Can Charmonium be a Probe for QGP in Small Collision Systems?

Captain R. Singh
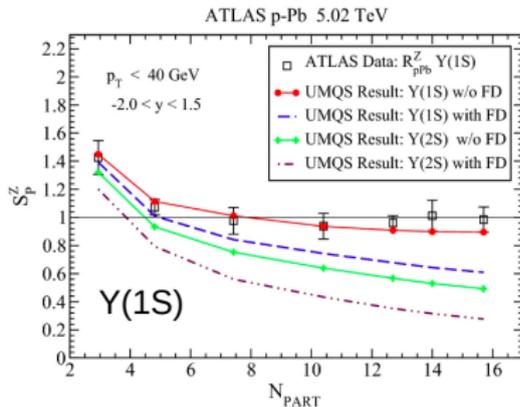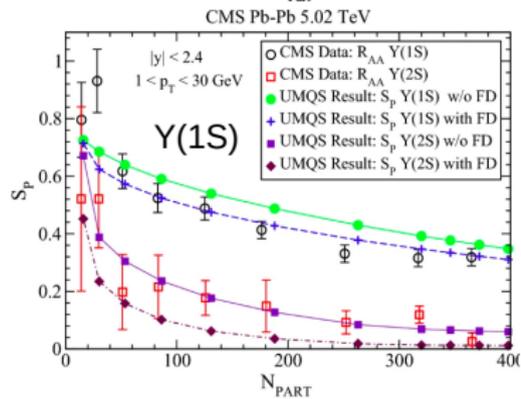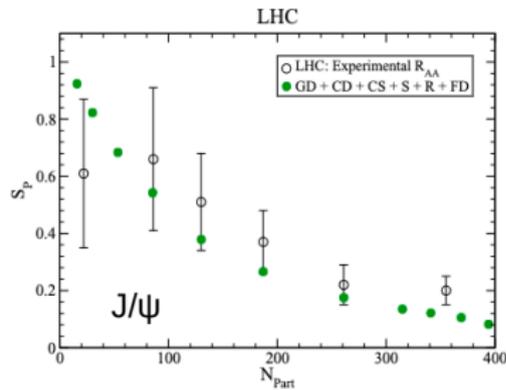
Hot QCD Matter, Sept. 04-06, 2025

Indian Institute of Technology Bhilai

Captain R Singh

Can Charmonium be a Probe for QGP in Small Collision Systems?

Hot QCD Matter 2025

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Motivations 2.0: search for QGP in pp collisions

- A substantial influence of the medium on observables at high multiplicities has been observed, e.g., collective flow, strangeness enhancement, etc.

Medium Evolution
The Mechanisms
UMQS Formalism
Observables
Summary
so far ...

Motivations 2.0: search for QGP in pp collisions

- A substantial influence of the medium on observables at high multiplicities has been observed, e.g., collective flow, strangeness enhancement, etc.

- Multiparticle Ridge–like Correlations

(d) CMS N ≥ 110, 1.0GeV/c<p_T<3.0GeV/c

CMS pp $\sqrt{s}$ = 13 TeV, $N_{trk}^{offline}$ ≥ 105

$1 < p_T < 3$ GeV/c

$\frac{1}{N_{trig}} \frac{d^2 N^{pair}}{d\Delta\eta \, d\Delta\phi}$

Ratio of yields to ($\pi^+ + \pi^-$)

$2K_S^0$

$\Lambda + \bar{\Lambda} (\times 2)$

$\Xi^- + \bar{\Xi}^+ (\times 6)$

$\Omega^- + \bar{\Omega}^+ (\times 16)$

ALICE
pp, $\sqrt{s}$ = 7 TeV
p–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
Pb–Pb, $\sqrt{s_{NN}}$ = 2.76 TeV
PYTHIA8
DIPSY
EPOS LHC

$\langle dN_{ch}/d\eta \rangle_{|\eta|<0.5}$

CMS pp $\sqrt{s}$ = 7 TeV: JHEP09(2010)091.   Phys. Lett. B 765, 193 (2017)

