Nuclear suppression of forward heavy flavor production from fully coherent energy loss

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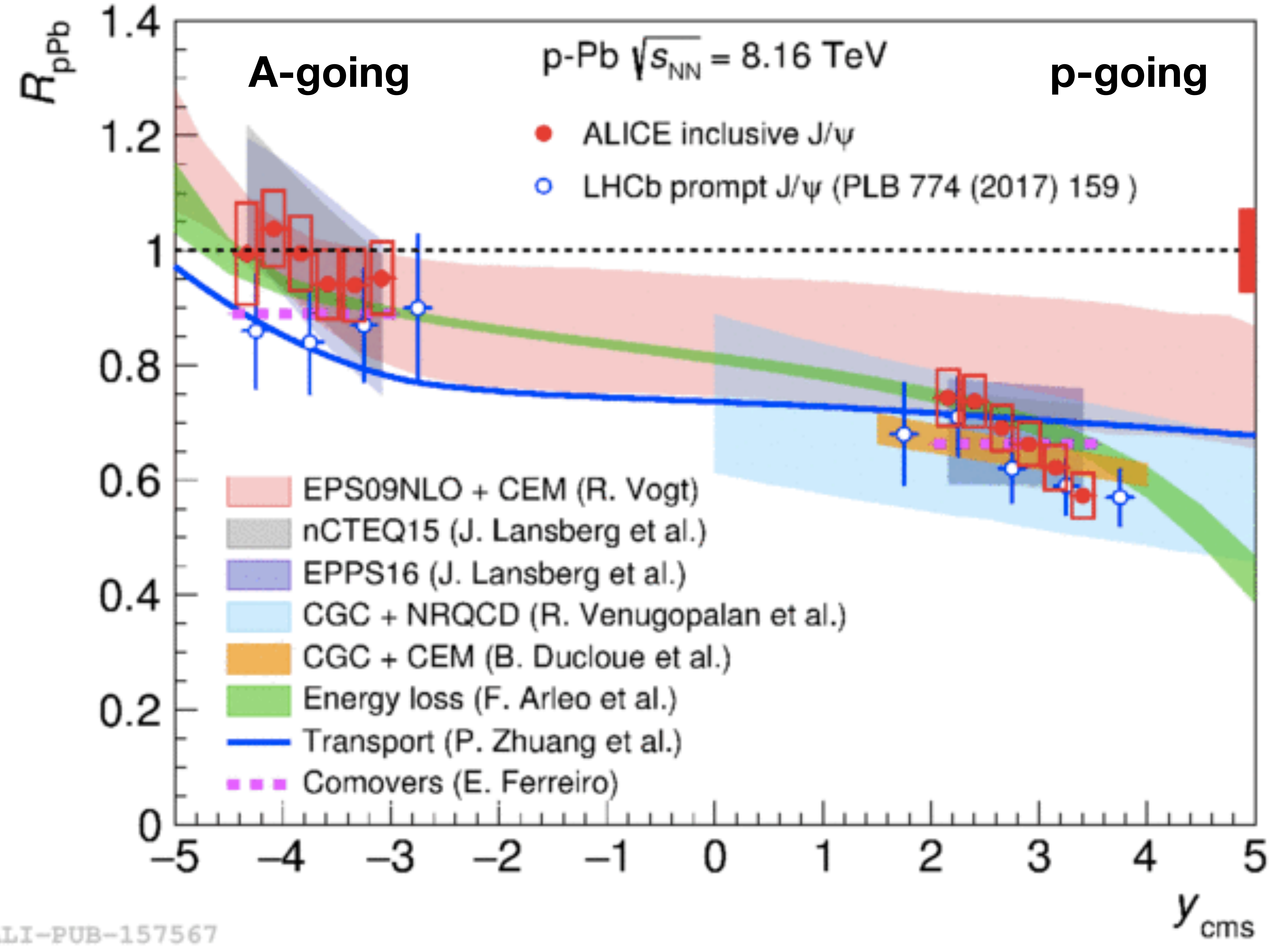
and Forward Calorimeter Upgrade in ALICE
@Tsukuba, March 13, 2023

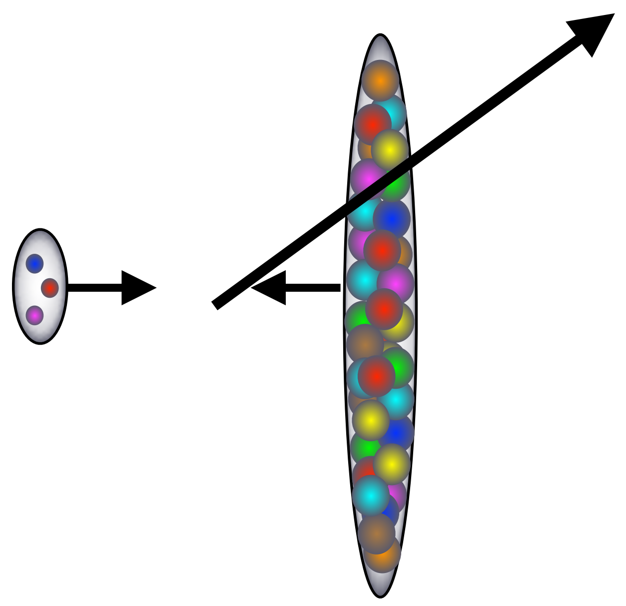
Heavy flavor production in forward pA collisions

Nuclear modification factor:

$$R_{pA} = \frac{1}{A}\frac{d\sigma_{pA}}{d\sigma_{pp}}$$

ALICE-PUB-157567





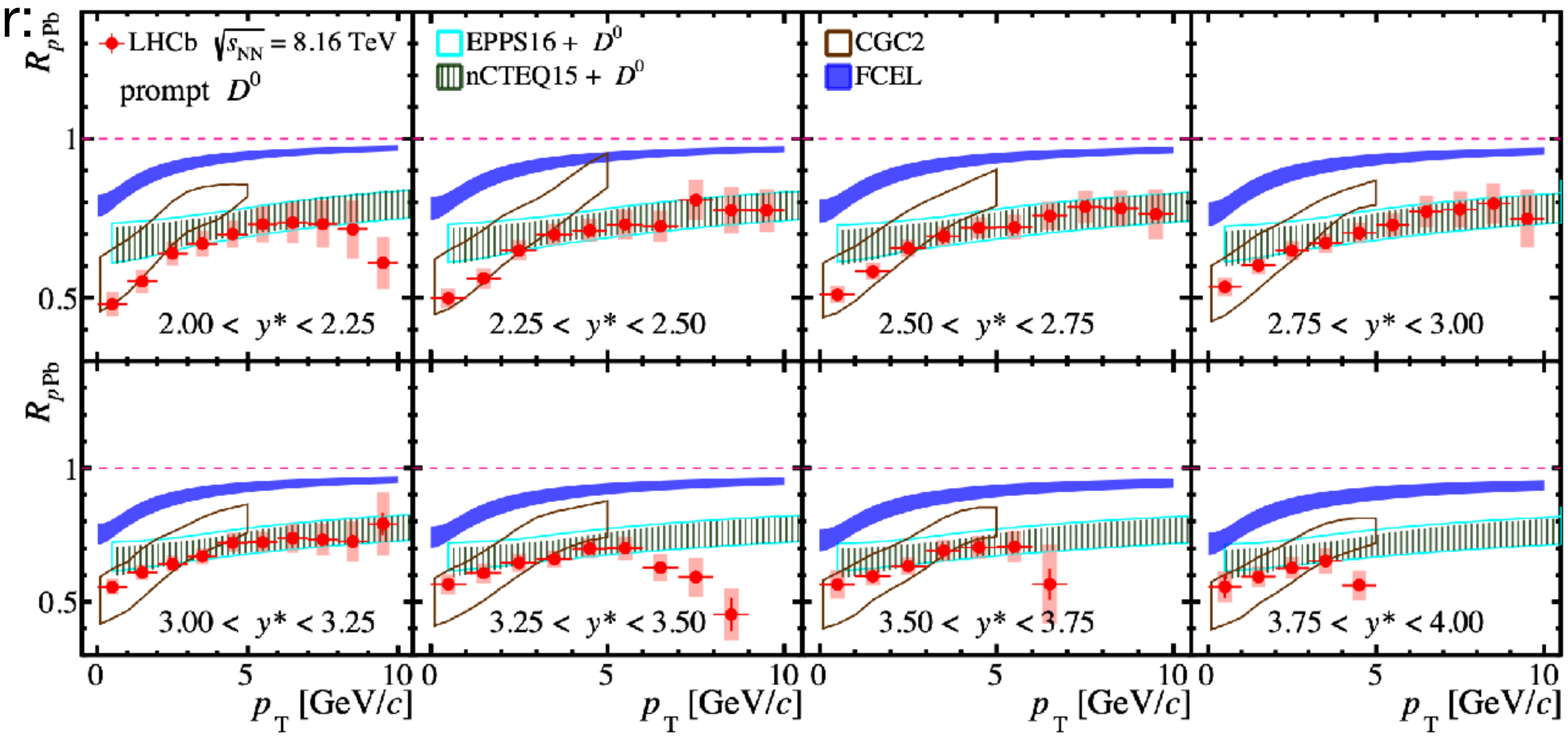
- Nuclear suppression of forward heavy flavor production (J/ψ, D,…) in pA collisions at the LHC measured by ALICE, LHCb
- Issue: how to understand the data?

Heavy flavor production in forward pA collisions

LHCb collaboration, [arXiv:2205.03936 [nucl-ex]].

Nuclear modification factor:

