Fully Coherent Energy Loss in pA and AA collisions

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Exploring Quark-Gluon Plasma through soft and hard probes

Serbian Academy of Science and Arts

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Program

- Recap on Fully Coherent Energy Loss (FCEL)

- FCEL effects on hadron suppression in pA

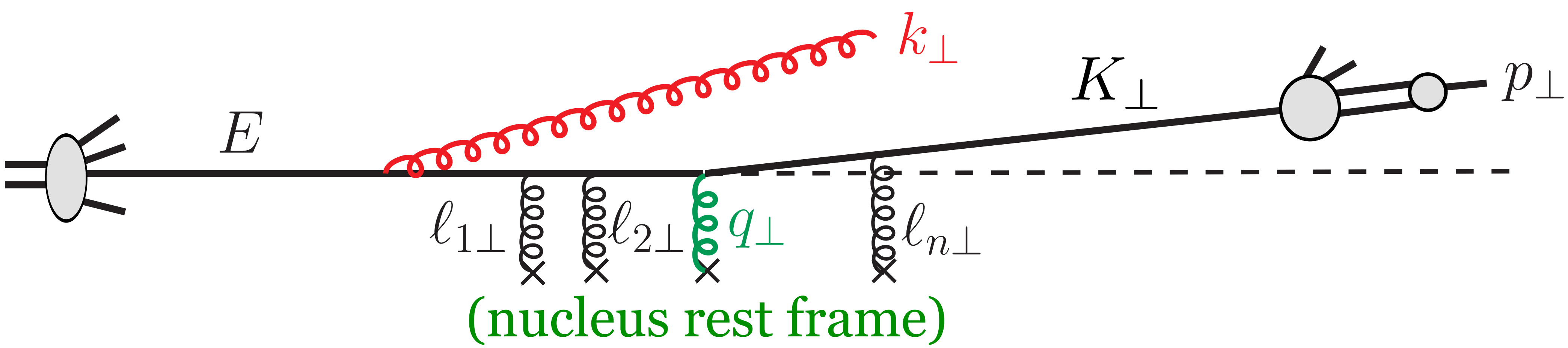
  FCEL = *cold nuclear matter effect*

- J/ψ suppression in AA expected from FCEL

FCEL = induced radiative energy loss of fast color charge in small-angle scattering

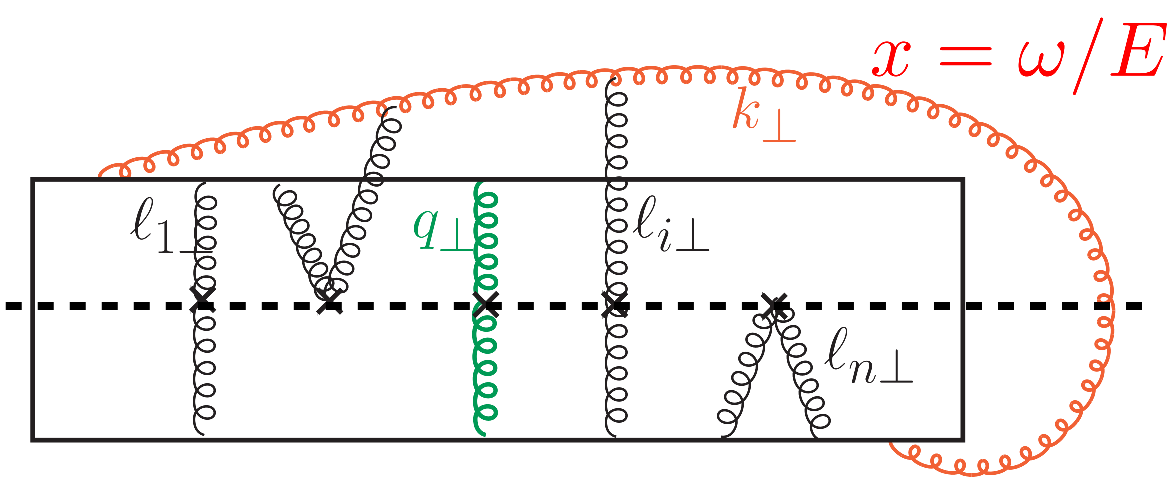
typical situation : hadron production in pA collisions

$1 \to 1$ forward processes



- tagged hadron with 'hard' $p_\perp \Rightarrow$ hard $K_\perp = \dfrac{p_\perp}{z}$
- parent parton undergoes:
  - *single* hard exchange $q_\perp \simeq K_\perp = p_\perp / z$
  - soft rescatterings $\ell_\perp^2 = \left(\sum \vec{\ell}_{i\perp}\right)^2 \sim \hat{q}L \sim Q_s^2 \ll K_\perp^2$
- recoil parton assumed to be soft

→ *induced* radiation in pA *vs* pp collisions



- from initial-final state interference
- associated to large $t_{\rm f} \gg L$

fully coherent radiation

$\Longrightarrow$ induced radiation spectrum scales in $x = \omega/E$

$$x \frac{{\rm d}I}{{\rm d}x}\bigg|_{1\to 1} = (C_1 + C_2 - C_t)\frac{\alpha_s}{\pi} \log\left(1 + \frac{\hat{q}L}{x^2 K_\perp^2}\right)$$

$\Longrightarrow$ average FCEL

$$\Delta E = E \int_0^1 {\rm d}x\, x \frac{{\rm d}I}{{\rm d}x} \propto \alpha_s \frac{\sqrt{\hat{q}L}}{K_\perp} E \qquad (E \simeq x_1 E_{\rm p})$$

one main input: $\hat{q}L$

transport coefficient $\hat{q}$

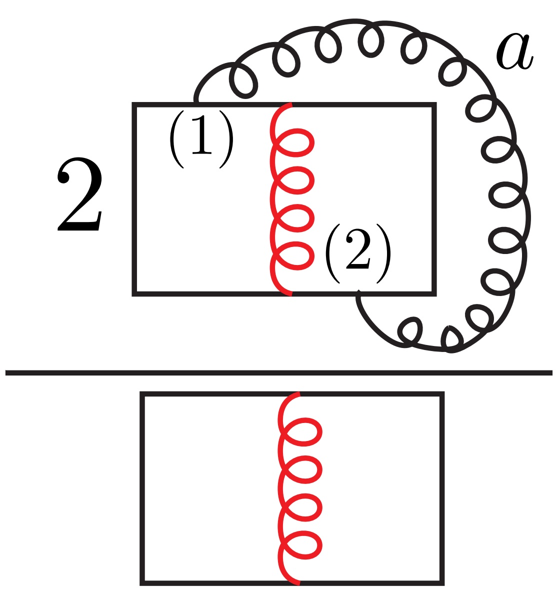
$$\hat{q} = \hat{q}(x_2) = \hat{q}_0 \left(\frac{10^{-2}}{x_2} \right)^{0.3} \quad \text{for } x_2 < 10^{-2}$$

$$\hat{q}_0 = 0.07 \pm 0.02 \text{ GeV}^2/\text{fm}$$

however: FCEL is totally different from shadowing or saturation

FCEL also present when $\hat{q} = \hat{q}_0$ for $x_2 > 10^{-2}$

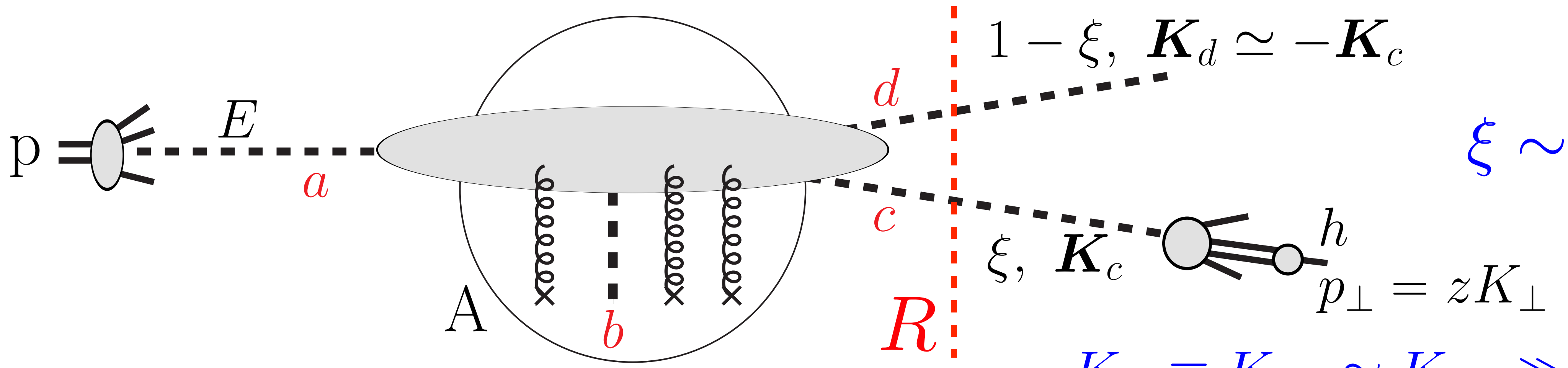
general rule for color factor



$$= 2\, T^a_{(1)} T^a_{(2)} = (T^a_{(1)})^2 + (T^a_{(2)})^2 - (T^a_{(1)} - T^a_{(2)})^2$$

$$= C_1 + C_2 - C_t$$

$1 \to 2$ forward processes



$\xi \sim 1/2$

$K_\perp \equiv K_{c\perp} \simeq K_{d\perp} \gg \sqrt{\hat{q}L}$

$|\vec{K}_c + \vec{K}_d| \lesssim \sqrt{\hat{q}L}$

to leading-log: *radiated gluon does not probe the dijet*

→ effectively equivalent to $1 \to 1$

$$x\frac{\mathrm{d}I}{\mathrm{d}x}\bigg|_{1\to 2} = \sum_R \rho_R\,(C_a + C_R - C_b)\,\frac{\alpha_s}{\pi}\log\left(1+\frac{\hat{q}L}{x^2 M^2_{\mathrm{dijet}}}\right)$$

C_R dijet global color charge (Casimir) in state *R*

ρ_R proba for dijet to be produced in color state *R*

to leading-log: generalizes to $1 \to n$ processes

FCEL effect is an established, first-principle result

$1 \to 1$ forward processes

- Arleo, S.P., Sami PRD 83 (2011)
  - opacity expansion • $g \to Q\bar{Q}$ mediated by *octet* t-channel exchange
- Armesto et al PLB 717 (2012), JHEP 1312 (2013)
  - opacity expansion • $q \to q$ with *singlet* t-channel exchange
- S.P., Arleo, Kolevatov PRD 93 (2016)
  - opacity expansion • all $1 \to 1$ processes • rule for color factor
- Munier, S.P., Petreska PRD 95 (2017)
  - saturation formalism • hard process: $q \to q, \ g \to g$

$1 \to 2$ forward processes

- Liu, Mueller PRD 89 (2014)
  - saturation formalism • hard process: $g \to q\bar{q}, \ q \to qg$
- S.P., Kolevatov JHEP 01 (2015)
  - opacity expansion • hard process: $q \to qg, \ g \to gg$
- Jackson, S.P., Watanabe (work in progress)
  - all $1 \to 2$ processes • beyond leading-log (equivalently: all ξ)

features to keep in mind :

- FCEL inherent to forward scattering in target rest frame

  with color in both initial and final state

- forward scattering $\Leftrightarrow E_{\rm target\ frame} \gg K_\perp$

  $\Longrightarrow$ *FCEL applies to broad rapidity range in c.m. frame*

- $\Delta E \propto E$ ⟶ crucial for phenomenology

FCEL effects on hadron nuclear suppression in pA collisions

How to estimate FCEL effects knowing FCEL spectrum?