- Enhancement of Multi-strange Particles $\longrightarrow$
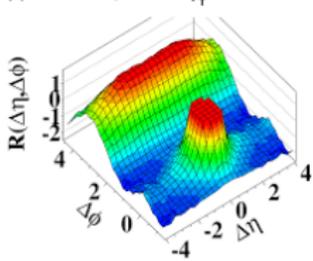
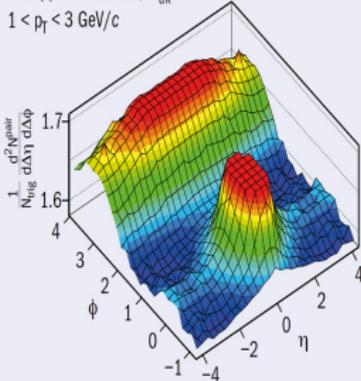ALICE Collaboration, Nature Phys. 13, 535 (2017)

Motivations 2.0: search for QGP in pp collisions

- A substantial influence of the medium on observables at high multiplicities has been observed; e.g. collective flow, strangeness enhancement, etc.

expecting the unexpected ...

- These observations allow us to explore the QGP-like medium behavior in ultra-relativistic pp collisions at LHC energies.

- This may provide deep insights into the pp baseline, which is necessary for the interpretation of the heavy-ion collisions.

Medium Evolution
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The Mechanisms
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UMQS Formalism
○○

Observables
○○○

Summary
○○

QGP Cooling: medium temp. & its evolution plays an essential role in deciding charmonium yield modification

The initial temperature T_0 is at $\tau = \tau_0$, where τ_0 is medium thermalization time.

$$T_0 = \left[\frac{90}{g_k 4\pi^2} C' \frac{1}{A_T \tau_0} \frac{dN}{d\eta} \right]^{1/3}$$

1+1D hydrodynamic evolution with IInd order viscous correction:

$$\frac{dT}{d\tau} = -\frac{T}{3\tau} + \frac{T^{-3}\phi}{12a\tau}, \quad \frac{d\phi}{d\tau} = -\frac{2aT\phi}{3b} - \frac{1}{2}\phi \left[\frac{1}{\tau} - \frac{5}{\tau}\frac{dT}{d\tau} \right] + \frac{8aT^4}{9\tau}$$

Gubser flow: 2+1D hydrodynamic evolution with IInd order viscous correction:

$$\frac{d\hat{\epsilon}}{d\rho} = -\left(\frac{8}{3}\hat{\epsilon} - \hat{\pi} \right) \tanh(\rho), \quad \frac{d\hat{\pi}}{d\rho} = -\frac{\hat{\pi}}{\hat{\tau}_\pi} + \tanh(\rho) \left(\frac{4}{3}\hat{\beta}_\pi - \hat{\lambda}\hat{\pi} - \hat{\chi}\frac{\hat{\pi}^2}{\hat{\beta}_\pi} \right)$$

where, conformal time, $\rho = -\sinh^{-1}\left(\frac{1 - q^2\tau^2 + q^2 x_T^2}{2q\tau} \right)$ & $q = \frac{1}{r}$

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Effective Temperature

⇒ Quarkonia ($\tilde{\mathcal{Q}}$) do not get thermalized with medium as other light flavors do,

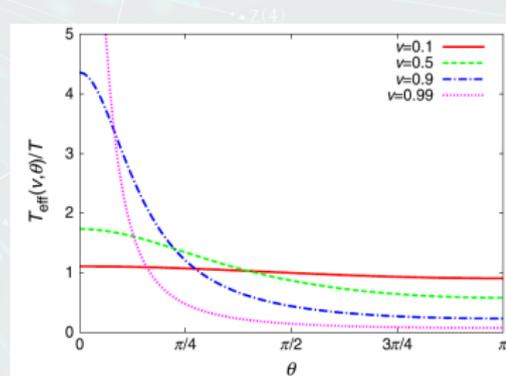The effective temperature is a consequence of the Relativistic Doppler Shift (RDS).

$$T_{eff}(\theta, \tau, |v_r|) = \frac{T(\tau)\sqrt{1-|v_r|^2}}{1-|v_r|\,\cos\theta}$$

- $T_{eff} > T$ at $0 < \theta \le \pi/4$, while elsewhere, $T_{eff} < T$
- at $\theta \sim \pi/2$ and $v_r \sim 1$, quarkonia becomes effectively cold and thus stable.

