

# Quantum Regeneration of Bottomonium

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based on [Phys. Rev. D 108 \(2023\) 1, L011502](#) with N. Brambilla, M. Escobedo, A. Islam, M. Strickland, A. Tiwari, A. Vairo

## Theory

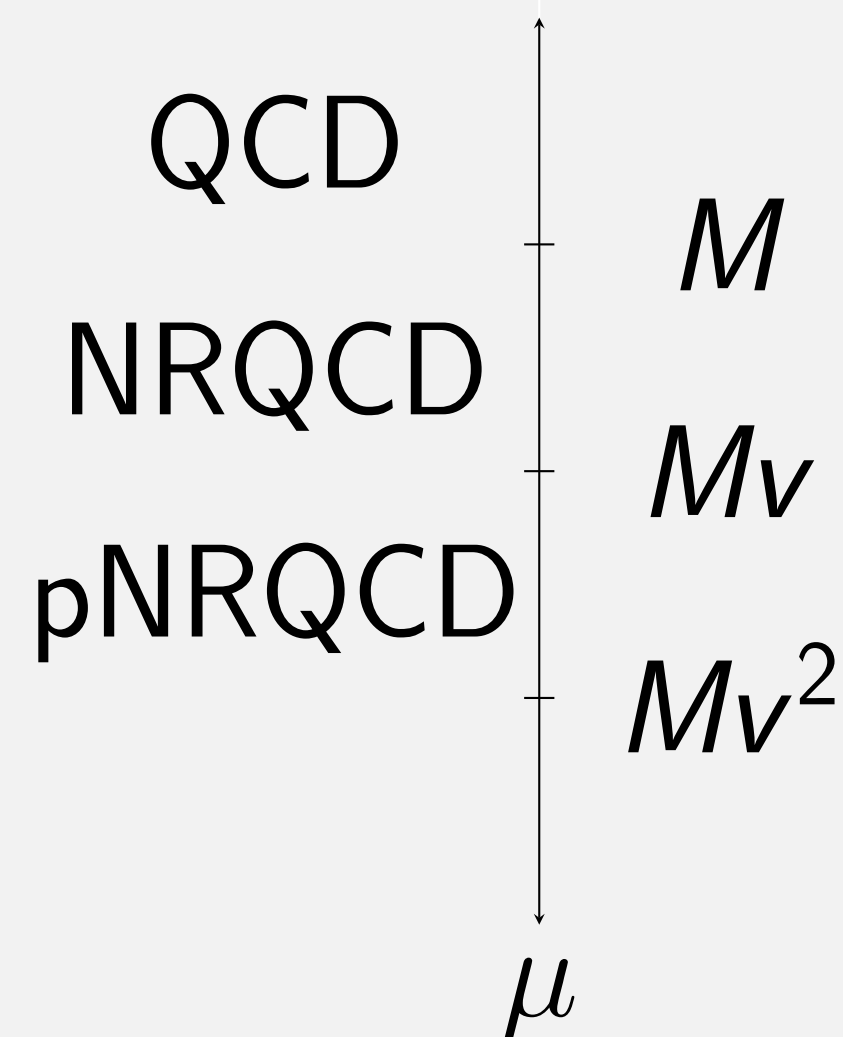
**Hierarchy of Scales** We consider  $Q\bar{Q}$  states characterized by quark mass  $M$ , Bohr radius  $a_0$  and binding energy  $E$  in a strongly coupled medium of temperature  $T$  realizing the hierarchy of scales:

$$M \gg 1/a_0 \gg \pi T \sim gT \gg E.$$

**pNRQCD** Potential nonrelativistic QCD (pNRQCD) is an EFT

of the strong interaction obtained from full QCD via nonrelativistic QCD (NRQCD) by the sequential integrating out of the hard ( $M$ ) and soft ( $Mv$ ) scales. The resulting theory contains color singlet and octet heavy-heavy bound states and ultrasoft ( $Mv^2$ ) gluons and is ideally suited to describe low lying bound states of small radius.

**Open Quantum Systems** The OQS formalism allows for the rigorous treatment of a quantum system coupled to and evolving out of equilibrium with an environment. The combined system is characterized by the system intrinsic time scale  $\tau_S \sim 1/E$ , the environment time scale  $\tau_E \sim 1/(\pi T)$  and the relaxation time  $\tau_R \sim 1/(a_0^2(\pi T)^3)$  which characterizes the time scale of the interaction between the system and the environment. We consider the regime  $\tau_R, \tau_S \gg \tau_E$  which characterizes quantum Brownian motion and in which the evolution of the system is insensitive to its history, i.e., Markovian.



