fully coherent induced gluon radiation

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- main focus: *fully coherent* induced radiation
  - ✦ crucial for phenomenology

    J/psi nuclear suppression in pA (and AB)

    ⟶ see talk of F. Arleo in Etretat 2013
  - ✦ interesting theoretically

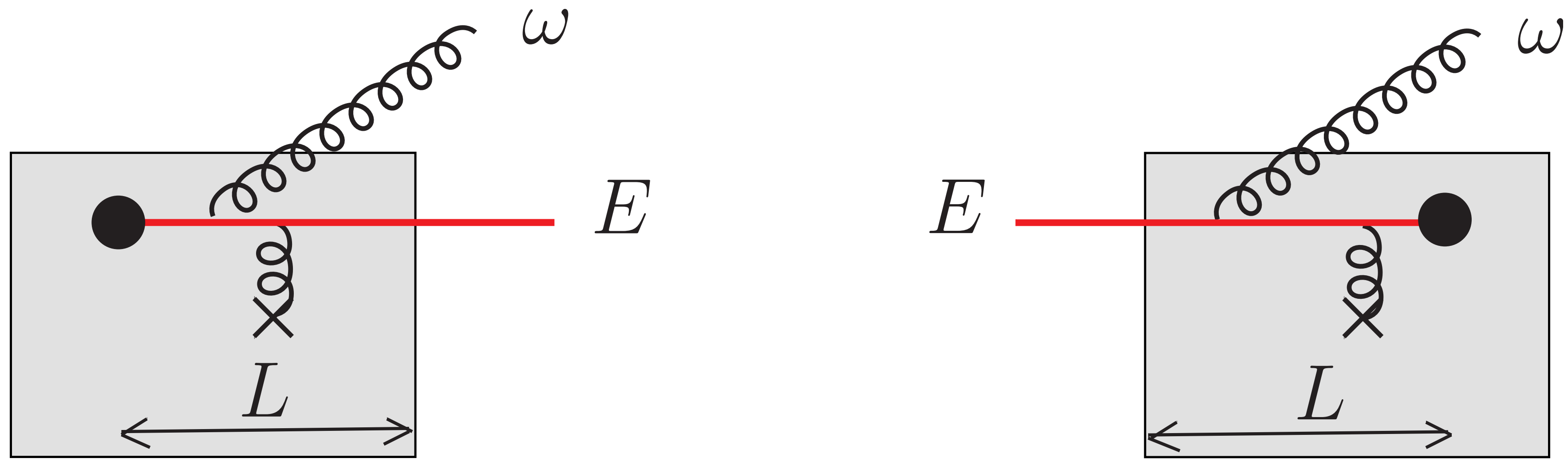
- talk based on:

Arleo, S.P., Sami 1006.0818	[APS10]
Arleo & S.P. 1212.0434	[AP12]
S.P., Arleo, Kolevatov 1402.1671	[PAK14]
S.P. & Kolevatov 1405.4241	[PK14]

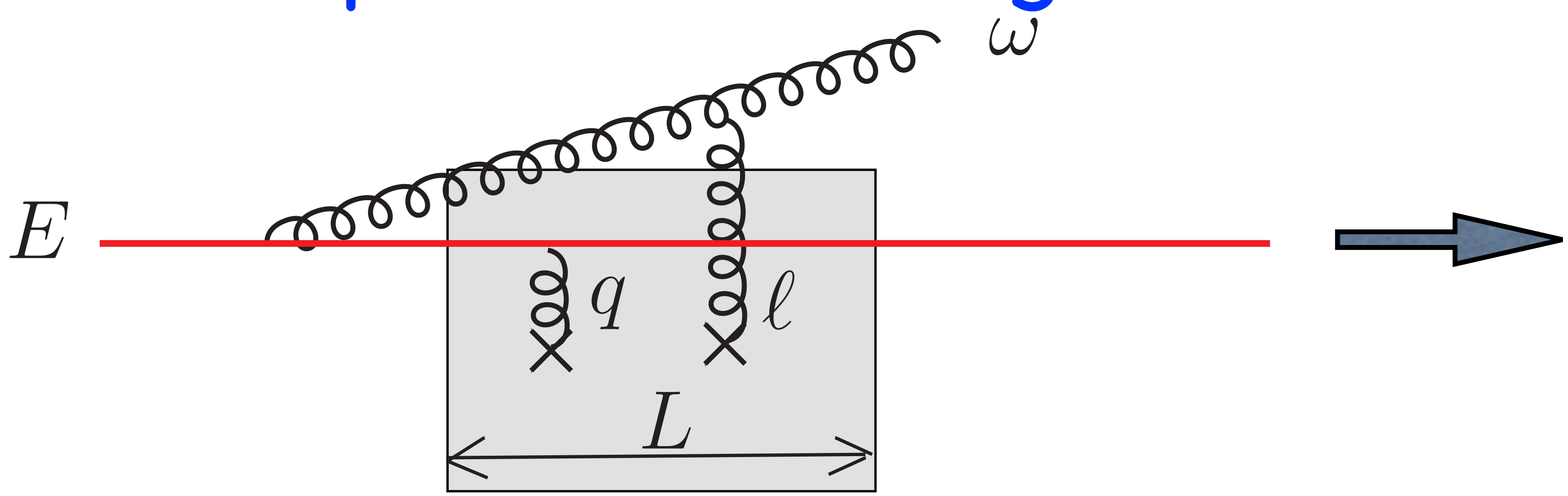
in general, features of medium-induced radiation depend on specific kinematic situation

- two main cases (S.P. & Smilga 0810.5702)

(1) energetic parton suddenly produced or annihilated in nuclear medium

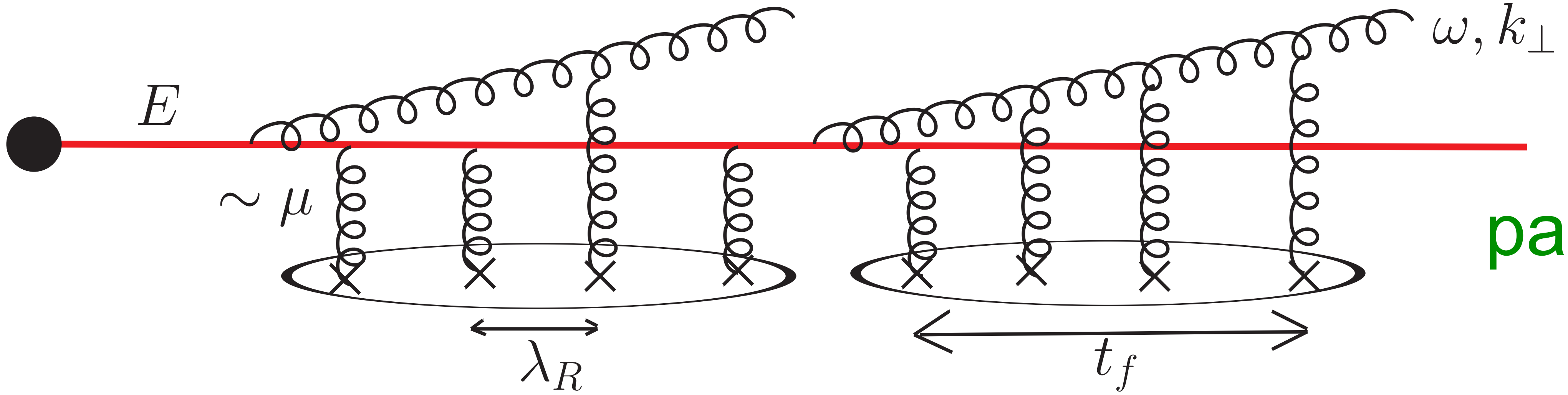


(2) forward scattering of fast 'asymptotic parton' crossing a nuclear medium



fully coherent radiation

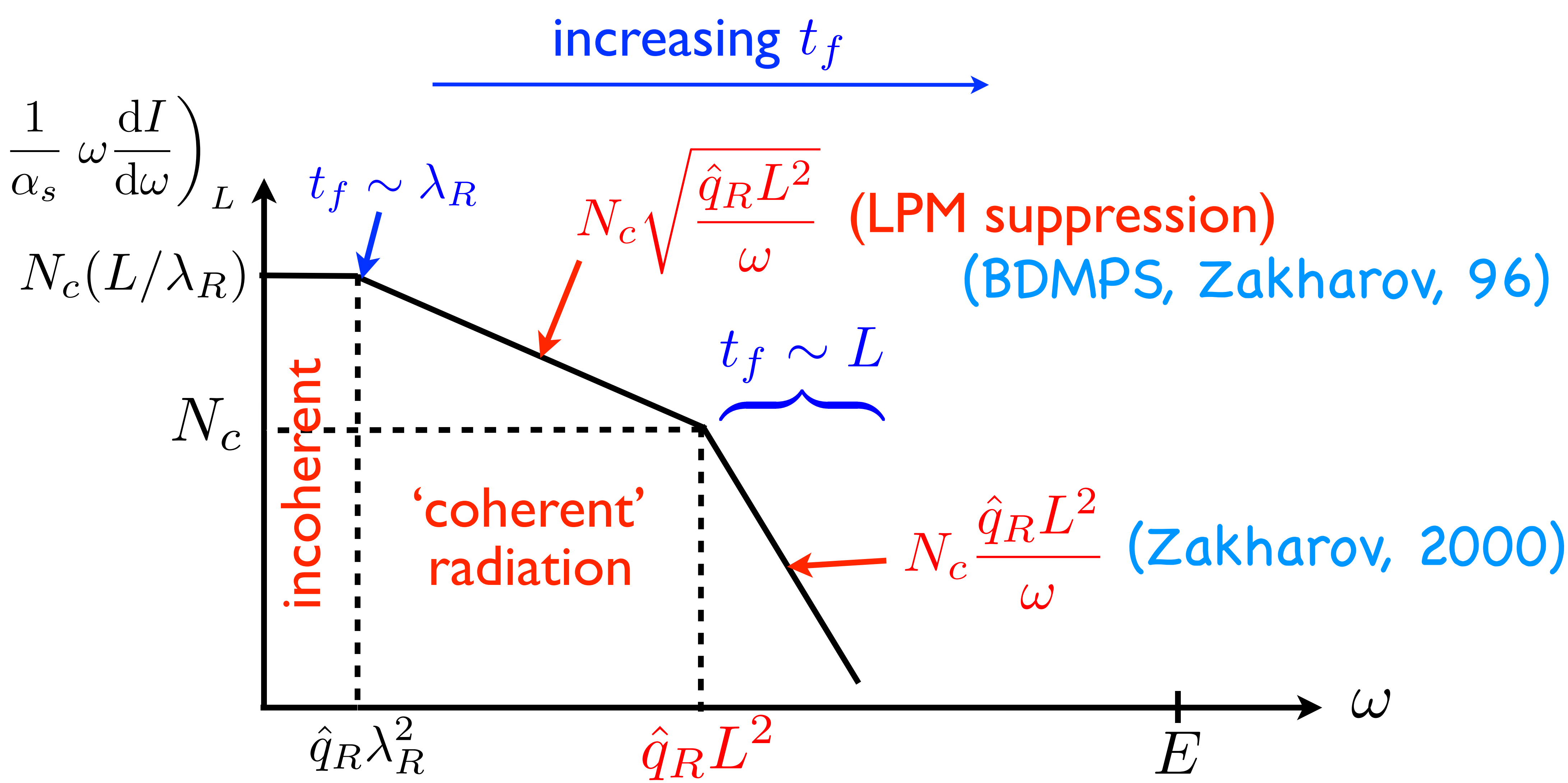
(1) energetic parton suddenly produced in medium



