Extracting the Heavy-Quark Potential from Bottomonium Observables in Heavy-Ion Collisions

Xiaojian Du

In collaboration with Shuai Liu, Ralf Rapp

Cyclotron Institute and Department of Physics and Astronomy
Texas A&M University

Seminar
Brookhaven National Laboratory
Upton, NY
2019.07.09

TEXAS A&M UNIVERSITY

Outline

X. Du, S. Liu, R. Rapp, submitted to PLB

- Our Motivation: Learning QCD Force
    - Why quarkonium? What to expect from it?
- Our Tools: Quarkonium Transport Approach
    - Transport equation
    - Key coefficients, parameters and inputs
    - Probing strong/QCD force/potential with quarkonium
- We've learned: Quarkonium Production in A-A Collisions
    - J/ψ production: $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, $R_{AA}(\sqrt{s})$, …
    - Υ(1S,2S,3S) production : $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, …
    - Comparison between charmonium and bottomonium: $R_{AA}(\sqrt{s})$, …
    - Υ(1S) as a probe of in-medium heavy quark-antiquark potential
- We are learning: Extraction of In-Medium Heavy Quark-Antiquark Potential
    - Joint study of heavy quark (open heavy flavor)/quarkonium (hidden heavy flavor)
    - Selecting relevant data points
    - Indicating a strong potential
- Summaries

Outline

- Our Motivation: Learning QCD Force
  - Why quarkonium? What to expect from it?

X. Du, S. Liu, R. Rapp, submitted to PLB

- Our Tools: Quarkonium Transport Approach
  - Transport equation
  - Key coefficients, parameters and inputs
  - Probing strong/QCD force/potential with quarkonium
- We've learned: Quarkonium Production in A-A Collisions
  - J/ψ production: $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, $R_{AA}(\sqrt{s})$, …
  - Υ(1S,2S,3S) production : $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, …
  - Comparison between charmonium and bottomonium: $R_{AA}(\sqrt{s})$, …
  - Υ(1S) as a probe of in-medium heavy quark-antiquark potential
- We are learning: Extraction of In-Medium Heavy Quark-Antiquark Potential
  - Joint study of heavy quark (open heavy flavor)/quarkonium (hidden heavy flavor)
  - Selecting relevant data points
  - Indicating a strong potential
- Summaries

Quarkonium as Probe of Potential/Force

Heavy quarkonia ($Q\bar{Q}$ bound states), J/ψ, ψ(2S), ϒ(1S), ϒ(2S), ...as probes:

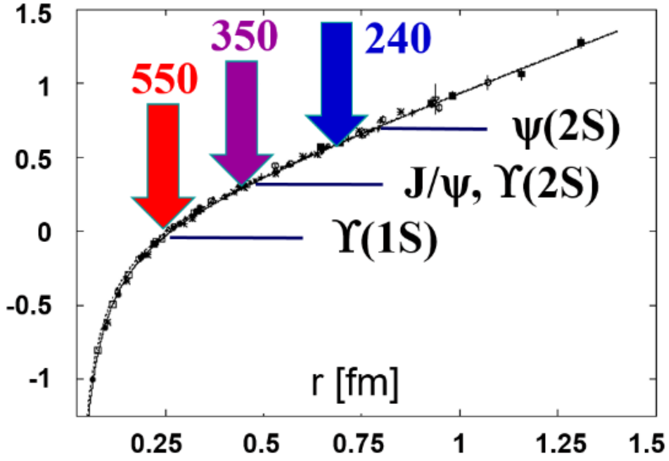
1. Hard scale (m >> T_{QGP}): pQCD baseline for primordial production
2. (Ultra-)Soft scale (v^2<<v<< 1): nonrelativistic potential picture works
3. Large binding ($E_{BINDING}$~mv^2>Tc): survive in QGP
4. Various species: bound at different parts of potential

Expect to be ideal for probing:

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

LHC RHIC SPS

T_0 T_0 T_0



Observables:

Nuclear Modification Factor (R_{AA})

$$R_{AA} = \frac{N_Y^{AA}}{N_{coll} N_Y^{pp}}$$

Elliptic Flow (v_2)

$$\frac{d^2N}{d^2p_T} = \frac{1}{2\pi}\frac{dN(p_T)}{p_T dp_T}(1 + 2v_2(p_T)\cos(2\phi) + \dots)$$

Outline

X. Du, S. Liu, R. Rapp, submitted to PLB

- Our Motivation: Learning QCD Force
  - Why quarkonium? What to expect from it?
- Our Tools: Quarkonium Transport Approach
  - Transport equation
  - Key coefficients, parameters and inputs
  - Probing strong/QCD force/potential with quarkonium
- We've learned: Quarkonium Production in A-A Collisions
  - J/ψ production: $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, $R_{AA}(\sqrt{s})$, …
  - ϒ(1S,2S,3S) production : $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, …
  - Comparison between charmonium and bottomonium: $R_{AA}(\sqrt{s})$, …
  - ϒ(1S) as a probe of in-medium heavy quark-antiquark potential
- We are learning: Extraction of In-Medium Heavy Quark-Antiquark Potential
  - Joint study of heavy quark (open heavy flavor)/quarkonium (hidden heavy flavor)
  - Selecting relevant data points
  - Indicating a strong potential
- Summaries

Transport Equation Approach

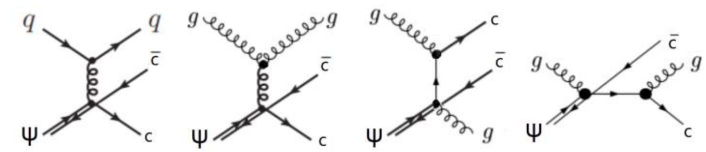
Kinetic Rate Equation

$$\frac{\mathrm{d}N_\Psi(\tau)}{\mathrm{d}\tau} = -\Gamma_\Psi(T(\tau))\left[N_\Psi(\tau) - N_\Psi^{\mathrm{eq}}(T(\tau))\right]$$

Primordial — Regeneration

Transport Coefficients

- Reaction Rates $\Gamma_\Psi(T(\tau))$ → NLO Quasi-Free, LO Gluo-Diss



- Equilibrium Limits $N_\Psi^{\mathrm{eq}}(T(\tau))$ → From Heavy quark conservation

$$N_\Psi^{\mathrm{eq}} = V_{\mathrm{FB}}\gamma_c^2 d_\Psi \int \frac{d^3p}{(2\pi)^3} f_\Psi^{\mathrm{eq}}(E_p;T)$$

Key Parameters

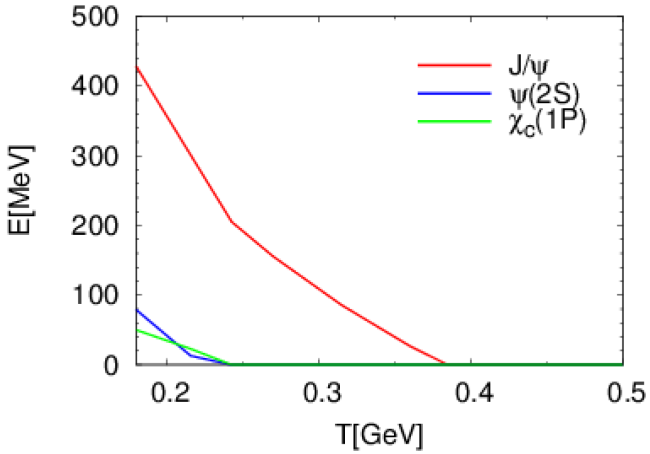
- Coupling α_s → Affects Reaction Rates. Fixed from Previous Calculations compared with data
- Thermal Relaxation Time → Modifies Equilibrium Limit. Extracted from Heavy Quark Diffusion Simulations

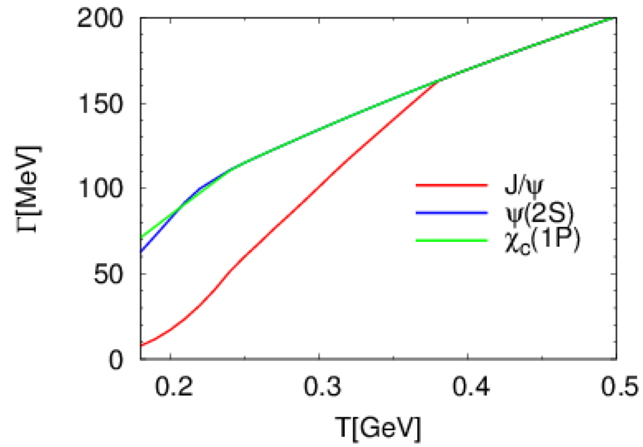
Key Inputs

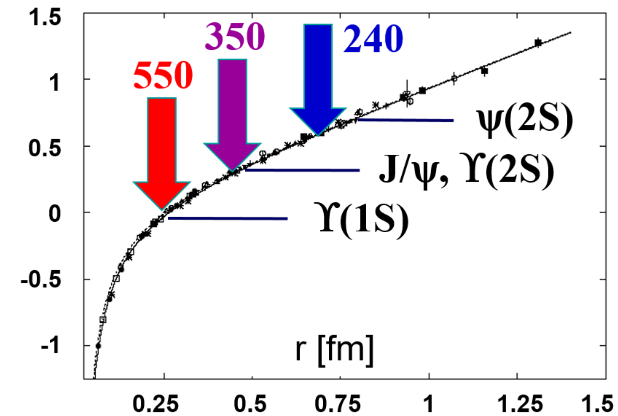
- In-Medium $Q\bar{Q}$ Potential/Binding Energy
- Heavy Quark/-onium pp Cross Section -> fugacity factor γ_c
- Initial State Effects (nPDF)
- Fireball Evolution

From Strong Force to Observables

In-Medium $Q\bar{Q}$ Potential → Quarkonium Binding Energies → Reaction Rates $\Gamma_\Psi(T(\tau))$ → Transport Model → Observables







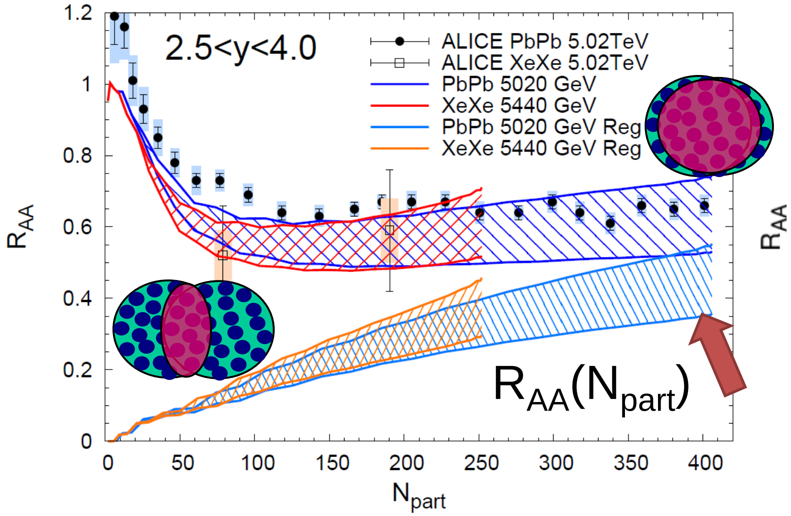
- Hierarchy:
  - →Different Melting temperatures for J/ψ, ψ(2S), ...
    Sequential Suppression …
    Sequential Regeneration ? …
- Probing In-Medium Potential

