Cold Nuclear Effects in J/ψ Production

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Talk based on

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

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

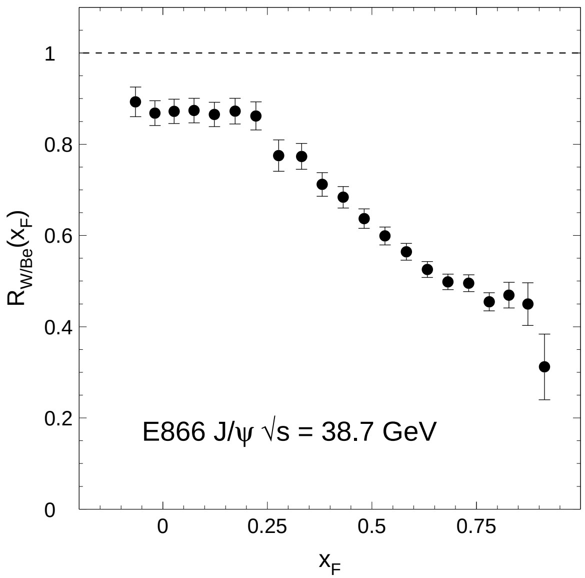
Arleo, S.P., JHEP 1303 (2013) 122

Arleo, Kolevatov, S.P., Rustamova, arXiv:1304.0901

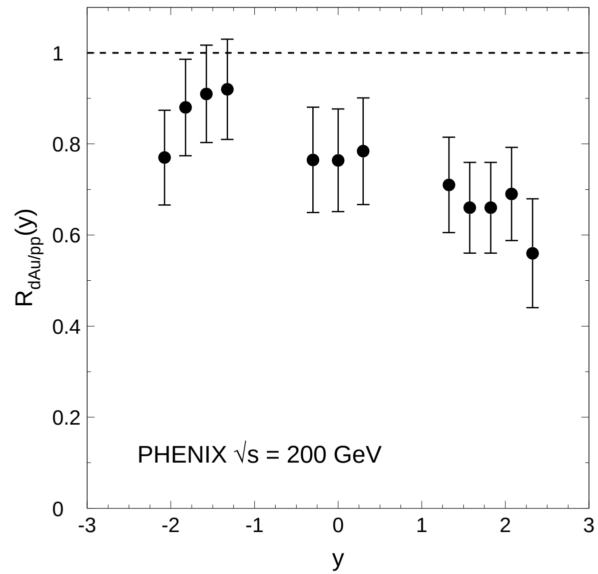
introduction

- strong nuclear suppression in p–A

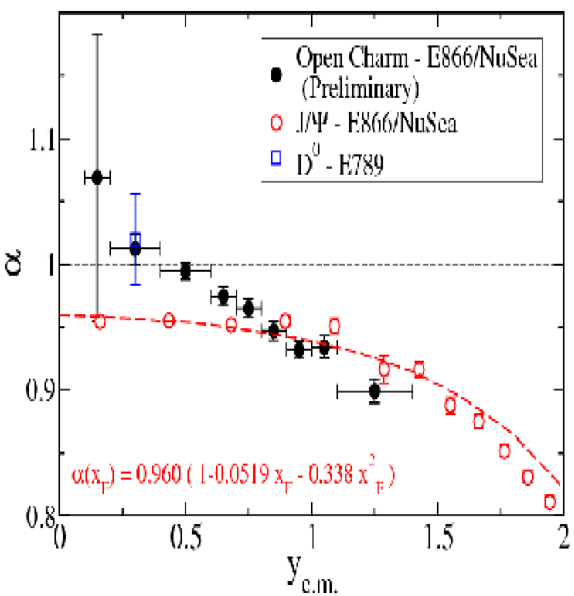
J/ψ
E866



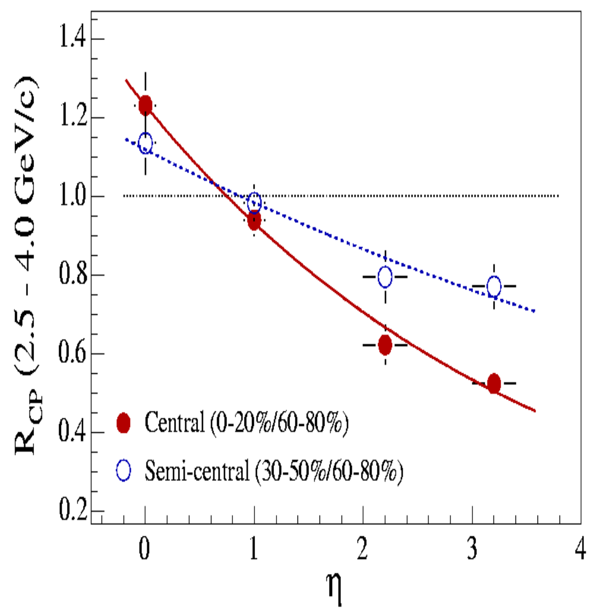
J/ψ
PHENIX



open
charm
E866



light
hadron
BRAHMS

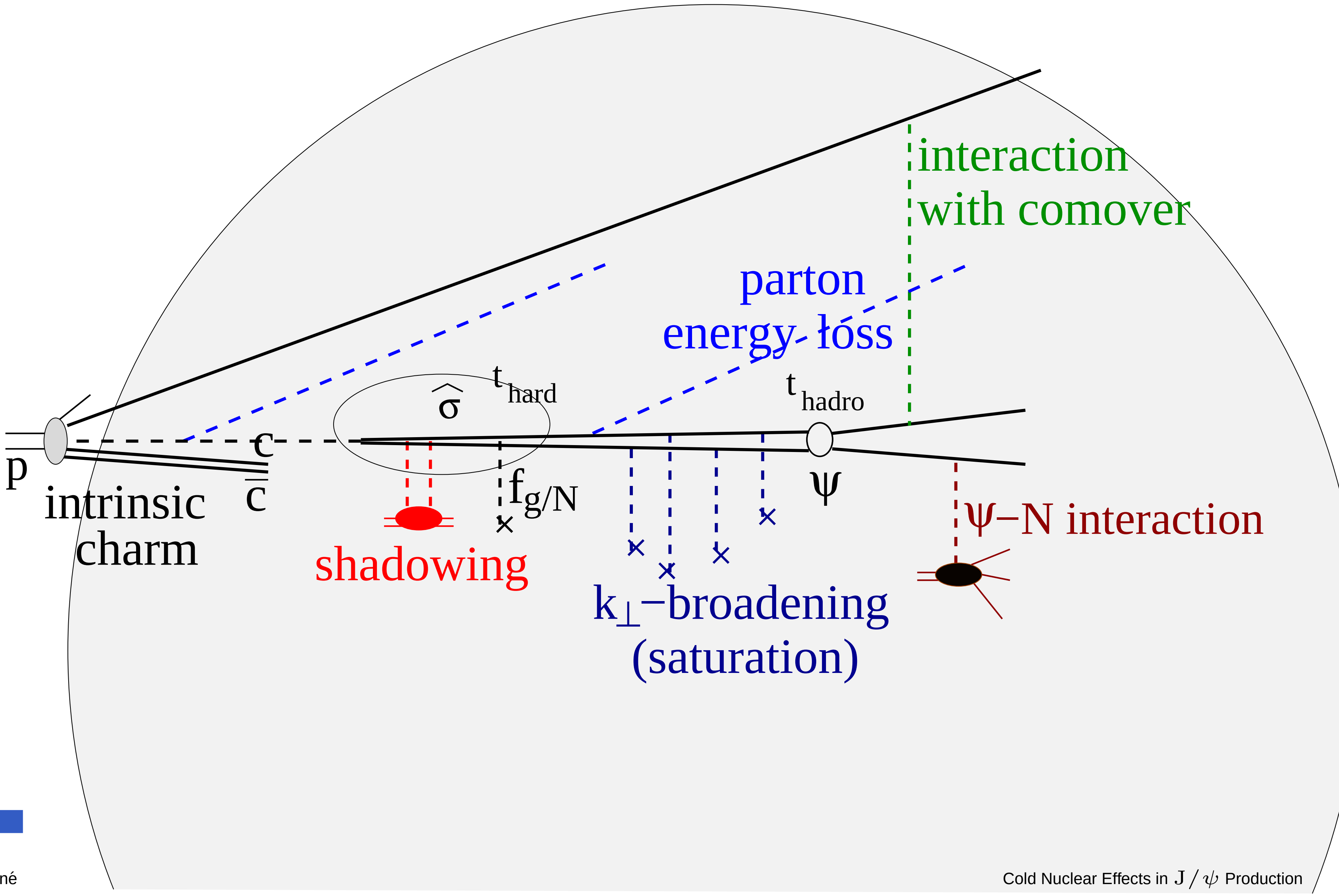


- understanding $R_{pA} = \frac{1}{A} \cdot \frac{\sigma_{pA}}{\sigma_{pp}}$ is crucial
  - disentangle various *cold* nuclear effects
