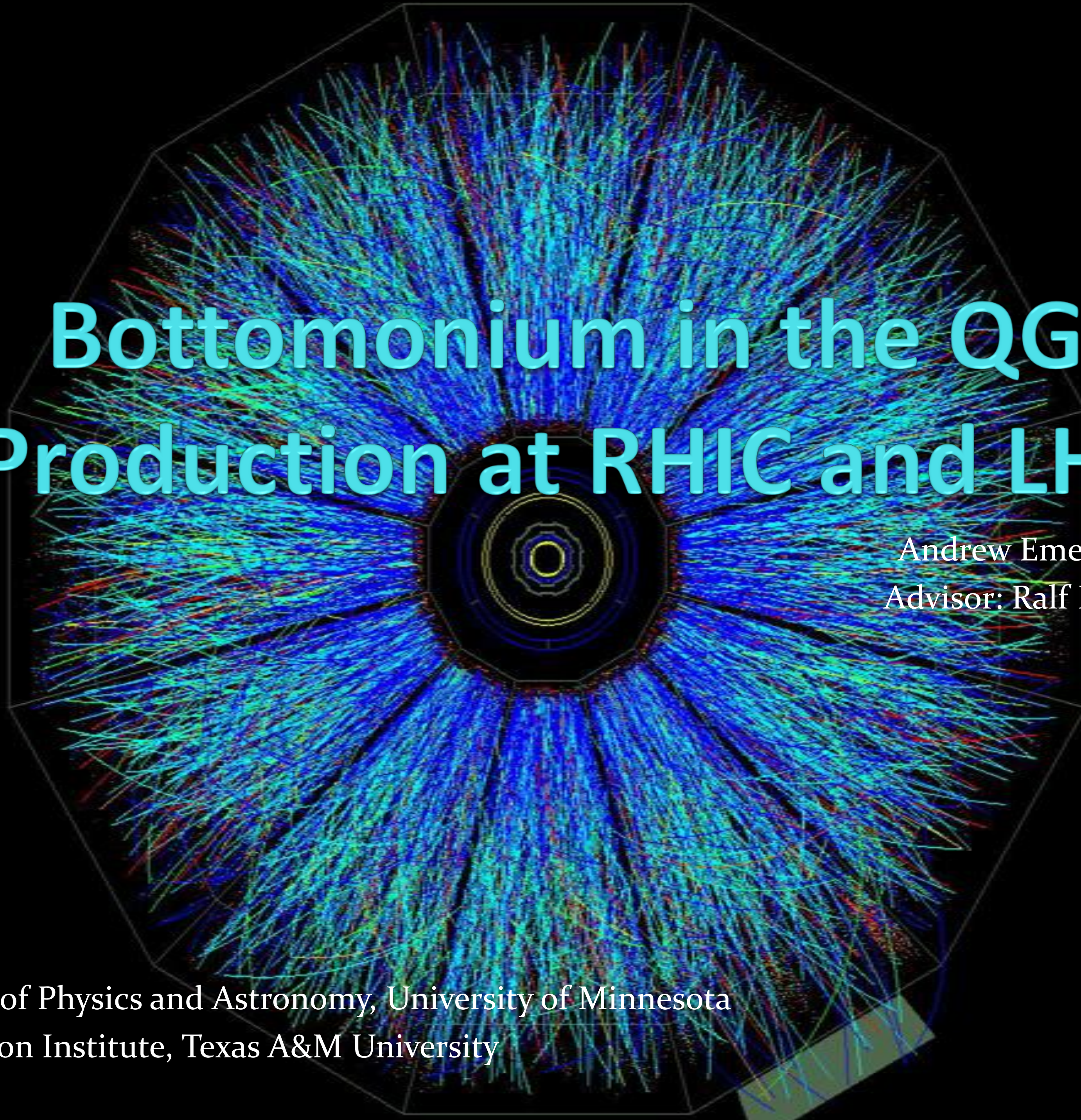

Bottomonium in the QGP: Production at RHIC and LHC

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