nuclear suppression in pA collisions from induced gluon radiation

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Rencontres QGP-France 2015

Etretat, 12-15 octobre 2015

Introduction

- understand pA suppression *before* hot effects in AA

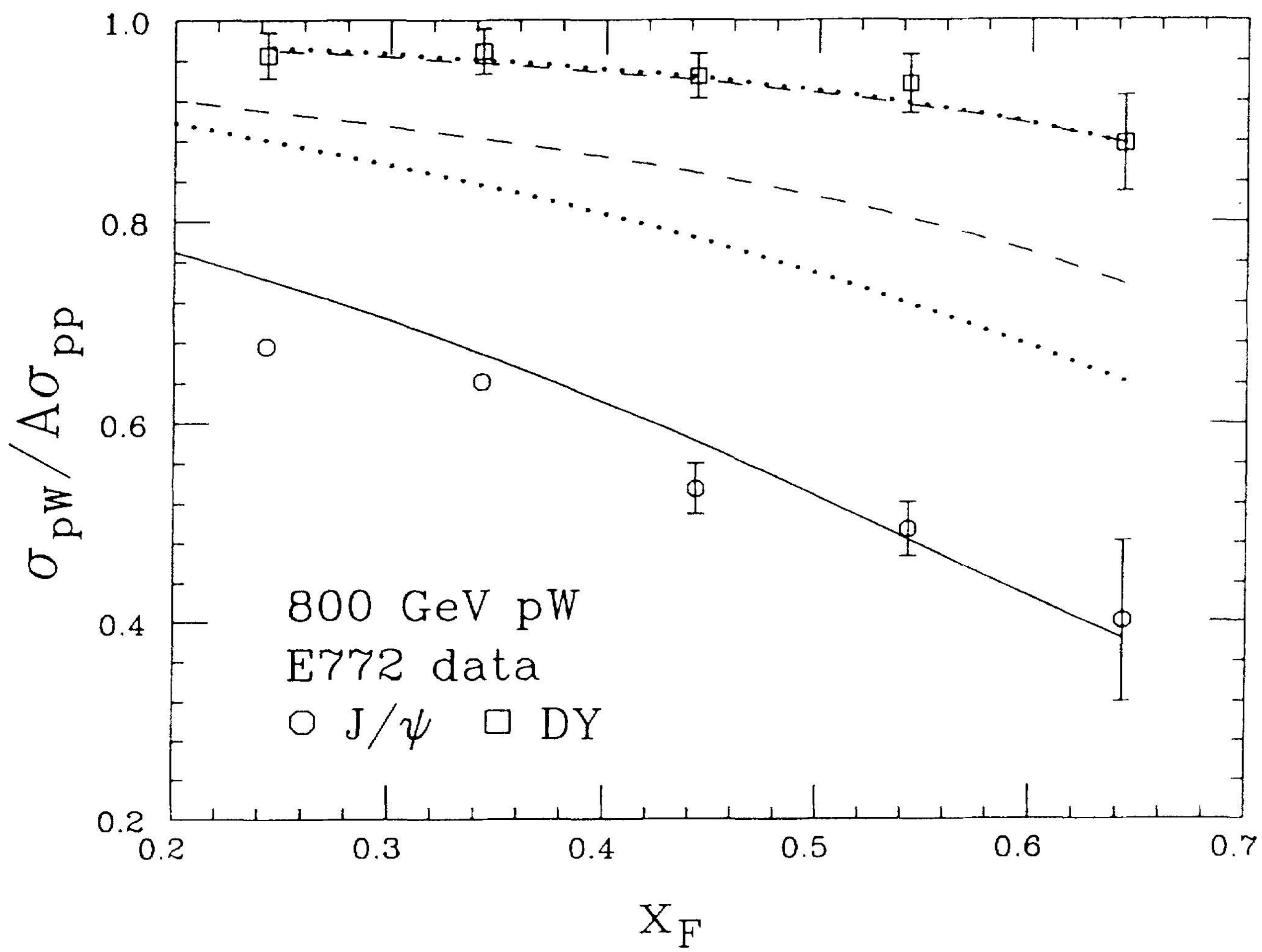
- several effects have been proposed:
    - in-medium ‘nuclear absorption’
    - CGC/saturation effects
    - shadowing/nPDF effects
    - parton *radiative* energy loss

no real consensus on relative importance of those effects

this talk: **parton energy loss**

(*might* be the *main* effect at large enough energy)

Gavin-Milana model for J/psi pA suppression (1992)



Gavin & Milana
PRL 68 (1992)1834

strong increase of J/psi suppression with x_{F} reproduced by *assuming*

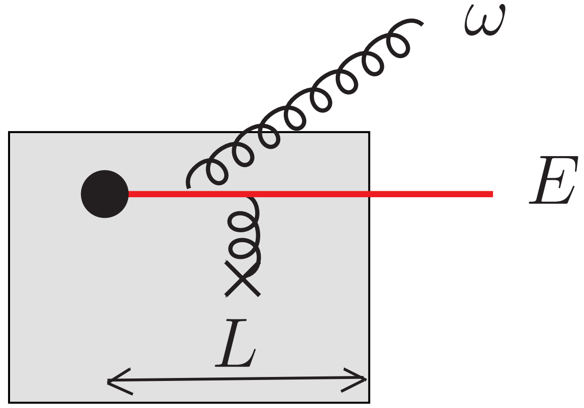
$$\Delta E_{\mathrm{parton}} \propto E$$

- at that time: spread belief that any *induced* ΔE should be bounded when $E \to \infty$
- Gavin-Milan 'explanation' was put aside

(still, $\Delta E \propto E$ advocated by some groups:
Frankfurt & Strikman 2007; Kopeliovich et al 2005)

bound on ΔE holds in specific situation (1):

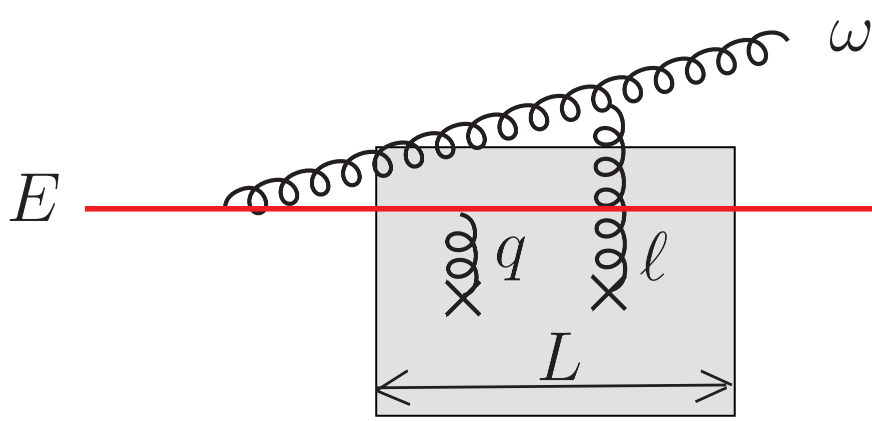
(1) parton suddenly produced in medium



$$\Delta E_{\mathrm{rad}} \sim \alpha_s \hat{q} L^2$$ (static medium)

... but not in situation (2):

(2) forward scattering of fast 'asymptotic parton'



$$\Delta E_{\mathrm{rad}} \sim \alpha_s \frac{\sqrt{\hat{q} L}}{M_\perp} E$$

fully coherent
energy loss

coherent induced radiation spectrum for $1 \to 1$ forward scattering

- Arleo, S.P., Sami   PRD 83 (2011) 114036   (APS10)
  - Feynman diagrams + opacity expansion
  - derivation at first order in opacity extrapolated to all orders
  - hard process: $g \to Q\bar{Q}$ mediated by *octet* t-channel exchange
- Armesto et al   PLB 717 (2012) 280, JHEP 1312 (2013) 052
  - semi-classical method + opacity expansion
  - harmonic oscillator approximation
  - hard process: $q \to q$ mediated by *singlet* t-channel exchange
- S.P., Arleo, Kolevatov   1402.1671 (2014)   (PAK14)
  - Feynman diagrams + opacity expansion
  - hard process: all $1 \to 1$
  - rigorous calculation for *Coulomb* rescattering
  - parton mass dependence
  - general rule for color factor

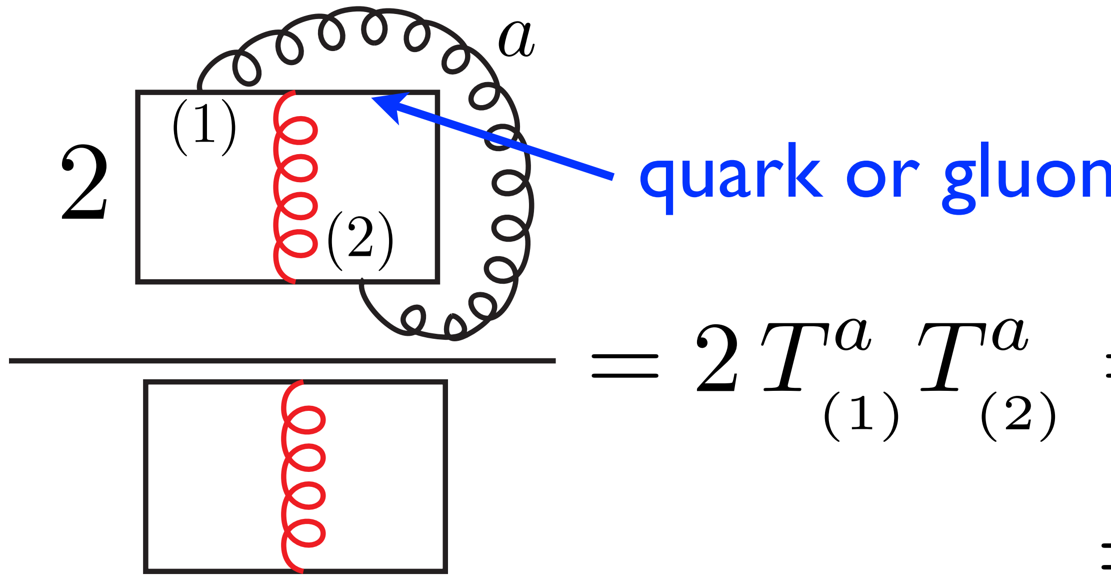
pocket formula for induced coherent spectrum (PAK14)

$$x \frac{\mathrm{d}I}{\mathrm{d}x}\bigg|_{1\to 1} = (C_R + C_{R'} - C_t)\,\frac{\alpha_s}{\pi}\,\log\left(1 + \frac{\Delta q_\perp^2(L)}{x^2 M_\perp^2}\right)$$