Angle averaged effective temperature;

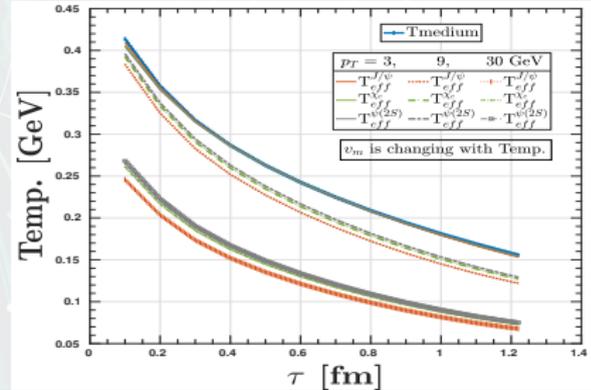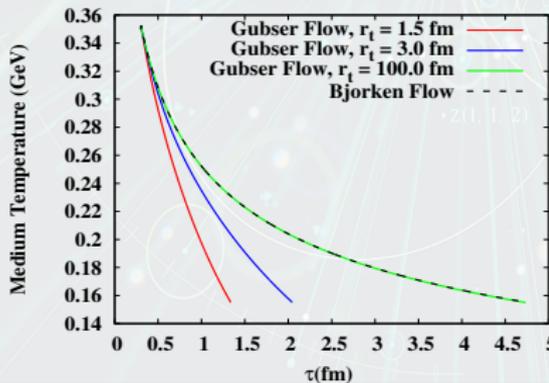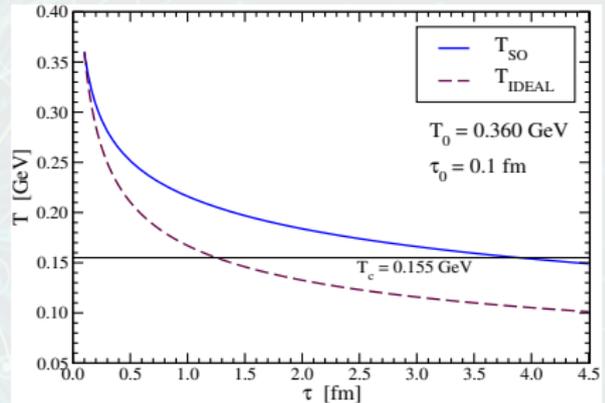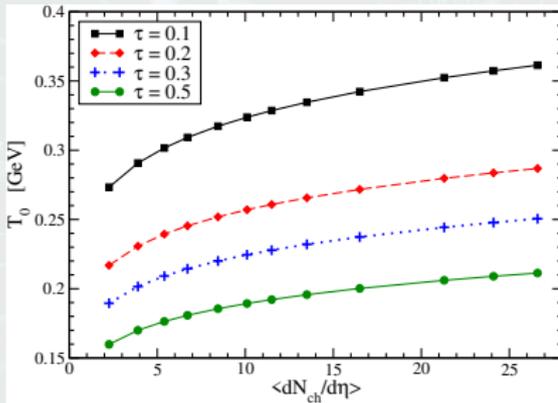$$T_{eff}(\tau, |v_r|) = T(\tau)\,\frac{\sqrt{1-|v_r|^2}}{2\,|v_r|}\,\ln\left[\frac{1+|v_r|}{1-|v_r|}\right]$$

... implies that the quarkonia feel a higher temp. in the forward direction (blue-shifted) and lower temp. in the backward direction (red-shifted).

