# Quarkonium Production in Heavy Ion Collisions: from Open Quantum System to Transport Equation

**Xiaojun Yao**

Collaborators: Berndt Müller, Steffen Bass, Thomas Mehen, Weiyao Ke, Yingru Xu

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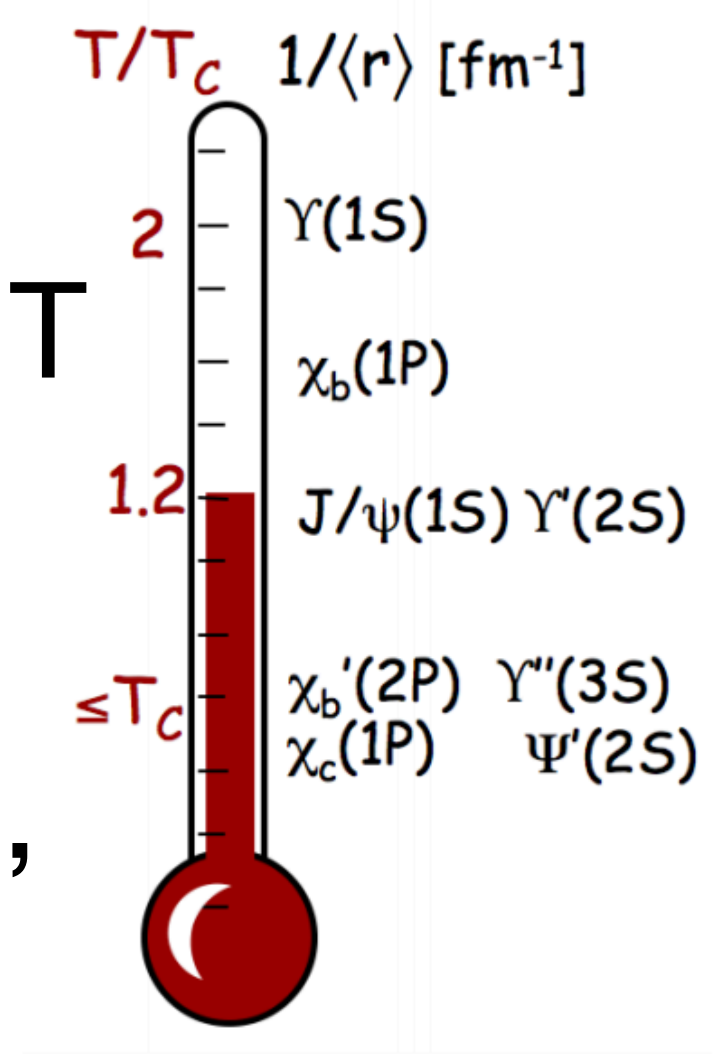
# Quarkonium Production in Heavy Ion Collisions

- Heavy quarkonium as **probe of QGP**:
  - **Static screening**: suppression of color attraction —> melting at high T states of different sizes have different melting T —> thermometer
  - **Dynamical screening**: dissociation induced by in-medium scattering, can happen even below melting T, imaginary potential
  - **Recombination**: unbound heavy quark pair forms quarkonium, can happen below melting T, crucial for phenomenology and theory consistency
- Cold nuclear matter effect, feed-down contributions



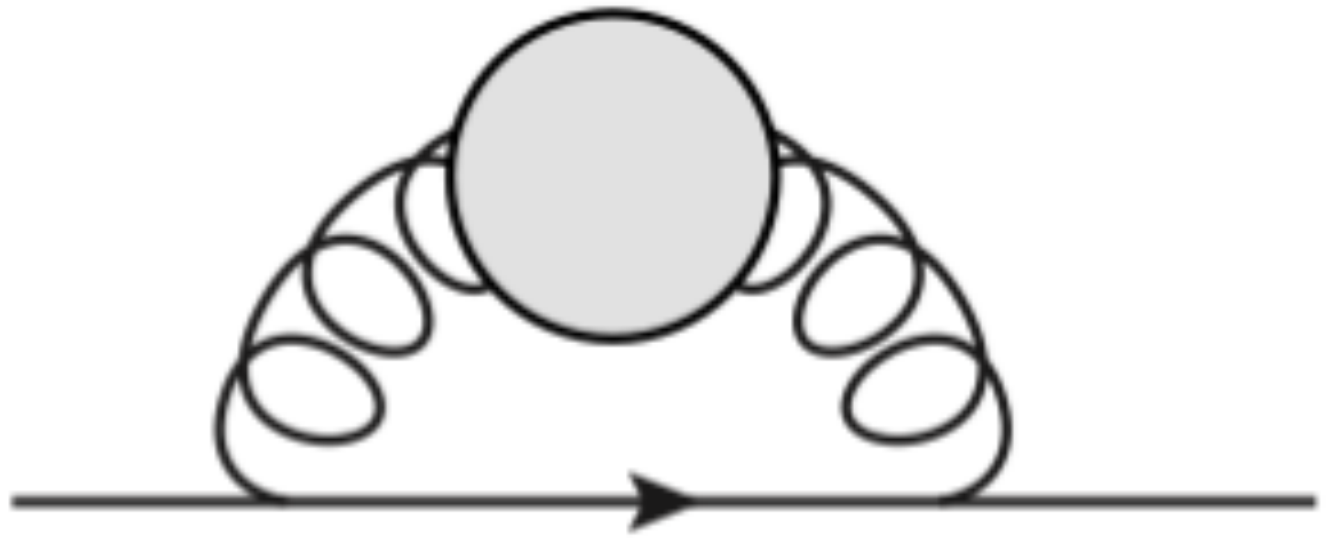

A.Mocsy, arXiv:0811.0337

# Plasma Screening Effects from Thermal Loops

- Static and dynamical screening effects in same theoretical framework

**Thermal loop correction**

**Propagator of color singlet (J/$\Psi$, Y(1S) …)**


- Real part of correction —> decrease in real part potential, static screening

- Imaginary part —> dissociation rate from optical theorem, provide theoretical guidance on dissociation term $C^{(-)}$ in transport equation

$$(\partial_t + \boldsymbol{v}\cdot\nabla) f(\boldsymbol{x},\boldsymbol{p},t) = -C^{(-)}(\boldsymbol{x},\boldsymbol{p},t) + C^{(+)}(\boldsymbol{x},\boldsymbol{p},t)$$

- **Can we put screening & recombination in same framework and learn theoretical guidance on recombination term? YES!**

# Open Quantum System

- Total system = system + environment: $H = H_S + H_E + H_I$

$$\rho(t=0) = \rho_S \otimes \rho_E$$

**System & environment**

**(Heavy quark pairs & QGP)**

**Unitary evolution**

**Time reversible**

$$U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)$$

**System & environment**

**Trace out (integrate out) environment**

$$\rho_S(t=0)$$

**System (heavy quark pairs)**

**Non-unitary**

**Time irreversible**

$$\mathrm{Tr}_E\Big[U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)\Big]$$



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# From Open Quantum System to Transport Equation

**Weak coupling to 2nd order: Lindblad equation**

$$\rho_S(t) = \rho_S(0) - i\Big[tH_S + \sum_{a,b}\sigma_{ab}(t)L_{ab}, \rho_S(0)\Big] + \sum_{a,b,c,d}\gamma_{ab,cd}\Big(L_{ab}\rho_S(0)L^{\dagger}_{cd} - \frac{1}{2}\{L^{\dagger}_{cd}L_{ab}, \rho_S\}\Big)$$

**Markovian approximation**

**Wigner transform**

**Boltzmann transport equation**

$$\frac{\partial}{\partial t}f_{nls}(\boldsymbol{x},\boldsymbol{k},t) + \boldsymbol{v}\cdot\nabla_{\boldsymbol{x}}f_{nls}(\boldsymbol{x},\boldsymbol{k},t) = \mathcal{C}^{(+)}_{nls}(\boldsymbol{x},\boldsymbol{k},t) - \mathcal{C}^{(-)}_{nls}(\boldsymbol{x},\boldsymbol{k},t)$$