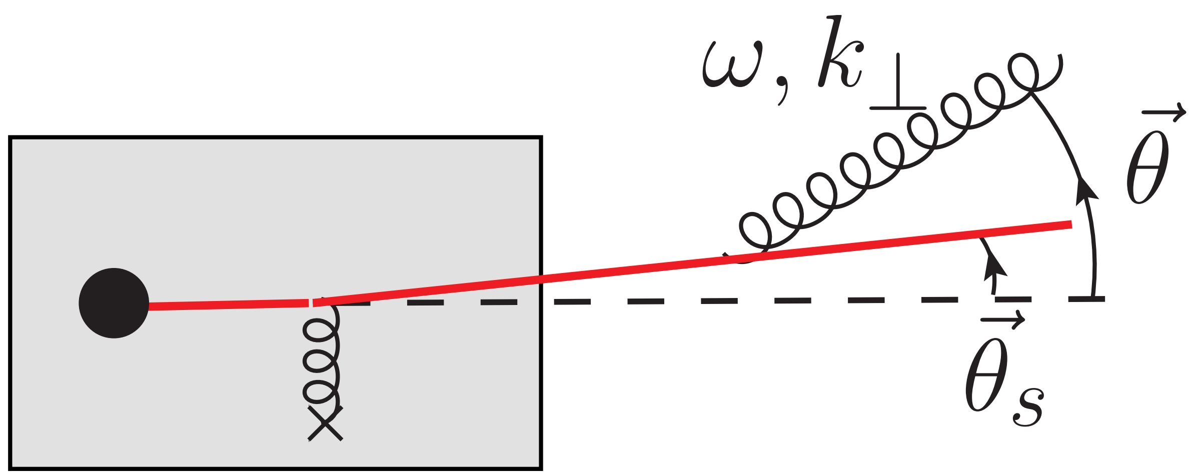
$E \to \infty$

parton color C_R

✦ induced radiation spectrum



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



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

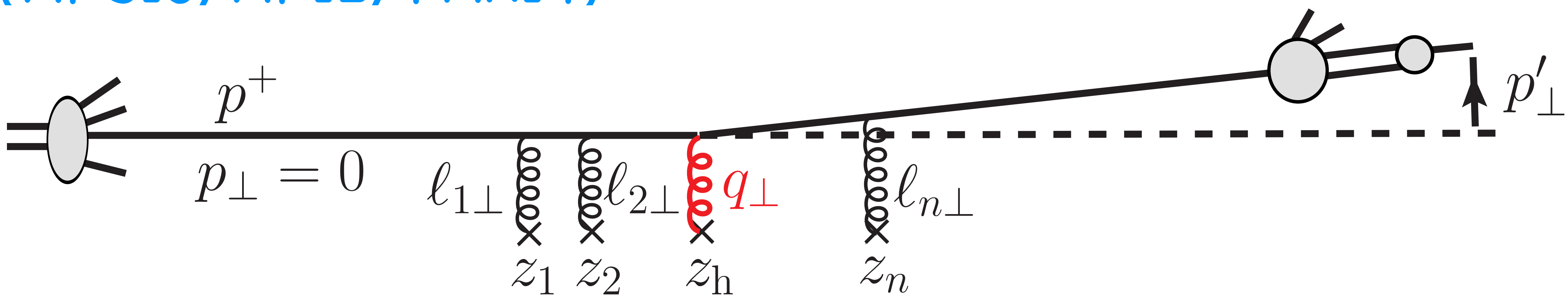
$\Rightarrow$ suppressed in $\omega \frac{dI}{d\omega}\Big)_{\text{ind}} \equiv \omega \frac{dI}{d\omega}\Big)_L - \omega \frac{dI}{d\omega}\Big)_{L=0}$

✦ average energy loss

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

(2) forward scattering of fast 'asymptotic parton' crossing a nuclear medium

setup: high-energy p-A collision in nucleus rest frame
(APS10, AP12, PAK14)



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

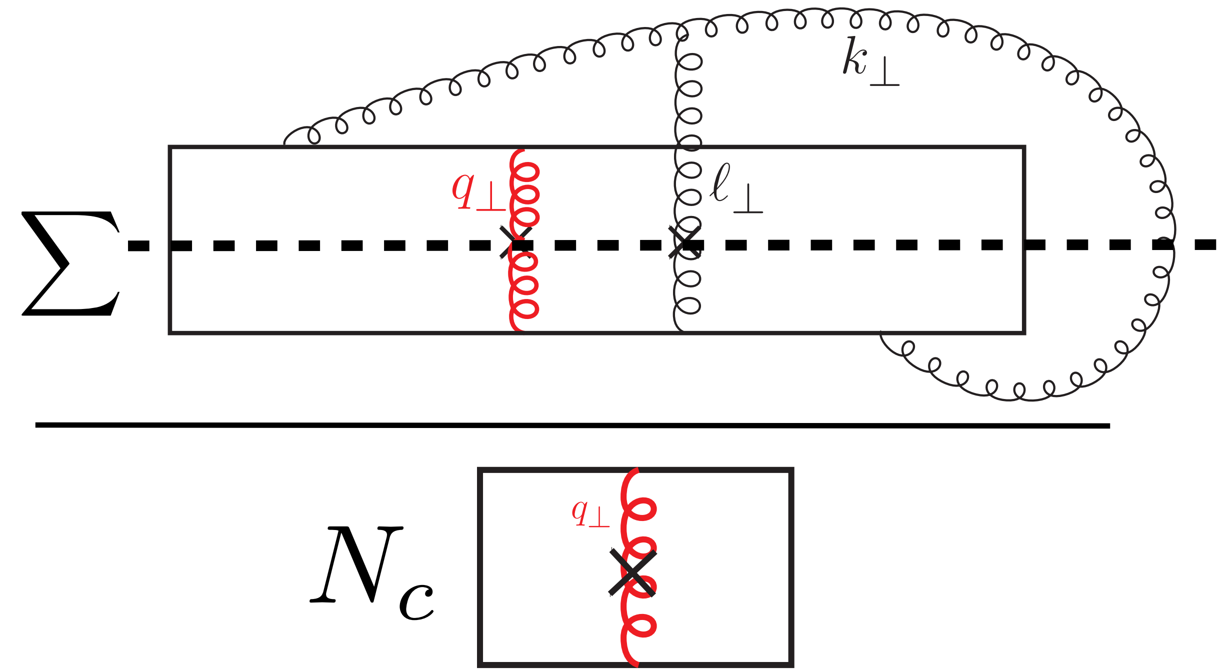
two transverse momentum scales: $\ell_\perp \ll q_\perp$

✦ derivation of induced spectrum

- use opacity expansion (Gyulassy, Levai, Vitev 2000)
- look for *soft radiation* with $k_\perp \ll q_\perp$ and $t_f \gg L$

first order in opacity:

$$x\frac{\mathrm{d}I^{(1)}}{\mathrm{d}x} = \frac{\alpha_s}{\pi^2}\frac{L}{\lambda_g}\int \mathrm{d}^2\boldsymbol{k}\int \mathrm{d}^2\boldsymbol{\ell}\, V(\boldsymbol{\ell})$$



$$V(\boldsymbol{\ell}) \equiv \frac{\mu^2}{\pi(\boldsymbol{\ell}^2+\mu^2)^2}$$

$$x \equiv \frac{\omega}{E} \ll 1$$

$$\Longrightarrow (2C_R - N_c)\left[\underbrace{-\frac{\boldsymbol{k}-\boldsymbol{\ell}}{(\boldsymbol{k}-\boldsymbol{\ell})^2}\cdot\frac{\boldsymbol{k}-x\boldsymbol{q}}{(\boldsymbol{k}-x\boldsymbol{q})^2}}_{-\int_{\boldsymbol{\ell}^2}\frac{\mathrm{d}\boldsymbol{k}^2}{\boldsymbol{k}^2}} + \underbrace{\frac{\boldsymbol{k}}{\boldsymbol{k}^2}\cdot\frac{\boldsymbol{k}-x\boldsymbol{q}}{(\boldsymbol{k}-x\boldsymbol{q})^2}}_{+\int_{x^2\boldsymbol{q}^2}\frac{\mathrm{d}\boldsymbol{k}^2}{\boldsymbol{k}^2}}\right]$$

$xq_\perp < k_\perp \Leftrightarrow \theta > \theta_s$ interference dominated by radiation *outside* the 'abelian cone' of opening θ_s

(Y. Dokshitzer, 'perturbative QCD for beginners')

