# Aspects of $J/\psi$ suppression in cold nuclear matter

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[based on a scenario by François Arleo]

First ReteQuarkonii Workshop

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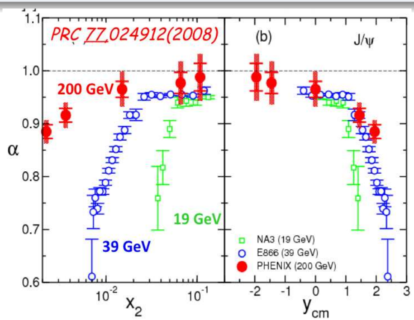
# Outline

- Motivations
  - baseline for heavy-ion collisions
  - . . . interesting in itself !
- Nuclear absorption
  - theoretical expectations, parametric estimates
  - phenomenology and data analyses
- Nuclear parton distributions
  - phenomenology
  - uncertainties
- Other effects
  - revisiting energy loss
  - energy conservation

# Understanding $J/\psi$ suppression in heavy-ion collisions

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




[ M. Leitch ]

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

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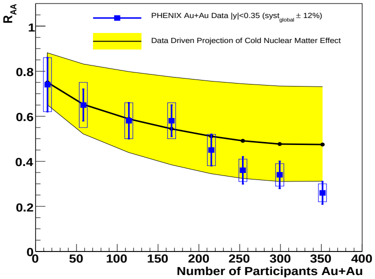


[ R. Granier de Cassagnac hep-ph/0701222 ]

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# $J/\psi$ 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 $J/\psi$ production dynamics
- Intrinsic charm in the proton
- Test of QCD factorization in media
- ...

# Nuclear absorption

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

## $J/\psi$ suppression in p A collisions (Glauber model)

[ Gerschel Hüfner 1988 ]

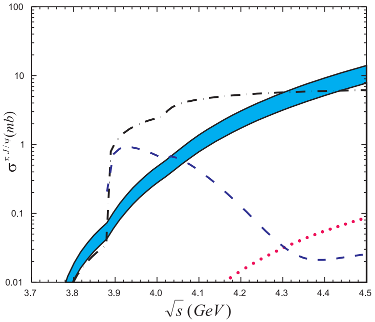
$$
\begin{aligned}
R_{pA} &= \frac{1}{A \ \sigma_{J/\psi N}} \int d\mathbf{b} \left(1 - e^{-T_A(\mathbf{b}) \ \sigma_{J/\psi N}}\right) \\
&\simeq \exp\left(-\rho \ \sigma_{J/\psi N} \ L\right) = \exp\left(-L/\lambda_{inel}\right) \qquad \lambda_{inel} = \left(\rho \ \sigma_{J/\psi N}\right)^{-1}
\end{aligned}
$$

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

# Theoretical approaches

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

- Short-distance (perturbative) QCD [ Bhanot Peskin 79 ]
- Quark exchange model [ Martins Blaschke Quack 95 ]
- D-meson exhange model [ Matinyan Müller 98 ]
- QCD sum rules [ Navarra Nielsen M. de Carvalho Krein 02 ]




- dotted: short-distance QCD
- dashed: c-exchange model
- dash-dotted: D-exchange model
- band: QCD sum rules

[ from Rapp Grandchamp 2003 ]

# Parametric estimates

In all approaches

- $\sigma_{J/\psi N}$ depends on the c.m. energy $\sqrt{s_{J/\psi \mathrm{N}}}$
- $\sigma_{\Upsilon N}/\sigma_{J/\psi N} = \mathcal{O}\left(r_b^2/r_c^2\right) = \mathcal{O}\left(m_c^2/m_b^2\right) \simeq 0.1$

However

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

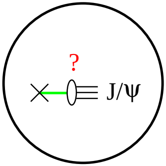
# Formation time effects

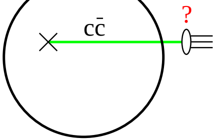
## Time-scales

- $c\bar{c}$ pair production time: $\tau_p \sim (2\ m_Q)^{-1} \simeq 0.05$ fm
- $\tau_p \lesssim$ color neutralization time

