

# Cold nuclear matter effects on charmonium production in RHIC and LHC energy domain



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# Motivation

- $J/\psi$  suppression is one of the oldest signature of QGP formation in relativistic nuclear collision (**T.Matsui and H.Satz, PLB, 1986**).
- Subsequent fixed target experiments: NA38, NA50, NA60 at CERN SPS and PHENIX at RHIC ,HERA-B at DESY and E772, E886, E906 at FERMILAB measured charmonia production cross section.
- They observed that charmonia production cross section in pA collisions increases less than linearly with the number of binary collisions  
 $\implies$  **Cold Nuclear Matter suppression or "normal" suppression**



1975-1982, U.S. PATENT

BROOKHAVEN NATIONAL LABORATORY

May 1986

PHYS. LETT. B

## $J/\psi$ SUPPRESSION BY QUARK-GLUON PLASMA FORMATION

T. Matsui  
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Laboratory for Nuclear Science  
Massachusetts Institute of Technology  
Cambridge, MA 02139, USA

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Brookhaven National Laboratory, Upton, NY 11973, USA

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31st 1986

### Jet quenching in dense matter

Miklós Gyulassy and Michael Plüme<sup>1</sup>

Nuclear Science Division, Lawrence Berkeley Laboratory, Berkeley CA 94720, USA

Received 23 March 1986

The quenching of hard jets in ultrarelativistic nuclear collisions is estimated emphasizing its sensitivity to possible changes in the energy loss mechanism in a quark-gluon plasma.



16 February 1986

PHYSICS LETTERS B

Physica Letters B 50 (1986) 271-286

### Induced gluon radiation in a QCD medium

R. Baier<sup>a</sup>, Yu.L. Dokshitzer<sup>b,c</sup>, S. Frixione<sup>d</sup>, D. Schiff<sup>e</sup>

<sup>a</sup> Laboratoire de Physique, Université de Bonn, D-5300 Bonn, Germany

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# Cold Nuclear Matter(CNM)

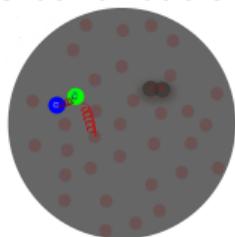
- **CNM effect is a convolution of several effects:**
  - Initial state effect
  - Final state effect
- Initial state effects prior to  $c\bar{c}$  production  $\implies$  a. Nuclear partons distribution function
  - b. Initial state parton energy loss
- Final state effects post of  $c\bar{c}$  production  $\implies$  a. Final state absorption<sup>1</sup>
  - b. Final state  $c\bar{c}$  energy loss

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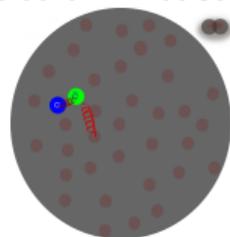
<sup>1</sup>S.K.Giri et.al;J. Subatomic Part. Cosmol. 4; 100132 (2025)[[Link](#)]

# How charmonia interact with normal nuclear matter??

- charmonia are produced by two step factorizable process in a nuclear collision.
  - Color  $c\bar{c}$  production by perturbative process sensitive to initial state effects
  - Color-neutral resonance state formation by non-perturbative soft gluon emission
- Based on the "color" state of nascent  $c\bar{c}$  pairs, three different kinematical regions can be identified:
  - **Color octet region**
  - **Resonance region**
  - **Transition region**
- Depending on the collision energy, production kinematics and system size, each region would have its contribution for the charmonia production measured experimentally



Transition region



Color octet region

# Brief theoretical formalism of charmonia production in pA collision

- The framework employed here to account the  $J/\psi$  production in leading order  $\implies$  **CEM**
- Production cross sections of any charmonia state is constant fraction of total  $c\bar{c}$  produced in the mass window

$$\frac{d\sigma_i}{dx_F} = 2F_i \int_{2m_c}^{2m_D} m \frac{d\sigma^{c\bar{c}}}{dx_F dm^2} dm \quad (1)$$

$$\frac{d\sigma^{c\bar{c}}}{dx_F dm^2} = \int_0^1 dx_1 dx_2 \delta(x_1 x_2 s_{NN} - m^2) \delta(x_F - x_1 + x_2)$$

$$\left\{ f_g^A(x_1, m^2) f_g^B(x_2, m^2) \sigma_{gg}(m^2) + \sum_{q=u,d,s} \left[ f_q^A(x_1, m^2) f_q^B(x_2, m^2) + f_q^A(x_1, m^2) f_q^B(x_2, m^2) \right] \sigma_{q\bar{q}}(m^2) \right\}$$