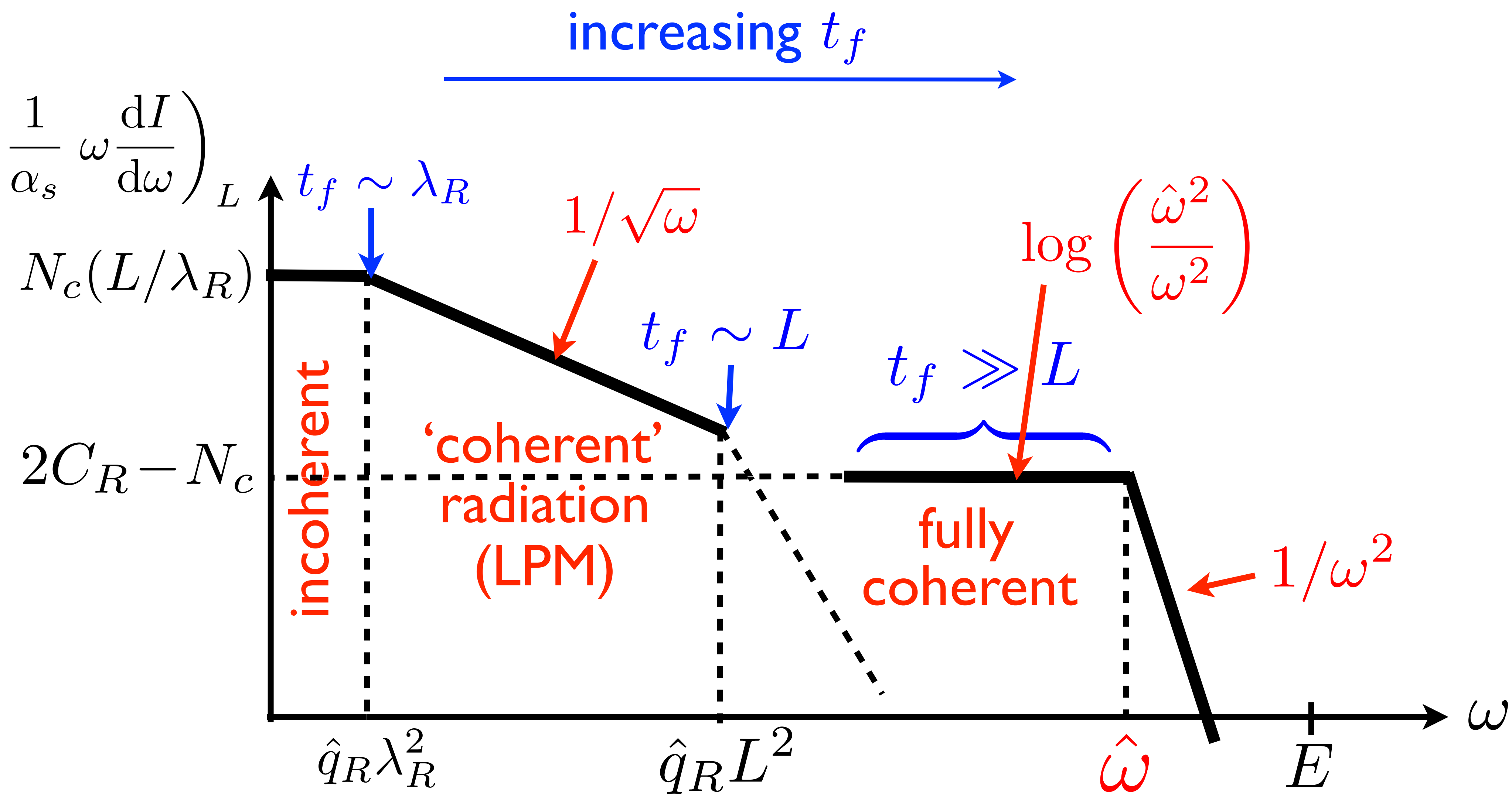
$k_\perp < \ell_\perp$ → radiation induced by additional $\ell_\perp$ must be *shaken off* by $\ell_\perp$

similar features at all orders in opacity (PAK14)

$$\rightarrow \quad x\frac{\mathrm{d}I}{\mathrm{d}x} = (2C_R - N_c)\frac{\alpha_s}{\pi}\log\left(\frac{\ell_\perp^2}{x^2 q_\perp^2}\right)$$

with $\ell_\perp^2 \sim \hat{q}L \sim Q_s^2$

a new scale: $\hat{\omega} \equiv \frac{\sqrt{\hat{q}L}}{q_\perp}E \sim \frac{\ell_\perp}{q_\perp}E \gg \hat{q}L^2$



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

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

orders of magnitude

p-Pb collision at $\sqrt{s} = 5\,\mathrm{TeV}$

$$\hat{q} = \hat{q}_{\mathrm{cold}} \sim 0.1\,\mathrm{GeV}^2/\mathrm{fm}$$

$$L \sim 10\,\mathrm{fm}$$

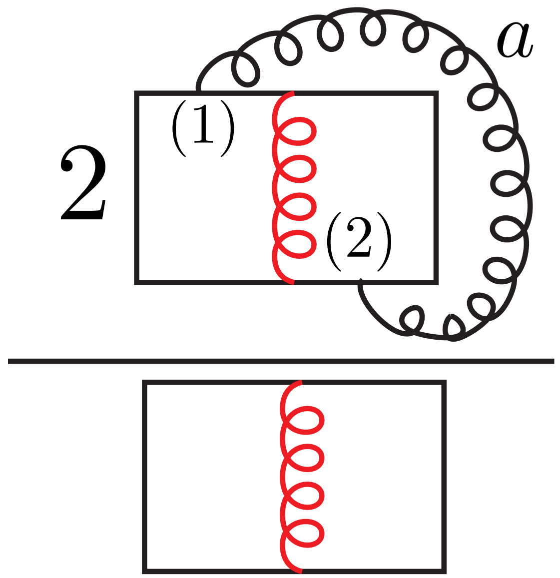
consider light hadron with:

$$p_T = 3\,\mathrm{GeV}\,; \quad y_{\mathrm{cm}} = 0 \qquad (\Rightarrow E_{\mathrm{cm}} \simeq 3\,\mathrm{GeV})$$

in nucleus rest frame: $E = \sqrt{s}\,\dfrac{p_T}{2m_p}e^y \sim 7.5\,\mathrm{TeV}$

$$\Rightarrow \hat{\omega} \simeq 2.5\,\mathrm{TeV} \gg \hat{q}L^2 \simeq 50\,\mathrm{GeV}$$

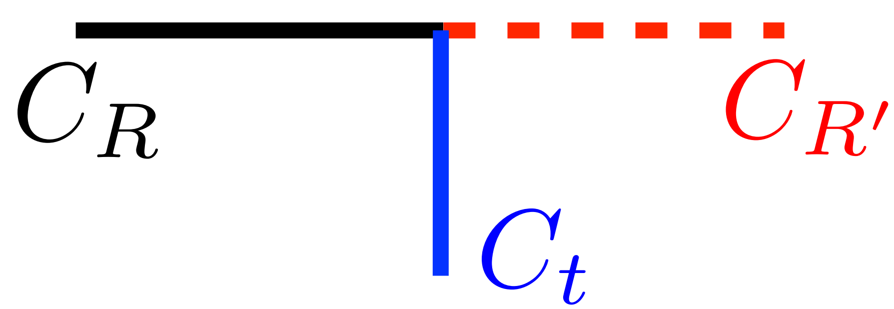
• color factor



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

$$= C_R + C_R - N_c$$

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



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

(PAK14)

fully coherent radiation is process-dependent

$\Longrightarrow \notin$ target/proj. wavefunction

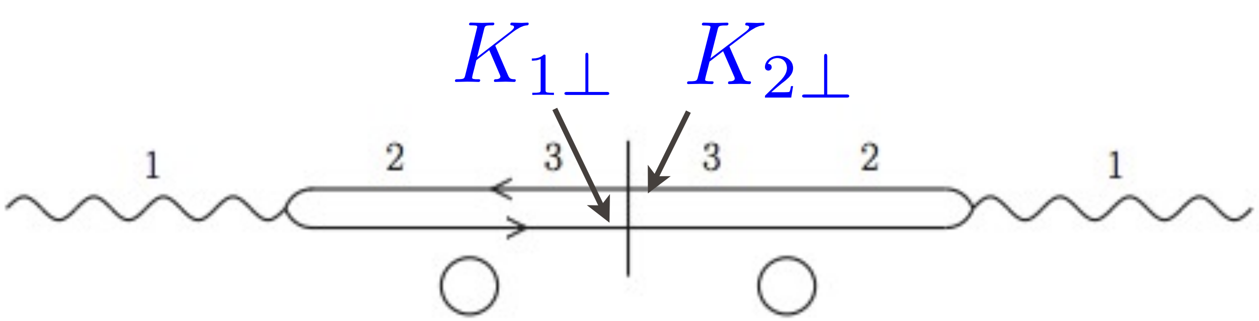
generalization to $1 \to 2$ hard forward processes

Liou & Mueller, 1402.1647 [LM14] and PK14

- LM14: dipole formalism; forward *symmetric* dijet

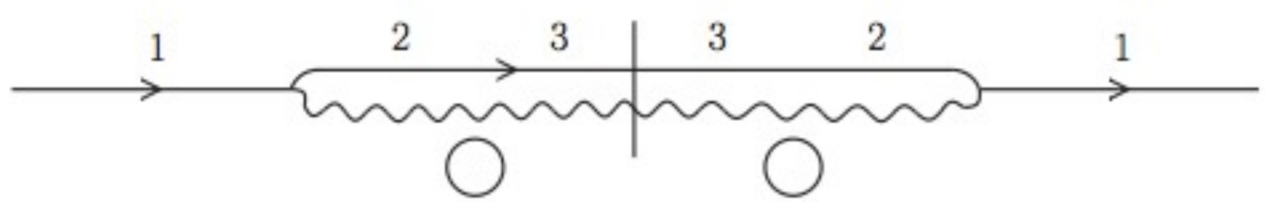
$$K_{1\perp}, K_{2\perp} \gg \ell_\perp \sim Q_s \quad \text{but} \quad |\vec{K}_{1\perp} + \vec{K}_{2\perp}| \lesssim Q_s$$

$g \to q\bar{q}$



$$\Rightarrow x\frac{\mathrm{d}I}{\mathrm{d}x} = x\frac{\mathrm{d}I}{\mathrm{d}x}\bigg|_{g\to g}$$

