Fully Coherent Energy Loss: from collider to cosmic ray energies

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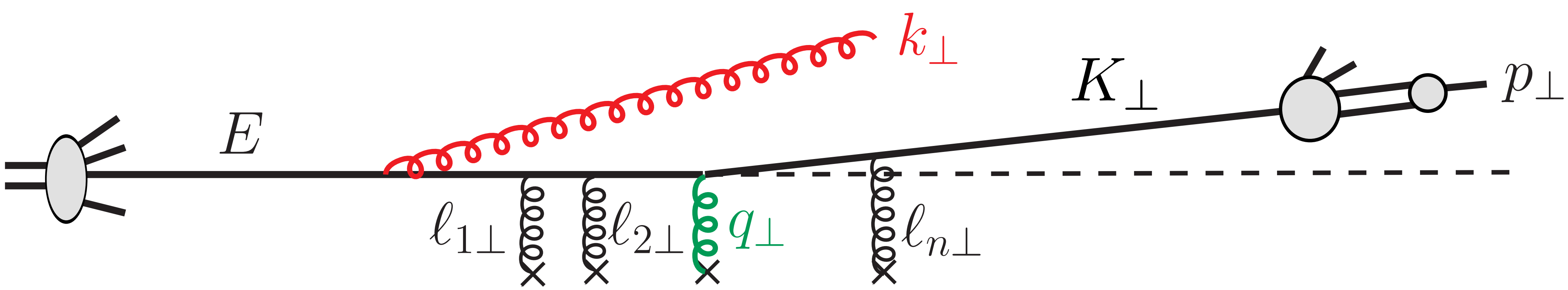
Program

- Recap on Fully Coherent Energy Loss (FCEL)
- FCEL effects on hadron suppression in pA collisions
- FCEL effects on atmospheric neutrino fluxes

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

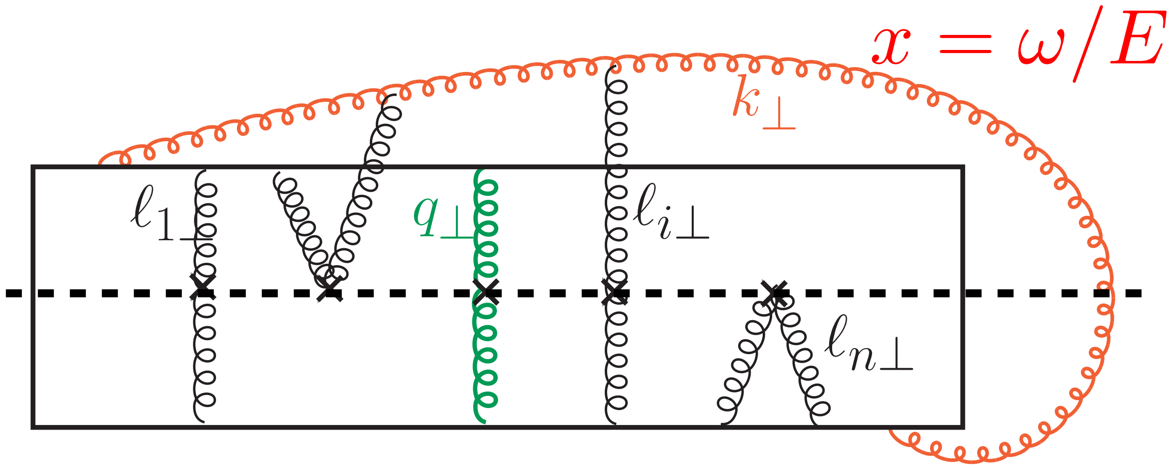
typical situation : hadron production in pA collisions

$1 \to 1$ 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 $\ell_\perp^2 = \left(\sum \vec{\ell}_{i\perp}\right)^2 \sim \underline{\hat{q}L \sim Q_s^2} \ll K_\perp^2$

$\longrightarrow$ *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

$$\Delta E = E\int_0^1 {\rm d}x\, x\frac{{\rm d}I}{{\rm d}x} \propto \alpha_s \frac{\sqrt{\hat{q}L}}{K_\perp} E$$

one main parameter

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

$xG(x) \sim x^{-\lambda} \quad (\lambda = 0.3)$ Golec-Biernat, Wüsthoff (1998)

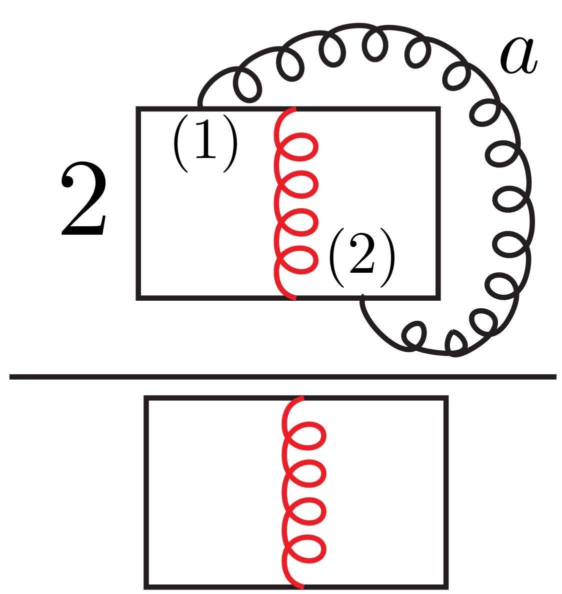
$$\Rightarrow \hat{q}(x_2) \equiv \hat{q}_0 \left(\frac{10^{-2}}{x_2}\right)^{0.3}$$

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

$\hat{q}_0$ consistent with :

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

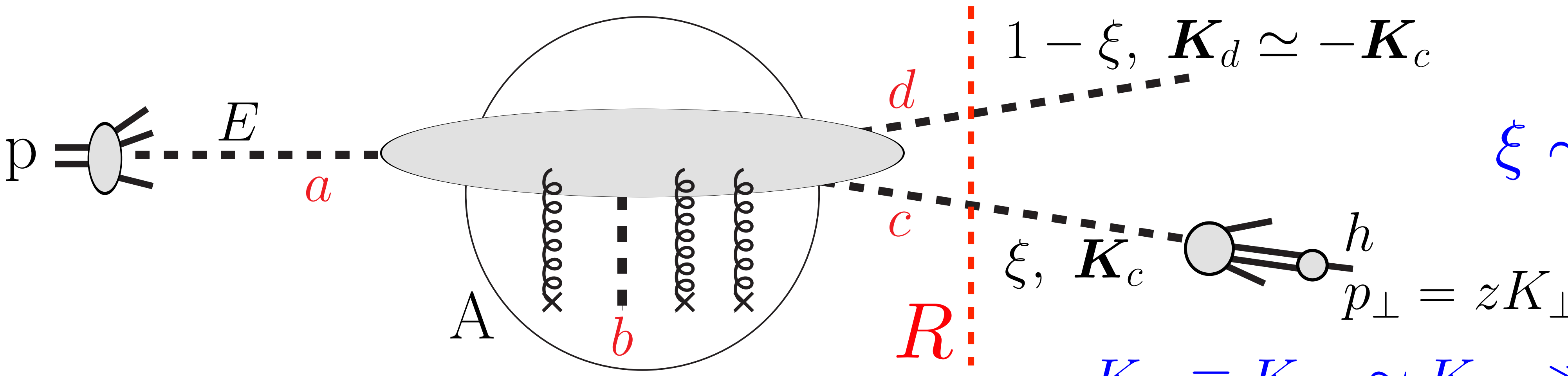
general rule for color factor



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

$$= C_1 + C_2 - C_t$$

$1 \to 2$ 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 $1 \to 1$

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

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

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

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

FCEL spectrum is an established, first-principle result

$1 \to 1$ forward processes

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

FCEL spectrum is an established, first-principle result

$1 \to 2$ 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 $1 \to 2$ partonic channels
  - matching with $1 \to 1 \;\; (\text{limit } \xi \to 0)$
  - beyond leading-log

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

- FCEL = consequence of first principles

  FCEL spectrum fully determined within pQCD

  $\longrightarrow$ small theoretical uncertainty

- $\Delta E \propto E$ $\longrightarrow$ 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

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

quenching weight

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

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

proba to radiate ε

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

justified in DLA

$\omega \mathrm{d}I/\mathrm{d}\omega$ 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** $y \equiv \frac{1}{2} \ln \frac{E+p^z}{E-p^z} = \ln \frac{E+p^z}{M_\perp} \simeq \ln \frac{2E}{M_\perp}$

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

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

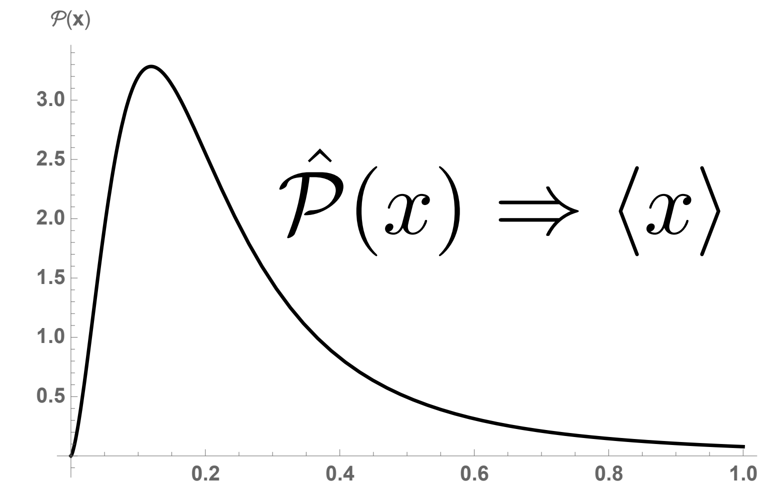
$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}(y)}{\mathrm{d}y} = \int_0^{x_{\max}} \mathrm{d}x \, \frac{\hat{\mathcal{P}}(x)}{1+x} \, \frac{\mathrm{d}\sigma_{\mathrm{pp}}\left(y + \ln\left(1+x\right)\right)}{\mathrm{d}y}$$

