nuclear suppression in pA collisions from induced gluon radiation

Stéphane Peigné
SUBATECH, Nantes
peigne@subatech.in2p3.fr

from studies with F. Arleo, R. Kolevatov, T. Sami

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Introduction

- understand pA suppression *before* hot effects in AA

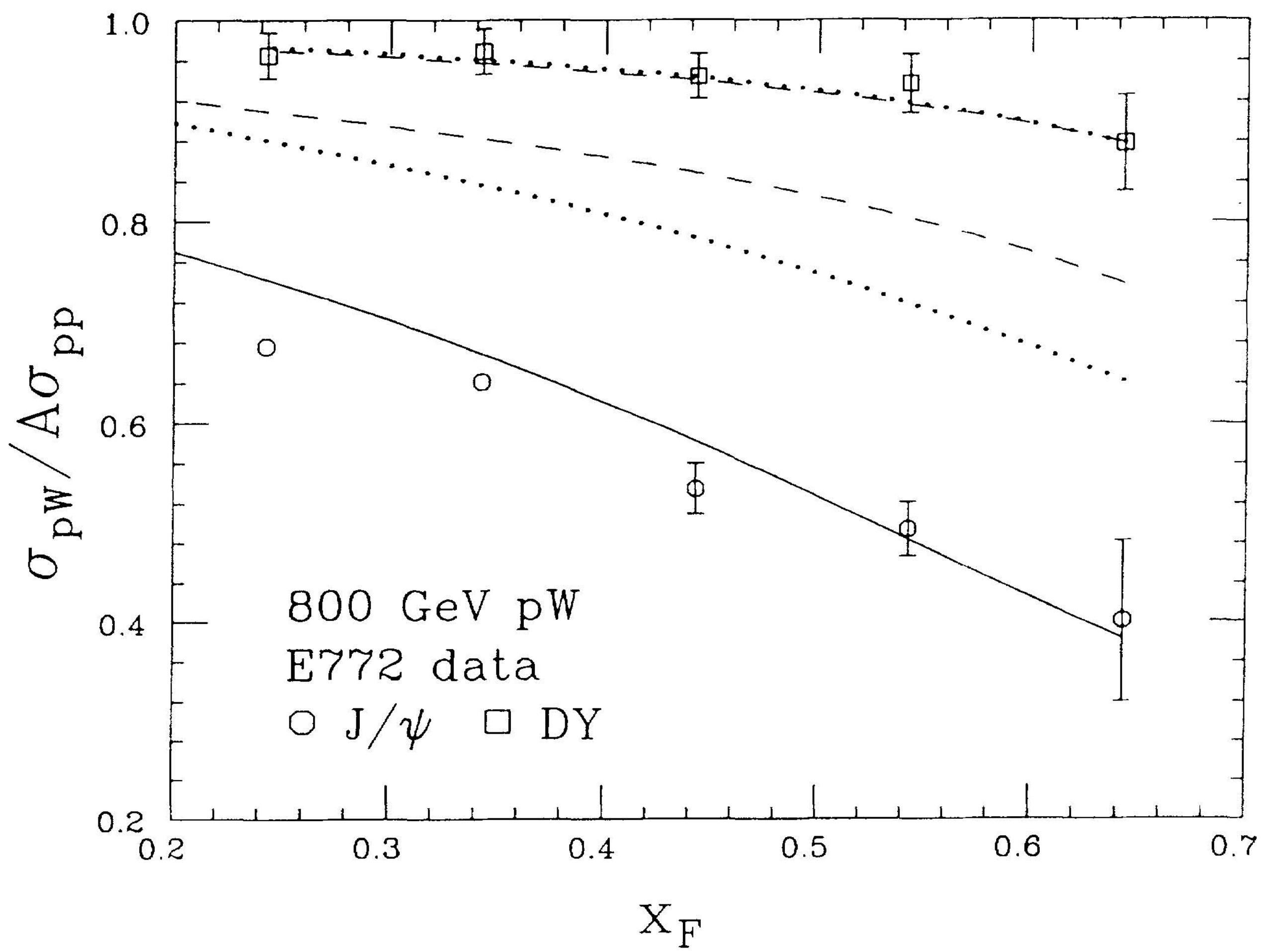
- several effects have been proposed:
    - in-medium 'nuclear absorption'
    - CGC/saturation effects
    - shadowing/nPDF effects
    - parton *radiative* energy loss

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*

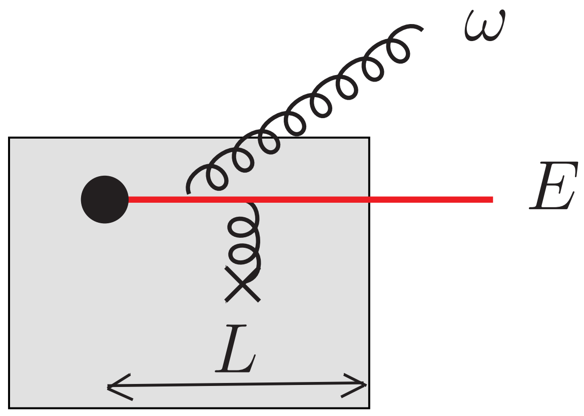
$$\Delta E_{\rm parton} \propto E$$

- 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):

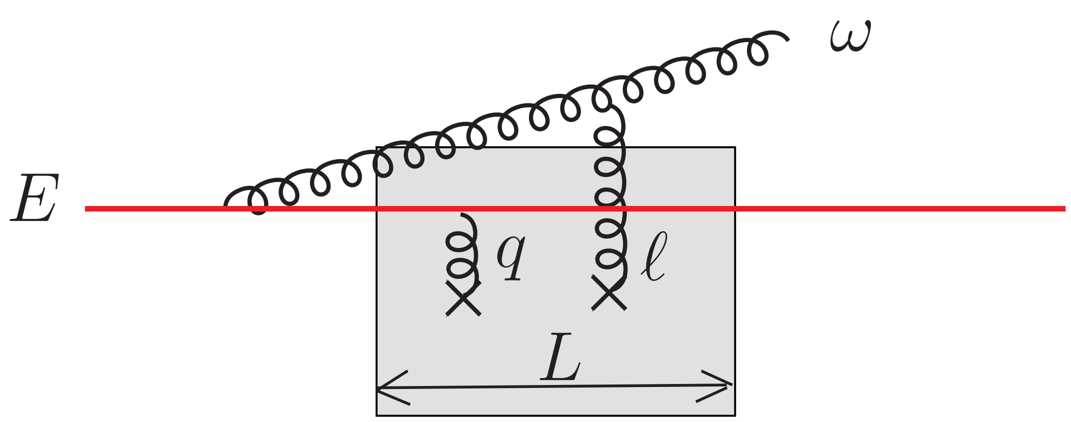
(1) parton suddenly produced in medium



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

... but not in situation (2):

(2) forward scattering of fast ‘asymptotic parton’

