J/ψ Nuclear Suppression from Parton Energy Loss

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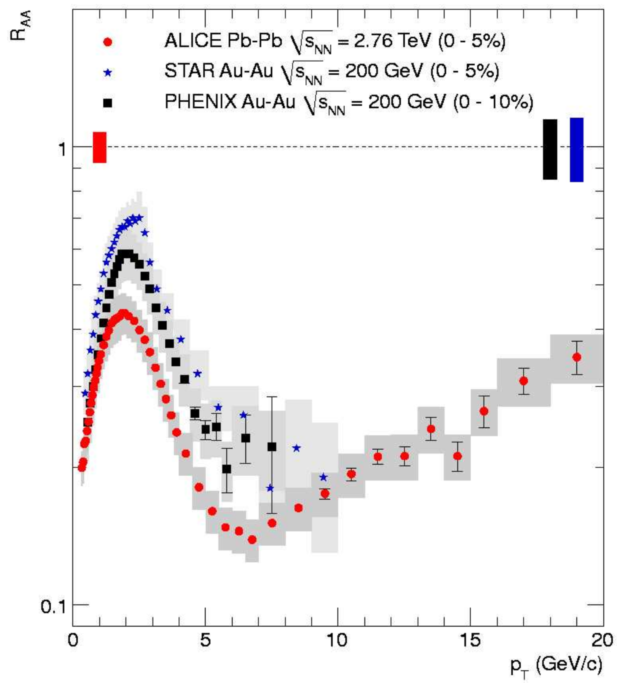
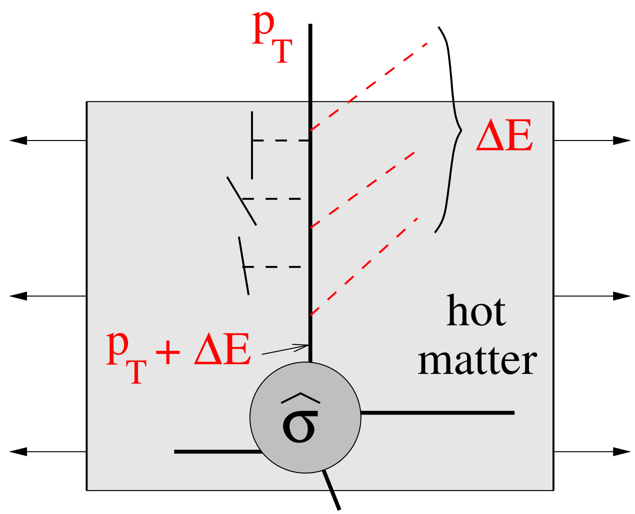
Introduction

- spectacular jet-quenching in A-A at RHIC and LHC

  due to *parton energy loss*





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

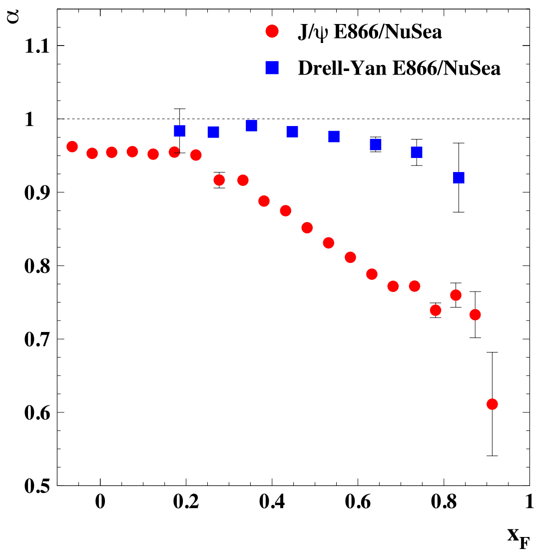
magnitude of R_{AA} can be explained only if

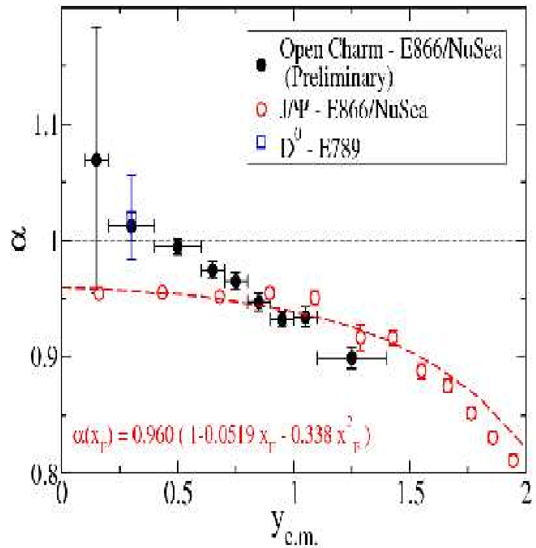
$$\hat{q} \equiv \frac{\mu^2}{\lambda} \sim \hat{q}_{hot} \sim 1 \, \mathrm{GeV}^2/\mathrm{fm} \gg \hat{q}_{cold} \sim 0.05 \, \mathrm{GeV}^2/\mathrm{fm}$$