XY T.Mehen, arXiv:1811.07027

# From Open Quantum System to Transport Equation

**Weak coupling to 2nd order: Lindblad equation**

$$\rho_S(t) = \rho_S(0) - i\Big[tH_S + \sum_{a,b} \boxed{\sigma_{ab}(t)L_{ab}}, \rho_S(0)\Big] + \sum_{a,b,c,d} \gamma_{ab,cd}\Big(\boxed{L_{ab}\rho_S(0)L^\dagger_{cd}} - \boxed{\frac{1}{2}\{L^\dagger_{cd}L_{ab}, \rho_S\}}\Big)$$

Static screening

Markovian approximation

Recombination

Dissociation

Wigner transform

**Boltzmann transport equation**

$$\frac{\partial}{\partial t} f_{nls}(\boldsymbol{x},\boldsymbol{k},t) + \boldsymbol{v}\cdot\nabla_{\boldsymbol{x}} f_{nls}(\boldsymbol{x},\boldsymbol{k},t) = \boxed{\mathcal{C}^{(+)}_{nls}(\boldsymbol{x},\boldsymbol{k},t)} - \boxed{\mathcal{C}^{(-)}_{nls}(\boldsymbol{x},\boldsymbol{k},t)}$$



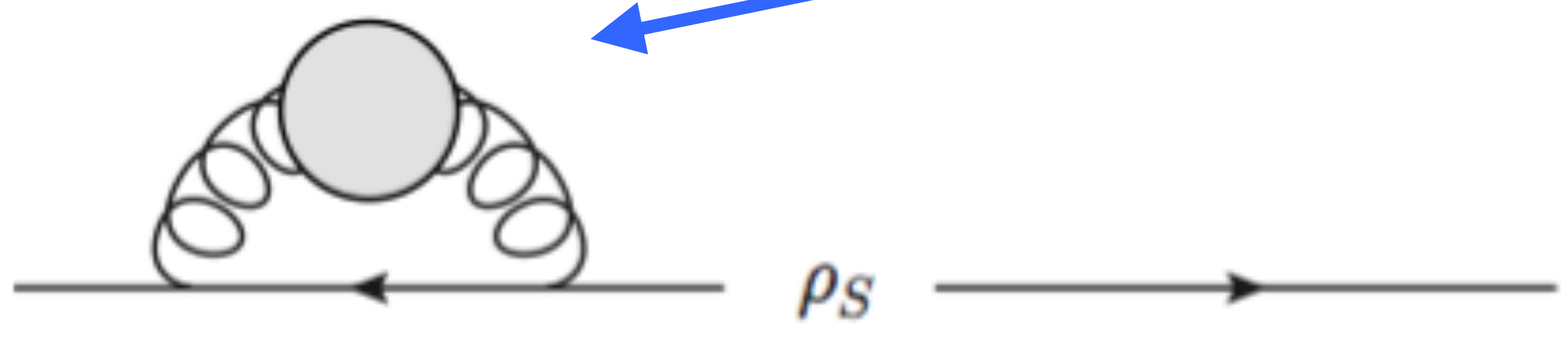
XY T.Mehen, arXiv:1811.07027

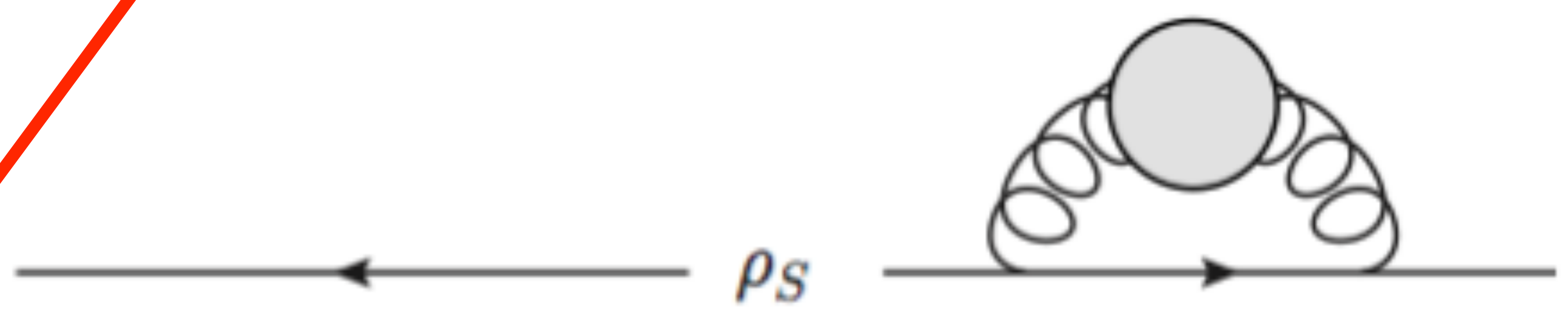
# Screening and Recombination in Same Framework

**Weak coupling to 2nd order: Lindblad equation**

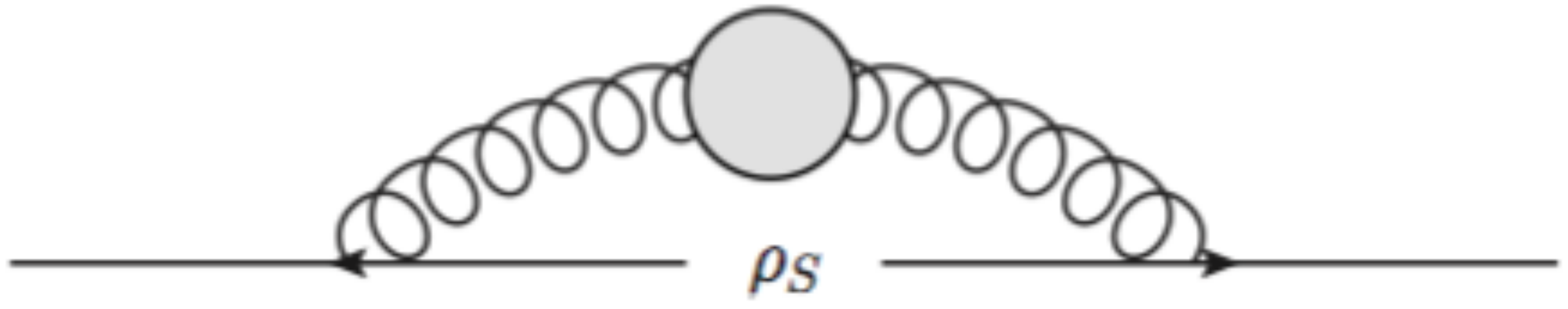
$$\rho_S(t) = \rho_S(0) - i\Big[tH_S + \sum_{a,b}\sigma_{ab}(t)L_{ab}, \rho_S(0)\Big] + \sum_{a,b,c,d}\gamma_{ab,cd}\Big(\boxed{L_{ab}\rho_S(0)L^\dagger_{cd}} - \boxed{\frac{1}{2}\{L^\dagger_{cd}L_{ab}, \rho_S\}}\Big)$$

**Same diagram as for screening**




**New diagram in this approach gives recombination**






XY T.Mehen, arXiv:1811.07027

# Two Key Assumptions Justified from Scale Hierarchy

- Two key assumptions:

1. **System interacts weekly with environment?**
2. **Markovian approximation (no memory effect)?**

