Extracting the in-Medium Color Force from Heavy-Ion Collisions

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Outline

- Introduction: Why Quarkonium
- Quarkonium Transport Approach
  - Rate Equation
- Advantage of Bottomonium
  - Comparison to Charmonium
- Statistical Extraction of the Heavy Quark Potential
  - Assembly Line
  - Ansatz for Potential
  - χ^2 Tests and Results
- Summary

Quarkonium in Heavy-Ion Collisions

Heavy Quarkonium, J/ψ, ψ(2S), ϒ(1S), ϒ(2S), ...as a probe:

1. Survive in QGP ($E_{BINDING}$>T_c),

2. Large masses (potential picture works),

3. Various species (hierarchy), …

Hierarchy:

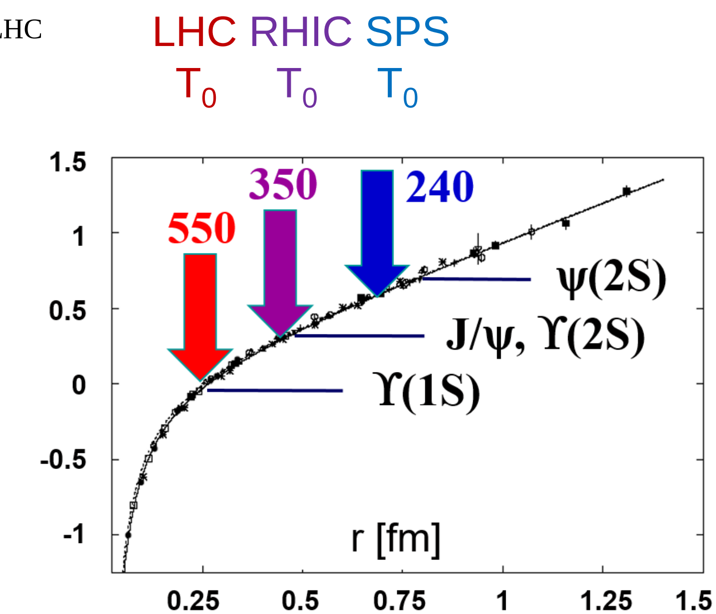
$T_{melt}[\psi(2S)] < T_0^{SPS} < T_{melt}[J/\psi, \Upsilon(2S)] < T_0^{RHIC} < T_{melt}[\Upsilon(1S)] < T_0^{LHC}$

For J/ψ, ψ(2S), ϒ(1S), ϒ(2S):

→ Bound at different parts of potential

→ Different melting temperatures

→ Systematic excitation functions: SPS, RHIC, LHC…



Ideal for probing:

strong force / $Q\bar{Q}$ potential in medium

Transport Approach

Kinetic Rate Equation

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

primordial regeneration

Transport Coefficients

- Reaction Rates $\Gamma_{\Upsilon}(T(\tau))$ → NLO Quasi-free (dominates small binding)
  LO Gluo-dissociation (dominates large binding)
- Equilibrium Limits $N_{\Upsilon}^{eq}(T(\tau))$ → From heavy quark conservation $N_{\Upsilon}^{eq} = V_{FB}\gamma_b^2 d_{\Upsilon}\int \frac{d^3p}{(2\pi)^3} f_{\Upsilon}^{eq}(E_p;T)$

Key Parameters

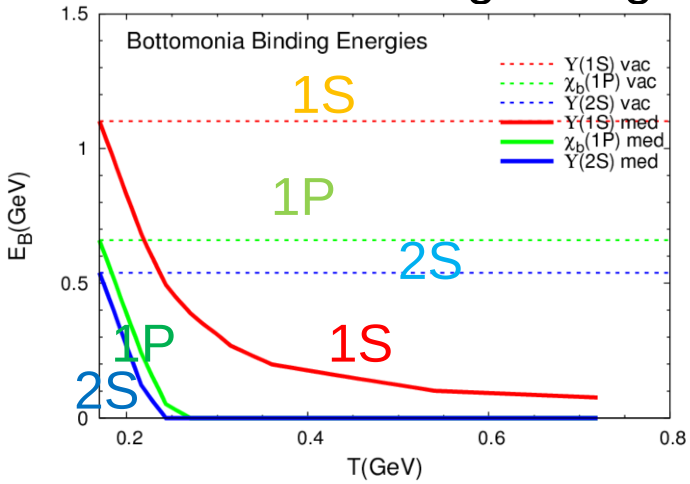
- Coupling α_s → Affects reaction rates
  Fixed from previous calculations compared with data
- Thermal Relaxation Time of Heavy Quarks → Modifies equilibrium limit
  Extracted from heavy quark diffusion simulations