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

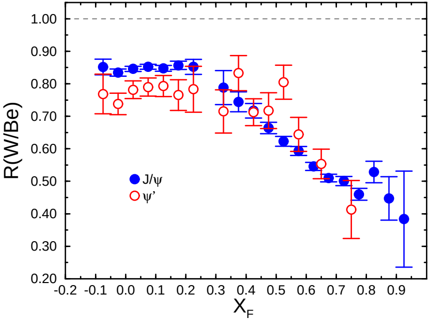
High energy: $t_f = \gamma(x_2)\,\tau_f \gg R$




- Transition occurs at $E_{J/\psi} \simeq 200$ GeV corresponding to $x_F = 0.25$ at FNAL ($E_{beam} = 800$ GeV)

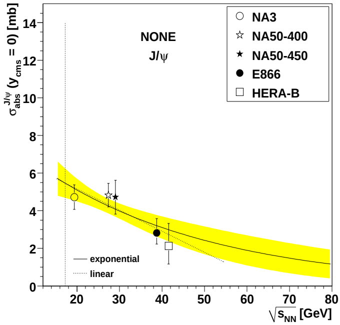
# Formation time effects




[ 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 $\psi'$ data at higher energies (RHIC/LHC)

# Energy dependence from data




[ Lourenço Vogt Wöhri 08 ]

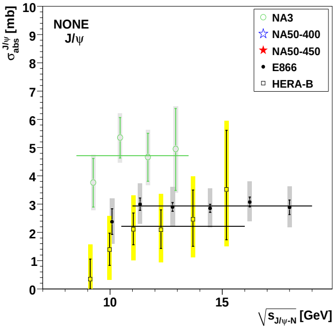
- Slight decrease of $\sigma_{J/\psi N}$ vs. $\sqrt{s_{\rm NN}}$
- Prediction of $\sigma_{J/\psi N}$ at $\sqrt{s_{\rm NN}} = 17.3$ GeV

[ see also Arnaldi Cortese Scomparin 10 ]

# Energy dependence from data

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

$$s_{J/\psi N} = x_1 \; s_{NN} = \mathcal{O}\left(\frac{m_{J/\psi}{}^2}{x_2}\right)$$




[ Lourenço Vogt Wöhri 08 ]

Apparent tension among data sets

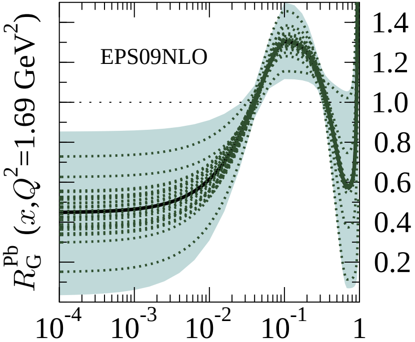
- shortcoming of the theoretical approach or experimental issue?
- no scaling in $x_2$
- suggests suppression effects other than nuclear absorption

# nuclear PDF

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

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

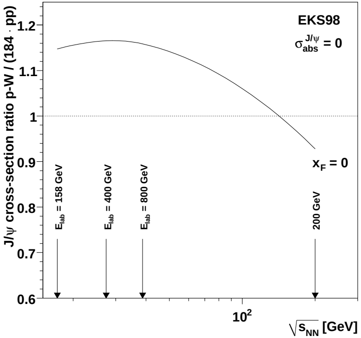
- $x_2 \ll 10^{-1}$ : shadowing
- $x_2 \sim 10^{-1}$ : antishadowing




[ Eskola Paukkunen Salgado 09 ]

- Significant effects
  - scaling with $x_2$ (like nuclear absorption)
  - probably dominant suppr. mechanism at high energy (at mid-rapidity)
  - spoils the extraction of $\sigma_{J/\psi N}$ from data
- 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

