Quarkonium suppression in p-A collisions from parton energy loss

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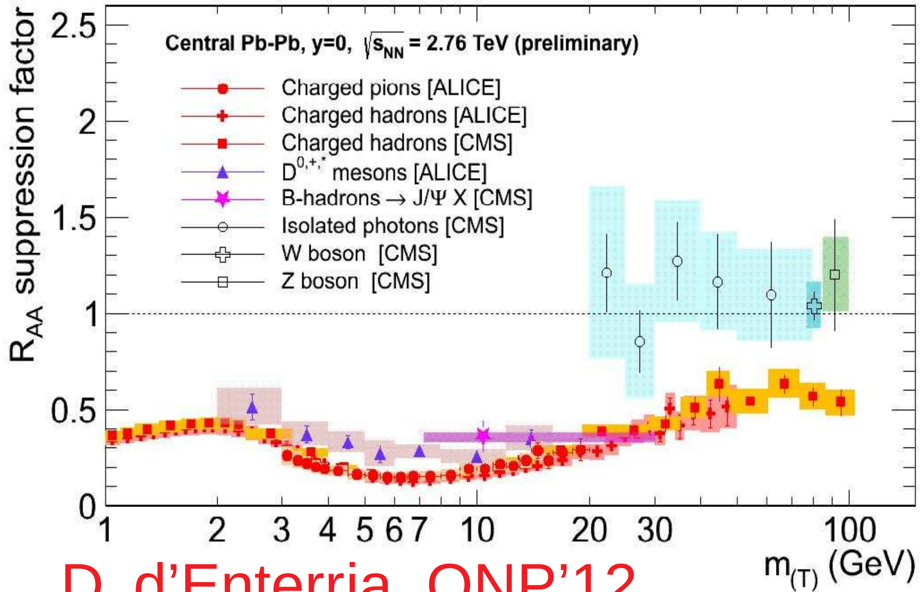
Heavy Quark Production in Heavy-Ion Collisions

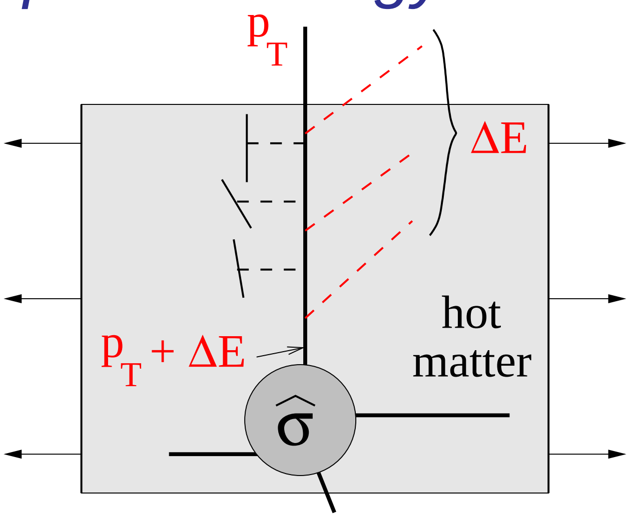
Utrecht, The Netherlands, Nov. 14-17, 2012

1. motivations

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



D. d'Enterria, QNP'12



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

magnitude of R_{AA} can be fitted if

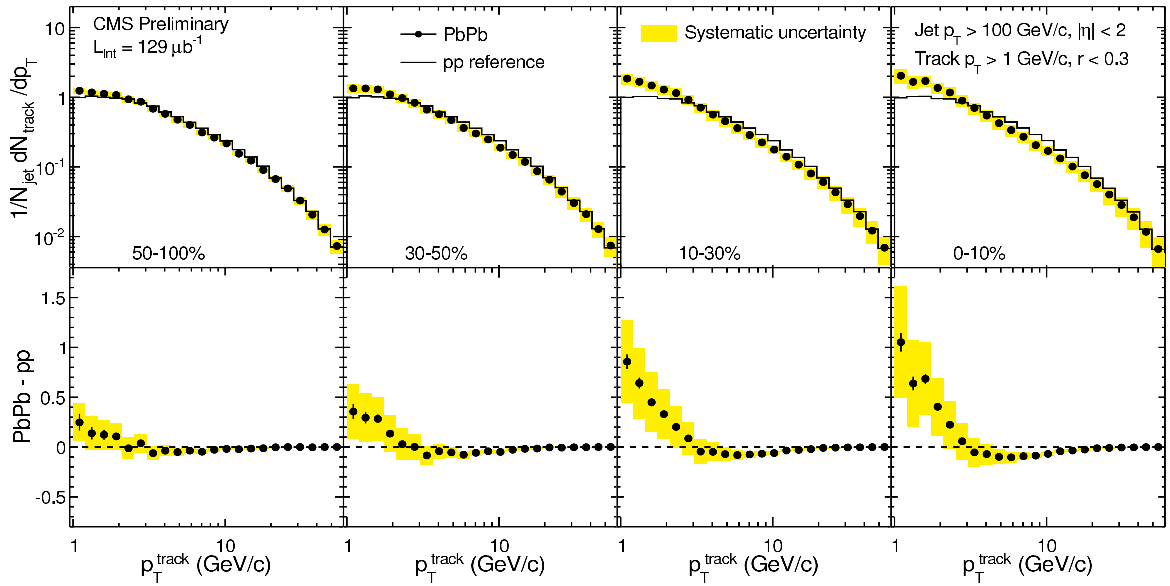
$$\hat{q} \equiv \frac{\mu^2}{\lambda} \sim \hat{q}_{hot} \sim 1\,\mathrm{GeV}^2/\mathrm{fm} \gg \hat{q}_{cold} \sim 0.05\,\mathrm{GeV}^2/\mathrm{fm}$$

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

jet modification in A-A qualitatively consistent with induced gluon radiation predicted by PQCD:

