Coupled Transport Equations for Quarkonium Production in Heavy Ion Collisions

Xiaojun Yao
MIT

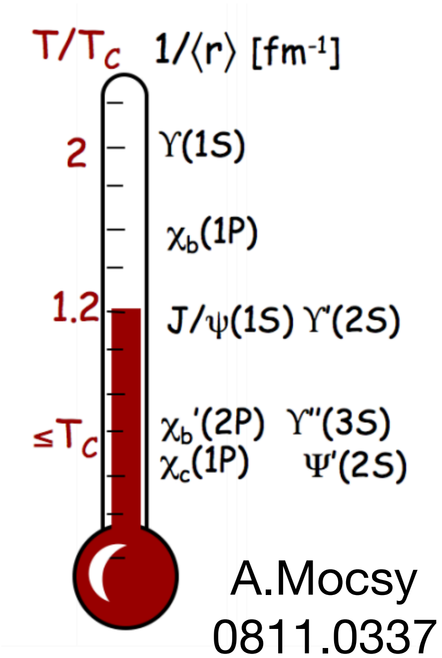
Collaborators: Berndt Müller, Steffen A. Bass, Weiyao Ke, Yingru Xu,

arXiv: 2004.06746

Hard Probe 2020
June 1, 2020

Quarkonium as Probe of Quark-Gluon Plasma

- Heavy quarkonium as **probe of QGP**:



A.Mocsy
0811.0337

  - **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

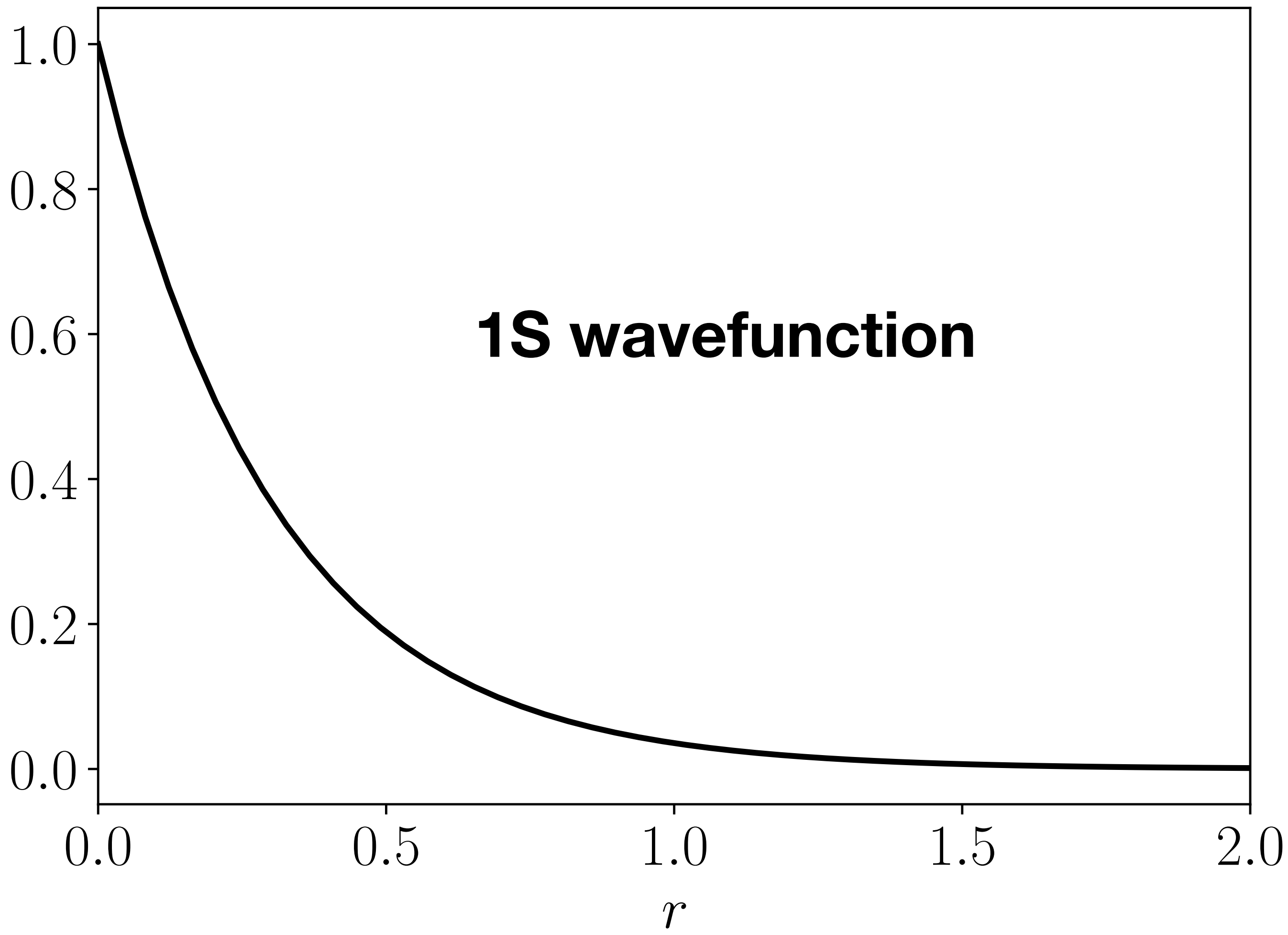
  - **Recombination**: unbound heavy quark pair forms quarkonium, can happen below melting T, crucial for charmonium phenomenology and theory consistency

- Cold nuclear matter effect, feed-down contributions

Recent Theoretical Insights from Open System

In vacuum, quarkonium described by Schrödinger equation

$$i\frac{\partial}{\partial t}\psi(r) = \Big[-\frac{\nabla^2}{M}+V(r)\Big]\psi(r)$$



Start with 1S, **closed** system
1S probability is conserved

$$|\psi(t=0)\rangle = |1S\rangle$$

$$|\langle 1S|\psi(t)\rangle|^2 = 1$$

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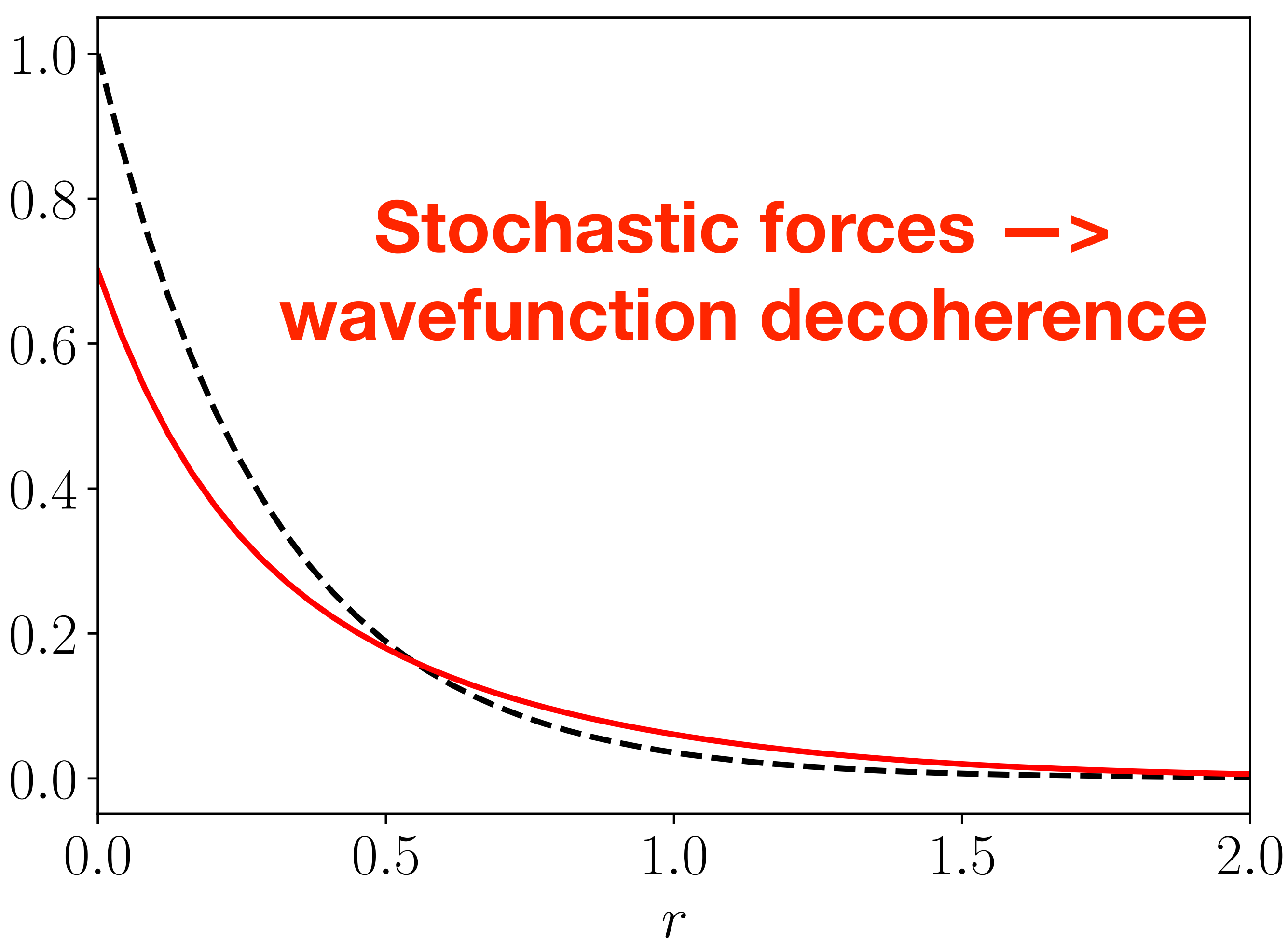
Recent Theoretical Insights from Open System

In QGP, quarkonium described by stochastic Schrödinger equation

$$i\frac{\partial}{\partial t}\psi(r) = \Big[-\frac{\nabla^2}{M} + V(r)\Big]\psi(r) + \Big[-i\gamma(r) + \xi(r,t)\Big]\psi(r)$$



Start with 1S, **open** system
1S probability **NOT** conserved

$$|\psi(t=0)\rangle = |1S\rangle$$

$$|\langle 1S|\psi(t)\rangle|^2 < 1$$

Dissociation of 1S

$$|\langle 2S|\psi(t)\rangle|^2 > 0$$ **if 2S exists**

Recombination of 2S !
from correlated pair

Y.Akamatsu, A.Rothkopf, PRD 85 (2012) 105011
J-P Blaizot, N.Brambilla, M.A.Escobedo, A.Vairo, R.Katz, P-B Gossiaux…

