$\mathbf{J/\psi}$ suppression in p-A collisions from parton energy loss

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Heavy Ion Collisions in the LHC Era

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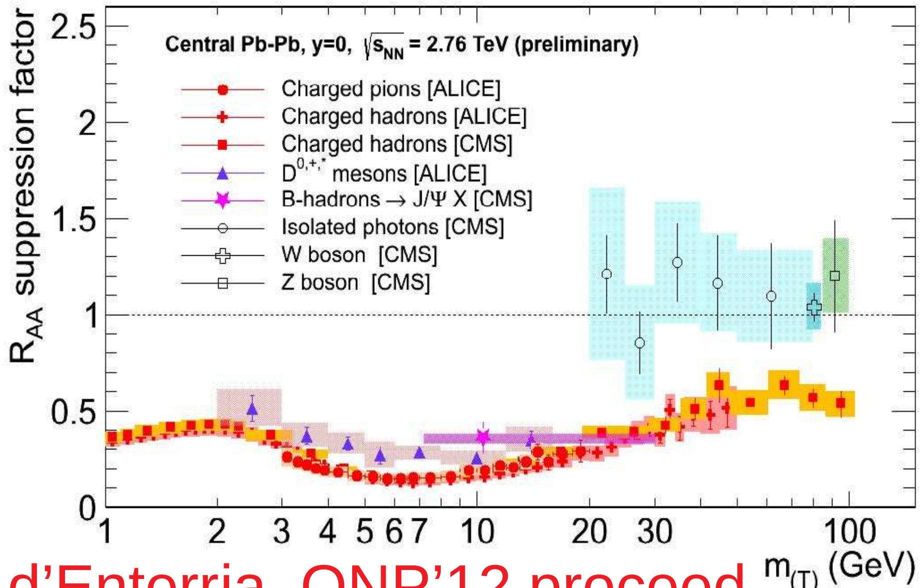
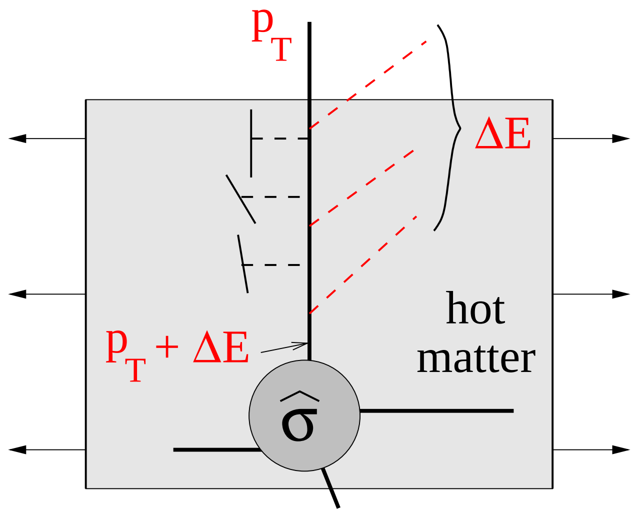
1. motivations

- spectacular jet-quenching in A-A collisions
  $\rightarrow$ *parton energy loss*



D. d'Enterria, QNP'12 proceed.



$$\Delta E \sim \alpha_s \, \hat{q} \, L^2$$

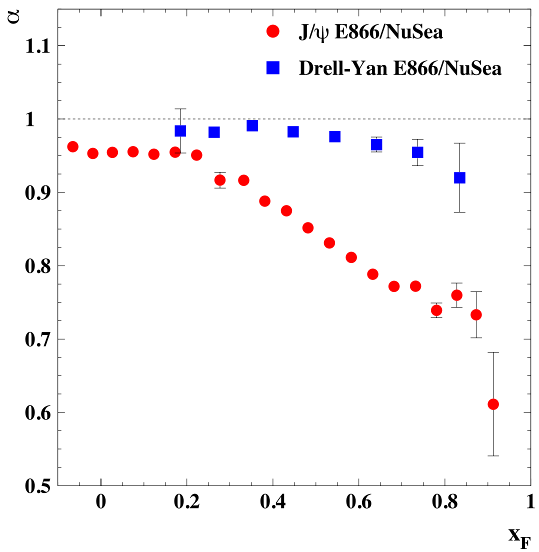
magnitude of $R_{AA} \sim \frac{1}{(1+\Delta E/p_T)^n}$ can be explained only if

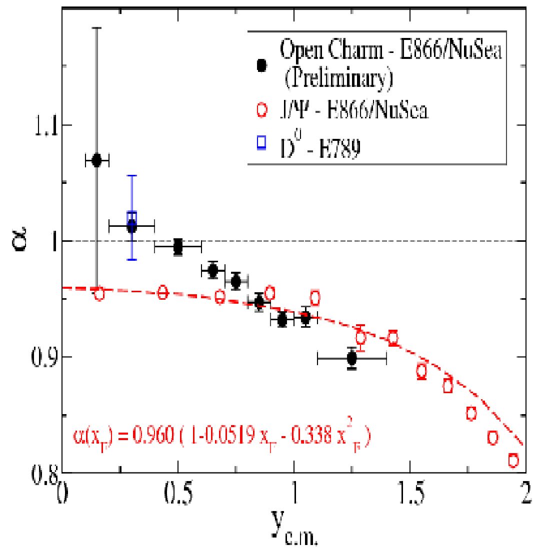
$$\hat{q} \equiv \frac{\mu^2}{\lambda} \sim \hat{q}_{hot} \sim 1 \, \mathrm{GeV}^2/\mathrm{fm} \gg \hat{q}_{cold} \sim 0.05 \, \mathrm{GeV}^2/\mathrm{fm}$$

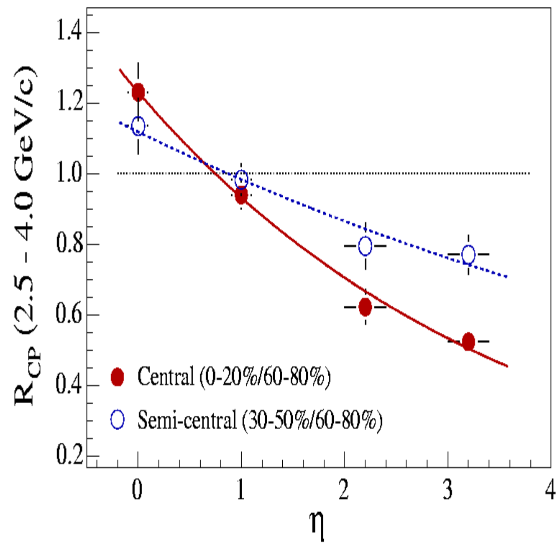
$\Rightarrow$ jet-quenching $=$ prominent QGP signal