$$R_{pA} = \frac{1}{A}\frac{d\sigma_{pA}}{d\sigma_{pp}}$$



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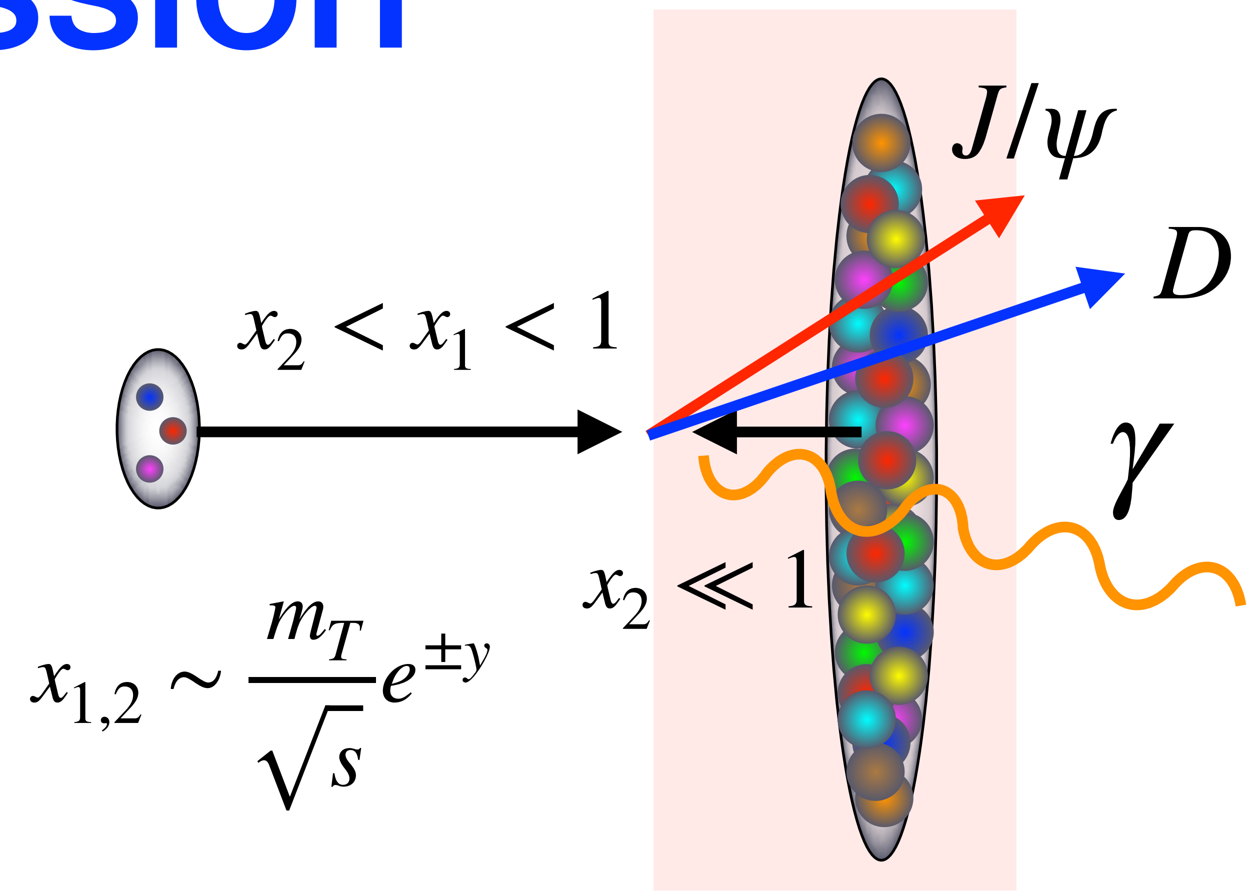
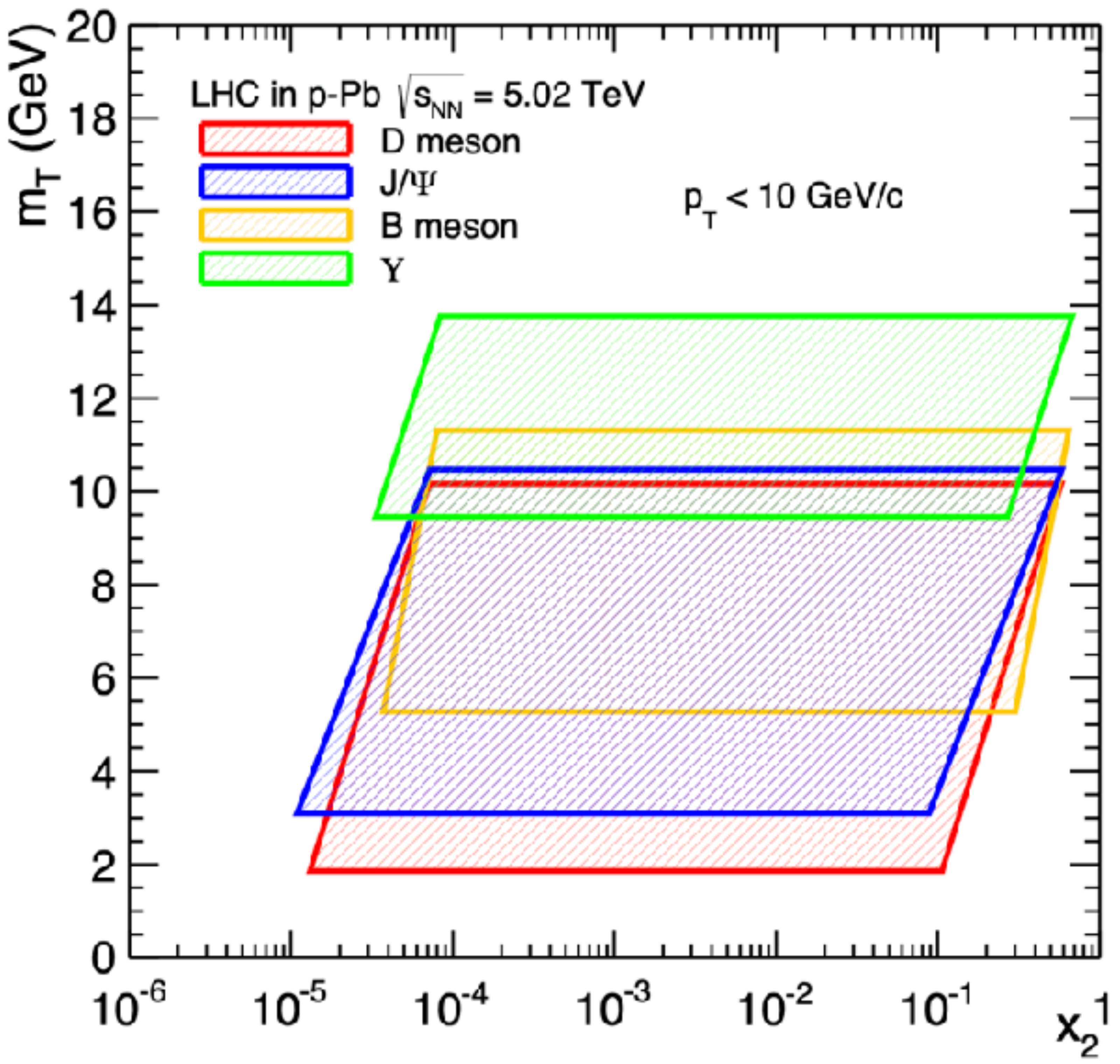
- Issue: how to understand the data?

Possible origins of the nuclear suppression



- Shadowing of nuclear parton distribution functions (nPDFs) at small Bjorken-x (forward: p-going)
- Coherent energy loss effect in nuclear medium
- Gluon saturation effect
- … or all of them



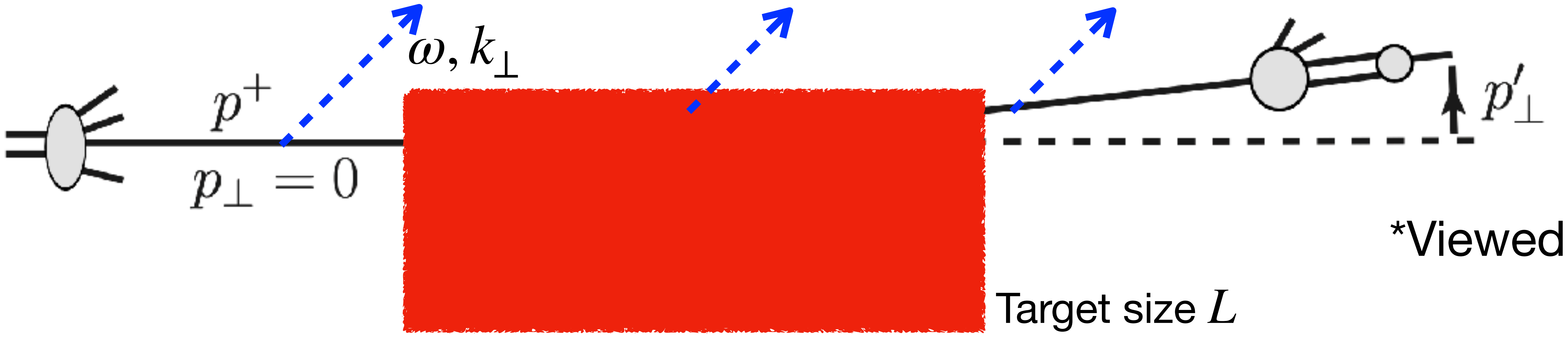
Heavy flavor production, sensitive to gluons in the target, helps us disentangle distinct cold nuclear matter (CNM) effects at the LHC.

This talk → coherent energy loss, predicted from first principle.

Saturation: Talk by Fujii (Mon, 13)

Energy loss in pA collisions (1/2)

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



*Viewed in target rest frame

Soft gluons are induced in pA collisions due to multiple scatterings of the fast parton in the target nucleus. → energy loss!

Three regimes depending on the gluon formation time t_f:

- Bethe-Heitler regime: $t_f \sim \omega/k_\perp^2 < \lambda$
- Landau-Pomeranchuk-Migdal (LPM) regime: $\lambda \ll t_f \ll L$
- Fully coherent (Long formation time) regime: $L \ll t_f$

λ**:** parton mean free path in medium

Energy loss in pA collisions (2/2)

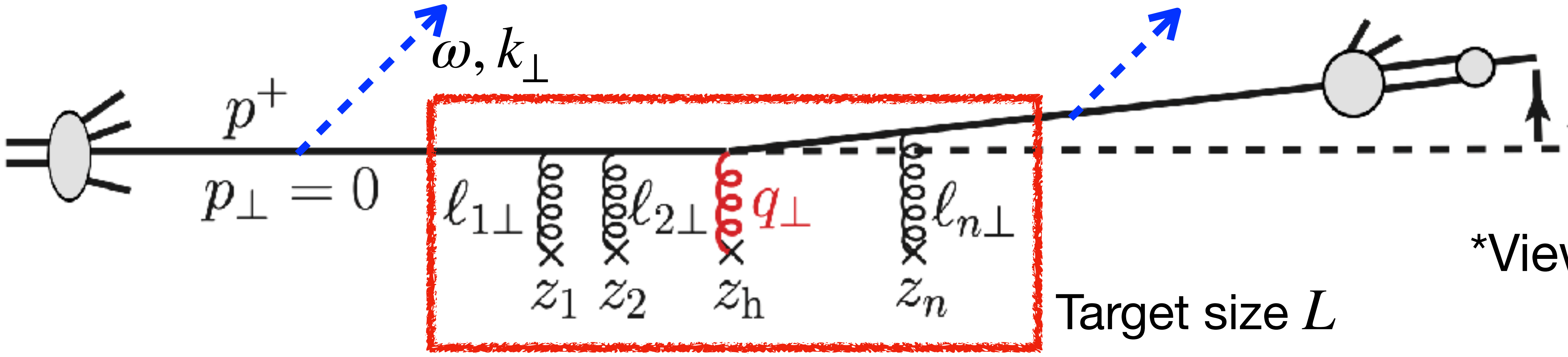
Peigne, Smilga, Phys. Usp. 52, 659 (2009)

- Bethe-Heitler regime: $k^+ \ll \mu^2 \lambda$
  - Each scattering center acts as an independent source of radiation
  - μ: typical transverse momentum exchange in a single scattering
- Landau-Pomeranchuk-Migdal (LPM) regime: $\mu^2 \lambda \ll k^+ \ll \hat{q} L^2$
  - Energetic parton is suddenly produced in medium
  - A group of t_f / λ scattering centers acts as a single radiator
  - $\hat{q} = \mu^2 / \lambda$: transport coefficient in cold nuclear medium
- Fully coherent (Long formation time) regime: $\hat{q} L^2 \ll k^+$
  - Energetic parton crosses medium.
  - All scattering centers act as a source of radiation (fully coherent over medium)

→ important for forward hadron production

Setup and parametric dependence of FCEL

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



$l_\perp \sim \sqrt{\hat{q}L} \ll q_\perp, p'_\perp$

*Viewed in target rest frame

One hard scattering + multiple soft scattering

- Fully coherent E-loss (FCEL) effect for large formation time $t_f \gg L$

$$\Delta E_{\rm FCEL} = \int_0^E d\omega \, \boxed{\omega \frac{dI}{d\omega}} \sim \alpha_s \frac{\sqrt{\hat{q}L}}{Q_{\rm hard}} E$$

Induced gluon spectrum

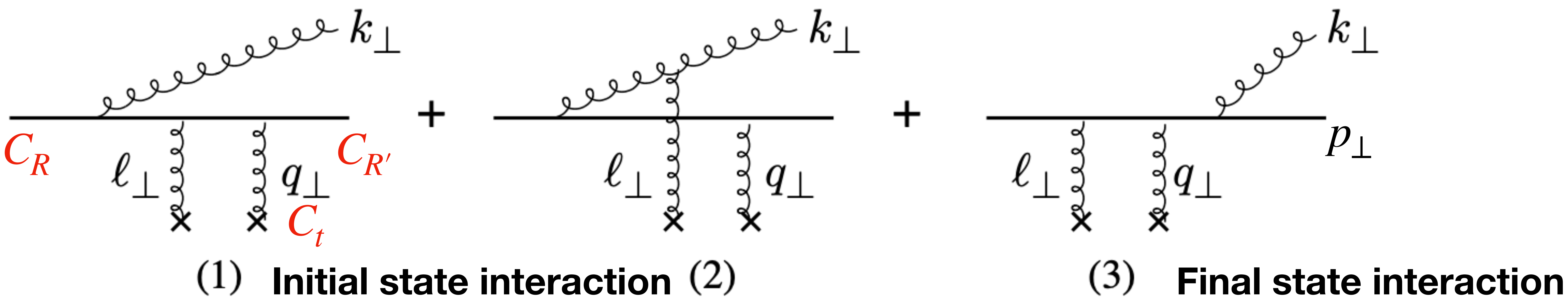
- Landau-Pomeranchuk-Migdal (LPM) effect for small formation time $t_f \lesssim L$

$$\boxed{\Delta E_{\rm FCEL} \gg \Delta E_{\rm LPM}} \sim \alpha_s \hat{q} L^2$$

cf. jets in QGP

Baier, Dokshitzer, Mueller, Peigne, Schiff, NPB484, 265 (1997), Zakharov, JETP Lett.63, 952 (1996),….

