Quarkonia as a Potential Probe for QGP in small collision systems

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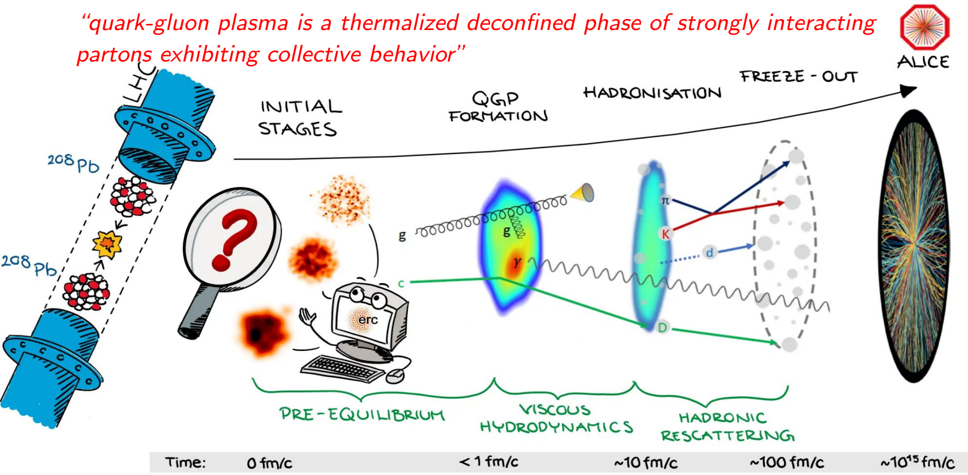
Exotic Quarkonia in Heavy-ion Collisions

Heavy-ion Collision & QGP

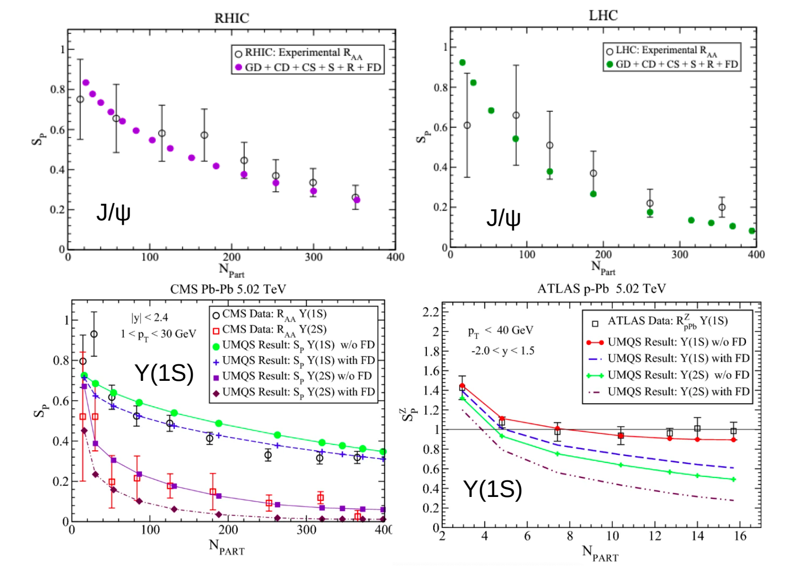
"quark-gluon plasma is a thermalized deconfined phase of strongly interacting partons exhibiting collective behavior"



Baseline of the model

Unified Model of Quarkonia Suppression incorporates various mechanisms which effectively modify quarkonia yield in relativistic heavy-ion collisions

Phys. Rev. C 92, 034916 (2015), Eur. Phys. J. C 79, 147 (2019)



UMQS: Unified Model of Quarkonia Suppression

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

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

- The analytical solution:

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

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

Shadowing Effect

- The modification of parton densities in nuclei affects the production yield in A−A and/or p−A collisions.
- We use the EPS09 parametrization to obtain the shadowing: $S^i(A, x, \mu)$ for nucleus with mass A, momentum fraction x and scale μ.

$$S^i_\rho(A, x, \mu, \vec{r}) = 1 + N_\rho(S^i(A, x, \mu) - 1)\frac{\int dz \rho_A(\vec{r}, z)}{\int dz \rho_A(0, z)}$$

  where N_ρ is determined by the following normalization condition: $\frac{1}{A}\int d^2r dz \rho_A(s) S^i_\rho(A, x, \mu, \vec{r}) = S^i(A, x, \mu)$

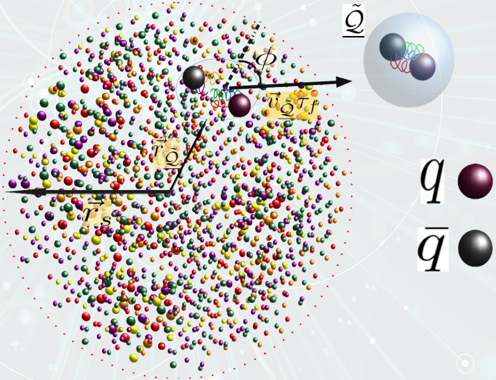
- The suppression factor due to CNM effect is thus determined by,

$$S_{sh} = R_{AB}(N_{part}; b) = \frac{dN_{AB}/dy}{T_{AB}(b) d\sigma_{pp}/dy}$$

... major contribution by Ramona Vogt

SMech: Color Screening

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



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

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

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

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

here ϕ is azimuthal angle between $\vec{r}_{\tilde{\underline{\mathcal{Q}}}}$ and p_T