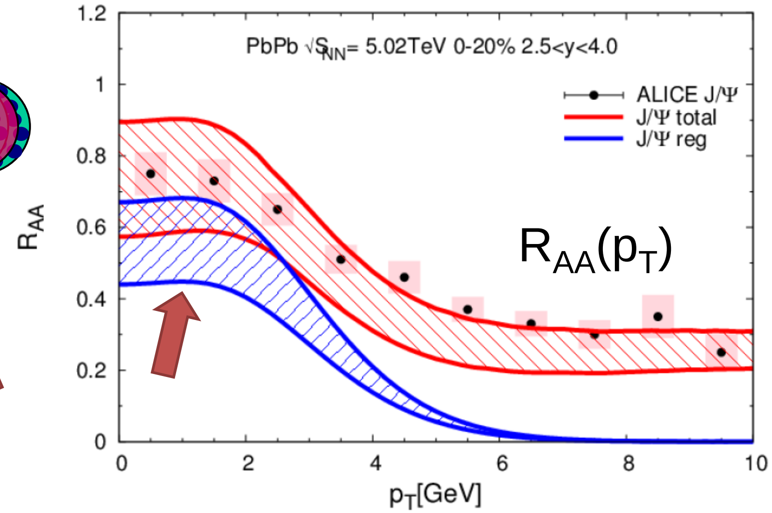
Outline

X. Du, S. Liu, R. Rapp, submitted to PLB

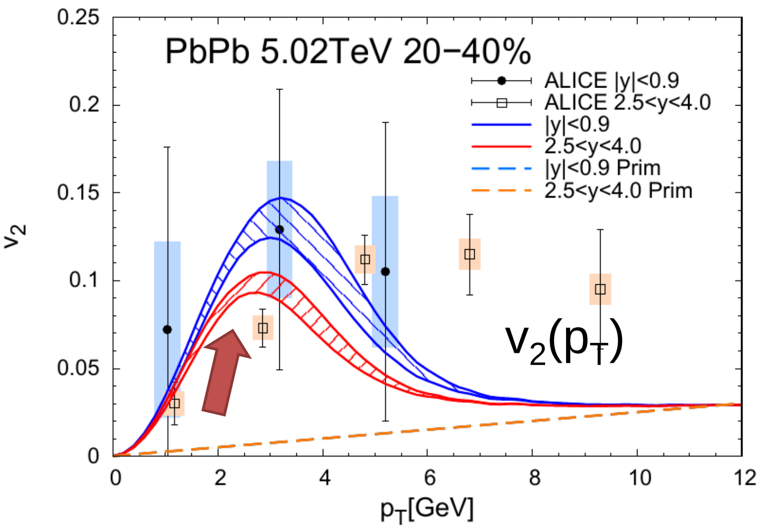
- Our Motivation: Learning QCD Force
  - Why quarkonium? What to expect from it?
- Our Tools: Quarkonium Transport Approach
  - Transport equation
  - Key coefficients, parameters and inputs
  - Probing strong/QCD force/potential with quarkonium
- We've learned: Quarkonium Production in A-A Collisions
  - J/ψ production: $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, $R_{AA}(\sqrt{s})$, …
  - ϒ(1S,2S,3S) production : $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, …
  - Comparison between charmonium and bottomonium: $R_{AA}(\sqrt{s})$, …
  - ϒ(1S) as a probe of in-medium heavy quark-antiquark potential
- We are learning: Extraction of In-Medium Heavy Quark-Antiquark Potential
  - Joint study of heavy quark (open heavy flavor)/quarkonium (hidden heavy flavor)
  - Selecting relevant data points
  - Indicating a strong potential
- Summaries

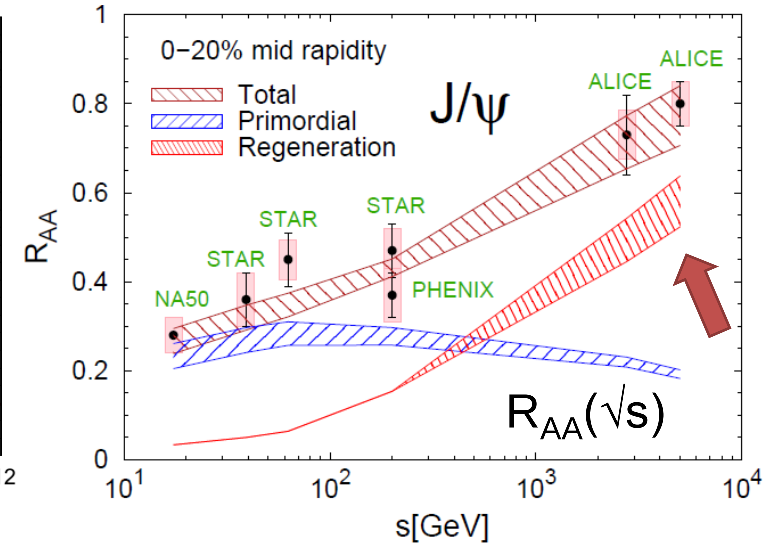
J/ψ Production in AA





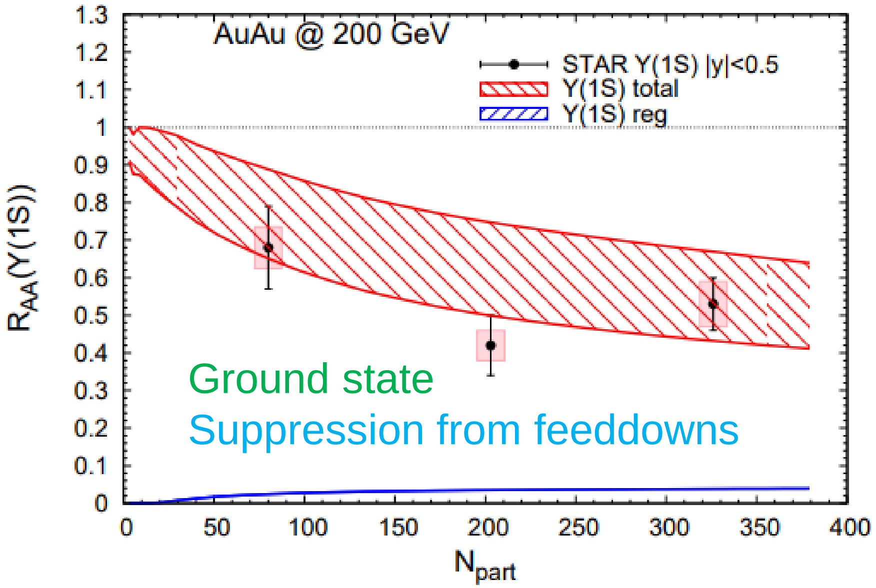
See:
PLB785 (2018) 419
ALI-PREL-126572
PRL119 (2017) 242301
…

