Aspects of J/ψ suppression in cold nuclear matter

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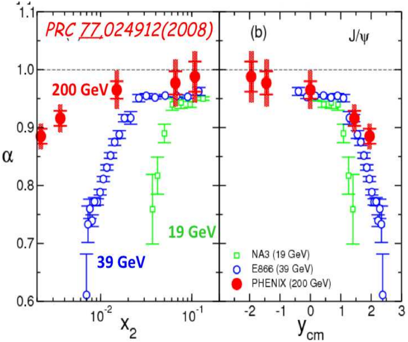
Outline

- Motivations
  - baseline for heavy-ion collisions. . . yet interesting in itself !
- Nuclear absorption
  - theoretical expectations, parametric estimates
  - phenomenology and data analyses
- Nuclear parton distributions
  - phenomenology
  - uncertainties
- Energy loss effects
  - revisiting scaling properties
  - energy loss model and comparison to data

Understanding J/ψ suppression in heavy-ion collisions

Significant J/ψ suppression reported in p A collisions from fixed-target experiments to RHIC



[M. Leitch]

- Might dramatically confuse the interpretation of J/ψ suppression in heavy-ion collisions due to Debye screening in quark-gluon plasma
- Need for precise data and systematic studies

J/ψ suppression in CNM as a probe of QCD processes

Heavy-quark system in a controlled environment

Ideal playground to test QCD phenomena

Lots of physics involved !

- Heavy-quarkonium hadron interaction
- Time-evolution of a $Q\overline{Q}$ dipole, dynamics of hadronization
- Parton distributions in nuclei, saturation
- Parton propagation in dense medium, energy loss processes
- Test of J/ψ production dynamics
- Intrinsic charm in the proton
- Test of QCD factorization in media
- . . .

Nuclear absorption

J/ψ weakly bound state (binding energy $\epsilon_0 \sim 0.7$ GeV)
Inelastic interaction in the final state, e.g. $J/\psi + N \to D + \overline{\Lambda}_c$

J/ψ suppression in p A collisions (Glauber model)

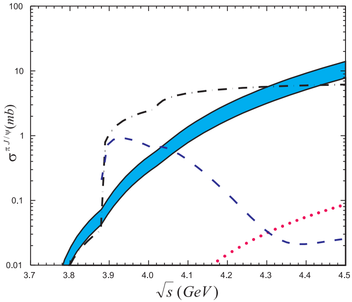
$$R_{pA} = \frac{1}{A\ \sigma_{J/\psi N}} \int d\mathbf{b} \left(1 - e^{-T_A(\mathbf{b})\ \sigma_{J/\psi N}}\right)$$

$$\simeq \exp\left(-\rho\ \sigma_{J/\psi N}\ L\right) \qquad (L \sim A^{1/3})$$

Crucial ingredient: J/ψ N inelastic cross section $\sigma_{J/\psi N}$

Theoretical approaches

Various attempts to compute $\sigma_{J/\psi N}$



[from Rapp Grandchamp 2003]

In all approaches

$\sigma_{J/\psi N} \sim$ mb . . . but depends somehow on the c.m. energy $\sqrt{s_{J/\psi \mathrm{N}}}$

Parametric estimates

In perturbative QCD: $\sigma_{J/\psi h} \sim \alpha_s \, {r_{J/\psi}}^2 \, \left[xG^h(x)\right]$

- Bohr radius $r_{J/\psi} \sim (\alpha_s \, m_Q)^{-1}$ and typical $x \sim (\epsilon_0 / E_{J/\psi})$

Parametric estimates (neglecting logs)

- $\sigma_{\Upsilon N} \simeq (m_c/m_b)^2 \times \sigma_{J/\psi N} \simeq 0.1 \; \sigma_{J/\psi N}$
- $\sigma_{J/\psi N} \propto \left(s_{J/\psi \mathrm{N}}\right)^{\delta}$ with $xG(x) \sim x^{-\delta}$ ($\delta \simeq 0.25$)

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However

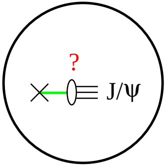
$\sigma_{J/\psi N}$ not relevant at high energy because of formation time effects