Key Inputs

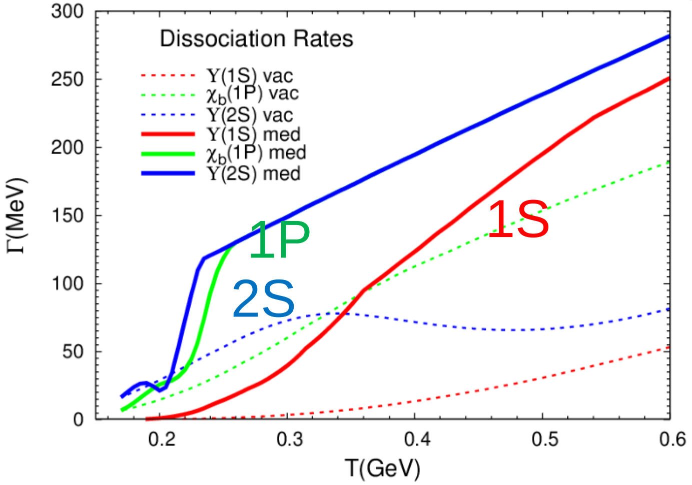
- In-Medium $Q\bar{Q}$ Potential/Binding Energy → Reaction Rates
- Heavy Quark/-onium pp Cross Section → fugacity factor γ_b → Equilibrium Limit
- Initial State Effects (nPDF)
- Fireball Evolution

Binding Energy and Reaction Rates

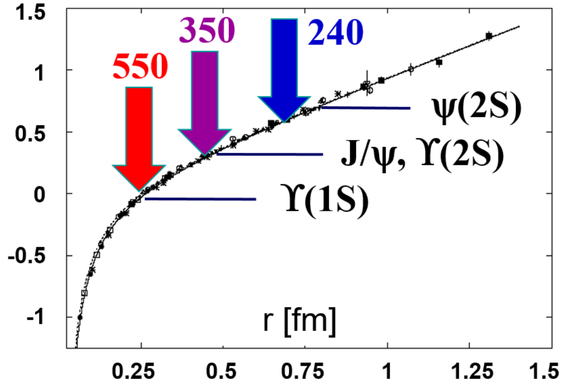
Bottomonium Binding Energies



Reaction Rates $\Gamma_{\Upsilon}(T(\tau))$



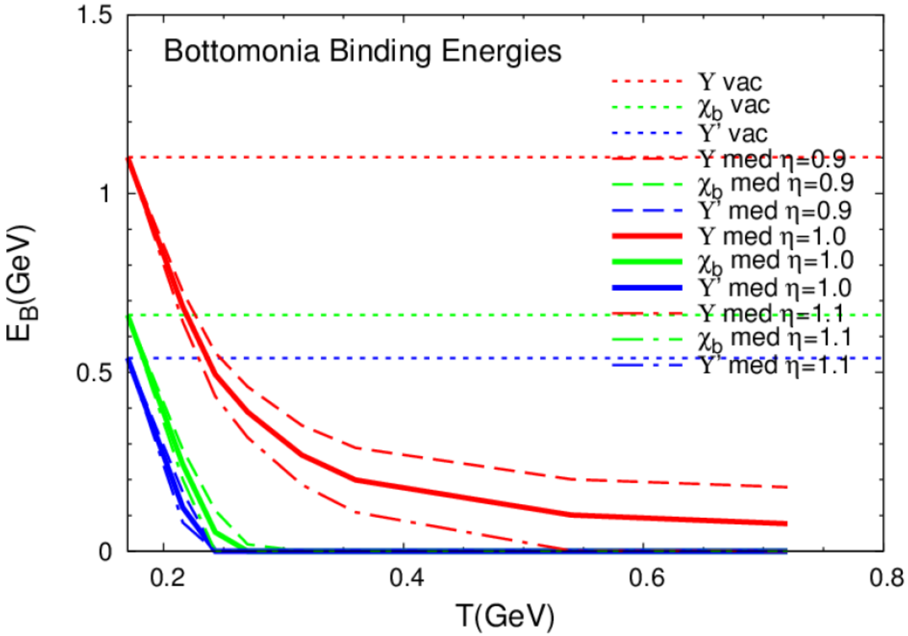
X. Du, M. He, R. Rapp, PRC96 (2017) 054901