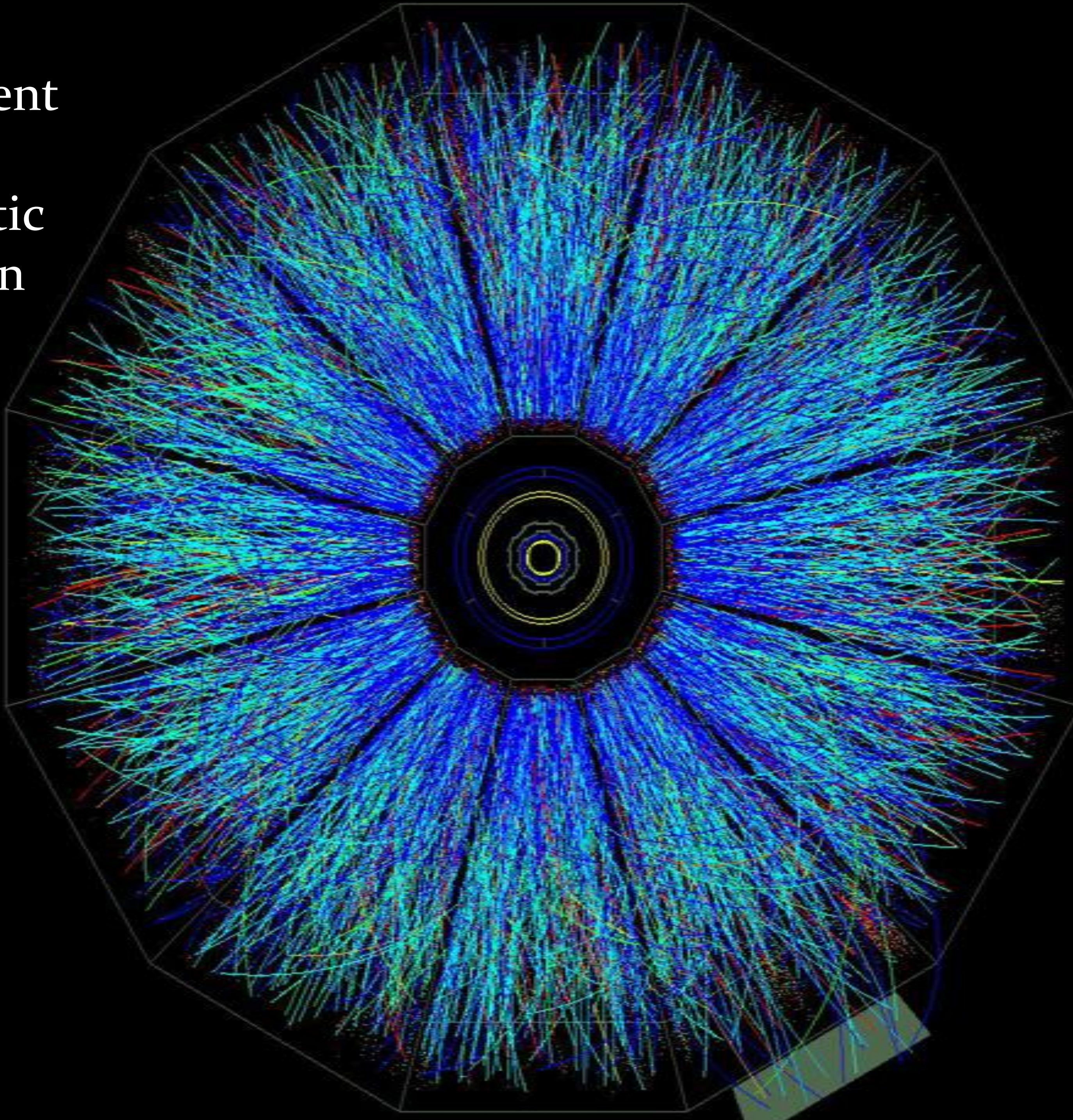
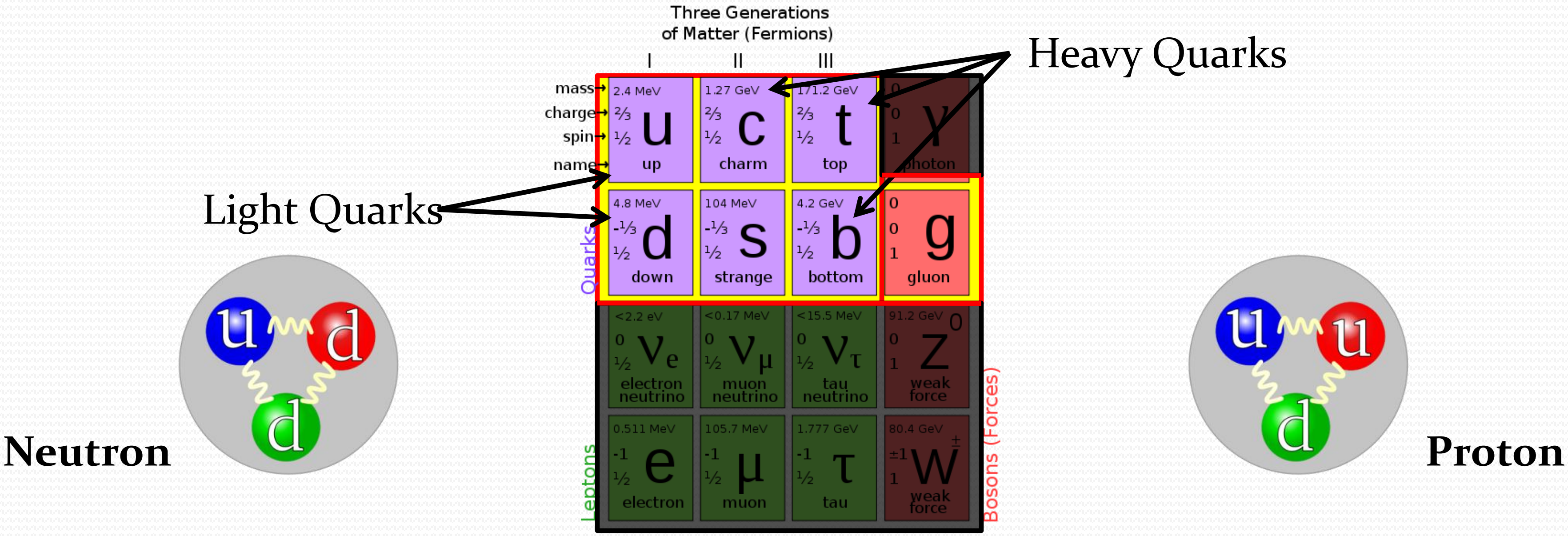
STAR Experiment at the Relativistic Heavy Ion Collider (RHIC)