Formation time effects

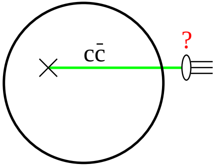
Time-scales

c-quark production time: $\tau_p \sim {m_Q}^{-1} \simeq$ 0.1 fm
J/ψ formation time: $\tau_f \sim (m_{2S} - m_{1S})^{-1} \sim \epsilon_0^{-1} \simeq$ 0.3 fm

Low energy: $t_f = \gamma(x_2)\,\tau_f \ll R$

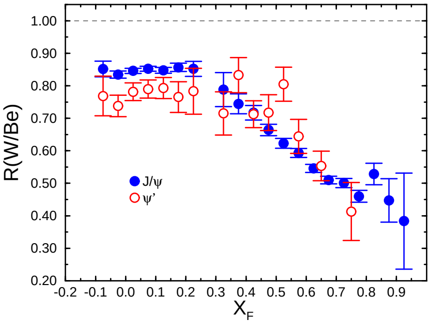


High energy: $t_f = \gamma(x_2)\,\tau_f \gg R$



- Above $E_{J/\psi} \simeq 40$ GeV hadronization outside of the nucleus
- Corresponds to $\sqrt{s_{\rm NN}} \simeq 25$ GeV (at $x_F = 0$), between SPS and FNAL
- Negligible absorption at high energy (?) as $(t_f \gg) t_h \gg R$

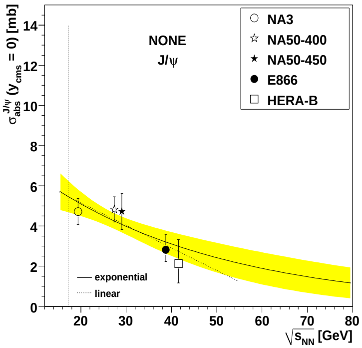
Formation time effects



[E866/NuSea Leitch et al. 99]

- E866/NuSea measurements consistent with formation time effects
  - low x_F: $R^{\psi'} < R^{J/\psi}$
  - large x_F: $R^{\psi'} \simeq R^{J/\psi}$
- Need ψ' data at higher energies (RHIC/LHC)

Energy dependence from data

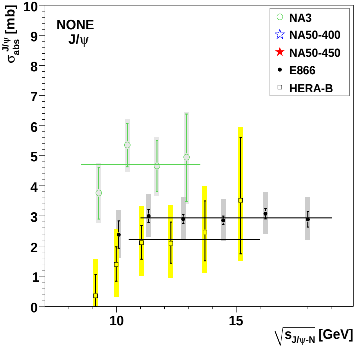


[Lourenço Vogt Wöhri 08]

- Slight decrease of $\sigma_{J/\psi N}$ vs. $\sqrt{s_{\mathrm{NN}}}$

What about $\sigma_{J/\psi N}$ vs. $\sqrt{s_{J/\psi \mathrm{N}}}$?

Energy dependence from data



[Lourenço Vogt Wöhri 08]

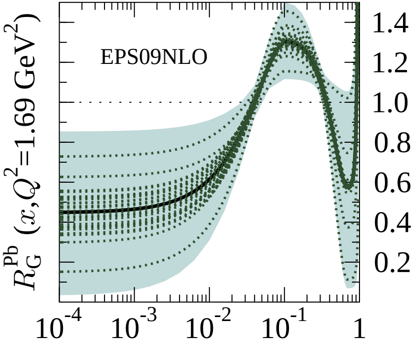
- No energy dependence observed
- Apparent tension among data sets
  - shortcoming of the theoretical approach or experimental issue?
- Delicate extrapolation at higher energies

nuclear PDF

At mid-rapidity: $gg \to c\bar{c}\ X$

$$R^{J/\psi} \sim \frac{G^A(x_2, m_{J/\psi})}{G^p(x_2, m_{J/\psi})} \neq 1$$

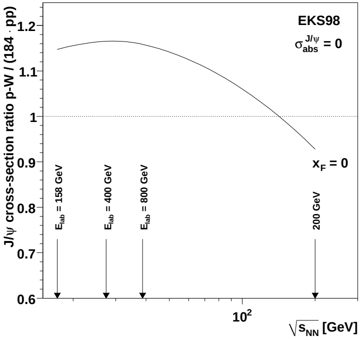
- $x_2 \ll 10^{-1}$: shadowing
- $x_2 \sim 10^{-1}$: antishadowing



