coherent gluon radiation in proton-nucleus collisions

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from collaboration with F. Arleo, R. Kolevatov, T. Sami, S. Munier, and E. Petreska

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Introduction

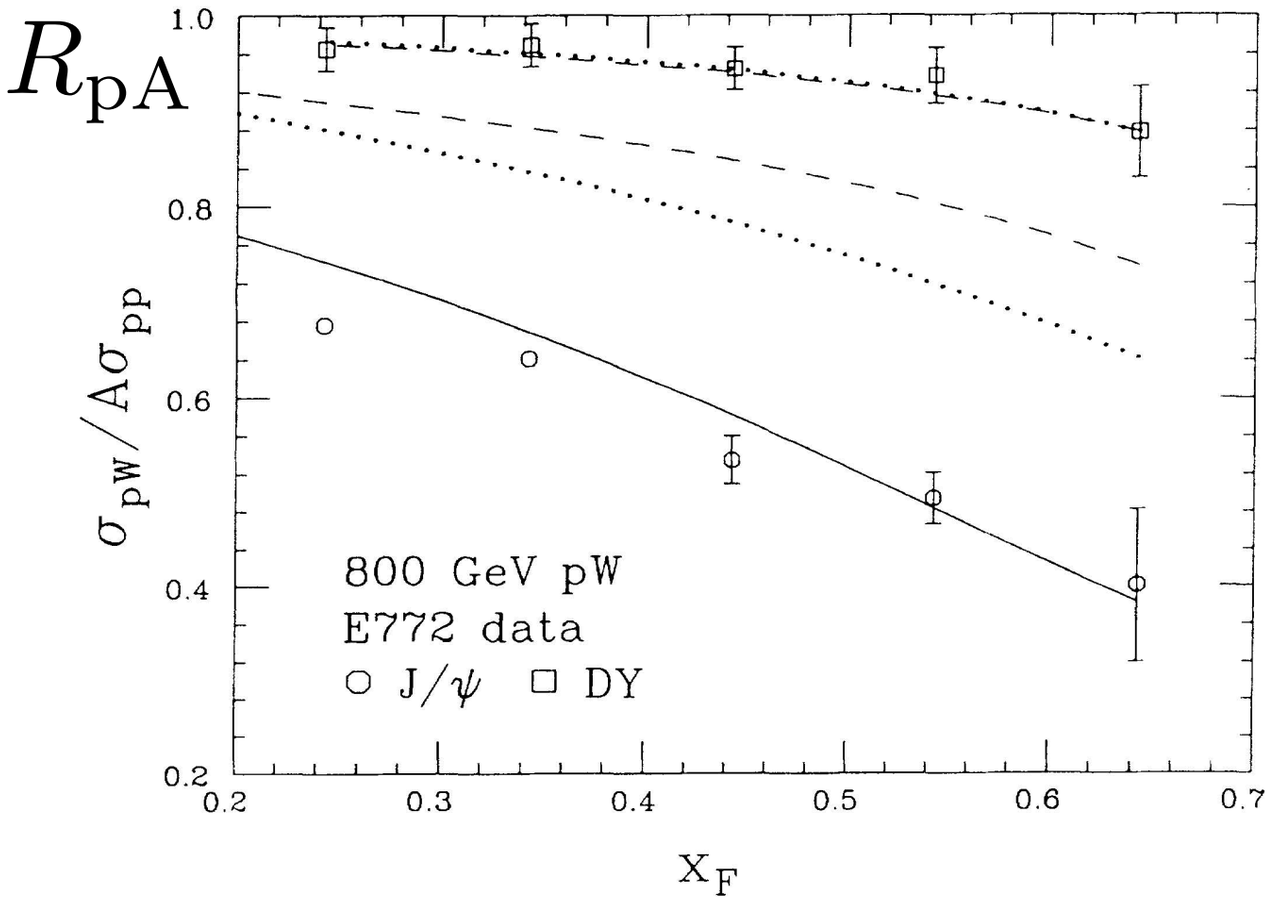
- understand hadron suppression in pA *before* AA
- several effects have been proposed:
  - in-medium 'nuclear absorption'
  - CGC/saturation effects
  - shadowing/nPDF effects
  - parton *radiative* energy loss

no real consensus on relative importance of those effects (especially at collider energies)

this talk: parton radiative energy loss

(could be the main effect in pA,
with also crucial consequences for AA)

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



Gavin & Milana
PRL 68 (1992)1834

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

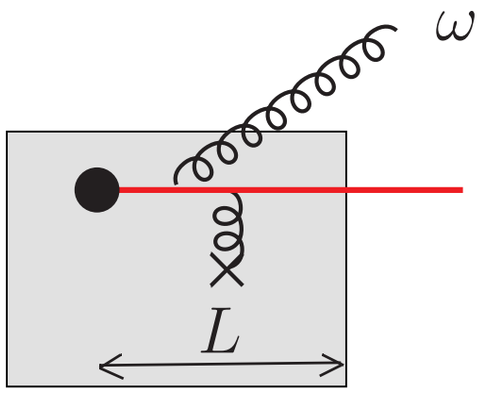
$$\Delta E_{\rm parton} \propto E$$

- 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):

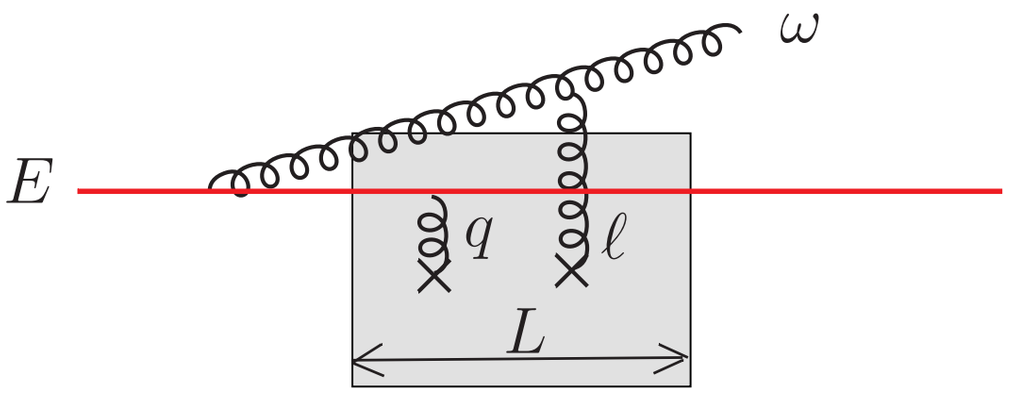
(1) parton suddenly produced in QCD medium



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

... but not in situation (2):

(2) forward scattering of fast 'asymptotic parton'