- the escape probability of $\tilde{\underline{\mathcal{Q}}}$ from the screening region

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

Captain R. Singh, et al., Phys. Rev. C 92, 034916 (2015)

Color Screening as the Function of Centrality

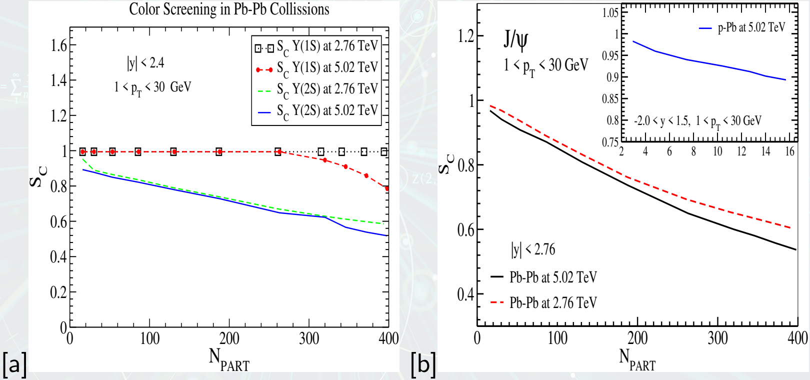


Figure: **(a)** Color screening for $\Upsilon(1S)$ and $\Upsilon(2S)$ versus N_{PART} in Pb−Pb Collisions at LHC energies. **(b)** Same is plotted for J/ψ. In inset J/ψ suppression due to color screen is plotted in p−Pb collision at $\sqrt{s_{NN}} = 5.02$ TeV at mid rapidity.

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

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

- In the QGP medium, heavy quarkonia may disappear if the thermal width becomes large enough, such that the $q\bar{q}$ state melts in the continuum.
- here, dissociation is induced by appearance of an imaginary part in the potential.
- Singlet potential for quarkonia: Georg Wolschin et. al, Phys. Rev. C 87, 024911 (2013)

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

- 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, $J_{nl}^{ql'} = \int_0^\infty drrg_{nl}^*(r)h_{ql'}(r)$. Georg Wolschin et al., Phys. Lett. B 707, 534 (2012)

- Using the gluonic dissociation cross-section, the dissociation time constant $\Gamma_{gd,nl}$ can be written as:

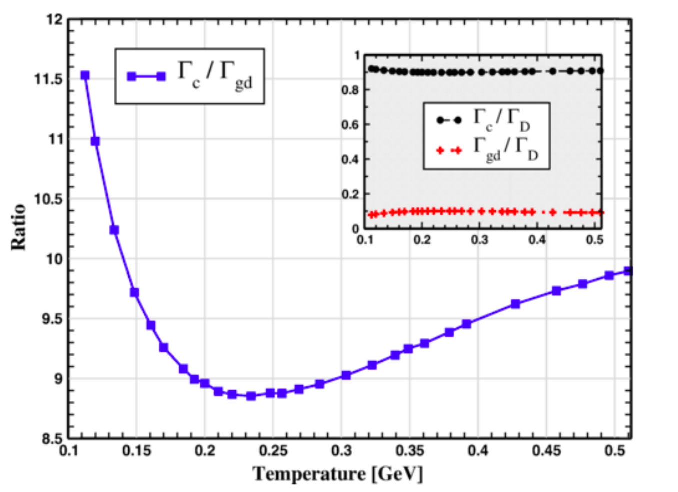
$$\Gamma_{gd,nl}(\tau, p_T, b) = \frac{g_d}{4\pi^2} \int_0^\infty \int_0^\pi \frac{dp_g \, d\theta \, \sin\theta \, p_g^2 \sigma_{d,nl}(E_g)}{e^{\left\{\frac{\gamma E_g}{T_{eff}}(1+v_{\tilde{Q}} \cos\theta)\right\}} - 1}$$

Captain R. Singh, et al., Eur. Phys. J. C 79, 147 (2019)

- 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

GIE2S: S. Ganesh et al., J. Phys. G 45, 035003 (2018)

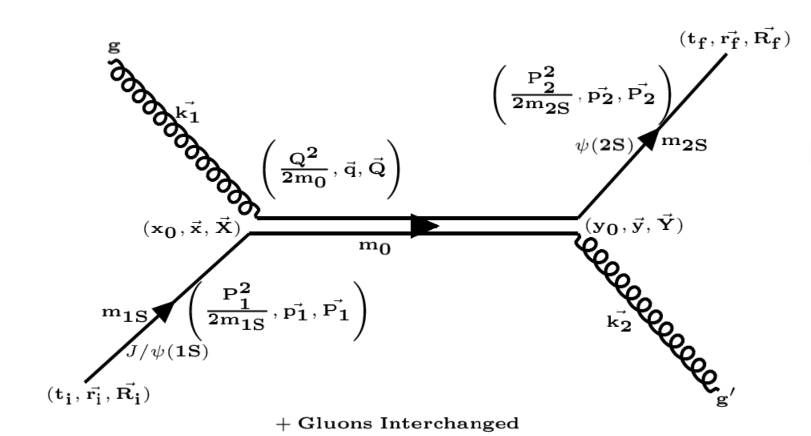


Figure: Feynman diagrams for gluon induced excitation of $1S$ state to $2S$ state. The second diagram is just the first diagram with gluons interchanged.