$q \to qg$

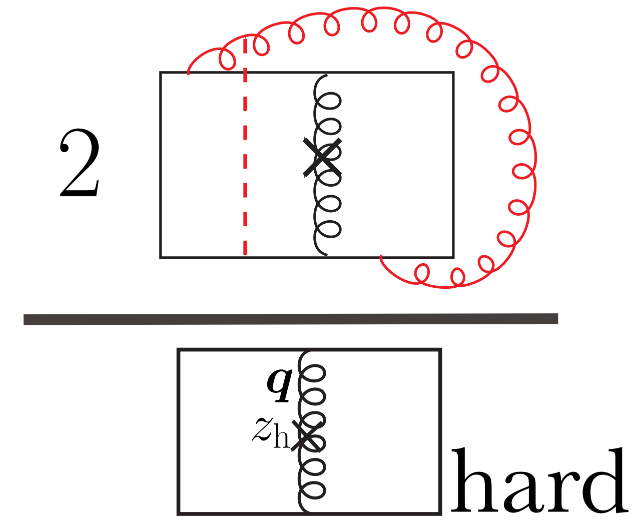


$$\Rightarrow x\frac{\mathrm{d}I}{\mathrm{d}x} = \frac{4}{5}\, x\frac{\mathrm{d}I}{\mathrm{d}x}\bigg|_{g\to g}$$

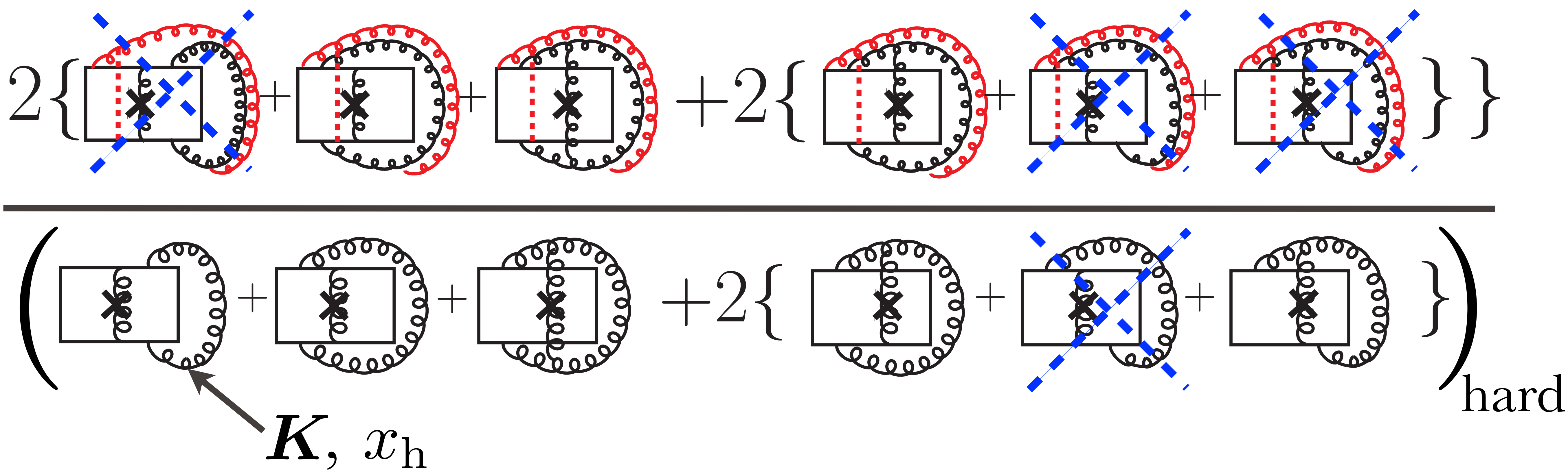
how can we understand similarity between $1 \to 1$ and $1 \to 2$ processes, and interpret 'strange' factor 4/5 ?

spectrum associated to $q \to qg$ in opacity expansion and large N_c limit (PK14)

for $g \to g$, hard process is trivial



for $q \to qg$, hard process is less trivial:



- explicit calculation

$$\Rightarrow \quad x\frac{\mathrm{d}I}{\mathrm{d}x}\bigg|_{q\to qg} = \kappa_{q\to qg}\cdot N_c\cdot\frac{\alpha_s}{\pi}\log\left(\frac{\Delta q_\perp^2(L)}{x^2\boldsymbol{K}^2}\right)$$

$$\kappa_{q\to qg} \equiv \frac{(\boldsymbol{K}-x_{\mathrm{h}}\boldsymbol{q})^2}{(\boldsymbol{K}-x_{\mathrm{h}}\boldsymbol{q})^2+(1-x_{\mathrm{h}})^2\boldsymbol{K}^2}$$

log arises from $x^2K_\perp^2 \ll k_\perp^2 \ll \hat{q}L \sim \ell_\perp^2$

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

at time t_f, radiated gluon does not probe size $\Delta r_\perp$ of qg pair ⟹ $qg \sim$ pointlike

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

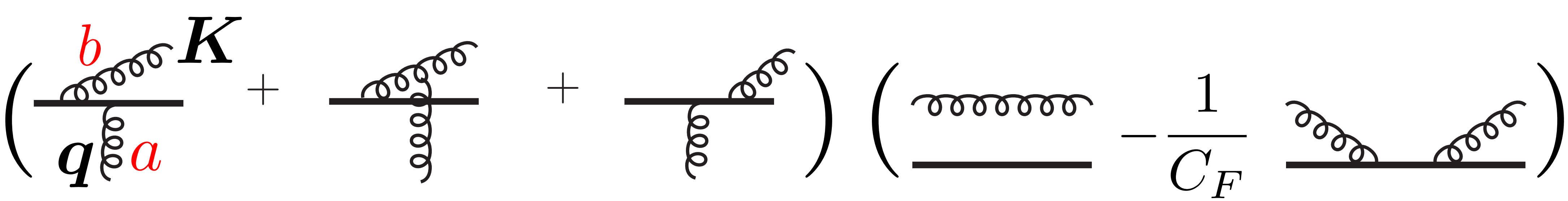
- interpretation of factor $\kappa_{q\to qg}$

$\ast$ final pointlike qg pair can be in 3 color reps:

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

$\ast$ diagrams *with induced gluon* which are suppressed when $N_c \gg 1$ are those where final qg pair is in $\mathbf{3}$ (recall $q \to q$ has color factor $2C_F - N_c \underset{N_c\to\infty}{\longrightarrow} 0$)

⟹ same result can be obtained by removing 'triplet' component of final qg in production amplitude



$$= \mathcal{M}_{\rm hard}^{\bar{\mathbf{6}}\oplus\mathbf{15}} = T^a T^b \left(\frac{\boldsymbol{K}}{\boldsymbol{K}^2} - \frac{\boldsymbol{K}-\boldsymbol{q}}{(\boldsymbol{K}-\boldsymbol{q})^2}\right) \Rightarrow \frac{|\mathcal{M}_{\rm hard}^{\bar{\mathbf{6}}\oplus\mathbf{15}}|^2}{|\mathcal{M}_{\rm hard}|^2} = \quad \cdots \quad = \kappa_{q\to qg}$$

$\kappa_{q\to qg} =$ proba to produce qg pair in $\bar{\mathbf{6}} \oplus \mathbf{15}$ subspace

$$= \frac{(\boldsymbol{K} - x_{\rm h}\boldsymbol{q})^2}{(\boldsymbol{K} - x_{\rm h}\boldsymbol{q})^2 + (1-x_{\rm h})^2\boldsymbol{K}^2} \xrightarrow[q_\perp \ll K_\perp]{x_{\rm h} = 1/2} \frac{4}{5}$$

- color factor

$qg \sim$ pointlike ⟶ result must depend only on total color charge, and be given by same rule as for $1 \to 1$

qg is in $R' = \bar{\mathbf{6}}$ or $\mathbf{15}$

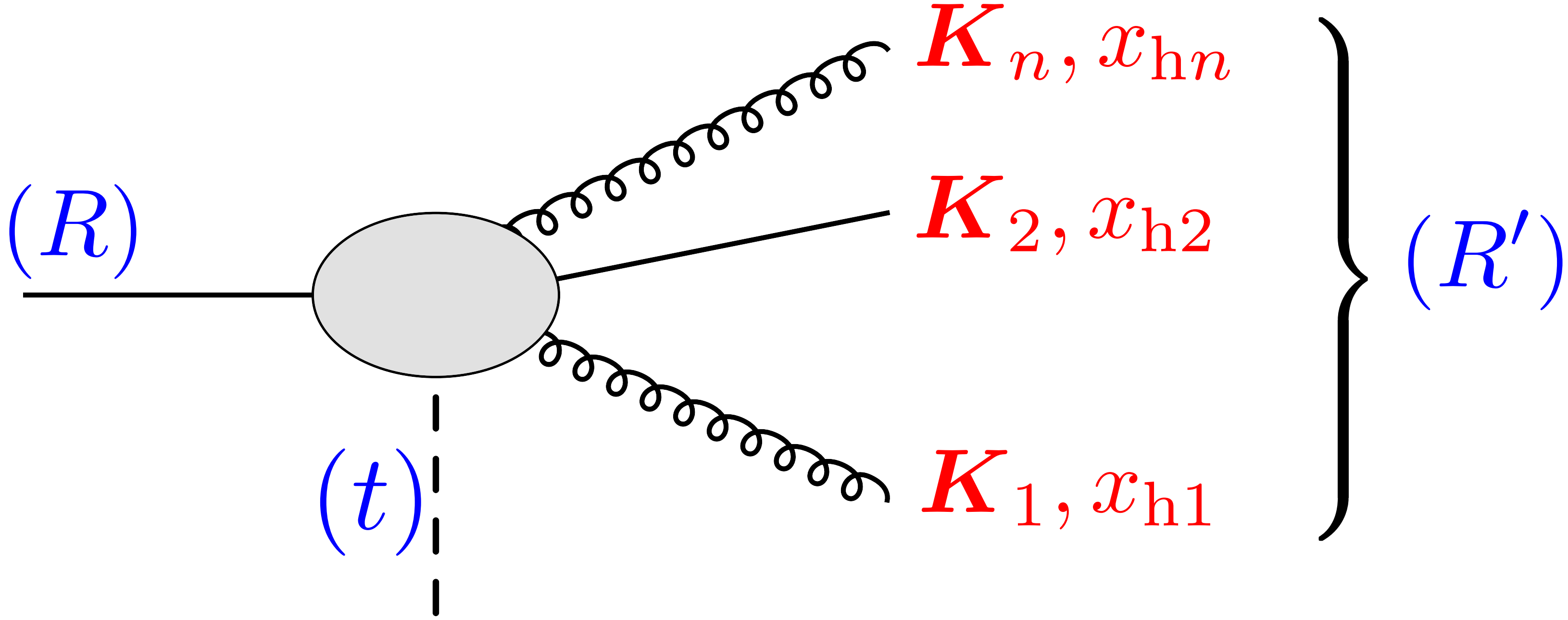
$$C_{\bar{\mathbf{6}}} \simeq C_{\mathbf{15}} \simeq \frac{3}{2}N_c$$