- generalizes results found previously in particular cases
- captures correct limiting behaviour at small x
- at large x : proper normalization requires working beyond harmonic oscillator approximation (PAK14)

$$x = \frac{\omega}{E}\,; \quad \Delta q_\perp^2(L) = \hat{q}L\,; \quad \Delta E \equiv \int_0^E \mathrm{d}\omega\,\omega\,\frac{\mathrm{d}I}{\mathrm{d}\omega} \propto \alpha_s \frac{\sqrt{\hat{q}L}}{M_\perp}\,E$$

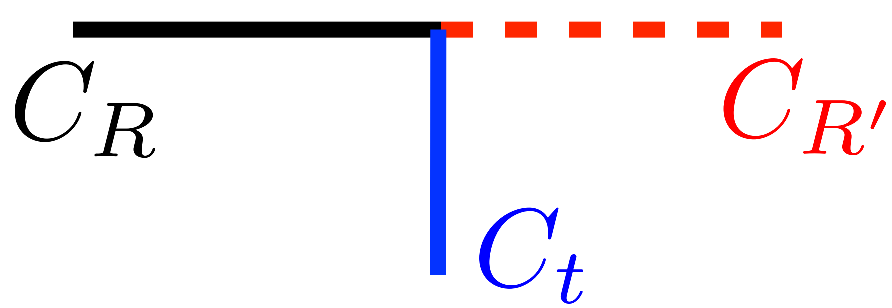
color factor given by interference term:



$$= 2\,T^a_{(1)}T^a_{(2)} = (T^a_{(1)})^2 + (T^a_{(2)})^2 - (\overbrace{T^a_{(1)} - T^a_{(2)}}^{T^a(\mathbf{8})})^2$$

$$= C_R + C_R - N_c$$

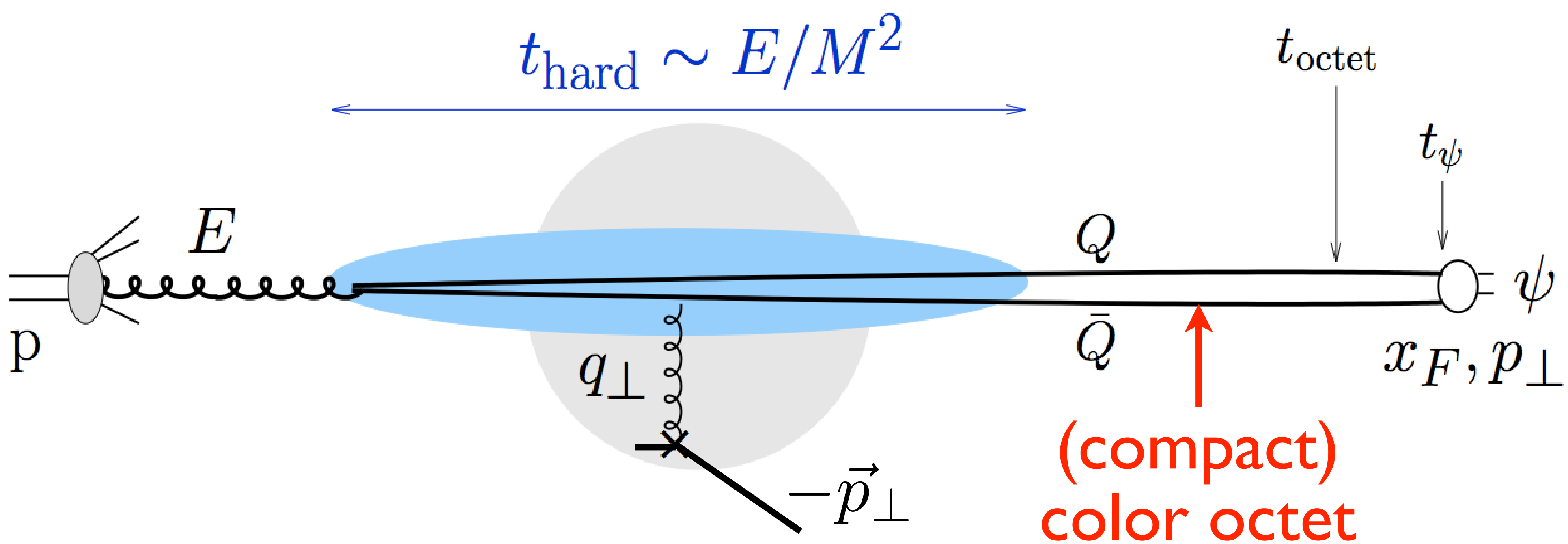
$1 \to 1$ forward scattering with $C_R \neq C_{R'}$



$$\Longrightarrow \quad \boxed{C_R + C_{R'} - C_t}$$

application to phenomenology: model for quarkonium pA suppression

Arleo, S.P., 1204.4609 and 1212.0434 (AP12)
Arleo, Kolevatov, S.P., Rustamova 1304.0901 (AKPR13)



$x_{\rm F} > x_{\rm F}^{\rm crit}$

$p_\perp > \Delta q_\perp(L)$

at large $x_{\rm F}$: recoil parton ($-\vec{p}_\perp$) must be 'soft'

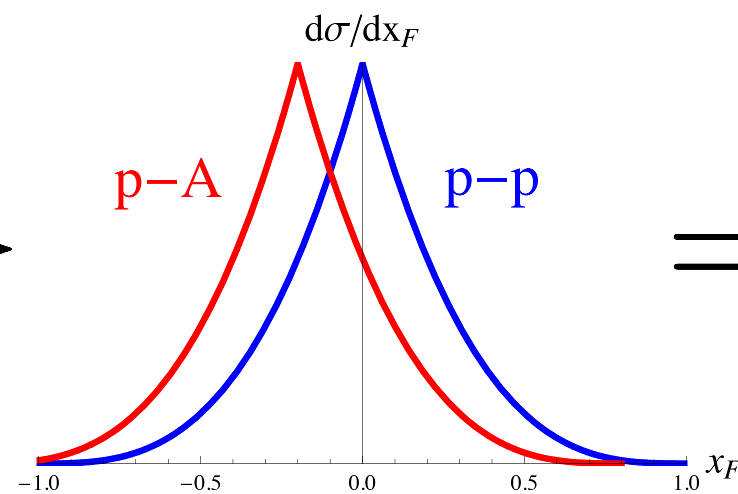
→ $1 \to 1$ forward process

→ coherent radiation associated to $g \to Q\bar{Q}$

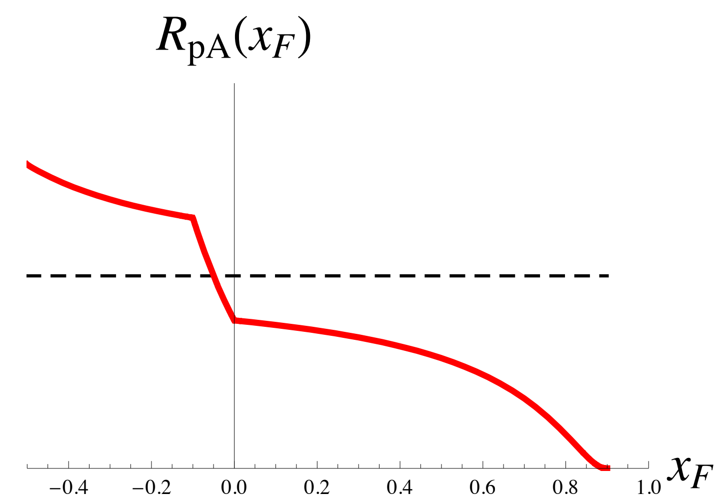
$$\frac{1}{A}\frac{\mathrm{d}\sigma^{\psi}_{\mathrm{pA}}}{\mathrm{d}E}(E) = \int_0^{\varepsilon^{\max}} \mathrm{d}\varepsilon\, \mathcal{P}(\varepsilon, E, \ell^2_{\mathrm{A}})\, \frac{\mathrm{d}\sigma^{\psi}_{\mathrm{pp}}}{\mathrm{d}E}(E+\varepsilon)$$