- strong nuclear suppression also seen in p-A

J/ψ | open charm | light hadron







E866/NuSea | BRAHMS

huge suppression at large x_{F} / large rapidity
might also arise from ΔE_{parton} (*in cold matter*):

$\Delta E_{pA} \propto \sqrt{\hat{q}_{cold}}\, E$ *is large* (despite small $\hat{q}_{cold}$)

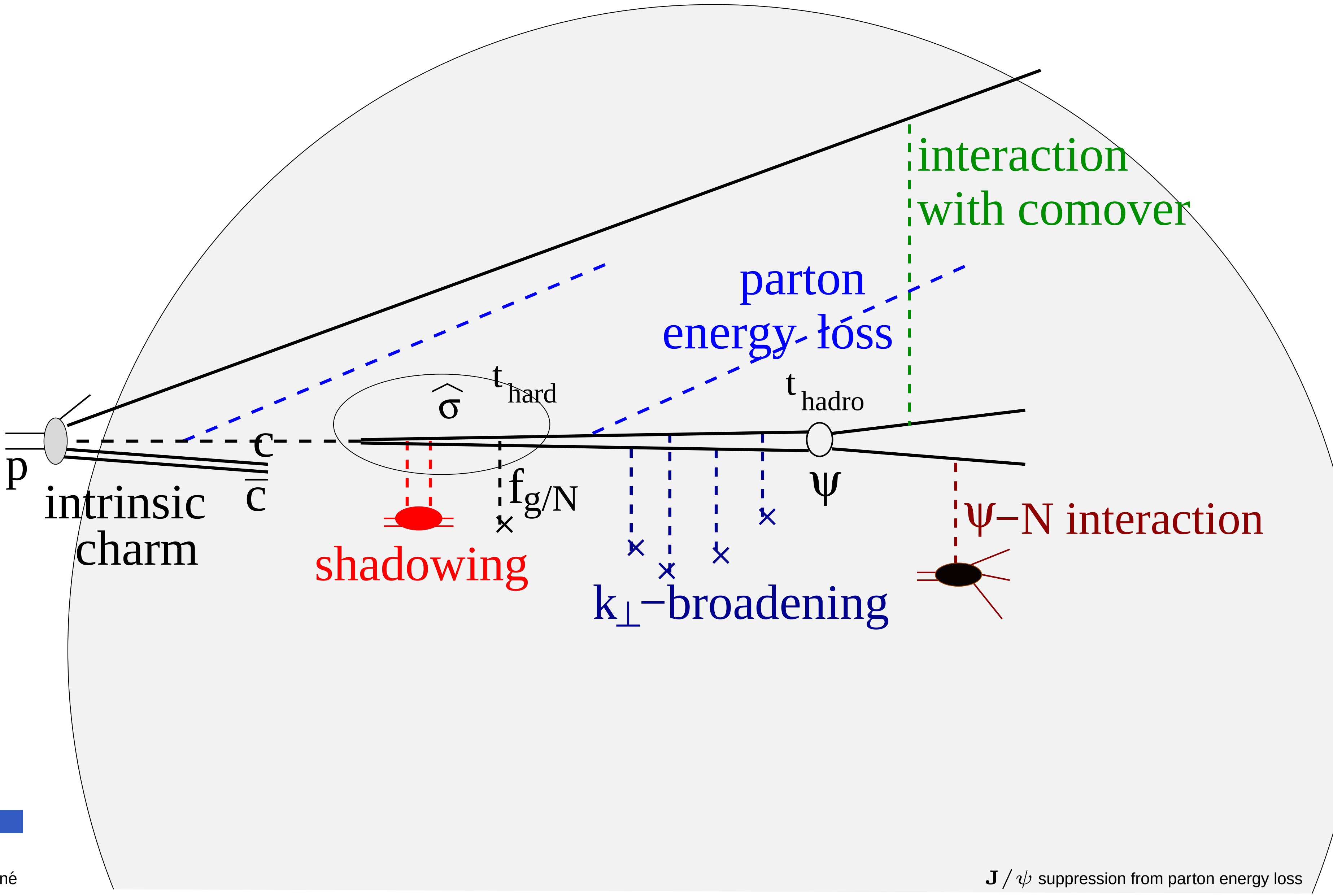
- focus here on quarkonium production
  - intrinsic hard scale $M = M_{Q\bar{Q}} \sim 3\,\mathrm{GeV}$
  - rich data for nuclear suppression

    but same physics expected in *open charm*

    and *light hadron* production in p-A

- understanding $R_{pA}^{J/\psi} = \frac{\sigma_{pA}^{J/\psi}}{A\sigma_{pp}^{J/\psi}}$ is crucial
  - constrain quarkonium production models in p-p
  - disentangle various *cold* nuclear effects
  - prerequisite to address J/ψ suppression in A-A

2. nuclear effects in J/ψ production



many effects involved

- when $t > t_{hadro}$
  - $\psi\, N$ interaction $\leftrightarrow \sigma_{\psi\, N} \equiv \sigma_{abs}$
  - interaction of ψ with comovers
- when $t < t_{hadro}$
  - parton distributions in nuclei (shadowing)
  - parton propagation in dense medium (k_T-broadening, saturation)
  - induced parton energy loss
- CEM, CSM, COM, intrinsic charm, . . . ?

- when are J/ψ quantum numbers fixed?

relevant time-scales:

$$t_{hard}^{c\bar{c}} \sim \frac{E}{M} \cdot \frac{1}{M}$$

$$t_{hadro}^{\psi} \sim \frac{E}{M} \cdot \frac{1}{M_{\psi'} - M_{\psi}}$$

($E = J/\psi$ energy in nucleus rest frame)

$$\Rightarrow t_{hard}^{c\bar{c}} \ll t_{hadro}^{\psi}$$

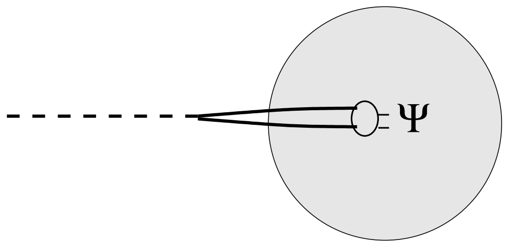
but octet $c\bar{c}$ lifetime t_{octet} unknown

$$t_{hard} \leq t_{octet} \sim ? \leq t_{hadro}$$

$\rightarrow$ consider simplifying kinematical limits

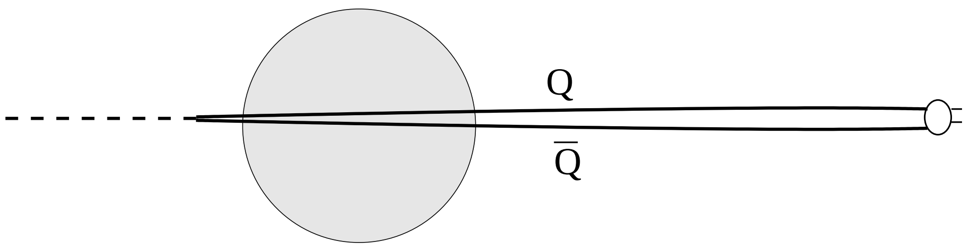
two opposite limits

- $t_{hadro} < L$ ($\Leftrightarrow x_{\mathrm{F}} < x_{\mathrm{F}}^{critical}$)