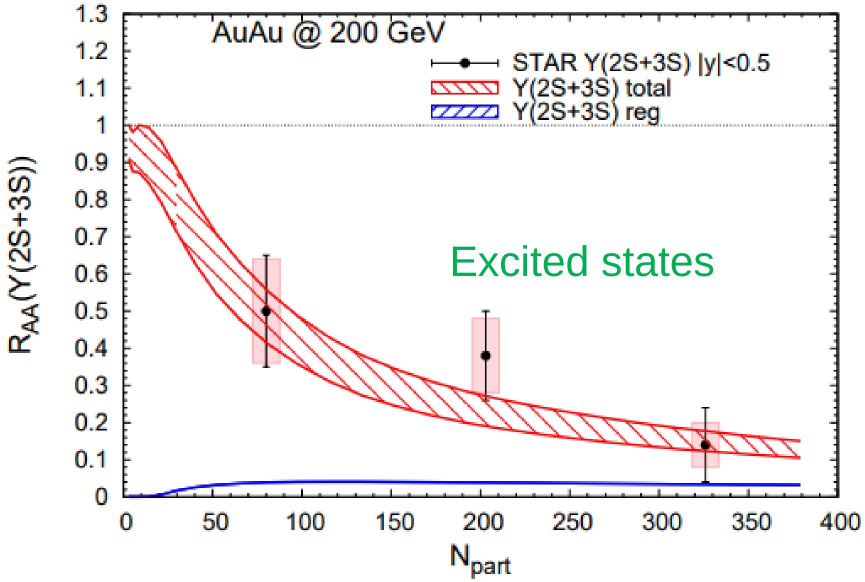




Charmonium
Large
Regeneration

Bottomonium $R_{AA}(N_{part})$ at RHIC

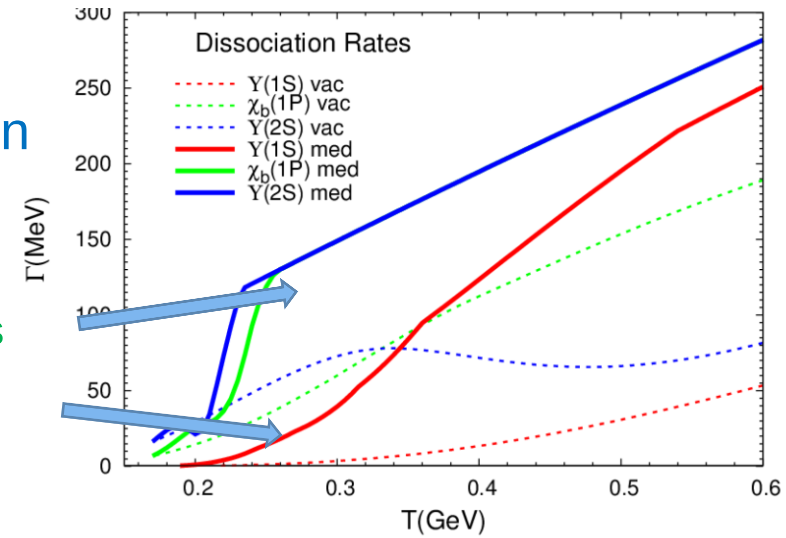


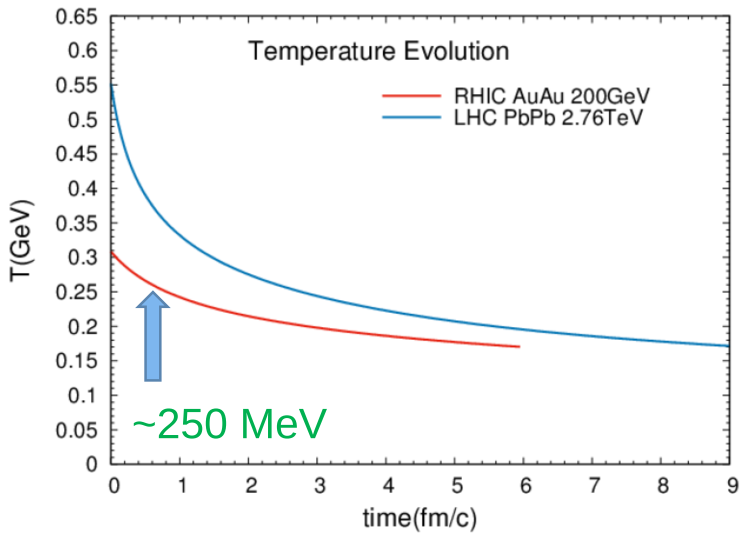


Sequential Suppression

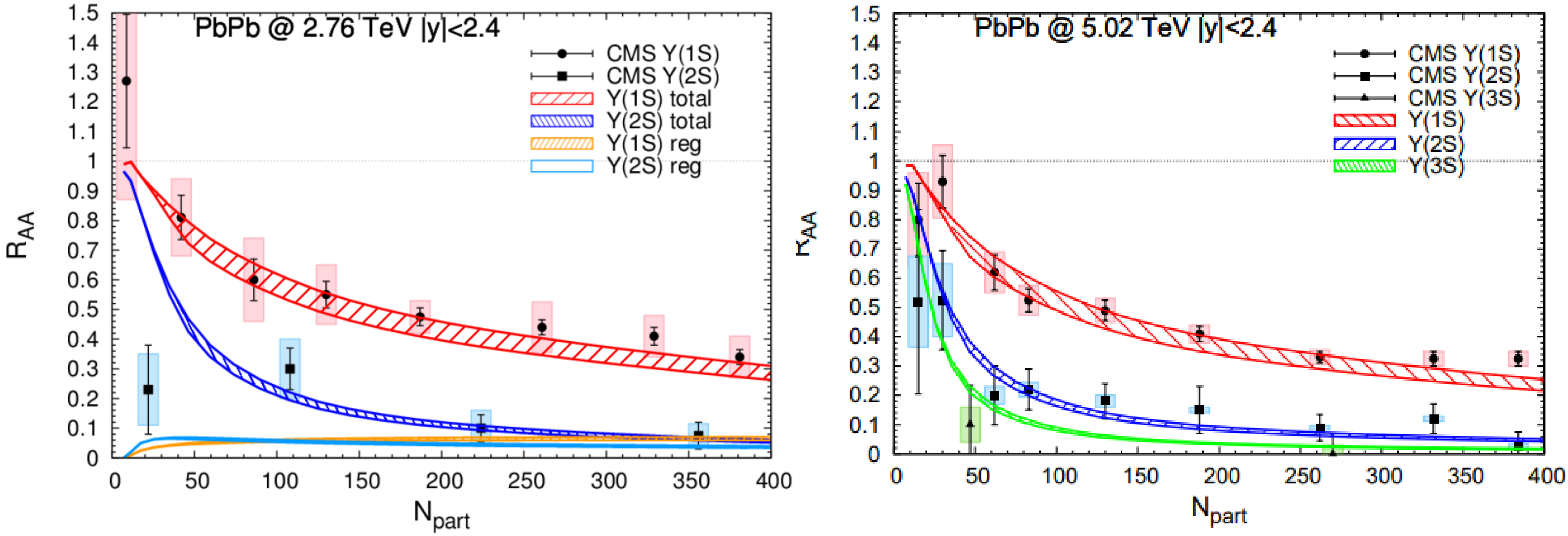
Excited states

Ground state



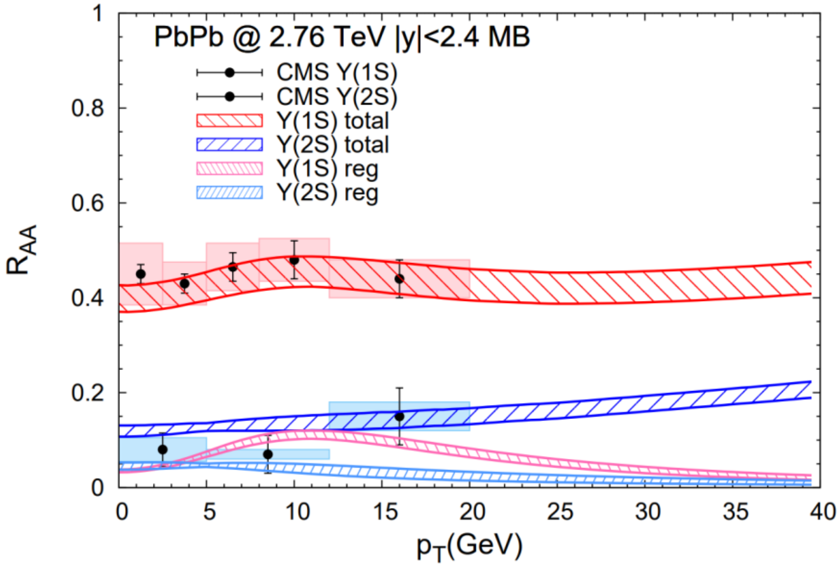


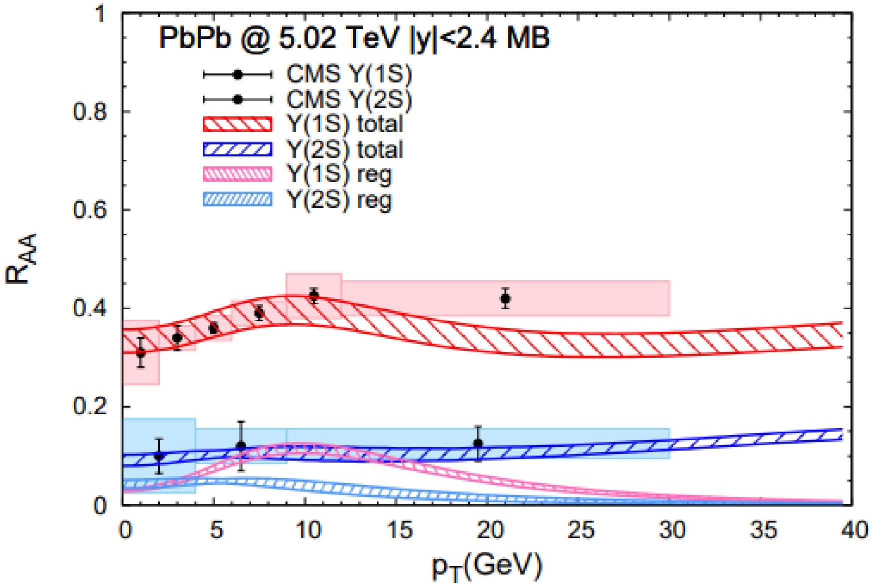
Bottomonium $R_{AA}(N_{part})$ at the LHC

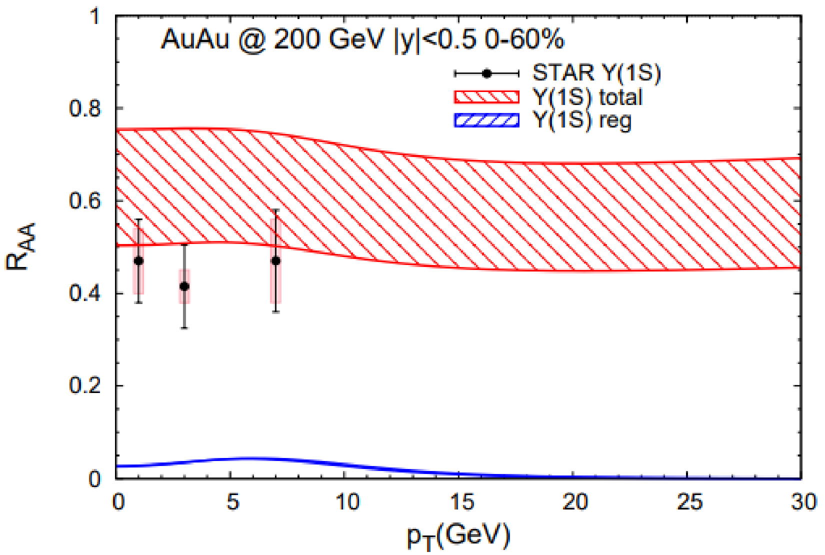


- Sequential suppression
- Direct Υ(1S) suppression, small regeneration
- Regeneration may not be negligible for Υ(2S)

Bottomonium $R_{AA}(p_T)$

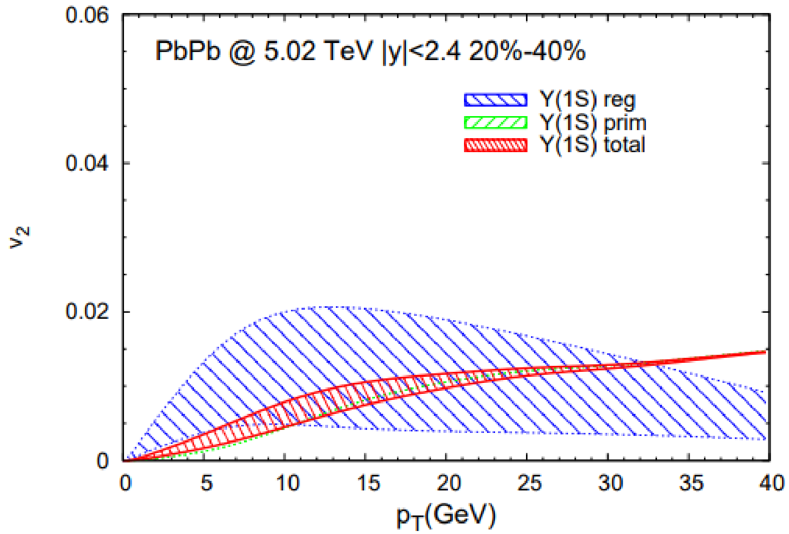


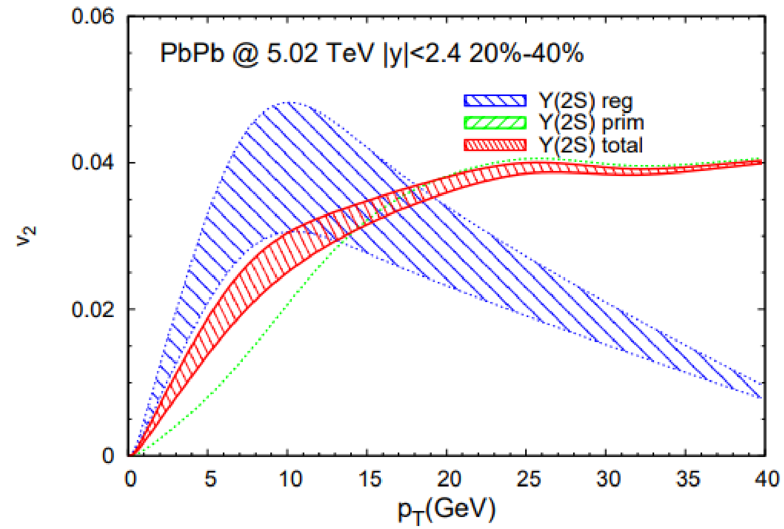




- No peak at low-p_T
- Non-thermalized b-quarks induces small p_T-dependence for bottomonium

