

# Quarkonia as a probe of Quark-Gluon-Plasma (QGP)

Small (p+Pb), Light-Ion (O+O) Collisions

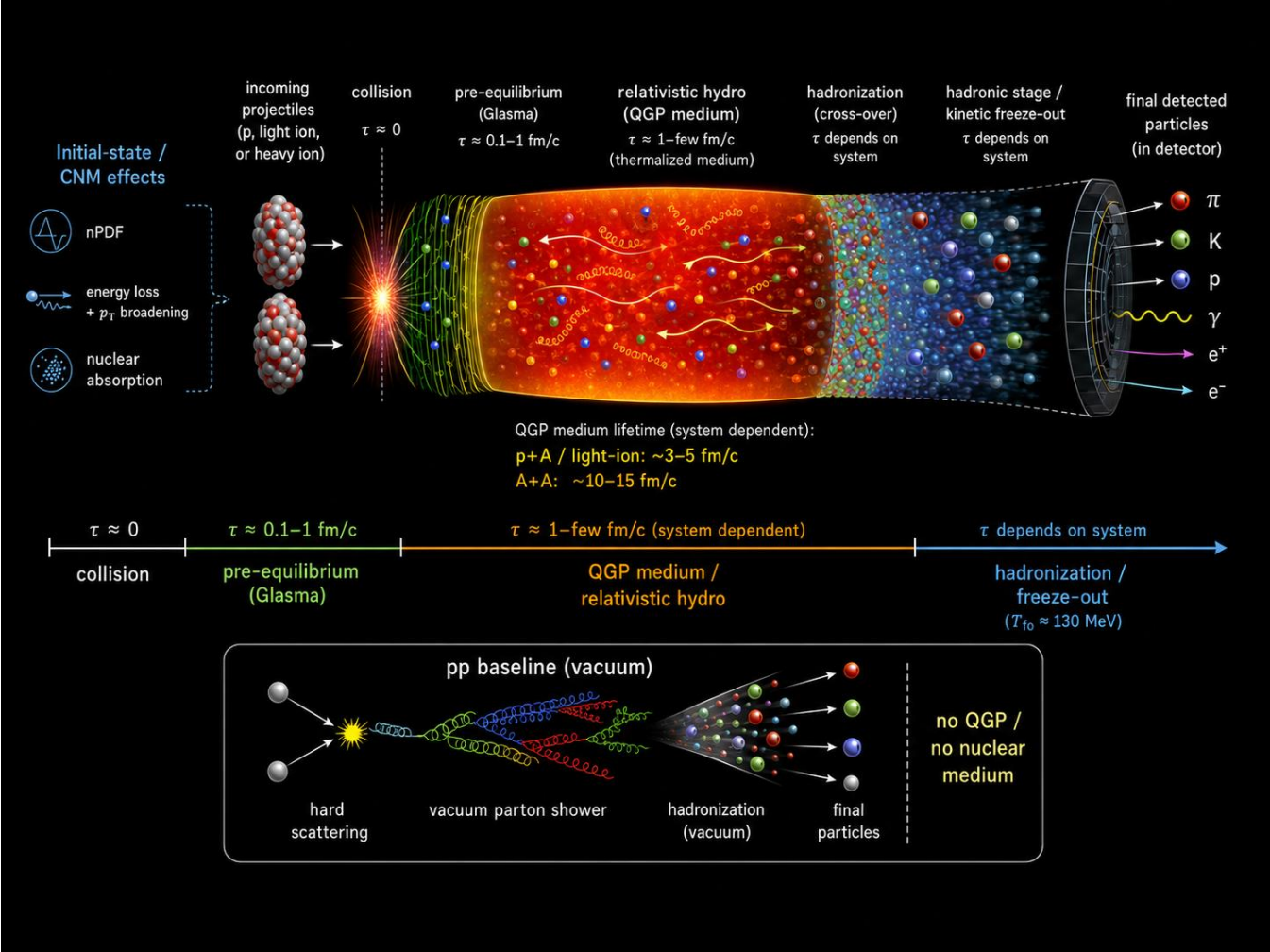
Sabin Thapa

2026 CFNS Summer School on the Physics of the Electron-Ion Collider (EIC)



U.S. DEPARTMENT OF  
**ENERGY**

# Relativistic Nuclear Collisions

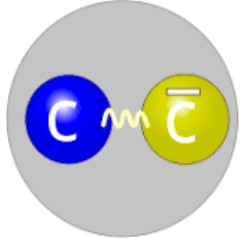


- Study QCD matter at **extreme conditions**

- Recreate conditions of "**Big Bang**" in the lab [RHIC, LHC]

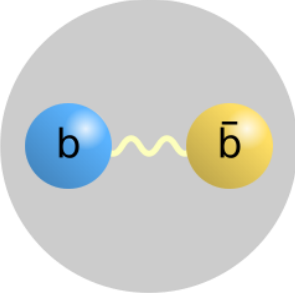
- Probes of QGP:**

  - Quarkonia

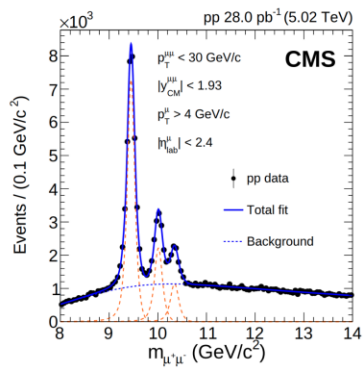


**[Charmonium, Bottomonium]**

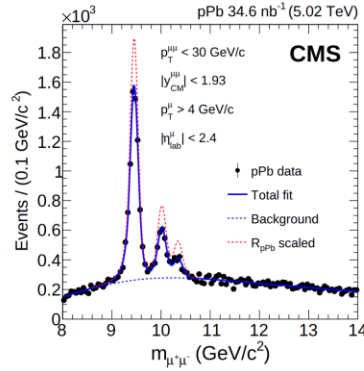
- Jets, etc ....



