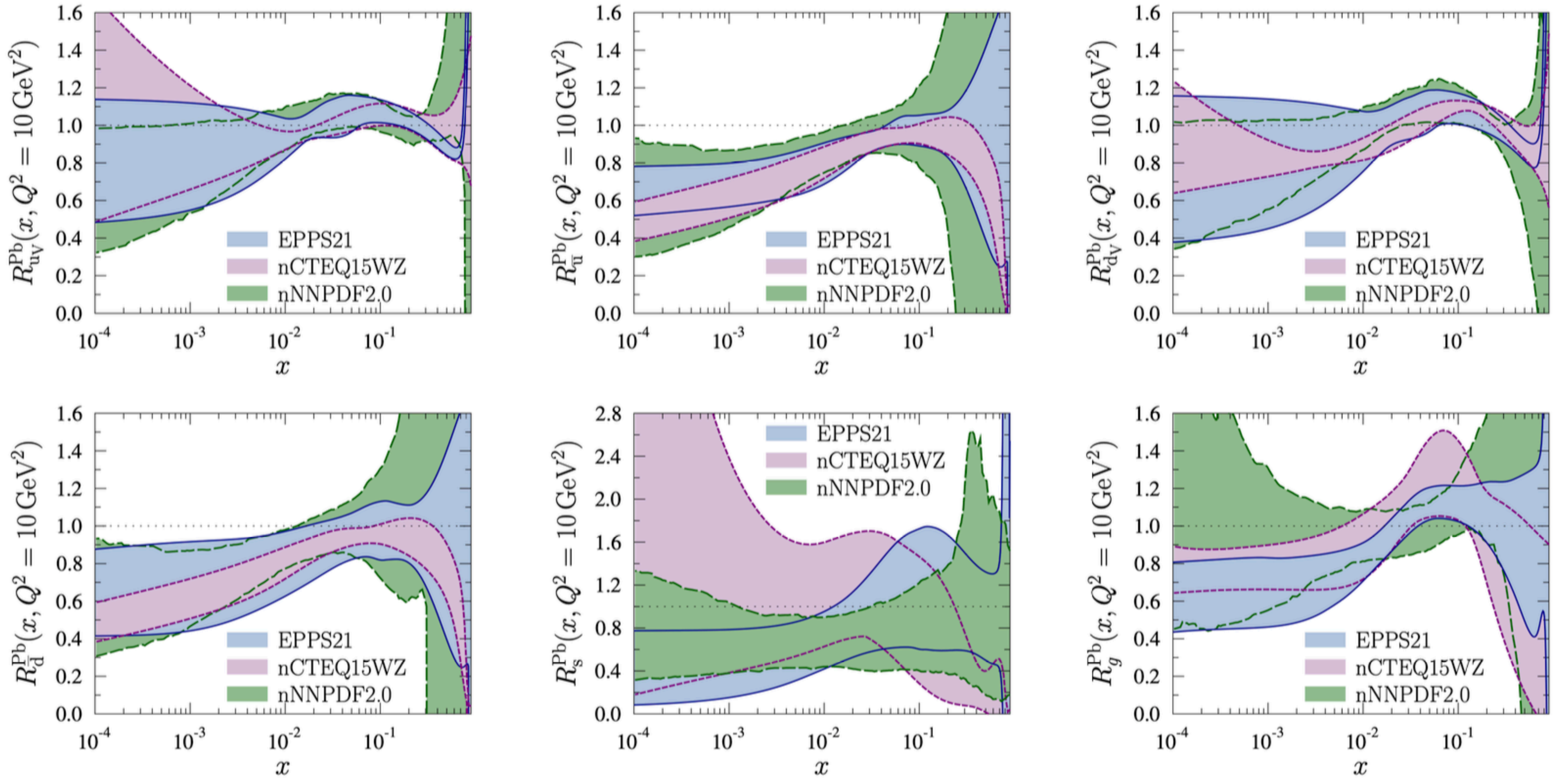
Nuclear PDFs

$$R_i^A(x, Q^2) = \frac{f_i^{p/A}(x, Q^2)}{f_i^p(x, Q^2)}$$

- $R^A > 1$ for $x \gtrsim 0.8$: Fermi motion
- $R^A < 1$ for 0.25 or $0.3 \lesssim x \lesssim 0.8$: EMC effect
- $R^A > 1$ for $0.1 \lesssim x \lesssim 0.25$ or 0.3: Antishadowing
- $R^A < 1$ for $x \lesssim 0.1$: Shadowing



nPDFs from Global data fitting

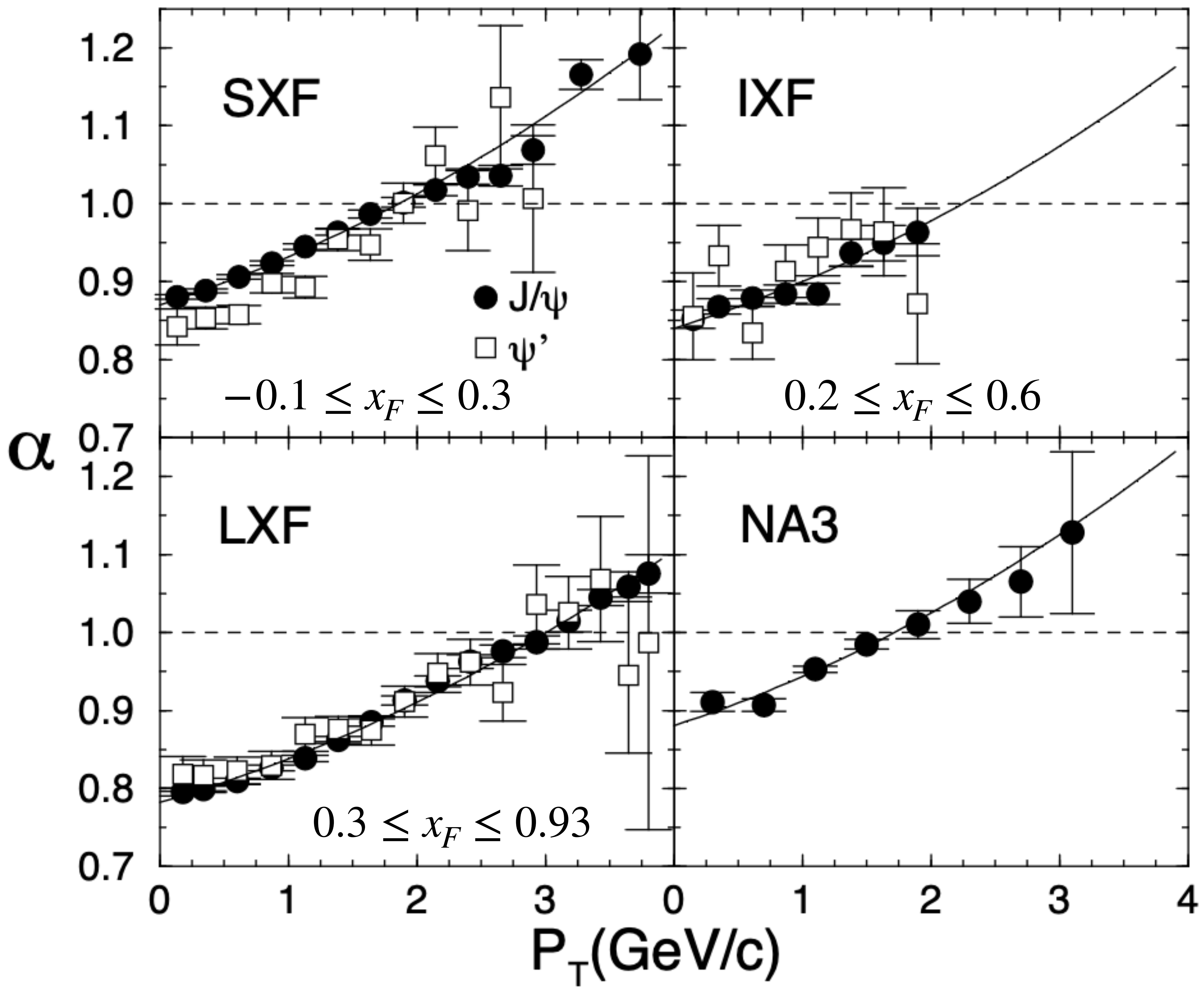


Uncertainties from different sets: EPPS, nCTEQ, NNPDF,…

FCEL

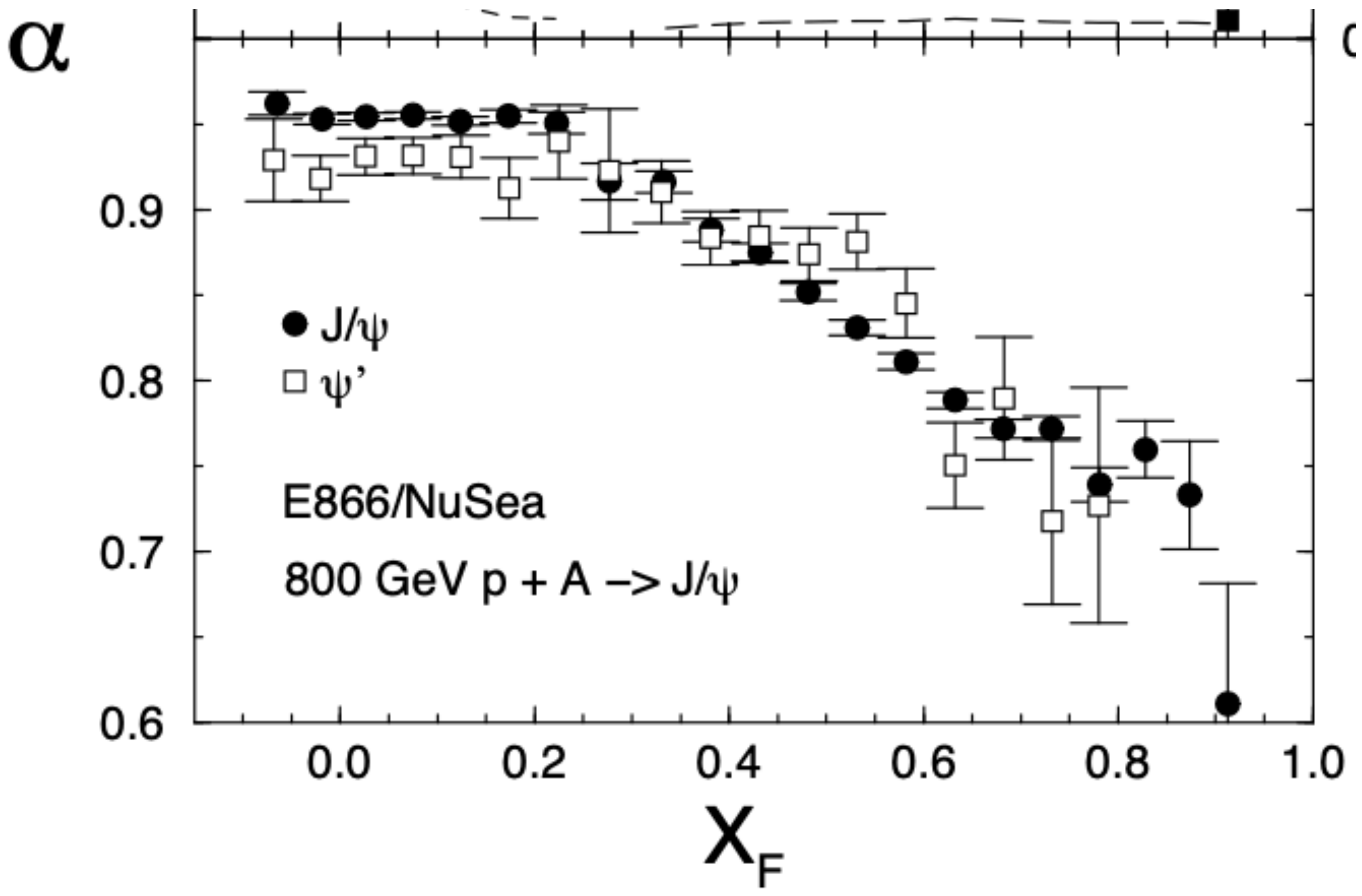
Nuclear suppression of hadron production

J/ψ in pA @ FNAL ($\sqrt{s_{NN}} = 38.7\,\mathrm{GeV}$)



$$\sigma_A = \sigma_N A^\alpha$$

FNAL E866/NuSea Collab., PRL84, 3256 (2000).