Bottomonium $v_2(p_T)$ at LHC

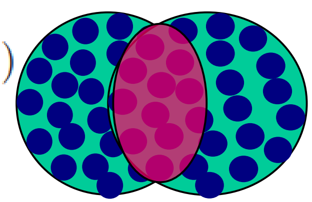


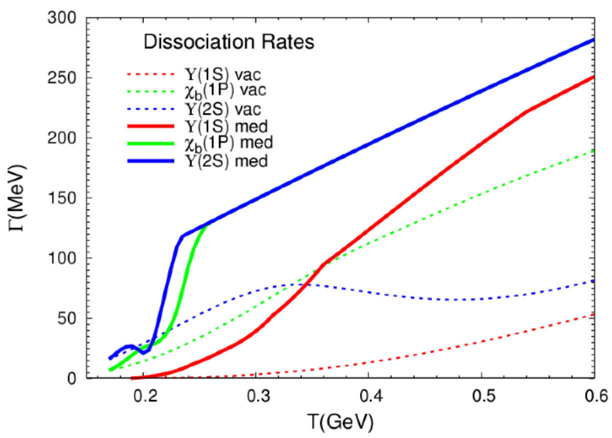


elliptic flow v_2:

Anisotropy of production

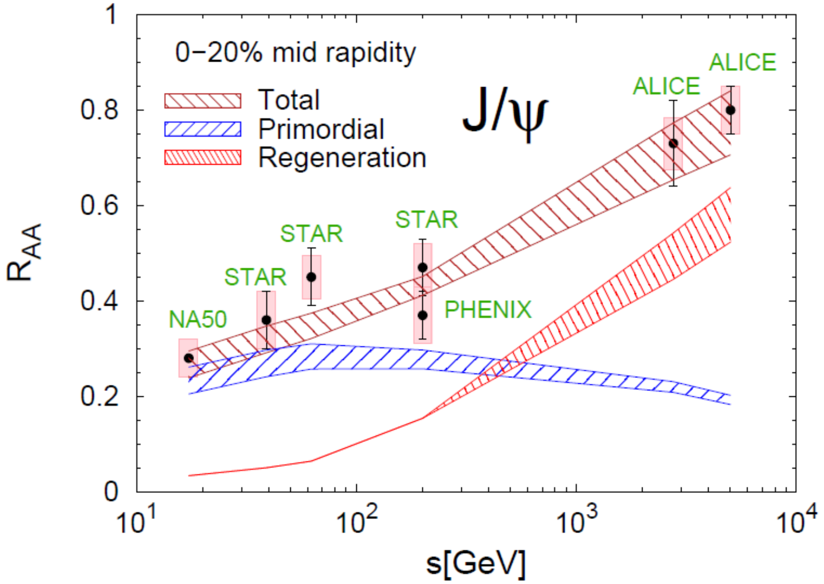
$$\frac{d^2N}{d^2p_T} = \frac{1}{2\pi}\frac{dN(p_T)}{p_T dp_T}(1 + 2v_2(p_T)\cos(2\phi) + \ldots)$$



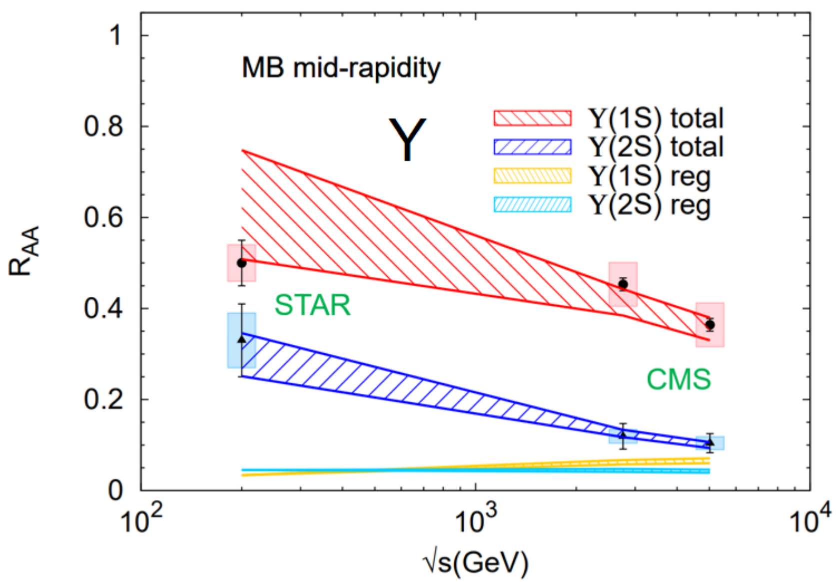


Both destruction and coalescence occur early for Υ(1S), later for Υ(2S)

Difference of Charmonium/Bottomonium



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



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

Charm/Bottom-onium difference:

Charmonium:

→ Large regeneration

Bottomonium:

→ Small regeneration

J/ψ and Υ(2S):

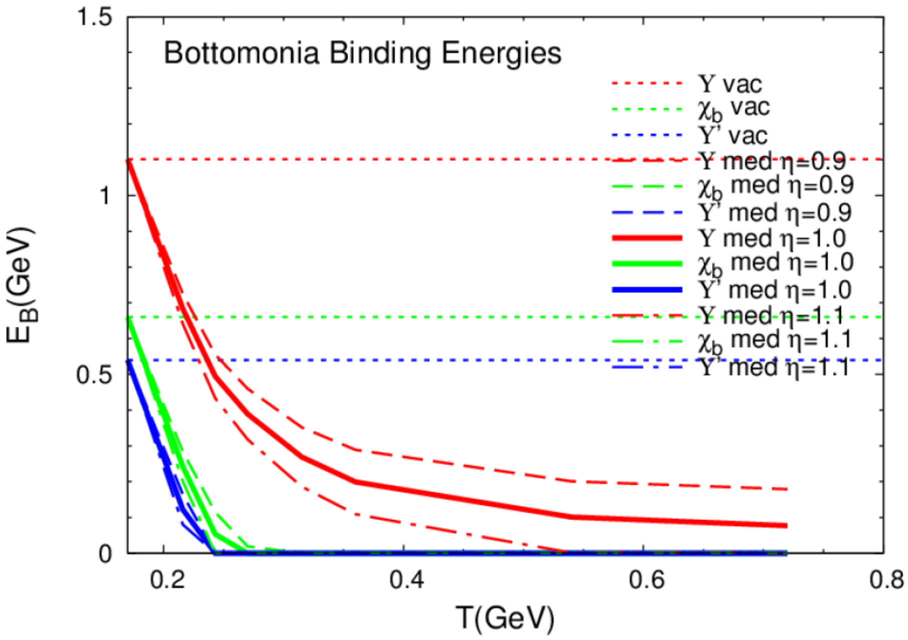
Similar binding energies

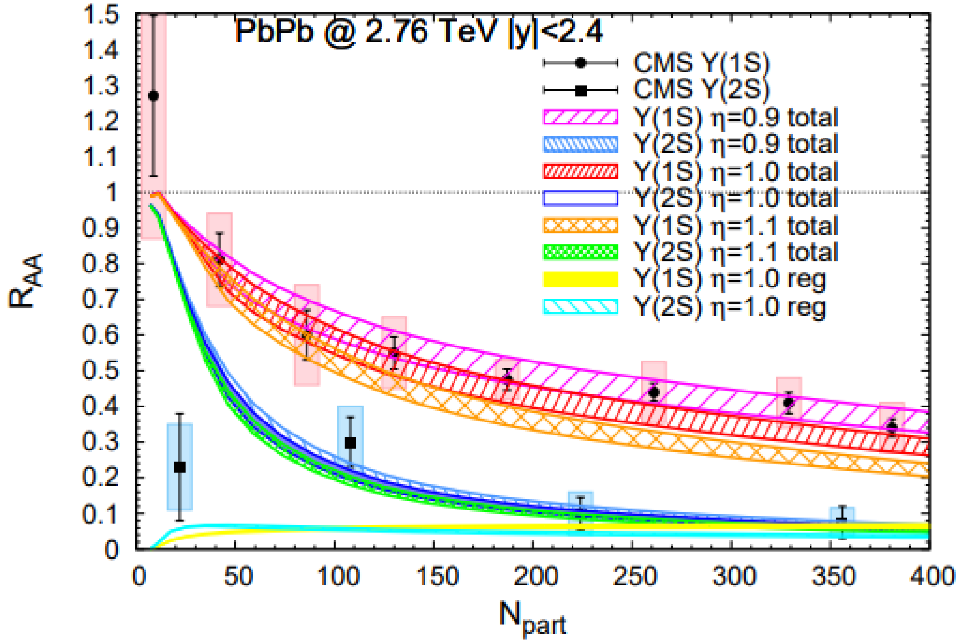
BUT

Different excitation functions

→ Due to Large regeneration for J/ψ

Υ(1S) as a Probe of In-Medium Potential





Again: Potential→ Binding Energies → Reaction Rates → R_{AA} Observables

- Significant binding energy dependence of the Υ(1S) R_{AA}
- Small regeneration (clean probe)

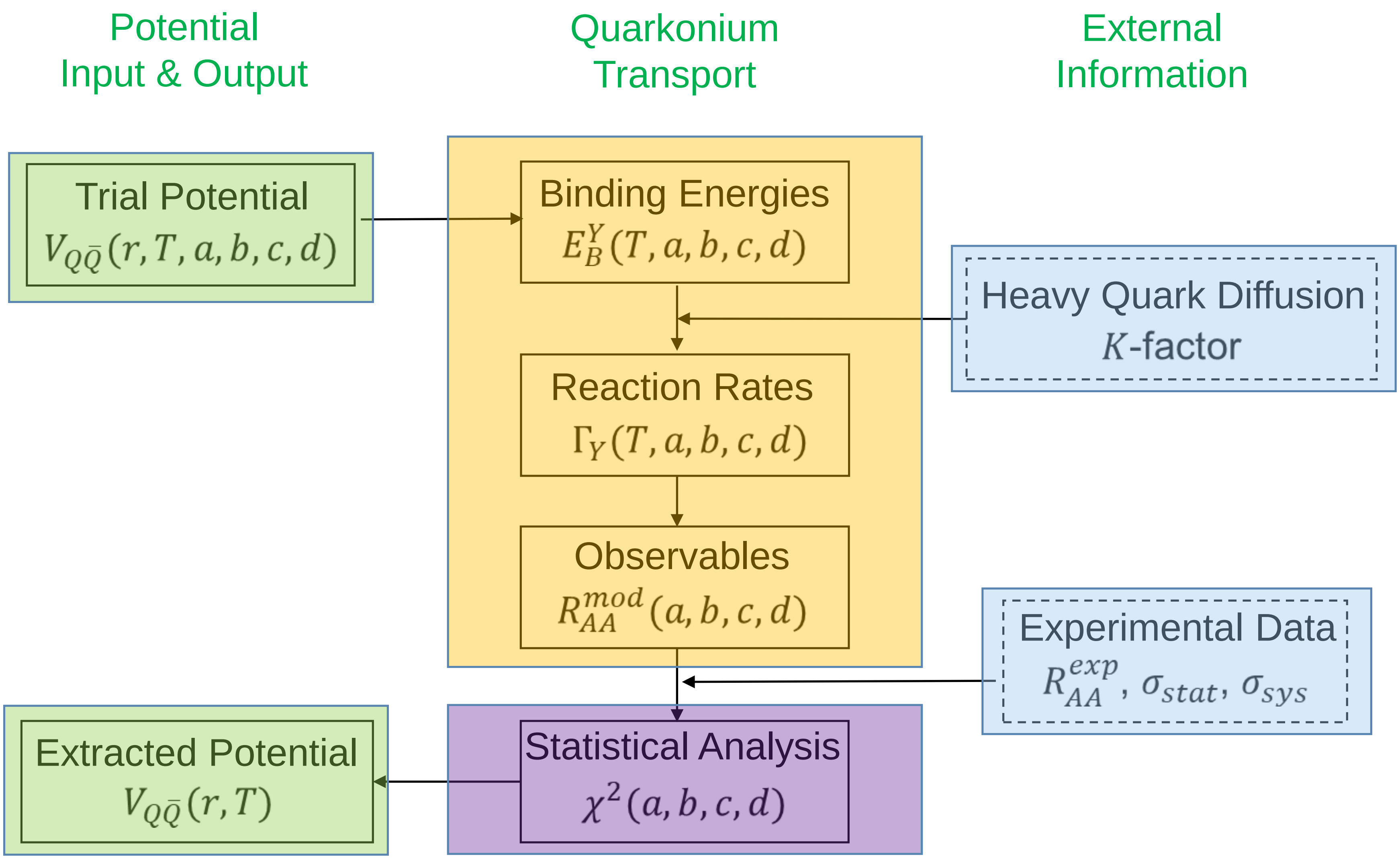
Υ(1S) is ideal for probing in-medium $Q\bar{Q}$ potential