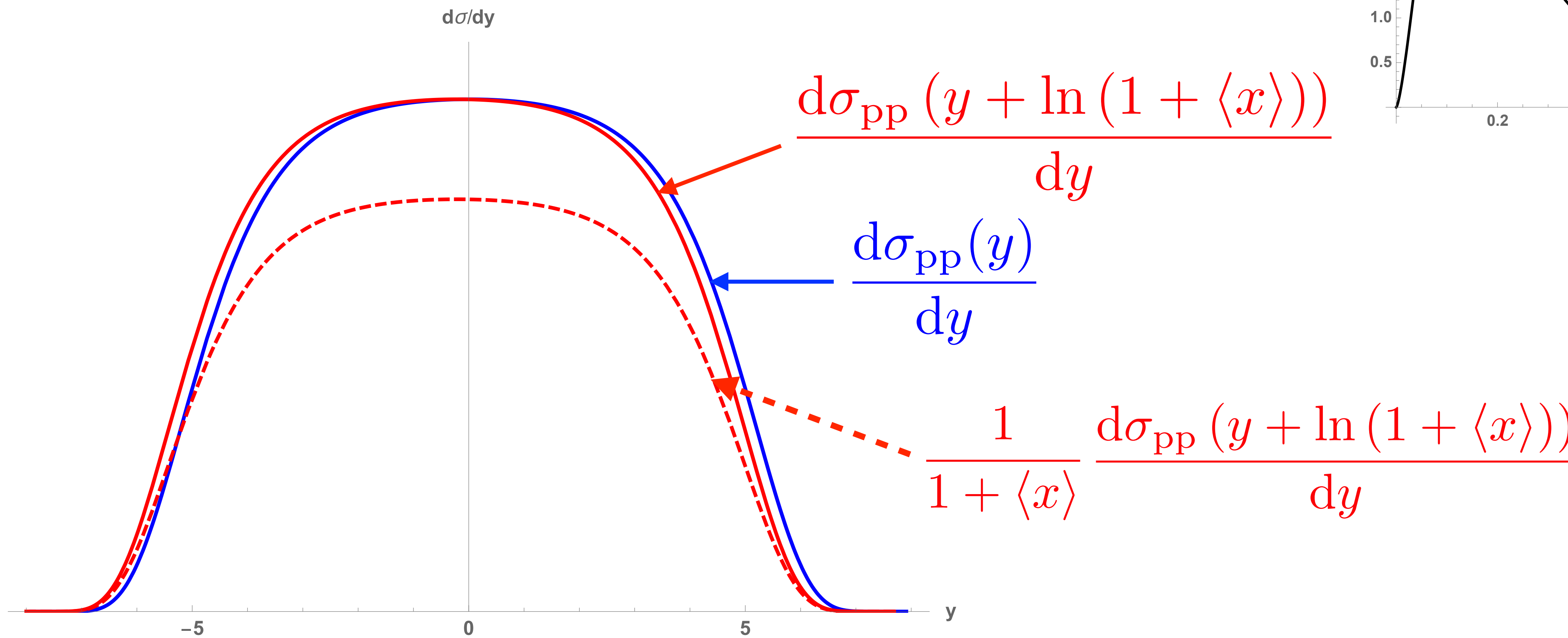
Goal:

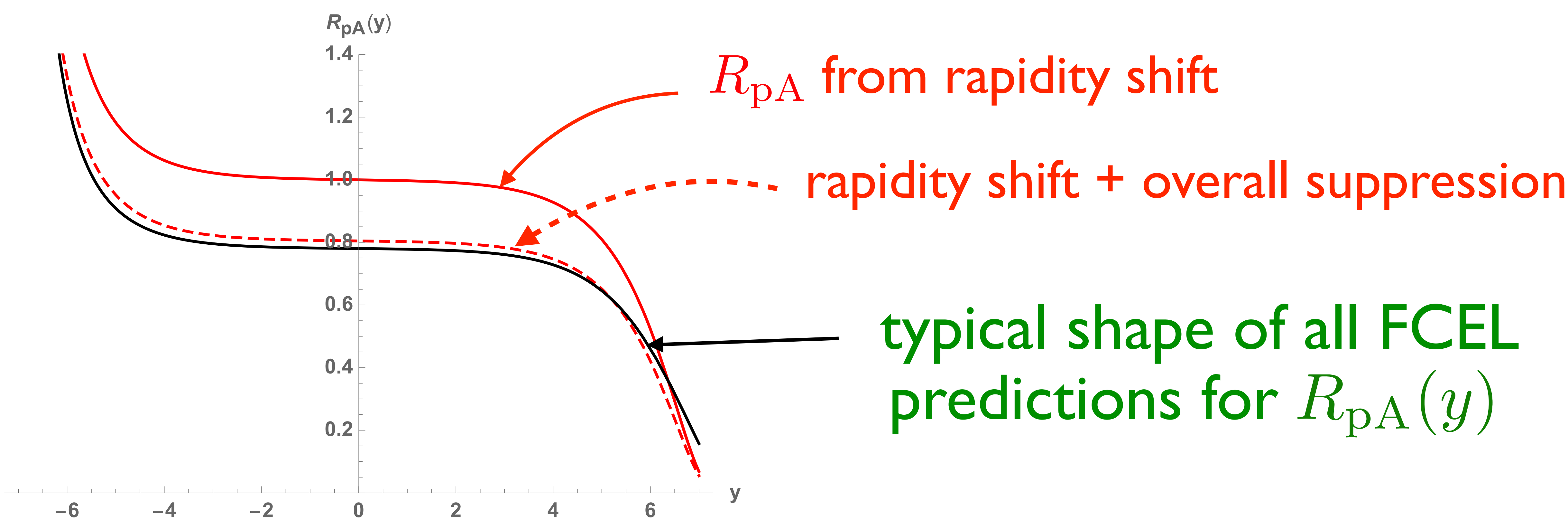
- *knowing* $\mathrm{d}\sigma_{\mathrm{pp}}$, which $\mathrm{d}\sigma_{\mathrm{pA}}$ to expect from *sole* FCEL effect ?
  - $\mathrm{d}\sigma_{\mathrm{pp}}$ taken as parametrization of pp data
  - $\hat{\mathcal{P}}(x)$ theoretical input
- don't predict absolute cross sections, but the *ratio* R_{pA}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

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

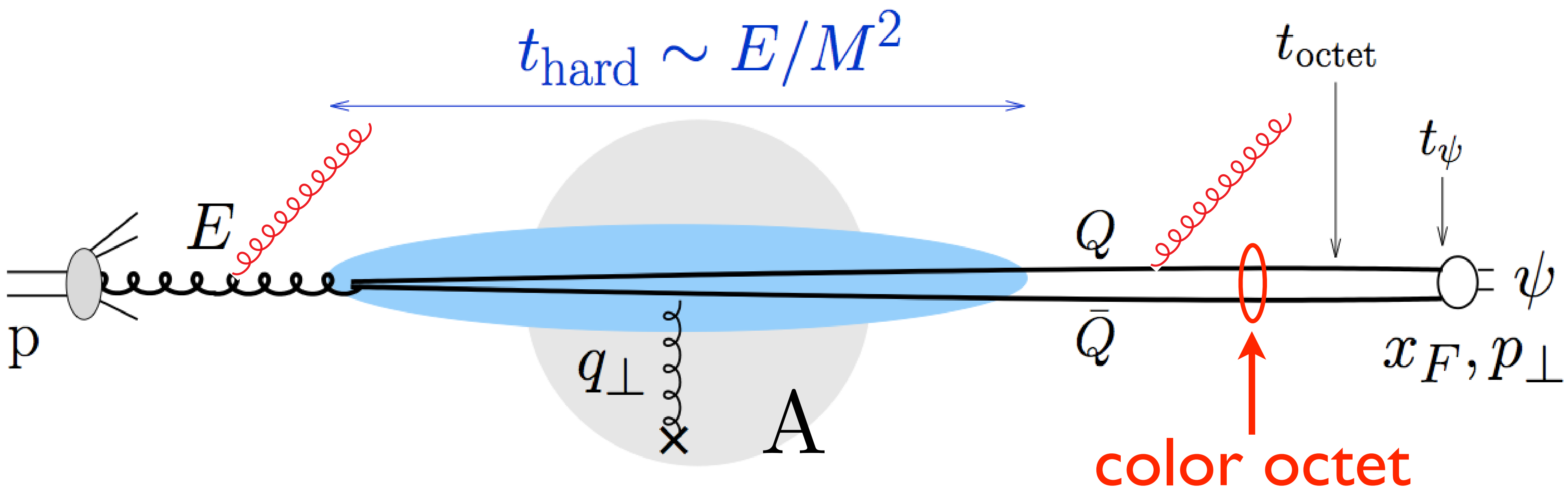
$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}(y)}{\mathrm{d}y} = \int_0^{x_{\max}} \mathrm{d}x \, \frac{\hat{\mathcal{P}}(x)}{1+x} \, \frac{\mathrm{d}\sigma_{\mathrm{pp}}\left(y+\ln\left(1+x\right)\right)}{\mathrm{d}y}$$







