Bottomonium in Heavy Ion Collisions: AA case

Quarkonia as Tools

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NSF UCDAVIS

Outline

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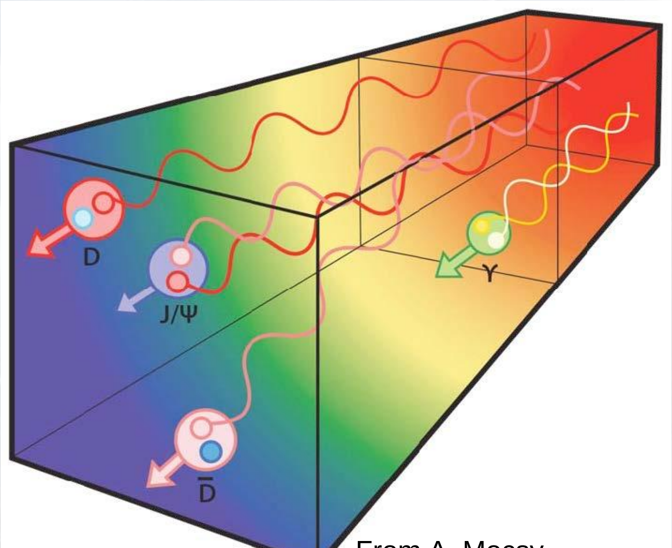
- Bottomonia measurements: “go heavy or go home” in AA.
- Bottomonium.
  - what can beauty (+ charm) bound states tell us about **Hot QCD**
  - How **hot** does it get?
  - Is **color** deconfined?
- – Bottomonium measurements:
  - Double ratios, RAA, centrality, pT, y, $\sqrt{s}$.
    - – STAR: pp, dAu, AuAu, $\sqrt{s}$=200 GeV 1S, 2S+3S, UU $\sqrt{s}$=193 GeV.
      - » PLB 735 (2014) 127, PRC 94 (2016) 64904
    - – PHENIX: pp, AuAu $\sqrt{s}$=200 GeV 1S+2S+3S, PRC 91, 024913 (2015)
    - – ALICE: PbPb 2.76 TeV, 5.02 TeV 1S, 2S
      - » PLB 738 (2014) 361, arXiv:1805.04387 (to appear in PLB)
    - – CMS, PbPb 2.76 TeV, 5.02 TeV 1S, 2S, 3S.
      - » PRL 109, 222301 (2012), PRL 120 (2018) 142301, arXiv:1805.09215 (to appear in PLB)

Bottomonium states in AA

- States are massive, produced early
  - pQCD can estimate production
- Sensitive to temperature and deconfined color fields: input from Lattice QCD
  - Debye screening, Landau damping
    - Re and Im V(r, T)
  - Different states have different sizes/binding energy
    - Sequential suppression
- Cold-nuclear matter
  - Initial state effects: e.g. nPDF, energy loss
  - Final state: absorption/co-mover interaction
- Regeneration
  - Uncorrelated heavy-quarks can pair up
- Bottomonium: a cleaner probe than charmonium...
  - 3 states are accessible experimentally
    - Differentiate between initial and final state effects
  - expect some small CNM effects (shadowing/nPDF)
  - expect small regeneration effects



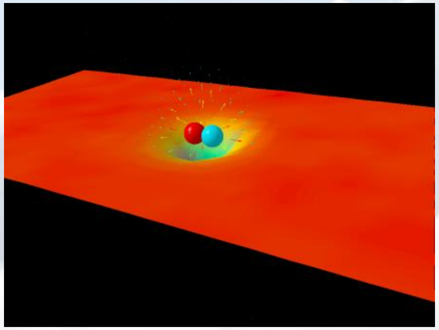
From A. Mocsy

Heavy Quark Potential at High T

- Quarkonium suppression: longstanding QGP signature
  - Original idea: High T leads to QCD Debye screening

QED: $V \sim -\frac{a_{eff}}{r}$ $V \sim -\frac{a_{eff}}{r} e^{-\frac{r}{r_D(T)}}$

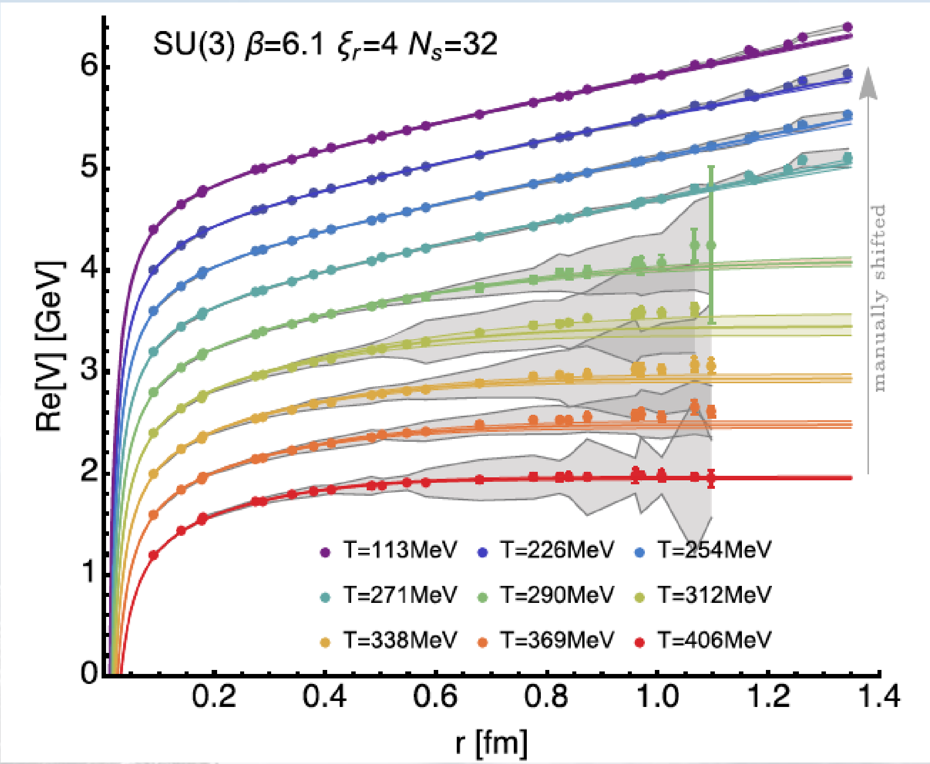
$T = 0$ $T > T_C$

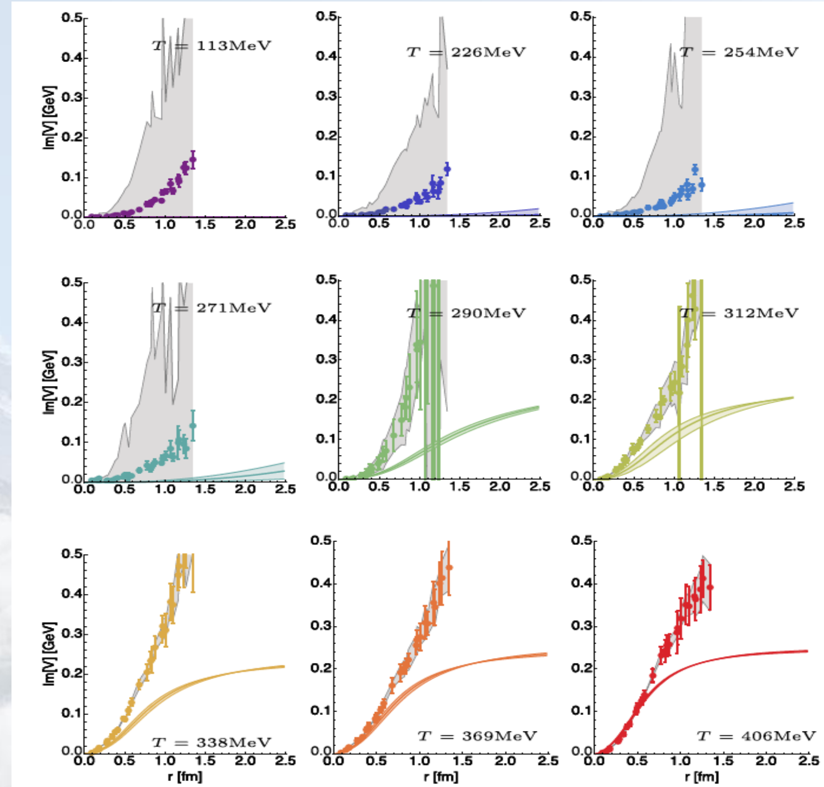


QCD:

- T=0, Cornell potential: $V = -\frac{\alpha}{r} + \sigma r + c$
- Presence of Debye mass in Cornell potential, screening of potential at large r.
- Screening prevents heavy quark bound states from forming!
- **Original idea of J/ψ suppression**:
  - Matsui and Satz, *Phys. Lett. B* **178** (1986) 416
- What do the latest calculations in lattice QCD say?

Lattice QCD Heavy Quark Potential



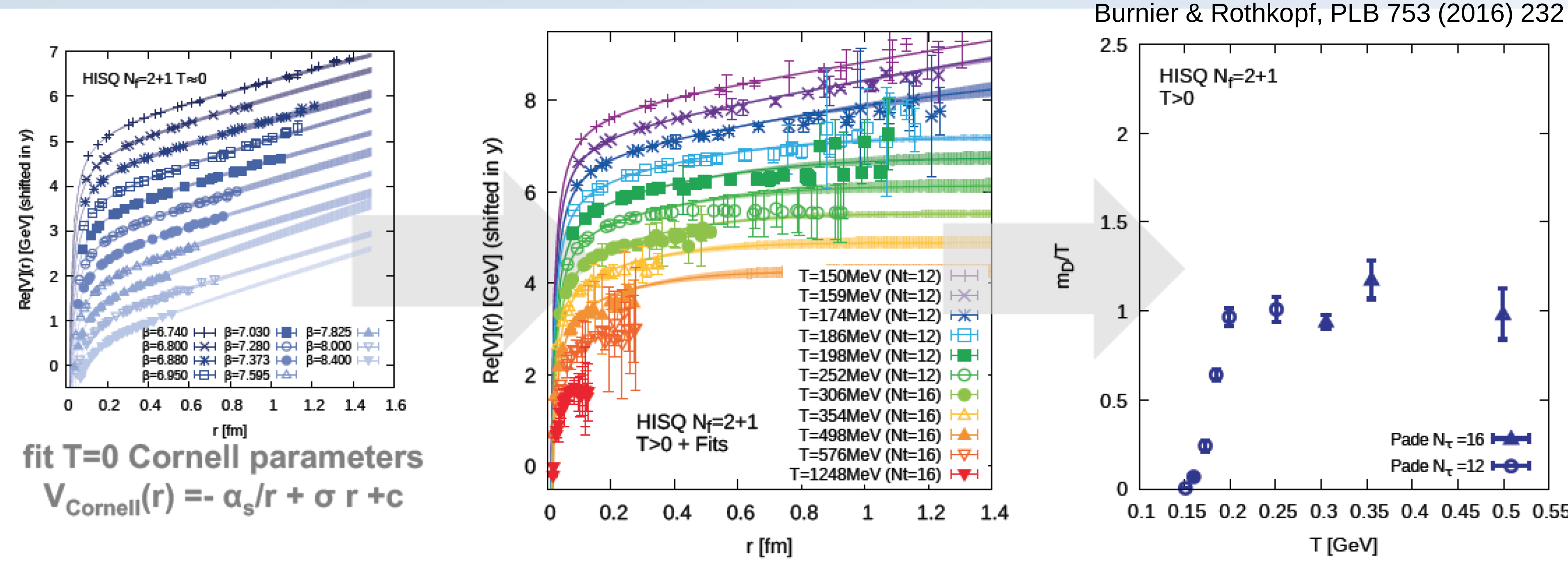


Y. Burnier & A. Rothkopf
PRD 95 054511 (2017)

- Lattice calculations confirm screening effects
  - **Screening: Re V**
  - **Landau damping, gluodissociation: Im V**
  - Both contribute to Quarkonium Suppression