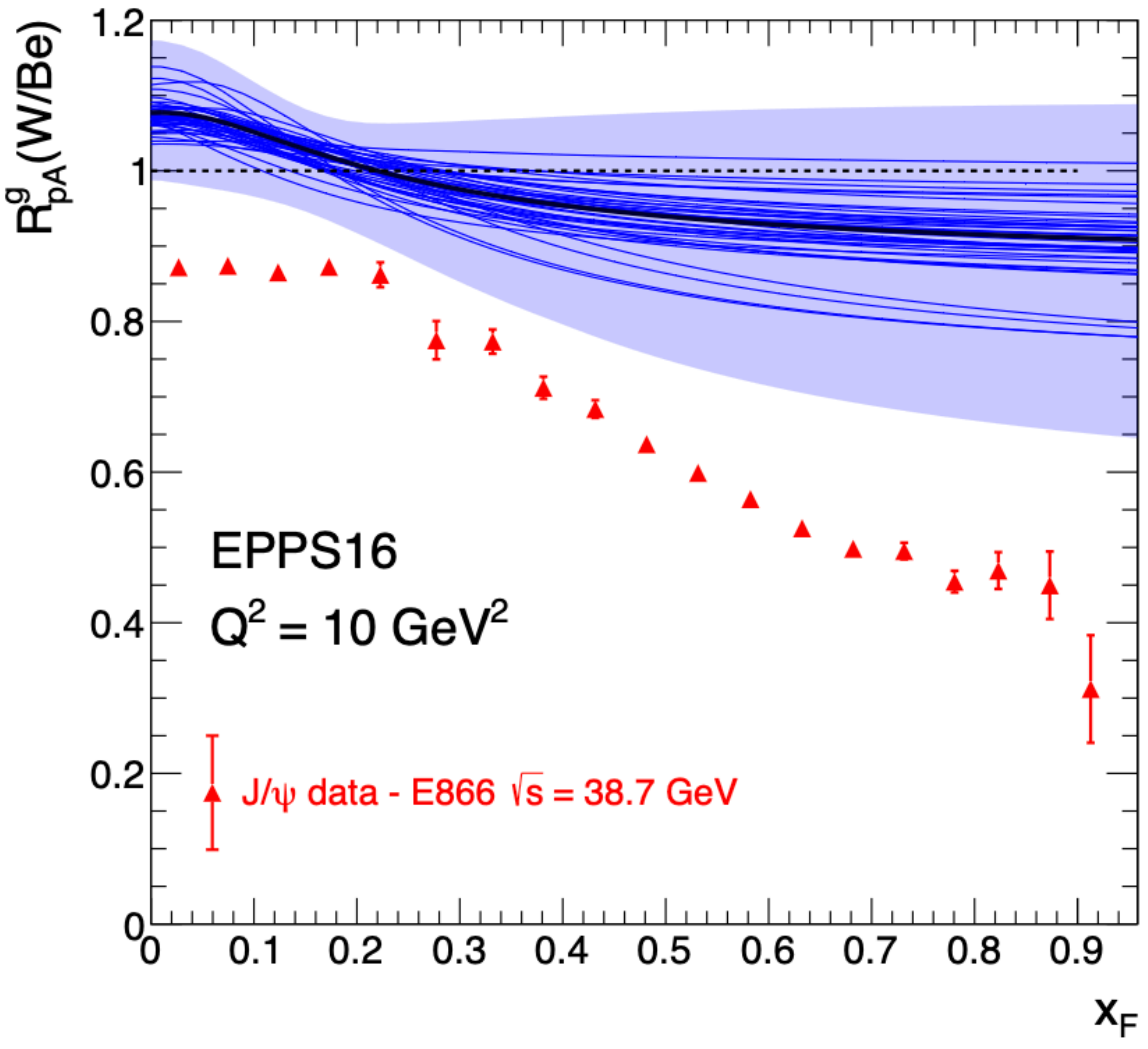


- Hadron (J/ψ) yields are strongly suppressed
  - at forward rapidity (large $x_F = x_1 - x_2$)
  - at low p_T

What is the origin of it?

J/ψ suppression from nPDFs

arXiv:2506.17454 [hep-ph]



- ❖ nPDFs alone cannot describe J/ψ suppression at FNAL.
- ❖ Additional suppression is required to explain the strong suppression.
- ❖ A produced heavy quark pair has a color charge in the final state, which is similar to the small-angle scattering of an asymptotic charge. → FCEL

FCEL energy loss

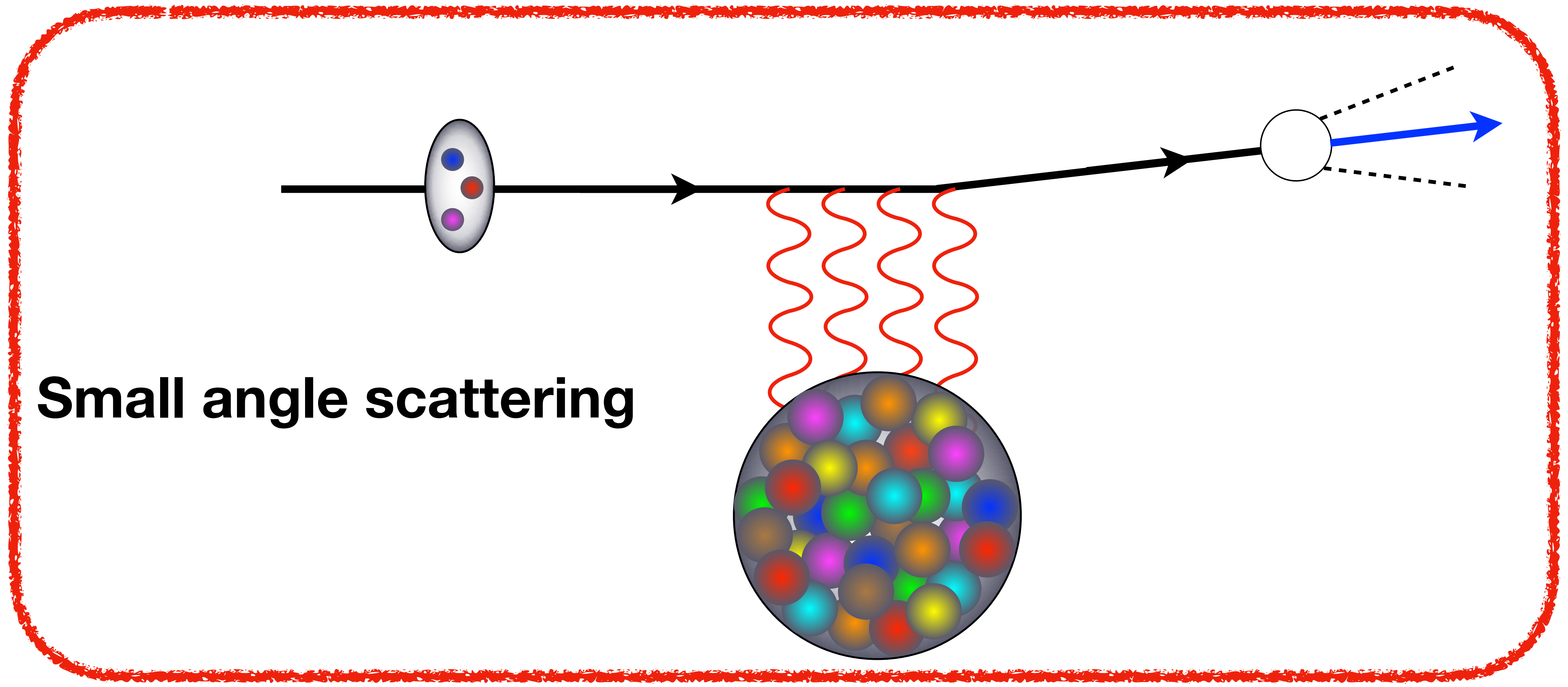
FCEL E-loss arises from the interference between gluon emission amplitudes off the initial-state and final-state partons.

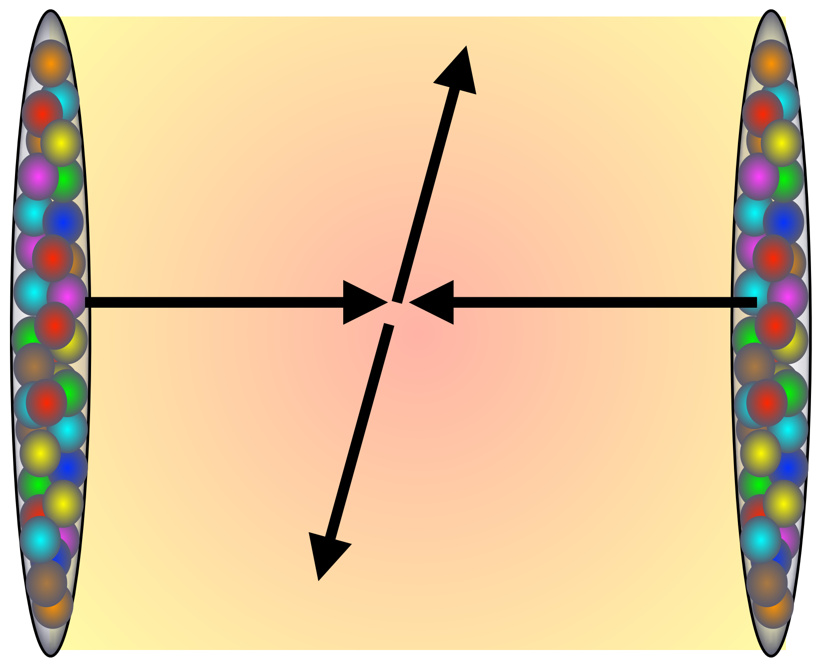
Parametric dependence of FCEL E-loss

$$\Delta E_{\text{FCEL}} \sim \alpha_s \frac{\sqrt{\hat{q}L}}{Q_{\text{hard}}} E \qquad Q_{\text{hard}} = p_T, M_\Upsilon, M_{\text{dijet}}, \cdots$$

✓ Important for **small angle** scattering, e.g., hadron production in pA collisions.

✓ $\Delta E/E$ cannot vanish as $E \to \infty$: important at all energies.

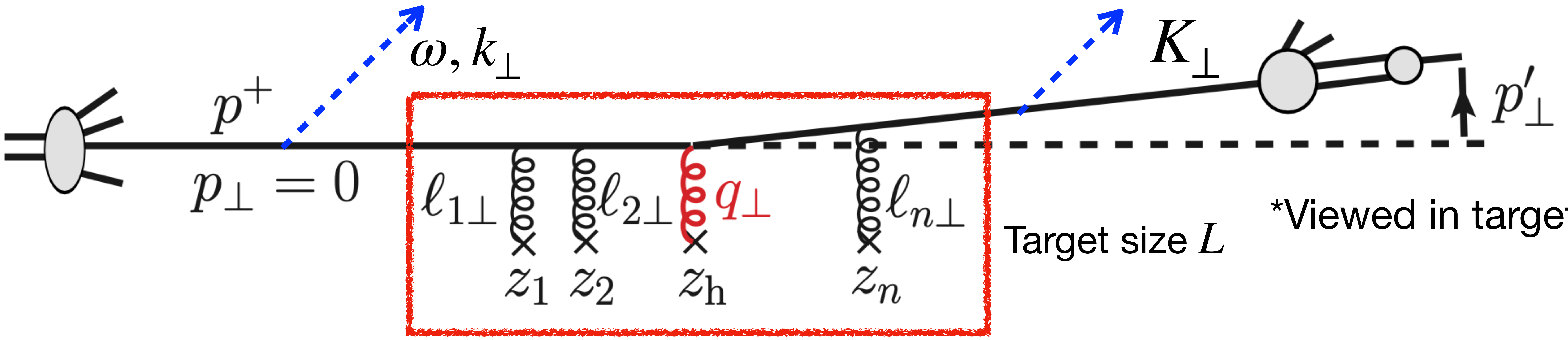




Cf. Large angle scattering

Setup of FCEL

Forward scattering of fast asymptotic parton with $E(\to \infty)$ crossing a nuclear medium



❖ Parent parton from the projectile undergoes:

✓ single hard scattering with $q_\perp$ an exchanged momentum.

✓ multiple soft scatterings: $l_\perp^2 = \left(\sum l_{i\perp}\right)^2 \sim \hat{q}L \ll q_\perp^2, K_\perp^2$.

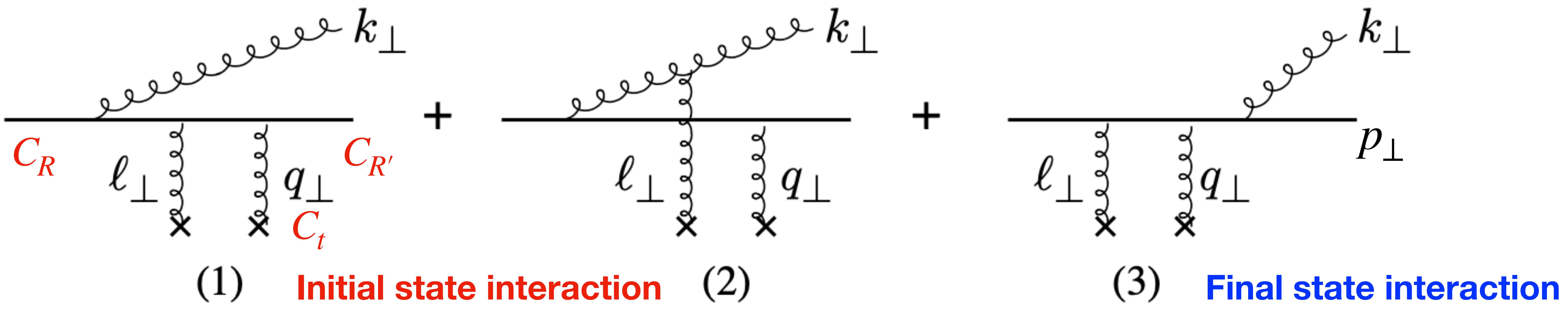
❖ Radiated gluons: soft ($x = k^+/p^+ \ll 1$) and small angle ($k_\perp \ll k^+$) radiation

❖ Hadron of $p'_\perp = zK_\perp$ is tagged.

❖ Recoiled parton assumed to be soft; kinematics remains the same (LT).

Induced gluon spectrum in LLA

For massive particle, $p_\perp \to m_\perp$



❖ The "induced" $k_\perp$-integrated gluon spectrum $dI/d\omega$, given by interference terms $\mathrm{Re}[(1+2)(3)^*]$ in leading-log approximation (**LLA**).

