Centrality and p_t dependence of J/ψ suppression in pA from induced gluon radiation

François Arleo[1], Rodion Kolevatov[2], Stephane Peigné[2], Maryam Rustamova[2]

[1]LAPTh Annecy & LLR Palaiseau

[2]SUBATECH, Nantes

Workshop on pA collisions at the LHC
6–10 May 2013, Trento, Italy

Outline

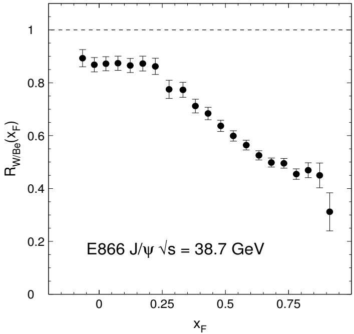
- Motivations
  - J/ψ suppression data in p A collisions
  - Energy loss parametrization of suppression data
- Revisiting energy loss
  - New scaling properties from medium-induced coherent radiation
- Phenomenology
  - Model for J/ψ and Υ suppression in p A collisions
  - Comparison with data and LHC predictions

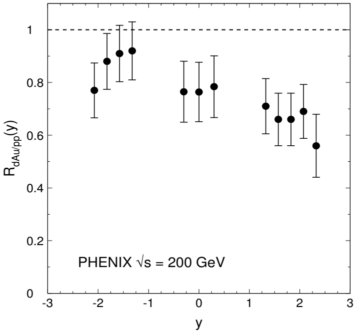
References

- F. Arleo, S. Peigné, PRL 109 (2012) 122301 [1204.4609] & JHEP 1303 (2013) 122 [1212.0434]
- F. Arleo, RK, S. Peigné, M. Rustamova, arXiv:1304.0901

J/ψ suppression in p A collisions at forward rapidities

- J/ψ suppression due to dissociation in QGP suggested as a probe of temperature in AA [Matsui, Satz '86]
- A strong suppression is seen already in pA at large x_F at various $\sqrt{s}$





- Weaker suppression in the Drell-Yan process

J/ψ suppression in p A collisions

Many mechanisms suggested as a source of the suppression...

- Nuclear absorption
  - requires unrealistically large cross section
- nPDF effects and saturation
  - constrained by Drell-Yan
- Intrinsic charm
  - assuming a large amount of charm in the proton
- Parton energy loss
  - requires $\Delta E \propto E$, ruled out for incoherent IS and FS radiation

...their relative importance is still debated

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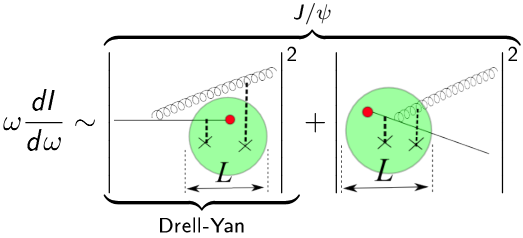
This talk: the J/ψ suppression from *coherent* parton energy loss

Gavin–Milana model

Simple model assuming (mean) energy loss via the induced initial and final state radiation

$$\Delta E \propto E \; L \; M^{-2}$$

allows for description of both Drell-Yan and J/ψ suppression at high x_F [Gavin Milana 1992]



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Caveats

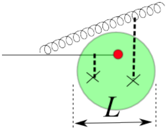
- Based on ad hoc assumption $\Delta E \propto E$ for the scaling properties of IS and FS induced radiation
- Failure to describe Υ suppression
- $\Delta E \propto E$ claimed to be incorrect in the high energy limit due to uncertainty principle

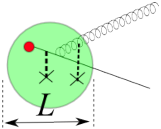
A bound on energy loss

Purely initial/final state induced radiation comes from short formation times while large formation times cancel out [Brodsky Hoyer 93]

$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \quad \Rightarrow \quad \Delta E \sim \omega \lesssim k_\perp^2 \; L \sim \hat{q} \; L^2$$

- Bound independent of the parton energy
- Energy loss cannot be arbitrarily large in a finite medium
- Gavin–Milana model is apparently ruled out