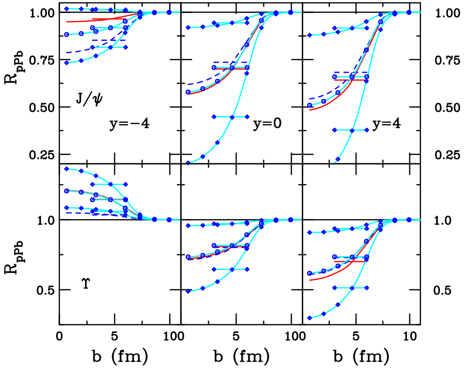



[ Lourenço Vogt Wöhri 08 ]

## Expected suppression at mid-rapidity

- SPS to FNAL : 10 – 20% $J/\psi$ enhancement
- RHIC : 10 – 30% $J/\psi$ suppression (?)
- LHC : 30 – 70% $J/\psi$ suppression (??)

# Centrality dependence



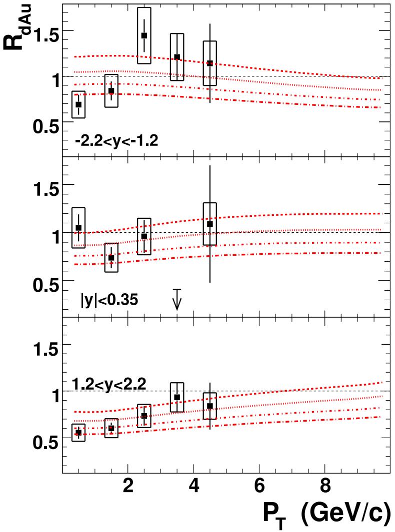

[ Vogt 10 ]

- Inhomogeneous shadowing proportional to the local nuclear density

[ Klein Vogt 03 ]

- Enhanced effects in most central collisions
- Need for centrality-dependent p A data
- Similar predictions in A A collisions vs. $N_{\text{part}}$

# Transverse momentum dependence




[ Ferreiro Fleuret Lansberg Rakoto.abe 10 ]

- Weak $p_\perp$ dependence from
  - $x_\perp \propto \left(m^2_{J/\psi} + p^2_\perp\right)^{1/2}$
  - QCD evolution $\mu^2 \sim x^2_\perp s$
- Need precise data and larger $p_\perp$
- Might be spoiled by the Cronin effect

# 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 |
|---|---|---|---|---|---|---|
| $\sigma^{\mathrm{nPDF}}_{J/\psi \mathrm{N}}$ (mb) | $3.4 \pm 0.2$ | $3.5 \pm 0.2$ | $4.0 \pm 0.2$ | $5.2 \pm 0.2$ | $6.0 \pm 0.2$ | $3.6 \pm 0.2$ |
| $\chi^2/\mathrm{ndf}$ | 1.4 | 1.4 | 1.5 | 1.5 | 1.7 | 1.4 |

[ FA Tram 06 ]

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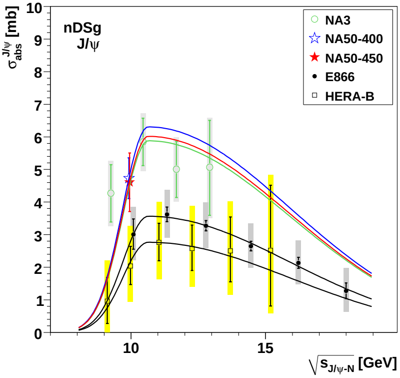
- Possible energy dependence of $\sigma_{J/\psi N}(\sqrt{s_{J/\psi \mathrm{N}}})$ for specific nPDF sets

# 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

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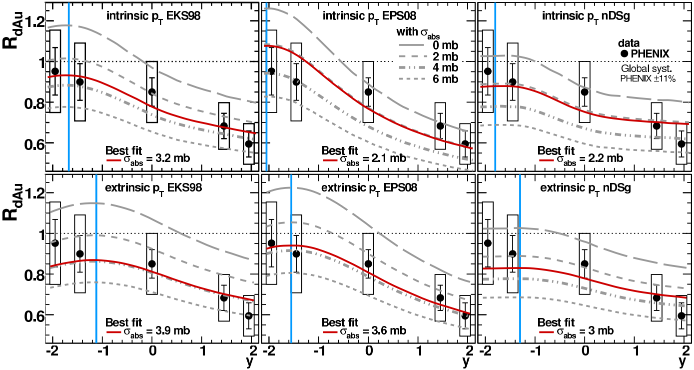