$$(\ell^2_{\mathrm{A}} = \Delta q^2_{\perp}(L_{\mathrm{A}}))$$

energy shift $\Rightarrow$

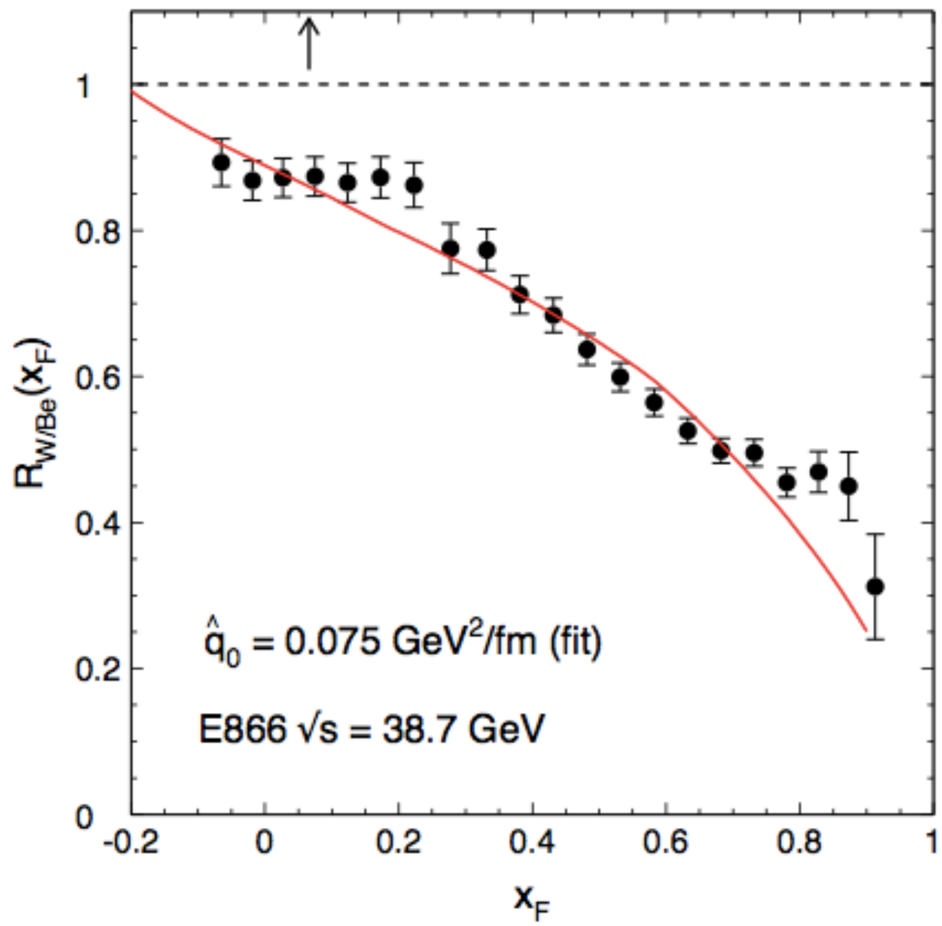


$\Rightarrow$



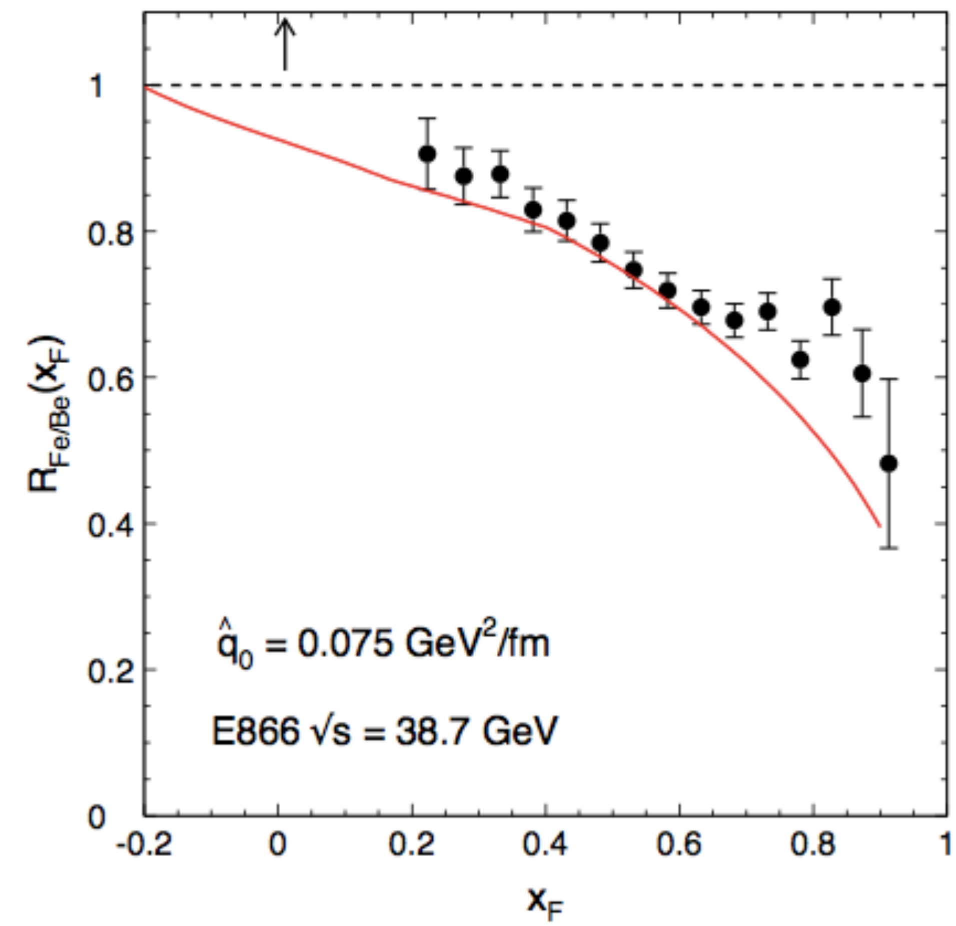
- $\mathrm{d}\sigma^{\psi}_{\mathrm{pp}}/\mathrm{d}x_{\mathrm{F}}$ taken from experimental data
- $\mathcal{P}(\varepsilon, E, \ell^2_{\mathrm{A}}) = \frac{\mathrm{d}I}{\mathrm{d}\varepsilon} \exp\left\{-\int_{\varepsilon}^{\infty} \mathrm{d}\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\right\}$
- $\hat{q}(x_2) \equiv \hat{q}_0 \left(\frac{10^{-2}}{x_2}\right)^{0.3}$ $\hat{q}_0$ single parameter

$\hat{q}_0$ fixed from W/Be E866 J/ψ suppression data...



...and used to predict $R_{\mathrm{pA}}^{\mathrm{J}/\psi}$ for other A, $\sqrt{s}$

E866 Fe/Be

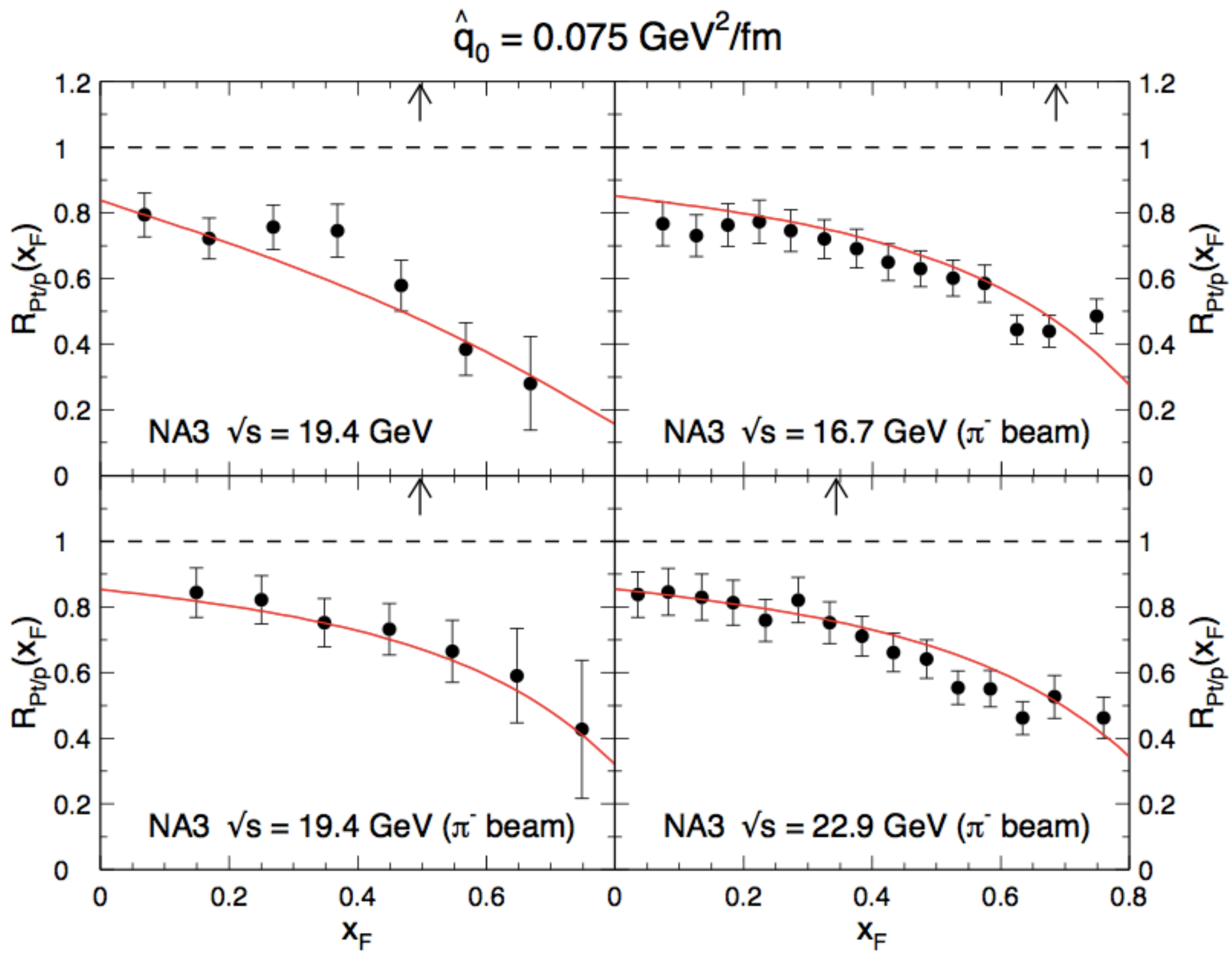


A–dependence well reproduced

$\hat{q}_0$ corresponds to $Q^2_{\mathrm{sp}}(x = 10^{-2}) = 0.11 - 0.14\ \mathrm{GeV}^2$