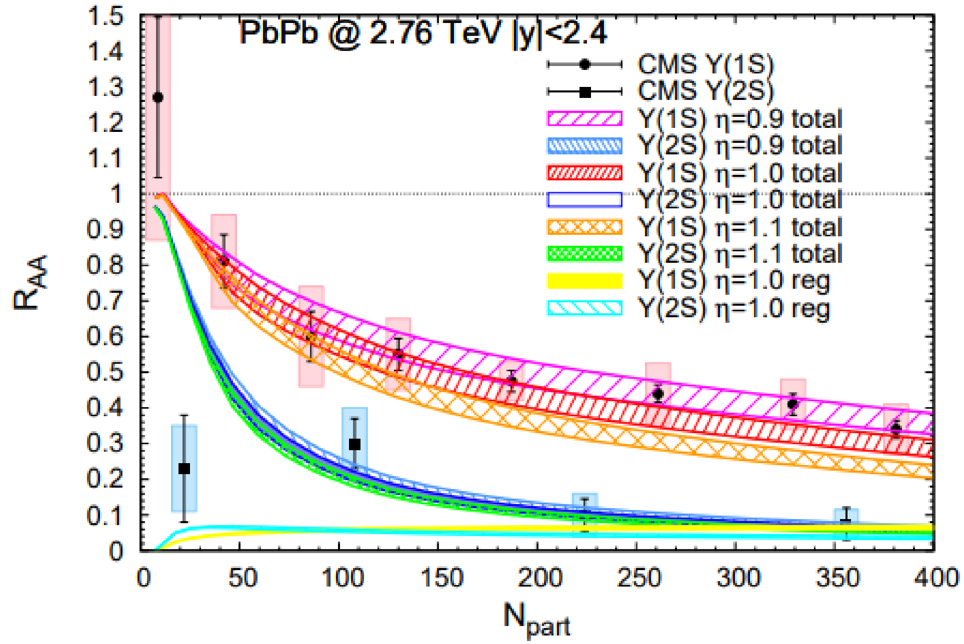


- Hierarchy:
  - ⟶Different Melting temperatures for Y(1S), Y(2S) ..
- Probing In-Medium Potential

Bottomonium: Sensitivity to Binding Energy

Binding Energies → Reaction Rates → (Transport) R_{AA} Observables

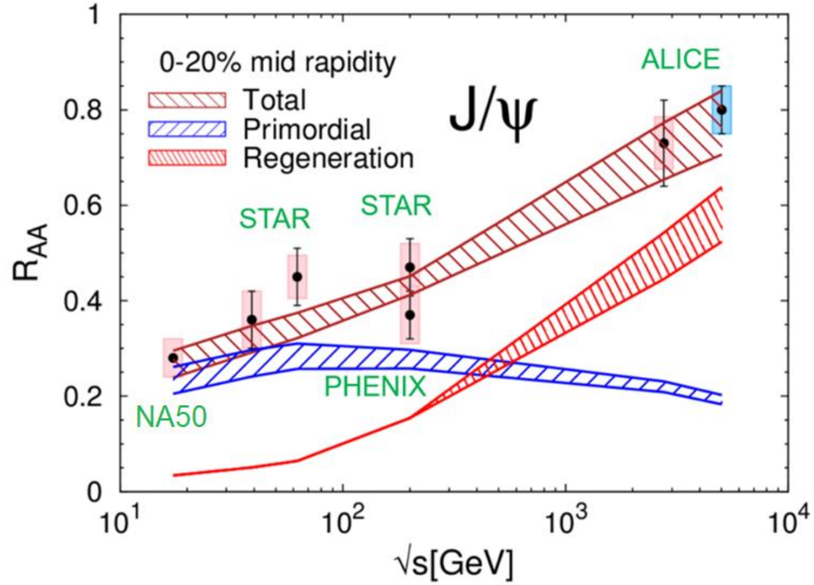


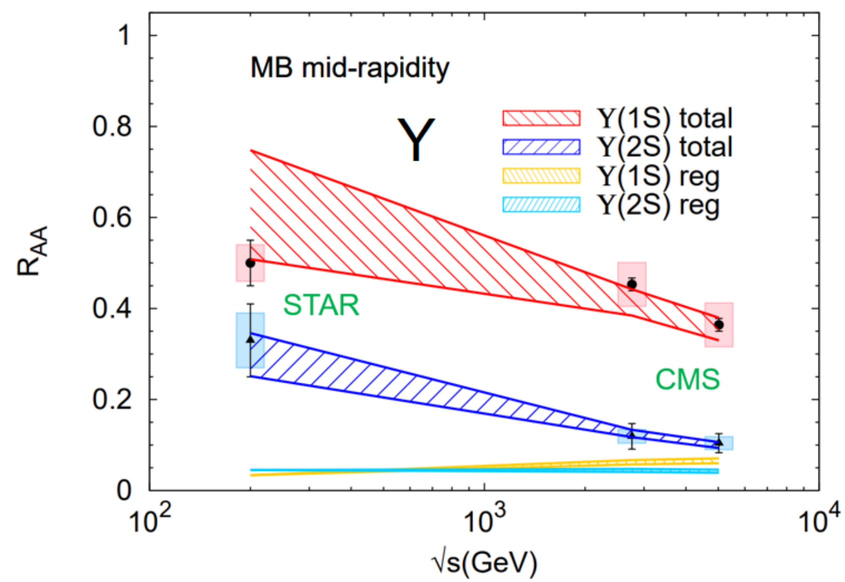


- Significant binding energy dependence of the $\Upsilon(1S)$ R_{AA}

X. Du, M. He, R. Rapp, PRC96 (2017) 054901

Bottomonium: Small Regeneration





R. Rapp, X. Du, NPA967 (2017) 216

- J/ψ Excitation Function:

→ Demonstration of regeneration

- Bottomonia have species

- J/ψ and Υ(2S):

