Bottomonium suppression in p+Pb collisions at LHC energies

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Primary references:

M. Strickland, S. Thapa, & R. Vogt (2024). Bottomonium suppression in 5.02 and 8.16 TeV p-Pb collisions, arXiv:2401.16704.

S. Thapa, R. Vogt, M. Strickland, R. Rapp, B. Wu, & J. Boyd (In Prep). Semi-classical treatment of bottomonium suppression in p-Pb collisions.

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HEFTY COLLABORATION

U.S. DEPARTMENT OF ENERGY

Outline

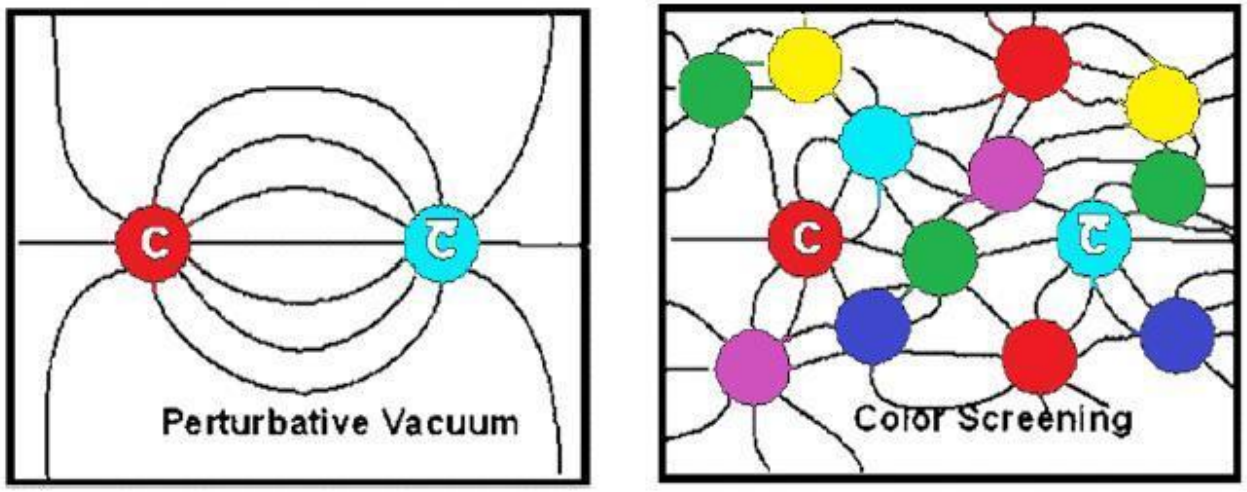
- **INTRODUCTION & MOTIVATION**
- **COLD NUCLEAR MATTER EFFECTS**
  - **Nuclear Modification of Parton Distribution Functions (nPDFs)**
  - **Energy Loss & Momentum Broadening**
- **HOT NUCLEAR MATTER EFFECTS**
  - **Quantum & Semi-Classical Transport Models**
- **RESULTS**
- **CONCLUSION & OUTLOOK**

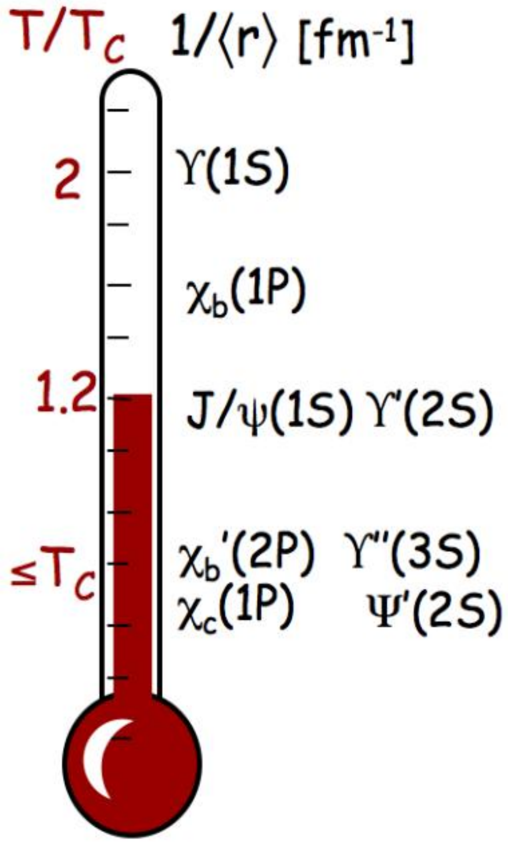
INTRODUCTION & MOTIVATION

- **Asymptotic freedom of QCD:** deconfined phase of QCD matter at high temperature / density, **Quark Gluon Plasma (QGP),** glimpse of early universe shortly after Big Bang, recreated in HIC at RHIC and LHC

Quarkonia as Probe of QGP

Static screening (Matsui, Satz, 1986): *inside QGP, color attraction in Quarkonia suppressed due to Debye Screening,* different mass/binding energies, **Sequential melting at High T**





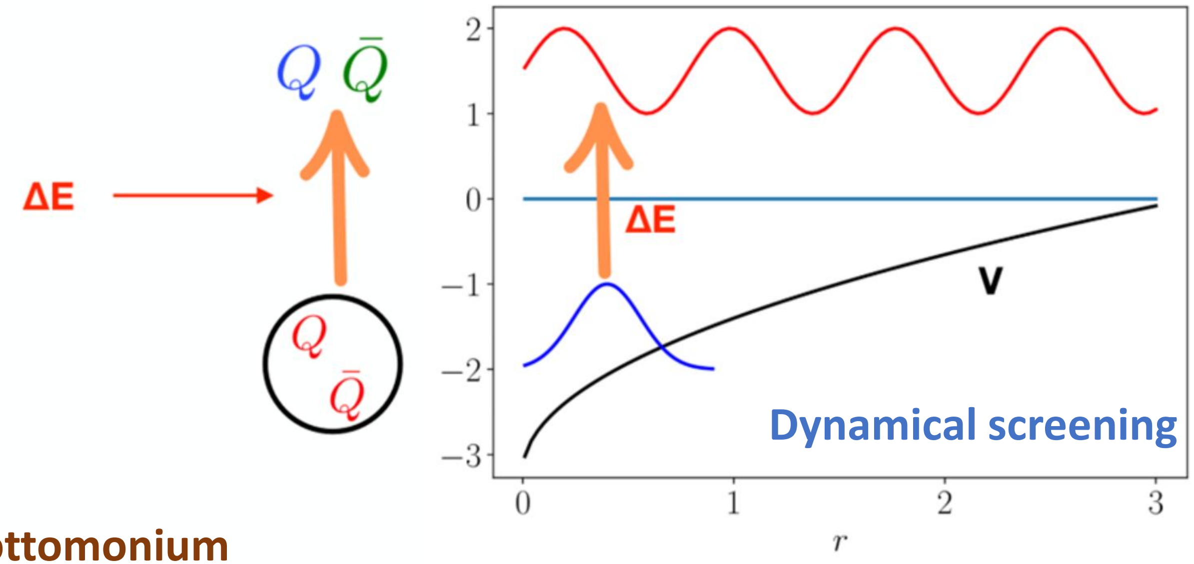
QGP thermometer

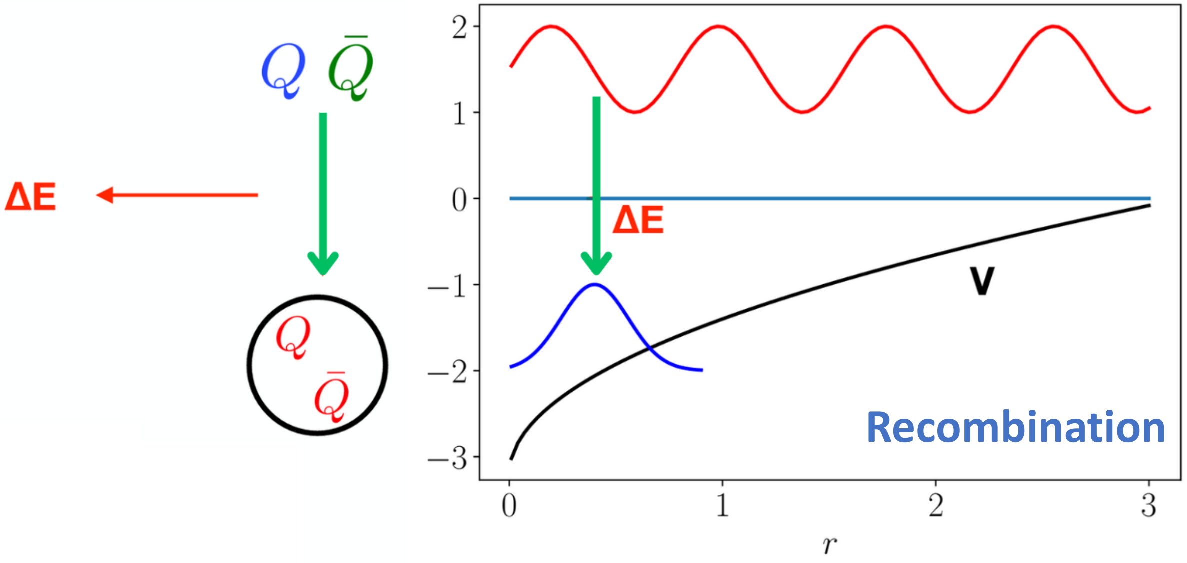
Mocsy, Petreczky, and Strickland, 1302.2180

Quarkonia (Bottomonia) as Probe of QGP

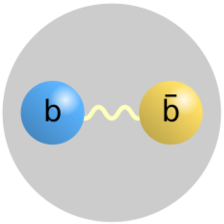
- **Dynamical screening**: quarkonia dissociation induced by dynamical process in the QGP, imaginary potential

- **Recombination**: unbound heavy quark pair (re)combine into bound quarkonium state, can happen below melting temperature Thews, Schroedter, Rafelski, PRC 63, 054905 (2001), arXiv:hep-ph/0007323





Bottomonium

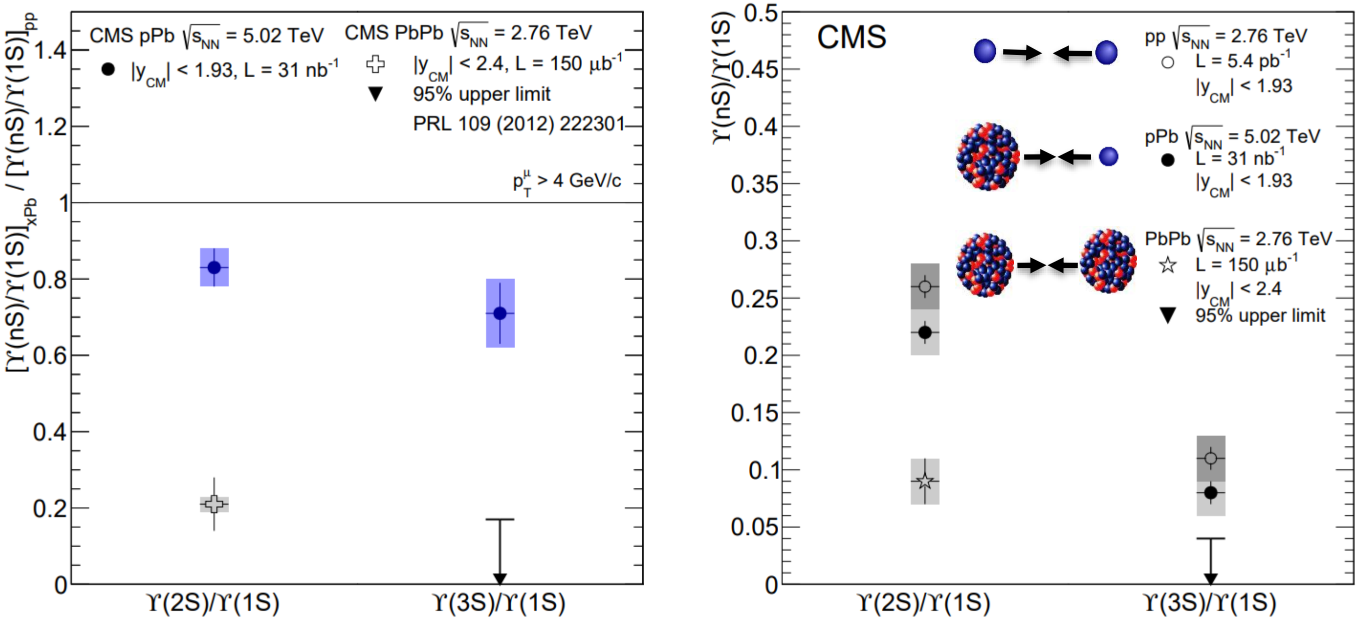


- Heavy m ~ 10 GeV
- Produced early (has history of QGP)
- Non-relativistic ($v << 1$, v_b~ 0.1)
- Scale separation (EFTs like pNRQCD)
- No (/less) regeneration E. Emerick, X. Zhao, and R. Rapp, 1111.6537