$\mathrm{d}I/\mathrm{d}\omega$ depends on partonic channel, and final color C_R

$1 \to 1$ forward processes

$$\frac{1}{A}\frac{\mathrm{d}\sigma^h_{\mathrm{pA}}}{\mathrm{d}E}(E,\sqrt{s}) = \int_0^{\varepsilon_{\max}} \mathrm{d}\varepsilon\, \underline{\mathcal{P}(\varepsilon, E)}\, \frac{\mathrm{d}\sigma^h_{\mathrm{pp}}}{\mathrm{d}E}(E+\varepsilon, \sqrt{s})$$

quenching weight

simplest quenching weight built from $\mathrm{d}I/\mathrm{d}\omega$:

$$\mathcal{P}(\varepsilon, E) = \frac{\mathrm{d}I}{\mathrm{d}\varepsilon} \exp\left\{-\int_\varepsilon^\infty \mathrm{d}\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\right\}$$

justified in DLA

proba to radiate ε

proba to have no extra harder radiation with $\omega_k \gtrsim \varepsilon$

$\omega \mathrm{d}I/\mathrm{d}\omega$ scales in $\omega/E \;\Rightarrow$

$$\hat{\mathcal{P}}(x) = \frac{\mathrm{d}I}{\mathrm{d}x}\, \exp\left\{ -\int_x^{\infty} \mathrm{d}x' \frac{\mathrm{d}I}{\mathrm{d}x'} \right\} \qquad (x = \varepsilon/E)$$

$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}E}(E) = \int_0^{x_{max}} \mathrm{d}x\, \hat{\mathcal{P}}(x)\, \frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}E}\left(E(1+x) \right)$$ (energy rescaling)

$$\Rightarrow \frac{\sigma_{\mathrm{pA}}}{A\sigma_{\mathrm{pp}}} = \int \mathrm{d}x\, \frac{\hat{\mathcal{P}}(x)}{1+x} \simeq \frac{1}{1+\langle x \rangle}$$

FCEL suppresses total cross section

- in terms of rapidity $y \equiv \frac{1}{2}\ln\frac{E+p^z}{E-p^z} = \ln\frac{E+p^z}{M_\perp} \simeq \ln\frac{2E}{M_\perp}$

$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}(y)}{\mathrm{d}y} = \int_0^{x_{\mathrm{max}}} \mathrm{d}x\, \frac{\hat{\mathcal{P}}(x)}{1+x}\, \frac{\mathrm{d}\sigma_{\mathrm{pp}}\left(y + \ln(1+x)\right)}{\mathrm{d}y}$$

FCEL $\Longrightarrow$ rapidity shift $= \ln(1+x)$

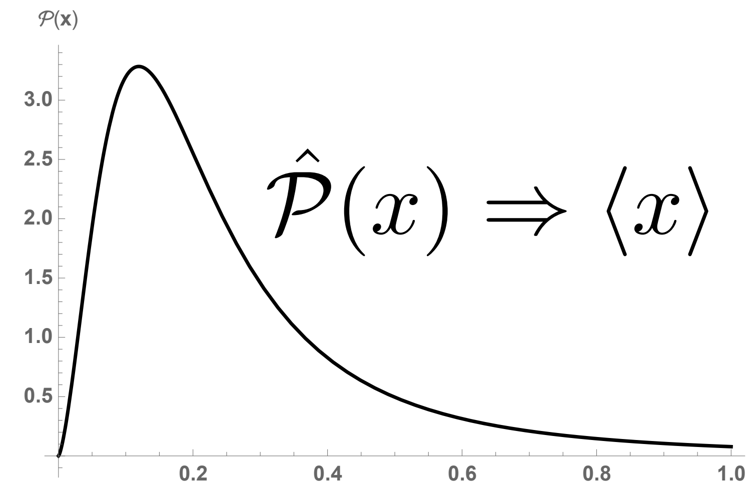
$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}(y)}{\mathrm{d}y} = \int_0^{x_{\max}} \mathrm{d}x\, \frac{\hat{\mathcal{P}}(x)}{1+x}\, \frac{\mathrm{d}\sigma_{\mathrm{pp}}\left(y+\ln\left(1+x\right)\right)}{\mathrm{d}y}$$

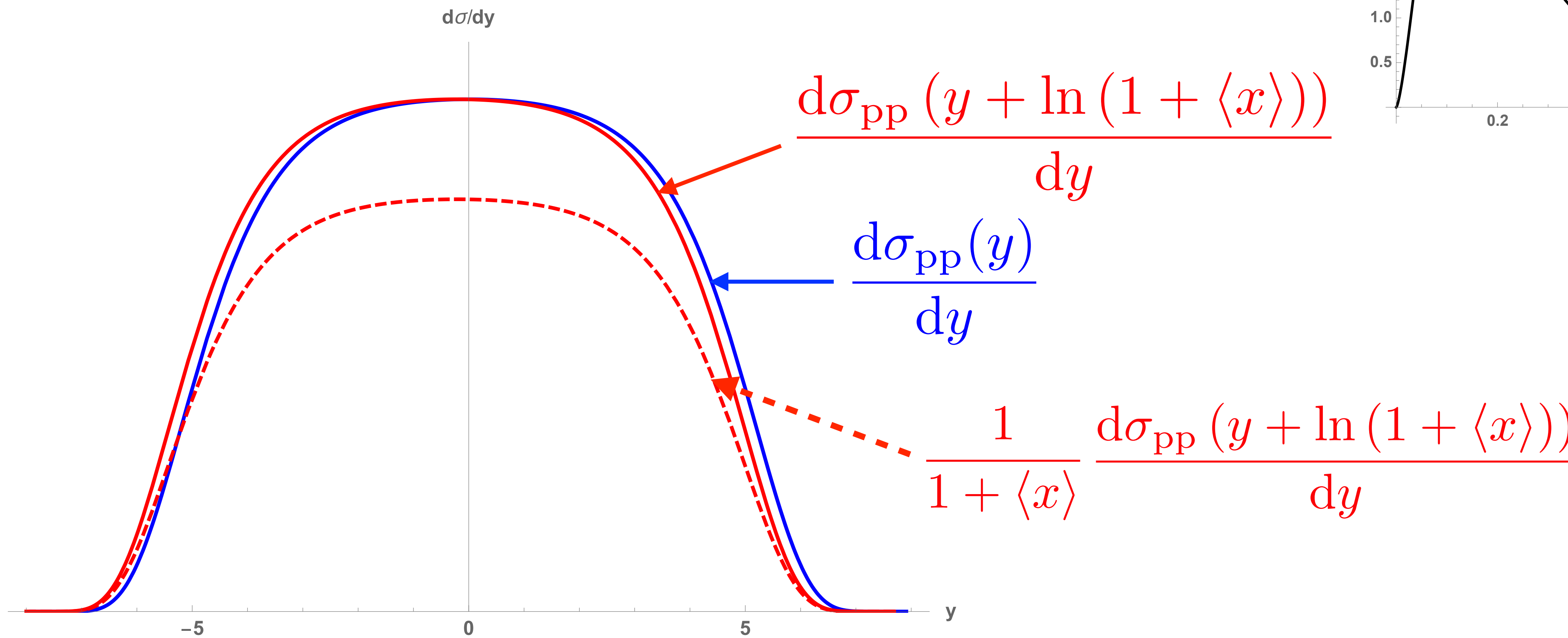
Goal:

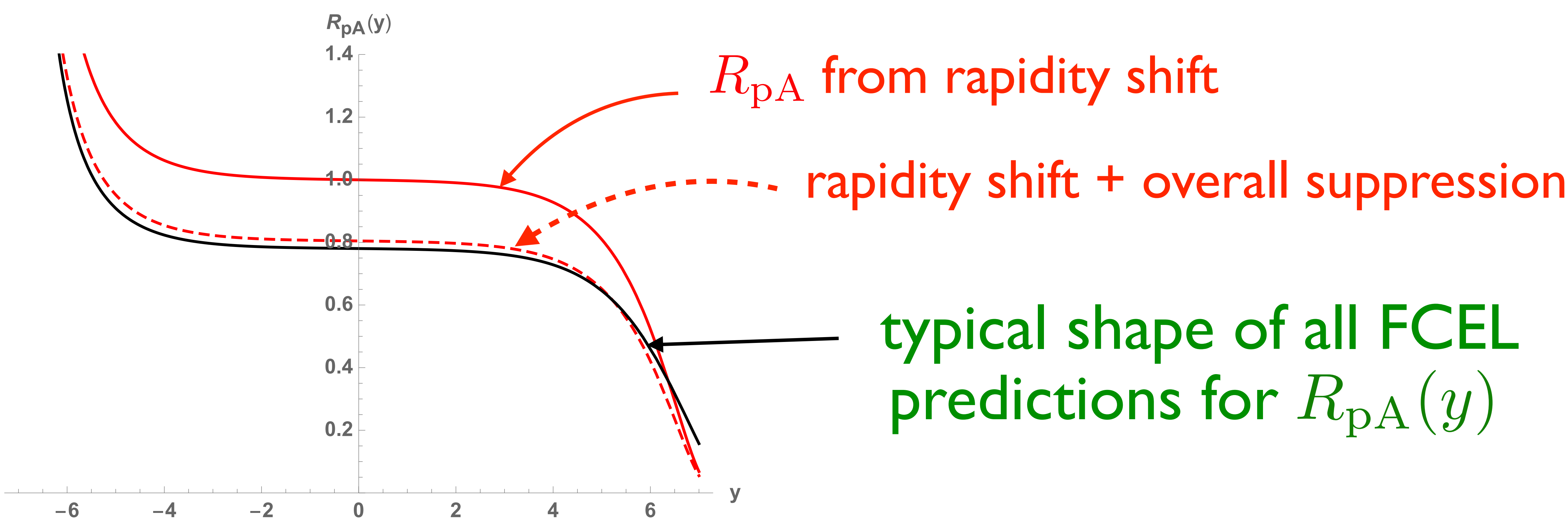
- *knowing* $\mathrm{d}\sigma_{\mathrm{pp}}$, which $\mathrm{d}\sigma_{\mathrm{pA}}$ to expect from *sole* FCEL effect ?
    - $\mathrm{d}\sigma_{\mathrm{pp}}$ taken as parametrization of pp data
    - $\hat{\mathcal{P}}(x)$ (i.e. $\mathrm{d}I/\mathrm{d}\omega$) : only theoretical input
- don't predict absolute cross sections, but the *ratio* R_{pA} :

$$R_{\mathrm{pA}}^{\mathrm{FCEL}}(y) = \frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}}{\mathrm{d}y} \Big/ \frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}y}$$