Transition Rate

- From the diagram we obtained the net amplitude of the process;

$$M = \int d^3 r_i \int d^3 r_f \langle S_{1S}(r_i) | G(r_i, r_f, R_i, R_f) | S_{2S}(r_f) \rangle$$

- Transition cross Section;

$$\sigma_{1S\to 2S} = \frac{2C_g \pi^7}{E_{1S} m_{2S}} k_1 M^2 \left(k_1 - \frac{k_1^2}{2m_{2S}} - \Delta m \right)$$

- The Transition Rate $\Gamma_{1S\to 2S}$;

$$\Gamma_{1S\to 2S} = \int \frac{1}{4\pi^2} E_g^2 \sin(\theta) f_g(E_g, v_{rel}, \theta)\, \sigma_{1S\to 2S}\, dE_g\, d\theta$$

$$= \frac{g_d}{4\pi^2} \int \frac{E_g T_{eff}\, \sigma_{1S\to 2S}}{v_{rel}\gamma} \ln\left[\frac{e^{\frac{\gamma E_g}{T_{eff}}(1+v_{rel})} - 1}{e^{\frac{2\gamma E_g v_{rel}}{T_{eff}}} \left(e^{\frac{\gamma E_g}{T_{eff}}(1-v_{rel})} - 1 \right)} \right] dE_g$$

- The fraction of the number of $1S$ particles converted to $2S$

$$\Delta n_{1S\to 2S} = 1 - \exp\left(-\int_{\tau_0}^{\tau_{QGP}} \Gamma_{1S\to 2S}\, dt\right)$$

- The increment in $\psi(2S)$ yield is then obtained by;

$$S_{1S\to 2S} = \frac{N_{J/\psi}}{N_{\psi(2S)}} \Delta n_{1S\to 2S}.$$

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

Gluonic excitation from $1S \to 2S$ for the bottomonium. $\Upsilon(1S) \to \Upsilon(2S)$ is found to be negligible

GIE2S transition rate and decay width

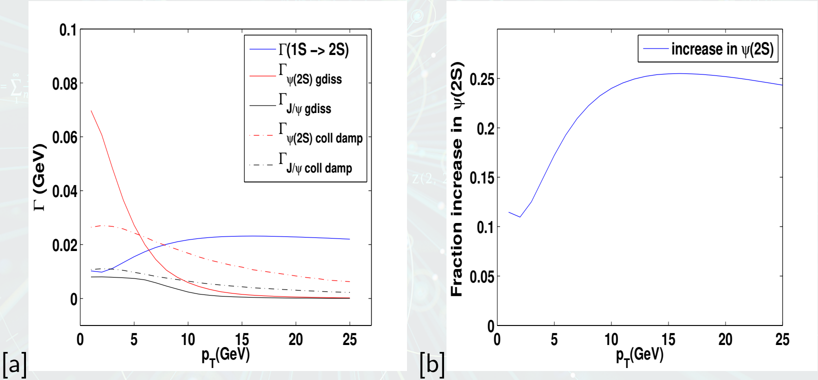


Figure: **(a)** Comparison of Γ_{diss} due to gluonic dissociation and collisional damping with $\Gamma_{1S\to 2S}$. Depicted Γ_{diss} due to gluonic dissociation is averaged over all bins. **(b)** The fractional increase in $\psi(2S)$ as a function of p_T, for medium velocity equal to $0.5c$.

RMech: Regeneration due to Gluonic de-excitation

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

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

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

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

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

- The relative velocity:

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

Captain R. Singh, et al., Phys. Rev. C 92, 034916 (2015)

Quarkonium Survival Probability, S_P

- The net production of $\underaccent{\tilde}{\mathcal{Q}}$s includes hot and cold nuclear matter effects.
- The initially suppressed $\underaccent{\tilde}{\mathcal{Q}}$s due to shadowing effect is given as;

$$N^{i}_{\tilde{\mathcal{Q}}(nl)}(\tau_0, p_T, b) = N_{\tilde{\mathcal{Q}}(nl)}(\tau_0, b)\, S_{sh}(p_T, b)$$

- The modified solution of transport equation can be rewritten as:

$$N^{f}_{\tilde{\mathcal{Q}}(nl)} = \epsilon(\tau_{QGP})\left[N^{i}_{\tilde{\mathcal{Q}}(nl)}(\tau_0) + N^2_{q\bar{q}}\int_{\tau_0}^{\tau_{QGP}} \Gamma_{F,nl}(\tau)[V(\tau, b)\epsilon(\tau)]^{-1} d\tau\right]$$

- The survival probability:

$$S^{\tilde{\mathcal{Q}}}_{sgc}(p_T, b) = \frac{N^{f}_{\tilde{\mathcal{Q}}(nl)}(p_T, b)}{N_{\tilde{\mathcal{Q}}(nl)}(\tau_0, b)}$$