Xiaojun Yao, 2020

INTRODUCTION & MOTIVATION

- Observables at RHIC and LHC reveal a smooth transition between proton-proton, proton-nucleus, and nucleus-nucleus collisions   N. Armesto (2024), EPJ Web of Conferences 171, 11001 (2018)
- In LHC p-Pb collisions, excited bottomonium states $\Upsilon(2S)$ and $\Upsilon(3S)$ are suppressed more than the ground state $\Upsilon(1S)$, a pattern that cannot be explained solely by CNM effects.
- **Short-Lived QGP?** The differential suppression of excited Υ states indicates that final-state interactions—potentially due to a transient QGP in small systems—play a significant role, necessitating further investigation of Υ in p-Pb collisions at LHC energies



CMS Collaboration, 1312.6300, 2202.11807

CNM EFFECT: Nuclear Modification of Parton Distribution Functions (nPDFs)

- The parton densities / structure functions of bound nucleons **modified** from those in free nucleons

$$F_j^A(x_2, \mu_F^2, k_T) = R_j(x_2, \mu_F^2, A) F_j^p(x_2, \mu_F^2, k_T)$$

- NLO EPPS21 (24 params, 49 total sets, 1 central and 48 error sets) nPDFs used

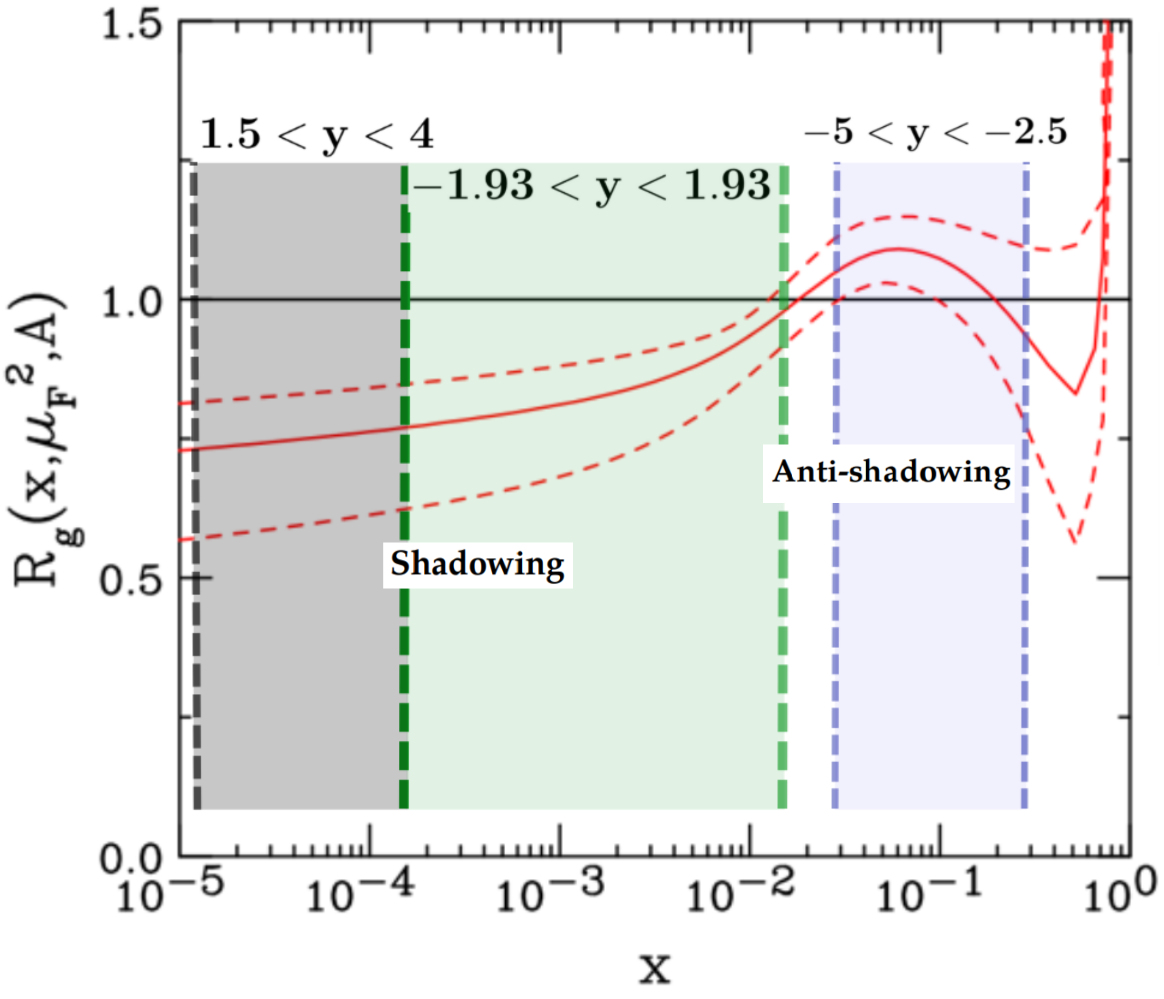
Eskola et al. (2021). 2112.12462

- Υ production cross section in p+p and p+A by Color Evaporation Model (CEM) given by,

$$\sigma_{\mathrm{CEM}}(pp) = F_C \sum_{i,j} \int_{4m^2}^{4m_H^2} d\hat{s} \int dx_1\, dx_2 \times F_i^p(x_1, \mu_F^2, k_{T_1})\, F_j^p(x_2, \mu_F^2, k_{T_2})\, \hat{\sigma}_{ij}(\hat{s}, \mu_F^2, \mu_R^2)$$

$$\sigma_{\mathrm{CEM}}(pA) = F_C \sum_{i,j} \int_{4m^2}^{4m_H^2} d\hat{s} \int dx_1\, dx_2 \times F_i^p(x_1, \mu_F^2, k_T)\, F_j^A(x_2, \mu_F^2, k_T)\, \hat{\sigma}_{ij}(\hat{s}, \mu_F^2, \mu_R^2)$$

R. Vogt (2023), 2304.09356

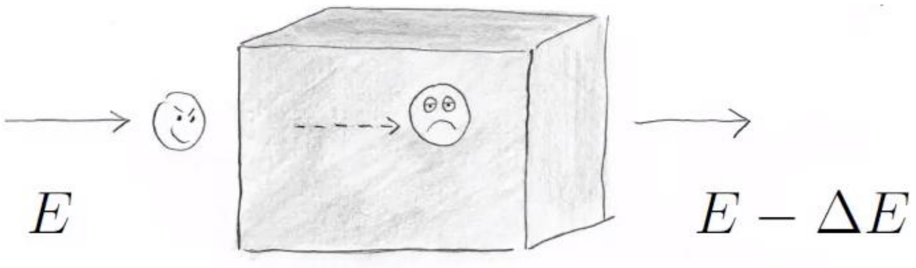


R. Vogt et al hep-ph/9502270, 1508.01286, 1609.06042

CNM EFFECT: Energy Loss & Momentum Broadening

While passing through a medium (hot QGP, *cold nucleus, …*):

- a parton can lose energy due to collisions (Bjorken, 1982)
- and / or via induced gluon radiation (Gyulassy, Wang (1993) nucl-th/9306003)



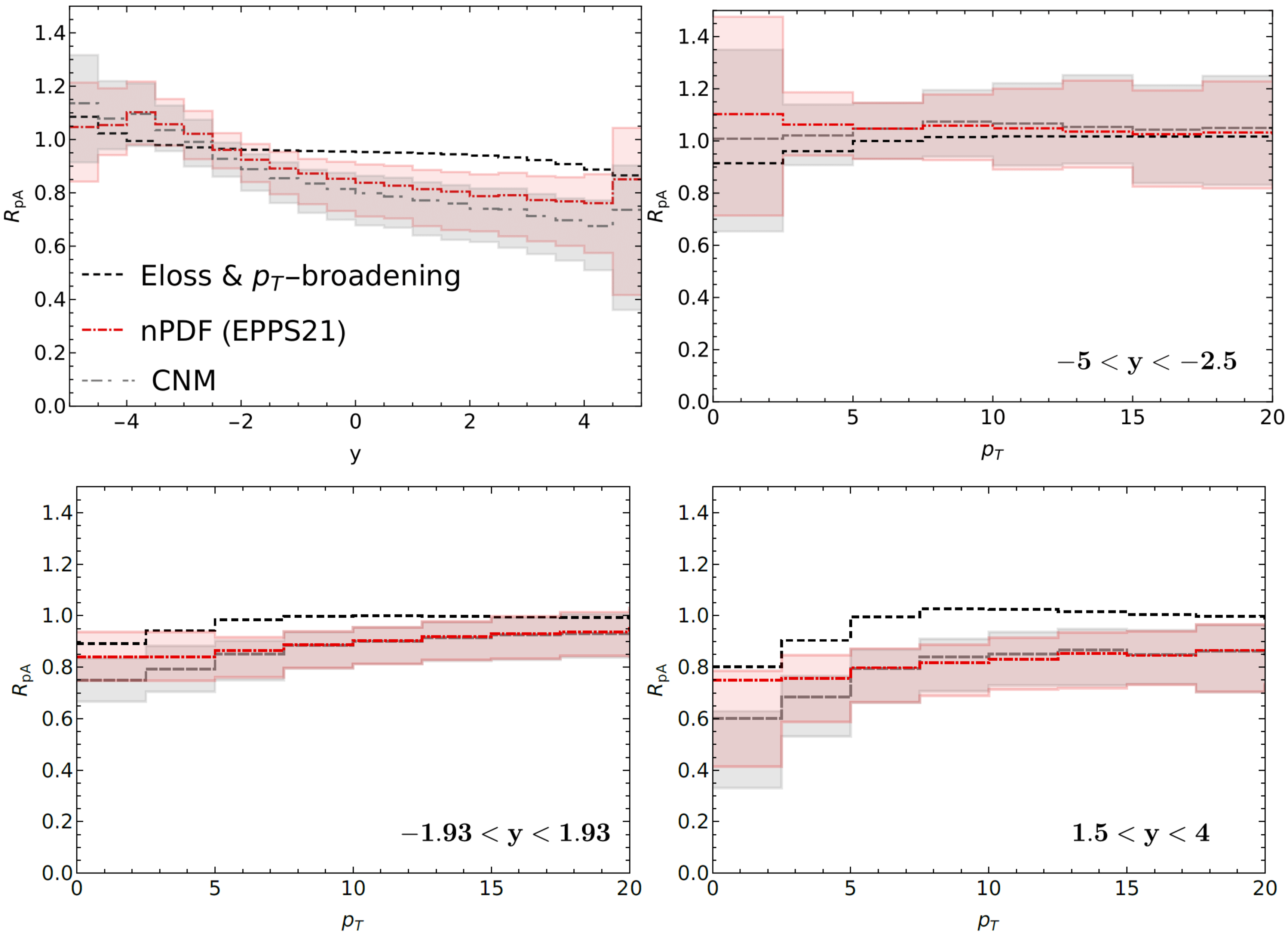
- The produced Υ states lose energy and undergo momentum broadening in the cold QCD matter, encoded in Quenching weight
- In terms of the **rapidity shift δy** & **transverse momentum broadening δp_T**, the quarkonium double differential cross section:

$$\frac{1}{A}\frac{d\sigma^{\psi}_{pA}}{dy\,d^2p_T}(y,p_T) = \int_0^{2\pi}\frac{d\varphi}{2\pi}\int_0^{\delta y_{\max}(y)} d\delta y\,\hat{\mathcal{P}}(e^{\delta y}-1,\ell^2)\frac{d\sigma^{\psi}_{pp}}{dy\,d^2p_T}(y+\delta y,|\vec{p}_T-\delta\vec{p}_T|)$$

$\hat{q}$ = transport coefficient,
L_A = effective path length of nucleus A

Arleo, Kolevatov, Peigne, Rustamova (2013), 1304.0901
Arleo & Peigne, Rustamova (2013), 1212.0434

Modification of ϒ Production due to CNM EFFECTs at 8 TeV p+Pb



HNM EFFECT: KSU-Munich Approach

Open Quantum System (OQS) + pNRQCD

Following the hierarchy of scales, **M >> 1/a$_0$ >> (π) T ~ m$_D$ >> E$_b$**, at NLO pNRQCD [1] in E_b / T, we obtain Lindblad Master Equation [2], evolution of system density matrix:

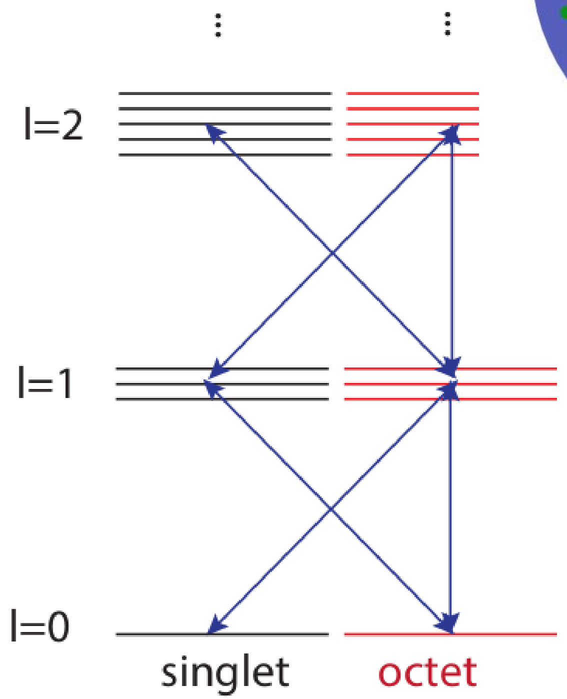
$$\rho_S(t) = Tr_E(\rho_{tot}(t)) \quad \xrightarrow[1/r \gg T \sim m_D \gg E]{}$$

$$\frac{d\rho(t)}{dt} = -i\left[H, \rho(t)\right] + \sum_{n=0}^{1}\left(C_i^n \rho(t) C_i^{n\dagger} - \frac{1}{2}\left\{C_i^{n\dagger} C_i^n, \rho(t)\right\}\right)$$