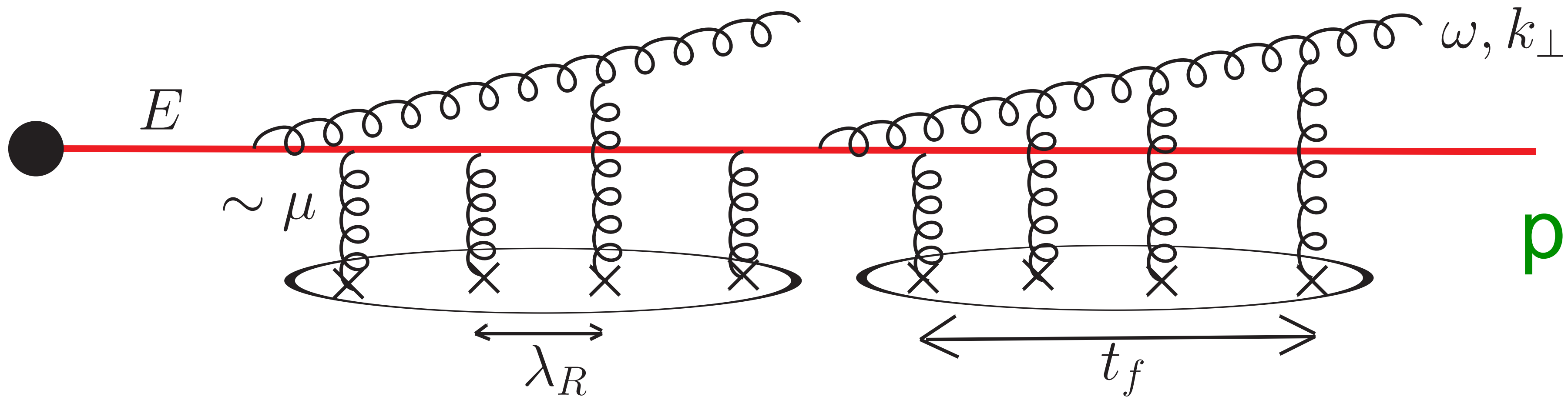


$$\Delta E_{\rm rad} \sim \alpha_s \frac{\sqrt{\hat{q} L}}{M_\perp} E$$

fully coherent
energy loss

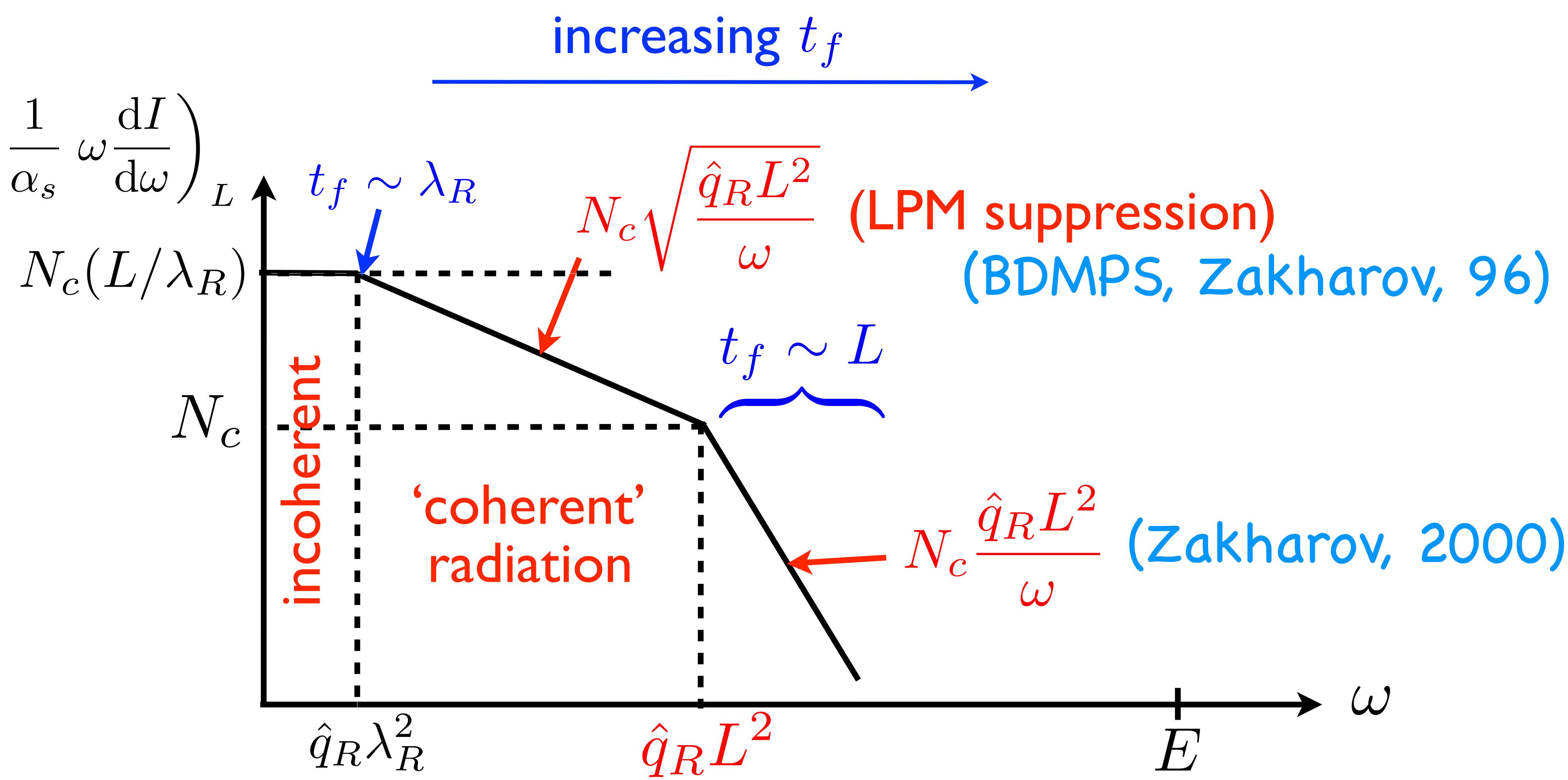
features of induced *radiative* energy loss

(1) energetic parton suddenly produced in medium

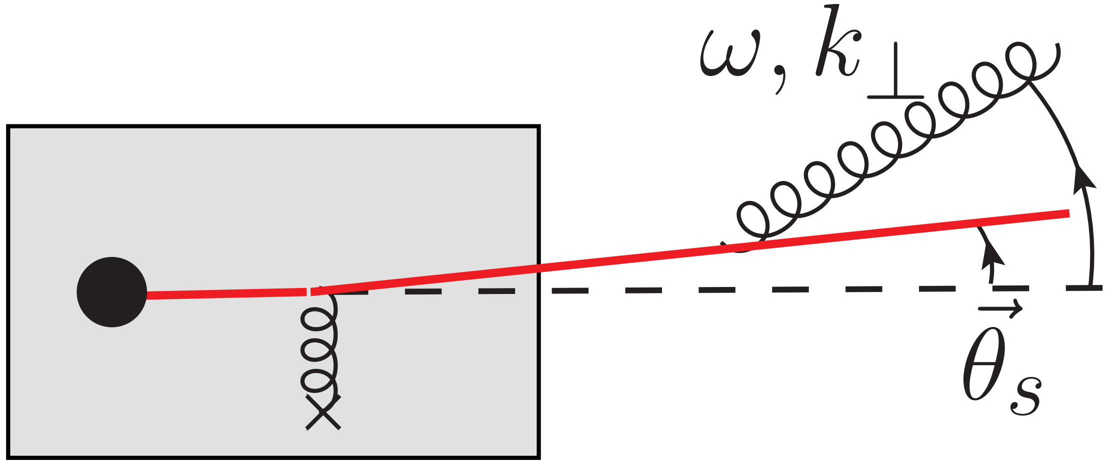


$E \to \infty$

parton color C_R



when ω exceeds $\hat{q}_R L^2$, t_f saturates at $t_f \sim L$ due to suppression of $t_f \gg L$



$$t_f \sim \frac{\omega}{k_\perp^2} \gg L \;\Rightarrow\; \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_L \sim \int \frac{\mathrm{d}^2\vec{\theta}}{(\vec{\theta}-\vec{\theta}_s)^2}$$ L-independent

$\Rightarrow$ suppressed in $$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_{\mathrm{ind}} \equiv \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_L - \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_{L=0}$$

average energy loss

$$\Delta E = \int \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_L \sim \alpha_s N_c \hat{q}_R L^2 \sim \alpha_s C_R \hat{q} L^2 \quad (\hat{q} \equiv \hat{q}_g)$$

higher orders in α_s modify the L-dependence

$$\Delta p_\perp^2 \sim \hat{q} L \left[1 + \underbrace{\mathcal{O}\left(\alpha_s \ln^2\left(\frac{L}{l_0}\right)\right)}\right] \sim \hat{q}_{\text{eff}} L$$

pt-broadening induced by radiation (in DLA)

Liou, Mueller, Wu (2013)

$$\Longrightarrow \quad \Delta E \sim \alpha_s \hat{q}_{\text{eff}} L^2 \sim \alpha_s \hat{q} L^2 \left[1 + \frac{\alpha_s N_c}{2\pi} \ln^2\left(\frac{L}{l_0}\right)\right]$$

B. Wu (2014)

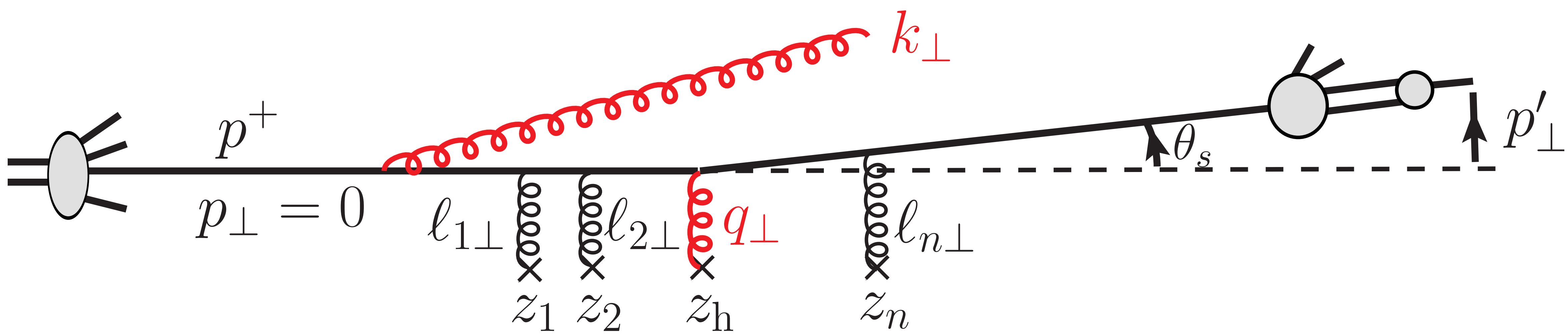
but ΔE remains bounded in situation (1)