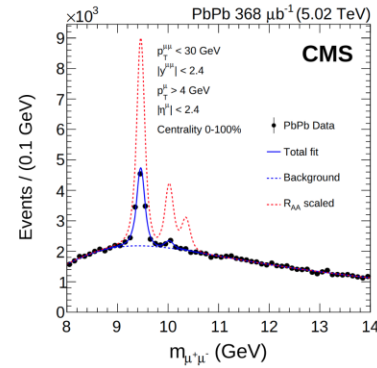
# MOTIVATION



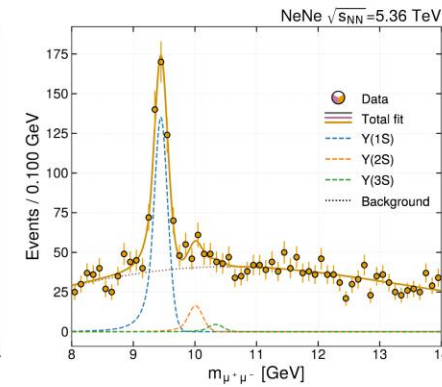
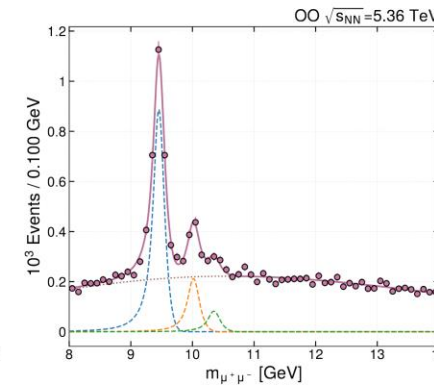
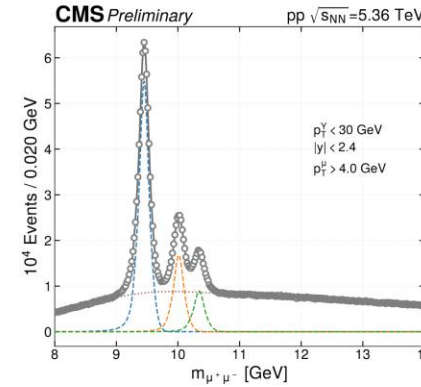
(a) pp collisions



(b) pPb collisions



(c) PbPb collisions



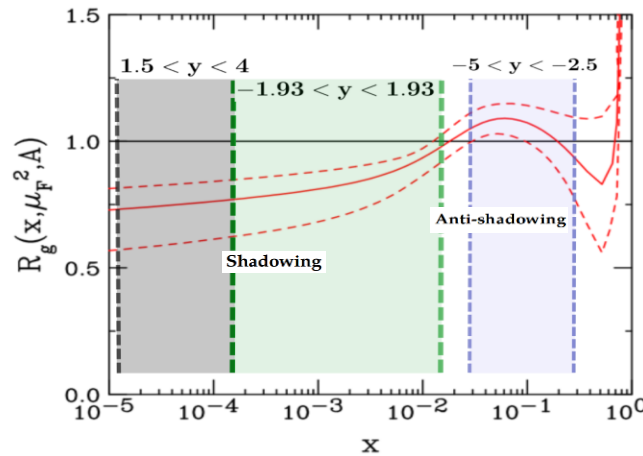
- **Established:** QGP is formed in Ultra-relativistic **heavy-Ion collisions (Pb+Pb, Au+Au)**
- **Question:** Is QGP formed in **small & light-ion collision systems?**
- **Challenge:** If QGP is formed, how do we isolate the hot QGP signal from the cold QCD medium?

# CNM EFFECTS

# nPDF

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

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



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

$$\sigma_{\text{CEM}}(pp) = F_C \sum_{i,j} \int_{4m^2}^{4m_H^2} d\hat{s} \int dx_1 dx_2 \times F_i^p(x_1, \mu_F^2, k_{T1}) F_j^p(x_2, \mu_F^2, k_{T2}) \hat{\sigma}_{ij}(\hat{s}, \mu_F^2, \mu_R^2)$$

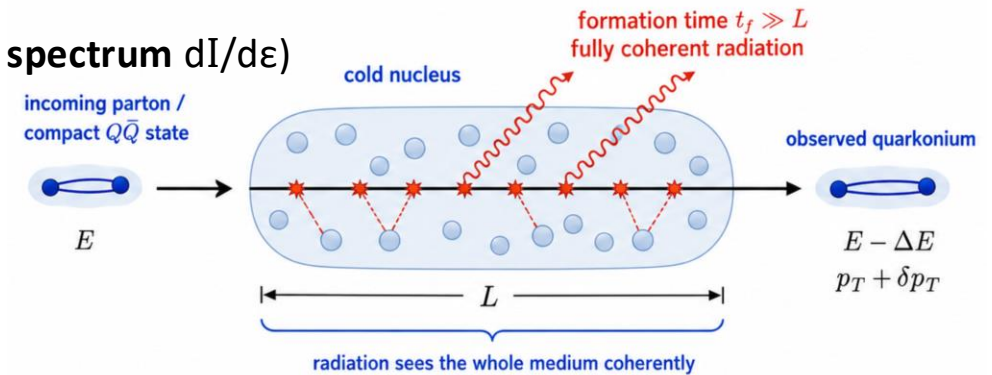
$$\sigma_{\text{CEM}}(pA) = F_C \sum_{i,j} \int_{4m^2}^{4m_H^2} d\hat{s} \int dx_1 dx_2 \times F_i^p(x_1, \mu_F^2, k_T) F_j^A(x_2, \mu_F^2, k_T) \hat{\sigma}_{ij}(\hat{s}, \mu_F^2, \mu_R^2)$$

R. Vogt et al [hep-ph/9502270](https://arxiv.org/abs/hep-ph/9502270), [1508.01286](https://arxiv.org/abs/1508.01286), [1609.06042](https://arxiv.org/abs/1609.06042)  
 Eskola et al. (2021). [2112.12462](https://arxiv.org/abs/2112.12462)