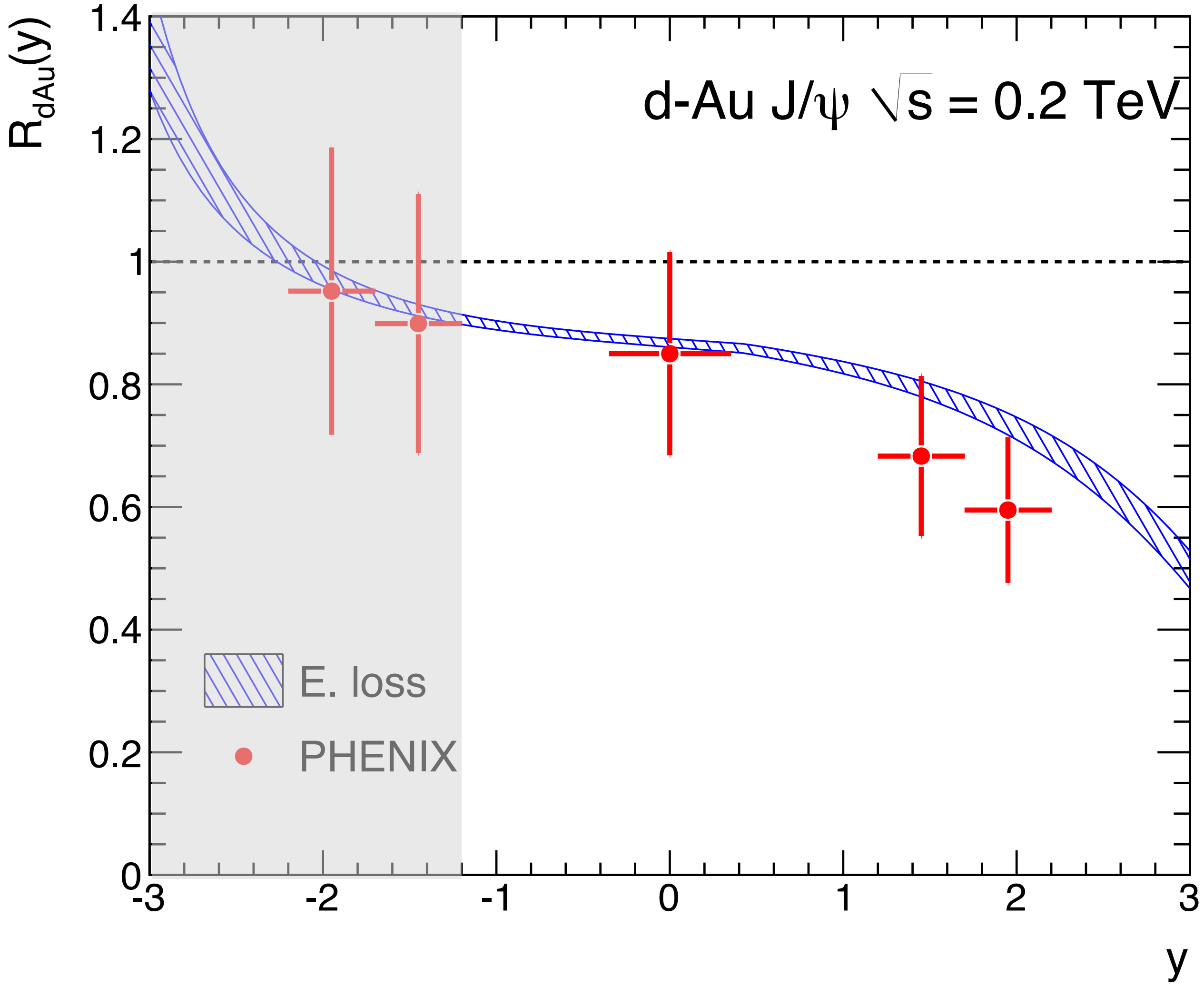
consistent with fits to DIS data   Albacete et al (AAMQS) 2011

J/ψ NA3 Pt/p

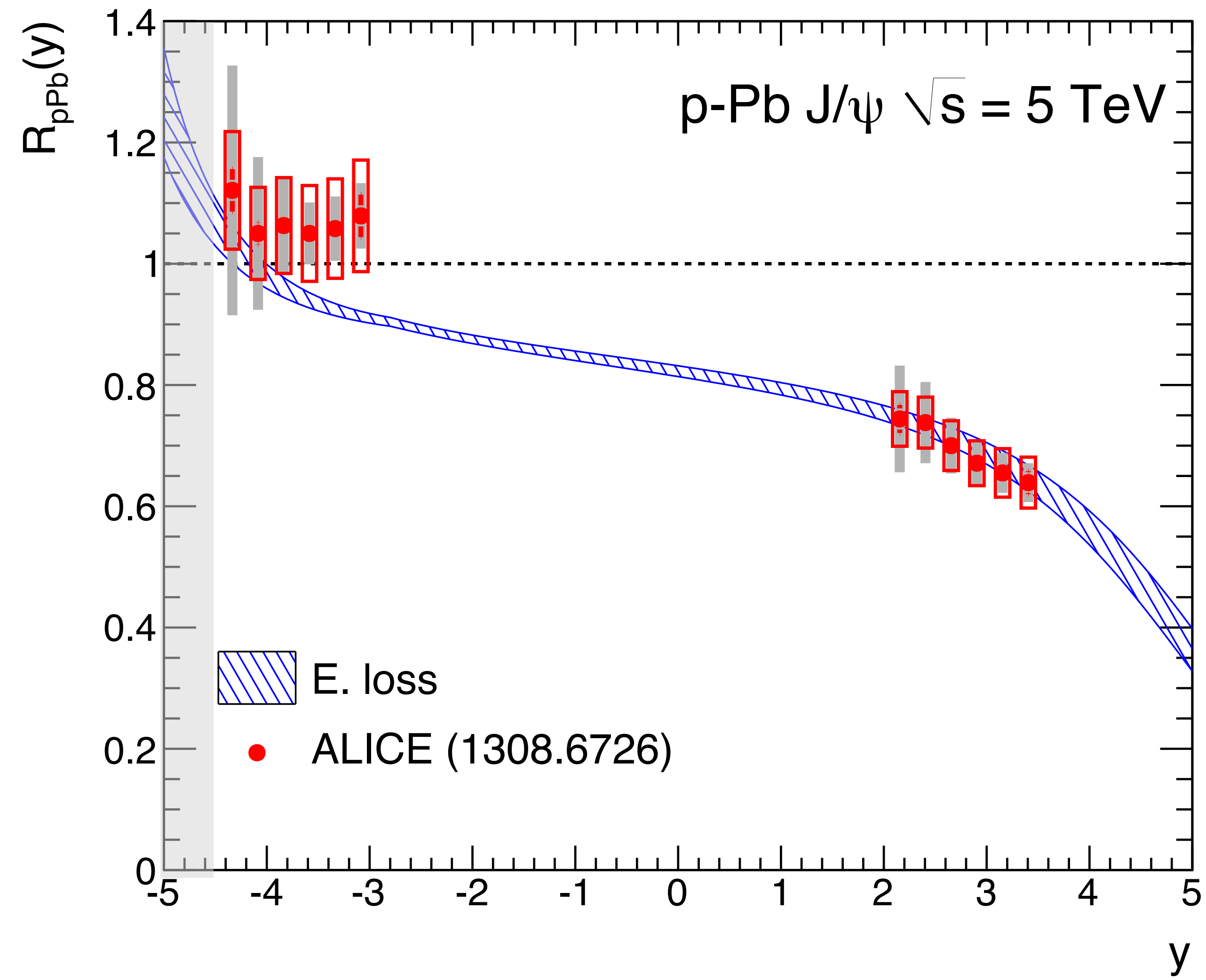


$\hat{q}_0$ = 0.075 GeV^2/fm
NA3 √s = 19.4 GeV
NA3 √s = 16.7 GeV (π⁻ beam)
NA3 √s = 19.4 GeV (π⁻ beam)
NA3 √s = 22.9 GeV (π⁻ beam)
$R_{Pt/p}(x_F)$
x_F
0
0.2
0.4
0.6
0.8
1
1.2

RHIC d-Au (PHENIX)



LHC p-Pb (ALICE)



coherent radiation *alone* "explains" J/psi pA suppression

from fixed target to collider energies

(nPDF/saturation *alone* cannot achieve such global description)

→ coherent energy loss $\Delta E \propto E$ *leading* effect

$p_\perp$-dependence of J/psi suppression (AKPR13)

