Enhancement of $\psi(2S)$ in p-Pb collision at LHC as an indication of QGP formation

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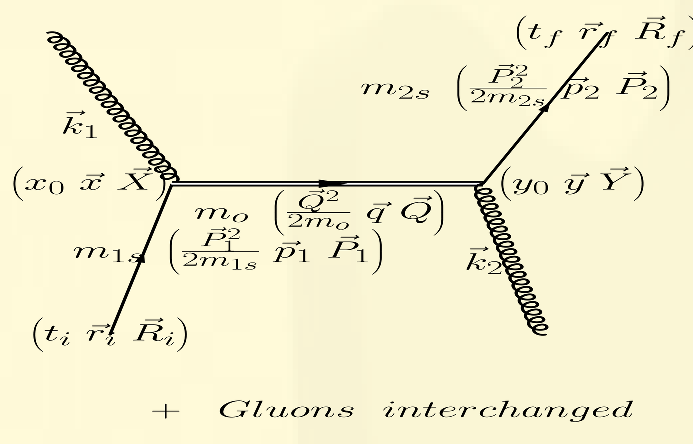
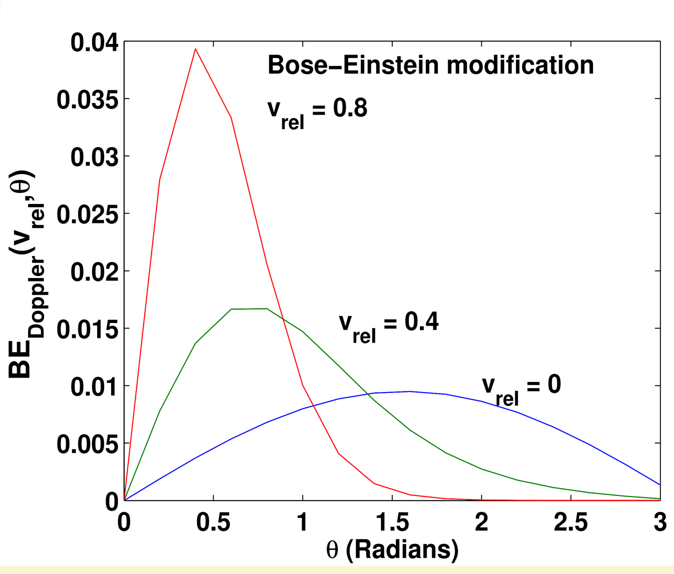
Abstract

Proton-nucleus collisions serve as an important baseline for the understanding and interpretation of the nucleus-nucleus collisions. These collisions have been employed to characterize the cold nuclear matter effects at SPS and RHIC energies for the past several years, as it was thought that Quark-Gluon Plasma (QGP) is not formed in such collisions. However, at the Large Hadron Collider (LHC), there seems a possibility that QGP is formed during proton-lead (p−Pb) collisions. In this work, we have derived an expression for gluon induced excitation of J/ψ to $\psi(2S)$, using pNRQCD, and show that the relative enhancement of $\psi(2S)$ vis a vis J/ψ, especially at high p_T, gives further indication that the QGP is indeed formed in p−Pb collisions at the most central collisions at LHC energy. J/ψ and $\psi(2S)$ suppression effects seen at ALICE are also qualitatively explained.

Transition from $1S \to 2S$

Feynman diagrams for gluon induced excitation of $1S$ state to $2S$ state. The second diagram is just the first diagram with gluons interchanged.





- The gluon distribution function:

$$f_g(E_g, v_{rel}, \theta) = \frac{g_d}{e^{\frac{\gamma E_g}{T}(1-v_{rel}\cos(\theta)} - 1}$$

where g_d is the number of gluon degree of freedom.

- $1S \to 2S$ transition cross-section is calculated using the potential non-relativistic perturbative QCD (pNRQCD) formulation:

$$\sigma = \frac{C_g(2\pi)^2}{16 m_{1S} m_{2S}} k_1 \times M_c^2 \int_0^{\pi} \left[f_{BE} \sin^2\alpha \sqrt{\frac{m_{2S}}{2\Delta}} k_2^4 \right] d\alpha$$