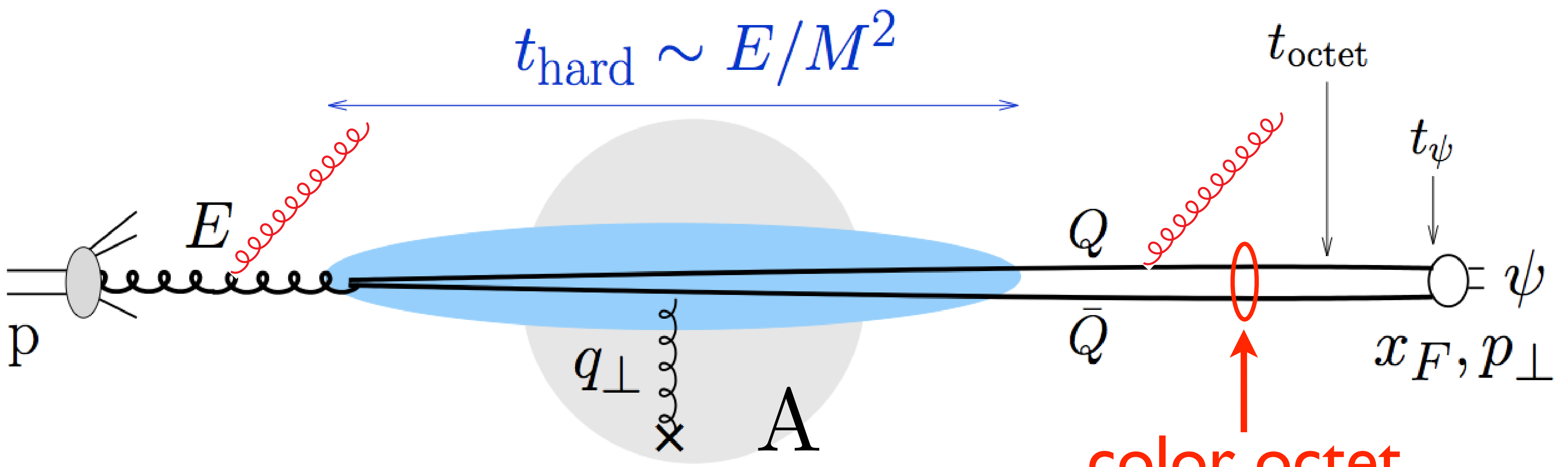
$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}(y)}{\mathrm{d}y} = \int_0^{x_{\max}} \mathrm{d}x \; \frac{\hat{\mathcal{P}}(x)}{1+x} \; \frac{\mathrm{d}\sigma_{\mathrm{pp}}\left(y + \ln\left(1+x\right)\right)}{\mathrm{d}y}$$







FCEL in pA quarkonium production



$x_{\mathrm{F}} > x_{\mathrm{F}}^{\mathrm{crit}}$
small $p_\perp$

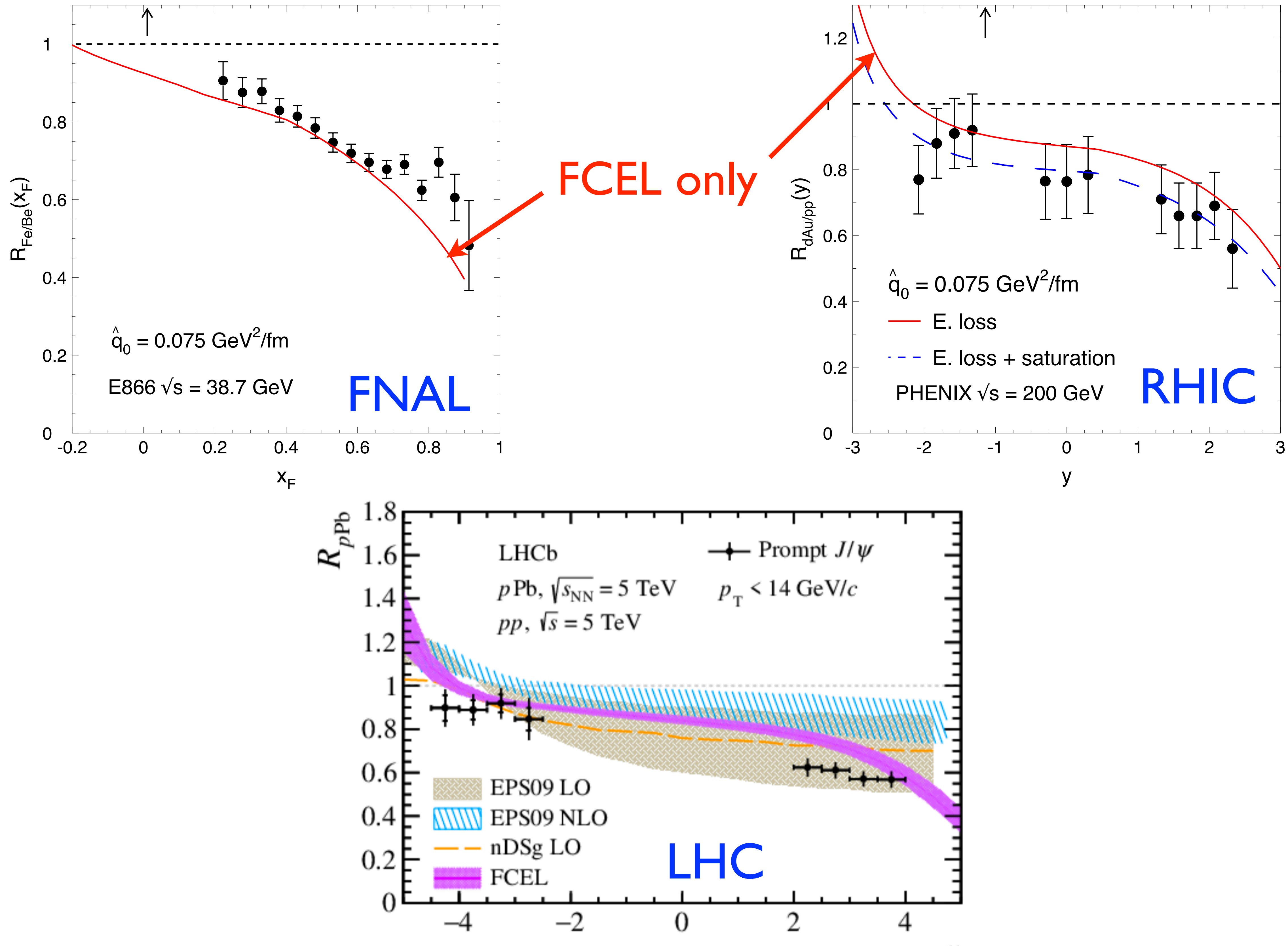
(CEM or COM at leading order)

→ FCEL associated to $1 \to 1$ process $g \to Q\bar{Q}\,[8]$

→ $C_1 + C_2 - C_t = N_c$ in $\dfrac{\mathrm{d}I}{\mathrm{d}x}$ and $\hat{\mathcal{P}}(x)$

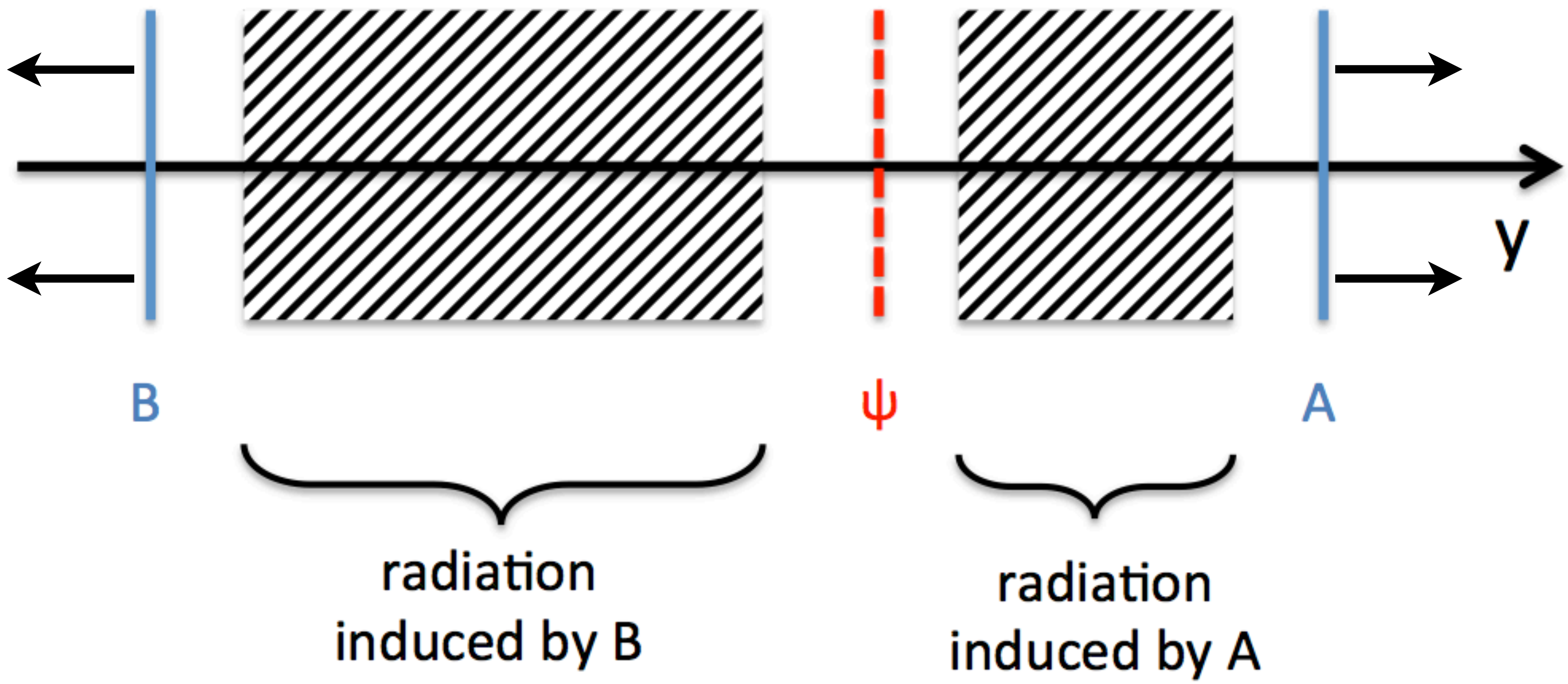
$$\Rightarrow R_{\mathrm{pA}}^{J/\psi}$$