(2) $1 \to 1$ hard forward scattering

- Arleo, S.P., Sami PRD 83 (2011) 114036
  - 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

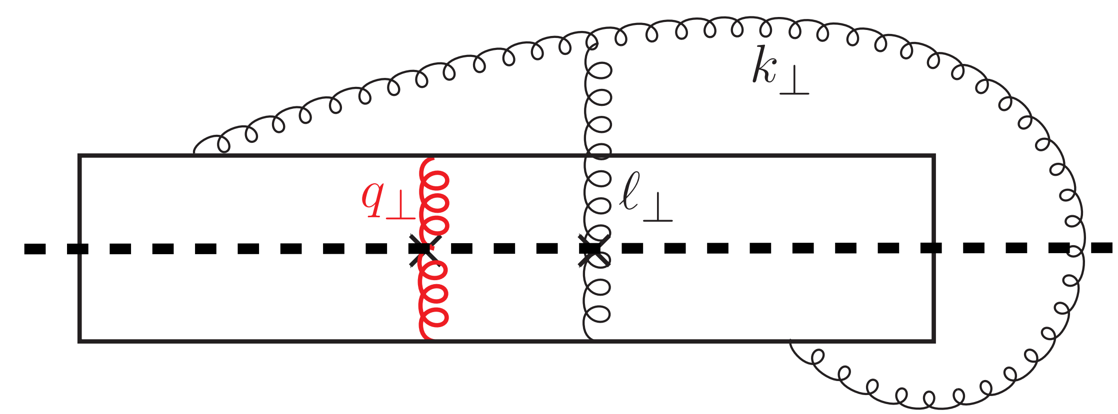
setup: high-energy p-A collision in nucleus rest frame

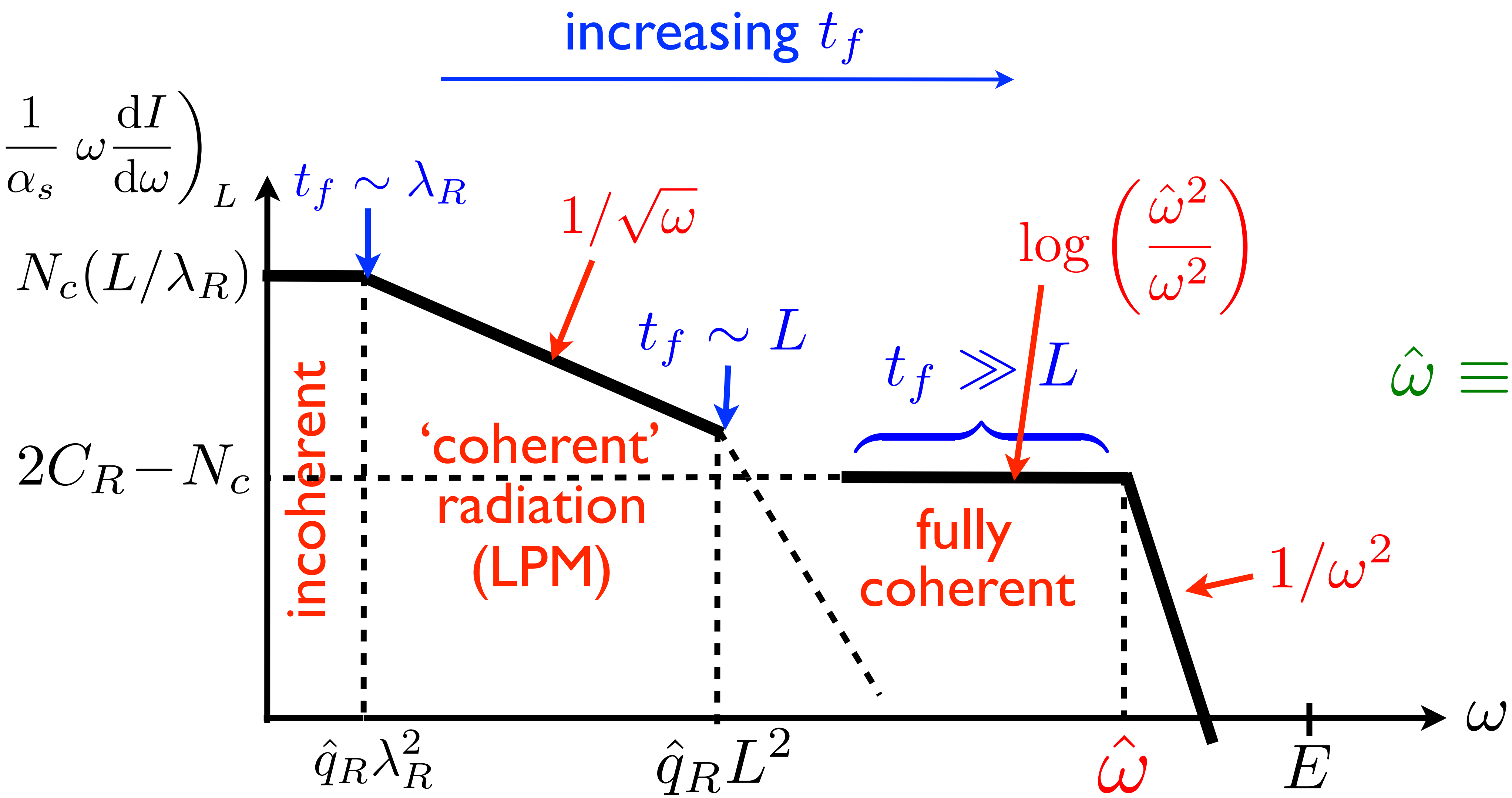
(PAK14)



- tag energetic hadron with $p'_\perp|_{\rm hard} \gg \sqrt{\hat{q}L}$
- parent parton suffers:
  - *single* hard exchange $q_\perp \simeq p'_\perp$
  - soft rescatterings $\ell_\perp^2 = (\sum \vec{\ell}_{i\perp})^2 \sim \hat{q}L \sim Q_s^2 \ll q_\perp^2$

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



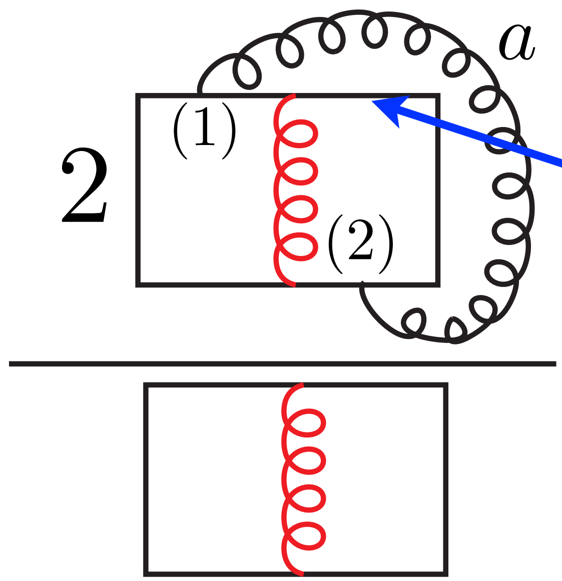


$$\hat{\omega} \equiv \frac{\sqrt{\hat{q}L}}{M_\perp}E$$

$$\Delta E_{\rm coh} \sim \alpha_s \hat{\omega} \sim \alpha_s \frac{\sqrt{\hat{q}L}}{M_\perp} E \quad (\gg \Delta E_{\rm LPM} \sim \alpha_s \hat{q} L^2\,)$$

from ***fully coherent*** domain: $t_f \sim \frac{\omega}{k_\perp^2} \sim \frac{\hat{\omega}}{\hat{q}L} \gg L$