# Energy Loss & Momentum Broadening

While passing through a medium (*cold nucleus*, ...):

- a parton can lose energy due to collisions (Bjorken, 1982) and / or via induced gluon radiation (Gyulassy, Wang (1993) [nucl-th/9306003](https://arxiv.org/abs/nucl-th/9306003))
- The produced  $\Upsilon$  states lose energy and undergo momentum broadening in the **cold QCD matter**, encoded in **Quenching weight** (probability density for a particle with energy E to lose energy  $\epsilon$ , obtained from the radiation spectrum  $dI/d\epsilon$ )



- In terms of the **rapidity shift  $\delta y$  & transverse momentum broadening  $\delta p_T$** , the quarkonium double differential cross section:

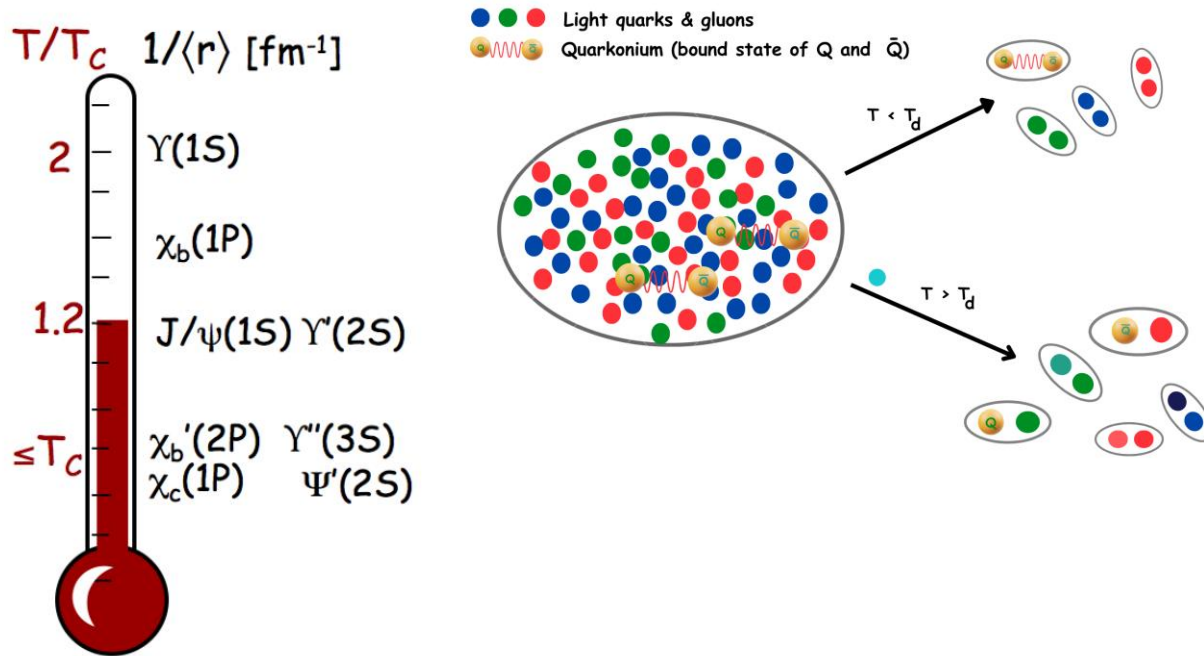
$$\frac{1}{A} \frac{d\sigma_{pA}^{\psi}}{dy d^2p_T}(y, p_T) = \int_0^{2\pi} \frac{d\varphi}{2\pi} \int_0^{\delta y_{\text{max}}(y)} d\delta y \hat{\mathcal{P}}(e^{\delta y} - 1, \ell^2) \frac{d\sigma_{pp}^{\psi}}{dy d^2p_T}(y + \delta y, |\vec{p}_T - \delta \vec{p}_T|)$$

Arleo, Kolevatov, Peigne, Rustamova (2013), [1304.0901](https://arxiv.org/abs/1304.0901)  
 Arleo & Peigne, Rustamova (2013), [1212.0434](https://arxiv.org/abs/1212.0434)

# **HNM EFFECT**

# Quarkonia in the QGP

- **Static color screening** by Matsui, Satz (1986): inside the QGP, color attraction in Quarkonia suppressed due to Debye Screening, different radii/mass/binding energies, sequential melting at high T



## QGP thermometer

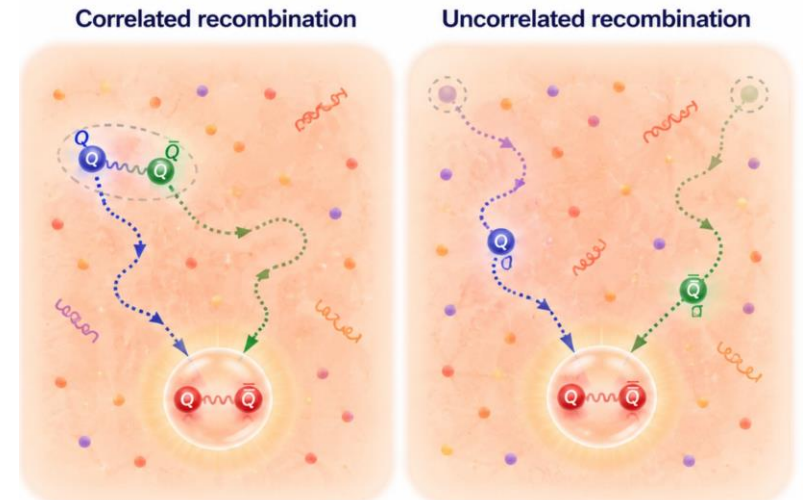
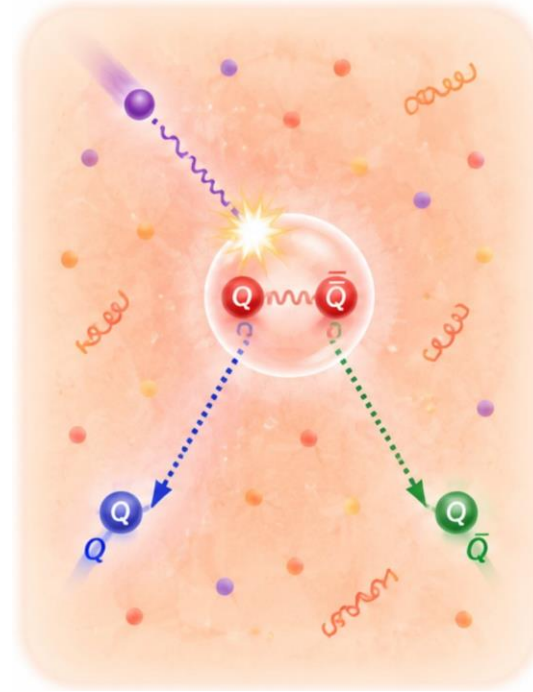
Mocsy, Petreczky, and Strickland, [1302.2180](#)

