Energy loss in cold nuclear matter and suppression of forward hadron production.

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

[1]LAPTh Annecy & LLR Palaiseau

[2]SUBATECH, Nantes

3rd NeD/TURIC Workshop, 9–14.VI.2014, Hersonissos, Crete

Outline

- Motivations
  - Forward hadron suppression in p A collisions
  - Energy loss interpretation of suppression data
- Scaling properties of medium induced radiation
  - Asymptotic parton
  - Parton produced in medium
- Coherent induced radiation
  - The setup
  - The induced radiation spectrum
  - Phenomenology

References

- F. Arleo, S. Peigné JHEP 1303 (2013) 122 [1212.0434]
- F. Arleo, RK, S. Peigné, M. Rustamova JHEP 1305(2013)155 [1304.0901]
- S. Peigné, F. Arleo, RK arxiv:[1402.1671]
- S. Peigné, RK arxiv:[1405.4241]

A tool to study hot and dense matter

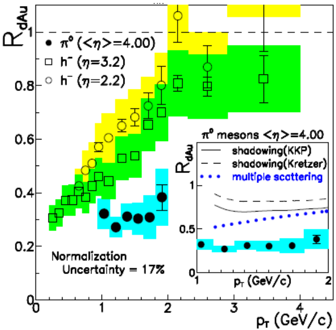
- Study of hadron spectra w.r.t. scaled *pp* and C_{entral}/P_{eripheral} ratios

$$R_{AA/pA}(y, p_t) = \frac{\left.\frac{d^2\sigma}{dydp_t}\right|_{AA/pA}}{\langle N_{\rm coll}\rangle \left.\frac{d^2\sigma}{dydp_t}\right|_{AA/pA}}; \quad R_{CP} = \frac{\langle N_{\rm coll}\rangle_P \left.\frac{d^2\sigma}{dydp_t}\right|_{AA/pA,\ C}}{\langle N_{\rm coll}\rangle_C \left.\frac{d\sigma}{dydp_t}\right|_{AA/pA,\ P}}$$

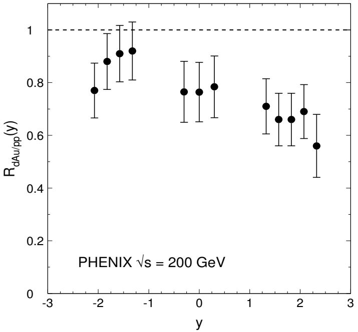
- Suppression already seen in $p(d)A$ data
  - Quarkonia production (starting from SPS energies)
  - Forward light hadron production at RHIC
  - Dihadron correlations
- The proper interpretation is important
  - Baseline for hot matter effect studies
  - Initial state of fast nucleus and production mechanisms

Examples of suppression in RHIC *dAu* data

Pions



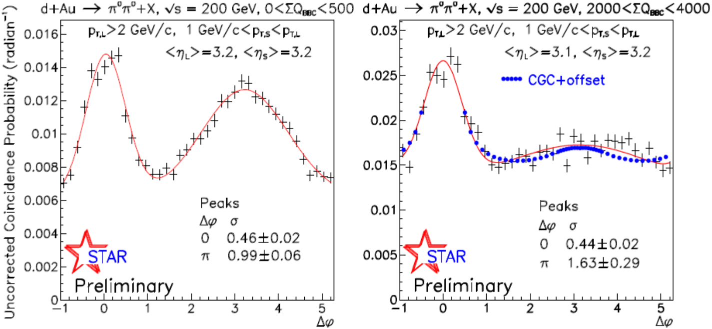
J/Ψ



Small-x part of parton distribution is probed from the target side

Examples of suppression in RHIC *dAu* data

Two-pion correlations at forward rapidity, coincidence probability



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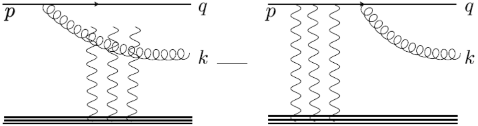
Interpretation of forward hadron suppression

So far two reasonable interpretations exist:

- Saturation of gluon densities in nuclear target
  - Smaller target parton densities at low x
    $\Rightarrow$ suppression [Jalilian-Marian'04]
  - Momentum transfer from target partons $k_t \sim Q_s \sim$few GeV
    $\Rightarrow$ dissociation of quarkonia [Fujii Gelis Venugopalan'06]
    $\Rightarrow$ forward dijet decorrelation [T.Lappi, H.Mantysaari'12].



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- Parton energy loss interpretation
  - Due to induced gluon radiation projectile parton distribution has to be taken at higher x values where it is depleted
  - Only qualitative explanations in some cases.