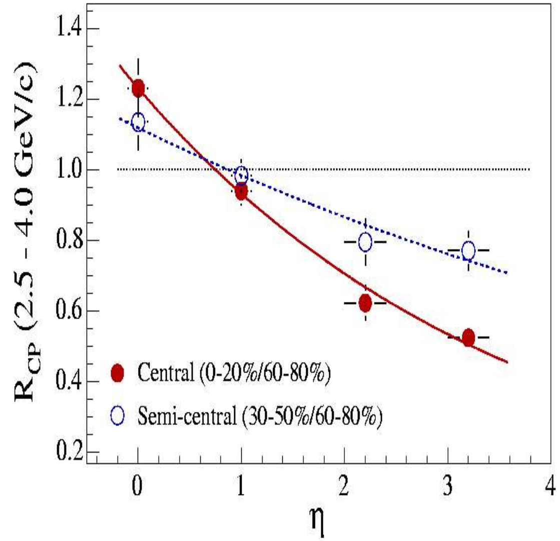
$\Rightarrow$ jet-quenching $=$ prominent QGP signal

- strong nuclear suppression also seen in p-A

J/ψ | open charm | light hadron







E866/NuSea | BRAHMS

huge suppression at large $x_{\rm F}$ / large rapidity

might also be explained by ΔE_{parton} (*in cold matter*) !

- $\hat{q}_{cold}$ small $\Rightarrow$ large suppression arises from *specific parametric behaviour* of ΔE at large x_{F}

$$\Delta E|_{\mathrm{large}\ x_{\mathrm{F}}} \propto E$$

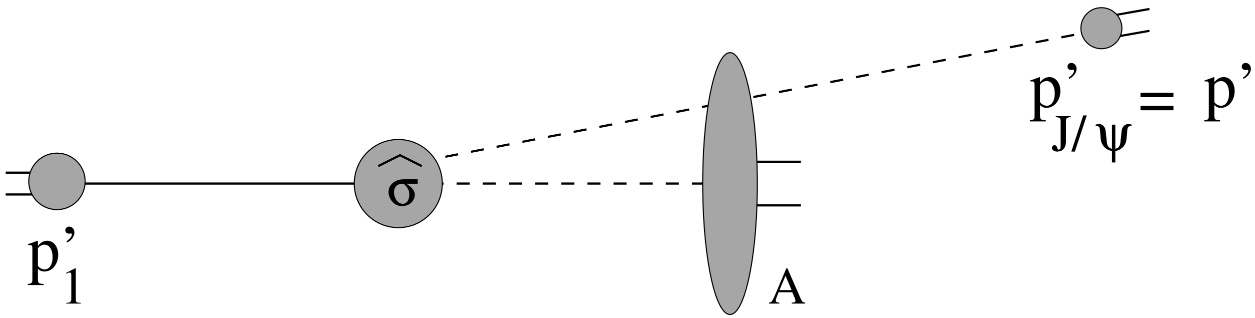
- in the following, focus on large x_{F} J/ψ production
  - intrinsic hard scale $M = M_Q$
  - more data than for open charm

we expect same physics to apply to *open charm*

and *light hadron* production (but not to Drell-Yan)

Model

in c.m. frame of elementary p-N collision (*primed frame*):



$$\frac{\mathrm{d}\sigma^{\psi}_{pA}}{\mathrm{d}x_{\mathrm{F}}}(x_{\mathrm{F}}) = \frac{\mathrm{d}\sigma^{\psi}_{pp}}{\mathrm{d}x_{\mathrm{F}}}(x_{\mathrm{F}} + \delta x_{\mathrm{F}}(\varepsilon) \equiv \tilde{x}_{\mathrm{F}}(\varepsilon))$$

shift in x_{F} takes into account energy loss ε
of J/ψ partonic parent through nucleus

- $x_{\mathrm{F}} = \frac{p'_{\parallel}}{p'_{1\parallel}} = 2\frac{M_{\perp}}{\sqrt{s_{NN}}}\sinh y'$
- ε defined in *nucleus rest frame* (where $E_{J/\psi} = E$)
  $\Rightarrow$ need to relate x_{F} to E

$\tilde{x}_{\mathrm{F}} = x_{\mathrm{F}} + \delta x_{\mathrm{F}} \leftrightarrow E + \varepsilon$ in nucleus rest frame remark:

- model can address $x_{\mathrm{F}} = 0$
  ($x_{\mathrm{F}} = 0$ corresponds to large E in nucleus frame and can thus be affected by parton energy loss)

- simplify following by choosing large x_{F}:

$$x_{\mathrm{F}} \gg \frac{M_\perp}{\sqrt{s}} \Rightarrow x_{\mathrm{F}} \simeq \frac{E}{E_1} \Rightarrow \delta x_{\mathrm{F}} \simeq \frac{\varepsilon}{E_1}$$

$$\frac{\mathrm{d}\sigma^{\psi}_{pA}}{\mathrm{d}x_{\mathrm{F}}}(x_{\mathrm{F}}) = \frac{\mathrm{d}\sigma^{\psi}_{pp}}{\mathrm{d}x_{\mathrm{F}}}\left(x_{\mathrm{F}} + \frac{\varepsilon}{E_1}\right)$$

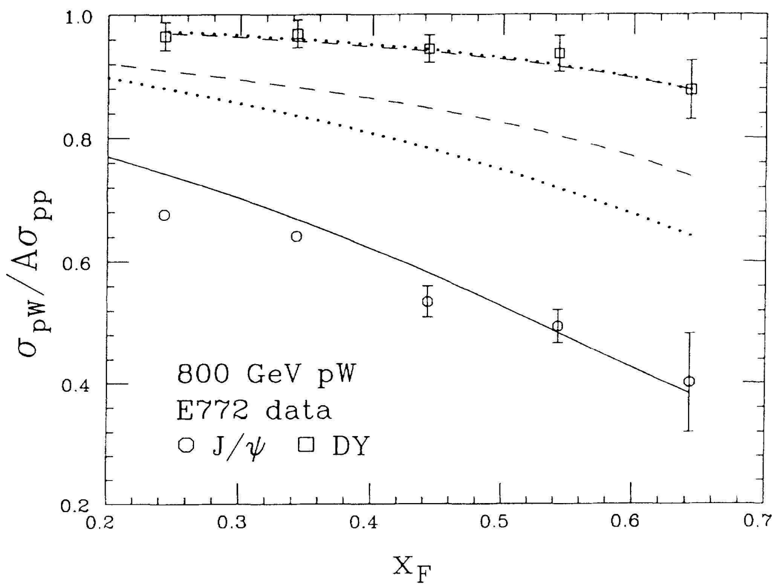
latter model for J/ψ nuclear suppression in p-A
first proposed by Gavin & Milana (1992), with:

- $\varepsilon =$ *average* ΔE
- ad hoc choice $\Delta E \propto E \cdot L \cdot \frac{1}{M^2}$

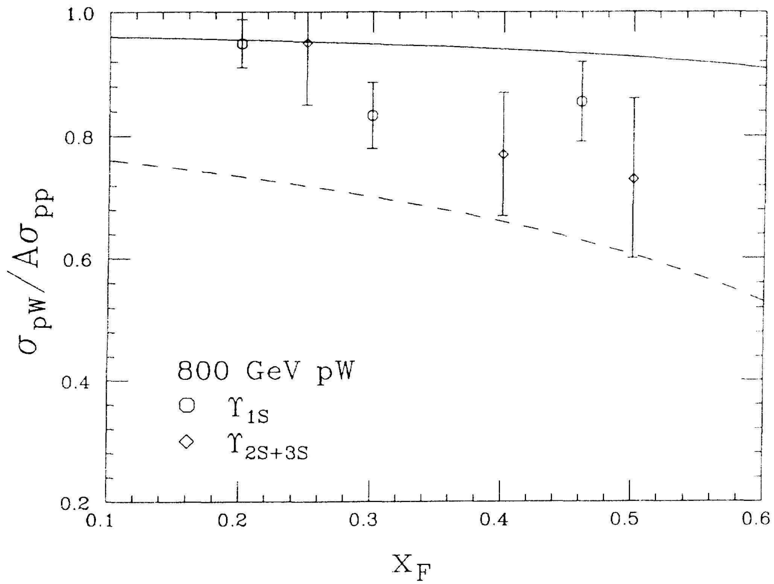
(assumed to hold for both J/ψ and DY production)

fixed fractional energy loss $\frac{\varepsilon}{E} = \frac{\Delta E}{E} = \mathrm{cst.}$
yields good description of E772 J/ψ data