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The bound applies to:

- Hadron production in nuclear DIS and Drell-Yan in p A collisions
- Jets and hadrons produced in hadronic collisions at large angle

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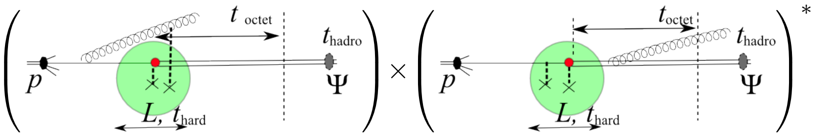
However

- In certain situations induced radiation has different scaling properties [Arleo Peigné Sami 10]

Revisiting energy loss scaling properties

Induced gluon radiation dominated by large formation times

$$\max(L, t_{\text{hard}}) \ll t_f \sim \frac{\omega}{k_\perp^2} \ll t_{octet} \sim \frac{E}{M}\tau_\psi \sim \frac{E}{Mk_\perp} \Rightarrow \Delta E \propto \frac{\sqrt{\hat{q}L}}{M} E$$



- Requires small angle scattering of energetic color charge in the medium rest frame
- Comes from interference between gluon emissions in the initial and final state

Revisiting energy loss scaling properties

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Applies to:

- Production of light and open heavy-flavour hadrons at forward rapidities in the medium rest frame (nuclear matter or QGP)
- Production of heavy-quarkonium if color neutralisation occurs on long time-scales $t_{\rm octet} \gg t_{\rm hard}$

Medium-induced gluon spectrum

Gluon spectrum $dI/d\omega \sim$ Bethe-Heitler spectrum of massive (color) charge

$$\omega \frac{dI}{d\omega}\bigg|_{\text{ind}} = \frac{N_c \alpha_s}{\pi} \left\{ \ln\left(1 + \frac{E^2 \Delta q_\perp^2}{\omega^2 M_\perp^2}\right) - \ln\left(1 + \frac{E^2 \Lambda_{\rm QCD}^2}{\omega^2 M_\perp^2}\right) \right\}$$

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

- $\Delta E \propto E$ neither initial nor final state effect nor 'parton' energy loss: arises from coherent radiation
- Physical origin: broad t_f interval : $L, t_{\text{hard}} \ll t_f \ll t_{\text{octet}}$ for medium-induced radiation

Model for heavy-quarkonium suppression

[Arleo Peigné 1212.0434]

$$\frac{1}{A}\frac{d\sigma^{\psi}_{\mathrm{pA}}}{dE}(E,\sqrt{s}) = \int_0^{\varepsilon_{\max}} d\varepsilon\, \mathcal{P}(\varepsilon, E|\Delta q^2_\perp)\, \frac{d\sigma^{\psi}_{\mathrm{pp}}}{dE}(E+\varepsilon,\sqrt{s})$$

- pp cross section fitted from experimental data

$$E\,\frac{d\sigma^{\psi}_{\mathrm{pp}}}{dE} = \frac{d\sigma^{\psi}_{pp}}{dy} \propto \left(1 - \frac{2M_\perp}{\sqrt{s}}\cosh y\right)^{n(\sqrt{s})}$$

- $\mathcal{P}(\epsilon)$: quenching weight, scaling function of $\hat{\omega} = \sqrt{\hat{q}L}/M_\perp \times E$
- Effective length L_{eff} is given by Glauber model, $L_{pp} = 1.5$ fm

$$\hat{q}(L_{eff} - L_{pp}) = \left(\langle N_A^{\mathrm{part}}\rangle_\psi - 1\right)\frac{\sigma_{\mathrm{broad}}}{\sigma_{\mathrm{inel}}}\mu_\perp^2 = \hat{q}\,\frac{\langle N_A^{\mathrm{part}}\rangle_\psi - 1}{\sigma_{\mathrm{inel}}\rho_0}$$

Transport coefficient

- $\hat{q}$ related to gluon distribution in a target nucleon [BDMPS 1997]