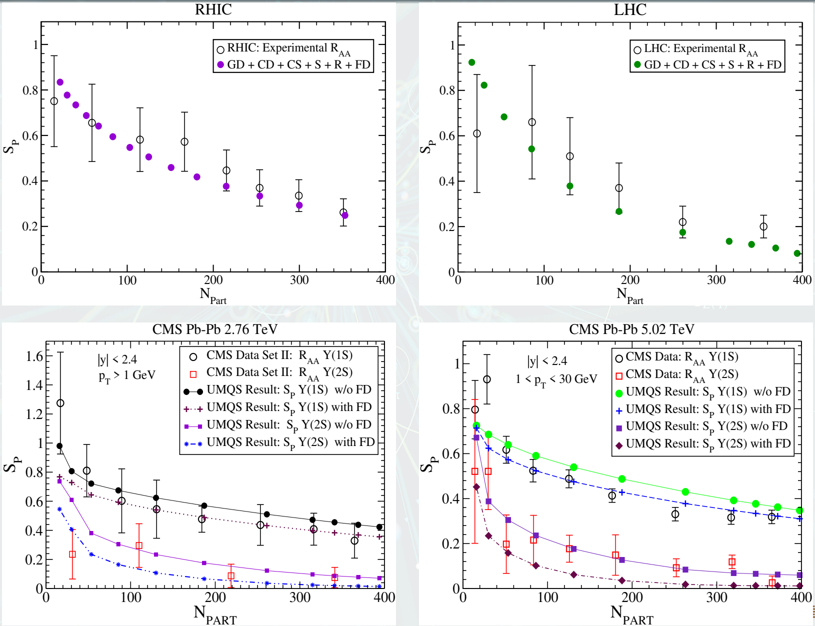
Net Survival Probability, S_P

⇒ quantifying the medium effect in AA collisions

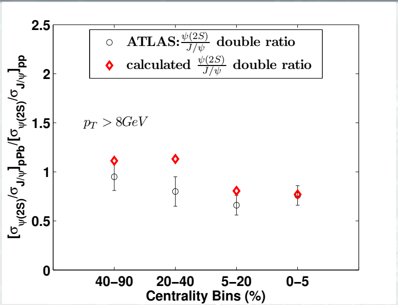
- The yield incorporating CD and GD: $S_{sgc}^{\tilde{\mathcal{Q}}}(p_T, b) = \frac{N^f_{\tilde{\mathcal{Q}}(nl)}(p_T, b)}{N_{\tilde{\mathcal{Q}}(nl)}(\tau_0, b)}$
- The net probabilty: $S_P^{\tilde{\mathcal{Q}}(nl)}(p_T, b) = S_{sgc}^{\tilde{\mathcal{Q}}}(p_T, b) \times S_c^{\tilde{\mathcal{Q}}}(p_T, b) \times S_{1S\to 2S}$
- The Feed-down: $S_{P,FD}^{\tilde{\mathcal{Q}}(I)} = \frac{\sum_{I\le J} C_{IJ} N_{\tilde{\mathcal{Q}}(J)}(\tau_0, b) S_P^{\tilde{\mathcal{Q}}(J)}(p_T, b)}{\sum_{I\le J} C_{IJ} N_{\tilde{\mathcal{Q}}(J)}(\tau_0, b)}$

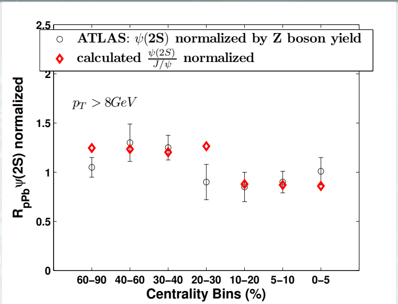
The nuclear modification factor, R_{AA}, is the experimentally measured quantity equivalent to the survival probability, S_P;

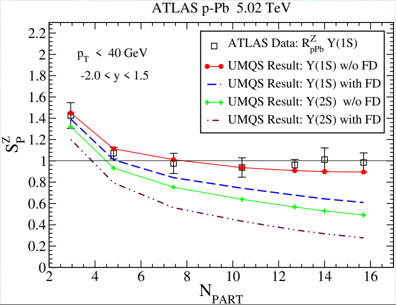
$$R_{AA}^{\tilde{\mathcal{Q}}} = \frac{d^2 N_{AA}^{\tilde{\mathcal{Q}}}/dp_T d\eta}{N_{coll} d^2 N_{pp}^{\tilde{\mathcal{Q}}}/dp_T d\eta} \equiv \frac{\tilde{\mathcal{Q}} \text{ Yield in A}-\text{A}}{N_{coll} \times \tilde{\mathcal{Q}} \text{ Yield in p}-\text{p}} \equiv S_P^{\tilde{\mathcal{Q}}}$$

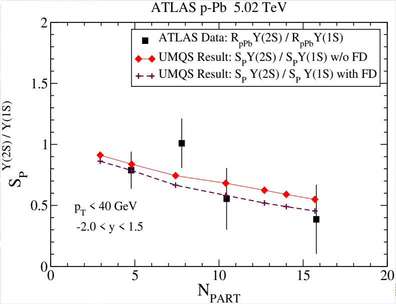

RHIC
RHIC: Experimental R_AA
GD + CD + CS + S + R + FD
S_P
N_Part
LHC
LHC: Experimental R_AA
GD + CD + CS + S + R + FD
S_P
N_Part
CMS Pb-Pb 2.76 TeV
|y| < 2.4
p_T > 1 GeV
CMS Data Set II: R_AA Υ(1S)
CMS Data Set II: R_AA Υ(2S)
UMQS Result: S_P Υ(1S) w/o FD
UMQS Result: S_P Υ(1S) with FD
UMQS Result: S_P Υ(2S) w/o FD
UMQS Result: S_P Υ(2S) with FD
S_P
N_PART
CMS Pb-Pb 5.02 TeV
|y| < 2.4
1 < p_T < 30 GeV
CMS Data: R_AA Υ(1S)
CMS Data: R_AA Υ(2S)
UMQS Result: S_P Υ(1S) w/o FD
UMQS Result: S_P Υ(1S) with FD
UMQS Result: S_P Υ(2S) w/o FD
UMQS Result: S_P Υ(2S) with FD
S_P
N_PART