## Evolution Equations

**Lindblad Equation** In a strongly coupled medium in the temperature regime  $\pi T \gtrsim E$ , the evolution of the bottomonium density matrix  $\rho$  takes the form of a Lindblad equation ([JHEP 08 \(2022\) 303](#))

$$\frac{d\rho}{dt} = -i[H, \rho] + \sum_n (C_n \rho(t) C_n^\dagger - \frac{1}{2} \{C_n^\dagger C_n, \rho\}).$$

The Hamiltonian  $H$  contains the kinetic term and an attractive singlet or repulsive octet Coulomb potential corresponding to the respective color state of the quarkonium. Interactions with the medium are encoded in the collapse operators  $C_n$ , and medium corrections to the potential are contained in  $H$ .

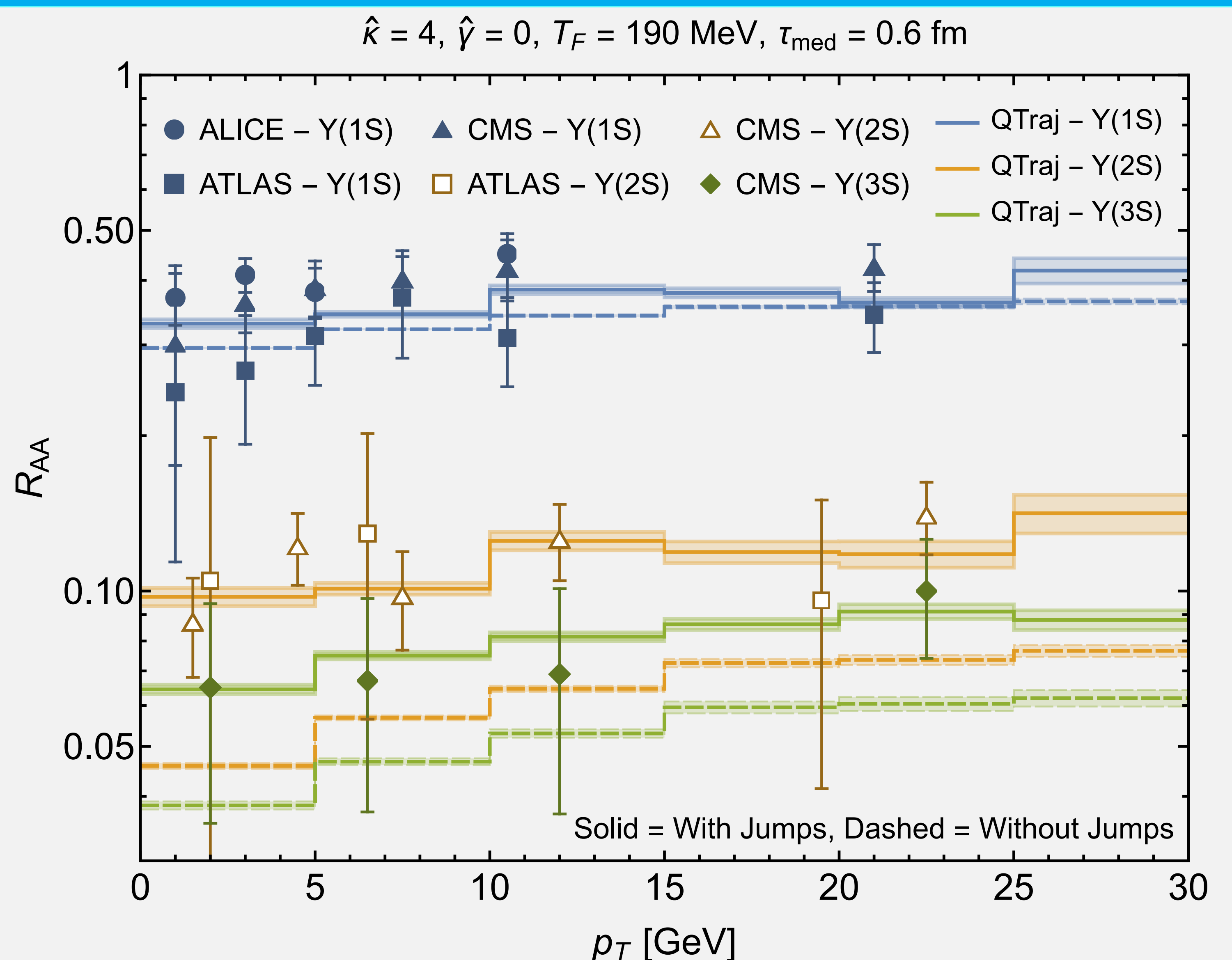
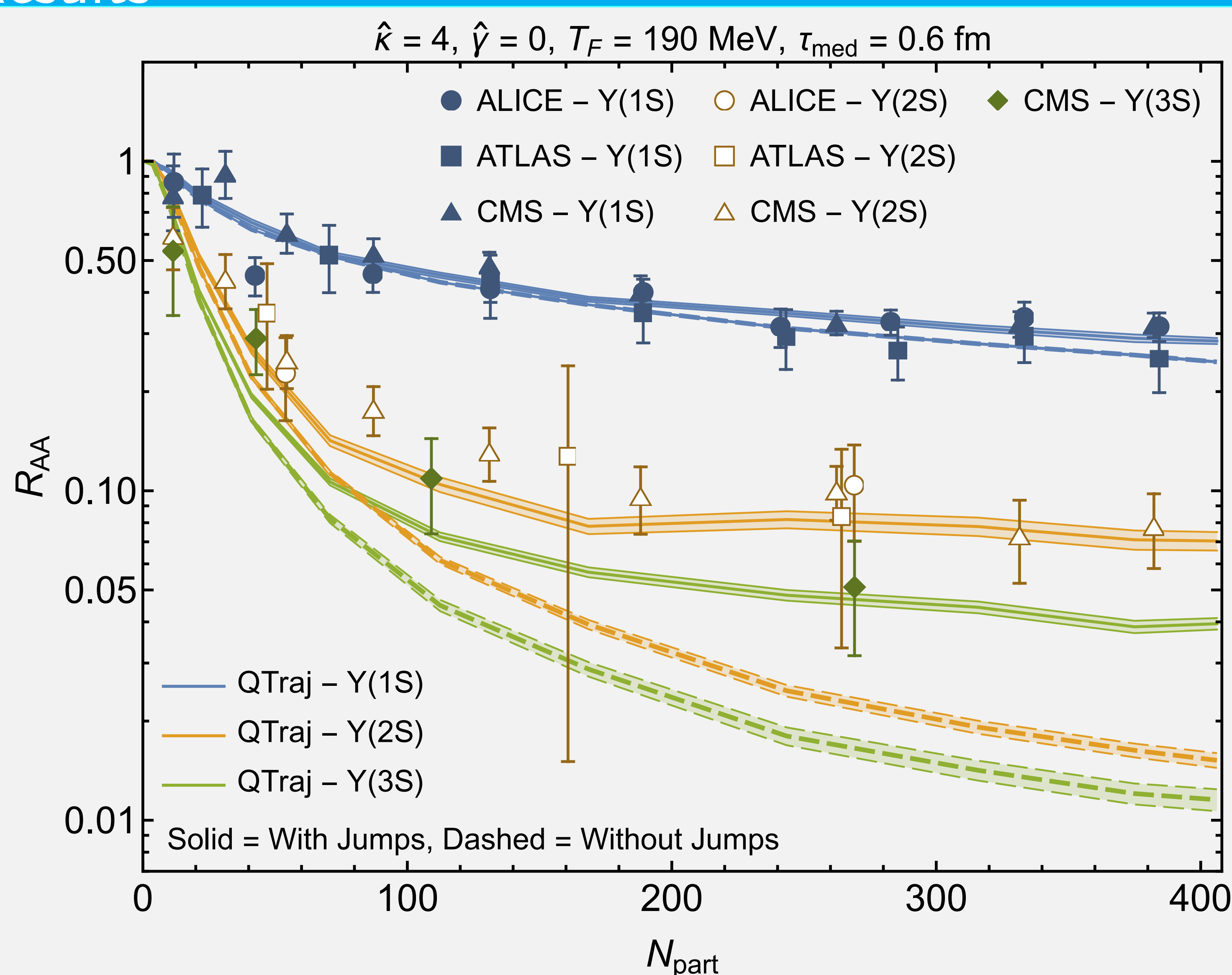
**Transport Coefficients** Interactions with the strongly-coupled medium are determined by the non-perturbative transport coefficients  $\hat{\kappa}$  and  $\hat{\gamma}$