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

- Typical value for x depends on $t_{\rm hard} \sim \frac{1}{M}\frac{E}{M} \sim 1/(m_p x_2)$:
  - $t_{\rm hard} \lesssim L \Rightarrow x = x_0 \simeq (m_N L)^{-1}$;
  - $t_{\rm hard} > L \Rightarrow x \simeq x_2$;

Using $xG(x) \sim x^{-0.3}$ for $x \ll 1$,

$$\hat{q}(x) = \hat{q}_0 \left(\frac{10^{-2}}{x}\right)^{0.3} \qquad x = \min(x_0, x_2)$$

$\hat{q}_0$ only free parameter of the model

Procedure

1. Fit $\hat{q}_0$ from J/ψ E866 data in p W collisions:
   $\hat{q}_0 = 0.075\ \mathrm{GeV}^2/\mathrm{fm}$
2. Predict J/ψ and Υ suppression for all nuclei and c.m. energies

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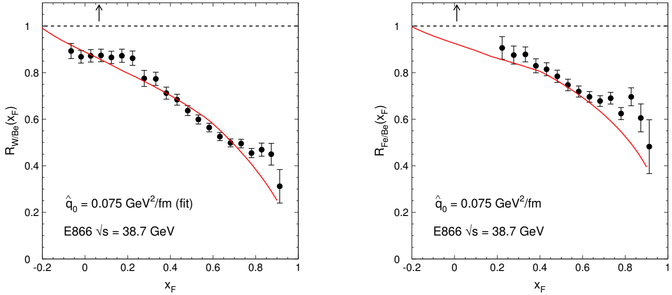

- Fe/Be ratio well described, supporting the L dependence of the model

Extrapolating to other energies

Two competing mechanisms might alter heavy-quarkonium suppression

- Nuclear absorption if hadron formation occurs inside the medium

$$t_{\text{form}} = \gamma\ \tau_{\text{form}} \lesssim L$$

  - Low $\sqrt{s}$ and/or negative x_F, indicated later assuming $\tau_{\text{form}} = 0.3$ fm

Extrapolating to other energies

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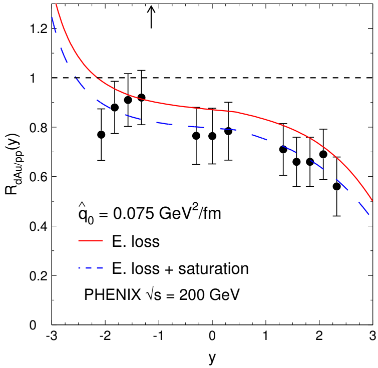
- nPDF/saturation effects when $Q_s^2 \sim m_c^2$

$$R_{\rm pA} = R_{\rm pA}^{\rm E.loss}(\hat{q}) \times \ \mathcal{S}_{\rm A}^{\rm sat}(Q_s)/\mathcal{S}_{\rm p}^{\rm sat}(Q_s)$$

$\mathcal{S}_{\rm A}^{\rm sat}(Q_s)$ taken from CGC calculations [Fujii Gelis Venugopalan 2006]

- No additional parameter: $Q_s^2(x, L) = \hat{q}(x)L$ [Mueller 1999]
- $Q_s^2(x = 10^{-2}) = 0.11 - 0.14\ \text{GeV}^2$ consistent with fits to DIS data [Albacete et al AAMQS 2011]

RHIC predictions



- Good agreement at all rapidity
- Saturation effects improve the agreement, but taken alone reproduce neither shape nor the magnitude of the suppression

$p_\perp$ dependence

Most general case. The p_t broadening: $|\Delta\vec{p}_\perp| = \hat{q}L_{\rm eff}$

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

- Parametrization consistent with pp experimental data

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

- For $\mathcal{P}(\varepsilon, E)$ peaked at small ε

$$R^{\psi}_{\rm pA}(y, p_\perp) \simeq R^{\rm loss}_{\rm pA}(y, p_\perp)\cdot R^{\rm broad}_{\rm pA}(p_\perp)$$