Outline

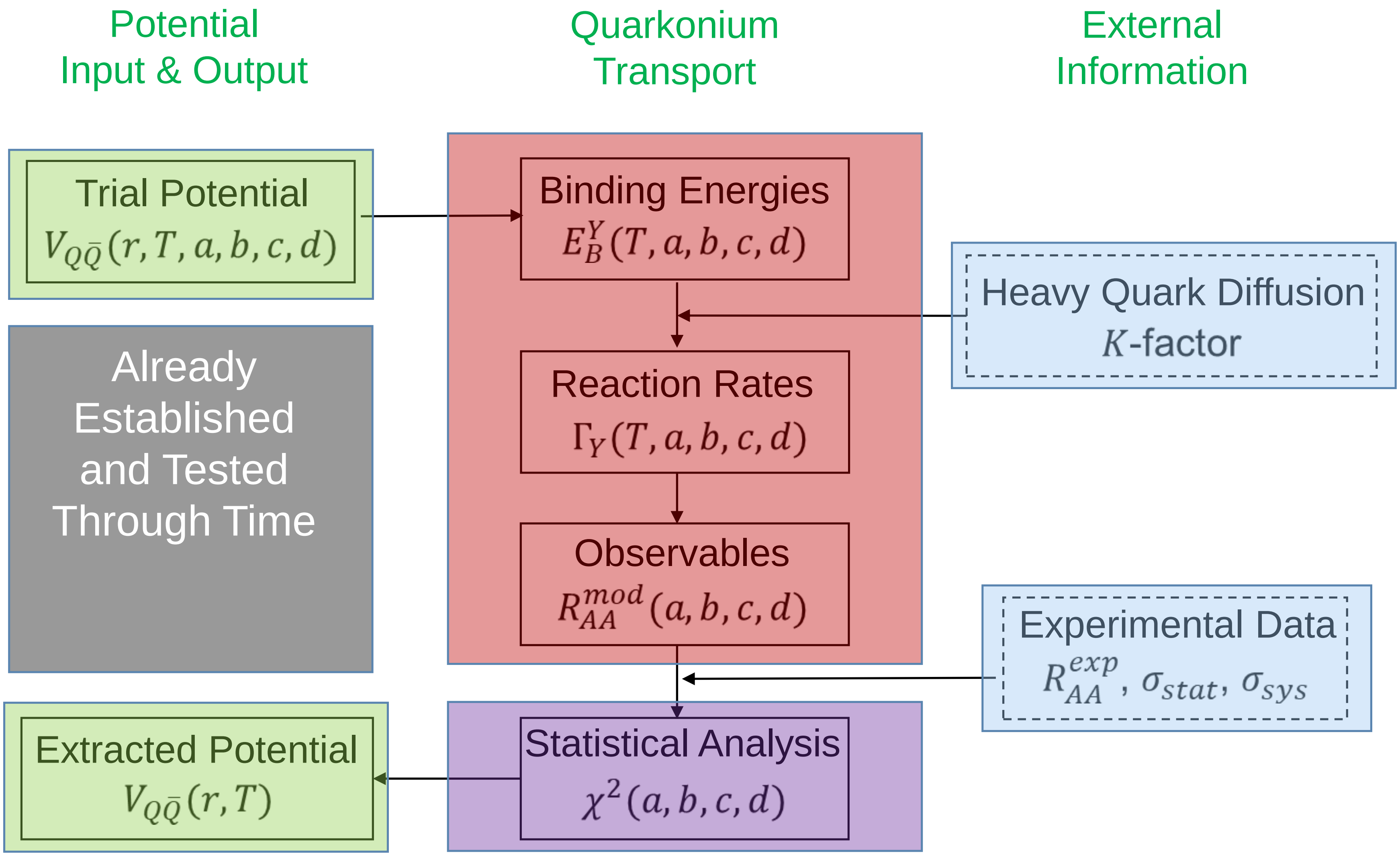
X. Du, S. Liu, R. Rapp, submitted to PLB

- Our Motivation: Learning QCD Force
  - Why quarkonium? What to expect from it?
- Our Tools: Quarkonium Transport Approach
  - Transport equation
  - Key coefficients, parameters and inputs
  - Probing strong/QCD force/potential with quarkonium
- We've learned: Quarkonium Production in A-A Collisions
  - J/ψ production: $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, $R_{AA}(\sqrt{s})$, …
  - Υ(1S,2S,3S) production : $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, …
  - Comparison between charmonium and bottomonium: $R_{AA}(\sqrt{s})$, …
  - Υ(1S) as a probe of in-medium heavy quark-antiquark potential
- We are learning: Extraction of In-Medium Heavy Quark-Antiquark Potential
  - Joint study of heavy quark (open heavy flavor)/quarkonium (hidden heavy flavor)
  - Selecting relevant data points
  - Indicating a strong potential
- Summaries

