Bottomonium Production in Heavy Ion Collisions from Coupled Boltzmann Equations

Xiaojun Yao
University of Washington

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

arXiv: 2004.06746

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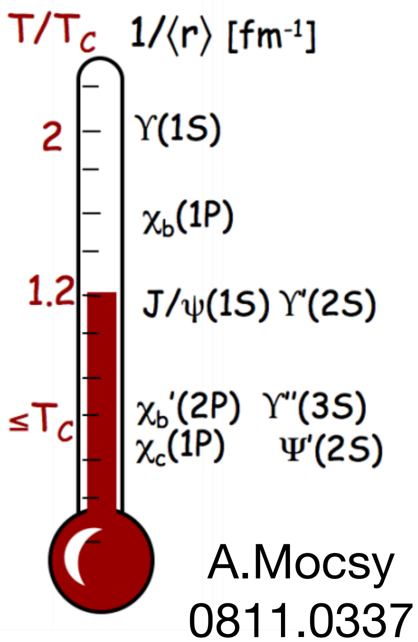
Quarkonium as Probe of Quark-Gluon Plasma

- **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

  - **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

Contents

- What are coupled Boltzmann equations?
- Why do we use them?
- How do they work compared with experimental data?

Coupled Transport Equations of Heavy Flavors

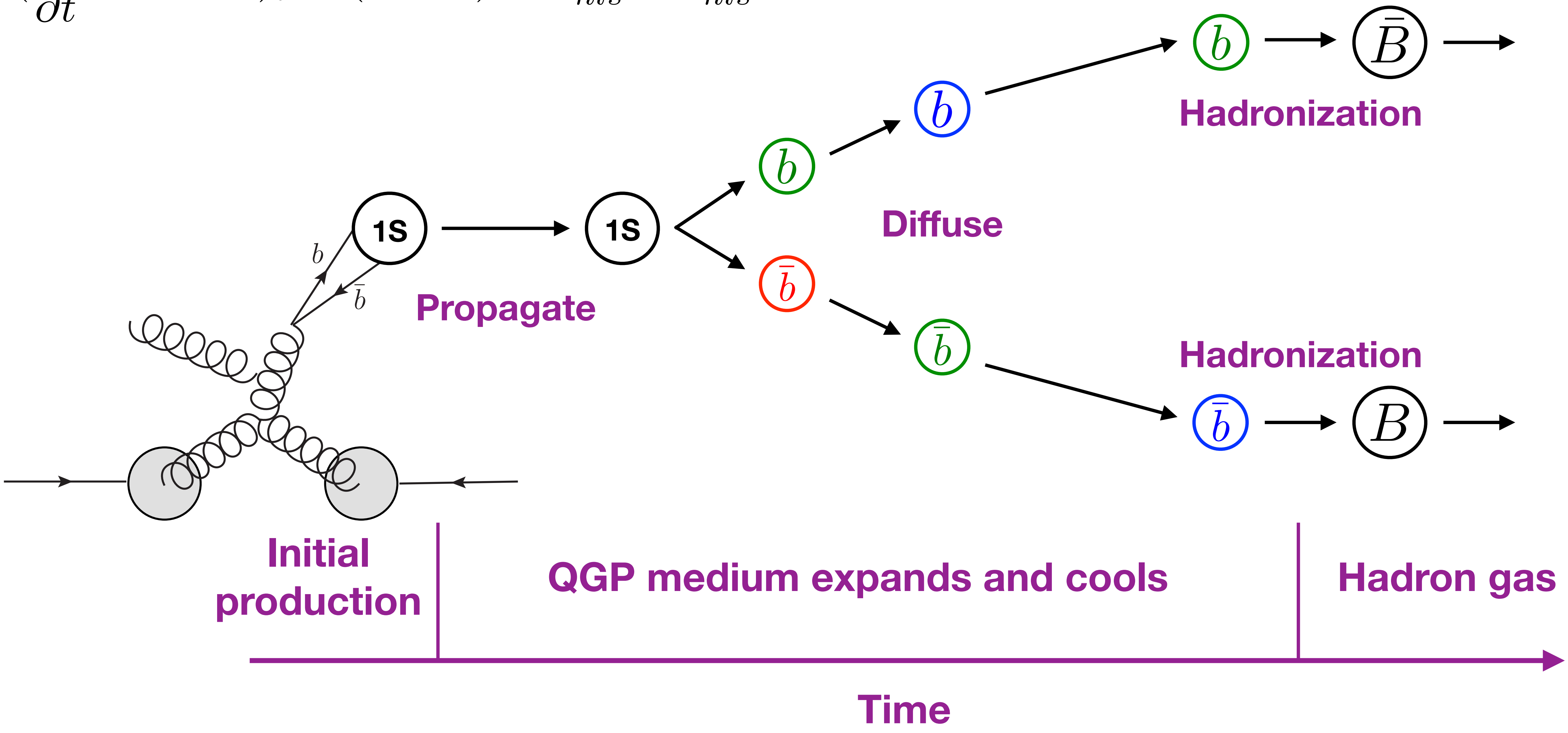
Open heavy quark antiquark

$C_{Q\bar{Q}}$: HQ scattering; +: recombination; −: dissociation

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