$\longrightarrow$ nuclear suppression from σ_{abs} *within* nucleus

- $t_{hadro} > L$ ($\Leftrightarrow x_{\mathrm{F}} > x_{\mathrm{F}}^{critical}$)

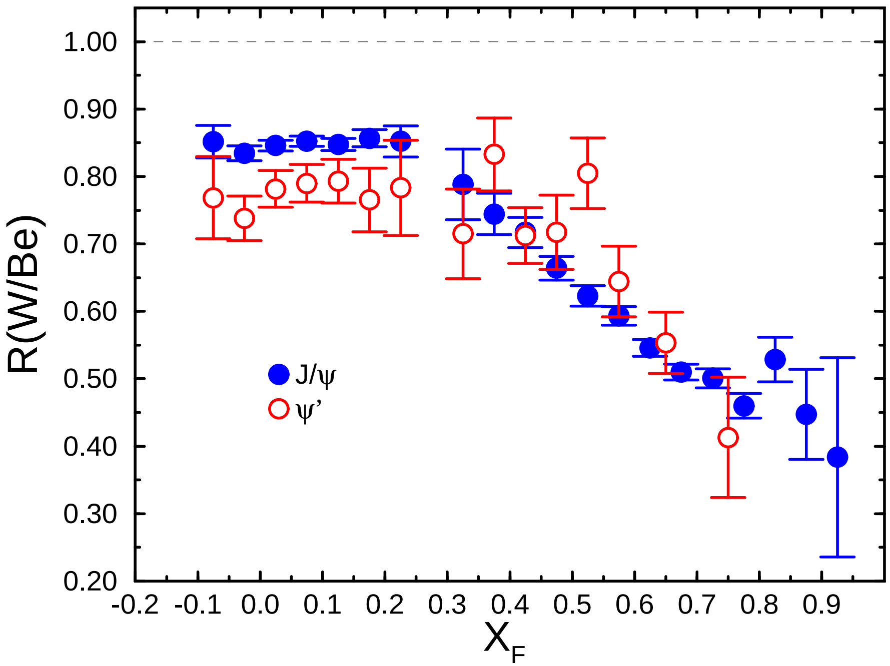


$\longrightarrow$ compact octet $Q\bar{Q}$ ($r_{Q\bar{Q}} \sim 1/M$) through nucleus

$\longrightarrow \sigma_{abs}$ irrelevant

- note: large $\sqrt{s} \Rightarrow x_{\mathrm{F}}^{critical} < 0$

3. J/ψ suppression at large E



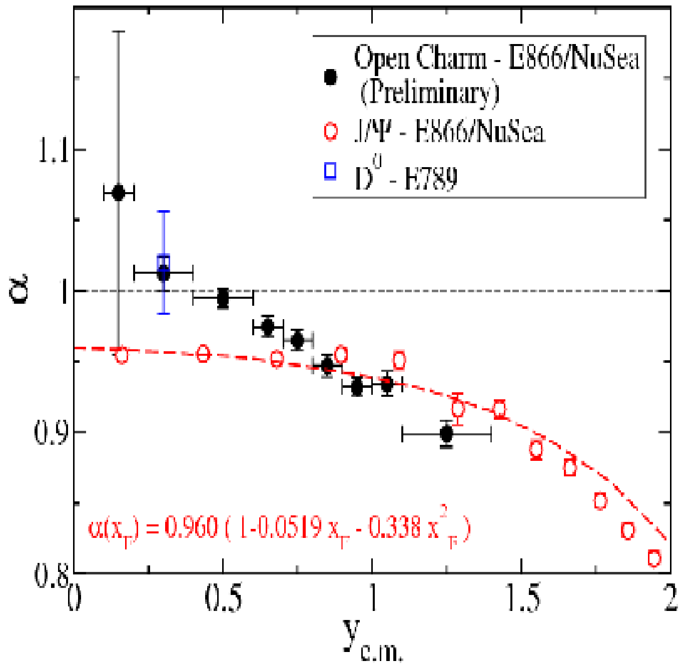
E866/NuSea Leitch et al. 99

$$E_{beam} = 800\,\text{GeV}$$

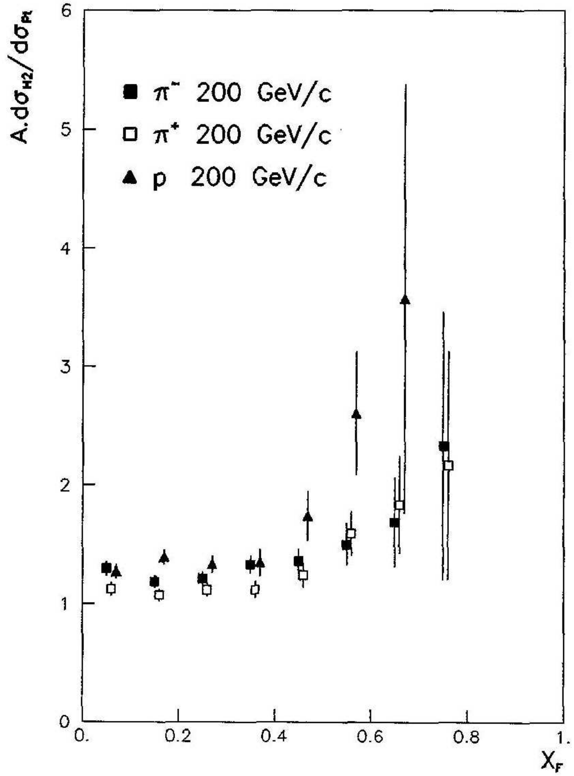
$$x_{\text{F}} = 0.5 \Rightarrow t_{hadro} \sim \tau \frac{x_F E_{beam}}{M} \simeq 40\,\text{fm} \gg R_W \simeq 7\,\text{fm}$$

large x_{F} E866 data lies in domain $t_{hadro} \gg L$

- at large $x_{\rm F}$, irrelevance of σ_{abs} supported by data:
  - suppression $\nearrow$ with $x_{\rm F}$ (when $c\bar{c}$ more compact!)
  - $R^{\psi'} \simeq R^{J/\psi}$ (whereas $r_{\psi'} > r_{J/\psi} \Rightarrow \sigma_{abs}^{\psi'} > \sigma_{abs}^{\psi}$ $\Rightarrow R^{\psi'} < R^{J/\psi}$ as observed at low $x_{\rm F}$)
  - similar suppression for open charm