FCEL in quarkonium production



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

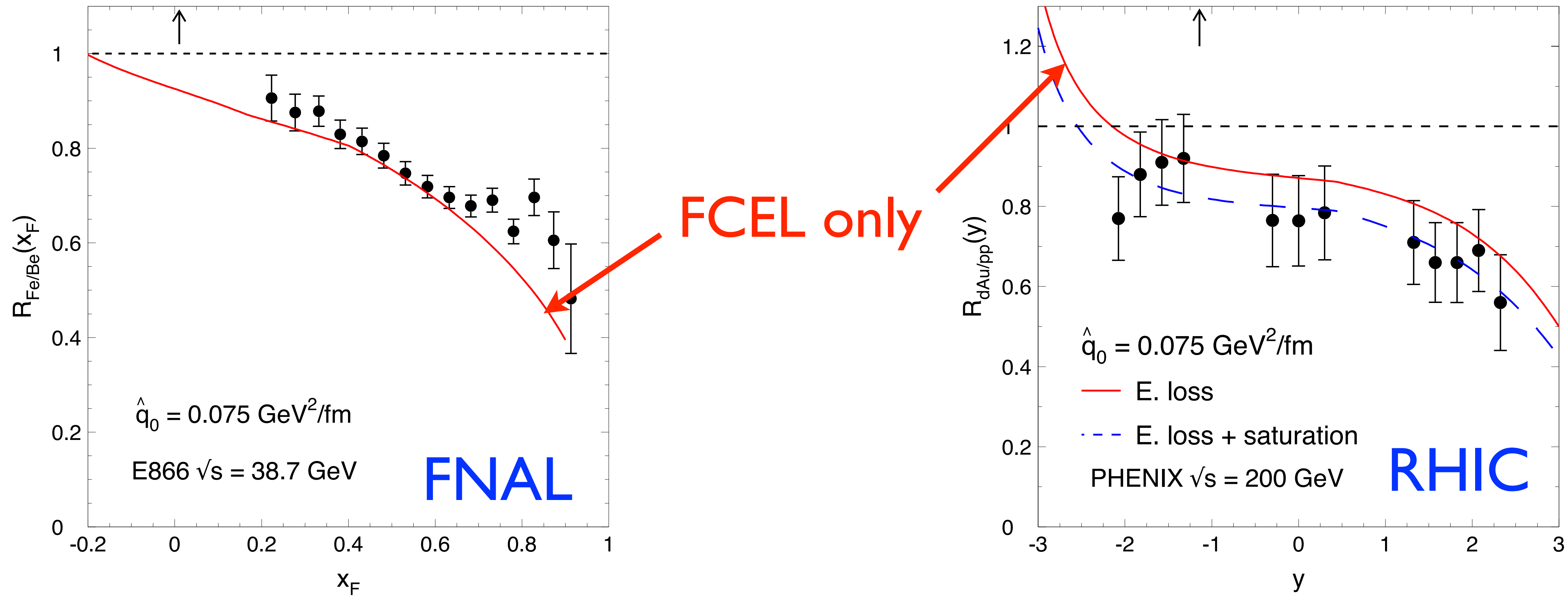
(CEM or COM at leading order)

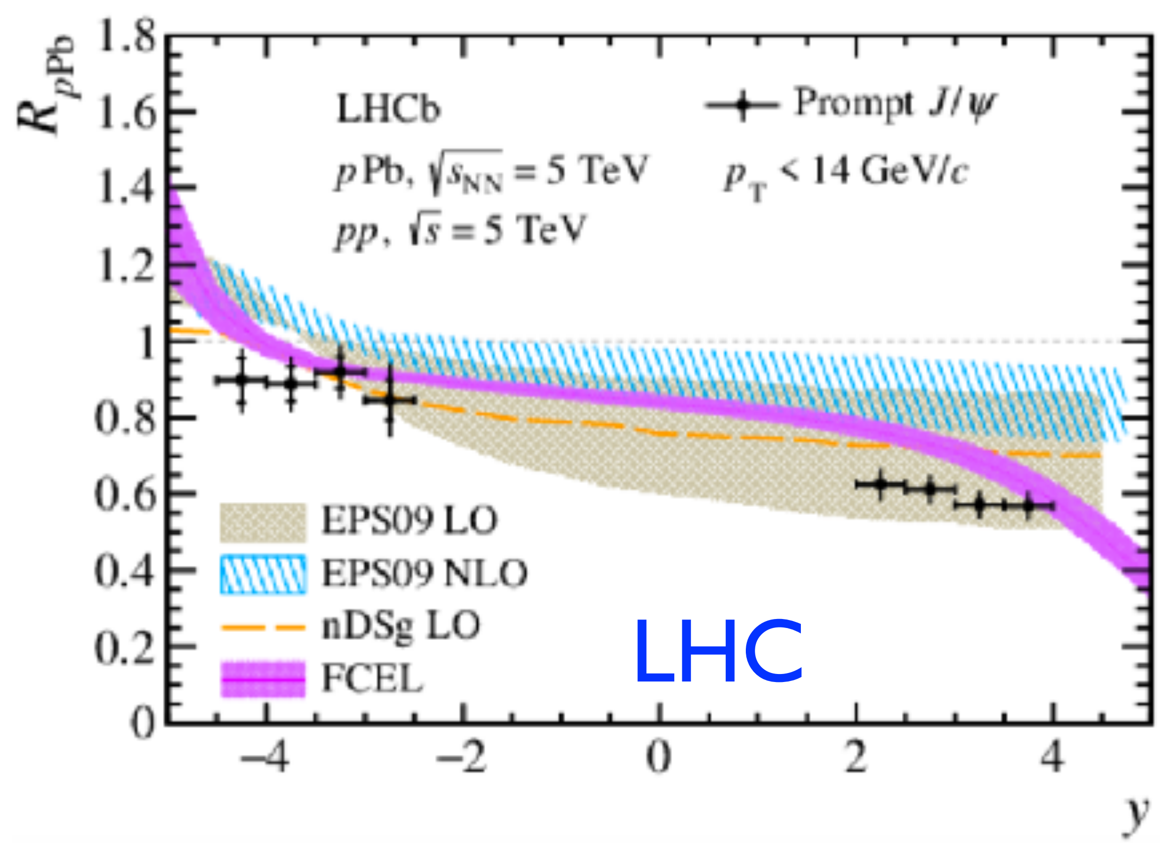
→ FCEL associated to $1 \to 1$ process $g \to Q\bar{Q}\,[8]$

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

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

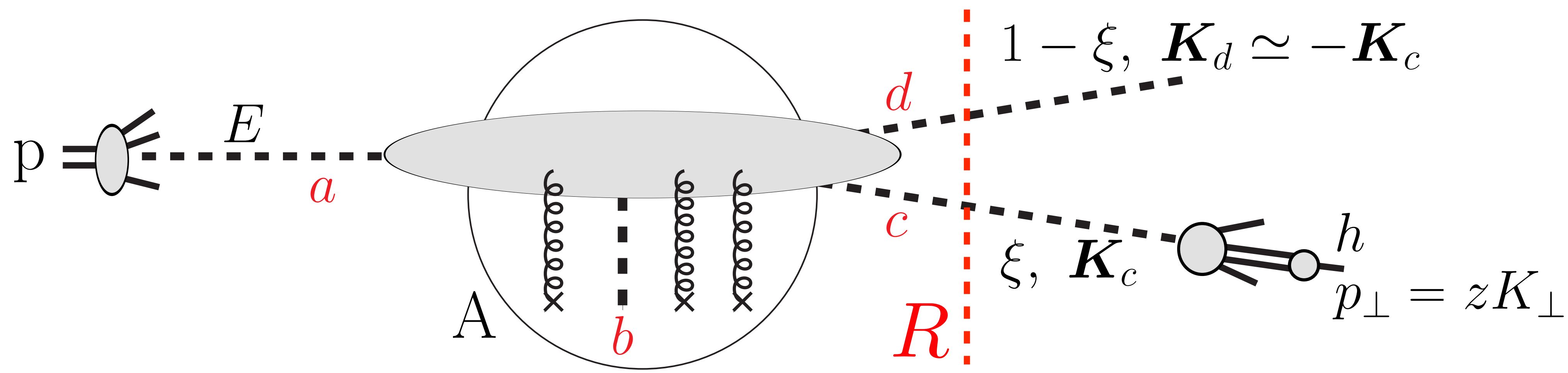
Arleo and Peigne, PRL109, 122301 (2012), JHEP03, 122 (2013)





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

$1 \to 2$ forward processes



$$\frac{\mathrm{d}\sigma^h_{\mathrm{pp}}(E_h)}{\mathrm{d}E_h} = \sum_R \int \mathrm{d}\xi\, \rho_R(\xi)\, \frac{\mathrm{d}\sigma^h_{\mathrm{pp}}(E_h,\xi)}{\mathrm{d}E_h\,\mathrm{d}\xi} \qquad \rho_{\mathrm{R}}(\xi) = \frac{|\mathcal{M}_{\mathrm{hard}} \cdot \mathbb{P}_{\mathrm{R}}|^2}{|\mathcal{M}_{\mathrm{hard}}|^2}$$

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

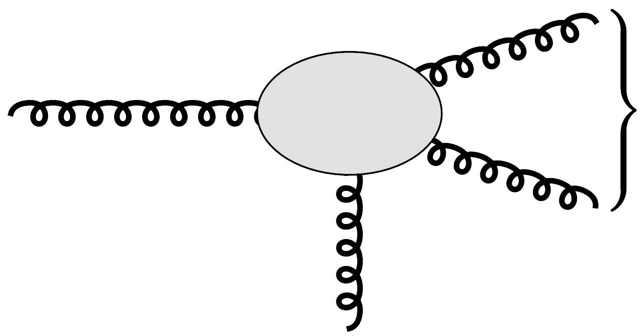
$$\hat{\mathcal{P}}_R(x) = \frac{\mathrm{d}I_R}{\mathrm{d}x} \exp\left\{-\int_x^\infty \mathrm{d}x' \frac{\mathrm{d}I_R}{\mathrm{d}x'}\right\}$$