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

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



Propagate

Diffuse

Hadronization

Hadronization

Initial production

QGP medium expands and cools

Hadron gas

Time

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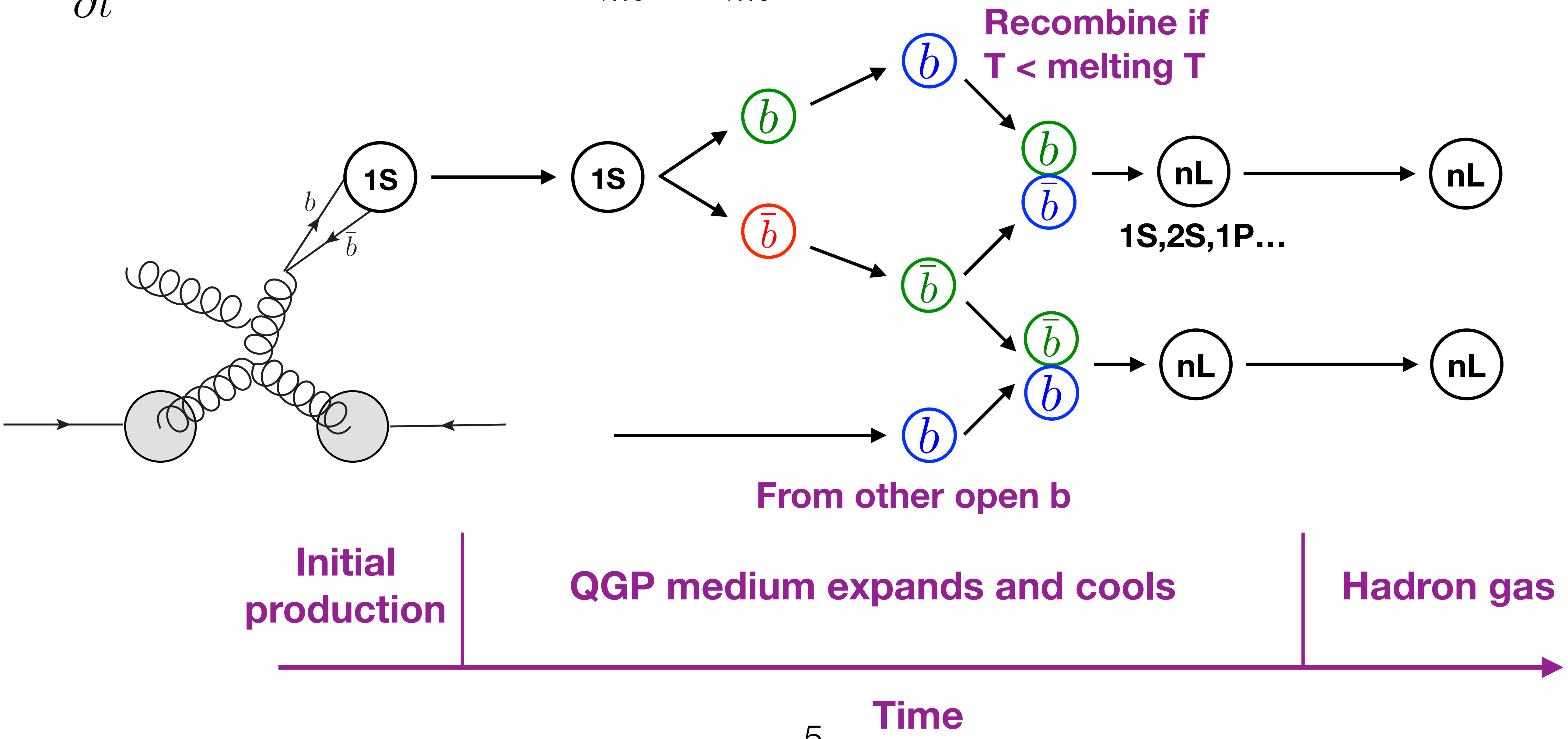

Recombine if T < melting T

1S,2S,1P...

From other open b

Initial production

QGP medium expands and cools

Hadron gas

Time

Coupled Transport Equations of Heavy Flavors

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$C_{Q\bar{Q}}$: HQ scattering; +: recombination; −: dissociation

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

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

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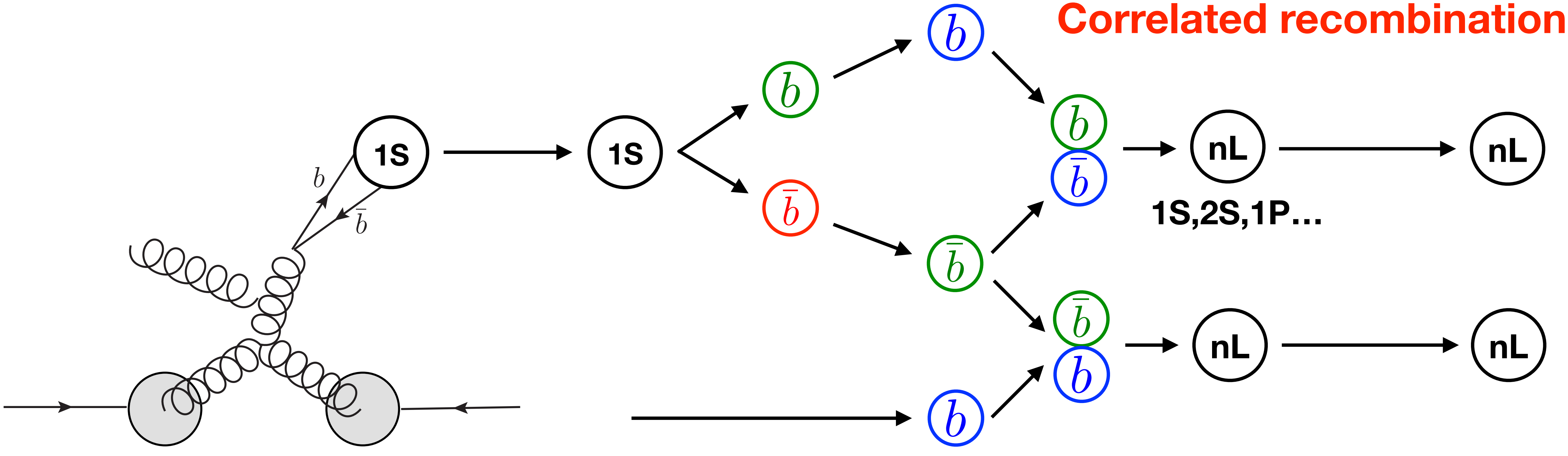