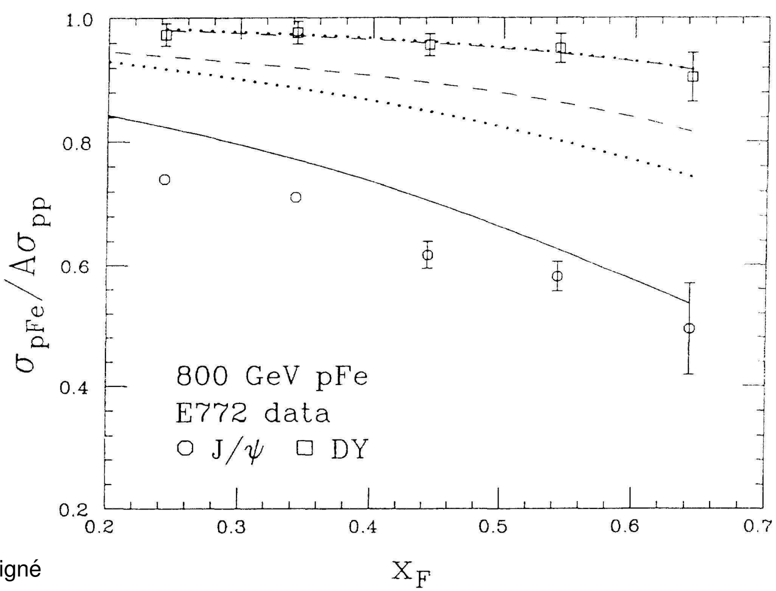
Gavin-Milana model vs. E772 p-A data



$M\uparrow$ $\Longrightarrow$



$\Downarrow$ $L\downarrow$



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

$\Rightarrow$ dependence

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

is too sharp

model recently revisited

- Arleo, S.P., Sami, 1006.0818
  - physical interpretation of $\Delta E_{J/\psi} \propto E$ at large $x_{\rm F}$
  - dependence $\Delta E(E, L, M, \hat{q})$ from first principles
- Arleo, S.P., Rustamova, work in progress
  - use *energy loss probability distribution* $P(\varepsilon)$ to describe p-A J/ψ data

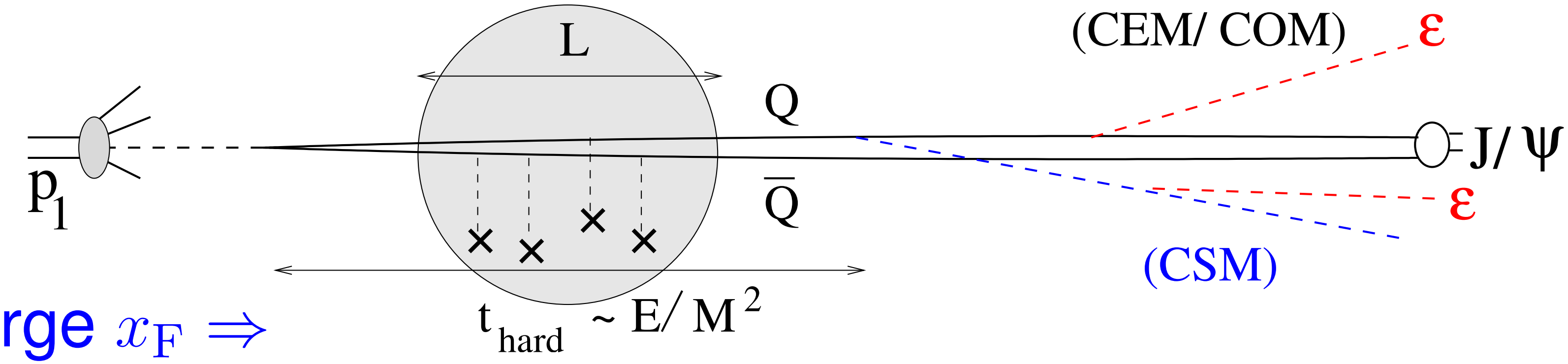
$$\frac{{\rm d}\sigma^{\psi}_{pA}}{{\rm d}x_{\rm F}}(x_{\rm F}) = \int_0^{\varepsilon_{max}} d\varepsilon \, P(\varepsilon) \, \frac{{\rm d}\sigma^{\psi}_{pp}}{{\rm d}x_{\rm F}} \left(x_{\rm F} + \frac{\varepsilon}{E_1} \right)$$

$P(\varepsilon)$ crucial for quantitative purposes:

- ε exhibits large fluctuations around ΔE
- $x_{\rm F} \to 1 \Rightarrow \varepsilon \leq \varepsilon_{max} = (1 - x_{\rm F}) E_1 \ll \Delta E$

(model $P(\varepsilon) = \delta(\varepsilon - \Delta E)$ breaks down when $x_{\rm F} \to 1$)

Why $\Delta E_{J/\psi} \propto E$ at large x_F



large $x_F \Rightarrow$

- J/ψ hadronizes outside nucleus
- $c\bar{c}$ pair remains *color octet* for a long time