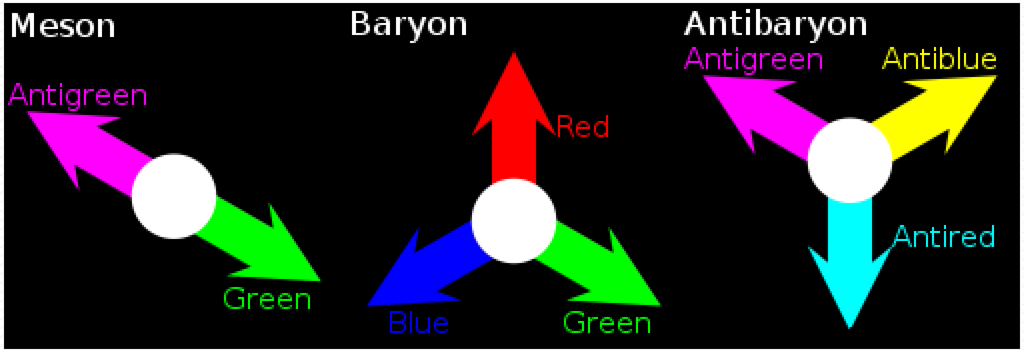
Quarks and the Strong Force

- The strong nuclear force governs the stability of hadrons.
- Predicted by theory, early pp collisions made first confirmation of quarks:



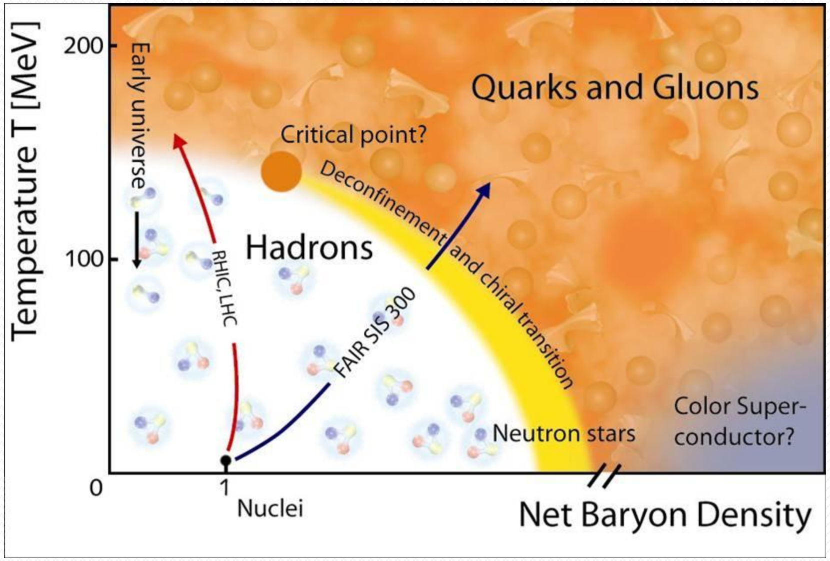
Quantum Chromo-dynamics

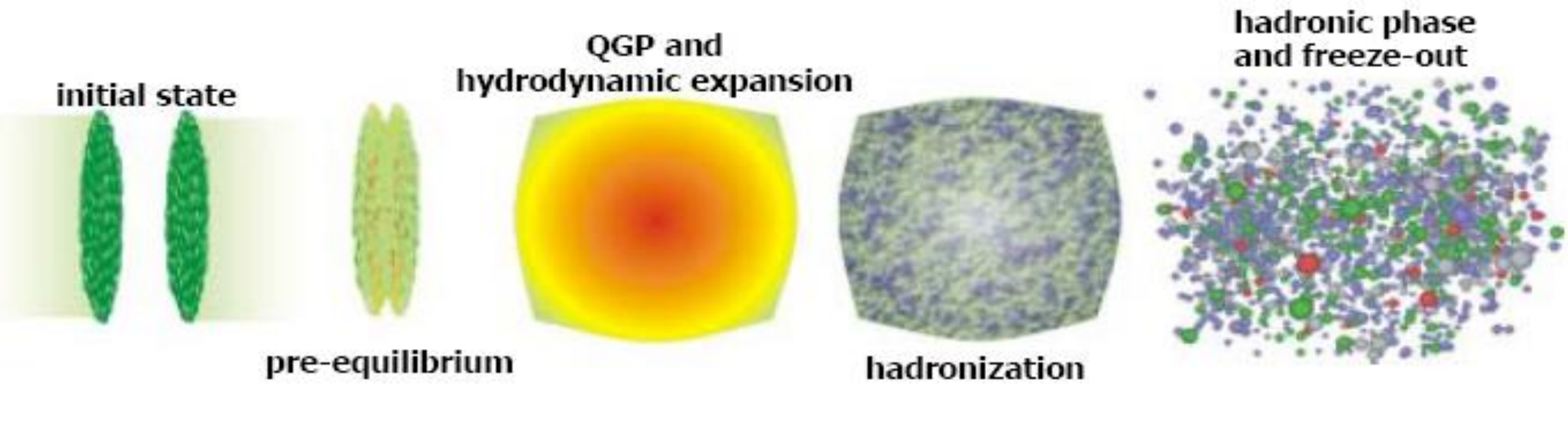
- The strong force is governed by Quantum Chromo-Dynamics (QCD), where interactions are mediated by gluons.
- Each quark and gluon has a color charge: red, green, blue.
- QCD gives two unusual properties of quarks and gluons:
  - Confinement of color charges: Potential ∝ Separation
  - Asymptotic freedom