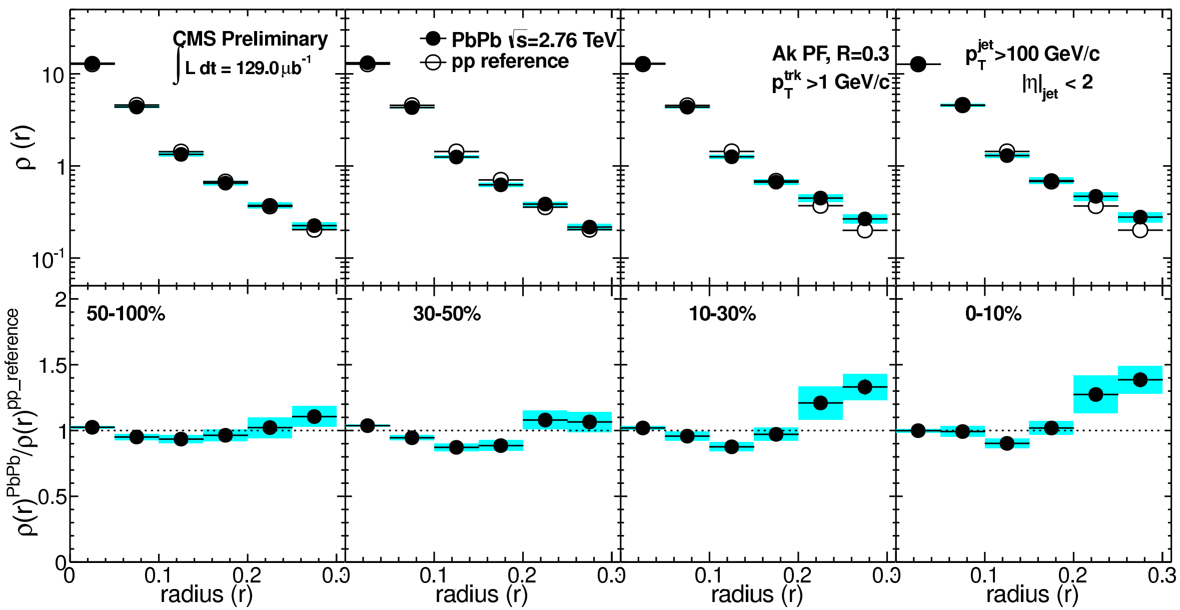
p_T-spectrum of tracks inside jet cone

→ *soft* induced radiation



differential jet shapes

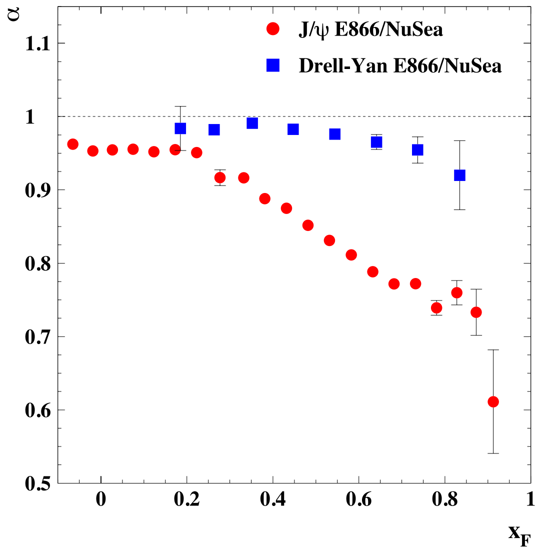
→ *large angle* induced radiation

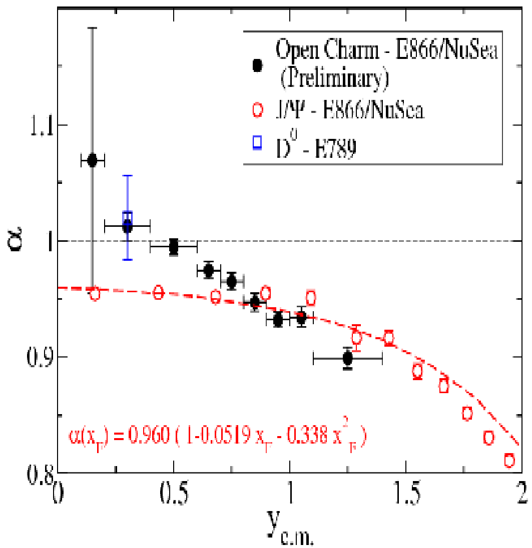


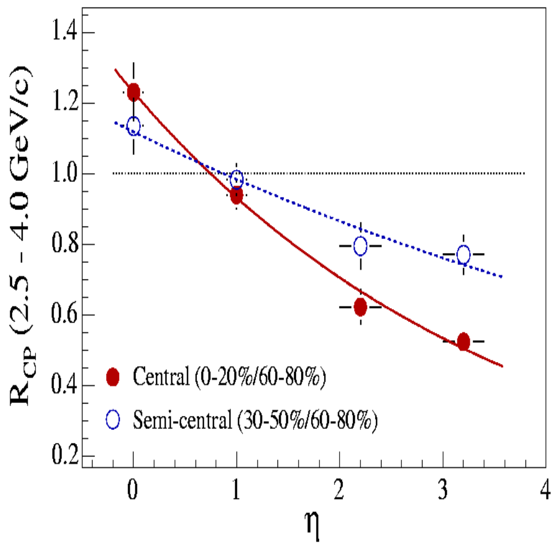
G. Roland, QM'12

- strong nuclear suppression also seen in p-A

J/ψ | open charm | light hadron





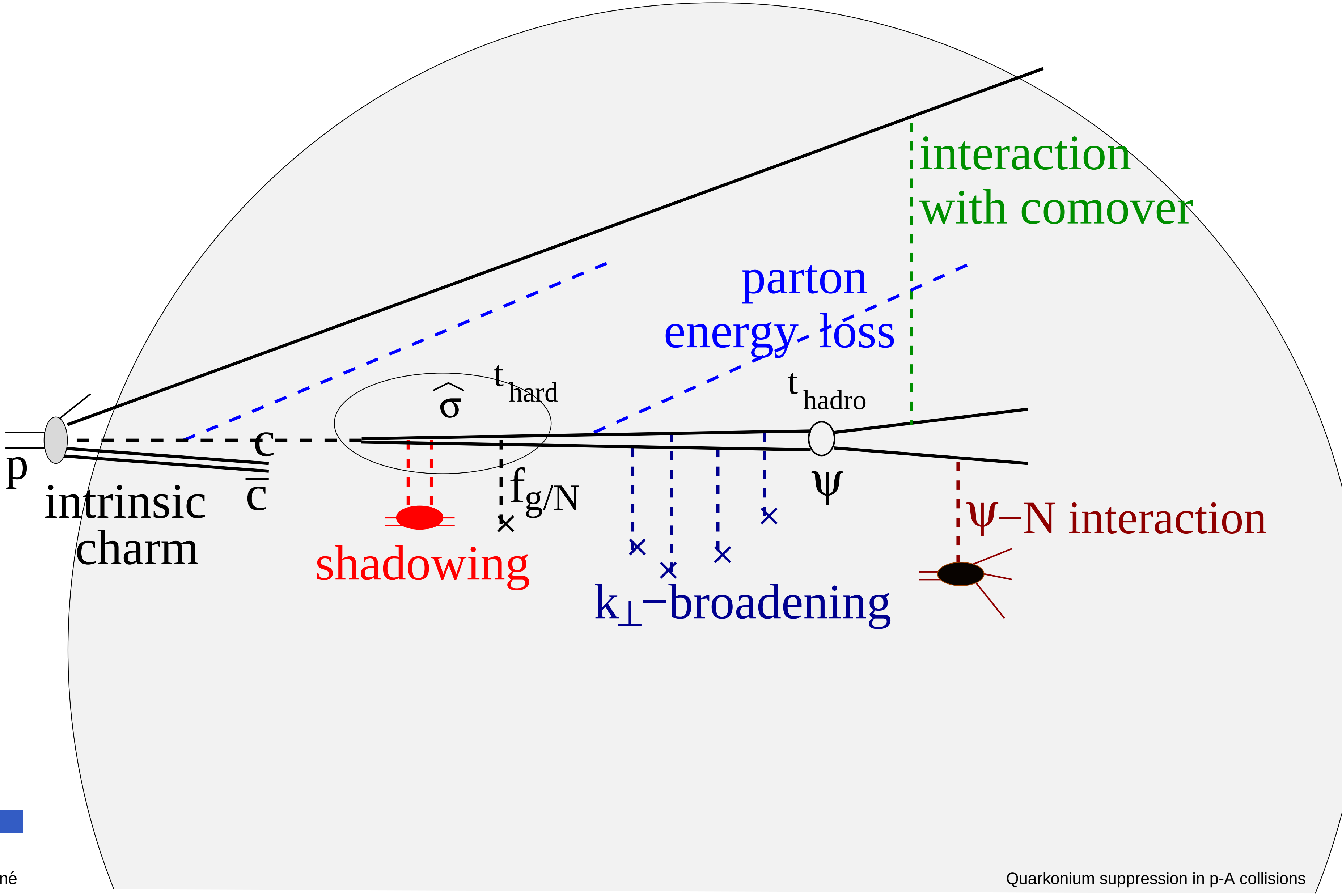


E866/NuSea | BRAHMS

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

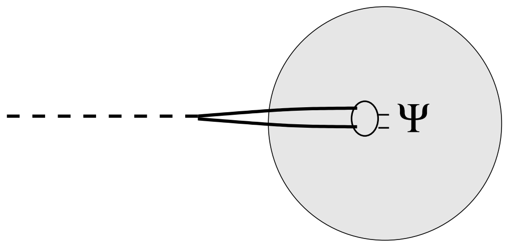
$\Delta E \propto \sqrt{\hat{q}_{cold}}\, E$ *is large* (despite small $\hat{q}_{cold}$)