$\Rightarrow$

$$2\,T^a_{\mathbf{3}}T^a_{R'} = C_{\mathbf{3}} + C_{R'} - C_{\mathbf{8}}$$
$$\simeq \frac{N_c}{2} + \frac{3}{2}N_c - N_c$$
$$= N_c$$

conjecture for $1 \to n$ hard forward processes

(PK14)



$x_{hi} \sim \mathcal{O}(1)$

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

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

proba for n-parton state to be produced in color rep (R')

conjecture proven for all $1 \to 1$, $q \to qg$, and also $g \to q\bar{q}$, $g \to gg$

summary

- *features of coherent radiation are the same for $1 \to 1$ and $1 \to 2$: universal log, process-dependent prefactor*

- *radiation sees final parton system as pointlike*

  → *conjecture for all $1 \to n$ processes*

- *results for fully coherent spectra follow from first principles of QCD radiation and color algebra, and can be obtained in different formalisms*

- *fully coherent radiation expected in all hard forward processes with color in both initial and final parton states*

$$\Delta E_{coh} \propto E \qquad (\gg \Delta E_{\mathrm{LPM}})$$

→ *pA suppression of J/psi, but also di-jet, light hadron...*

Back-up

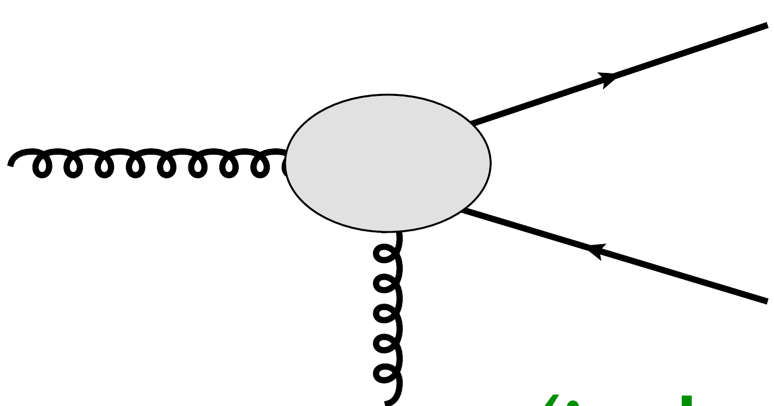
two checks of the conjecture:

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

explicit calculation:

$$x\frac{\mathrm{d}I}{\mathrm{d}x}\bigg|_{g\to q\bar{q}} = N_c\frac{\alpha_s}{\pi}\log\left(\frac{\Delta q_\perp^2(L)}{x^2 Q_{\mathrm{hard}}^2}\right) \qquad \text{(LM14)}$$

using conjecture:



dominantly in $R' = \mathbf{8}$
when $N_c \gg 1$ $(P_{\mathbf{8}} = 1)$

(independently of x_{h})

$\Longrightarrow$ $N_c + N_c - N_c = N_c$

$q\bar{q}$ pointlike and octet $\Longrightarrow$ same result as $g \to g$

(APS10, PAK14)

2) $g \to gg$

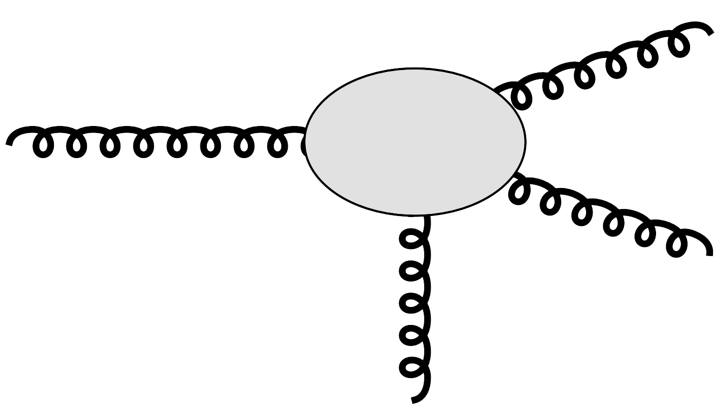
explicit calculation (PK14)

$$x\frac{\mathrm{d}I}{\mathrm{d}x}\bigg|_{g\to gg} = \kappa_{g\to gg} N_c\,\frac{\alpha_s}{\pi}\,\log\left(\frac{\Delta q_\perp^2(L)}{x^2 Q_{\rm hard}^2}\right)$$

$$\kappa_{g\to gg} \equiv 1 + \frac{(\boldsymbol{K} - x_{\rm h}\boldsymbol{q})^2}{(\boldsymbol{K} - x_{\rm h}\boldsymbol{q})^2 + x_{\rm h}^2(\boldsymbol{K}-\boldsymbol{q})^2 + (1-x_{\rm h})^2\boldsymbol{K}^2}$$

remark: $\kappa_{g\to gg} = 5/3$ when $x_{\rm h} = 1/2$ and $q_\perp \ll K_\perp$

using conjecture:

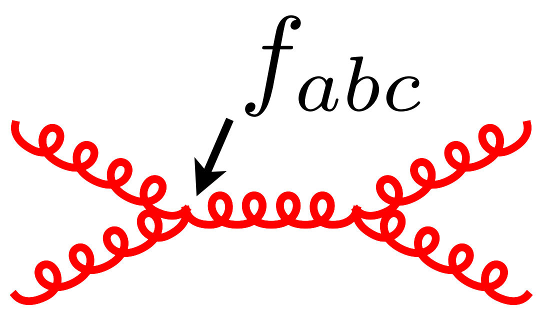


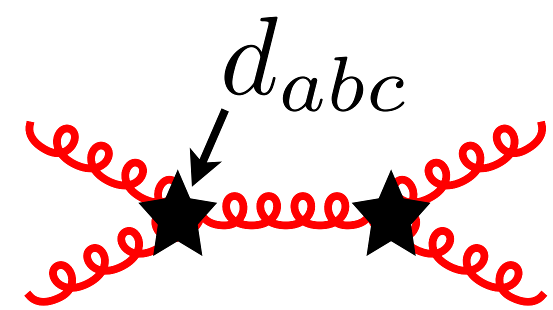
$$\mathbf{8}\otimes\mathbf{8} = \mathbf{1}\oplus\mathbf{8_s}\oplus\mathbf{8_a}\oplus\underbrace{(\mathbf{10}\oplus\overline{\mathbf{10}})}_{2N_c;}\oplus\mathbf{27}\oplus\mathbf{0}$$

$$C_{R'} \simeq 0;\quad N_c;\quad N_c;\quad 2N_c;\quad 2N_c;\quad 2N_c$$

$$\Longrightarrow \sum_{R'} P_{R'}(C_R + C_{R'} - C_t) = \sum_{R'} P_{R'} C_{R'} = (2 - P_{\mathbf{8_a}} - P_{\mathbf{8_s}})\, N_c$$

$P_{\mathbf{8_a}}$ and $P_{\mathbf{8_s}}$ can be simply calculated using pictorial rules for color projection operators:

$\mathcal{P}_{\mathbf{8_a}} = \frac{1}{N_c}$ 

$\mathcal{P}_{\mathbf{8_s}} = \frac{N_c}{N_c^2 - 4}$ 

Y. Dokshitzer, ‘PQCD (and Beyond)’, 1995

$$\Longrightarrow (2 - P_{\mathbf{8_a}} - P_{\mathbf{8_s}})\, N_c = \quad \ldots \quad = \kappa_{g\to gg}\, N_c$$

(remark: $P_{\mathbf{8_s}}$ and $P_{\mathbf{8_a}}$ depend on x_{h})

J/psi suppression in pA and AB collisions

predictions for J/psi suppression
from fully coherent energy loss
compared to available low pT data

from fixed target to collider energies

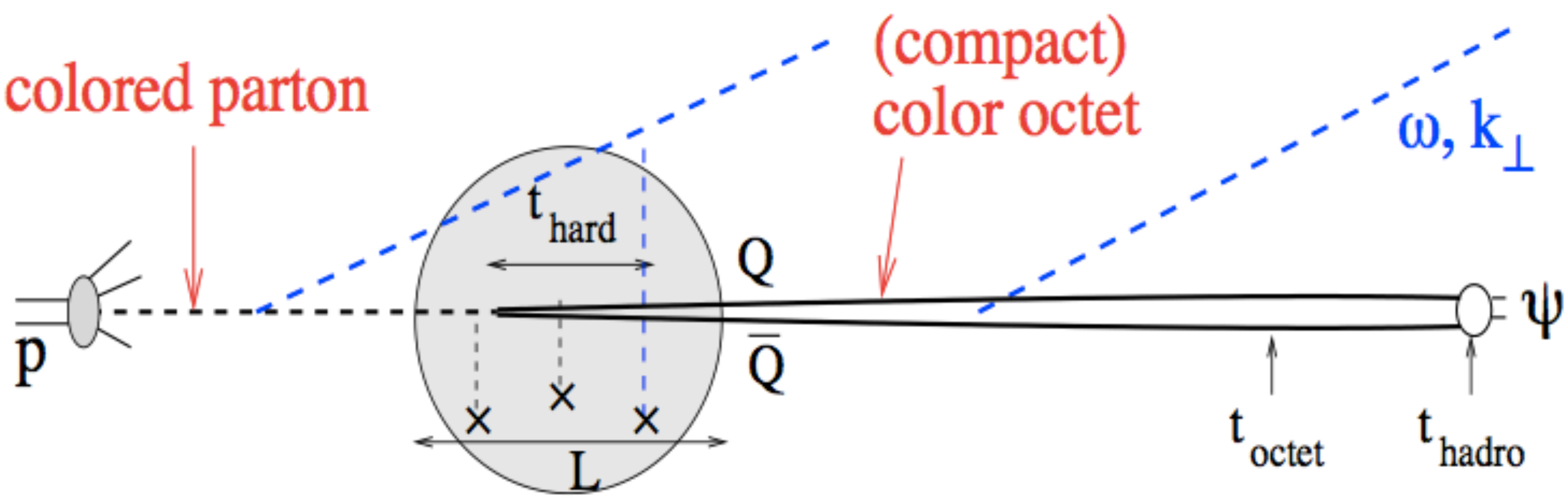
Arleo, S.P., 1204.4609 and 1212.0434 [AP12]