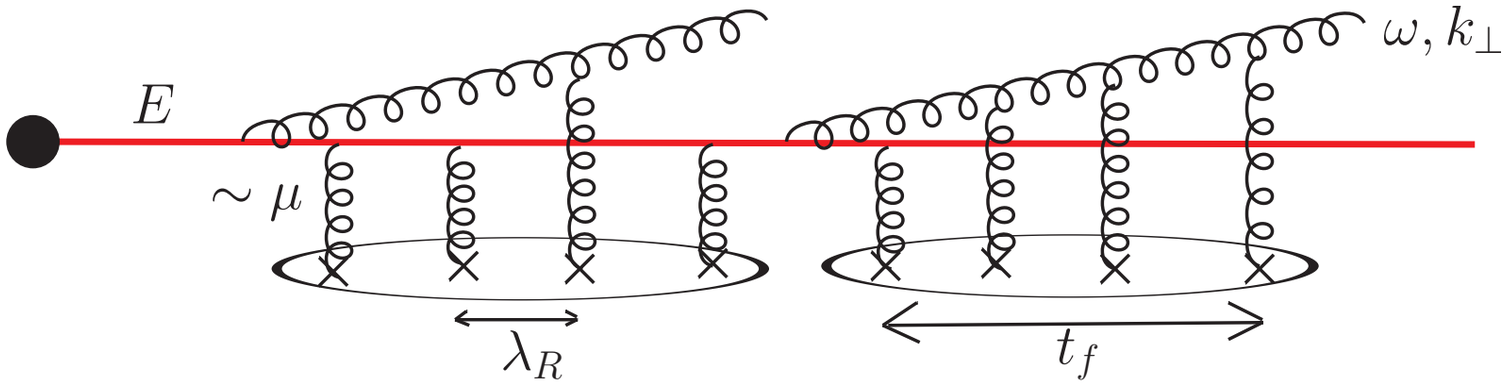


$$\Delta E_{\rm rad} \sim \alpha_s \frac{\sqrt{\hat{q}L}}{M_\perp} E$$

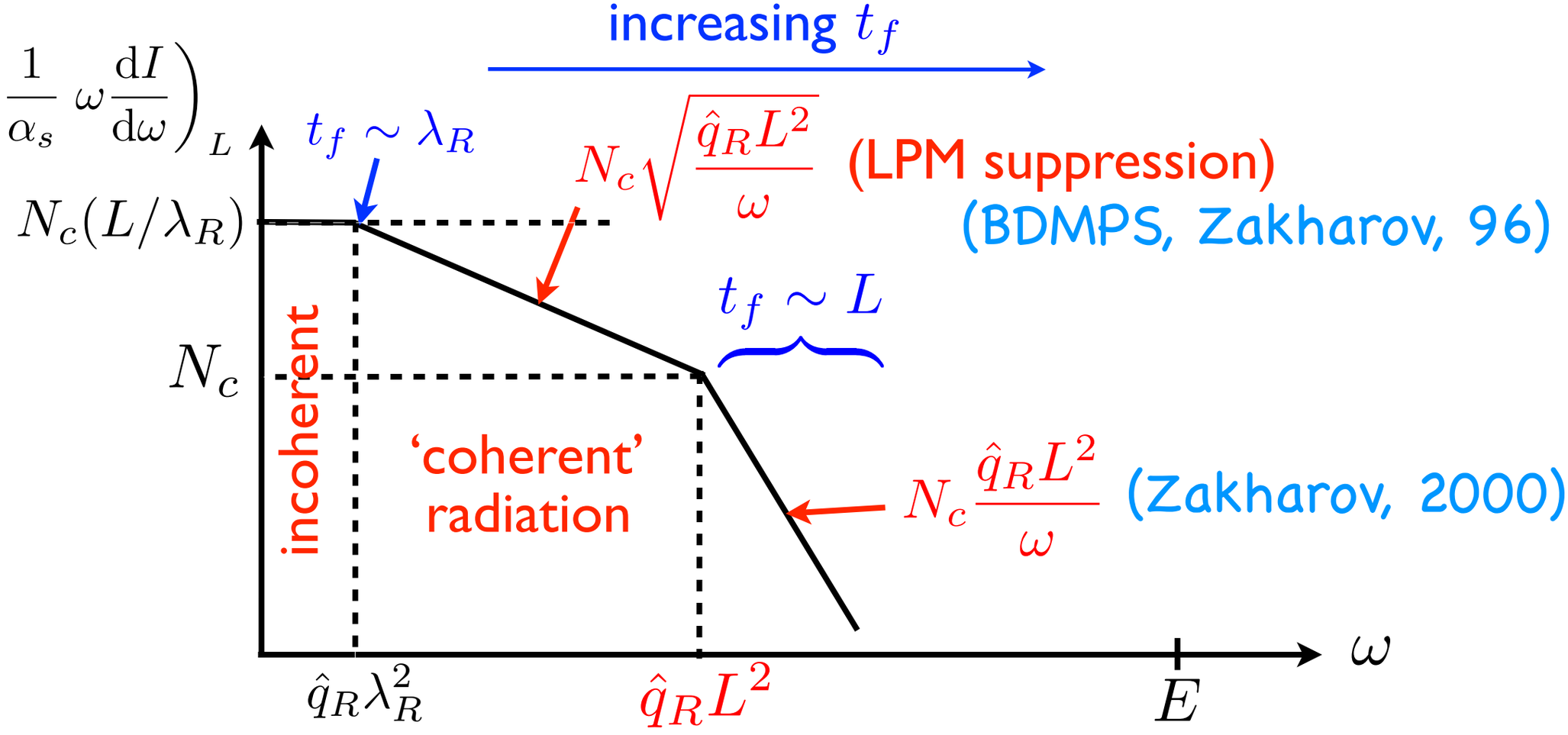
fully coherent energy loss

features of induced radiative energy loss

(1) energetic parton suddenly produced in medium



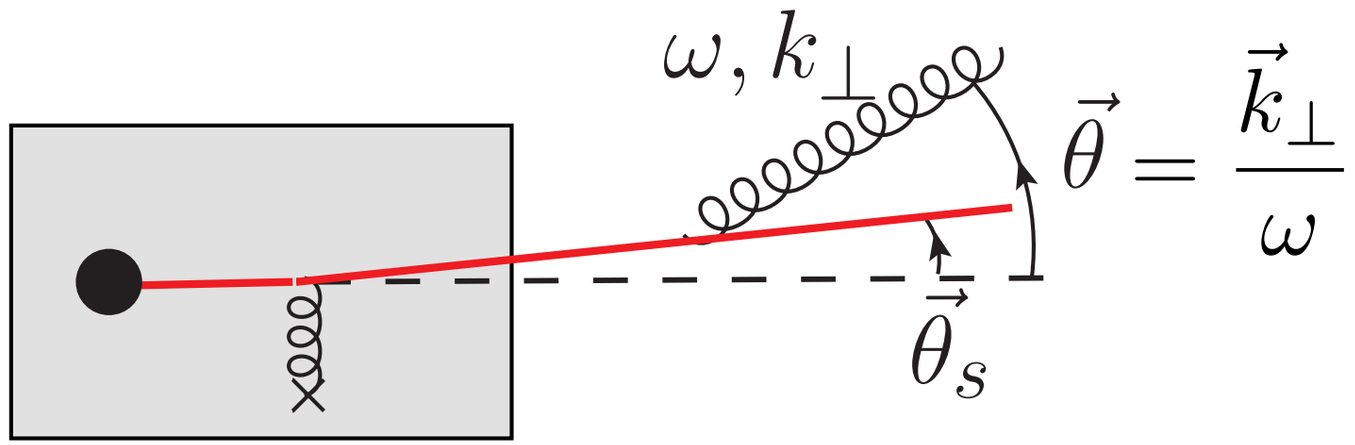
$E \to \infty$
parton color C_R



when ω exceeds $\hat{q}_R L^2$, additional suppression

due to suppression of $t_f \gg L$ $(\Longrightarrow t_f$ saturates, $t_f \sim L)$

$$t_f \sim \frac{\omega}{k_\perp^2} \gg L \Longrightarrow$$



$$\Rightarrow \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_L \sim \int \frac{\mathrm{d}^2\vec{\theta}}{(\vec{\theta}-\vec{\theta}_s)^2} \quad L\text{-independent}$$