Correlated recombination

From other open b

Uncorrelated recombination

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; important for charmonium but negligible for bottomonium

- Recombination in most transport calculations: uncorrelated

$$\propto f_Q f_{\bar{Q}}$$

$$\propto f^{(\mathrm{eq})}_{\mathrm{onia}}$$

- **How to incorporate correlated recombination in semiclassical transport? Need 2-particle distribution**

XY T. Mehen, 2009.02408, 2102.01736

Coupled Transport Equations of Heavy Flavors

Open heavy quark antiquark

$C_{Q\bar{Q}}$: HQ scattering; +: recombination; −: dissociation

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

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

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

$$f_{Q\bar{Q}}(\boldsymbol{x}_Q, \boldsymbol{p}_Q, \boldsymbol{x}_{\bar{Q}}, \boldsymbol{p}_{\bar{Q}}, t) \neq f_Q(\boldsymbol{x}_Q, \boldsymbol{p}_Q, t) f_{\bar{Q}}(\boldsymbol{x}_{\bar{Q}}, \boldsymbol{p}_{\bar{Q}}, t)$$

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: diffusion + radiation

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

Compare w/ LHC Data on Upsilon at 5.02 TeV

Coulomb potential —> no bottomonium mass change at finite T (lattice evidence)

Initial conditions: momentum: Pythia + nPDF EPPS16; position: Trento, binary collision

2+1D viscous hydro calibrated; HQ dynamics calibrated

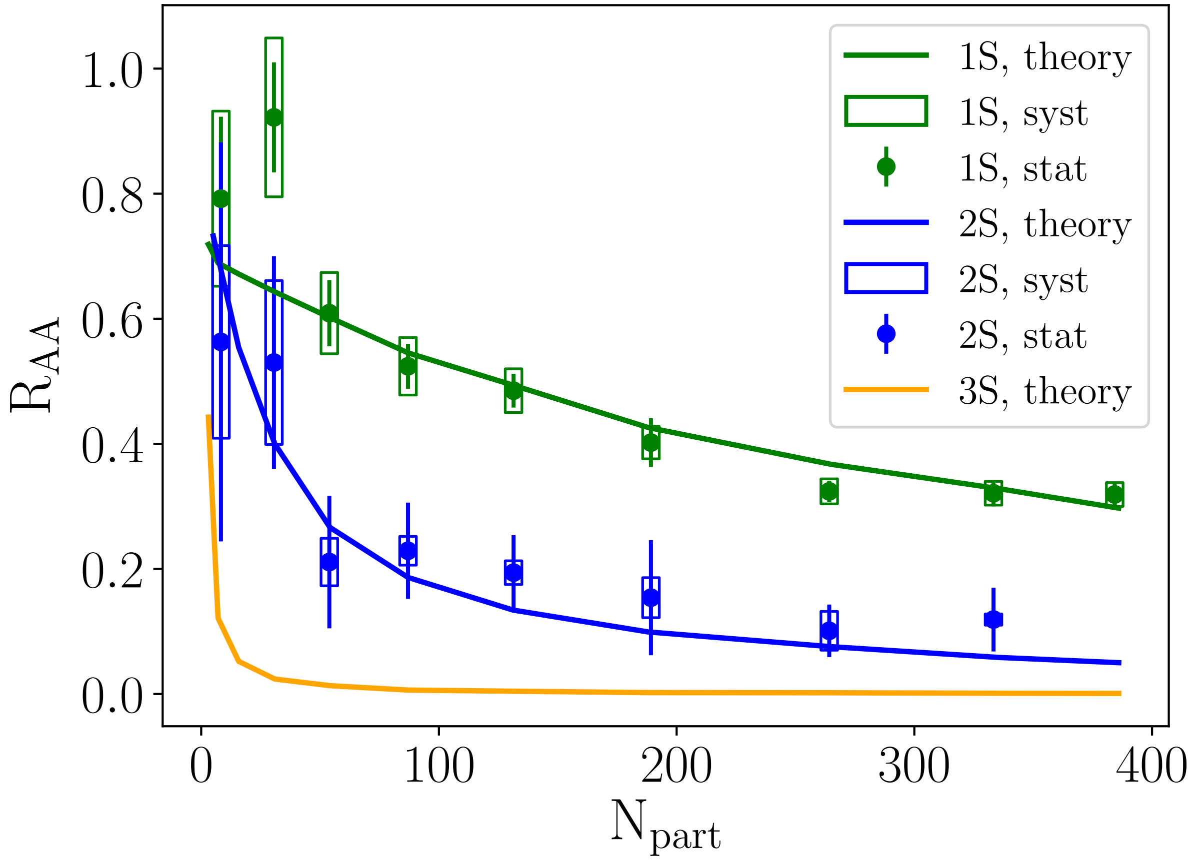
Bottomonium: 1S, 2S, 3S, 1P, 2P; **no recombination for 3S, 2P**