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



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

FCEL effects on J/ψ suppression in AB collisions

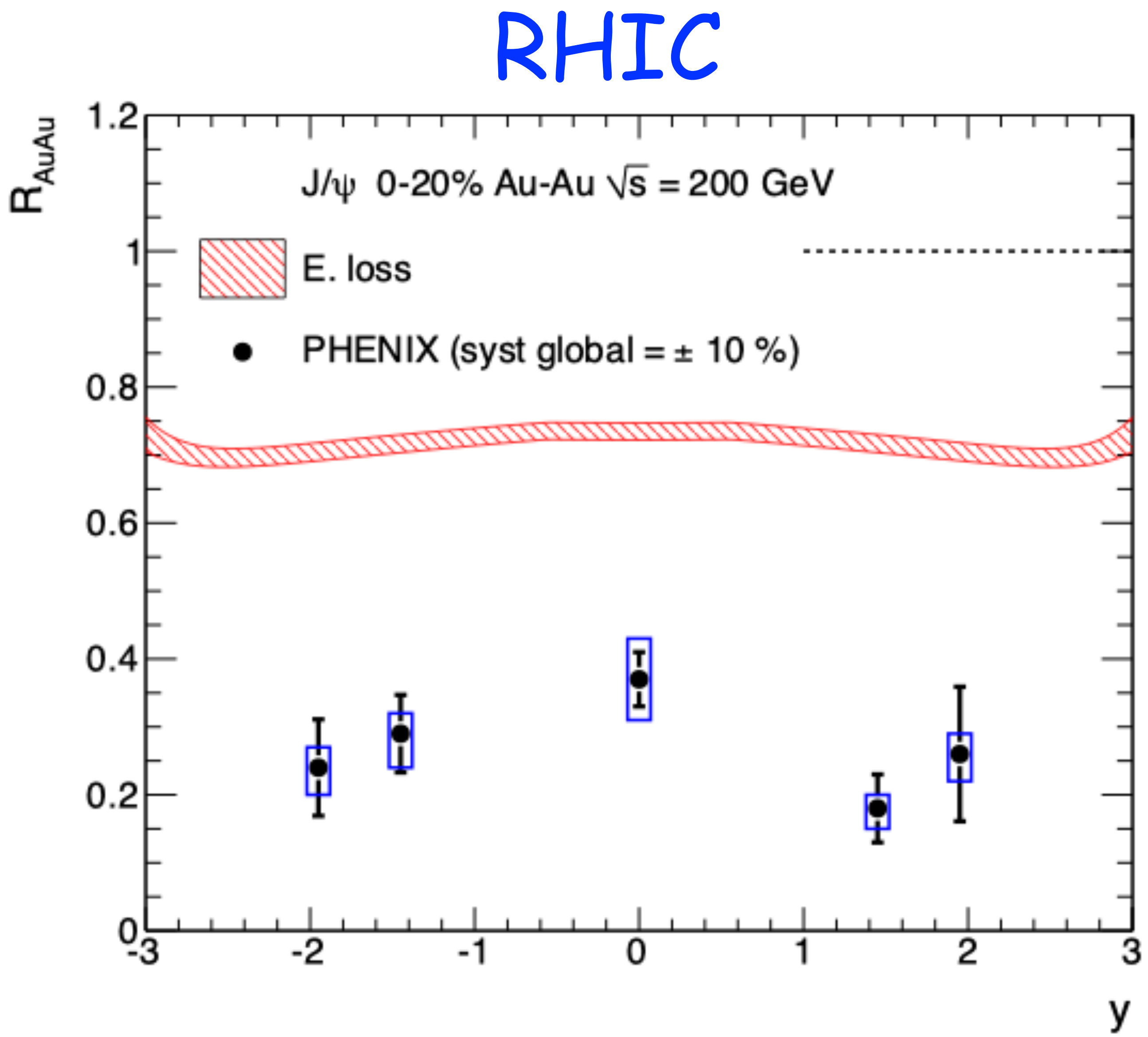


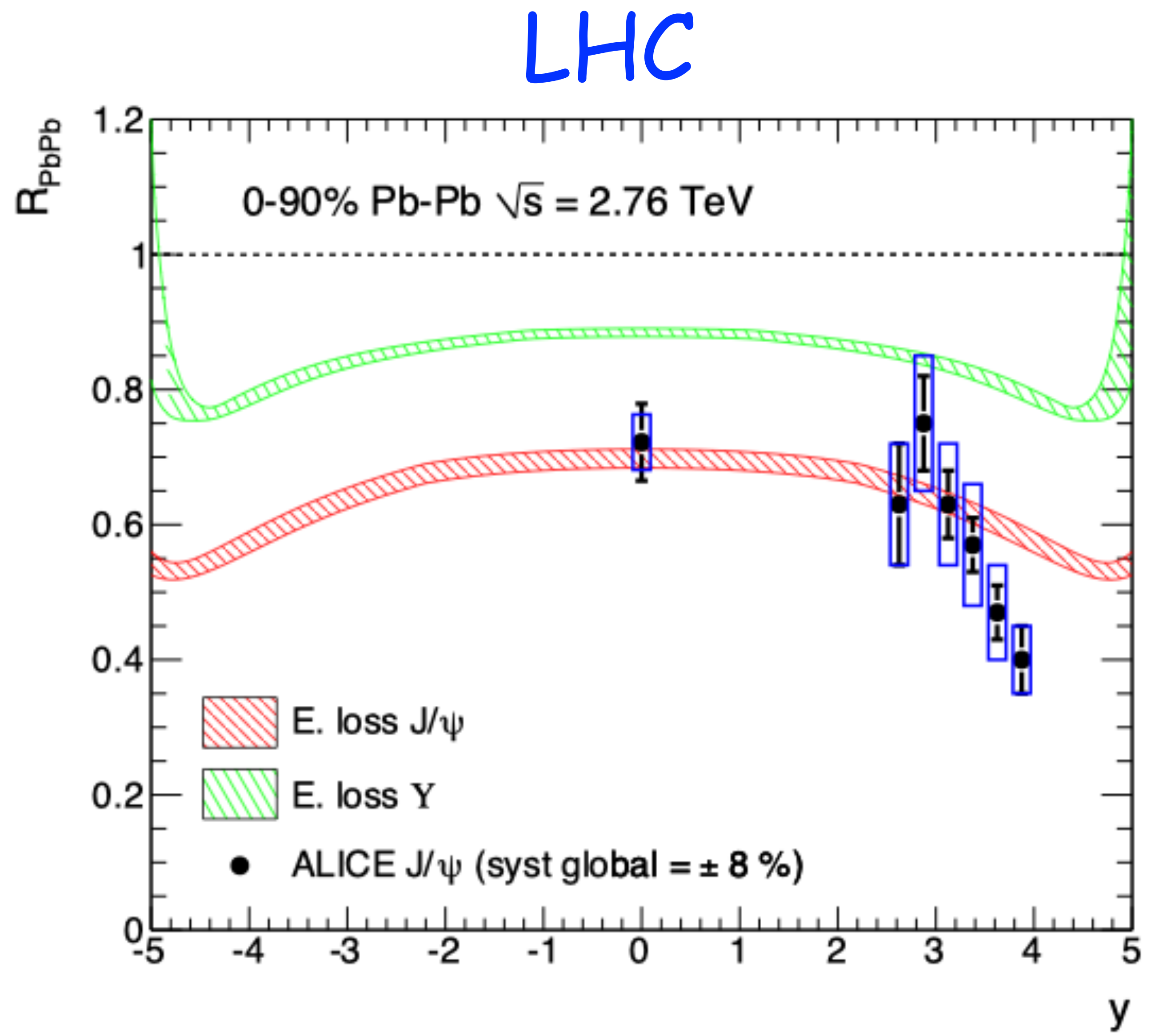
$$\frac{1}{AB}\frac{\mathrm{d}\sigma_{\mathrm{AB}}^{\psi}}{\mathrm{d}y}(y) = \int_0^{\delta y^{\max}(y)} \mathrm{d}\delta y_{\mathrm{B}}\, \hat{\mathcal{P}}_{\mathrm{B}}(\varepsilon_{\mathrm{B}}) \int_0^{\delta y^{\max}(-y)} \mathrm{d}\delta y_{\mathrm{A}}\, \hat{\mathcal{P}}_{\mathrm{A}}(\varepsilon_{\mathrm{A}}) \frac{\mathrm{d}\sigma_{\mathrm{pp}}^{\psi}}{\mathrm{d}y}(y + \delta y_{\mathrm{B}} - \delta y_{\mathrm{A}})$$

⟹ baseline for cold FCEL effect in AA

Arleo, S.P. JHEP 10 (2014) 073

J/ψ suppression in AB collisions

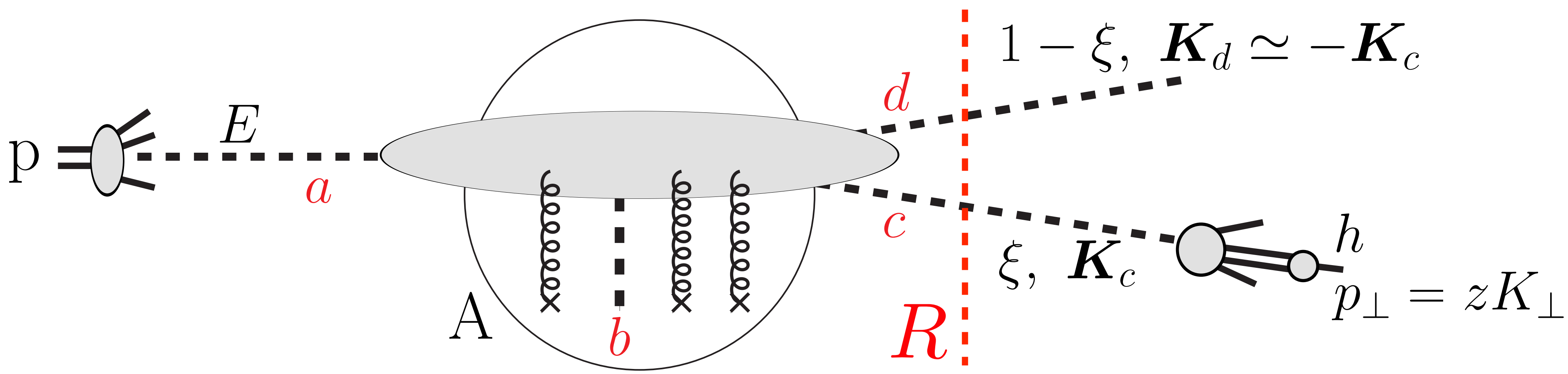




→ *cold* FCEL effect should not be ignored in AA

Arleo, S.P. JHEP 10 (2014) 073

$1 \to 2$ forward processes



$$\frac{\mathrm{d}\sigma^h_{\mathrm{pp}}(E_h)}{\mathrm{d}E_h} = \sum_R \int \mathrm{d}\xi\, \rho_R(\xi)\, \frac{\mathrm{d}\sigma^h_{\mathrm{pp}}(E_h,\xi)}{\mathrm{d}E_h\, \mathrm{d}\xi}$$

$$\rho_{\mathrm{R}}(\xi) = \frac{|\mathcal{M}_{\mathrm{hard}} \cdot \mathbb{P}_{\mathrm{R}}|^2}{|\mathcal{M}_{\mathrm{hard}}|^2}$$

$$\frac{1}{A}\frac{\mathrm{d}\sigma^h_{\mathrm{pA}}(y)}{\mathrm{d}y} = \int_0^{x_{\max}} \frac{\mathrm{d}x}{1+x} \int \mathrm{d}\xi \sum_{\mathrm{R}} \rho_{\mathrm{R}}(\xi)\, \hat{\mathcal{P}}_{\mathrm{R}}(x)\, \frac{\mathrm{d}\sigma^h_{\mathrm{pp}}(y+\ln(1+x),\xi)}{\mathrm{d}y\, \mathrm{d}\xi}$$

effective quenching weight

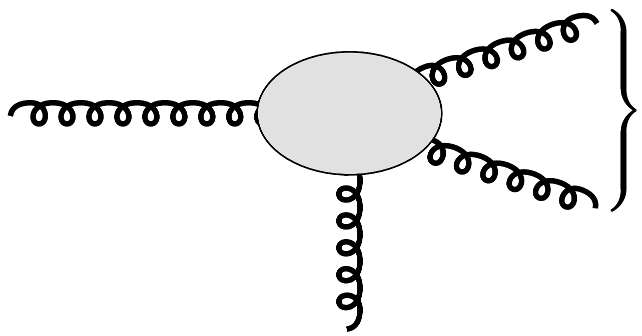
$$\hat{\mathcal{P}}_R(x) = \frac{\mathrm{d}I_R}{\mathrm{d}x} \exp\left\{ -\int_x^\infty \mathrm{d}x' \frac{\mathrm{d}I_R}{\mathrm{d}x'} \right\}$$