  - prerequisite for hadron suppression in A-A
- focus here on quarkonium production
  - intrinsic hard scale $M = M_{Q\bar{Q}} \sim 3\,\mathrm{GeV}$
  - rich data for nuclear suppression

main message of this talk:

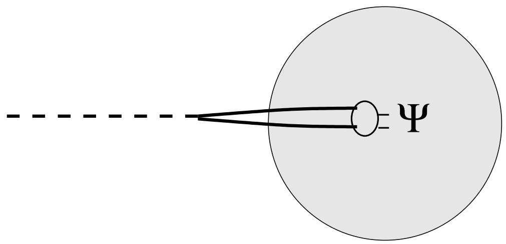
J/ψ nuclear suppression in p–A
arises dominantly from
parton energy loss through nucleus

J/ψ suppression: qualitative features



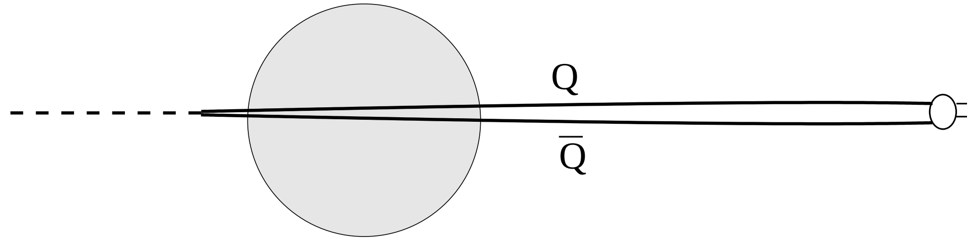
two opposite limits

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



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

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

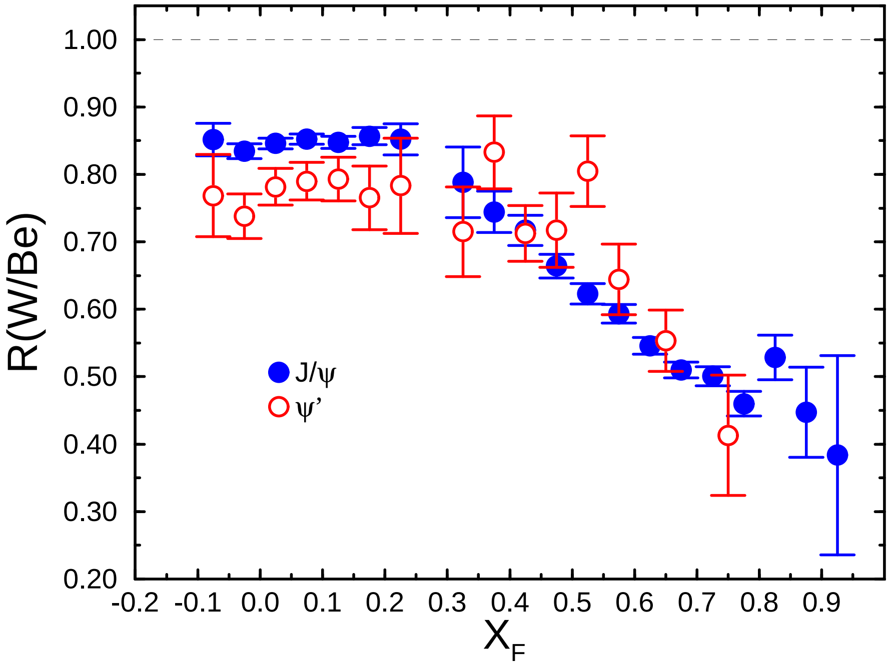


$\longrightarrow$ compact octet $Q\bar{Q}$ ($r_{Q\bar{Q}} \sim 1/M$) through nucleus