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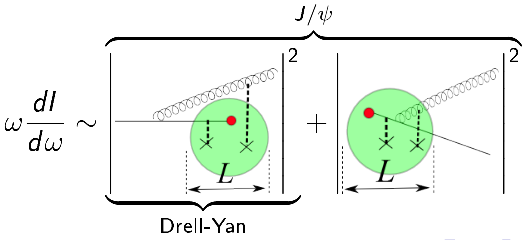
This talk: Mechanism of *coherent* parton energy loss in forward light hadron, di-jet and quarkonia production in pA collisions

Gavin–Milana model of J/ψ suppression

First attempt to describe J/ψ suppression via E-loss [Gavin Milana'92]
Energy loss via the induced initial and final state radiation and scaling (the average) as

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

allows for description of both Drell-Yan and J/ψ suppression at high x_F in E866 ($\sqrt{s} = 38.7$ GeV)



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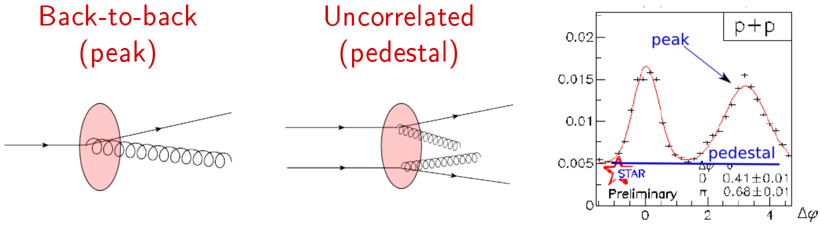
Caveats

- Based on ad hoc assumption $\Delta E \propto E$ for the scaling properties of IS and FS induced radiation
- Failure to describe Υ suppression
- $\Delta E \propto E$ is incorrect for the purely IS and FS induced radiation

Note however the $\Delta E \propto E$ scaling.

Forward di-jet suppression from energy loss [Strikman, Vogelsang'10

Target rest frame:



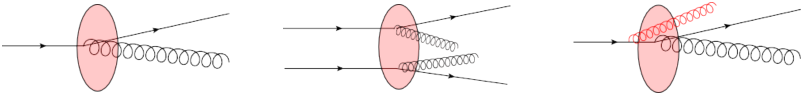
- Back2back fwd jets come from splitting of a parton with $x \sim 1$
- Extra rescatterings in nuclear target lead to induced radiation
  $\Rightarrow$ higher x_{proj} needed to produce a dijet with same kinematics
- Suppression is less for uncorrelated contribution
  (both nucleons can contribute in *dAu*, smaller shift in x_{proj})

Qualitative explanation relying on importance of energy loss

Forward di-jet suppression from energy loss [Strikman, Vogelsang'10

Target rest frame:

Back-to-back (peak)	Uncorrelated (pedestal)	Back-to-back with extra gluon



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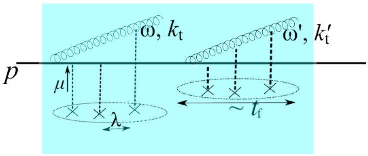
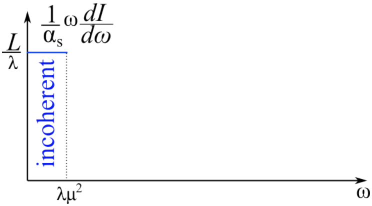
Qualitative explanation relying on importance of energy loss

Energy loss of asymptotic parton

Radiation formation time: $t_f = \omega / k_t^2$

- Small ω, $t_f < \lambda$, $L/\lambda \Rightarrow$
  Independent radiation at each scattering
  $$\omega \left.\frac{dI}{d\omega}\right|_L = \frac{L}{\lambda}\omega \left.\frac{dI}{d\omega}\right|_{\text{single}} \sim \frac{L}{\lambda}\alpha_s$$





Energy loss of asymptotic parton

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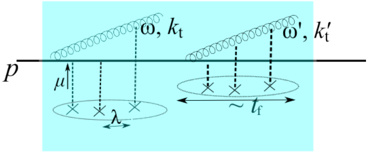

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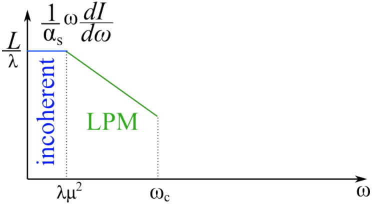
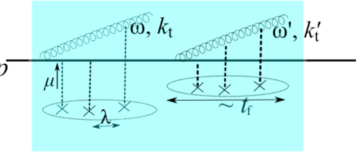
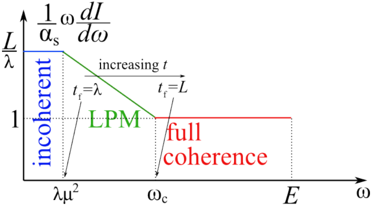
  Independent radiation at each scattering
  $$\omega \left.\frac{dI}{d\omega}\right|_L = \frac{L}{\lambda}\omega \left.\frac{dI}{d\omega}\right|_{\text{single}} \sim \frac{L}{\lambda}\alpha_s$$
- Larger ω, $\lambda \ll t_f \ll L$
  $$\Leftrightarrow \lambda\mu^2 \ll \omega \ll \omega_c \equiv \frac{\mu^2 L^2}{\lambda}$$
  $$t_f = \frac{\omega}{k_t^2(t_f)} = \frac{\omega}{t_f/\lambda\mu^2} = \sqrt{\frac{\lambda\omega}{\mu^2}}$$
  Medium acts as effective scatt. centers,
  $$\omega \left.\frac{dI}{d\omega}\right|_L \sim \frac{L}{t_f(\omega)}\omega \left.\frac{dI}{d\omega}\right|_{\text{single}} \sim \sqrt{\frac{\omega_c}{\omega}}\alpha_s$$