Phys. Rev. D 87, 114005 (2013)

$\Rightarrow$ initial(T_0), medium & effective temp

Medium Evolution
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The Mechanisms
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UMQS Formalism
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Observables
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Summary
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Non-Adiabatic Evolution of Charmonium

- The Initial state of quarkonia is determined by solving the zero-temperature Hamiltonian.

$$H_0 = \frac{p^2}{2\mu} + \sigma r - \frac{\alpha_{eff}}{r}$$

- as thermalization occurs in the medium, the zero-temperature Hamiltonian evolves into its finite temperature counterpart;

$$H(\tau) = \frac{p^2}{2\mu} + V_{eff}, \quad \text{where} \quad V_{eff}(r) = \frac{\hbar^2 l(l+1)}{2mr^2} + V(r, m_D)$$
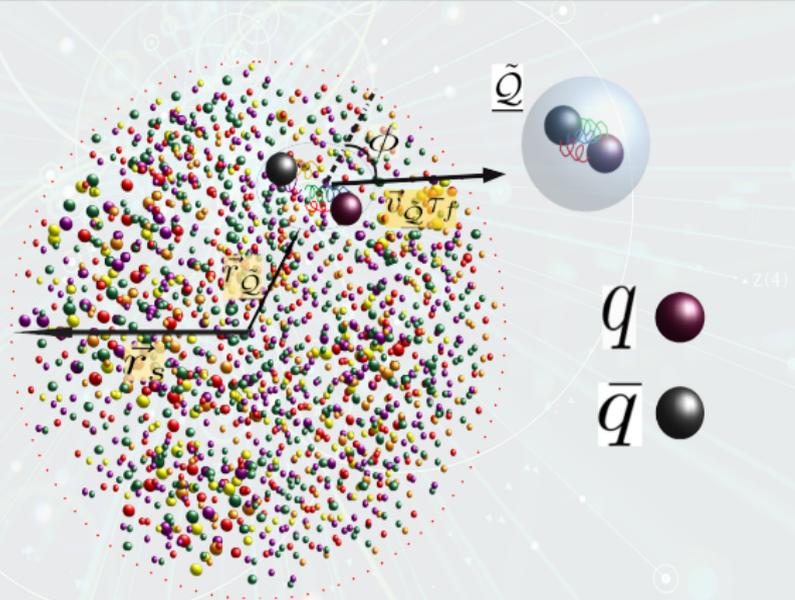
- The initial charmonia states evolve until the temperature drops below T_c.
- The probability of finding the particle in a particular bound state at $\tau = \tau_{QGP}$;

$$
\begin{aligned}
P_{J/\psi} &= |\langle \psi(\tau_c)|J/\psi\rangle|^2 \\
P_{\psi(2S)} &= |\langle \psi(\tau_c)|\psi(2S)\rangle|^2 \\
P_{\chi_c(1P)} &= |\langle \psi(\tau_c)|\chi_c(1P)\rangle|^2
\end{aligned}
$$

SMech: Color Screening

$\Rightarrow$ free-flowing partons screened-out the color charges which bind the $q - \bar{q}$ pair together

Matsui & Satz 1986: implant $\tilde{\mathcal{Q}}$ in QGP and observe their modification in terms of production in A−A collisions with elementary (p−p) collisions:

$\tilde{\mathcal{Q}}$ escape probability

- The $q\bar{q}$ pairs formed inside screening region at a point $\vec{r}_{\tilde{\mathcal{Q}}}$, may escape the region, if $|\vec{r}_{\tilde{\mathcal{Q}}} + \vec{v}_{\tilde{\mathcal{Q}}}\tau_f| > r_s$,

$$\cos(\phi) \geq Y; \quad Y = \frac{(r_s^2 - r_{\tilde{\mathcal{Q}}}^2)m_{\tilde{\mathcal{Q}}(nl)} - \tau_{nl}^2 p_T^2/m_{\tilde{\mathcal{Q}}(nl)}}{2\, r_{\tilde{\mathcal{Q}}}\, p_T\, \tau_{nl}}$$

- The distribution function for the production of $q\bar{q}$ in hard collisions at a distance r,

$$f(r) \propto \left(1 - \frac{r^2}{R_T^2}\right)^{\alpha} \theta(R_T - r)$$

- The integration over ϕ_{max} along with the r gives the escape probability of $\tilde{\mathcal{Q}}$ from the screening region

$$S_c^{\tilde{\mathcal{Q}}(nl)}(p_T, b) = \frac{2(\alpha + 1)}{\pi R_T^2} \int_0^{R_T} dr\, r\, \phi_{max}(r) \left\{1 - \frac{r^2}{R_T^2}\right\}^{\alpha}$$

SMech: Collisional Damping, dominates at $m_D \gg E$

$\Rightarrow$ decay width induced by damping of the low-frequency gauge fields

- at high-temperature heavy quarkonia disappear because the thermal width becomes so large that $q\bar{q}$ state melts in the continuum.