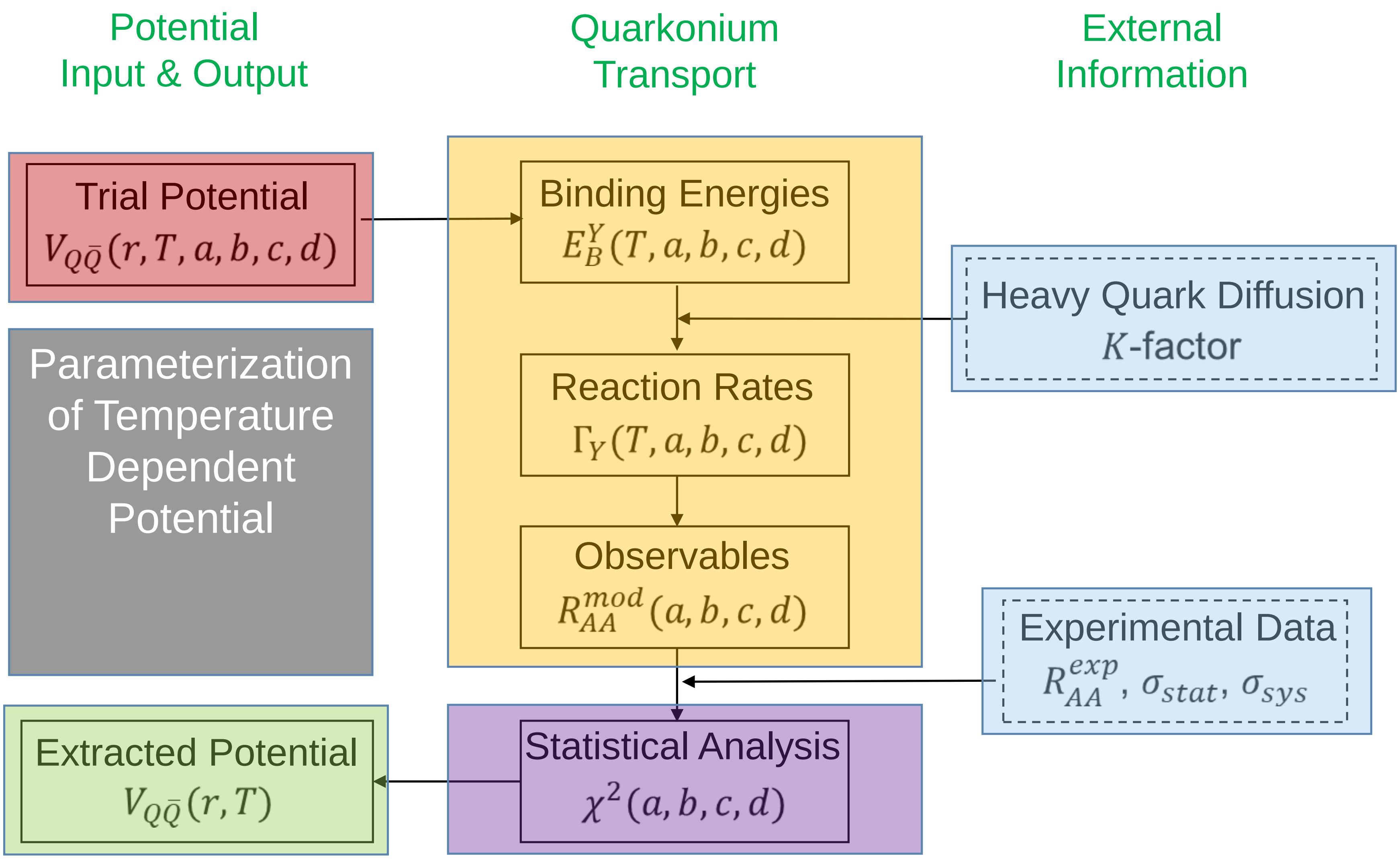
Extracting In-Medium Potential



Extracting In-Medium Potential



Extracting In-Medium Potential



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

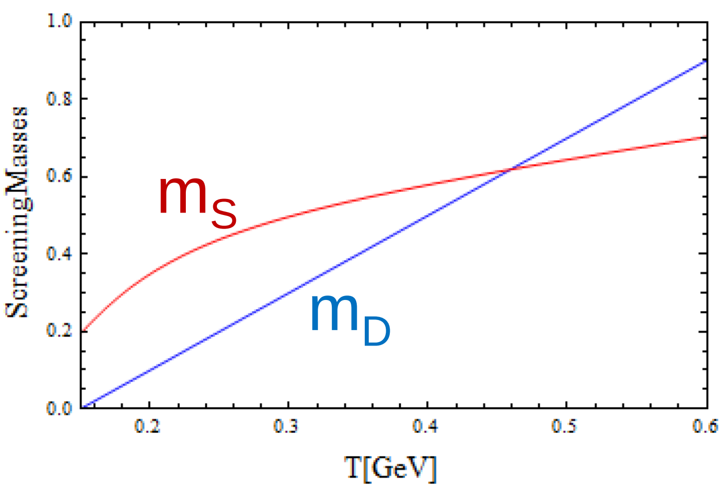
String

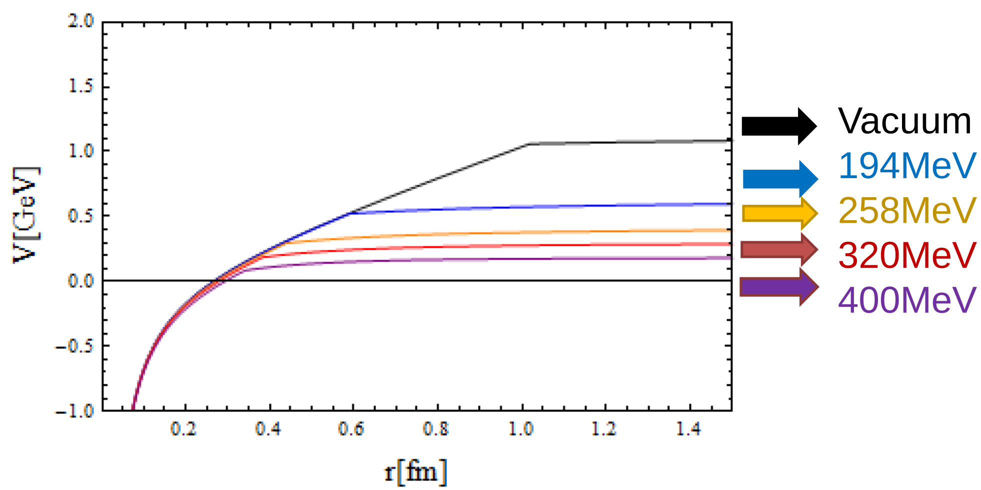
α_s, σ
Fit to vacuum spectroscopy

Screening Masses

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

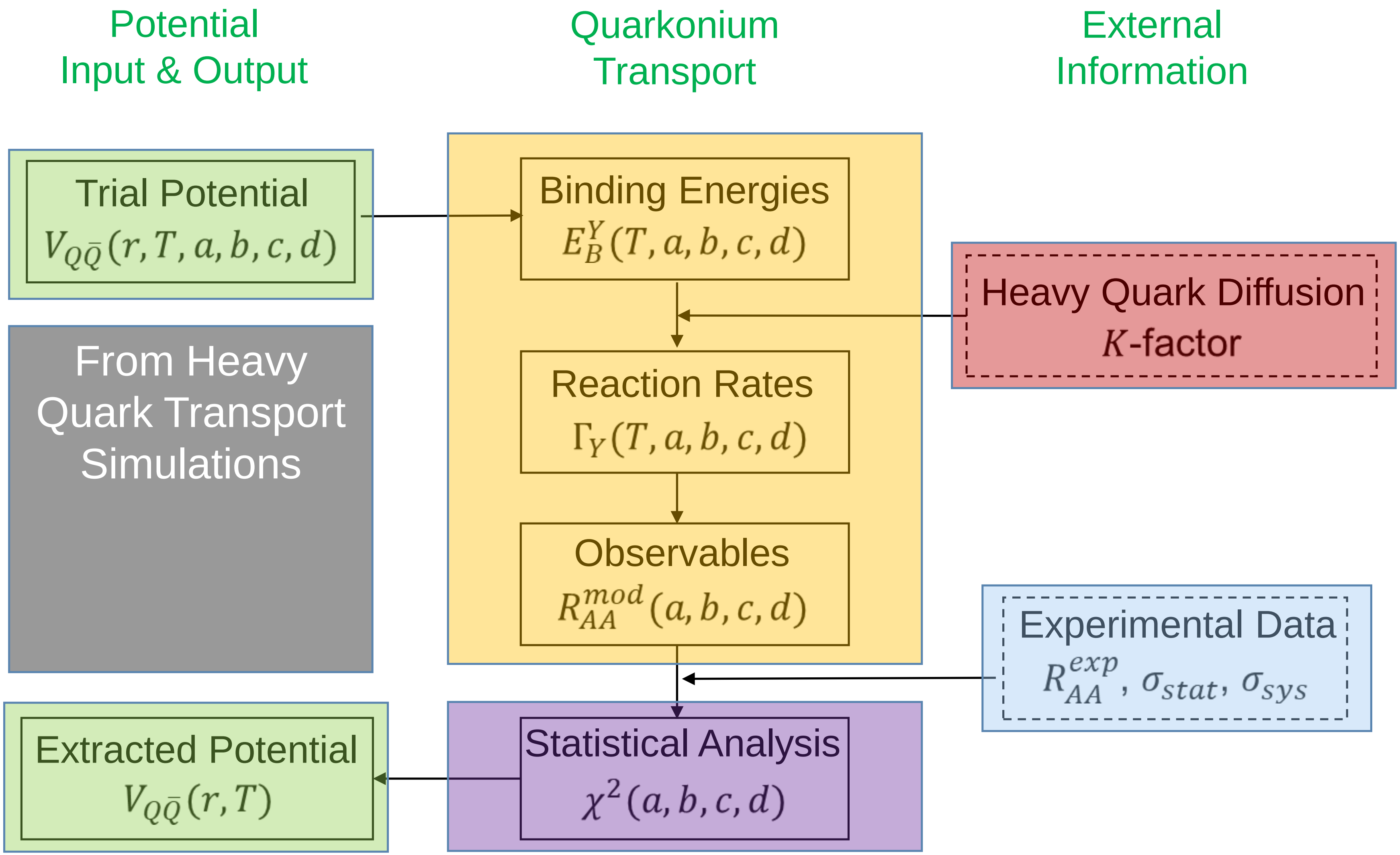
$$m_S = m_v + b\left(\sqrt{(T-T_0)^2 + (dT_0)^2} - dT_0\right) - c\left(\sqrt{(T-T_0)^2 + (dT_0)^2} - (T-T_0) - dT_0\right)$$





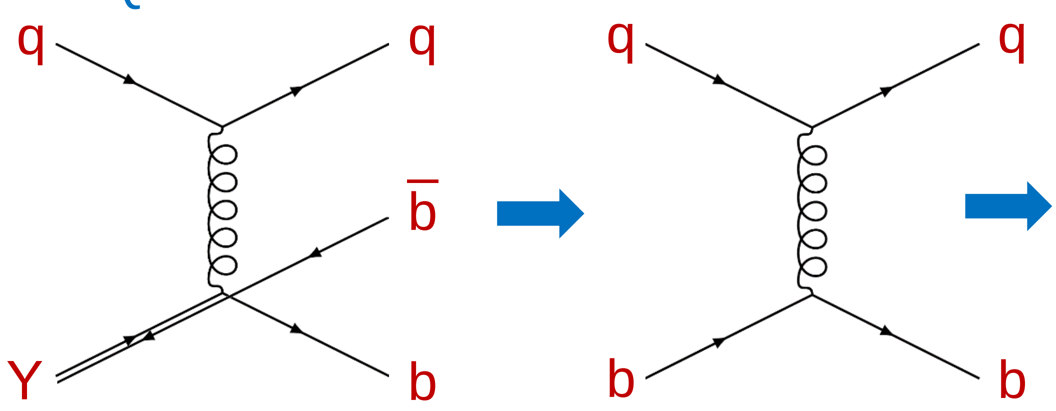
In relevant parameter space, sensitive parameters: a (~m_D/T) & b (~m_S/T at high-T)

Extracting In-Medium Potential



K-factor

Quasi-free



same as
perturbative collisional process
in open heavy flavor

K-factor:

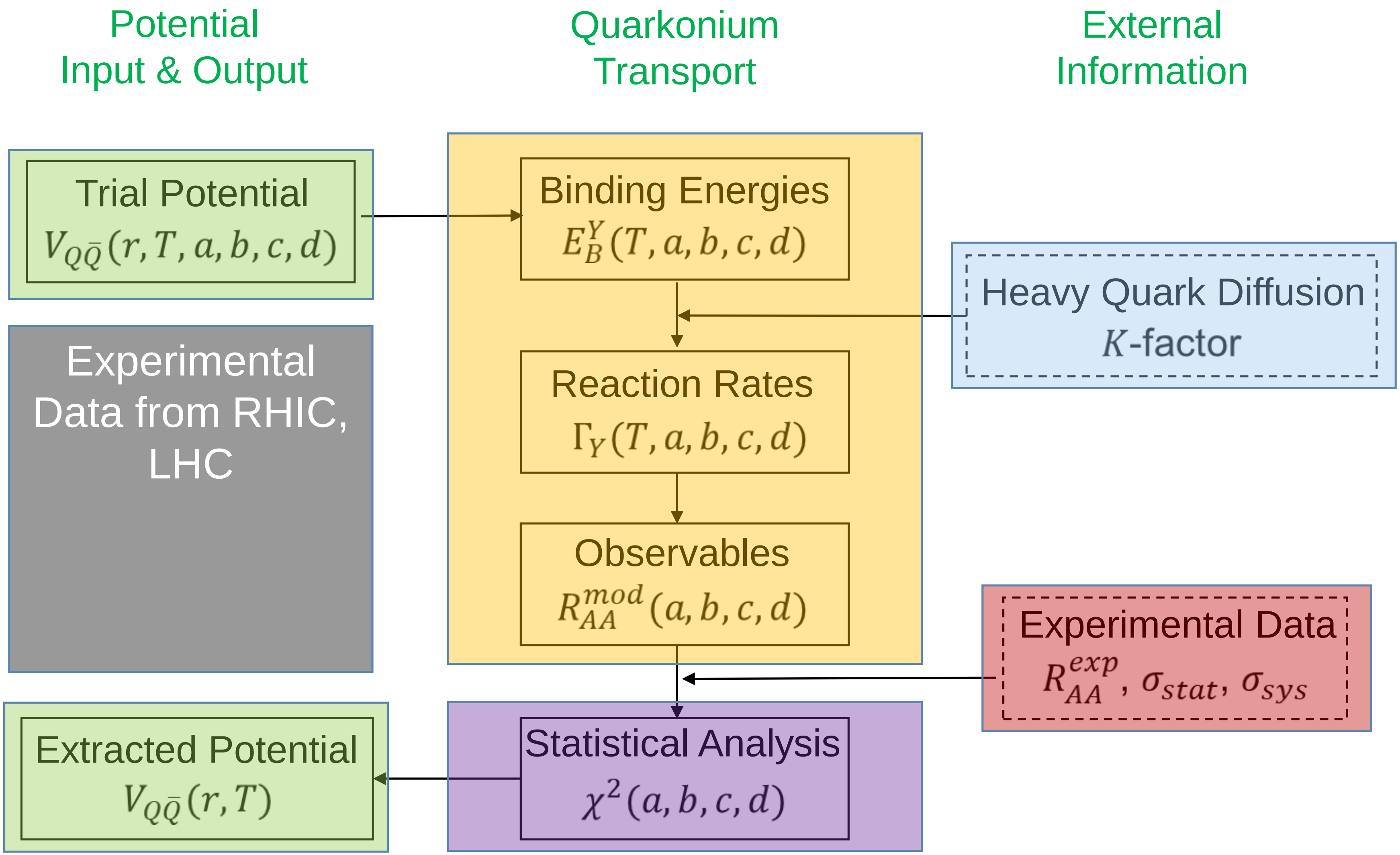
- Multiplication to pQCD calculated Reaction Rates
- Accounts for nonperturbative effects
- Open heavy-flavor suggests K-factor > 5