Energy loss of asymptotic parton

- Even larger $\omega \gg \omega_c$
  (Small medium $L < \sqrt{\lambda E/\mu^2} \Leftrightarrow \omega_c < E$)
  - $t_f \gg L$
  - Comes from interference of initial- and final-state emissions
  - Medium acts as a single scatt. center $k_t^2 \sim \frac{L}{\lambda}\mu^2$, similar to Gunion-Bertch
  - Dominant contribution to the E-loss
    $\Delta E \sim \alpha_s E \ln \frac{\langle k_t^2(L)\rangle}{\Lambda^2}$



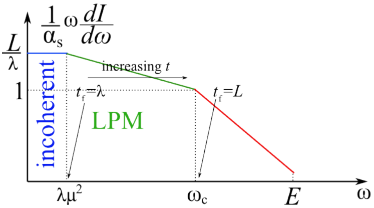


Parton born in medium

Different setup: instantly produced parton radiates w/o medium

$$\omega \left.\frac{dI}{d\omega}\right|_{\mathrm{ind}} = \omega \left.\frac{dI}{d\omega}\right|_{L} - \omega \left.\frac{dI}{d\omega}\right|_{L=0}$$

- $\omega < \omega_c \Leftrightarrow t_f < L$
  - same as for asympt. charge
- $\omega > \omega_c$
  - $t_f \geq L$ cancels out in the induced spectrum
  - Left with radiation of $k_t^2 \sim \omega/L$
  - $\omega \frac{dI}{d\omega} \sim \alpha_s \frac{1}{\omega}$



$$\Delta E \sim \alpha\omega_c \sim \alpha_s \frac{\mu^2 L^2}{\lambda}$$

Coherent vs incoherent E-loss

Initial/final state energy loss

Interference btw. initial and final state emissions can be neglected

- prompt photons, Drell-Yan, weak bosons
- jets and hadrons produced at large angles

Coherent energy loss (asymptotic parton)

Comes from interference between IS and FS emission amplitudes

- Long formation times of induced radiation
- Color charge must be resolved in hard process
- Medium modifications to ΔE due to extra rescatterings – *induced radiation* – also scale as E [Arleo, Peigné, Sami 2011]

Coherent induced radiation, the setup

Working in target rest frame

- tag on final energetic compact color object with $M_t^2 \gg \hat{q}L$
- energetic parent parton suffers
  - single hard exchange $q_t^2 \gg \hat{q}L$
  - multiple semihard $\ell_t^2 \sim \hat{q}L \ll q_t^2$

$\omega \frac{dI}{d\omega}$ derived in the opacity expansion [Gyulassy,Levai,Vitev 2000]

Coherent induced radiation, the setup

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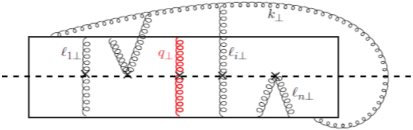
Focus on the part of the induced spectrum which gives $\Delta E \sim E$

- Implies induced radiation with $t_f \gg L$
- Purely Initial State and Final State radiation are affected by the medium only for $t_f \lesssim L \Rightarrow$ negligible
- Only interference terms contribute at $t_f \gg L$



Coherent induced radiation, the setup

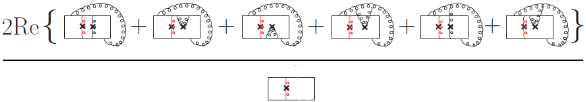
Compact color object in a final state:

- Same color representation for incoming and outgoing object
    - Elastic scattering of a color charge (q or g) tagged with $q_t \gg \hat{q}L$ in the final state
    - $g \to q\bar{q}$, $3 \otimes \bar{3} = 1 \oplus 8$
- Different color representations
    - Production of a dijet:
      $q \to qg$, $3 \otimes 8 = 3 \oplus \bar{6} \oplus 15$
      $g \to gg$, $8 \otimes 8 = 1 \oplus 8_a \oplus 8_s \oplus 10 \oplus \overline{10} \oplus 27$

Lowest order in opacity, same color representation

$q \to q$ and $g \to g(q\bar{q})$ case:

$$x \frac{dI}{dxd^2k_t} = \frac{\alpha_s}{\pi^2} \int \frac{dzd^2\ell}{C_R \lambda_R} V(\ell)$$



$x \equiv \omega_g/E$ – energy fraction carried by the soft gluon.
q_t (or M_t) dependence enters via the final state gluon emission vertex.