Interpreting the T>0 potential

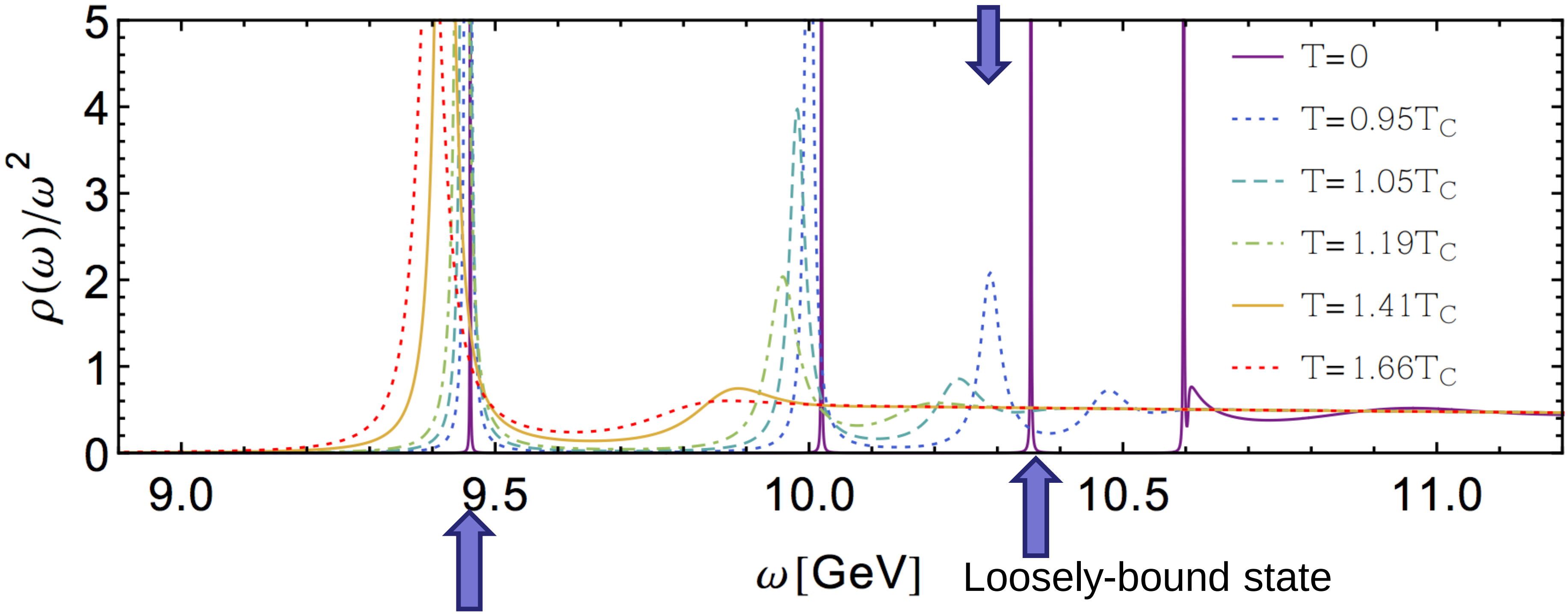
Burnier & Rothkopf, PLB 753 (2016) 232



- Combine non-perturbative T=0 Cornell potential and perturbative medium:
  - Re[V](r,T) and Im[V](r,T) from one T-dependent parameter: Debye mass, m_D.
  - Lattice results from Re[V] are well described by tuning m_D, smooth onset for $T>T_c$.
  - Im[V] predictions based on m_D are slightly lower.

Sequential Melting of Bottomonia

$Q\bar{Q}$ state properties change at high temperature



Loosely-bound state

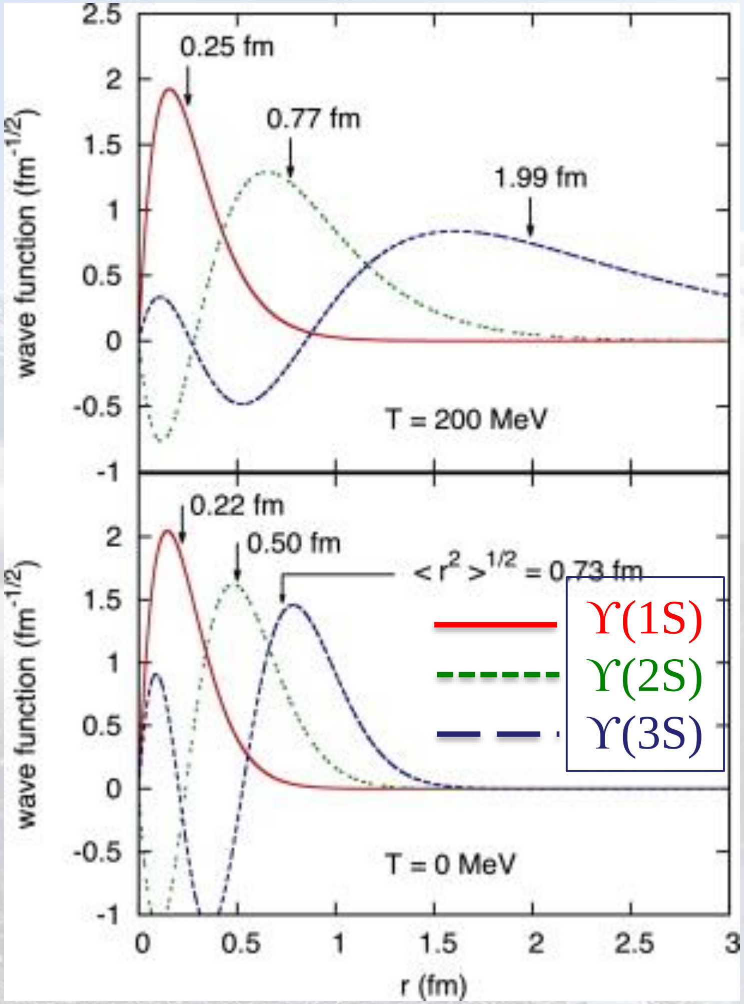
Tightly-bound state

Burnier, Kaczmarek, Rothkopf, JHEP (2015) 2015: 1

- As temperature increases:
  - The peaks broaden and their masses shift to lower values.
  - Highest states broaden and shift first, followed sequentially by lower states.
  - Peaks eventually disappear completely —> States melt.
  - **ϒ**(1S), **ϒ**(2S) and **ϒ**(3S) melt at 2.66TC, 1.25TC and 1.01TC.
- Sequential melting of **ϒ** states is sensitive to color deconfinement!

Bottomonia spectroscopy as a tool

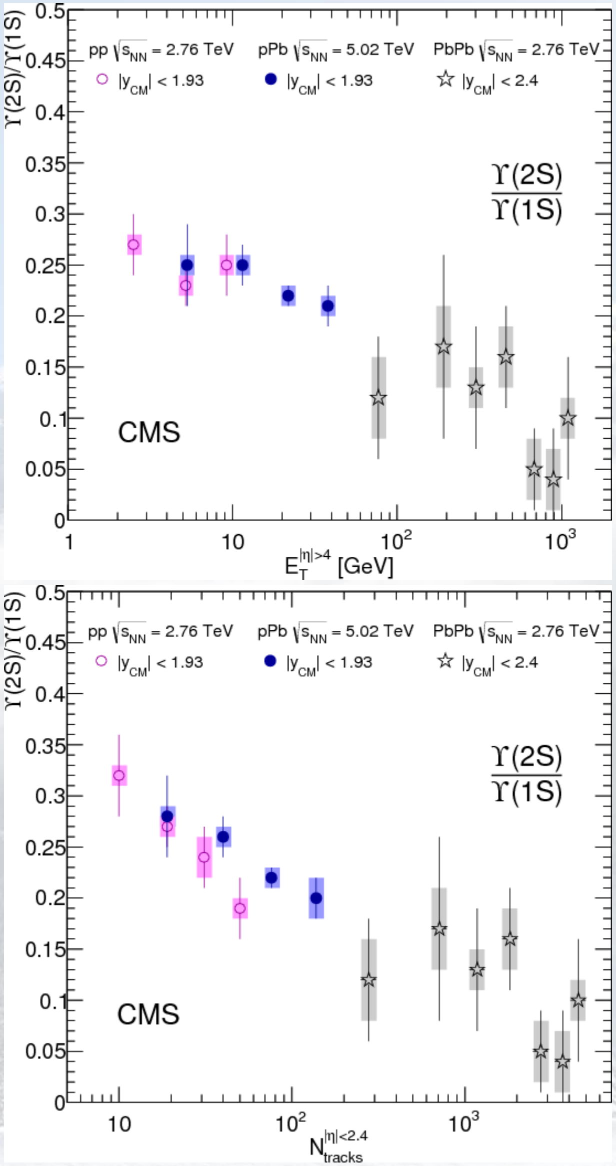
- ∏→ μμ : 3 states to study
  - Hot Nuclear Matter Effects
    - Different sizes, binding energies.
    - Sequential melting.
  - Expectation:
  - ϒ(1S) almost no melting
  - ϒ(2S) likely to melt
  - ϒ(3S) fully melted?
    - Feed-down is important.
- Recombination/coalescence
  - ∏(1S) recombination → much smaller effect than for J/ψ.
    - Ko et al. PRC 85, 014902 (2012)



Brezinski & Wolschin PLB 707 (2012) 534

Bottomonia: from pA to AA

- pA measurements are crucial to study CNM effects.
  - Necessary step before discussing possible Hot Nuclear Matter effects.
    - e.g. ratios vs. activity in pp, pA, AA.
    - Extrapolation from pA to AA not trivial.
- Bottomonia:
- Cold Nuclear Matter Effects
    - Shadowing small near y~0
    - Small hadronic absorption for ϒ(1S).
      - Lin & Ko, PLB 503 (2001) 104
    - Nuclear breakup ~ before formation time.
    - Comover Interaction Model: AA and pA?
      - Ferreiro and Lasberg: JHEP 10 (2018) 094