E_{bind}[J/ψ] ≈ E_{bind}[Υ(2S)]

but

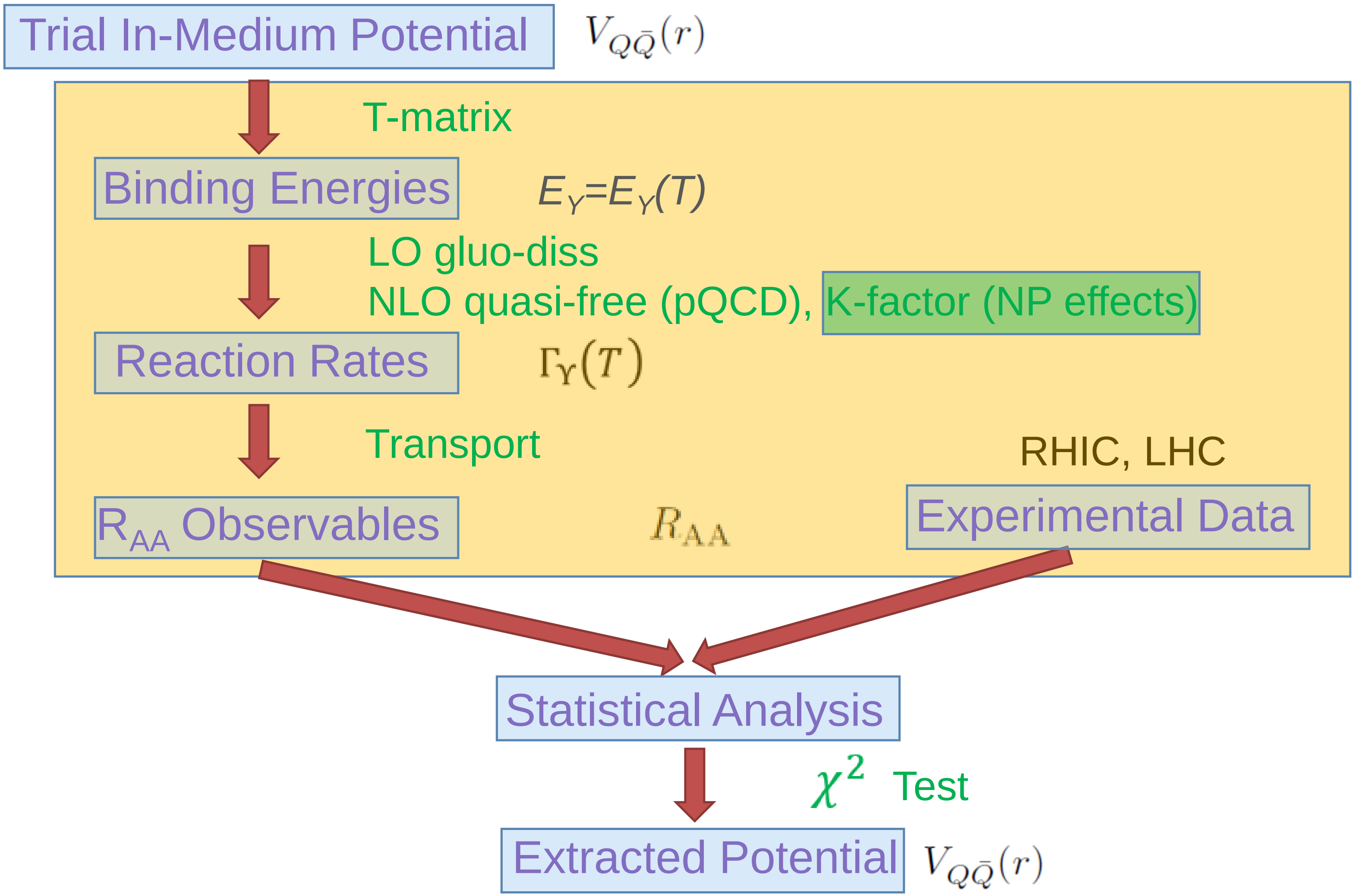
Different excitation functions

→ Due to larger regeneration for J/ψ

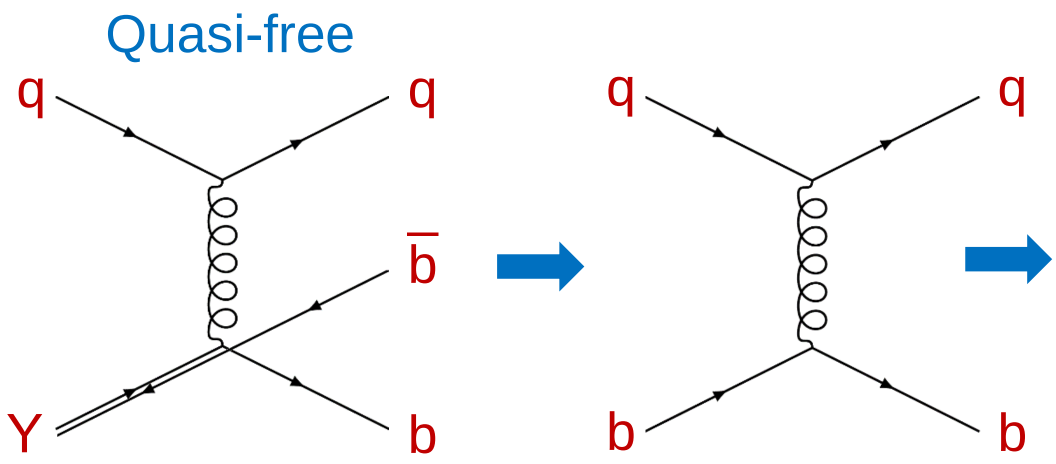
- Bottomonium:

→ Clean and suitable for probing in-medium potential !