CEM/COM: $t_{octet} \sim \frac{1}{\Lambda} \cdot \frac{E}{M} \gg t_{hard} \sim \frac{E}{M^2} \gg L$

CSM: $t_{octet} \sim t_{hard}$ *by definition*

in CSM J/ψ is produced in association with hard gluon

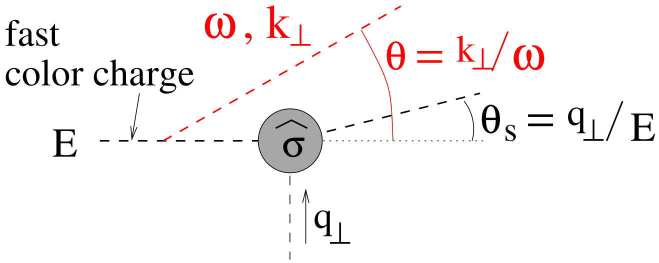
$\Rightarrow$ *independently of J/ψ production model:*

partonic process $\Leftrightarrow$ small angle scattering of color charge

leaves room for radiation with $t_{hard} \ll t_f \ll t_{had}$

associated gluon radiation spectrum turns out to be similar to that of 'asymptotic color charge'

- asymptotic charge



$\Rightarrow$ QED: radiation only if $\theta_s \neq 0$

QCD: radiation even if $\theta_s = 0$ due to *color rotation*

focus on non-abelian contribution: $\theta_s \to 0$

$$\omega \frac{dI}{d\omega} \sim \frac{N_c \alpha_s}{\pi} \int_{\theta_0^2}^{\theta_g^2} \frac{d\theta^2}{\theta^2 + \theta_M^2} \quad ; \quad \theta_g \equiv \frac{q_\perp}{\omega} ; \, \theta_0 \equiv \frac{\Lambda}{\omega} ; \, \theta_M \equiv \frac{M}{E}$$

- $\theta \leq \theta_g \Leftrightarrow k_\perp \leq q_\perp$: $q_\perp$ must resolve gg fluctuation
- $\theta \geq \theta_0 \Leftrightarrow k_\perp \geq \Lambda$: PQCD consistency

$$\Rightarrow \omega \frac{dI}{d\omega} \sim \frac{N_c \alpha_s}{\pi} \left\{ \ln \left(1 + \frac{q_\perp^2 E^2}{\omega^2 M^2} \right) - \ln \left(1 + \frac{\Lambda^2 E^2}{\omega^2 M^2} \right) \right\}$$

- charge produced at large $x_{\rm F}$ in p-A

$$\omega \, \frac{dI}{d\omega}\Big|_{\rm ind} = \omega \, \frac{dI}{d\omega}\Big|_{pA} - \omega \, \frac{dI}{d\omega}\Big|_{pp}$$

non-abelian contribution: $p_\perp^2(J/\psi)\big|_{pA} = p_\perp^2(J/\psi)\big|_{pp}$

slight modifications compared to asymptotic case:

- $\theta_g^2 \equiv \frac{q_\perp^2}{\omega^2} \to \Delta\theta_g^2 \equiv \frac{\Delta q_\perp^2}{\omega^2}$; $\quad \Delta q_\perp^2 = \hat{q}\, L \geq \Lambda^2$
- $M^2 \to M_\perp^2 \equiv M^2 + q_\perp^2$

$$\Rightarrow \omega \frac{dI}{d\omega} \sim \frac{N_c \alpha_s}{\pi} \left\{ \ln\left(1 + \frac{\hat{\omega}^2}{\omega^2}\right) - \ln\left(1 + \frac{\omega_0^2}{\omega^2}\right) \right\}$$

$$\hat{\omega} \equiv \frac{\sqrt{\Delta q_\perp^2}}{M_\perp} E \quad ; \quad \omega_0 \equiv \frac{\Lambda}{M_\perp} E$$

$$\Delta E = \int d\omega \, \omega \, \frac{dI}{d\omega}\Big|_{\rm ind} = N_c \alpha_s (\hat{\omega} - \omega_0) = N_c \alpha_s \frac{\sqrt{\hat{q}\, L} - \Lambda}{M_\perp} E$$