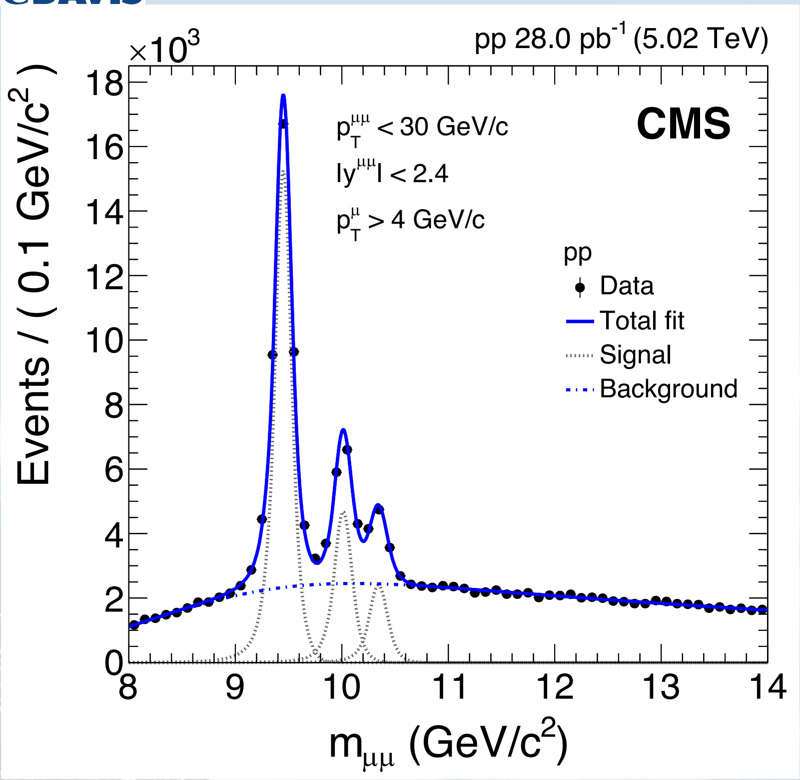


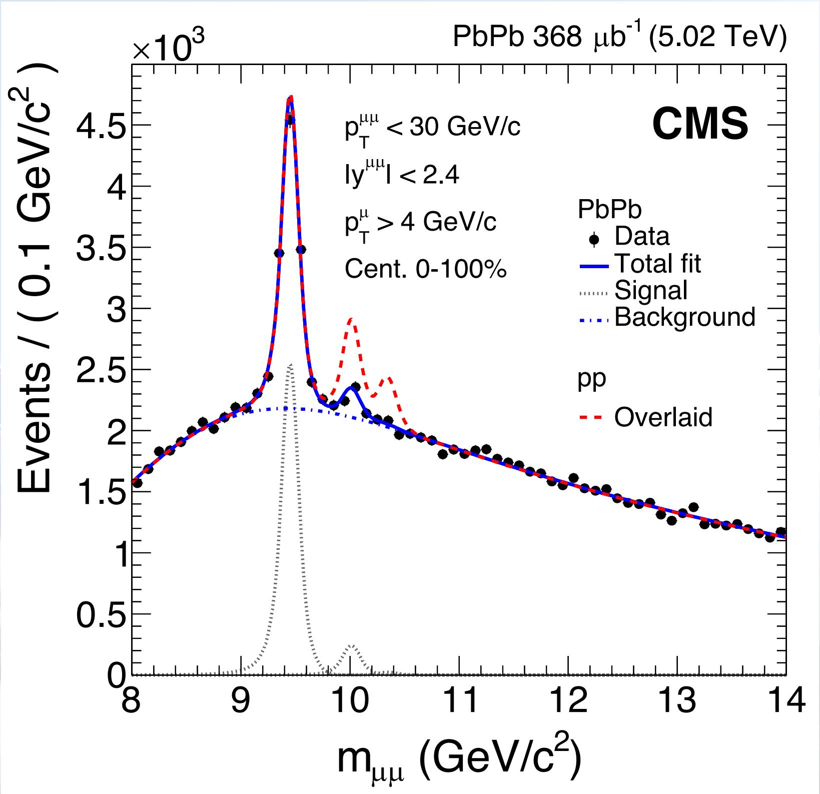
Bottomonia in AA

Υ Relative and Absolute Modification

- Observables:
  - Double Ratio of excited to ground state yields
    - Relative modification of excited states compared to ground state
      - Cancellation of efficiency and acceptance corrections
      - Cancellation of initial state effects, e.g. nuclear shadowing of PDF's
    - $\frac{\frac{\Upsilon(\mathrm{nS})}{\Upsilon(1\mathrm{S})}_{PbPb}}{\frac{\Upsilon(\mathrm{nS})}{\Upsilon(\mathrm{nS})}_{pp}} = \frac{R_{AA}(\Upsilon(nS))}{R_{AA}(\Upsilon(1S))}$
  - Nuclear Modification Factor, R_{AA} $\quad R_{AA} = \frac{1}{N_{coll}} \frac{N(\Upsilon)_{PbPb}}{N(\Upsilon)_{pp}}$
    - Ratio of invariant yields (or cross section) from PbPb to pp
    - Scaled by the number of nucleon-nucleon collisions
    - Absolute modification from pp to AA

□ Double ratio Graphically

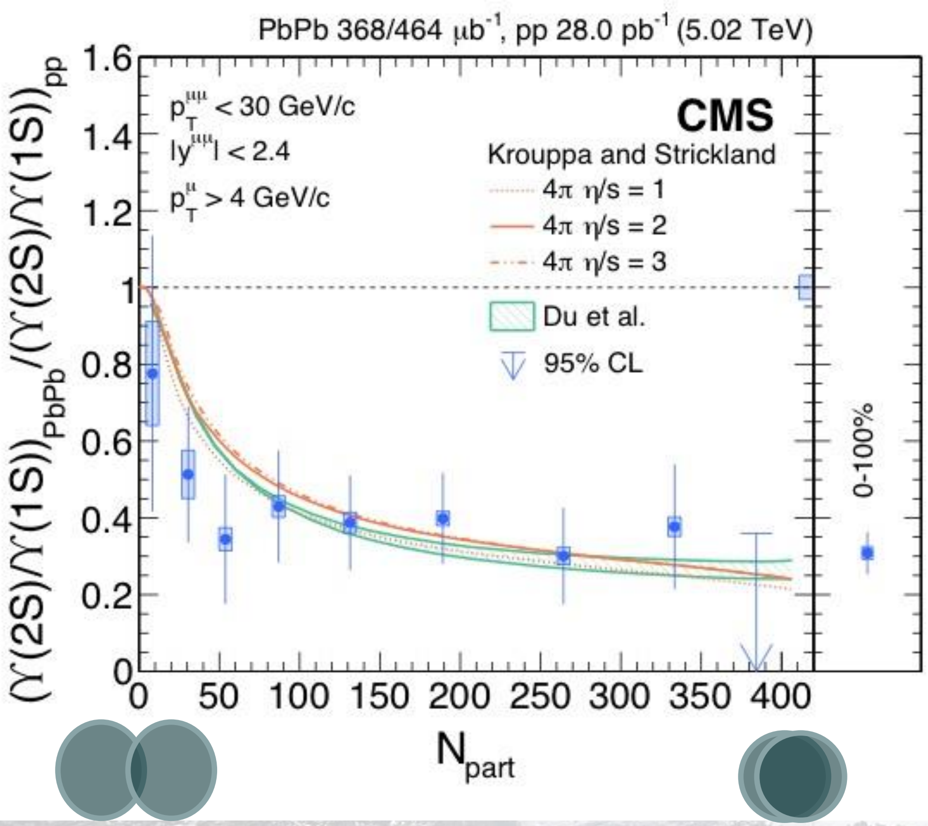




CMS: PRL 120 (2018) 142301

- Visual representation of Double Ratio
- pp shapes scaled to 1S in PbPb and overlayed on PbPb data:
  – Relative suppression of excited states.
  – Strong relative suppression of 3S state!

ϒ(2S) Double Ratio vs. Centrality



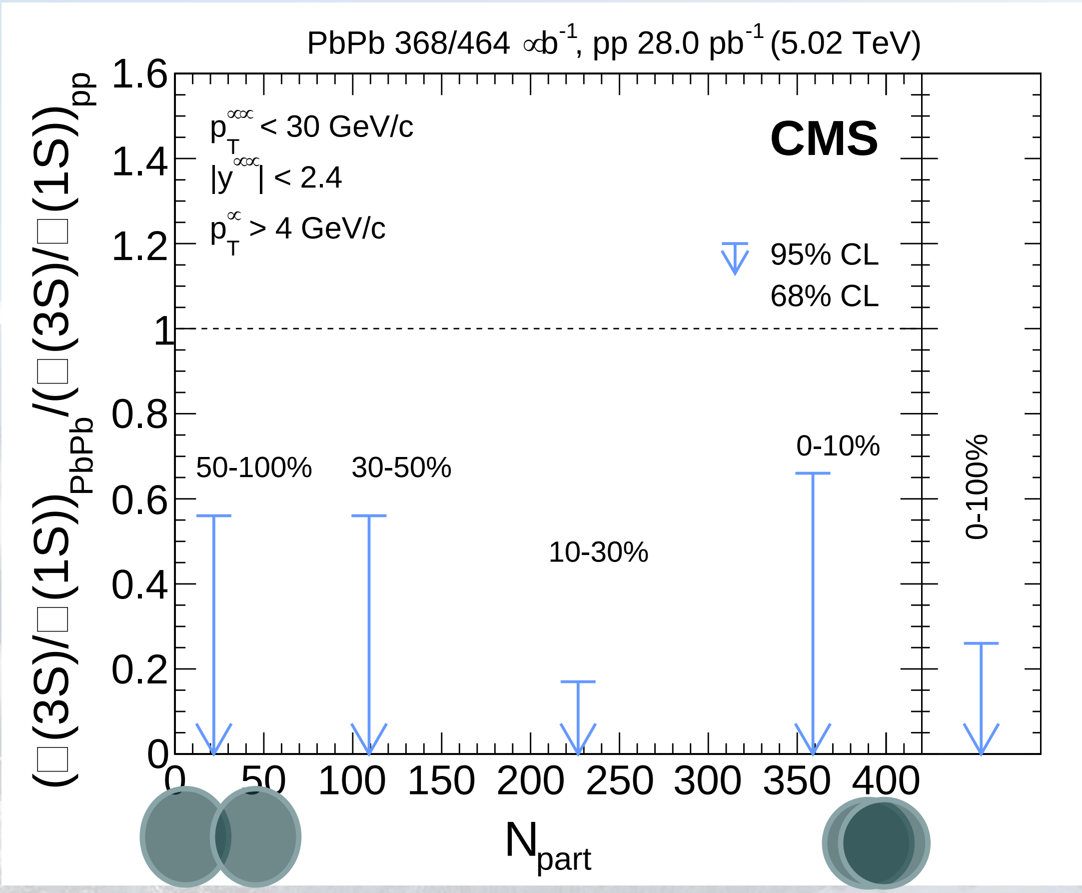
Peripheral collisions Central collisions

CMS: PRL 120 (2018) 142301

- – Larger suppression toward more central events
- – Consistent with unity in most peripheral bin
- **Comparison to theory:**
  - – Model: Strickland et al.
  - – Containing bottomonia evolved using anistropic hydrodynamics
    - Curves:
    - $\frac{4\pi\eta}{s} = \{1,2,3\}, T_0 = \{641, 632, 629\} MeV$
  - – Consistent with our data
    - Similar results by Rapp et al.