$\longrightarrow \sigma_{abs}$ irrelevant

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

J/ψ suppression at large E



E866/NuSea Leitch et al. 99

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

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

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

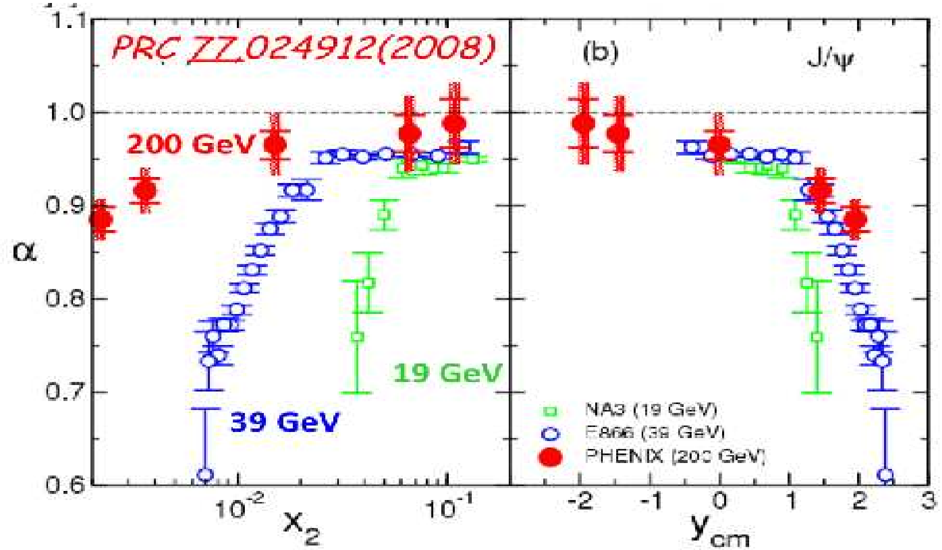
$$(x_\mathrm{F} = 0.5 \Rightarrow t_{hadro} \sim 40\,\mathrm{fm})$$

$x_\mathrm{F} \geq 0.2$ 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!)
- $R^{\psi'} \simeq R^{\mathrm{J}/\psi}$ (also suggests no comover interaction)

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



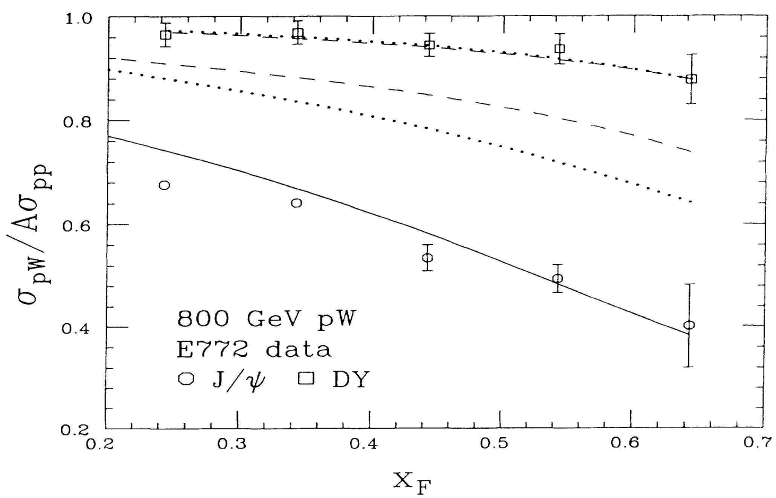
M. Leitch

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

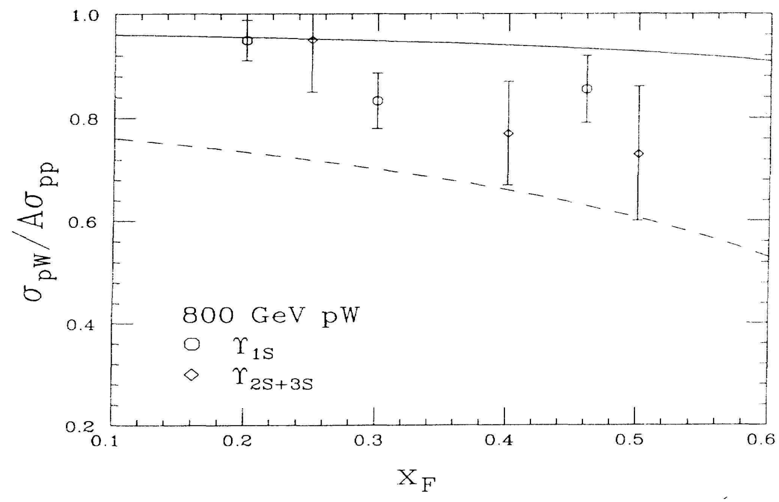
- remaining effects
  - parton energy loss
  - $k_\perp$-broadening (saturation)

$\Delta E_{\mathrm{J}/\psi}$: a brief history

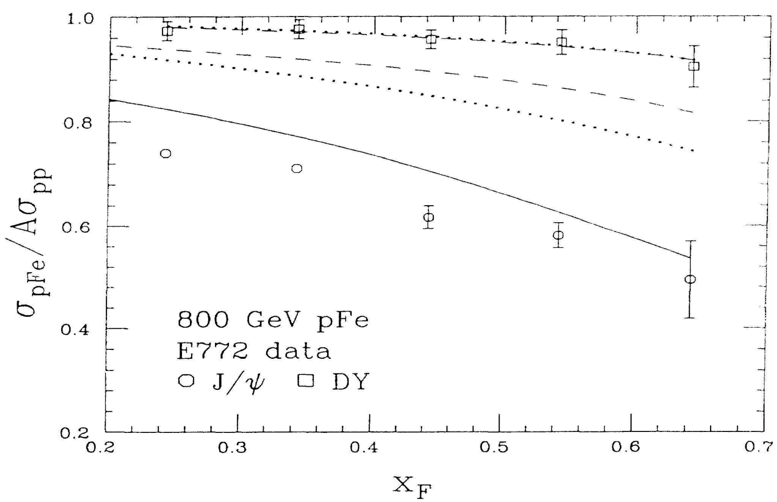
Gavin-Milana 92: ad hoc $\Delta E \propto E \Rightarrow$ fits $R_{\mathrm{pW}}^{\mathrm{J}/\psi}$...



$M\uparrow$ $\Longrightarrow$



$\Downarrow$ $L\downarrow$



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

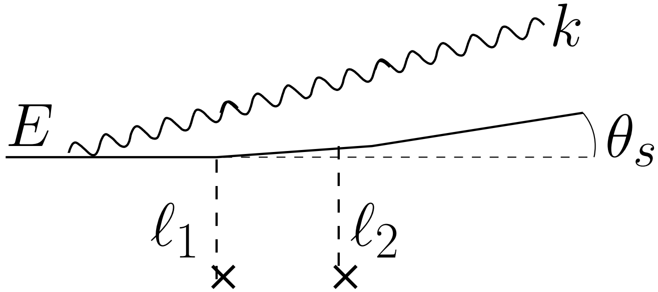
L, M dependence

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

seems too sharp

Brodsky-Hoyer 93: bound on energy loss?