- Justified from separation of scales and effective field theory (potential NRQCD)

$$M \gg Mv \gg Mv^2 \gtrsim T \gtrsim m_D$$

$v^2 \sim 0.3$ charmonium

$v^2 \sim 0.1$ bottomonium

1. **Dipole interaction between quarkonium and QGP** $rT \sim \frac{T}{Mv} \lesssim v$
2. **System relaxation time >> environment correlation time (coarse graining)**

$$(rT)^2 T \ll T$$

# What Have We Achieved?

- Derive Boltzmann transport (rate) equation from QCD using **separation of scales**, provide validity condition of Boltzmann transport equation

$$M \gg Mv \gg Mv^2 \gtrsim T \gtrsim m_D$$

- Static screening, dissociation and recombination in **same theoretical framework**, provide theoretical guidance on recombination term

- Recombination of quarkonium depends on **real-time** open heavy flavor distributions, which can be obtained from transport of open heavy flavors

- Detailed balance and thermalization can be demonstrated **dynamically** from coupled transport equations of open and hidden heavy flavors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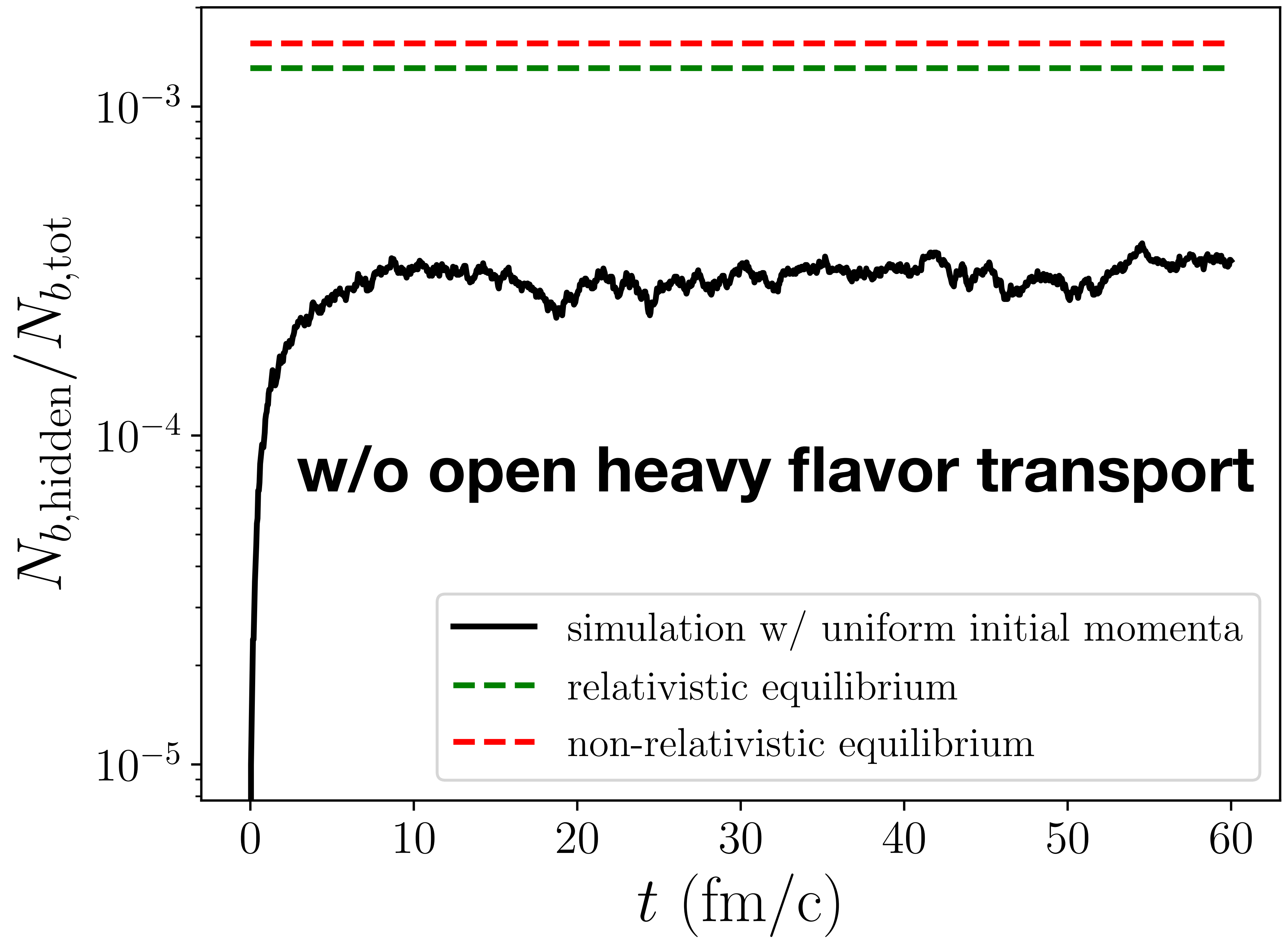
# Detailed Balance and Thermalization

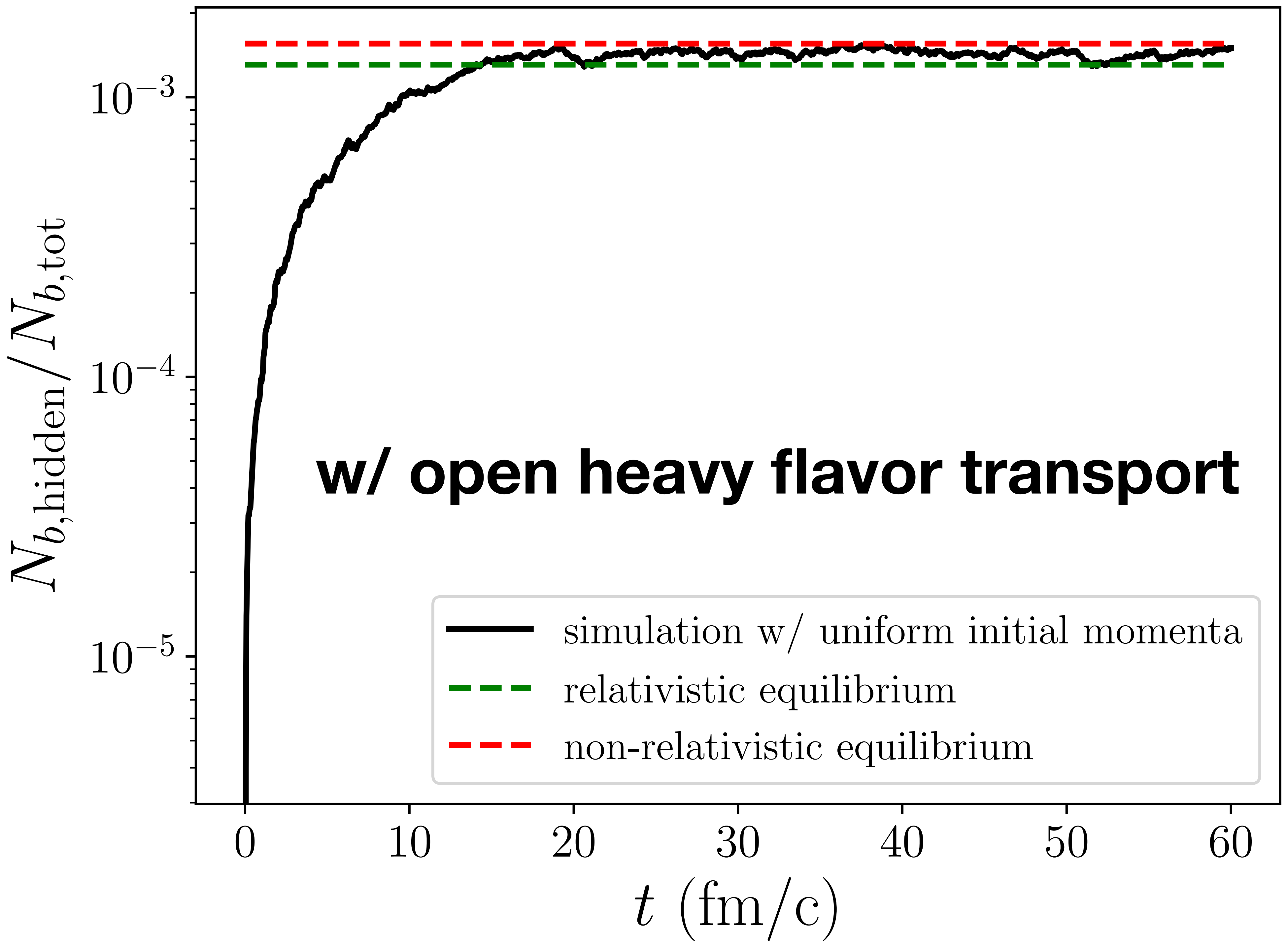
**Setup**:
- QGP box w/ const T=300 MeV, Υ(1S) & b quarks, total b flavor = 50 (fixed)
- Initial momenta sampled from uniform distributions 0-5 GeV
- Turn on/off open heavy quark transport