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

FCEL in light hadron production

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

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



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

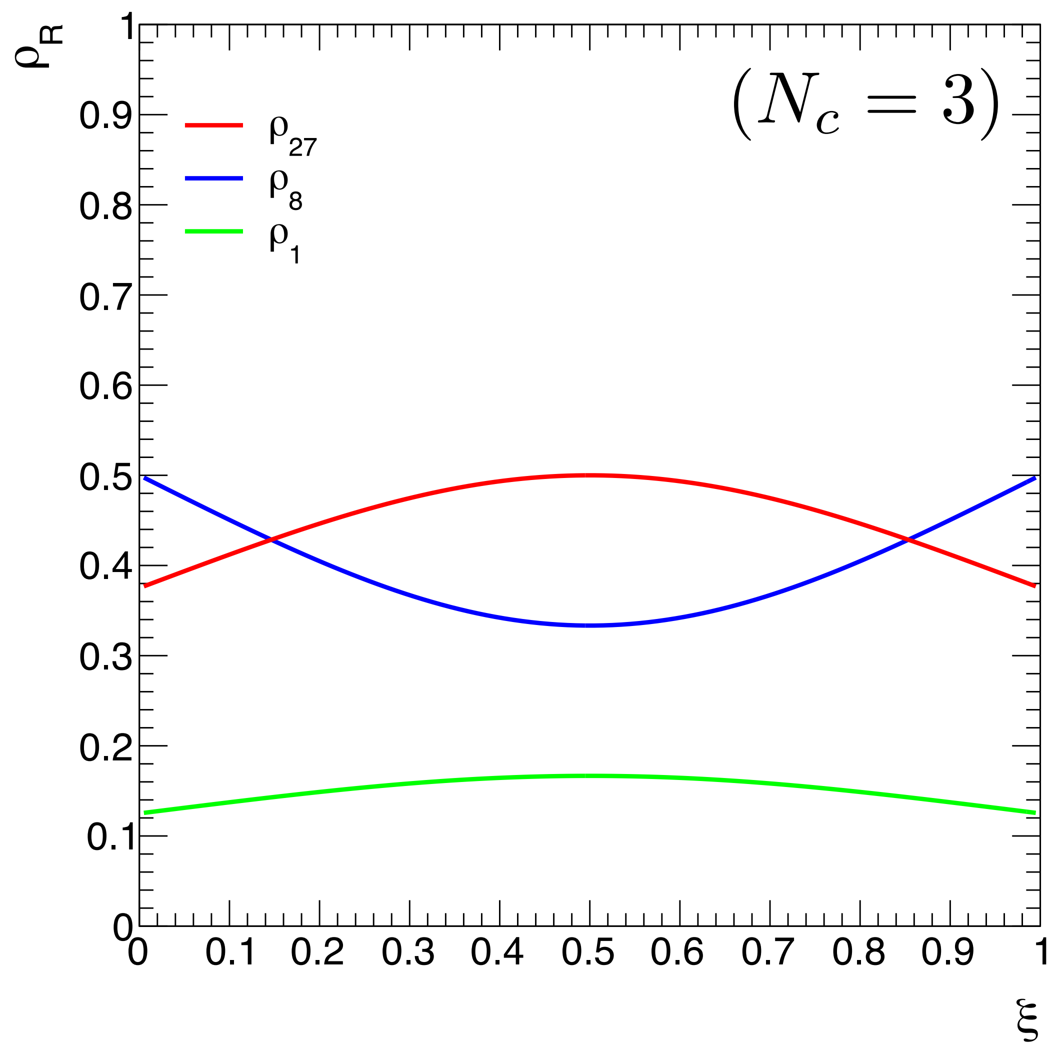
color projectors $\mathbb{P}_{\mathrm{R}}$

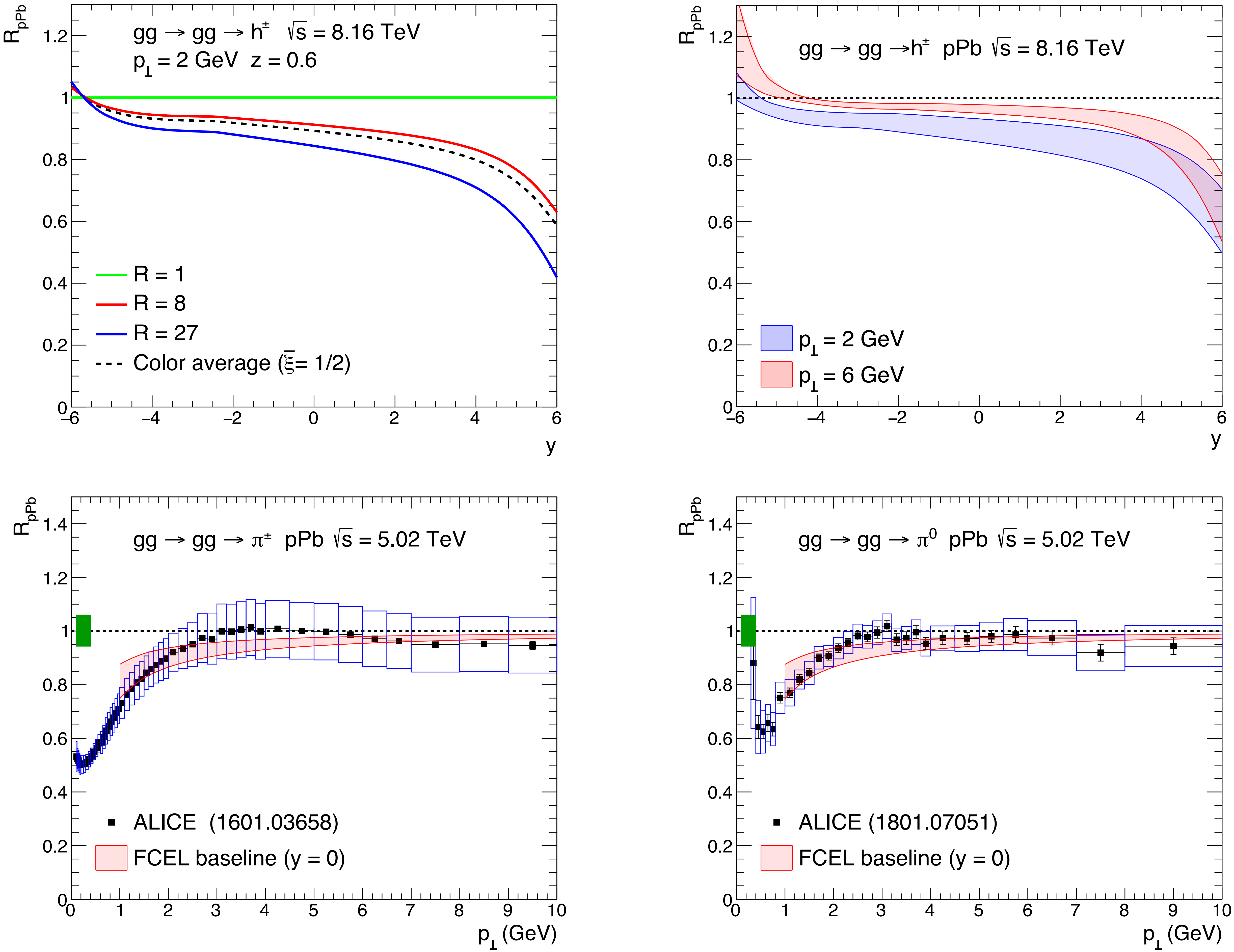
$\mathbf{1}$	$\frac{1}{N^2-1}$
$\mathbf{8_a}$	$\frac{1}{N}$
$\mathbf{8_s}$	$\frac{N}{N^2-4}$
$\mathbf{10} \oplus \overline{\mathbf{10}}$	$\frac{1}{2}\left[\; - \;\right] - \mathbb{P}_{\mathbf{8_a}}$
$\mathbf{27}$	$\left(\frac{1}{2} + 2\right)\left(\frac{1}{2}\left[\; + \;\right] - \mathbb{P}_{\mathbf{8_s}} - \mathbb{P}_{\mathbf{1}}\right)$
$\mathbf{0}$	$\left(\frac{1}{2} - 2\right)\left(\frac{1}{2}\left[\; + \;\right] - \mathbb{P}_{\mathbf{8_s}} - \mathbb{P}_{\mathbf{1}}\right)$