Assembly Line



K-factor



same as
perturbative collisional process
in open heavy flavor

K-factor:

- Multiplication to pQCD calculated Reaction Rates
- Accounts for nonperturbative effects
- Open heavy-flavor suggests K-factor > 5

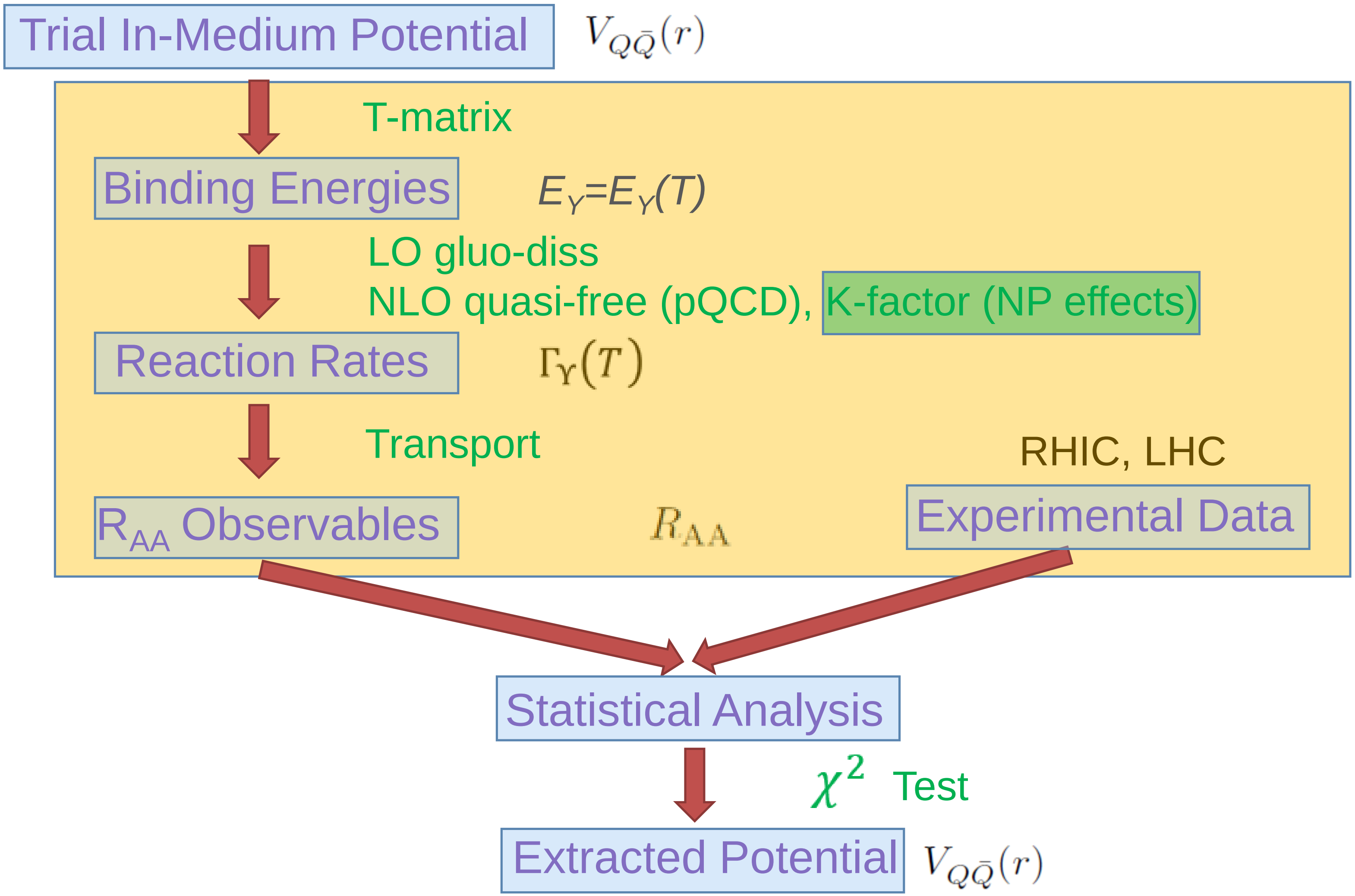
R. Rapp, et al, NPA979 (2018) 21-86
S. Cao ,et al, arXiv: 1809.07894
R. Rapp, arXiv: 1901.06440

Ds(2πT):

•pQCD: ~30

•Required by phenomenology: 2~5

Assembly Line



Trial Potential

$$V_{Q\bar{Q}}(r) = -\frac{4}{3}\alpha_s\left(\frac{e^{-m_D r}}{r} + m_D\right) + \min\left(\sigma r, \frac{\sigma}{m_S}\right)$$