XY, B.Müller arXiv:1709.03529

**Υ(1S) percentage v.s. time**




**Υ(1S) percentage v.s. time**




**Dissociation-recombination interplay drives to detailed balance**

**Open heavy flavor transport necessary to drive kinetic equilibrium of quarkonium**

# Collision Event Simulation

- Initial production:

  PYTHIA 8.2: NRQCD factorization — Sjostrand, et al, Comput. Phys.Commun.191 (2015) 159; Bodwin, Braaten, Lepage Phys. Rev. D 51, 1125 (1995)

  Nuclear PDF: EPS09 (cold nuclear matter effect) — Eskola, Paukkunen, Salgado, JHEP 0904 (2009) 065

  Trento, sample position, hydro. initial condition — Moreland, Bernhard, Bass, Phys. Rev. C 92, no. 1, 011901 (2015)

- Medium background: 2+1D viscous hydrodynamics (calibrated)

  Song, Heinz, Phys.Rev.C77,064901(2008)
  Shen, Qiu, Song, Bernhard, Bass, Heinz, Comput. Phys. Commun.199,61 (2016)
  Bernhard, Moreland, Bass, Liu, Heinz, Phys. Rev. C 94,no.2,024907(2016)

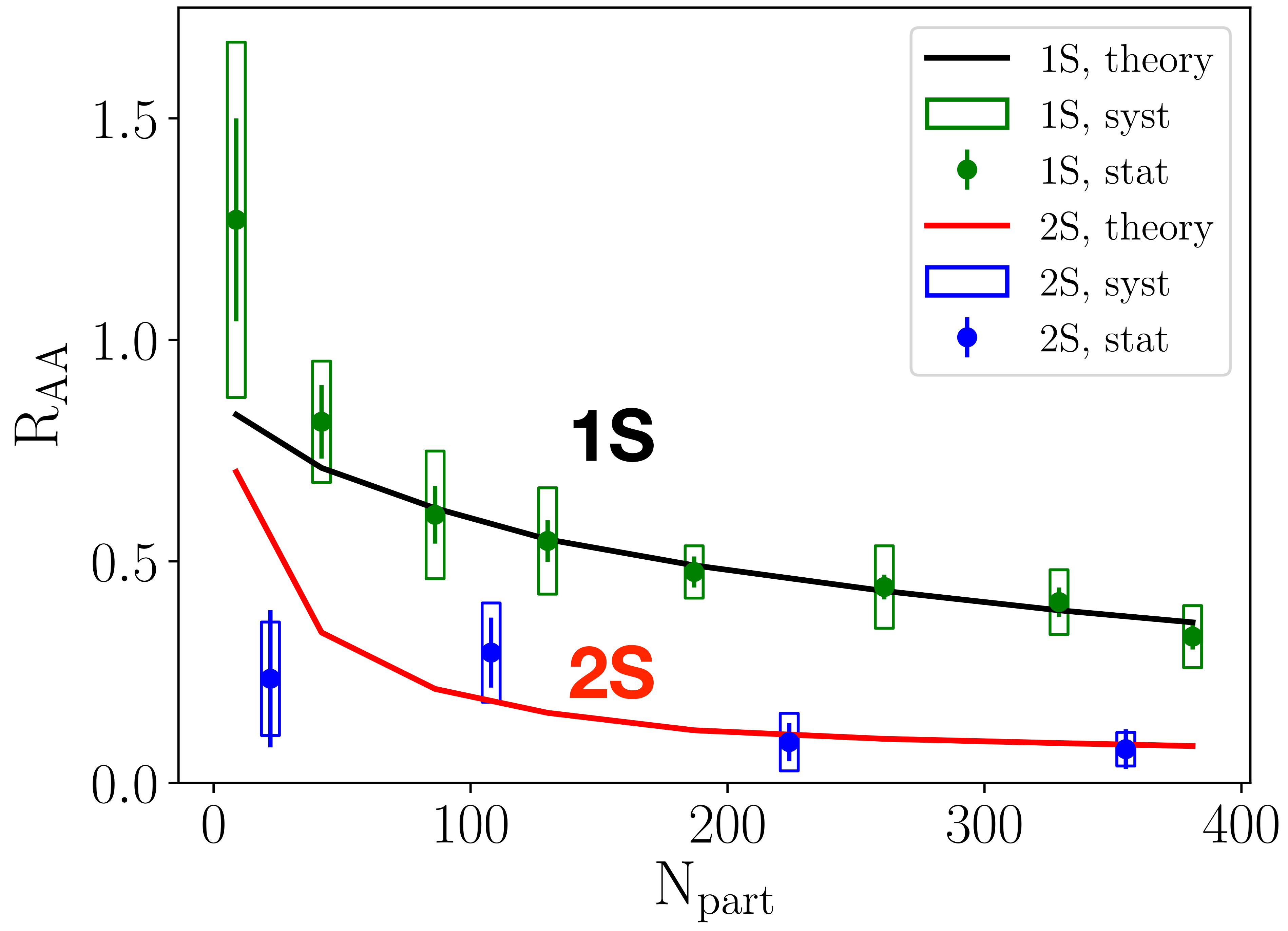
- Study bottomonium (scales are well-separated); include 1S 2S; ~26% 2S feed-down to 1S in hadronic phase (from PDG); initial production ratio 1S : 2S ~ between 3:1 to 4:1 (PYTHIA)