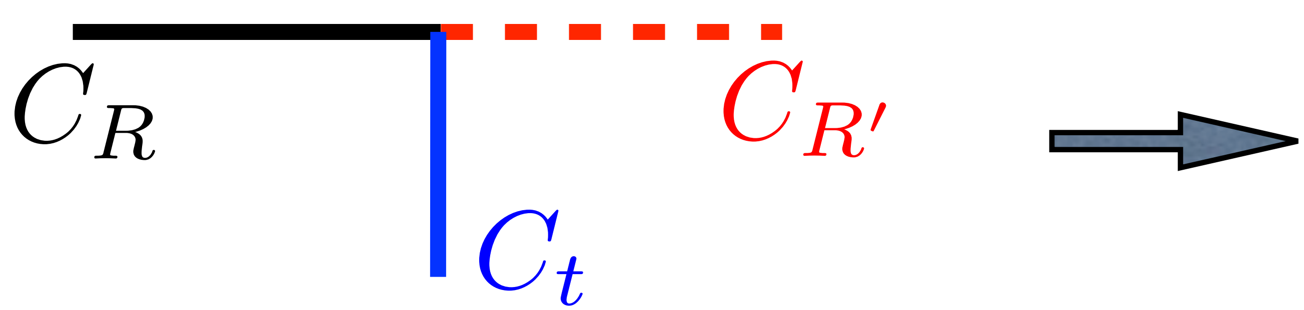
- color factor given by interference term:



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

$$= C_R + C_R - N_c$$

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



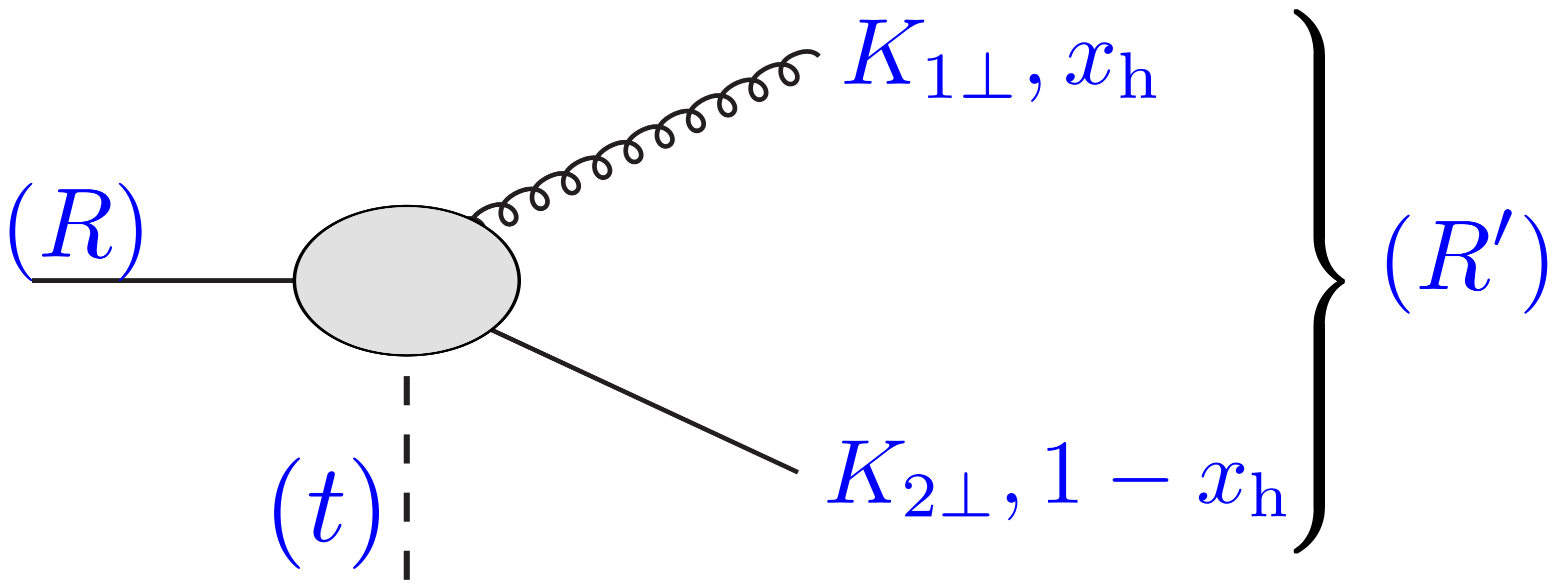
$$\boxed{C_R + C_{R'} - C_t}$$

explicit calculation (PAK14) $\Longrightarrow$
general (*approximate*) *pocket formula*
for induced coherent spectrum:

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

- 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
  (see PAK14 for exact expression)

generalization to $1 \to 2$ hard forward 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

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

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

same as for $1 \to 1$

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

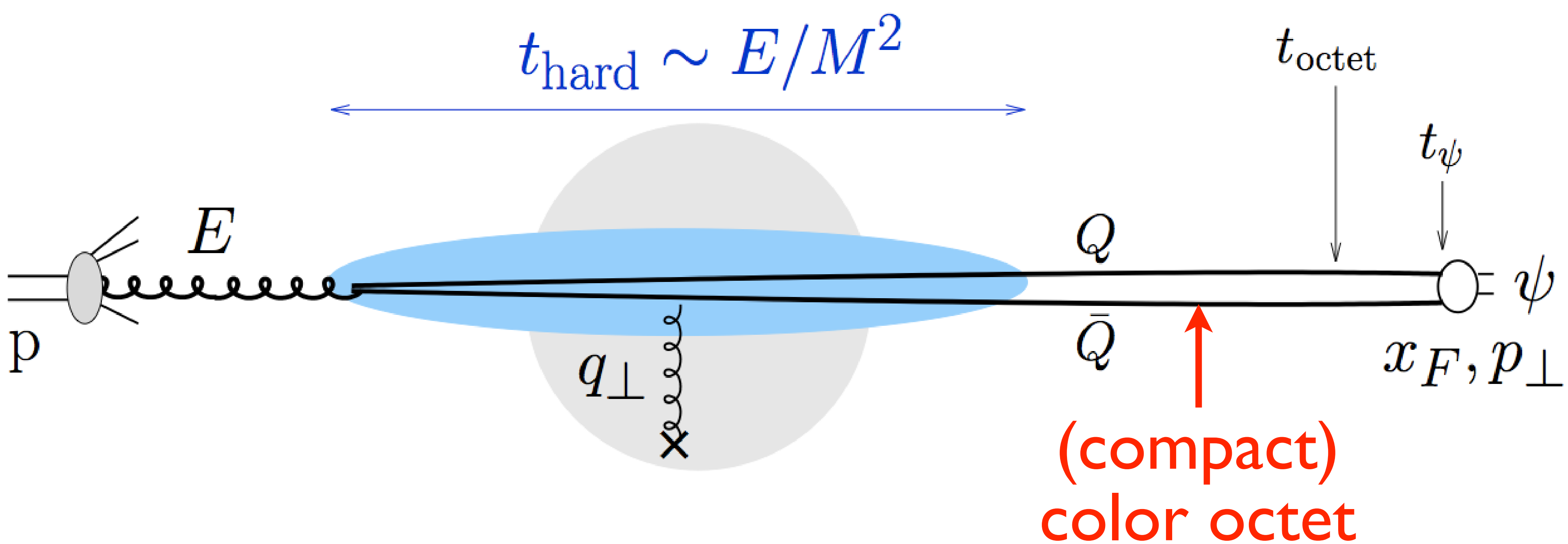
(should trivially generalize to $1 \to n$ processes)

model for quarkonium pA suppression

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

$x_F > x_F^{crit}$

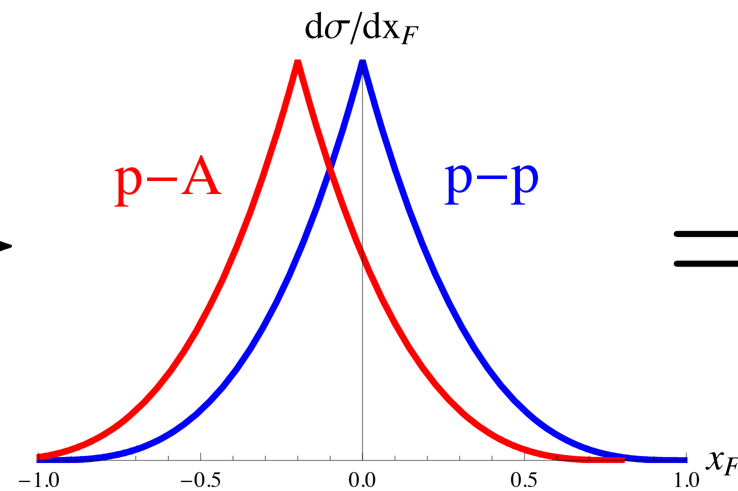
small $p_\perp$



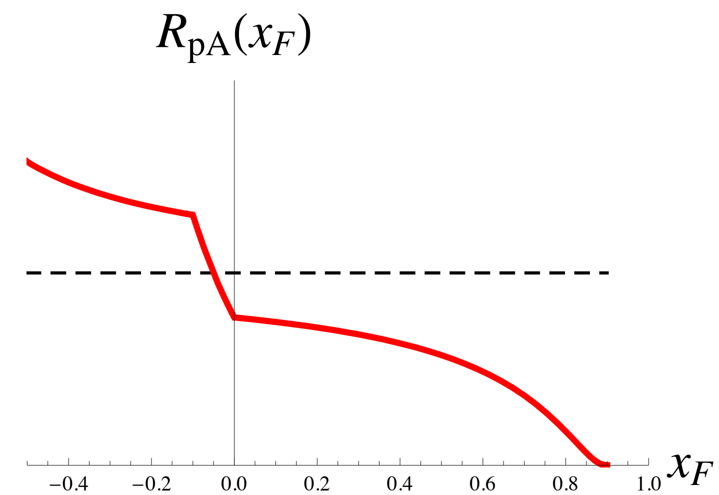
→ coherent radiation associated to $g \to Q\bar{Q}$