- J/ψ nuclear suppression depends on projectile



stronger suppression in p-Pt than in π-Pt

NA3 Badier et al. 83

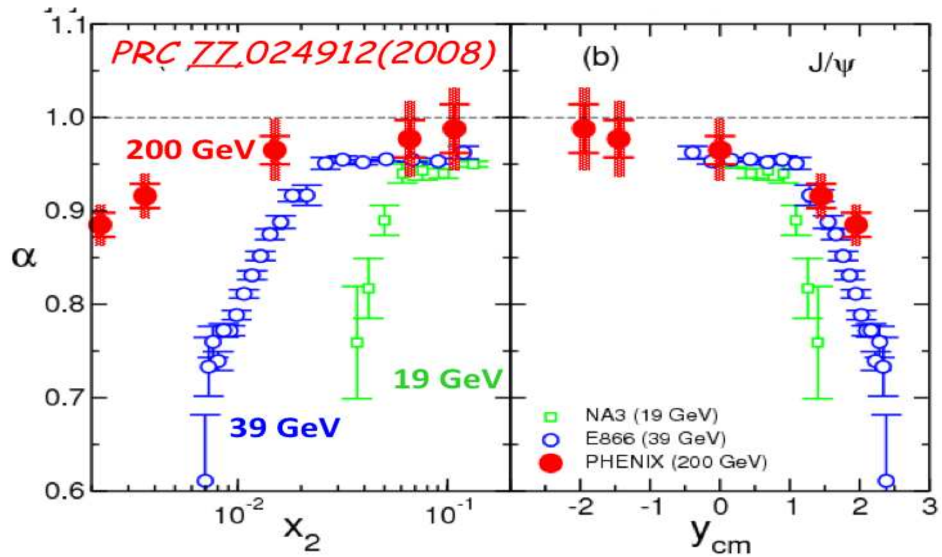
- no nuclear suppression in $\gamma^* A \to J/\psi + X$

$R_{in}(Sn/C) = 1.13 \pm 0.08$ NMC Amaudruz et al. 92

$\Rightarrow$ attributing suppression *at large* E to σ_{abs} is misleading

suppression at large E must be due to other effects

- hint: suppression does not scale in x_2



M. Leitch

$\Rightarrow$ shadowing (nPDFs) should be a minor effect

parton energy loss? saturation effects? intrinsic charm?

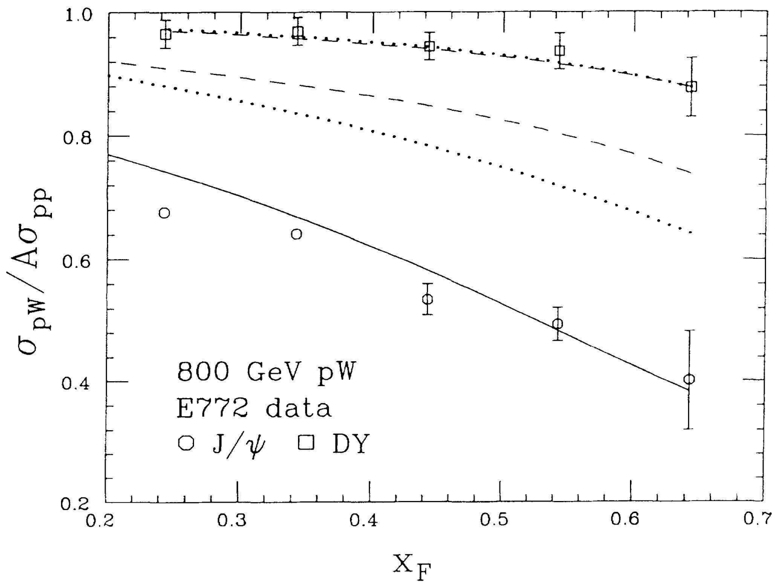
STAY TUNED...

4. energy loss in J/ψ production

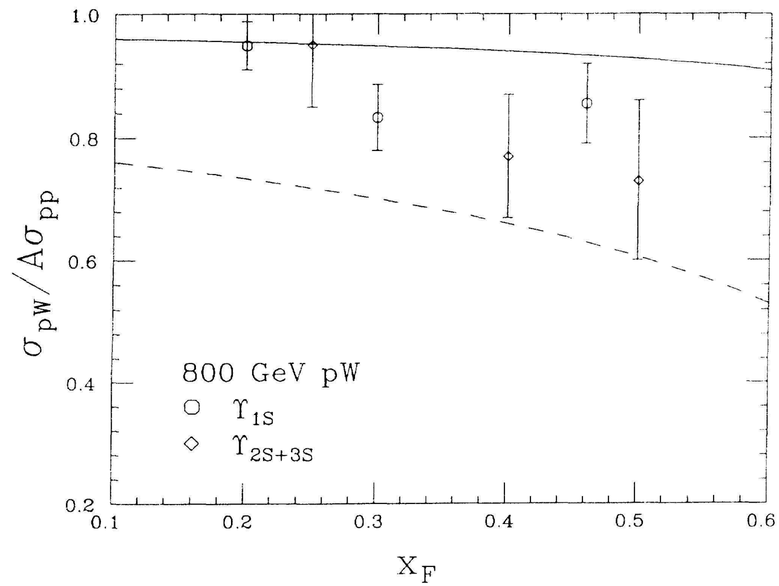
a brief history of $\Delta E_{parton} \propto E$

- Gavin-Milana (1992)
- Brodsky-Hoyer (1993)
- Arleo, S.P., Sami (2010)