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

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

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

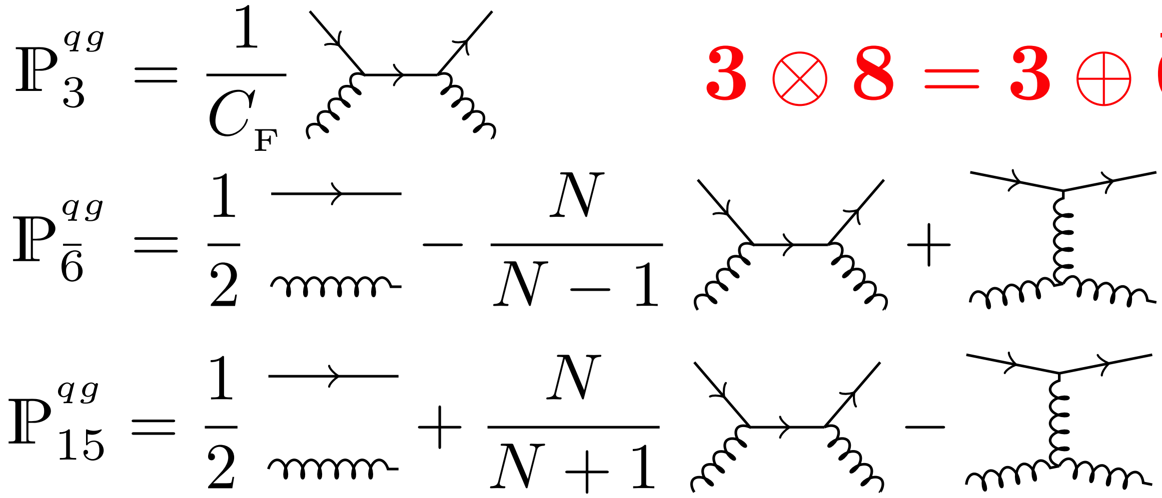




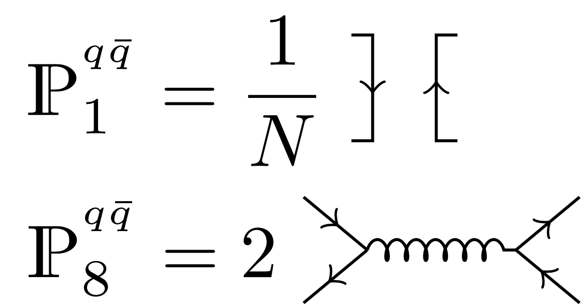
$gg \to gg \to h^\pm$ $\sqrt{s}$ = 8.16 TeV
$p_\perp$ = 2 GeV z = 0.6
R = 1
R = 8
R = 27
Color average ($\bar{\xi}$= 1/2)
R_{pPb}
y
$gg \to gg \to h^\pm$ pPb $\sqrt{s}$ = 8.16 TeV
$p_\perp$ = 2 GeV
$p_\perp$ = 6 GeV
$gg \to gg \to \pi^\pm$ pPb $\sqrt{s}$ = 5.02 TeV
ALICE (1601.03658)
FCEL baseline (y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

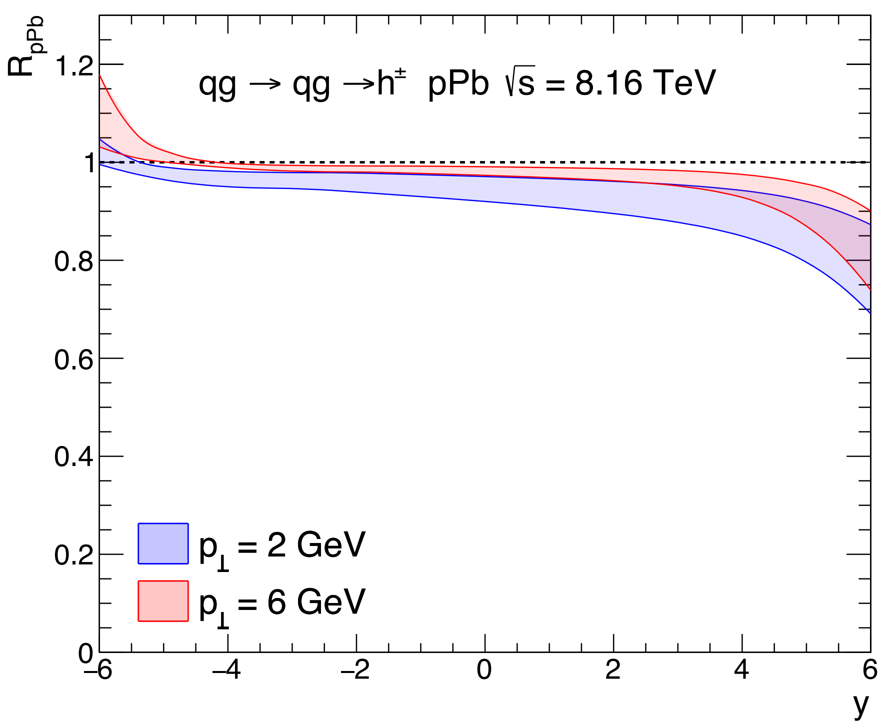
$\mathbf{3} \otimes \mathbf{8} = \mathbf{3} \oplus \bar{\mathbf{6}} \oplus \mathbf{15}$



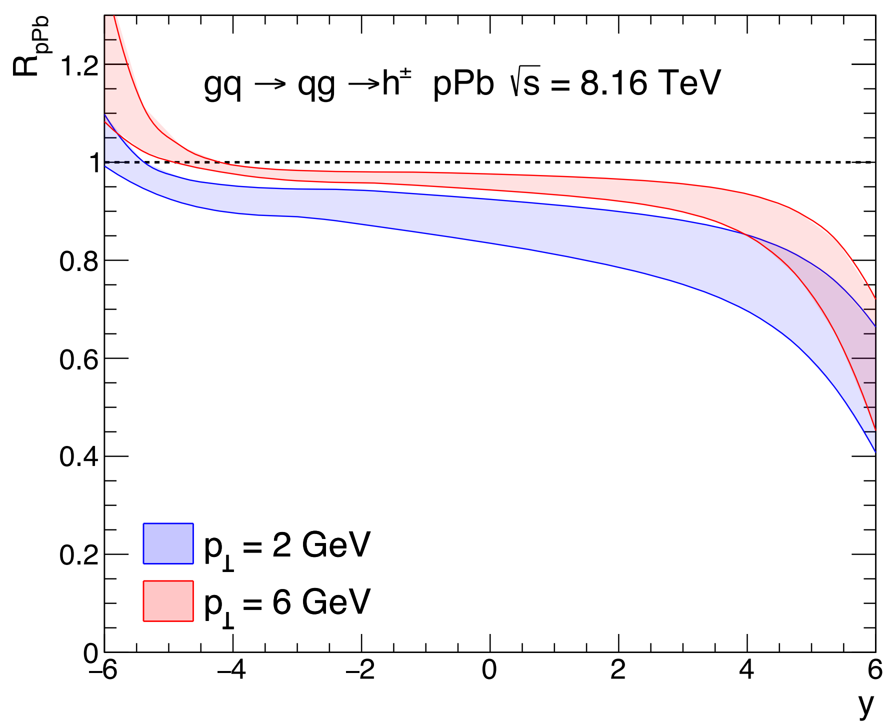
$\mathbf{3} \otimes \bar{\mathbf{3}} = \mathbf{1} \oplus \mathbf{8}$