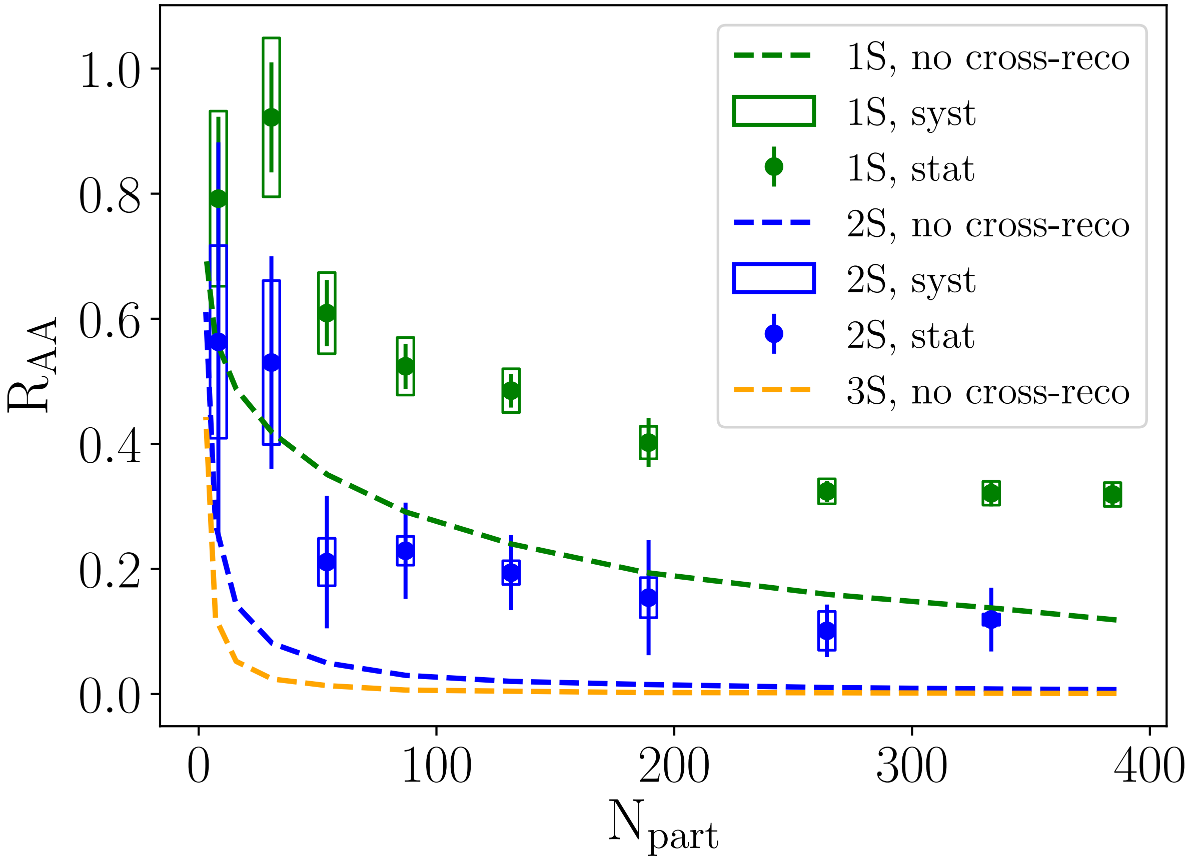
Feed-down networks

e.g. no 2S—>1S, 1S—>1P etc

with cross-talk (correlated) recombination

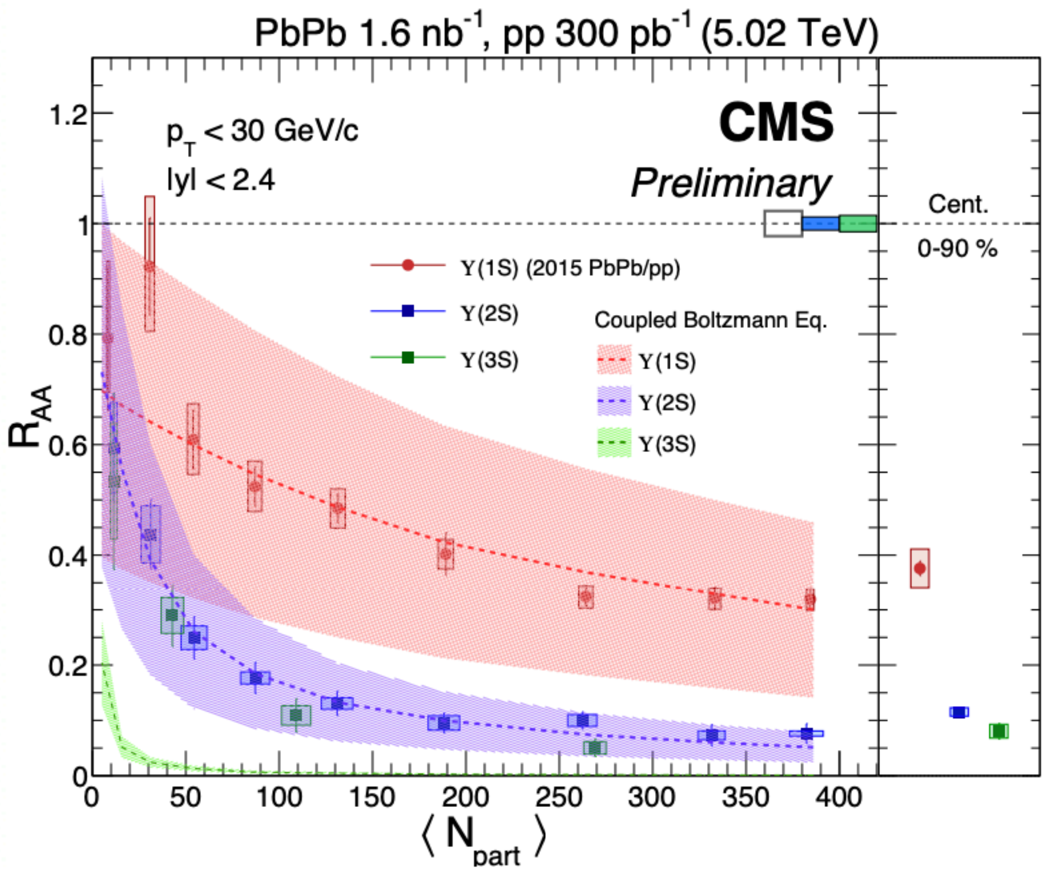
without cross-talk recombination