Arleo, Kolevatov, S.P., Rustamova 1304.0901 [AKPR13]

Arleo, S.P. 1407.5054 [AP14]

model for quarkonium pA suppression (AP12)

$x_F > x_F^{critical}$



➡ coherent radiation

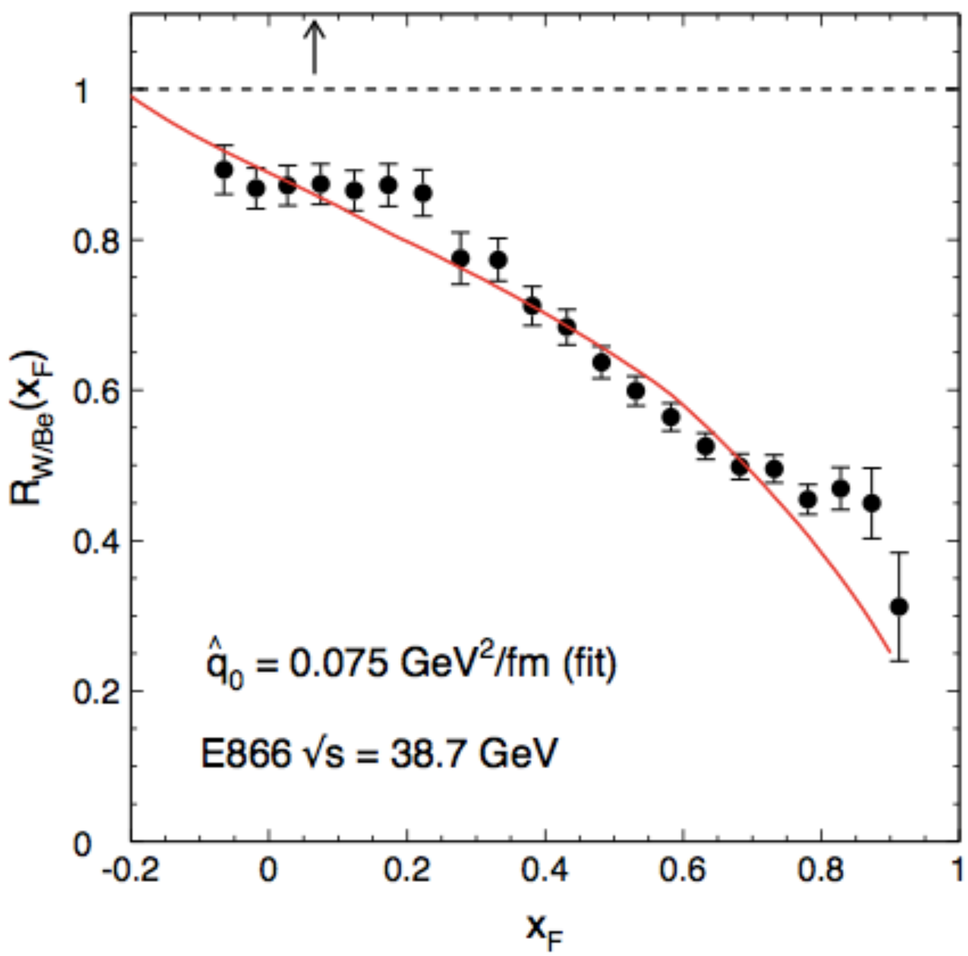
- arises from $t_{hard}, L \ll t_f \ll t_{octet}$
- depends on L via $\Delta q_\perp^2 = \hat{q}\, L \ll M$

use standard way to implement energy loss:

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

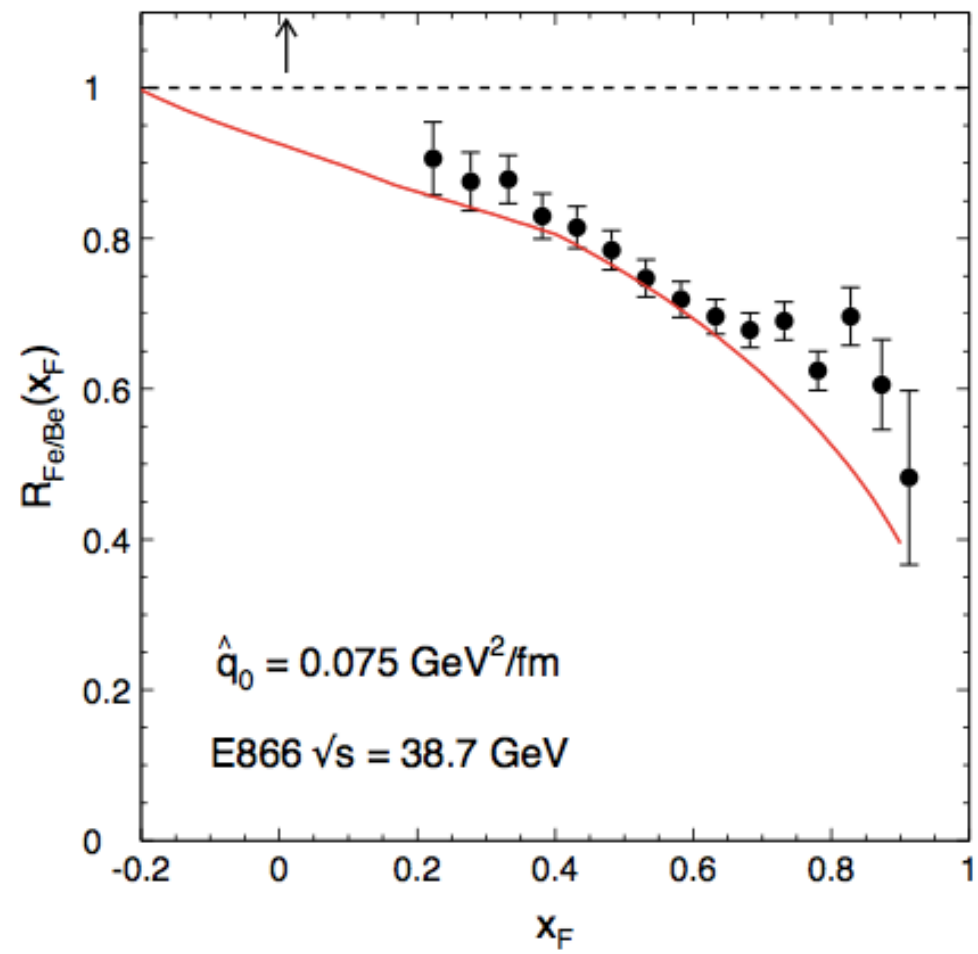
J/psi suppression in pA

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



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

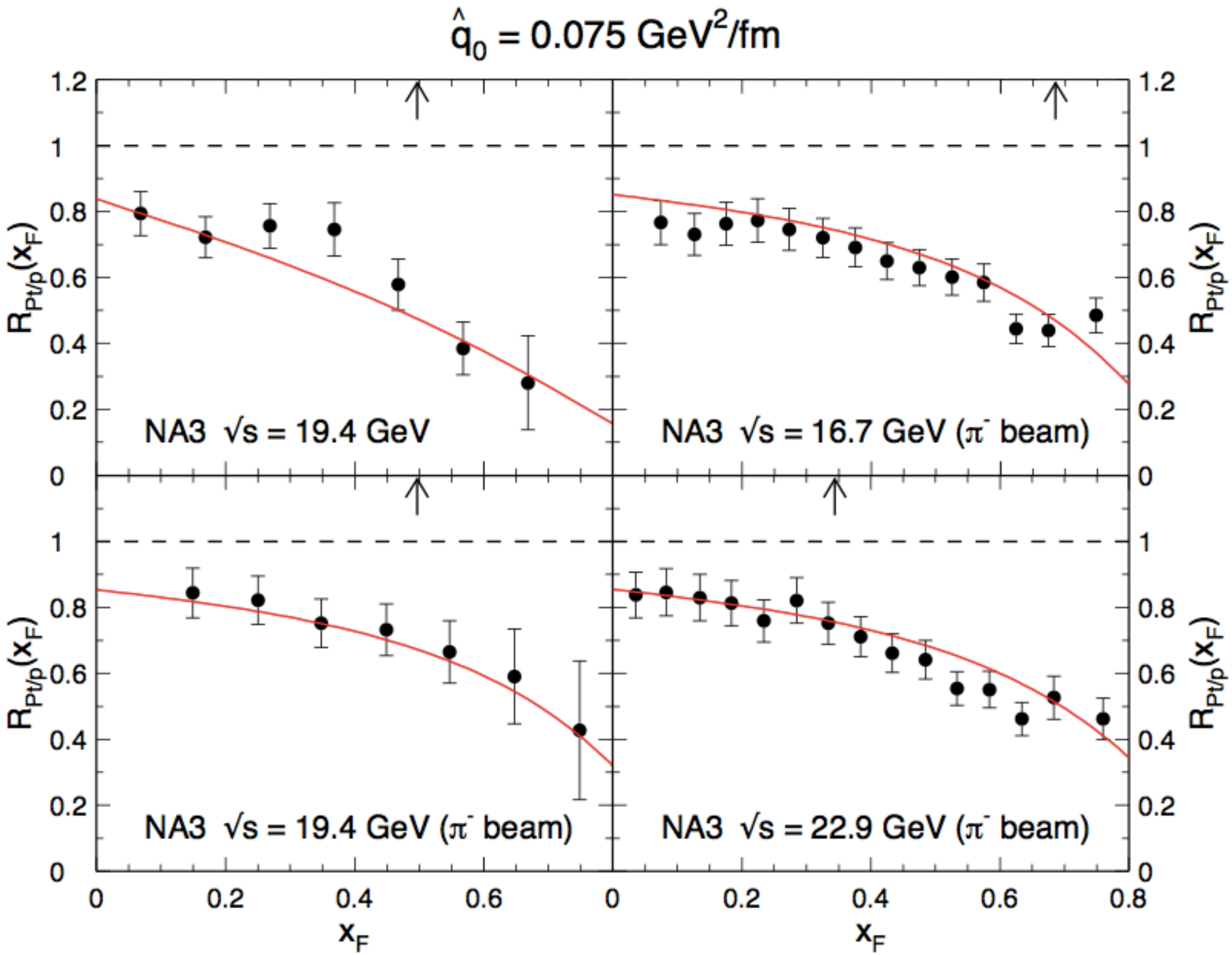
E866 Fe/Be



A–dependence well reproduced

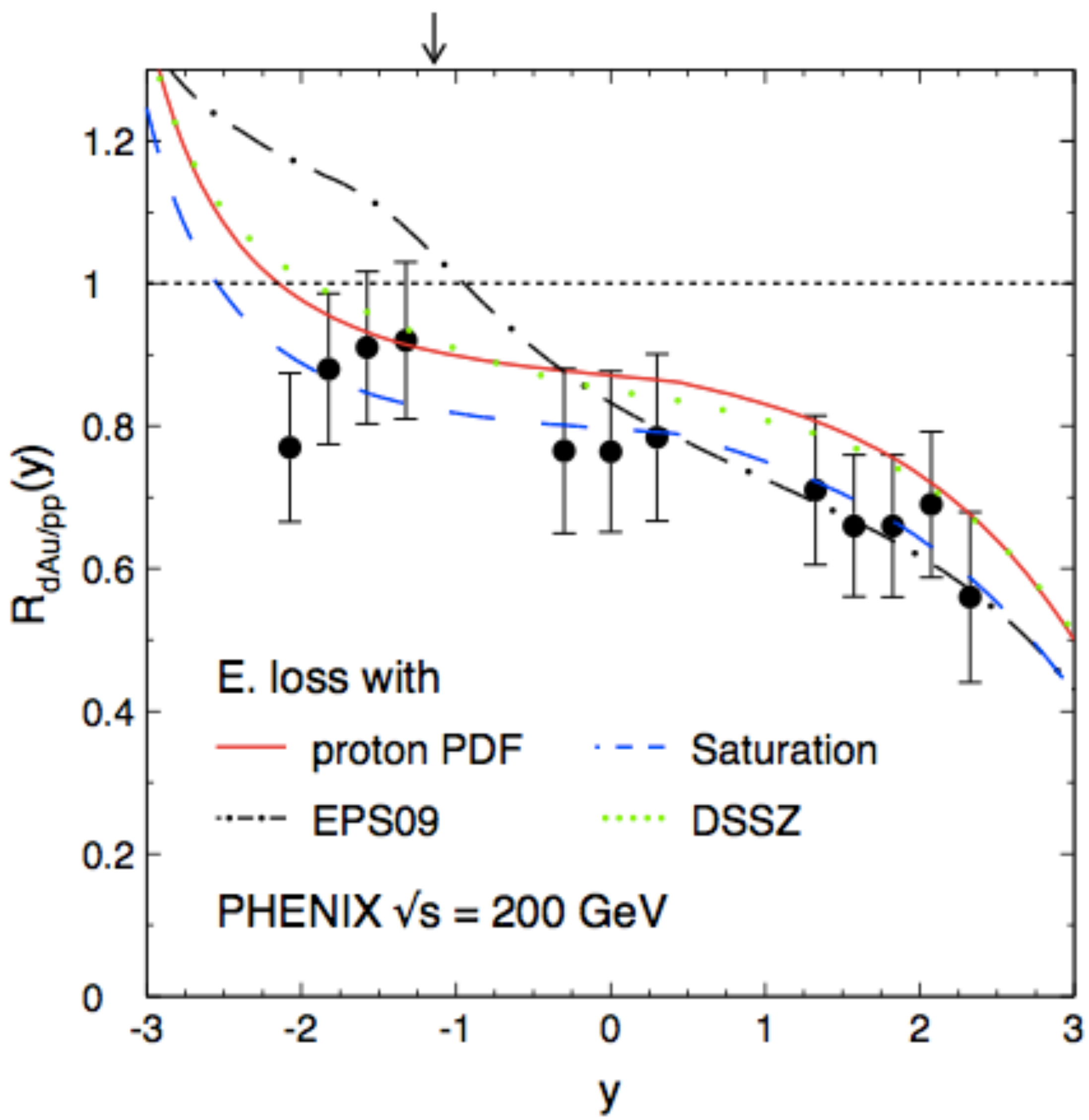
(AP12)

J/ψ NA3 Pt/p

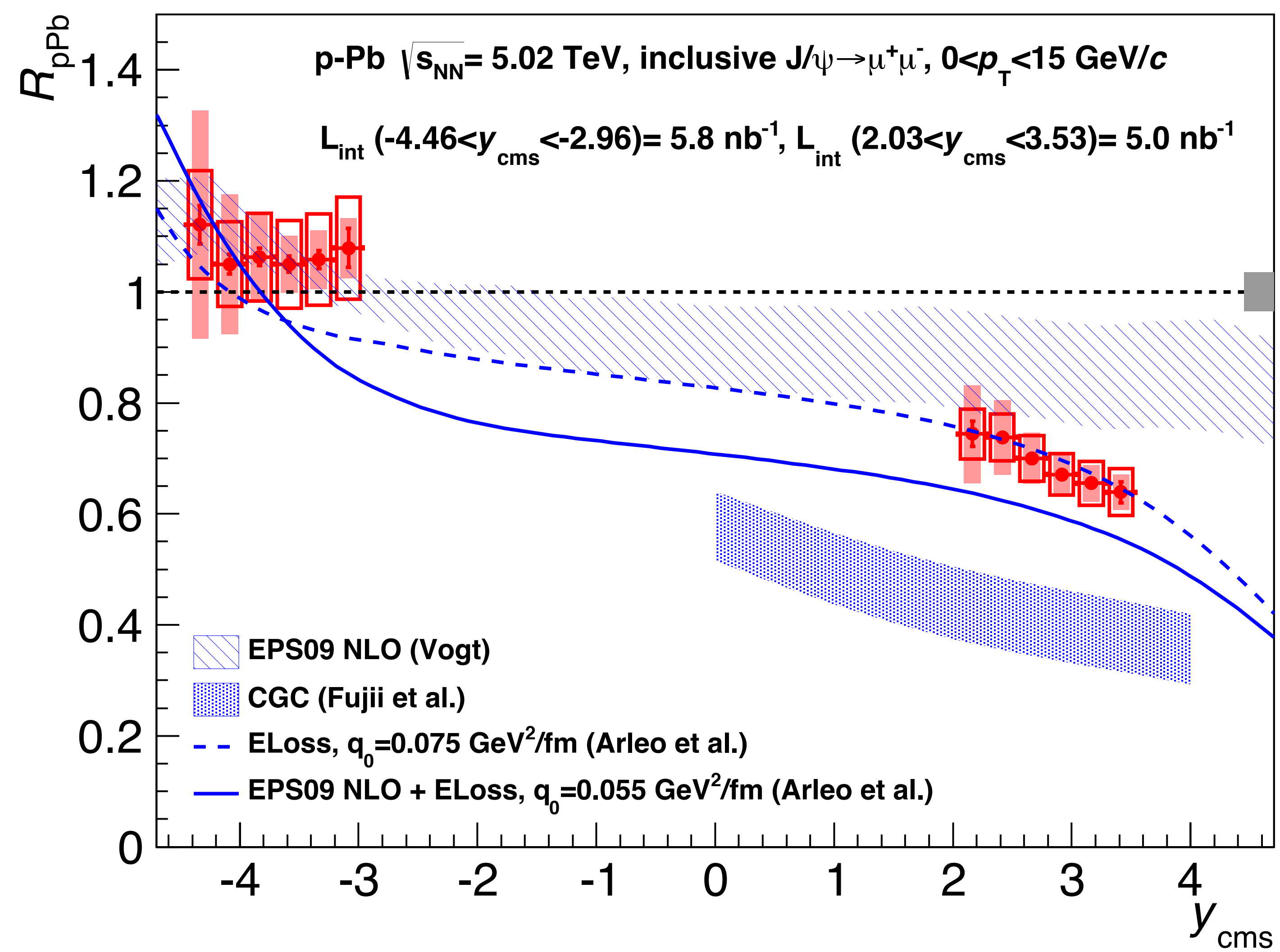


(AP12)

RHIC d-Au
(PHENIX)



LHC p-Pb
(ALICE)