# Upsilon in 2760 GeV PbPb Collision

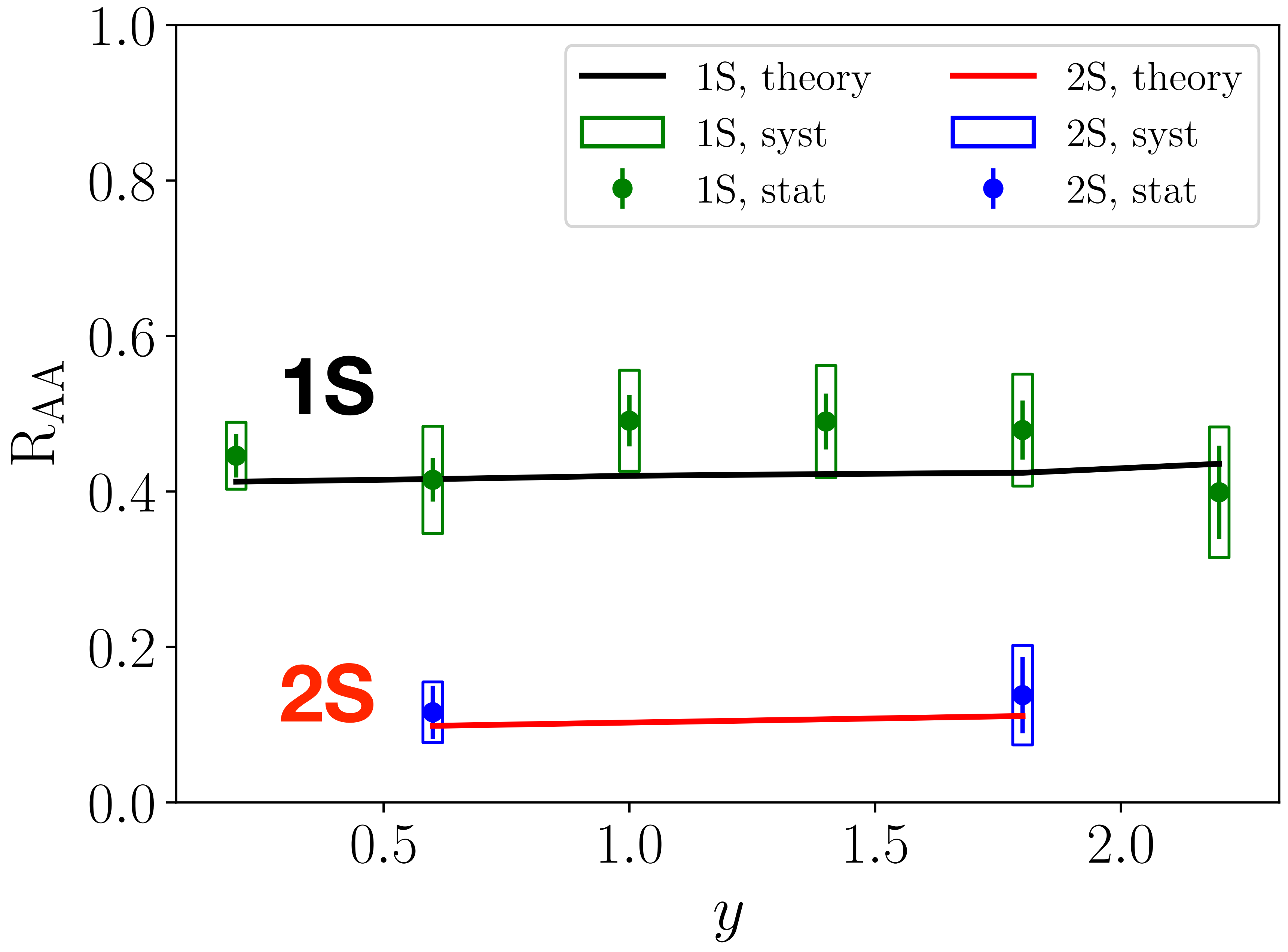
Fix $\alpha_s = 0.3$

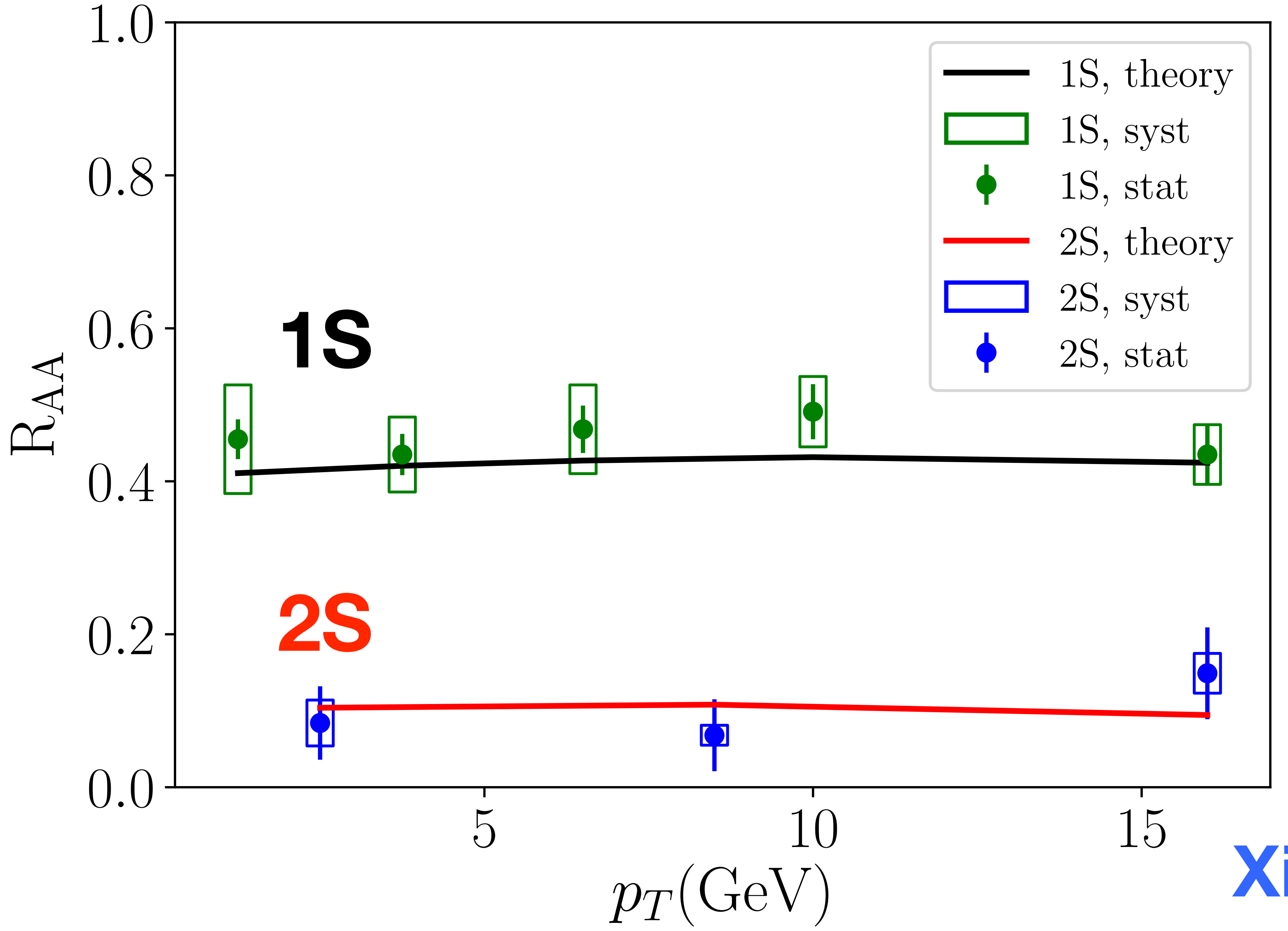
Tune $T_{\mathrm{melt}}(2S) = 210\ \mathrm{MeV}$