Correlated v.s. Uncorrelated Recombination

- **Correlated recombination:** heavy quark pair from **same** initial hard vertex / dissociation

- **Uncorrelated recombination:** heavy quark pair from **different** initial hard vertices; crucial contribution to charmonium production; negligible for bottomonium

- Recombination in most transport calculations: uncorrelated $\propto f_Q f_{\bar{Q}}$ $\propto f_{\mathrm{onia}}^{(\mathrm{eq})}$

- **How to incorporate correlated one in semiclassical transport?**

- **Need 2-particle distribution**, derive recombination from open quantum system + effective field theory (separation of scales, weak coupling, Markovian, gradient expansion)

XY T.Mehen,1811.07027

XY, W.Ke, Y.Xu, S.A.Bass, T.Mehen, B.Müller, 2002.04079

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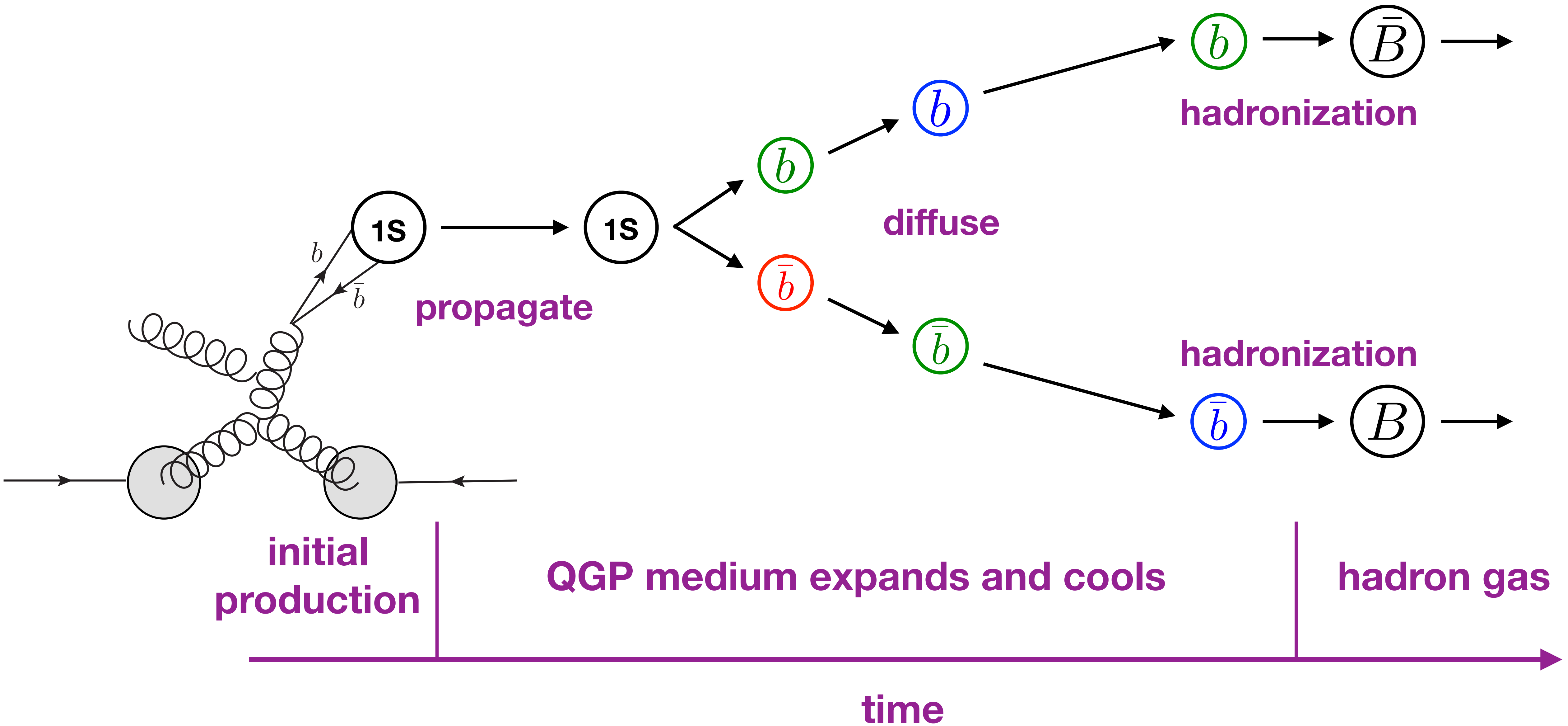
Coupled Transport Equations of Heavy Flavors

open heavy quark antiquark

$$\left(\frac{\partial}{\partial t} + \dot{\boldsymbol{x}}_Q \cdot \nabla_{\boldsymbol{x}_Q} + \dot{\boldsymbol{x}}_{\bar{Q}} \cdot \nabla_{\boldsymbol{x}_{\bar{Q}}}\right) f_{Q\bar{Q}}(\boldsymbol{x}_Q, \boldsymbol{p}_Q, \boldsymbol{x}_{\bar{Q}}, \boldsymbol{p}_{\bar{Q}}, t) = \mathcal{C}_{Q\bar{Q}} - \mathcal{C}^+_{Q\bar{Q}} + \mathcal{C}^-_{Q\bar{Q}}$$

each quarkonium state
nl = 1S, 2S,1P etc.

$$\left(\frac{\partial}{\partial t} + \dot{\boldsymbol{x}} \cdot \nabla_{\boldsymbol{x}}\right) f_{nls}(\boldsymbol{x}, \boldsymbol{p}, t) = \mathcal{C}^+_{nls} - \mathcal{C}^-_{nls}$$



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Coupled Transport Equations of Heavy Flavors

open heavy quark antiquark

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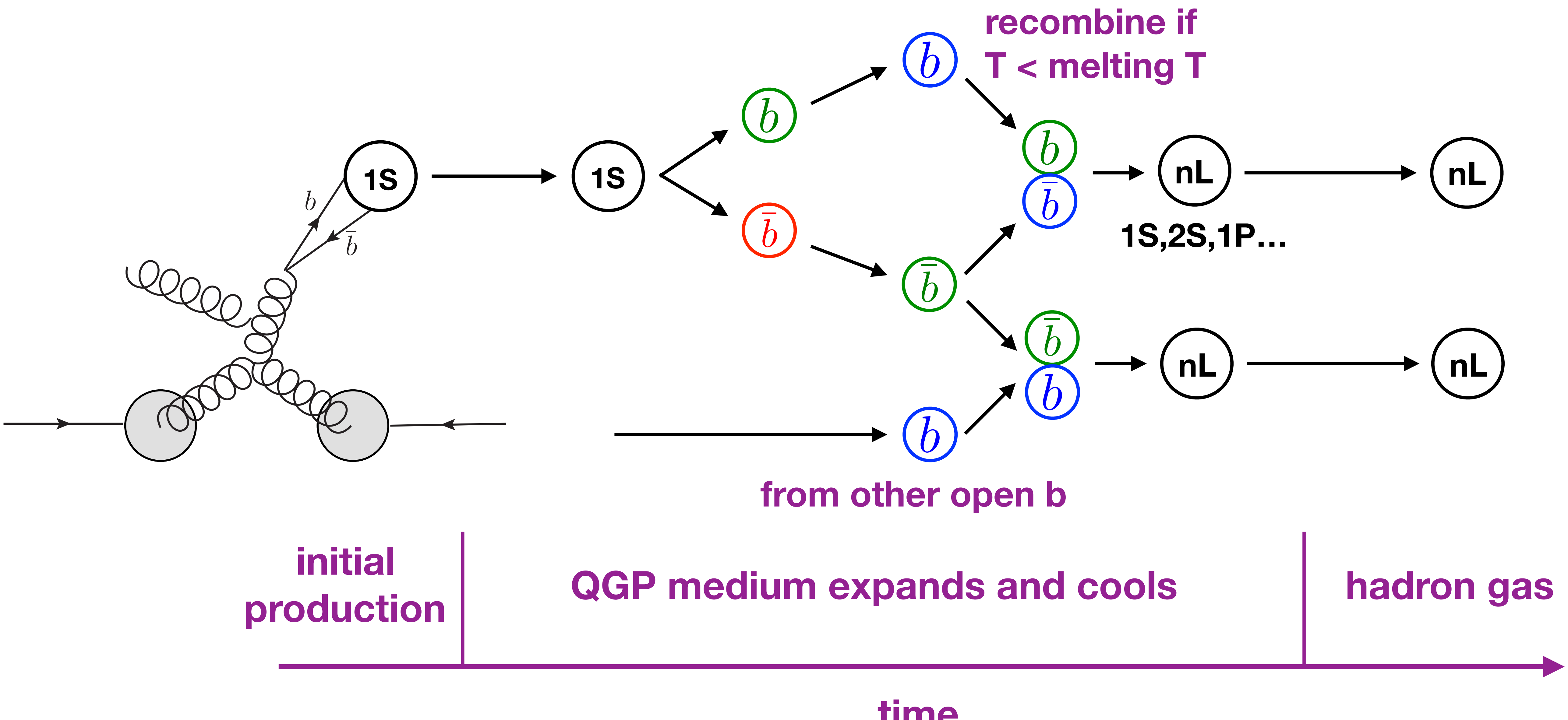