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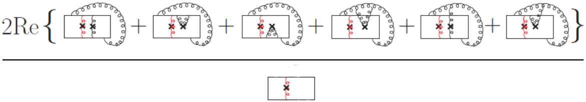

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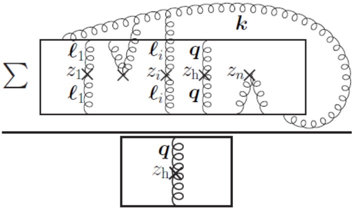
The answer:

$q(g) \to q(g)$: $$x\frac{dI}{dx} = (2C_R - N_c)\frac{\alpha_s}{\pi}\frac{L}{\lambda_g}\ln\left(1 + \frac{\mu^2}{x^2q^2}\right)$$

$g \to q\bar{q}$: $$x\frac{dI}{dx} = N_c\frac{\alpha_s}{\pi}\frac{L}{\lambda_g}\ln\left(1 + \frac{\mu^2}{x^2M_t^2}\right)$$

All orders in opacity

$$x \frac{\mathrm{d}I^{(n)}}{\mathrm{d}x} = \frac{\alpha_s}{\pi^2} \int \mathrm{d}^2\boldsymbol{k} \left[\prod_{i=1}^{n} \int \frac{\mathrm{d}z_i}{C_R \lambda_R} \int \mathrm{d}^2\boldsymbol{\ell}_i \, V(\boldsymbol{\ell}_i) \right]$$



[Peigné, Arleo, RK 1402.1671]

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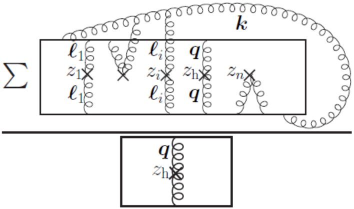

For $L \gg \lambda$

$q(g) \to q(g)$: $$x\frac{dI}{dx} = (2C_R - N_c)\frac{\alpha_s}{\pi}\ln\left(1 + \frac{\mu^2\frac{L}{\lambda_g}\ln\frac{L}{\lambda_g}}{x^2 q^2}\right)$$

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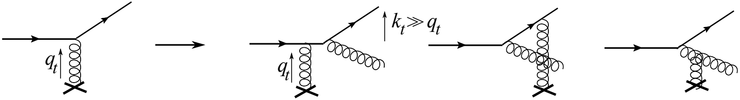
[Peigné, Arleo, RK 1402.1671]

Lowest order in opacity, change of color representation

$q \to qg$ case.

Model for a 2-jet production

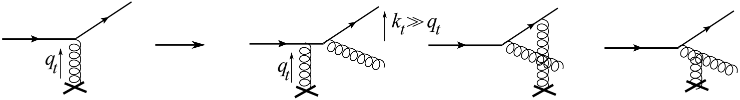


The production amplitude squared:

Lowest order in opacity, change of color representation

$q \to qg$ case.

Model for a 2-jet production



The production amplitude squared:

1^{st} order in opacity:

- 1 additional soft gluon
- 1 additional soft scattering
- $\sim 10^2$ possible arrangements, but LOTS of simplifications

Lowest order in opacity, change of color representation

$q \to qg$ case.

- Focus on radiation with long formation times, $t_f \gg t_{\mathrm{hard}}$
  - soft g emission in the amplitude from incoming q line and in the conjugate from outgoing q or g line

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- Take $N_c \to \infty \Rightarrow$ non-planar graphs are suppressed $(\frac{1}{N_c^2})$

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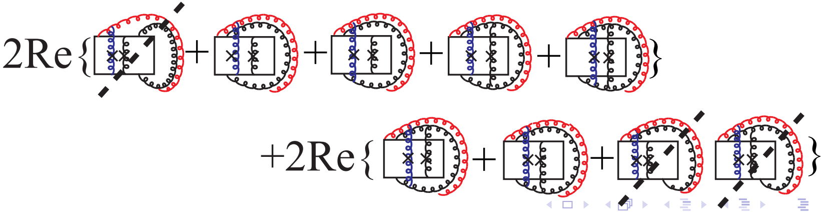

The spectrum

[Peigné, RK 1405:4241

Lowest order:

$$x\frac{dI^{(1)}}{dx}\bigg|_{q\to qg} = \left[1+\frac{(1-x_h)^2\boldsymbol{K}^2}{(\boldsymbol{K}-x_h\boldsymbol{q})^2}\right]^{-1}\frac{N_c\alpha_s}{\pi}\frac{L}{\lambda_g}\log\left(\frac{\mu^2}{x^2\boldsymbol{K}^2}\right)$$

The spectrum

[Peigné, RK 1405:4241

All orders:

$$x\frac{dI}{dx}\bigg|_{q\to qg} = \sum_{n=1}^{\infty} x\frac{dI^{(n)}}{dx}\bigg|_{q\to qg} = \kappa_{q\to qg}\frac{N_c\alpha_s}{\pi}\log\left(\frac{\Delta q_\perp^2(L)}{x^2\boldsymbol{K}^2}\right)$$

$$\kappa_{q\to qg} \equiv \frac{(\boldsymbol{K}-x_h\boldsymbol{q})^2}{(\boldsymbol{K}-x_h\boldsymbol{q})^2+(1-x_h)^2\boldsymbol{K}^2}.$$

The spectrum

[Peigné, RK 1405:4241]

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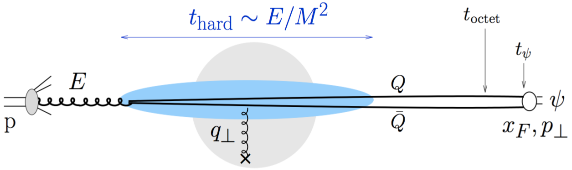
$$\kappa_{q\to qg} \equiv \frac{(\boldsymbol{K}-x_h\boldsymbol{q})^2}{(\boldsymbol{K}-x_h\boldsymbol{q})^2+(1-x_h)^2\boldsymbol{K}^2}.$$