2. nuclear effects in J/ψ production



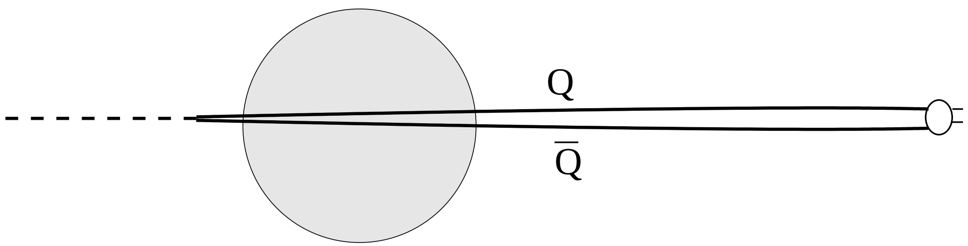
two opposite limits

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



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

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

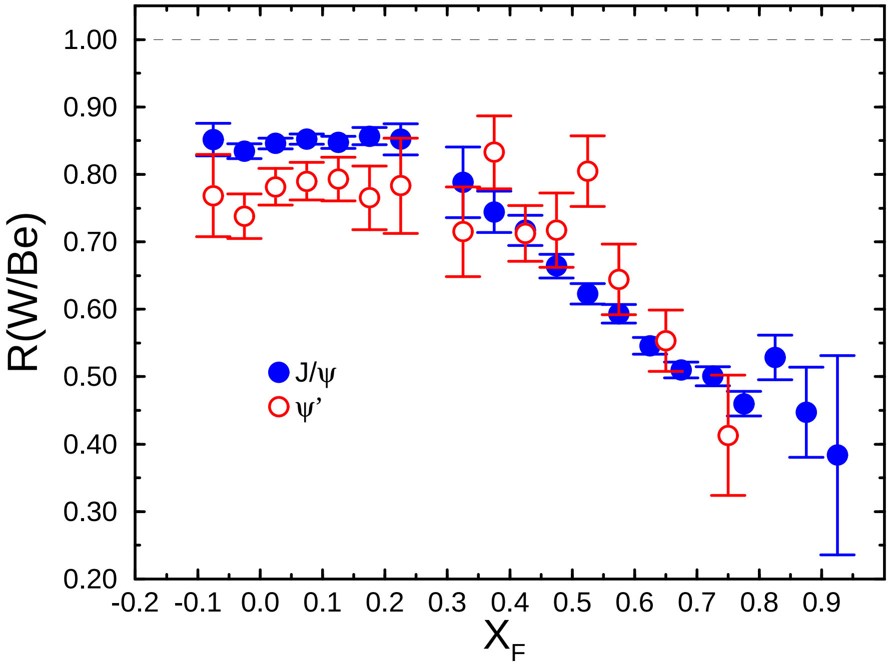


$\longrightarrow$ compact octet $Q\bar{Q}$ ($r_{Q\bar{Q}} \sim 1/M$) through nucleus

$\longrightarrow \sigma_{abs}$ irrelevant

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

J/ψ suppression at large E



E866/NuSea Leitch et al. 99

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

$$t^{\psi}_{hadro} \sim \frac{E(x_{\mathrm{F}})}{M} \cdot \frac{1}{M_{\psi'} - M_{\psi}}$$

$$\Rightarrow x_{\mathrm{F}}^{critical} \simeq 0.1$$

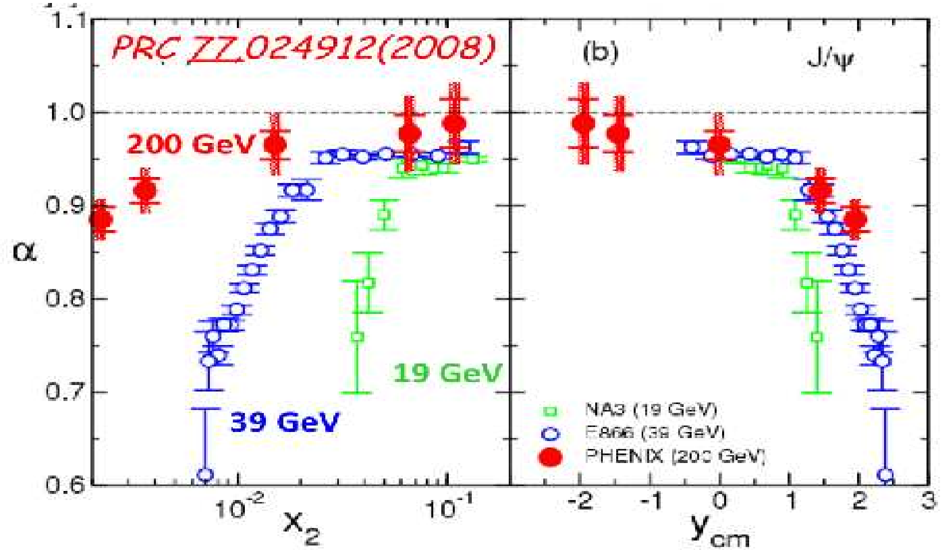
$$x_{\mathrm{F}} = 0.5 \Rightarrow t_{hadro} \sim 40\,\mathrm{fm}$$

$x_{\mathrm{F}} \geq 0.2$ E866 data lies in domain $t_{hadro} > L$

$\rightarrow \sigma_{abs}$ is irrelevant, as confirmed by data:

- suppression $\nearrow$ with x_{F} (when $c\bar{c}$ more compact!)
- $R^{\psi'} \simeq R^{J/\psi}$ (also suggests no comover interaction)

- another hint: J/ψ suppression does not scale in x_2



M. Leitch

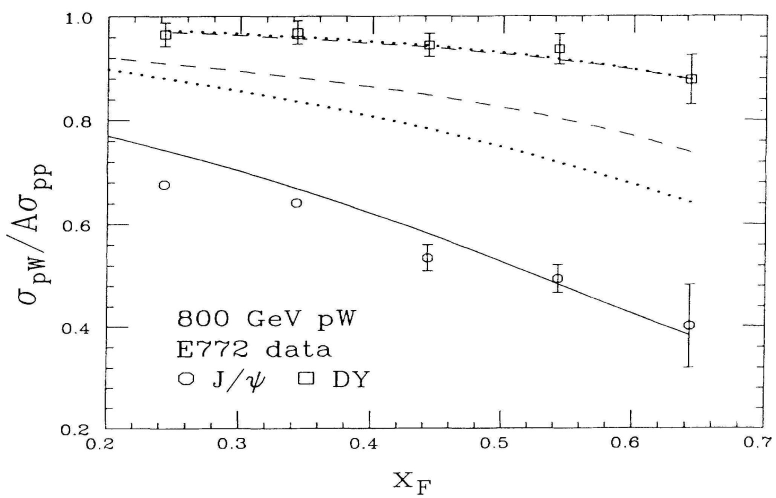
$\Rightarrow$ shadowing (nPDFs) should be a minor effect