Induced gluon spectrum for $1 \to 1$ processes



- "Induced" gluon spectrum is obtained from first principle, and given by interference terms: Re(initial final*)

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

Only initial or final state radiation: power corrections

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

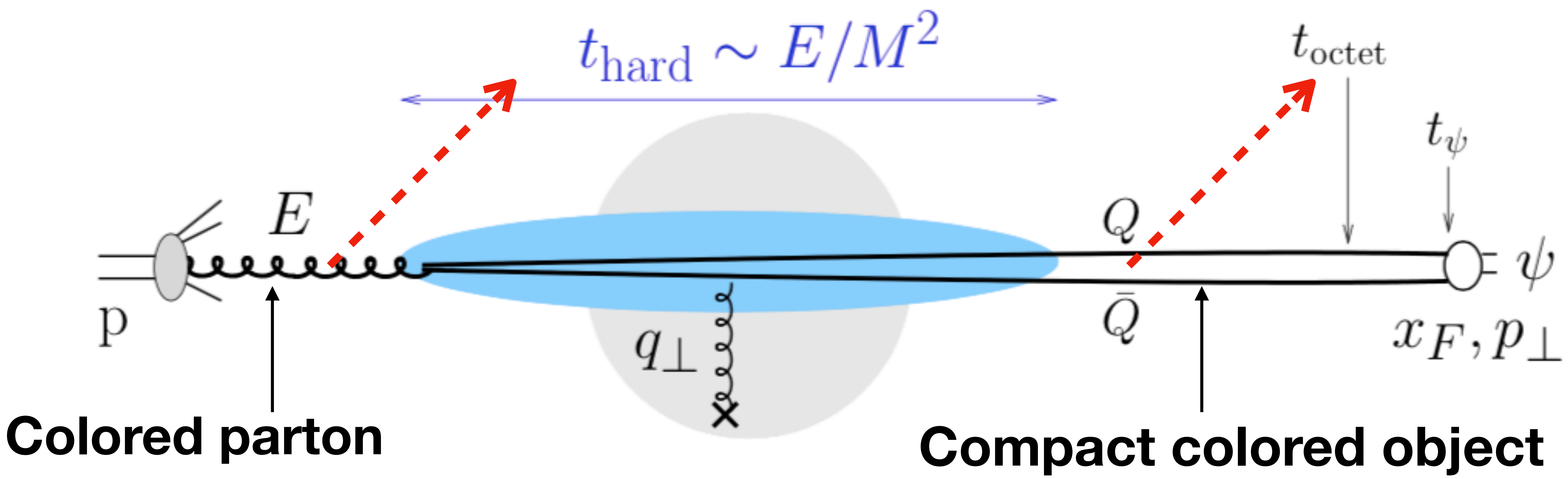
e.g.) $g \to g$: $F_c = N_c + N_c - N_c = N_c$

$q \to g$: $F_c = C_F + N_c - C_F = N_c$

…

Arleo, Peigne, Sami, PRD83, 114036 (2011)
Peigne, Arleo, Kolevatov, PRD93, no.1, 014006 (2016)
Munier, Peigne, Petreska, PRD95, no.1, 014014 (2017)

Model for phenomenology



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

Both initial and final state particle must be colorful, otherwise $F_c = 0$; $c\bar{c}[1]$ shows no suppression.

Quarkonium is assumed to be produced via $gg \to c\bar{c}[8]$:

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

Energy shift (rapidity shift) due to FCEL

Normalized quenching weight in double-log approximation (DLA):

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

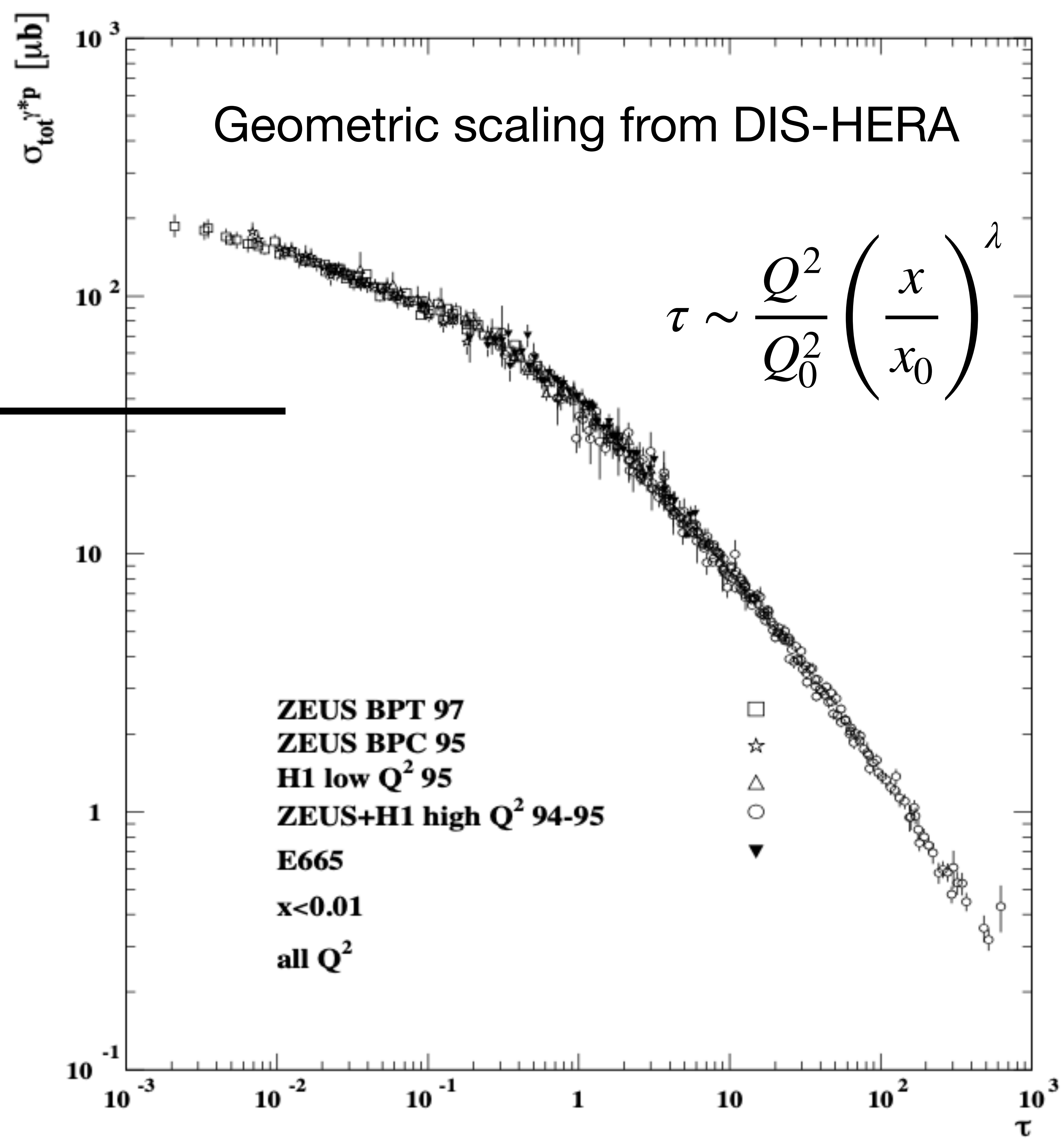
cf. Baier, Dokshitzer, Mueller, Schiff, JHEP09, 033 (2001)

Transport coefficient

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

$$\hat{q} \simeq \frac{4\pi^2\alpha_s C_R}{N_c^2 - 1}\rho x f_{g/A}(x) = \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$$

- ρ: target nucleon number density
- $xf_{g/A}$: gluon density of the nucleus
- C_R: Casimir charge of parton in R
- $\hat{q}_0$: to be fixed by fitting data
- QCD evolution is not considered for simplicity
- L: determined by Glauber theory



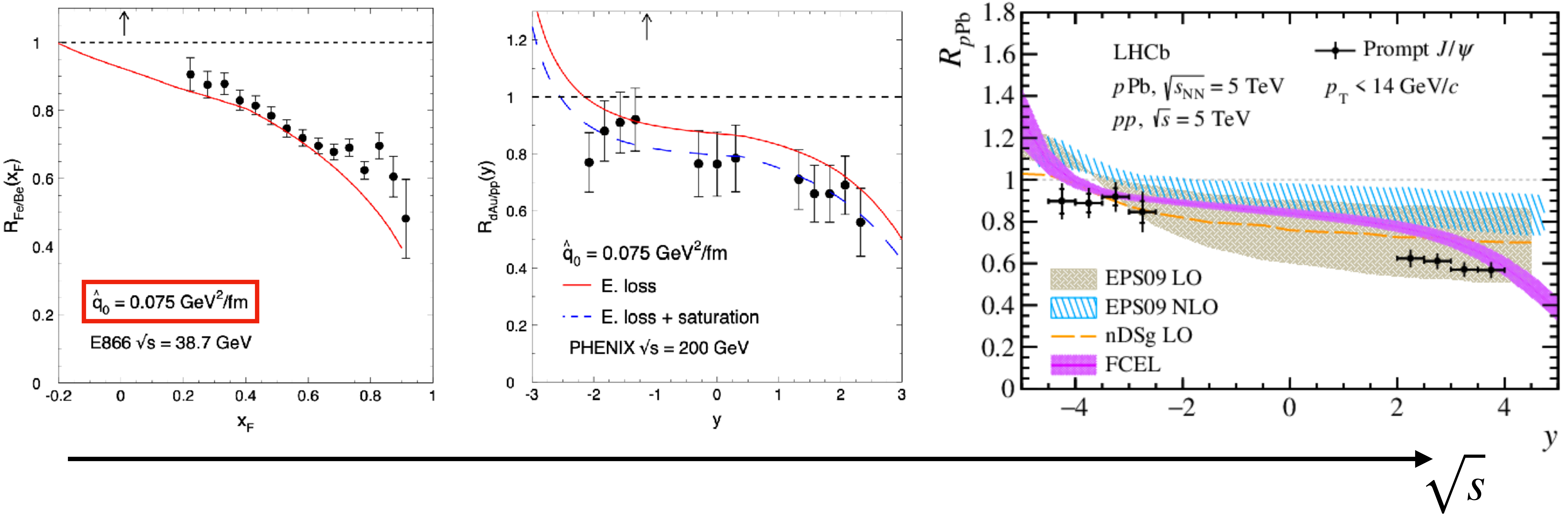
Golec-Biernat and Wusthoff, PRD59, 014017 (1998), PRD60, 114023 (1999)
Stasto, Golec-Biernat, Kwiecinski, PRL86, 596 (2001)