❖ $|(1+2)|^2$ and $|(3)|^2$ cancel out (power suppressed) in $dI/d\omega$.

$$\omega \frac{dI}{d\omega}\bigg|_{2\to 1} \approx F_c \frac{\alpha_s}{\pi}\left[\ln\left(1+\frac{l_{A\perp}^2 E^2}{\omega^2 p_\perp^2}\right) - \mathrm{pp}\ (l_{A\perp} \to l_{p\perp})\right]$$

Arleo, Peigne, Sami, PRD83, 114036 (2011)
Peigne, Arleo, Kolevatov, PRD93, 014006 (2016)
Munier, Peigne, Petreska, PRD95, 014014 (2017)
Armesto, Ma, Martinez, Mehtar-Tani and Salgado,PLB717, 280 (2012)

$F_c = C_R + C_{R'} - C_t$ with $R(R')$, t being a color rep. of incoming (outgoing) and t-channel particle. **Color charge = Casimir**.

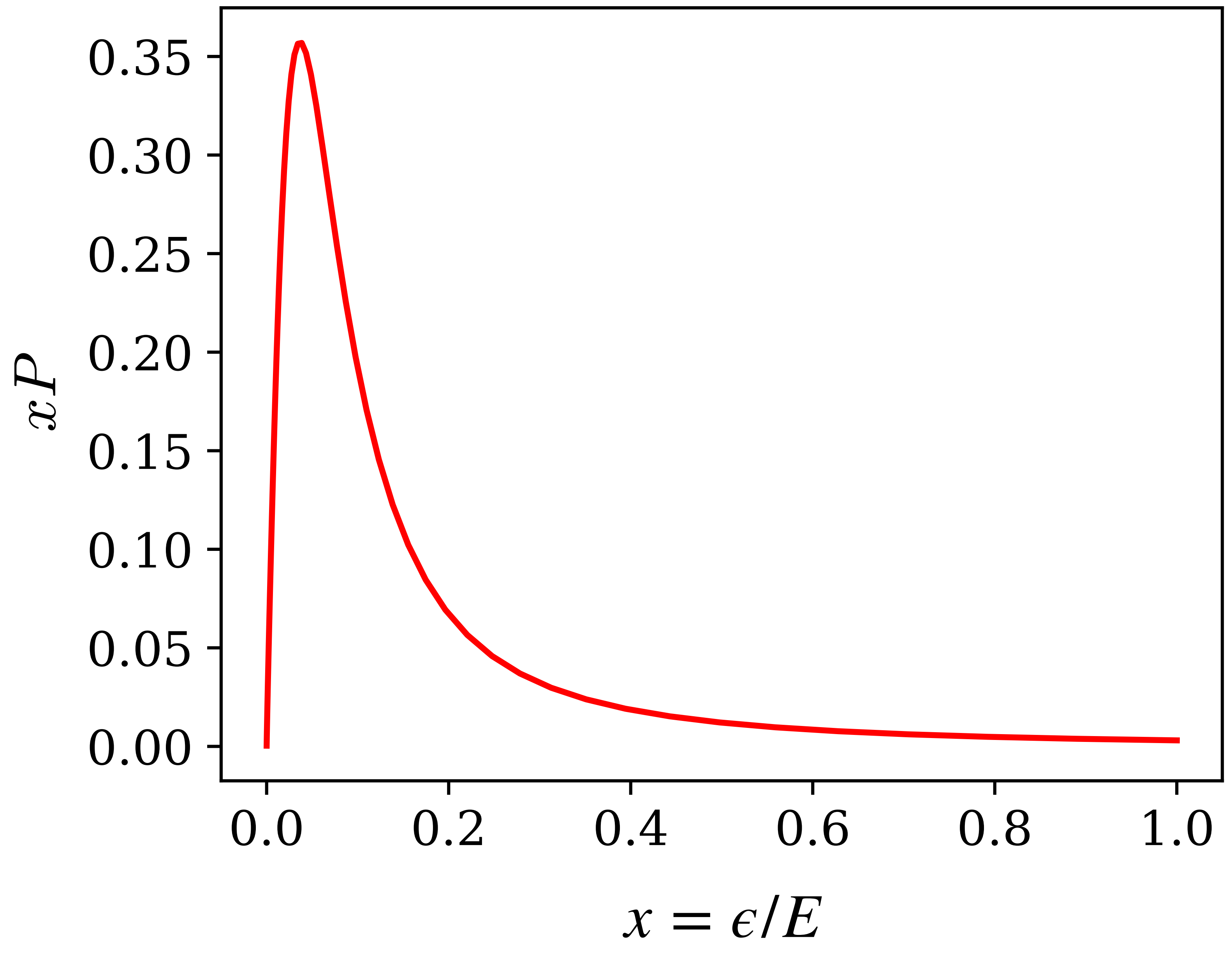
Phenomenology in LLA: e.g. J/ψ production

$$E\frac{d\sigma_{pA\to J/\psi+X}}{d^3p} = A\int_0^{\epsilon_{\max}} d\epsilon\ \mathscr{P}(\epsilon)\ E\frac{d\sigma_{pp\to J/\psi+X}}{d^3p}\Bigg|_{E\to E+\epsilon}$$

Energy (rapidity) shift

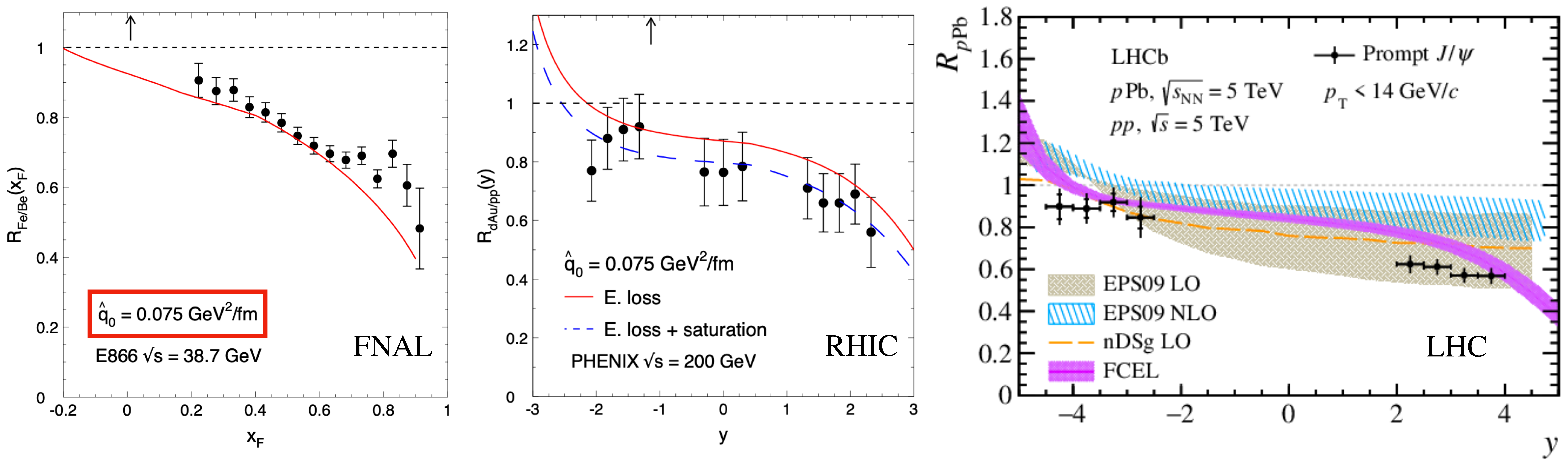
$$\mathscr{P}(\epsilon) \simeq \frac{dI}{d\epsilon}\exp\left\{-\int_\epsilon^\infty d\omega\frac{dI}{d\omega}\right\}$$

- Probability distribution (**quenching weight**) derived in double-log approx. (DLA). Baier, Dokshitzer, Mueller, Schiff, JHEP09, 033 (2001)
- As shown in the LPM E-loss, the induced gluon spectrum controls the shape of the quenching weight, leading to hadron quenching in the cold nuclear medium.
- To derive the induced spectrum, we resum all orders in opacity $\bar{n} = L/\lambda$.



J/ψ suppression and FCEL effect

Arleo and Peigne, PRL109, 122301 (2012), JHEP03, 122 (2013)



❖ FCEL describes the $\sqrt{s}$ dep. from FNAL to LHC.

❖ Parameters are fixed at FNAL.

❖ FCEL is different from gluon saturation. There is FCEL effect even at high-x.

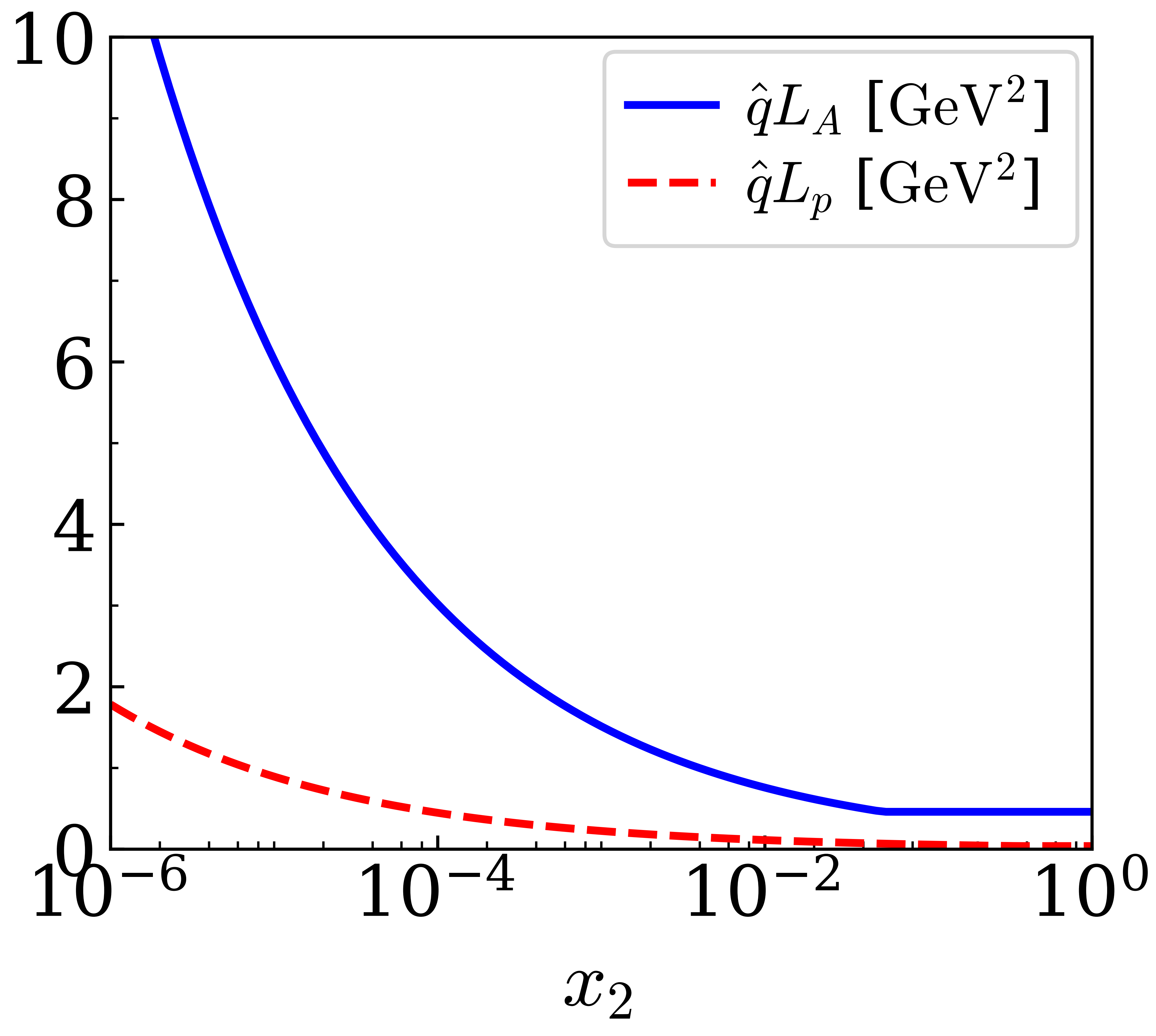
Transport coefficient

- $l_\perp^2 \simeq \hat{q}L$ is the only free parameter in the model.
- Parametrization of the transport coefficient:

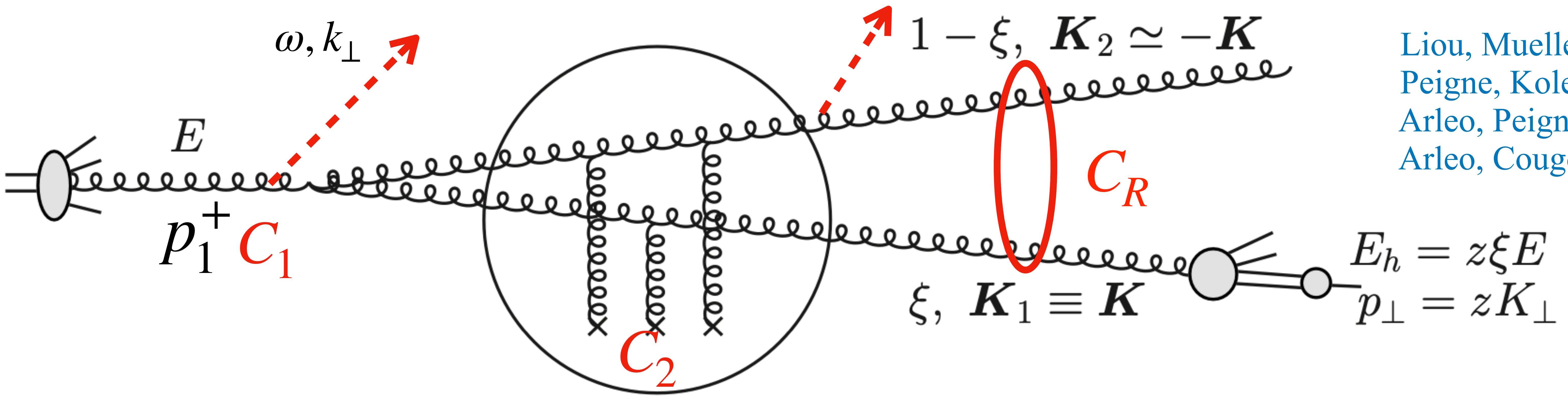
$$\hat{q} \sim \hat{q}_0 \left(\frac{10^{-2}}{x} \right)^{0.3}$$