- B-H consider asymptotic charge in QED model:



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

$\Rightarrow$ find no medium-induced radiation and conclude:

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

$\longrightarrow$ seems to rule out Gavin-Milana assumption $\Delta E \propto E$

- B-H argument fails in QED when $\theta_s|_{\mathrm{pA}} > \theta_s|_{\mathrm{pp}}$
- argument fails in QCD:

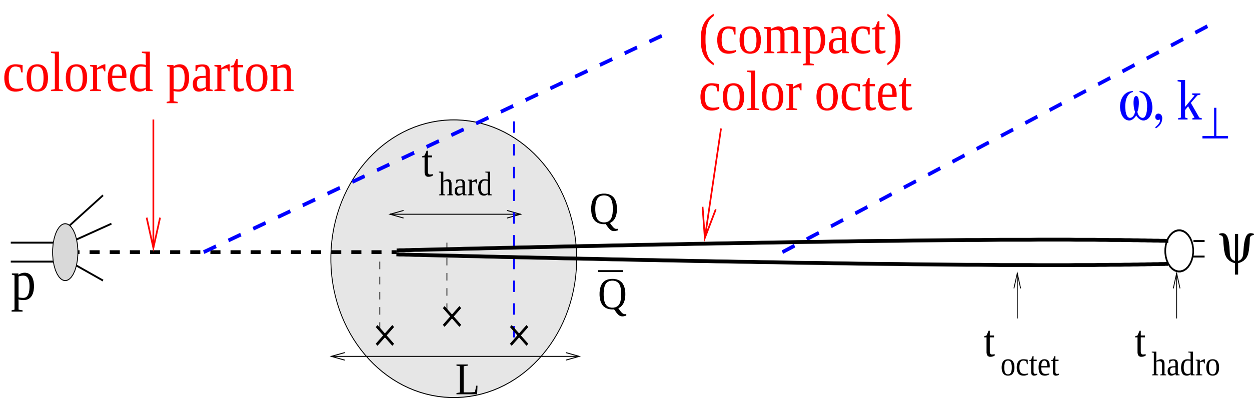
$\Delta E \propto E$ due to *charge color rotation*

(see: Gunion Bertsch 82)

$\Delta E_{\mathrm{J}/\psi}$ revisited

Arleo, S.P., Sami (2011)

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



- assumption: $Q\bar{Q}$ remains *color octet* and *compact* ($r_\perp \sim 1/M$) during time $t_{octet} \gg t_{hard}, L$

(true in CEM, COM... but should be more general)

$\Rightarrow \omega \frac{dI}{d\omega}\Big|_{ind} \sim$ radiation off "asymptotic color charge"

$$\Delta E_{ind} \sim N_c \alpha_s \frac{\sqrt{\Delta q_\perp^2}}{M_\perp} E \propto E \sqrt{L/M^2}$$

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

model for J/ψ suppression

Arleo, S.P., JHEP 1303 (2013) 122

- 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 way to implement 'higher-twist' loss

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

($\frac{\mathrm{d}\sigma^{\psi}_{pp}}{\mathrm{d}x_{\mathrm{F}}}$ taken from p–p data)

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

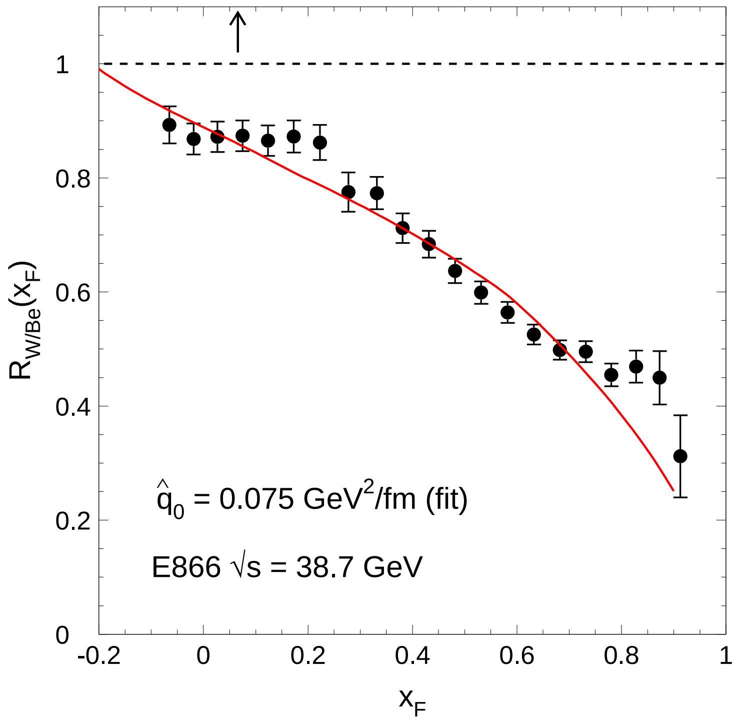
$$\hat{q} = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\,\rho\, xG(x)$$ Baier et al 97

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

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

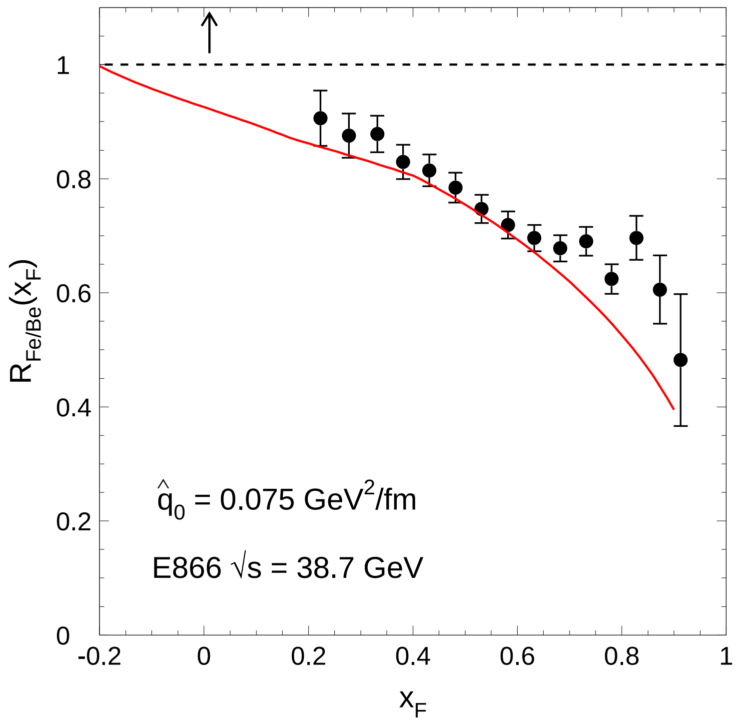
J/ψ suppression from fixed-target to collider energies