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Coupled Transport Equations of Heavy Flavors

open heavy quark antiquark

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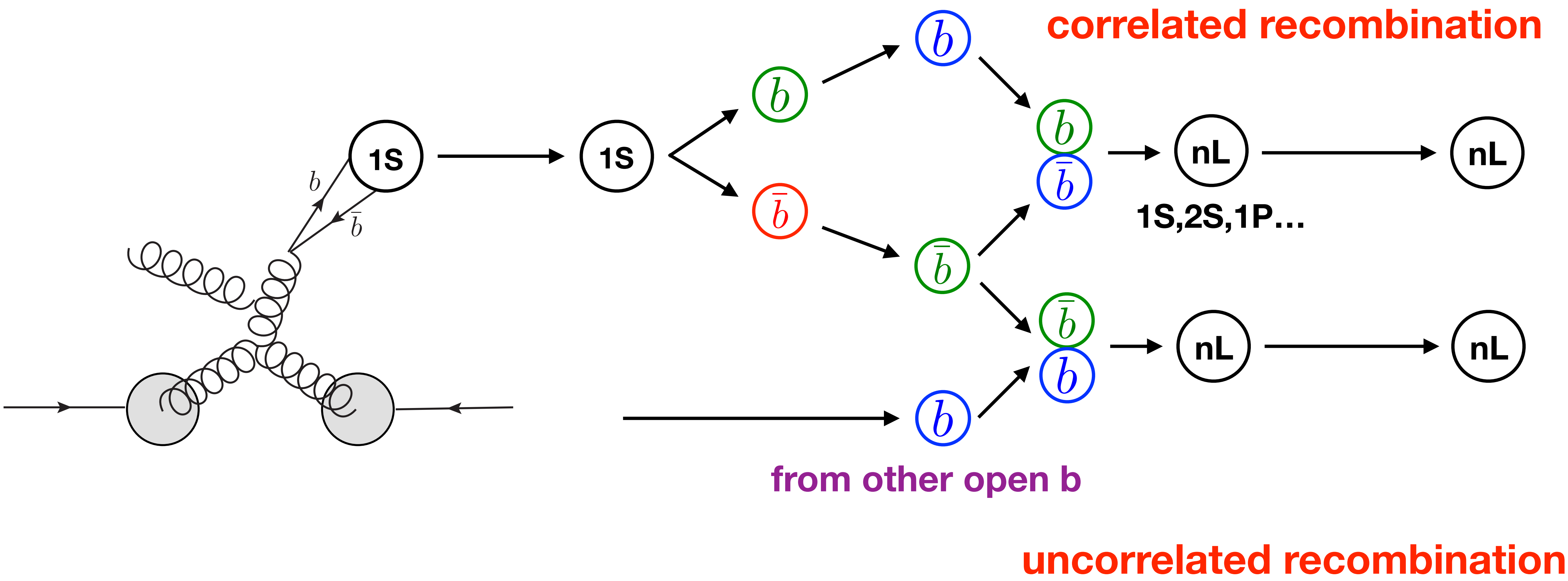

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Coupled with Transport of Open Heavy Flavor

open heavy quark antiquark

$$(\frac{\partial}{\partial t} + \dot{\boldsymbol{x}}_Q \cdot \nabla_{\boldsymbol{x}_Q} + \dot{\boldsymbol{x}}_{\bar{Q}} \cdot \nabla_{\boldsymbol{x}_{\bar{Q}}}) f_{Q\bar{Q}}(\boldsymbol{x}_Q, \boldsymbol{p}_Q, \boldsymbol{x}_{\bar{Q}}, \boldsymbol{p}_{\bar{Q}}, t) = \mathcal{C}_{Q\bar{Q}} - \mathcal{C}^{+}_{Q\bar{Q}} + \mathcal{C}^{-}_{Q\bar{Q}}$$

each quarkonium state
nl = 1S, 2S,1P etc.

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

Can handle both correlated and uncorrelated recombination

$$\mathcal{C}_{Q\bar{Q}} = \mathcal{C}_Q + \mathcal{C}_{\bar{Q}}$$

Each independently interact with medium:
(1) Potential between pair screened
(2) Potential depends on color, average over

We use “Lido” for open heavy flavor transport

W.Ke, Y.Xu, S.A.Bass, PRC 98, 064901 (2018)

Upsilon in 5020 GeV PbPb Collision

Coulomb potential $\alpha_s = 0.3 \quad \alpha_s^{\rm pot} = 0.36$

Pythia + nPDF: EPPS16

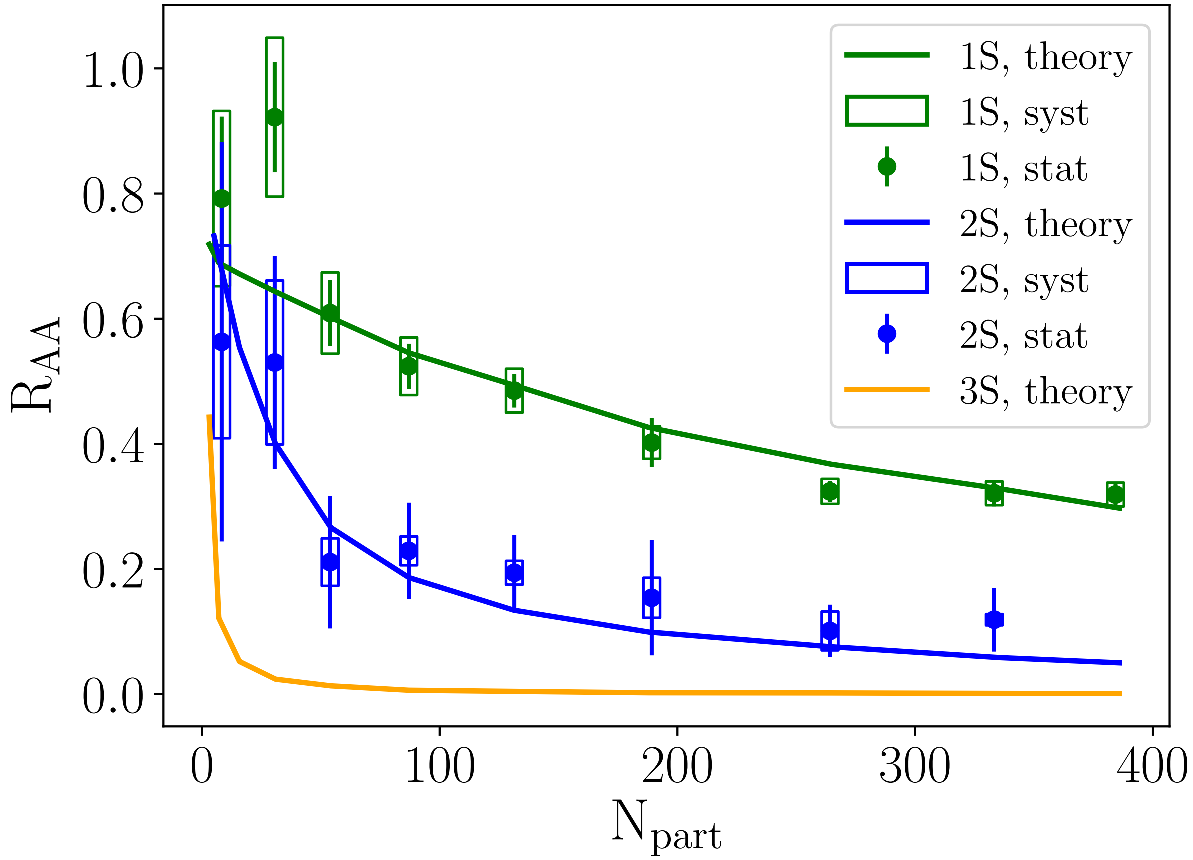
2+1D viscous hydro (calibrated)