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

average energy loss

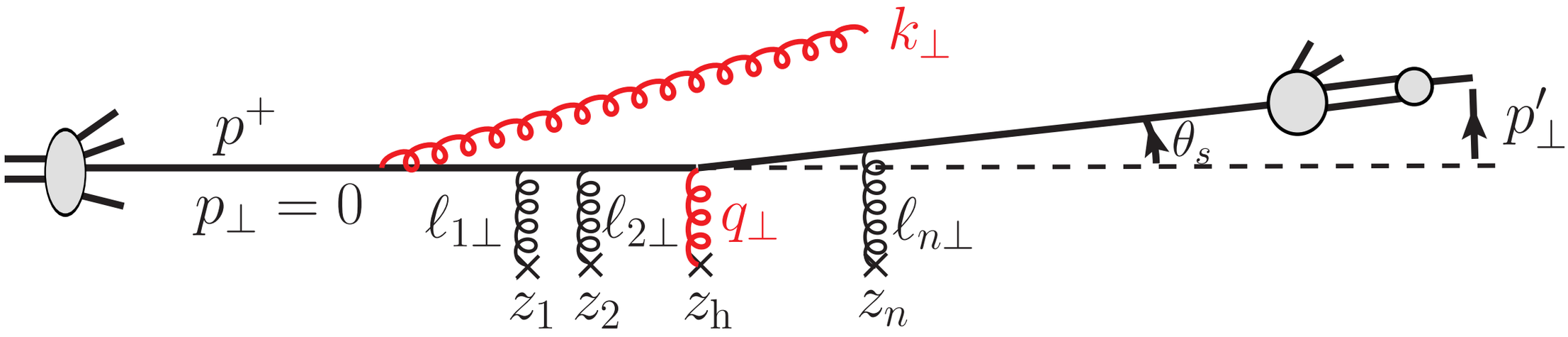
$$\Delta E = \int \mathrm{d}\omega\, \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big)_L \sim \alpha_s N_c \hat{q}_R L^2 \sim \alpha_s C_R \hat{q} L^2 \quad (\hat{q} \equiv \hat{q}_g)$$

(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 (PAK14) 1402.1671 (2014) PRD 93 (2016) 014006
  - opacity expansion
  - hard process: all $1 \to 1$
  - rigorous calculation for *Coulomb* rescattering
  - parton mass dependence
  - general rule for color factor
- Munier, S.P., Petreska 1603.01028
  - saturation formalism
  - hard process: $q \to q,\ g \to g$

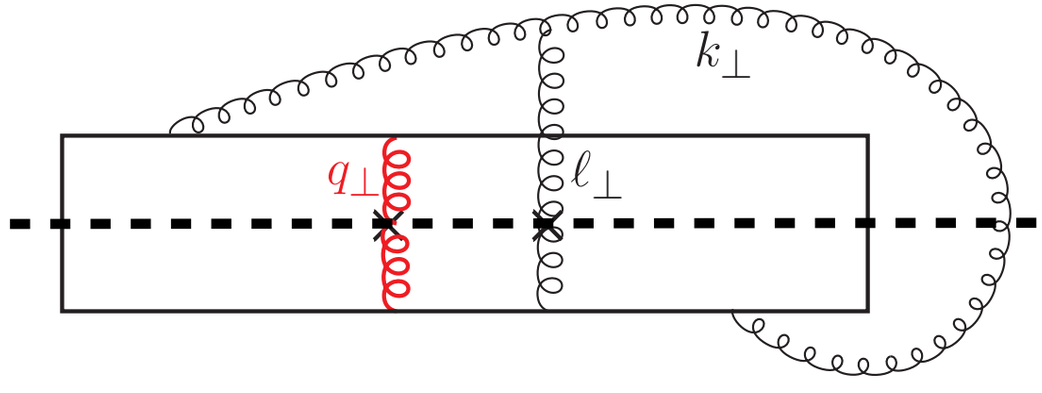
setup: high-energy p-A collision in nucleus rest frame

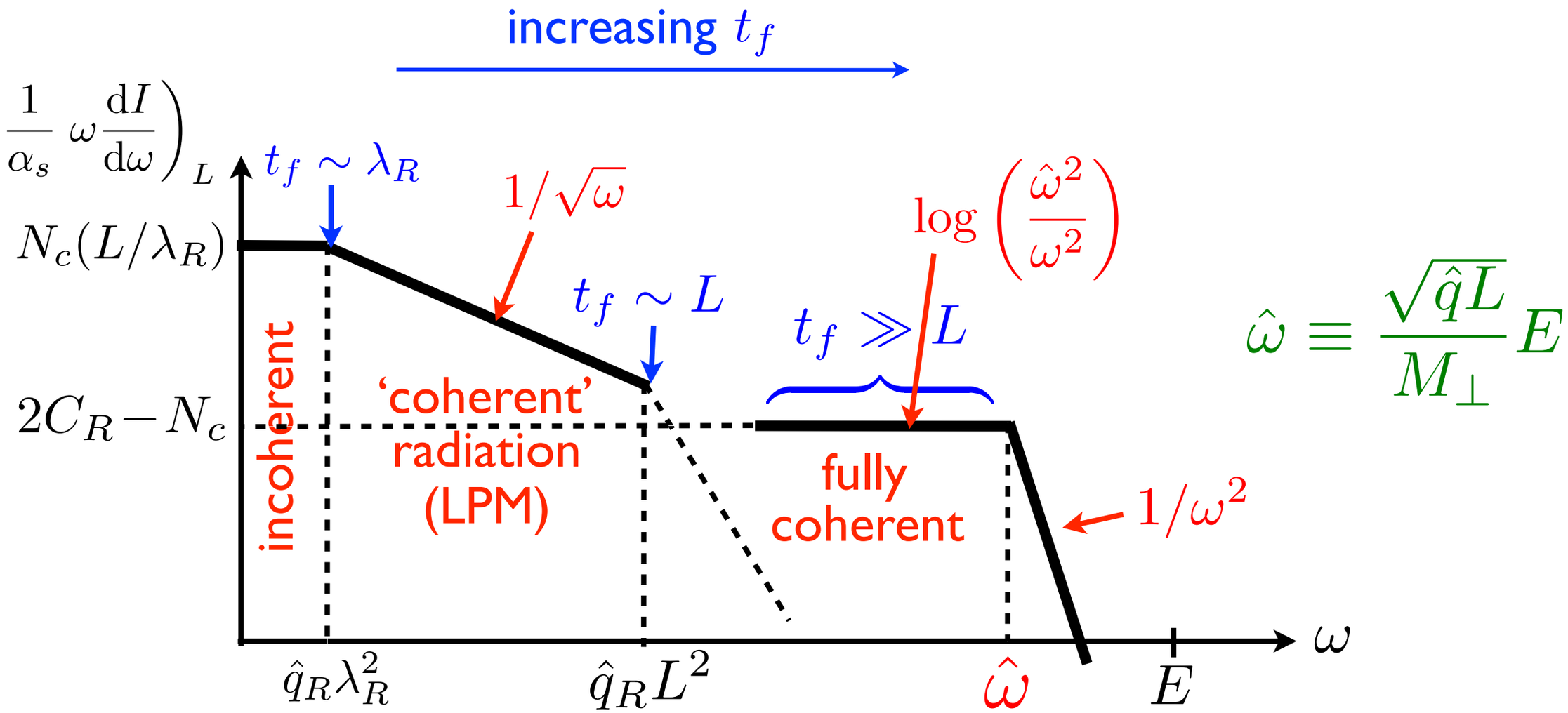
(PAK14)



- 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 $\ell_\perp^2 = (\sum \vec{\ell}_{i\perp})^2 \sim \hat{q}L \sim Q_s^2 \ll q_\perp^2$

new:
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: $t_f \sim \dfrac{\omega}{k_\perp^2} \sim \dfrac{\hat{\omega}}{\hat{q}L} \gg L$