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



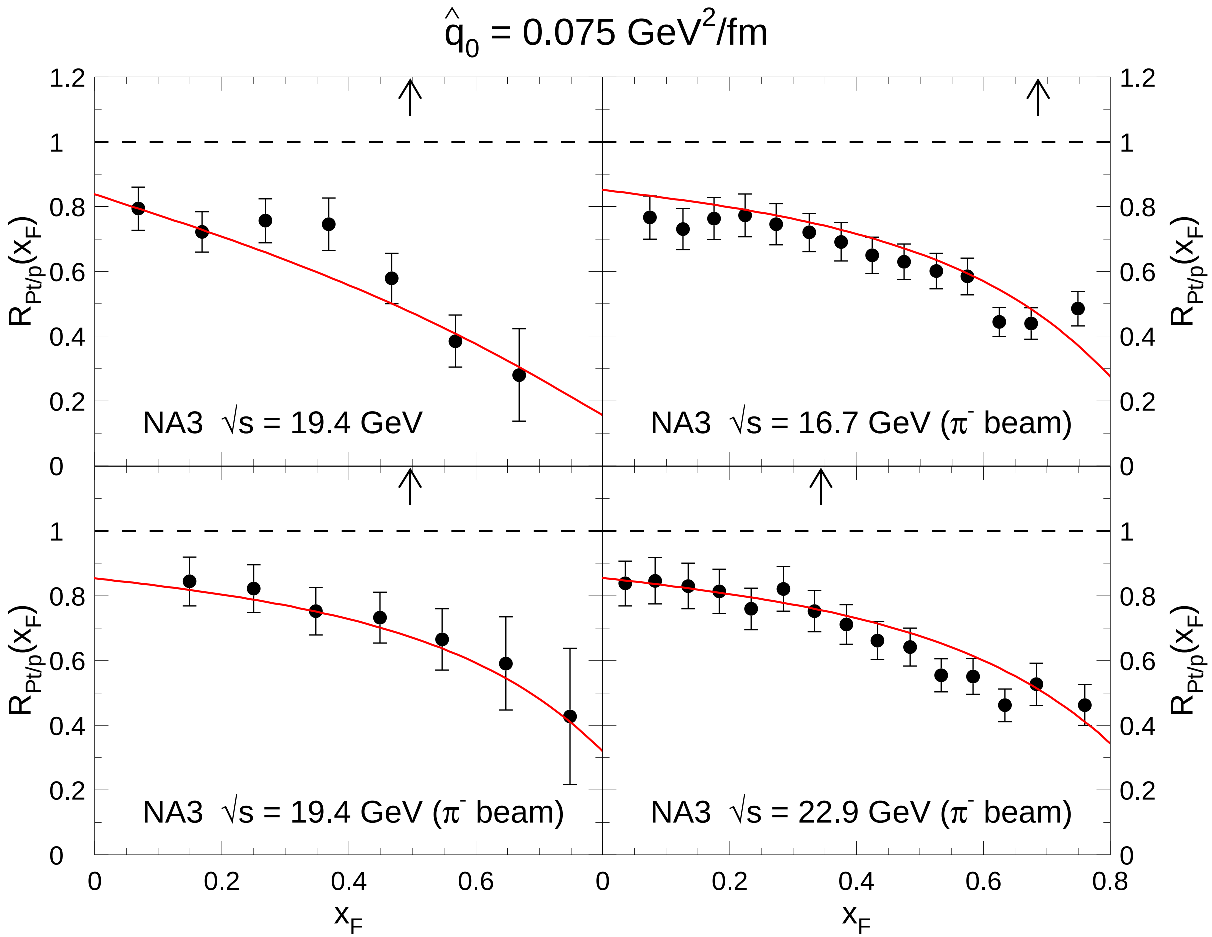
...and used to predict $R_{\rm pA}^{J/\psi}$ for other A, $\sqrt{s}$

E866 Fe/Be



A–dependence well reproduced

J/ψ NA3 Pt/p



$\sqrt{s}$–dependence OK

- RHIC, LHC: $x_2 \ll 0.01 \Rightarrow$

nPDF (shadowing) / saturation effects become sizeable

  - choice (i): use various nPDF sets (EPS09, DSSZ)
  - choice (ii): saturation

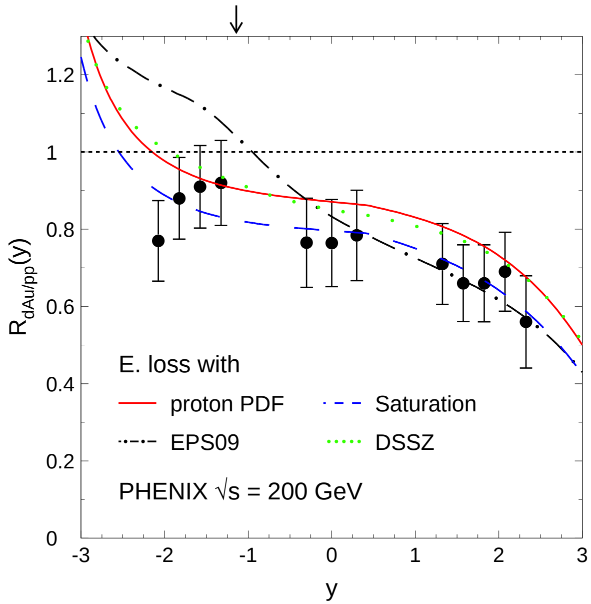
$Q_s^2 = \hat{q}(x)\, L$ Mueller 99, Baier 03

$R_{pA}^{\mathrm{sat}}(x, A) \simeq \frac{a}{(b+Q_s^2(x,L))^\alpha}$ Fujii, Gelis, Venugopalan 06

