Coherence in High Energy Interactions of QQ^{bar} State through Random Color Fields

H. FUJII (U Tokyo, Komaba)
With T. Matsui

For Discussion of High-Energy pA Collisions

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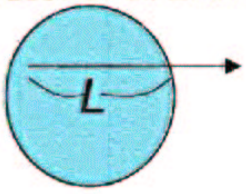
Introduction

J/ψ suppression as a signal of QGP

- **In the plasma**
  No J/ψ in the screened potential Matsui-Satz PLB178(86)
- **CERN NA38 found the suppression in O-U !** NA38, PLB220(89)
- **Understood as "Nuclear Suppression"** Gerschel-Hufner, ZPC56 (92)
  Kharzeev et al. ZPC74(97)

$$\frac{\sigma_{AB}}{AB\sigma_{\rm pp}} = \exp(-\sigma_{\rm abs}n_0L)$$

$$\sigma_{\rm abs} = 6 \sim 7\rm mb$$

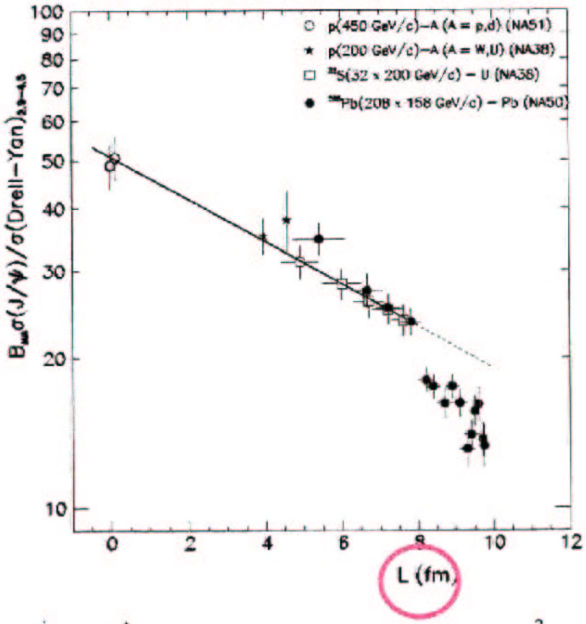


- **CERN NA50 found further suppression in Pb-Pb !** NA50, PLB410(97)

CERN-SPS data and fit

- A model is needed to define 'L'
- The same 'L-scaling' fits pA and AB data up to S-U → BASELINE
- Pb-Pb data are observed well below the baseline

Abreu et al., ep-99-013-fig6



L-scaling assumes the indept. absorption by N in A

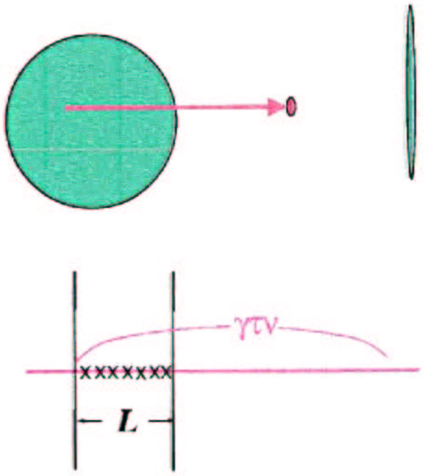
But COHERENCE should be more important at higher energies

Lorentz dilation of the internal
QQ motion in the A-rest frame.

⇨ Simultaneous action of multiple colls.

τ~1/BE: time scale of J/ψ
γ: Lorentz factor
L_{in}: length scale of inel. int.

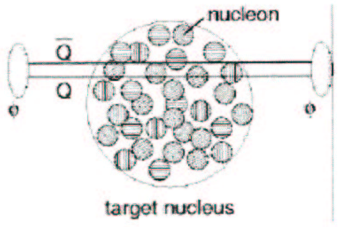
J/ψ
τ~1/0.6GeV~0.3fm/c
γ=10 → $\gamma\tau$=3fm/c
γ=100 → $\gamma\tau$=30fm/c

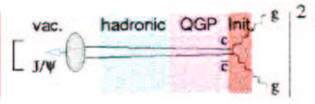


Nuclear effects on the J/ψ production should be re-examined

-- AA is too complicated; pA will be the better place to study the baseline.