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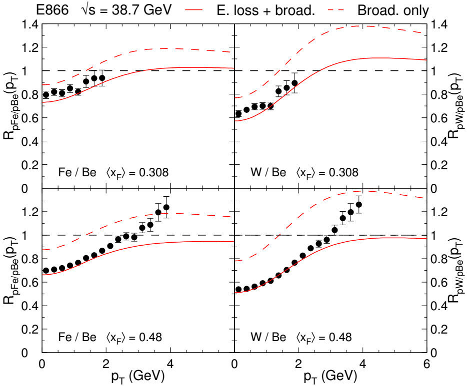
$$R^{\psi}_{\rm pA}(y, p_\perp) \simeq R^{\rm loss}_{\rm pA}(y, p_\perp) \cdot R^{\rm broad}_{\rm pA}(y, p_\perp)$$

- Overall depletion due to parton energy loss
- Possible Cronin peak due to momentum broadening

$$R^{\rm broad}_{\rm pA}(y, p_\perp) \equiv \int_\varphi \frac{\mu(|\vec{p}_\perp - \Delta\vec{p}_\perp|)}{\mu(p_\perp)}\, \frac{\nu(E, \vec{p}_\perp - \Delta\vec{p}_\perp)}{\nu(E, p_\perp)};$$

$$R^{\rm loss}_{\rm pA}(y, p_\perp) \equiv \int_\varepsilon \mathcal{P}(\varepsilon, E) \left[\frac{E}{E+\varepsilon}\right] \frac{\nu(E+\varepsilon, p_\perp)}{\nu(E, p_\perp)}$$

E866 p_t dependence



- Good description of $R_{pA/pB}$ for $p_t \lesssim 3$ GeV
- Possible reasons for discrepancy at $p_t > 3$ GeV:
  - Model calculations at fixed x_F rather than averaging
  - p_t dependence from fit to E789 pp data at $x_F = 0$.

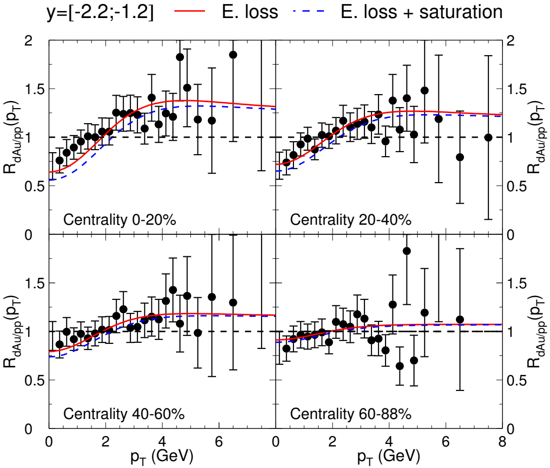
Centrality

Centrality dependence is given by L_{eff}

- Experimental situation [PHENIX 08, ALICE 12]
  - Centrality selection via multiplicity in target fragmentation region N_A^{ch}
  - N_A^{ch} is strongly correlated with N_A^{part}
- The model
  - $L_{\mathrm{eff}} = L_{pp} + \dfrac{\langle N_A^{\mathrm{part}} \rangle_\psi - 1}{\sigma_{\mathrm{inel}} \rho_0}$
  - Glauber model estimates of $\langle N_A^{\mathrm{part}} \rangle_\psi$ with constraints on N_A^{part}
    - for dAu – estimate of $\langle N_{\mathrm{coll}}^{\mathrm{tagged}N} \rangle_\psi$ with constraints on the overall N_A^{part}

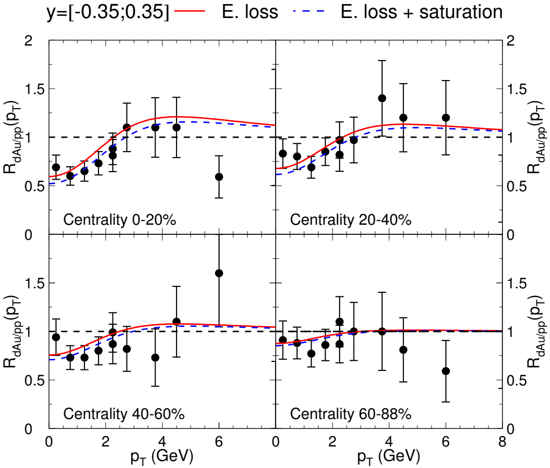
[Arleo, RK, Peigné, Rustamova 1304.0901]