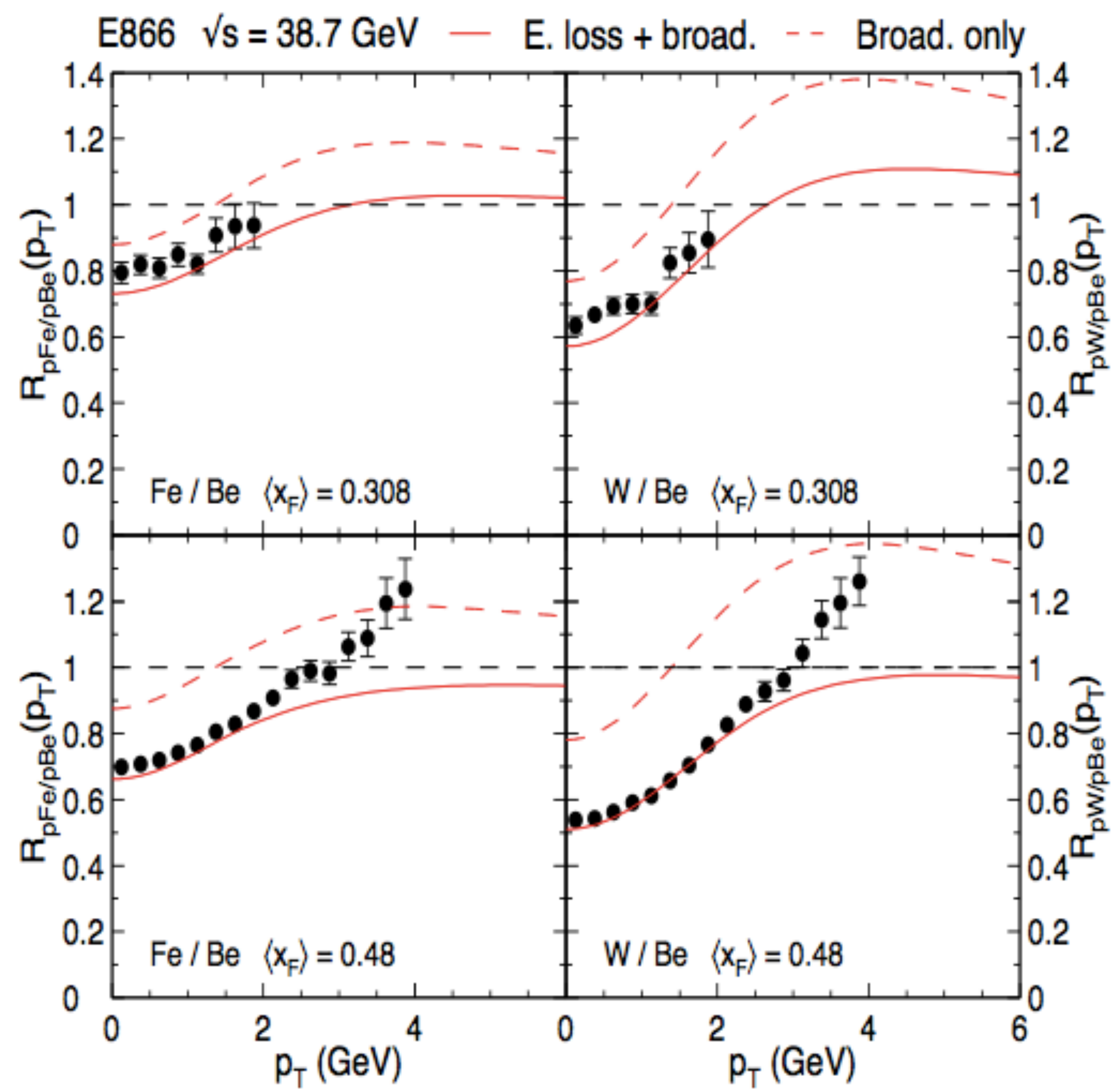
- energy loss + $p_\perp$-broadening of pointlike $c\bar{c}$:

$$\frac{1}{A}\frac{\mathrm{d}\sigma^{\psi}_{\mathrm{pA}}}{\mathrm{d}E\,\mathrm{d}^2\vec{p}_\perp} = \int_\varphi \int_\varepsilon \mathcal{P}(\varepsilon)\,\frac{\mathrm{d}\sigma^{\psi}_{\mathrm{pp}}}{\mathrm{d}E\,\mathrm{d}^2\vec{p}_\perp}\left(E+\varepsilon, \vec{p}_\perp - \Delta\vec{p}_\perp\right)$$

no free parameter:
$\Delta p_\perp$ induces ΔE

$\Delta p_\perp \rightarrow$ Cronin effect
L. Kluberg et al (1977)

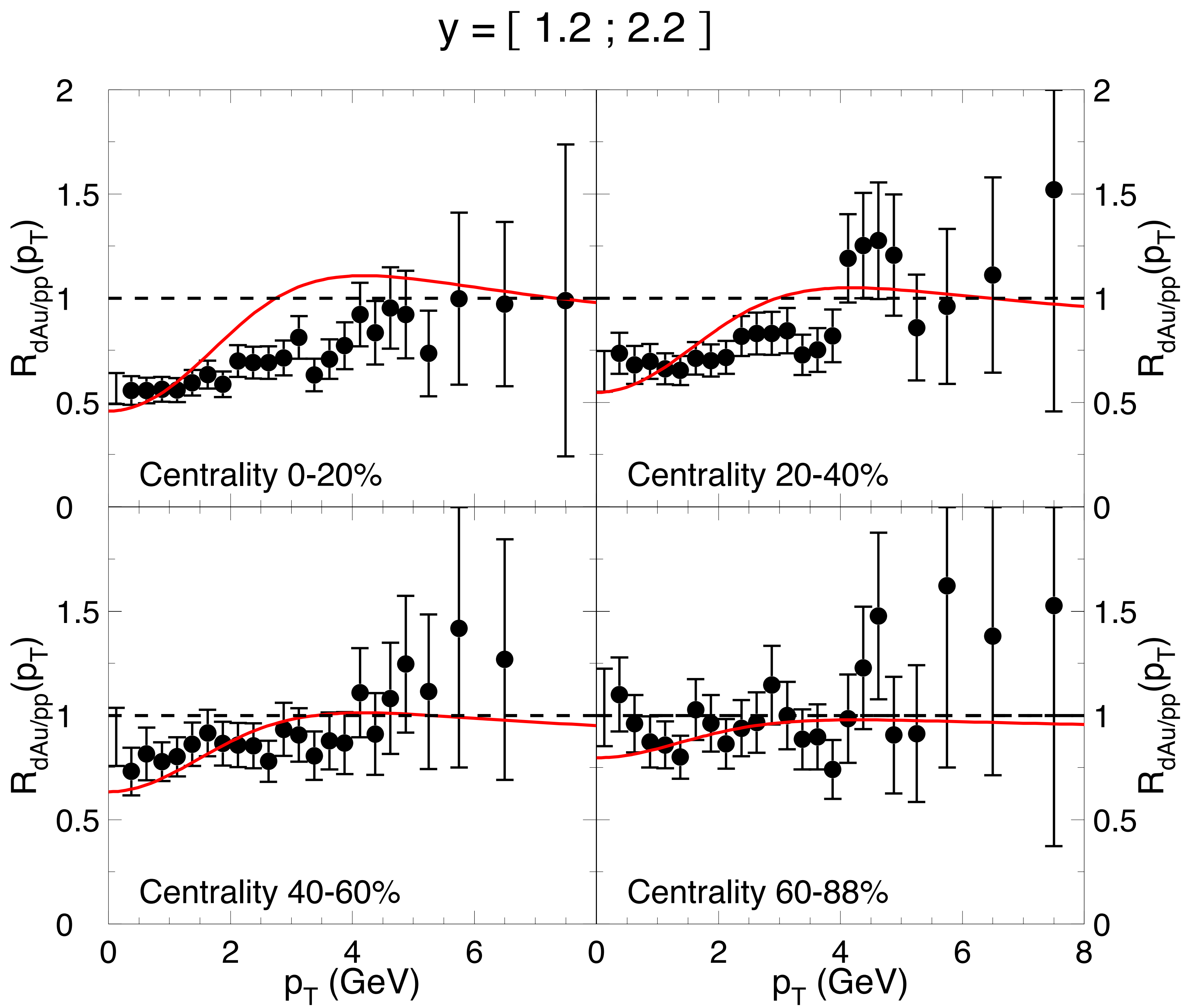
energy loss $\rightarrow$ normalization



remark: $\frac{1}{A}\frac{\mathrm{d}\sigma^{\psi}_{\mathrm{pA}}}{\mathrm{d}E}$ is insensitive to Cronin effect