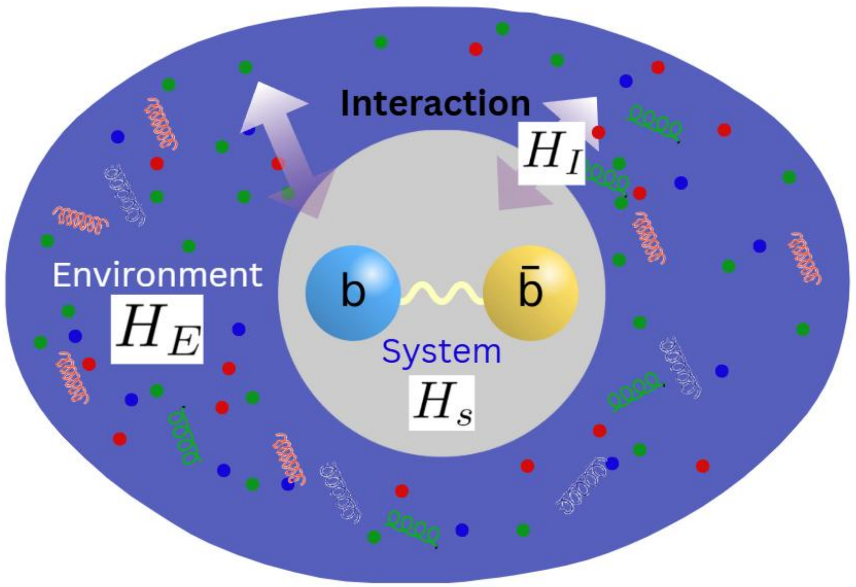
[1] Brambilla et al (2022/23), 2205.10289, 2302.11826, Strickland & Thapa (2023) 2305.17841, QTRAJ 1.0 (2021), 2107.06147
[2] G. Lindblad, Commun. Math. Phys. 119, 48 (1976); V. Gorini, A. Kossakowski, and E.C. Sudarshan, J. Math. Phys. 17, 821 (1976)

Jump/Collapse Operators:

➔ Effect of the medium causing transition between singlet & octet states



Bottomonia as an Open Quantum System



Six collapse operators:

1. singlet → octet
2. octet → singlet
3. octet → octet

KSU-Munich Input Parameters: Transport Coefficients of Bottomonia

The imaginary part of the potential responsible for the decay of the Υ states in the medium *(dynamical screening from QGP medium),* and depend on the transport coefficients, kappa (***κ***) and gamma (**γ**).

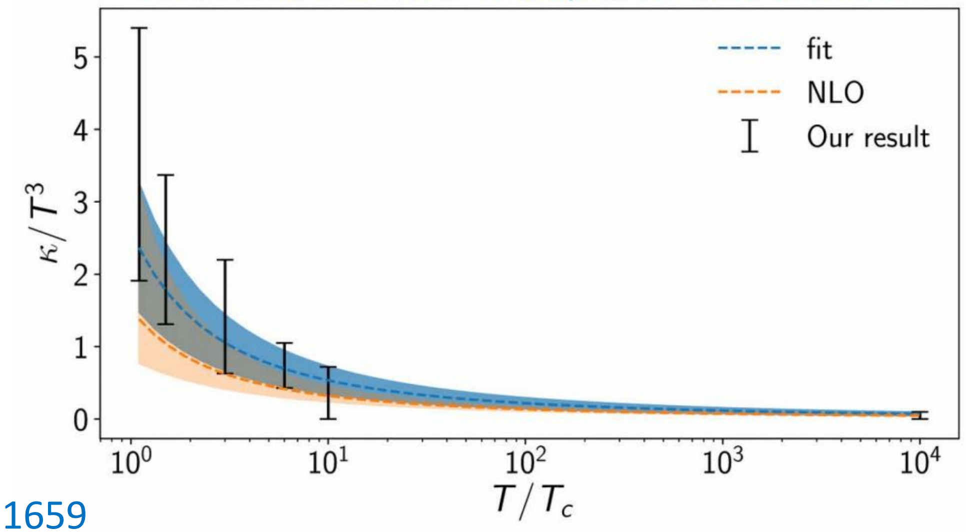
$$H = \begin{pmatrix} h_s + \mathrm{Im}(\Sigma_s) & 0 \\ 0 & h_o + \mathrm{Im}(\Sigma_o) \end{pmatrix}$$

$$\kappa = \frac{g^2}{18}\int_0^\infty dt \left\langle \left\{ \tilde{E}^{a,i}(t,\mathbf{0}), \tilde{E}^{a,i}(0,\mathbf{0}) \right\} \right\rangle,$$

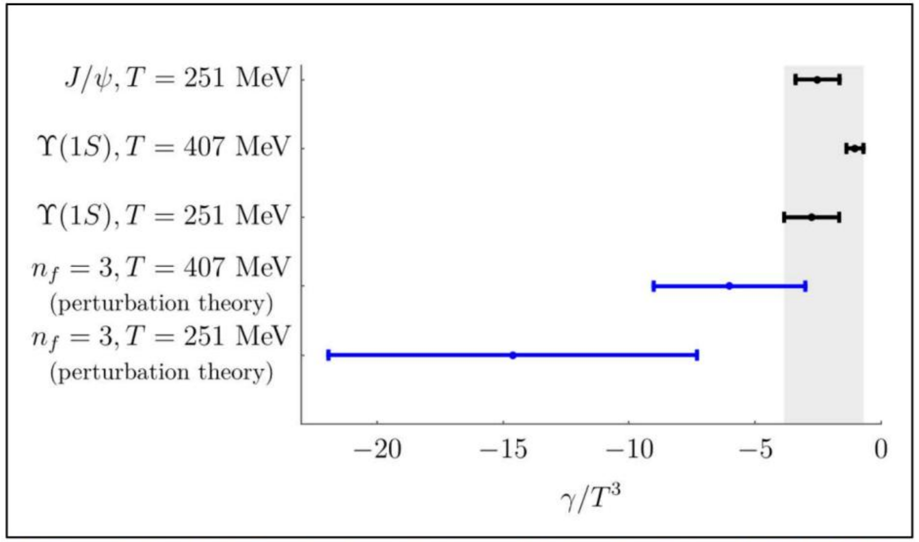
$$\gamma = -i\frac{g^2}{18}\int_0^\infty dt \left\langle \left[\tilde{E}^{a,i}(t,\mathbf{0}), \tilde{E}^{a,i}(0,\mathbf{0}) \right] \right\rangle,$$

Larsen, Meinel, Mukherjee, Petreczky (2019) 1908.08437
Bala, Kaczmarek, Larsen, Mukherjee, Parkar, Petreczky, Rothkopf, Weber (2022) 2110.11659

N. Brambilla, V. Leino, P. Petreczky, and A. Vairo, 2007.10078



- The effect of the QGP medium in the quarkonia states (Υ(nS)) are encoded in the heavy quark transport coefficients) **[constrained by the Lattice QCD calculations]**
- ***κ*(T):** heavy quark momentum **diffusion coefficient** responsible for the large thermal width in the QGP medium, extracted from NLO fits to recent lattice measurements, {5,6,7} for pA at LHC energies
- **γ(T):** dispersive, responsible for the thermal mass shift (= 0 for Υ states), less constrained
- **Additional input → QGP Temperature from aHydro**



N. Brambilla, M. A. Escobedo, A. Vairo and P. Vander Griend, 1903.08063.

HNM EFFECT: TAMU (semi-classical transport model)

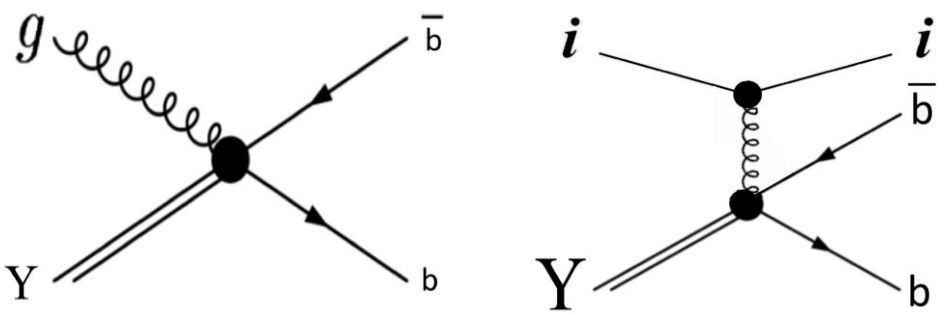
Kinetic Rate Equation, describes the evolution of number of quarkonia states in the QGP **in terms of loss and gain terms:**

$$\frac{dN_\Upsilon(\tau)}{d\tau} = -\Gamma_\Upsilon(T(\tau))[N_\Upsilon(\tau) - N_\Upsilon^{\rm eq}(\tau)]$$

Equilibrium Limit: depends on $b\bar{b}$ cross section and the thermal environment ($N_\Upsilon^{eq}(\tau) = V_{FB}(\tau)\gamma_b^2(\tau)n_\Upsilon(m_\Upsilon;\tau)$

Reaction Rate: medium effect on bound Υ states

(cause decay of bound states into unbound $b\bar{b}$ pairs)



Primordial Suppression:

$$\frac{dN_\Upsilon^{\rm prim}(\tau)}{d\tau} = -\Gamma_\Upsilon(T(\tau))N_\Upsilon^{\rm prim}(\tau)$$

Primordially produced Υ states that **survive** the QGP fireball expansion:

$$N_\Upsilon^{\rm prim}(\tau_f) = -N_\Upsilon^{\rm prim}(\tau_{\rm init})e^{-\int_{\tau_{\rm init}}^{\tau_f}\Gamma_\Upsilon(T(\tau'))d\tau'}$$

Regeneration:

Rapp, Zhao, Emerick (2012) 1111.6537, Du, He (2017/18), 1706.08670, 1808.10014
Rapp, Wu (2024) 2404.09881

$$\frac{dN_\Upsilon^{\rm reg}(\tau)}{d\tau} = -\Gamma_\Upsilon(T(\tau))[N_\Upsilon^{\rm reg}(\tau) - N_\Upsilon^{\rm eq}(\tau)]$$

Solution of this equation gives the number of regenerated Υ states:

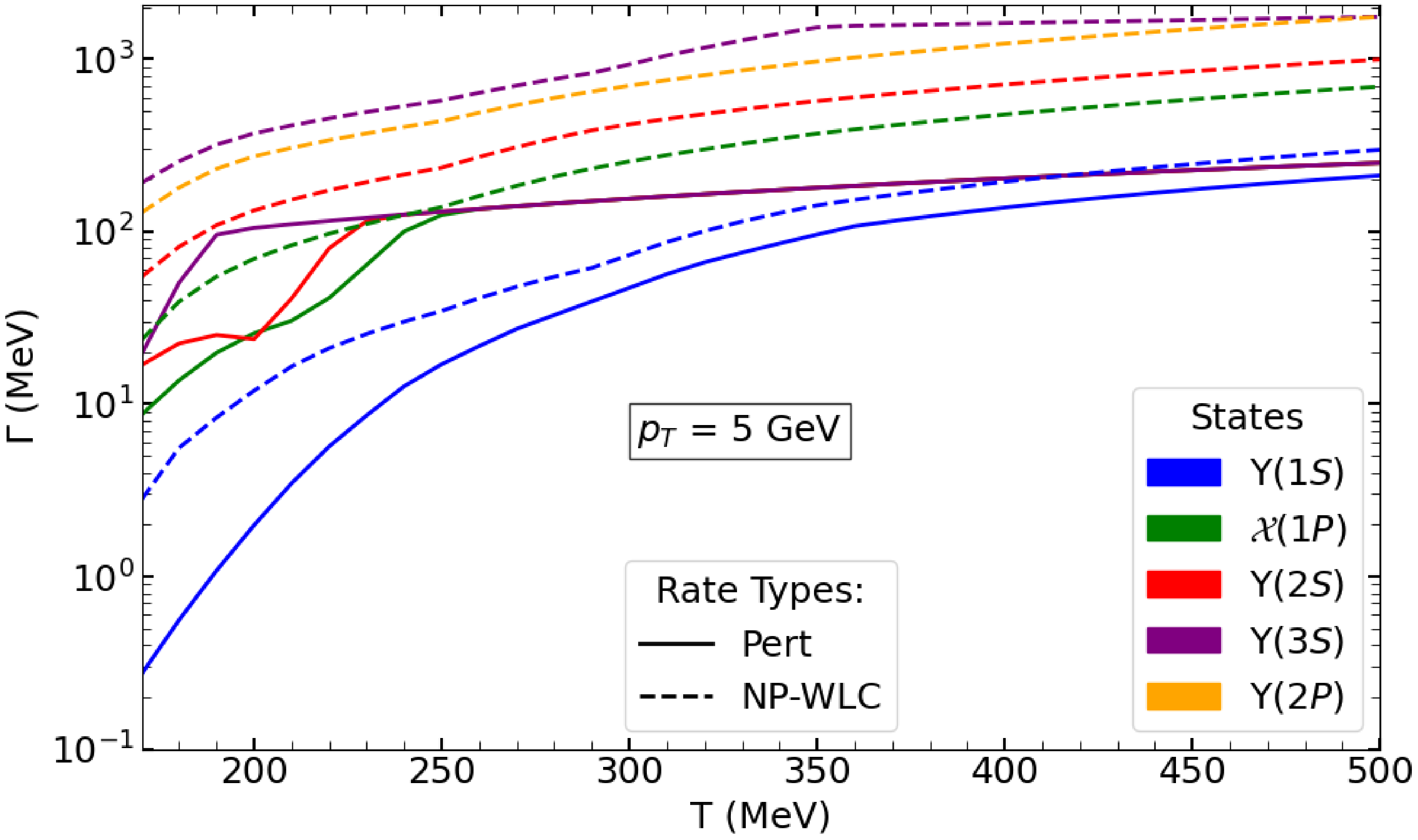
$$N_\Upsilon^{\rm reg}(\tau) = \int_{\tau_{\rm diss}}^{\tau}\Gamma_\Upsilon(T(\tau'))N_\Upsilon^{\rm eq}(\tau')e^{-\int_{\tau'}^{\tau}\Gamma_\Upsilon(\tau'')d\tau''}d\tau'$$