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

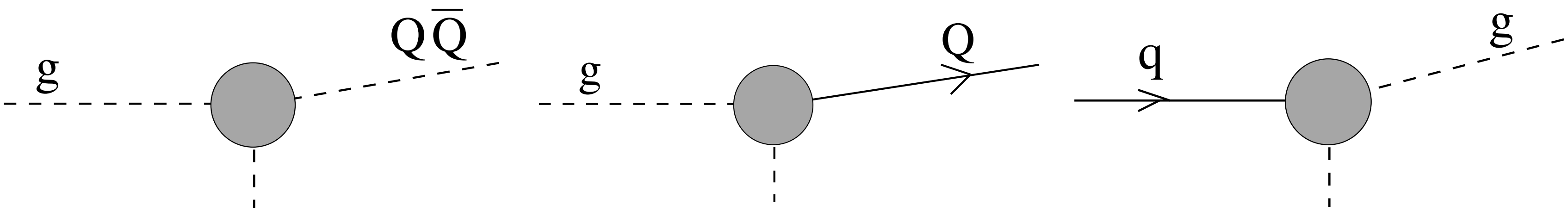
In summary:

- physical origin of $\omega \frac{dI}{d\omega}$ and $\Delta E_{J/\psi} \propto E$ at large $x_{\rm F}$:

  (medium-induced) soft gluon radiation with $t_f \gg t_{hard}$

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

  quarkonium open charm light hadron



does not apply to Drell-Yan production

- parametric form of $\omega \frac{dI}{d\omega}$ and $\Delta E(L, M)$ specified

$$\frac{\Delta E}{E} \sim \frac{\sqrt{L}}{M}$$

  - similar to ΔE_{rad} of asymptotic *color* charge
  - smoother than Gavin-Milana choice $\frac{\Delta E}{E} \sim \frac{L}{M^2}$

Brodsky-Hoyer bound on energy loss (1993)

- look for radiation with $t_f \gg L$ off *asymptotic particle*
- choose $p_\perp^2\big|_{pA} = p_\perp^2\big|_{pp}$ ($\Leftrightarrow$ non-abelian contribution) in *abelian* model
- find no contribution from $t_f \gg L$ and conclude:

$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \Rightarrow \Delta E \lesssim L\langle k_\perp^2 \rangle$$

- argument fails in QCD: $\Delta E \propto E$ not forbidden by first principles
- argument fails in QED when $p_\perp^2\big|_{pA} = p_\perp^2\big|_{pp} + \Delta p_\perp^2$
- bound applies to *particle produced in a medium* (or undergoing large angle scattering)

Quenching weight $P(\varepsilon)$

$P(\varepsilon)$ = energy loss *probability distribution*; $\int d\varepsilon P(\varepsilon) = 1$

how to get normalized $P(\varepsilon)$ from $\frac{dI}{d\omega}$?

$(I \equiv \int_0^\infty d\omega \frac{dI}{d\omega} = \infty)$

- use *Poisson approximation* $\Leftrightarrow$
  assume *independent* successive losses ω_i

$$\mathcal{P}(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int \mathrm{d}\omega_i \frac{\mathrm{d}I(\omega_i)}{\mathrm{d}\omega} \right] \delta\left(\epsilon - \sum_{i=1}^{n} \omega_i \right) \exp\left[-I\right]$$

$P(\varepsilon)$ satisfies integral equation

$$\frac{\partial P(\varepsilon)}{\partial L} = \int_0^\infty d\omega \left[P(\varepsilon - \omega) - P(\varepsilon) \right] \frac{dI}{d\omega dL}$$

$=$ Landau kinetic equation for ionization losses (1944)

(Poisson approximation legitimate)

⚠ radiative losses: radiating ω_i takes time $t_f(\omega_i)$

- large $x_{\rm F}$ quarkonium production in p-A:

each medium-induced radiated gluon is emitted with

$$t_f(\omega_i) \sim \frac{\omega_i}{\Delta q_\perp^2} \gg t_{hard} \gg L$$

$\omega_i \sim \omega_j \Rightarrow$ emissions i and j are not independent

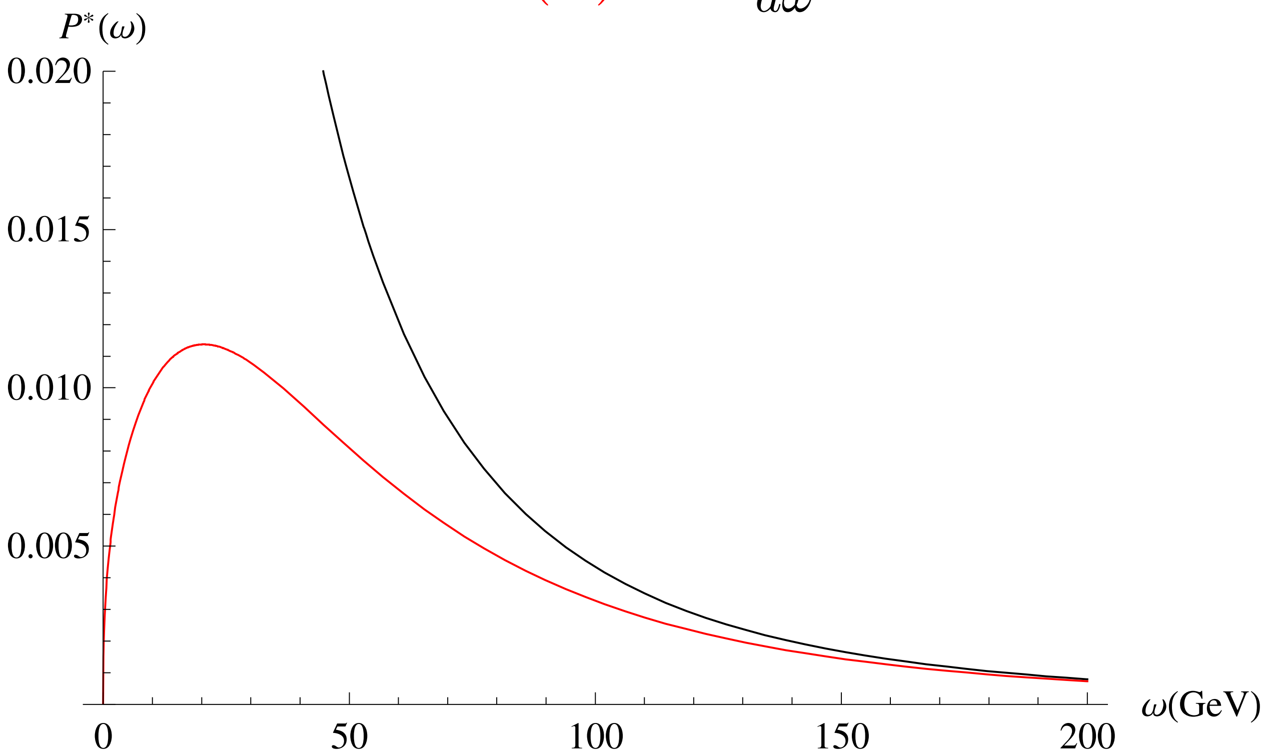
- for self-consistency, impose the constraint

$$\omega_1 \ll \omega_2 \ll \ldots \ll \omega_n$$

$$\Rightarrow P(\varepsilon) \simeq \frac{dI}{d\varepsilon} \exp\left\{-\int_\varepsilon^\infty d\omega \frac{dI}{d\omega}\right\} \equiv P^*(\varepsilon)$$

- $P^*(\varepsilon)$ only expression for quenching weight consistent with independent emissions

$P^*(\omega)$ vs. $\frac{dI}{d\omega}$



$E_1 = 800$; $\Lambda_{QCD} = 0.25$; $M_\perp = 3.25$ (GeV)

$\alpha_s = 0.5$; $x_{\mathrm{F}} = 0.5$; $A = 184$ (tungsten)

$\hat{q} = 0.144\,\mathrm{GeV}^2/\mathrm{fm}$

Comparing to the data

model

$$\frac{\mathrm{d}\sigma_{pA}^{\psi}}{\mathrm{d}x_{\mathrm{F}}}(x_{\mathrm{F}}) = \int_0^{\varepsilon_{max}} d\varepsilon\, P^*(\varepsilon)\, \frac{\mathrm{d}\sigma_{pp}^{\psi}}{\mathrm{d}x_{\mathrm{F}}}\left(x_{\mathrm{F}} + \frac{\varepsilon}{E_1}\right)$$