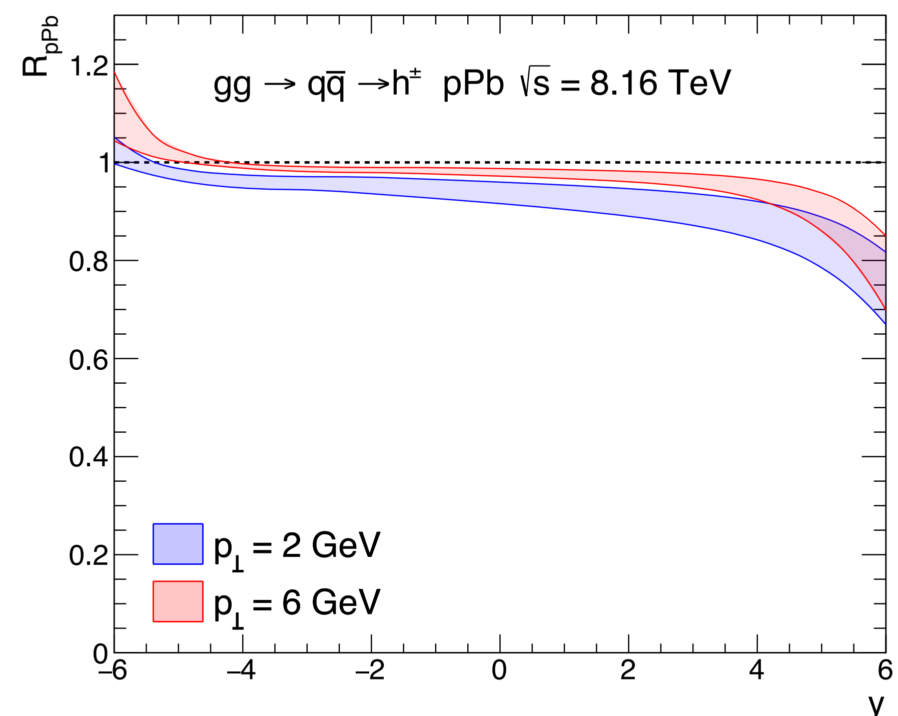
$q(g) \to qg$



$g(q) \to qg$



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

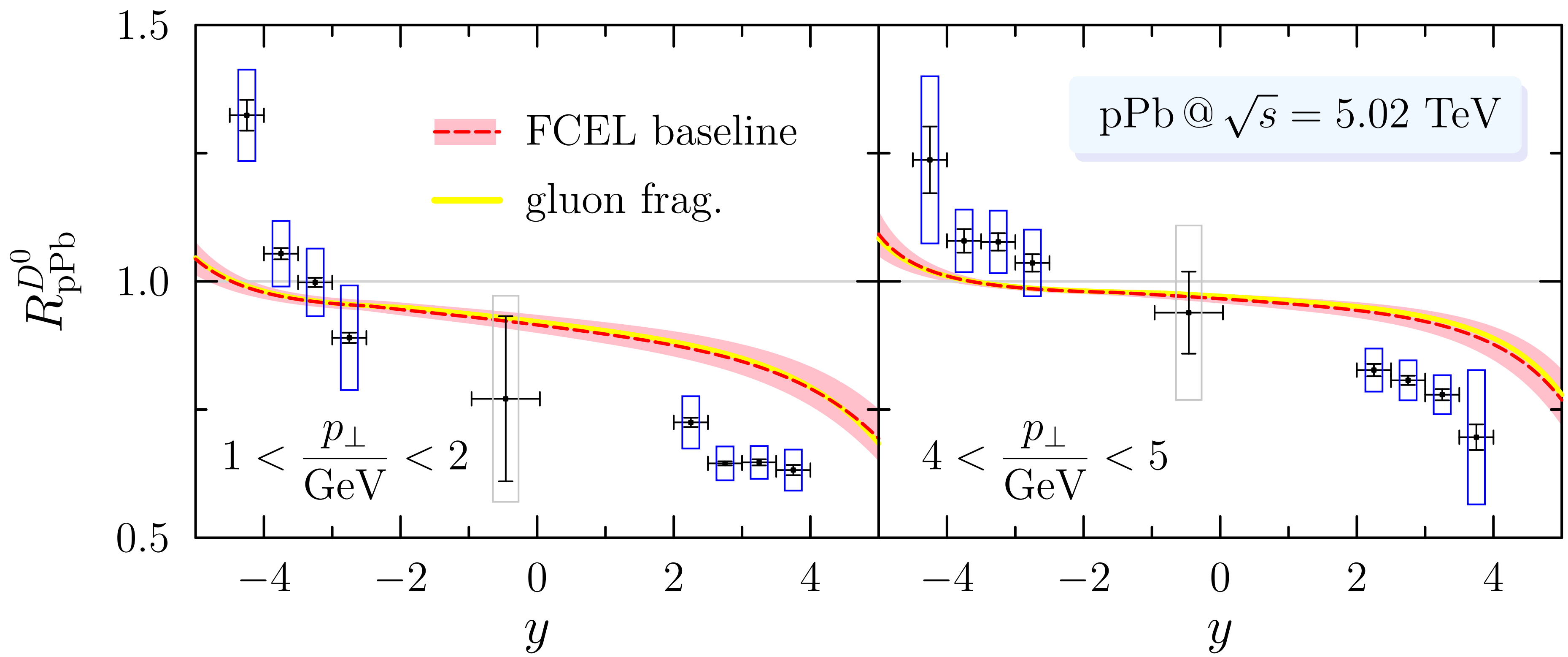


FCEL effect qualitatively similar for all partonic channels

FCEL in heavy flavour production

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

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



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

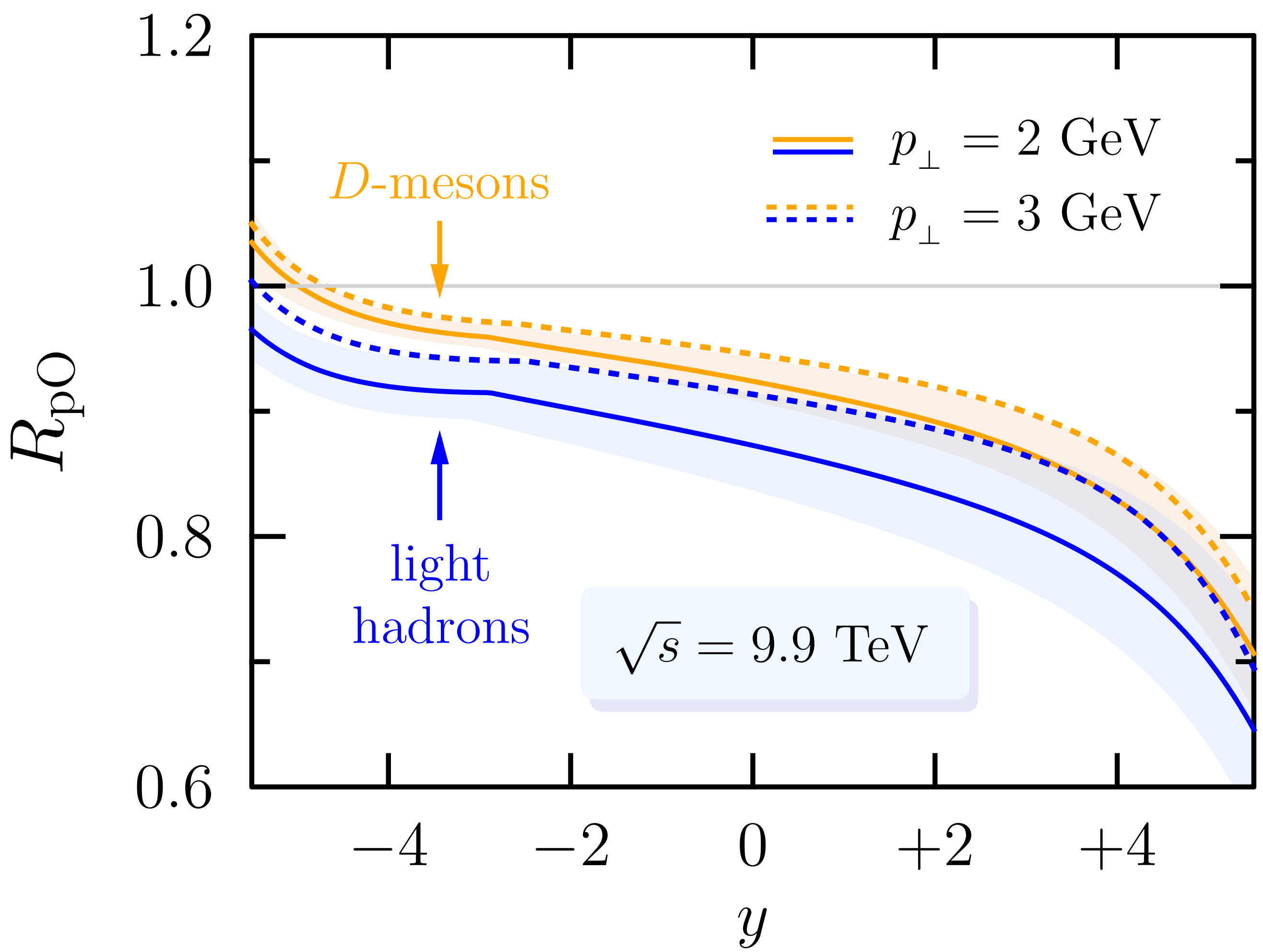
→ *no qualitative change expected from NLO channels*

FCEL predictions for pO collisions at LHC

Arleo, Jackson, S.P. 2112.10791 [hep-ph]

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

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



FCEL also substantial in proton collisions on *light* ions

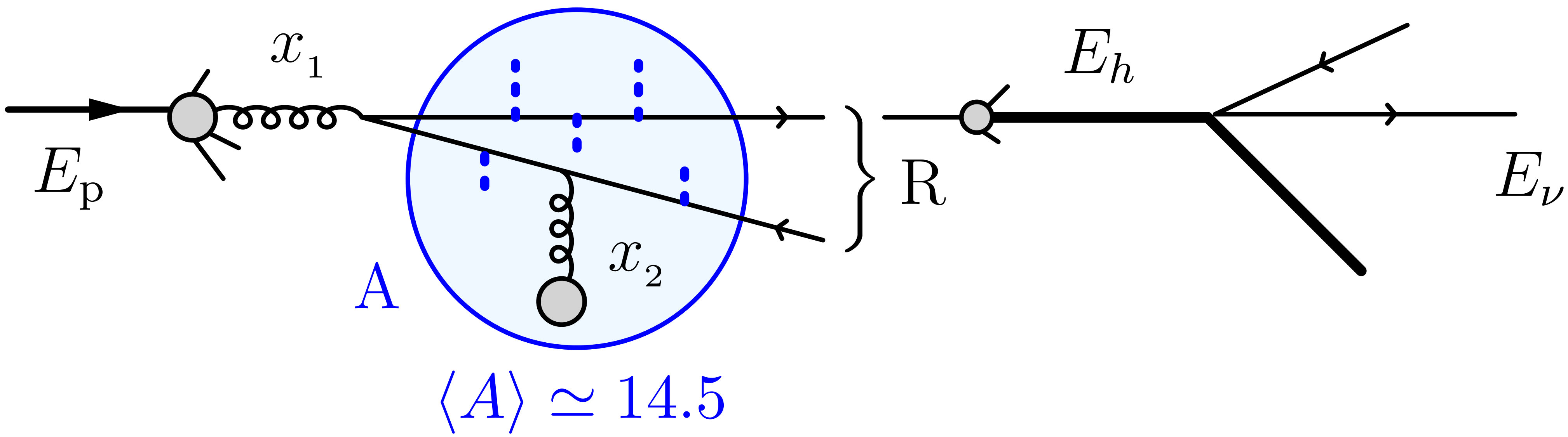
$$\Delta E \propto \alpha_s \frac{\sqrt{\hat{q}L}}{K_\perp} E \propto A^{1/6}$$

→ FCEL in collisions of cosmic rays with air nuclei

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

FCEL effect on inclusive atmospheric neutrino fluxes

Arleo, Jackson, S.P. 2112.10791 [hep-ph]