- remaining effects
  - parton energy loss
  - saturation

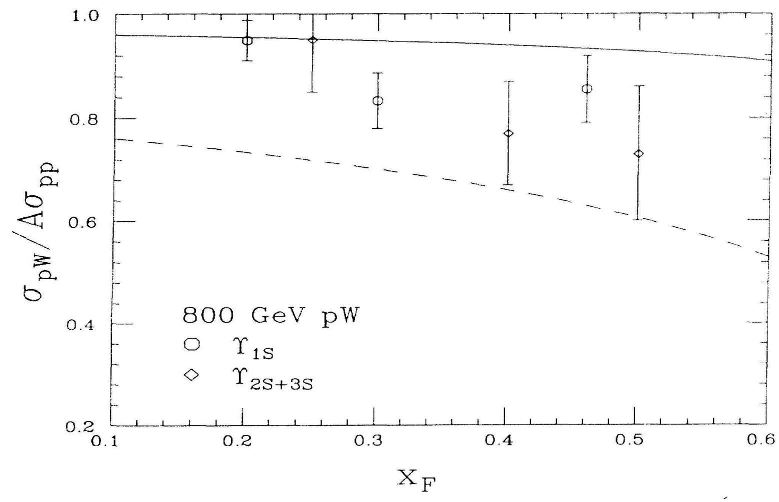
(intrinsic charm not discussed here)

3. $\Delta E_{J/\psi} \propto E$: a brief history

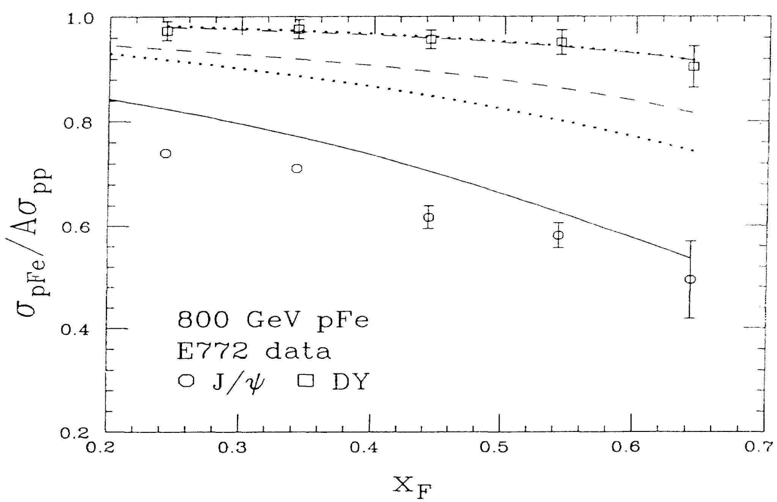
Gavin-Milana (1992): ad hoc $\Delta E_{J/\psi} \propto E \Rightarrow$ fits $R_{\rm pW}^{J/\psi}$ ...



$M\uparrow$
$\Longrightarrow$



$\Downarrow$ $L\downarrow$



...but predicted R_{pA}
at smaller L or larger M
exceeds the data $\Rightarrow$

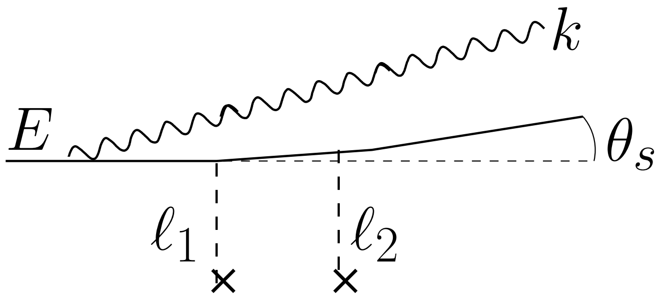
L, M dependence

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

seems too sharp

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

- consider asymptotic charge in *QED* model:



assume $\theta_s|_{\rm pA} = \theta_s|_{\rm pp}$
and formation time $t_f \gg L$

- $\Rightarrow$ find no contribution and conclude:

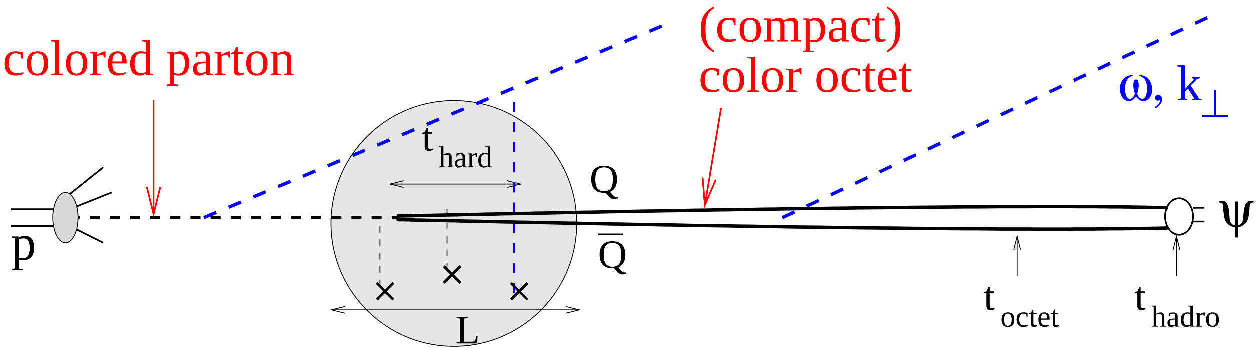
$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \Rightarrow \Delta E \lesssim L\langle k_\perp^2 \rangle \qquad \text{(B-H bound)}$$

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

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

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

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



- 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 $x_{\rm F} \nearrow$)

  $t_{hard}, L \ll t_f \ll t_{octet} \Rightarrow$ *medium-induced* radiation
  $\sim$ radiation off “asymptotic color charge”

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

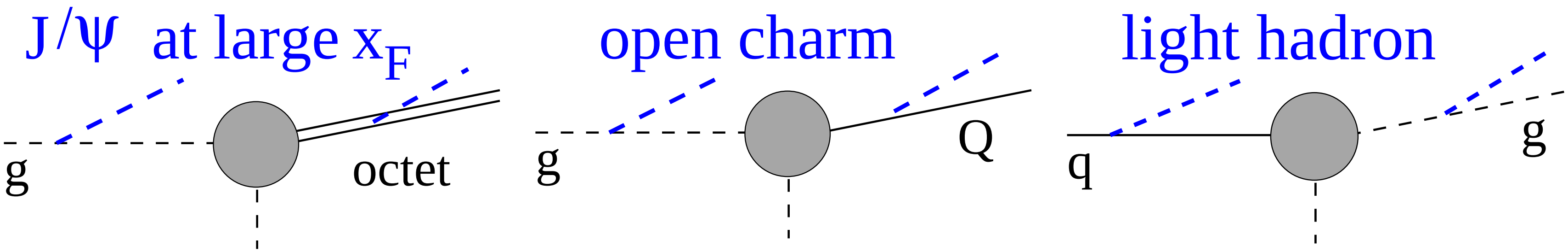
$$\Delta E = \int d\omega\, \omega\, \frac{dI}{d\omega}\Big|_{\rm ind} = N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2} - \Lambda}{M_\perp} E \propto E \sqrt{L/M^2}$$

- check: $r_\perp(t_f) \ll 1/k_\perp$; $\quad t_{hard} : t_f : t_{octet} \sim \frac{1}{M} : \frac{1}{\Delta q_\perp} : \frac{1}{\Lambda}$