  - Consistent with perturbative calculations
  - $\hat{q}_0 = 0.07 - 0.09\,\mathrm{GeV}^2/\mathrm{fm}$: fixed by fitting data
  - QCD evolution is not considered for simplicity
  - L: determined by Glauber theory

- In the small-x limit, we could read $\hat{q}L \sim Q_s^2$, but cannot derive it analytically. Baier, Dokshitzer, Mueller, Peigne and Schiff, NPB484, 265 (1997)



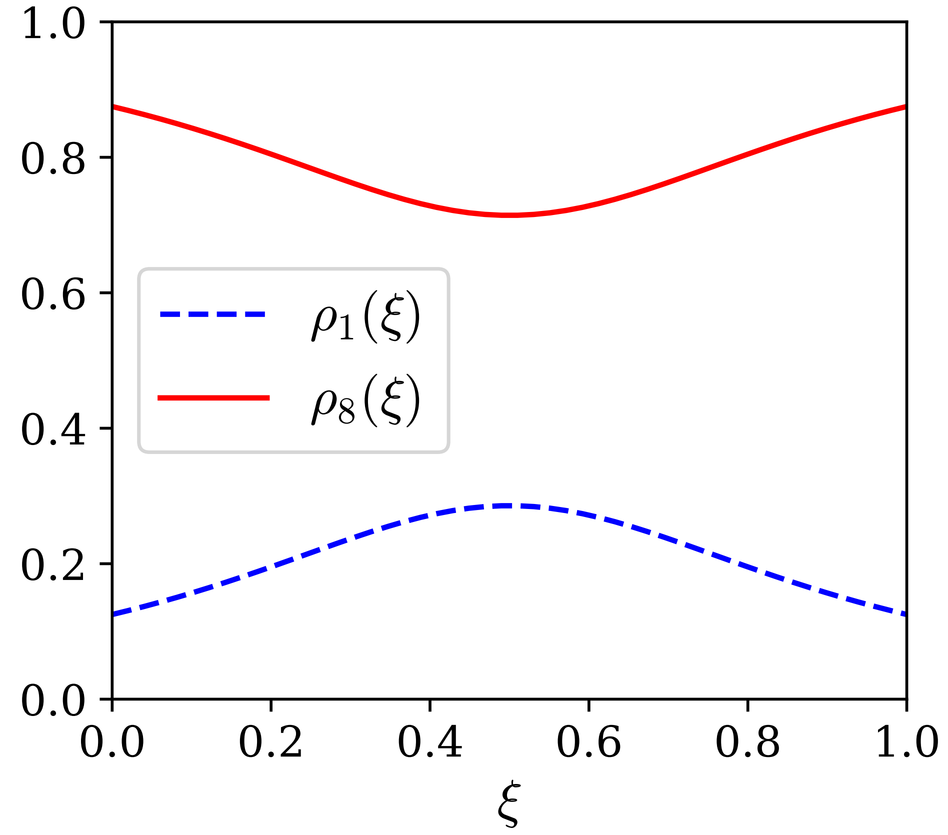
Induced gluon spectrum for $2 \to 2$ in LLA



Liou, Mueller, PRD89, no.7, 074026 (2014)
Peigne, Kolevatov, JHEP01, 141 (2015)
Arleo, Peigne, PRL125, no.3, 032301 (2020)
Arleo, Cougoulic, Peigne, JHEP09, 190 (2020)

Simplification: The induced soft gluon cannot probe the dijet constituents but see their global color state R in LLA (**PDA: Point-like Dijet Approximation**) with $\xi \sim 1/2$:

e.g. $gg \to Q\bar{Q} : \mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$



$$\omega \frac{dI}{d\omega}\bigg|_{2\to 2} = \sum_R \rho_R F_R \frac{\alpha_s}{\pi}\left[\ln\left(1 + \frac{l_{A\perp}^2 E^2}{\omega^2 K_\xi^2}\right) - \mathrm{pp}\right]$$

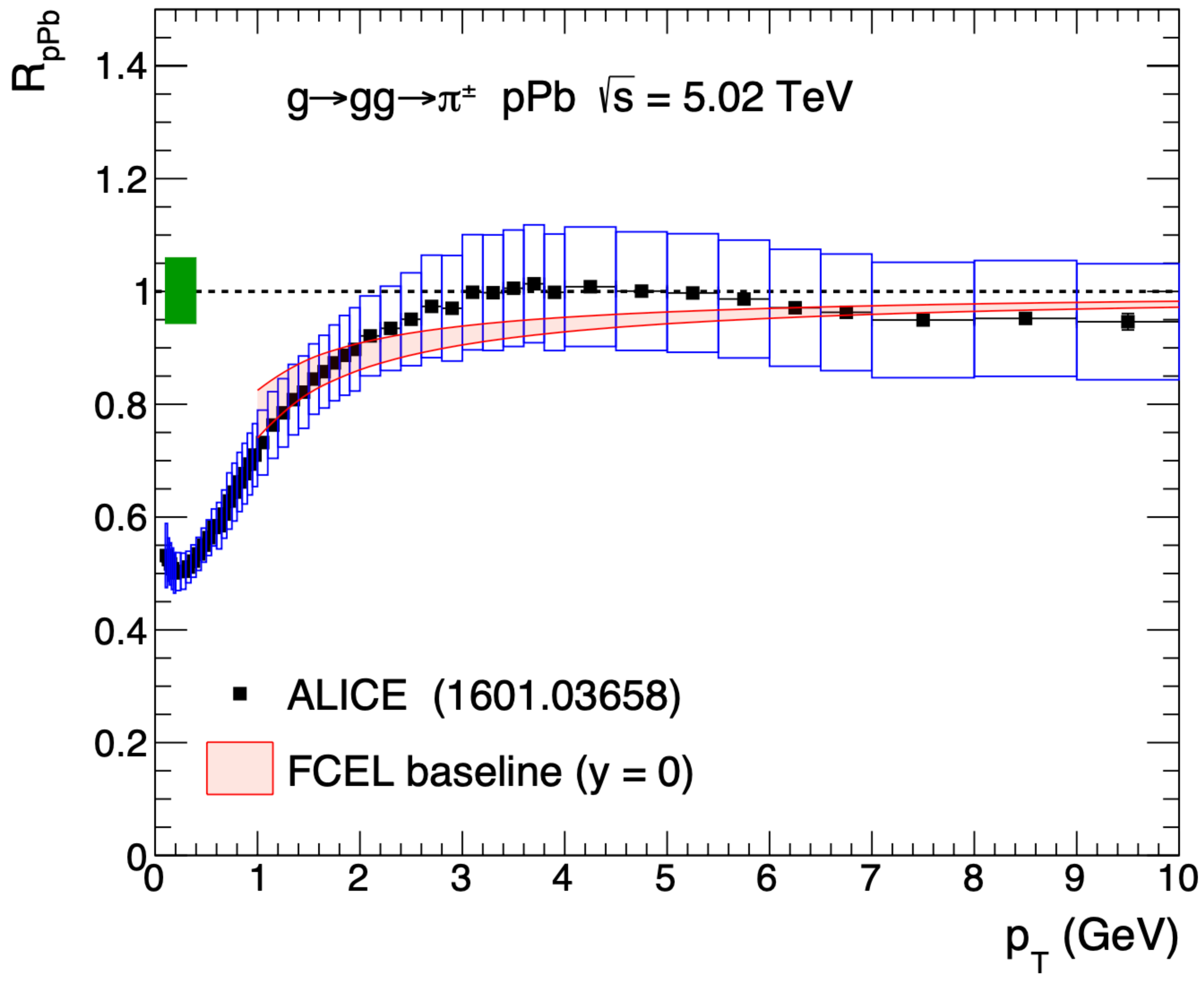
Dijet inv. mass

$F_R = C_1 + C_R - C_2$ with C_R global Casimir charge in R

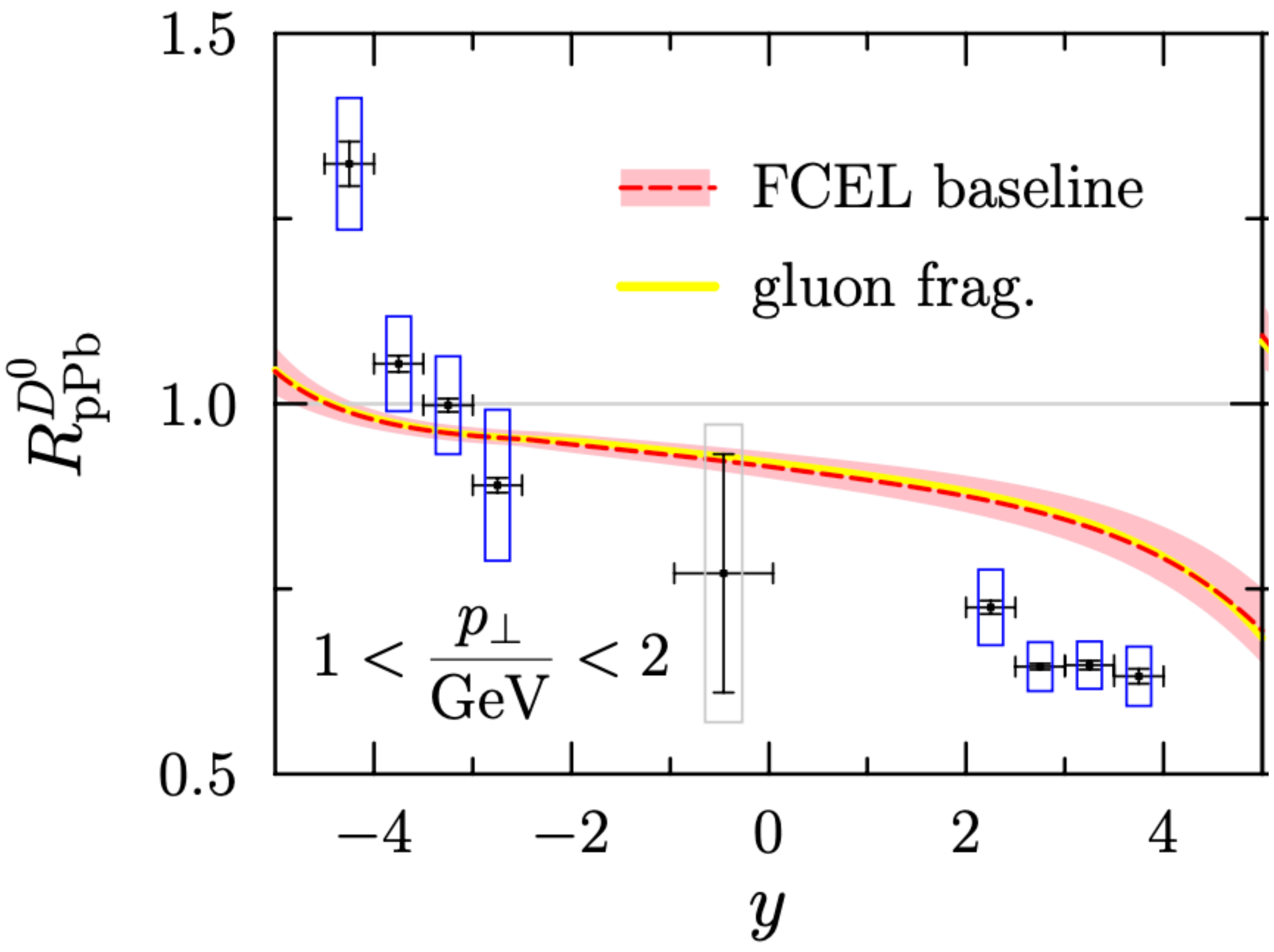
probability for dijet to be produced in color state R

Hadron quenching in LLA (PDA, $\xi = 1/2$)

Arleo, Peigne, PRL125, no.3, 032301 (2020)
Arleo, Cougoulic, Peigne, JHEP09, 190 (2020)



Arleo, Jackson, Peigne, JHEP01, 164 (2022)



❖ Significant suppression even without nuclear shadowing effect

❖ The suppression patterns depend on R of a produced parton pair.

Coherent radiation beyond LLA

G. Jackson, S. Peigné, **KW**, JHEP05, 207 (2024)

The medium-induced soft gluon radiation spectrum for all $2 \to 2$ partonic scattering channels, valid in the full kinematic range $0 \leq \xi \leq 1$.

$$\frac{dI}{dx} = \Phi_{\alpha\beta}\, S(x)_{\beta\alpha} = \mathrm{Tr}\left[\Phi \cdot S(x)\right] \quad \text{with} \quad x = \omega/E$$

Φ : color density matrix

Gauge-invariant matrix that quantifies the color entanglement of the underlying hard $2 \to 2$ scattering amplitude. It is a property of the hard process itself.

S : soft color matrix

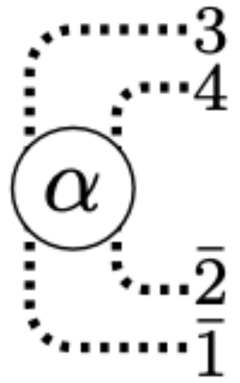
A matrix that describes the soft, medium-induced radiation. It depends on the kinematics (x, ξ) and medium properties.