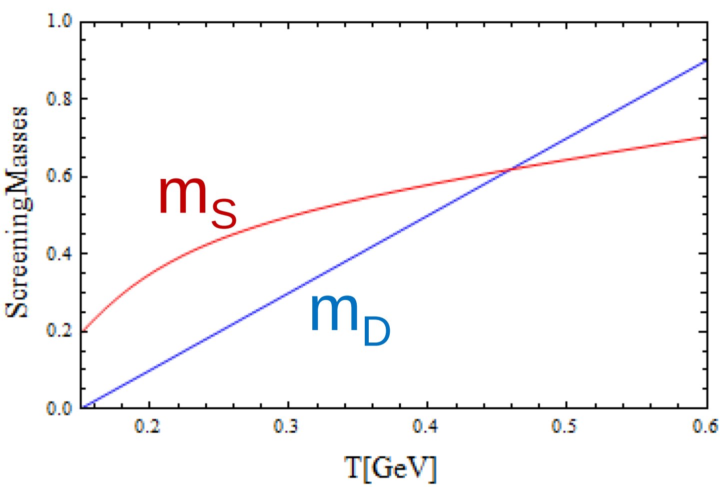
Coulomb

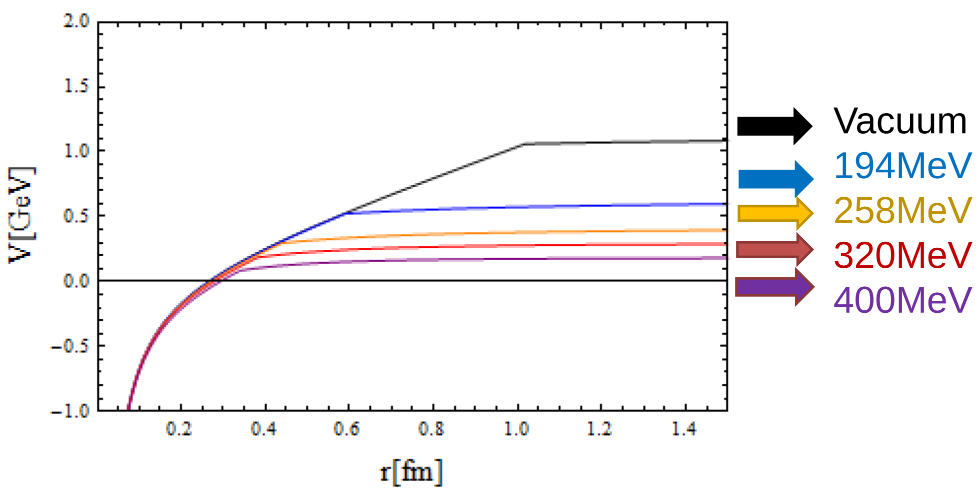
String

Screening Masses

$$m_D = a(T - T_o)$$

$$m_S = m_v + b\left(\sqrt{(T-T_0)^2 + (dT_0)^2} - dT_0\right) - c\left(\sqrt{(T-T_0)^2 + (dT_0)^2} - (T-T_0) - dT_0\right)$$





In relevant parameter space, sensitive parameters: a ($\sim m_D/T$) & b ($\sim m_S/T$ at high-T)

Assembly Line

Trial In-Medium Potential $V_{Q\bar{Q}}(r)$

T-matrix

Binding Energies $E_\Upsilon = E_\Upsilon(T)$

LO gluo-diss

NLO quasi-free (pQCD), K-factor (NP effects)

Reaction Rates $\Gamma_\Upsilon(T)$

Transport

R_{AA} Observables R_{AA}

RHIC, LHC

Experimental Data

Statistical Analysis

χ^2 Test

Extracted Potential $V_{Q\bar{Q}}(r)$

Statistical Analysis: χ^2 Test

Model Calculations with trial potential

$$\chi^2 = \sum_{i=1}^{N} \left(\frac{R_{AA}^{mod}(a,b,c,d) - R_{AA}^{exp}}{\sigma_{exp}} \right)^2$$

Data selection (Bottomonium data):
53 R_{AA} data points from RHIC to LHC energies

Multiple Collision Systems:
193GeV U-U, 200GeV Au-Au, 2.76TeV Pb-Pb, 5.02TeV Pb-Pb.

Multiple Rapidities:
mid-rapidity, forward rapidity.

Multiple Species:
1S,2S,3S,1S+2S+3S,2S+3S,…

Chi-square distribution degree of freedom:
53 data – 4 parameters=49

p-value

Assuming the model is correct, there is p-value chance that the data is at least this discrepancy from the model