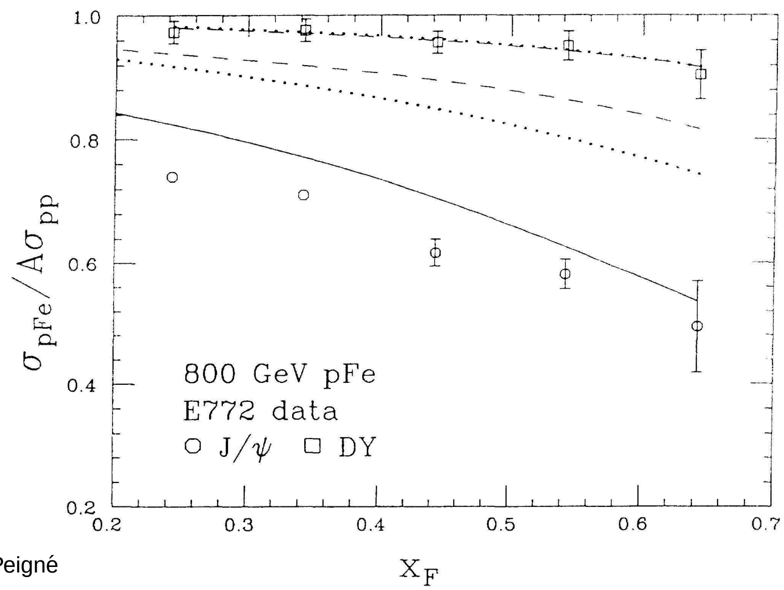
Gavin-Milana (1992): ad hoc $\Delta E \propto E$ for J/ψ *and* DY



$M\uparrow$ $\Longrightarrow$



$\Downarrow$ $L\downarrow$



predictions for
smaller L and larger M
tend to overestimate R_{pA}

$\Rightarrow L$, M dependence

$$\frac{\Delta E}{E} \propto L \cdot \frac{1}{M^2}$$

is too sharp

Brodsky-Hoyer (1993): bound on energy loss?

- look for radiation with $t_f \gg L$ off *asymptotic particle*
- choose $p_\perp^2\big|_{pA} = p_\perp^2\big|_{pp}$ and work in *QED model*
- $\Rightarrow$ find no contribution and conclude:

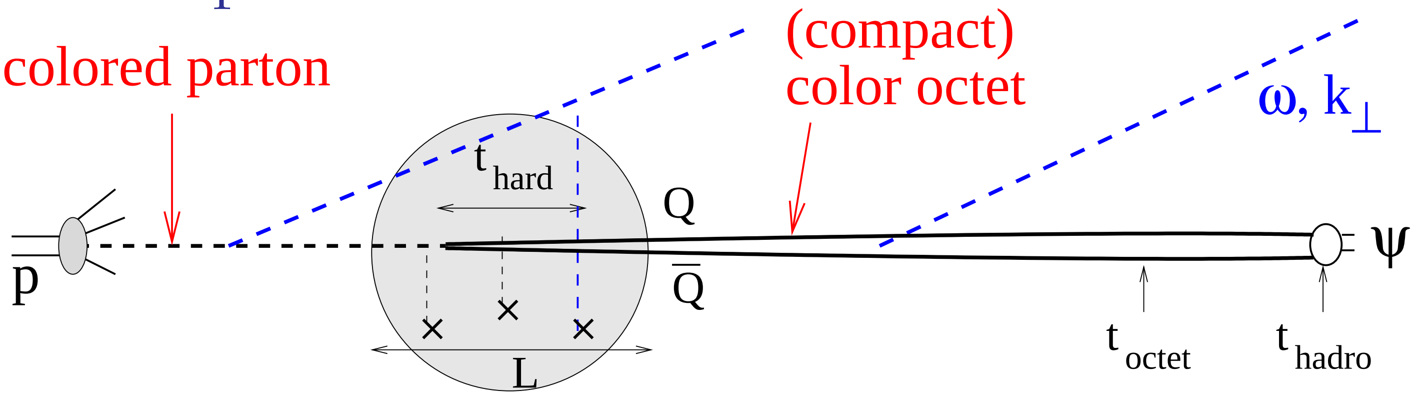
$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \Rightarrow \Delta E \lesssim L\langle k_\perp^2 \rangle \qquad \text{(B-H bound)}$$

$\longrightarrow$ seems to rule out Gavin-Milana phenomenology

- argument fails in QCD: $\Delta E \propto E$ due to fast charge *color rotation* (rather than angular deviation)
- argument fails in QED when $p_\perp^2\big|_{pA} = p_\perp^2\big|_{pp} + \Delta p_\perp^2$
- B-H bound only applies to *particle produced in a medium* (or undergoing large angle scattering)

Arleo, S.P., Sami, 1006.0818 [hep-ph]

large $x_{\rm F} > x_{\rm F}^{critical} \Rightarrow$



- main assumption: $Q\bar{Q}$ pair produced as *color octet* and remains octet for a long time $t_{octet} \gg t_{hard}, L$

true in all J/ψ production models when $x_{\rm F} \nearrow$

$\Rightarrow$ *medium-induced* radiation spectrum

$\sim$ radiation spectrum of "asymptotic color charge"

$$\Rightarrow \omega \frac{dI}{d\omega}\Big|_{ind} = \frac{N_c \alpha_s}{\pi} \left\{ \ln\left(1 + \frac{E^2 \Delta q_\perp^2}{\omega^2 M_\perp^2}\right) - \ln\left(1 + \frac{E^2 \Lambda^2}{\omega^2 M_\perp^2}\right) \right\}$$

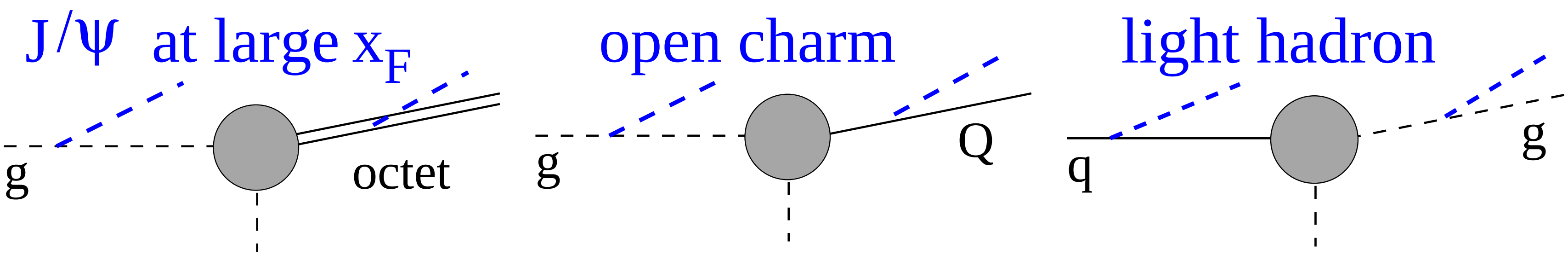
$$\Delta E = \int d\omega\, \omega\, \frac{dI}{d\omega}\Big|_{\rm ind} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2} - \Lambda}{M_\perp} E$$