- 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)

Theory vs. data on J/ψ production

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

Aaij et al. [LHCb], JHEP11, 181 (2021)



- The pp cross-section is taken from a fit to data.
- E-loss calculations with $\sqrt{L}$-dependence explain J/ψ suppression at FNAL, RHIC, LHC!
- nPDFs effect is expected to be small at lower $\sqrt{s}$.

p_T broadening in cold medium

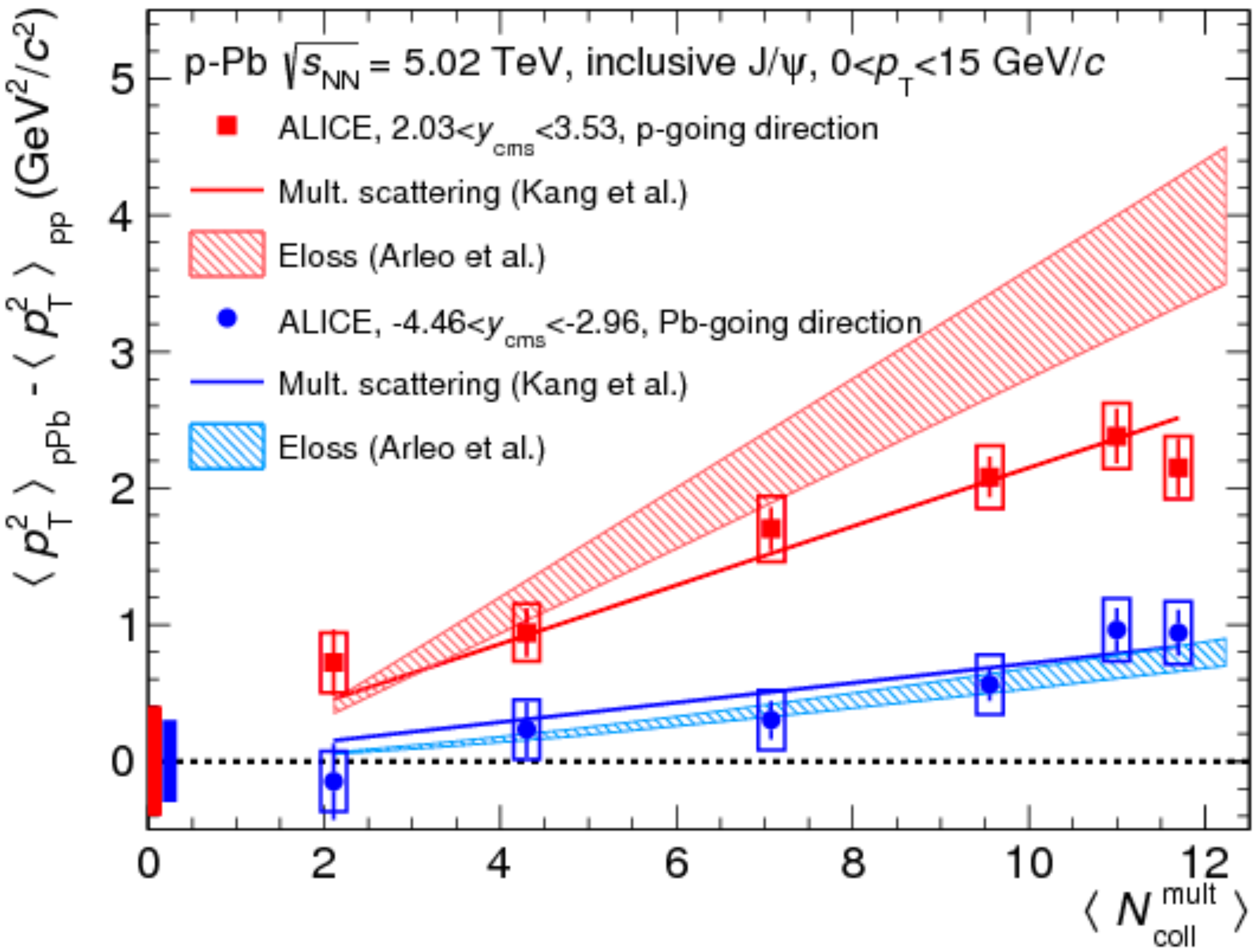
Adam *et al.* [ALICE], JHEP11, 127 (2015)

- A direct probe into the transport coefficient or saturation scale
- In the target rest frame, we may define:

Medium independent

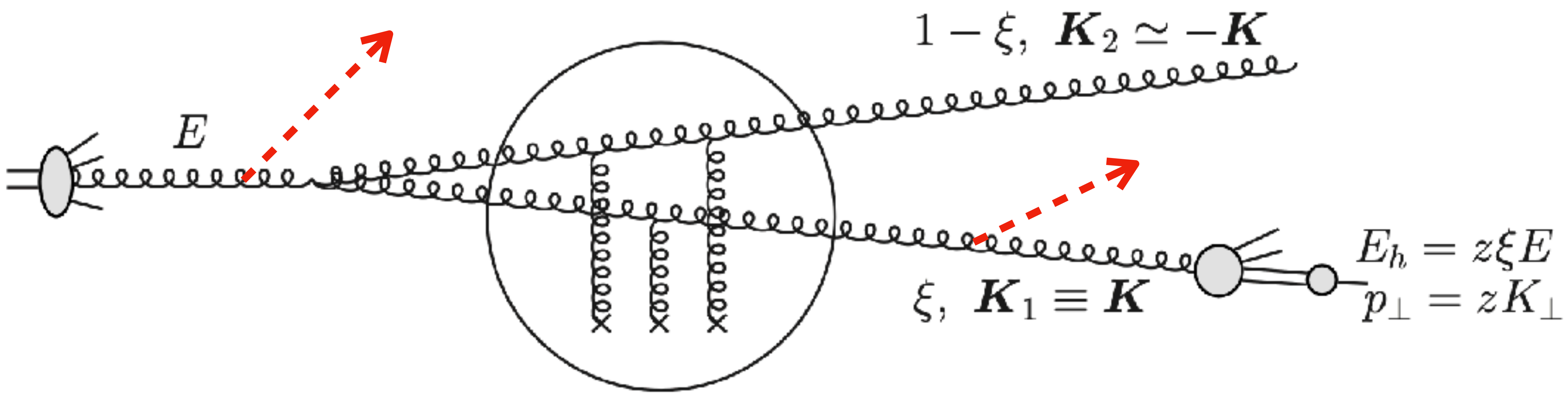
$$\langle p_T^2 \rangle_{pA} = \boxed{\langle p_T^2 \rangle_{vac}} + \boxed{\hat{q} L_A}$$

Multiple scattering effect in cold nuclear medium



FCEL model describes the trend correctly.

Induced gluon spectrum for $1 \to 2$ processes



Peigne, Kolevatov, JHEP01, 141 (2015)
Liou, Mueller, PRD89, no.7, 074026 (2014)

- Complicated but can be simplified.
- The induced soft gluon cannot probe the dijet constituents, but see their global color state R at leading-logarithmic approximation (point-like dijet approximation):

$$\ln\left(\frac{E^2 l_{A\perp}^2}{\omega^2 K_\perp^2}\xi(1-\xi)\right) \gg 1 \qquad \text{with } \xi \sim 1/2$$

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

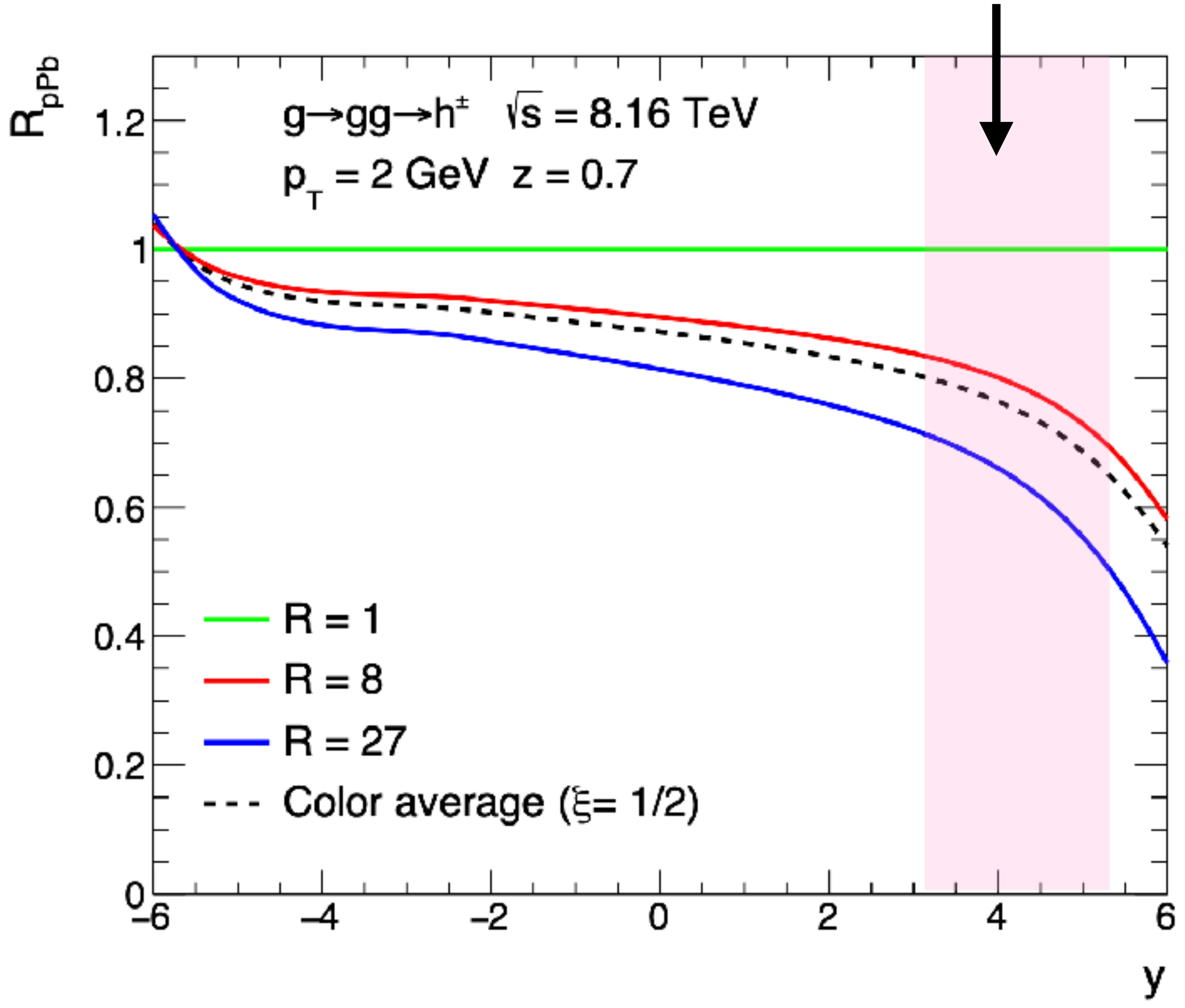
$$\Rightarrow \quad \omega \frac{dI}{d\omega}\bigg|_{a\to(bc)_R} = F_R \frac{\alpha_s}{\pi}\left[\ln\left(1+\frac{E^2 l_{A\perp}^2}{\omega^2 K_\xi^2}\right) - \ln\left(1+\frac{E^2 l_{p\perp}^2}{\omega^2 K_\xi^2}\right)\right]$$

