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Suppression of Prompt Quarkonium States in Electron-Nucleus Collisions

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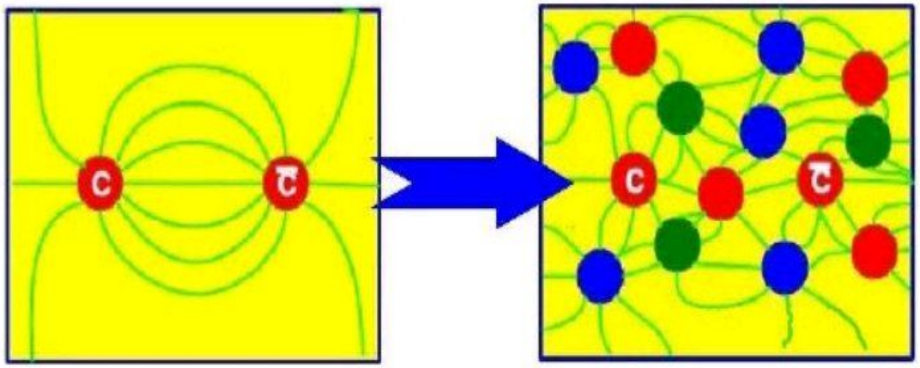
Introduction

- Quarkonium Production in reactions with nuclei is one of the most interesting QCD processes to be studied in matter
- Previous papers have studied the interaction of quarkonia with a medium (QGP) in Nucleus-Nucleus collisions

- We hope to do the same, but using CNM instead

Y. Makris et al. (2019)



T. Matsui et al. (1986)

- Presents new theoretical challenges for research; thermal wavefunction broadening will vanish, other effects may be more subtle

$$d\sigma(a+b\to\mathcal{Q}+X)=\sum_n d\sigma(a+b\to Q\overline{Q}(n)+X)\langle\mathcal{O}_n^{\mathcal{Q}}\rangle$$

Quarkonium production at intermediate and high p_T

- Our eventual goal is to generate full cross section predictions-starting with NRQCD

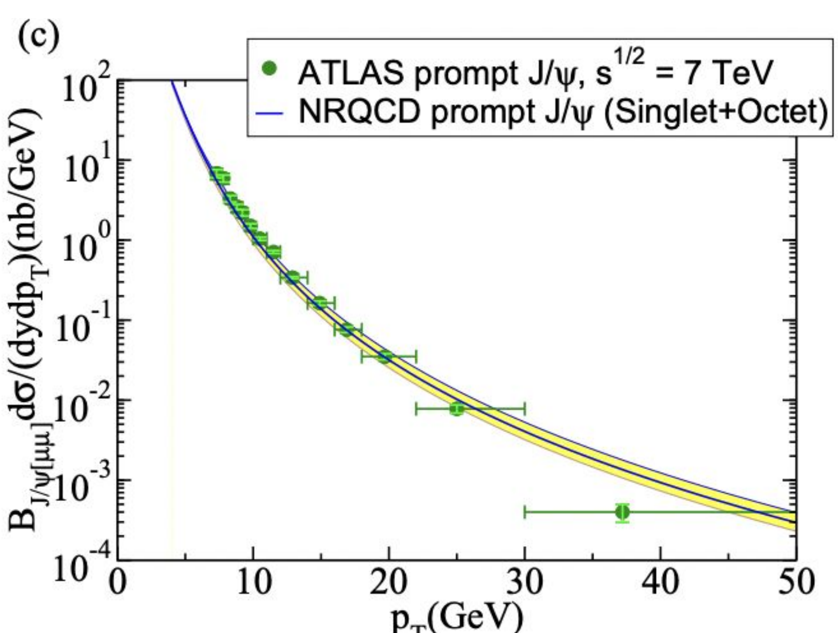
J. Bodwin *et al.* (1995)