Matching with LLA results

dI/dx is independent of the color basis, but S can be diagonalized in some basis.

(1) Matching for $\xi = 1/2$: Diagonal in s-channel basis

$$\langle \alpha | = \frac{1}{\sqrt{K_\alpha}}$$

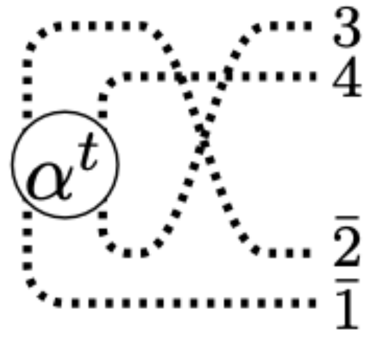


$$\left.\frac{dI}{dx}\right|_{\xi=1/2} = \frac{\alpha_s}{\pi x} \sum_\alpha \Phi^s_{\alpha\alpha} \left(C_1 + C_\alpha - C_2\right) \mathscr{L}_{\xi=1/2}$$

ρ_α : probability of the s-channel irreps. α

(2) Matching in $\xi = 0$ limit: Diagonal in t-channel basis

$$\langle \alpha^t | \equiv \frac{1}{\sqrt{K_{\alpha^t}}}$$

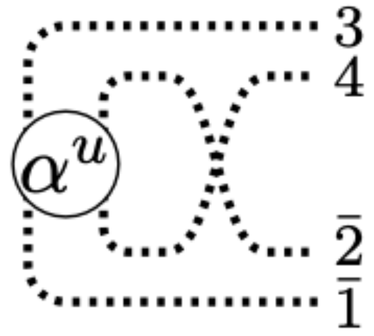


$$\left.\frac{dI}{dx}\right|_{\xi=0} = \frac{\alpha_s}{\pi x} \sum_{\alpha^t} \Phi^t_{\alpha_t\alpha_t} \left(C_1 + C_3 - C_{\alpha^t}\right) \mathscr{L}_{\bar{\xi}=1}$$

$\rho^t_{\alpha^t}$: probability of the t-channel irreps. α_t

(3) Matching in $\xi = 1$ limit: Diagonal in u-channel basis

$$\langle \alpha^u | \equiv \frac{1}{\sqrt{K_{\alpha^u}}}$$

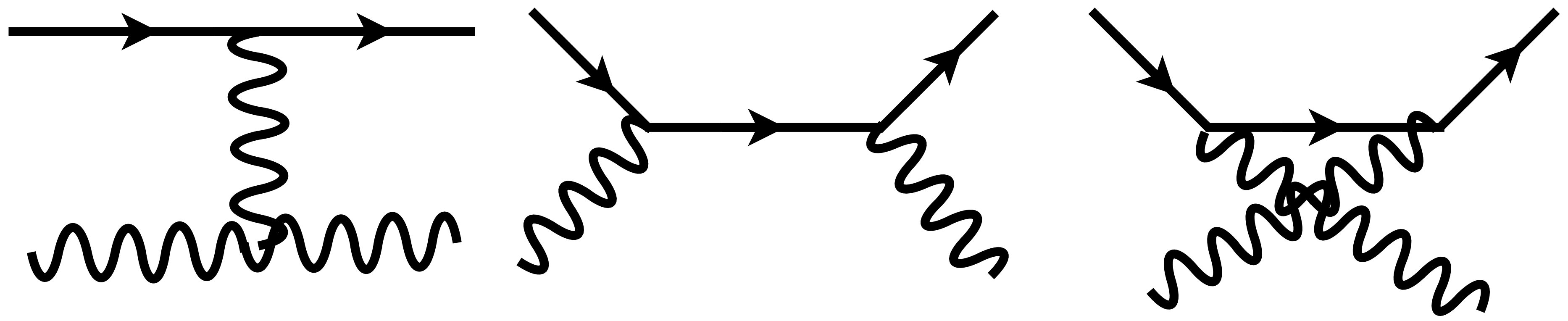


$$\left.\frac{dI}{dx}\right|_{\xi=1} = \frac{\alpha_s}{\pi x} \sum_{\alpha^u} \Phi^u_{\alpha^u\alpha^u} \left(C_1 + C_4 - C_{\alpha^u}\right) \mathscr{L}_{\xi=1}$$

$\rho^u_{\alpha^u}$: probability of the u-channel irreps. α_u

Illustration: Fully Coherent Energy Loss vs. Gain

Quark-gluon scattering processes



$\alpha = (\mathbf{3}, \bar{\mathbf{6}}, \mathbf{15})$ in s,u-channel

$\alpha = (\mathbf{1}, \mathbf{8})$ in t-channel

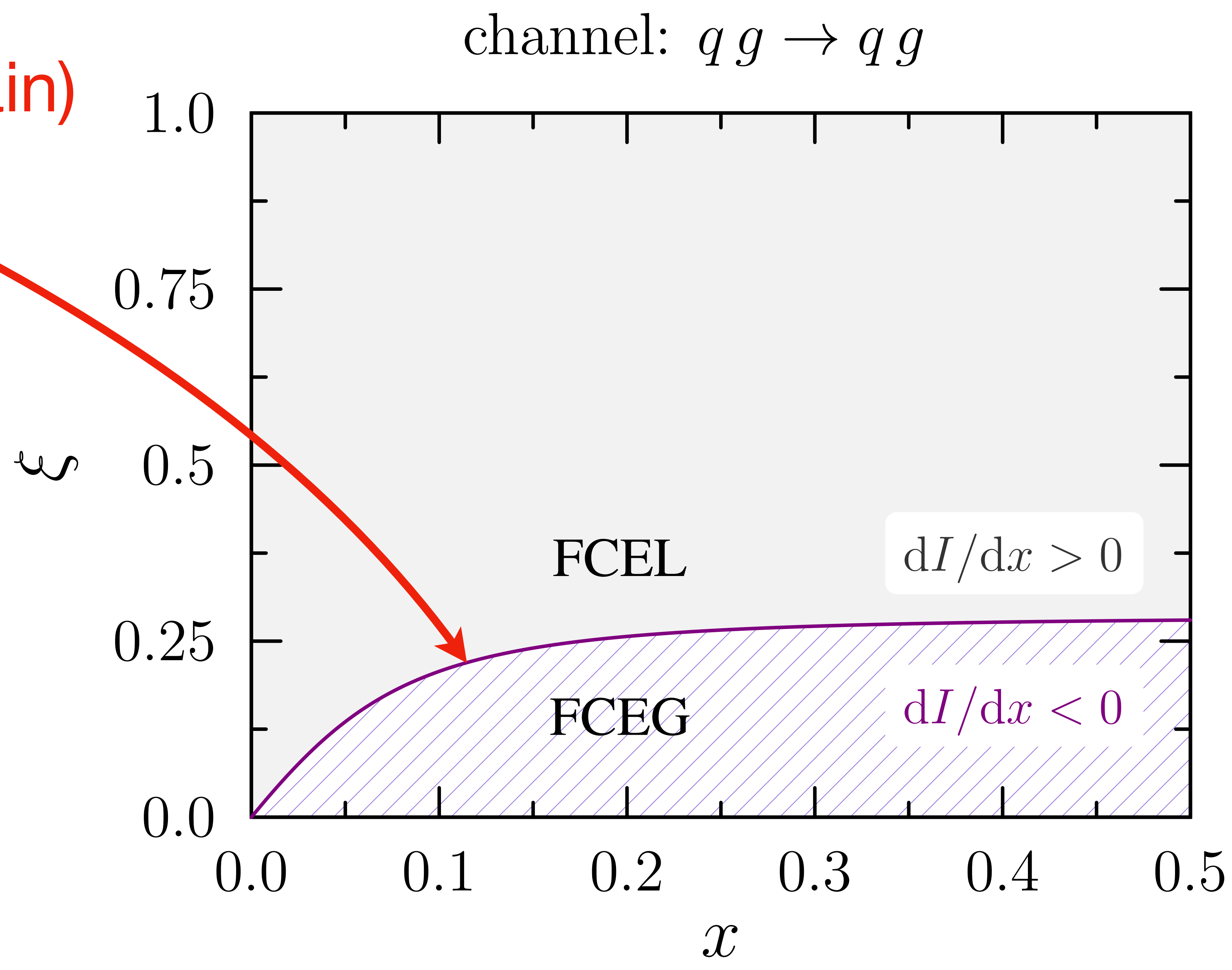
$$\left.\frac{dI^{2\to2}}{dx}\right|_{\xi=1/2} = \frac{\alpha_s}{\pi x}\left[\rho_3\, C_3 + \rho_{\bar{6}}\, C_{\bar{6}} + \rho_{15}\, C_{15}\right] \mathscr{L}_{\xi=1/2}$$

$$\left.\frac{dI^{2\to1}}{dx}\right|_{\xi=0} = \frac{\alpha_s}{\pi x}\left[\rho_1^t\,(2C_F) + \rho_8^t\,(2C_F - N_c)\right] \mathscr{L}_{\bar{\xi}=1}$$

$$\left.\frac{dI^{2\to1}}{dx}\right|_{\xi=1} = \frac{\alpha_s}{\pi x}\left[\rho_3^u\, N_c + \rho_{\bar{6}}^u\; - \rho_{15}^u\right] \mathscr{L}_{\xi=1}$$

$$\mathscr{L}_\xi \approx \log\left(1 + \frac{\xi^2 l_{A\perp}^2}{x^2 m_\perp^2}\right) - \mathrm{pp}$$

No energy loss (and gain) at the boundary



$l_{\perp A} = m_\perp/4,\ l_{\perp p} = m_\perp/10$

G. Jackson, S. Peigné and **KW**, JHEP05, 207 (2024) and [arXiv:2504.16647 [hep-ph]]

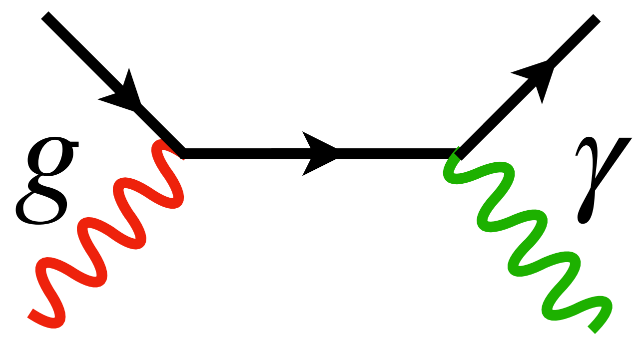
- The negative spectrum is not unphysical; we can interpret it as energy gain.
- We could construct a quenching weight from the new spectrum.