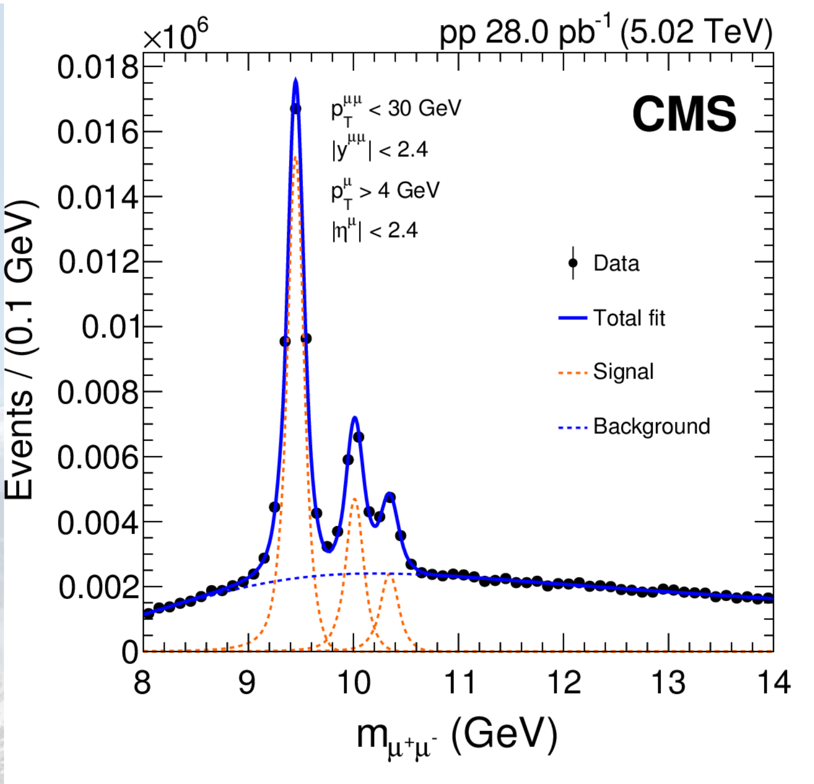
Υ(3S) : Strong suppression!

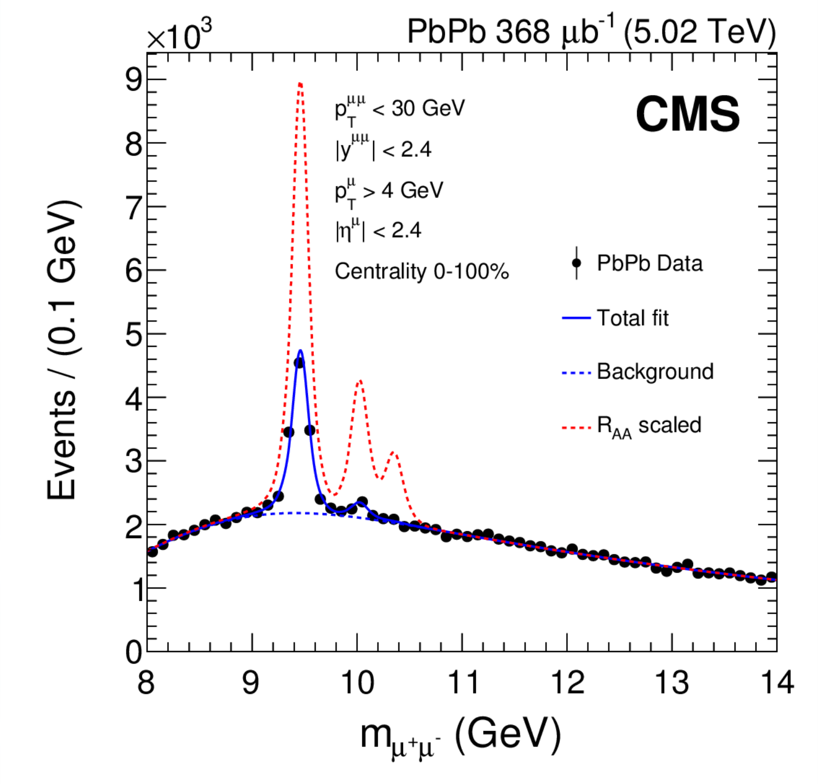
- Strong suppression of Υ(3S) relative to the 1S in all centralities
- Upper limits calculated in all cases
- Υ(3S) has smallest binding energy in Υ family
  - Sequential suppression of Υ states
  - Supports picture of melting in a color-deconfined QGP



CMS: PRL 120 (2018) 142301

Υ Absolute modification: Striking result



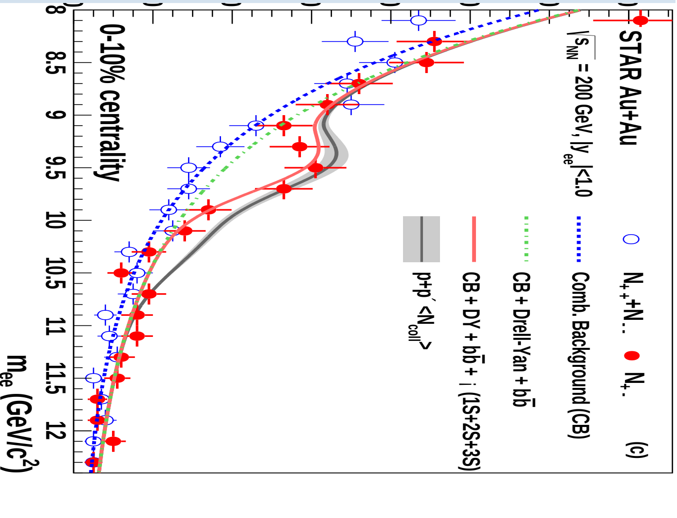


CMS arXiv:1805.09215
PLB in press

- Measure production in pp.
- Scale by number of binary nucleon-nucleon collisions, compare to AA measurement.
- Suppression observed!

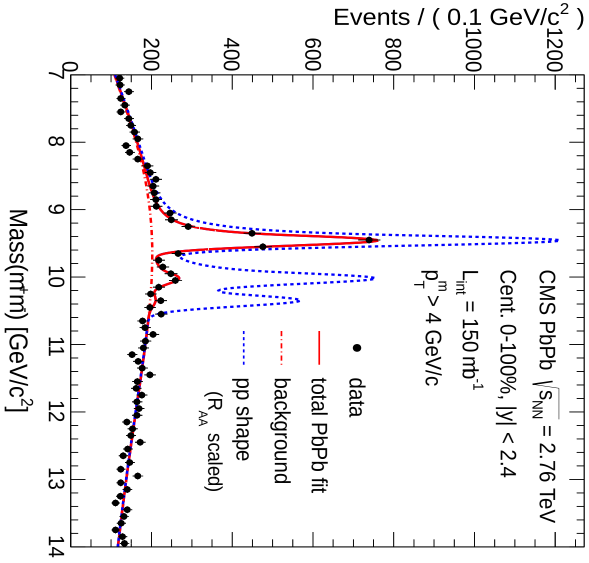
R_{AA} Graphically, RHIC and LHC

AuAu 200 GeV



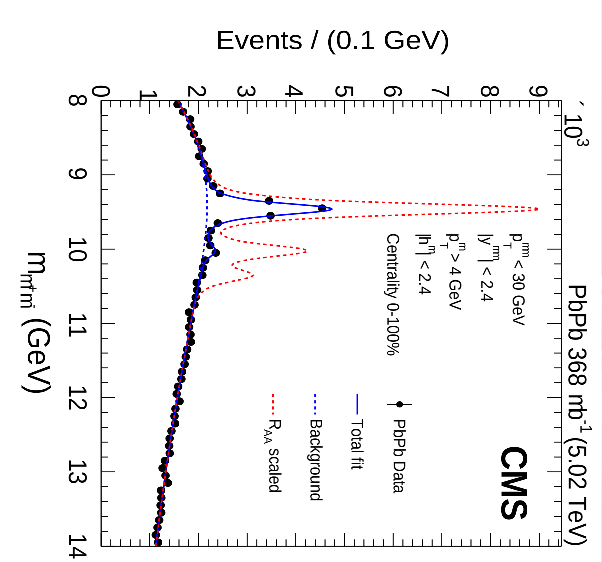
STAR: PLB 735 (2014) 127

PbPb 2.76 TeV



CMS: PLB 770 (2017) 357

PbPb 5.02 TeV

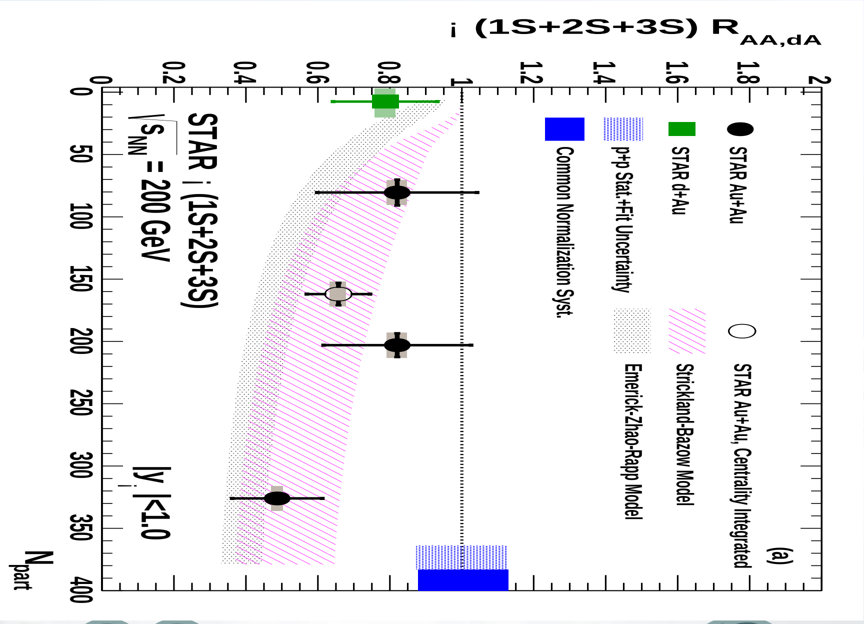


CMS: arXiv:1805.09215

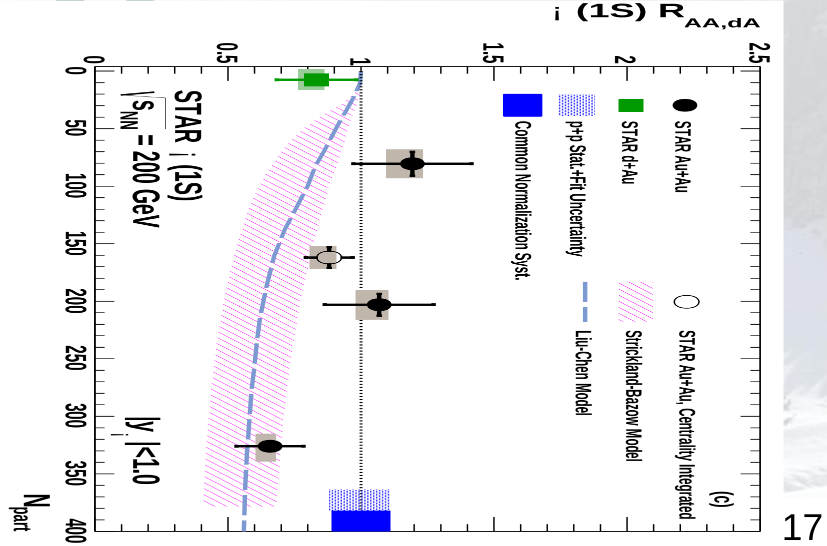
- Heavy ion data: dilepton invariant mass in ® region
- pp reference shape: overlay after scaling by number of binary collisions, N_{coll}
- Difference between Data and pp reference: evidence for ® suppression, $R_{AA} < 1$.