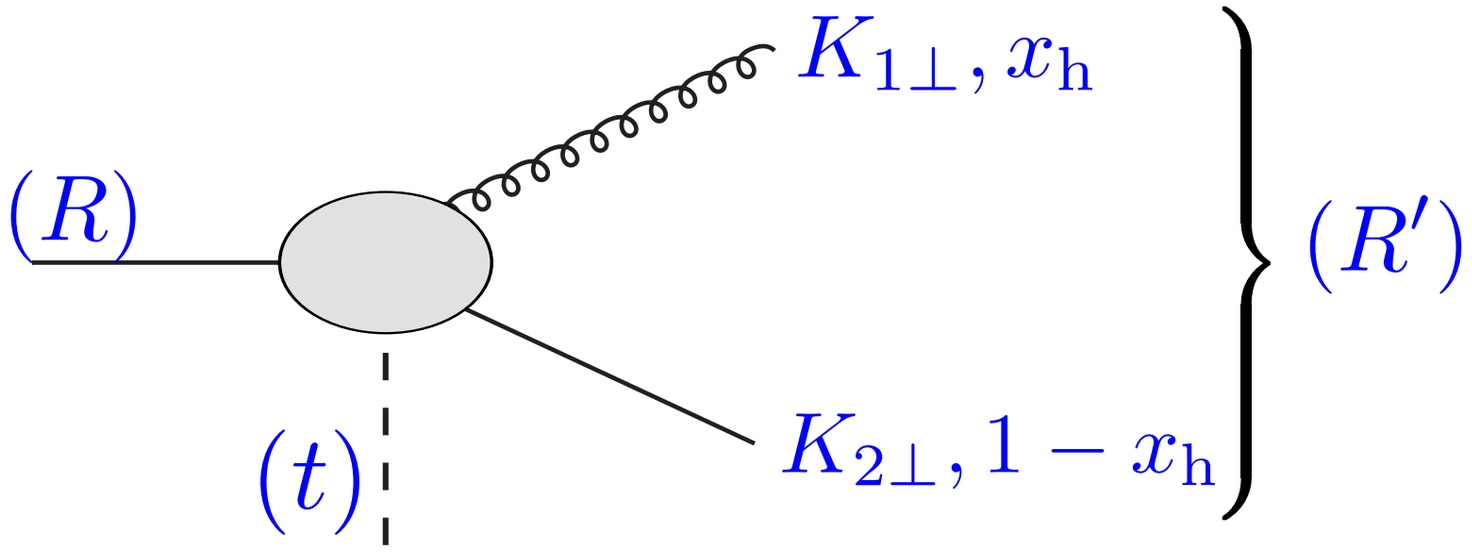
explicit calculation (PAK14) $\Longrightarrow$
general (*approximate*) *pocket formula*
for induced coherent spectrum:

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

- 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



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

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

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

- saturation formalism -- *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: $\log\left(\dfrac{\Delta q_\perp^2(L)}{x^2 K_\perp^2}\right)$

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

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

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)

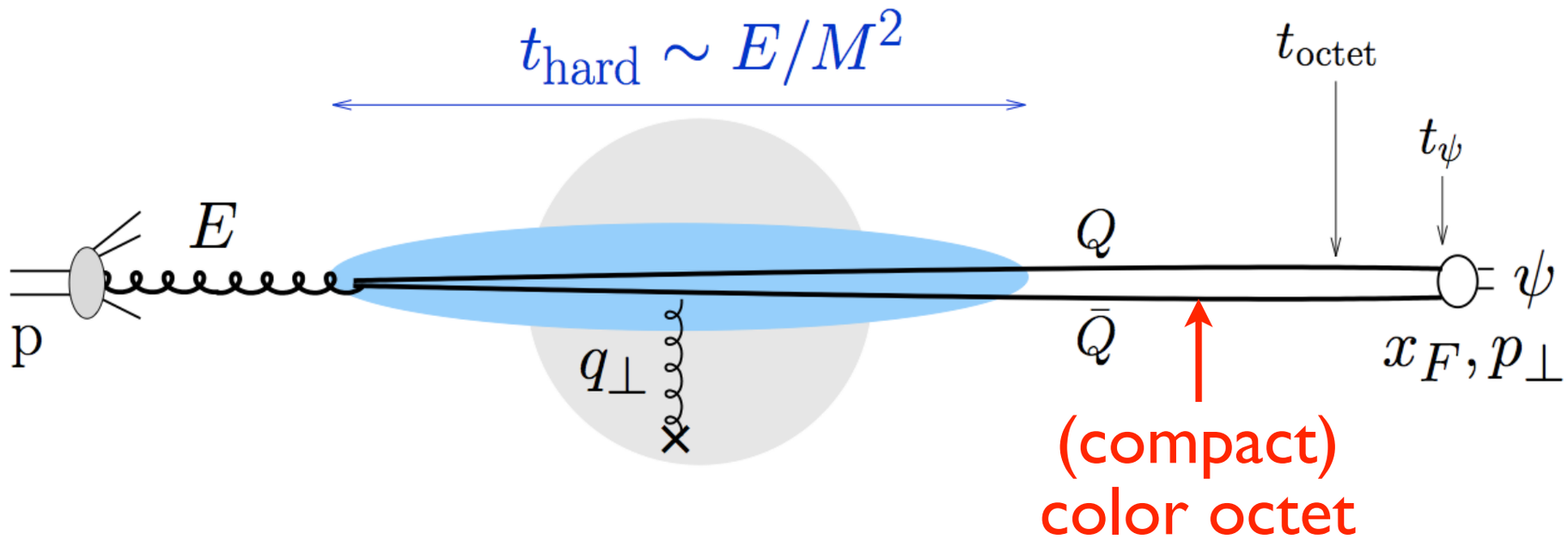
model for quarkonium pA suppression

Arleo, S.P., 1204.4609 and 1212.0434

Arleo, Kolevatov, S.P., Rustamova 1304.0901

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

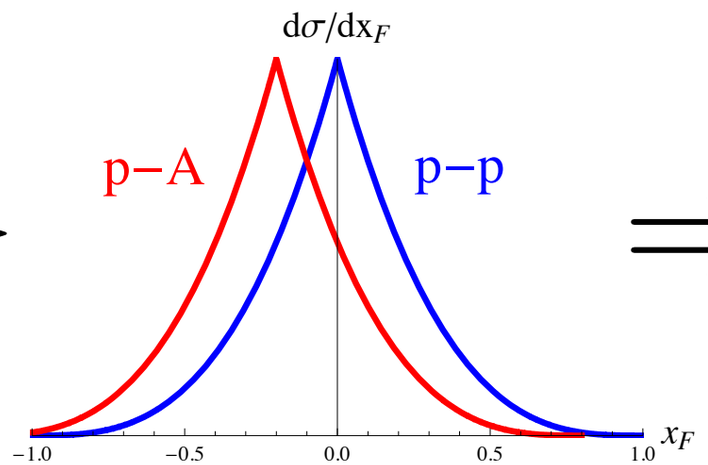
small $p_\perp$



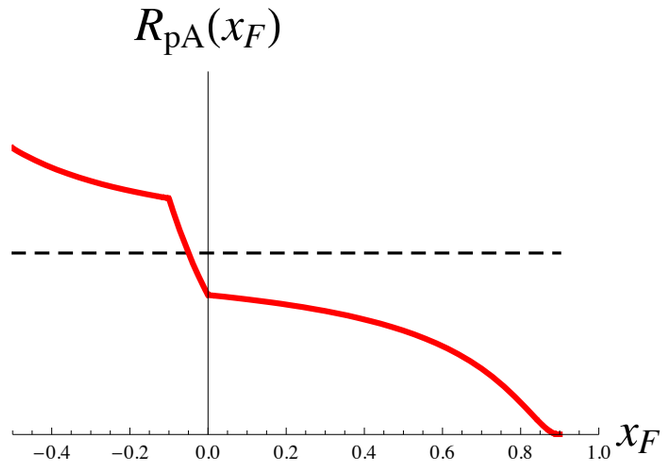
⟹ coherent radiation associated to $g \to Q\bar{Q}$