$$\frac{1}{A}\frac{d\sigma_{pA}^{\psi}}{dE}(E) = \int_0^{\varepsilon^{max}} d\varepsilon\, \mathcal{P}(\varepsilon, E, \ell_A^2)\, \frac{d\sigma_{pp}^{\psi}}{dE}(E+\varepsilon)$$

energy shift $\Rightarrow$



$\Rightarrow$

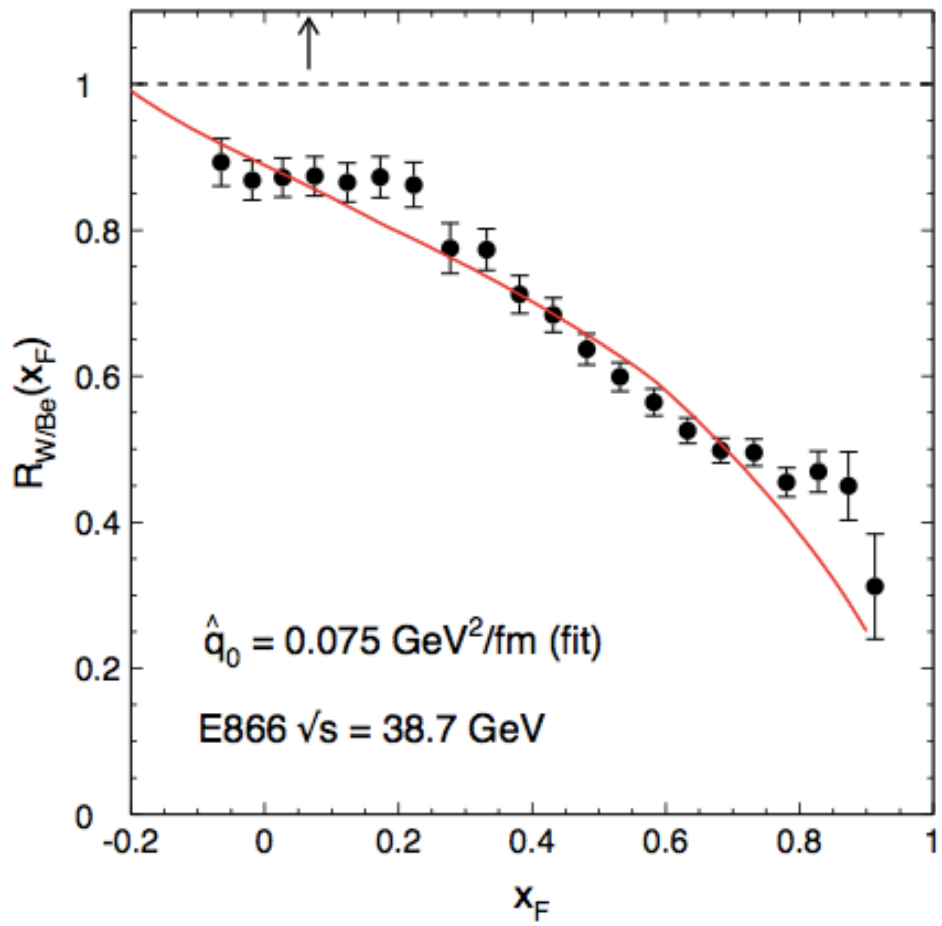


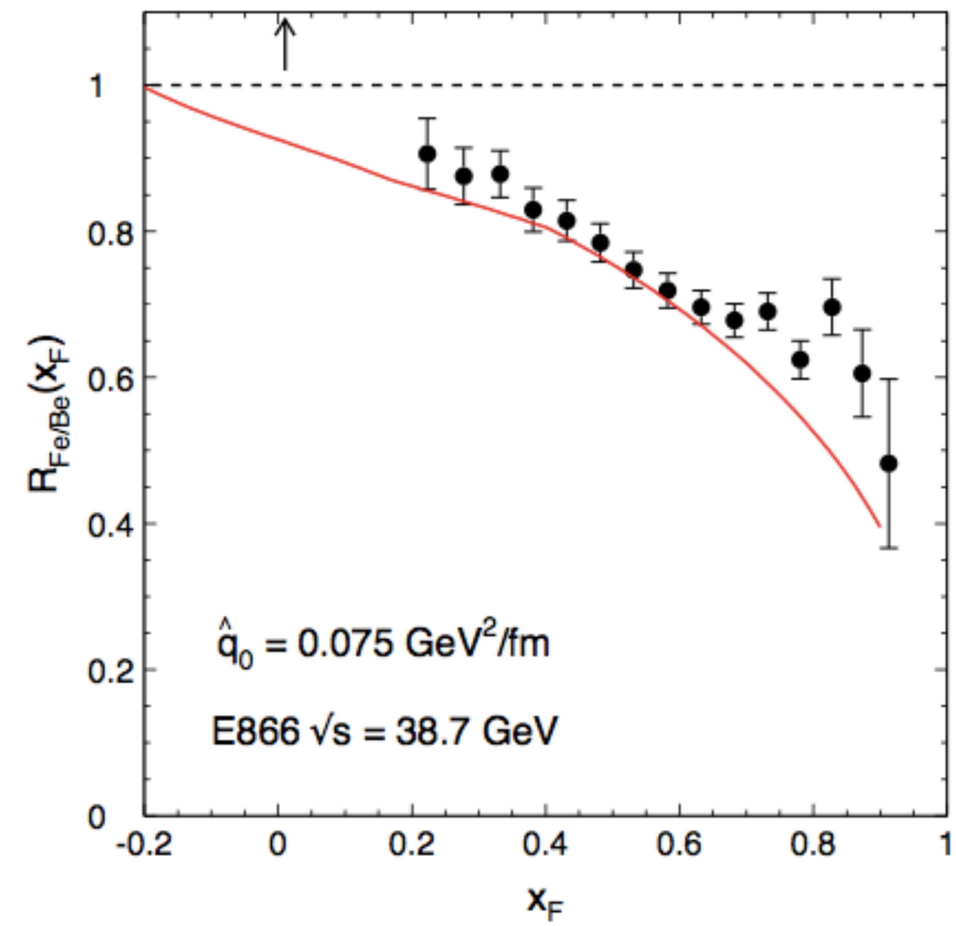
- $d\sigma_{pp}^{\psi}/dx_F$ taken from experimental data
- $\mathcal{P}(\varepsilon, E, \ell_A^2) = \frac{dI}{d\varepsilon} \exp\left\{-\int_{\varepsilon}^{\infty} d\omega \frac{dI}{d\omega}\right\}$
- $\hat{q}(x_2) \equiv \hat{q}_0 \left(\frac{10^{-2}}{x_2}\right)^{0.3}$ $\hat{q}_0$ single parameter