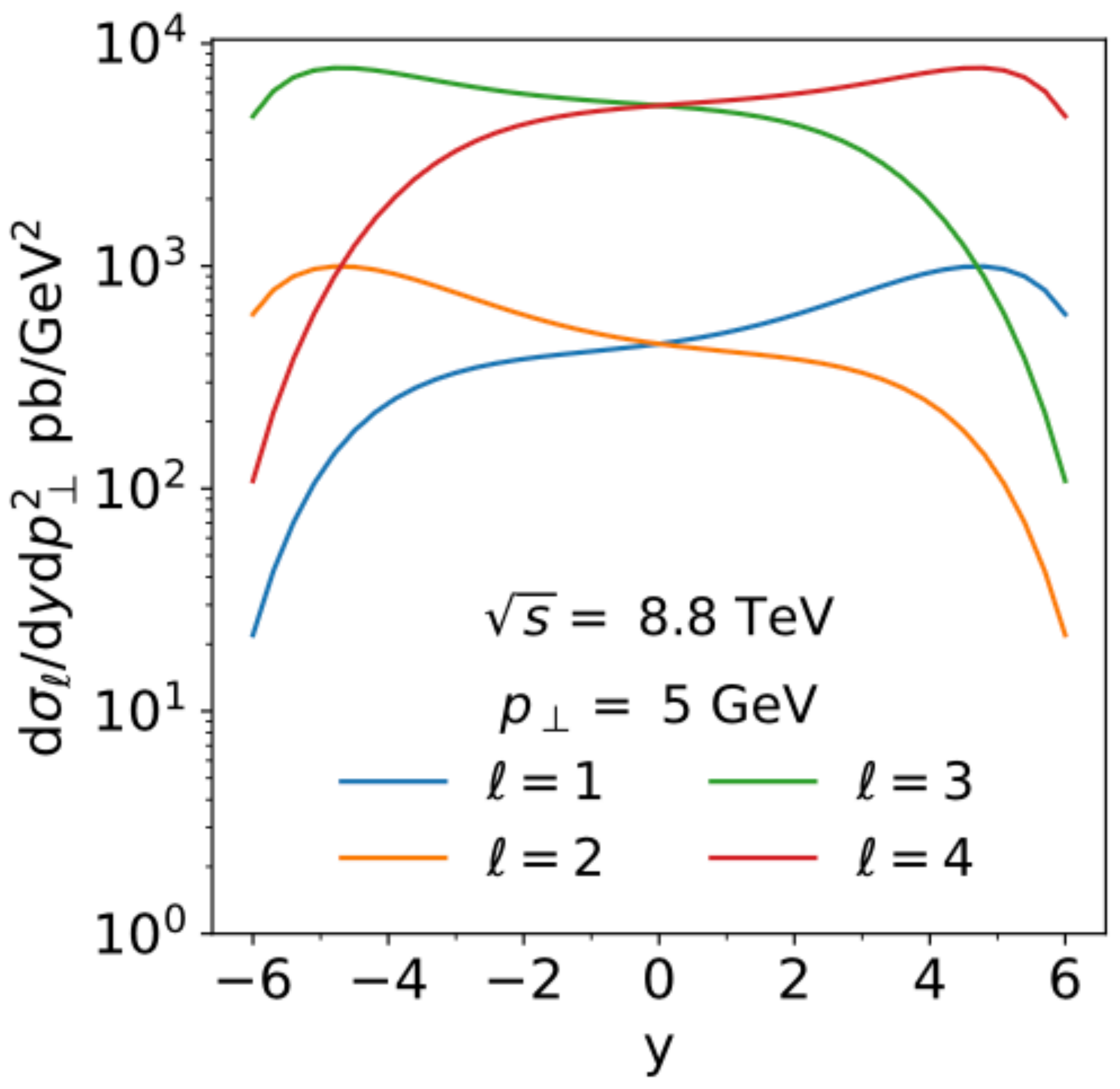
Photon production and FCEG

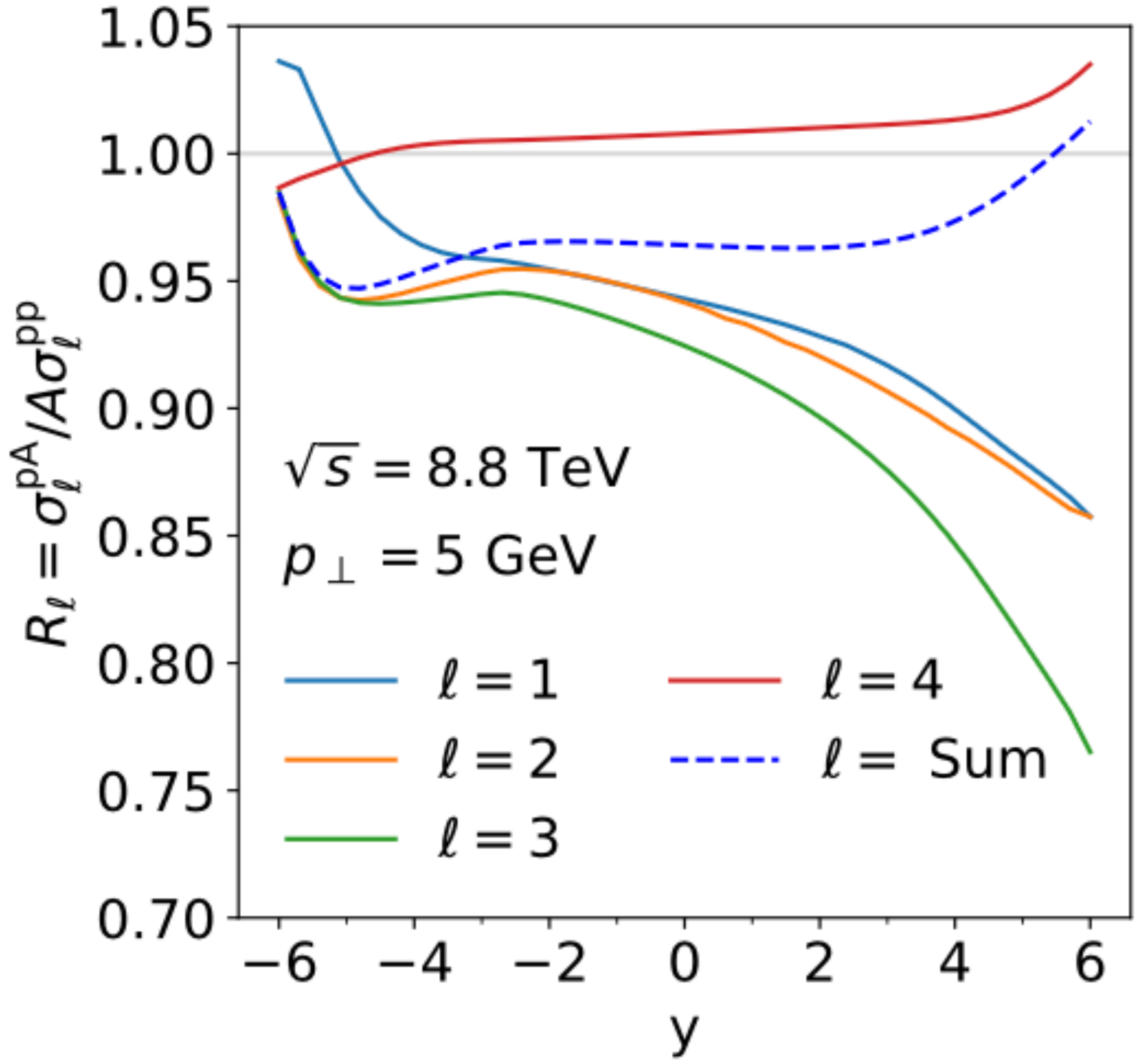
F. Arleo, D. Bourgeais, M. Guilbaud, G. Jackson and V. V. Torres, [arXiv:2512.02640 [hep-ph]].

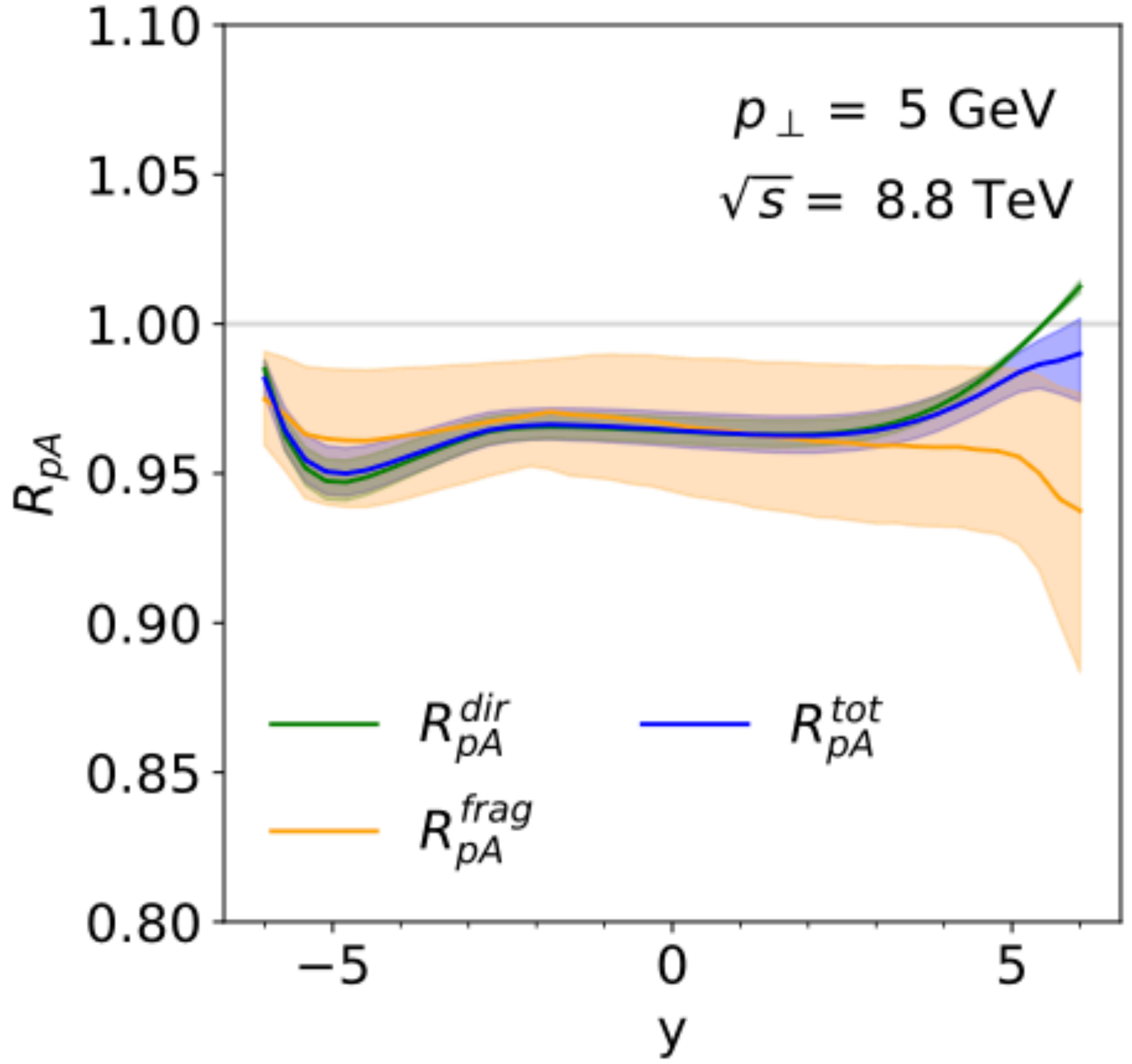
ℓ	Process	R	C_ℓ
1	$q\bar{q} \to g\gamma$	**8**	N_c
2	$\bar{q}q \to g\gamma$	**8**	N_c
3	$gq \to q\gamma$	**3**	N_c
4	$qg \to q\gamma$	**3**	$-1/N_c$