- ✓ High energy plasma particles which slam into the bound states cause them to have shorter lifetimes, i.e., **large spectral widths**

- **Dynamical screening: dissociation induced by dynamical process, imaginary potential**

RL. Thews, M. Schroedter, J. Rafelski  
 Phys.Rev.C 63, 054905 (2001), [arxiv: hep-ph/0007323](#)

- **Regeneration/Recombination:** unbound heavy quark pair forms quarkonium, can happen below melting T

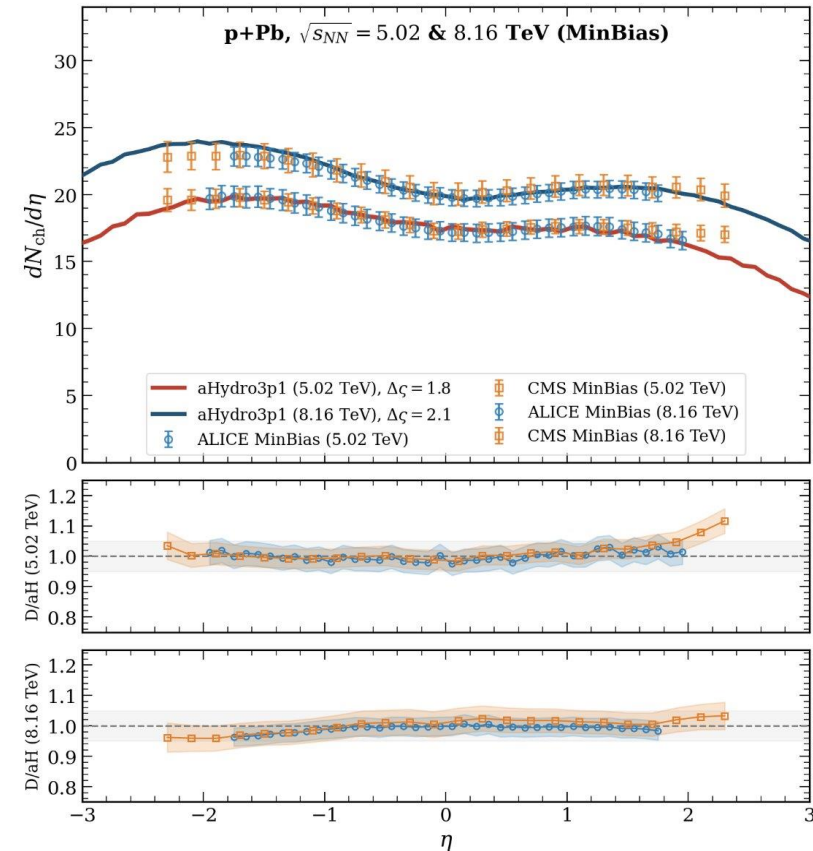
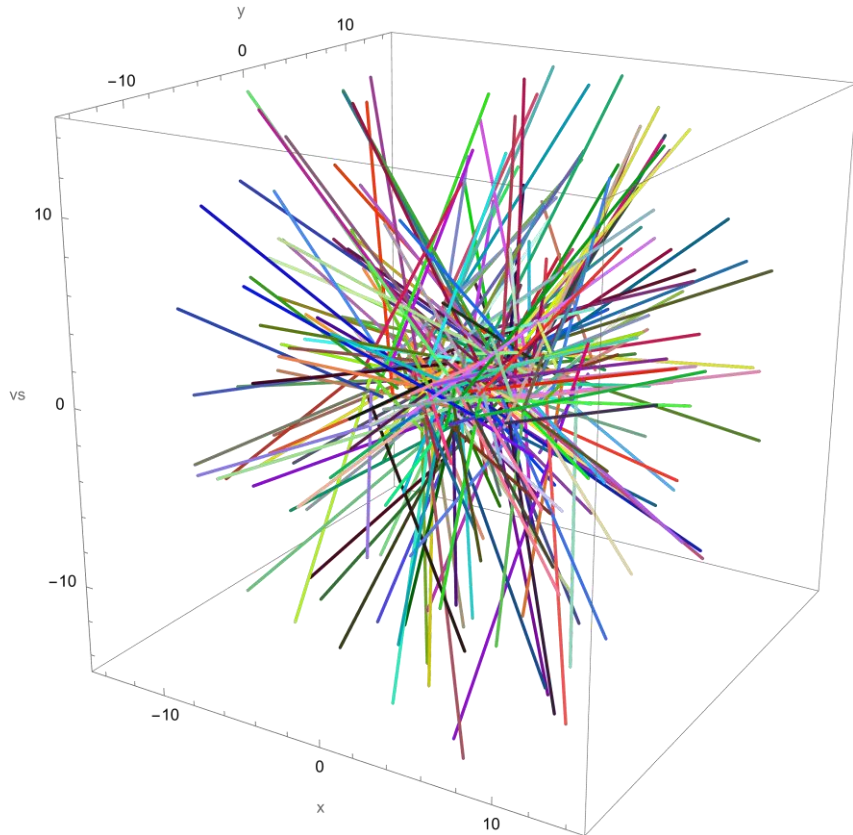


# Models: Quarkonia Transport in QGP

# QGP Background: Relativistic Hydrodynamics (3+1 D)

- Background temperature evolution of QGP provided by **relativistic hydrodynamics**.
- aHydroQP: excellent description of **identified hadron spectra**.