$2 \to 1$ kinematics $\Longrightarrow$ focus on low $p_\perp \lesssim M$

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

E866 Fe/Be





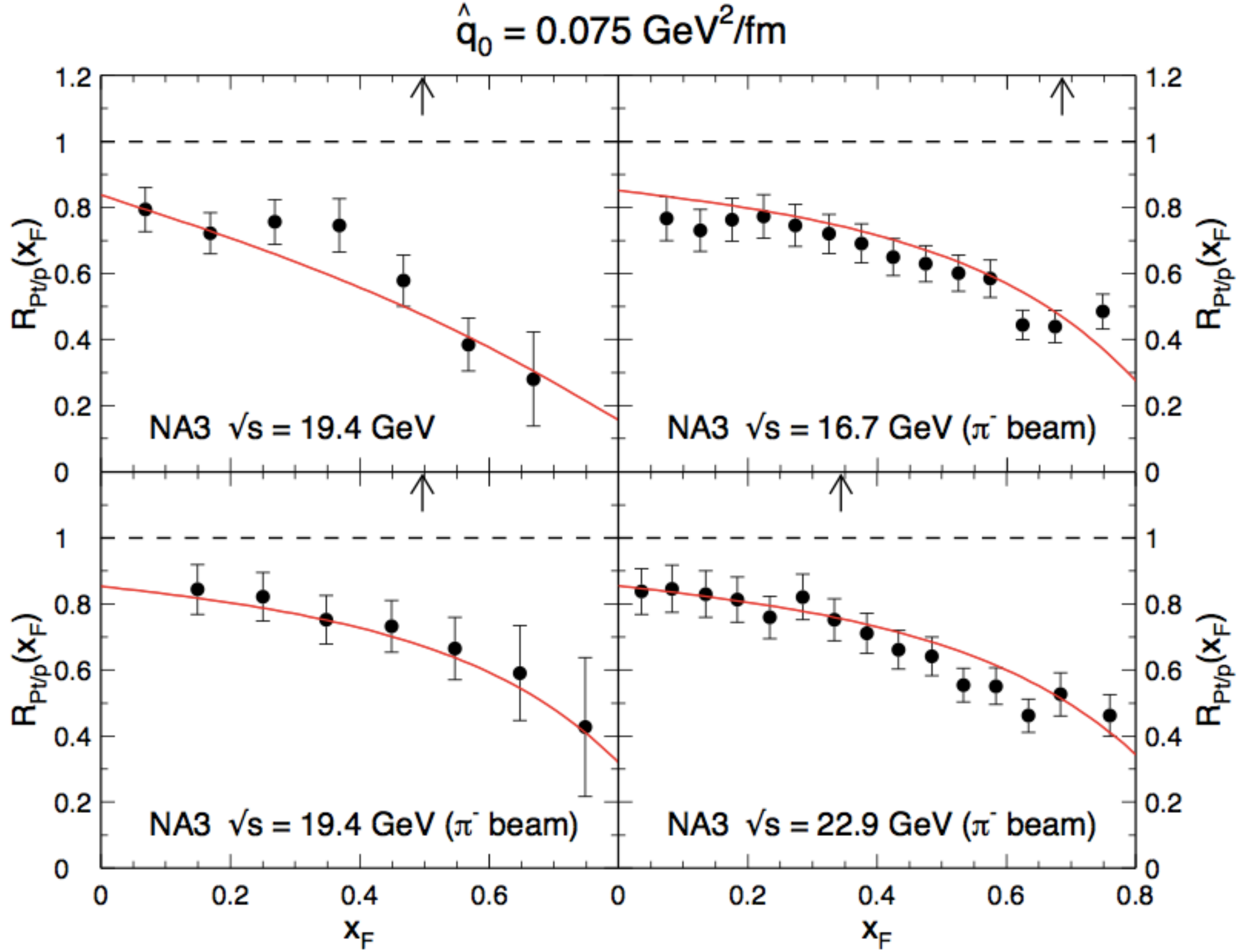
...and used to predict $R_{\rm pA}^{{\rm J}/\psi}$ for other A, $\sqrt{s}$

A–dependence well reproduced

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

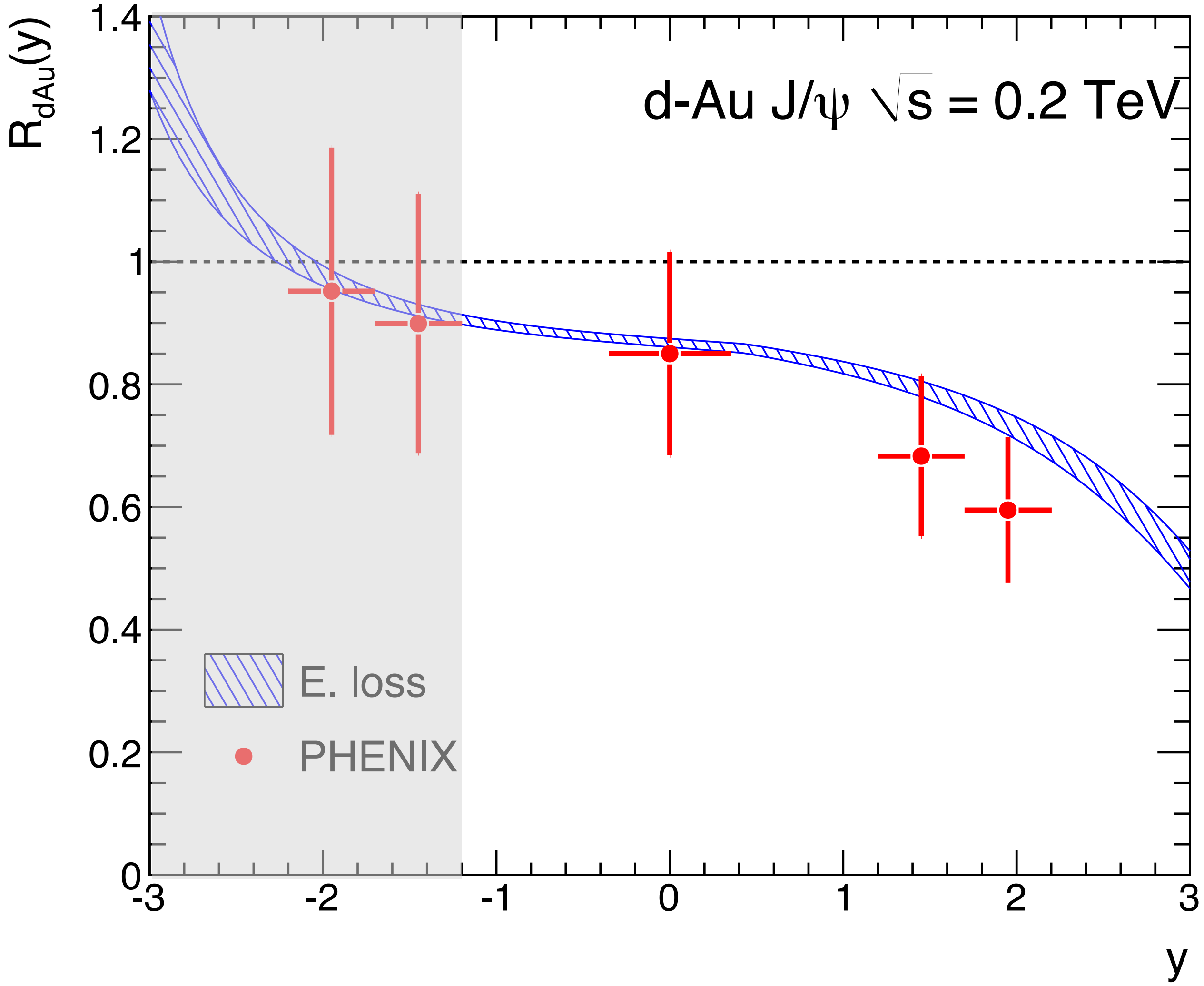
consistent with fits to DIS data   Albacete et al (AAMQS) 2011