Tune $V_s = -C_F \dfrac{0.42}{r}$



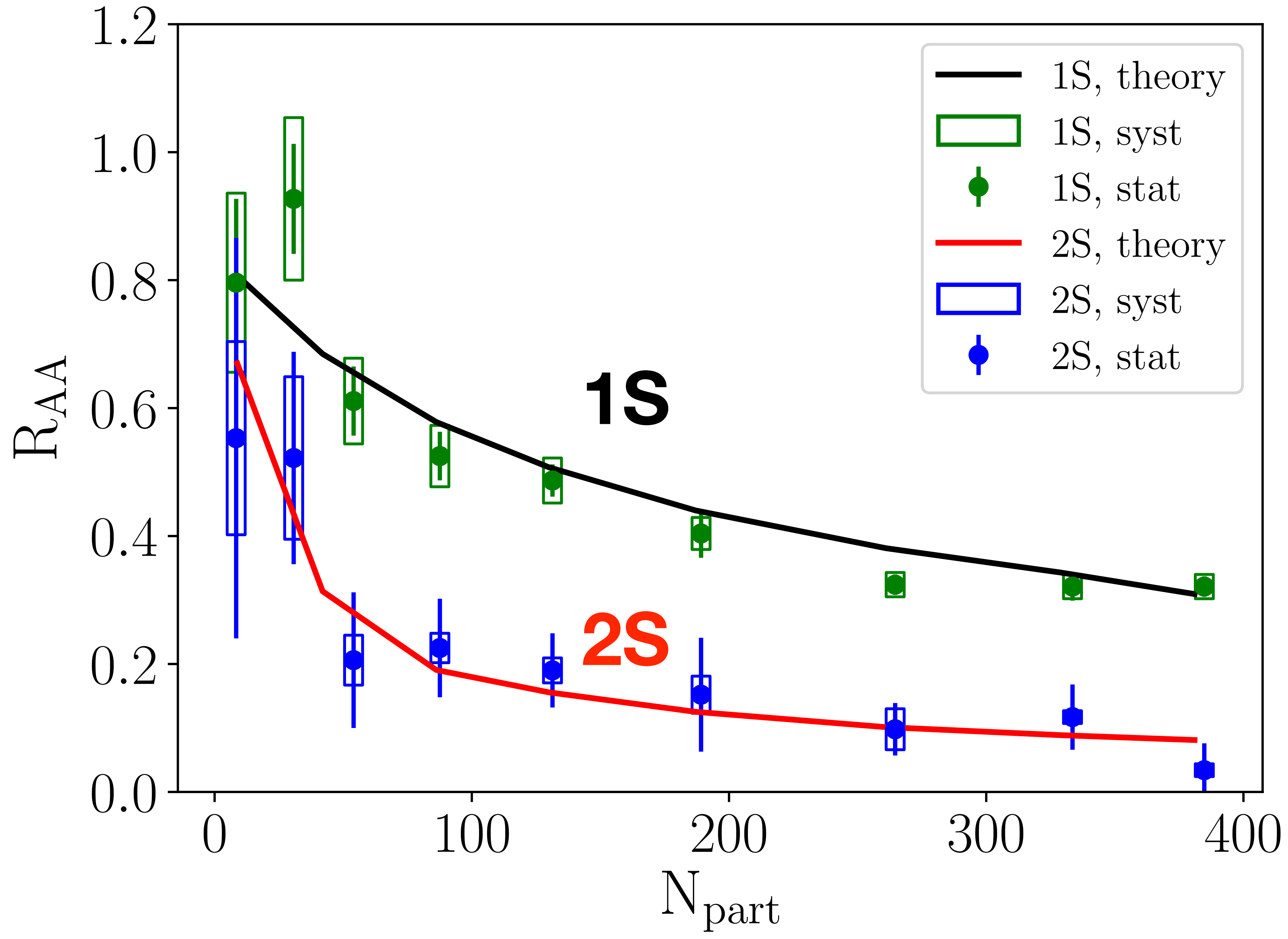

XY, W.Ke, Y,Xu, S,Bass, B.Müller arXiv:1807.06199

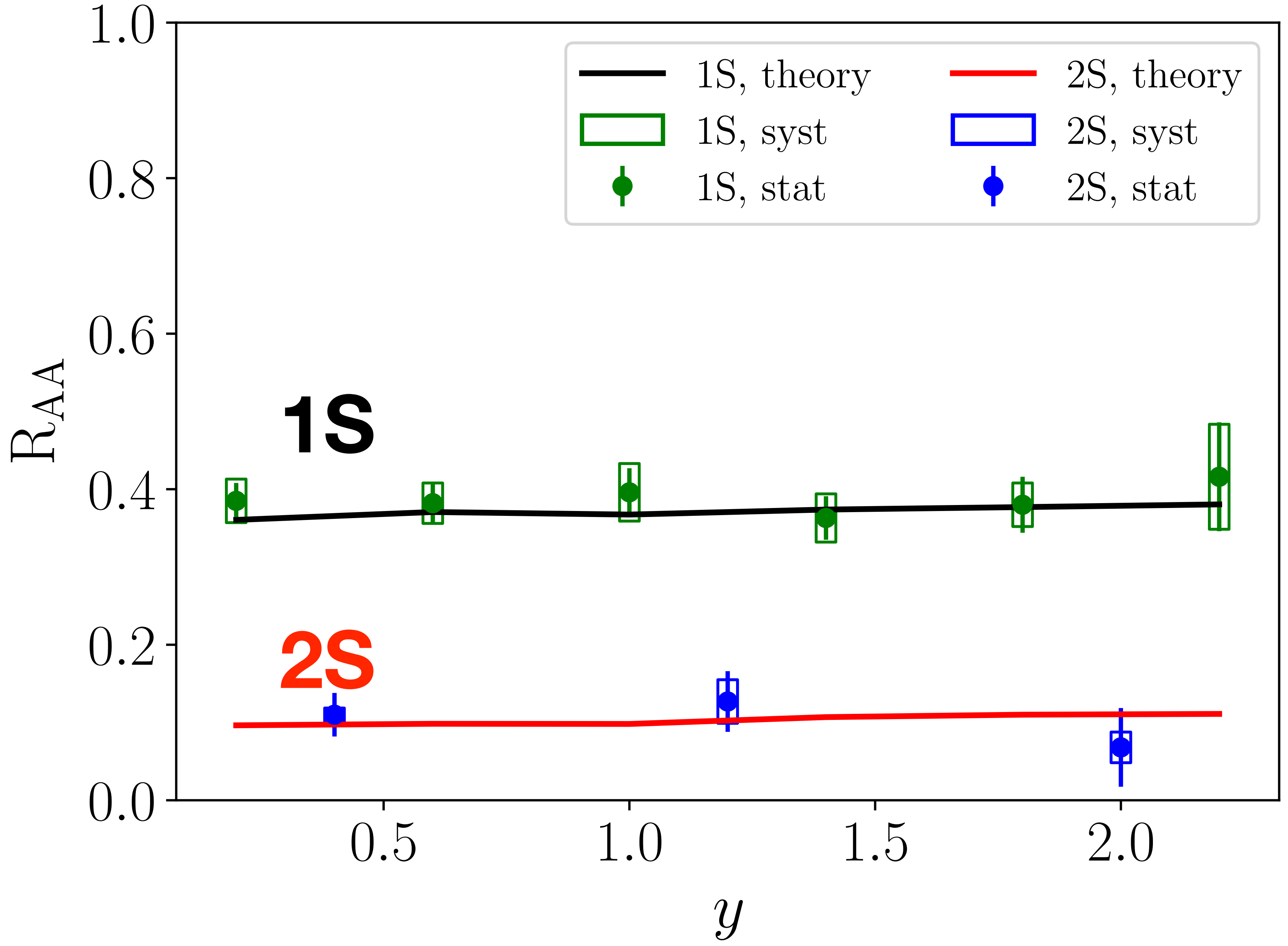


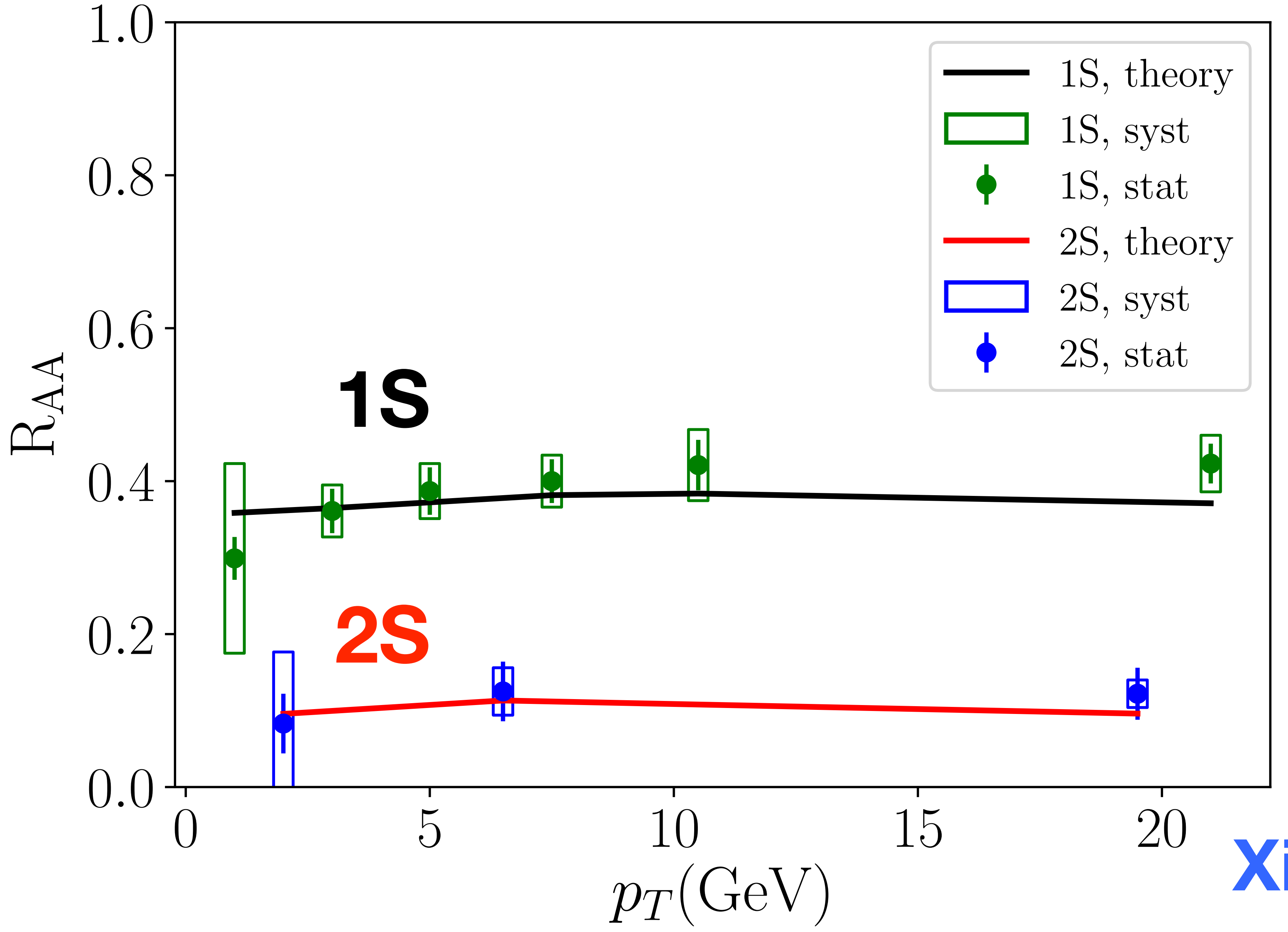



# Upsilon in 5020 GeV PbPb Collision

Use same set of parameters