RHIC predictions



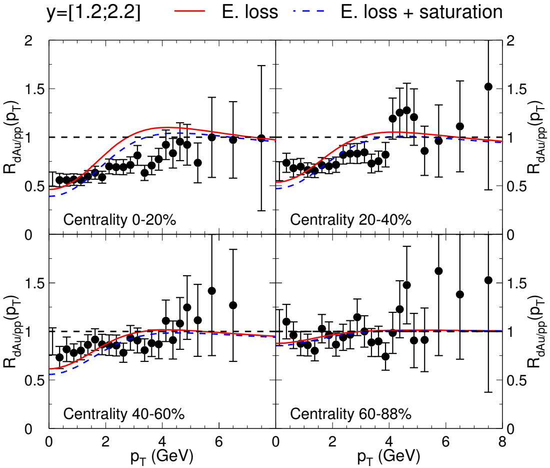
- Good description of $p_\perp$ and centrality dependence at $y = -1.7$

RHIC predictions



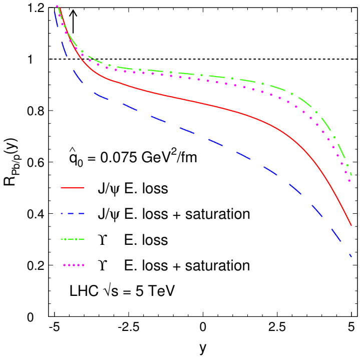
- Good description of $p_\perp$ and centrality dependence at $y = 0$

RHIC predictions



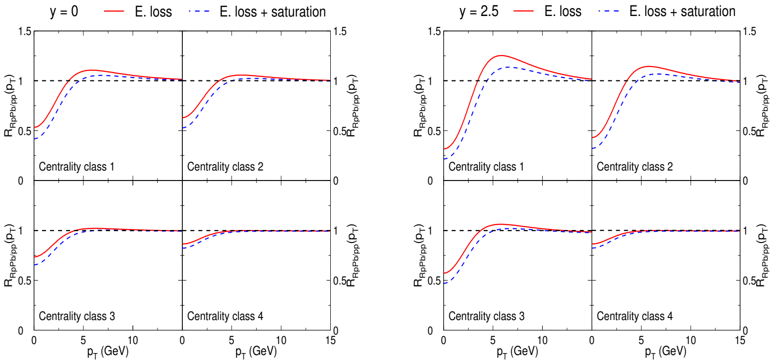
- Good description of $p_\perp$ and centrality dependence at $y = 1.7$

LHC predictions



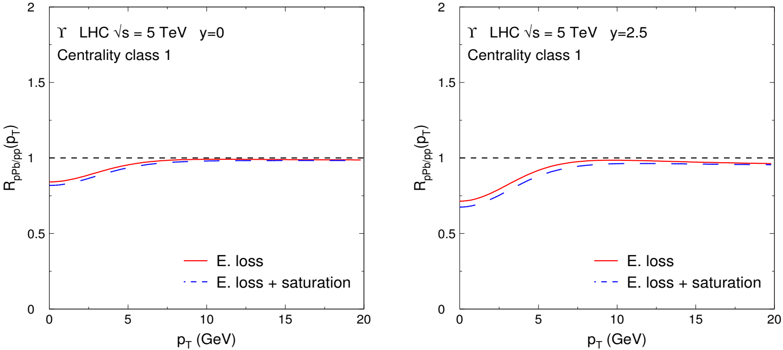
- Moderate effects ($\sim 20\%$) around mid-rapidity, smaller at $y < 0$
- Large effects above $y \gtrsim 2 - 3$
- Slightly smaller suppression expected in the Υ channel