Reaction Rates of Bottomonia in TAMU Approach

➢ Calculated in **two different scenarios**, both evaluated within the thermodynamic T-matrix approach by TAMU,

TAMU-P: treats only 1S, 2S, 1P, 3S states separately, 2P & 3S states have same rates (Reik, Rapp (2010), 1005.0769)

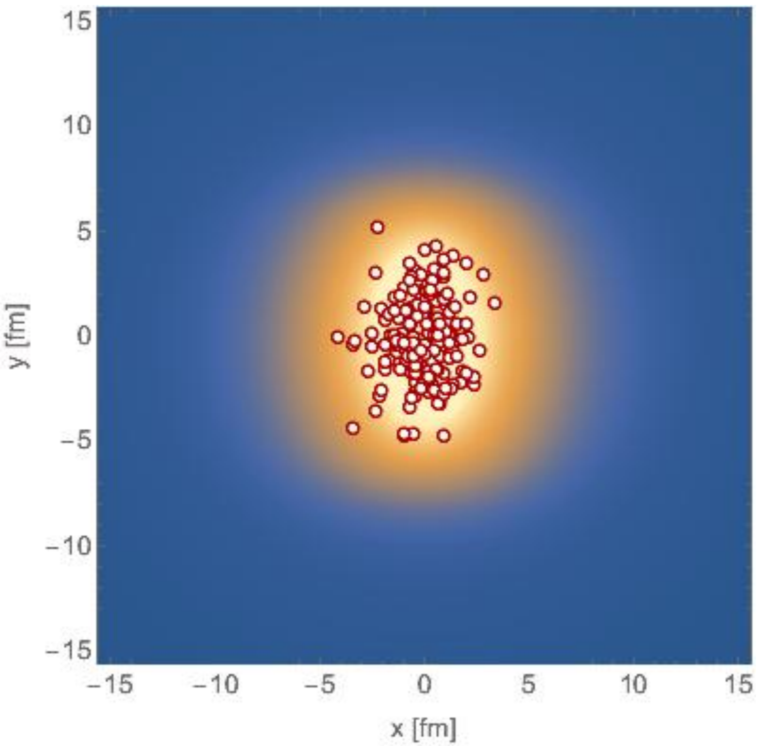
TAMU-NP: treats all bottomonium states (1S, 2S, 1P, 3S, 2P, …)
Z Tang, B Wu, A Hanlon, S Mukherjee, P Petreczky, R Rapp (2025), 2502.09044

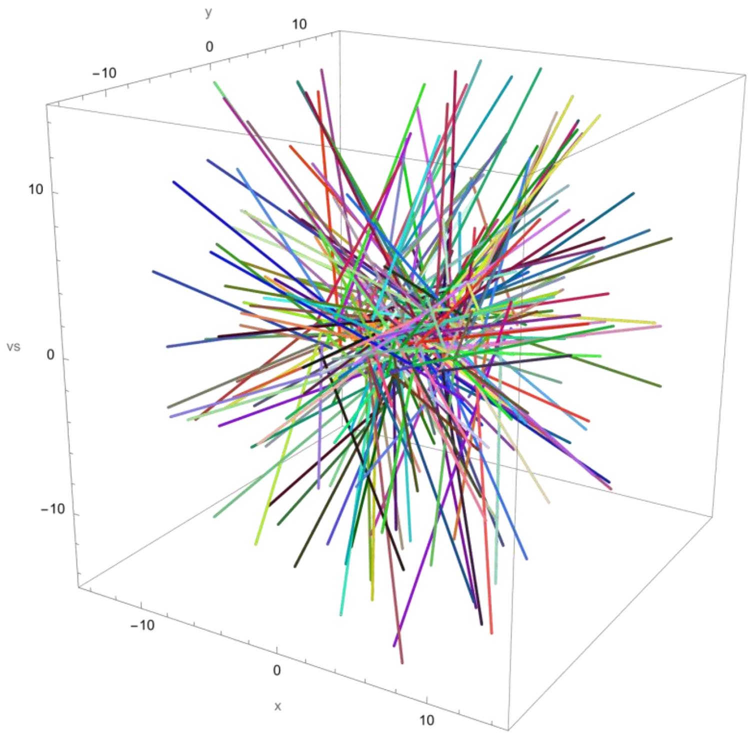


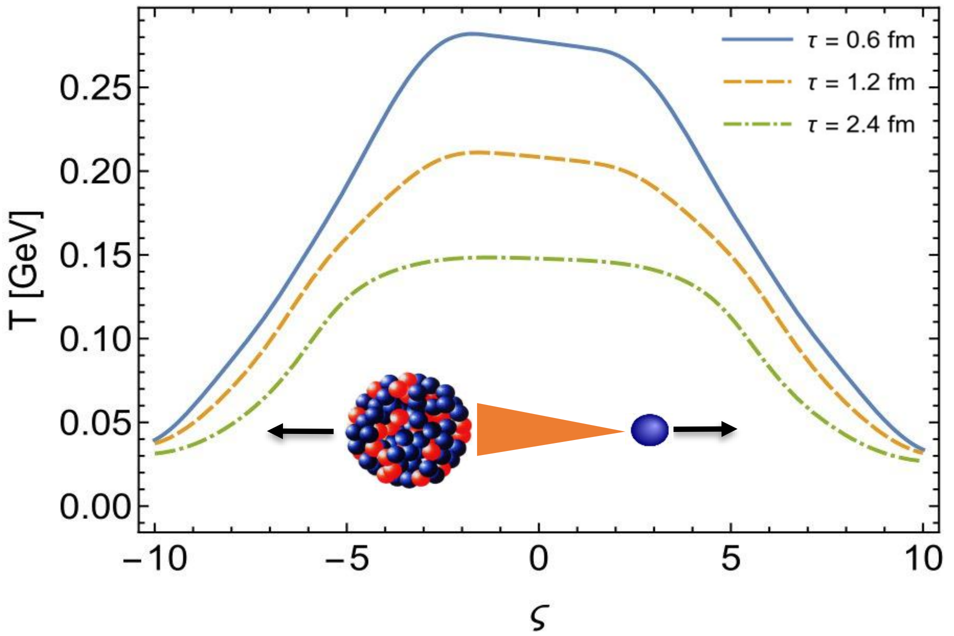
QGP Background Evolution: (3+1)D aHydro

- Backgroud Temperature evolution of QGP provided by anisotropic hydrodynamics.
- Quasiparticle anisotropic hydrodynamics (aHydroQP): good description of identified hadron spectra.

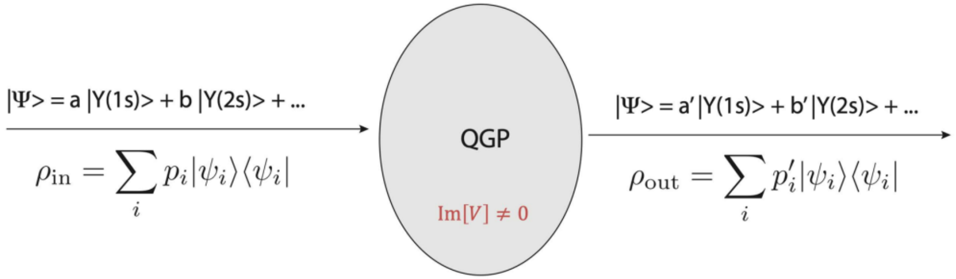
Alqahtani, Nopoush, Strickland (2015), [1509.02913,](1509.02913) (2017), [1712.03282](1712.03282)





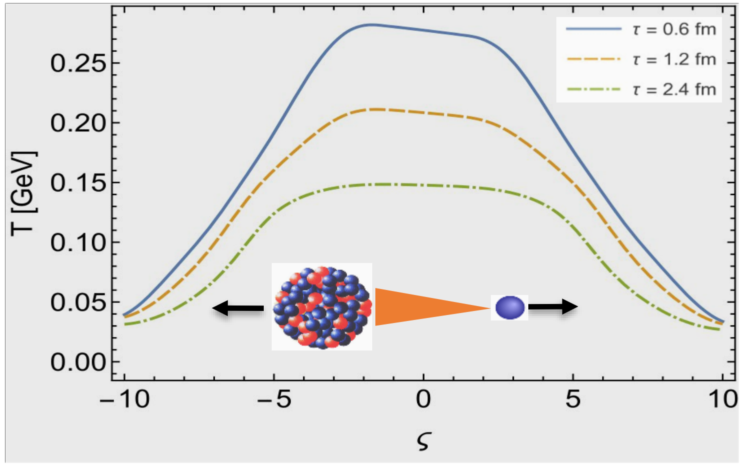


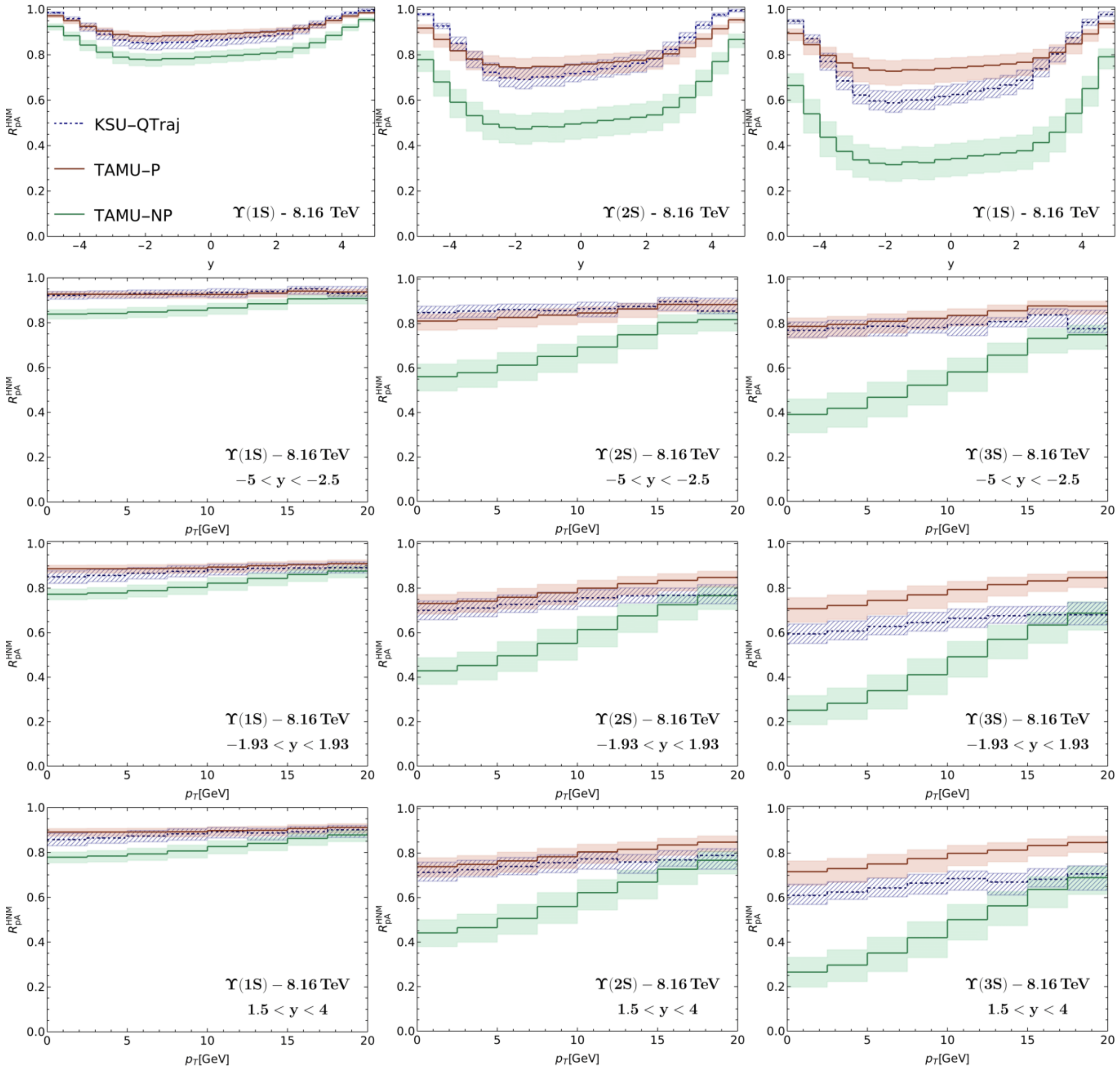
Υ Suppression due to HNM EFFECTs at 8.16 TeV p+Pb