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

energy shift $\Longrightarrow$



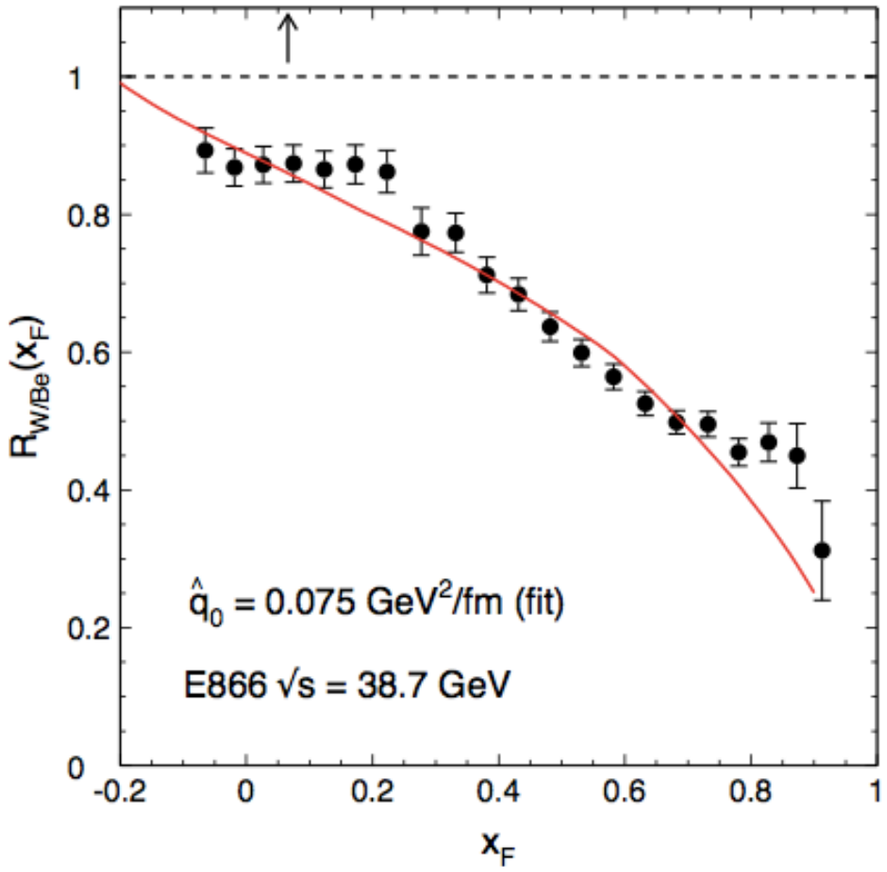
$\Longrightarrow$



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

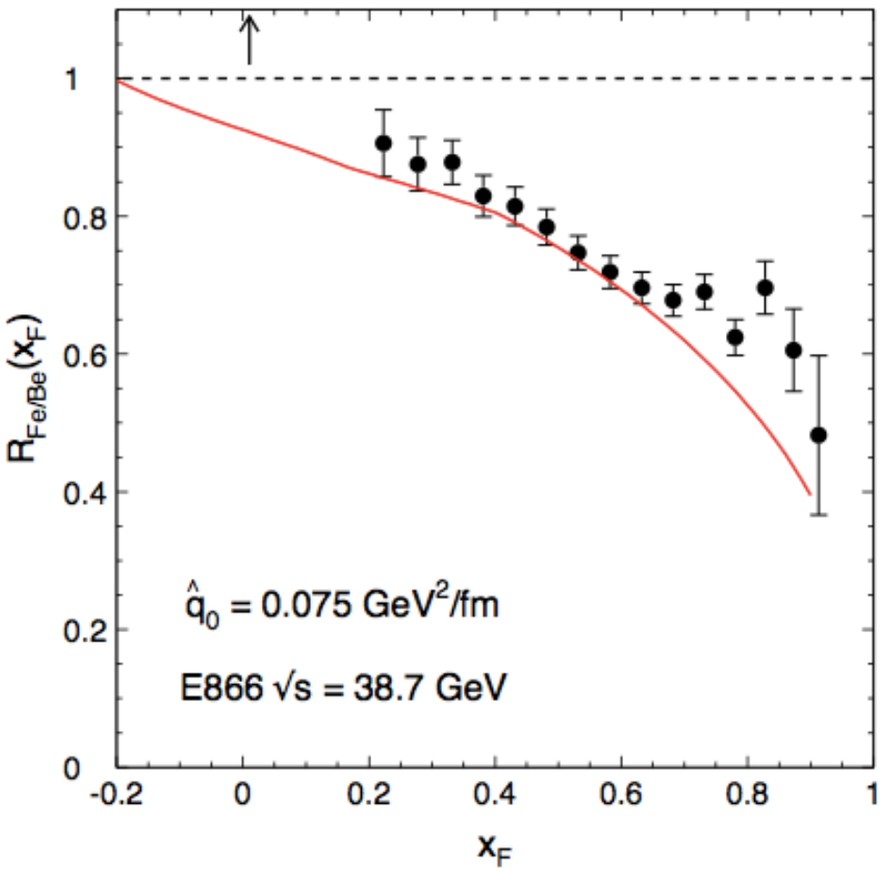
$2 \to 1$ kinematics $\Longrightarrow$ focus on low $p_\perp \lesssim M$