Our results also consistent with ATLAS data presented by Songkyo Lee (Tu 14:00)



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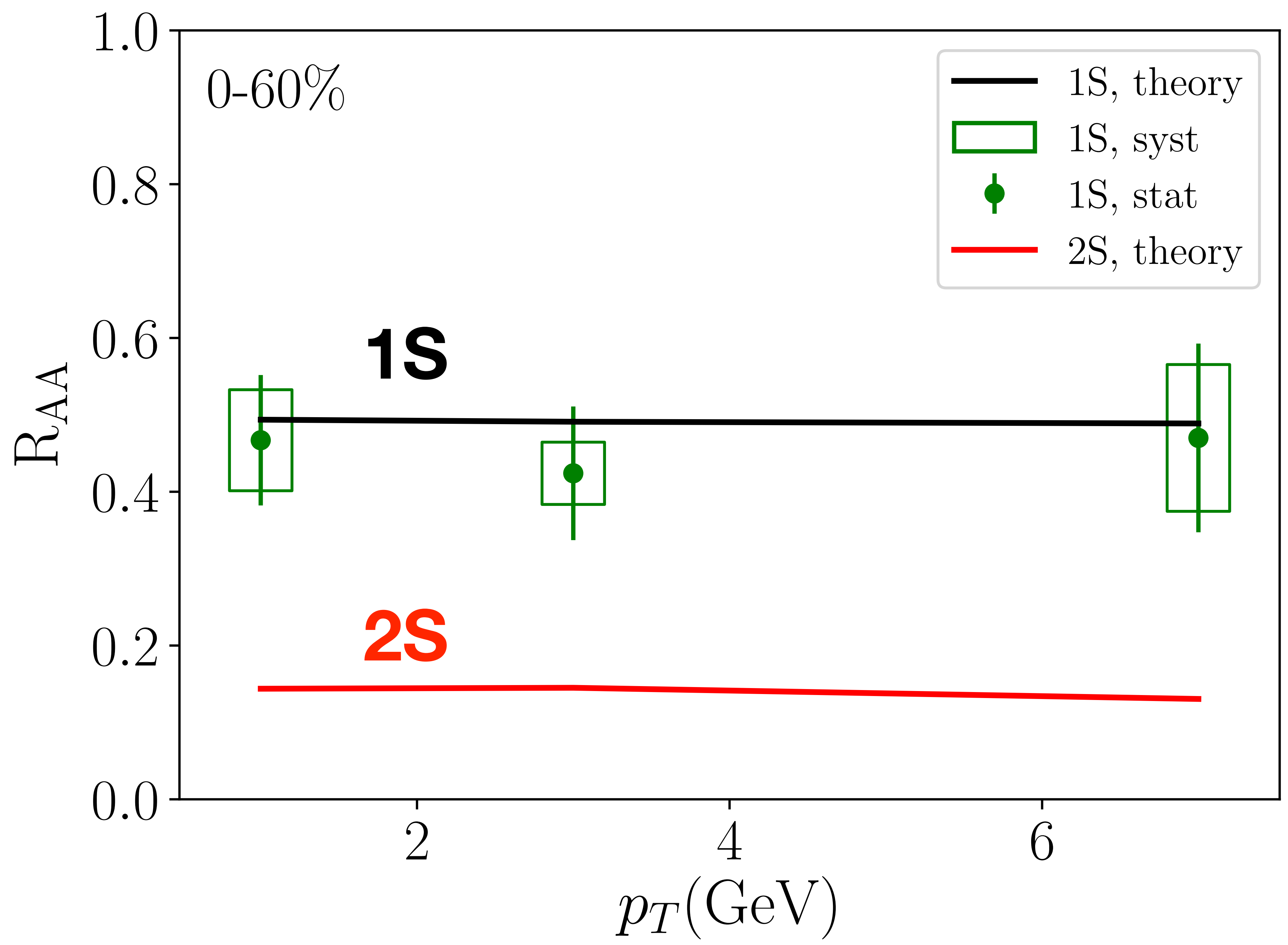
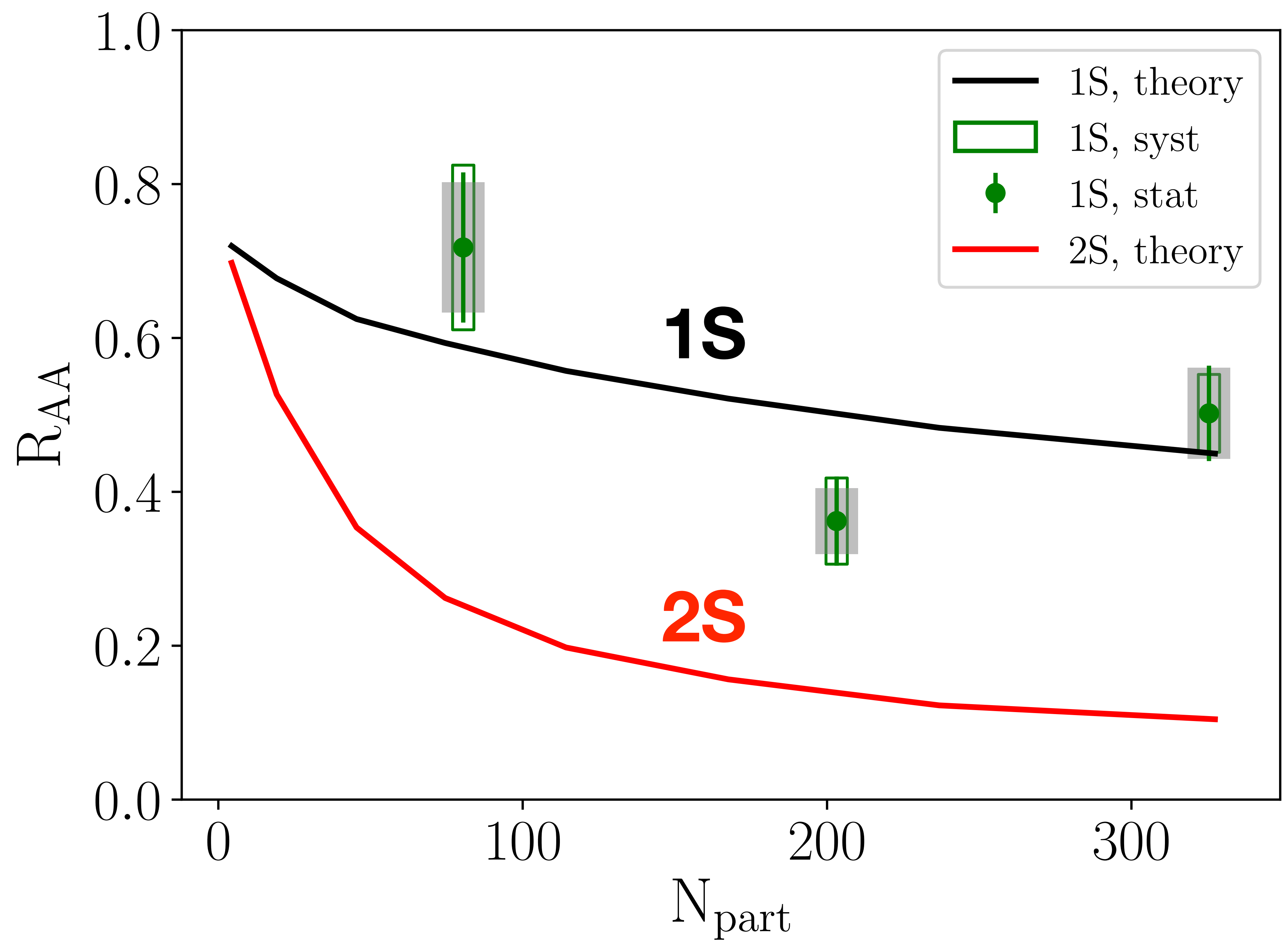
# Upsilon in 200 GeV AuAu Collision