Survival probability

$$SP(n,l) = \frac{|\langle n,l|\psi(t_f)\rangle|^2}{|\langle n,l|\psi(t_0)\rangle|^2}$$





Combining All Effects

The total suppression of the Bottomonia states coming from different contributions (CNM and HNM),

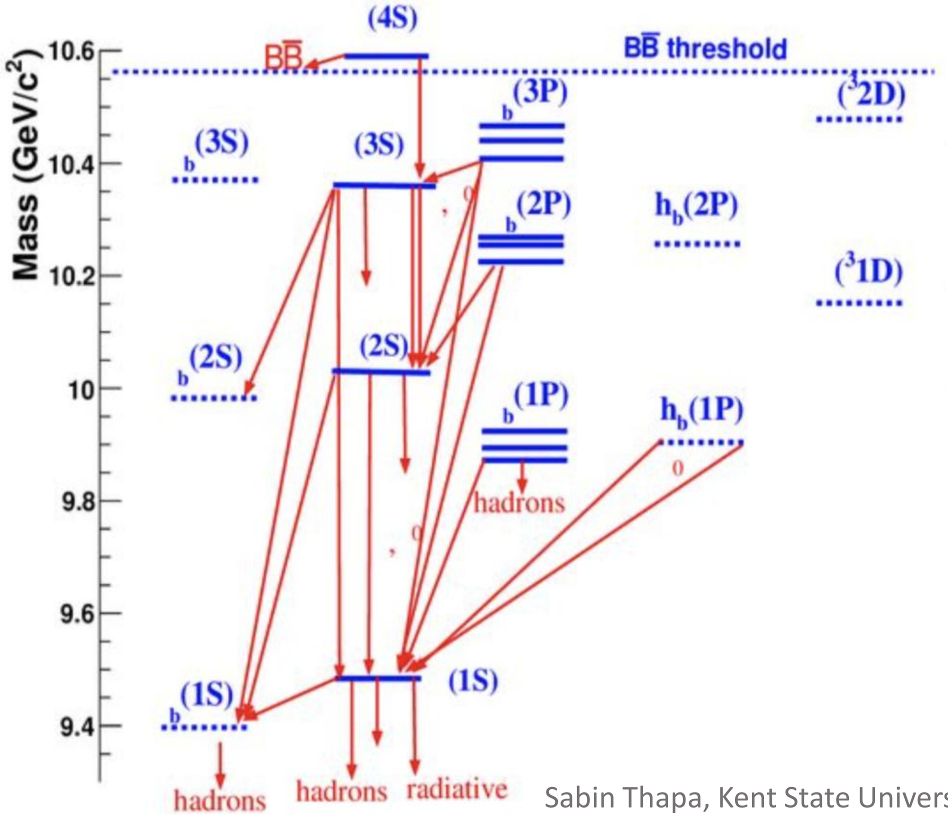
$$R_{pA}^{\Upsilon} = R_{pA}^{\rm CNM} \times R_{pA}^{\rm HNM} ,$$

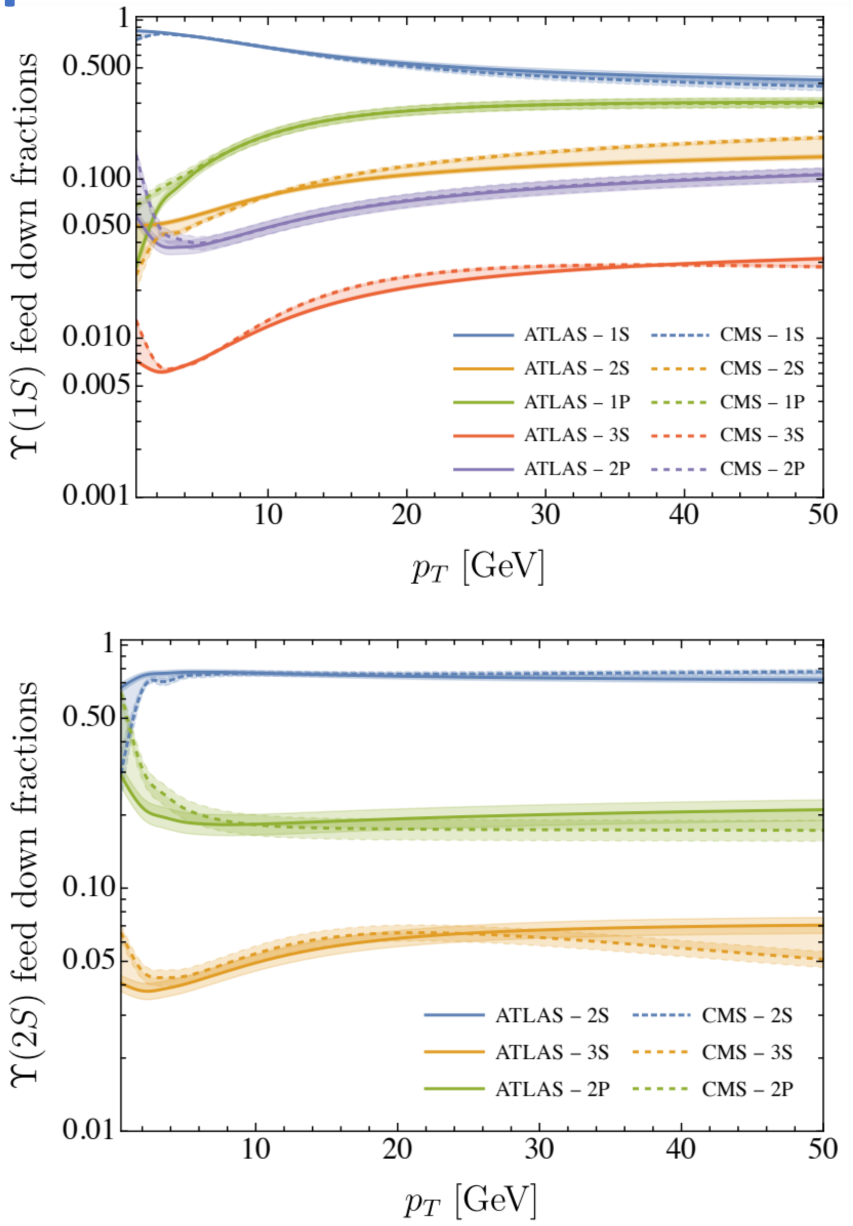
$$R_{pA}^{\rm CNM} = R_{pA}^{\rm nPDF} \times R_{pA}^{\rm eloss,broad} ,$$

Feed-down Contribution

- Approx. 75% of $\Upsilon(1S)$ and $\Upsilon(2S)$ yield from **direct production**, but important feed-down contributions from the 1P and 2P states
- All known excited state feed-down channels included as,

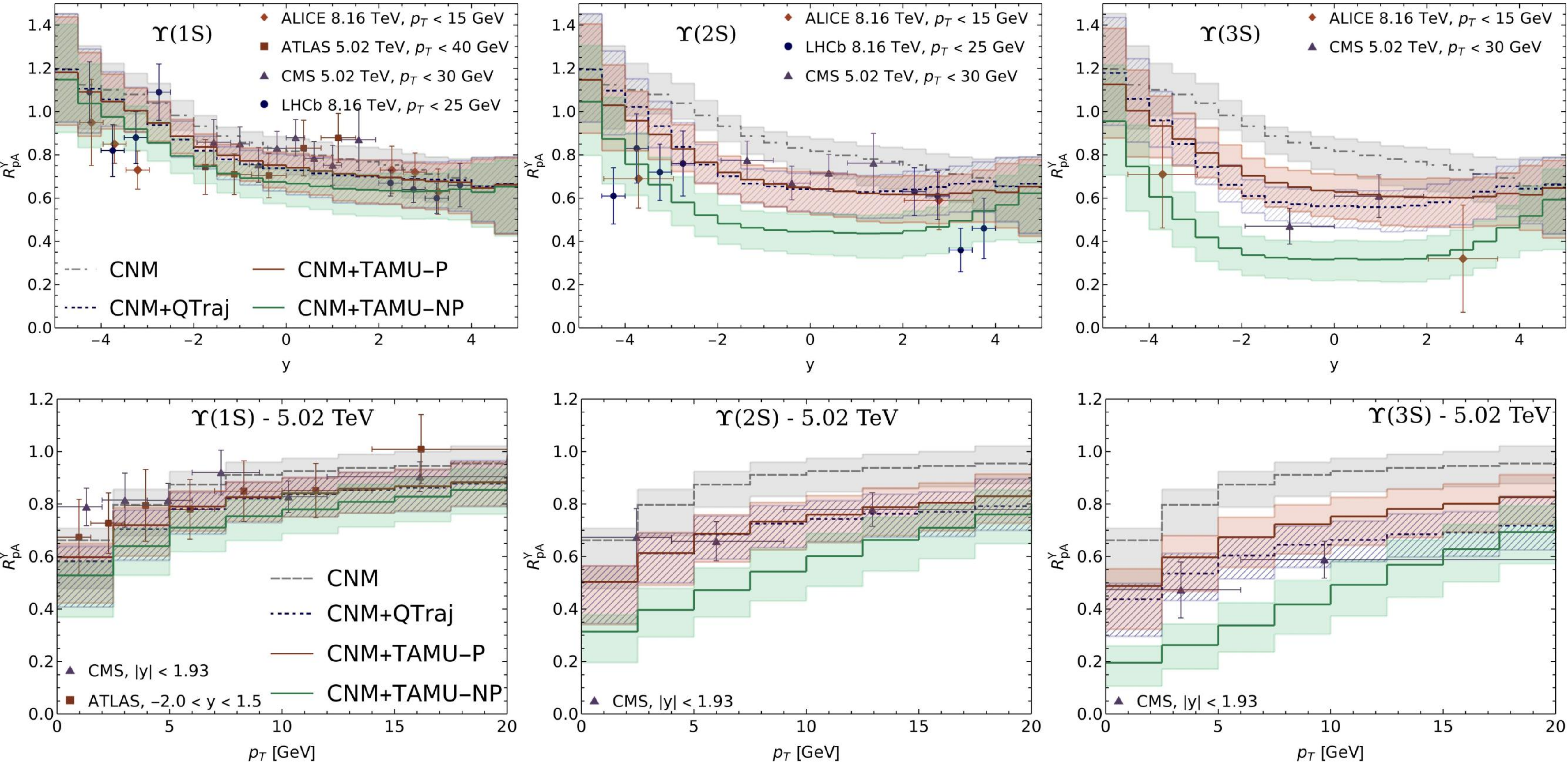
$$R^i_{pA}(p_T, y, \phi) = \frac{\left(F \cdot R^{\Upsilon}_{pA}(p_T, y, \phi) \cdot \vec{\sigma}_{\text{direct}}\right)^i}{\vec{\sigma}^i_{\text{exp}}}$$