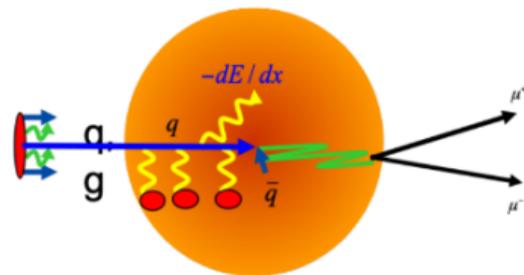
Nuclear Modification



# Introduction of Initial state energy loss

- In presence of energy loss:  $x'_{1q(g)} \longrightarrow x_{1q(g)}$

$$x'_{1q(g)} = x_{1q(g)} + \Delta x_{1q(g)}$$



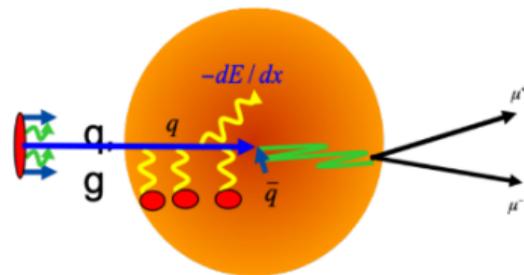
<sup>2</sup>S.K.Giri et. al; Eur. Phys. J. C 85; no.3; 264 (2025)[[Link](#)]

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- Now:  $\Delta x_{1q} = \frac{\Delta E_q}{E_h}$      $\Delta x_{1g} = (9/4)\Delta x_{1q}$
- BH formalism:  $\Delta x_{1q} \approx \frac{\alpha_i}{E_h} \langle L_A \rangle$
- BDMPS formalism:  $\Delta x_{1q} \approx \frac{\beta_i}{E_h} \langle L_A^2 \rangle$



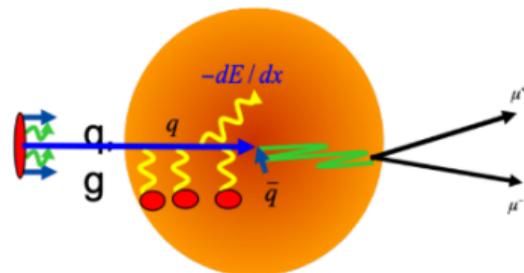
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- This initial state energy loss parameter  $\alpha_i$  and  $\beta_i$  estimated by analyzing the Drell-Yan data<sup>2</sup>

<sup>2</sup>S.K.Giri et. al; Eur. Phys. J. C 85; no.3; 264 (2025)[[Link](#)]

# Account of final state energy loss

- Feynman variable(or longitudinal momentum fraction) $\implies x_F = (P^*/P_{cms}^*)$

$P^*$  : Momentum of  $c\bar{c}$ pair in cms frame

$P_{cms}^*$  : Maximum momentum of  $c\bar{c}$ pair in cms frame

- If  $c\bar{c}$  pair lose some fraction of energy in the medium:  $x'_F \longrightarrow x_F$

$$x'_F = x_F + \Delta x_F$$

- $x'_F = \frac{(P^* + \Delta P^*)}{P_{cms}^*}$        $\Delta P^*$  : Momentum loss in the nuclear medium

- again taking two known path length dependence energy loss scaling:

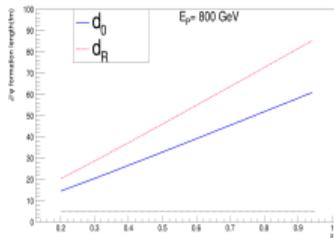
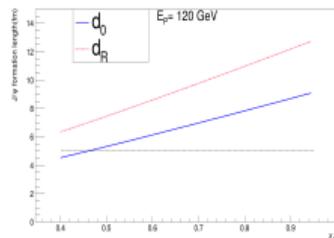
$$\Delta P \approx \alpha_f \langle L_A \rangle$$

$$\Delta P \approx \beta_f \langle L_A \rangle^2$$

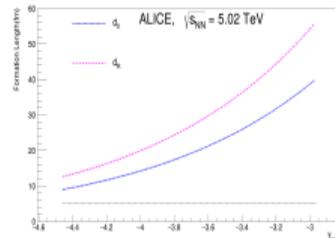
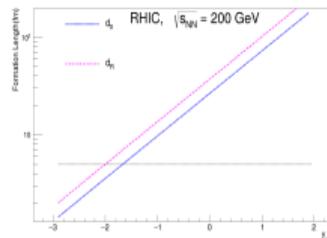
# Selection of data

- Find the formation length of the charmonia state in kinematic domain of a particular experiments
- Formation Length:  $d_{0(R)} = \frac{P_L}{M} \tau_{0(R)} = \gamma \beta c T_{0(R)}$
- If this formation length is less compared to the system size  $\implies$  **Final state absorption**
- If it is greater than system size  $\implies$  **Final state energy loss**
- E866, E906 experiments at Fermilab, PHENIX at RHIC and experiments at LHC offers an opportunity to measure second one

$d_{0(R)}$



$x_F$



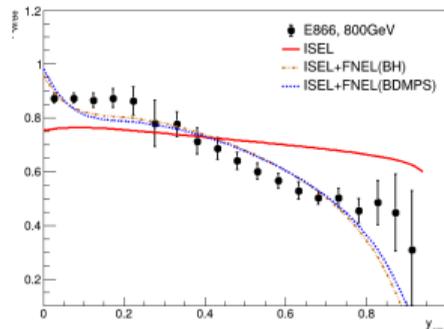
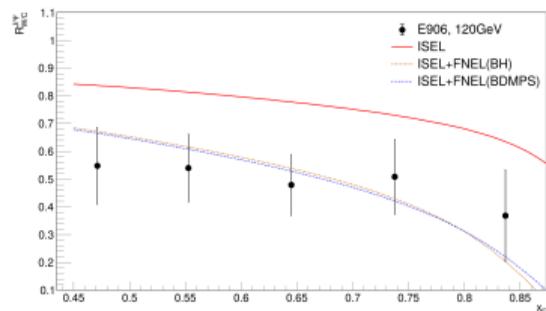
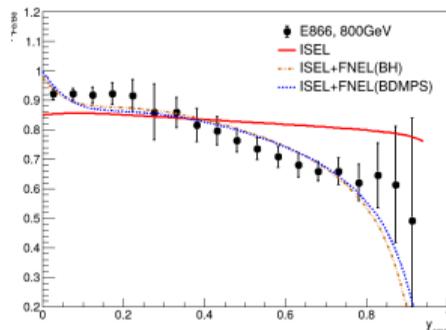
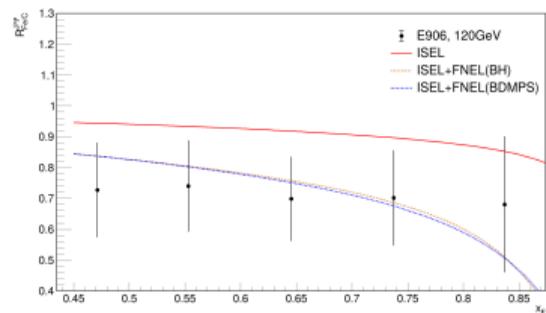
$y_{cms}$

# Experimental data table summary

- Plethora of data measuring  $J/\psi$  production in  $p - A$  collisions are now available from fixed target and collider facilities:
  - NA38, NA50, NA60 at CERN-SPS
  - E772, E886, E906 at FERMILAB
  - HERA-B at DESY
  - PHENIX at BNL-RHIC
  - ALICE, LHCb at CERN-LHC
- According to kinematic regions of measurements,  $J/\psi$  data has been analyzed for the following experiments:

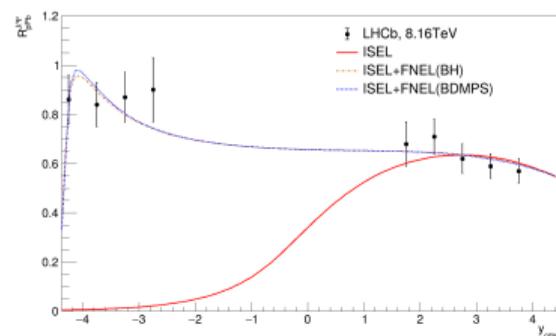
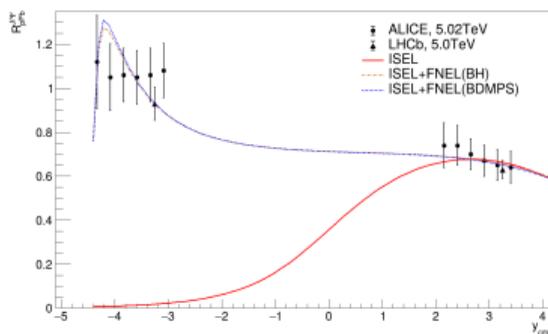
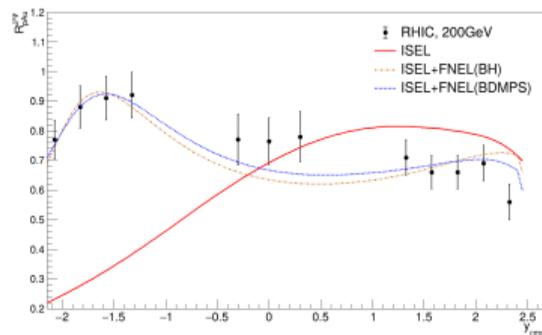
Expt.(GeV)	Collision system	Phase space
E906, $E_{LAB}=120$	$p - C, Fe, W$	$0.4 < x_F < 0.85$
E866, $E_{LAB}=800$	$p - Be, Fe, W$	$-0.10 < x_F < 0.93$
PHENIX, $\sqrt{s_{NN}}=200$	$p - p, d - Au$	$ y_{cms}  < 0.35, 1.2 <  y_{cms}  < 2.2$
ALICE, $\sqrt{s_{NN}}=5020$	$p - p, p - Pb$	$2.5 <  y_{cms}  < 4$
LHCb, $\sqrt{s_{NN}}=8160$	$p - p, p - Pb$	$1.5 < y_{cms} < 4.0, -5 < y_{cms} < -2.5$

# Result: Fixed target experiments



- Available data from lower collision energy at Fermilab  $\sqrt{s_{NN}} = 15.08 \text{ GeV}$  to top LHC  $\sqrt{s_{NN}} = 8.16 \text{ TeV}$  and RHIC  $\sqrt{s_{NN}} = 200 \text{ GeV}$  energies explored
- Along with considering all initial state effects, three pictures of final state are considered 1. **No final state energy loss** 2. **linear energy loss of  $c\bar{c}$  pair** and 3. **quadratic energy loss of  $c\bar{c}$  pair**
- Data unable to discriminate between two model of energy loss

# Result: Collider experiments



- With increasing the centre of mass energy, the  $c\bar{c}$  specific energy loss  $dE/dx$  shows increasing trend
- This specific energy loss  $-dE/dx$  varies from **1.25 (GeV/fm)** ( $E_{LAB} = 120\text{ GeV}$ ) to **30 (GeV/fm)** ( $\sqrt{s_{NN}} = 8.16\text{ TeV}$ ).

# Summary and conclusions

- Here in this work, we analyzed all available data on  $J/\psi$  measurements in asymmetric pA collisions over a broad range of energy
- We try to make a quantitative estimation on the  $c\bar{c}$  energy loss inside Cold Nuclear Matter
- EPPS21NLO nPDF and CT18ANLO free proton PDF has been taken for initial nuclear modification
- Initial state energy loss is incorporated from our previous work on parton energy loss through Drell-Yan process
- A systematic study has been done and an increasing trend of energy loss observed with respect to its own energy in the CNM medium
- A promising quantitative prediction would be given for the newly happened small collision systems  $O - O$ ,  $Ne - Ne$ ,  $p - O$  at LHC energies

Thank you!

*For your kind attention!*

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