Quarkonium production & modification:

disentangling cold & hot nuclear effects in small collisions at LHC & RHIC

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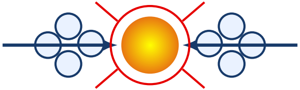
Motivation



QGP fireball

Heavy-ion collisions

Pb+Pb/Au+Au create a hot, expanding QCD medium.

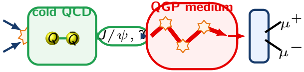
LHC: TeV scale; RHIC: 200 GeV.

cold QCD effects + possible QGP

Small collision systems

p+Pb and O+O help isolate cold nuclear matter from possible hot-medium effects.

O+O: 5.36 TeV and 200 GeV.



Quarkonia

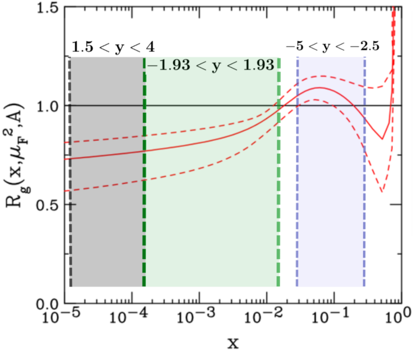
Produced early; survival encodes cold and hot QCD interactions, with clean dimuon decay channels.

Observables:

$$R_{AA}(p_T, y) = \frac{1}{\langle N_{\mathrm{coll}} \rangle} \frac{d^2 N_{AA}/dp_T dy}{d^2 N_{pp}/dp_T dy}$$

$$\mathcal{D}^{AA}_{nS/1S} = \frac{\left[N_{\Upsilon(nS)}/N_{\Upsilon(1S)} \right]_{AA}}{\left[N_{\Upsilon(nS)}/N_{\Upsilon(1S)} \right]_{pp}} \simeq \frac{R_{AA}^{\Upsilon(nS)}}{R_{AA}^{\Upsilon(1S)}}$$

Cold Nuclear Matter Effects



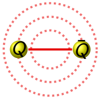
- **Nuclear PDFs:** parton densities inside bound nucleons differ from free protons.

$$f_i^A(x, Q^2) = R_i^A(x, Q^2)\, f_i^p(x, Q^2)$$

- **Momentum broadening (Cronin effect):** multiple scatterings increase transverse momentum, $p_T^2 \to p_T^2 + \Delta p_T^2$.
- **Energy loss:** pre-resonant $Q\bar{Q}$ pairs lose energy (coherently) while crossing cold nuclear matter via medium-induced gluon radiation.
- **Nuclear absorption:** pre-resonant $c\bar{c}$ may break up before exiting the nucleus. Mainly charmonia at RHIC; LHC formation times are longer, bottomonia compact.

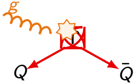
CNM must be constrained; by itself it does not naturally explain strong $\Upsilon(2S), \Upsilon(3S)$ suppression.

QGP Effects on Quarkonia



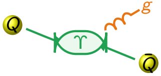
Debye / static screening

Color force is screened; weak states melt first.



Dynamical dissociation

Thermal particles break bound states, giving large widths.



Recombination

Unbound heavy quarks can meet again and regenerate quarkonium.

KSU–Munich: OQS approach

Open Quantum System + pNRQCD at NLO density matrix evolution

$$\dot{\rho} = -i[H,\rho] + \sum_n \left(C_n \rho C_n^\dagger - \tfrac{1}{2}\{C_n^\dagger C_n, \rho\} \right).$$

Density matrix evolves in the QGP background.

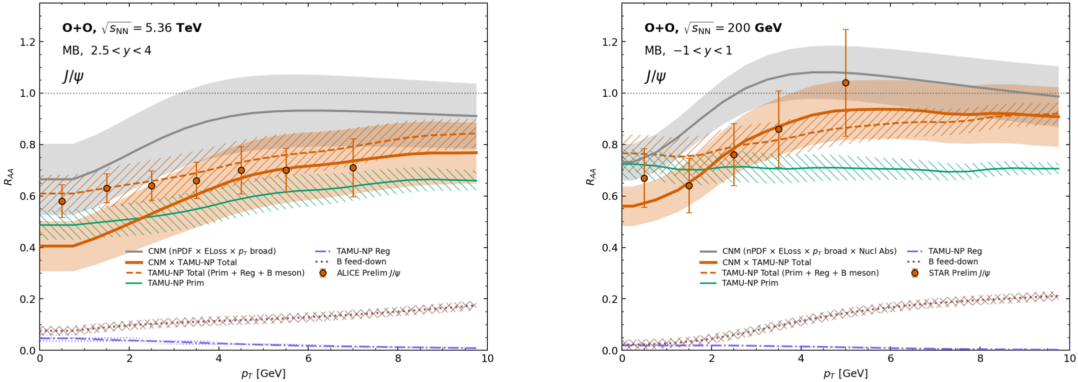
TAMU: semiclassical transport

Rate equation with loss and gain:

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

Gain term accounts for recombination/regeneration.

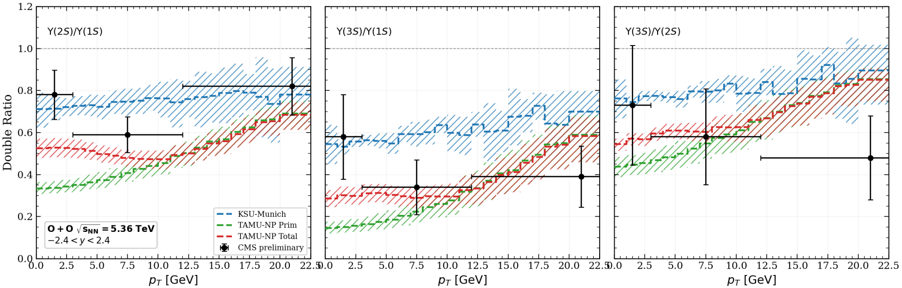
O+O Charmonia: LHC and RHIC



Across LHC and RHIC energies, CNM constrains the cold-QCD contribution; hot-medium effects modify the final J/ψ yield.

Thapa, Wu, Fu, Vogt & Rapp: Charmonia production in O+O collisions at LHC & RHIC (in prep)

O+O Bottomonia: Sequential Suppression



- Excited states are more fragile than $\Upsilon(1S)$.
- CNM alone does not naturally produce the hierarchy.
- Hot-medium suppression in addition to CNM is needed in the calculation.
- KSU–Munich and TAMU descriptions support a hot, short-lived QGP medium in small collisions.

Thapa, Wu, Vogt & Rapp: $\Upsilon(nS)$ in 5.36 TeV O+O collisions (in prep)

Thank you!