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

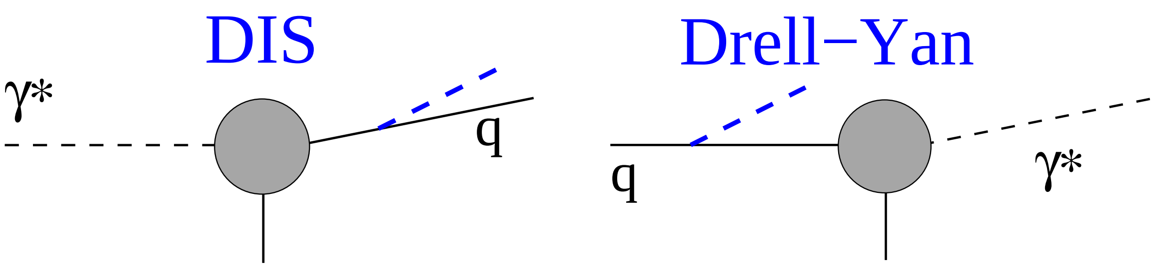
medium-induced radiation with *large* $t_f \propto E$

$\Delta E \propto E$ 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



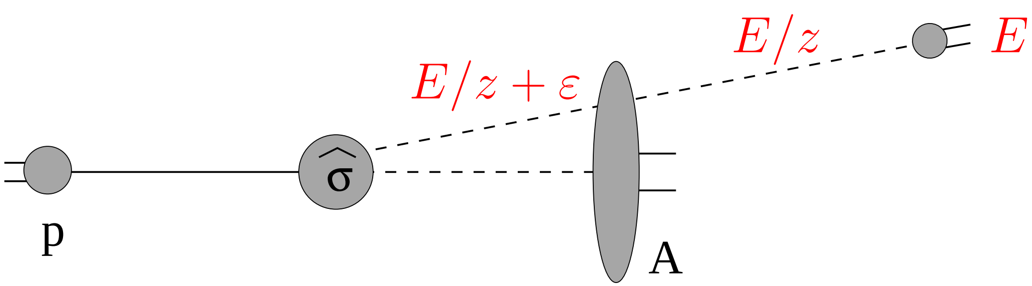
$\Rightarrow \Delta E_{cold} \propto L^2$

4. model for J/ψ nuclear suppression

Arleo, S.P., PRL 109 (2012) 122301

- medium-induced $\Delta E \sim \alpha_s \frac{\Delta q_\perp}{M_\perp} E$ is *higher-twist*:
  - collinear-safe, process dependent
  - suppressed by $1/M_\perp$
- use *standard recipe* to implement 'higher-twist' loss

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



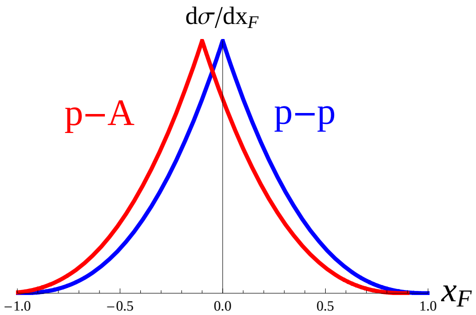
$$z' \equiv \frac{E/z}{E/z+\varepsilon}$$

$$P(\varepsilon, E) = \frac{1}{E} F\left(\frac{\varepsilon}{E}\right) \Rightarrow \frac{\mathrm{d}\sigma_{pA}}{\mathrm{d}x_{\mathrm{F}}} \sim \int dz\, dz'\, \frac{d\hat{\sigma}}{dx_{\mathrm{F}}}\left(\frac{E(x_{\mathrm{F}})}{z\, z'}\right) \mathcal{F}_{loss}(z')\, D(z)$$

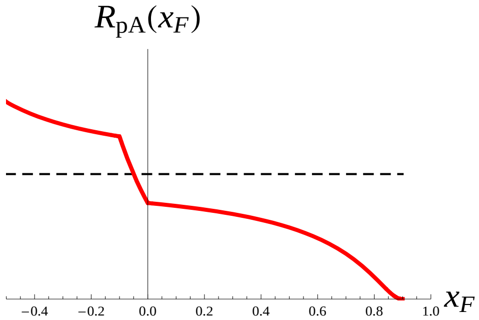
$$\frac{1}{A}\frac{\mathrm{d}\sigma_{pA}}{\mathrm{d}x_{\mathrm{F}}} = \int \mathrm{d}z'\, \mathcal{F}_{loss}(z')\, \frac{\mathrm{d}\sigma_{\mathrm{pp}}}{\mathrm{d}x_{\mathrm{F}}}\left(\frac{E(x_{\mathrm{F}})}{z'}\right)$$

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

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



$\Longrightarrow$



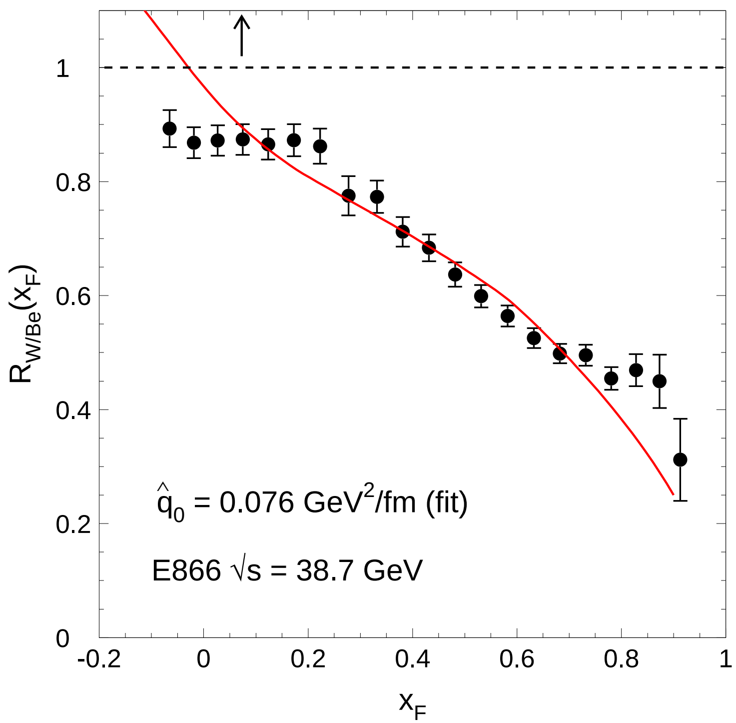
model depends on single parameter $\hat{q}$ (via $\Delta q_{\perp}^2 = \hat{q}\, L$)

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

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

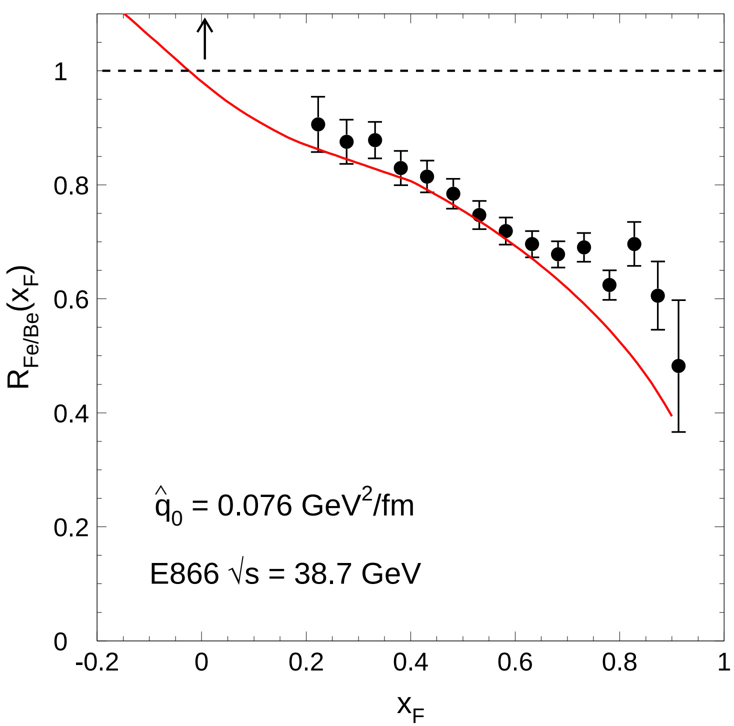
$\hat{q} = \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3}$ has smooth x-dependence