[Eskola Paukkunen Salgado 09]

- Significant effects
  - Might be dominant suppression mechanism at high energy (and $y = 0$)
  - spoils the extraction of $\sigma_{J/\psi N}$ from data
  - scaling with x_2 (like nuclear absorption)
- Very large uncertainties
  - lack of small x data in e A and p A collisions
  - saturation at very small x_2 $(m_{J/\psi} \sim Q_s(x_2))$ [Gelis Fujii Venugopalan 06]

From SPS to RHIC & LHC



[Lourenço Vogt Wöhri 08]

Expected suppression at mid-rapidity

- SPS to FNAL : 10 – 20% J/ψ enhancement
- RHIC : 10 – 30% J/ψ suppression (?)
- LHC : 30 – 70% J/ψ suppression (??)
- AFTER would study the transition region

Absorption vs. nPDF effects

Major difficulty

Disentangle nuclear absorption from nPDF effects

- $\sigma_{J/\psi N}$ can't be determined with precision better than a factor 2

	Proton	nDS	nDSg	EKS98	EPS08	HKM
$\sigma_{J/\psi N}^{\rm nPDF}$ (mb)	3.4 $\pm$ 0.2	3.5 $\pm$ 0.2	4.0 $\pm$ 0.2	5.2 $\pm$ 0.2	6.0 $\pm$ 0.2	3.6 $\pm$ 0.2
$\chi^2/{\rm ndf}$	1.4	1.4	1.5	1.5	1.7	1.4

[FA Tram 06]

Absorption vs. nPDF effects

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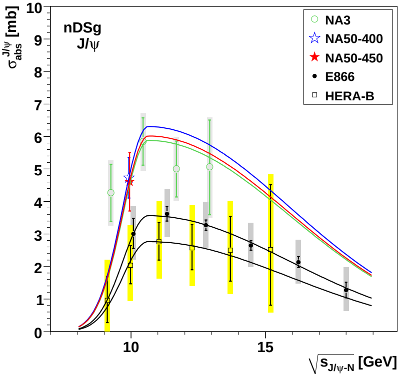
Disentangle nuclear absorption from nPDF effects

- $\sigma_{J/\psi N}$ can't be determined with precision better than a factor 2
- Possible energy dependence of $\sigma_{J/\psi N}(\sqrt{s_{J/\psi \mathrm{N}}})$ for specific nPDF sets

Absorption vs. nPDF effects



[Lourenço Vogt Wöhri 08]

- Energy dependence visible if strong nPDF effects

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- Possible dependence on the partonic process

[Ferreiro Fleuret Lansberg Rakotozafindrabe 08]

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[Ferreiro Fleuret Lansberg Rakotozafindrabe 08]

Various possibilities

- compare (1s), (2s) and (1p) states
- compare charmonia and bottomonia
- compare hidden and open heavy flavor production

Intrinsic charm

J/ψ production from the charm Fock component of the proton

[Brodsky Hoyer 89]

$$|p\rangle = |uud\rangle + |uudg\rangle + \cdots + |uud\,c\bar{c}\rangle + \ldots$$

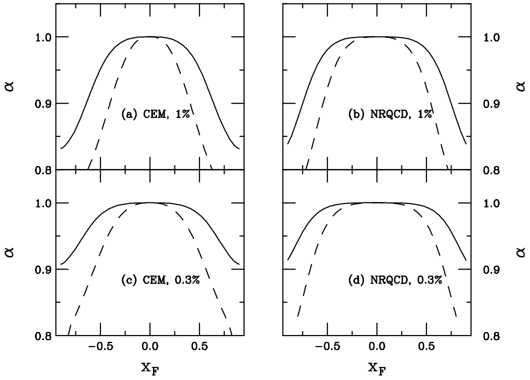
Qualitative features

- $c\bar{c}$ freed from the hadronic interaction on the front surface of the target

$$\alpha \simeq 2/3$$

- More important at large x_F
- x_F scaling (as seen in data)
- Crucially depends on the amount of charm in the proton
- Also affects open heavy flavor production