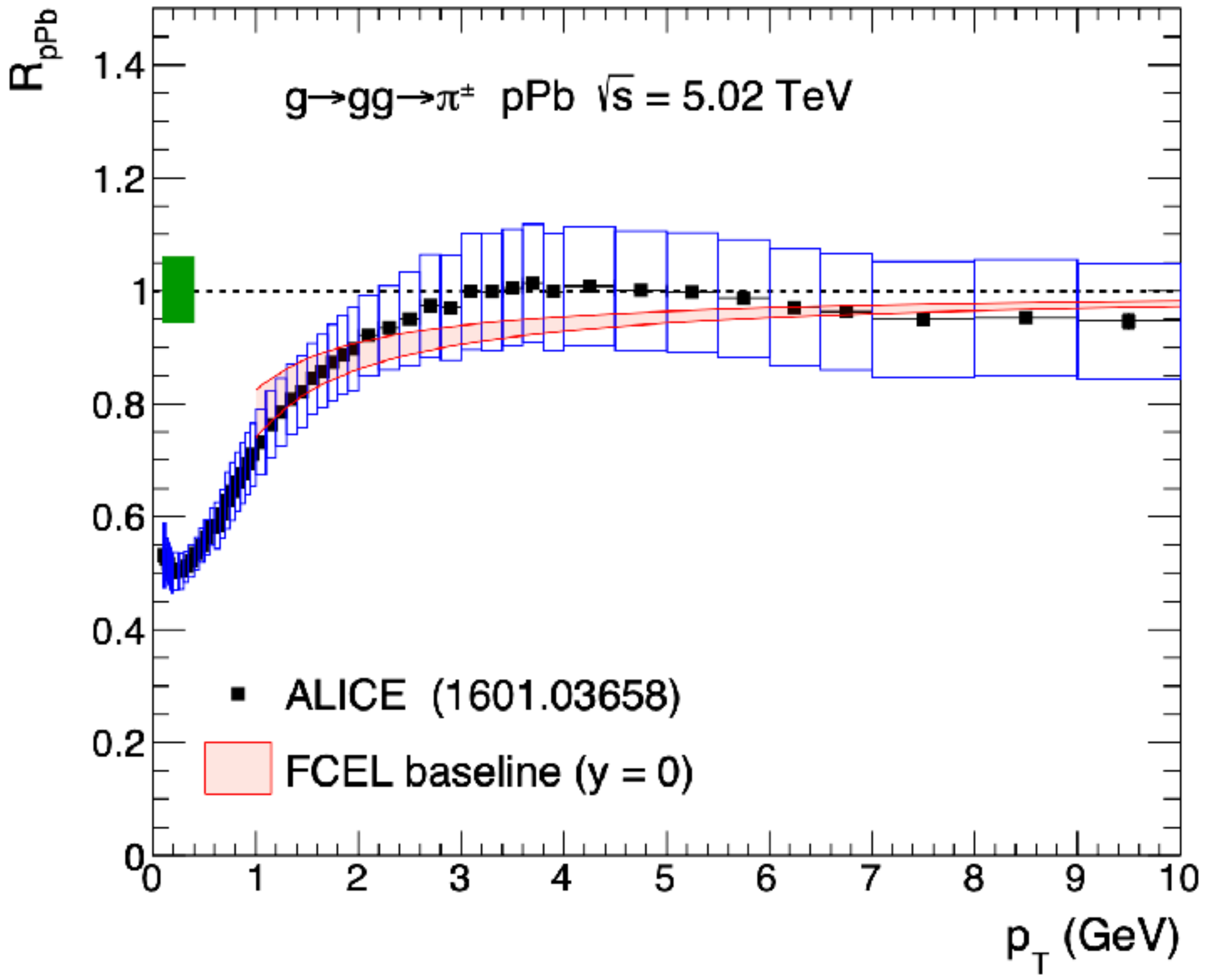
Dijet mass:
$K_\xi^2 = K_\perp^2/(\xi(1-\xi))$

Light hadron production

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

Can be explored with FoCal

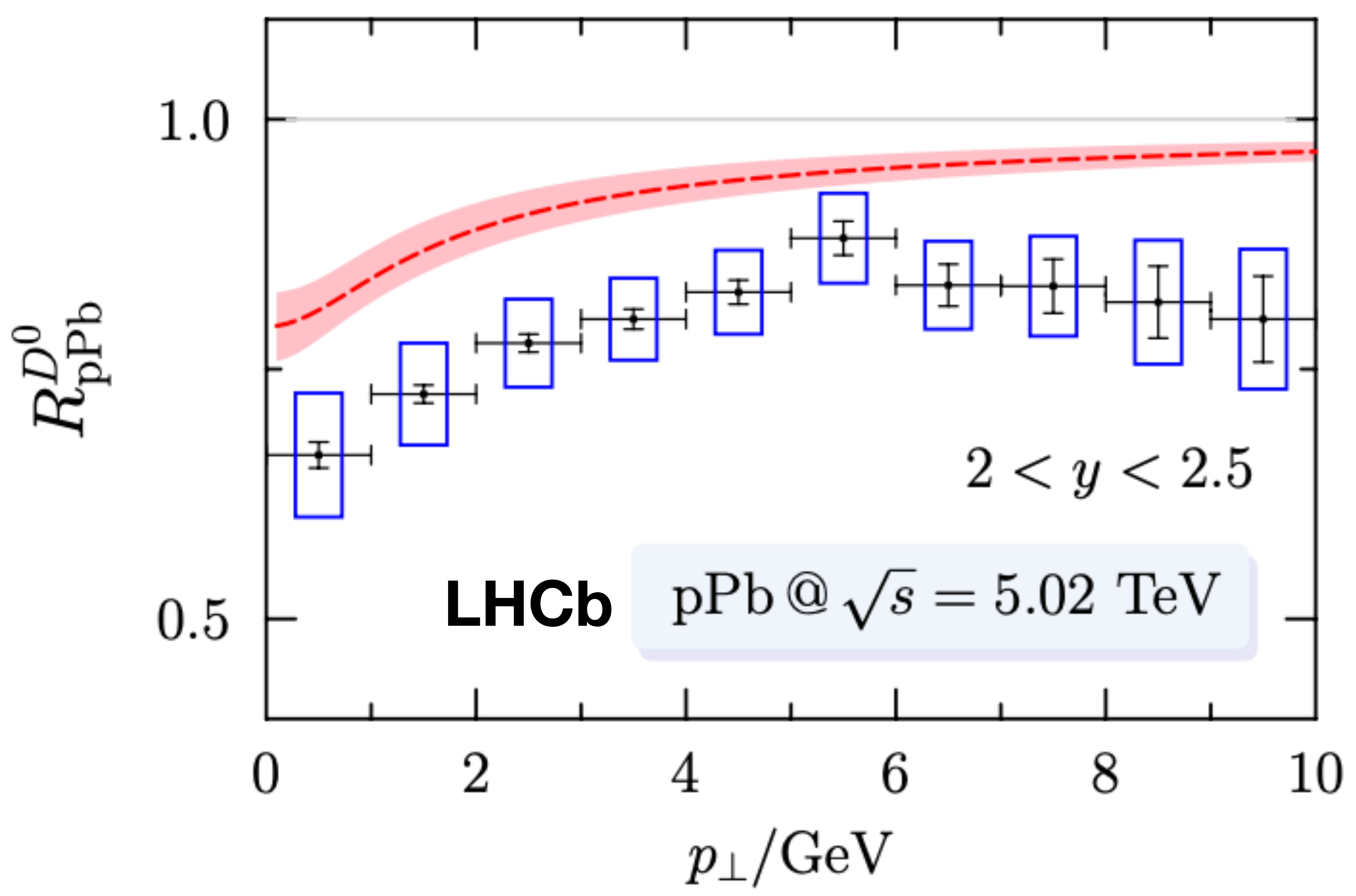


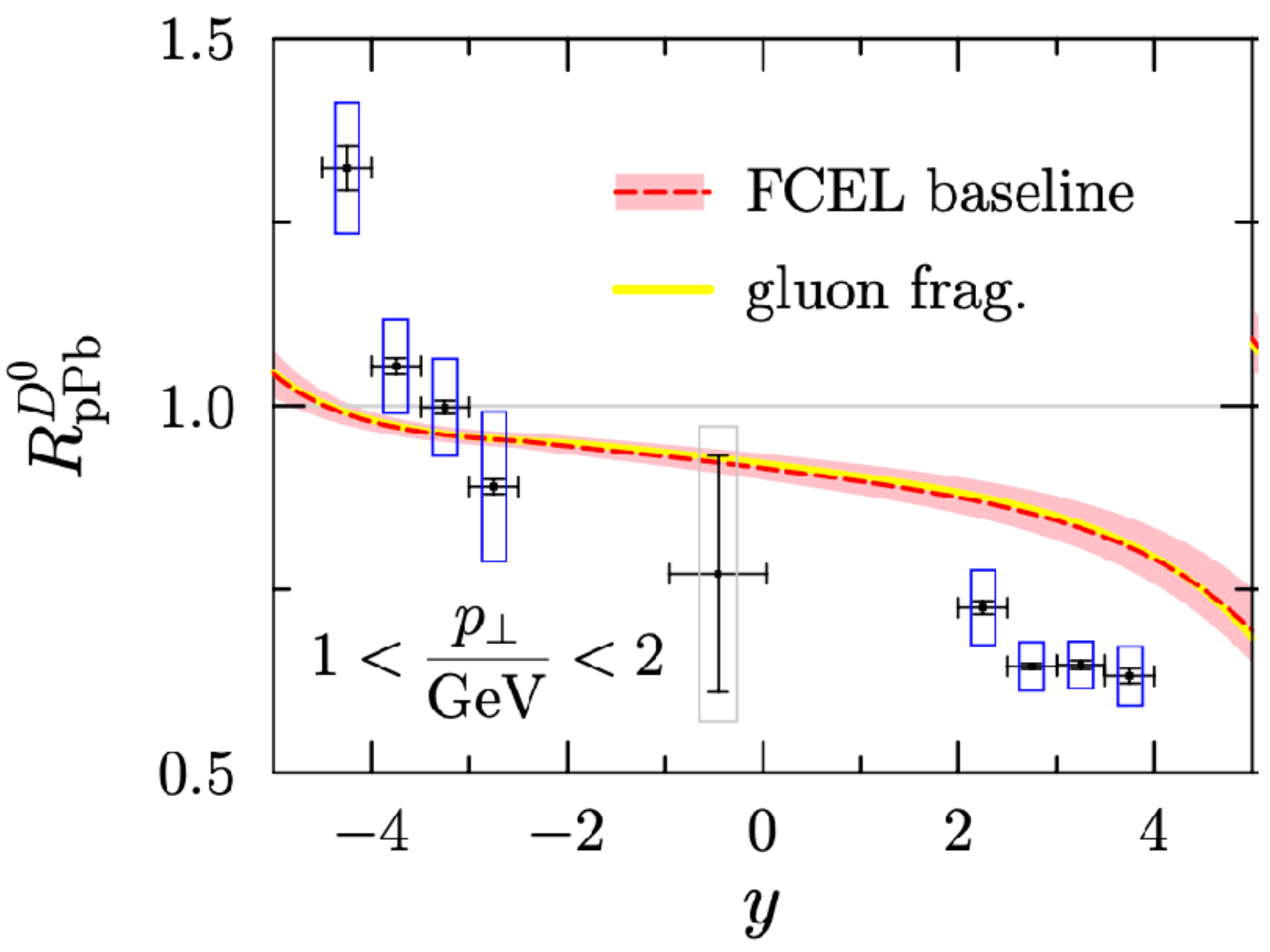


- The pp cross-section is taken from a fit to data.
- Color irreducible representations: $\mathbf{8 \otimes 8 = 1 \oplus 8_a \oplus 8_s \oplus 10 \oplus \overline{10} \oplus 27 \oplus 0}$
- The suppression patterns depend on R of a produced parton pair.