Bottomonium: 1S, 2S, 3S, 1P, 2P

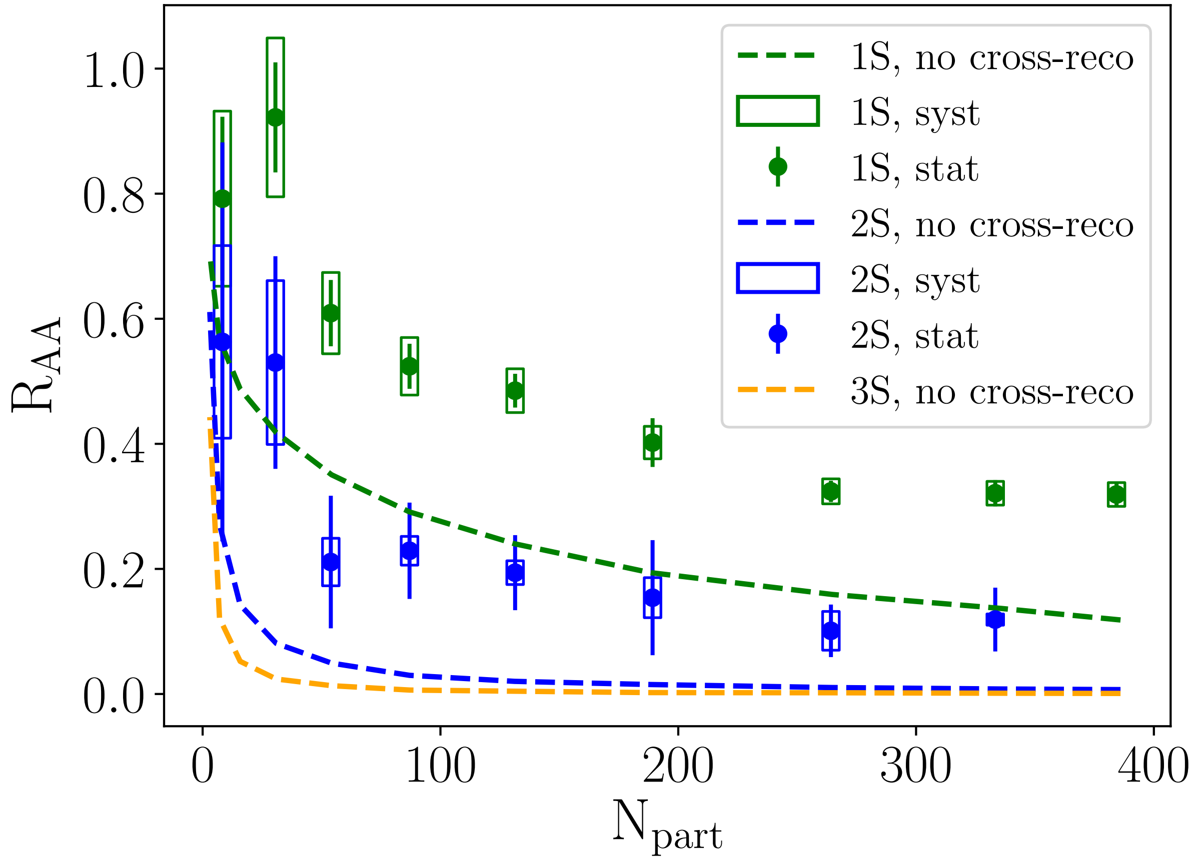
Feed-down networks

e.g. no 2S—>1S, 1S—>1P etc

with cross-talk (correlated) recombination

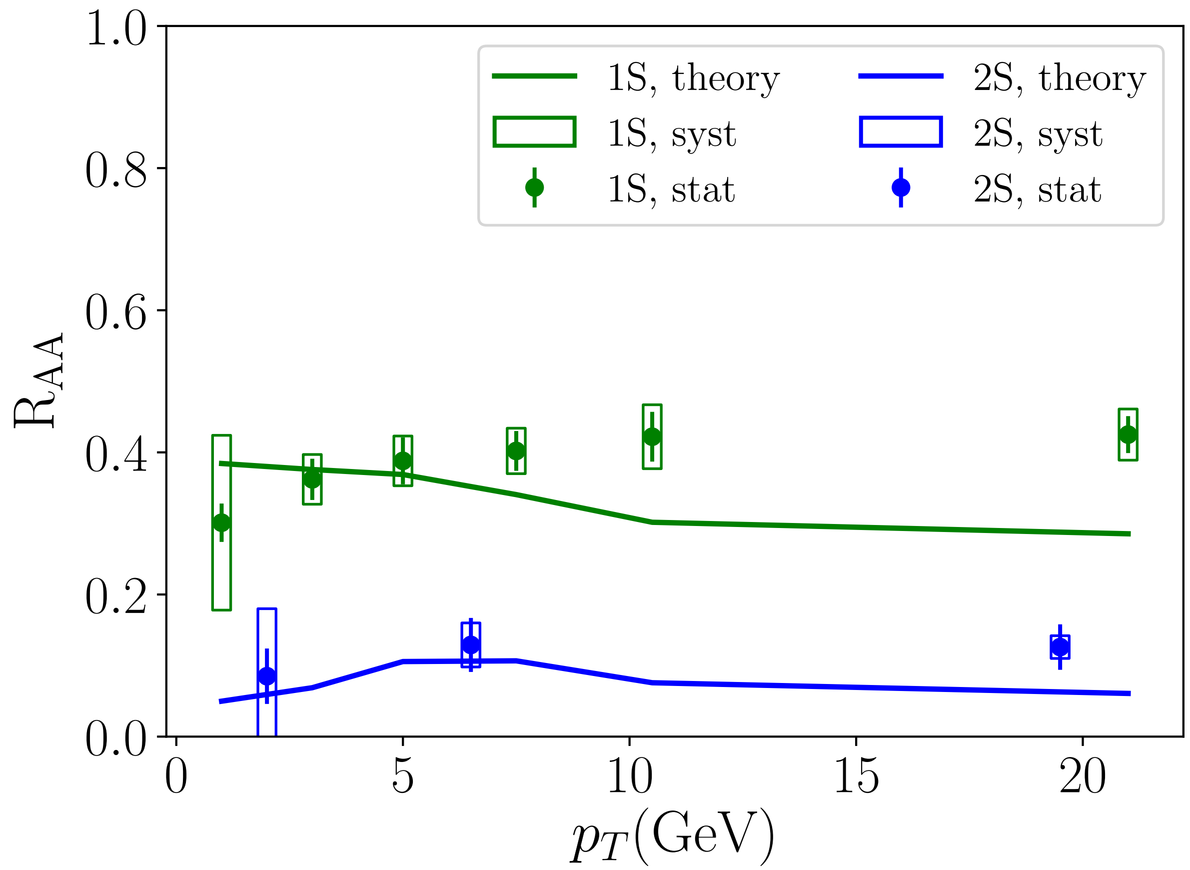


without cross-talk recombination



CMS arXiv:1805.09215

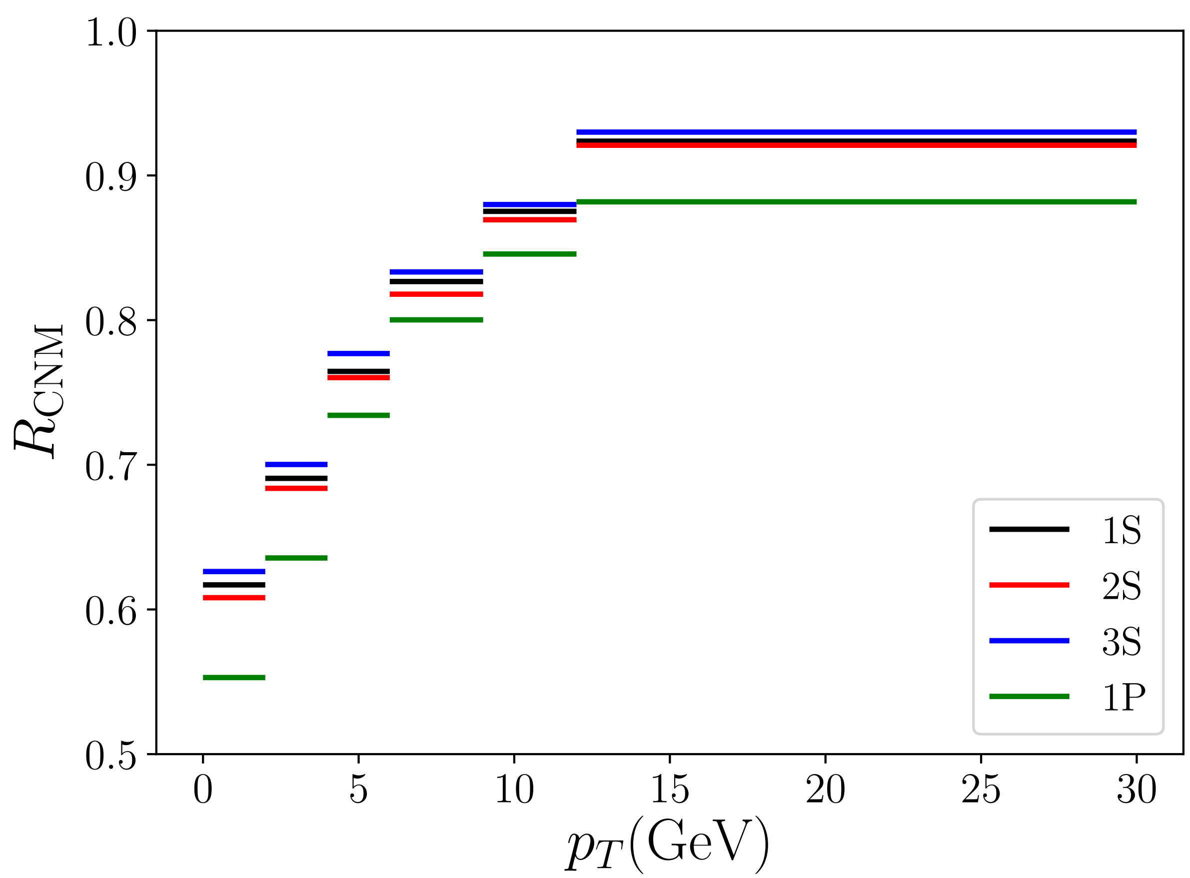