Extreme Conditions

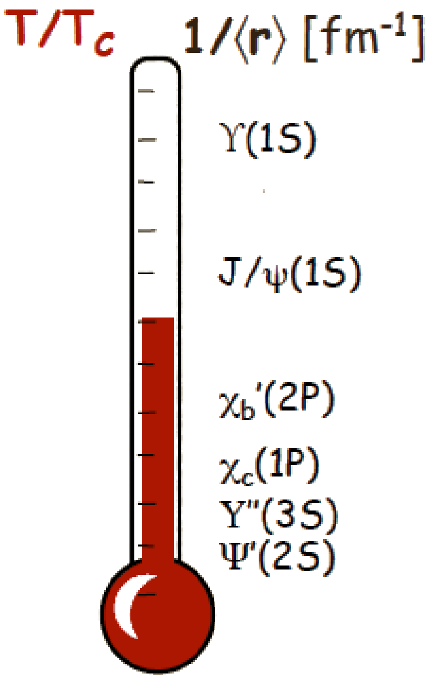
- QCD predicts the new de-confined state of matter formed around $T_c \cong 180$ MeV ($\sim 10^{12}$ K): the Quark-Gluon Plasma (QGP).
- The creation and exploration of the QGP has been a primary science goal of relativistic heavy-ion colliders.
- However, the QGP is a transient state, existing for only $\sim 10^{-22}$ s. A probe is necessary




initial state
pre-equilibrium
QGP and
hydrodynamic expansion
hadronization
hadronic phase
and freeze-out

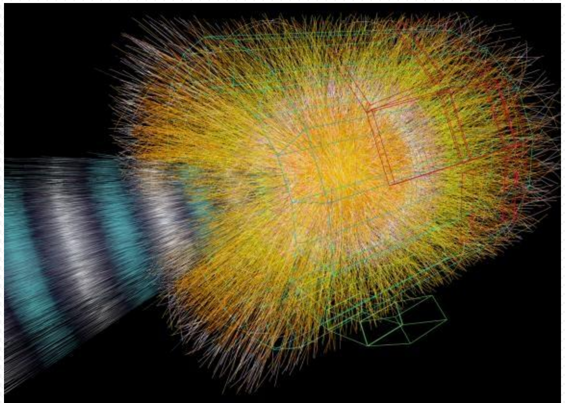
Heavy Quarkonia

- Bound states of hidden flavor heavy quarkonia do not melt until well above T_c .
- These can be used as signatures of the QGP
  - Well studied $c\bar{c}$ -> J/ψ
  - Less studied $b\bar{b}$ -> Υ
- The complex interactions of the QGP requires a strong theoretical understanding in order to interpret experimental results.



Heavy Quarkonia: ϒ

- The ϒ bound state is less studied than its cousin J/ψ.
- However, this particle provides a better signature of the QGP.
  - Survives up to 3-4 T_C
  - ϒ yields unchanged during latter, cooler (hadronic) phases
  - True probe of the first ~10 fm/c (~10^{-23} s) of the QGP



ϒ In-medium

- Primordial production of ϒ is affected by cold nuclear matter (CNM) effects: nuclear absorption and nuclear shadowing.
- Produced in N-N collisions at high energy, ϒ undergoes several effects while in the QGP:
  - Suppression from dissociation due to scattering
  - Regeneration of ϒ from recombined b b̄
  - Decay of higher bound states to ϒ

Particle	Percent of Primordial ϒ(1s)
X_b(1p) decay to ϒ(1s)	27%
X_b(2p) decay to ϒ(1s)	10%
ϒ(2s) [ϒ'] Decay to ϒ(1s)	11%
ϒ(3s) [ϒ''] Decay to ϒ(1s)	1%

Binding Models

- Heavy quarkonia resonances occur through one of two binding scenarios:

<u>Weak Binding</u>

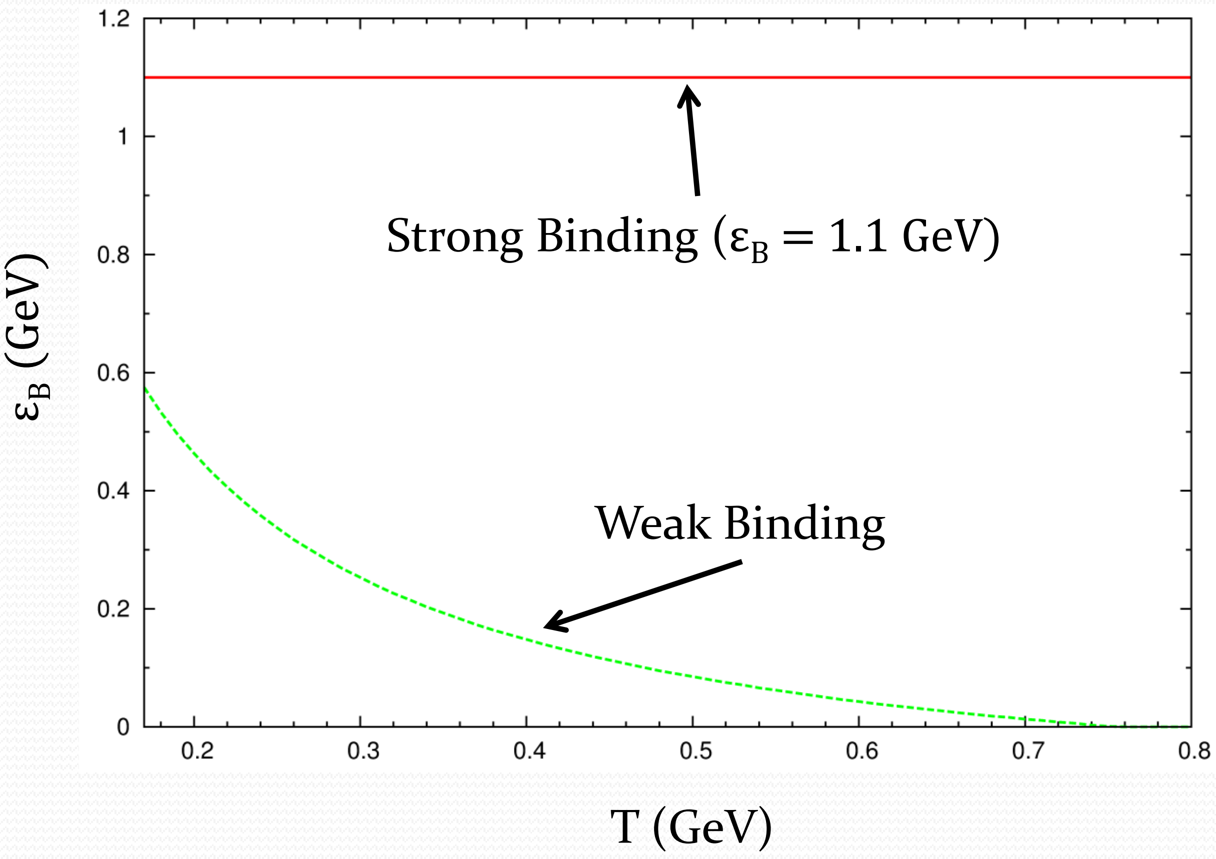
- In-medium bound state mass, binding energy, and unbound masses, satisfying:

$$\varepsilon_B(T) = 2m_b - m_\Upsilon$$

<u>Strong Binding</u>

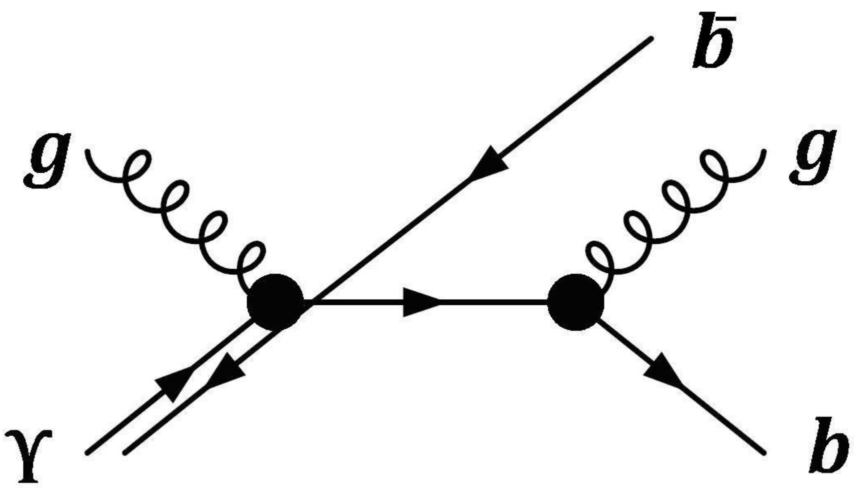
- Fixed, vacuum bound state mass with m_b = 5.280 GeV/c^2.

Υ Binding Energy

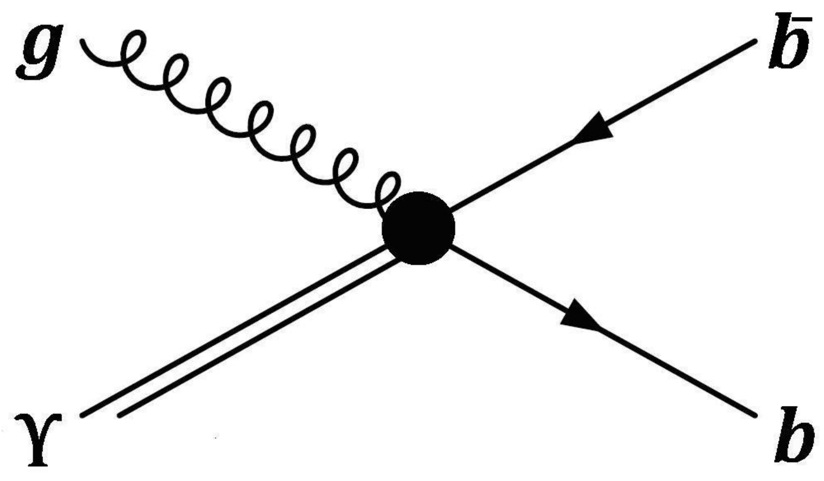


Dissociation Mechanisms

- Each binding scenario has a corresponding dissociation mechanism that is most efficient:



Weak Binding – Quasi-free Dissociation



Strong Binding – Gluo Dissociation

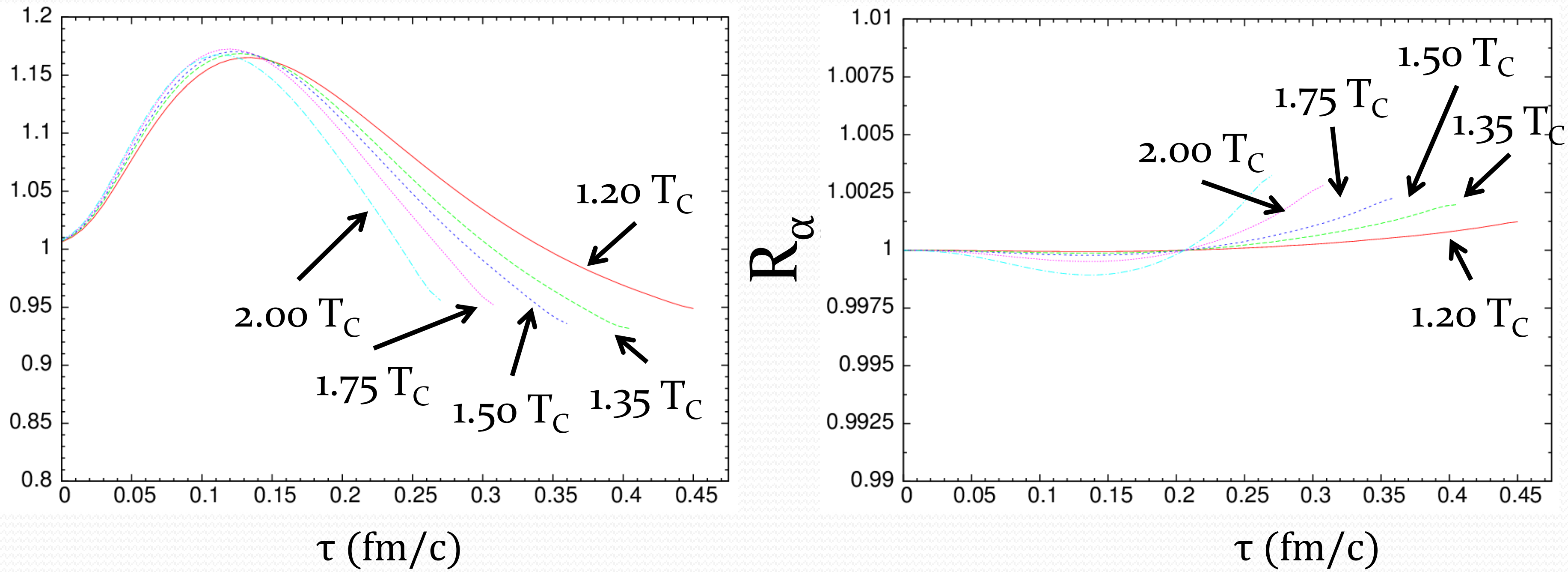
Euclidean Correlator Ratios

- Euclidean correlator ratios indicate in-medium effects on particle spectral functions:
- This property of ϒ states is related to their spectral functions, readily calculable in numerical lattice QCD (lQCD) calculations.

$$R_\alpha(\tau,T)=\frac{G_\alpha(\tau,T)}{G_\alpha^{rec}(\tau,T)}=\frac{\int_0^\infty \sigma_\alpha(\omega,T)\mathrm{K}(\omega,\tau,T)d\omega}{G_\alpha^{rec}(\tau,T)}$$

- The denominator is of the same form, evaluated at low temperature.
- Lattice QCD calculations indicate that R_α remains close to unity.

Correlator Ratios: New Insight



- The strong binding scenario remains close to unity (within 1%).
- This motivates necessity to revisit the strong binding scenario as the relevant model of ϒ in the QGP.

Improvements and Updates

- In [L. Grandchamp et. al. PRC 73 (2006)], a study of Υ production at RHIC and LHC was made using these models.
- Better understanding of the physics of Υ production and correlator ratio calculations have motivated an necessary update
- This update will yield a better insight into bottomonia in the QGP.

Collision Model: Fireball

- A kinetic-theory rate-equation approach was used to model the collision and ϒ production

$$\frac{dN_{\Upsilon}}{d\tau} = -\Gamma_{\Upsilon}\left(N_{\Upsilon} - N_{\Upsilon}^{eq}\right)$$

- The fireball evolves as a function of time, allowing implementation of temperature dependence.
- CNM effects, suppression, regeneration, and feed-down included.
- For simplification, feed-down from ϒ” is ignored, and χ_b(1p) and χ_b(2p) states are not differentiated.

Nuclear Modification Factor

- The nuclear modification factor (R_{AA}) is used to characterize particle production in NN collisions with respect to pp collisions.

$$R_{AA}^{Total} = \frac{N_{\Upsilon}^{Total}}{N_{collision} \dfrac{\sigma_{pp \to \Upsilon}}{\sigma_{pp}^{inelastic}}}$$

- This is a valuable tool used to analyze experimental data, and to compare theory to experiment.

Probing the QGP in Experiment:

- The nuclear modification factor was calculated for two different cases:

<u>Reletavistic Heavy Ion Collisder (RHIC):</u>

• AuAu collisions at E_{CMS}= 200 GeV.

• Used $\sigma_{Nuc.\ Abs.}$= [2.0,3.1] mb

• Cannot (yet) resolve ϒ, ϒ′, and ϒ″ states separately.

• Give combined ϒ(1s+2s+3s) R_{AA}

• Compare to STAR data

<u>Large Hadron Collider (LHC):</u>

• PbPb collisions at E_{CMS} = 2.76 TeV.