Intrinsic charm phenomenology

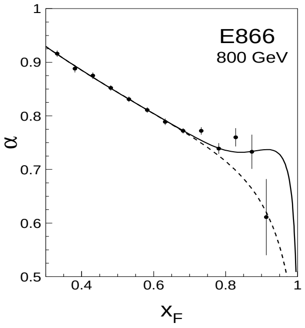


[Vogt 99]

- Might affect J/ψ nuclear production at FNAL say above $x_F \simeq 0.25$
- Larger effects at lower center-of-mass energy
- Unable to reproduce (alone) E866/NuSea data given the current constraints on charm in the proton ($\lesssim 1\%$)

Intrinsic charm phenomenology

[Kopeliovich Potashnikova Schmidt 10]



- Nuclei transparent to IC components in the projectile
  - relative "enhancement" of open and hidden heavy-flavor production
- Consistent with SELEX data on open charm production
- Slight effect on J/ψ suppression at large x_F

Energy loss

Picture

The incoming parton loses energy due to multiple scattering in the nuclear target, shifting its momentum fraction by an amount $\Delta x_1 = \epsilon / E_p$

Consequence on J/ψ supression

$$R_{pA}(x_1) \simeq \int d\epsilon \, \mathcal{P}(\epsilon) \times f_i(x_1 + \Delta x_1(\epsilon)) / f_i(x_1)$$

- $\mathcal{P}(\epsilon)$: probability distribution [Baier Dokshitzer Mueller Schiff 01]
- Significant suppression from the steep PDF especially at large x_1
- No suppression expected as long as $\Delta x_1 \ll x_1$

Energy loss phenomenology

Gavin-Milana model

[Gavin Milana 92]

- $\langle \epsilon \rangle \propto E_i \to \Delta x_1 \propto x_1$: x_1 scaling of J/ψ suppression
- Should also affect Drell-Yan nuclear dependence
- Energy loss processes also in the final state

Energy loss phenomenology

Gavin-Milana model

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- $\langle\epsilon\rangle \propto E_i \rightarrow \Delta x_1 \propto x_1$: x_1 scaling of J/ψ suppression
- Should also affect Drell-Yan nuclear dependence
- Energy loss processes also in the final state

Caveats

- Ad hoc assumption regarding E, L, and M dependence of parton energy loss
- Failure to describe Υ suppression
- $\Delta E \propto E$ claimed to be incorrect in the high energy limit due to uncertainty principle – so-called Brodsky-Hoyer bound

Energy loss phenomenology

Induced gluon radiation needs to resolve the medium [Brodsky Hoyer 93]

$$t_f \sim \frac{\omega}{k_\perp^2} \lesssim L \qquad \omega \lesssim k_\perp^2 \; L \sim \hat{q} \; L^2$$

- Bound independent of the parton energy
- Energy loss cannot be arbitrarily large in a finite medium
- Apparently rules out energy loss models as a possible explanation

However, not true in general in QCD [FA Peigné Sami 10]

Revisiting energy loss scaling properties

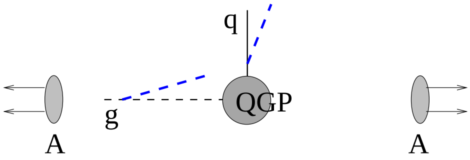
Two cases whether gluon radiation is coherent or incoherent

(i) Incoherent radiation in the initial/final state

Radiation of gluons with large formation times cancels out in the induced gluon spectrum, leading to $t_f \sim L$

$$\Delta E \propto \hat{q} L^2$$

- Hadron production in nuclear DIS and Drell-Yan in p A collisions
- Jets and hadrons produced in hadronic collisions at large angle (e.g. jet quenching in heavy-ion collisions)



Revisiting energy loss scaling properties

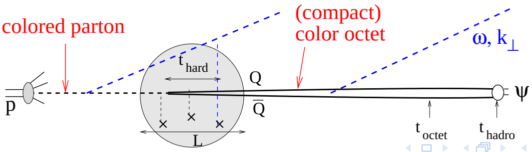
Two cases whether gluon radiation is coherent or incoherent