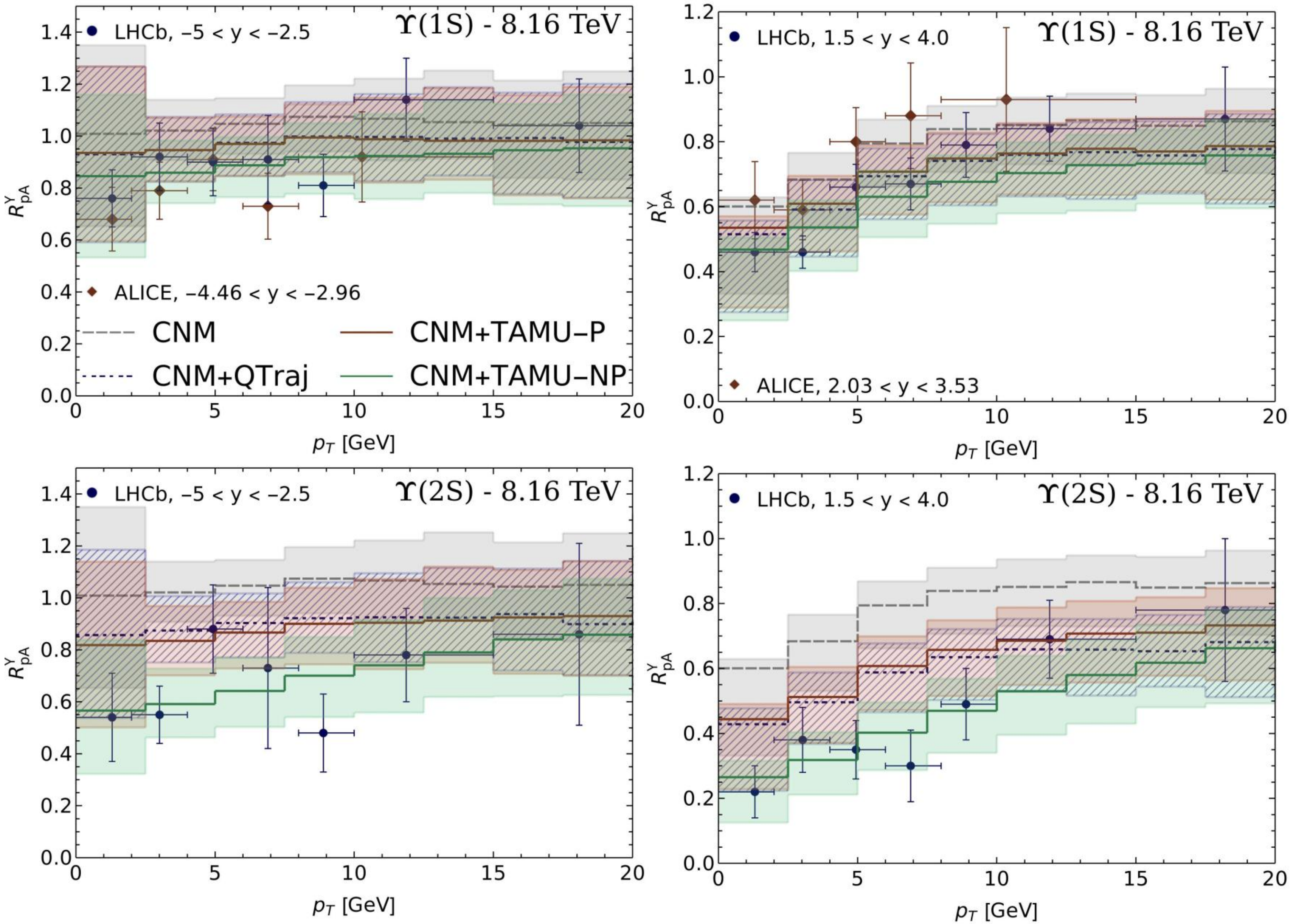


Boyd, Thapa, and Strickland (2023), 2307.03841

RESULTS: R_{pA} vs y (top row), vs p_T (bottom row, 5.02 TeV p+Pb, Midrapidity)



RESULTS: R_{pA} vs p_T (8.16 TeV p+Pb, Forward & Backward Rapidity)



CONCLUSION & OUTLOOK

- Including all the effects (CNM and HNM effects) provides reasonable description of available data given current experimental and theoretical uncertainties.
- For Υ(1S), final state interactions with QGP gives a small correction to the CNM effects (nPDF, Coherent Energy Loss, and Transverse Momentum Broadening).
- But for the Υ(2S) and Υ(3S) states, including QGP-induced suppression together with the CNM effects is essential to explain the experimental data.
- Provides further evidence for the production of a hot, but short-lived QGP in the p-Pb collisions.
- Examined the reaction rates from TAMU in small collision systems, consistent predictions from both KSU-Munich & TAMU approaches.
- Next, study charmonia suppression and regeneration in p+Pb and d+Au collisions. Systematic understanding of pA collision helps to understand AA collisions.
- In AA collisions QGP-induced suppression is the dominant effect, but CNM effects are needed for quantitative understanding.

Thank you!

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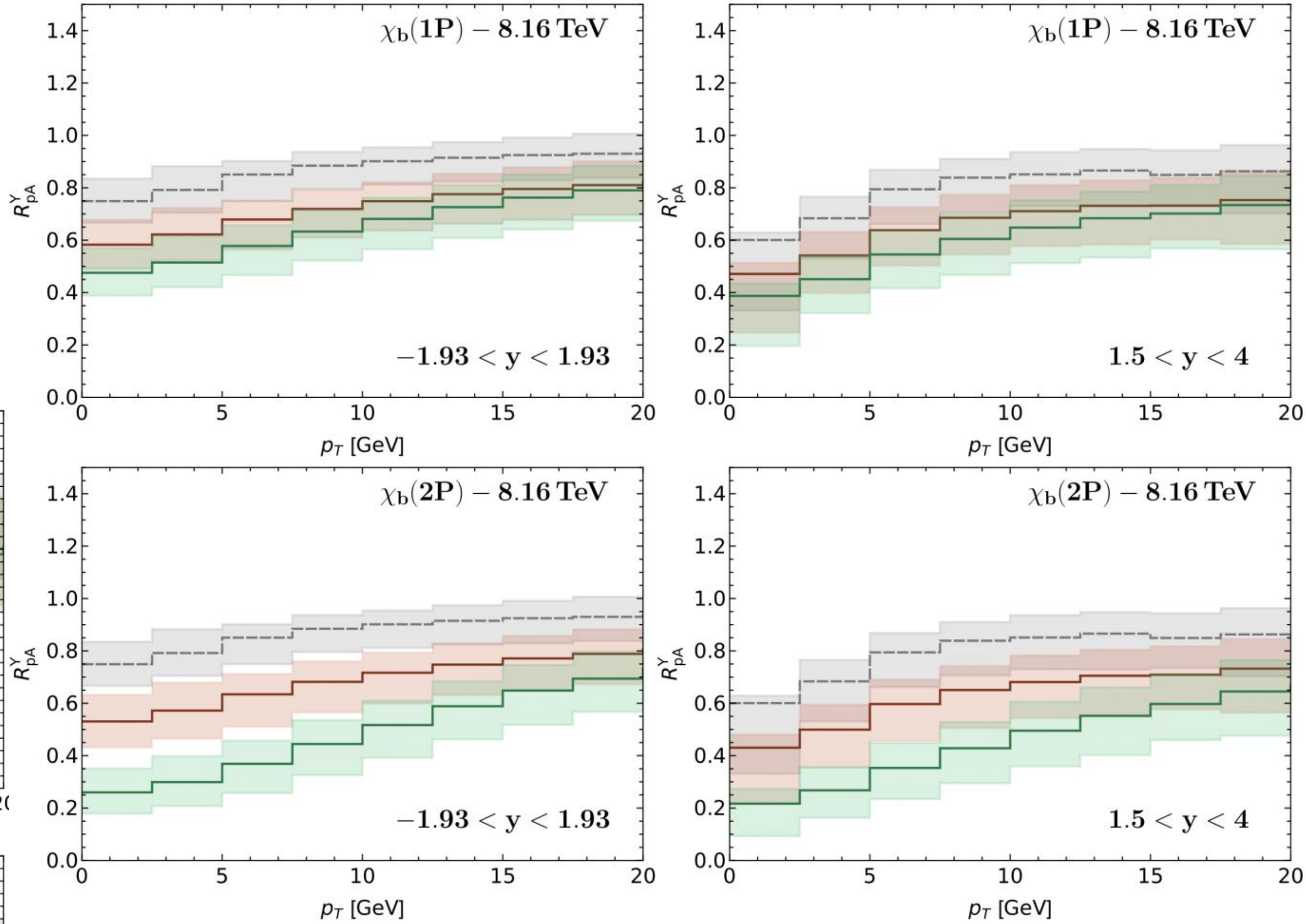
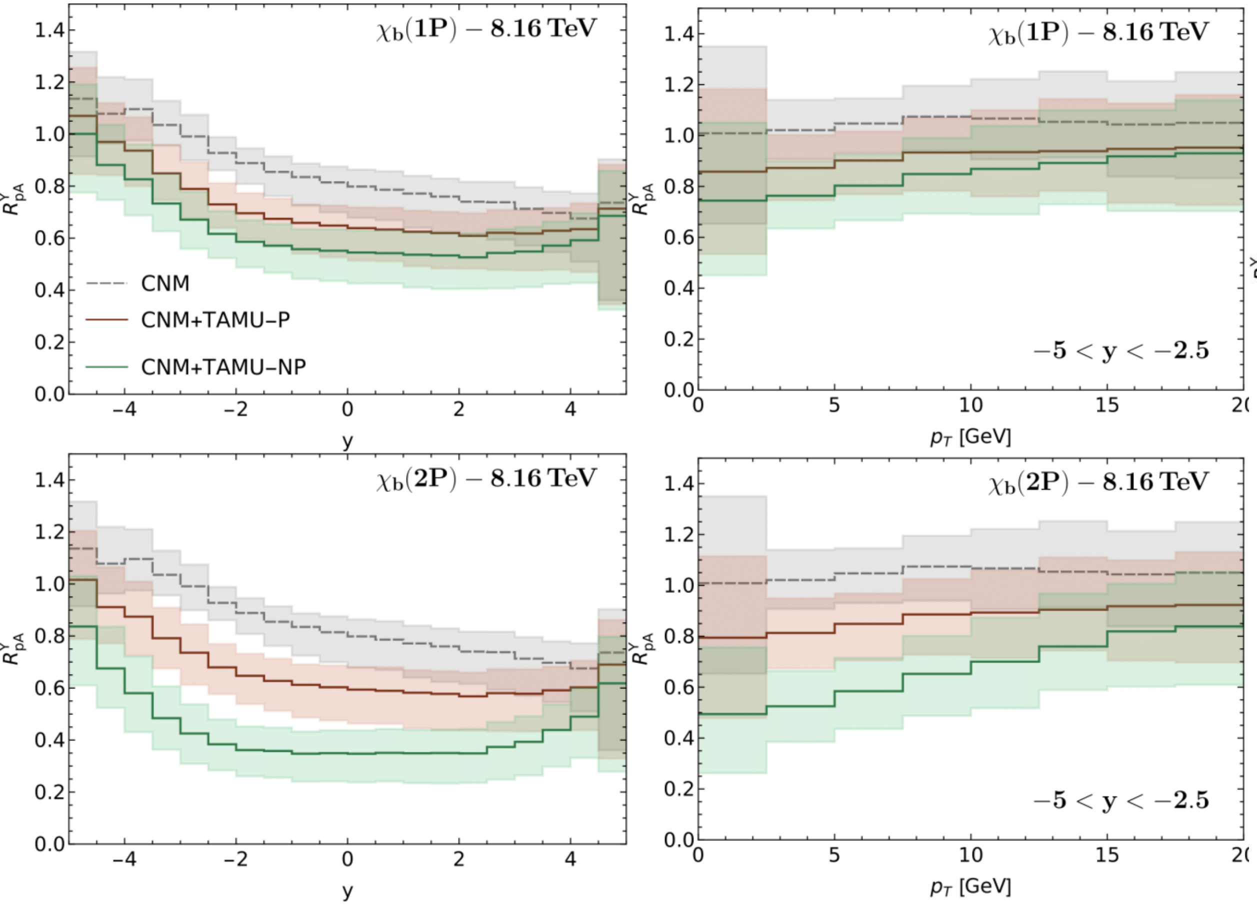
Backup slides

PREDICTIONS FOR $\chi_b(\mathrm{nP})$

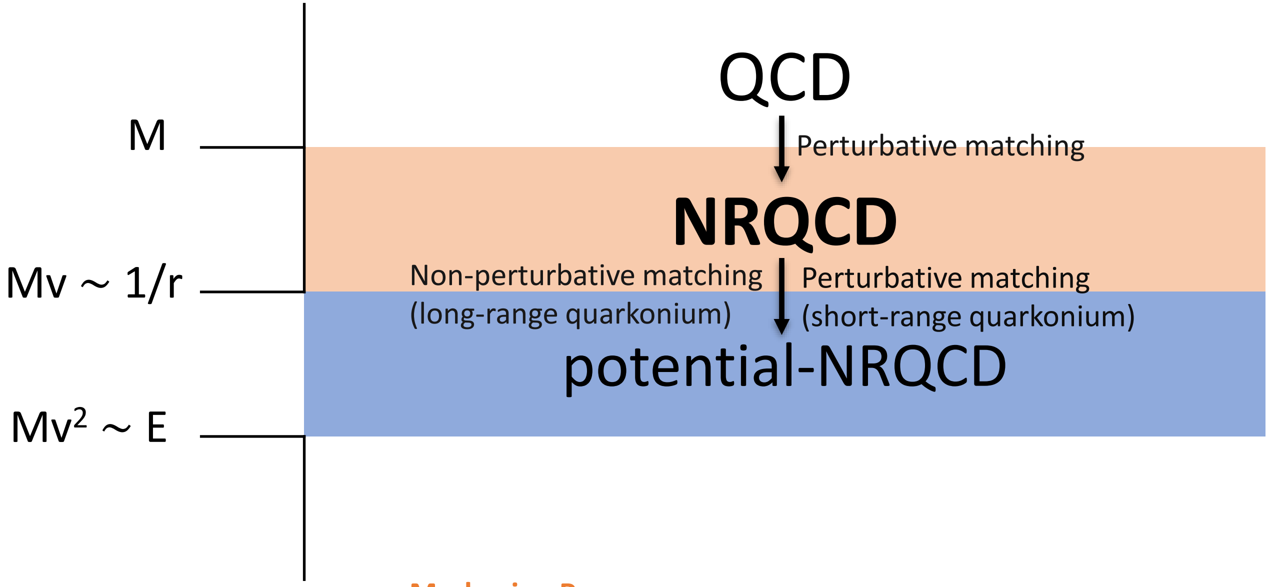




Bottomonia: pNRQCD

Separation of Scales

Separation of scales in vacuum: M >> Mv >> Mv^2



G.Bodwin, E.Braaten, G.Lepage, hep-ph/9407339

N.Brambilla A.Pineda, J.Soto, A.Vairo hep-ph/9907240

Inside QGP: thermal scales: **T**

Markovian Process
(During system relaxation, environment correlation has lost)