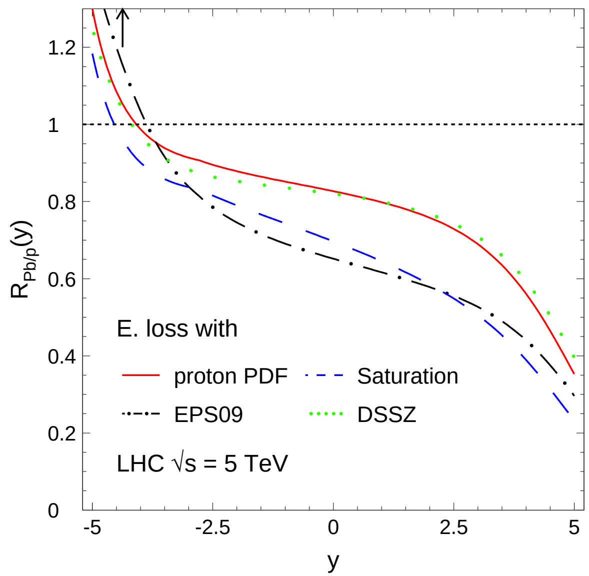
'CGC effect' accounts for broadening of $c\bar{c}$ *relative* $p_\perp$,

an effect previously proposed Benesh, Qiu, Vary 94

RHIC (PHENIX) d-Au



LHC p-Pb



- from fixed-target to RHIC, x_{F}–dependence of $R_{pA}^{\mathrm{J}/\psi}$ can be described by *parton energy loss* alone
  - adding saturation to ΔE improves agreement with RHIC data
  - saturation/nPDF effects alone cannot explain fixed-target data