(ii) Coherent radiation (interference) in the initial/final state

Induced gluon spectrum dominated by large formation times

$$\Delta E \propto \frac{\sqrt{\hat{q} L}}{M}\, E$$

- 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

$$\Delta E = \int d\omega\, \omega\, \frac{dI}{d\omega}\bigg|_{\rm ind} = N_c \alpha_s \frac{\sqrt{\hat{q}L} - \Lambda_{\rm QCD}}{M_\perp}\, E$$

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

Model for heavy-quarkonium suppression

[FA Peigné 1204.4609]

$$\frac{d\sigma_{pA}^{\psi}}{dx_F}(x_F, \sqrt{s}) = \int_0^{\epsilon_{\max}} d\epsilon\, \mathcal{P}(\epsilon)\, \frac{d\sigma_{pp}^{\psi}}{dx_F}(x_F + \delta x_F(\epsilon))$$

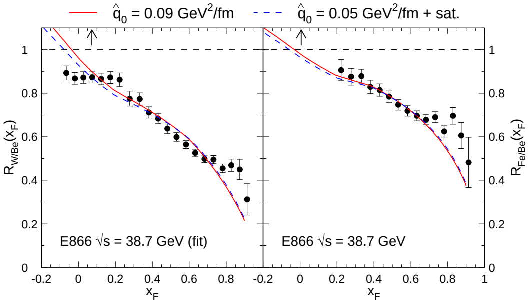
- pp cross section fitted from experimental data

$$\frac{d\sigma_{pp}^{\psi}}{dx_F} \propto (1-x')^n/x' \qquad x' \equiv \sqrt{x_F^2 + 4M_\perp^2/s}$$

- Shift given by $\delta x_F(\epsilon) \simeq \epsilon/E_{\text{beam}}$
- $\mathcal{P}(\epsilon)$: quenching weight, scaling function of $\hat{\omega} = \sqrt{\hat{q}L}/M_\perp \times E$
- Length L given by $L = 3/2\ r_0\ A^{1/3}$
- $\hat{q}_0$ only free parameter of the model

Procedure

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



- $\hat{q}_0 = 0.09 \text{ GeV}^2/\text{fm}$
- Fe/Be ratio well described, supporting the L dependence of the model

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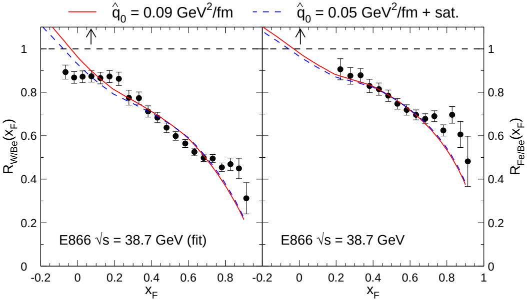

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Let's investigate J/ψ suppression at other energies