ϒ Nuclear Modification in STAR

- All data in STAR acceptance |y|<1
  - dAu, and two most peripheral Au+Au bins: consistent with no suppression
  - Suppression in the most central Au+Au bin:
  - Consistent with expectations for hot & cold nuclear matter
- Calculations:
  - Strickland & Bazow (Nucl. Phys. A 879 (2012) 25):
    - Includes estimate of heavy quarkonium potential, Re and Im.
    - Evolution through anisotropic hydro.,
    - T: 428 – 442 MeV (Depending on η/s, to match dN/dη)
  - Emerick, Zhao & Rapp:
    - attempt to include both Hot & Cold nuclear effects.
    - T_0 = 330 MeV.
- First combined dAu, AuAu analysis:
  - Peripheral R_{AA} similar to R_{dAu}.
  - Hint of stronger suppression for more central collisions, but not enough data to conclude difference with dAu



STAR: PLB 735 (2014) 127



□(1S), □(2S), □(3S) R_{AA} at 2.76 TeV

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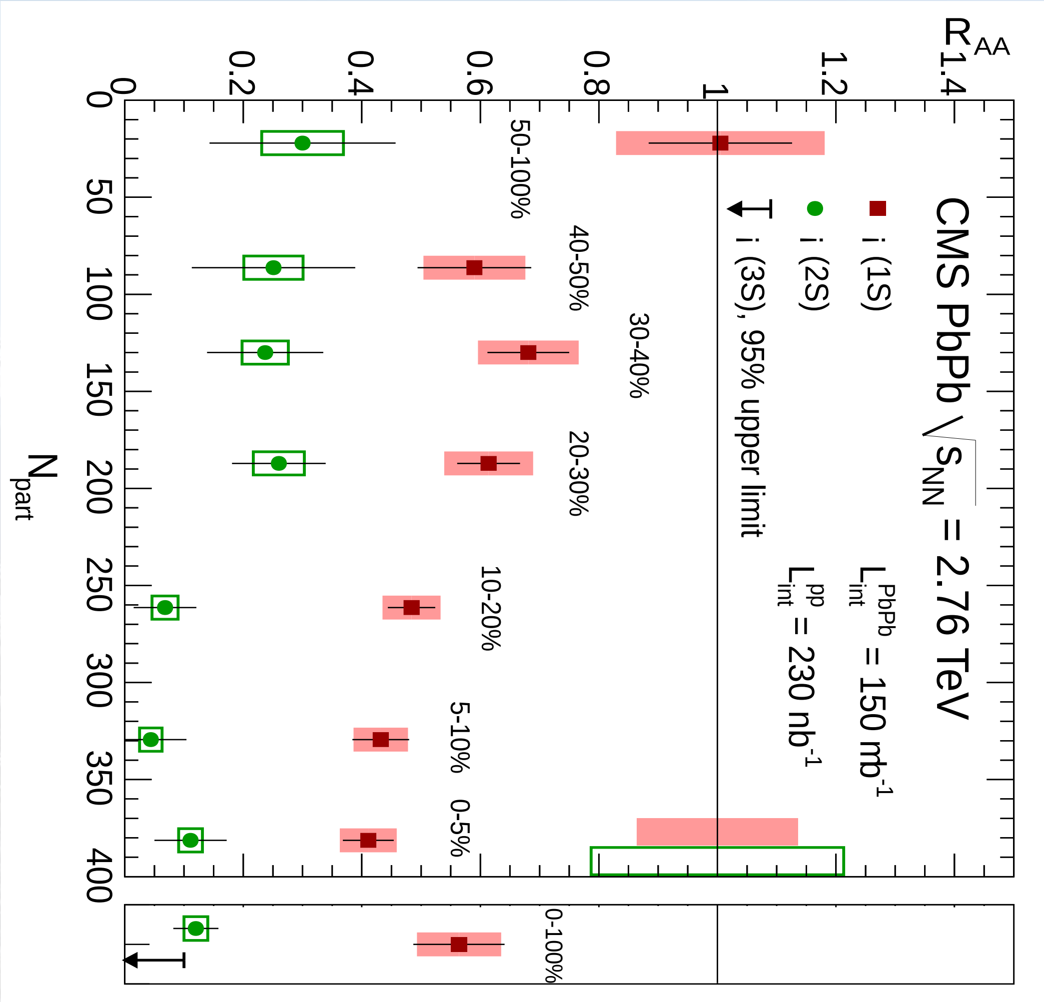
- 2011 150 /μb
  - ®(1S) R_{AA}, 7 centrality bins
    - First results on ®(2S) R_{AA}
      - Clear suppression of ®(2S)
  - ®(1S) suppression
    - Excited state suppression removes feeddown contribution.
    - 60-70% Υ(1S) directly produced.
    - Is direct Υ(1S) suppressed?
  - Centrality integrated



PRL 109, 222301 (2012)

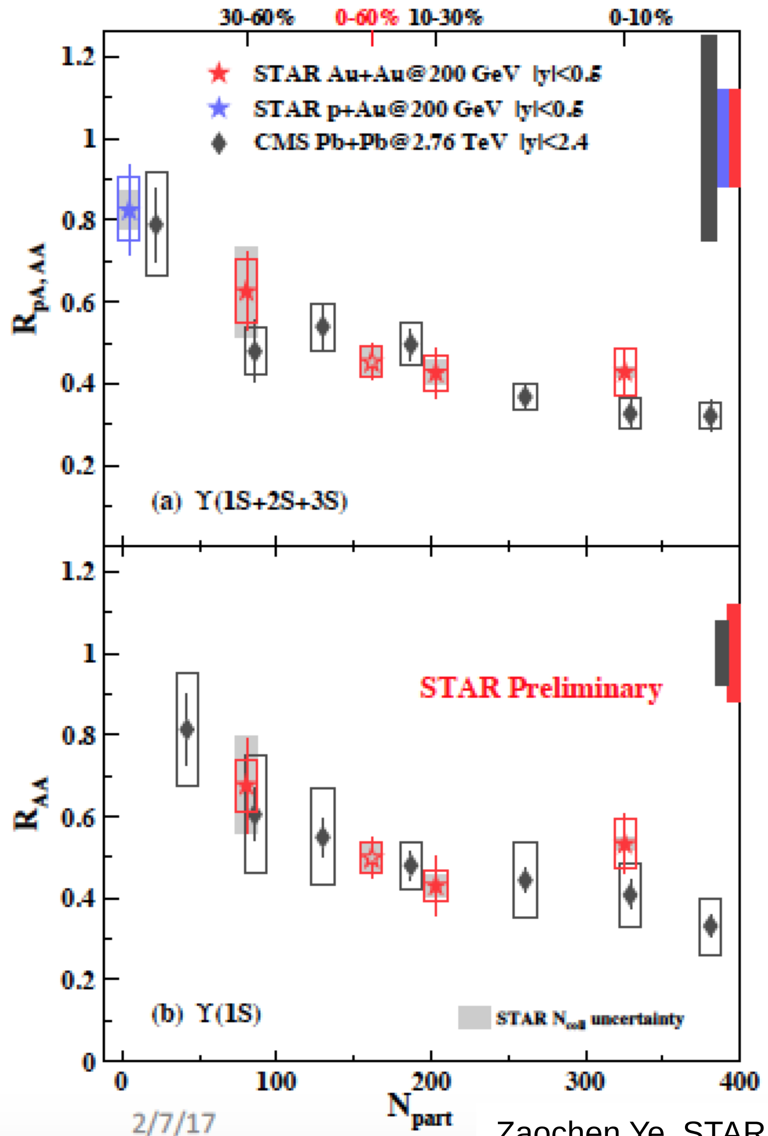
$R_{AA}(\Upsilon(1S)) = 0.56 \pm 0.08$ (stat.) ± 0.07 (syst.)

$R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.04$ (stat.) ± 0.02 (syst.)

$R_{AA}(\Upsilon(3S)) < 0.1$ (at 95% C.L.)

- **Observation of sequential suppression of ® in order of their binding energy**