Case 1: **MV >> T** Quantum Optical Limit ($\tau_R >> \tau_E$ & $\tau_R >> \tau_S$)

Case 2: **T >> Mv^2** Quantum Brownian Motion ($\tau_R >> \tau_E$ & $\tau_S >> \tau_E$)

Medium relaxation time / Environment correlation time: $\tau_E \sim 1/T$

Intrinsic Time Scale of System: $\tau_S \sim 1/(Mv^2) \sim 1/(w_i - w_j)$

System relaxation time: $\tau_R \sim$ 1/self-energy [$\langle p(t) \rangle \sim e^{-t/t\_rel}$]

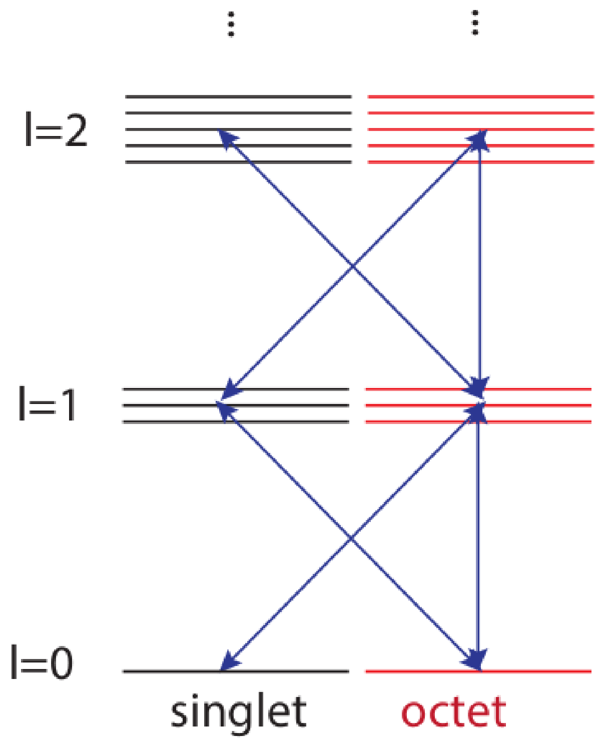
System = Quarkonium (Bottomonium)

KSU-Munich Approach: OQS + pNRQCD

- Reduced density matrix of the bottomonium (system) evolves by Lindblad equation
- DoF: singlet and octet states
- System density matrix & Hamiltonian decomposed into singlet & octet

$$\rho(t) = \begin{pmatrix} \rho_s(t) & 0 \\ 0 & \rho_o(t) \end{pmatrix}$$

$$\frac{d\rho(t)}{dt} = -i\left[H, \rho(t)\right] + \sum_{n=0}^{1}\left(C_i^n \rho(t) C_i^{n\dagger} - \frac{1}{2}\left\{C_i^{n\dagger} C_i^n, \rho(t)\right\}\right)$$



The imaginary part of the potential causing the decay of the Υ states in the medium *(dynamical screening from QGP medium),* and depend on the transport coefficients, kappa and gamma.

$$H = \begin{pmatrix} h_s + \mathrm{Im}(\Sigma_s) & 0 \\ 0 & h_o + \mathrm{Im}(\Sigma_o) \end{pmatrix}$$

$$\begin{aligned} \mathrm{Im}\left(\Sigma_s\right) &= \frac{r^2}{2}\gamma + \frac{\kappa}{4MT}\{r_i, p_i\}, \\ \mathrm{Im}\left(\Sigma_o\right) &= \frac{N_c^2 - 2}{2(N_c^2 - 1)}\left(\frac{r^2}{2}\gamma + \frac{\kappa}{4MT}\{r_i, p_i\}\right) \end{aligned}$$

<u>**Jump/Collapse Operators:**</u>

$$\begin{aligned} C_i^0 &= \sqrt{\frac{\kappa}{N_c^2 - 1}}\begin{pmatrix} 0 & 1 \\ 0 & 0 \end{pmatrix}\left(r_i + \frac{ip_i}{2MT} + \frac{\Delta V_{os}}{4T} r_i\right) \\ &\quad + \sqrt{\kappa}\begin{pmatrix} 0 & 0 \\ 1 & 0 \end{pmatrix}\left(r_i + \frac{ip_i}{2MT} + \frac{\Delta V_{so}}{4T} r_i\right), \\ C_i^1 &= \sqrt{\frac{\kappa(N_c^2 - 4)}{2(N_c^2 - 1)}}\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}\left(r_i + \frac{ip_i}{2MT}\right), \end{aligned}$$

$V_s = -C_F\alpha_s/r$ $\quad$ $V_o = C_F\alpha_s/8r$

QTRAJ-NLO 2205.10289, QTRAJ 1.0 2107.06147

KSU-Munich Numerical Solution: Quantum Trajectories (QTraj)

Partial and **Total** decay widths:

$$\Gamma_n = C_n^\dagger C_n \qquad \Gamma = \sum_n \Gamma_n$$

Reorganize Lindblad equation by defining

$$H_{\text{eff}} = H - \frac{i}{2}\Gamma$$

$$\frac{d\rho(t)}{dt} = -iH_{\text{eff}}\,\rho(t) + i\rho(t)H_{\text{eff}}^\dagger + \sum_n C_i^n \rho(t) C_i^{n\dagger}$$

Non-unitary "no jump" evolution

Can treat this "quantum jump" term stochastically

- Can be reduced to the solution of a large set of **"quantum trajectories"** in which we solve a 1D Schrödinger equation with a non-Hermitian Hamiltonian $\boldsymbol{H}_{\text{eff}}$, subject to stochastic quantum jumps.
- **Jump Operators (also called Collapse/Lindblad operators)** encode transitions between different color/angular momentum states (obeying selection rules)
- The evolution with the non-Hermitian $\boldsymbol{H}_{\text{eff}}$ preserves the color and angular momentum state of the system (but not norm).
- For **each physical trajectory** (path through the QGP), we average over a large set of independent quantum trajectories
- **Embarrasingly Parallel**

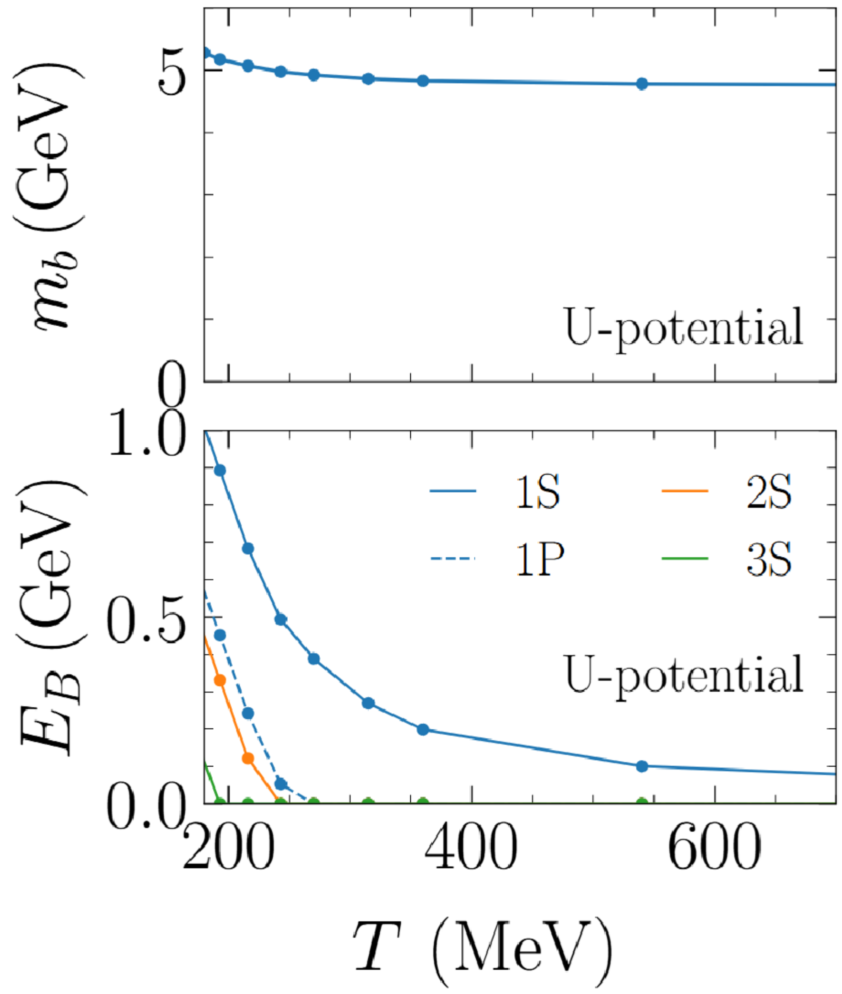
- Sampled 3D trajectories for bottomonium states → **Monte Carlo (MC) Sampling**
- **Initial transverse positions** for the bottomonium production in p-Pb sampled using MC using binary collision overlap profile of proton and Pb nucleus.
- **Initial transverse momentum and momentum rapidities** → MC sampled using distribution function (used in pp-parametrization).
- Temperature evolution → 3+1D aHydroQP
- Quantum Dynamics of each sampled physical trajectories → **Using NLO Qtraj** → Solve the real-time 3D Schrödinger equation with a complex potential and stochastically sampled jumps →Lindblad equation\
- Then find the survival probability of S-and P-wave states
  - L = 40 GeV^{-1}
  - Points: 2048
  - Physical Trajectories: 160,000
  - 20 Quantum Trajectories,Per physical Trajectory

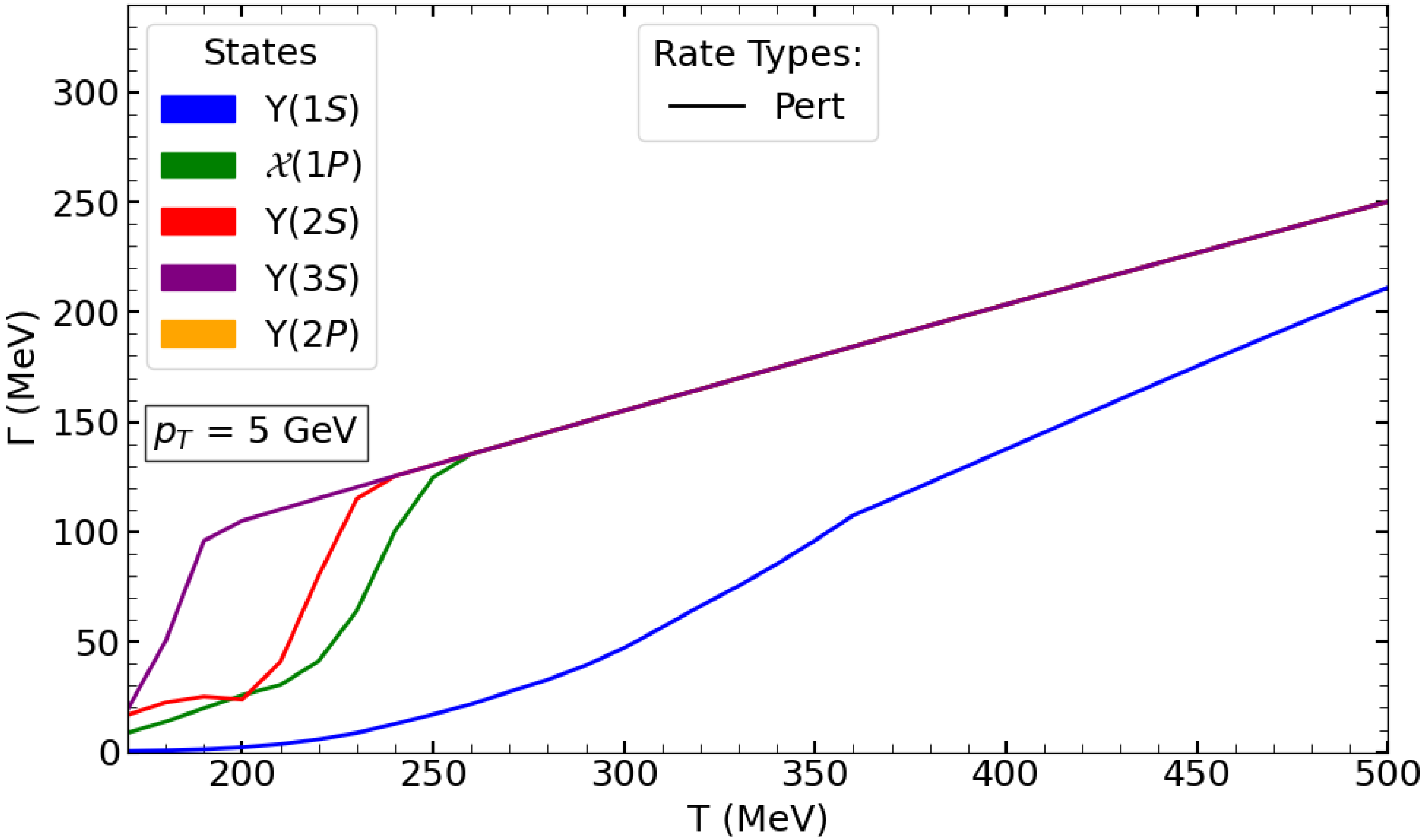
Survival probability

$$SP(n,l) = \frac{|\langle n,l|\psi(t_f)\rangle|^2}{|\langle n,l|\psi(t_0)\rangle|^2}$$