$$\hat{\kappa} = \frac{1}{T^3 6N_c} \int_0^\infty dt \left\langle \left\{ \tilde{E}^{a,i}(t, \mathbf{0}), \tilde{E}^{a,i}(0, \mathbf{0}) \right\} \right\rangle,$$
$$\hat{\gamma} = -\frac{i}{T^3 6N_c} \int_0^\infty dt \left\langle \left[ \tilde{E}^{a,i}(t, \mathbf{0}), \tilde{E}^{a,i}(0, \mathbf{0}) \right] \right\rangle,$$

where  $\tilde{E}^{a,i}(t, \mathbf{0})$  are chromo-electric fields connected by a temporal Wilson line in the adjoint representation ensuring gauge invariance.  $\hat{\kappa}$  and  $\hat{\gamma}$  are related to the in-medium width and mass shift of the ground state and can be extracted from unquenched lattice measurements of these quantities.

**Solution Methods** Monte Carlo methods provide a computationally less expensive alternative to directly solving the Lindblad equation.

## Results



From ([Phys. Rev. D 108 \(2023\) 1, L011502](#)). The ratio of  $\Upsilon(1S)$ ,  $\Upsilon(2S)$  and  $\Upsilon(3S)$  yields (normalized to number of participating nucleons) in Pb-Pb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV as a function of number of participating nucleons (left) and transverse momentum (right). Data points are experimental measurements of the ALICE, ATLAS and CMS collaborations (see paper for references). Dotted lines represent results obtained taking into account only dissociation; solid lines represent inclusion of recombination. Recombination is necessary to match experimental data (specifically for the excited states) and double ratios (figures in paper).