$$\propto (C_a + C_R - C_b)$$

FCEL in light hadron production

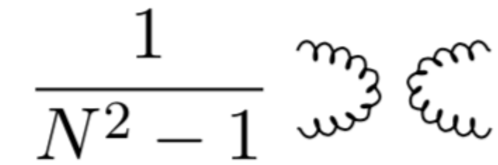
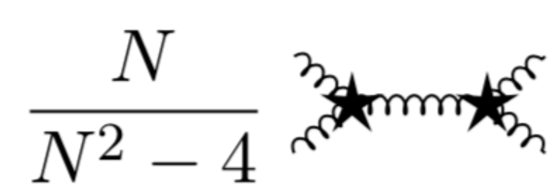
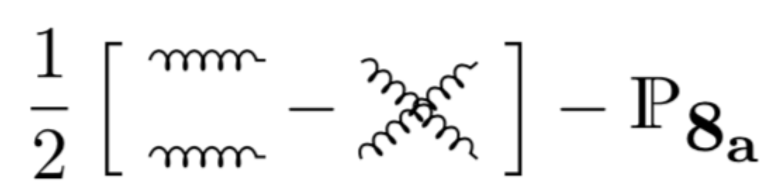
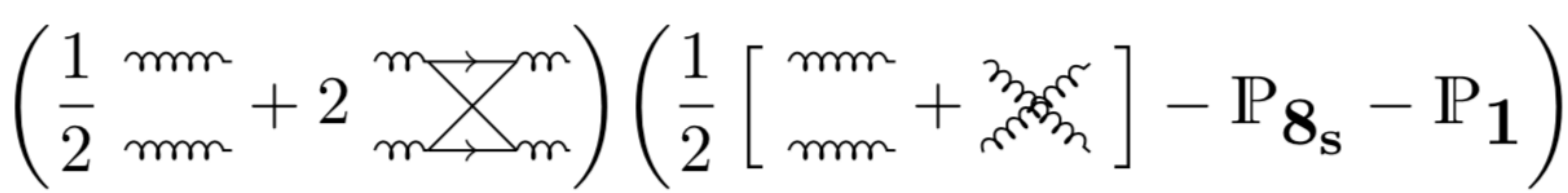
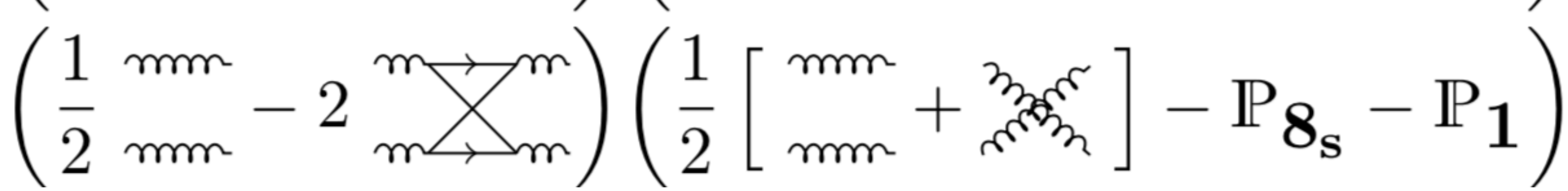
Arleo, Cougoulic, S.P. JHEP 09 (2020) 190

- assume one dominant channel: $g \to gg$



$$8 \otimes 8 \overset{(\mathrm{SU}(N_c))}{=} \mathbf{1} \oplus \mathbf{8_s} \oplus \mathbf{8_a} \oplus (\mathbf{10} \oplus \overline{\mathbf{10}}) \oplus \mathbf{27} \oplus \mathbf{0}$$

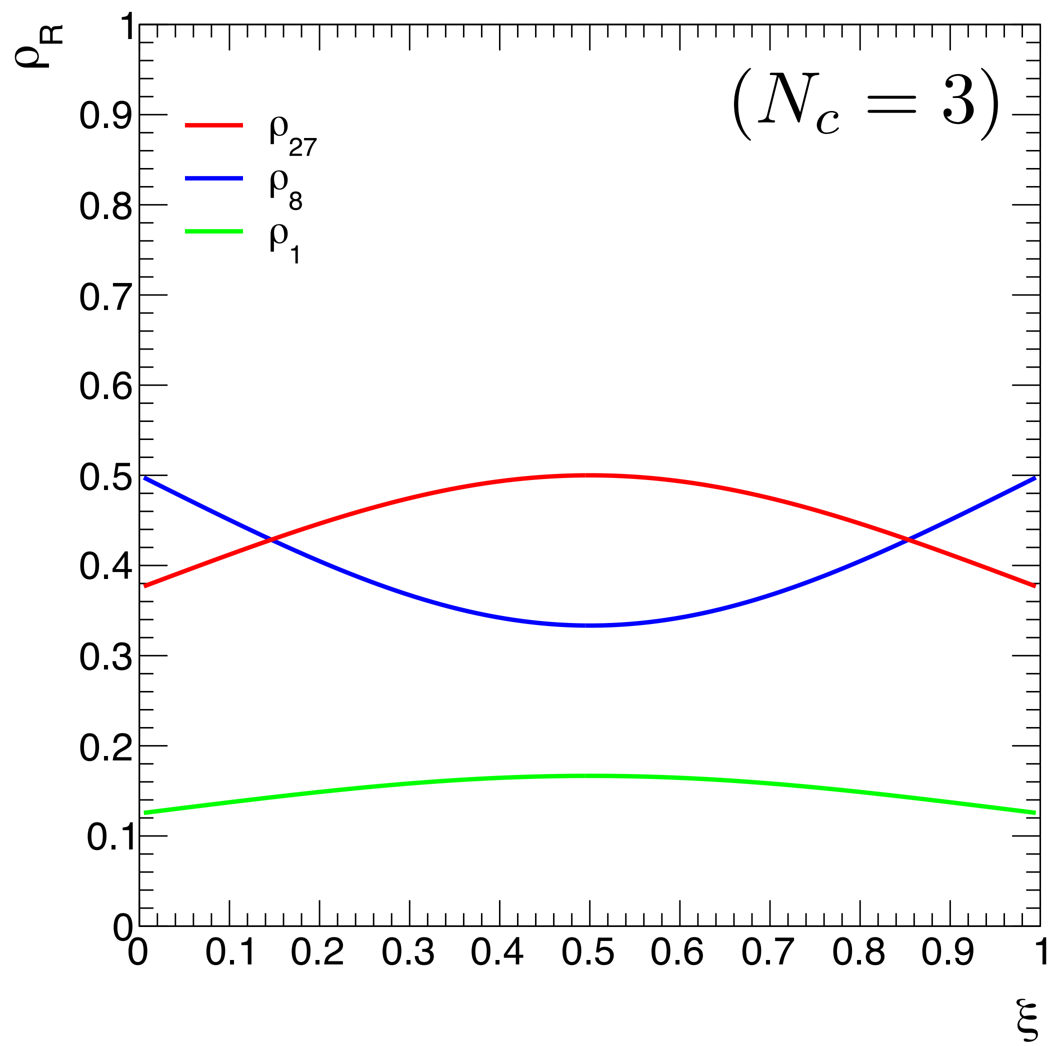
color projectors $\mathbb{P}_{\mathrm{R}}$

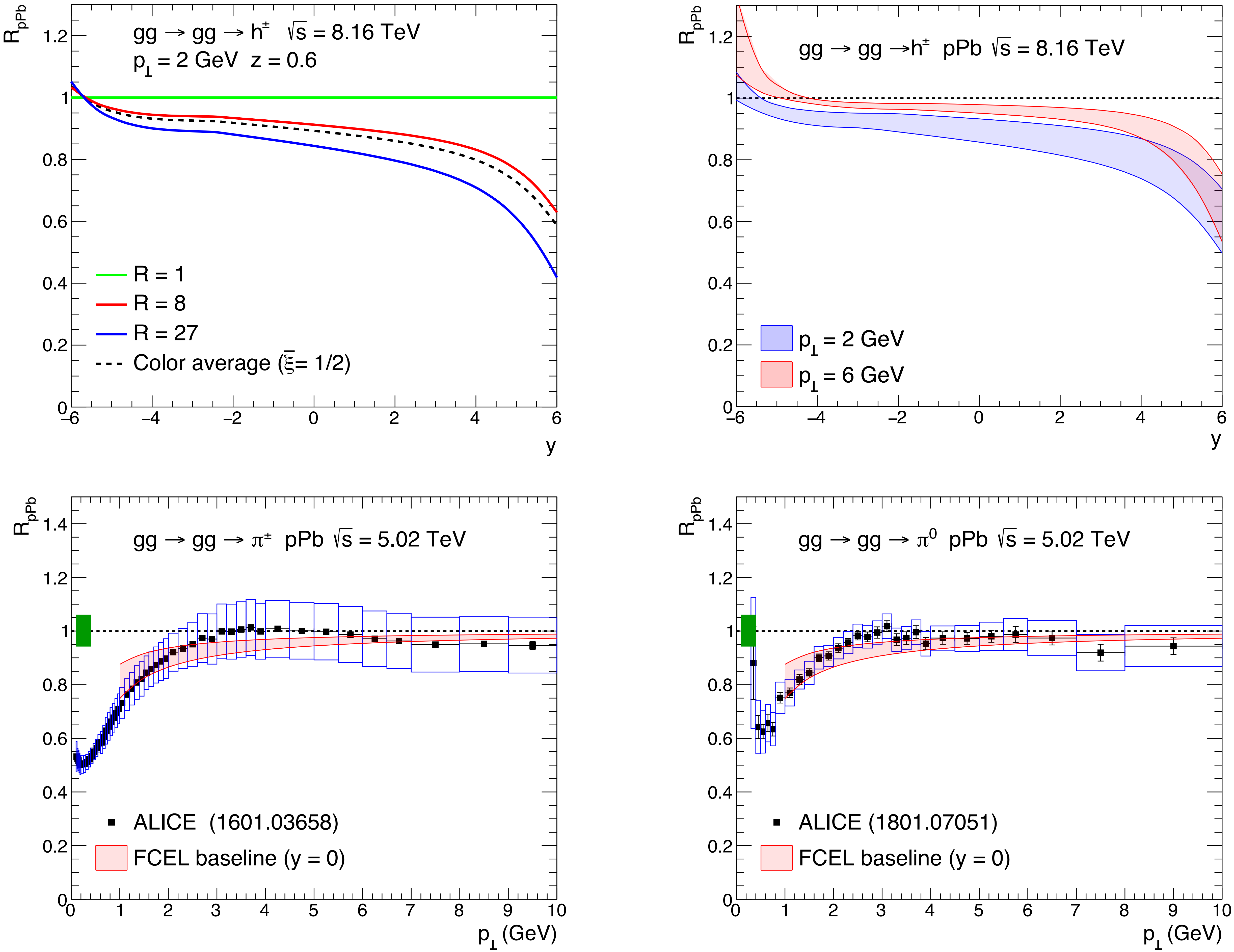
$\mathbf{1}$	
$\mathbf{8_a}$	
$\mathbf{8_s}$	
$\mathbf{10} \oplus \overline{\mathbf{10}}$	
$\mathbf{27}$	
$\mathbf{0}$	

color probabilities $\rho_{\mathrm{R}}(\xi) = \frac{|\mathcal{M}_{\mathrm{hard}} \cdot \mathbb{P}_{\mathrm{R}}|^2}{|\mathcal{M}_{\mathrm{hard}}|^2}$

$$\rho_{\mathbf{8_a}} = \frac{\xi^2 + (1-\xi)^2 - 1/2}{1 + \xi^2 + (1-\xi)^2} \quad ; \quad \rho_{\mathbf{10}} = 0 \quad ; \quad \rho_{\mathbf{8_s}} = \frac{1/2}{1 + \xi^2 + (1-\xi)^2} \quad ;$$

$$\rho_{\mathbf{1}} = \frac{4}{N_c^2 - 1}\rho_{\mathbf{8_s}} \quad ; \quad \rho_{\mathbf{27}} = \frac{N_c + 3}{N_c + 1}\rho_{\mathbf{8_s}} \quad ; \quad \rho_{\mathbf{0}} = \frac{N_c - 3}{N_c - 1}\rho_{\mathbf{8_s}} \quad .$$