Upsilon in 5020 GeV PbPb Collision

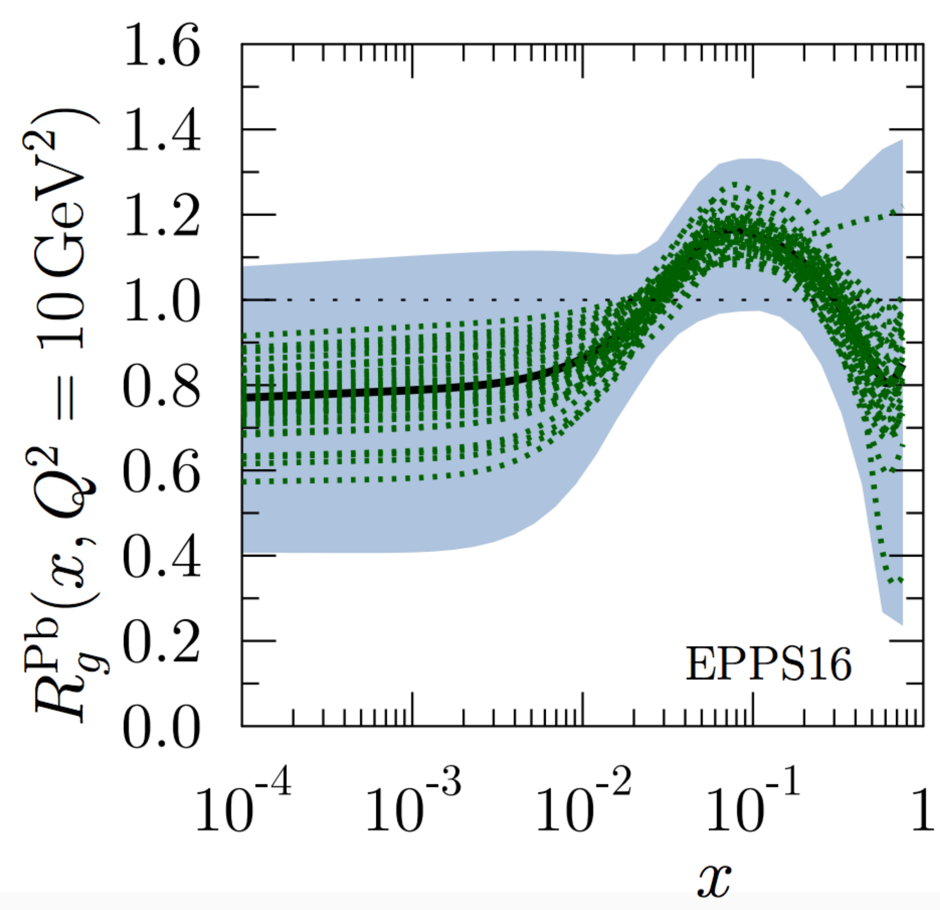


At mid rapidity

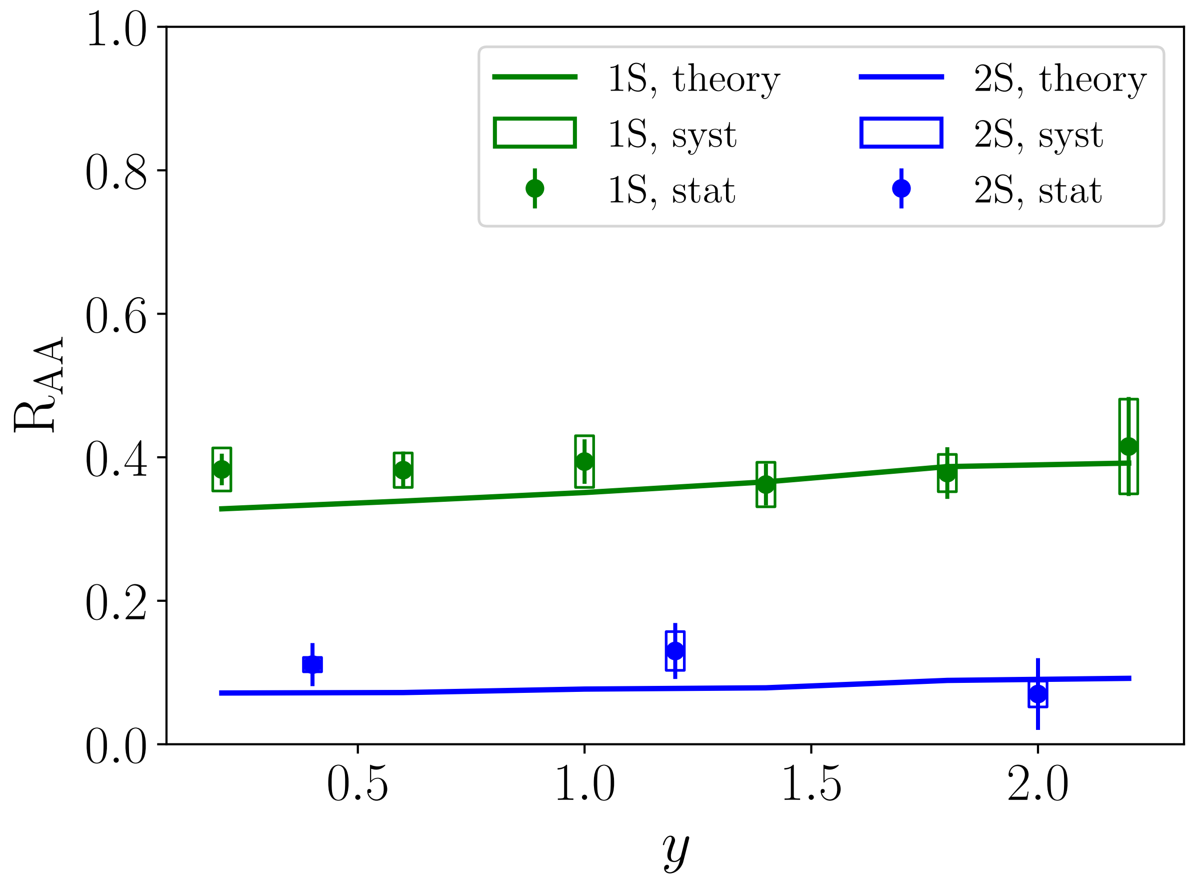
$$\text{CNM} \sim [R_g^{Pb}(x)]^2$$

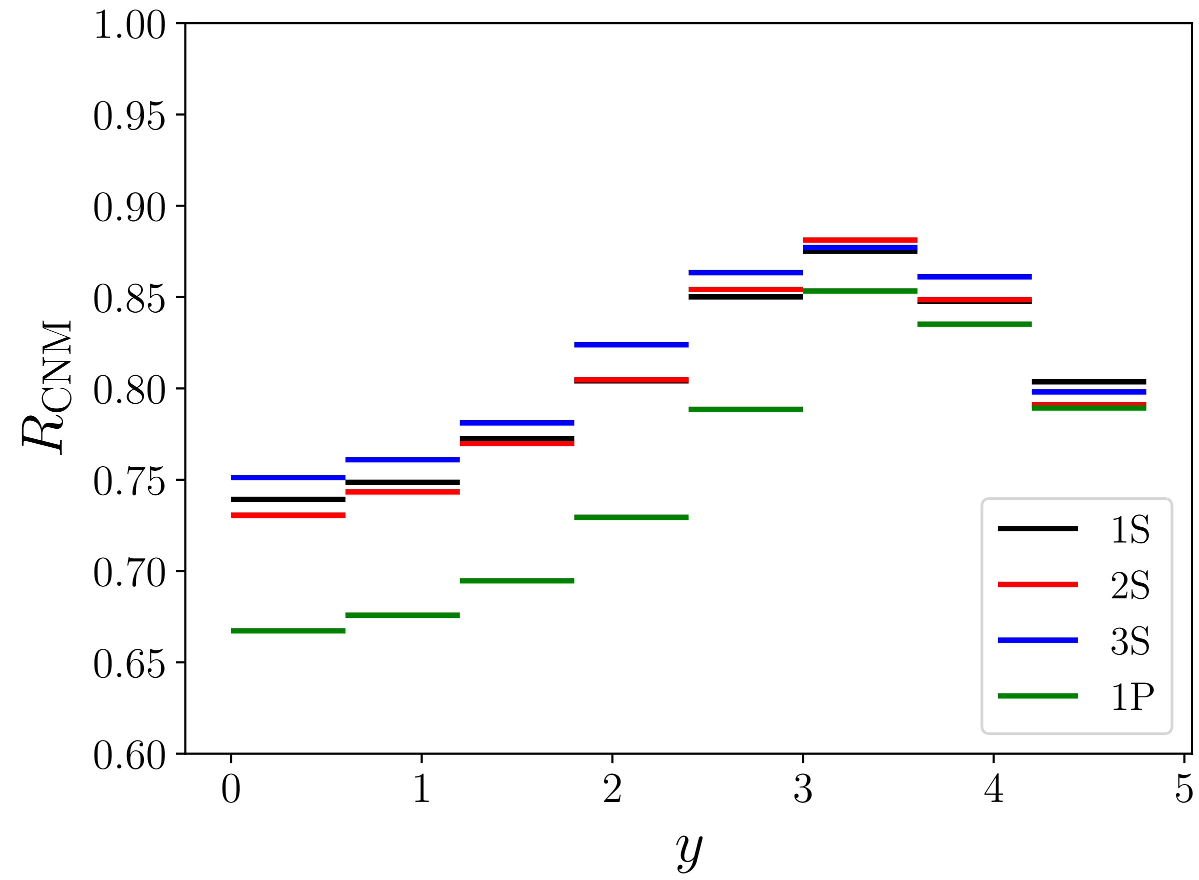
$$x \sim \frac{2m_T}{\sqrt{s}}$$





Upsilon in 5020 GeV PbPb Collision