LHC predictions



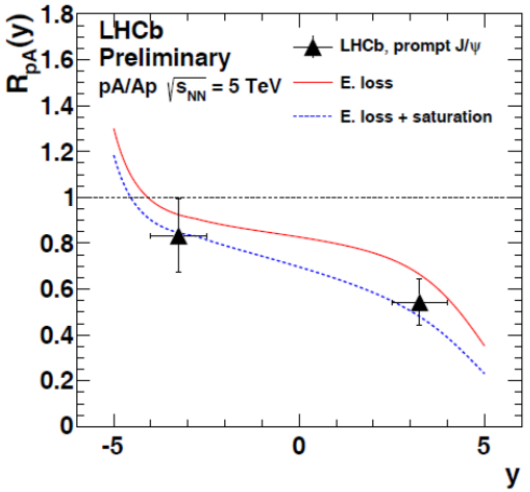
- Suppression expected up to $p_\perp \simeq 3$–4 GeV
- Possible enhancement in most central collisions

LHC predictions



- Weaker suppression in the Υ channel, which however extend to slightly larger $p_\perp$

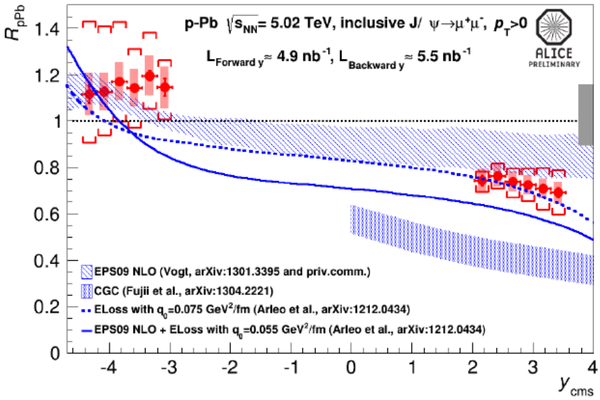
Comparison with LHCb



Theoretical predictions:
JHEP 1303 (2013) 122
[arXiv:1212.0434]

From Fanfan Jing's talk on Monday

Comparison with ALICE

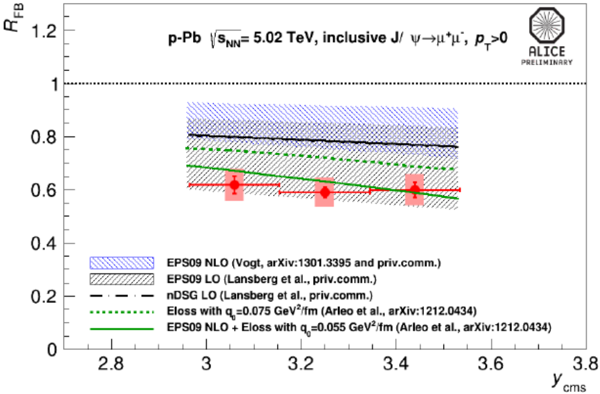


Uncertainties:

- uncorrelated (box around points)
- partially correlated ([])
- 100% correlated (grey box)

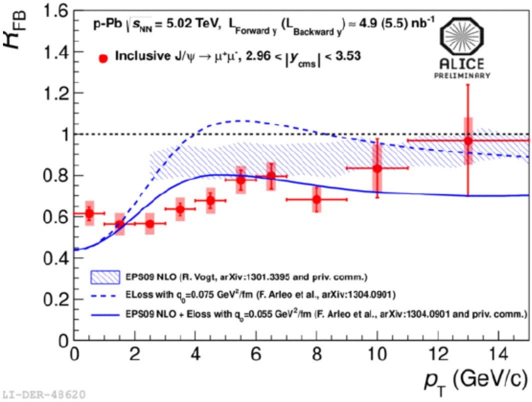
From Roberta Arnaldi's talk

Comparison with ALICE



From Roberta Arnaldi's talk

Comparison with ALICE



- The R_{FB} ratio shows a p_T dependence with a stronger suppression at low p_T
- theoretical predictions including energy loss show strong nuclear effects at low p_T, in fair agreement with the data