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



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

E866 Fe/Be

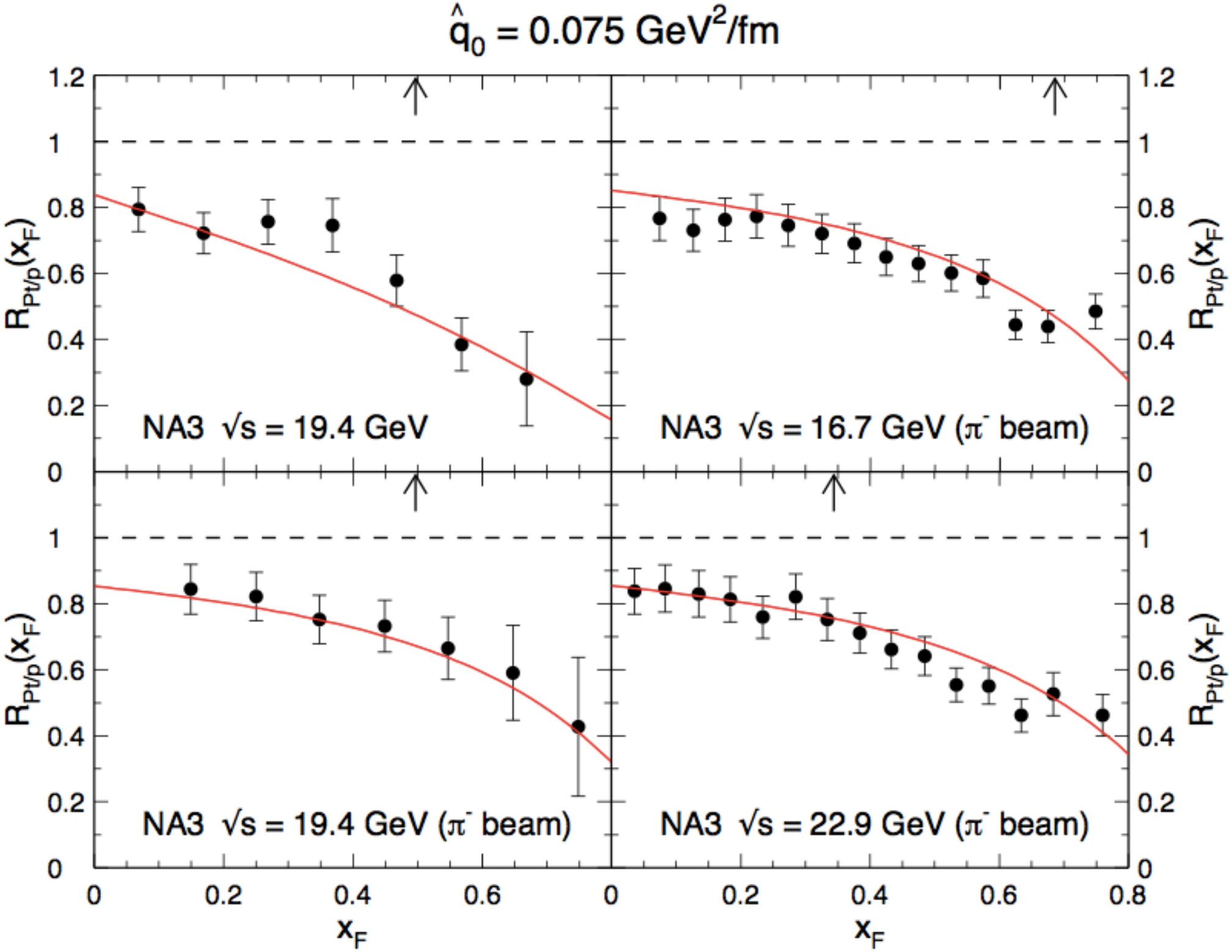


A–dependence well reproduced

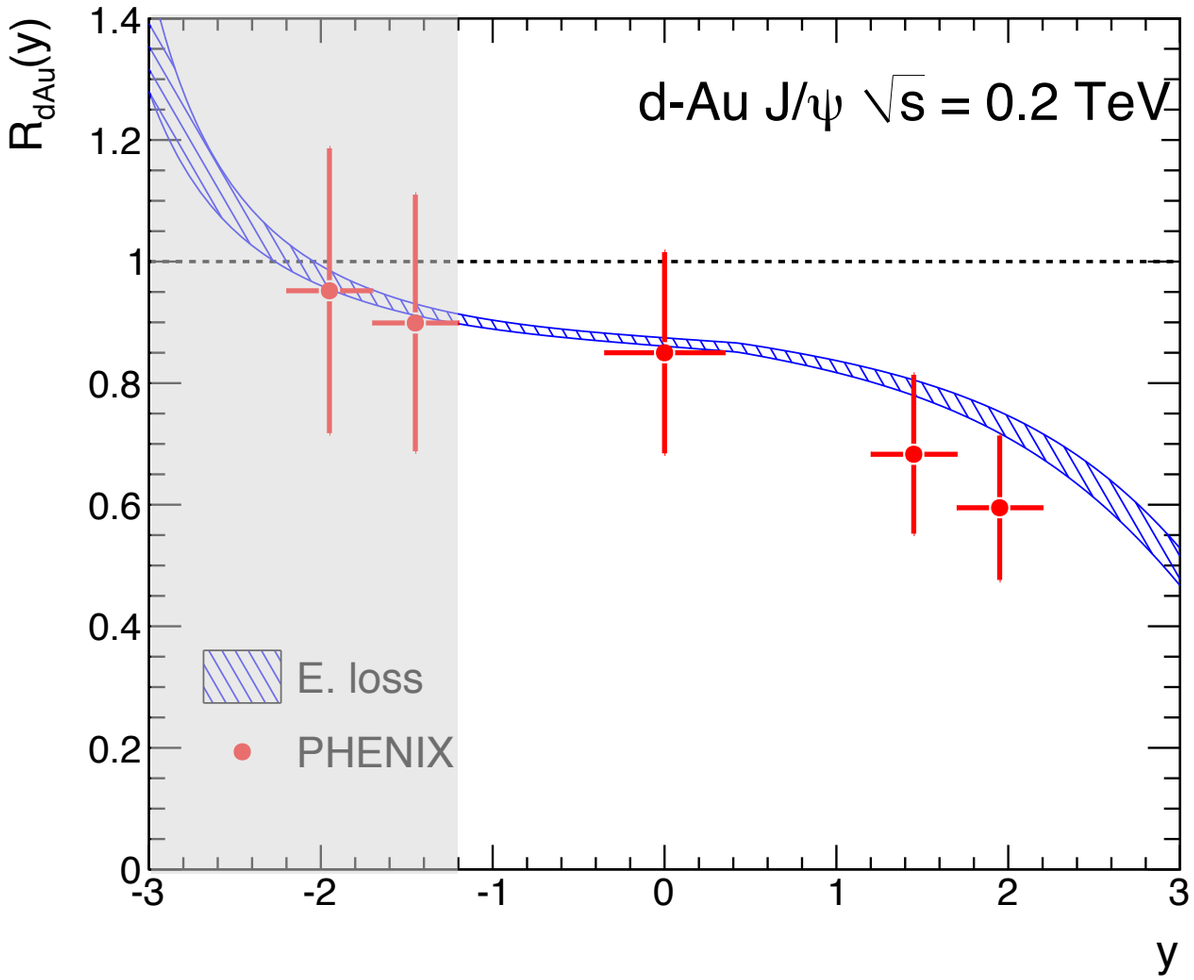
$\hat{q}_0$ corresponds to $Q^2_{sp}(x = 10^{-2}) = 0.11 - 0.14$ GeV^2