Study of the high energy behavior of the penetration probability of a bound state





No discussion on the ψ production in pA, AA coll here ...

Basics

High-energy multiple-scattering → Eikonal approach

For a charged scalar particle,

$$\sqrt{(p-gA)^2+m^2}\psi(r) = (E-gA^0)\psi(r), \qquad E,p \gg |gA|$$

Eikonal phase

$$\psi(r) = e^{i\phi(r)}e^{ikz} \qquad E=\sqrt{m^2+k^2}$$

$$v\nabla_z\phi + gv_\mu A^\mu \sim 0$$

$$\phi \sim -\frac{1}{v}\int_{-\infty}^{z} dz' g v_\mu A^\mu(x,y,z')$$

- Transverse position of the particle is frozen
- Phase is integrated along the trajectory

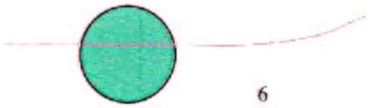


Illustration with U(1)

Nemenov, Sov.J.Nucl.Phys.34('81)726
Lyuboshitz-Podgoretskii, JETP 54('81) 827
Baym, Adv.Nucl.Phys.22('96)101

prob $\propto |\langle\varphi|U|\varphi\rangle|^2 \sim$

Eikonal phases for e-e+ at impact parameters x y

$$U = e^{i\delta(\mathbf{x})}e^{-i\delta(\mathbf{y})} \sim e^{i\mathbf{r}\mathbf{q}}, \qquad \mathbf{q} = -\frac{1}{v}\nabla_\perp \int_{-\infty}^{\infty} ev_\mu A^\mu(\mathbf{x},z)dz$$

A_{mu}: classical fields of atoms

-- NB. propagation includes various excited e-e+ states

Fields 'A' are random:

$$\overline{q_i q_j} = \frac{1}{2}\langle q^2\rangle\delta_{ij} \; \underline{\propto L}, \qquad \overline{e^{i\mathbf{r}\mathbf{q}}\, e^{-i\bar{\mathbf{r}}\mathbf{q}}} = e^{-\frac{1}{4}\langle q^2\rangle(r-\bar{r})^2}$$

$$\boxed{\begin{aligned} P(L) &= \int d\mathbf{r}d\bar{\mathbf{r}}\rho(\mathbf{r})\rho(\bar{\mathbf{r}})e^{-\frac{1}{4}\langle q^2\rangle(r-\bar{r})^2} \\ &= \begin{cases} 1-\frac{1}{2}\langle q^2\rangle\langle r^2\rangle & \text{for small } L \\ \int d\mathbf{r}\rho^2(\mathbf{r})\cdot\frac{4\pi}{\langle q^2\rangle} & \text{for large } L \end{cases} \end{aligned}}$$

$$\rho(r) \equiv \int dz\varphi^2(r,z)$$

High energy color dipole in random fields

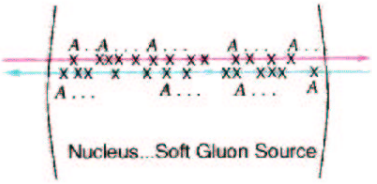
- **Importance of the color DoF in the strong interaction**

Non-abelian eikonal factor

$$U(\mathrm{x},\mathrm{y};A) = W(\mathrm{x};A)W^\dagger(\mathrm{y};A), \qquad W(\mathrm{x}) = \mathcal{P}e^{ig\int_{-\infty}^{\infty}dx^+A^{a-}(\mathrm{x},x^+)t^a}$$

Each component of WF with fixed x is rotated in the color and complex space

- **Eikonal factors with definite colors**



$$U_{\mathrm{ss}}(\mathrm{x},\mathrm{y}) = \frac{1}{N}\mathrm{Tr}(W(\mathrm{x})W^+(\mathrm{y}))$$

$$U^a_{\mathrm{as}}(\mathrm{x},\mathrm{y}) = \sqrt{\frac{2}{N}}\mathrm{Tr}(W(\mathrm{x})W^+(\mathrm{y})t^a)$$