From Roberta Arnaldi's talk

Summary

- Energy loss $\Delta E \propto E$ due to coherent radiation
  - Neither initial nor final state effect
  - Parametric dependence of $dI/d\omega$ and ΔE predicted
- Heavy-quarkonium suppression predicted for wide range of $\sqrt{s}$
  - Good agreement with all existing data vs. x_F (y) and $p_\perp$
  - Natural explanation for the large x_F J/ψ suppression
  - Model supplemented consistently by saturation effects
  - Supports the assumption of long-lived color octet $Q\bar{Q}$ pairs
  - Fair agreement with the LHC pPb data on J/ψ

Backup – Quenching weight

- Poisson approximation assuming independent emission can be used for radiation with $t_f \lesssim L$ [BDMS 2001]

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

- $\Delta E \propto E$ comes from radiation with $t_f(\omega_i) \sim \omega_i / \Delta q_\perp^2 \gg L$

  For $t_f(\omega_i) \sim t_f(\omega_j) \gg L \Rightarrow$ emissions i and j are not independent

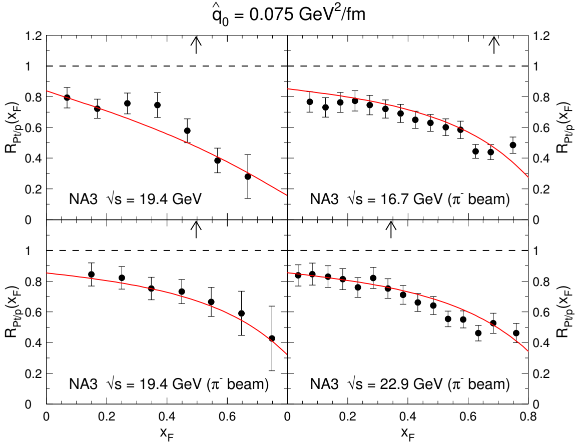
- For self-consistency, constrain $\omega_1 \ll \omega_2 \ll \ldots \ll \omega_n$

$$P(\epsilon) \simeq \frac{dI(\epsilon)}{d\omega} \exp\left\{ - \int_{\epsilon}^{\infty} d\omega \frac{dI}{d\omega} \right\}$$

Backup – L_{eff} vs centrality

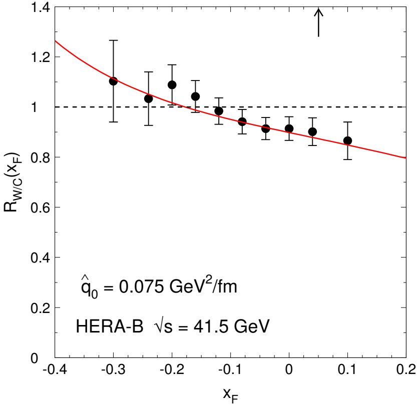
Glauber, RHIC					Glauber, LHC				
class	$N_p^{\text{min}};\ N_p^{\text{max}}$	$\frac{P(\text{class})}{P(N\geq1)}$	$\langle N_c\rangle$	L_{Au}	class	$N_p^{\text{min}};\ N_p^{\text{max}}$	$\frac{P(\text{class})}{P(N\geq1)}$	$\langle N_c\rangle$	L_{Pb}
A	11; 197	0.28	15.9	12.87	1	12; 208	0.246	14.8	13.46
B	8; 12	0.24	10.9	9.62	2	9; 12	0.215	10.5	9.55
C	5; 8	0.23	7.0	7.17	3	5; 8	0.215	6.5	6.29
D	2; 4	0.29	3.6	3.84	4	1; 5	0.428	2.4	3.39

Backup – SPS



- Agreement when $x_F > x_F^{min}$ (and even below)
- Natural explanation from the different suppression in p A vs π A

Backup – HERA-B



- Also good agreement in the nuclear fragmentation region ($x_F < 0$)
- Enhancement predicted at very negative x_F