- The Rate Constant $\Gamma_{1S\to 2S}$ is obtained by integrating the $1S \to 2S$ transition cross-section, σ, with the gluon distribution function:

$$\Gamma_{1S\to 2S} = \frac{1}{4\pi^2} \int \frac{E_g g_d T \sigma}{v_{rel}\gamma} \times \ln\left[\frac{e^{\frac{\gamma E_g}{T}(1+v_{rel})} - 1}{e^{\frac{2\gamma E_g v_{rel}}{T}} \left(e^{\frac{\gamma E_g}{T}(1-v_{rel})} - 1 \right)} \right] dE_g.$$

- **The $\psi(2S)$ Enhancement Factor:** The fraction of the number of $1S$ particles converted to $2S$ is then given by:

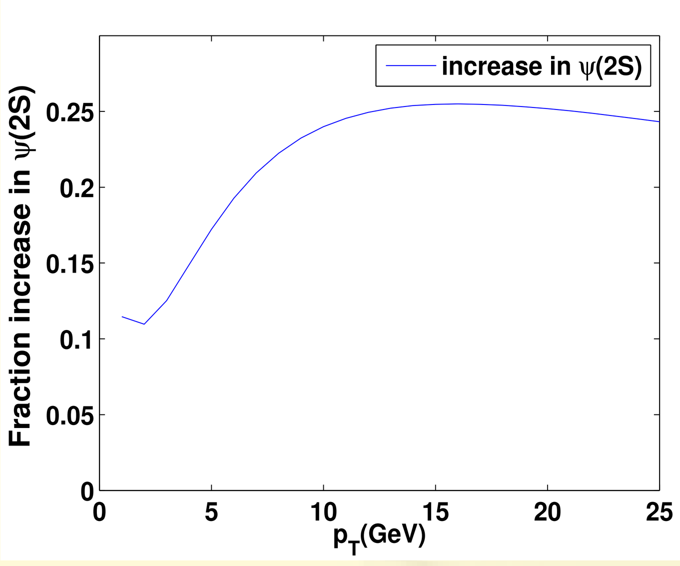
$$\Delta n_{1S\to 2S} = 1 - \exp\left(- \int_{t_0}^{t_{QGP}} \Gamma_{1S\to 2S}\, dt \right)$$

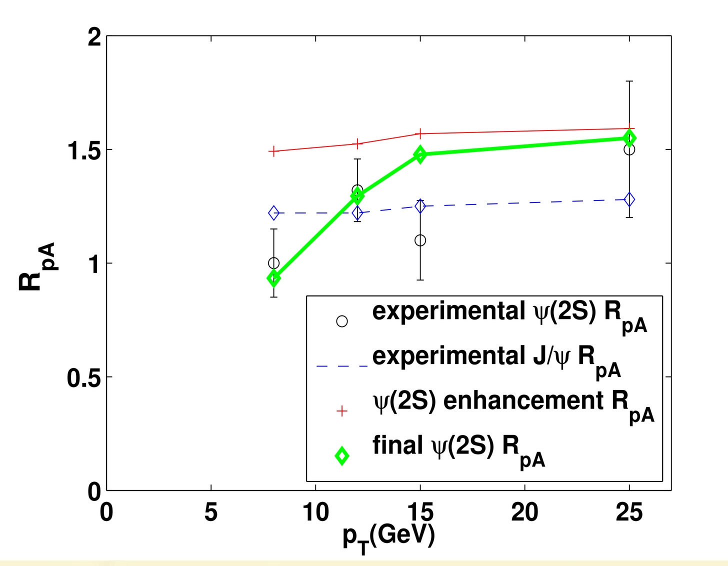
The variables t_0 and t_{QGP} indicate the thermalization time and lifetime of the QGP.

- The increment in $\psi(2S)$ yield is then:

$$\frac{N_{J/\psi}}{N_{\psi(2S)}} \Delta n_{1S\to 2S}, \qquad (1)$$

where $\frac{N_{J/\psi}}{N_{\psi(2S)}}$ is the ratio of number of initial J/ψ to $\psi(2S)$.