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

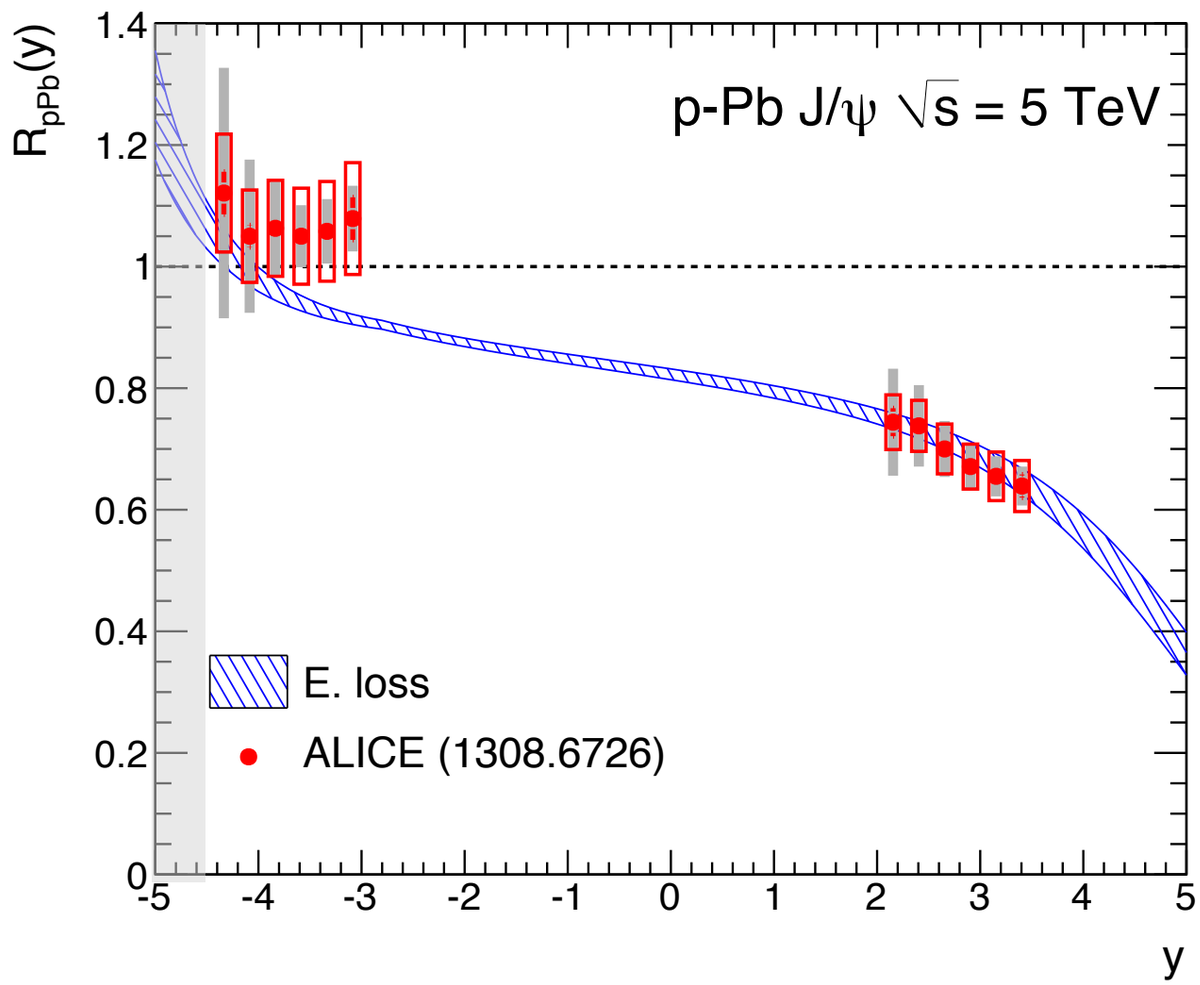
J/ψ NA3 Pt/p


$\hat{q}_0 = 0.075$ GeV^2/fm
$R_{Pt/p}(x_F)$
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)
x_F

RHIC d-Au (PHENIX)



LHC p-Pb (ALICE)



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

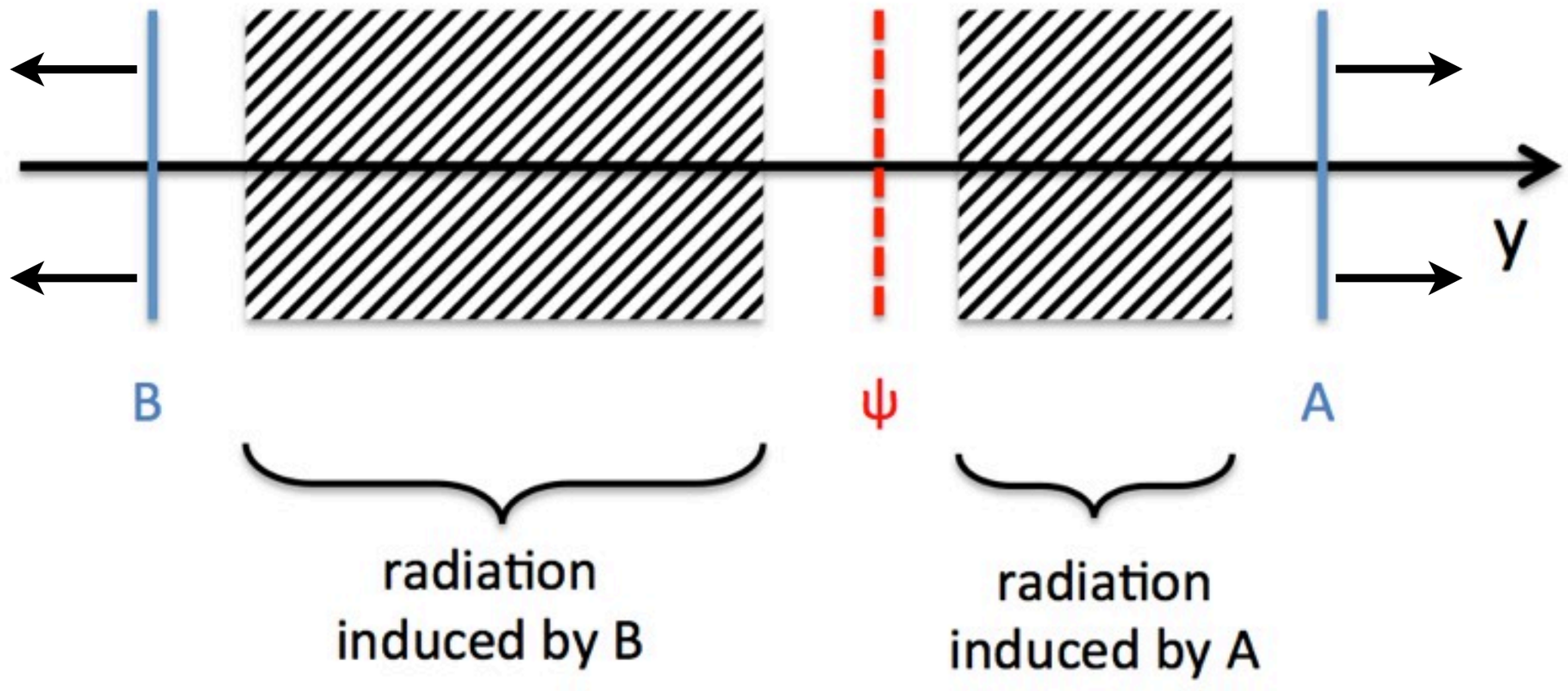
from fixed target to collider energies

(nPDF/saturation effects *might* be sizeable at collider energies, but cannot achieve such global description)