Results p-A


ATLAS: $\frac{\psi(2S)}{J/\psi}$ double ratio
calculated $\frac{\psi(2S)}{J/\psi}$ double ratio
$p_T > 8GeV$
$[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pPb}/[\sigma_{\psi(2S)}/\sigma_{J/\psi}]_{pp}$
40–90
20–40
5–20
0–5
Centrality Bins (%)


ATLAS: ψ(2S) normalized by Z boson yield
calculated $\frac{\psi(2S)}{J/\psi}$ normalized
$p_T > 8GeV$
R_{pPb} ψ(2S) normalized
60–90
40–60
30–40
20–30
10–20
5–10
0–5
Centrality Bins (%)


ATLAS p-Pb 5.02 TeV
p_T < 40 GeV
-2.0 < y < 1.5
ATLAS Data: R^Z_{pPb} Y(1S)
UMQS Result: Y(1S) w/o FD
UMQS Result: Y(1S) with FD
UMQS Result: Y(2S) w/o FD
UMQS Result: Y(2S) with FD
S^Z_P
N_{PART}


ATLAS p-Pb 5.02 TeV
ATLAS Data: R_{pPb}Y(2S) / R_{pPb}Y(1S)
UMQS Result: S_PY(2S) / S_PY(1S) w/o FD
UMQS Result: S_P Y(2S) / S_P Y(1S) with FD
p_T < 40 GeV
-2.0 < y < 1.5
S_P Y(2S) / Y(1S)
N_{PART}

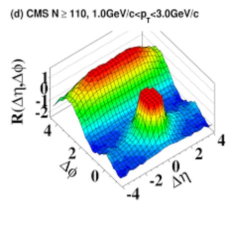
The hunt for QGP in A-A collision was about to settle, but then something unexpected happened in the grand caves under the Jura mountain!!! the baseline used for QGP investigations got corrupted...

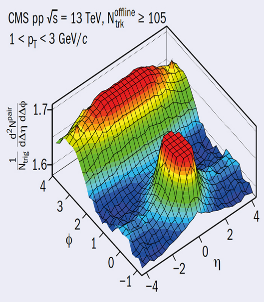
- A simultaneous fit to all particles at $\sqrt{s} = 7$ TeV pp collision gives a freeze-out temperature, $T_{fo} = 163 \pm 10$ MeV: indicates a higher initial temperature, $T_0 > T_c \approx 155$ MeV ALICE Collaboration, Nature Phys. 13, 535 (2017)
- A substantial influence of the medium on observables at high multiplicities has been observed, e.g., collective flow, strangeness enhancement, etc.

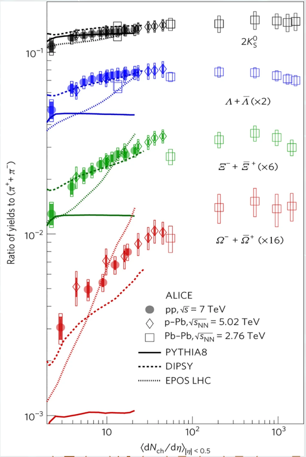
Motivations 2.0: search for QGP in pp collisions

- 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







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)

... on the view of these observations

- We attempted to investigate charmonium yield modification in *pp* collisions at the LHC energies using the UMQS model.
- The current study may provide a comprehensive insights into the *pp* baseline, which is necessary for the interpretation of quarkonia yield modification in the heavy-ion collisions.
- The medium temp. & its evolution plays an essential role in deciding charmonium yield modification in ultra relativistic collisions.

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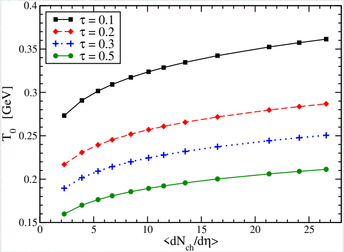
- The current study may provide a comprehensive insights into the *pp* baseline, which is necessary for the interpretation of quarkonia yield modification in the heavy-ion collisions.
- The medium temp. & its evolution plays an essential role in deciding charmonium yield modification in ultra relativistic collisions.
- … but does such a small system possess enough temp. for QGP to exist??

QGP Thermal Profile

$\Rightarrow$ initial temperature T_0 at $\tau = \tau_0$

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

Ref: R. C. Hwa et al., Phys. Rev. D 32, 5 (1985).

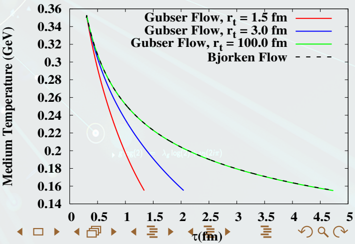


$\Rightarrow$ Gubser flow: 2+1D hydrodynamic evolution with IInd order viscous correction:

$$\frac{d\hat{\epsilon}}{d\rho} = -\left(\frac{8}{3}\hat{\epsilon} - \hat{\pi}\right)\tanh(\rho)$$

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

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



Non-Adiabatic Evolution: Captain R. Singh et al.,Phys. Rev. D 112, 014017 (2025)

- 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;

$$H(\tau) = \frac{p^2}{2\mu} + V_{eff}, \quad \text{where} \quad V_{\text{eff}}(r) = \frac{\hbar^2 l(l+1)}{2mr^2} + V(r, m_D)$$

- The probability of finding the particle in a particular bound state at $\tau = \tau_{QGP}$;