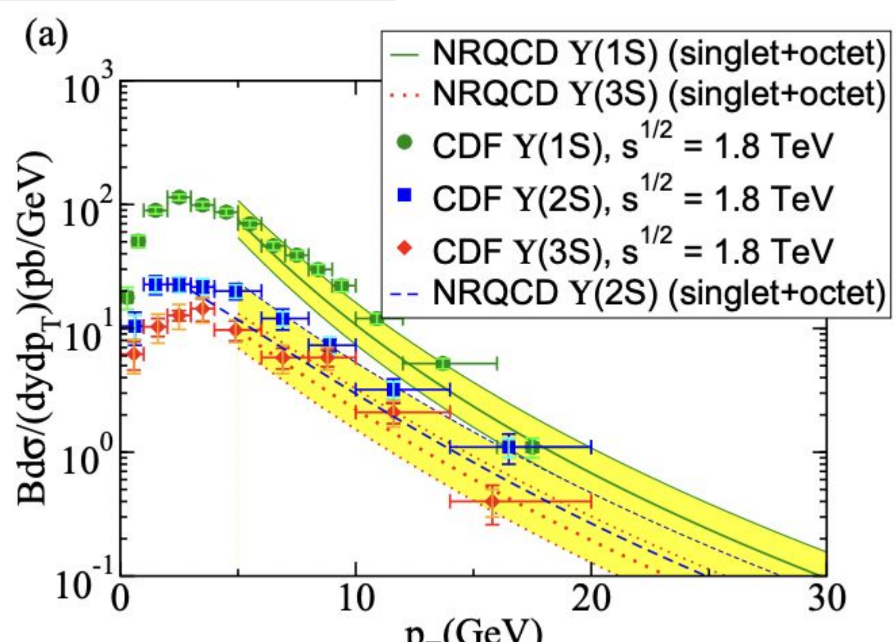
Example for J/ψ

$$d\sigma(J/\psi) = d\sigma(Q\bar{Q}([^3S_1]_1))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_1) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^1S_0]_8))\langle\mathcal{O}(Q\bar{Q}([^1S_0]_8) \to J/\psi)\rangle$$
$$+ d\sigma(Q\bar{Q}([^3S_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3S_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_0]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_0]_8) \to J/\psi)\rangle$$
$$+ d\sigma(Q\bar{Q}([^3P_1]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_1]_8) \to J/\psi)\rangle + d\sigma(Q\bar{Q}([^3P_2]_8))\langle\mathcal{O}(Q\bar{Q}([^3P_2]_8) \to J/\psi)\rangle + \cdots$$

- Figures shown are for QCD production

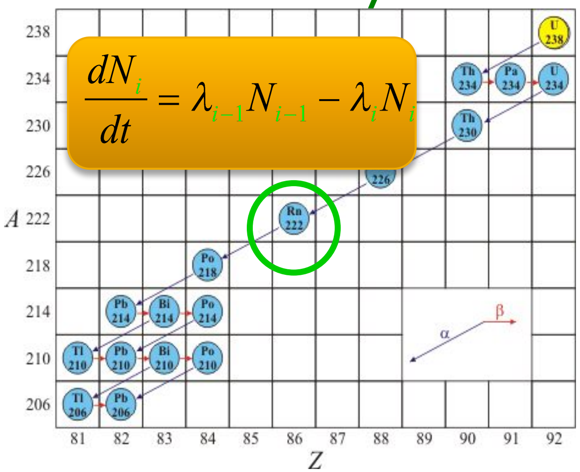
R. Sharma *et al.* (2011)





Time evolution of quarkonium states

Very rough analogy with a radioactive decay chain

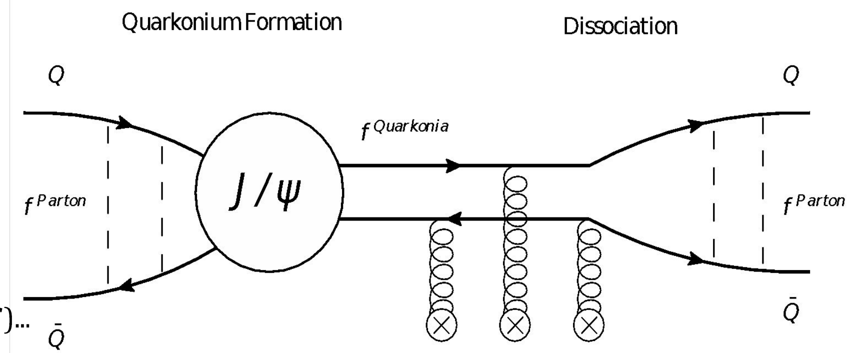


- Competing effects-the energetic, heavy quark pairs ("partons") binding into quarkonia vs. dissociating into free quarks