Use same set of parameters
Cold nuclear matter effect ~ 0.72
(use p-Au data of STAR)



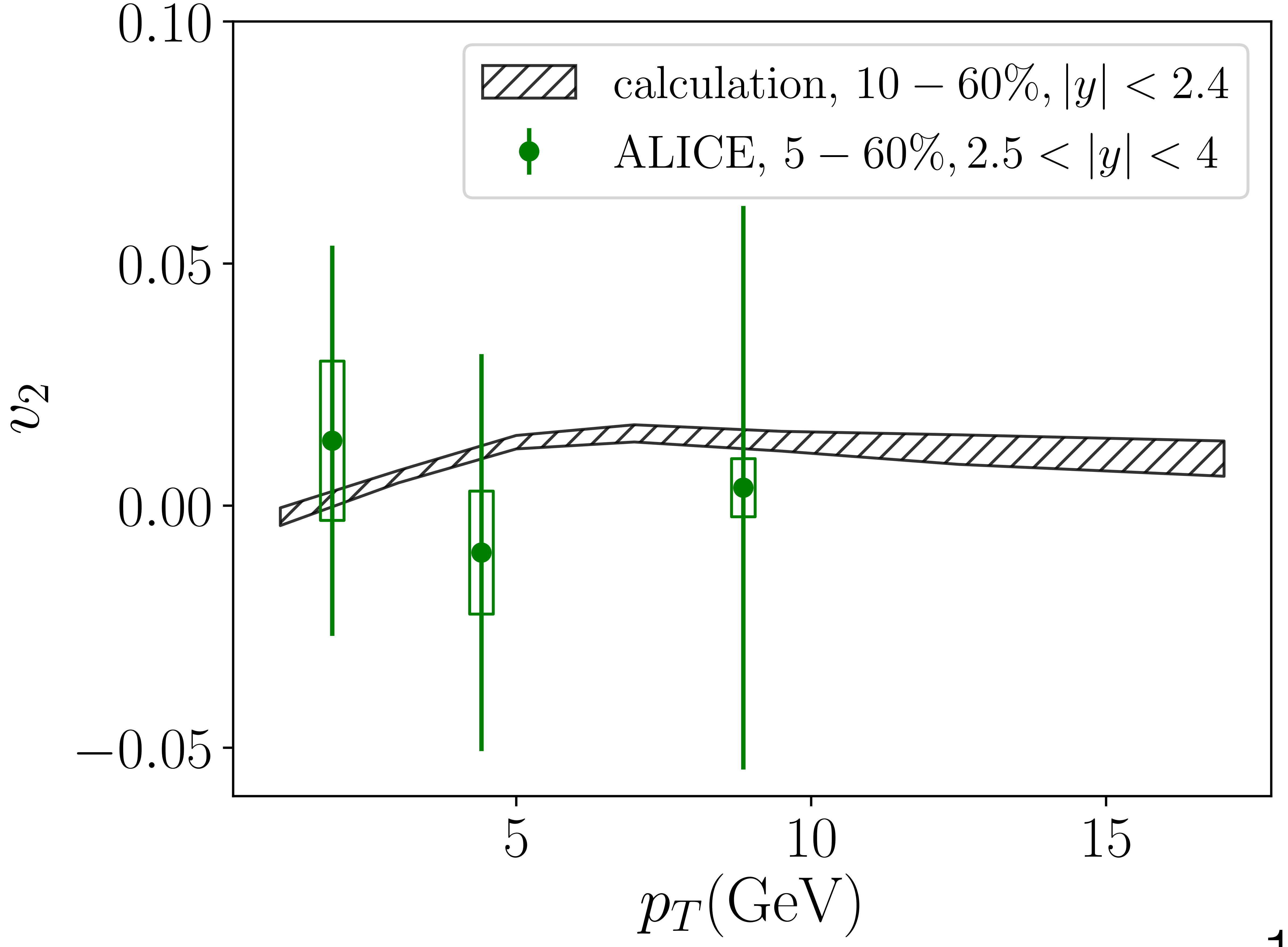




In our calculation, direct 1S (non-feed-down) is suppressed in central collisions by ~ 15%

# Upsilon Azimuthal Anisotropy in 5020 GeV PbPb

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}(1 + 2v_2\cos(2\phi) + \cdots)$$

Υ(1S)




**Υ(2S) in 10-60%, |y| < 2.4:**

$$v_2 = 0.0299 \pm 0.0025$$

Consistent with CMS data on Υ(1S) and Υ(2S)

ALICE results, see talk by Xiaozhi Bai (Tu 14:20)

CMS results, see talk by Jaebeom Park (Tu 16:20)

# Conclusions

- Open quantum system + **separation of scales** —> Boltzmann transport equation in theoretically controlled way $M \gg Mv \gg Mv^2 \gtrsim T \gtrsim m_D$
- Screening and recombination in same framework, approach detailed balance dynamically
- Phenomenological results on Upsilon at RHIC and LHC, suppression and azimuthal anisotropy
- Precision era, theory and experiment comparison (machine learning)
- If $T \gg Mv^2$ —> open quantum system in limit of quantum Brownian motion

Y.Akamatsu, M.Asakawa, A.Rothkopf

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