CNM dependence on rapidity: mild for y<2.4

2+1D hydro —> QGP effect rapidity independent

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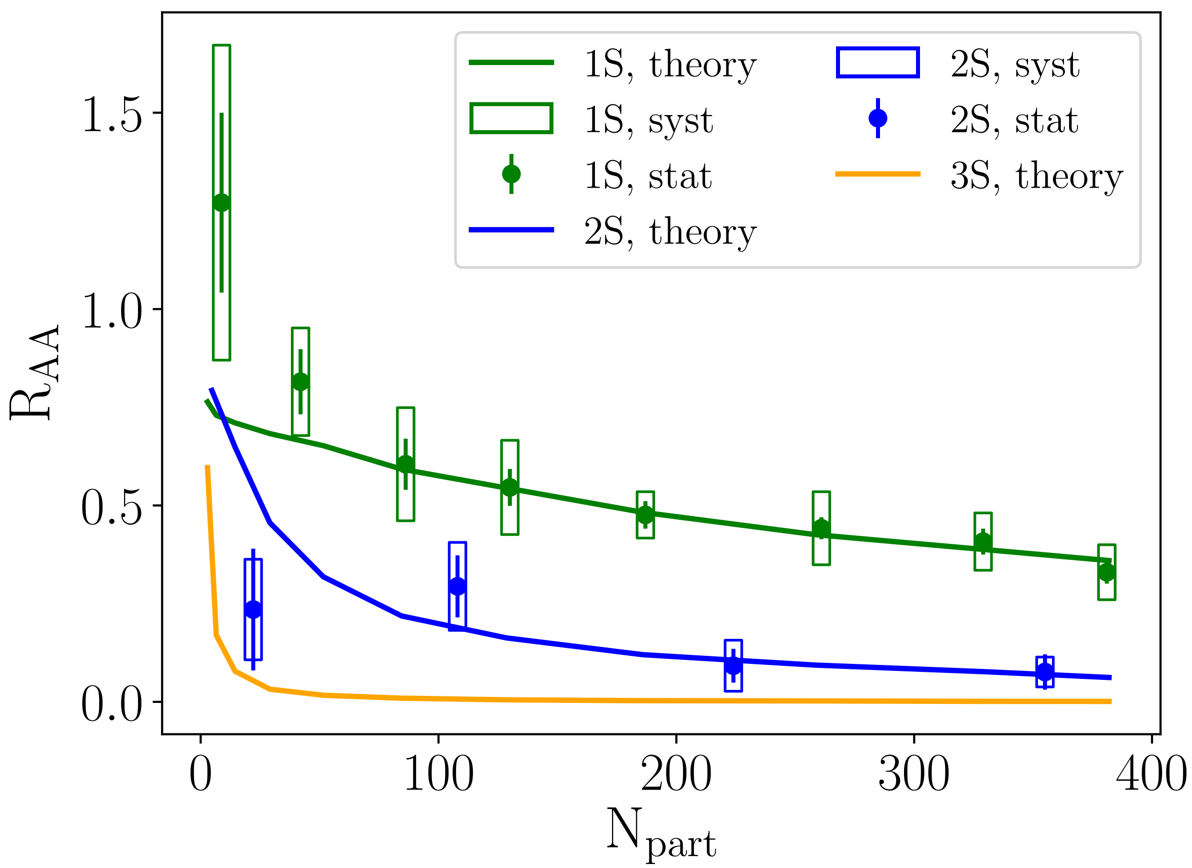
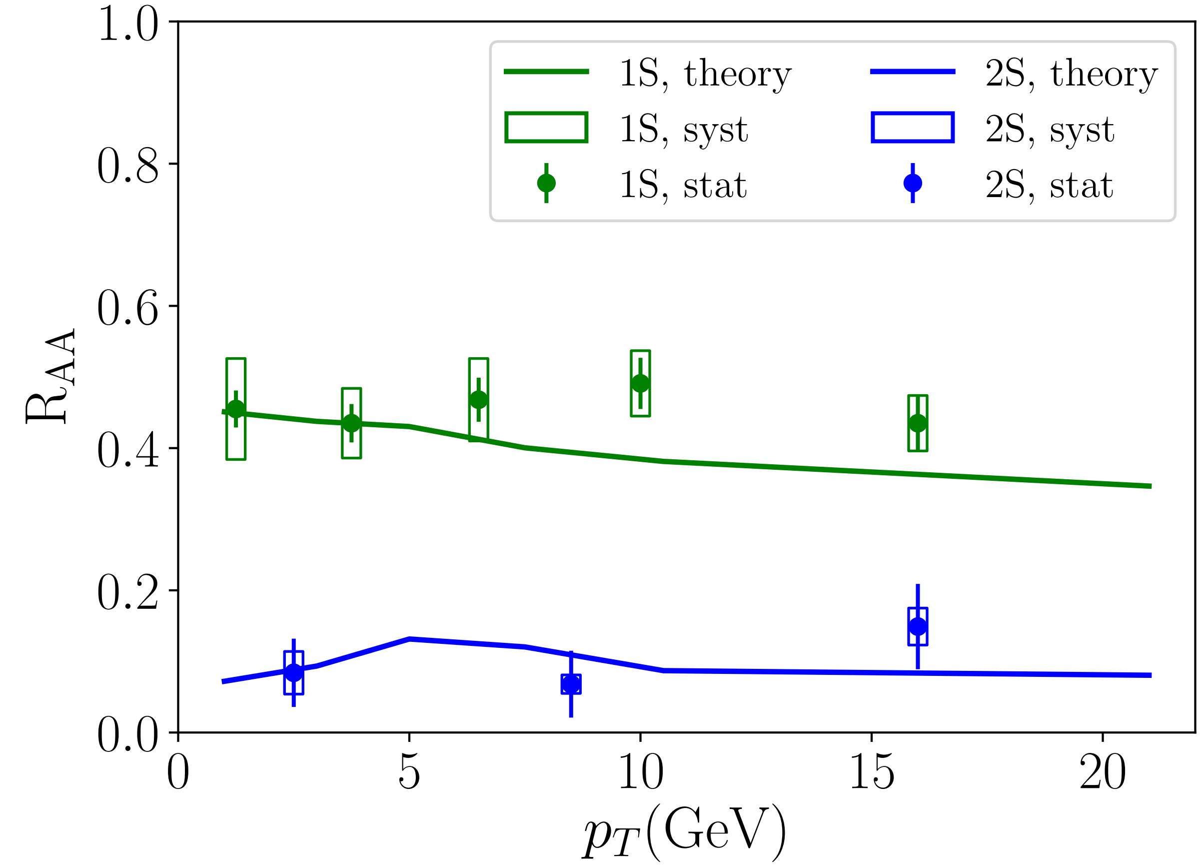
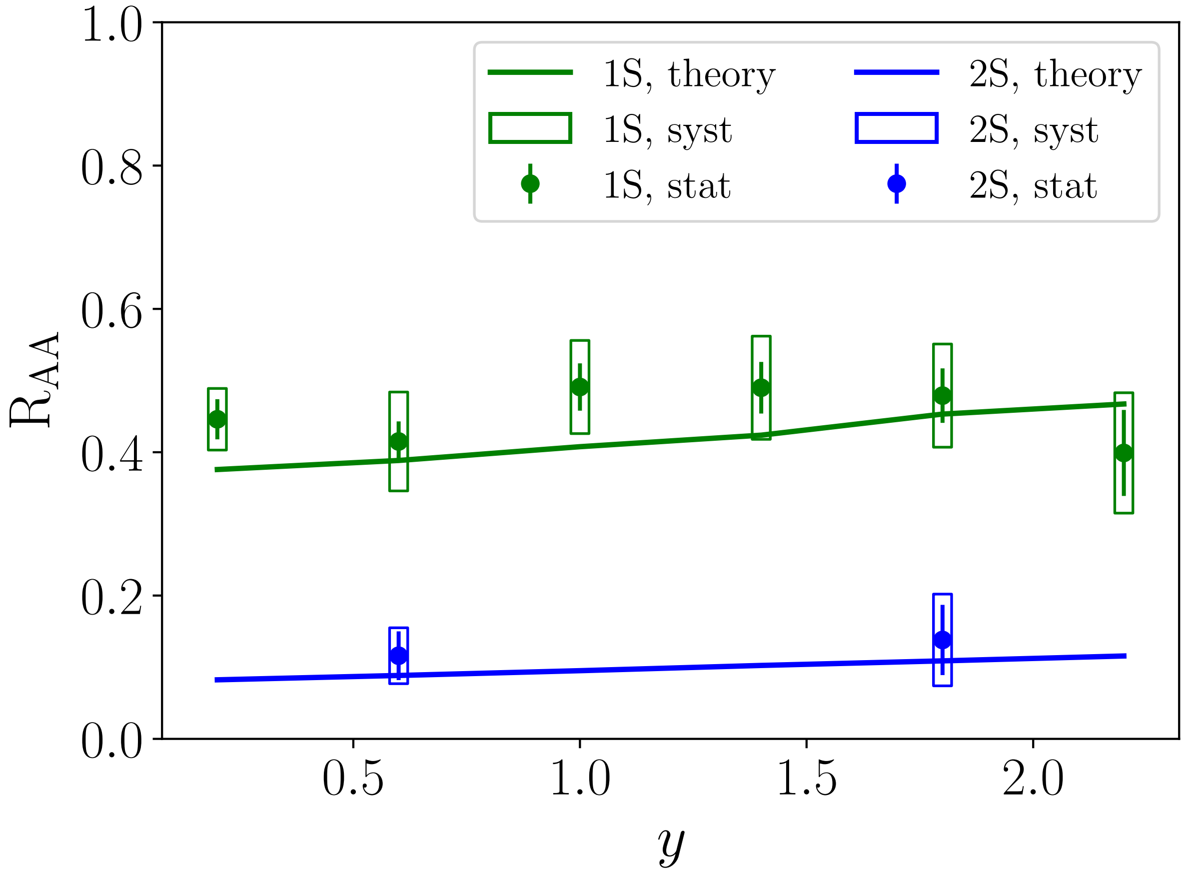
Upsilon in 2760 GeV PbPb Collision