Open heavy flavor production

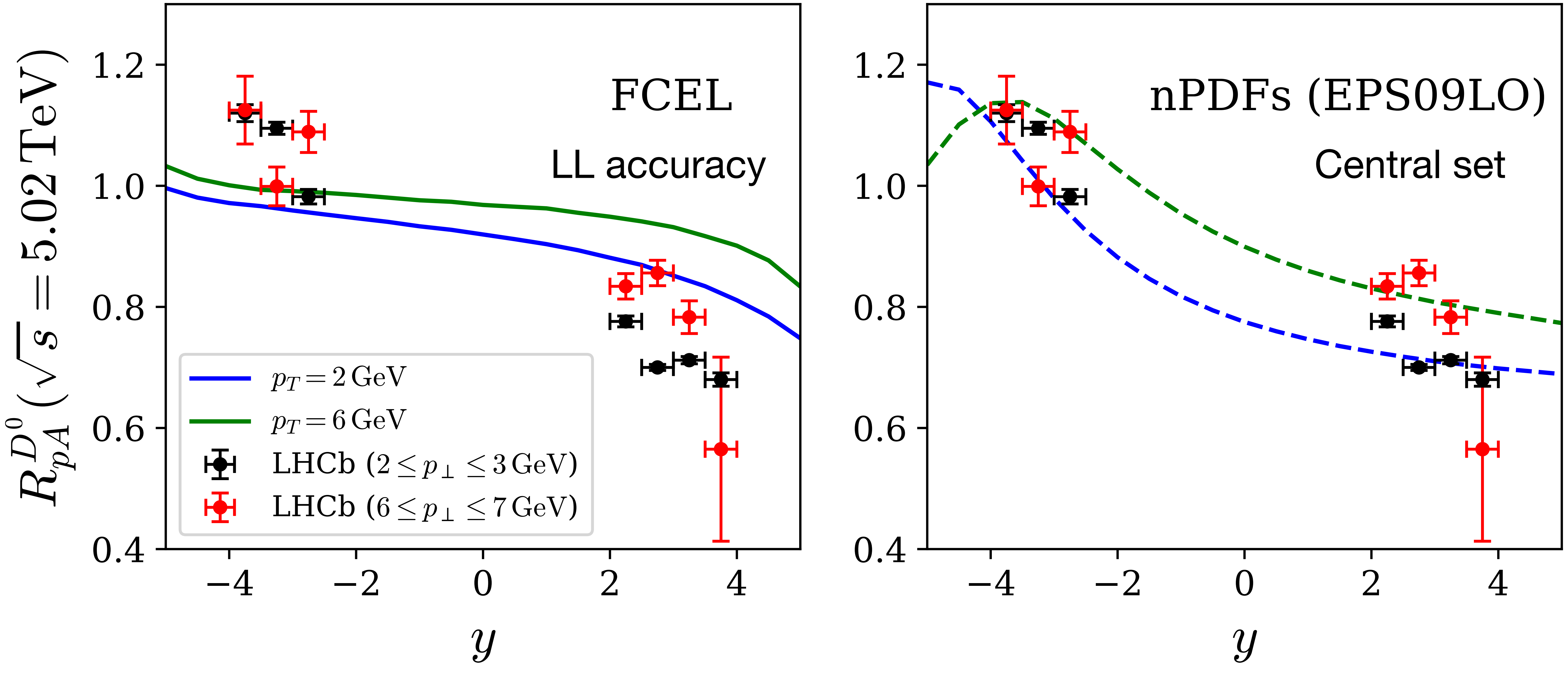
Arleo, Jackson, Peigne, JHEP01, 164 (2022)





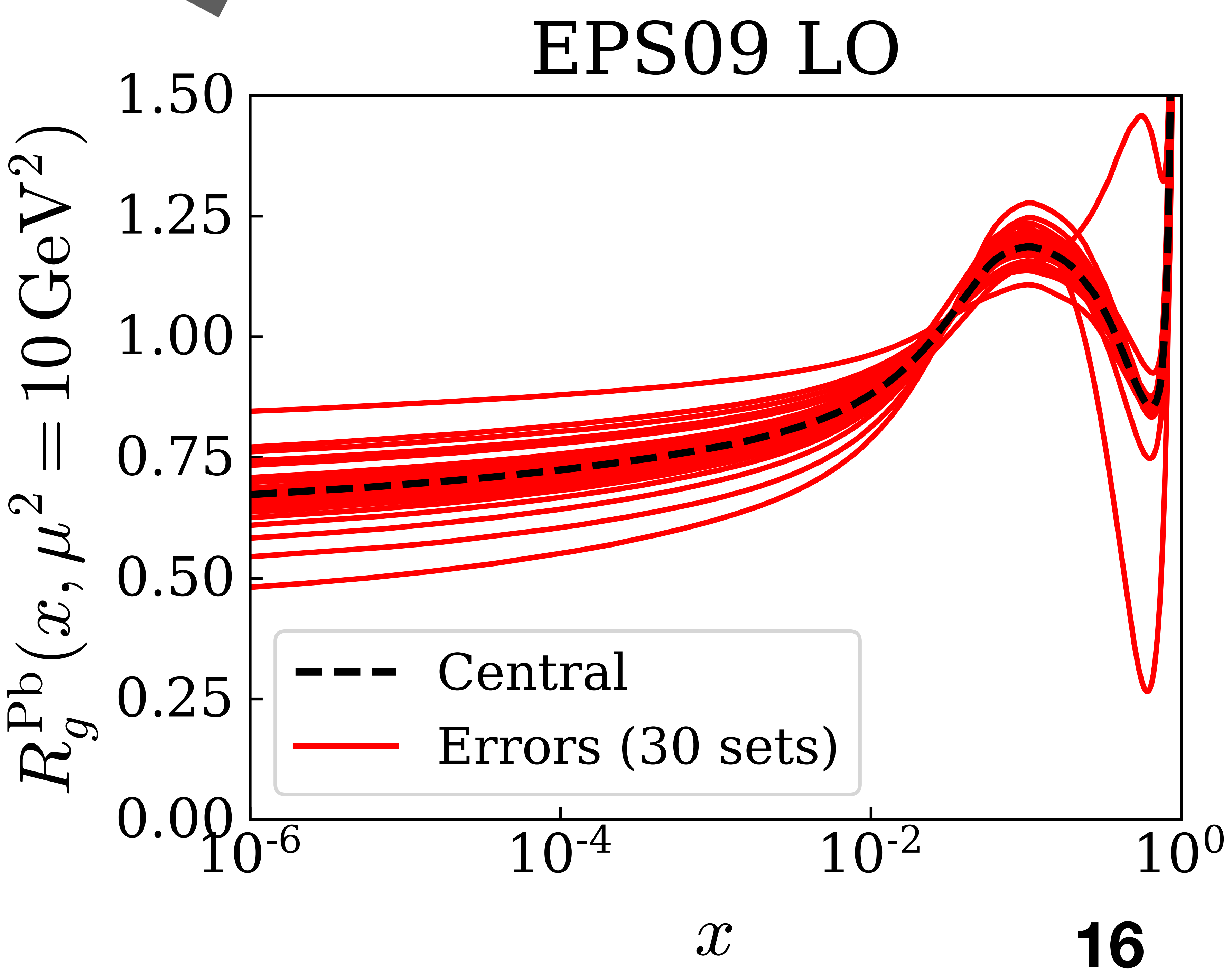
- The pp cross-section is taken from a fit to data.
- FCEL accounts for half of the nuclear suppression of low $p_\perp$ D-meson.

Extra suppression from nPDFs at small-x



Arleo, Jackson, Peigne, **KW**, in progress

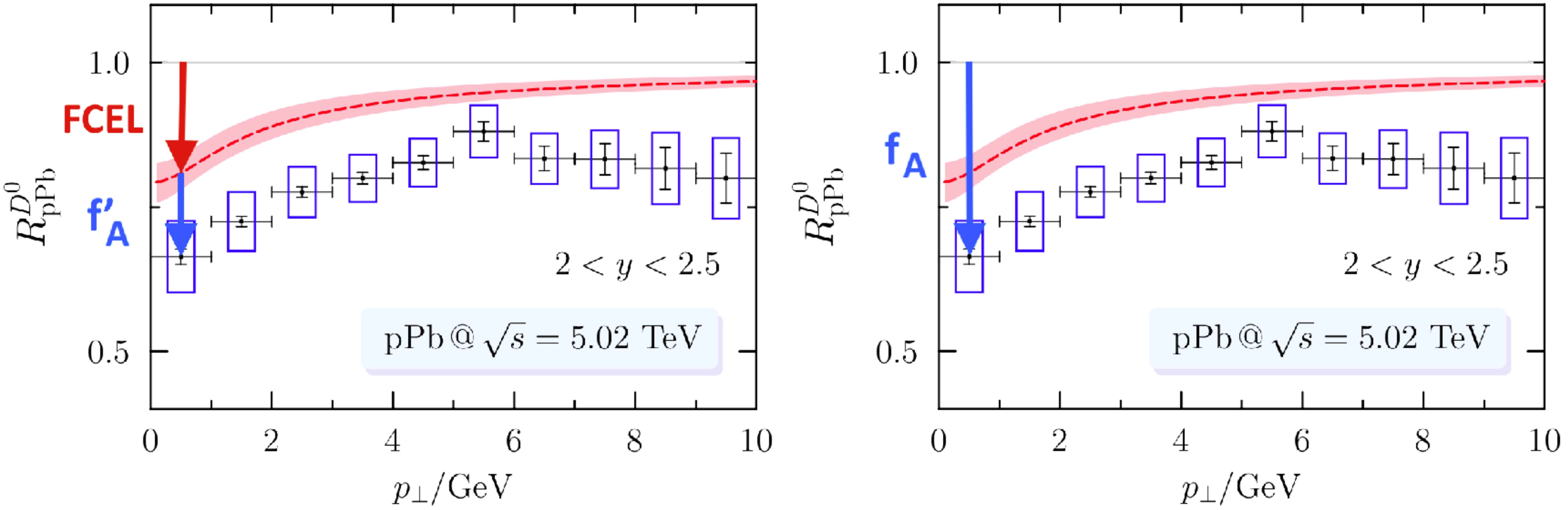
only the central set is shown, but individual uncertainty sets are accompanied.



- nPDFs (f_A) are customarily fitted by QCD global data analysis without FCEL.
- FCEL and nPDFs can be implemented in the same framework (collinear factorization); we should combine them eventually!