$$f^{Parton} = \sum_{g,\bar{Q}Q} g,\bar{Q}Q(\text{spin,color})$$

$$f^{Quarkonia} = \sum_{States} J/\psi, \psi(2s), \chi_c$$

$$...\Upsilon(1s), \Upsilon(2s), \Upsilon(3s), \chi_b(1S)\chi_b(2S)...$$



- Dynamics reduces to a kinetic approximation

$$\begin{aligned}
\partial_t f^{Parton}(E,t) &= -\frac{1}{\langle\tau_{\text{form}}(E,t)\rangle} f^{Parton}(E,t) \\
&\quad + \frac{1}{\langle\tau_{\text{diss}}(E,t)\rangle} f^{Quarkonia}(E,t) \\
\partial_t f^{Quarkonia}(E,t) &= +\frac{1}{\langle\tau_{\text{form}}(E,t)\rangle} f^{Parton}(E,t) \\
&\quad - \frac{1}{\langle\tau_{\text{diss}}(E,t)\rangle} f^{Quarkonia}(E,t)
\end{aligned}$$

Initial conditions: perturbatively produced, QQ-bar states

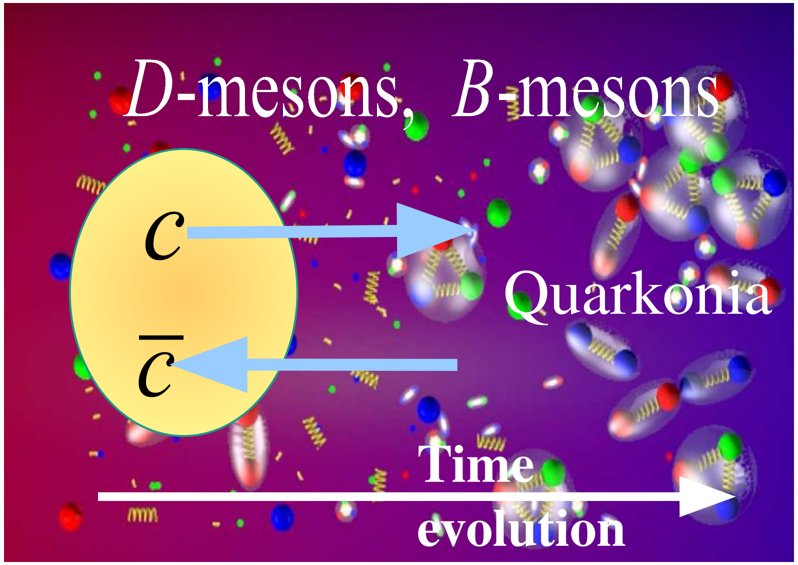
$$\begin{aligned}
f^{Parton}(E,t=0) &= \frac{dN^{Parton}}{dp_T} \\
f^{Quarkonia}(E,t=0) &= 0
\end{aligned}$$

This is the effect of the medium
Well-understood asymptotic limits

Effects of the medium

- Formation time is not strictly defined. Interactions occur on this time scale of about 1 fm

- Dissociation time – includes momentum broadening and thermal effects-in CNM Lambda(T) is replaced with Lambda_o in the equation below



$$P_{f\leftarrow i}(\chi\mu_D^2\xi,T) = \left|\frac{1}{2(2\pi)^3}\int d^2\mathbf{k}dx\,\psi_f^*(\Delta\mathbf{k},x)\psi_i(\Delta\mathbf{k},x)\right|^2$$

$$= \left|\frac{1}{2(2\pi)^3}\int dx\;\mathrm{Norm}_f\mathrm{Norm}_i\,\pi\,e^{-\frac{m_Q^2}{x(1-x)\Lambda(T)^2}}e^{-\frac{m_Q^2}{x(1-x)\Lambda_0^2}}\right.$$

$$\left.\times\frac{2[x(1-x)\Lambda(T)^2][\chi\mu_D^2\xi+x(1-x)\Lambda_0^2]}{[x(1-x)\Lambda(T)^2]+[\chi\mu_D^2\xi+x(1-x)\Lambda_0^2]}\right|^2.$$