- here, dissociation occurs not because of the screening of the color charges but the appearance of an imaginary part in the potential.

- Singlet potential for quarkonia:

$$V(r, m_D) = \frac{\sigma}{m_D}(1 - e^{-m_D r}) - \alpha_{eff}\left(m_D + \frac{e^{-m_D r}}{r}\right)$$

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

- inelastic parton scattering dominates at $m_D \gg E$ and given as;

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

SMech: Gluonic Dissociation, dominates at $m_D \ll E$

$\Rightarrow$ gluon induced transition from color singlet state to color octet state

- Gluonic dissociation cross section is given as;

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

where, $\alpha_s^u = 0.59$; and $J_{nl}^{ql'} = \int_0^\infty dr r g_{nl}^*(r) h_{ql'}(r)$.

- Using the gluonic dissociation cross-section, the dissociation time constant $\Gamma_{gd,nl}$ can be written as:
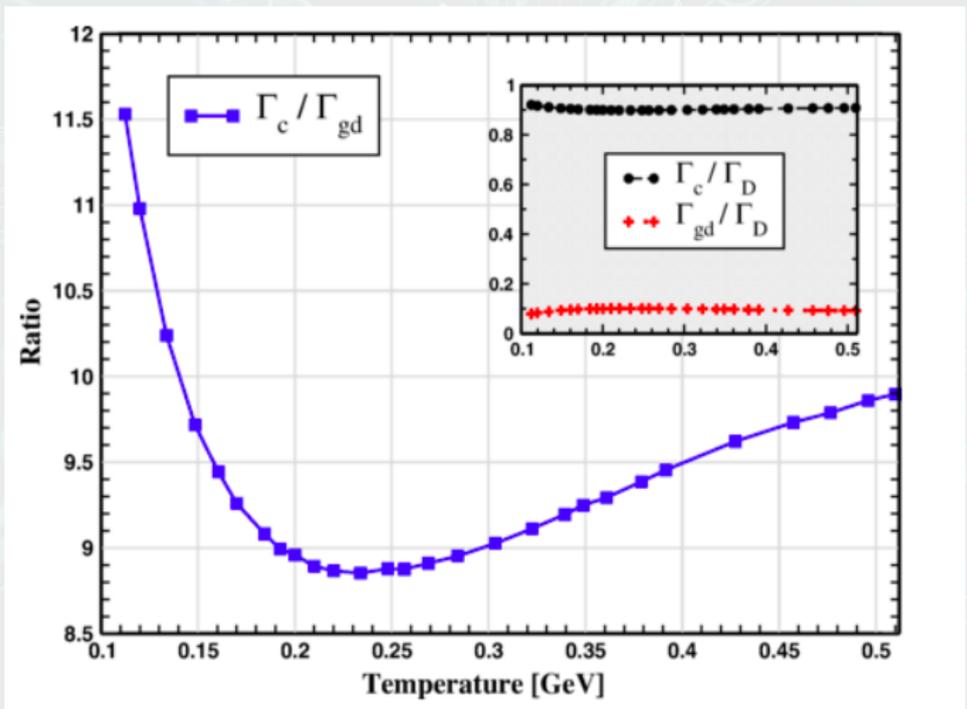
$$\Gamma_{gd,nl}(\tau, p_T, b) = \frac{g_d}{4\pi^2} \int_0^\infty \int_0^\pi \frac{dp_g \, d\theta \, \sin\theta \, p_g^2 \sigma_{d,nl}(E_g)}{e^{\left\{ \frac{\gamma E_g}{T_{eff}} (1 + v_{\underline{Q}} \cos\theta) \right\}} - 1}$$