[ Ferreiro Fleuret Lansberg Rakotozafindrabe 08 ]

nPDF effects different at LO and at NLO

- larger $x_2$ probed in $2 \to 2$ processes

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Various possibilities

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

# 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 $J/\psi$ supression

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

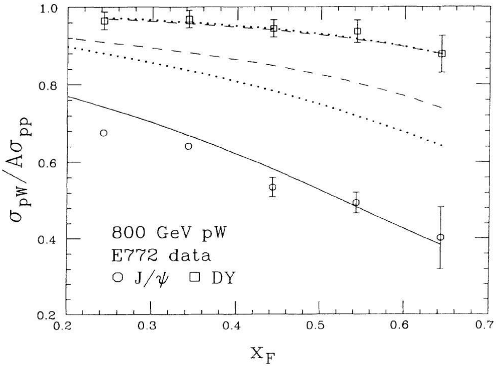
- $\mathcal{P}(\epsilon)$: probability distribution [ Baier Dokshitzer Mueller Schiff 01 ]
- Significant suppression from the steep PDF especially at large $x_1$
- No suppression expected as long as $\Delta x_1 \ll x_1$

# Energy loss phenomenology

## Gavin-Milana model

[ Gavin Milana 92 ]

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



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## Brodsky-Hoyer bound on energy loss

[ Brodsky Hoyer 93 ]

Assumption: Induced gluon radiation needs to resolve the medium

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

- 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

# Revisiting energy loss

[ FA Peigné Sami 10 ]

(i) For a parton produced in the medium, radiation of gluons with large formation times cancels out in the induced gluon spectrum

$$\left.\frac{dI}{d\omega}\right|_{\rm ind} = \left.\frac{dI}{d\omega}\right|_{\rm pA} - \left.\frac{dI}{d\omega}\right|_{\rm pp}$$

leading to Brodsky-Hoyer bound for DIS, DY, large-$p_\perp$ jets...

(ii) For a color charge produced nearly collinearly to an initial state parton, interference terms dominate the induced spectrum

- induced radiation dominated by large formation times : no bound !
- energy loss proportional to the parton energy $\Delta E \sim \alpha_s \, \frac{\langle \Delta q_\perp \rangle}{M} \, E$

## Qualitative consequences

- Might explain $J/\psi$ suppression at large $x_F$ due to the propagation of the color octet $c\bar{c}$ state in the nucleus
- Should also affect open charm production, not DY nor DIS on nuclei

# Energy conservation

- As $x_F \to 1$ the probability for no-gluon emission leads to a Sudakov suppression [ Kopeliovich Nemchik Potashnikova Johnson Schmidt 05 ]

$$S(x_F) \sim (1 - x_F)^{dn_g/dy} \simeq (1 - x_F)$$

- Probability much smaller in nuclei because of final state inelastic interaction

$$S^{pA}(x_F) \sim (1 - x_F)^{dn_g^A/dy} \simeq (1 - x_F)^{\alpha} \qquad \alpha > 1$$

Consequences

- Looks like an effective energy loss scaling like the parton energy
- $J/\psi$ suppression at large $x_F$
- Should also affect other hard processes: DIS at large $z$, DY and hadron production at large $y$

# Conclusion

Many processes at work !

- Nuclear absorption
  - $\sigma_{J/\psi N}$ relevant when $J/\psi$ formed in the nucleus
  - extraction of $\sigma_{J/\psi N}$ from data is delicate
- nPDF effects
  - probably the dominant source $J/\psi$ suppression at LHC at mid-rapidity
  - large uncertainties
- Large $x_F$ suppression
  - still not fully understood
  - new developments on energy loss
  - role of energy conservation

Analyses of p A quarkonium data highly needed