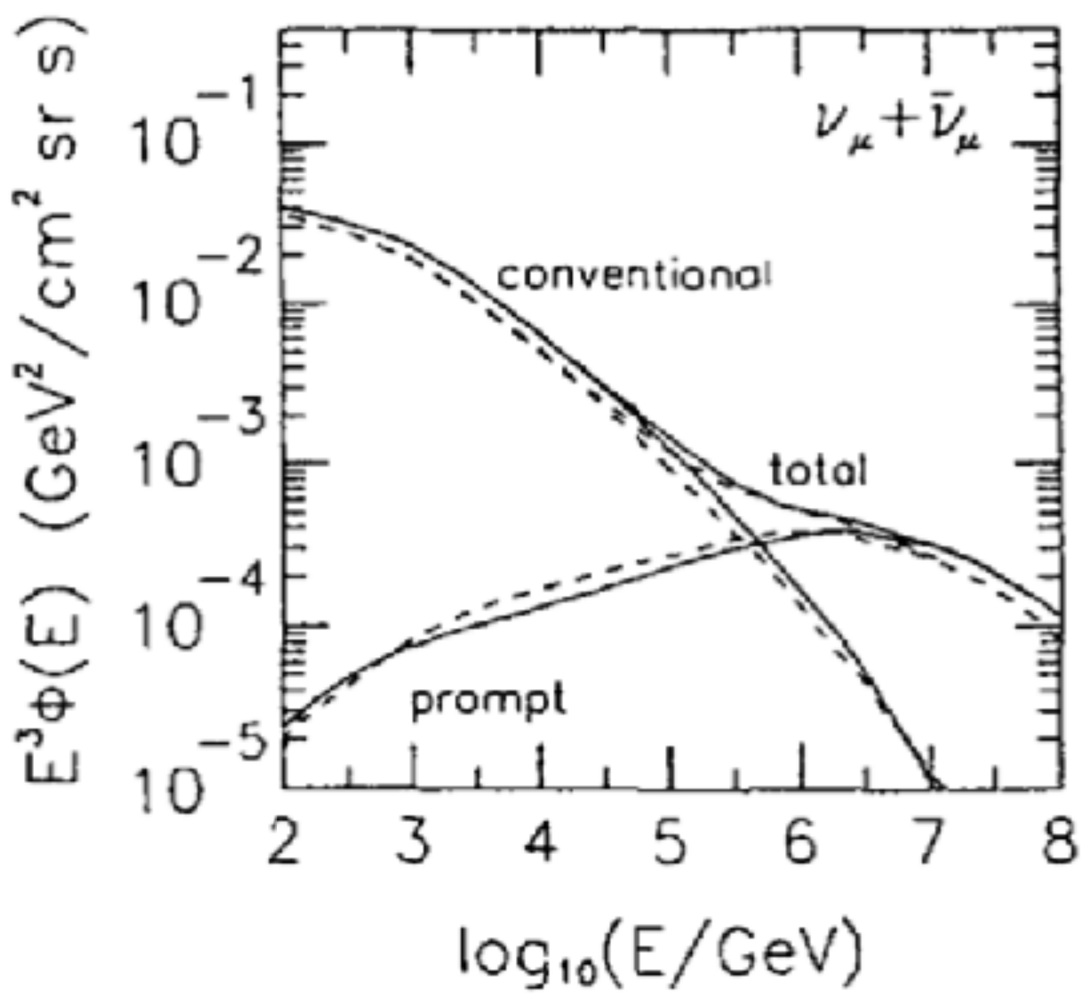


- atmospheric neutrinos from short-lived *D* mesons (prompt) or long-lived π, K mesons (conventional source)

- prompt neutrinos = main background to astrophysical ν's calculation of neutrino fluxes addressed in many studies

- analytic Z-moment method

Lipari, Astroparticle Physics 1 (1993) 195
Thunman et al, Astroparticle Physics 5 (1996) 309



Z-moment method

Monte Carlo cascade simulation

- event generators for extensive air showers

Fletcher, Gaisser, Lipari, Stanev, PRD 50 (1994) 5710
Fedynitch et al, PRD 100 (2019) 10, 103018

(SIBYLL)

ν flux obtained using Z-moment method:

initial CR flux

hadron generation Z-moment

$$\Phi_\nu(E_\nu) = \frac{\Phi_{\rm p}(E_\nu)}{1 - Z_{\rm pp}} \sum_h \frac{Z_{{\rm p}h}\, Z_{h\nu}}{1 + B_h E_\nu \cos\theta/\varepsilon_h}$$

focus on prompt ν's :

$$Z_{{\rm p}h}(E) \propto \int_0^1 \frac{{\rm d}x_{\rm F}}{x_{\rm F}}\, \Phi_{\rm p}\left(\frac{E}{x_{\rm F}}\right) \frac{{\rm d}\sigma^c_{\rm pA}}{{\rm d}x_{\rm F}}\left(x_{\rm F}; \frac{E}{x_{\rm F}}\right) \equiv \Omega(E)$$

FCEL rescales $x_{\rm F} \to x_{\rm F}/z$ with proba $\mathcal{F}(z)$ $\left(z = \frac{1}{1+x}\right)$

$$\longrightarrow \quad \Omega^{\rm FCEL}(E) = \int_0^1 {\rm d}z\, \mathcal{F}(z)\, \Omega(E/z)$$

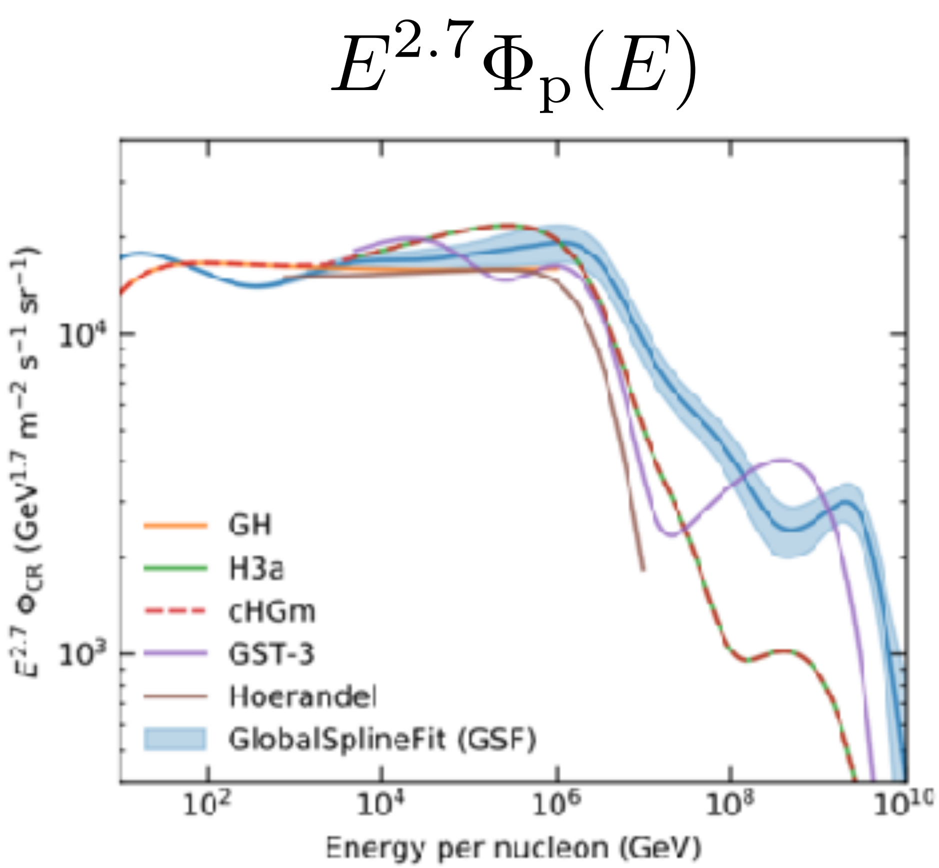
$$\Rightarrow \quad R_\nu(E) \equiv \frac{\Omega^{\rm FCEL}(E)}{\Omega(E)} = \int_0^1 {\rm d}z\, \mathcal{F}(z)\, \frac{\Omega(E/z)}{\Omega(E)} < 1$$

- ideal case : $\Phi_{\rm p}(E) \propto E^{-\gamma}$ and $d\sigma^{c}_{\rm pp}/dx_{\rm F}$ scales in $x_{\rm F}$