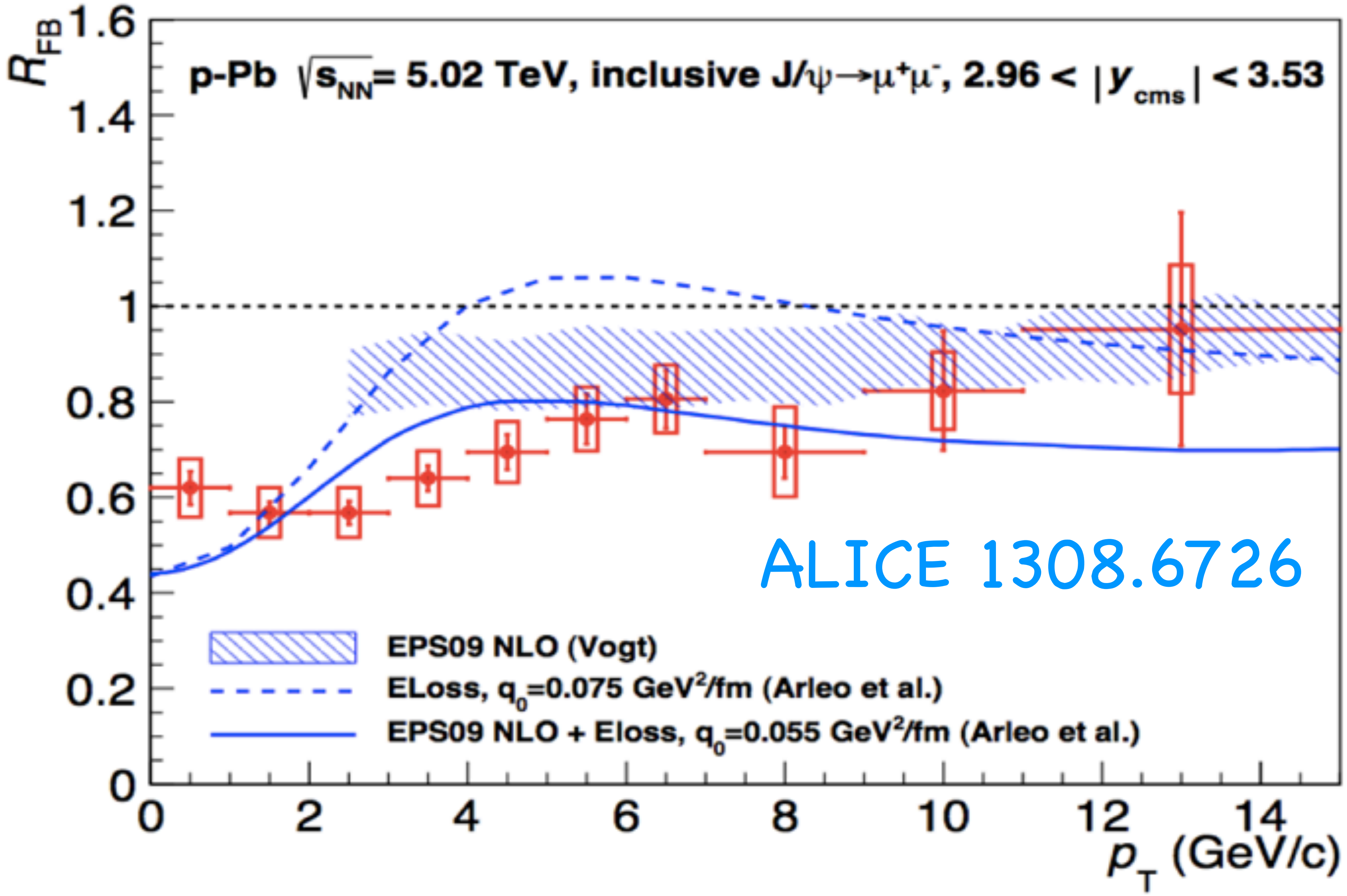
$p_\perp$-dependence of J/psi suppression (AKPR13)

RHIC d-Au (PHENIX)



$p_\perp$-dependence of J/psi suppression (AKPR13)

LHC p-Pb (ALICE)



at collider energies:

'Cronin effect' seems overestimated by the model

at RHIC and LHC, x_{F} is not large

$$x_{\mathrm{F}} = \frac{2M_{\perp}}{\sqrt{s}} \sinh y$$

RHIC $\sqrt{s} = 200\,\mathrm{GeV}$ $\quad p_{\perp} = 3\,\mathrm{GeV}\,;\; y = 1.7 \;\Rightarrow\; x_{\mathrm{F}} \simeq 0.12$

LHC $\sqrt{s} = 5\,\mathrm{TeV}$ $\quad p_{\perp} = 6\,\mathrm{GeV}\,;\; y = 3 \;\Rightarrow\; x_{\mathrm{F}} \simeq 0.027$

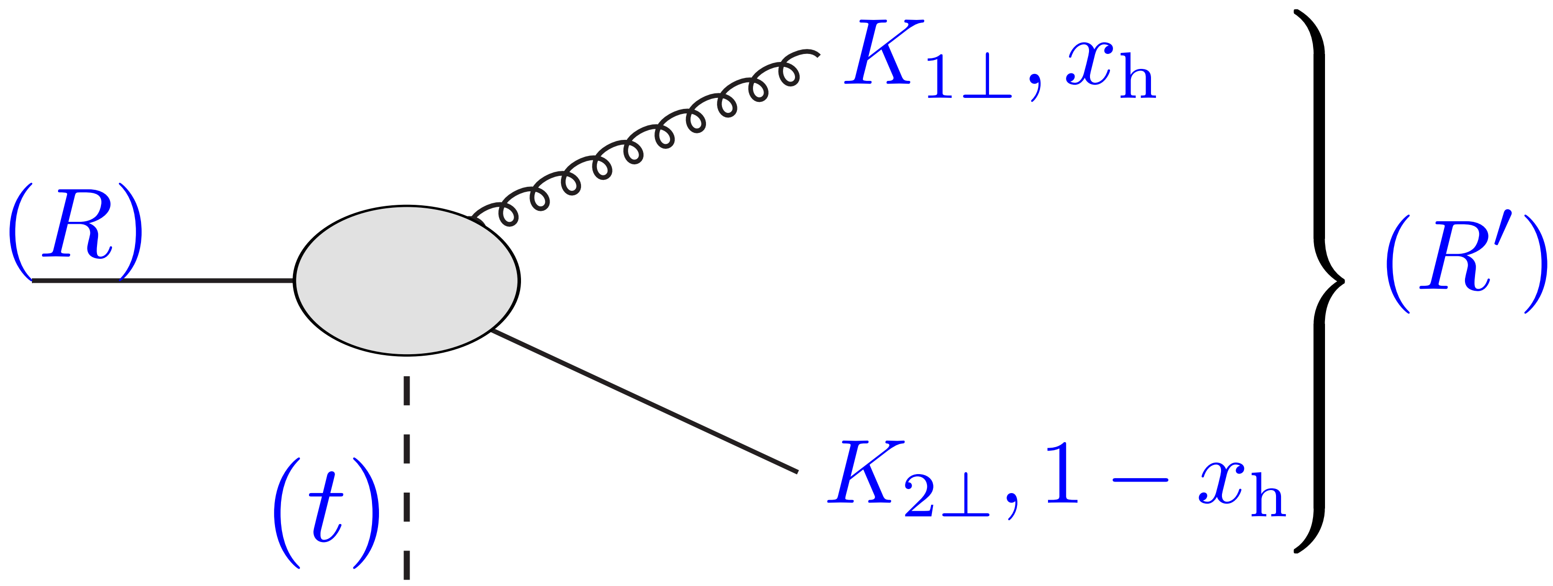
$c\bar{c}$ pair is not really *leading* !

assuming $1 \to 1$ process becomes invalid

→ consider $1 \to n$

influence on $R_{\mathrm{pA}}(y)$ and $R_{\mathrm{pA}}(p_{\perp})$?

coherent induced radiation in $1 \to n$ processes



$x_{\rm h} \sim \mathcal{O}\,(1)$

$K_{i\perp} \sim \mathcal{O}\,(Q_{\rm hard})$

$$K_{1\perp}, K_{2\perp} \gg Q_s \quad \text{but} \quad |\vec{K}_{1\perp} + \vec{K}_{2\perp}| \lesssim Q_s$$

- dipole formalism -- forward *symmetric* dijet $(x_{\rm h} = 1/2)$

  Liou & Mueller PRD 89 (2014) 074026

  $g \to q\bar{q}\,, \quad q \to qg$

- Feynman diagrams + opacity expansion

  S.P., Kolevatov JHEP 01 (2015) 141

  $q \to qg\,, \quad g \to gg$

- leading log is always the same: $\log\left(\frac{\Delta q_\perp^2(L)}{x^2 K_\perp^2}\right)$

to leading log: $x^2 K_\perp^2 \ll k_\perp^2 \ll \hat{q}L \;\Rightarrow$

$$xK_\perp \ll k_\perp \Leftrightarrow 1/k_\perp \gg \Delta r_\perp \sim v_\perp t_f \sim (K_\perp/E)\cdot(\omega/k_\perp^2)$$

radiated gluon does not probe size $\Delta r_\perp$ of dijet

→ effectively the same as for $1 \to 1$ processes

$$x\frac{\mathrm{d}I}{\mathrm{d}x}\bigg|_{1\to 2} = \sum_{R'} P_{R'} \underbrace{(C_R + C_{R'} - C_t)\frac{\alpha_s}{\pi}\log\left(\frac{\Delta q_\perp^2(L)}{x^2 Q_{\mathrm{hard}}^2}\right)}_{\text{same as for } 1\to 1}$$

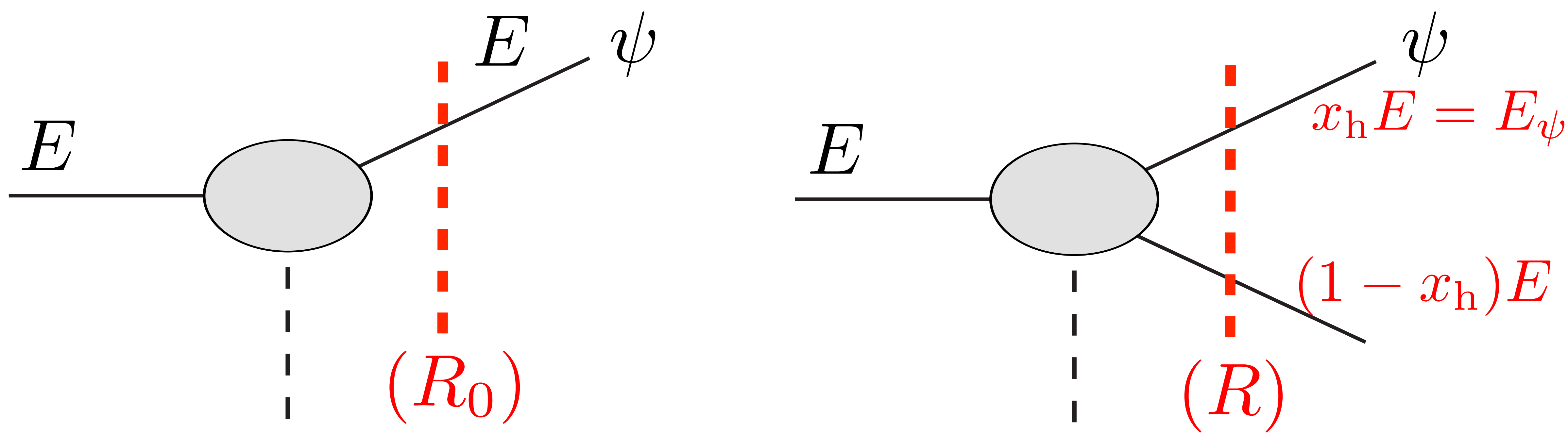
proba for 2-parton state to be produced in color rep R'

$$P_{R'} = \frac{|\mathcal{M}_{\mathrm{hard}}^{R'}|^2}{|\mathcal{M}_{\mathrm{hard}}|^2}$$