Effective Temperature, T_{eff}

- Because of heavy mass scale and formation time, quarkonia does not share the same temperature with medium .
- Proposed effective temperature [8]

$$T_{eff}(v_{rel}, \theta) = \frac{T(b,\tau)\sqrt{1 - v_{rel}^2}}{1 - v_{rel}cos\theta} \quad here, \quad T(b,\tau) = T_0 \left[\frac{N_\beta}{N_{\beta_0}} \frac{\tau_0}{\tau} \right]^{1/3}$$

Introduction

Quark-Gluon Plasma (QGP) is a deconfined state of quarks and gluons, and is currently a subject of much theoretical and experimental research. Signatures of QGP include heavy quarkonium (J/ψ or Υ) suppression, collective flow and photon/dilepton production etc. In this work, we attempt to explore the yield enhancement of the charmonium state $\psi(2S)$ w.r.t. J/ψ, at high p_T, as a possible indication of the presence of QGP in p+Pb collisions. One possible explanation for yield enhancement is secondary recombination of c and $\bar{c}$ pair. However, it is unlikely to be a reason for $\psi(2S)$ enhancement at high p_T in the case of p−Pb collision. Furthermore, secondary recombination depends quadratically on the number of c and $\bar{c}$ pairs, which would be very less for p−Pb collision. We argue that a possible reason for $\psi(2S)$ enhancement could be due to the gluon induced excitation of $J/\psi(1S)$ to $\psi(2S)$. We further argue that in a medium of equilibrated gluon distribution, this gluon induced excitation increases with p_T of J/ψ.

Bottomonium Suppression Mechanisms

- ***Color Screening*** $\Rightarrow$ The color screening model used in the present work is based on pressure profile in the transverse plane and cooling law for pressure based on QPM EOS for QGP. The cooling law for pressure is given by:

$$p(\tau, r) = A + \frac{B}{\tau^q} + \frac{C}{\tau} + \frac{D}{\tau^{c_s^2}};$$ where A, B, C and D are constants [2, 3].

Calculated $p(\tau, r)$ at initial time $\tau = \tau_i$ and screening time $\tau = \tau_s$ and by combining the pressure profiles, we get the screening radius, r_s.

The Color screening survival probability, S_c:

$$S_c(p_T, N_{part}) = \frac{2(\alpha+1)}{\pi R_T^2} \int_0^{R_T} dr\, r\, \phi_{max}(r) \left\{ 1 - \frac{r^2}{R_T^2} \right\}^{\alpha},$$

- ***Collisional damping*** $\Rightarrow$ Soft gluons mediate between $q\bar{q}$ pairs cause dissociation.

The potential used in this work is given as [4]:

$$V(r, m_D) = \frac{\sigma}{m_D}(1 - e^{-m_D r}) - \alpha_{eff}\left(m_D + \frac{e^{-m_D r}}{r} \right) - i\alpha_{eff} T_{eff} \int_0^{\infty} \frac{2\, z\, dz}{(1+z^2)^2} \left(1 - \frac{\sin(m_D\, r\, z)}{m_D\, r\, z} \right)$$

Using above potential we calculated collisional damping:

$$\Gamma_{damp} = \int [\psi^\dagger\, [Im(V)]\, \psi] dr$$

- ***Gluonic Dissociation*** $\Rightarrow$ The gluonic dissociation cross section [4] as;

$$\sigma_{diss,nl}(E_g) = \frac{\pi^2 \alpha_s^u E_g}{N_c^2} \sqrt{\frac{m}{E_g + E_{nl}}} \left(\frac{l|J_{nl}^{q,l-1}|^2 + (l+1)|J_{nl}^{q,l+1}|^2}{2l+1} \right)$$

Gluonic dissociation factor, $\Gamma_{gdiss,nl}$;

$$\Gamma_{gdiss,nl} = \frac{g_d}{2\pi^2} \int_0^{\infty} \frac{dp_g\, p_g^2 \sigma_{diss,nl}(E_g)}{e^{\frac{\gamma E_g}{T_{eff}}(1 - v_{rel}\cos(\theta)} - 1}\ ;\ g_d = 16$$

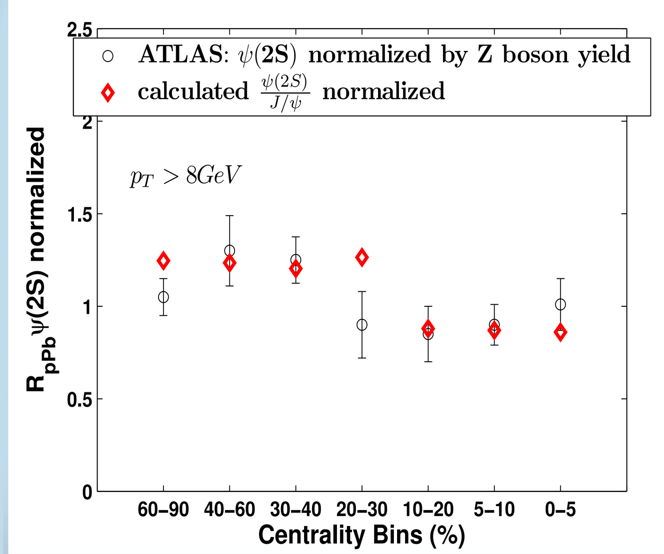
The gluonic dissociation along with collisional damping: $\Gamma_D = \Gamma_{damp} + \Gamma_{gdiss}$.