- For $x_h = 1/2$ the spectrum coinsides with the result obtained in the saturation formalism ($\kappa_{q\to qg} = 4/5$) [Liou, Mueller 1402.1647]
- A conjecture guided by the outlined spectra
$$x\frac{dI}{dx}\Big|_{1\to n} = \left[\sum_{R'} P_{R'}(C_R + C_{R'} - C_t)\right]\frac{\alpha_s}{\pi}\log\left(\frac{\Delta q_\perp^2(L)}{x^2\boldsymbol{K}^2}\right)$$
- Prefactor 5/3 for $g\to gg$ case (checked by an explicit calculation, coincides with saturation result [Mueller, private comm.])

Model for heavy-quarkonium suppression

Physical picture and assumptions



- Color neutralization happens on long time scales: $t_{\rm octet} \gg t_{\rm hard}$
- Hadronization happens outside of the nucleus: $t_\psi \gg L$
- $c\bar{c}$ pair produced by gluon fusion
- Medium rescattering do not resolve the octet $c\bar{c}$ pair

Model for heavy-quarkonium suppression

Energy shift

[Arleo Peigné 1212.0434]

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

- pp cross section fitted from experimental data

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

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

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

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

Procedure

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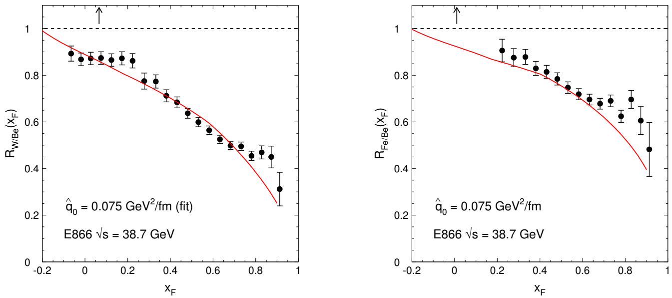
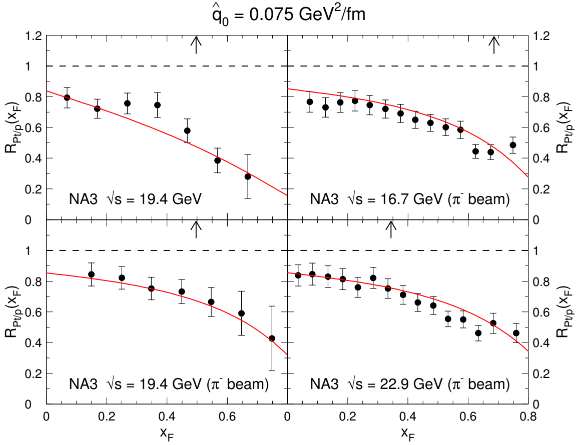
2. Predict J/ψ and Υ suppression for all nuclei and c.m. energies



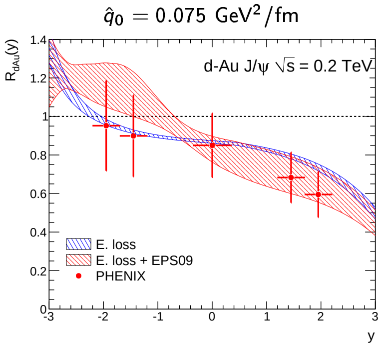
- Fe/Be ratio well described, supporting the L dependence of the model

SPS



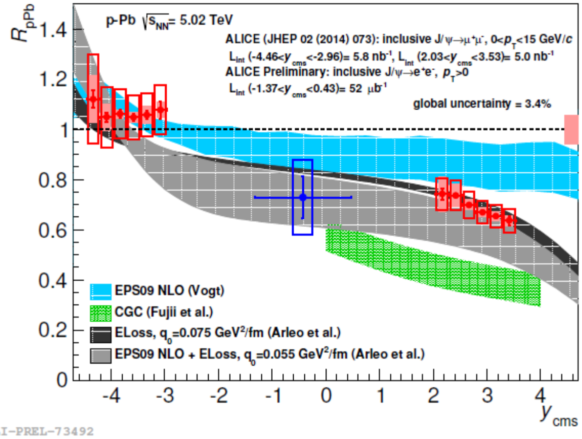
- Agreement when $x_F > x_F^{min}$ (and even below)
- Natural explanation of the different suppression in p A vs π A from $n_{\pi p} = 1.4$ vs. $n_{\pi p} = 4.3$

RHIC



- Good agreement at all rapidity
- nPDF effects may improve the agreement
- Smaller experimental uncertainties would help

Comparison with preliminary ALICE data



- $R_{pA}(y)$: good agreement despite large uncertainty on normalization

Summary

- An honest pQCD calculation of the induced spectrum.
  - Neither initial nor final state effect
  - $dI/d\omega$ and ΔE have specific parametric dependence
- Heavy-quarkonium suppression predicted for wide range of $\sqrt{s}$
  - Good agreement with all existing data for J/ψ including rapidity (x_F, $p_\perp$ and centrality dependence
  - Model in good agreement with LHC p Pb preliminary data

Outlook

- The coherent energy loss taken alone underestimates suppression of ψ' at the LHC.
- Application to forward light hadron production is foreseen.