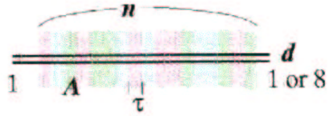
$$U^{ba}_{\mathrm{aa}}(\mathrm{x},\mathrm{y}) = 2\mathrm{Tr}(W(\mathrm{x})t^aW^+(\mathrm{y})t^b)$$

NB. Color transparency is obvious: Uss=1 and Uas=0 if x=y

High energy color dipole in random fields (cont'd)

- **Target average**
  - Model of Buchmuller-Hebecker, Kovner-Wiedemann, etc.

Divide the target into small zones, and expand each eikonal factor in *gA*



$$\overline{A^a(\mathbf{x},n)A^b(\mathbf{y},n')} \equiv \delta_{nn'}\delta^{ab}C(\mathbf{x}-\mathbf{y}),$$

with $A = g\Delta x^+ A^{a-}$

NB. No color coherence beyond the zone → Stochastic in color DoF
Propagation still includes various excited QQ$^{\mathrm{bar}}$ states

e.g.,

$$\begin{aligned} \overline{U}_{\mathrm{SS}}(\mathbf{x},\mathbf{y}) &= \frac{1}{N}\mathrm{Tr}\overline{W(\mathbf{x})W^\dagger(\mathbf{y})}_{(n)} \\ &= \frac{1}{N}\mathrm{Tr}\overline{W(\mathbf{x})W^\dagger(\mathbf{y})}_{(n-1)}(1-C_F v(\mathbf{r})) \\ &= (1-C_F v(\mathbf{r}))^n \\ &\sim e^{-nC_F v(\mathbf{r})} \end{aligned}$$

with $v(\mathbf{r}) = C(0) - C(\mathbf{r})$

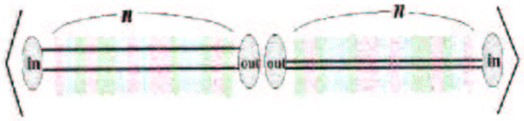
Explicit form of the matrix $\overline{U(\mathrm{x},\mathrm{y})U^\dagger(\bar{\mathrm{x}},\bar{\mathrm{y}})} \equiv K(\mathrm{r},\bar{\mathrm{r}},\mathrm{R}-\bar{\mathrm{R}})$

... a product of four W's

For a thin target and a small bound state

$$K_{\mathrm{aa}} = 1 - \frac{\kappa}{N}[N^2(\mathrm{R}-\bar{\mathrm{R}})^2 + (N^2-3)(\mathrm{r}-\bar{\mathrm{r}})^2 + (\mathrm{r}+\bar{\mathrm{r}})^2]$$

$$K_{\mathrm{as}} = (N^2-1)\frac{\kappa}{N}\mathrm{r}\cdot\bar{\mathrm{r}}$$



$$K_{\mathrm{sa}} = \frac{\kappa}{N}\mathrm{r}\cdot\bar{\mathrm{r}}$$

$$K_{\mathrm{ss}} = 1 - \frac{N^2-1}{2N}\kappa(\mathrm{r}^2+\bar{\mathrm{r}}^2)$$

with $v(r) = C(0) - C(r) \sim \kappa r^2$

For a thick target, exponentiate this result

Penetration of a small, singlet bound state

$$S = \int d\mathbf{r} d\bar{\mathbf{r}} \rho(\mathbf{r})\rho(\bar{\mathbf{r}}) K_{\mathrm{SS}}(\mathbf{r}, \bar{\mathbf{r}}, 0)$$