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

quarkonium suppression in AB collisions

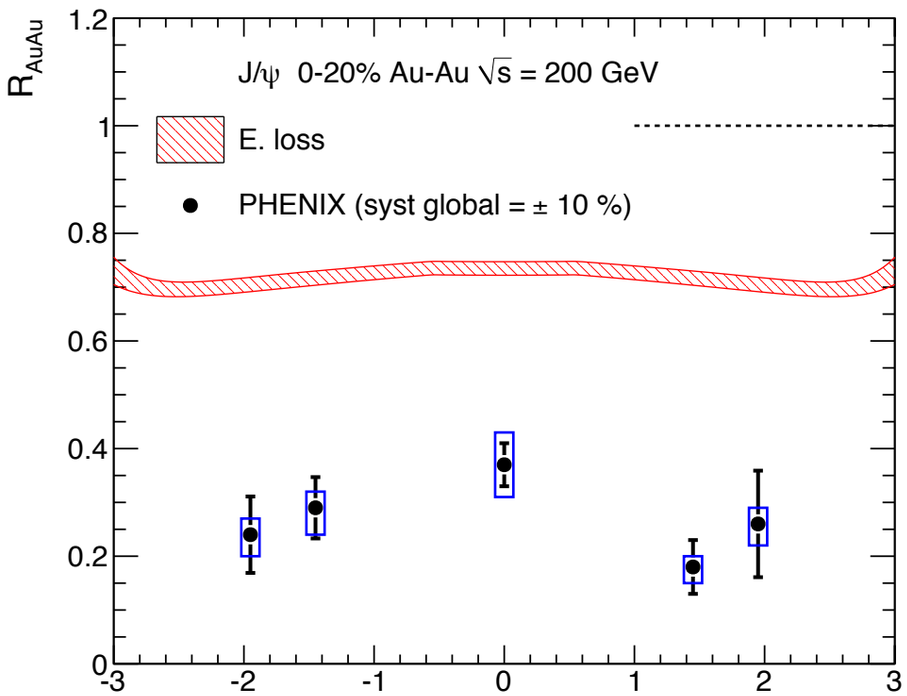
Arleo, S.P. 1407.5054

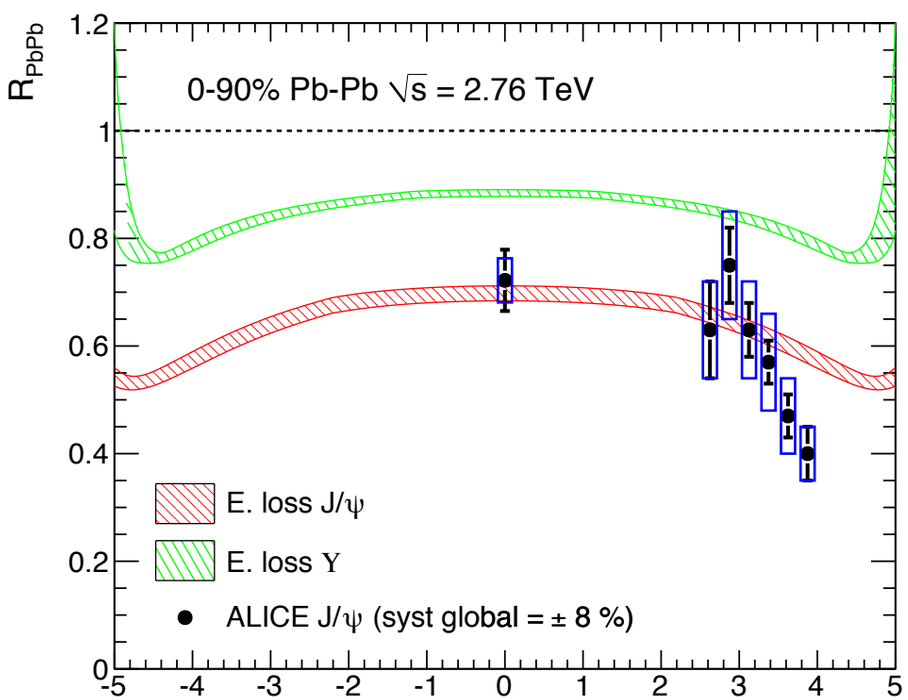


$$\frac{1}{AB}\frac{\mathrm{d}\sigma^{\psi}_{\mathrm{AB}}}{\mathrm{d}y}(y) = \int_0^{\delta y^{\max}(y)} \mathrm{d}\delta y_{\mathrm{B}}\, \hat{\mathcal{P}}_{\mathrm{B}}(\varepsilon_{\mathrm{B}}) \int_0^{\delta y^{\max}(-y)} \mathrm{d}\delta y_{\mathrm{A}}\, \hat{\mathcal{P}}_{\mathrm{A}}(\varepsilon_{\mathrm{A}})\,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

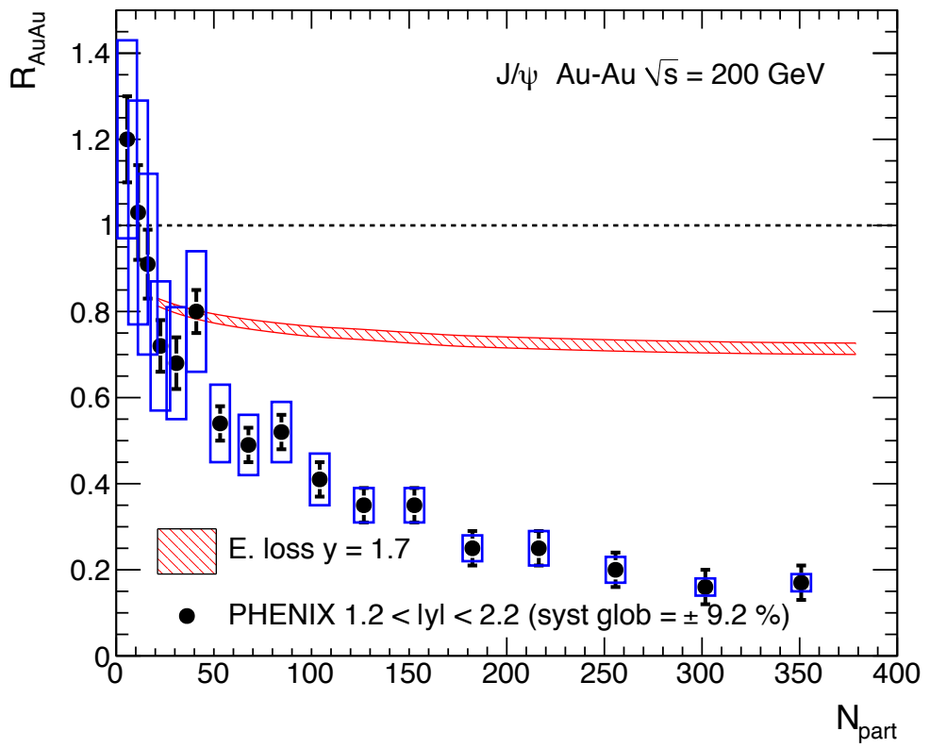
⟹ baseline for cold nuclear effects

J/psi suppression in AB collisions

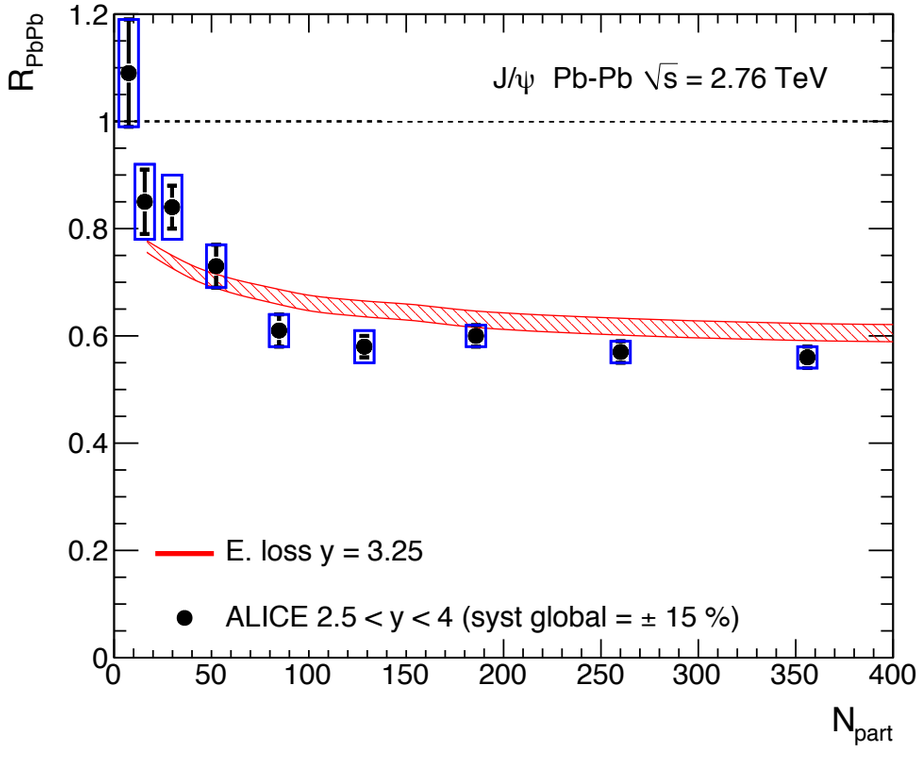




RHIC



LHC



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

Summary

medium-induced coherent radiation

- is a QCD prediction
  - found in different formalisms and setups
- seems quantitatively crucial for J/psi pA suppression
- should play a role in all $1 \to n$ partonic processes

e.g. in light hadron pA suppression at the LHC

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

- is a sizable *cold nuclear effect* in AA

⟶ should be included before extraction of 'hot' effects