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

Extracting In-Medium Potential



Experimental Data

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

• 193 GeV U-U	$\|y\|<1.0$	Y(1S), Y(1S+2S+3S)
• 200 GeV Au-Au	$\|y\|<0.5$	Y(1S), Y(2S+3S), Y(1S+2S+3S)
• 2.76 TeV Pb-Pb	$\|y\|<2.4$	Y(1S), Y(2S)
• 2.76 TeV Pb-Pb	$2.5<y<4.0$	Y(1S)
• 5.02 TeV Pb-Pb	$\|y\|<2.4$	Y(1S), Y(2S), Y(3S)
• 5.02 TeV Pb-Pb	$2.5<y<4.0$	Y(1S)

Multiple Collision Systems, Multiple Rapidities, Multiple Species, …

$R_{AA}(N_{part})$:
Most relevant data
for probing force

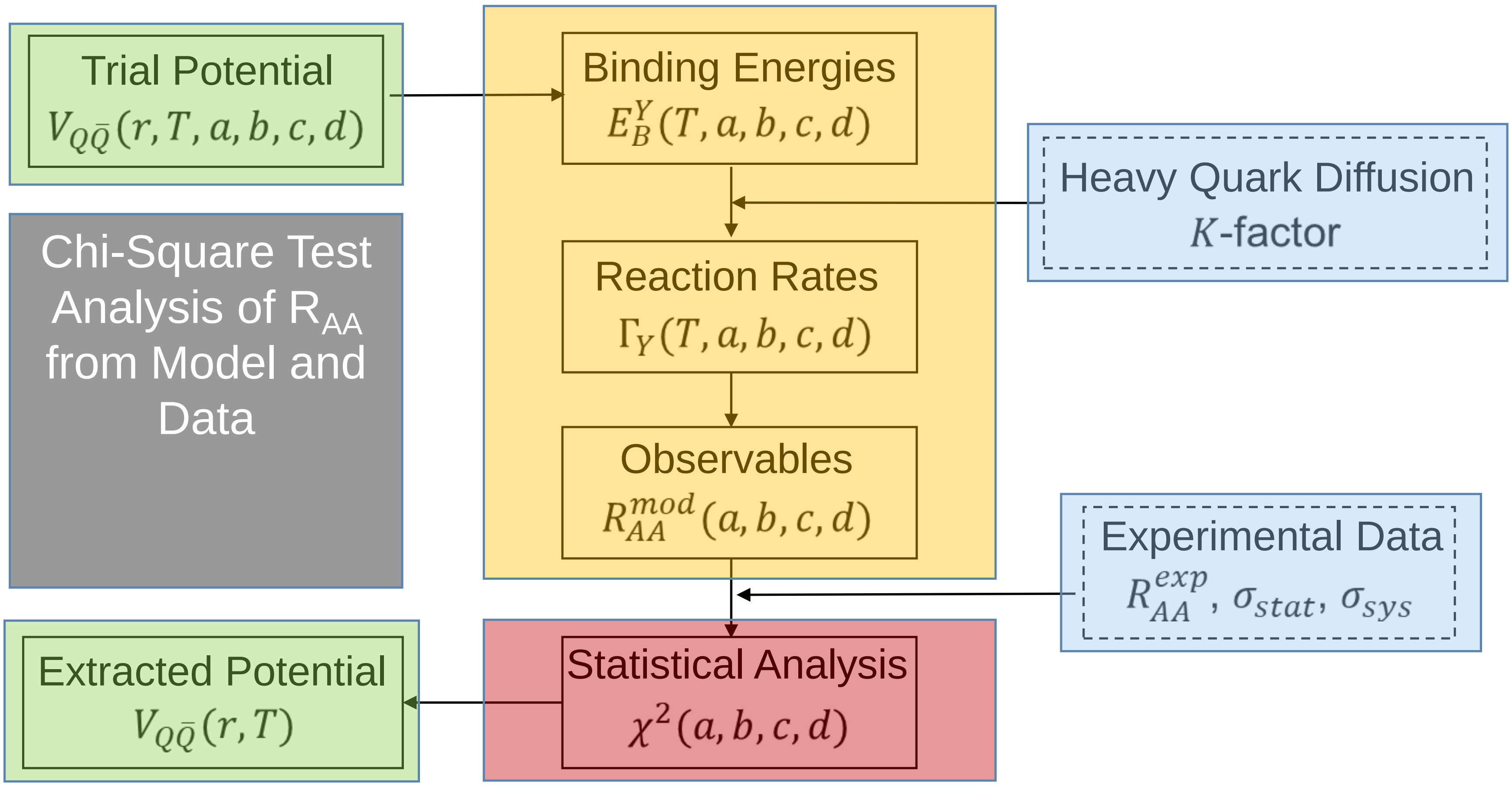
STAR Collaboration, L. Adamczyk et al., Phys. Rev. C 94(2016) 064904.
STAR Collaboration, Z. Ye, Nucl. Phys. A 967 (2017) 600.
CMS Collaboration, V. Khachatryan et al., Phys. Lett. B 770(2017) 357.
ALICE Collaboration, B.B. Abelev et al., Phys. Lett. B 738(2014) 361.
CMS Collaboration, A.M. Sirunyan et al., Phys. Lett. B790(2019) 270.
ALICE Collaboration, S. Acharya et al., Phys. Lett. B790(2019) 89.

Extracting In-Medium Potential

Potential Input & Output

Quarkonium Transport

External Information



Statistical Analysis: χ^2 Test

Model calculations with trial potential
$R_{AA}^{mod}(a,b,c,d)$

53 R_{AA} experimental data points
R_{AA}^{exp}, σ_{stat}, σ_{sys}

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

$$\sigma_{exp} = \sqrt{\sigma_{stat}^2 + \sigma_{sys}^2}$$

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

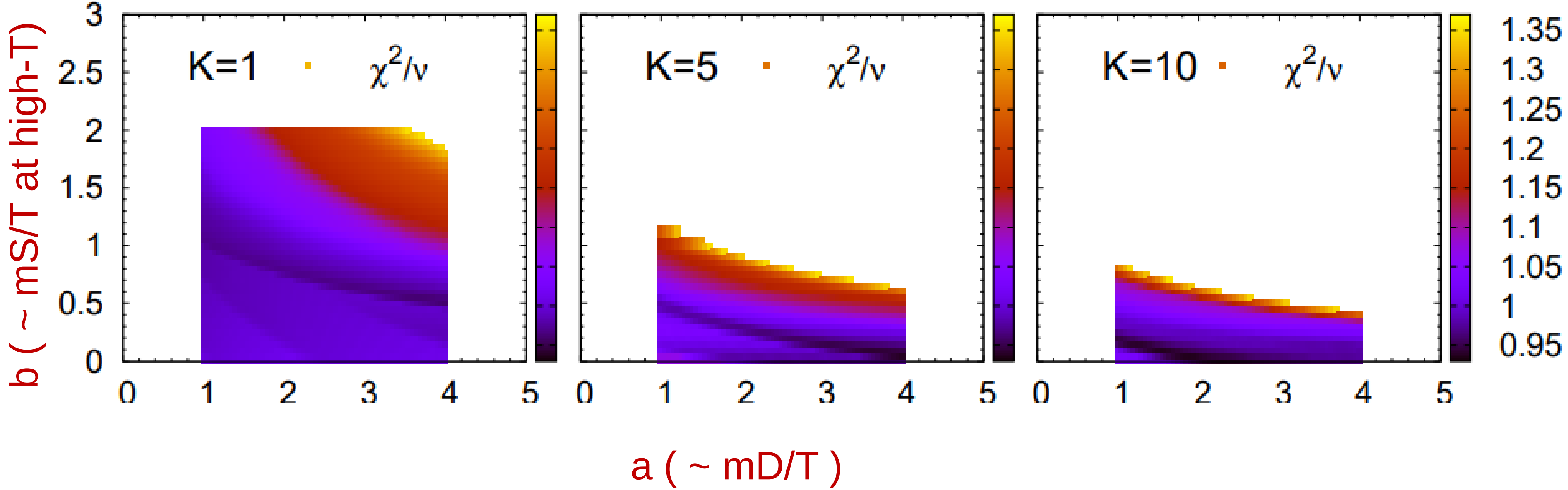
Chi-square distribution degree of freedom:
53 data – 4 parameters=49

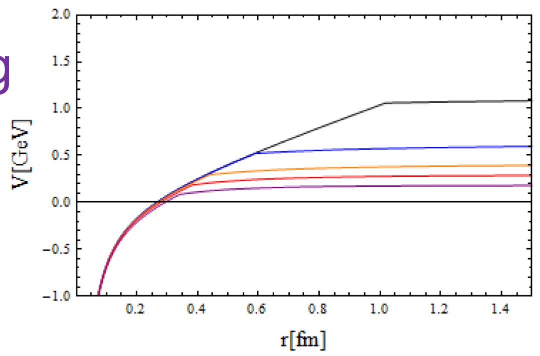
Accepted band
95% confidence: p-value>0.05