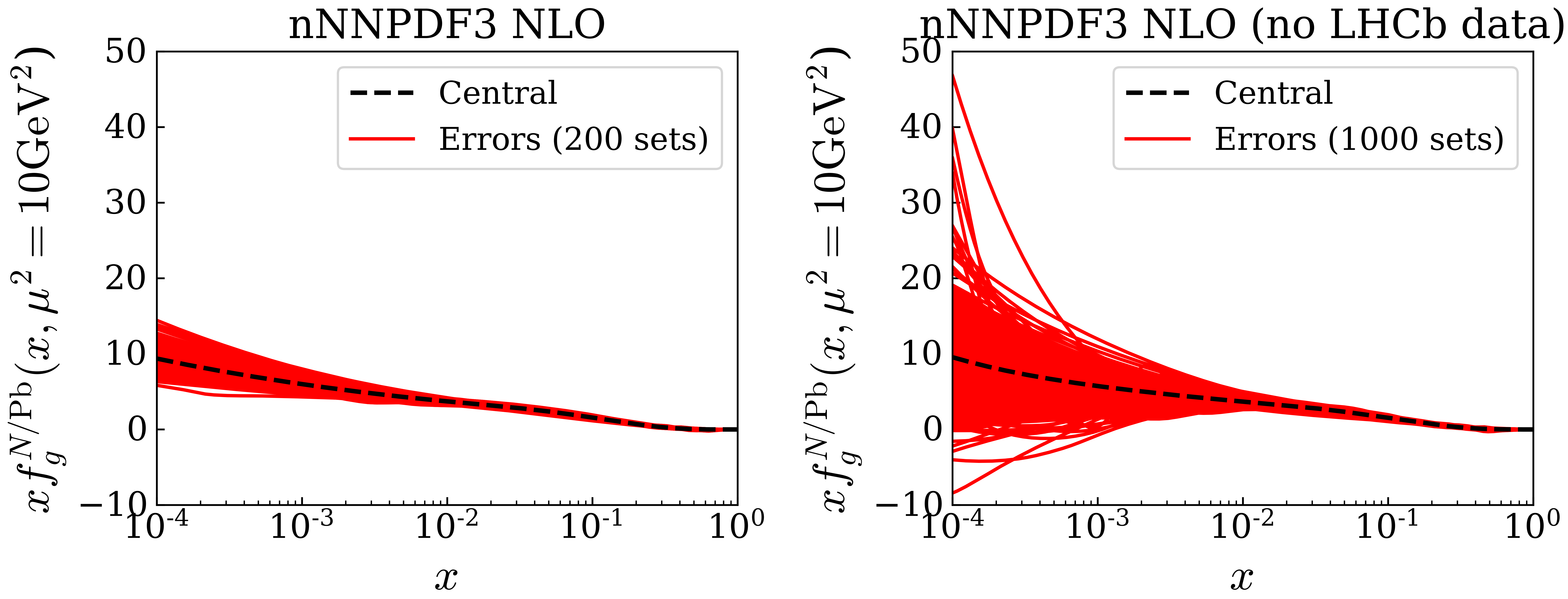
Perspectives

Arleo, Jackson, Peigne, **KW**, in progress



- $\chi^2(f'_A \,|\, \mathrm{FCEL} \cap \mathrm{LHCb})$ vs. $\chi^2(f_A \,|\, \mathrm{no\ FCEL} \cap \mathrm{LHCb})$
- nPDFs can be reweighed by implementing both FCEL and nPDFs.
- Remark: all hadron production in pA collisions can be affected by nPDFs and FCEL.

Significance of heavy flavor production



- QCD global data analysis w/ or w/o LHCb data on D-meson production in pp and pA.
- D-meson as well as J/ψ play a crucial role in reducing huge theoretical uncertainty!

Duwentaster, et al. [nCTEQ], PRD105, no.11, 114043 (2022), Khalek et al [NNPDF], EPJC82, no.6, 507 (2022)

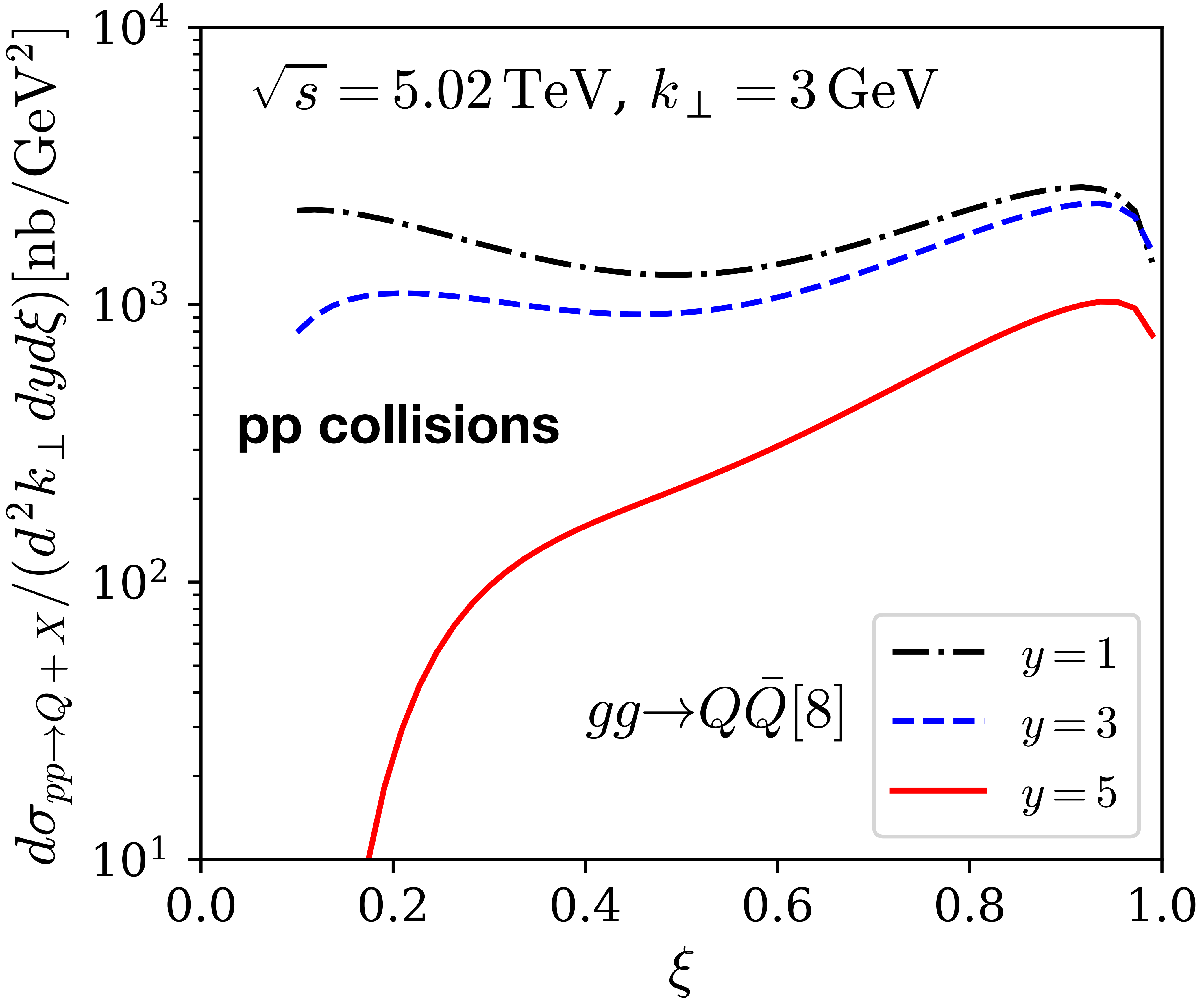
- Heavy flavors with FCEL have a high impact on gluon nPDFs at small-x.

An important step towards FCEL+nPDFs

$$\frac{d\sigma_{pA\to H+X}}{dyd^2p_\perp} \sim A\int_0^{x_{\max}} dx \int_{z_{\min}(x)}^{1} \frac{dz}{z^2} D_{Q\to H}(z) \int_{\xi_{\min}(x)}^{\xi_{\max}(x)} d\xi \frac{\hat{\mathscr{P}}_{[8]}(x,\xi,z)}{1+x}$$

$$\times \sum_{ij} \int dx_1 f_{i/p}(x_1) \int dx_2 f_{j/A}(x_2) \frac{d\hat{\sigma}_{ij\to Q\bar{Q}[8]}}{d\tilde{y}d^2k_\perp d\xi}\Bigg|_{\tilde{y}=y+\ln(1+x)}$$

Energy fraction: $x = \omega/E$



- Single heavy-quark can be largely produced at larger ξ at forward rapidity.
- Need to understand the induced spectrum (and quenching weight) for $1 \to 2$ processes beyond LL approximation for $\xi \neq 1/2$.
- The induced gluon can probe color transitions of a produced parton pair ($R \to R'$).

$1 \to 2$ processes beyond LL approximation

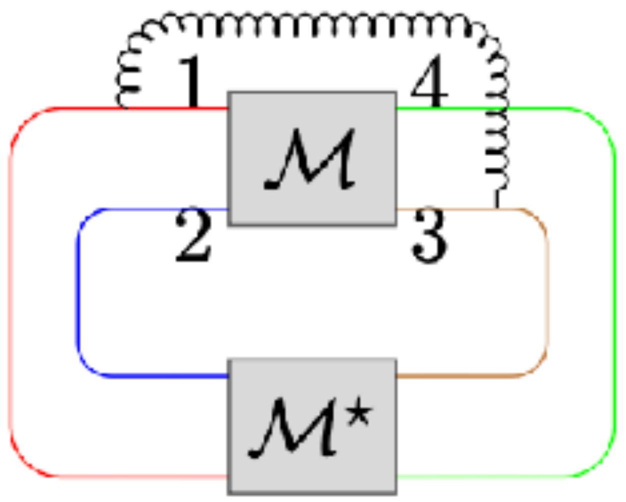
- Induced gluon spectrum beyond LL approximation:

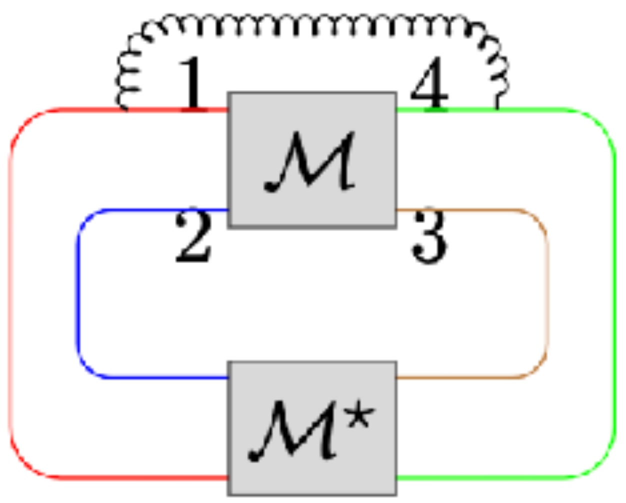
Jackson, Peigne, **KW**, in preparation

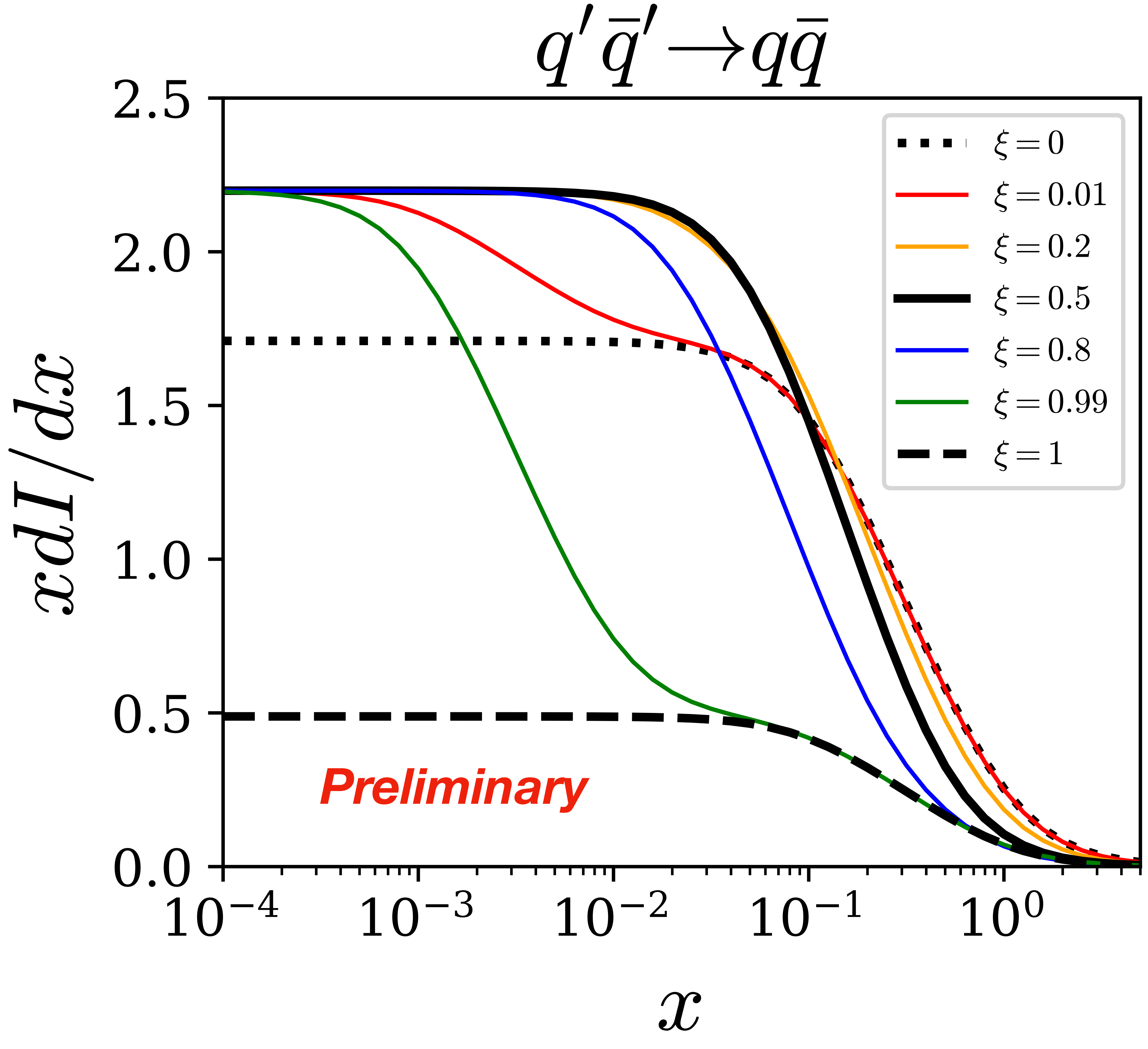
$$x\frac{dI}{dx} = \frac{\alpha_s}{\pi}\left(LT + \bar{L}\bar{T}\right)$$

$$L(\xi) = \ln\left(1 + \xi^2 \frac{E^2 l_{A\perp}^2}{\omega^2 K_\perp^2}\right) - \ln\left(1 + \xi^2 \frac{E^2 l_{p\perp}^2}{\omega^2 K_\perp^2}\right)$$

$$\bar{L} = L(1-\xi)$$

$\mathcal{T} = \frac{2}{\mathrm{Tr}_c |\mathcal{M}|^2}$ 

$\bar{\mathcal{T}} = \frac{2}{\mathrm{Tr}_c |\mathcal{M}|^2}$ 



- Nontrivial color transitions, included in T and $\bar{T}$.
- Good matching with $1 \to 1$ processes at $\xi = 0,1$ and $1 \to 2$ processes at $\xi = 1/2$.
- Can be applied to phenomenology.

Summary

- FCEL is a significant CNM effect for all hadron production in pA collisions.

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

- FCEL and nPDFs are required to describe heavy flavor production in pA collisions at the LHC, giving a new set of nPDFs.
- FCEL beyond LL approximation allows us to comprehensively study nuclear suppression of hadron production in pA collisions.
- **Remark:** FCEL can be essential for saturation hunting. Extensive study of FCEL and saturation effect is a future problem. cf. Bergabo and Jalilian-Marian, NPA 1018, 122358 (2022)

Thank you!

Backup

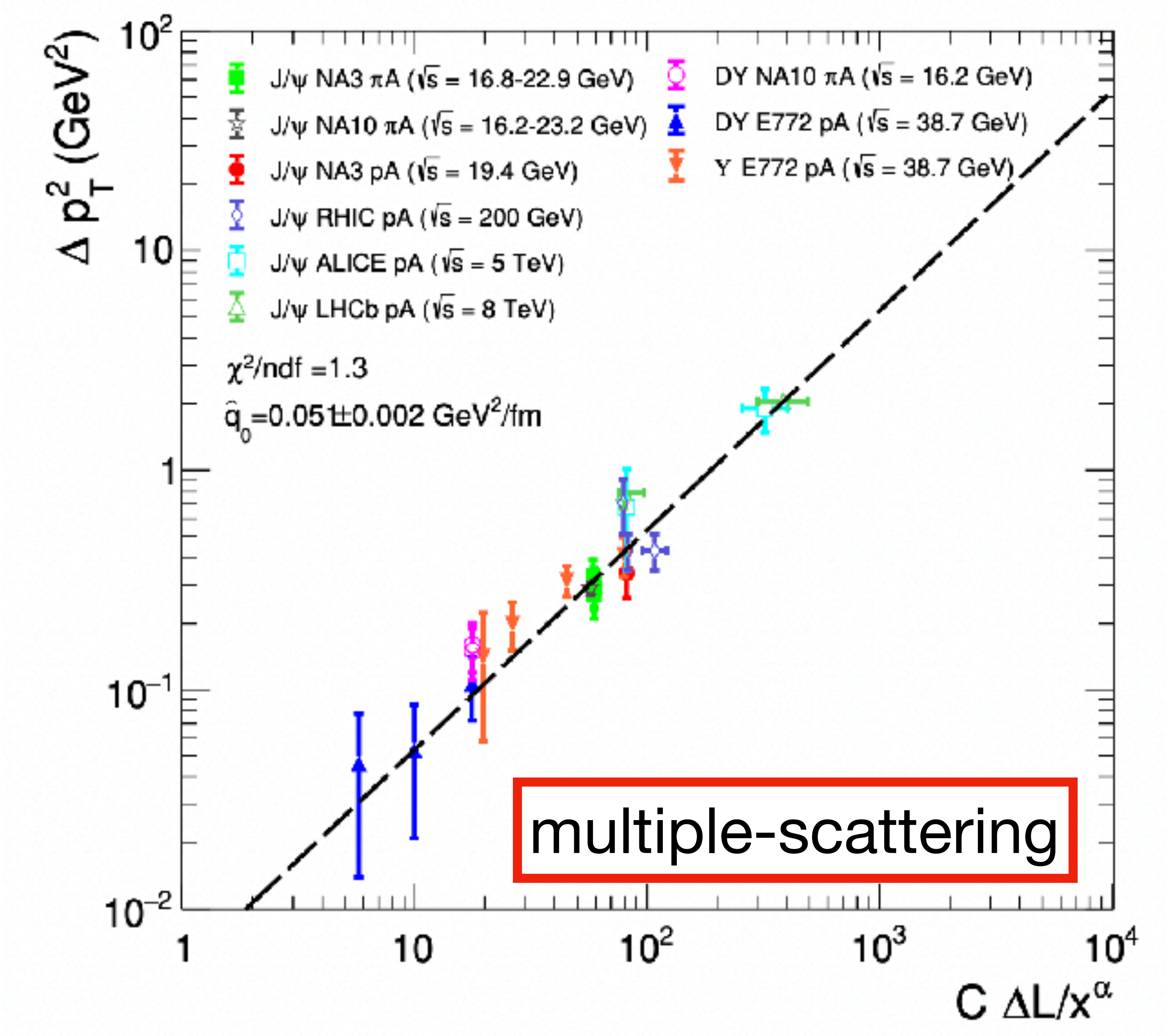
Transport coefficient and p_T broadening

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

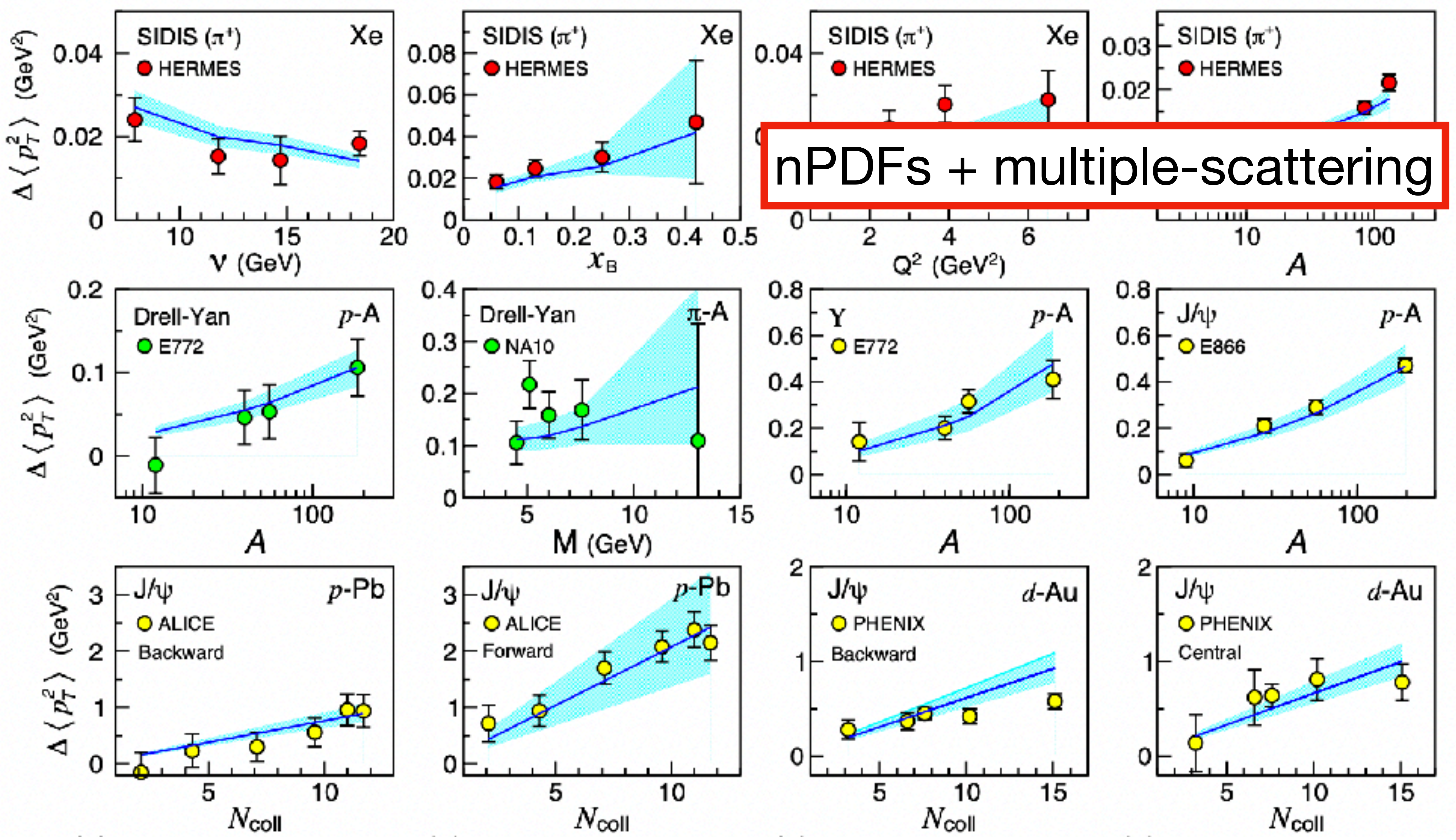
Small-x limit

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

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 say that the nonlinear saturation effect is seen. BFKL evolution could be seen.