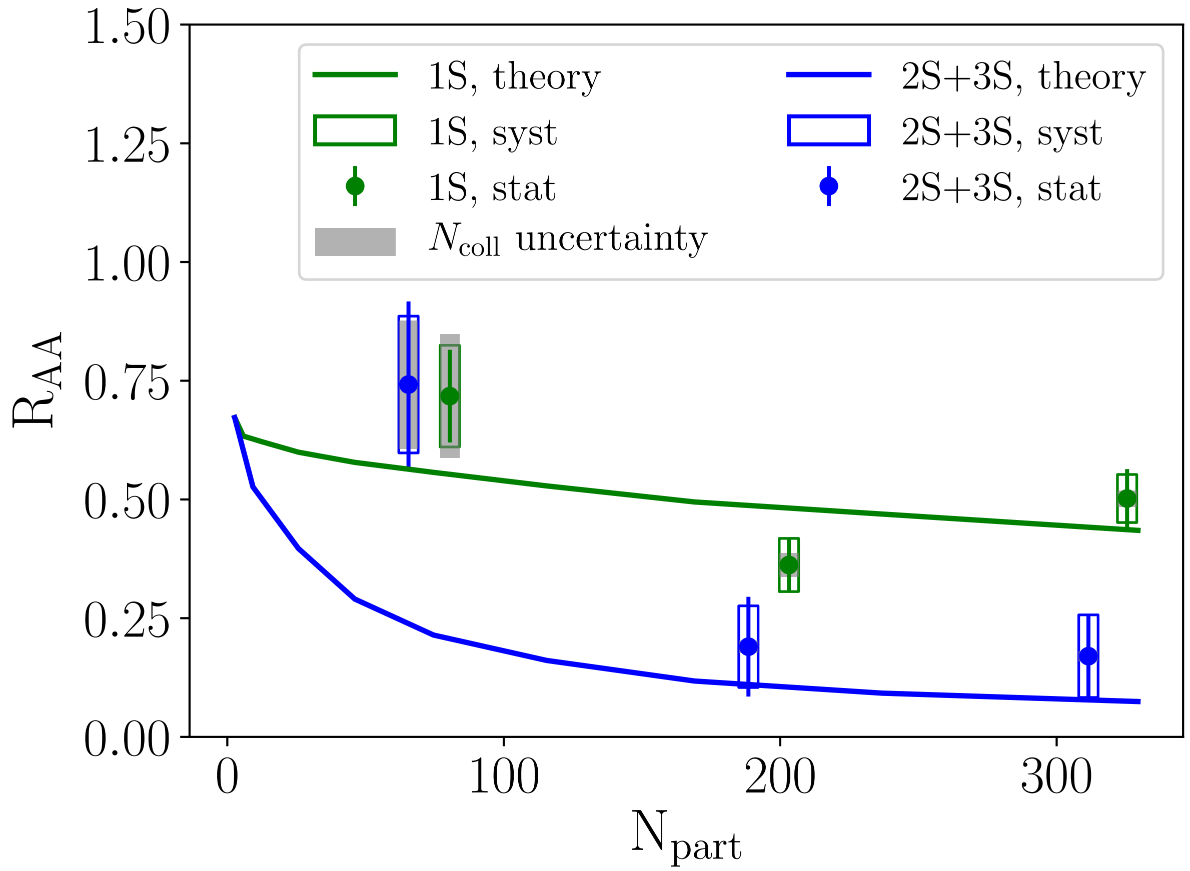


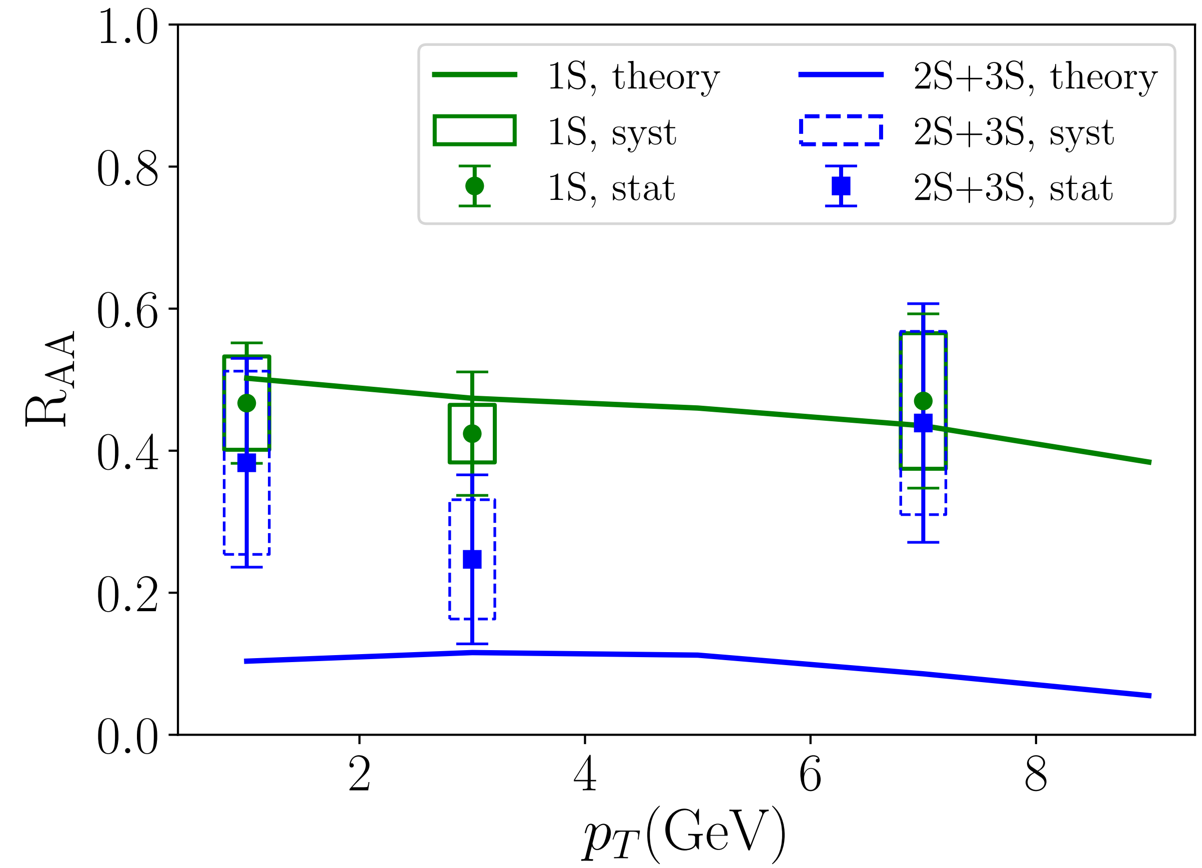


CMS Phys.Lett. B
770 (2017) 357-379

Upsilon in 200 GeV AuAu Collision

Cold nuclear matter effect ~ 0.72 (use p-Au data of STAR)





STAR Talks at QM 17&18

Need better understanding of CNM effect at 200 GeV AuAu

Discrepancy in Raa(2S+3S) at peripheral collisions? reduce uncertainty

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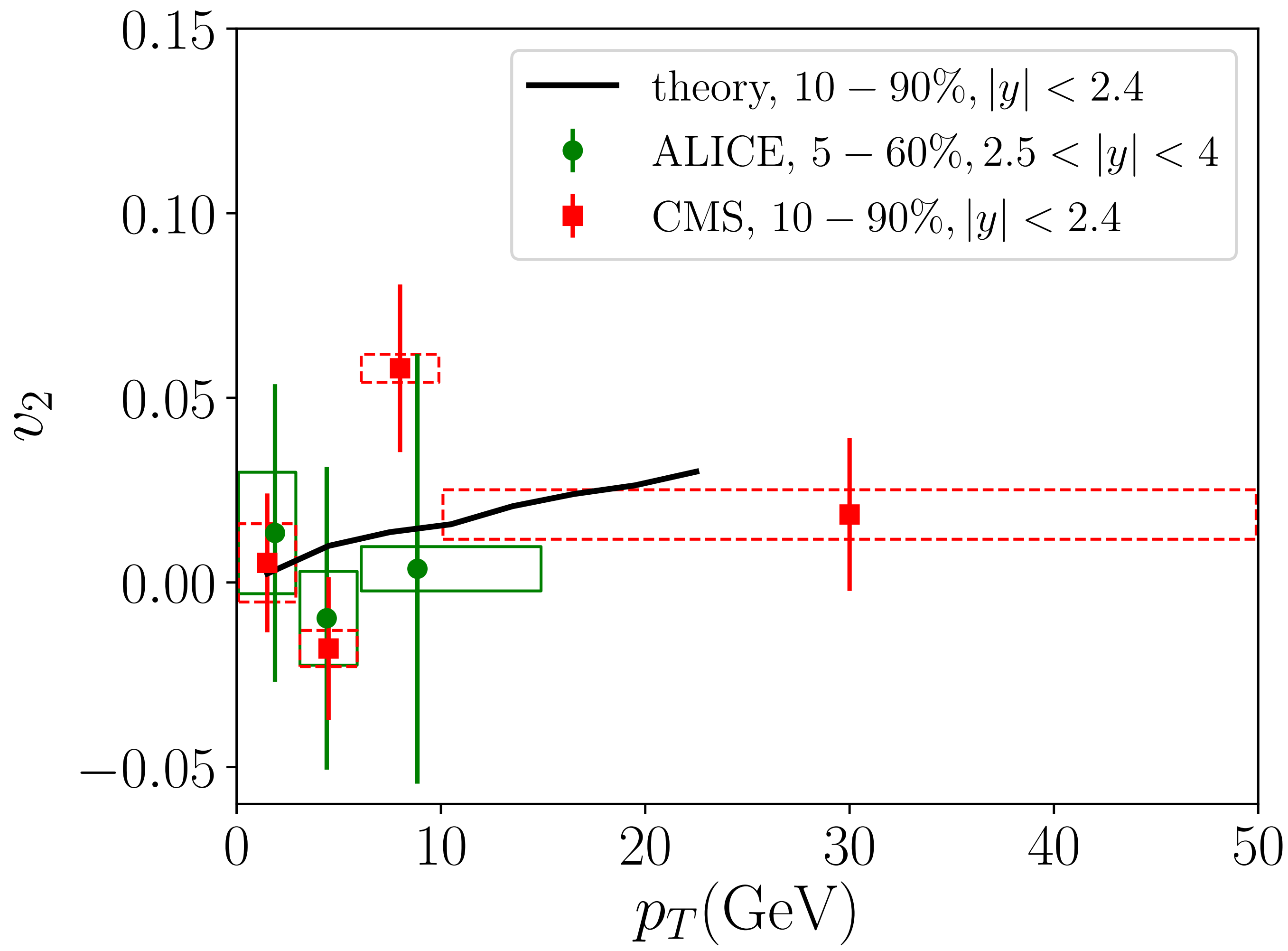
Upsilon(1S) Azimuthal Anisotropy in 5020 GeV PbPb

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



ALICE arXiv:1907.03169
CMS-PAS-HIN-19-002

v2: (1) path dependence, (2) reaction rates depend on relative velocity between quarkonium and hydro cell

recombination from uncorrelated b-quarks negligible (different for charm)

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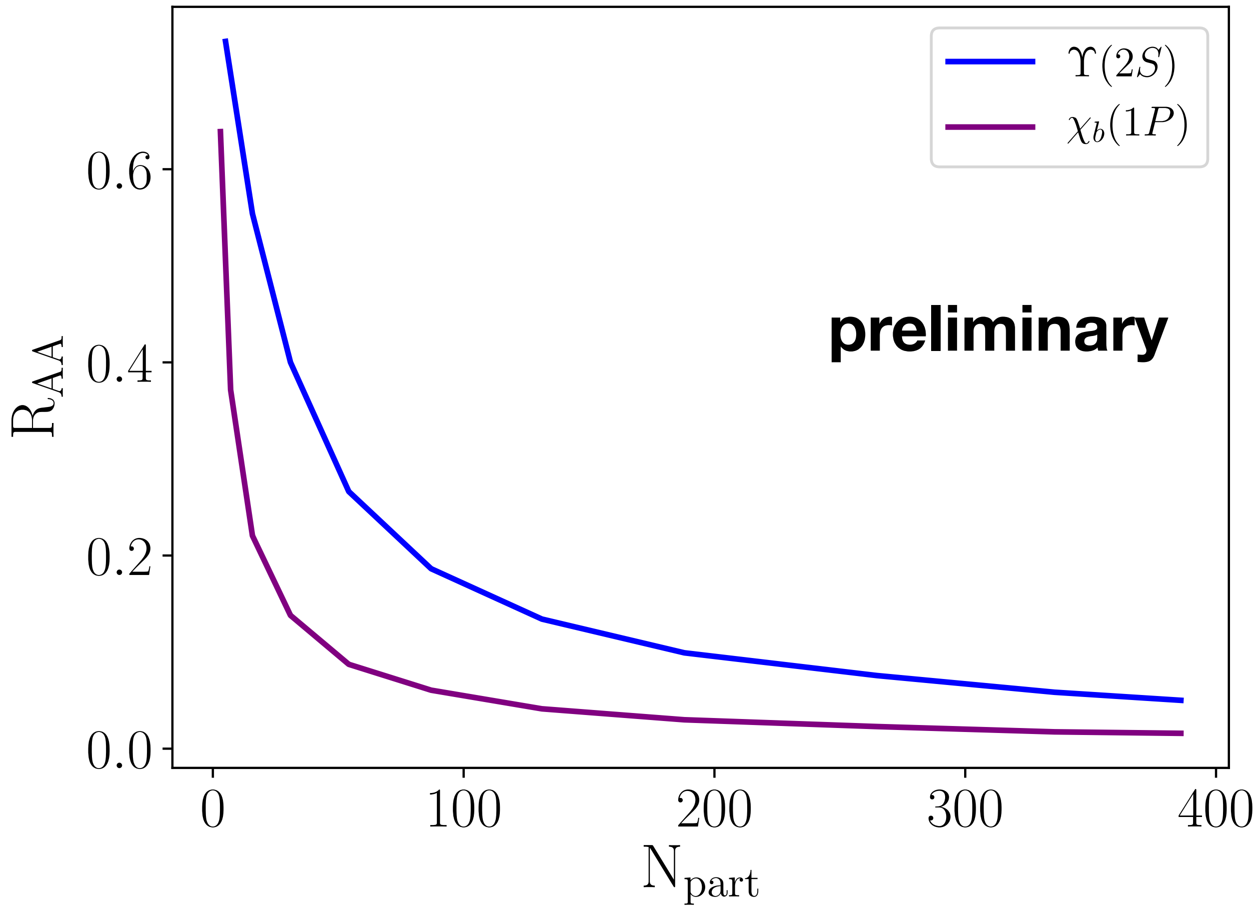
Experimental Test of Correlated Recombination

Correlated recombination predicts 1P more suppressed than 2S



Traditional sequential suppression argument based on hierarchy of binding energy or size —> Raa(2S) ~ Raa(1P), since their binding energies are close

In open quantum system based approach, correlated recombination rates (2S—>1P) ~ (1P—>2S) because of similar binding energy but primordial production cross section $\frac{\sigma_{1P}}{\sigma_{2S}} \sim 4.5$

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Conclusion

- Recent theoretical developments using open quantum system: wavefunction decoherence —> dissociation, recombination occurs at the same time
- Construct coupled transport equations of open heavy flavors and quarkonium, can handle correlated and uncorrelated recombination
- Bottomonium phenomenology, importance of correlated recombination
- **Experimental test: measure Raa(1P), compare with Raa(2S)**