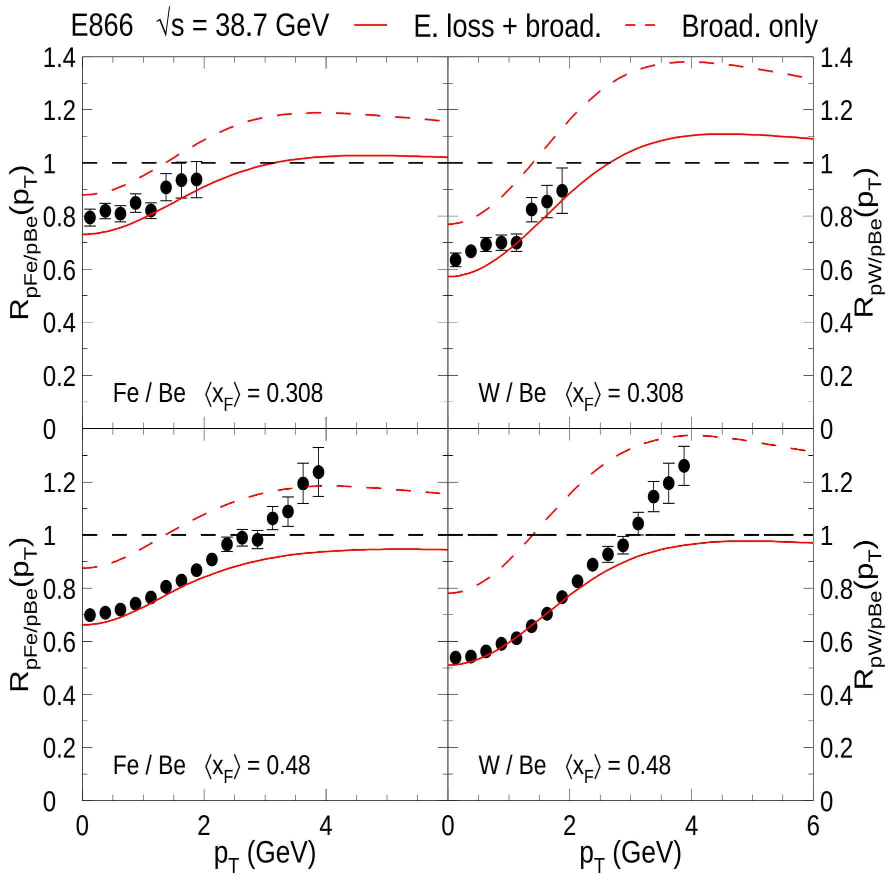
$p_\perp$-dependence

Arleo, Kolevatov, S.P., Rustamova, arXiv:1304.0901

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

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

E866

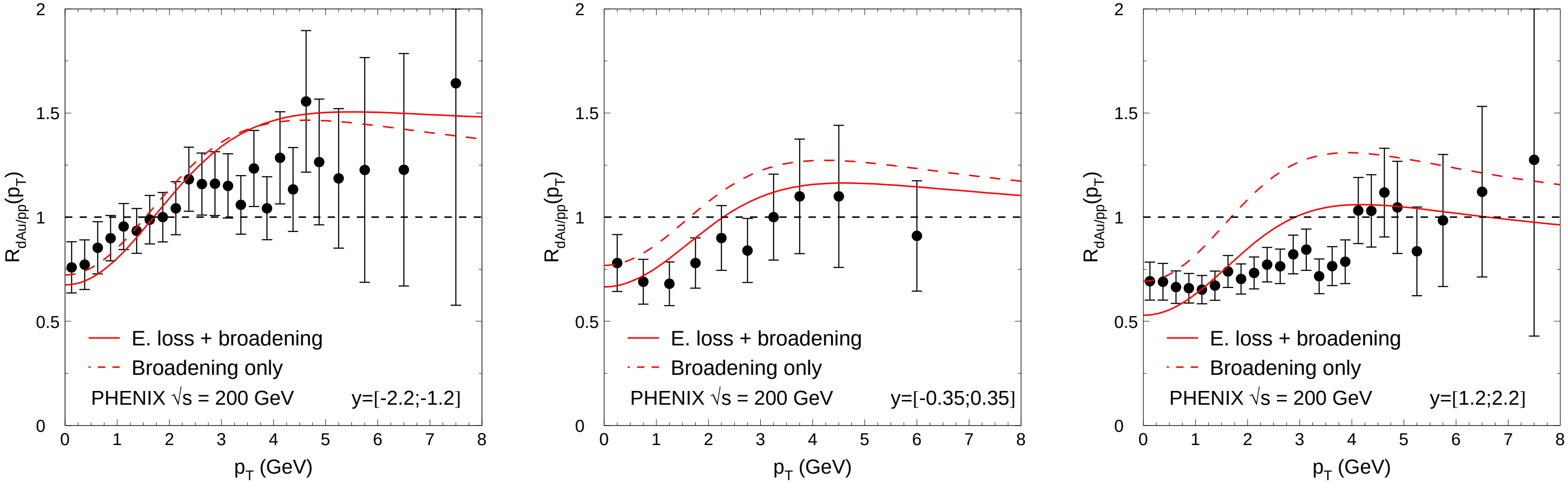


no free parameter: $\Delta p_\perp$ induces ΔE

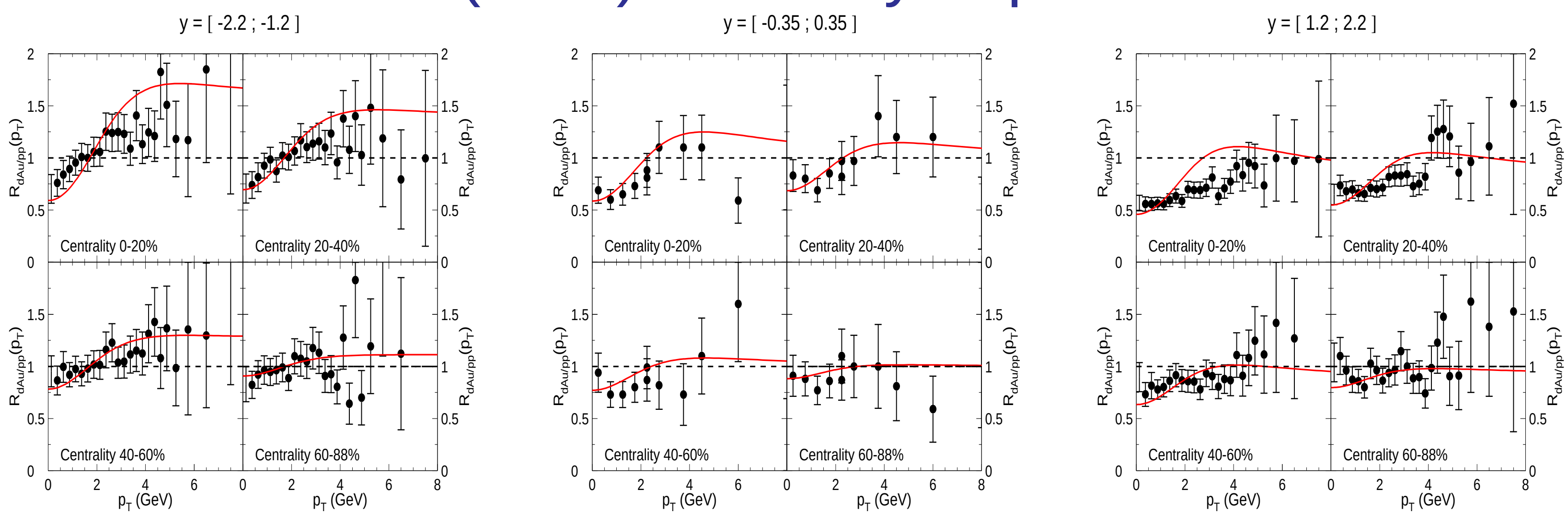
$\Delta p_\perp \longrightarrow$ Cronin effect

energy loss $\longrightarrow$ normalization

RHIC (d-Au) minimum bias

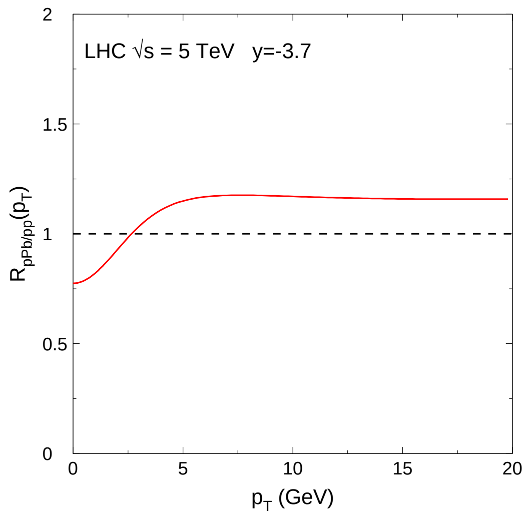


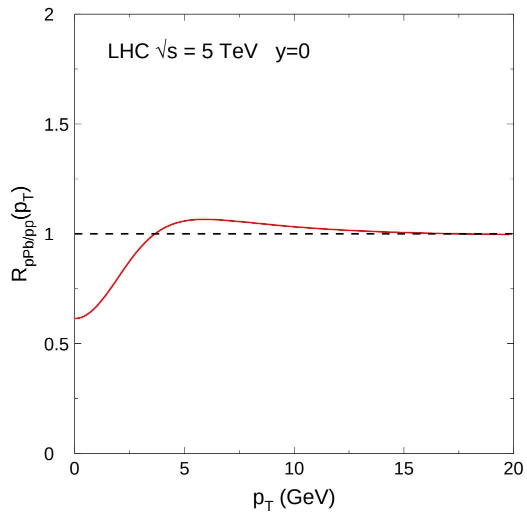
RHIC (d-Au) centrality dependence

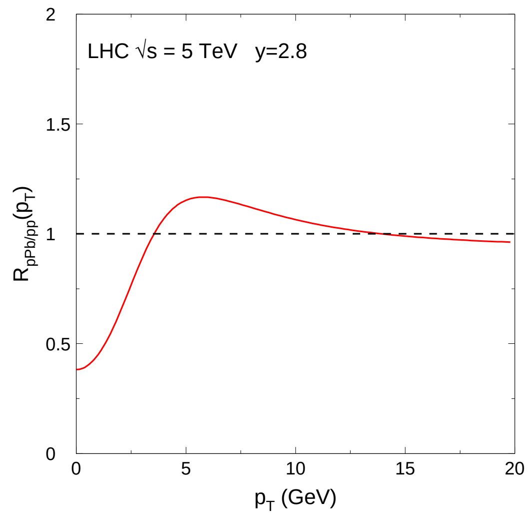


predictions for $R_{pA}^{J/\psi}$ at LHC (p-Pb)