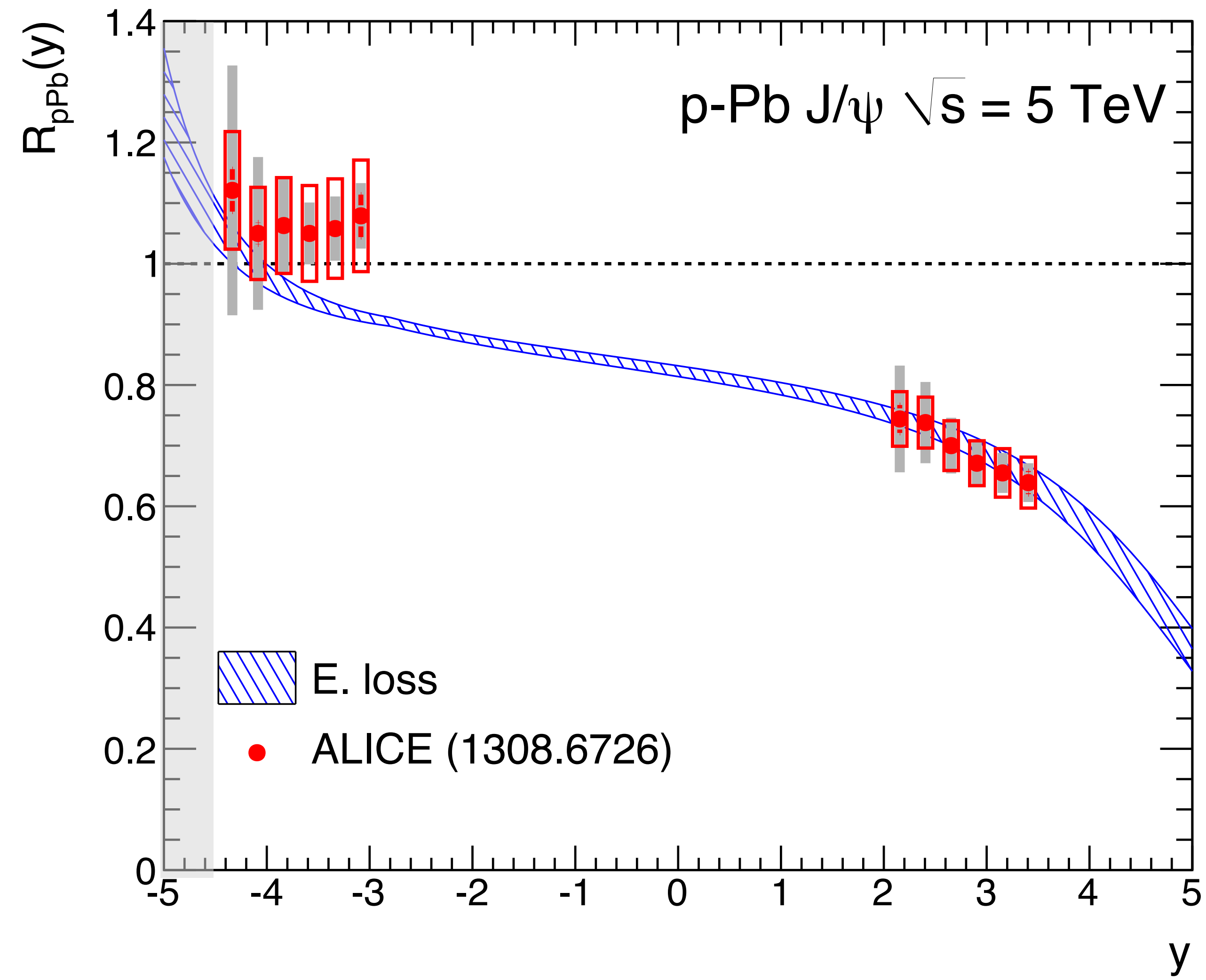
J/ψ NA3 Pt/p



$\hat{q}_0 = 0.075\ GeV^2/fm$
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

RHIC d-Au (PHENIX)   LHC p-Pb (ALICE)





nPDF/saturation effects might be sizeable at collider energies, but

coherent radiation *alone* “explains” J/psi pA suppression

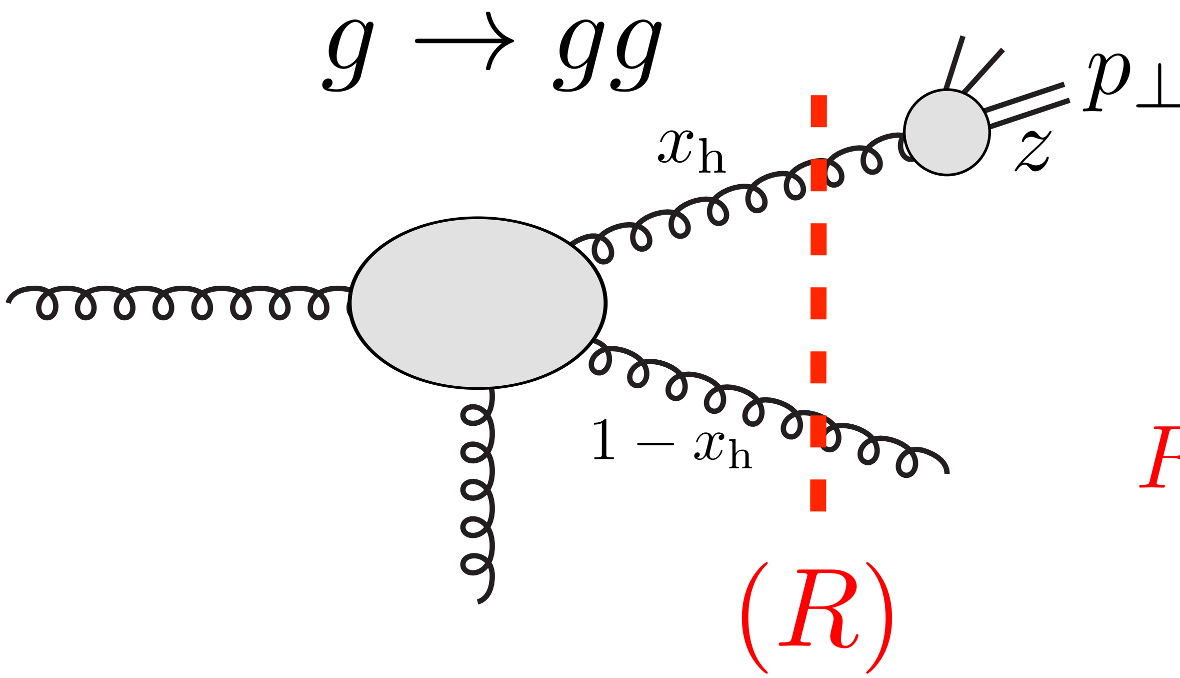
from fixed target to collider energies

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

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

model for light hadron suppression at the LHC

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



average over color representation of gg final state:

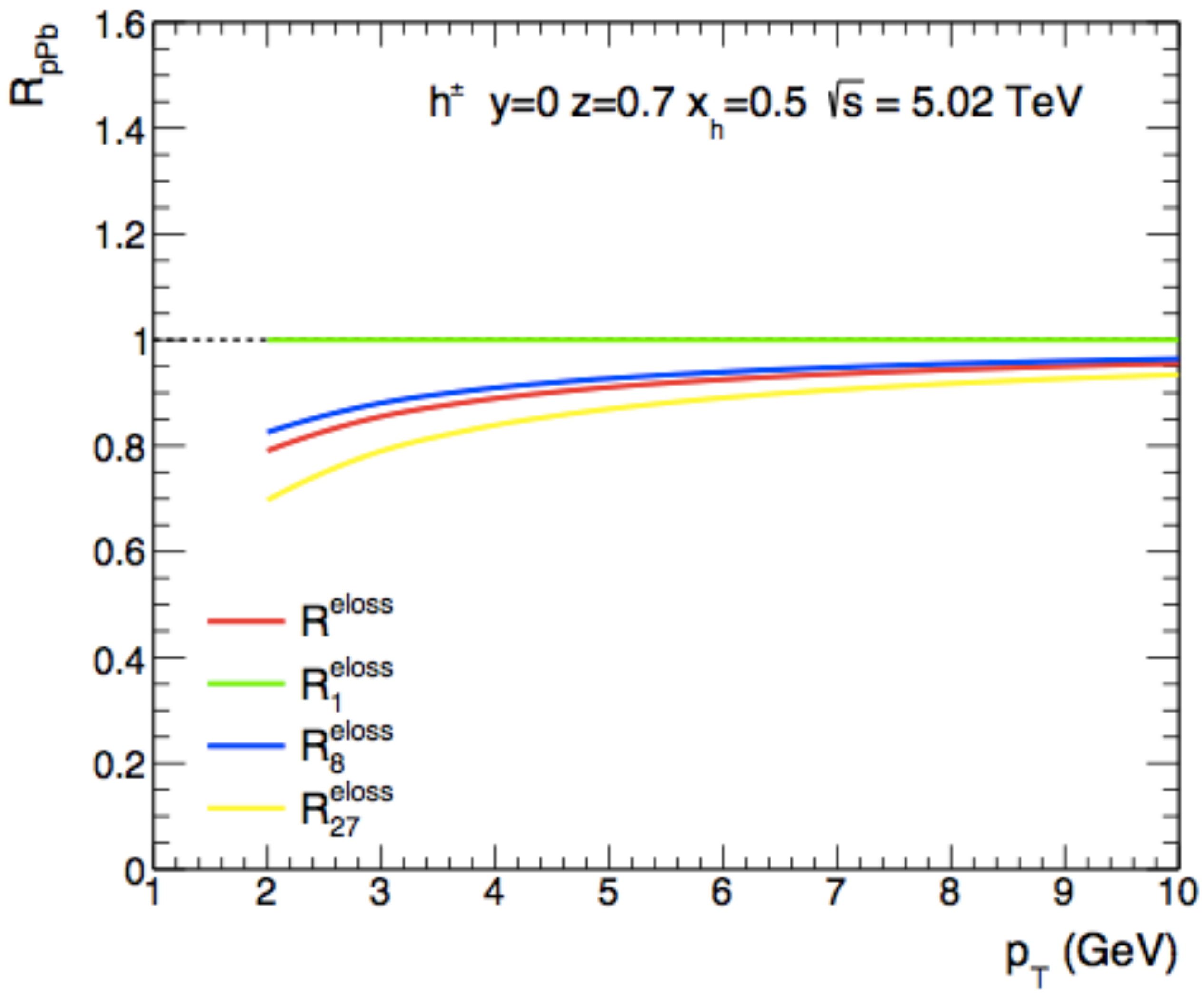
$$R^h_{\rm pA}(y, p_\perp) \simeq \sum_R \langle P_R(x_{\rm h}) \rangle_y \, R^R_{\rm pA}(y, p_\perp)$$