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

Net Survival Probability, S_P

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

- The yield incorporating CD and GD: $S^{\tilde{\mathcal{Q}}}_{sgc}(p_T, b) = \frac{N^f_{\tilde{\mathcal{Q}}(nl)}(p_T, b)}{N_{\tilde{\mathcal{Q}}(nl)}(\tau_0, b)}$
- The net probabilty: $S^{\tilde{\mathcal{Q}}(nl)}_P(p_T, b) = S^{\tilde{\mathcal{Q}}}_{sgc}(p_T, b) \times S^{\tilde{\mathcal{Q}}}_c(p_T, b) \times P^{\tilde{\mathcal{Q}}}_{nl}(p_T, b)$
- The Feed-down: $S^{\tilde{\mathcal{Q}}(I)}_{P,FD} = \frac{\sum_{I \leq J} C_{IJ} N_{\tilde{\mathcal{Q}}(J)}(\tau_0, b) S^{\tilde{\mathcal{Q}}(J)}_P(p_T, b)}{\sum_{I \leq J} C_{IJ} N_{\tilde{\mathcal{Q}}(J)}(\tau_0, b)}$

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- 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: $S_{P,FD}^{\tilde{\mathcal{Q}}(I)} = \frac{\sum_{I \leq J} C_{IJ} N_{\tilde{\mathcal{Q}}(J)}(\tau_0, b) S_P^{\tilde{\mathcal{Q}}(J)}(p_T, b)}{\sum_{I \leq J} C_{IJ} N_{\tilde{\mathcal{Q}}(J)}(\tau_0, b)}$
- R_{pp} may have the following form: $R_{pp}^{\tilde{\mathcal{Q}}} = \frac{dN^{\tilde{\mathcal{Q}}}_{final}/d\eta}{dN^{\tilde{\mathcal{Q}}}_{initial}/d\eta} \equiv S_P^{\tilde{\mathcal{Q}}}$

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

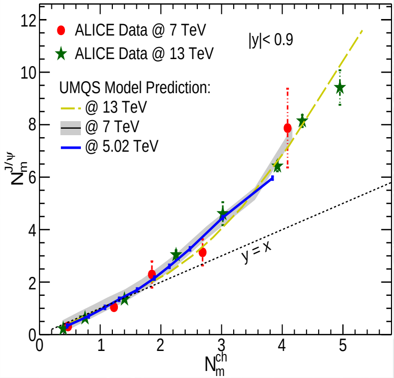
- Normalized yield:

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

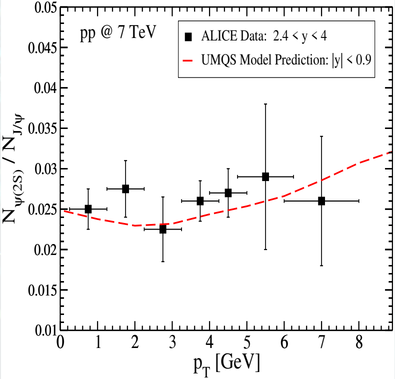
$N_m^{J/\psi}$ and N_m^{ch} are normalized by the corresponding mean values in minimum bias *pp* collisions.

⇒ putting all together we produced the possible observables proposed for *pp* collisions

UMQS results are also compared with data at various classes of multiplicities

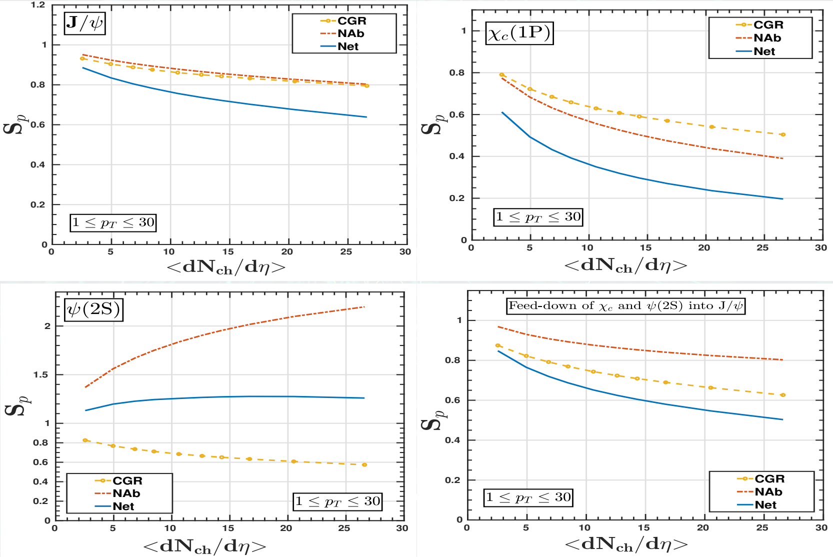


Eur. Phys. J. C 82, 542 (2022)



Phys. Rev. D 112, 014017 (2025)

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



⇒ unsettling faith!!!

... but, in the absence of the well established experimental observables, present findings remain INCONCLUSIVE !!!

$\Rightarrow$ unsettling faith!!!

... but, in the absence of the well established experimental observables, present findings remain INCONCLUSIVE !!!

The Rise of Fallen

Z. Phys. C 29, 135 (1985), Phys.Rev. C 65 024902 (2002), & many more

- Polarization being a **baseline** independent could be a better signature, if source of polarization are exactly known and distinguishable.
- Vorticity induced hyperons and lighter meson polarization is explored, but all these hadrons are formed at hadronisation stage.
- On the other hand, Quarkonia produced in initial hard collision, can provide the insights of whole evolution of vortical medium.