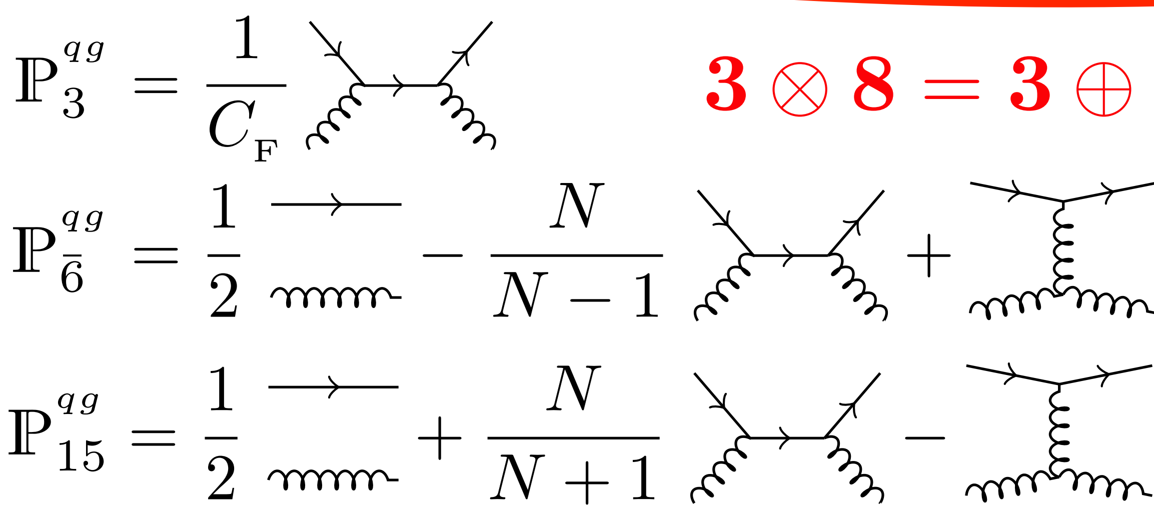




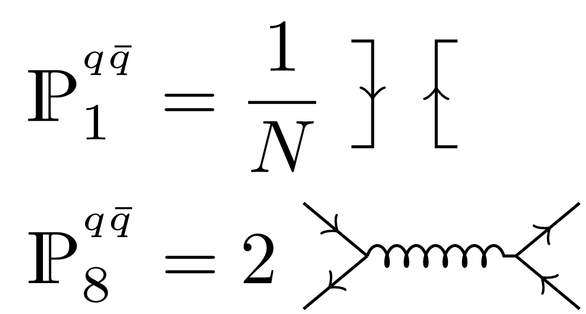
$gg \to gg \to h^{\pm}$ $\sqrt{s}$ = 8.16 TeV
$p_\perp$ = 2 GeV z = 0.6
R = 1
R = 8
R = 27
Color average ($\bar{\xi}$= 1/2)
R_{pPb}
y
$gg \to gg \to h^{\pm}$ pPb $\sqrt{s}$ = 8.16 TeV
$p_\perp$ = 2 GeV
$p_\perp$ = 6 GeV
$gg \to gg \to \pi^{\pm}$ pPb $\sqrt{s}$ = 5.02 TeV
ALICE (1601.03658)
FCEL baseline (y = 0)
$p_\perp$ (GeV)
$gg \to gg \to \pi^{0}$ pPb $\sqrt{s}$ = 5.02 TeV
ALICE (1801.07051)
FCEL baseline (y = 0)

- other channels : $q(+g) \to qg\,,\ g(+q) \to qg\,,\ g(+g) \to q\bar{q}$

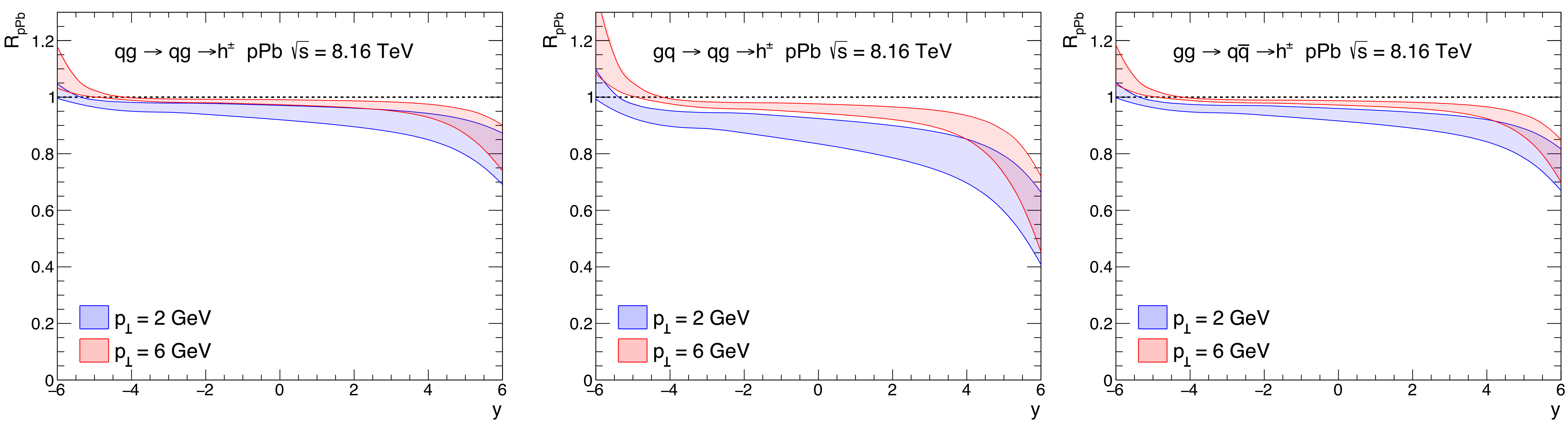
$\mathbf{3 \otimes 8 = 3 \oplus \bar{6} \oplus 15}$



$\mathbf{3 \otimes \bar{3} = 1 \oplus 8}$



$q(g) \to qg \qquad g(q) \to qg \qquad g(g) \to q\bar{q}$

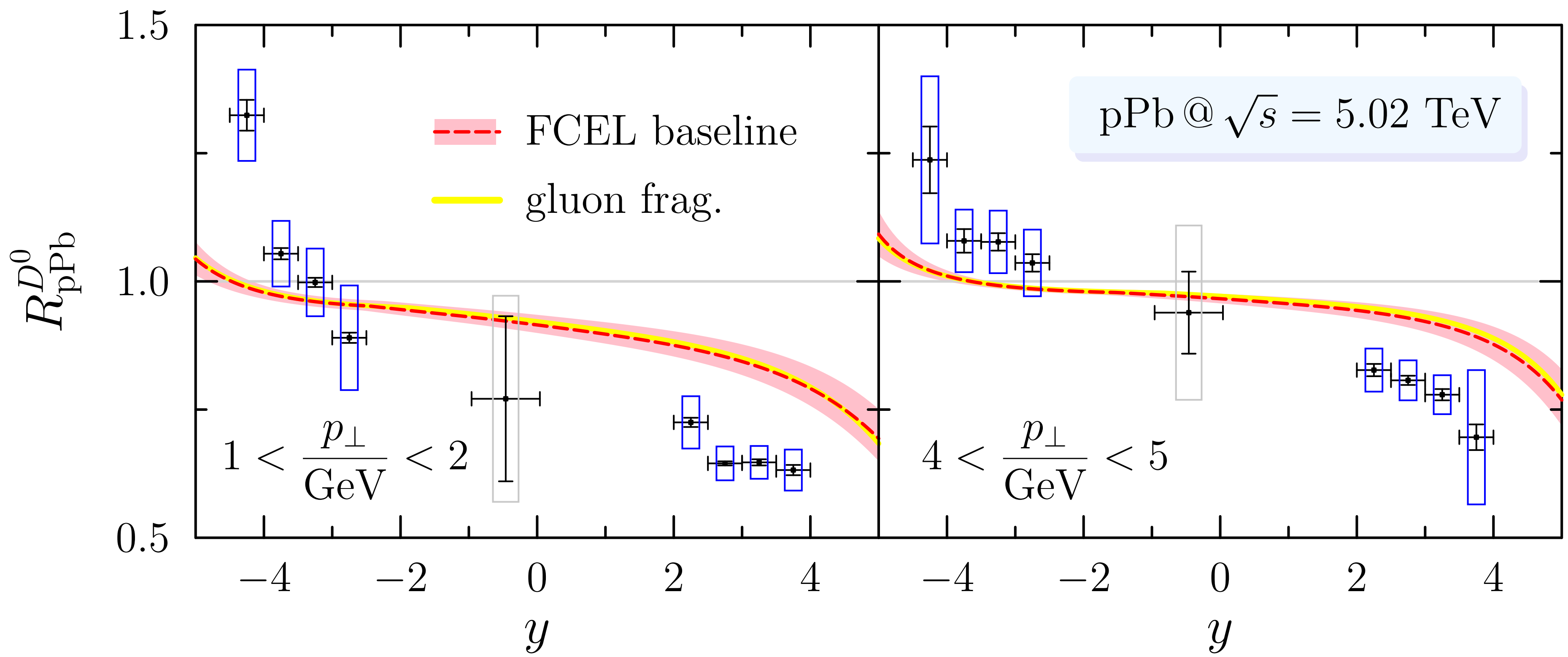


FCEL effect qualitatively similar for all partonic channels

FCEL in heavy flavour production

Arleo, Jackson, S.P. JHEP 01 (2022) 164

- dominant channel at LO : $g(+g) \to Q\bar{Q}$ $\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$



Aaij et al [**LHCb**], JHEP 10 (2017) 090

Abelev et al [**ALICE**], PRL 113 (2014) 232301

- some generic NLO channel : $g(+g) \to gG \to gQ\bar{Q}$

larger $M_{\rm dijet} \Rightarrow R_{\rm pA} \nearrow$ **vs** larger $\langle C_R \rangle \Rightarrow R_{\rm pA} \searrow$