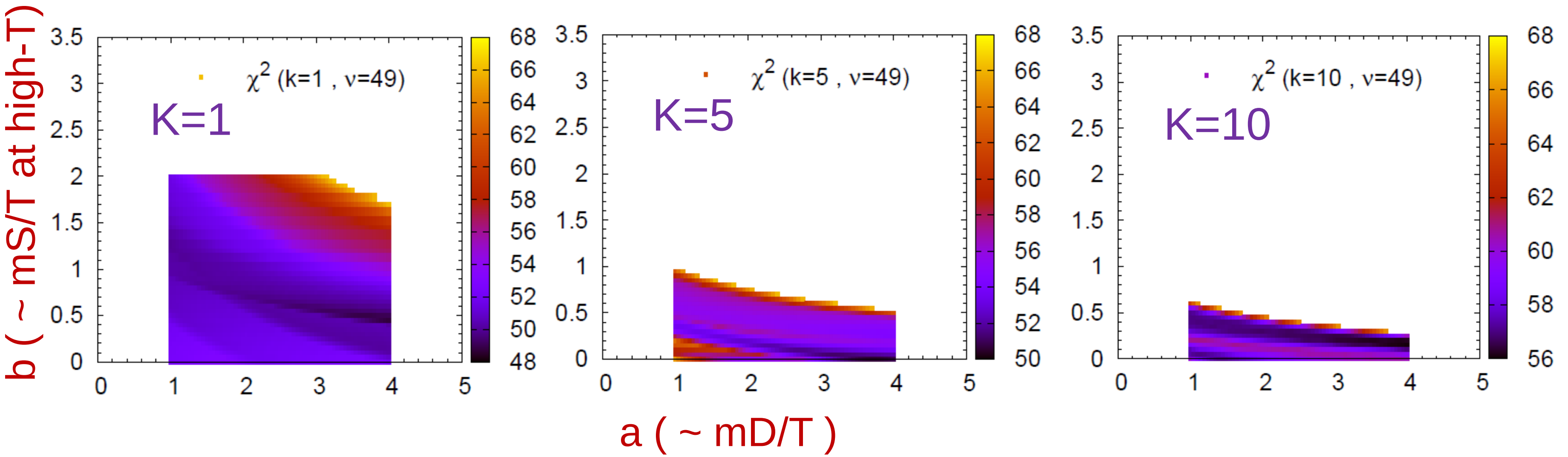
- Larger χ^2 smaller p-value
- Smaller χ^2 larger p-value

Accepted band
95% confidence: p-value>0.05

+

Best fit
Smallest χ^2
Largest p-value

Resultant Parameter Space



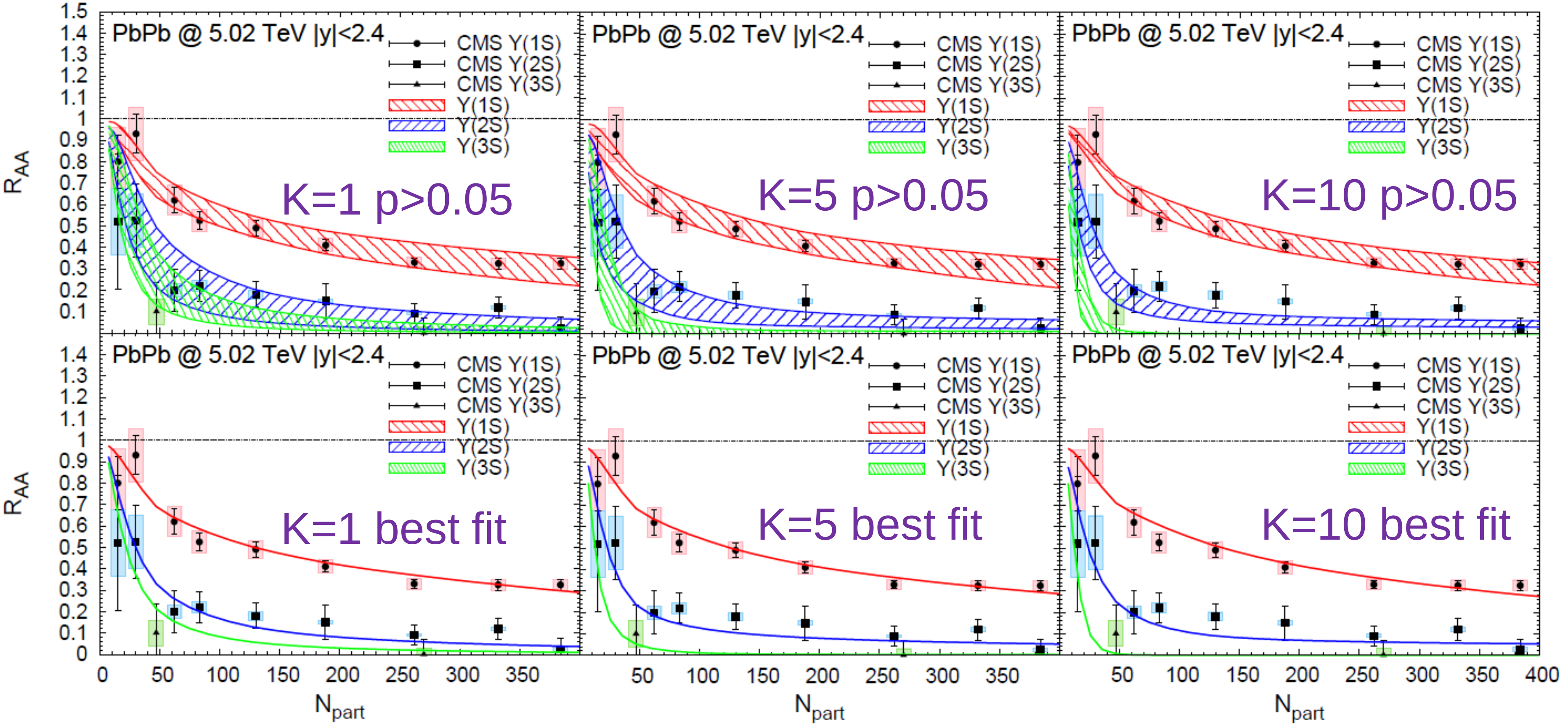
Smaller b → smaller m_S → stronger binding