Quarkonium Spin Alignment

Polarization refers to the alignment of the quarkonium spin with respect to a chosen axis in a reference frame.

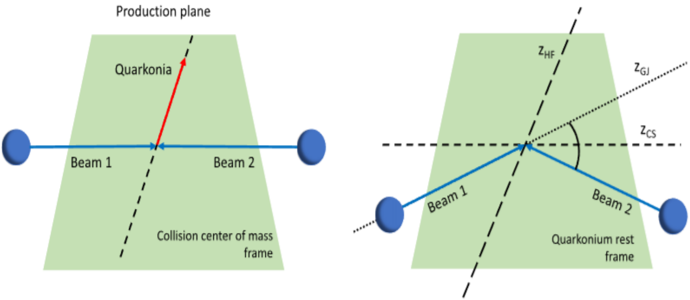


FIG. 1. Illustration of the three different definitions of the polarization axis, z, in the helicity (HF), Collins-Soper (CS), Gottfried-Jackson (GJ) reference frames, with respect to the direction of motion of the colliding beams (Beam 1 and Beam 2) and of the quarkonia.

Bhagyarathi Sahoo et al., Phys. Rev. C 109, 034910 (2024)

Quarkonia polarization measurement in experiments

- Quarkonia spin alignment is characterized by the component spin density matrix, ρ.
- The diagonal component ρ_{00} is considered as the proxy for quarkonia polarization in the experiments. Bhagyarathi Sahoo et al., Phys. Rev. C 109, 034910 (2024)
- It can be determined using the angular distribution of decay leptons;

$$\frac{dN}{d\Omega} \propto 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin^2\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$$

λ_θ, λ_ϕ and $\lambda_{\theta\phi}$ are the polarization parameters

$$\rho_{00} = \frac{1-\lambda_\theta}{3+\lambda_\theta}$$

- The deviation $\rho_{00} - 1/3$ quantifies the degree of alignment. $\rho_{00} < 1/3$ transverse polarization, $\rho_{00} > 1/3$ longitudinal polarization, unpolarized: $\rho_{00} = 1/3$

Effective Hamiltonian in presence of rotation

- The Source: wake field caused by quarkonia movement in medium, may produce local vortices in the medium. The direction of vortices would depend on the relative velocity between medium and quarkonia.
- The corresponding to spin vorticity coupling an effective Hamiltonian is constructed as; Captain R. Singh et al., arXiv:2512.18728

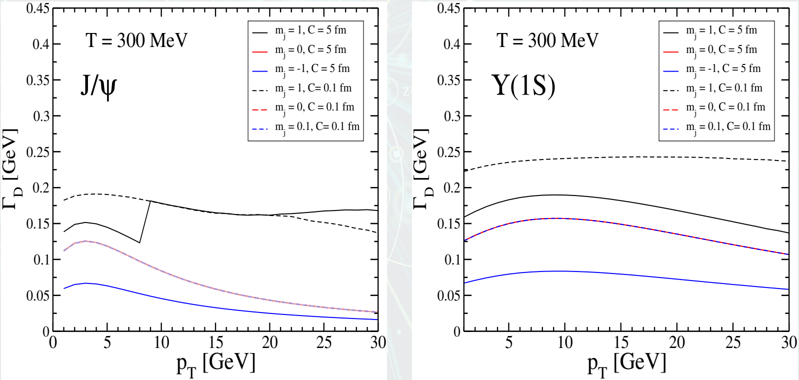
$$\mathcal{H} = \sum_{i=1,2}\left[\frac{1}{2m_i}(\boldsymbol{p}_i - m_i\boldsymbol{\omega}_i \times \mathrm{r}_i)^2 - \frac{m_i}{2}(\boldsymbol{\omega_i} \times \mathrm{r}_i)^2 - \boldsymbol{\omega_i}\cdot \mathrm{S_i}\right] + V(|\mathrm{r}_1 - \mathrm{r}_2|)$$

$$\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{d\psi(r)}{dr}\right) + 2m_\mu\left[(E - V(r)) - \frac{l(l+1)}{2m_\mu r^2} - \frac{m_j C}{2\pi r^2}\right]\psi(r) = 0$$

$$\mathrm{C} = \oint \vec{v}\cdot d\vec{l} = \oint \vec{\nabla}\times\vec{v}\cdot d\vec{S} = 2\pi\omega r^2$$

eigen energy and wavefunction obtained solving SE are used to account medium modified decay width for quarkonia.

⇒ Medium modified net decay width under the spin-vorticity coupling



Quarkonia Polarization based on in-medium effects

- We estimate the dissociation probability in a particular degenerate state;