• Used $\sigma_{Nuc.\ Abs.}$= [0.0,2.0] mb

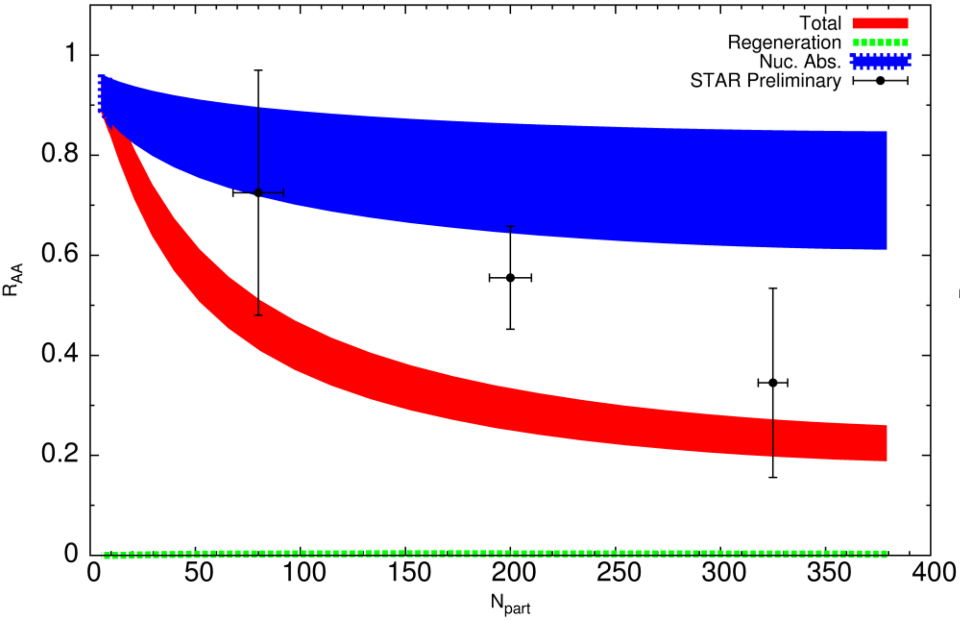
• Give ϒ(1s) R_{AA}

• Compare to CMS data

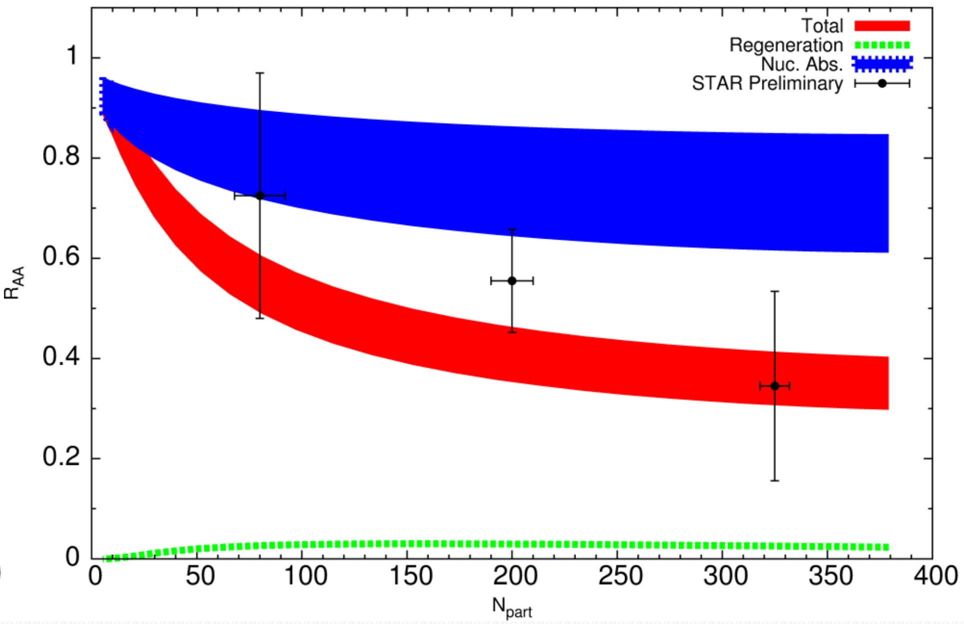
R_{AA} for higher ϒ states also calculated, though data only exists for these

Results: RHIC

Weak Binding – Quasi-Free Dissociation

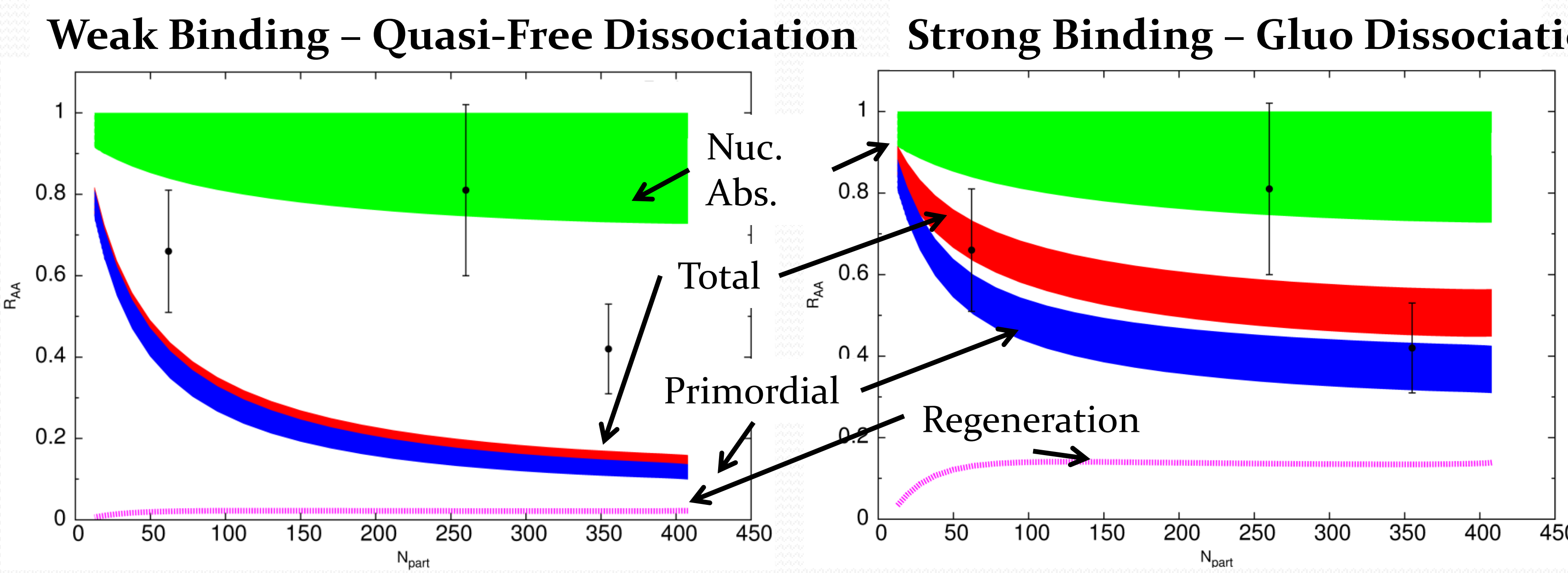


Strong Binding – Gluo Dissociation



- The strong binding scenario gives better agreement with data
- The regeneration component is negligible for both binding scenarios