- large $x_{\rm F} \Rightarrow t_{hard} : t_f : t_{octet} \sim \frac{1}{M} : \frac{1}{\Delta q_\perp} : \frac{1}{\Lambda}$

physical origin of $\Delta E_{J/\psi} \propto E$: *large* $t_f \propto E$

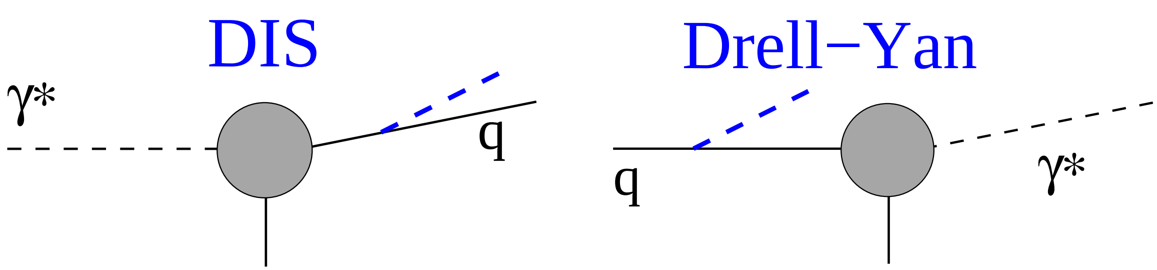
for medium-induced radiation

$\Delta E \propto E$ when color charge is scattered to final state:



$\Delta E \propto E$ neither initial nor final state, but *coherent* effect

- $\Delta E \propto E$ not valid for *incoherent* radiation



$\Rightarrow \Delta E_{cold} \propto L^2$

5. model for J/ψ nuclear suppression

Arleo, S.P., 1204.4609 [hep-ph]

- medium-induced $\Delta E \sim \alpha_s \frac{\Delta q_\perp}{M_\perp} E$
  - collinear-safe
  - suppressed by $1/M_\perp$

    $=$ higher-twist, process dependent

- use *standard recipe* to implement 'higher-twist' loss

$$\frac{\mathrm{d}\sigma_{pA}}{\mathrm{d}x_\mathrm{F}} \sim \int dz\, d\varepsilon\, \frac{d\hat{\sigma}}{dx_\mathrm{F}} \left(\frac{E(x_\mathrm{F})}{z} + \varepsilon \right) P(\varepsilon)\, D(z)$$

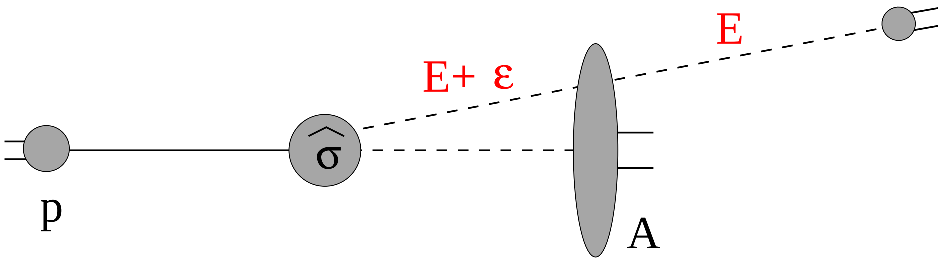
$$P(\varepsilon) = \frac{dI}{d\varepsilon} \exp\left\{ - \int_\varepsilon^\infty d\omega \frac{dI}{d\omega} \right\} = \frac{1}{E} F\left(\frac{\varepsilon}{E}\right)$$

$$\Rightarrow \frac{\mathrm{d}\sigma_{pA}}{\mathrm{d}x_\mathrm{F}} \sim \int dz\, dz'\, \frac{d\hat{\sigma}}{dx_\mathrm{F}} \left(\frac{E(x_\mathrm{F})}{z\, z'} \right) \mathcal{F}_{loss}(z')\, D(z)$$

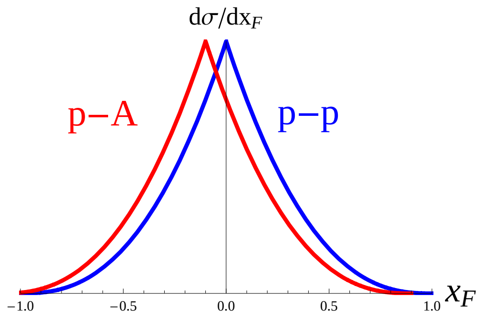
$$\frac{1}{A} \frac{\mathrm{d}\sigma_{pA}}{\mathrm{d}x_\mathrm{F}} = \int \mathrm{d}z'\, \mathcal{F}_{loss}(z')\, \frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}x_\mathrm{F}} \left(\frac{E(x_\mathrm{F})}{z'} \right)$$

$$\frac{1}{A}\frac{\mathrm{d}\sigma_{pA}^{\psi}}{\mathrm{d}x_{\mathrm{F}}}\left(x_{\mathrm{F}}(E)\right) = \int_0^{\varepsilon_{max}} d\varepsilon\, P(\varepsilon)\, \frac{\mathrm{d}\sigma_{pp}^{\psi}}{\mathrm{d}x_{\mathrm{F}}}\left(x_{\mathrm{F}}(E+\varepsilon)\right)$$

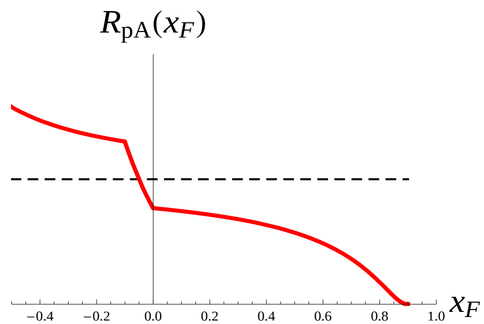
where $\frac{\mathrm{d}\sigma_{pp}^{\psi}}{\mathrm{d}x_{\mathrm{F}}}$ taken from experimental data



$$z' \equiv \frac{E}{E+\varepsilon}$$



$\Rightarrow$



model depends on single parameter $\hat{q}$ (via $\Delta q_\perp^2 = \hat{q}\, L$)

- include saturation effects

$$\hat{q} = \frac{4\pi^2 \alpha_s C_R}{N_c^2 - 1} \rho \, xG(x)$$ Baier et al 97

$$xG(x) \sim x^{-0.3}$$ Golec-Biernat Wusthoff 98

$$Q_s^2 \propto xG(x) \cdot L$$ Mueller 99

$$\Rightarrow Q_s^2(x, L) = \hat{q}(x)\, L$$ Baier 03

  - $\hat{q}(x) = \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$ has smooth x-dependence
  - saturation introduces no additional parameter