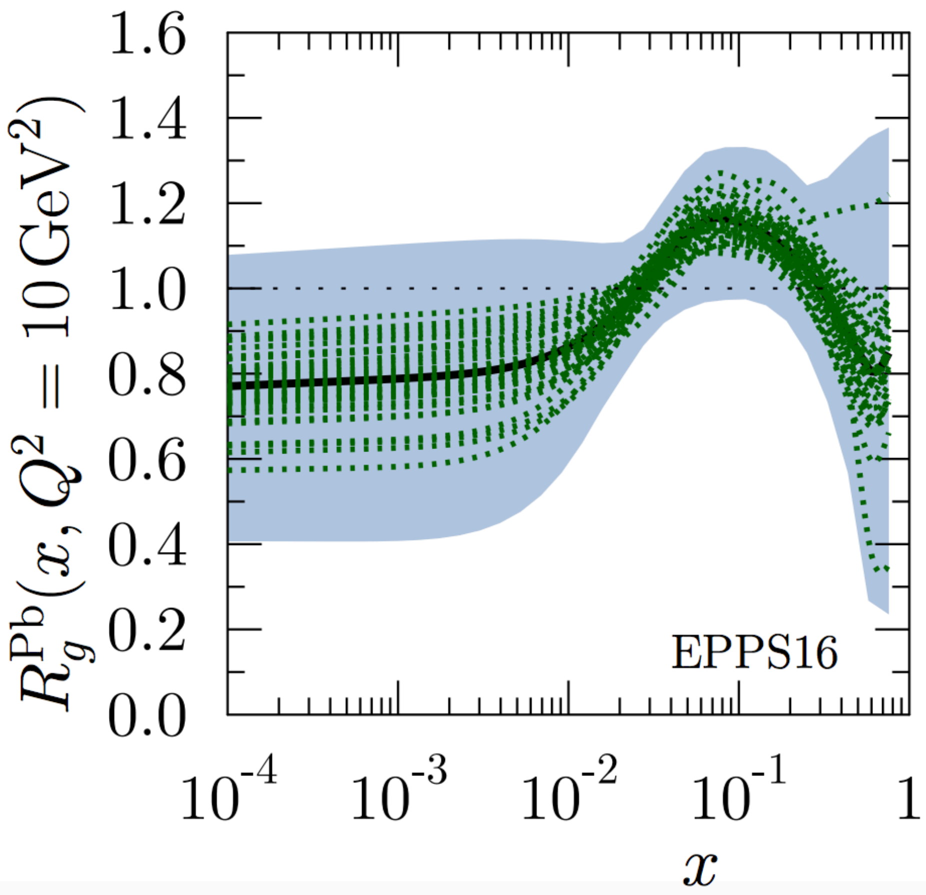




CMS arXiv:1805.09215

Uncertainty of nPDF and nPDF at RHIC Energy





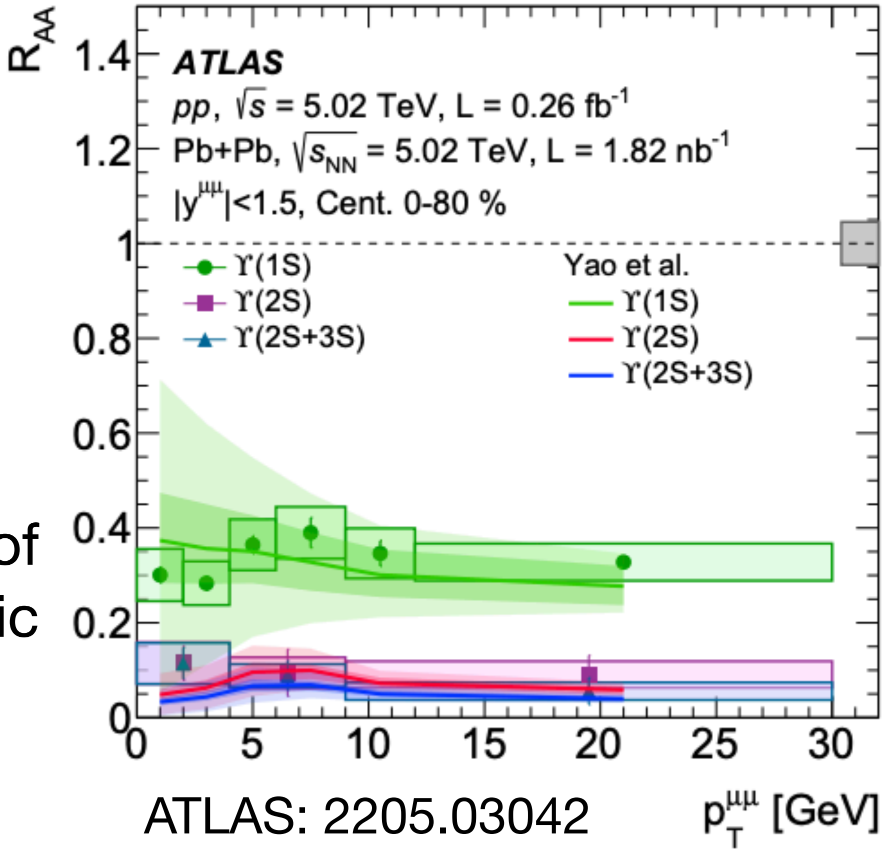
At mid rapidity

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