(should trivially generalize to $1 \to n$ processes)

- an important consequence:

suppose we don't know if ψ is produced via $1 \to 1$ or $1 \to 2$



induced coherent radiation is the same (leading log, and $R = R_0$)

$$\Rightarrow \quad \frac{1}{A}\frac{\mathrm{d}\sigma_{\rm pA}}{\mathrm{d}E}(E) = \int_0^{\varepsilon_{\rm max}} \mathrm{d}\varepsilon\, \underbrace{\mathcal{P}(\varepsilon, E)}\, \frac{\mathrm{d}\sigma_{\rm pp}}{\mathrm{d}E}(E+\varepsilon)$$

$\mathcal{P}(\varepsilon, E)$ is a scaling function of $x \equiv \varepsilon / E$ $\Longrightarrow$

$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\rm pA}}{\mathrm{d}E}(E) = \int_{z'_{min}}^{1} \mathrm{d}z'\, \mathcal{F}_{\rm loss}(z')\, \frac{\mathrm{d}\sigma_{\rm pp}}{\mathrm{d}E}\left(\frac{E}{z'}\right) \qquad z' \equiv \frac{E}{E+\varepsilon}$$

coherent radiation does not change dijet structure

→ all energies are rescaled by same factor z'

$$\frac{1}{A}\frac{\mathrm{d}\sigma^{\psi}_{\mathrm{pA}}}{\mathrm{d}E}(E_{\psi}) = \int_{z'_{min}}^{1} \mathrm{d}z' \underbrace{\mathcal{F}_{\mathrm{loss}}(z')}_{\text{same as for } 1\to 1} \frac{\mathrm{d}\sigma^{\psi}_{\mathrm{pp}}}{\mathrm{d}E}\left(\frac{E_{\psi}}{z'}\right)$$

$\Rightarrow$ predictions for $R^{\psi}_{\mathrm{pA}}(y)$ independent of dijet structure

- on the contrary: *Cronin effect* depends on dijet structure

$\Delta q_{\perp} \ll p_{\perp} \Rightarrow$

- dijet undergoes global *rotation* of angle $\theta_s = \frac{\Delta q_{\perp}}{E}$
- each dijet constituent undergoes same rotation: $\theta_s = \frac{\Delta p_{i\perp}}{E_i}$

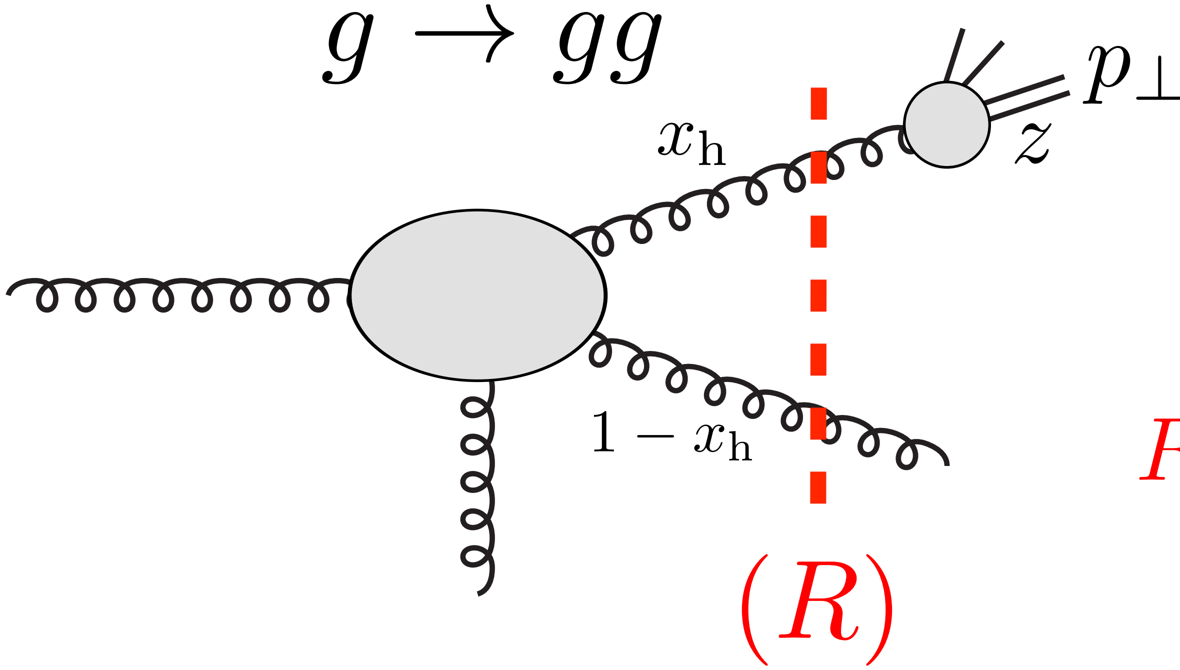
$$\Delta p_{i\perp} \propto E_i$$

$\Rightarrow$ predictions for $R^{\psi}_{\mathrm{pA}}(p_{\perp})$ depend on x_{h}

light hadron suppression at the LHC

Arleo, Kolevatov, S.P. (work in progress)

$g \to gg$



average over color representation of gg final state:

$$R^h_{\rm pA}(y, p_\perp) \simeq \sum_R \langle P_R(x_{\rm h}) \rangle_y \, R^R_{\rm pA}(y, p_\perp)$$

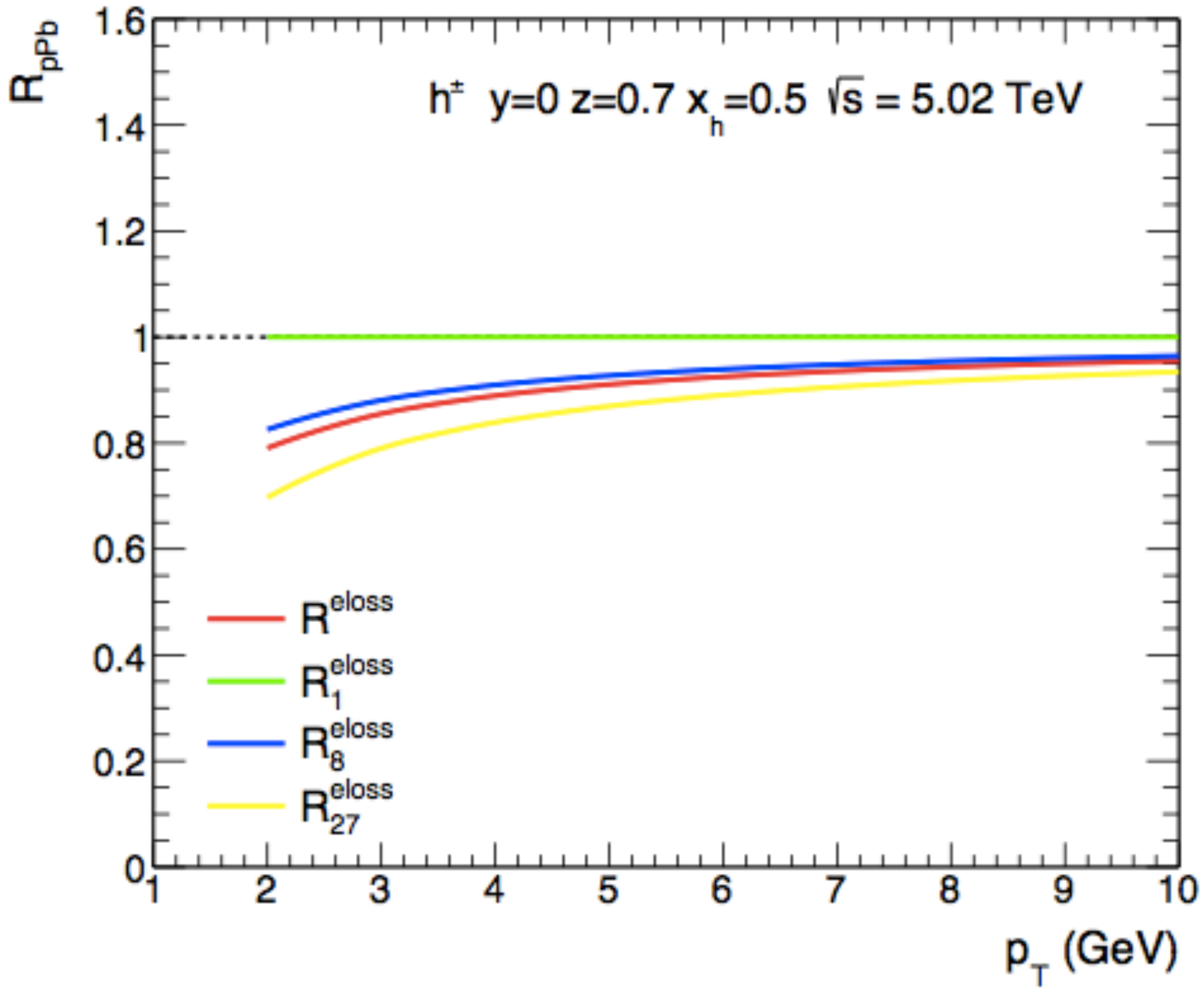
$$R^R_{\rm pA}(y, p_\perp) = \int_\delta \int_\varphi \mathcal{P}_R\left(x, \ell_{_{\rm A}}, P_\perp = \frac{p_\perp}{\langle z \rangle}\right) \frac{{\rm d}\sigma^h_{\rm pp}(y+\delta, \, \vec{p}_\perp - z x_{\rm h} \Delta \vec{p}^{\,R}_\perp)}{{\rm d}\sigma^h_{\rm pp}(y, \vec{p}_\perp)}$$