Larger b → larger m_S → weaker binding

In order to describe data, rates are approximately constant at relevant temperature (<400MeV)

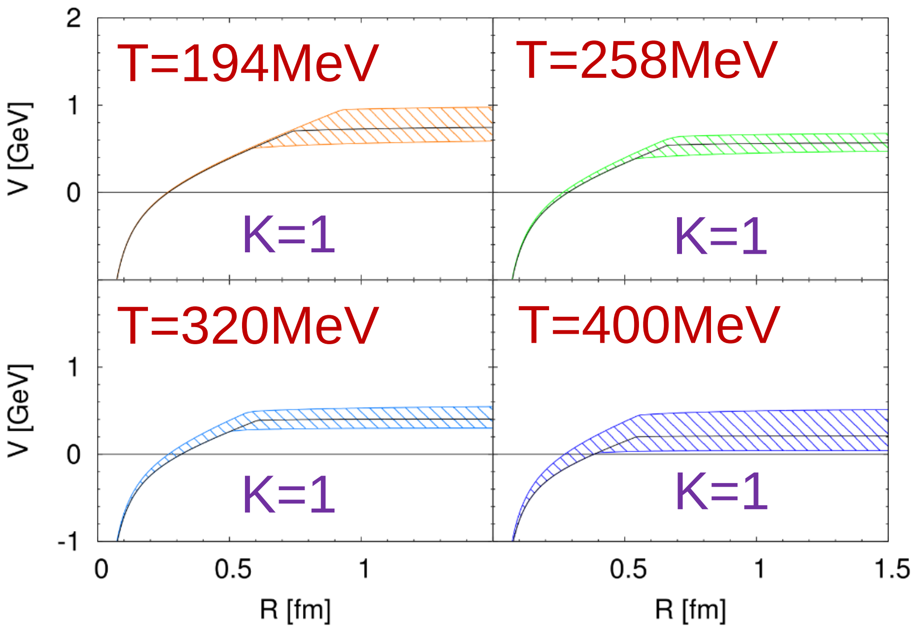
Thus Increasing K-factor requires stronger binding

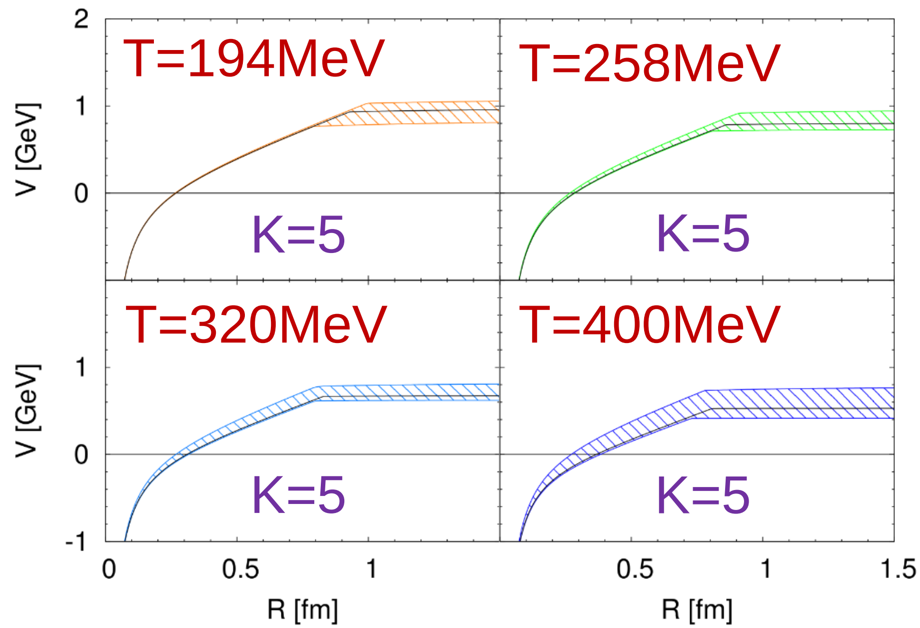
Resultant Bands of R_{AA}s



Good description of data with parameters selected by statistics

Resultant Bands of In-Medium Potential





$V^{best\text{-}fit}(r=1fm)$	K=1	K=5
T=194MeV	730MeV	940MeV
T=320MeV	400MeV	670MeV

K=1: allows for both weak/strong binding
K=5: suggests strong binding
K=10: even stronger..

Summary

- Bottomonium is ideal for probing the in-medium potential
  → R_{AA} observable is sensitive to in-medium potential
  → Has small regeneration contribution
  → Allows for more species (potentially more data constraints)

- Integration of open/hidden heavy flavor is important
  → A large K-factor is needed accounting for nonperturbative effects

- In-medium heavy-quark potential is strong
  → Statistics tell the story

Thank you!