→ *no qualitative change expected from NLO channels*

Summary

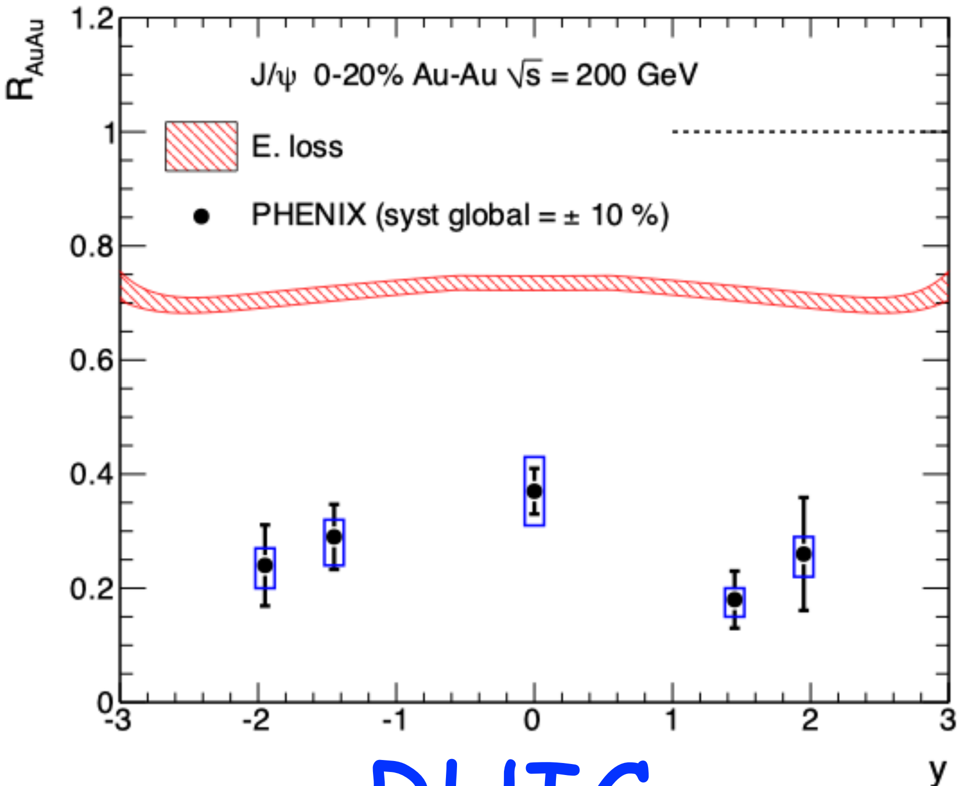
- FCEL is a QCD prediction and a significant effect :
  - contributes to *substantial* hadron suppression in pA
    from fixed target to LHC energies
  - is a sizable cold nuclear effect in AA
- FCEL predictions have a small theoretical uncertainty
  (*FCEL spectrum fully determined within pQCD*)
- FCEL at least as important as nPDF effects

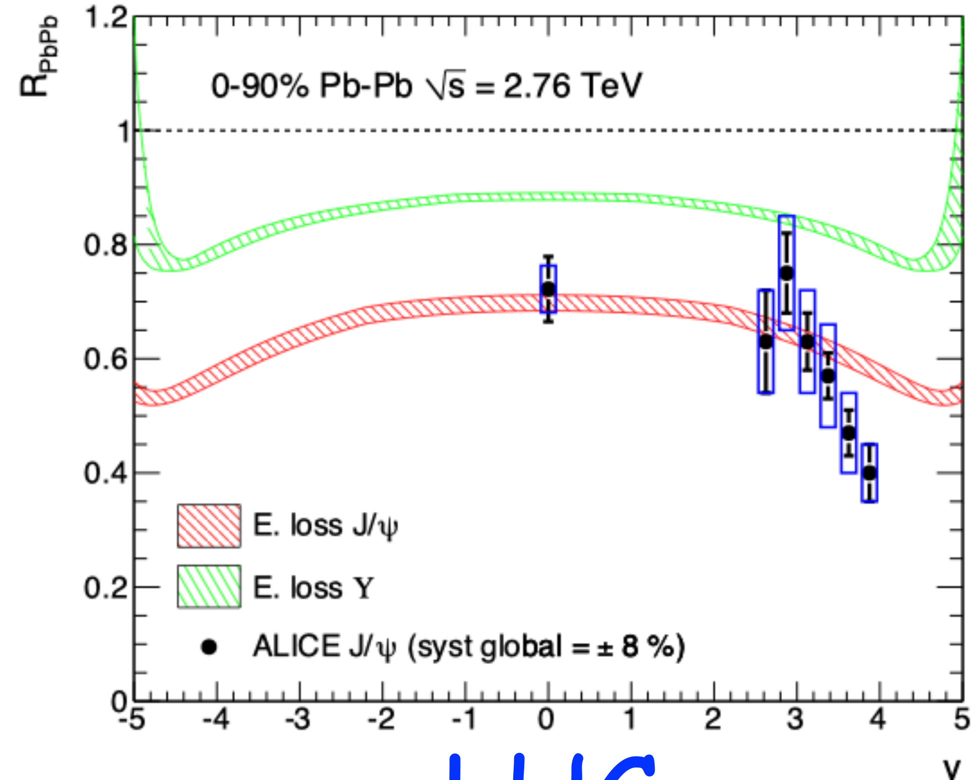
Outlook

- include FCEL in pA *before* extraction of nPDF sets
- include FCEL in AA before extraction of QGP effects