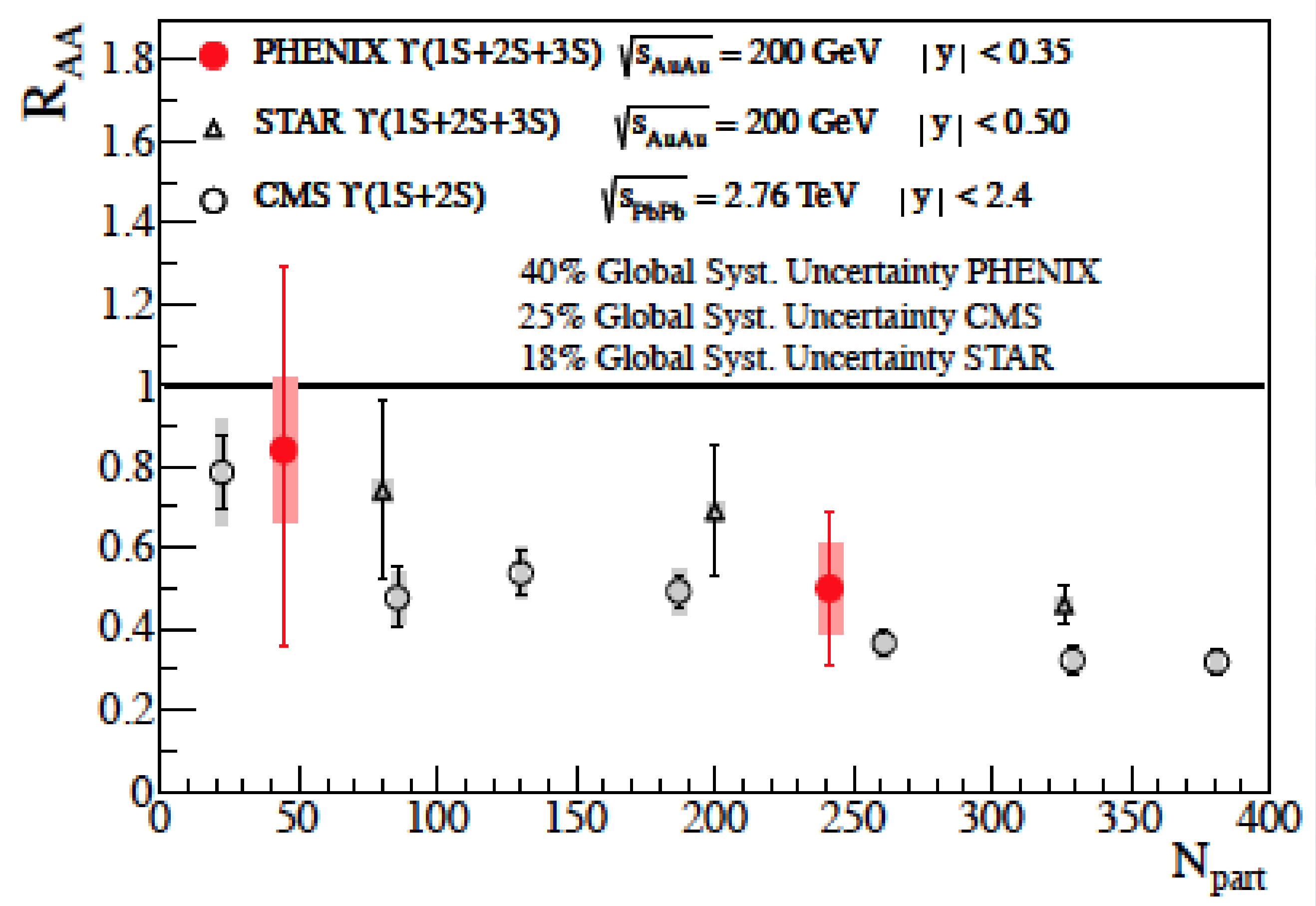
RHIC and LHC midrapidity comparison



Zaochen Ye, STAR, QM17

- 1S+2S+3S: via dielectrons and dimuons.
  - R_{pA}: slightly smaller than 1
  - Centrality dependence: more suppression in central events
  - R_{AA} in central events significantly smaller than R_{pA}
- Separation of 1S (bottom panel)
  - Centrality dependence RHIC vs LHC:
    - Similar suppression of ϒ(1S)!
    - Feeddown dominated?

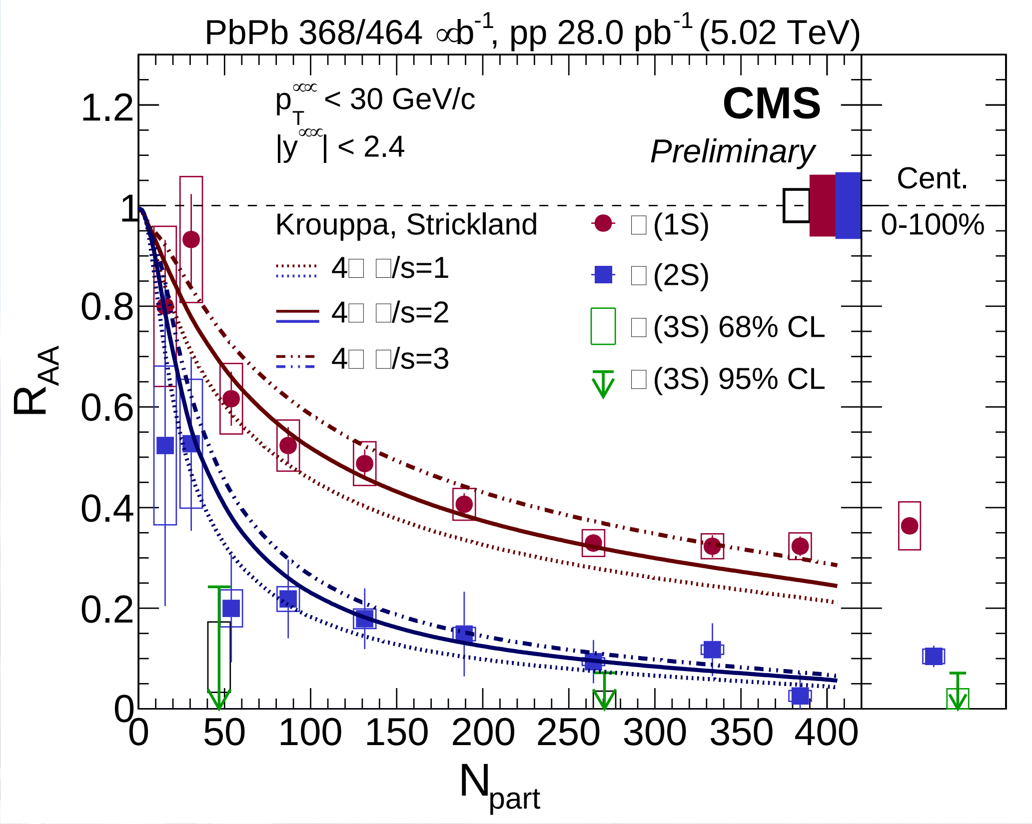
PHENIX: Υ results



- Suppression in central events of similar magnitude as STAR and CMS.

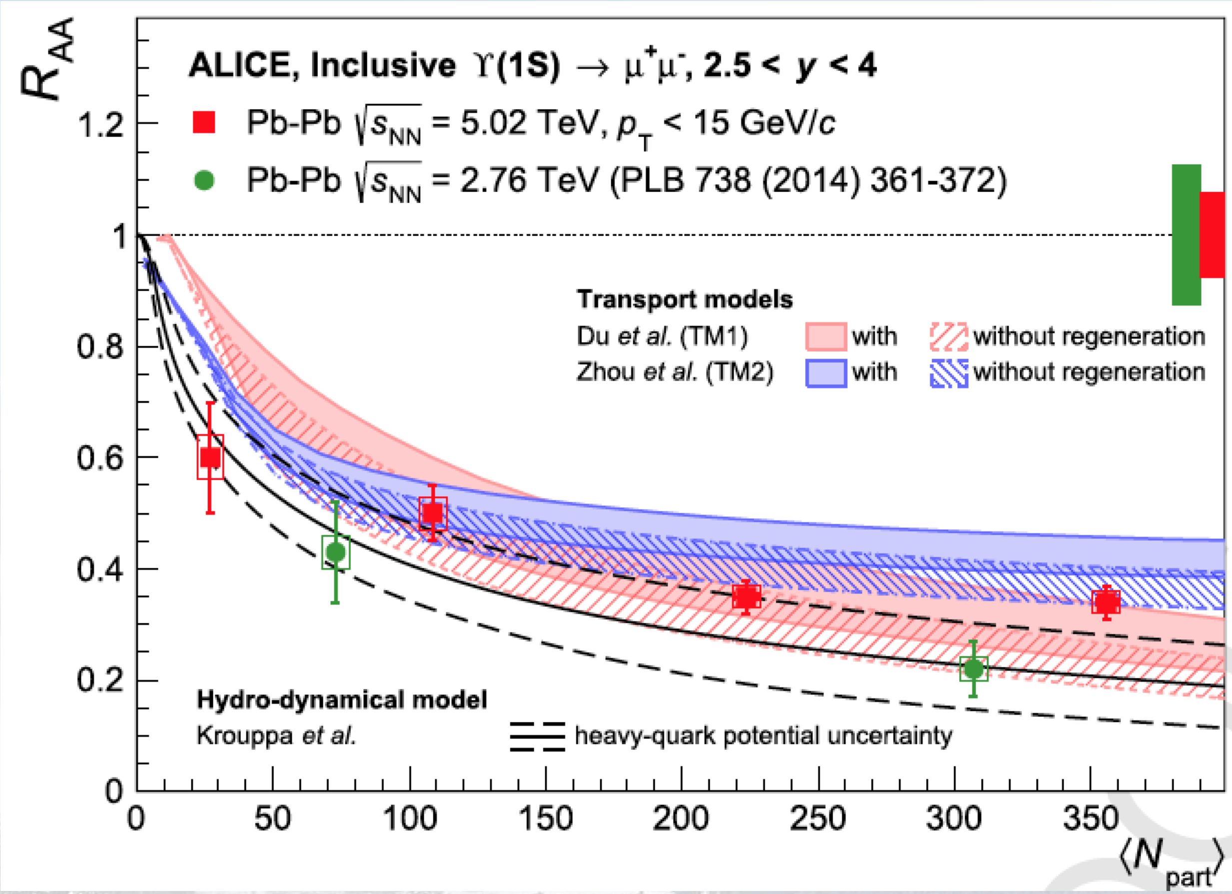
Υ(nS) R_{AA} vs. Centrality at 5.02 TeV

- Nuclear modification for the 3 S-states:
  - Sequential melting!
- Suppression of 1S and 2S:
  - Increasing for more central events
- R_{AA} Integrated results (0-100%)
  - 1S: 0.364 ± 0.014 ± 0.048
  - 2S: 0.104 ± 0.021 ± 0.014
  - 3S: 0.071 at 95% CL