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

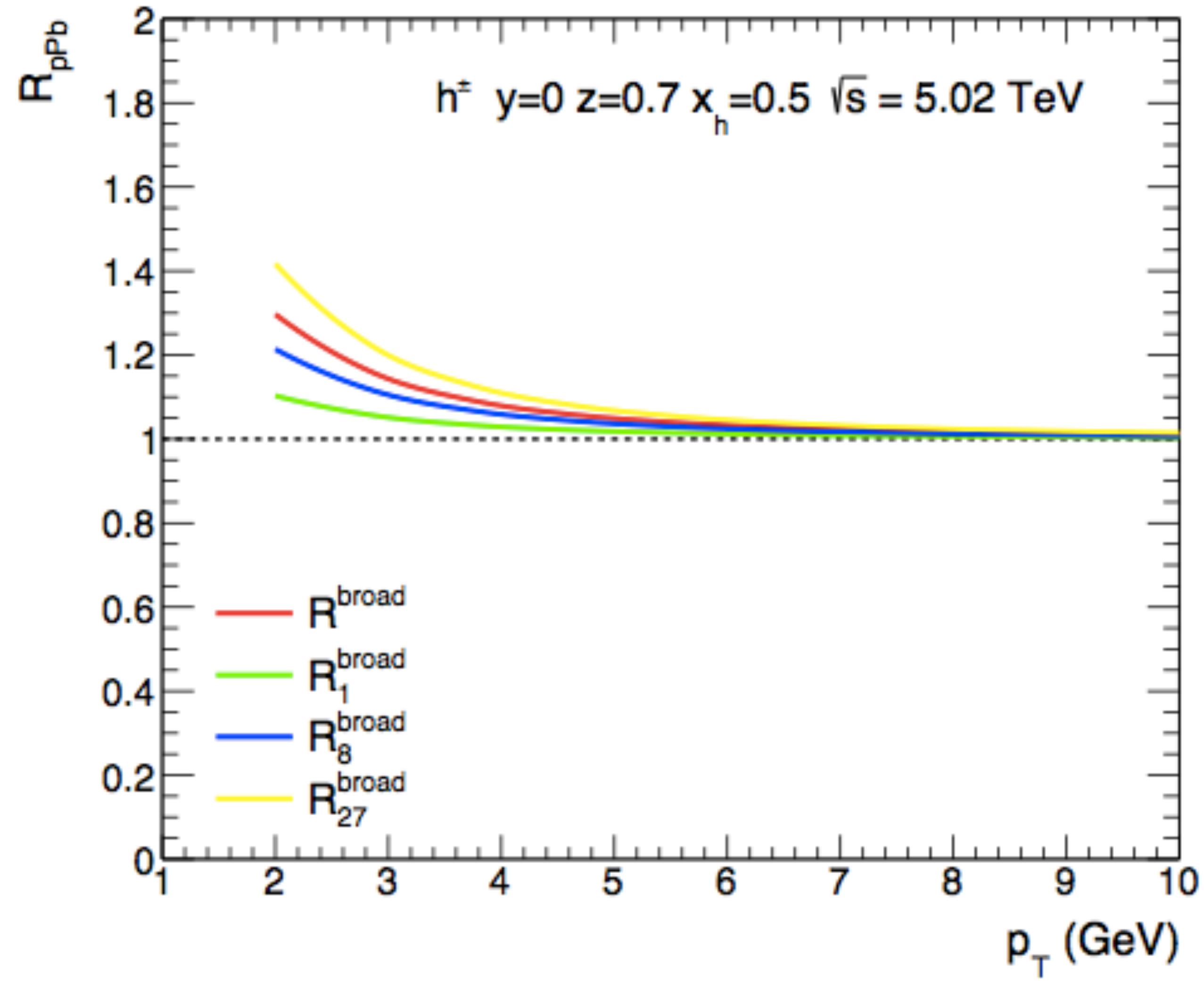
- $R = \mathbf{1, 8, 27} \quad (P_{\mathbf{10}} = 0)$
- broadening : $\quad (\Delta \vec{p}^{\,R}_\perp)^2 = \dfrac{N_c + C_R}{2N_c} \, \hat{q} L$

energy loss vs broadening at LHC

energy loss only

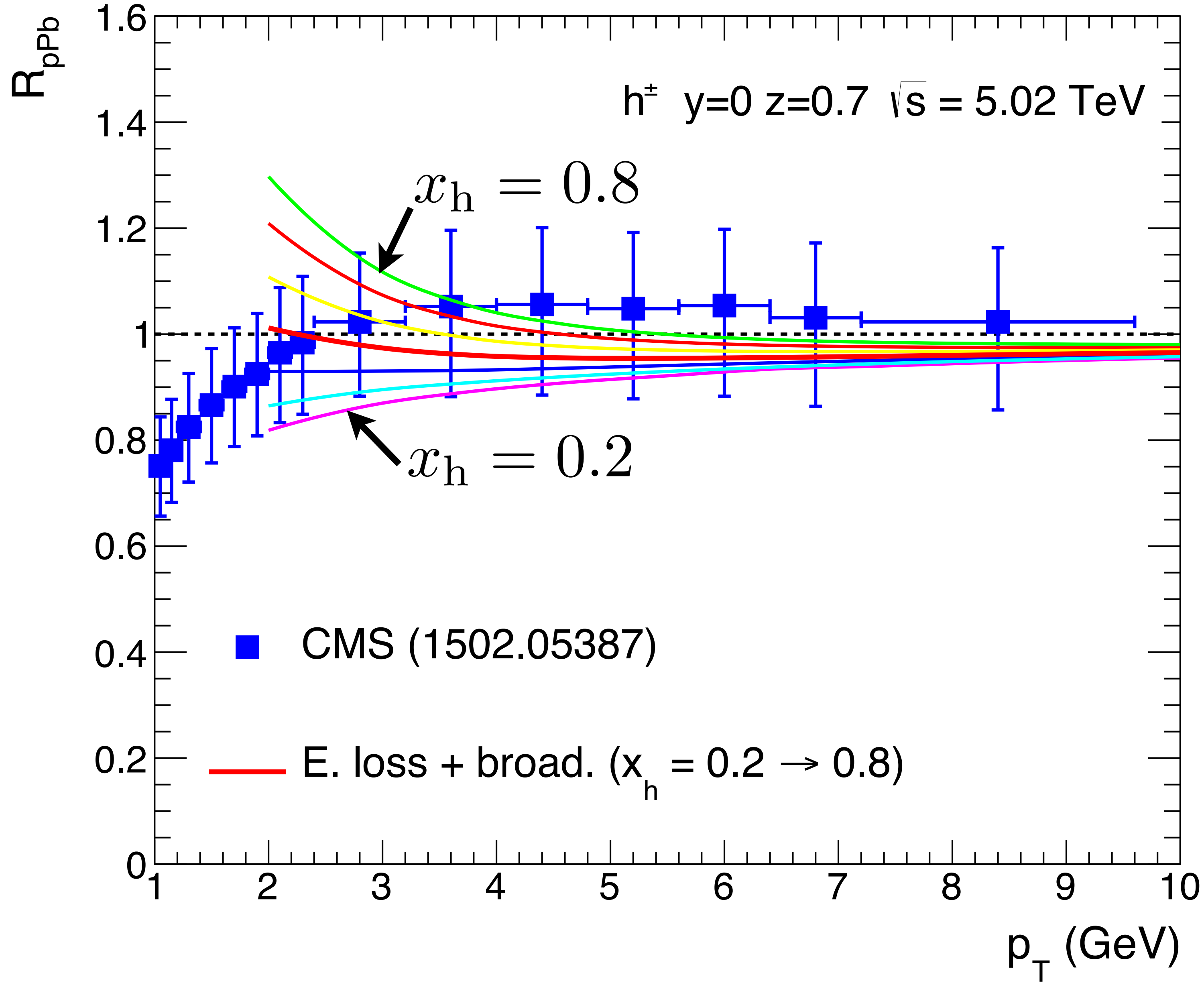


broadening only



- opposite trends between energy loss and broadening effects

light hadron suppression vs LHC data



- model consistent with CMS (and ALICE) data
- no Cronin enhancement at low x_{h}
- model is preliminary: large uncertainty on x_{h}
- x_{h} might be extracted from dijet correlations

Summary

induced coherent radiation

- is a QCD prediction
- explains $R_{\rm pA}^{J/\psi}(y)$ at all $\sqrt{s}$
- plays a role for all $1 \to n$ processes
- must be combined with 'Cronin' for $R_{\rm pA}(p_\perp)$