Backup

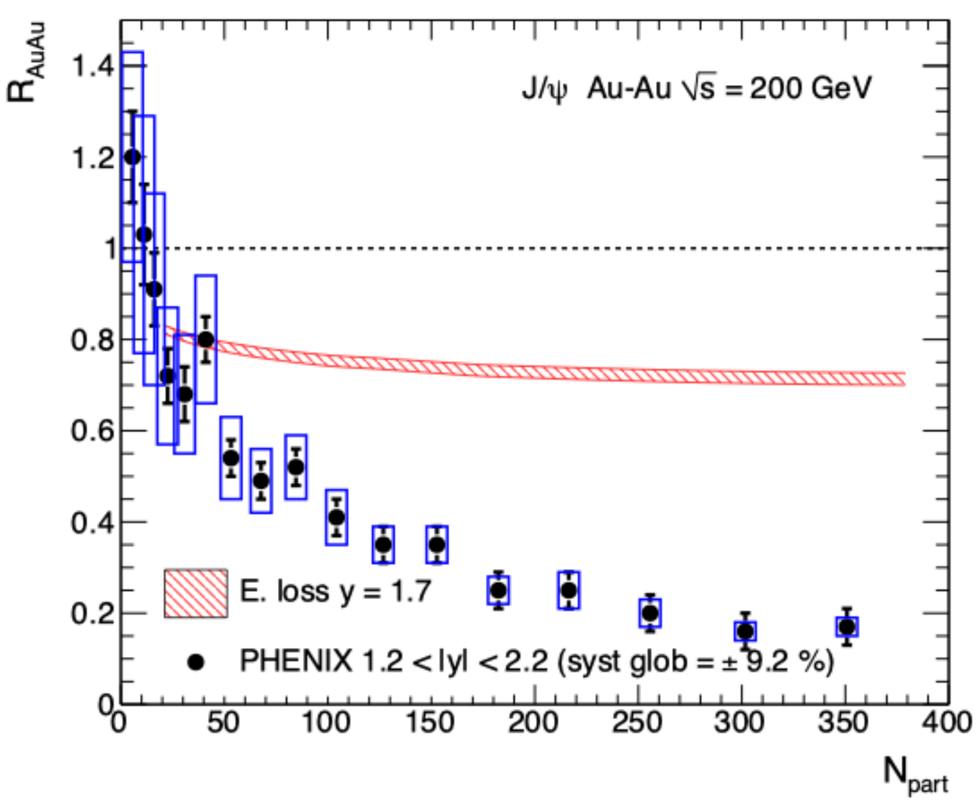
J/ψ suppression in AB collisions

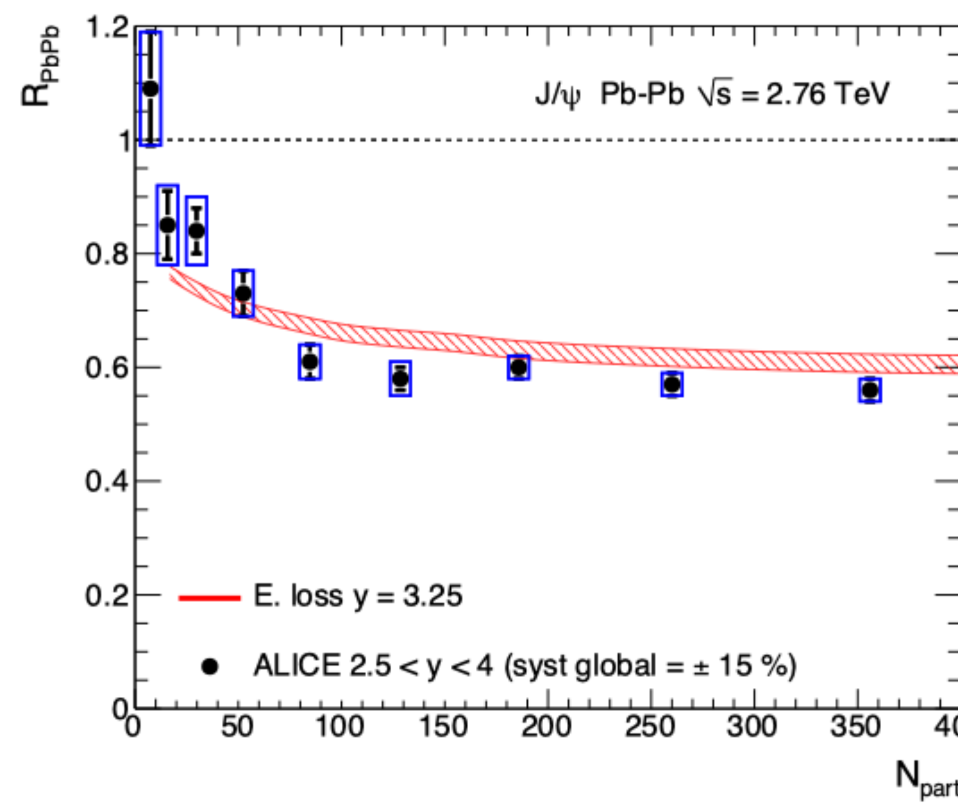




RHIC

LHC





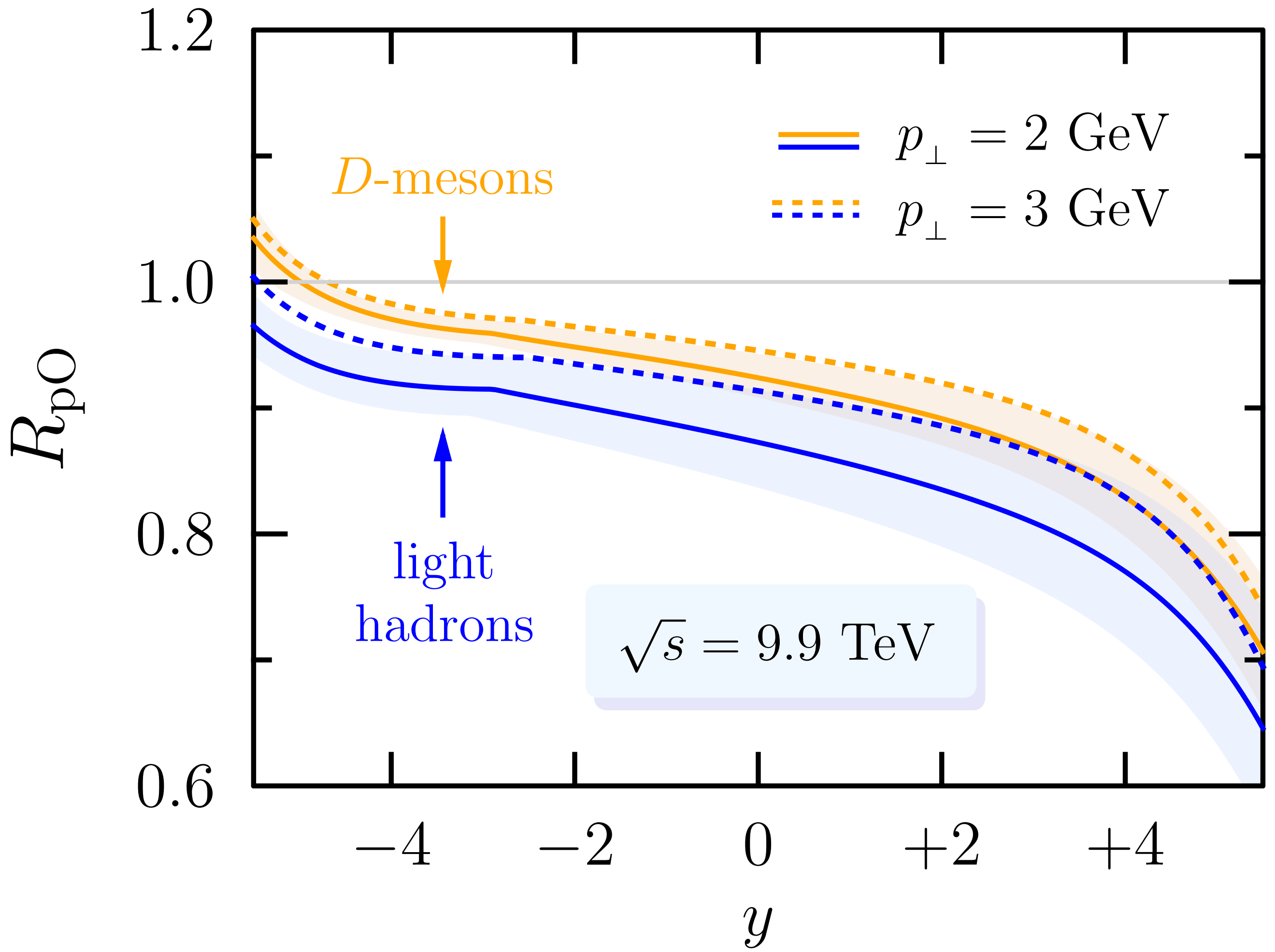
→ **sizeable cold energy loss effect in AA**

FCEL predictions for pO collisions at LHC

Arleo, Jackson, S.P. PLB 835 (2022)

- plan for pO run at LHC $\sqrt{s_{\rm NN}}({\rm pO}) = 9.9\ {\rm TeV}$

(program review in: Brewer et al, arXiv:2103.01939)



FCEL also substantial in proton collisions on *light* ions

$$\Delta E \propto \alpha_s \frac{\sqrt{\hat{q}L}}{K_\perp} E \propto A^{1/6}$$

→ FCEL in collisions of cosmic rays with air nuclei

$$(\sqrt{s_{\rm NN}} = 9.9\ {\rm TeV} \ \Rightarrow\ E_{\rm p} \simeq 5\times 10^7\ {\rm GeV})$$

parametrization of light hadron pp cross section

$$\frac{\mathrm{d}\sigma_{\mathrm{pp}}}{2\pi p_\perp \,\mathrm{d}p_\perp \,\mathrm{d}y} \propto \left(\frac{p_0^2}{p_0^2 + p_\perp^2}\right)^m \times \left(1 - \frac{2\ p_\perp}{\sqrt{s}} \cosh y\right)^n$$

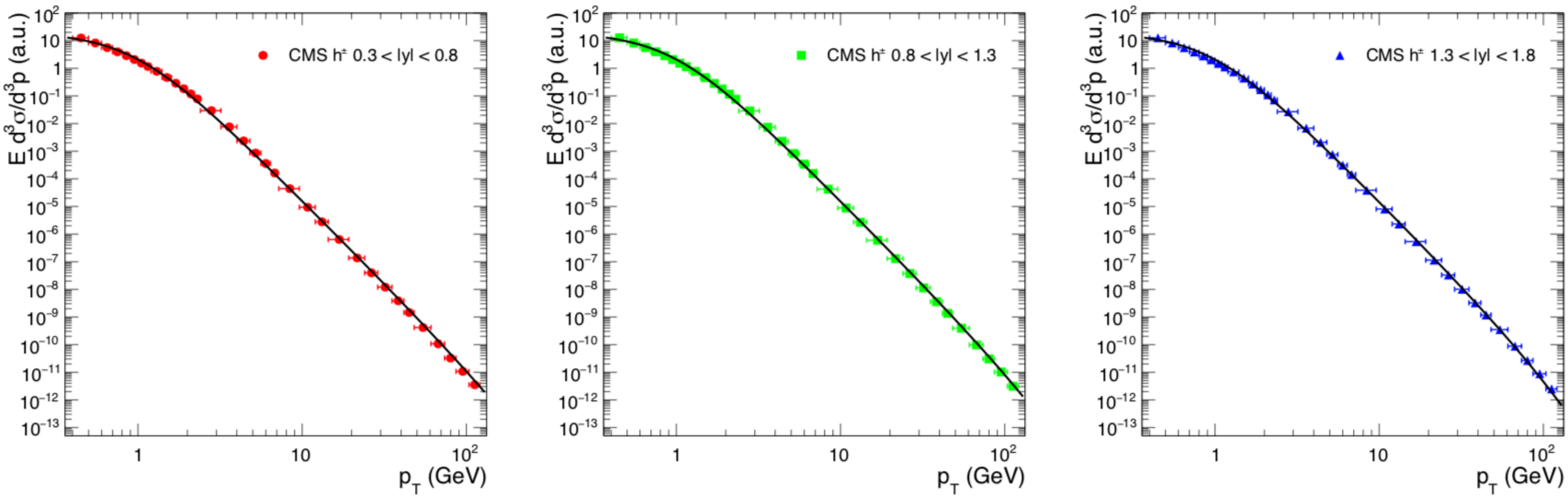
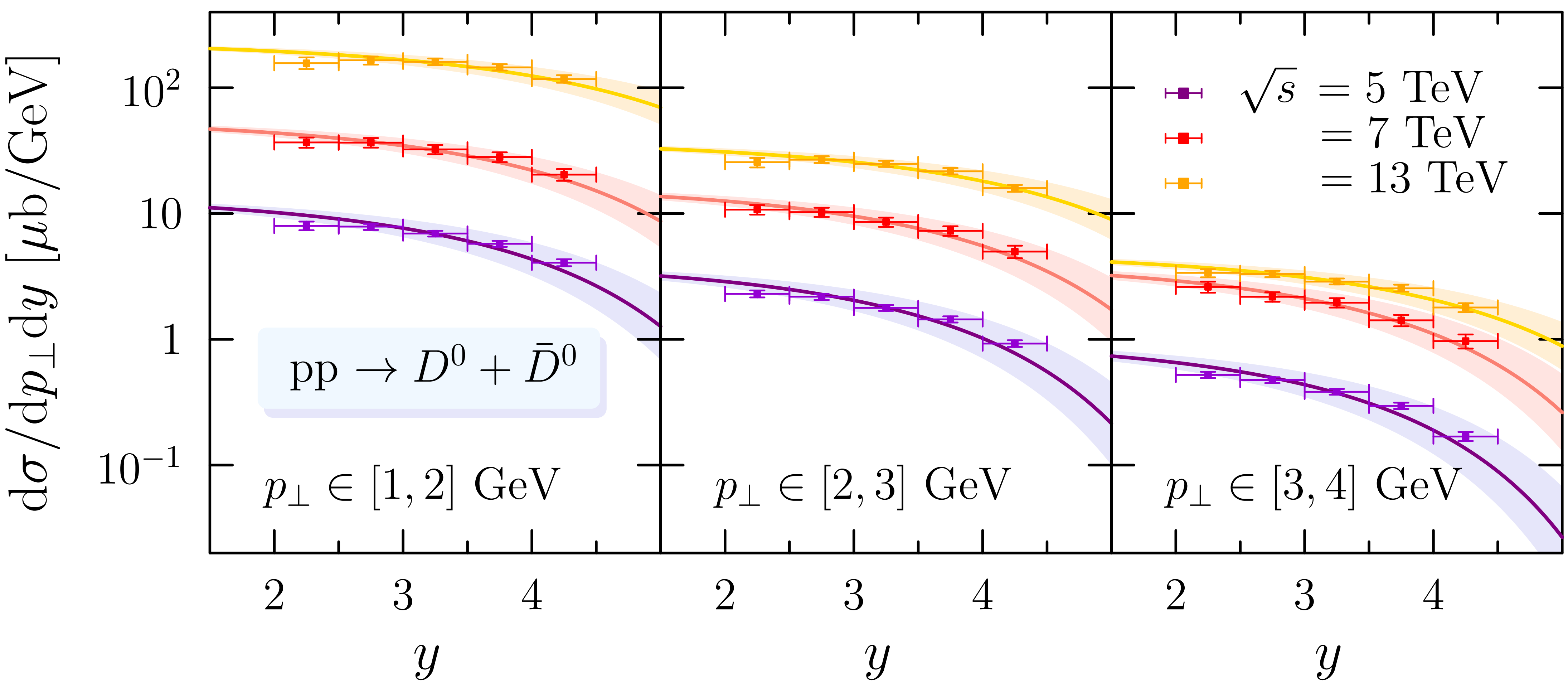


Figure 10. Charged hadron spectra measured by CMS in pPb collisions at $\sqrt{s} = 5.02$ TeV in the rapidity ranges $0.3 < |y| < 0.8$ (left), $0.8 < |y| < 1.3$ (center), $1.3 < |y| < 1.8$ (right) [72], compared to the parametrization (C.1).

Arleo, Cougoulic, S.P. JHEP 09 (2020) 190

parametrization of heavy meson pp cross section

$$\frac{d\sigma^H_{pp}}{dy\,dp_\perp} = \mathcal{N}(p_\perp)\left[(1-\chi)(1-\sqrt{\chi})\right]^n, \quad \chi \equiv 4\left(\frac{p_\perp^2+\mu_H^2}{s}\right)^{\frac{1}{2}}\cosh y$$



(LHCb pp data)

Arleo, Jackson, S.P. JHEP 01 (2022) 164

transport coefficient $\hat{q}$

$\hat{q} \propto xG(x)$ Baier et al (1997)

$xG(x) \sim x^{-\lambda}$ $(\lambda = 0.3)$ at small x

Golec-Biernat, Wüsthoff (1998)

(for lead nucleus)

$$\Rightarrow \begin{cases} \hat{q} = \hat{q}(x_2) = \hat{q}_0 \left(\dfrac{10^{-2}}{x_2} \right)^{0.3} & \text{for } x_2 < 10^{-2} \\ \hat{q} = \hat{q}_0 \ \text{for } x_2 > 10^{-2} & \end{cases}$$

$\hat{q}_0 = 0.07 \pm 0.02 \ \mathrm{GeV^2/fm}$ consistent with :

- $Q^2_{sp}(x = 10^{-2}) = 0.11 - 0.14 \ \mathrm{GeV^2}$ Albacete et al (2011)
- HERMES semi-inclusive eA DIS data Brooks, Lopez (2021)