- The net decay width is the sum of the gluonic dissociation and collisional damping mechanisms,

$$\Gamma_{D,nl} = \Gamma_{damp,nl} + \Gamma_{gd,nl}.$$

damping Vs dissociation

The ratio between the decay widths of collisional damping and gluonic dissociation for J/ψ as a function of temperature is shown. In the inset, the ratio of individual decay widths to the net decay width is illustrated with temperature

RMech: Regeneration due to Gluonic De-excitation

$\Rightarrow$ Formation of $\underline{\tilde{\mathcal{Q}}}$ due to correlated $q\bar{q}$ pair transition from octet to singlet

- The recombination cross section $\sigma_{f,nl}$:

$$\sigma_{f,nl} = \prod_{i=q,\bar{q}}^{\underline{\tilde{\mathcal{Q}}}=J/\psi, \Upsilon} \frac{g_d g_{\underline{\tilde{\mathcal{Q}}}}}{g_s^i g_c^i} \sigma_{d,nl} \frac{(s - M_{nl}^2)^2}{s(s - 4\,m_q^2)}.$$

- Recombination factor, $\Gamma_{F,nl}$;

$$\Gamma_{F,nl} = \langle \sigma_{f,nl} v_{rel} \rangle_{p,\bar{p}} = \frac{\int_{p_{q,min}}^{p_{q,max}} \int_{p_{\bar{q},min}}^{p_{\bar{q},max}} dp_q\, dp_{\bar{q}}\, p_q^2\, p_{\bar{q}}^2\, f_q\, f_{\bar{q}}\, \sigma_{f,nl}\, v_{rel}}{\int_{p_{q,min}}^{p_{q,max}} \int_{p_{\bar{q},min}}^{p_{\bar{q},max}} dp_q\, dp_{\bar{q}}\, p_q^2\, p_{\bar{q}}^2\, f_q\, f_{\bar{q}}}$$

- The relative velocity:

$$v_{rel} = \sqrt{\frac{(p_q^\mu p_{\bar{q}\mu})^2 - m_q^4}{p_q^2\, p_{\bar{q}}^2 + m_q^2(p_q^2 + p_{\bar{q}}^2 + m_q^2)}}.$$

UMQS Formulation

- $\tilde{\mathcal{Q}}$ production happens in two stages:
    i. Initial production during hard collision.
    ii. Secondary production via recombination.

- In medium $q\bar{q} \rightarrow \tilde{\underline{\mathcal{Q}}}$ and $\tilde{\underline{\mathcal{Q}}} \rightarrow q\bar{q}$ form a feedback system modeled by a coupled rate equation:

$$\frac{dN_{\tilde{\underline{\mathcal{Q}}}(nl)}}{d\tau} = \Gamma_{F,nl} N_q \, N_{\bar{q}} \, [V(\tau)]^{-1} - \Gamma_{D,nl} N_{\tilde{\underline{\mathcal{Q}}}(nl)}$$

- The analytical solution:

$$N^f_{\tilde{\underline{\mathcal{Q}}}(nl)}(\tau_{QGP}, b, p_T) = \epsilon(\tau_{QGP}, b, p_T)\Bigg[N_{\tilde{\underline{\mathcal{Q}}}(nl)}(\tau_0, b)$$

$$+ N^2_{q\bar{q}} \int_{\tau_0}^{\tau_{QGP}} \Gamma_{F,nl}(\tau, b, p_T)[V(\tau, b)\epsilon(\tau, b, p_T)]^{-1} d\tau \Bigg]$$

$$\epsilon(\tau_{QGP}, b, p_T) = \exp\left[-\int_{\tau_{nl}}^{\tau_{QGP}} \Gamma_{D,nl}(\tau, b, p_T) d\tau \right]$$

Net Survival Probability, S_P

$\Rightarrow$ how to "Quantify" the medium effect in pp collisions !!!