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



# Quantum Mechanical Model: Open Quantum System Approach

- **Goal: quantum transport of quarkonia in the QGP!**
- **Bottomonium: an open quantum system:** it interacts with QGP medium / environment
- Solve for Bottomonium density matrix inside QGP medium
- Hierarchy of scales,  $M \gg 1/a_0 \gg T \gg E_b$  (Brownian Motion Limit) at NLO pNRQCD in  $E_b/T$ , the **Lindblad-Gorini-**

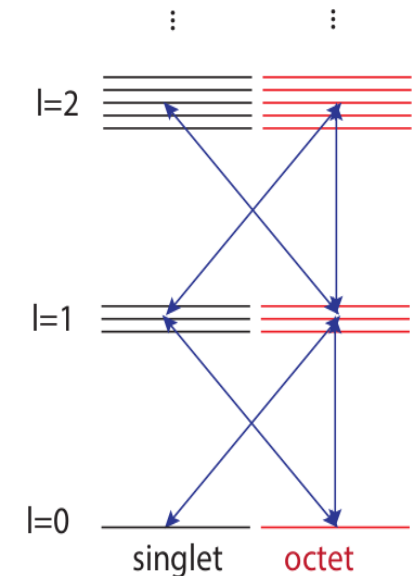
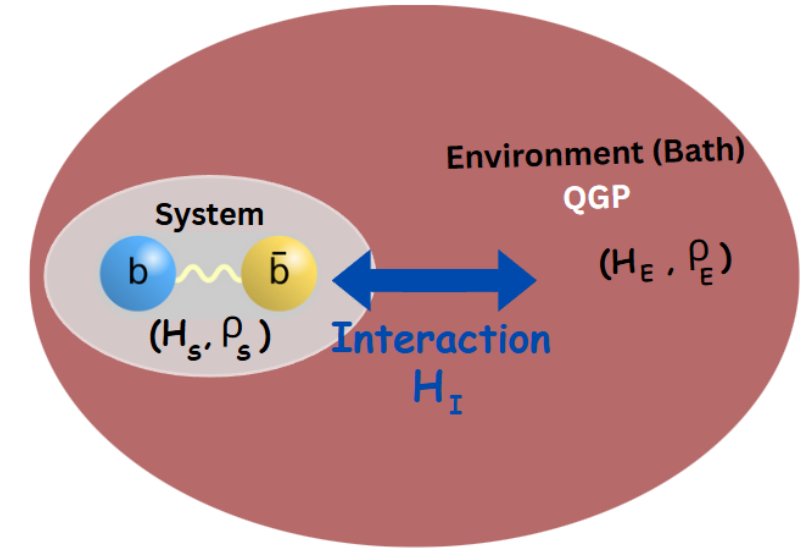
**Kossakowski-Sudarshan Master Equation:**

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

Brambilla, Escobedo, Islam, Strickland, Tiwari, Vairo & Vander Griend (2022/23), [2205.10289](#), [2302.11826](#),  
Strickland & Thapa (2023), [2305.17841](#)

- Solve using Quantum Trajectories (**QTRAJ Code**)

Omar et al. (2021) QTRAJ 1.0, [2107.06147](#)



# SEMI-CLASSICAL TRANSPORT MODEL: Kinetic Rate Approach

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

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

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

**Reaction Rate:** Medium effect on bound Upsilon states (cause decay of bound states into unbound  $b\bar{b}$  pairs) -- the thermodynamic T-matrix approach by TAMU