A conjecture

BACKUP

A conjecture

Motivation for a conjecture:

$$x\frac{dI}{dx}\bigg|_{1\to n} = \left[\sum_{R'} P_{R'}(C_R + C_{R'} - C_t)\right]\frac{\alpha_s}{\pi}\log\left(\frac{\Delta q_\perp^2(L)}{x^2\boldsymbol{K}^2}\right)$$

- Color factors for radiation accompanying elastic $R \to R'$

$$2T_R^a T_{R'}^a = (T_R^a)^2 + (T_{R'}^a)^2 + (T_R^a - T_{R'}^a)^2 = C_R + C_{R'} - C_t$$

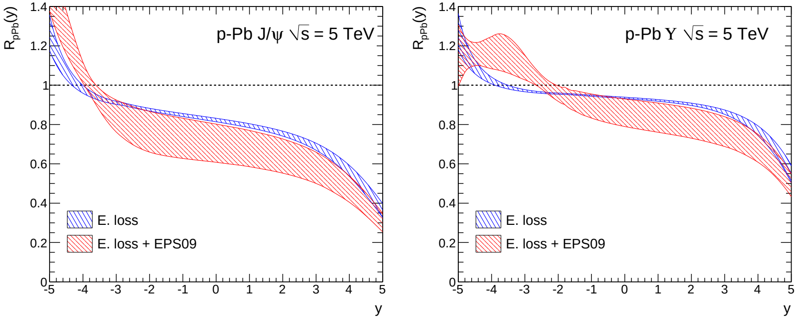
- Logarithmic integration in $\boldsymbol{k}_t$:
  - Compact object $|\boldsymbol{k}_t| \gg x|\boldsymbol{K}|$
  - Constrained by the broadening $\boldsymbol{k}_t \leq \hat{q}L$

LHC predictions

BACKUP

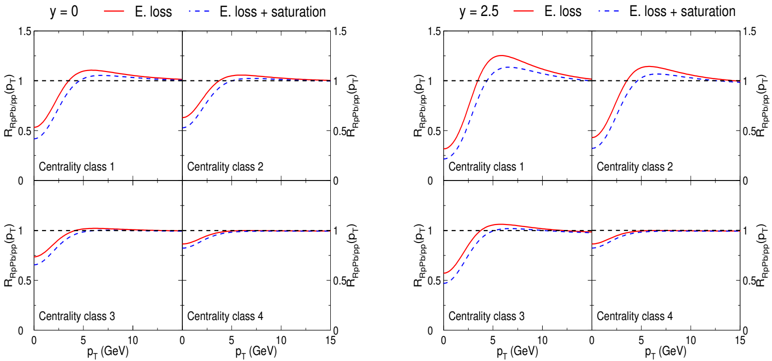
LHC predictions

Υ and J/ψ suppression with error bands



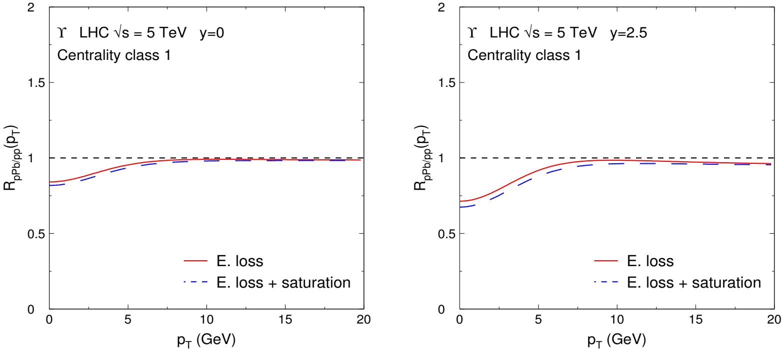
- Weaker suppression for Υ as a consequence of the coherent E-loss scaling properties $\Delta E \propto M_\perp^{-1}$

LHC predictions



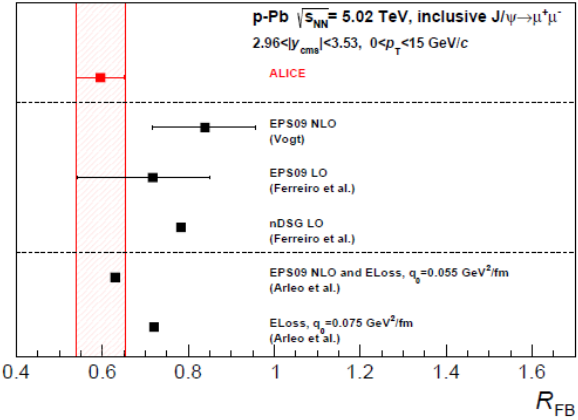
- Suppression expected up to $p_\perp \simeq 3$–4 GeV
- Possible enhancement in most central collisions