- R_{pp} may have the following form: $R_{pp}^{\tilde{\mathcal{Q}}} = \frac{dN_{final}^{\tilde{\mathcal{Q}}}/d\eta}{dN_{initial}^{\tilde{\mathcal{Q}}}/d\eta} \equiv S_P^{\tilde{\mathcal{Q}}}$

  Ref: M. Bleicher et al., Phys. Rev. C 87, 024907 (2013)

- The yield incorporating CD and GD: $S_{sgc}^{\tilde{\mathcal{Q}}}(p_T, b) = \frac{N_{\tilde{\mathcal{Q}}(nl)}^{f}(p_T, b)}{N_{\tilde{\mathcal{Q}}(nl)}(\tau_0, b)}$

- The net probabilty: $S_P^{\tilde{\mathcal{Q}}(nl)}(p_T, b) = S_{sgc}^{\tilde{\mathcal{Q}}}(p_T, b) \times S_c^{\tilde{\mathcal{Q}}}(p_T, b) \times P_{nl}^{\tilde{\mathcal{Q}}}(p_T, b)$

- The Feed-down: $S_{P,FD}^{\tilde{\mathcal{Q}}(I)} = \frac{\sum_{I \leq J} C_{IJ} N_{\tilde{\mathcal{Q}}(J)}(\tau_0, b) S_P^{\tilde{\mathcal{Q}}(J)}(p_T, b)}{\sum_{I \leq J} C_{IJ} N_{\tilde{\mathcal{Q}}(J)}(\tau_0, b)}$
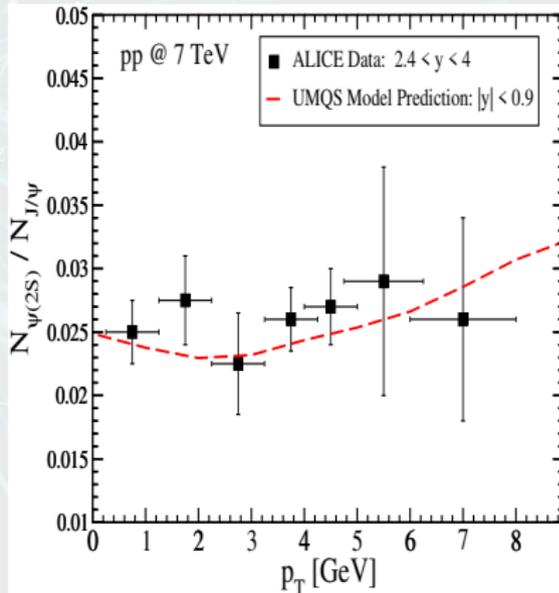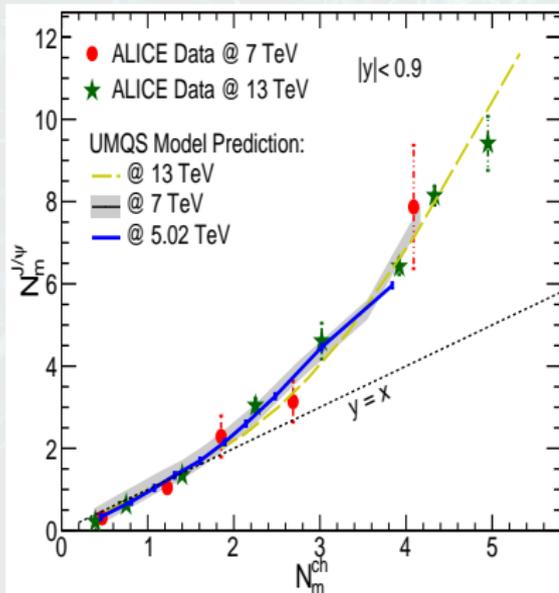
- Normalized yield:

$$N_m^{J/\psi} = \frac{dN_{J/\psi}/d\eta}{\langle dN_{J/\psi}/d\eta \rangle}, \qquad N_m^{ch} = \frac{dN_{ch}/d\eta}{\langle dN_{ch}/d\eta \rangle}$$