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

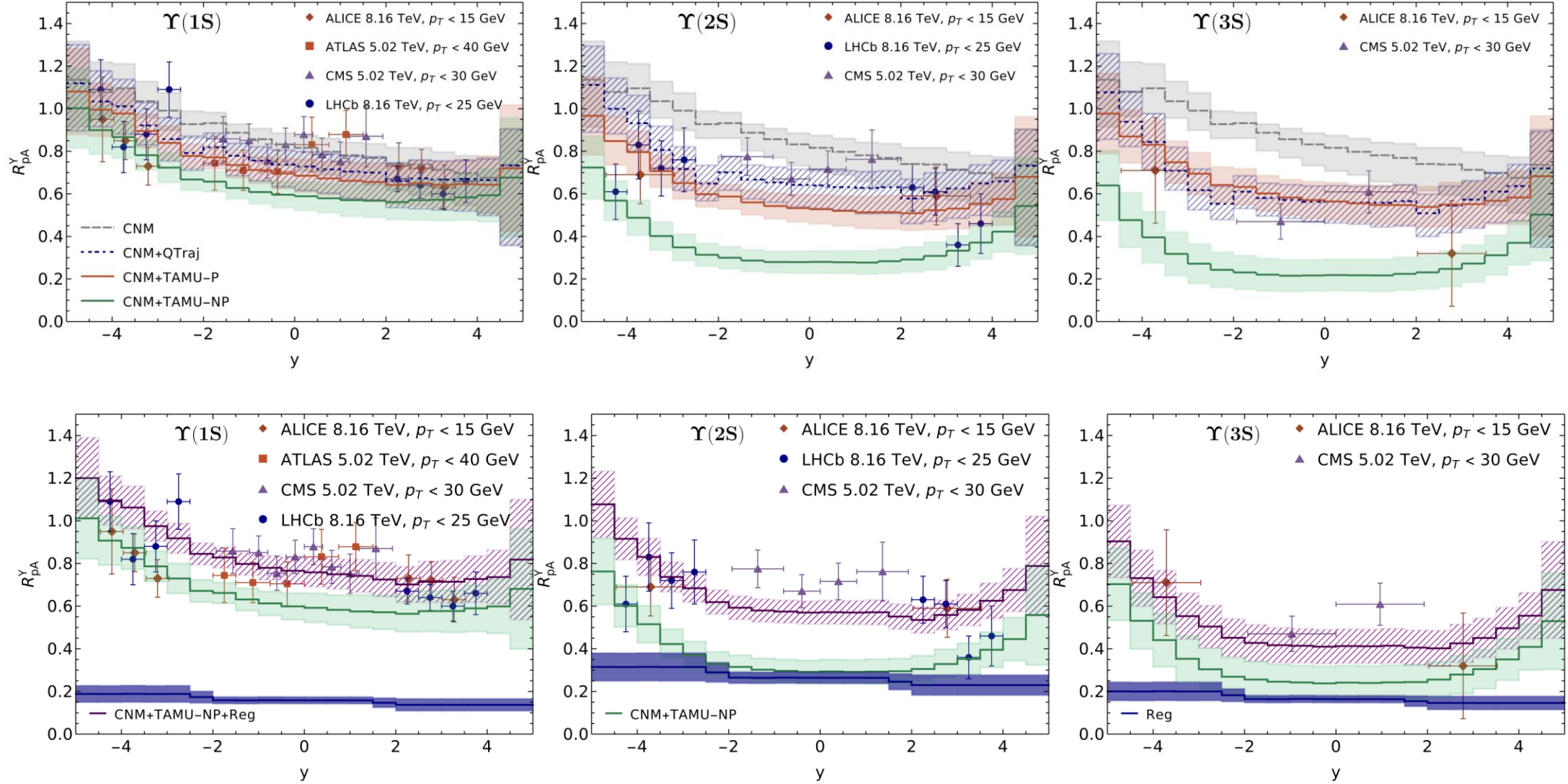
□ **Regeneration Part:**

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

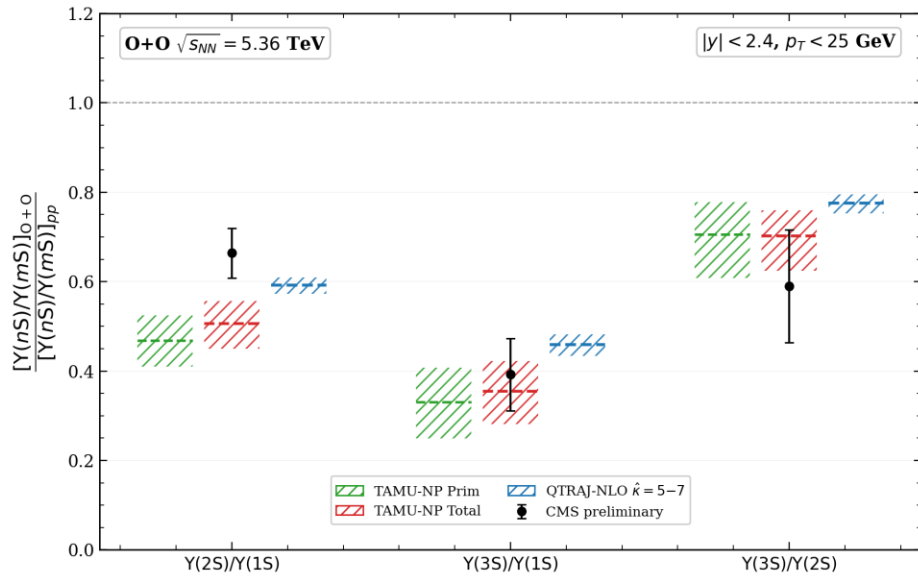
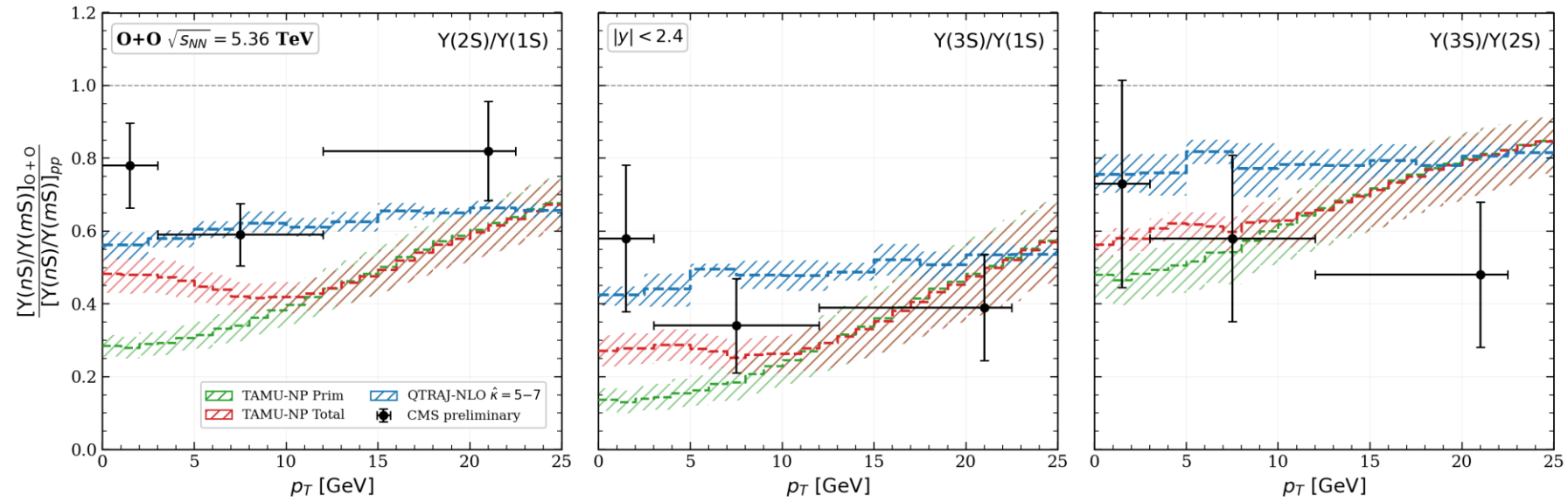
**Equilibrium Limit:** Depends on  $b\bar{b}$  cross section and the thermal environment (QGP fireball)