CMS PAS HIN-16-023
arXiv:1805.09215

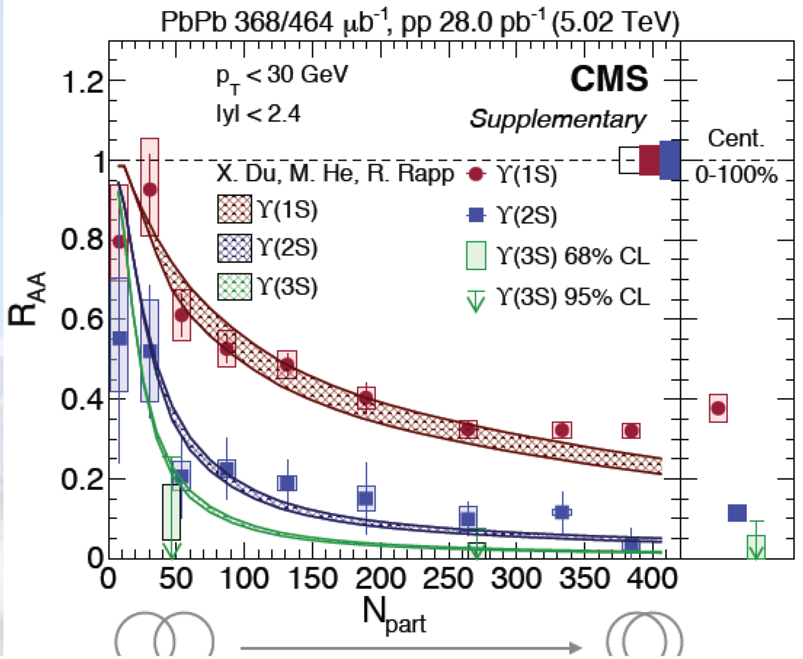
$\Upsilon(1S)$ R_{AA} in ALICE

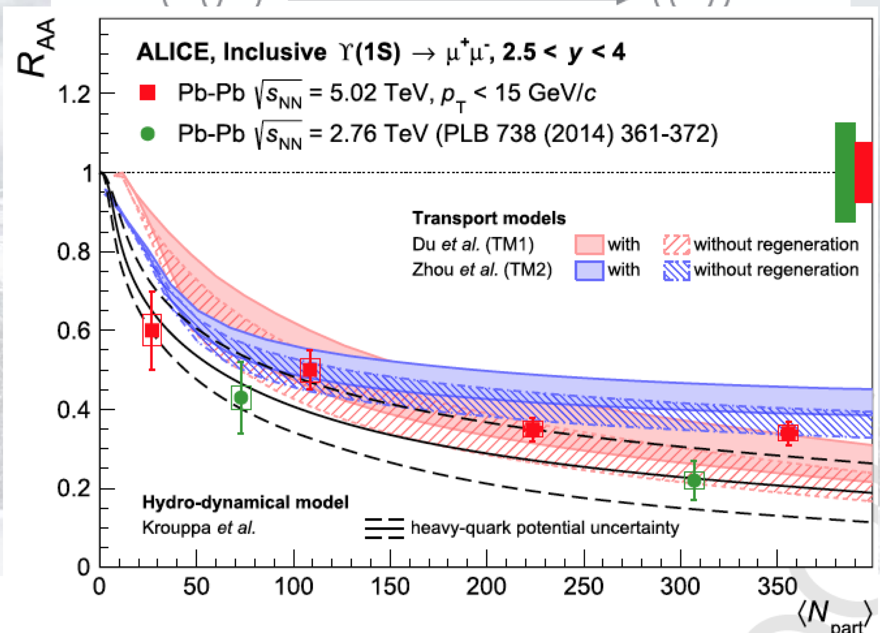


- Suppression increases for central events in ALICE kinematic region.
- Same trends seen in 2.76 and 5 TeV.
  - No energy difference within the ~20% uncertainties.

Comparison to Model, TAMU

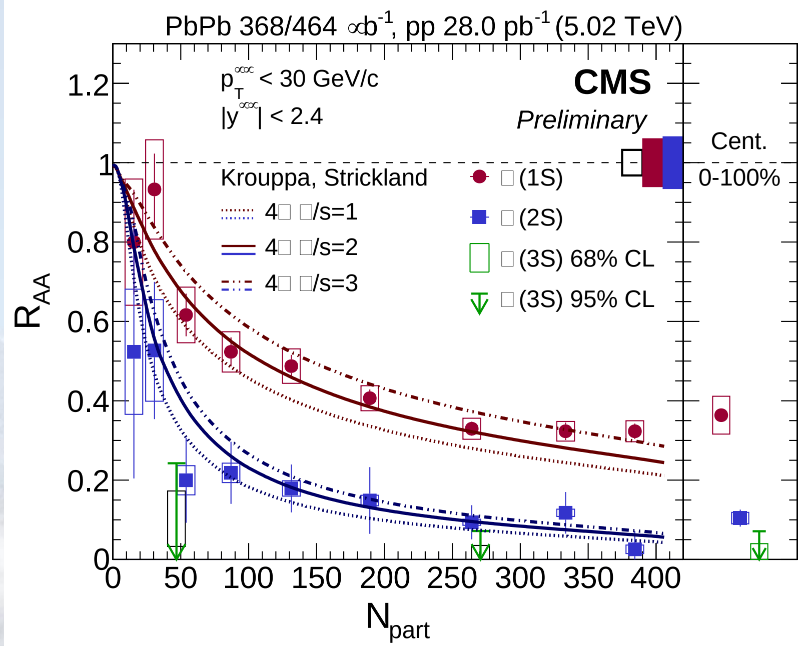
- Transport Model by R. Rapp
  - PRC 96 (2017) 054901
  - Re[V] and Im[V]
  - In-medium binding energies
  - Internal energy potentials
  - Feed down from excited states
  - Directly produced **ϒ**(1S) ~67%
  - Model QGP via Kinetic rate equation
  - Regeneration
- Melting temperatures:
  - **ϒ**(1S, 2S, 3S): 500, 240, 190 MeV
- Initial temperature:
  - 2.76 TeV: 520 - 750 MeV
  - 5.02 TeV: 7% increase
  - **ϒ**(1S) RAA: only slight decrease
  - Direct **ϒ**(1S) melts!

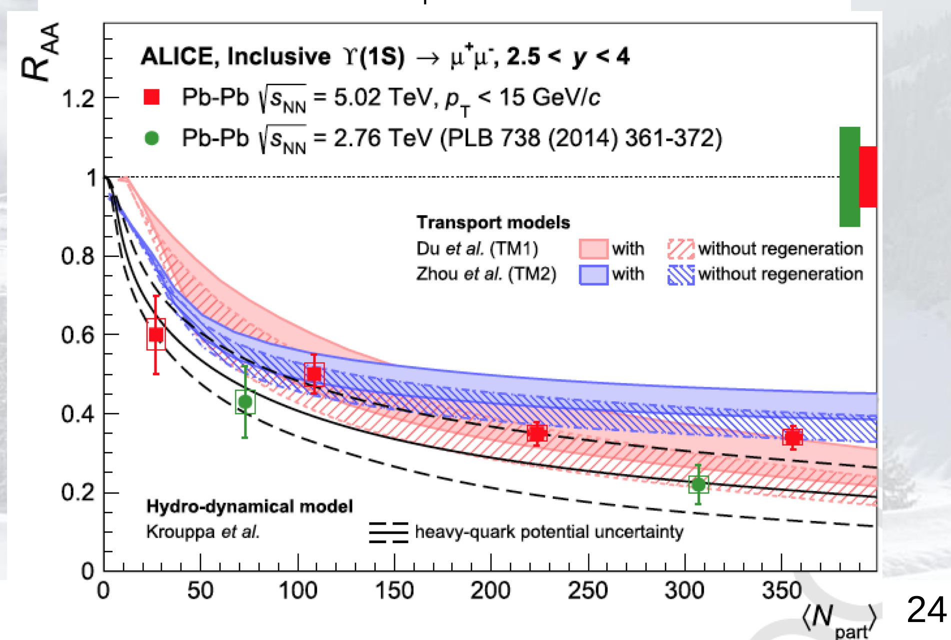




Comparison to Model, KSU

- Hydro Model by M. Strickland
  - Universe 2 (2016) 16
  - Re[V] and Im[V]
  - In-medium binding energies
  - Internal energy potentials
  - Feed down from excited states
  - Directly produced **ϒ**(1S) ~67%
  - Model QGP via Hydrodynamics
  - Momentum-space anisotropy
  - No regeneration
- Melting temperatures:
  - **ϒ**(1S, 2S, 3S): 600, 230, 170 MeV
- Initial temperature:
  - 2.76 TeV: 544 - 552 MeV
  - 5.02 TeV: 629 - 641 MeV (16% increase)
  - **ϒ**(1S) RAA: ~25% decrease
  - Direct **ϒ**(1S) melts!





Comparison to 2.76 TeV Results

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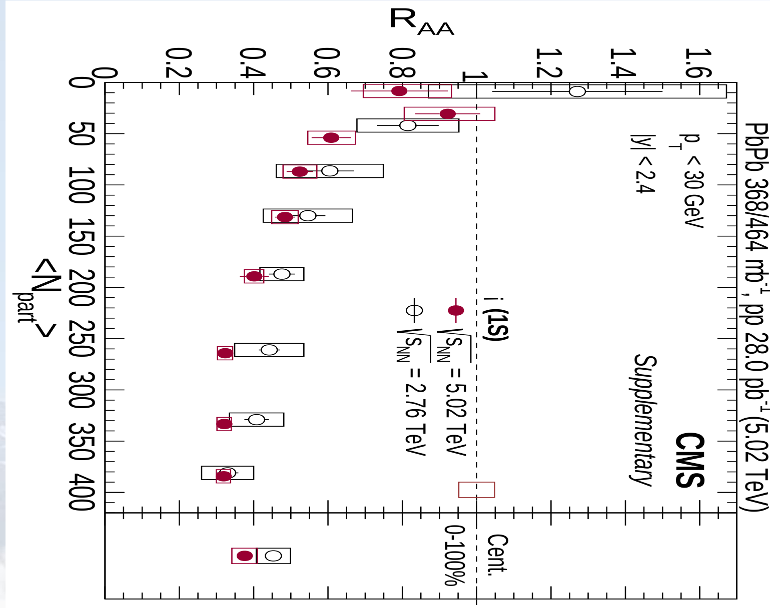
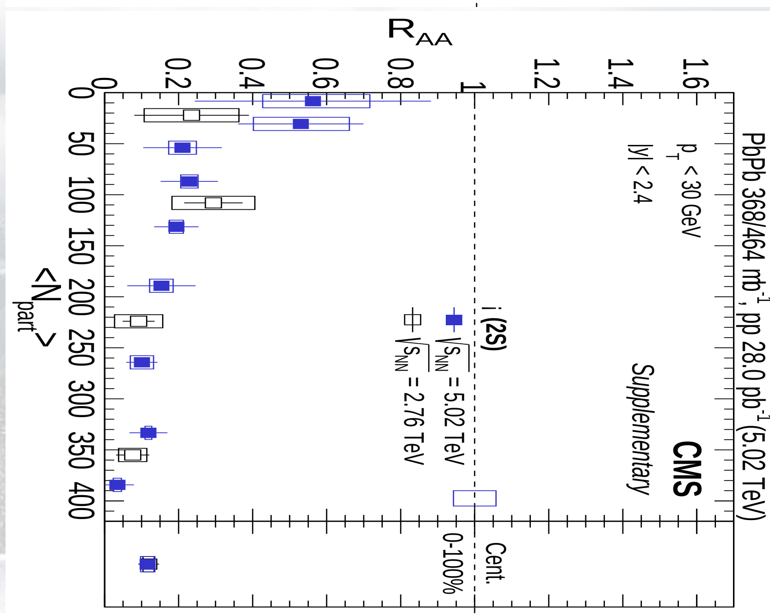
- Υ(1S):
  - Models expect increased suppression with larger $\sqrt{s}$
  - Larger suppression at higher energy? Can't really say:
    - Factor of 1.2 ± 0.15 (syst).
    - Need to reduce uncertainties below 10%.