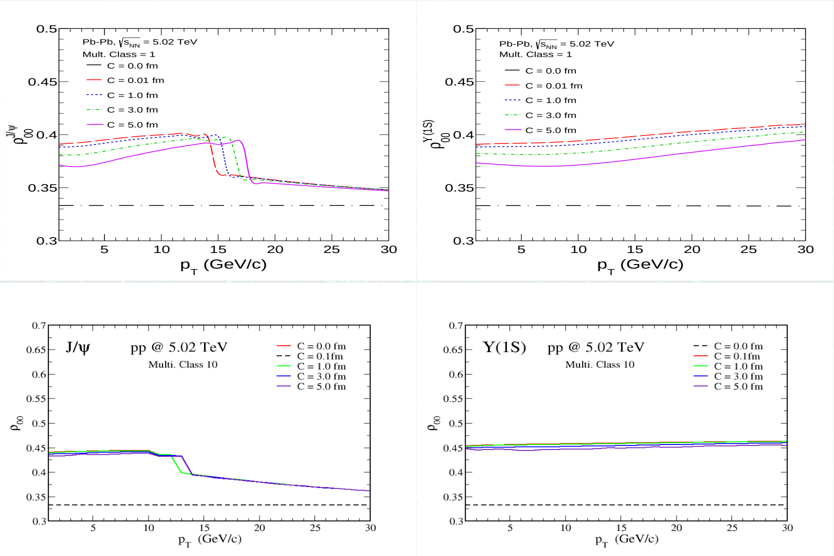
$$f_i = e^{\int_{\tau_0}^{\tau_f} \Gamma_{\mathrm{D,nl}}(\tau, p_{\mathrm{T}})\, d\tau}$$

- The net probability of dissociation in the 0^{th} state among $m_j = 1, 0, -1$ states, gives the ρ_{00} component of density matrix, defined as;

$$\rho_{00} = \frac{f_0}{f_+ + f_0 + f_-}$$

for minimal or vanishing medium effects ρ_{00} approaches to $1/3$.

Preliminary Results: J/ψ & $\Upsilon(1S)$ Polarization arXiv:2512.18728



Summary

- Being a baseline independent, findings on quarkonia polarization in Pb−Pb and *pp* collisions consistent, makes it suitable next generation probe for investigations on QGP.
- Investigation on charmonia yield modification in pp collisions can help to quantify the Hot QCD Matter effects as it excludes baryonic effects: No CNM.
- A thorough study is required to explore the role of $\underline{\tilde{Q}}$ dissociation and regeneration mechanisms on its spin-alignment, and vice-versa.
- Vorticity $\Rightarrow$ Polarization (primarily). In pp collisions, potential source of vorticity generation needs be more precisely accounted.

Thank you

my all time collaborators: M. Mishra, S. Ganesh, R. Sahoo, Jan-e Alam, B. Sahoo, S. Deb, M. Y. Jamal, P. Bagchi et al.

QGP thermal profile

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

$$T_0 = \left[\frac{90}{g_k 4\pi^2} C' \frac{1}{A_T \tau_0} \frac{dN}{d\eta}\right]^{1/3}$$ Eur. Phys. J. C 82, 542 (2022).

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

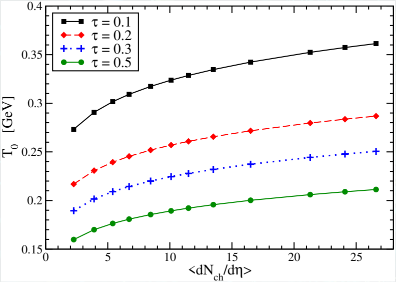
$$\frac{dT}{d\tau} = -\frac{T}{3\tau} + \frac{T^{-3}\phi}{12a\tau}, \quad \frac{d\phi}{d\tau} = -\frac{2aT\phi}{3b} - \frac{1}{2}\phi\left[\frac{1}{\tau} - \frac{5}{\tau}\frac{dT}{d\tau}\right] + \frac{8aT^4}{9\tau}$$

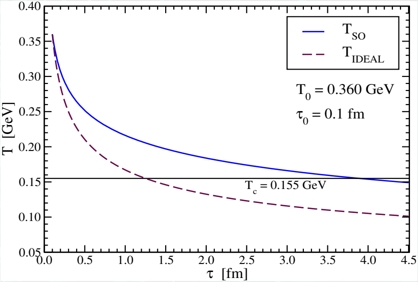
Gubser flow: 2+1D hydrodynamic evolution with IInd order viscous correction:

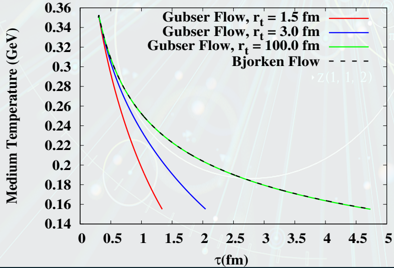
$$\frac{d\hat{\epsilon}}{d\rho} = -\left(\frac{8}{3}\hat{\epsilon} - \hat{\pi}\right)\tanh(\rho), \quad \frac{d\hat{\pi}}{d\rho} = -\frac{\hat{\pi}}{\hat{\tau}_\pi} + \tanh(\rho)\left(\frac{4}{3}\hat{\beta}_\pi - \hat{\lambda}\hat{\pi} - \hat{\chi}\frac{\hat{\pi}^2}{\hat{\beta}_\pi}\right)$$

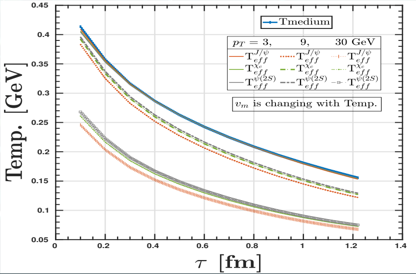
where, conformal time, $\rho = -\sinh^{-1}\left(\frac{1 - q^2\tau^2 + q^2 x_T^2}{2q\tau}\right)$ & $q = \frac{1}{r}$

⇒ initial (T_0), medium cooling profile & effective temp









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 $0 < \theta \leq \pi/4$, 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;

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

Phys.Rev.D87,114005(2013); Phys.Rev.D112,014017(2025)