- This has also been implemented for open heavy flavor

Dissociation time

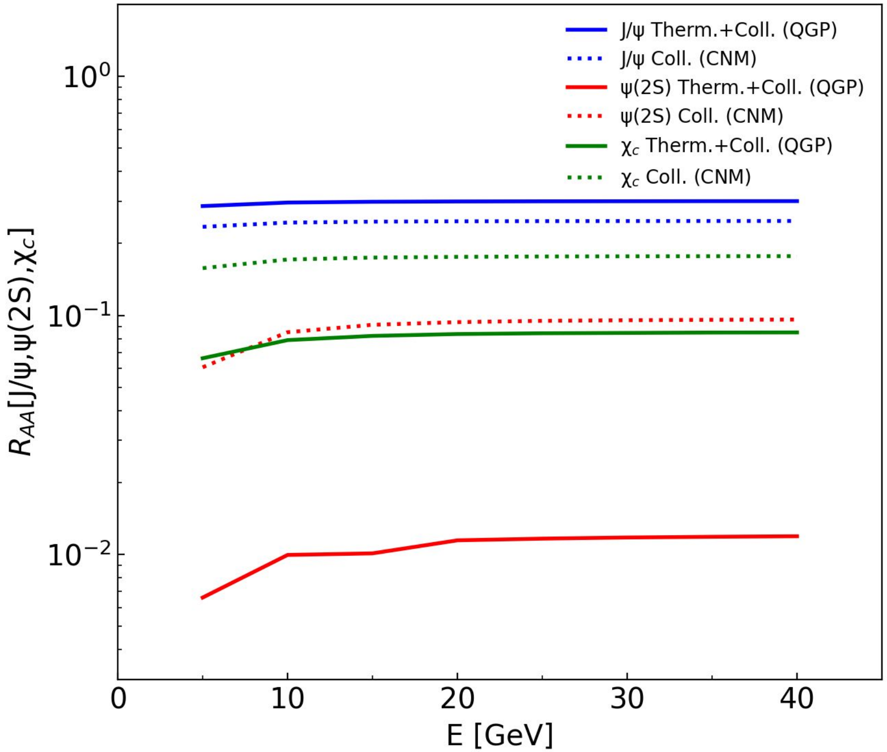
$$\frac{1}{t_{\mathrm{diss.}}} = -\frac{1}{P_{f\leftarrow i}(\chi\mu_D^2\xi,T)}\frac{dP_{f\leftarrow i}(\chi\mu_D^2\xi,T)}{dt}$$

S. Aronson *et al.* (2017)

Preliminary Results-Charmonium

- We first checked that eliminating the thermal wavefunction broadening does not significantly change supp
- Calculations were done using the 1st centrality class (0-10%)