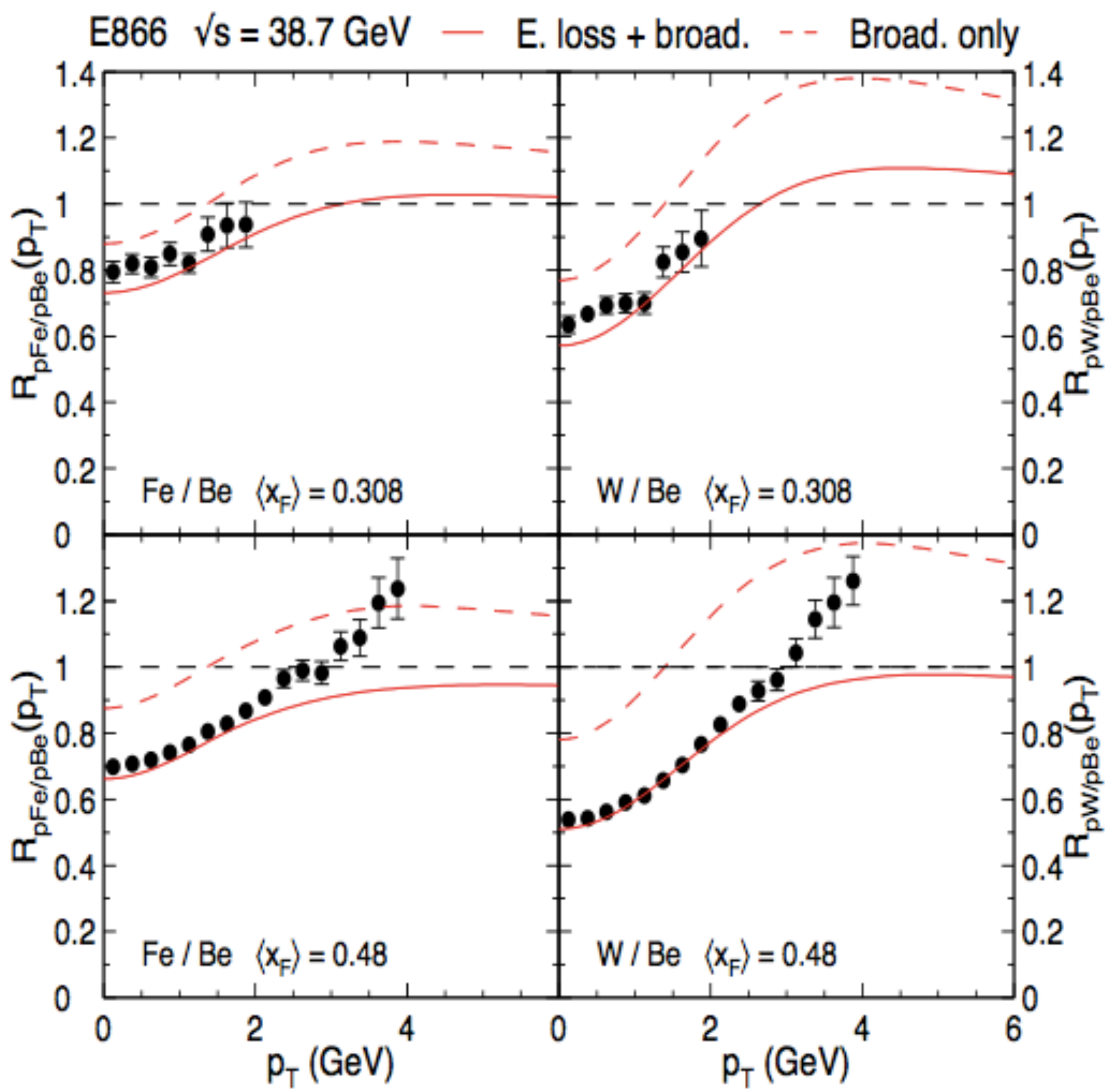


(AP12)

$p_\perp$-dependence (AKPR13)

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

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

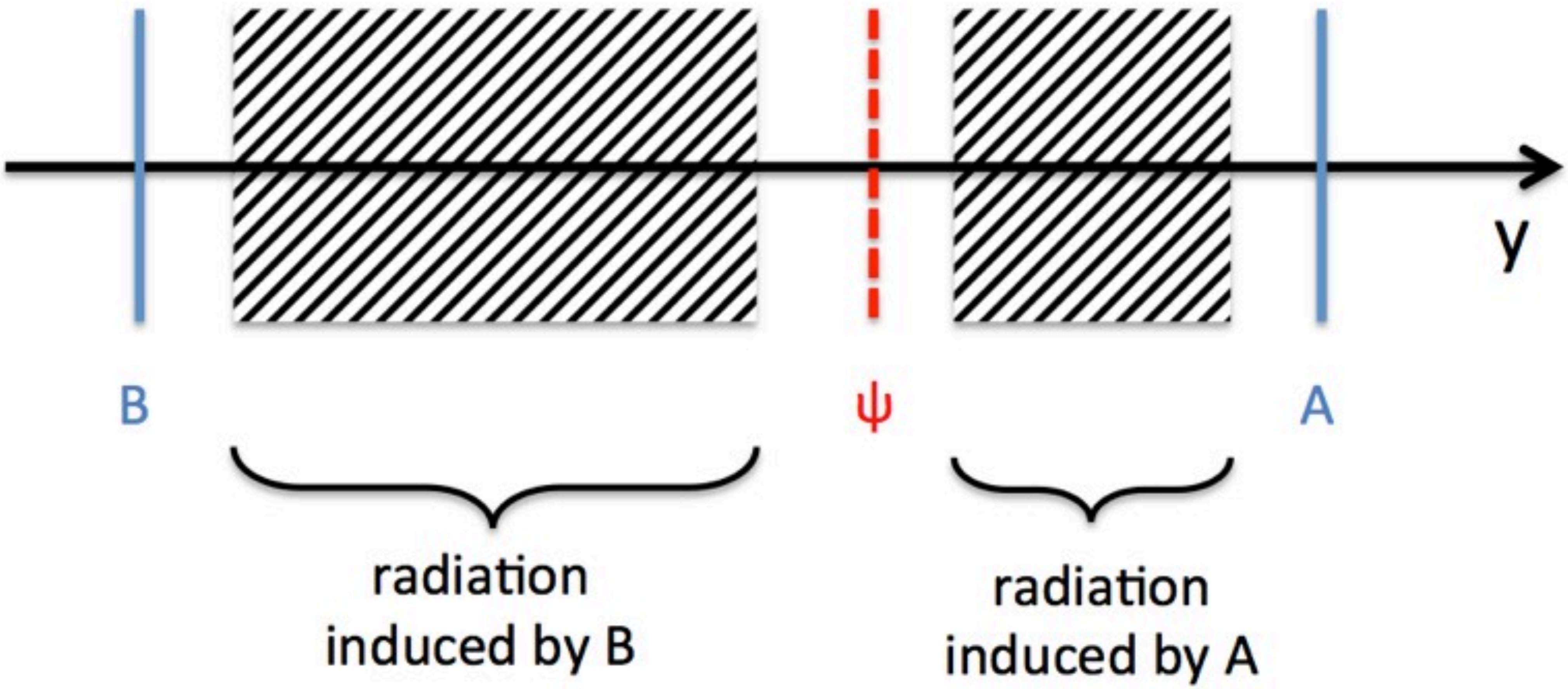


no free parameter:
$\Delta p_\perp$ induces ΔE

$\Delta p_\perp \longrightarrow$ Cronin effect

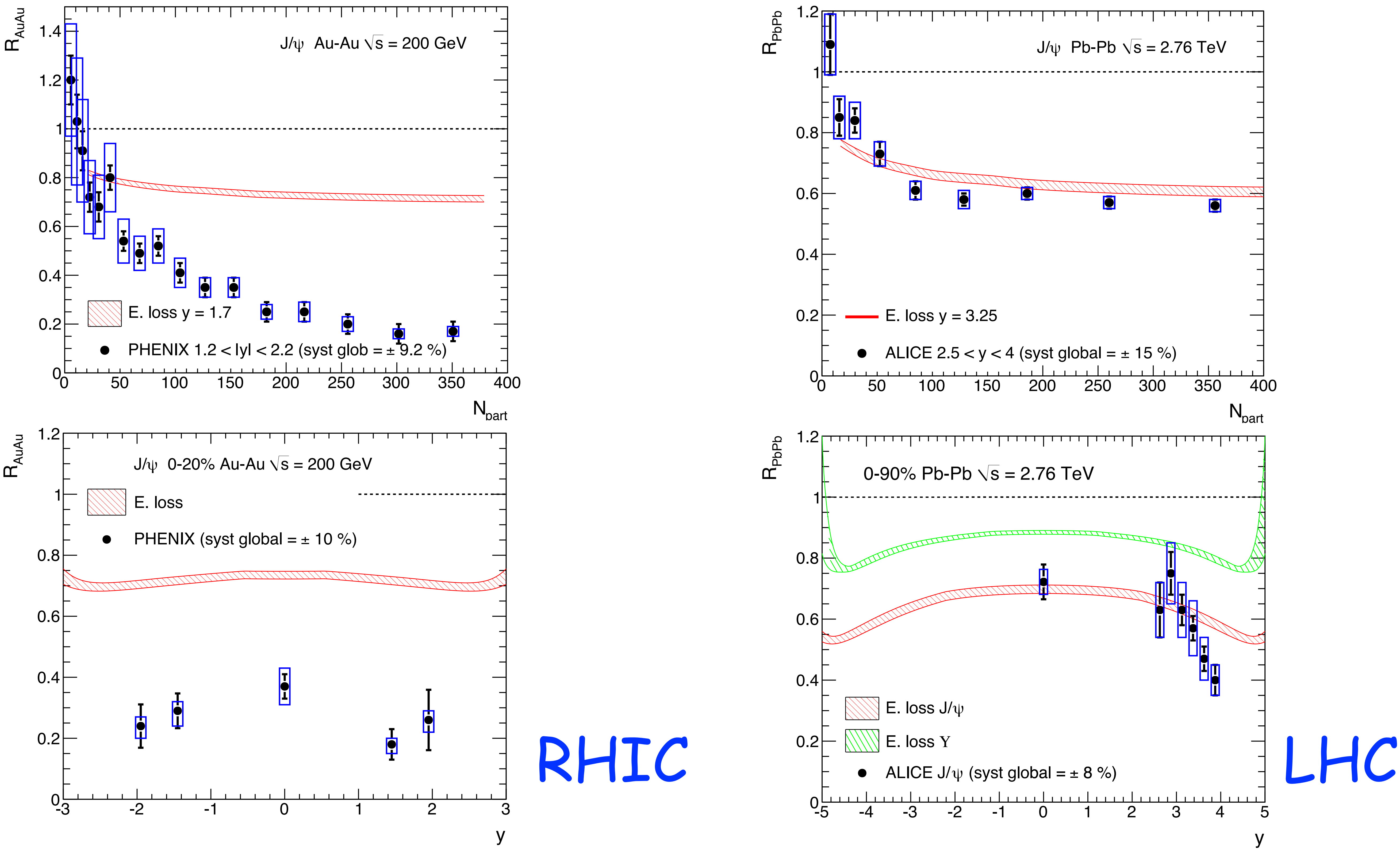
energy loss $\longrightarrow$ normalization

quarkonium suppression in AB collisions (AP14)



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

J/psi suppression in AB collisions (AP14)



→ baseline for cold nuclear effects