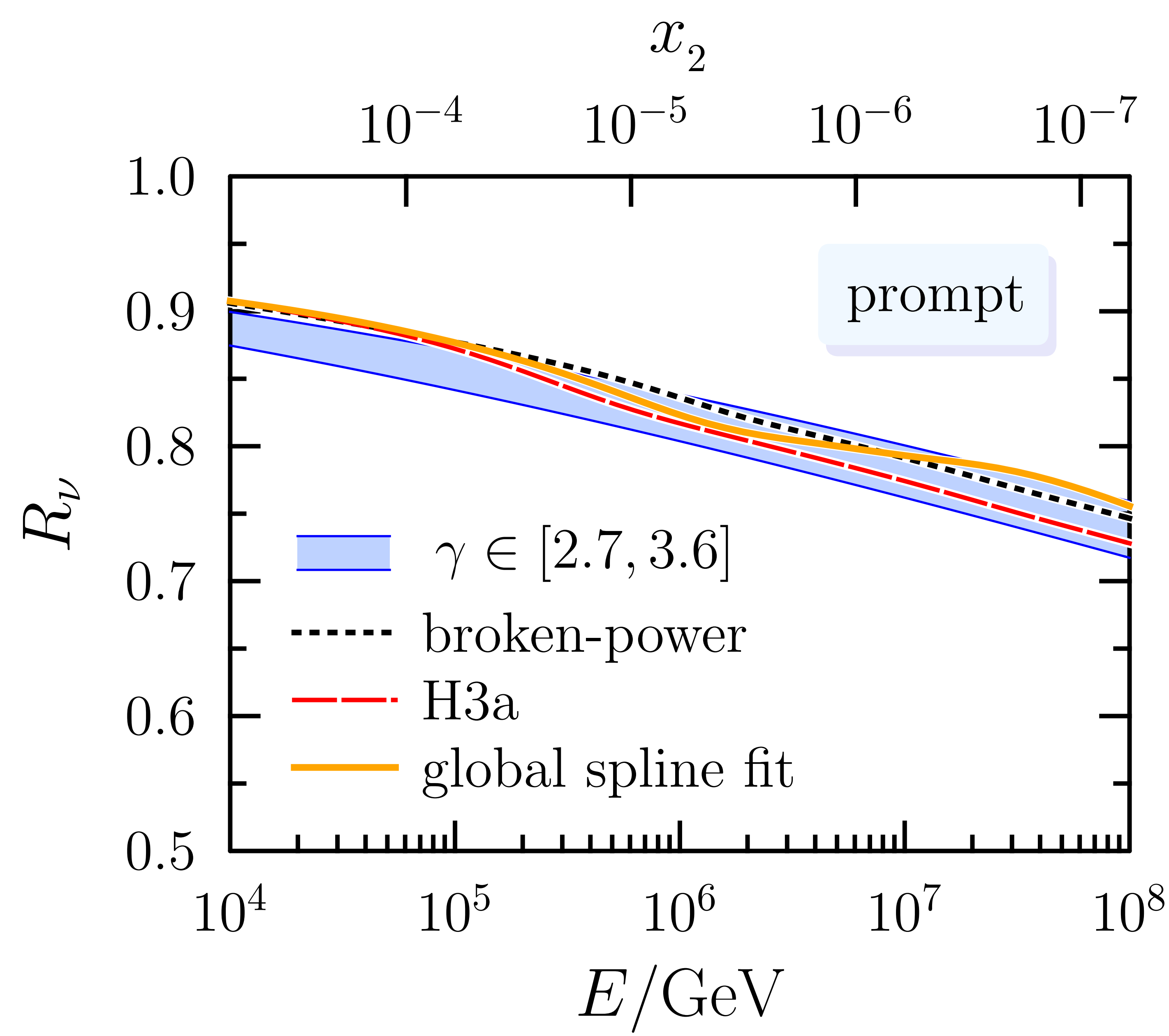
$$\Rightarrow \quad R_\nu(E) = \int_0^1 dz\, z^\gamma\, \mathcal{F}(z)$$

depends on E through $\hat{q}(x_2)$ with $x_2 \sim M^2_{c\bar{c}}/(4 m_{\rm p} E)$

$\gamma \in [2.7, 3.6]$ encompasses R_ν estimates with more realistic $\Phi_{\rm p}$ and $d\sigma^{c}_{\rm pp}$



Fedynitch et al
PoS (ICRC2017) 1019



Arleo, Jackson, S.P. 2112.10791 [hep-ph]

Summary

- FCEL is a QCD prediction and a significant effect :
  - contributes to *substantial* hadron suppression in pA
    from fixed target to LHC energies
  - suppresses atmospheric neutrinos
    prompt flux suppressed by 20-25% for $E_\nu = 10^6 ... 10^8 \text{ GeV}$
- FCEL predictions have a small theoretical uncertainty
- FCEL at least as important as nPDF effects

Outlook

- include FCEL *before* extraction of nPDF sets
- implement FCEL in full air shower simulations
  (CORSIKA, EPOS, QGSJET-III, SIBYLL)

Backup

parametrization of light hadron pp cross section

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

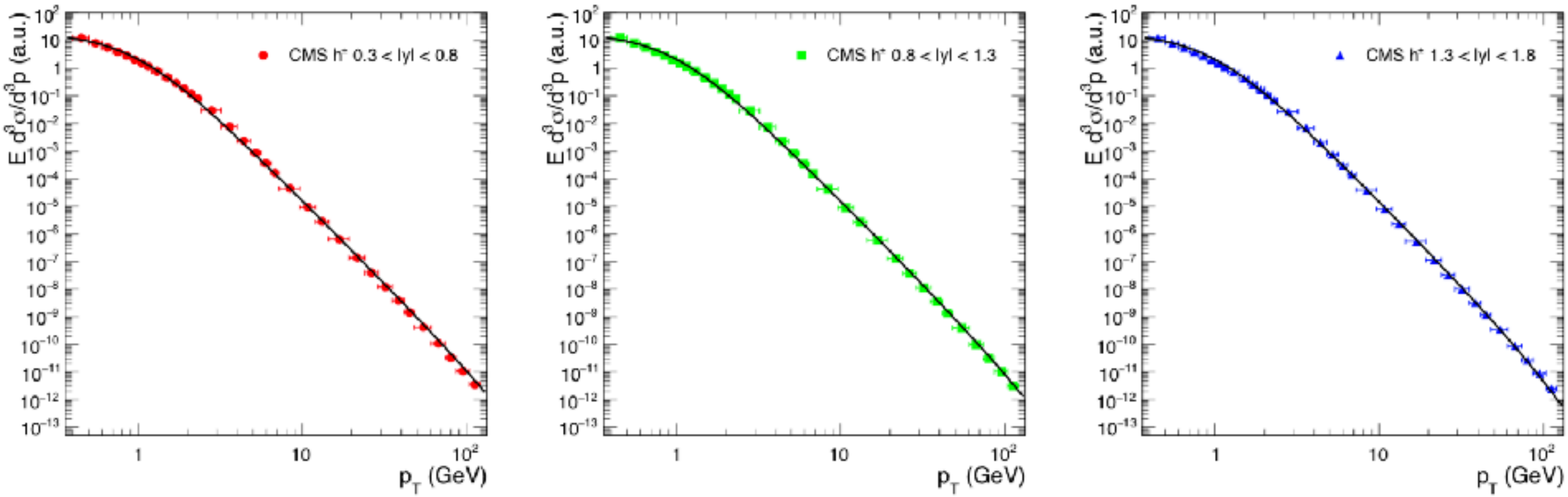


Figure 10. Charged hadron spectra measured by CMS in pPb collisions at $\sqrt{s} = 5.02$ TeV in the rapidity ranges $0.3 < |y| < 0.8$ (left), $0.8 < |y| < 1.3$ (center), $1.3 < |y| < 1.8$ (right) [72], compared to the parametrization (C.1).

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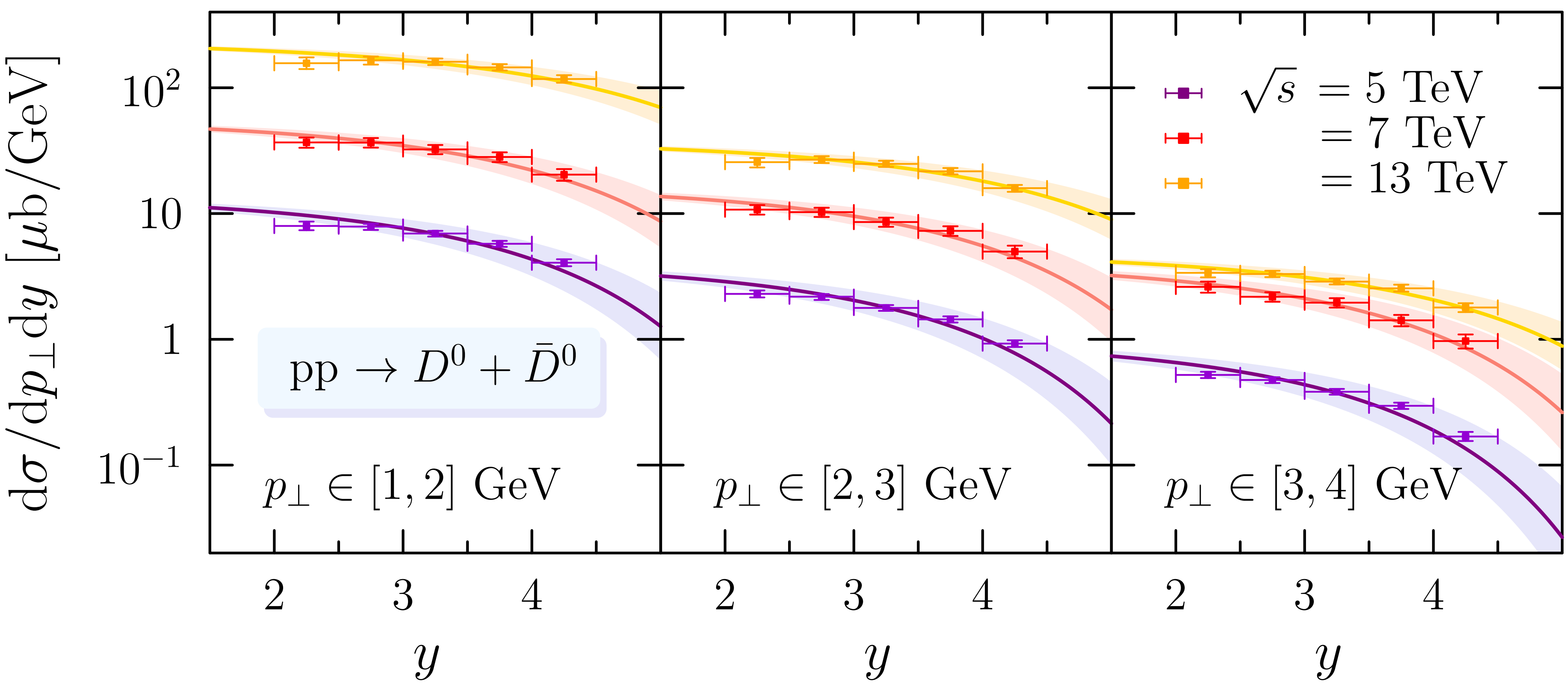
parametrization of heavy meson pp cross section

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



(LHCb pp data)

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