# Results

# Bottomonia in p+Pb LHC



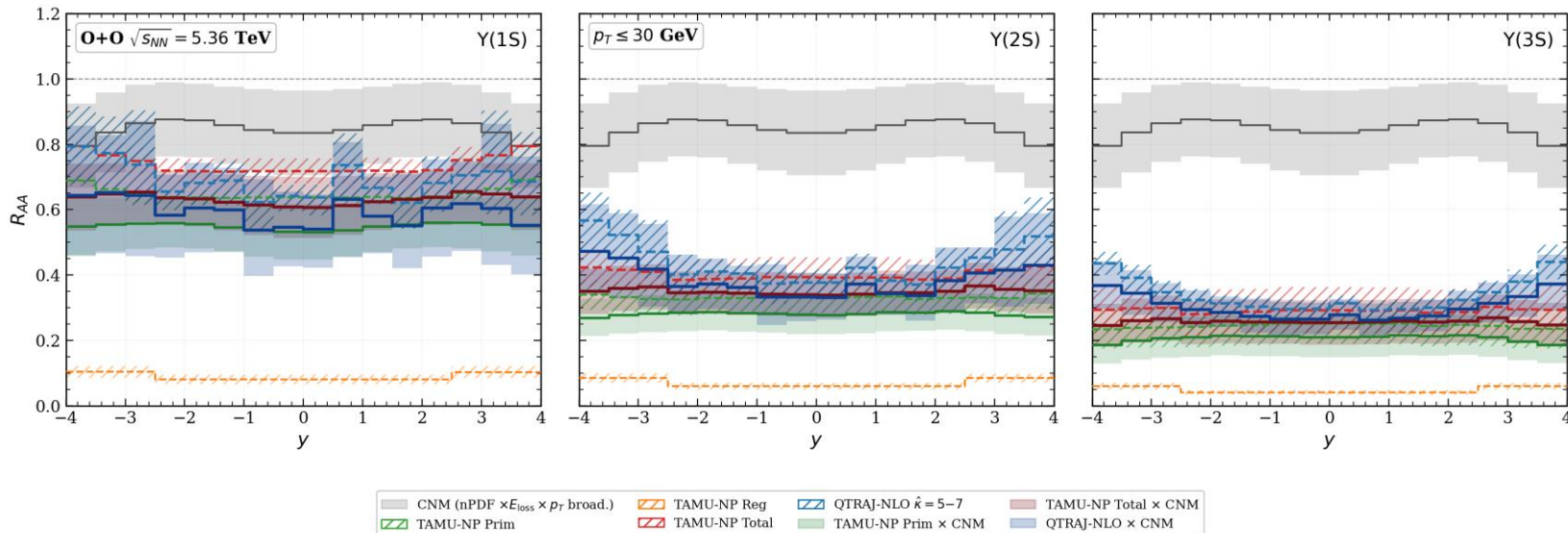
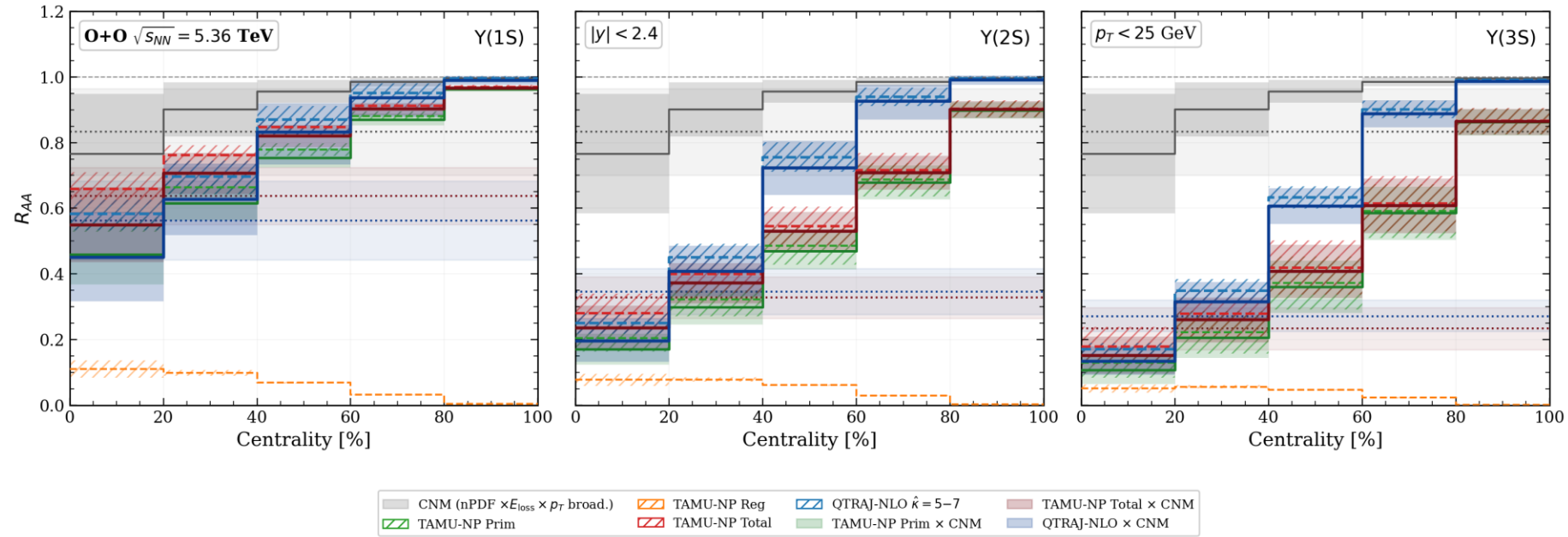
# Bottomonia in O+O LHC