- model (i) *without* or (ii) *with* saturation effects:

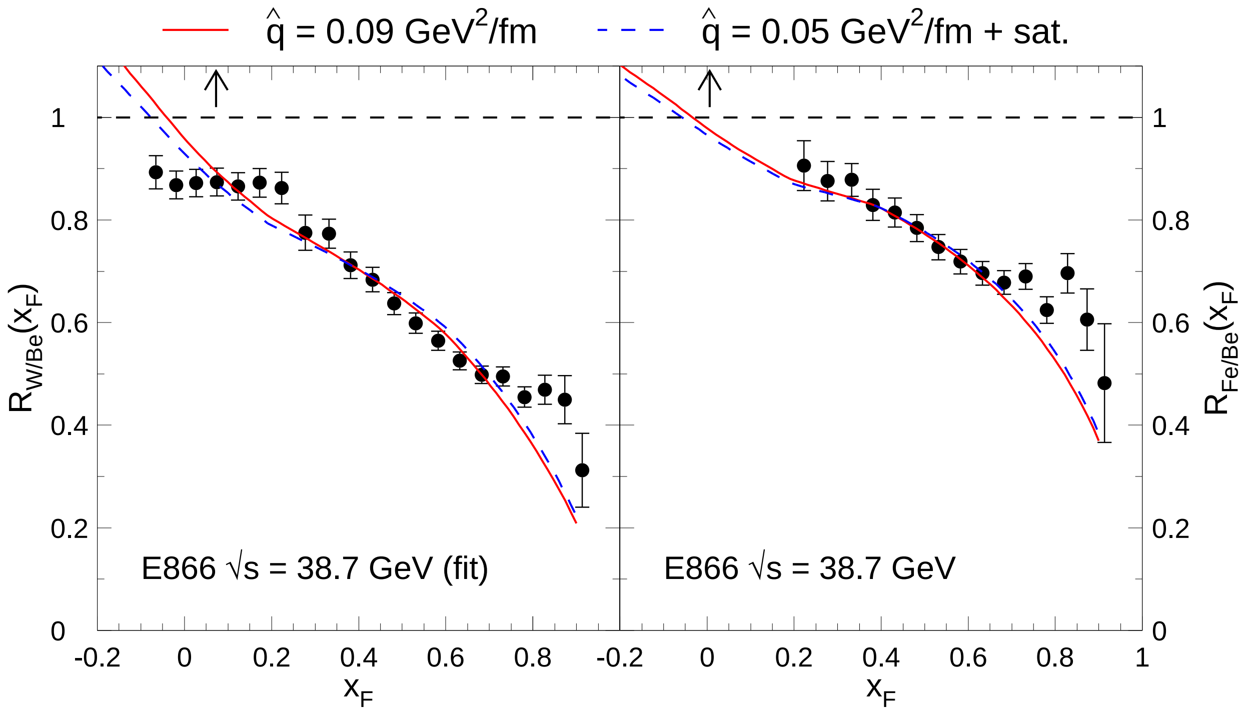
(i) $R_{pA} = R_{pA}^{\text{E.loss}}$ (ii) $R_{pA} = R_{pA}^{\text{E.loss}} \times R_{pA}^{\text{sat}}$

$$R_{pA}^{\text{sat}}(x_2, A) \simeq \frac{a}{(b + Q_s^2(x_2, L))^{\alpha}}$$

CGC effect from Fujii, Gelis, Venugopalan 99

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

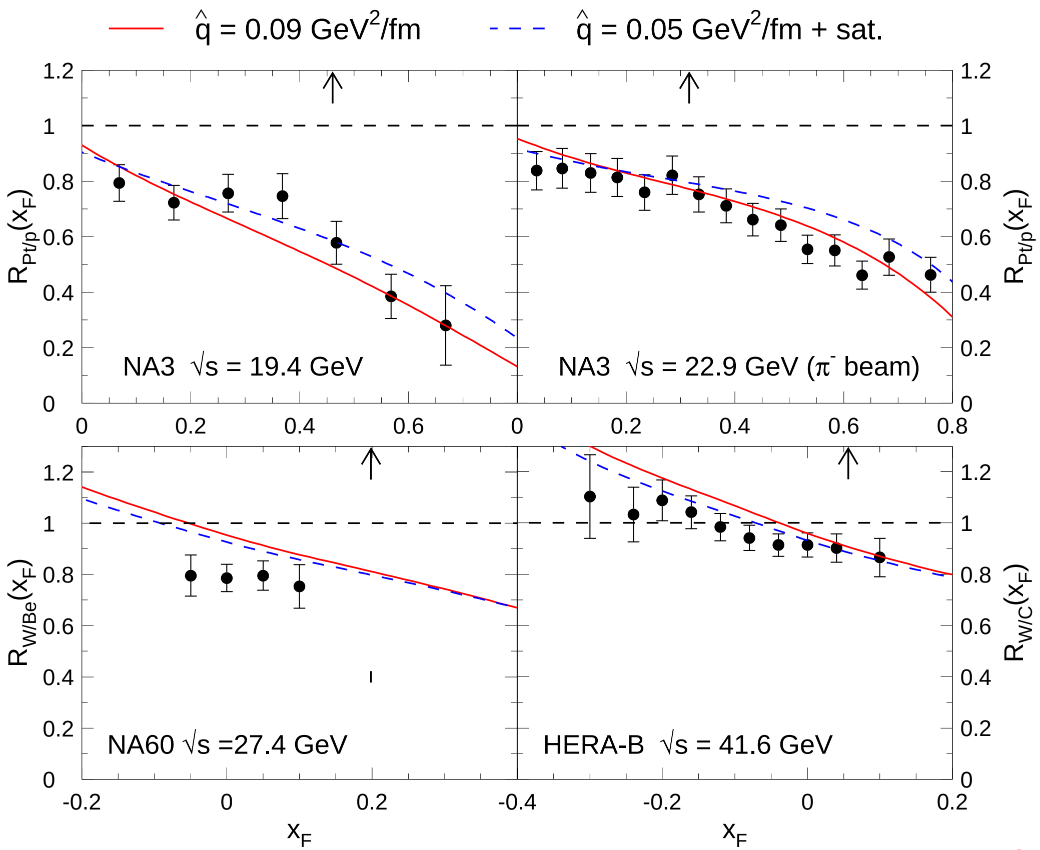
$\Rightarrow$ "predictions" for Fe/Be data



$\Rightarrow$ A-dependence is quite accurate

(E772 Υ data $\Rightarrow$ M-dependence also satisfactory)