+

Best fit
Smallest χ^2, Largest p-value

Resultant Parameter Space



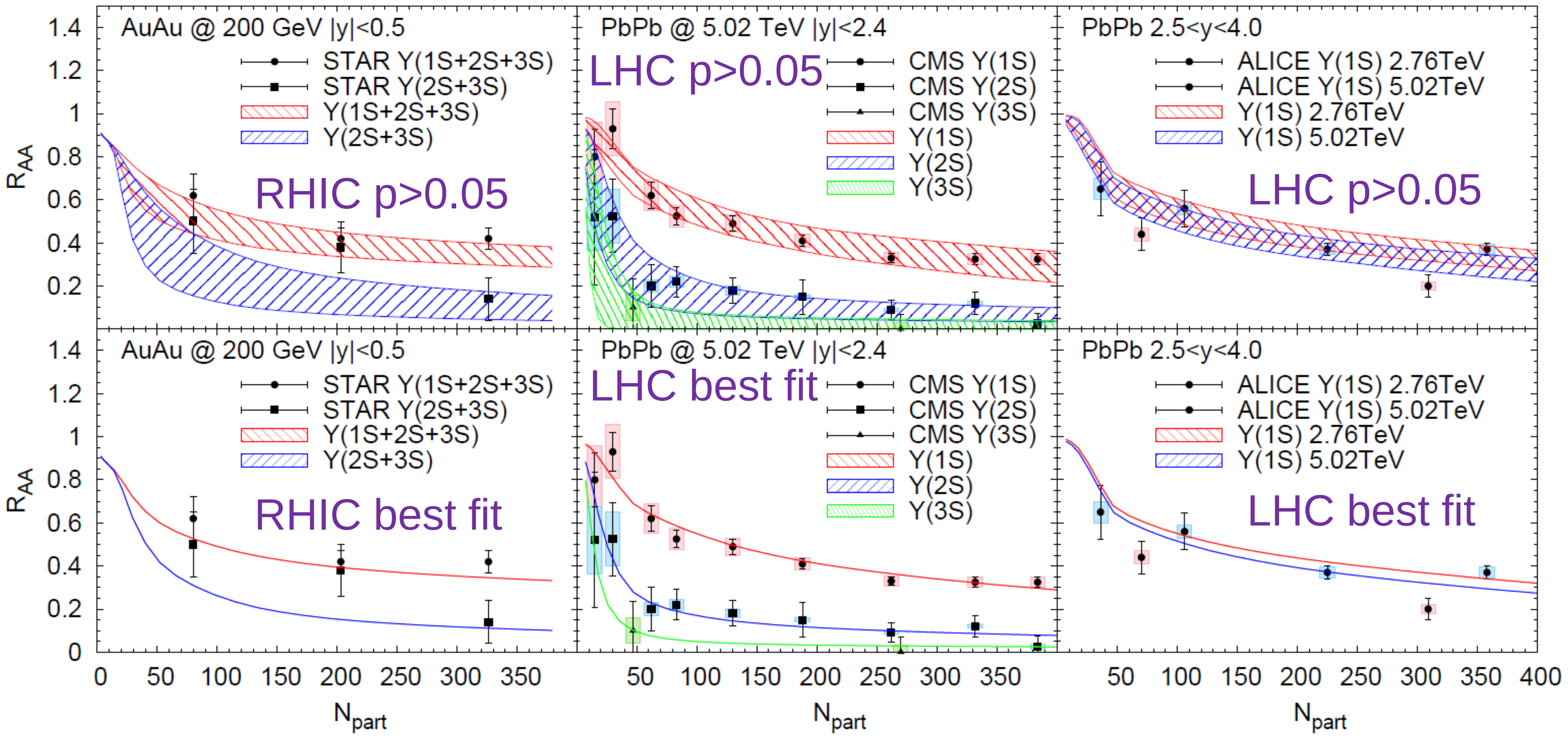


Smaller b $\rightarrow$ smaller m_S $\rightarrow$ larger r_s $\rightarrow$ stronger binding
Larger b $\rightarrow$ larger m_S $\rightarrow$ smaller r_s $\rightarrow$ weaker binding

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

Thus Increasing K-factor requires stronger binding

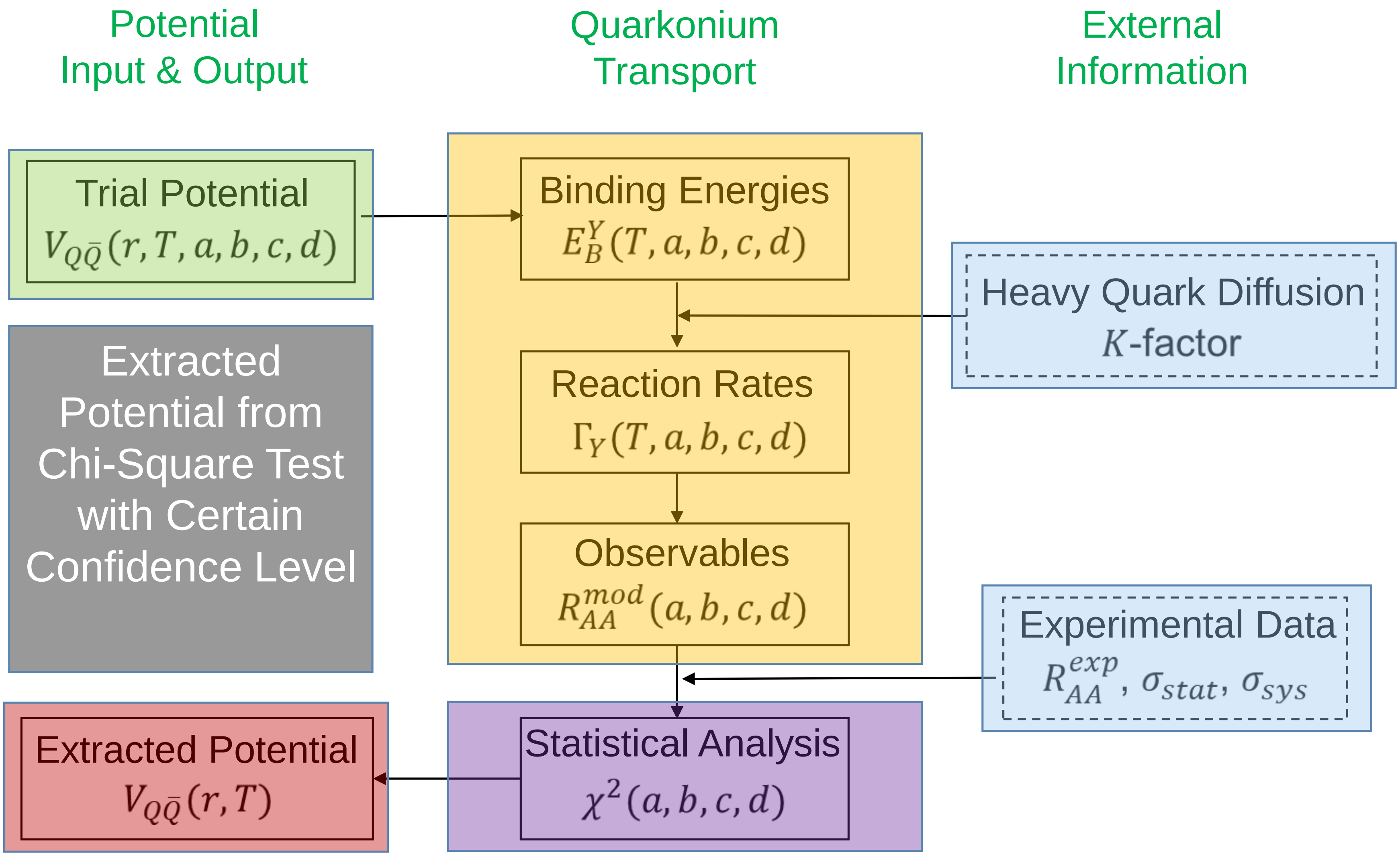
Part of K=5 Resultant Bands of R_{AA}s



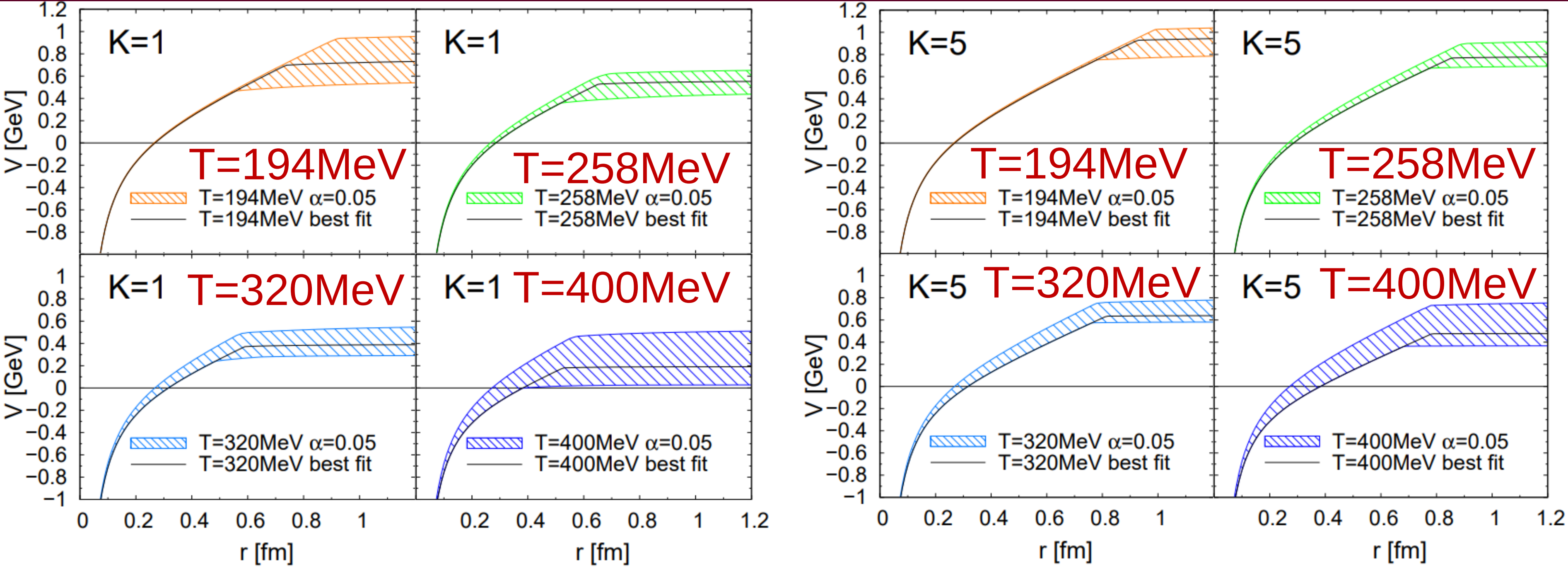
Overall good description of data with parameters selected by statistics

Few data points do not have constraint power

Extracting In-Medium Potential



Resultant Bands of In-Medium Potential



$V^{best\text{-}fit}(r=1fm)$	K=1	K=5
T=194MeV	~730MeV	~940MeV
T=320MeV	~400MeV	~630MeV

K=1: allows for both weak/strong binding

K=5: suggests strong binding

K=10: even stronger..

Outline

X. Du, S. Liu, R. Rapp, submitted to PLB

- Our Motivation: Learning QCD Force
  - Why quarkonium? What to expect from it?
- Our Tools: Quarkonium Transport Approach
  - Transport equation
  - Key coefficients, parameters and inputs
  - Probing strong/QCD force/potential with quarkonium
- We've learned: Quarkonium Production in A-A Collisions
  - J/ψ production: $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, $R_{AA}(\sqrt{s})$, …
  - ϒ(1S,2S,3S) production : $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v_2(p_T)$, …
  - Comparison between charmonium and bottomonium: $R_{AA}(\sqrt{s})$, …
  - ϒ(1S) as a probe of in-medium heavy quark-antiquark potential
- We are learning: Extraction of In-Medium Heavy Quark-Antiquark Potential
  - Joint study of heavy quark (open heavy flavor)/quarkonium (hidden heavy flavor)
  - Selecting relevant data points
  - Indicating a strong potential
- Summaries

Summaries

- Transport model is previously well tested in multiple aspects in heavy-ion collisions
  → J/ψ, ϒ, …
  → R_{AA}, v2, …

- Regeneration is importance for J/ψ, but not so important for ϒ
  → $R_{AA}(N_{part})$, $R_{AA}(p_T)$, $v2(p_T)$, $R_{AA}(\sqrt{s})$, …

- ϒ(1S) is ideal for probing in-medium heavy quark-antiquark potential/QCD force
  → ϒ(1S)'s observable is sensitive to in-medium potential
  → ϒ(1S) has small regeneration, is cleaner than charmonium

- QGP is a strongly coupled medium
  → Joint study of open/hidden heavy flavors is important
  → We should select the most relevant data points for probing the force

Thank you!