Thapa, Wu, Vogt & Ralf, Upsilon(nS) production in 5.36 TeV O+O collision, (In prep)

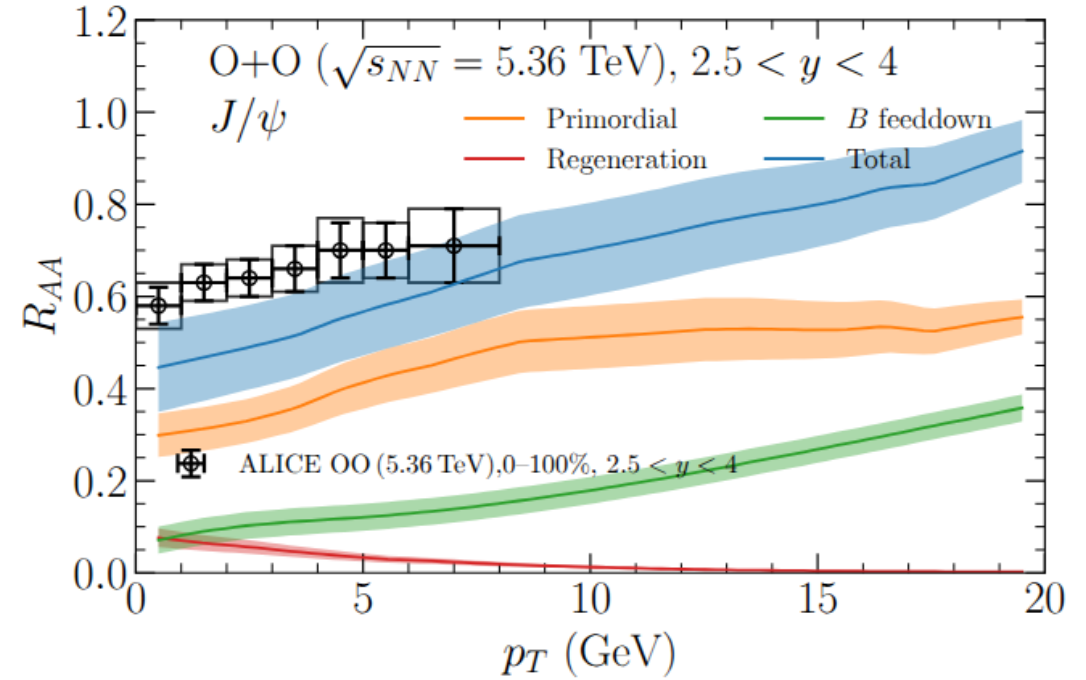
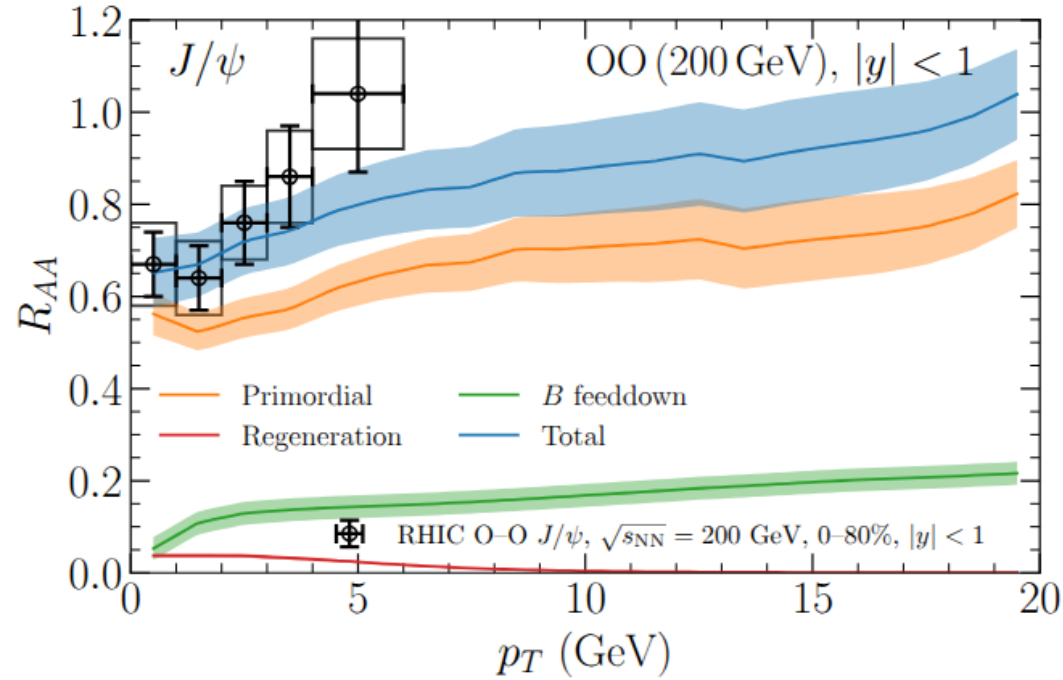
# Bottomonia in O+O LHC

Regeneration Component  
Computed by Biaogang Wu



Thapa, Wu, Vogt & Ralf, Upsilon(nS) production in 5.36 TeV O+O collision, (In prep)

# Charmonia in O+O LHC & RHIC



Thapa, Wu, Vogt & Ralf, Charmonia production in O+O collision at RHIC & LHC, (In prep)

- **By Biaogang Wu & Kaiyu Fu**  
**[TAMU, HEFTY]**

# CONCLUSIONS & OUTLOOK

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- Including QGP effects in the CNM effects provides reasonable description of available data given current experimental and theoretical uncertainties.
- **Even in small (p+Pb) & light-ion collision systems (O+O at LHC & RHIC), (short-lived) QGP formed!**

# Acknowledgement

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- Ralf Rapp
- Biaogang Wu
- Kaiyu Fu

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***Thank you!***

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