LHC predictions



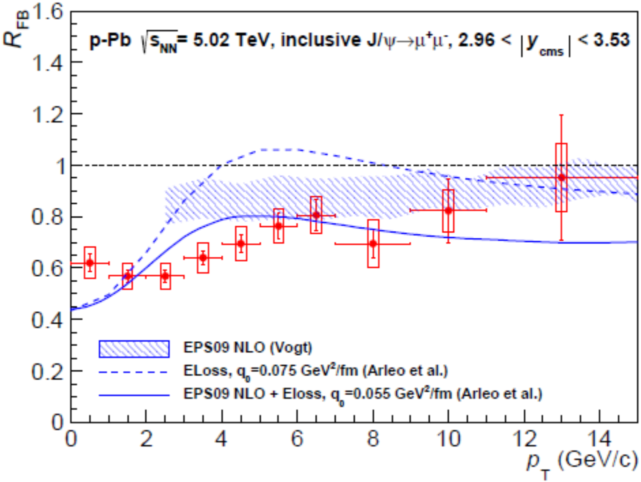
- Weaker suppression in the Υ channel, which however extend to slightly larger $p_\perp$

Comparison with preliminary ALICE data



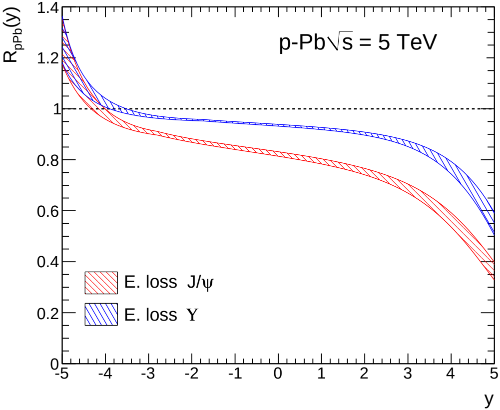
- No pp data at 5 TeV needed $\rightarrow$ smaller uncertainty
- Predictions with only nPDF underestimate the suppression

Comparison with preliminary ALICE data



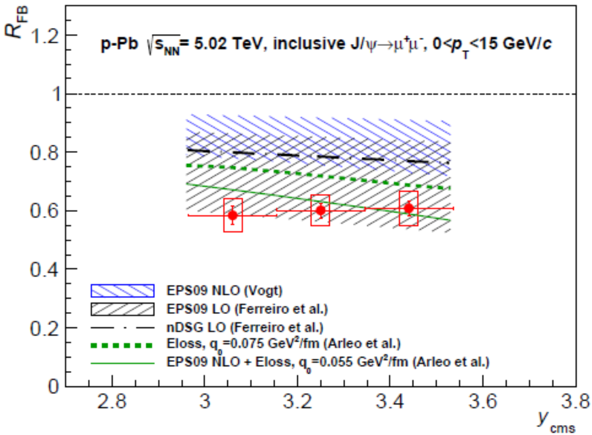
- $R_{FB}(p_\perp)$: good agreement, better agreement with energy loss supplemented by shadowing

Υ suppression at 7 TeV



- Weaker suppression for Υ as a consequence of the coherent E-loss scaling properties $\Delta E \propto M_{\perp}^{-1}$

Comparison with preliminary ALICE data



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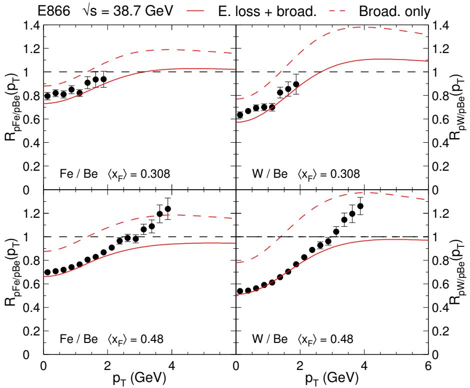
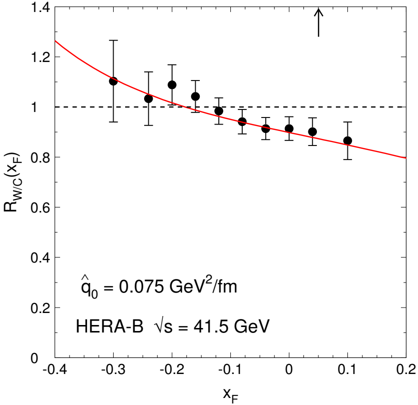
E866 p_t dependence



- 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 $x_F = 0$.

Backup - HERA-B



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

Backup – $L_{\rm eff}$ vs centrality

Glauber, RHIC					Glauber, LHC				
class	$N_p^{\rm min}$; $N_p^{\rm max}$	$\frac{P(\text{class})}{P(N\geq 1)}$	$\langle N_c \rangle$	$L_{\rm Au}$	class	$N_p^{\rm min}$; $N_p^{\rm max}$	$\frac{P(\text{class})}{P(N\geq 1)}$	$\langle N_c \rangle$	$L_{\rm Pb}$
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

Extrapolating to other energies

Two competing mechanisms might alter heavy-quarkonium suppression

- Nuclear absorption if hadron formation occurs inside the medium

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

  - Low $\sqrt{s}$ and/or negative $x_{\rm F}$, indicated on plots for $\tau_{\rm form} = 0.3$ fm ($\uparrow$)