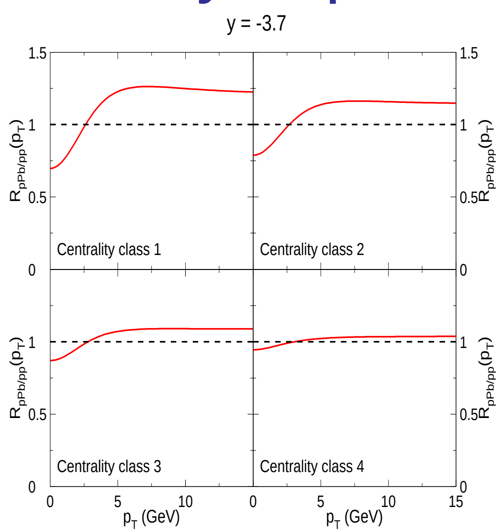
minimum bias

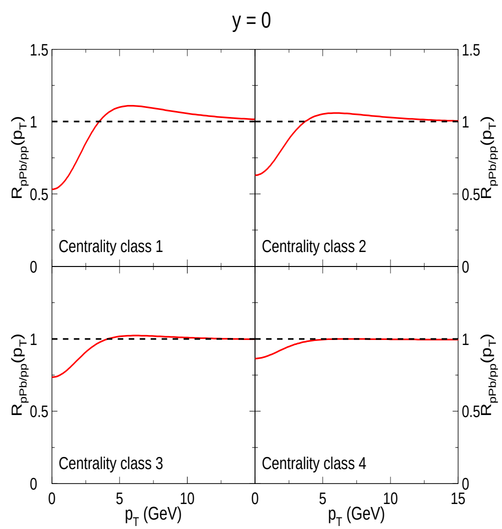


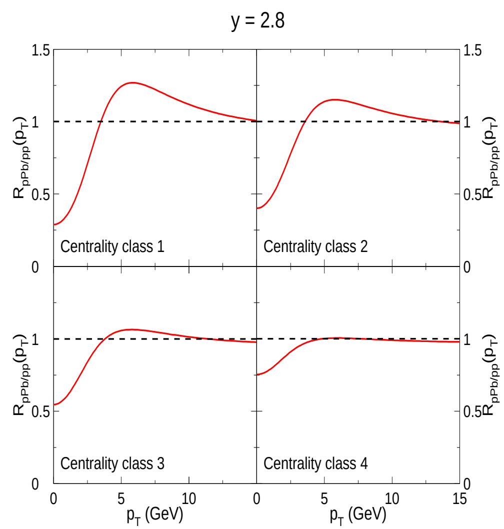




centrality dependence







summary

- parton ($c\bar{c}$) broadening + induced loss $\Delta E \propto E$ is a dominant effect in p-A J/ψ suppression

  explains shape of $R_{pA}^{\mathrm{J}/\psi}$, both in x_{F} and $p_{\perp}$
  from fixed-target to RHIC energies
  (RHIC, LHC: saturation/nPDFs may bring a
  10-20 % effect in normalization)

- parametric dependence of ΔE (and $dI/d\omega$) arises from true PQCD calculation

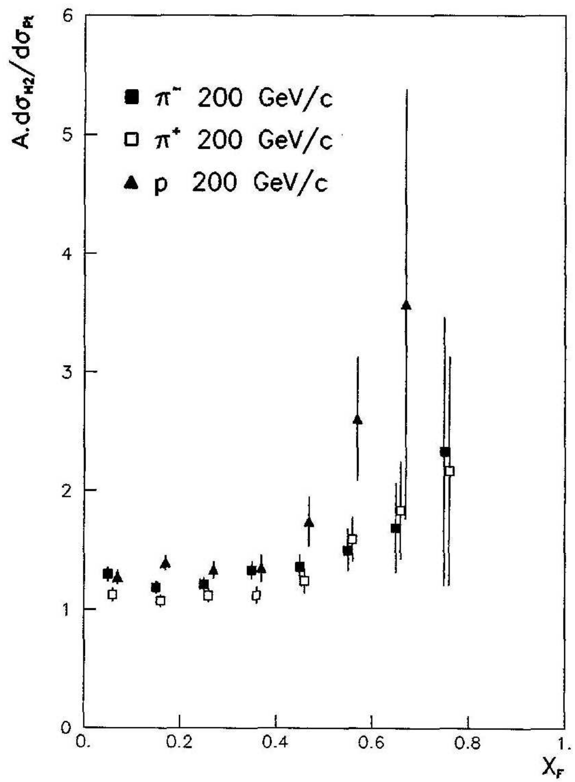
  $\Delta E \sim$ higher-twist effect, previously overlooked

$\rightarrow$ should have implications on other p-A processes:
open charm, light hadron ($p_{\perp} \gtrsim 1\,\mathrm{GeV}$)

THANK YOU!

BACK-UP SLIDES

- J/ψ nuclear suppression depends on projectile



stronger suppression in p-Pt than in π-Pt

NA3 Badier et al. 83

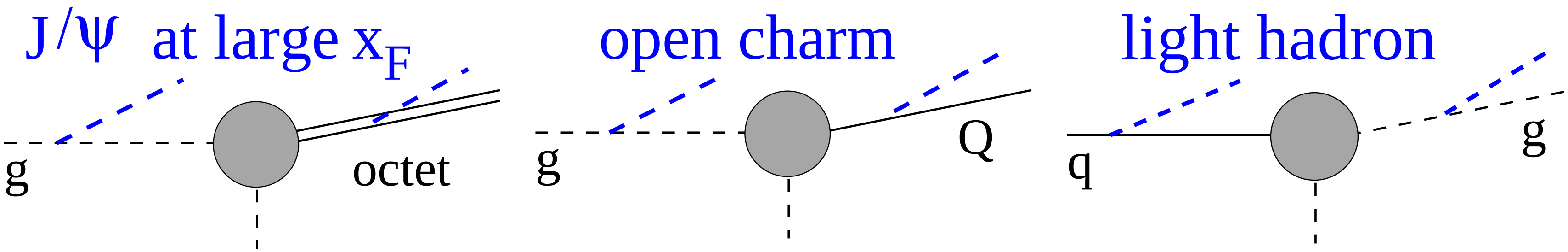
- no nuclear suppression in $\gamma^* A \to J/\psi + X$

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

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

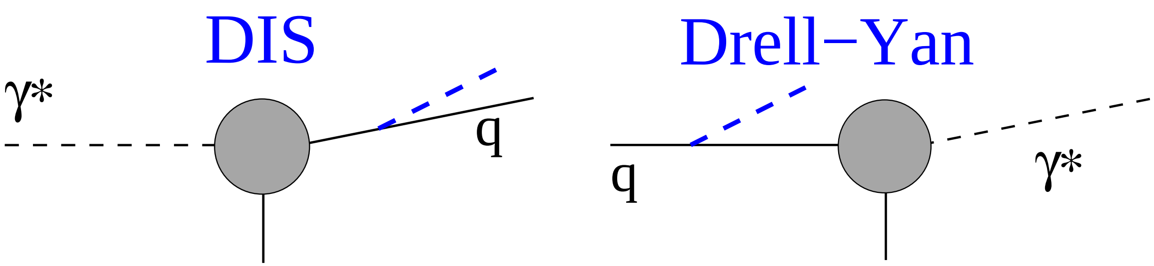
medium-induced radiation with *large* $t_f \propto E$

$\Delta E \propto E$ 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



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

parametrization of p-p cross section

$$\frac{\mathrm{d}\sigma^{\psi}_{\mathrm{pp}}}{\mathrm{d}y\,\mathrm{d}^2\vec{p}_\perp} = \mathcal{N} \times \left(\frac{p_0^2}{p_0^2+p_\perp^2}\right)^m \times \left(1-\frac{2M_\perp}{\sqrt{s}}\cosh y\right)^n$$

x_{F}-dependence

$p_\perp$-dependence