- **THIN target at high energies**

$$\begin{aligned} S &= \int d\mathbf{r} d\bar{\mathbf{r}} \rho(\mathbf{r})\rho(\bar{\mathbf{r}}) K_{\mathrm{SS}}(\mathbf{r}, \bar{\mathbf{r}}, 0) \\ &= \int d\mathbf{r} d\bar{\mathbf{r}} \rho(\mathbf{r})\rho(\bar{\mathbf{r}}) [1 - C_F(v(\mathbf{r}) + v(\bar{\mathbf{r}}))] \\ &= 1 - 2C_F\langle v\rangle \sim 1 - 2C_F\kappa\langle \mathbf{r}^2\rangle \underline{\equiv 1 - l/L_{\mathrm{in}}} \end{aligned}$$

- **THICK target at high energies**

$$K_{\mathrm{SS}}(\mathbf{r}, \bar{\mathbf{r}}, 0) = f_1\, e^{-n \ln 1/\lambda_1} + f_2\, e^{-n \ln 1/\lambda_2}$$

$$\ln 1/\lambda_1 \sim \kappa C_F (r - \bar{r})^2/2, \quad \ln 1/\lambda_2 \sim \kappa N (r + \bar{r})^2/4$$

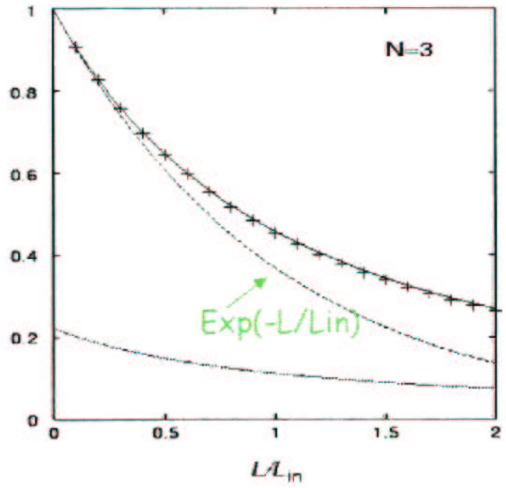
$$\begin{aligned} S &\sim \int d\mathbf{r} d\bar{\mathbf{r}} \rho(\mathbf{r})\rho(\bar{\mathbf{r}})\ f_1\ e^{-n\kappa C_F (r-\bar{r})^2/2} \\ &\sim \frac{1}{N^2} \frac{2\pi \int d\mathbf{r} \rho^2(\mathbf{r})}{n\kappa C_F} = \underline{\frac{1}{N^2} \frac{2\Delta\langle \mathbf{r}^2\rangle}{L/L_{\mathrm{in}}}} \end{aligned}$$

Result with a small Gauss wave packet

An analytic form fits the result very well:

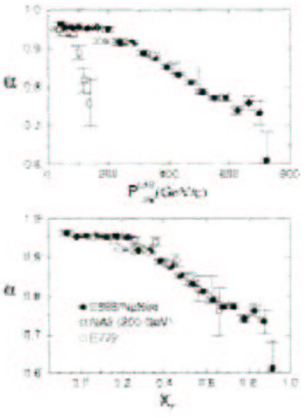
$$\boxed{S(L/L_{\mathrm{in}}) = \frac{2}{N^2} \frac{1}{1 + \frac{L}{L_{\mathrm{in}}}} + \frac{N^2 - 2}{N^2} \frac{1}{(1 + \frac{1}{2}\frac{L}{L_{\mathrm{in}}})^2}}$$

- Non-exponential
- Correct small-, large-L behavior
- Slow approach to the 1/L form



Discussions

- **To be more realistic**
  - Finite energy treatment; Interpolate from low to high En.
  - E-dependence of AA correlation, Q_s^2
  - Higher Fock components in the WF
  - Gluon radiations
  - Production process of QQ; QQ^{bar} in the gluon WF
- **Comparison with data**
  - x_F, p_t behavior of FNAL-E866 (800 GeV)
    - Cf. Kopeliovich et al. NPA 669 (01)
  - pA at RHIC (collider)



Summary

- Quantum mechanical treatment of a bound state penetration is very interesting and shows us a non-trivial feature, like 1/L
- Other QM effects: gluon radiations, energy dependence of the WF, …, may be important
- The model must be extended and checked using pA data at FNAL (and future pA@RHIC)
- The baseline of J/ψ production in AA should be re-examined at RHIC energy