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

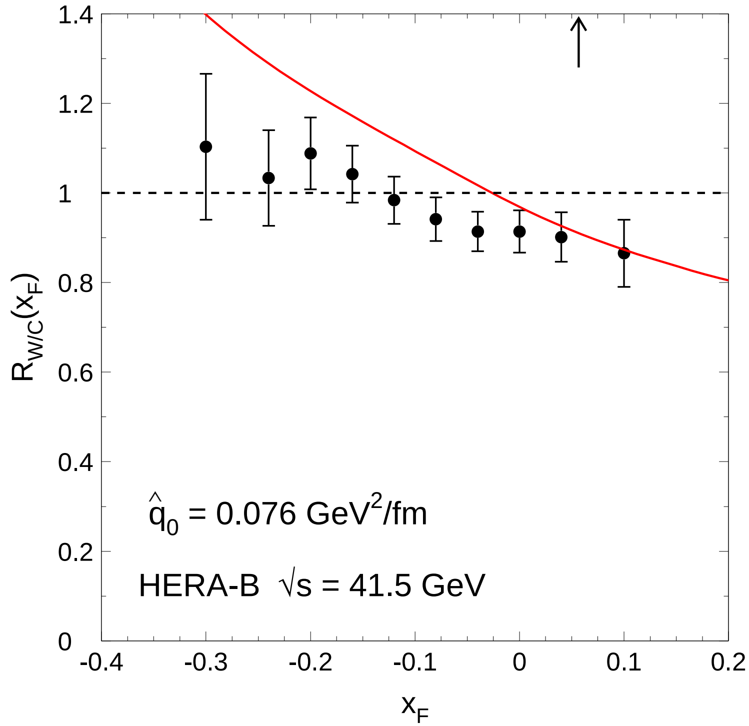


$$\hat{q}_0 \simeq 0.08\,\mathrm{GeV}^2/\mathrm{fm}$$

predictions for suppression at fixed-target energies



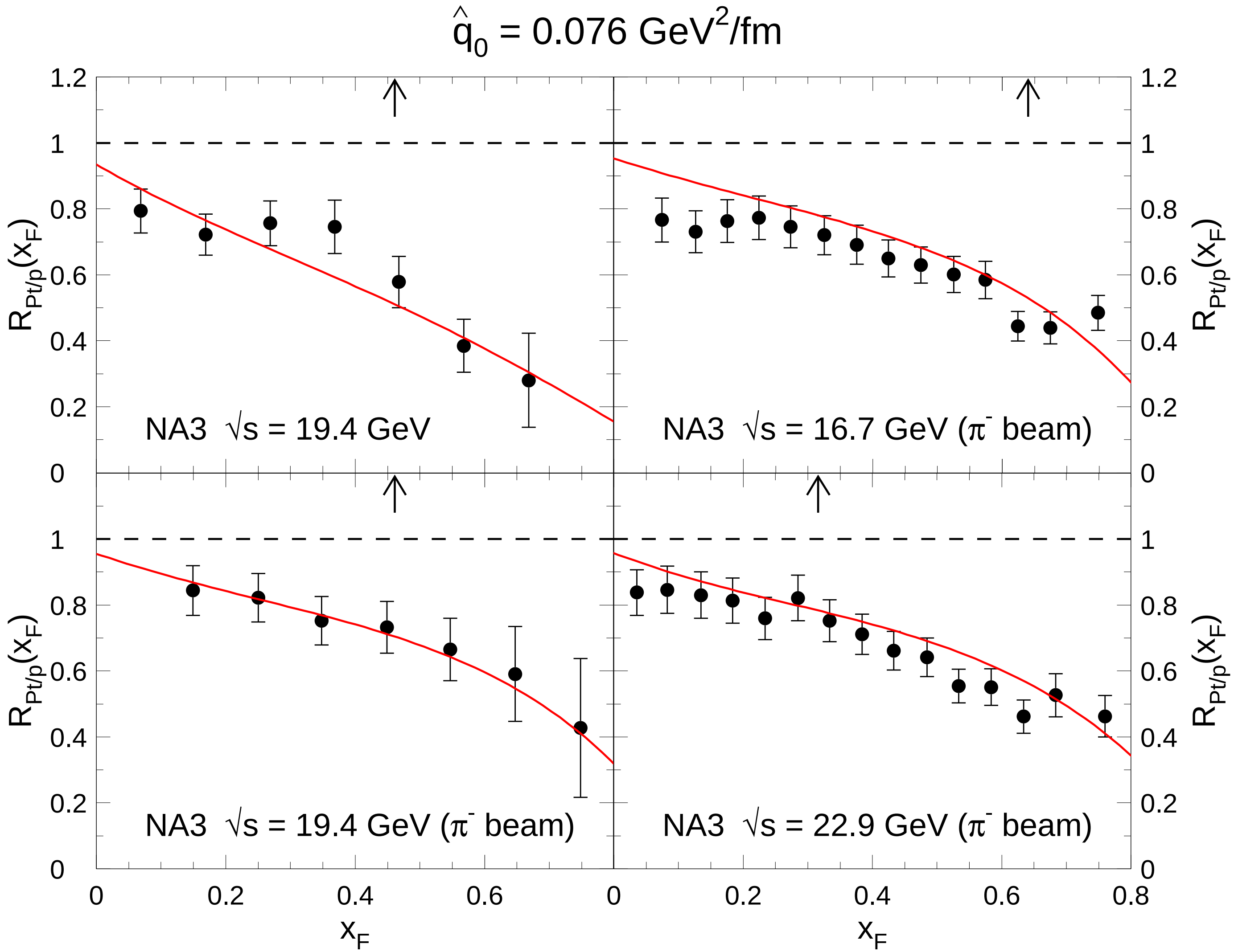
J/ψ E866 Fe/Be



J/ψ HERA-B W/C

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

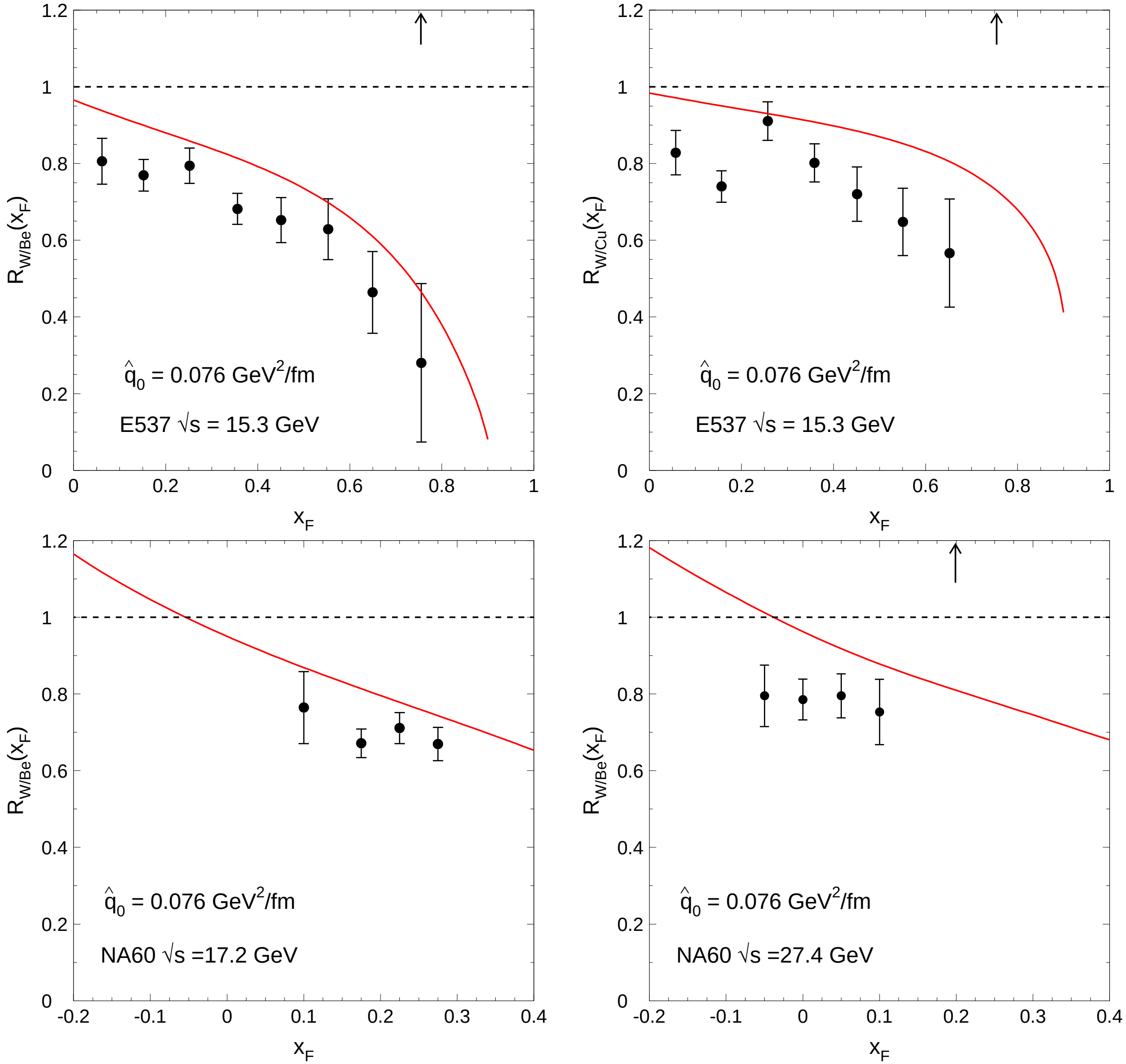
suggests *energy loss* remains substantial even when $t_{hadro} \lesssim L$


$\hat{q}_0$ = 0.076 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