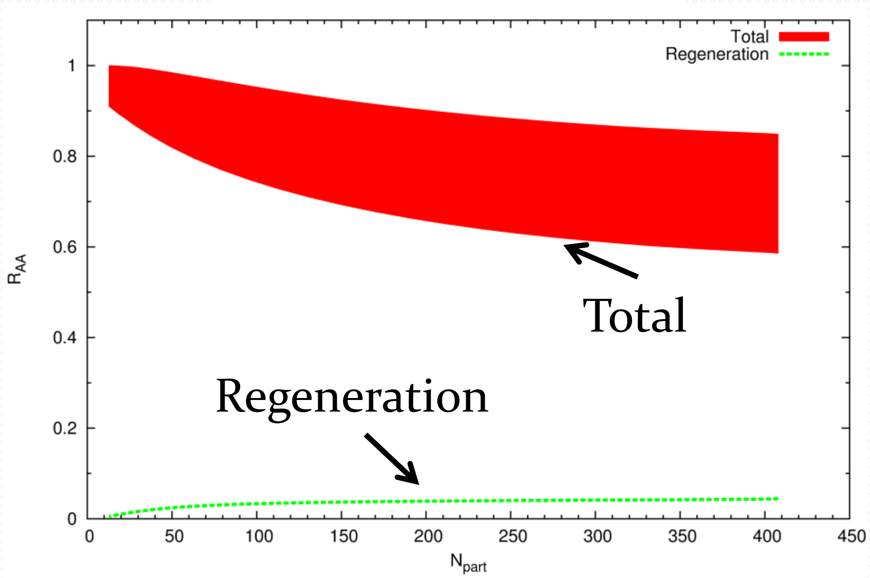
Results: LHC



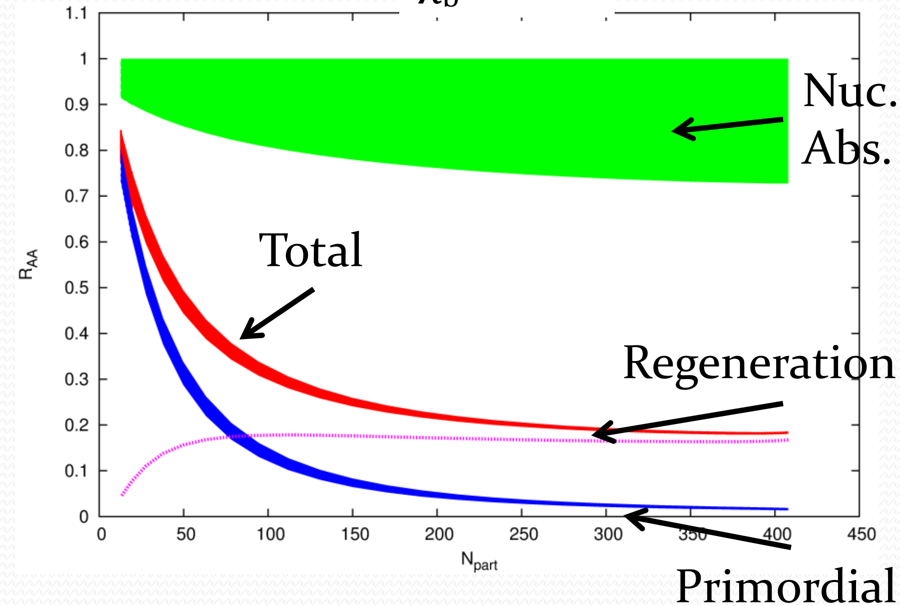
- The strong binding scenario shows much better agreement with data.
- Regeneration becomes significant at LHC
- Nuclear absorption is inconclusive

Results: LHC (cont.)

ϒ without feed-down



χ_b States



- As shown, the regeneration component is significant in the higher states.
- The suppression of the ϒ(1s) state alone is 60-85% depending on nuclear absorption. Yet is ~45-55% including feed-down.
- Right shows large suppression of χ_b state, with dominant regeneration component.

Further Improvements

- The following would improve quality of checks between theory and experiment:
  - Increased statistics and data collection capabilities
  - Resolving individual ϒ(nS) states at RHIC
  - Direct experimental measurement of ϒ production cross-sections at 2.76 TeV
  - Better theoretical calculations of χ_b production cross sections
  - Improvement of Strong Binding model, implementing in-medium effects to the bound state mass. Especially important for higher bound states.
  - Applying models to calculations of p_T spectra, adding another quantity to compare to data.

Conclusions:

- Modeled in medium ϒ particles with two binding scenarios: strong and weak
- Calculated Euclidean correlator ratios for each
- Used a kinetic-theory fireball model and rate-equation approach to calculate ϒ R_{AA}
- RHIC shows preference for strong binding model. Strong binding is appropriate model at LHC.
- Regeneration of ϒ is significant at LHC
- More experimental data, and improved strong binding model will improve these.

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