Extrapolating to other energies

Two competing mechanisms might alter heavy-quarkonium suppression

- Nuclear absorption if hadron formation occurs inside the medium

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

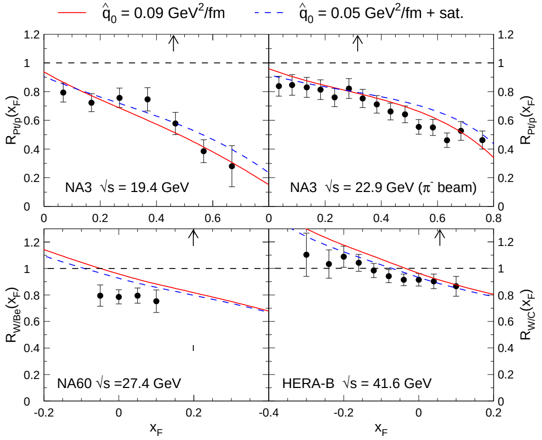
  - low $\sqrt{s}$ and/or negative x_F

- nPDF/saturation effects

$$Q_s^2(x_2) \sim \hat{q} L \sim m_c^2$$

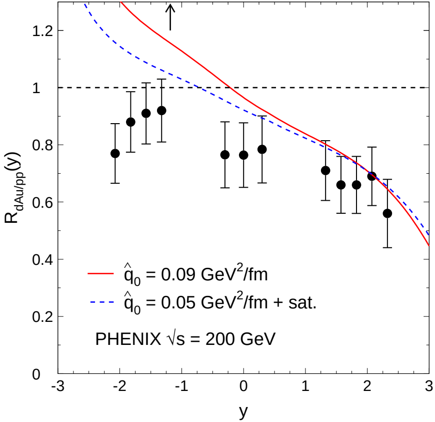
  - high $\sqrt{s}$ and/or positive x_F

SPS predictions



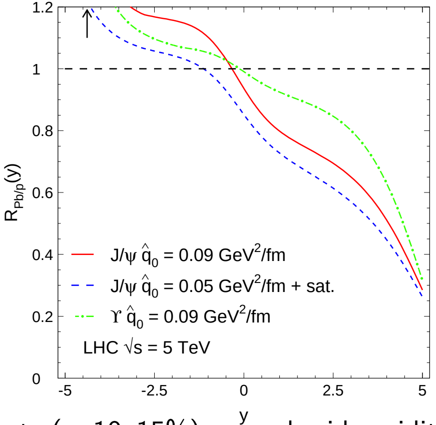
- Agreement when $x_F > x_F^{\min}$
- Room for J/ψ absorption, though weaker than previously thought

RHIC predictions



- Energy loss model fails in the most backward bins
- Saturation effects improve the agreement
- Smaller experimental uncertainties would help

LHC predictions



- Moderate effects ($\sim$ 10–15%) around mid-rapidity
- Large effects above $y \gtrsim 2 - 3$
- Saturation might be the dominant effect at the LHC
- Slightly smaller suppression expected in the Υ channel

Conclusion

Many processes at work !

- Nuclear absorption
  - formation time dynamics at not too high energy
  - possibly small at LHC
- nPDF effects
  - probably the dominant source of J/ψ suppression at LHC at $y = 0$
  - lots of uncertainties
- Energy loss
  - recently revisited
  - might solve the puzzle of J/ψ suppression at large x_F
  - picture breaks down when nuclear absorption plays a role

The challenge: disentangle those effects at a quantitative level

Why AFTER could play an interesting role

- Kinematics
  - $\sqrt{s} = 72$–115 GeV: Interesting "crossroad" between the various effects
  - Wide x_F range covered, covering both negative and positive regions
- Various nuclear targets
  - Testing L dependence, a priori different for each mechanism
- Various states: J/ψ, ψ', χ_c
  - Testing dynamics of color neutralization (energy loss) and hadronization (absorption)

Saturation

J/ψ production in p A collisions depends on the nuclear gluon distribution

$$G^A(x, Q^2) \neq \; A \; G^p(x, Q^2)$$

especially at small $x \ll 1$ due to saturation/shadowing

Heavy-quarkonium including saturation

$$R_{\rm pA} = R_{\rm pA}^{\rm E.loss}(\hat{q}) \times R_{\rm pA}^{\rm sat}(Q_s^2)$$

- $R_{\rm pA}^{\rm sat}$ parametrized as [Fujii Gelis Venugopalan 2006]

$$R_{\rm pA}^{\rm sat} = \left(\frac{2.65}{2.65 + Q_s^2 \; [\mathrm{GeV}^2]} \right)^{0.417}$$

- Saturation scale directly related to $\hat{q}$ through [Mueller 1999]

$$Q_s^2(x) \; = \; 2R \; \hat{q}(x)$$

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Heavy-quarkonium including saturation

$$R_{\rm pA} = R_{\rm pA}^{\rm E.loss}(\hat{q}) \times R_{\rm pA}^{\rm sat}(Q_s^2)$$

- Important at small x i.e. high $\sqrt{s}$ / large rapidity
- No additional parameter
- Reduces fitted transport coefficient: $\hat{q}_0 = 0.04$ GeV^2/fm
  - $Q_s^2(x = 10^{-2}) = 0.14$ GeV^2 consistent with AAMQS fits to DIS data

[Albacete et al AAMQS 2011]