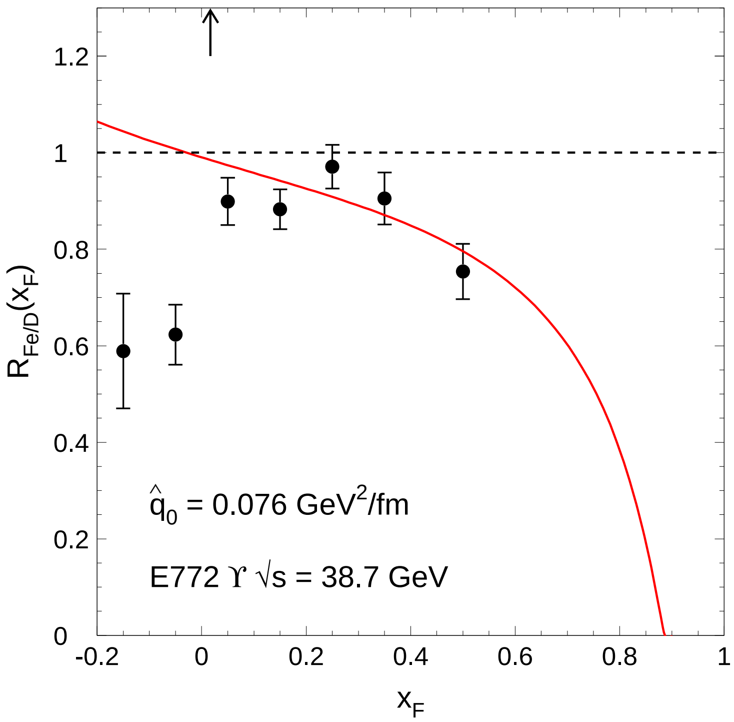
J/ψ NA3 Pt/p

J/ψ E537

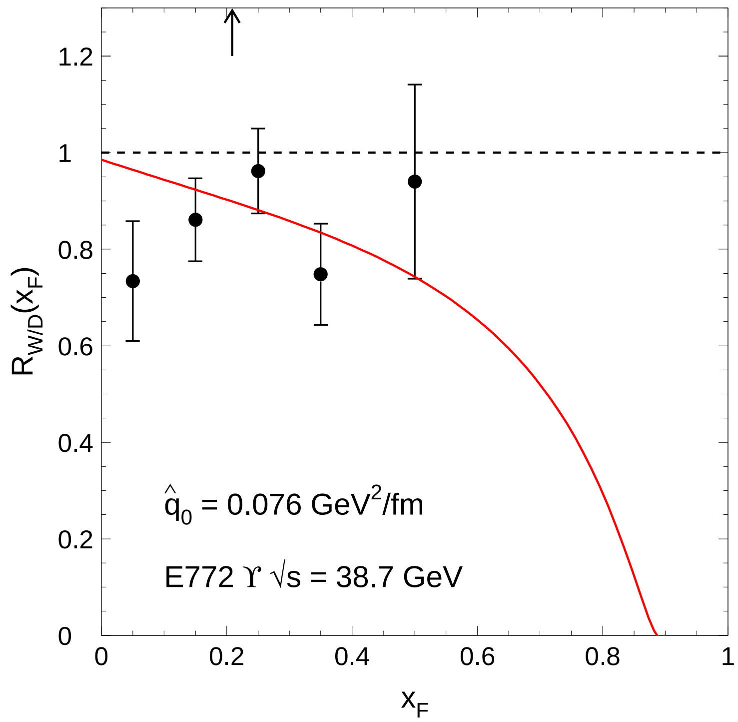
J/ψ NA60



Υ nuclear suppression



Υ E772 Fe/d



Υ E772 W/d

J/ψ and Υ suppression at collider energies

- RHIC, LHC: saturation effects come into play

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

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

saturation introduces no additional parameter

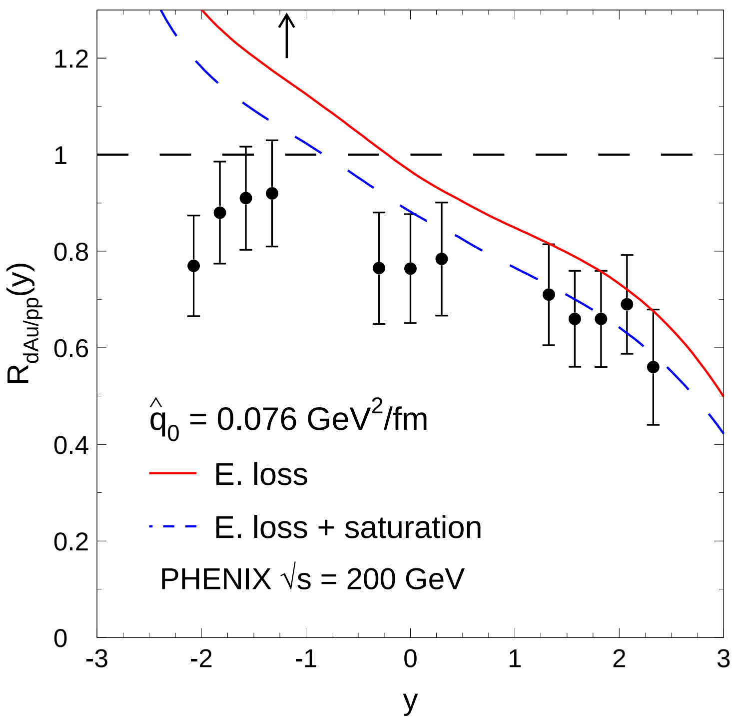
- energy loss (i) *without* or (ii) *with* saturation:

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

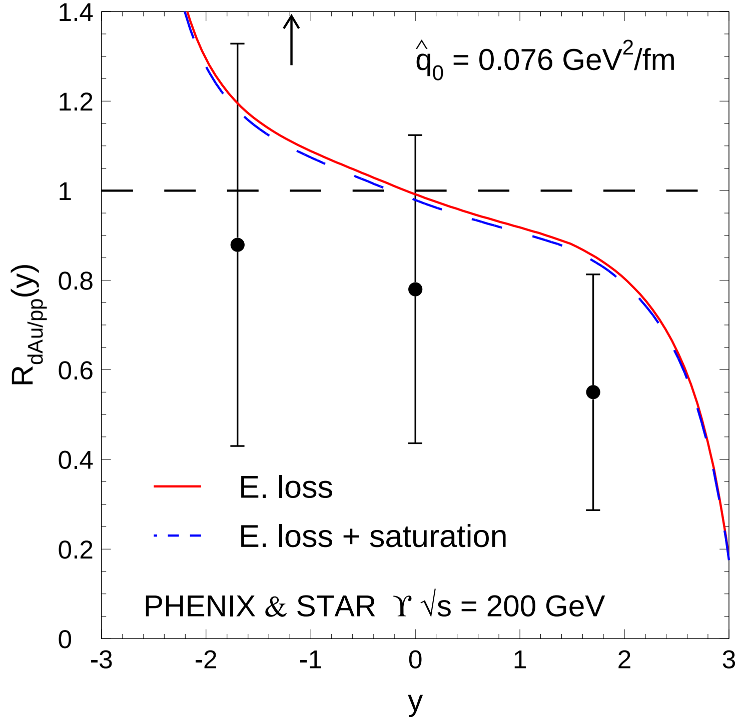
$$R_{pA}^{\mathrm{sat}}(x_2, A) \simeq \frac{a}{(b+Q_s^2(x_2,L))^{\alpha}}$$

CGC effect from Fujii, Gelis, Venugopalan 06

RHIC

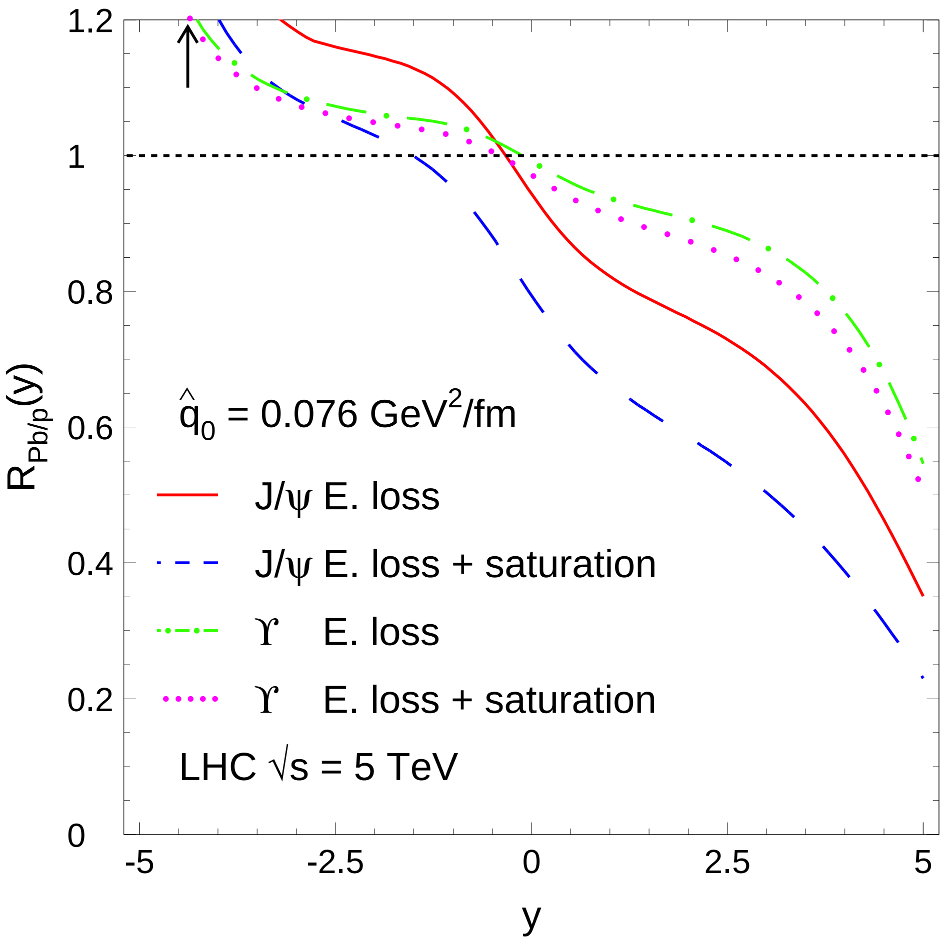


J/ψ PHENIX



Υ PHENIX & STAR

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



huge suppression predicted even at moderate rapidity
(*i.e.*, even at $x_F \ll 1$)

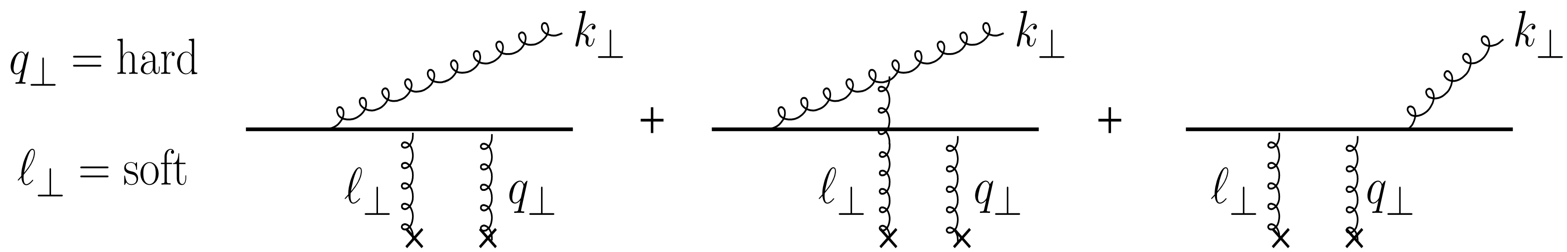
summary

- from fixed-target to RHIC, J/ψ suppression data can be described by *parton energy loss* alone
  - saturation alone does not explain fixed-target data
  - adding saturation to energy loss improves agreement with RHIC data
- good agreement between data and model supports:
  - $\Delta E \propto E$ as *the* dominant effect in p-A suppression
  - assumption of *long-lived* color-octet $Q\bar{Q}$ pair

dominance of energy loss can be further tested

in coming LHC p-A collisions

- parametric dependence of ΔE (and $dI/d\omega$) arises from true PQCD calculation ($\omega \ll E$, $t_f \gg L$, t_{hard})



$\Rightarrow$ *induced* radiation:

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\Big|_{\mathrm{ind}} \equiv \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}(q_\perp; \ell_\perp) - \omega \frac{\mathrm{d}I}{\mathrm{d}\omega}(q_\perp; \ell_\perp = 0)$$

- $\Delta E \sim$ energy loss of “asymptotic color charge”
- $\Delta E \sim$ higher-twist effect, previously overlooked

$\rightarrow$ should have implications on other processes:
open charm, light hadron production in p-A collisions