J/ψ suppression data at lower $\sqrt{s}$ or lower $x_{\rm F}$

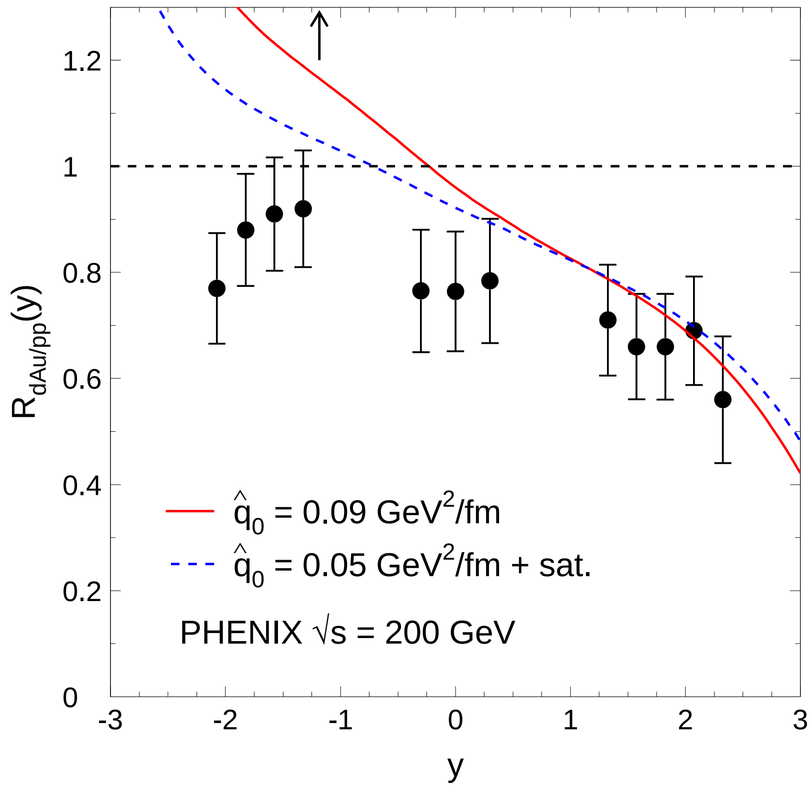


- agreement extends down to $x_{\rm F} < x_{\rm F}^{critical}$

  suggests *energy loss* remains substantial cause of suppression when $t_{hadro} \lesssim L$

- dependence on projectile type is reproduced

large $\sqrt{s}$: J/ψ PHENIX data

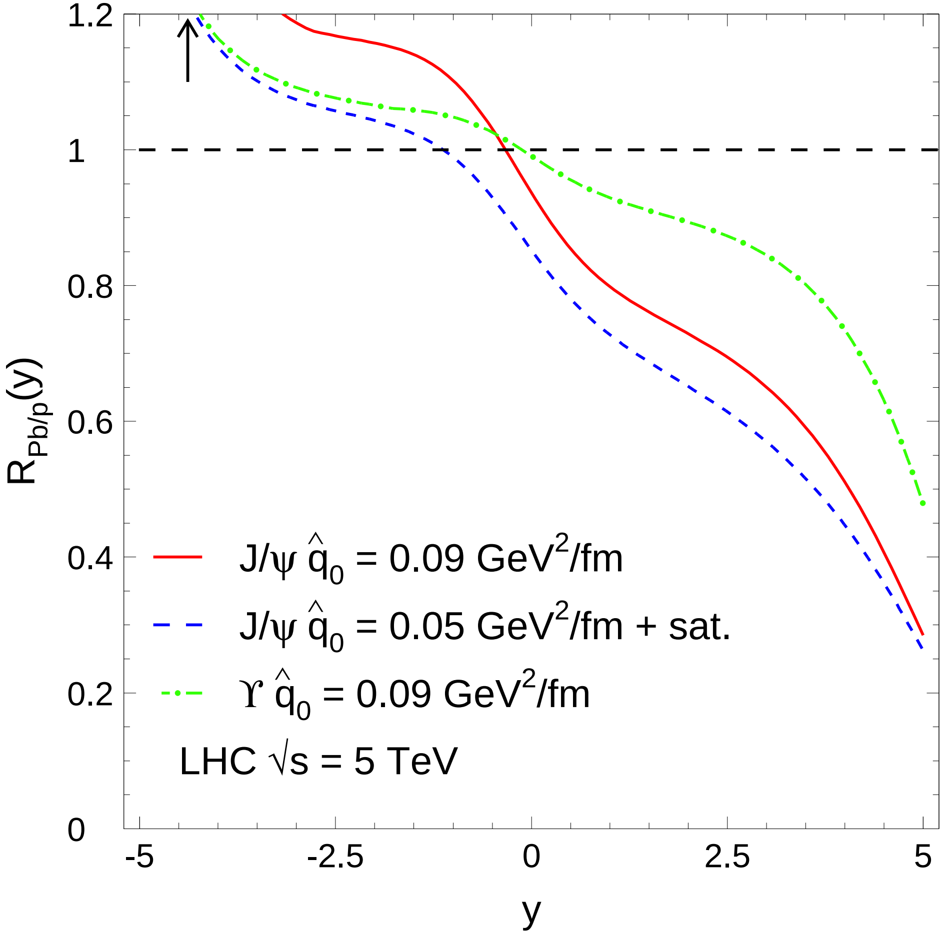


from fixed target to RHIC energies, data is described by:

- "energy loss + saturation" ($\hat{q} = 0.05\,\mathrm{GeV}^2/\mathrm{fm}$)
- "energy loss alone" ($\hat{q} = 0.09\,\mathrm{GeV}^2/\mathrm{fm}$)

saturation alone disagrees with suppression data

predictions for J/ψ and Υ in p-Pb collisions at LHC



huge suppression predicted even at moderate rapidity

(*i.e.*, even at $x_{\rm F} \ll 1$; for J/ψ, $y \lesssim 4 \Leftrightarrow x_{\rm F} \lesssim 0.05$)

summary

- quantitative agreement between data and model *(energy loss with* $\hat{q}_{cold} = 0.05\,\mathrm{GeV}^2/\mathrm{fm}$ + *saturation)* for slope *and* normalization of $R_{pA}(x_\mathrm{F})$ supports:
  - $\Delta E \propto E$ as a dominant effect in p-A suppression
  - parametric dependence of ΔE and $dI/d\omega$
  - assumption of *long-lived color-octet* $Q\bar{Q}$ *pair*
- similar energy loss should explain light hadron and open charm nuclear suppression

energy loss picture can be further tested
in approaching LHC p-A collisions