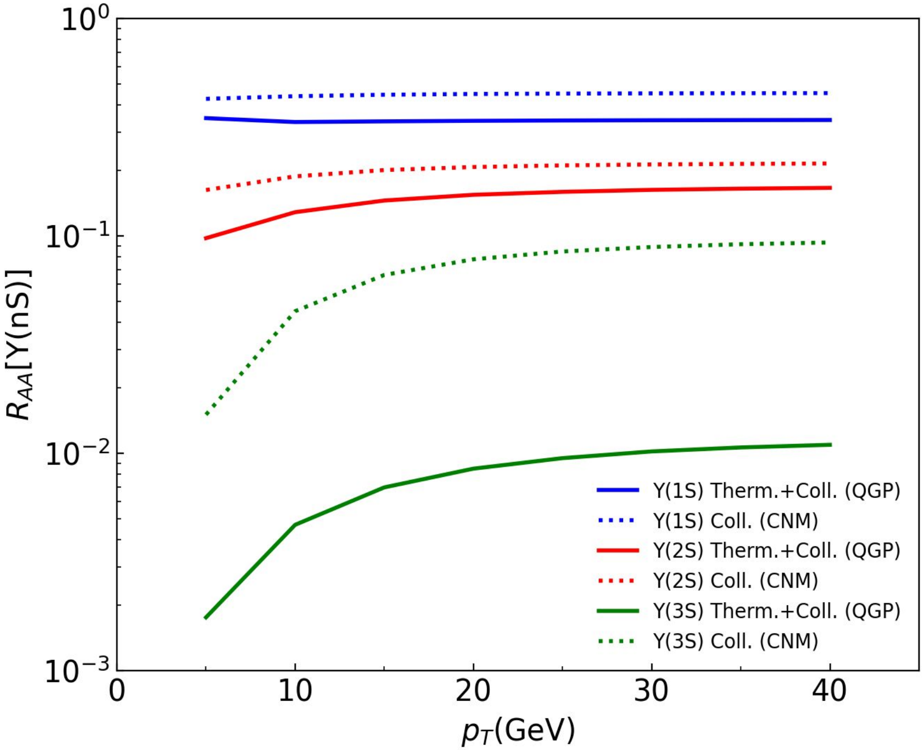
- The more suppressed a state is in QGP, the bigger the change was to CNM. Normally, suppression increased but for some it decreased (depends on parameters)

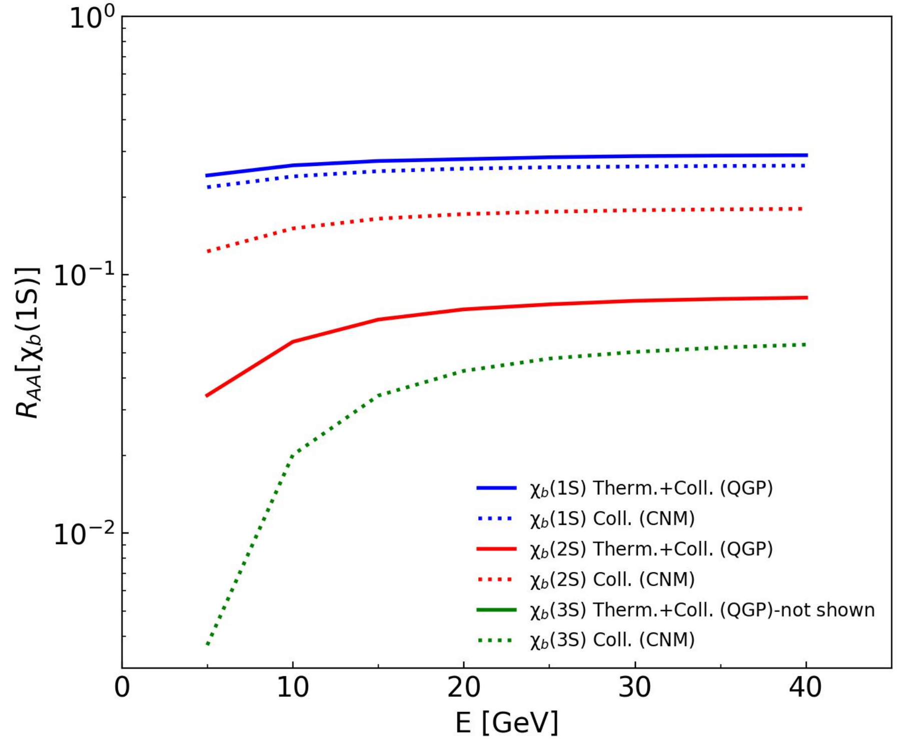


Comparison of suppression for prompt charmonium states between QGP (solid lines) and CNM (dotted lines)

Preliminary Results-Bottomonium

Comparison of suppression for prompt charmonium states between QGP (solid lines) and CNM (dotted lines)