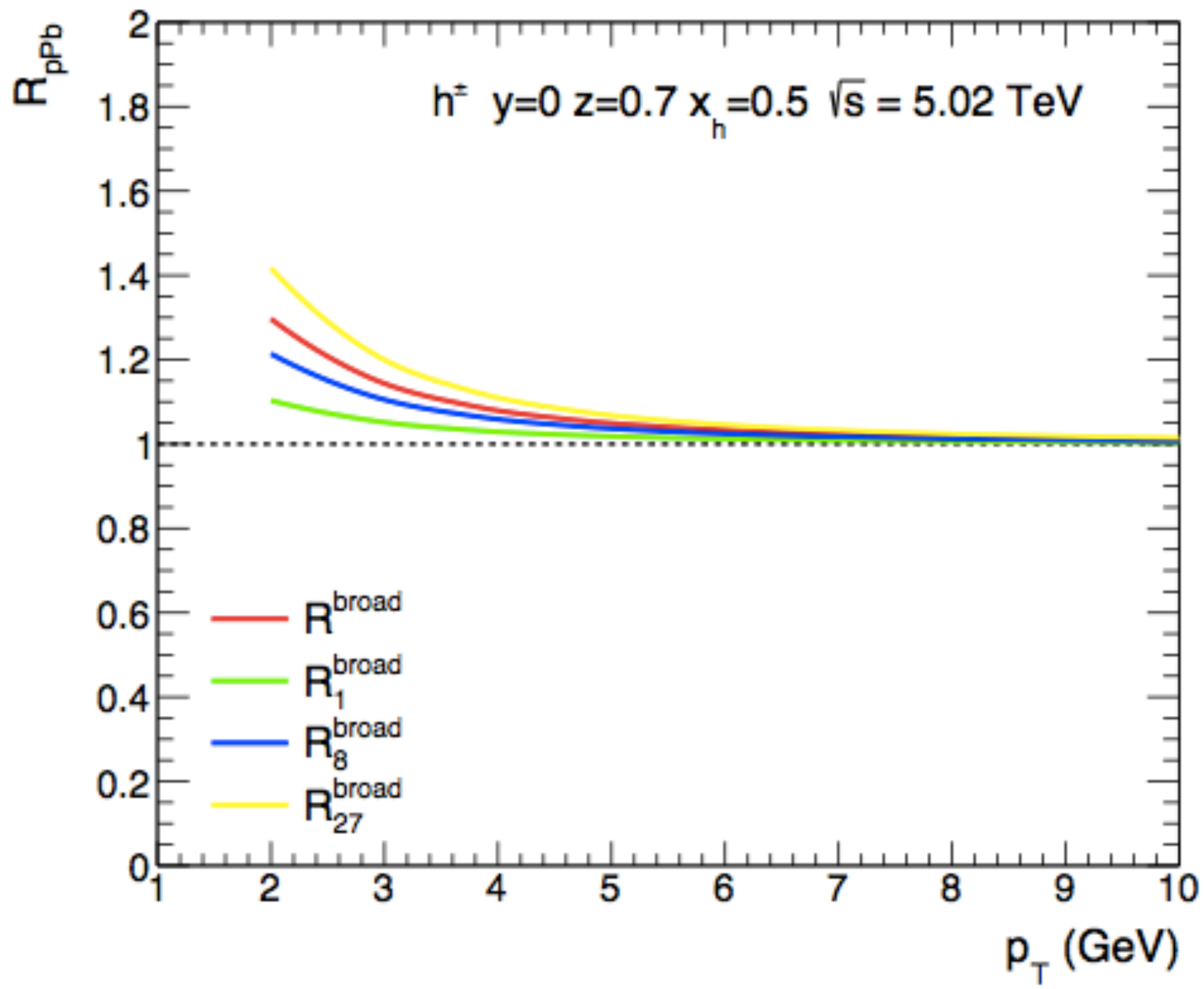
$$R^R_{\rm pA}(y, p_\perp) = \int_\delta \int_\varphi \mathcal{P}_R \left(x, \ell_{\rm A}, P_\perp = \frac{p_\perp}{\langle z \rangle} \right) \frac{{\rm d}\sigma^h_{\rm pp}(y + \delta, \, \vec{p}_\perp - z(1 - x_{\rm h}) \Delta \vec{p}^{\,R}_\perp)}{{\rm d}\sigma^h_{\rm pp}(y, \vec{p}_\perp)}$$

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

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

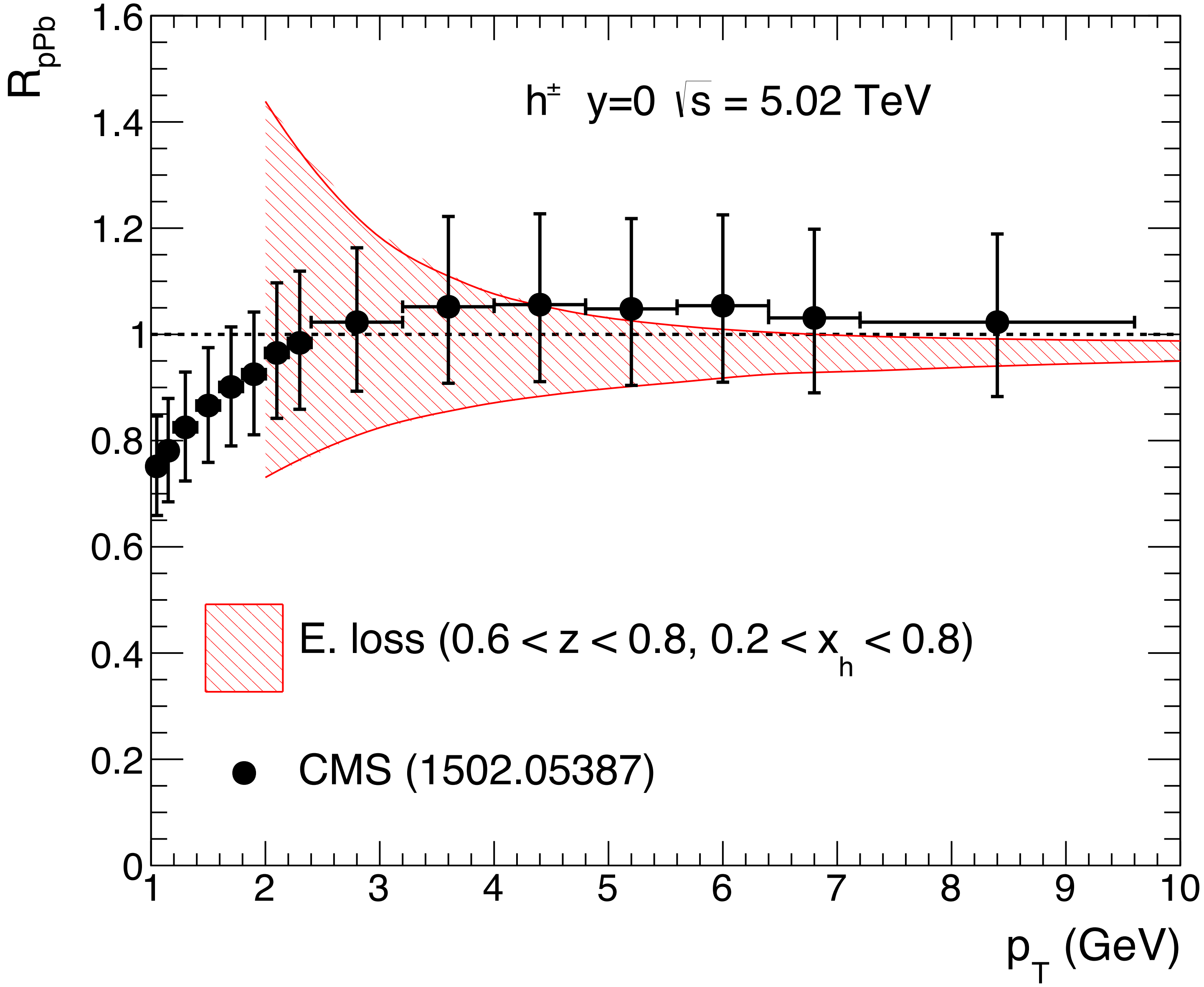
energy loss vs broadening at LHC





- opposite trends between energy loss and broadening effects

light hadron suppression vs LHC data



- model consistent with CMS (and ALICE) data
- model is still preliminary:
  large uncertainties on the variables z and $x_{\rm h}$

Summary

induced coherent radiation

- is a QCD prediction
  - found in different formalisms and setups
  - process-dependent (not included in nucleus wavefunction)

- seems quantitatively crucial for J/psi pA suppression

- should play a role for all $1 \to n$ partonic processes

→ calls for models of nuclear suppression with

nPDF/saturation effects + coherent energy loss

intrinsic to hadron wavefunction   *process-dependent*