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

  - Low $\sqrt{s}$ and/or negative x_F, indicated on plots for $\tau_{\text{form}} = 0.3$ fm ($\uparrow$)
- nPDF/saturation effects when $Q_s^2 \sim m_c^2$
  - Use nPDF's or parameterized suppression from CGC calculation [Fujii Gelis Venugopalan 2006]

$$R_{pA} = R_{pA}^{\text{E.loss}}(\hat{q}) \times \frac{G_A^{nPDF}(x_2, M_\perp)}{G_p(x_2, M_\perp)} \quad \text{or} \quad R_{pA} = R_{pA}^{\text{E.loss}}(\hat{q}) \times \frac{\mathcal{S}_A^{\text{sat}}(Q_s)}{\mathcal{S}_p^{\text{sat}}(Q_s)}$$

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

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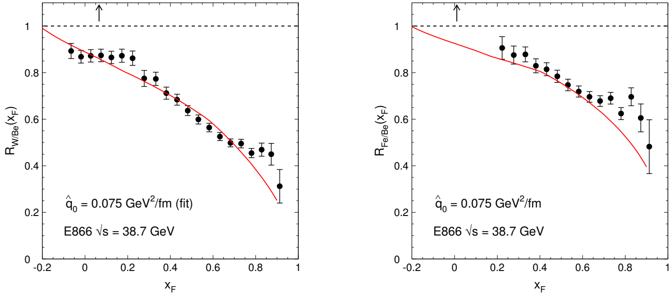

Quenching weight, $P(\epsilon|\Delta q_\perp^2)$

- Radiation with $t_f(\omega_i) \sim \omega_i/\Delta q_\perp^2 \gg L$
- Self-consistency constraint $\omega_1 \ll \omega_2 \ll \ldots \ll \omega_n$

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

Broadening. $\Delta q_\perp^2 = \hat{q}L$

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

$$\hat{q}(x) = \frac{4\pi^2\alpha_s C_R}{N_c^2-1}\,\rho\, xG(x,\hat{q}L) \simeq \hat{q}_0\,\left(10^{-2}/x\right)^{0.3}$$

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

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

$p_\perp$ dependence

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

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

- 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

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

$p_\perp$ dependence

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

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

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

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

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

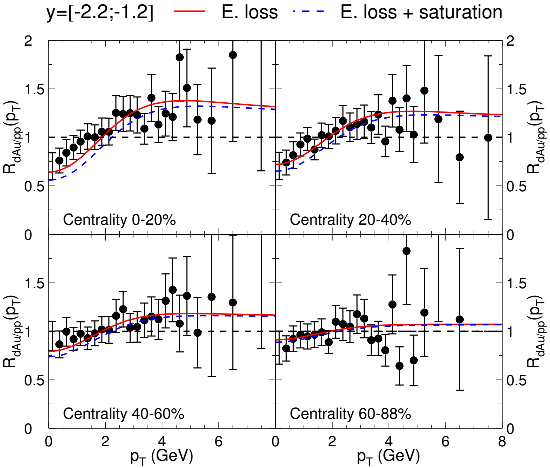
Centrality

Centrality dependence is given by $L_{\rm eff}$

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

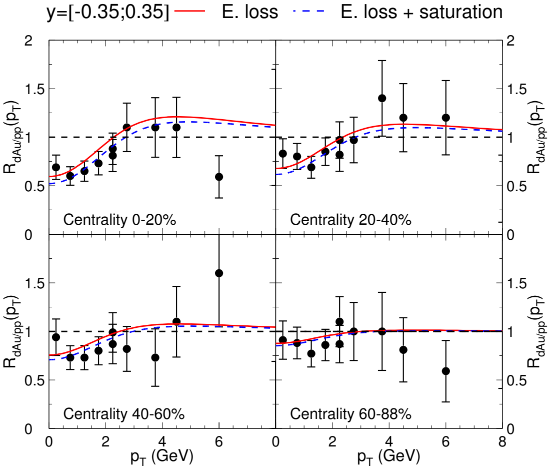
[Arleo, RK, Peigné, Rustamova 1304.0901]

RHIC: p_t and centrality dependence



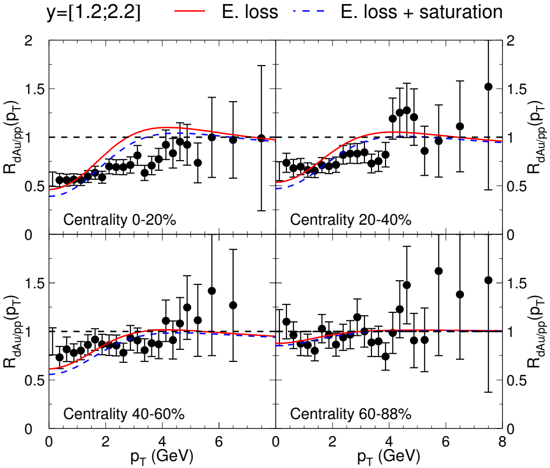
- Good description of $p_\perp$ and centrality dependence at $y = -1.7$

RHIC: p_t and centrality dependence



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

RHIC: p_t and centrality dependence



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