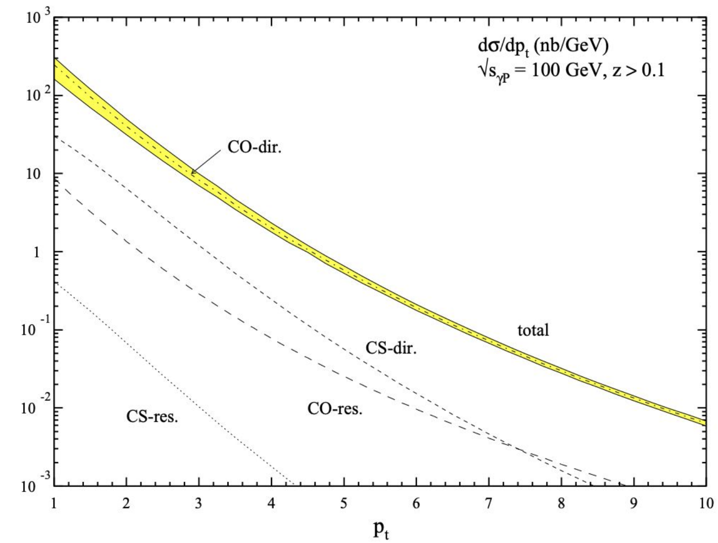


- The largest reduction in suppression is for the weakest bound states. Still, their suppression remains quite large-more than a factor of 10
- For the tightly bound states, the suppression in CNM can be slightly more or slightly less but still very significant

Steps for the Future

- Our results are for ReA of prompt states, relative to the e-p cross section without actual convolution

- ReA will be convolved with cross sections detailed in a paper by Beneke, Krämer, and Väntinnen



$$\frac{1}{B_{ll}}\frac{d\sigma^{ij}}{d\Omega dz dp_t} = \int_{x_{1,min}}^{1} dx_1\, f_{i/\gamma}(x_1,\mu_F) f_{j/p}(x_2,\mu_F)\,\frac{1}{16\pi\hat{s}^2}\,\frac{2x_1x_2p_t}{z(x_1-z)}$$

$$\times\frac{3}{8\pi}\left[\rho_{11}^{ij}+\rho_{00}^{ij}+(\rho_{11}^{ij}-\rho_{00}^{ij})\cos^2\theta+\sqrt{2}\,\mathrm{Re}(\rho_{10}^{ij})\sin 2\theta\cos\phi+\rho_{1,-1}^{ij}\sin^2\theta\cos 2\phi\right]$$

M. Beneke *et al.* (1997)

- Our interaction time is set to 1 fm-but relativity predicts boosts and we have to investigate how this affects dissociation

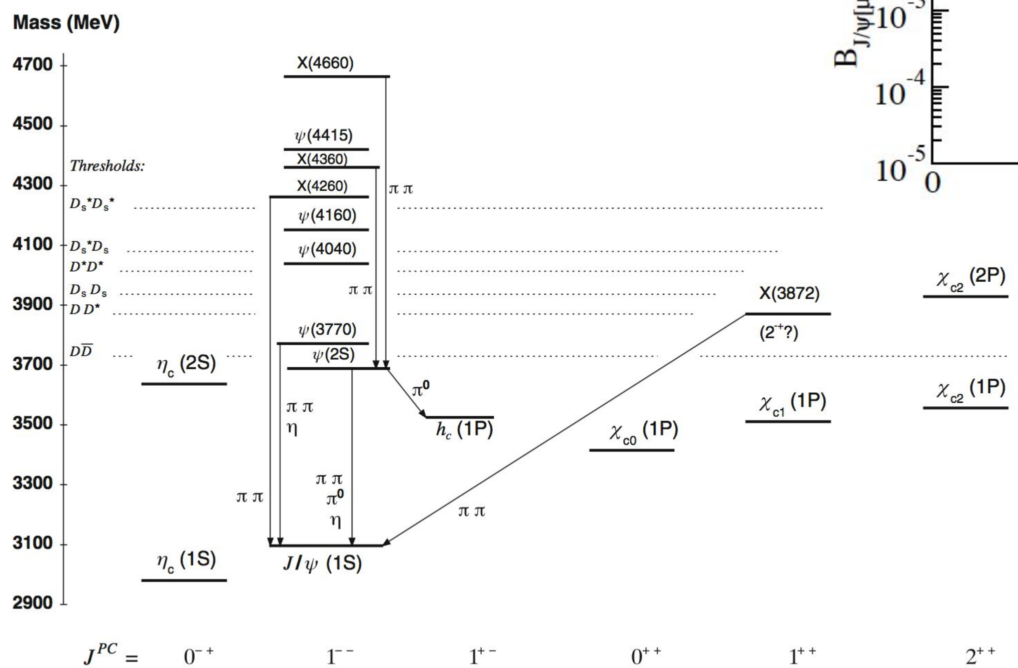
$$R_{AA} = \frac{1}{\langle N_{\text{coll.}}\rangle}\frac{d\sigma_{AA}^{\text{Quarkonia}}/dydp_T}{d\sigma_{pp}^{\text{Quarkonia}}/dydp_T}$$