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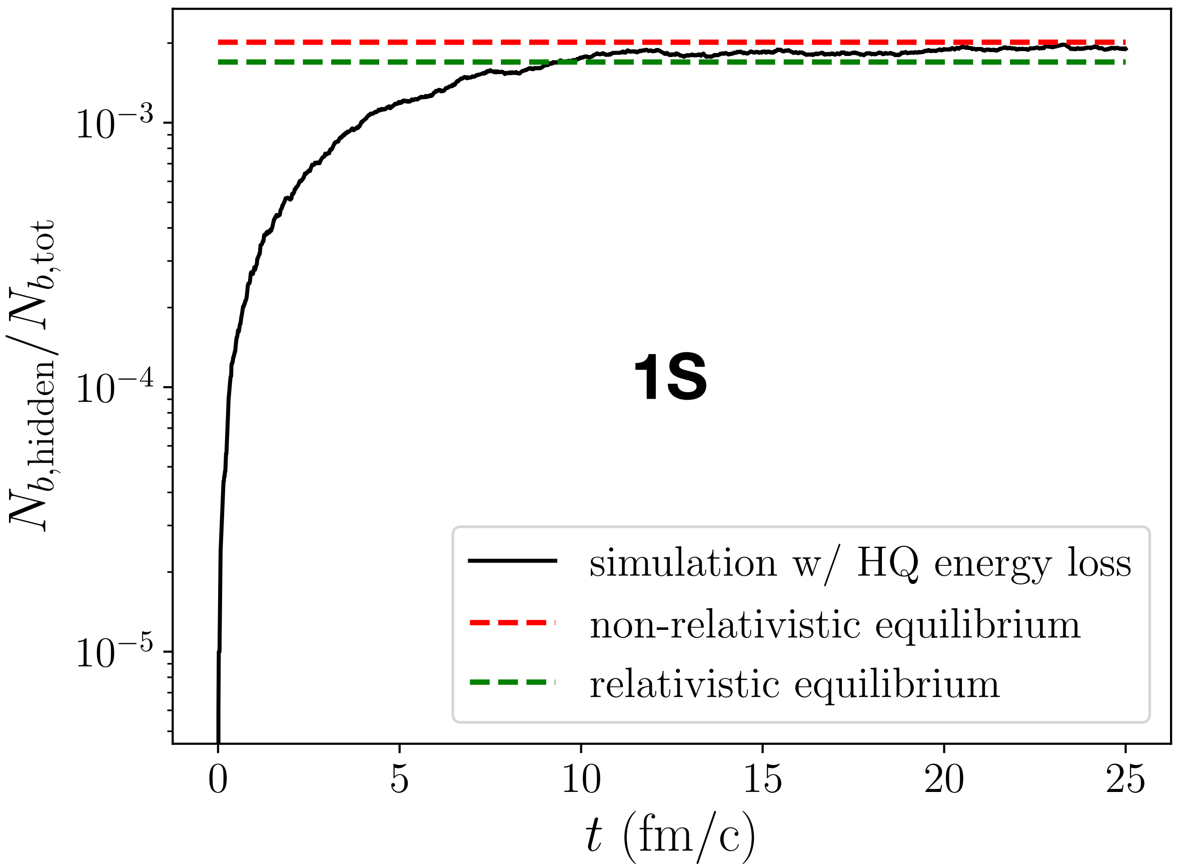
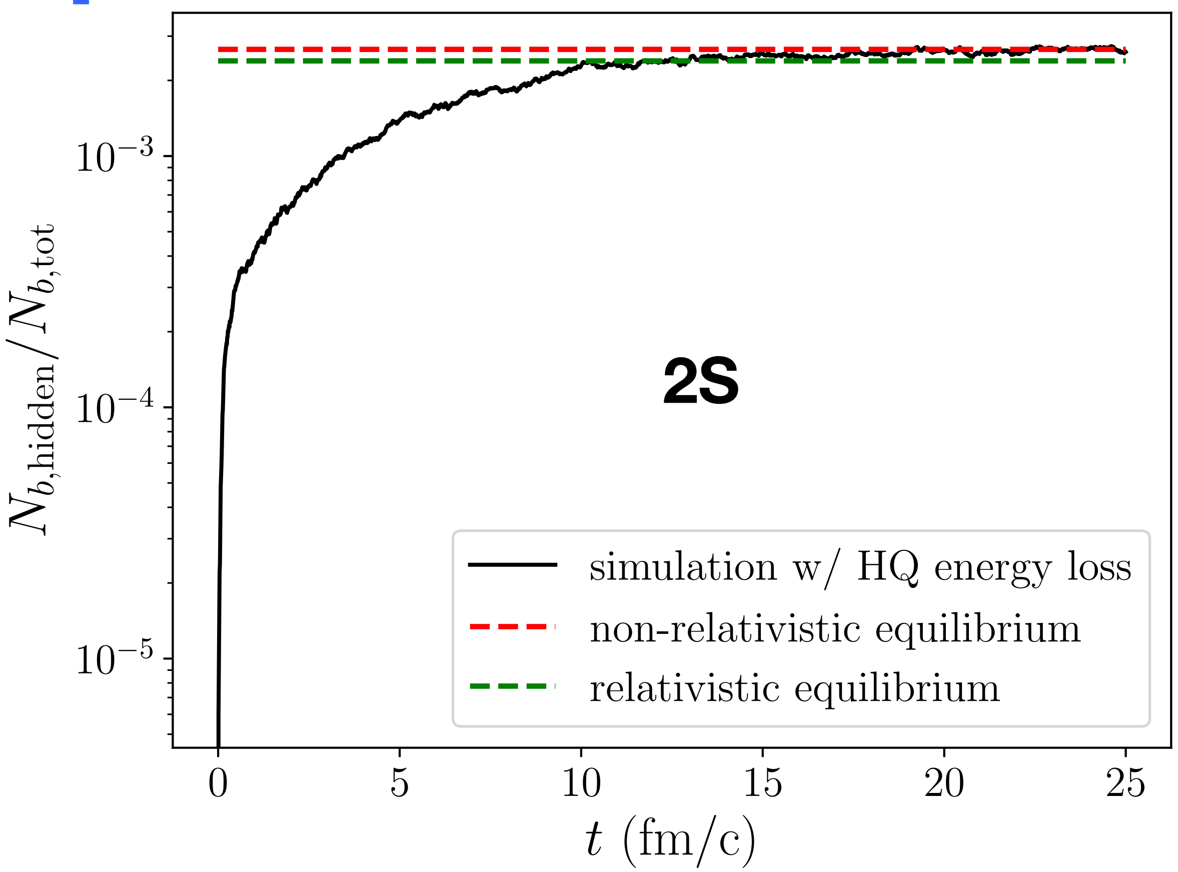
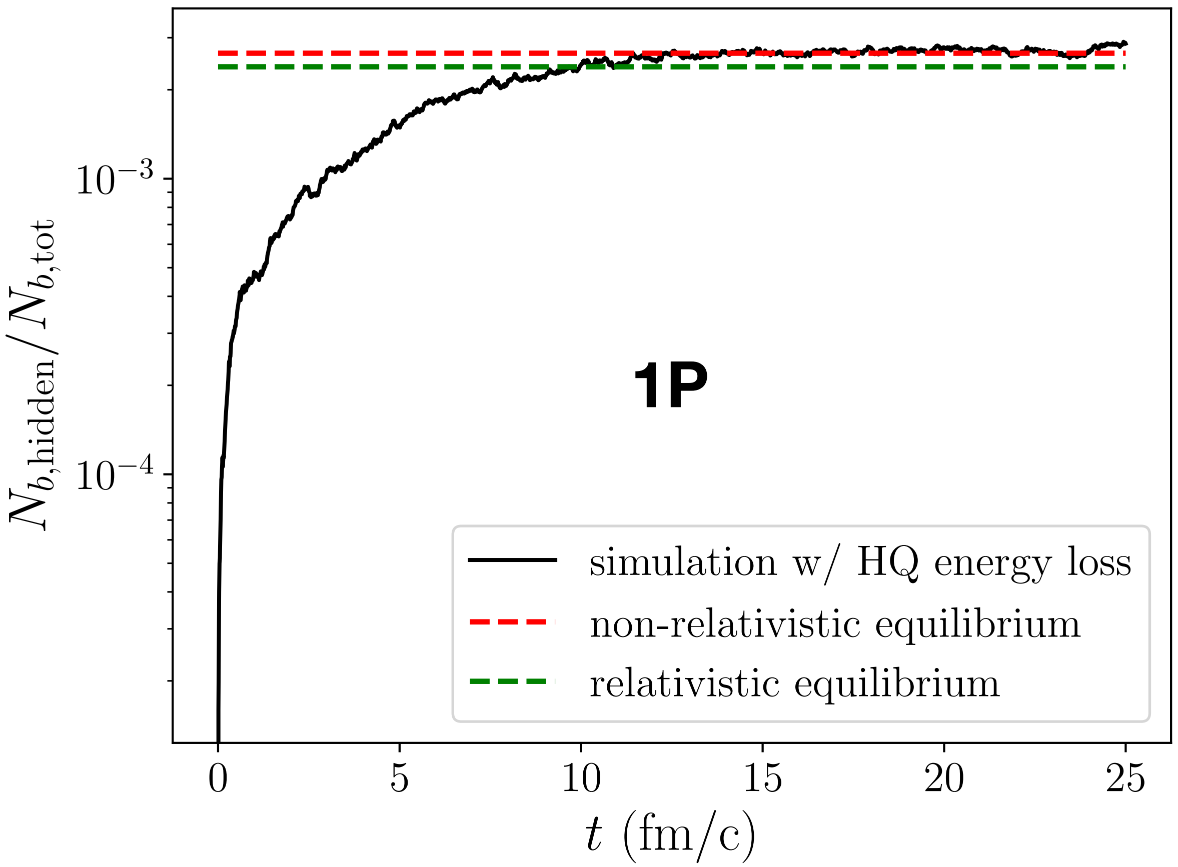
Backup



1S
simulation w/ HQ energy loss
non-relativistic equilibrium
relativistic equilibrium
10^{-3}
10^{-4}
10^{-5}
$N_{b,\mathrm{hidden}}/N_{b,\mathrm{tot}}$
0
5
10
15
20
25
t (fm/c)



2S
simulation w/ HQ energy loss
non-relativistic equilibrium
relativistic equilibrium
10^{-3}
10^{-4}
10^{-5}
$N_{b,\mathrm{hidden}}/N_{b,\mathrm{tot}}$
0
5
10
15
20
25
t (fm/c)



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