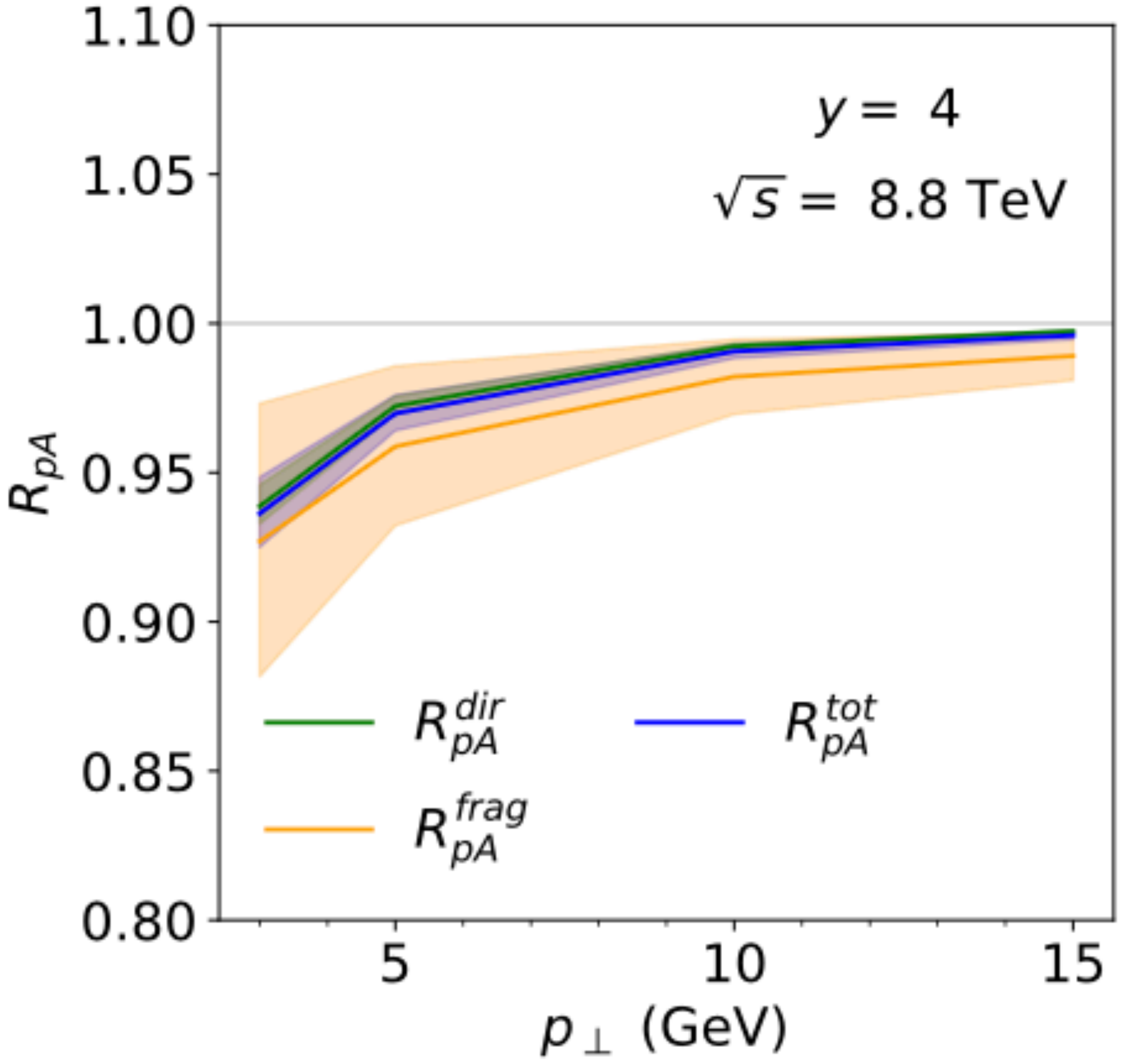
FCEG





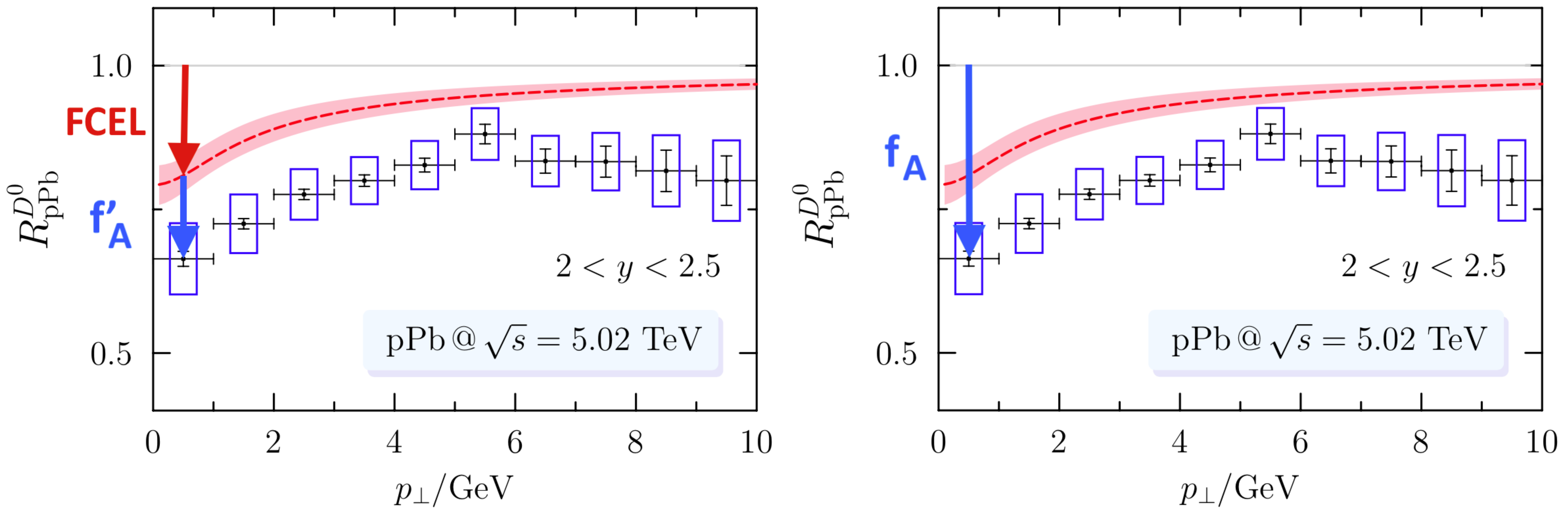




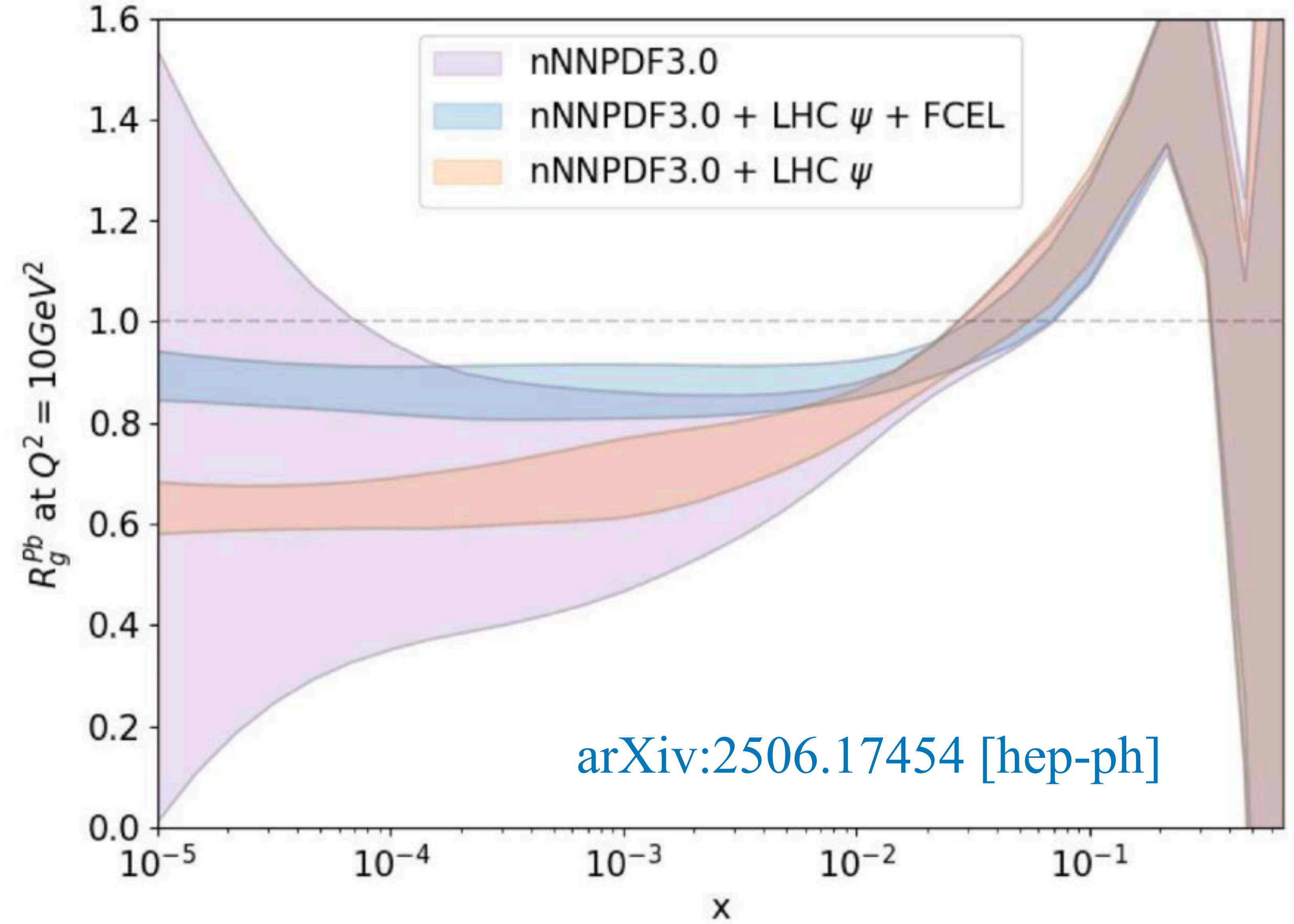


Perspectives

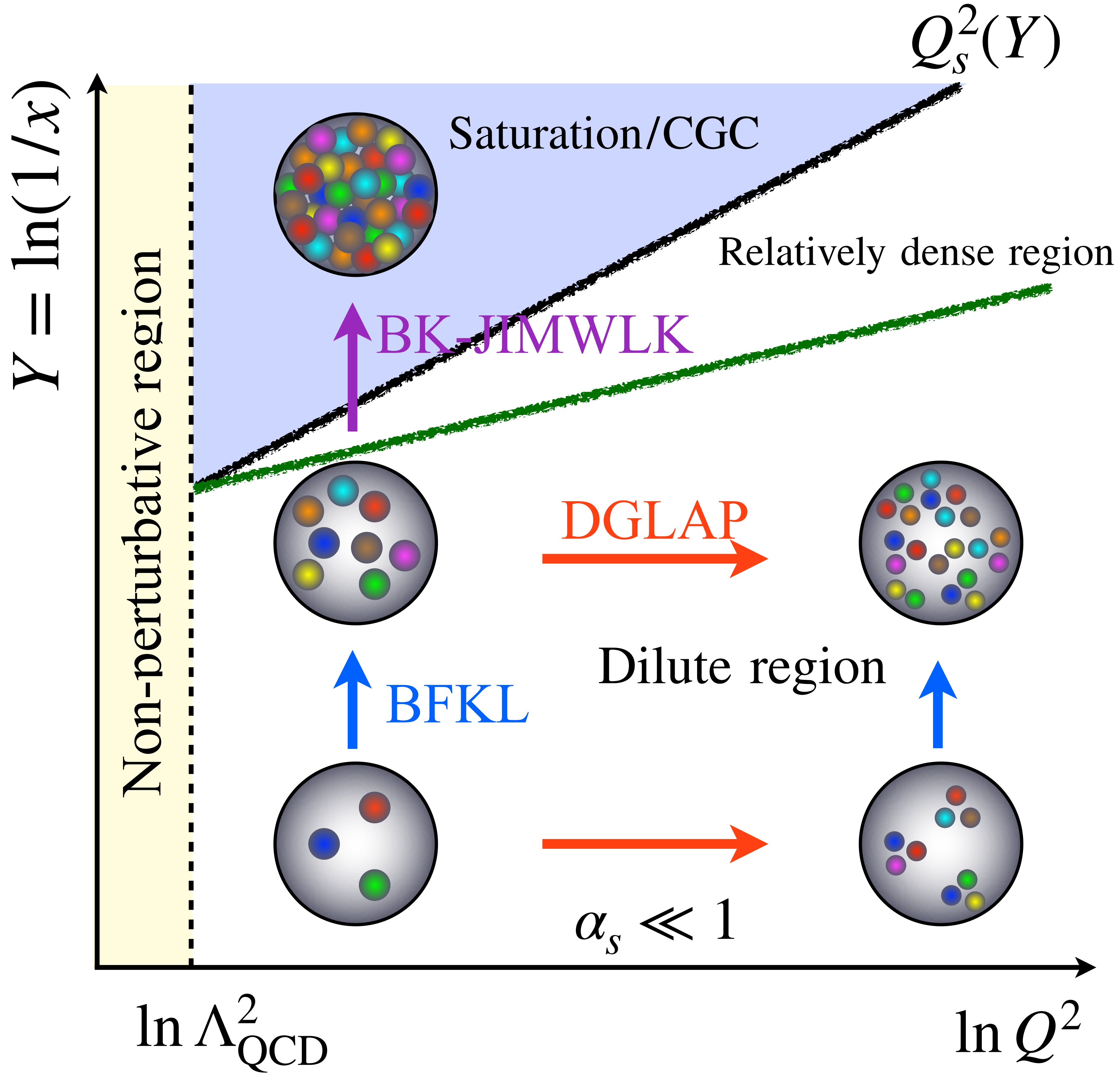
Biased nPDFs



- $\chi^2(f'_A \,|\,$ FCEL $\cap$ LHCb$)$ vs. $\chi^2(f_A \,|\,$ no FCEL $\cap$ LHCb$)$
- nPDFs can be reweighed by implementing both FCEL and nPDFs.



Color Glass Condensate (CGC): Dense gluonic matter



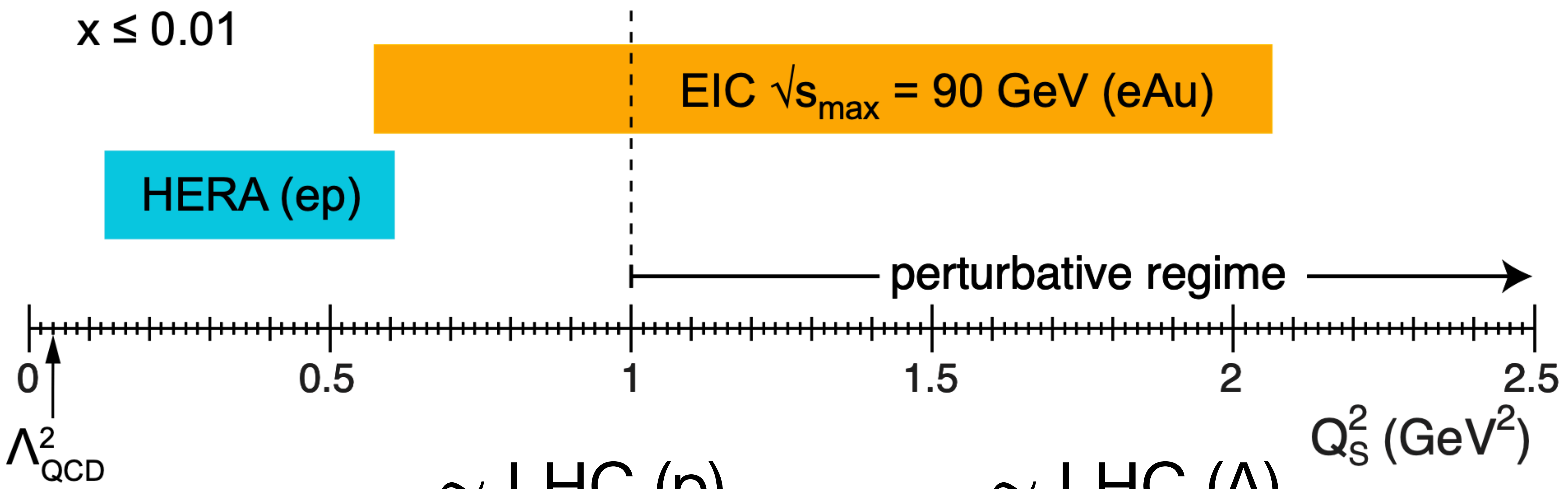
- QCD predicts that **ANY** hadrons and nuclei become a dense gluonic state, the so-called **Color-Glass-Condensate (CGC)**, at extremely high energy.

- In the CGC state, the gluon density inside nuclei is saturated, resulting in unique saturation phenomena.