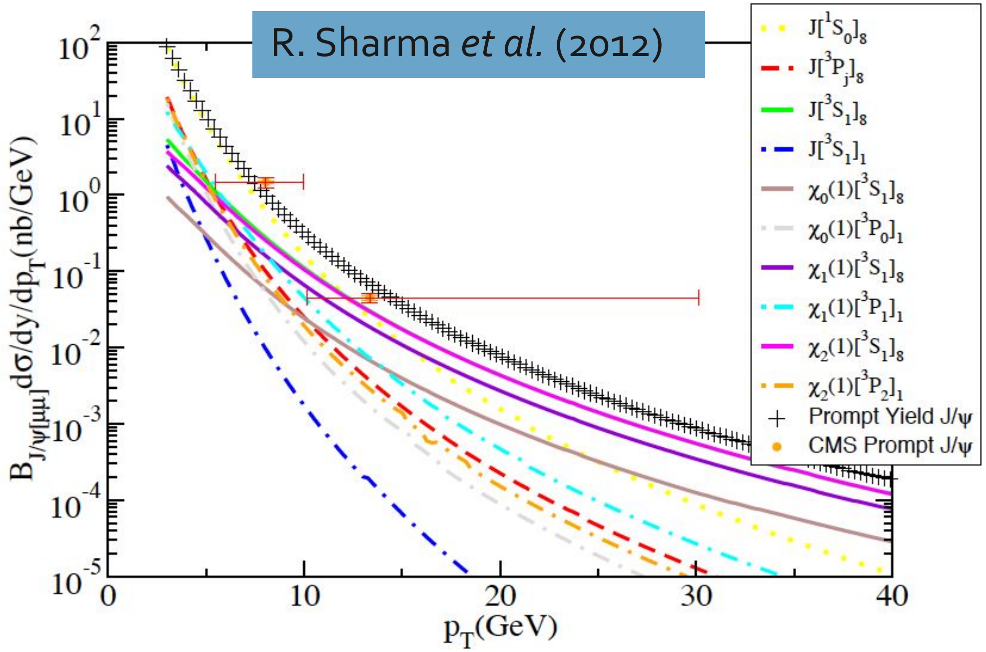
S. Aronson *et al.* (2017)

Feeddown is important

- Feedown will need to be accounted for in the results from our cross sections

Charmonium states





The following feeddowns are the largest contributions

$$\psi(2S): \quad \mathrm{Br}\left[\psi(2S) \to J/\psi + X\right] = 61.4 \pm 0.6\%$$

$$\chi_{c1}: \quad \mathrm{Br}\left[\chi_{c1} \to J/\psi + \gamma\right] = 34.3 \pm 1.0\%$$

$$\chi_{c2}: \quad \mathrm{Br}\left[\chi_{c2} \to J/\psi + \gamma\right] = 19.0 \pm 0.5\%$$

Conclusions

- Quarkonium production in reactions with nuclei is an important probe of nuclear matter-this will hold true at the EIC
- Previous papers have shown that collisional and thermal effects play a significant role in the suppression of quarkonium in a medium
- Promising preliminary results indicate that collisional effects may be more dominant than previously thought. In fact, the suppression of prompt states is comparable to what we have seen in QGP
- Final results for the cross sections could serve as a useful reference for experimental research at the EIC
- Relative cross section suppressions have been calculated, not including certain factors like feeddown and boosts of interaction time
- In the future, the relative cross section suppression will be convolved with NRQCD rates in e-p collisions to produce final phenomenological results
- In the future we can address various rapidities and CM energies