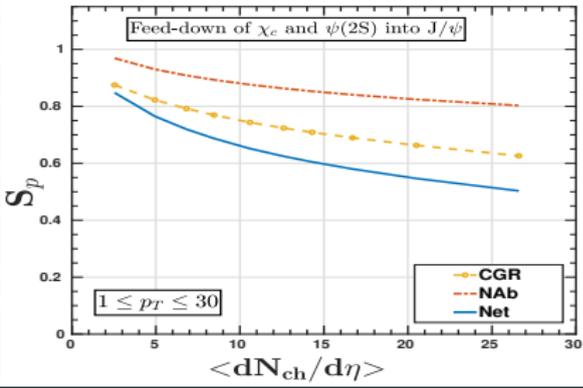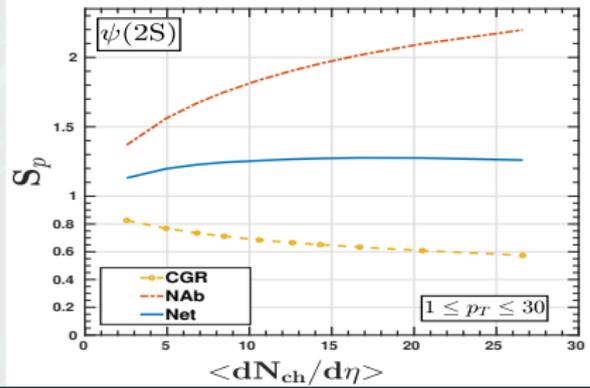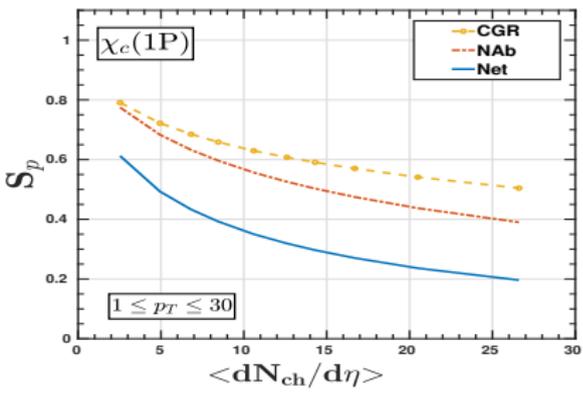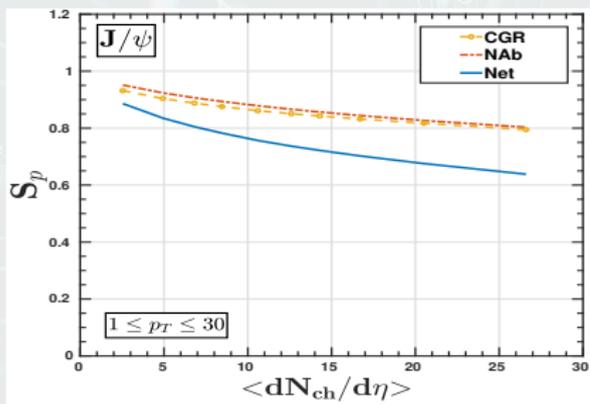$N_m^{J/\psi}$ and N_m^{ch} are normalized by the corresponding mean values in minimum bias pp collisions.

Normalized J/ψ yield

UMQS model results compared with experimental data at various classes of multiplicities

⇒ J/ψ, $\chi_c(1P)$ & $\psi(2S)$ yield modification with multiplicity at 13 TeV

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$\tilde{\mathcal{Q}}$ Polarization Based on Yield Modification:

obtained by incorporating $C = \oint \vec{\nabla} \times \vec{v} \cdot d\vec{S} = 2\omega\pi r^2$ and $\frac{m_j C}{2\pi r^2}$ in Hamiltonian

Summary

- Investigation on charmonia yield modification in pp collisions can help to quantify the Hot QCD Matter effects as it excludes baryonic effects: No CNM.

- Due to low charm yield in pp collision, J/ψ production by the recombination of un-correlated $c\bar{c}$ is almost zero: reduces the complexity.

- It suggests, $\psi(2S)$ like higher resonances could be a cleaner probe to investigate QGP in small systems due to their dissociation temperature.

- Vorticity $\Rightarrow$ Polarization (primarily). In pp collisions, most potential source of vorticity generation is vector boson force field $\Rightarrow$ polarization of $\tilde{\mathcal{Q}}$.

So, YES, Charmonium is a prominent probe to search for QGP in small collision systems.