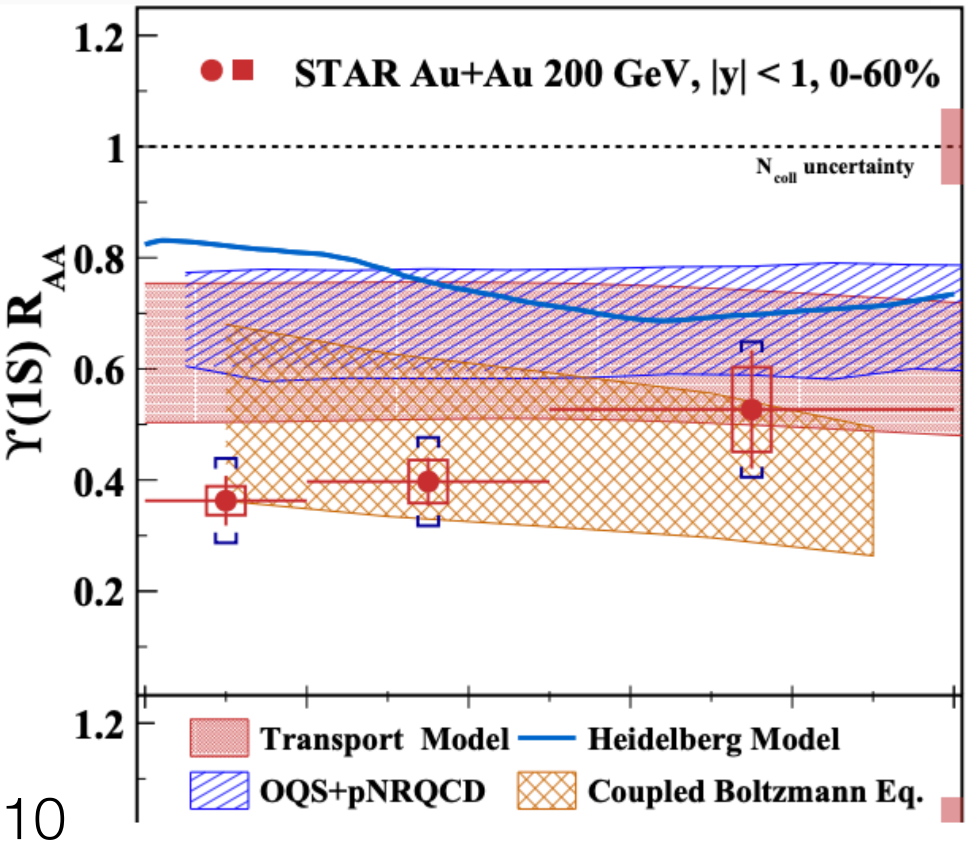
CNM

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

High p_T: breakdown of nonrelativistic treatment



ATLAS: 2205.03042



Input of nPDF:

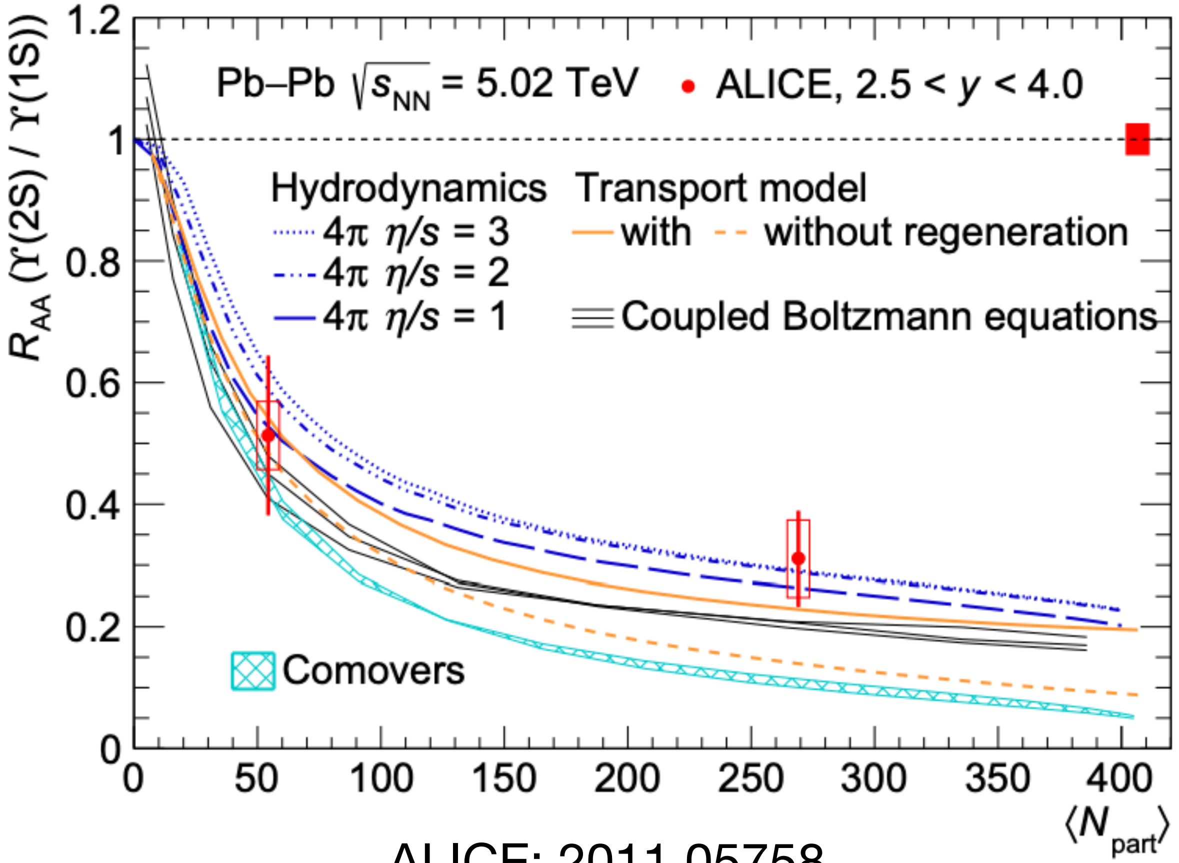
$R_{pAu} = 0.82$

$\pm 0.10(stat)$

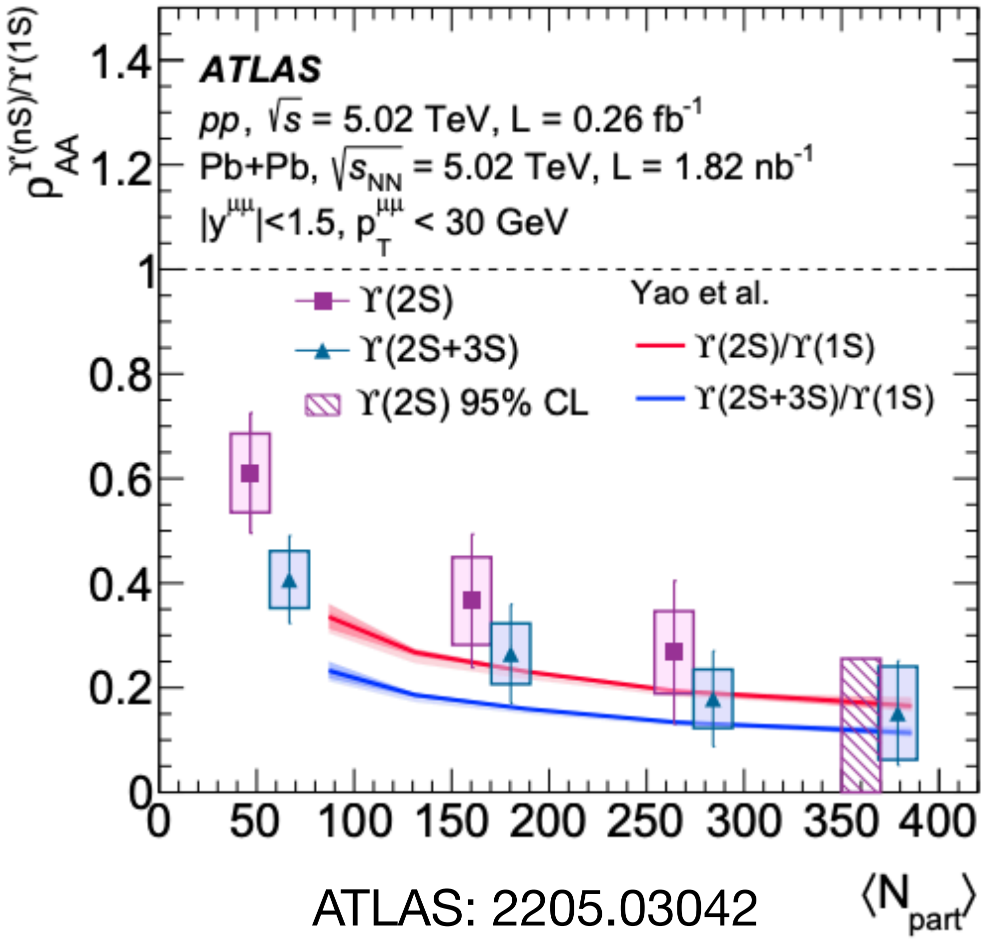
$\pm 0.08(syst)$

STAR: 2207.06568

Double Ratio and Flow Observables

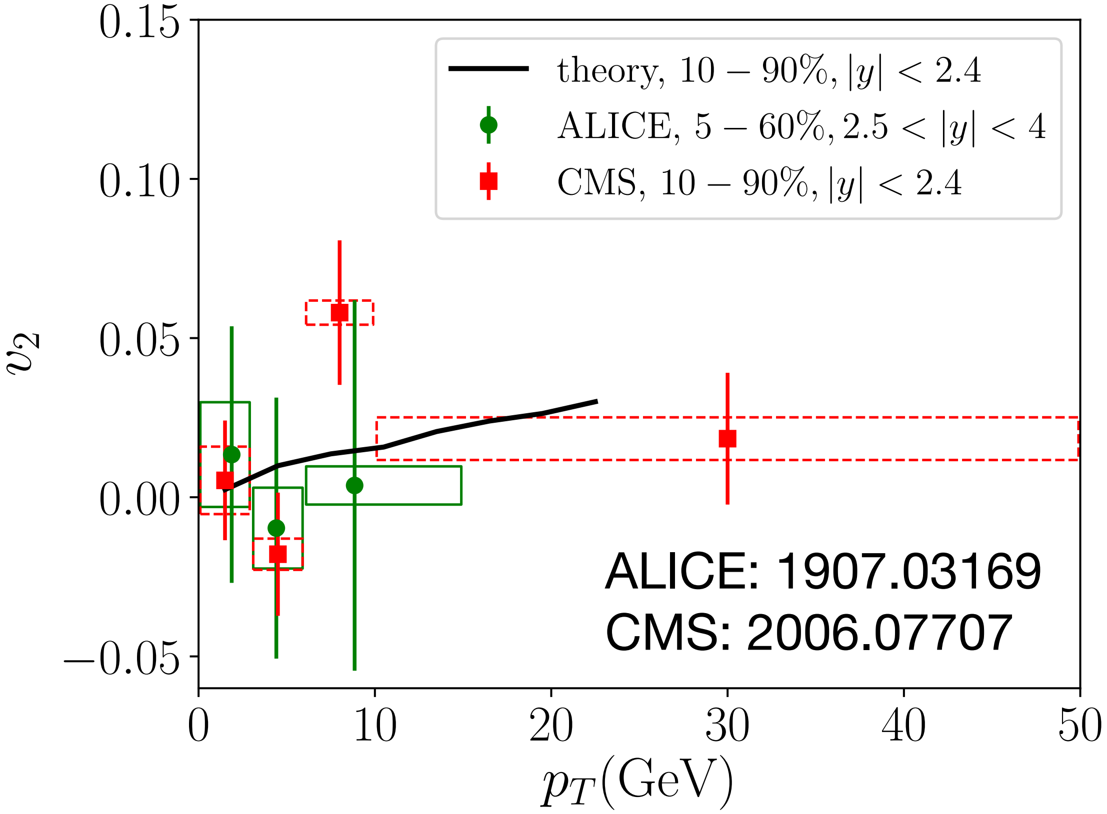


ALICE: 2011.05758



ATLAS: 2205.03042

R_{AA} ratios have much smaller nPDF uncertainty

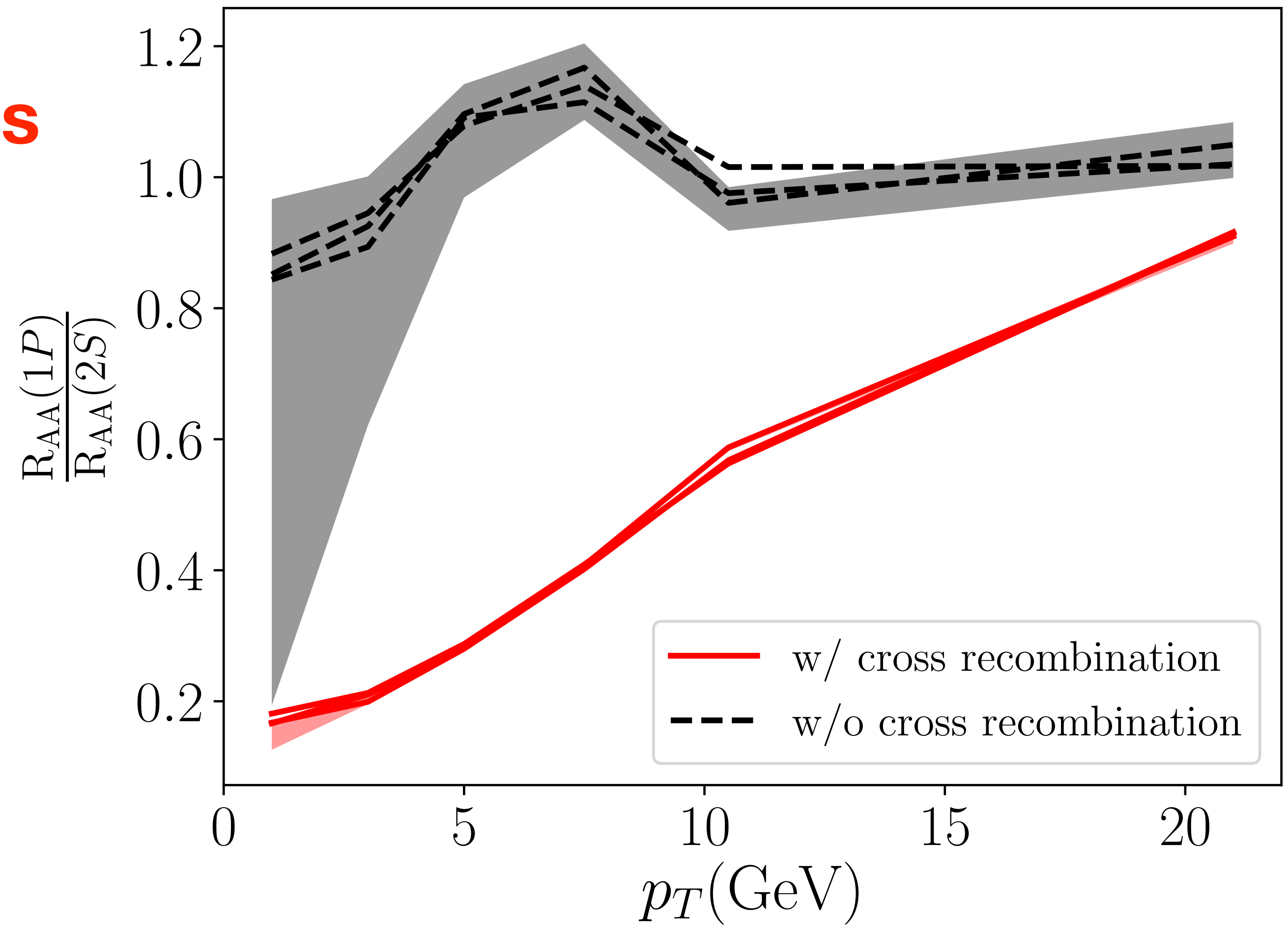


ALICE: 1907.03169
CMS: 2006.07707

More precise flow observables in LHC Run3

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 —> R_{AA}(2S) ~ R_{AA}(1P), since their binding energies are close

Correlated recombination rates (2S—>unbound—>1P) ~ (1P—>unbound—>2S) because of similar binding energy, but primordial production cross section

$$\frac{\sigma_{1P}}{\sigma_{2S}} \sim 4.5$$

Conclusion

- Coupled Boltzmann equations for open and hidden heavy flavors: correlated recombination (the Boltzmann equation for quarkonium is derived from open quantum system, see the review 2102.01736)
- Bottomonium phenomenology, importance of correlated recombination
- CNM uncertainty dominates, cancel out largely in double ratio observables, update by using EPPS21
- **Experimental test: measure R_{AA}(1P), compare with R_{AA}(2S)**
- Future consideration: include 3S recombination, charmonium