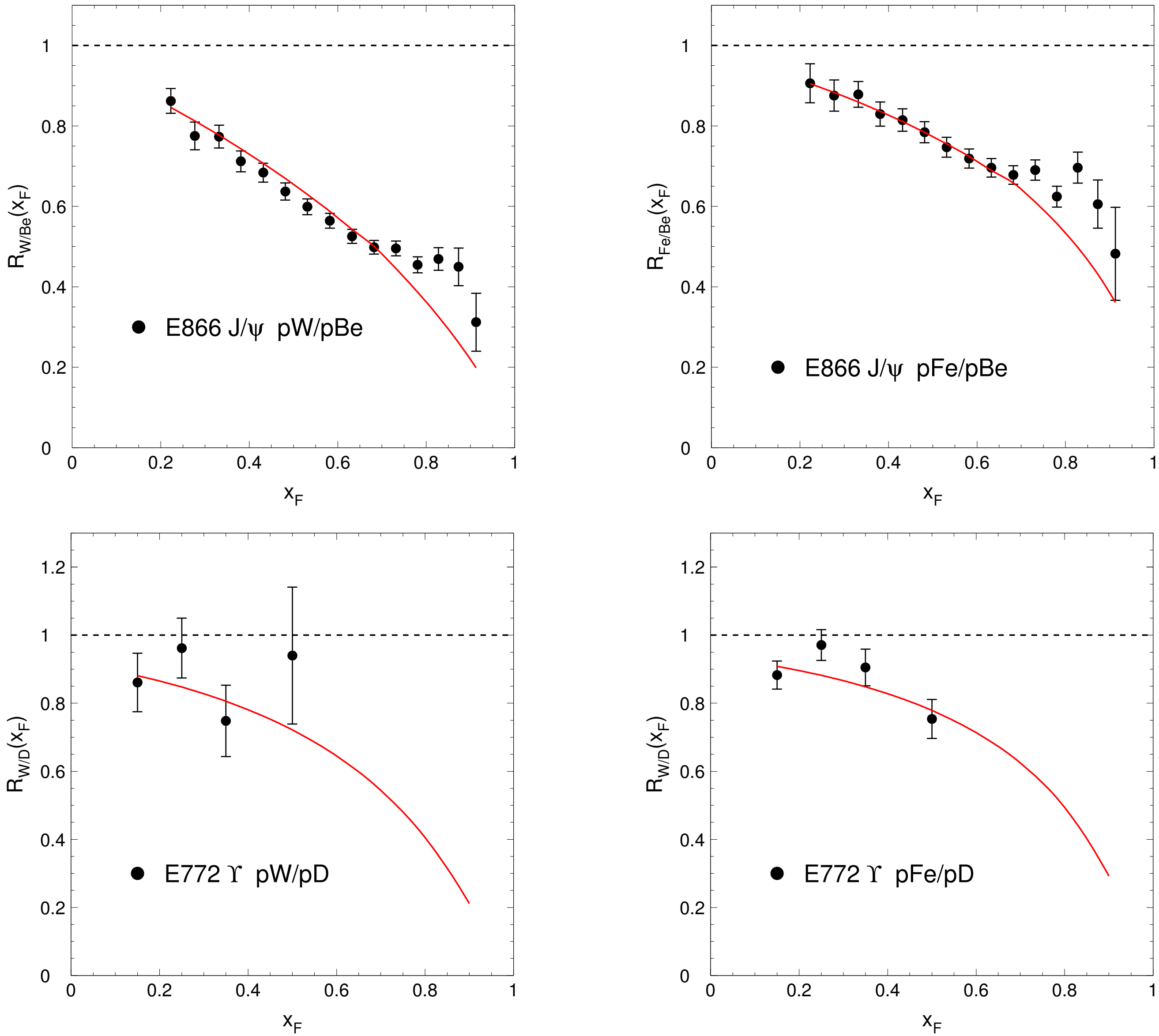
$$P^*(\varepsilon) = \frac{dI}{d\varepsilon}\, \exp\left\{- \int_{\varepsilon}^{\infty} d\omega \frac{dI}{d\omega}\right\}$$

$$\omega \frac{dI}{d\omega} = \frac{N_c \alpha_s}{\pi} \left\{ \ln\left(1 + \frac{\hat{\omega}^2}{\omega^2}\right) - \ln\left(1 + \frac{\omega_0^2}{\omega^2}\right) \right\}$$

depends on *single 'free'* parameter $\hat{q}$ (*via* $\hat{\omega} \equiv \frac{\sqrt{\hat{q}\,L}}{M_\perp}\, E$)

preliminary results

$\hat{q} = 0.144$



- value $\hat{q} = 0.144$ larger than $\hat{q} \sim 0.05$ obtained from e-A DIS or p-A Drell-Yan data

  $\longrightarrow$ at large x_{F} (small x_2) we expect sizeable part of suppression from shadowing of nPDFs

- data points at $x_{\mathrm{F}} > 0.8$ not included in the fit for $R_{pW}^{J/\psi}$

  ($x_{\mathrm{F}} \nearrow \Rightarrow$ subprocess $gg \to c\bar{c}$ becomes subdominant)

- quantitative agreement between model and data for slope *and* normalization of $R_{pA}(x_{\mathrm{F}})$ supports:
  - $\Delta E_{parton} =$ dominant effect in nuclear suppression
  - parametric dependence of $\Delta E \propto E$ and $\frac{dI}{d\omega}$

Summary and outlook

- ΔE seems essential to explain nuclear suppression
  - large p_T jet-quenching in A-A
  - large $x_{\rm F}$ hadron suppression in p-A

- simple features of ΔE have been overlooked

- understand nuclear suppression in p-A *before* A-A
  - $\Delta E \propto E$ should affect RHIC and LHC
    J/ψ and Υ p-A data *at large rapidity*

$\longrightarrow$ see Elena's talk