TAMU Approach (Perturbative Rates, TAMU-P Case)

- Uses finite-temperature internal-energy (U) potential from lQCD constraints
- Quasi-free approximation with perturbative coupling to QGP, includes inelastic scattering and gluon dissociation
- Predicts moderate in-medium, screening and dissociation rates, treats 1S, 1P, 2S and 3S states only (rates for 2P = 3S)

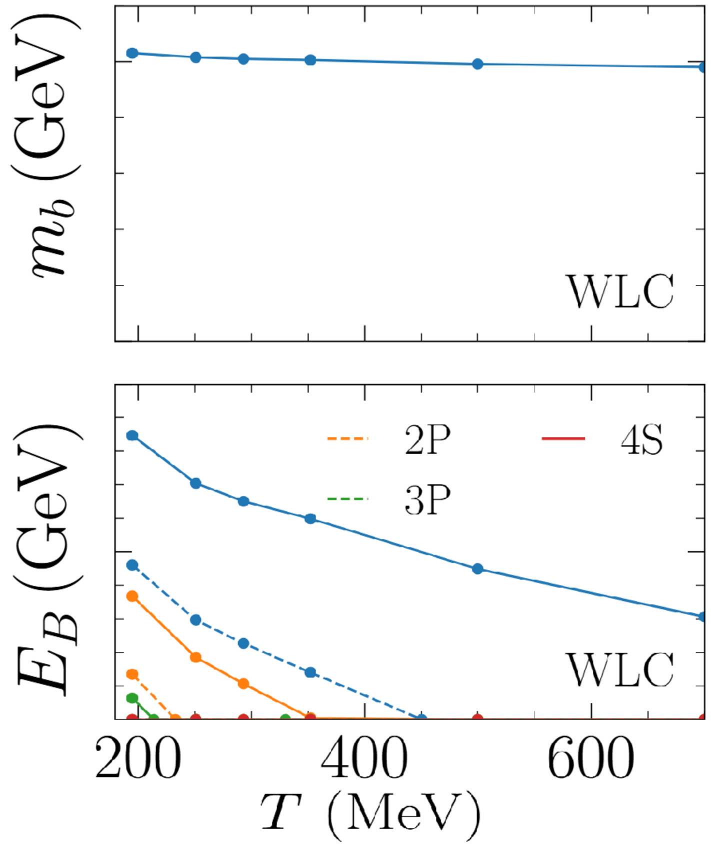




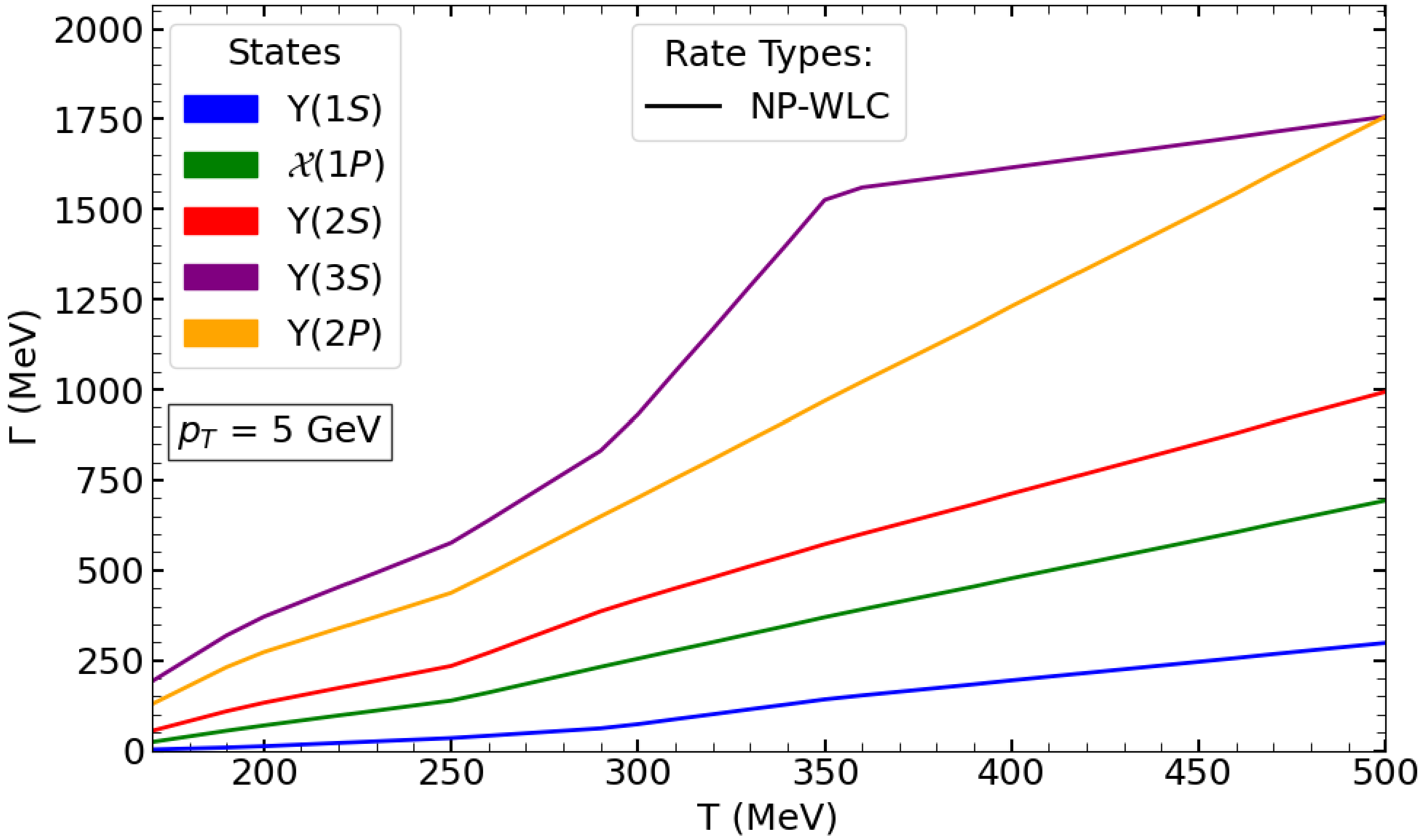
X. Du, M. He, R. Rapp (2017), 1706.08670, F. Riek & R. Rapp (2018), 1005.0769

TAMU Approach (Non-Perturbative Rates, TAMU-NP Case)

- Recent approach using in-medium potential constrained by nonperturbative Wilson line correlators (WLC)
- Weakly screened potential → substantial bottomonium binding in QGP
- Dissociation rates from T-matrix poles in the complex energy plane
- Predicts high in-medium dissociation rates
- Treats multiple states: 1S, 2S, 1P, 3S, 2P, …



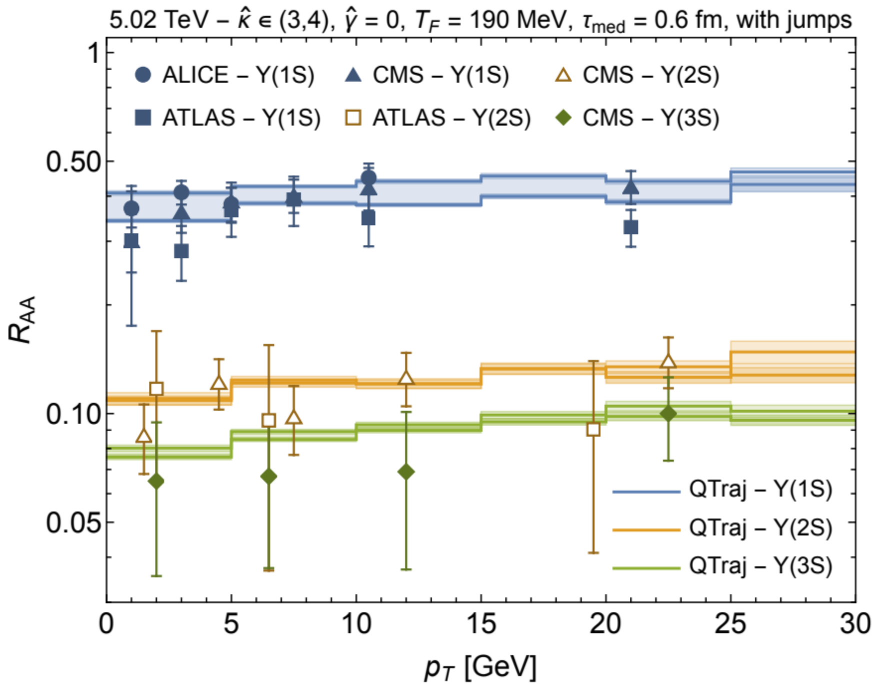
Z Tang, R Rapp (2023), 2304.02060

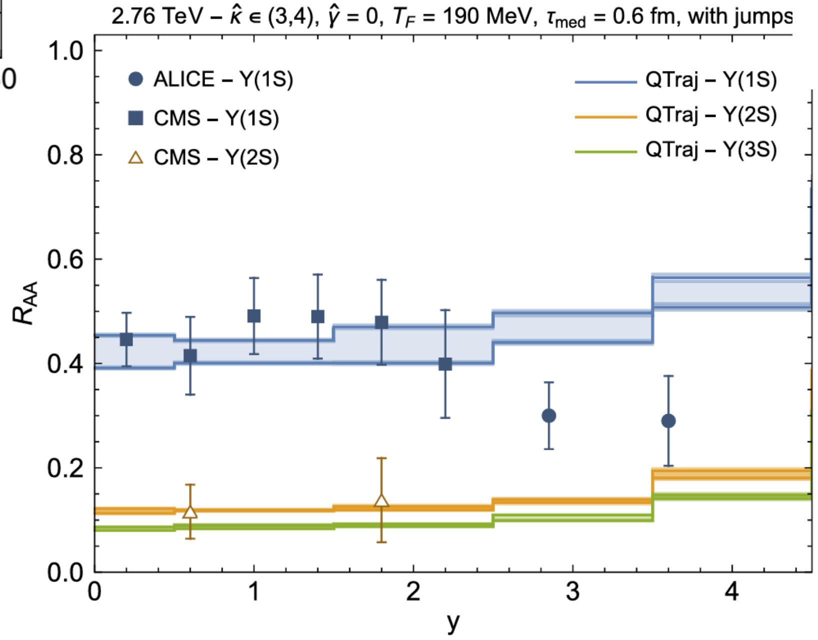


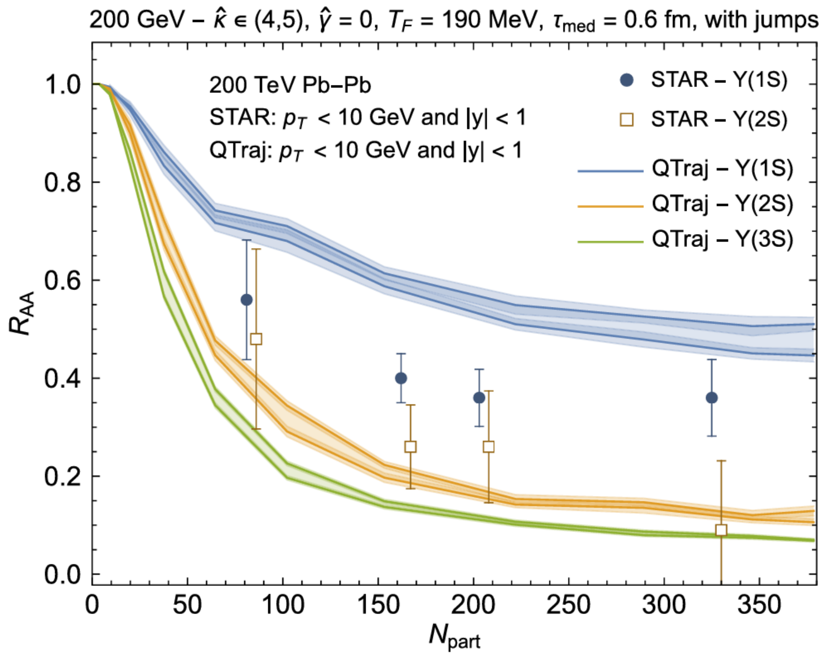
Z Tang, B Wu, A Hanlon, S Mukherjee, P Petreczky, R Rapp (2025), 2502.09044

Future: AA Collision

In AA collision at RHIC & LHC, the forward and backward rapidities, some additional effects needed!







M. Strickland & S. Thapa (2023) 2305.17841