Dynamical saturation scale:

$$Q^2_{sA} = \frac{Axf_{g/A}(x)}{S_\perp} \propto A^{1/3}x^{-0.3} \gg \Lambda^2_{QCD}$$

for heavier nuclei $A^{1/3} \sim 6$ (Pb, Au)



~ LHC (p) ~ LHC (A)

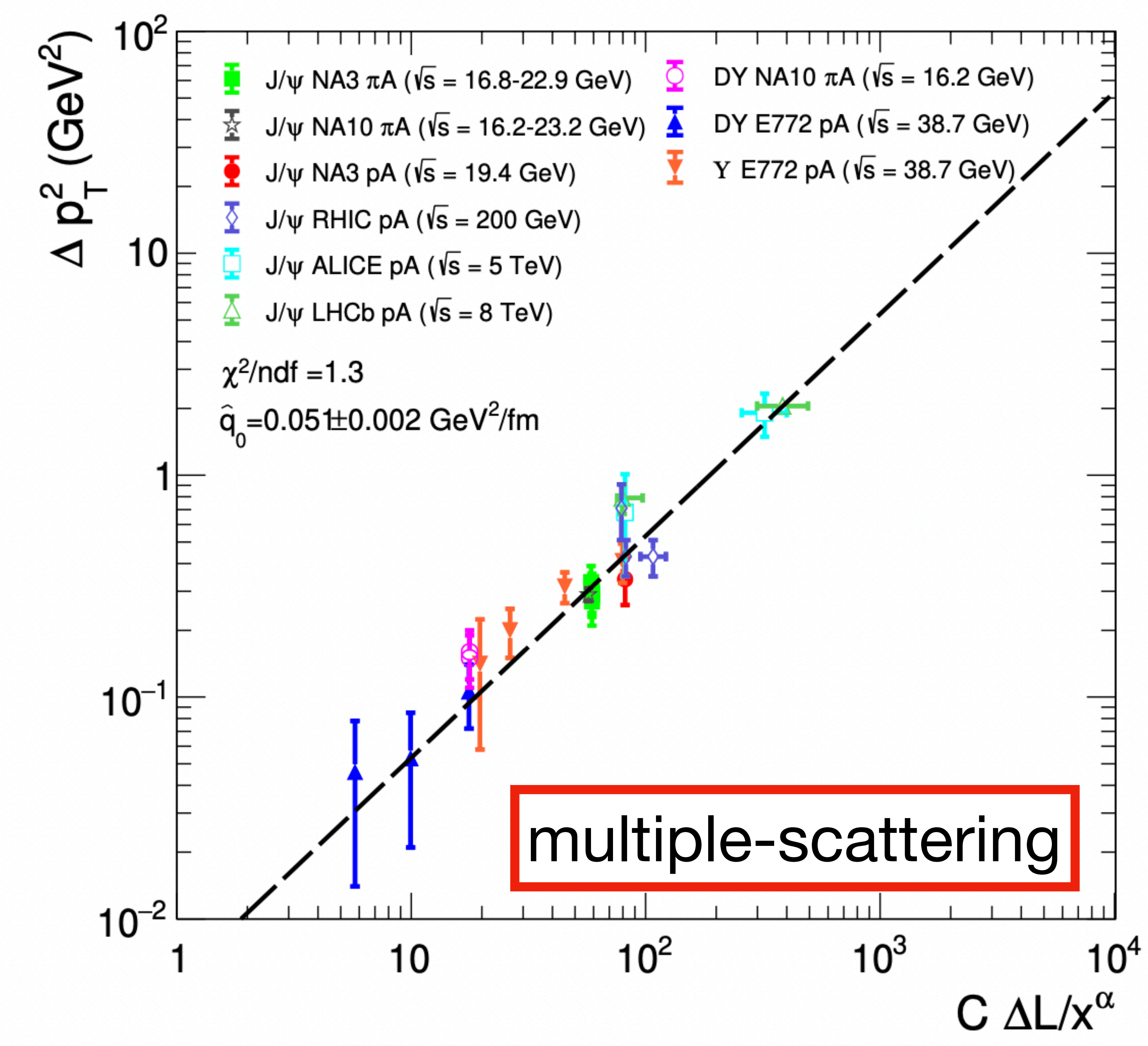
Remark on $\hat{q}$ and p_T broadening

$$\Delta\langle p_T^2\rangle_{pA} = \langle p_T^2\rangle_{pA} - \langle p_T^2\rangle_{pp} = \hat{q}(x)L_A \sim Q_{sA}^2$$

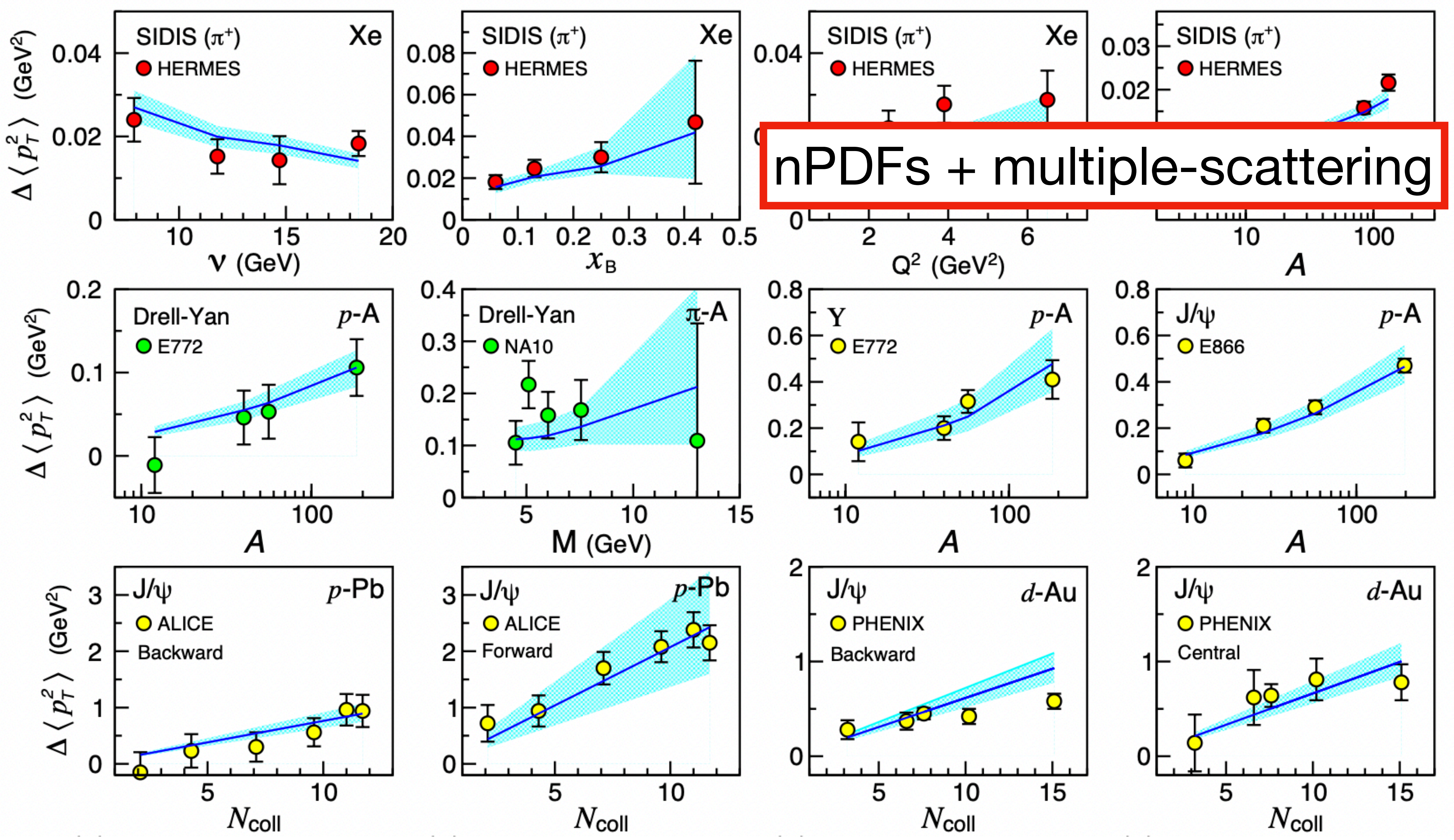
Baier, Dokshitzer, Mueller, Peigne and Schiff, NPB484, 265 (1997)
Liou, Mueller, and Wu, NPA916, 102 (2013)
Blaizot and Mehtar-Tani, NPA929, 202 (2014)

Conjecture in the small-x limit

Arleo and Naïm, JHEP07, 220 (2020)



Ru, Kang, Wang, Xing and Zhang, PRD103, no.3, L031901 (2021)



- $\hat{q}(x) \propto x^{-\alpha}$ with $\alpha = 0.25$-0.30 describes various data **from large-x to small-x.**
- Premature to conclude that the nonlinear saturation effect is seen. BFKL evolution could be seen.

Summary

- FCEL(G) is significant for all hadron production, including heavy flavors, in pA collisions at all energies. Meanwhile, Drell-Yan (IS) and SIDIS (FS) are still sensitive to LPM effect.

$$\Delta E_{\text{FCEL}} \sim \alpha_s \frac{\sqrt{\hat{q}L}}{Q_{\text{hard}}} E \gg \Delta E_{\text{LPM}} \sim \alpha_s \hat{q} L^2$$

- **Findings from pheno study**: FCEL should be more significant for particle production in pA collisions from low to high collision enegies.
- **Other theoretical developments**: In-medium DGLAP evolution kernal, renormalization group approach.
- **Outlook:** Saturation hunting and extracting precise information on nPDFs.
- **Puzzle**: Jet quenching and flow in small systems (not discussed in this talk).

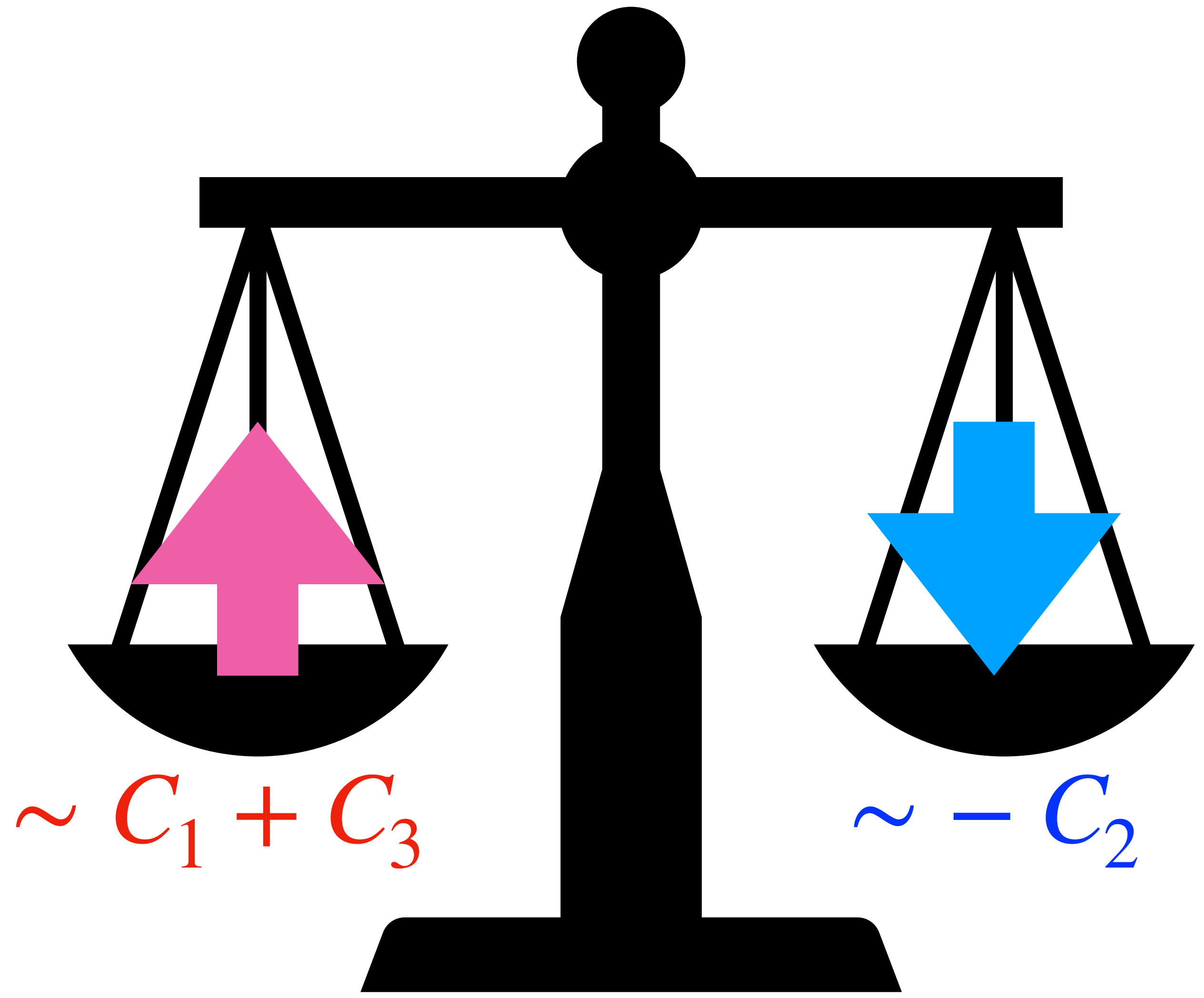
Thank you!

Backup

What is energy gain?

The "**induced**" spectrum $\frac{dI}{dx}$ is not positive definite, as it is the difference between radiation in pA and pp. A negative value means the projectile incurs less radiation within the nuclear target than it would in a vacuum.

Medium enhances abelian-like radiation (narrow radiation cone $\theta_s = q_\perp / E$)



When the reduction in non-abelian radiation ($\theta > \theta_s$) outweighs the increase in abelian radiation, the net induced spectrum is negative.

FCEG is a direct consequence of coherent, medium-induced radiation allowed by first principles.

Reference frame

❖ Hadron rest frame: $P^\mu = (M,0,0,0)$

❖ Infinite momentum frame (IMF): $P \gg M \Longrightarrow P^\mu = (P,0,0,P)$

In IMF, partonic picture is manifest. PDFs are number densities.

❖ Light-cone coordinate: $x^\pm = (t \pm z)/\sqrt{2}$

❖ Light-cone momentum: $p^\pm = (E \pm p_z)/\sqrt{2}$

❖ Rapidity: $y = \frac{1}{2} \ln \left(\frac{p^+}{p^-} \right)$

❖ "Longitudinal" momentum fraction: $x = k^+/P^+$

In IMF, $P^\mu \to (P^+,0^-,0_\perp)$

If $P^\mu = (P,0,0,-P)$, $P^\mu \to (0^+,P^-,0_\perp)$