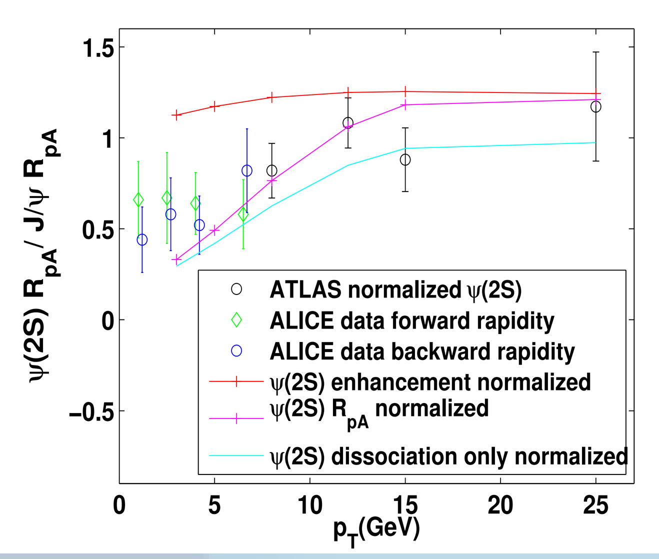
The suppression factor;

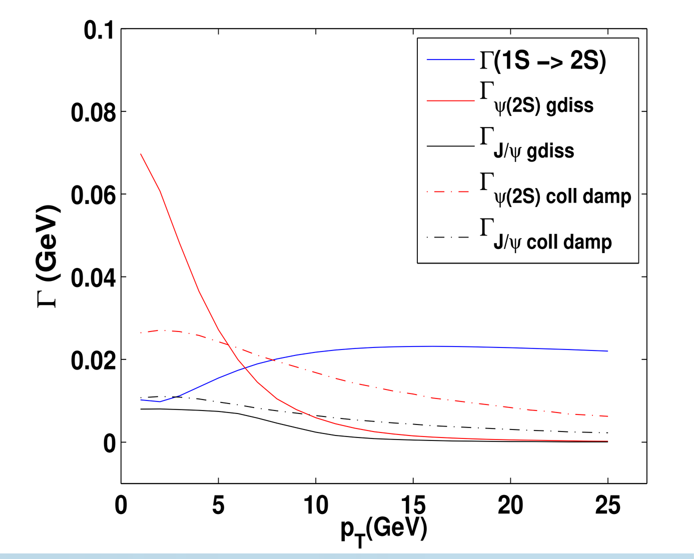
$$\epsilon(\tau) = exp\left[- \int_{\tau_0}^{\tau} \Gamma_D\, dt \right]$$

- ***Shadowing: A CNM Effect*** $\Rightarrow$ Initial-state nuclear effects on the parton densities.
- We use the EPS09 parameterization [5], to obtain the shadowing $S^i(A, x, \mu)$ for nucleus with mass A, momentum fraction x and scale μ.
- The CNM shadowing suppression factor is the determined by; $S_{sh} = \frac{d\sigma_{AB}/dy}{T_{AB}(b) d\sigma_{pp}/dy}$

Results: S_P Vs Centrality and p_T







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CONCLUSION

- We have found a differential enhancement of $\psi(2S)$ w.r.t. $J/\psi(1S)$ at higher transverse momentum using gluon induced $1S$ to $2S$ transition approach, which to a significant extent agrees with the preliminary ATLAS experimental data.
- The combined suppression seems to corroborate better with the experimental ATLAS data. Our simulations results also corroborate with the trend in ALICE results for $\psi(2S)$ for both p_T and rapidity dependence, where suppression is the dominant phenomenon.
- We expect that the enhancement of $J/\psi(1S)$ to $\psi(2S)$, as an increasing function of p_T, if confirmed experimentally, can be one definitive evidence for the presence of QGP in p−Pb collision.
- Even if there is no net enhancement at high p_T, $\psi(2S)$ enhancement seems to be required in order to predict the $\psi(2S)$ R_{pA}, especially at high p_T.

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