- Υ(2S):
  - Suppression level is consistent between the two energies
    - Larger role of regeneration for 2S state?
      - Rapp et al. arXiv:1706.08670



CMS 5.02 TeV R_{AA}: CMS PAS HIN-16-023 arXiv:1805.09215
CMS 2.76 TeV R_{AA}: PLB 770 (2017) 357

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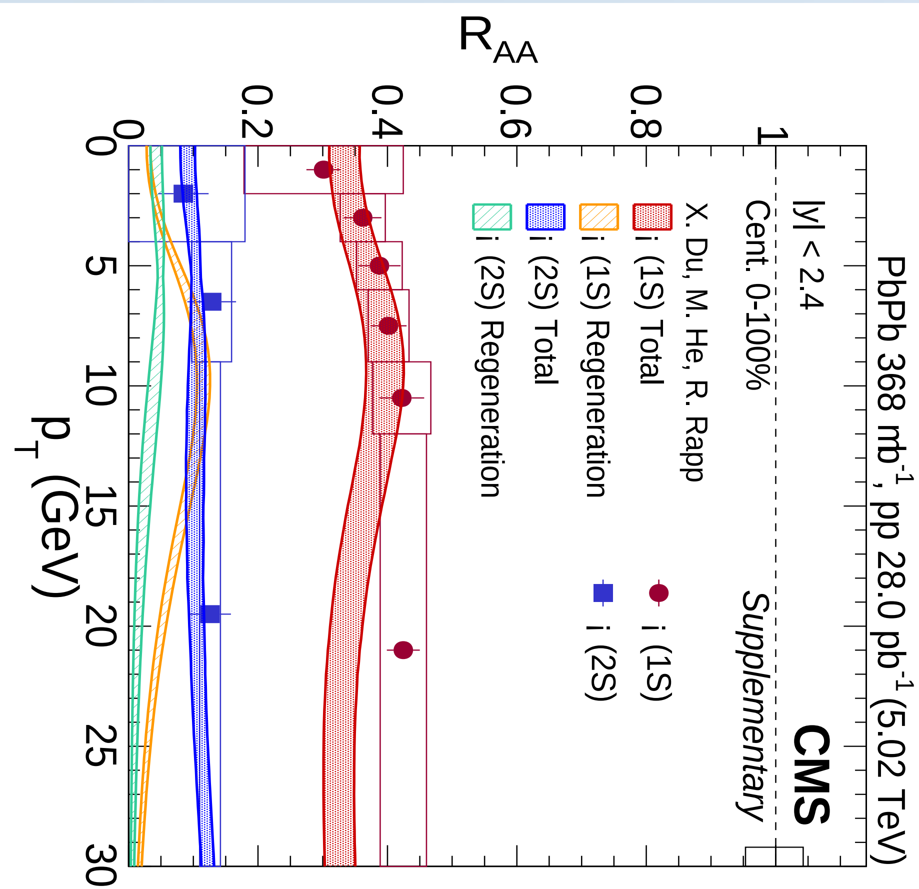
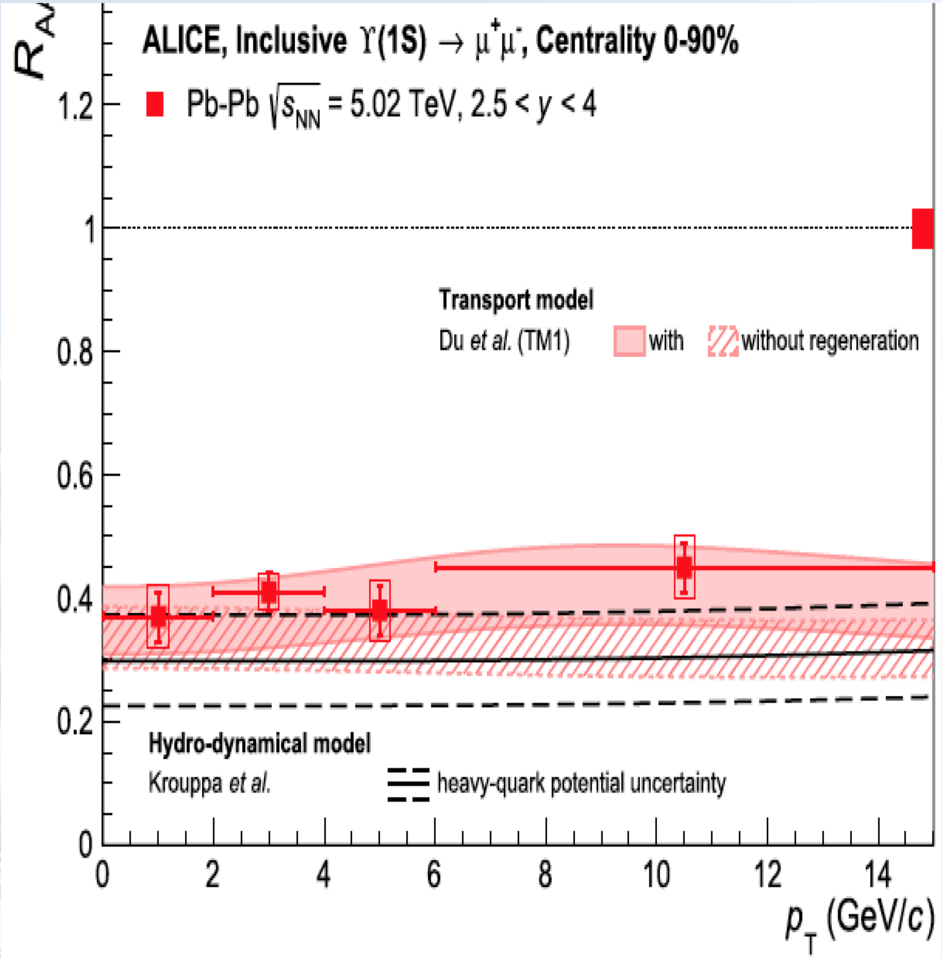
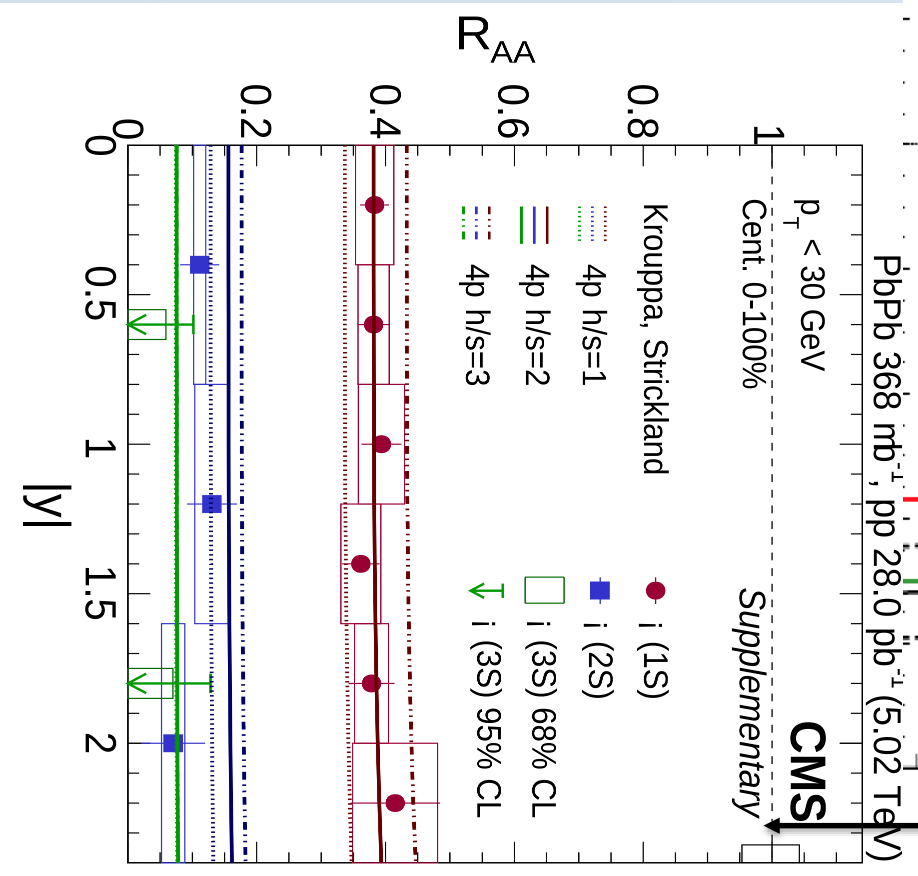
Υ R_{AA} p_T dependence

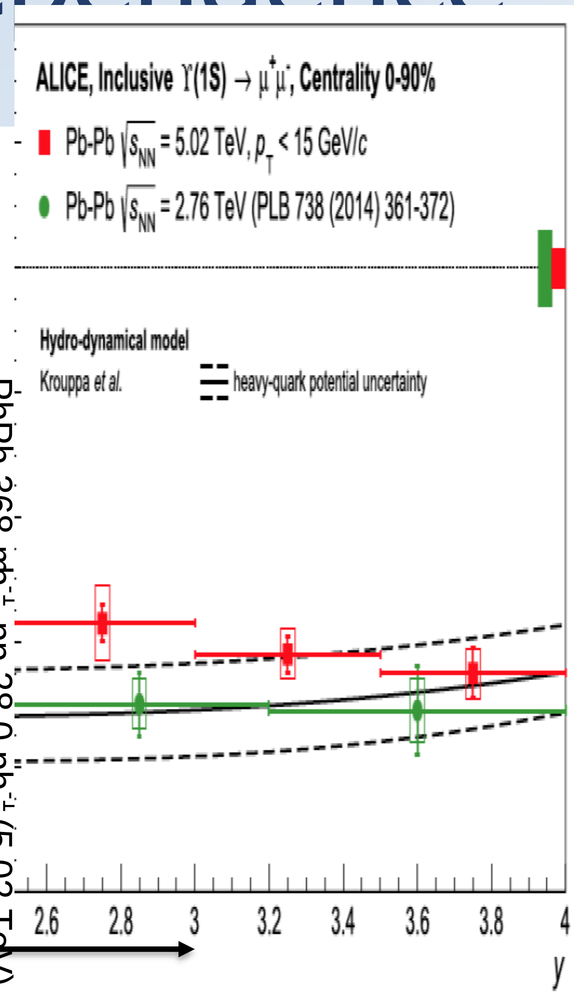


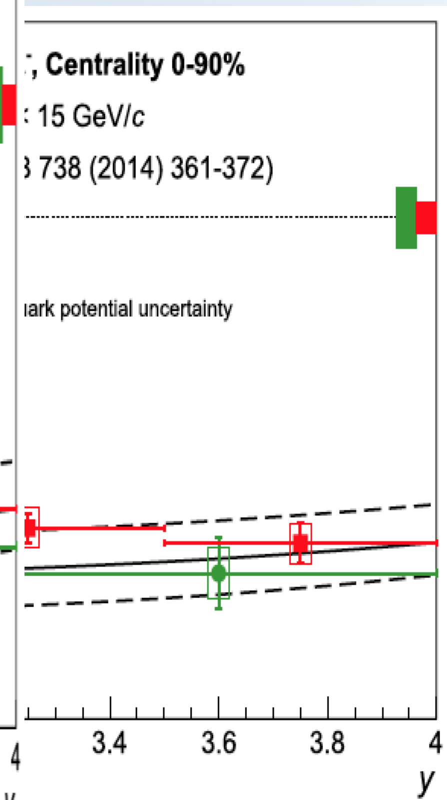


- Υ(nS): No significant dependence of R_{AA} on p_T,
- p_T , Rapp Model: Contributions from regeneration have different shapes.
  - Not visible within our uncertainties.

Υ R_{AA} y dependence

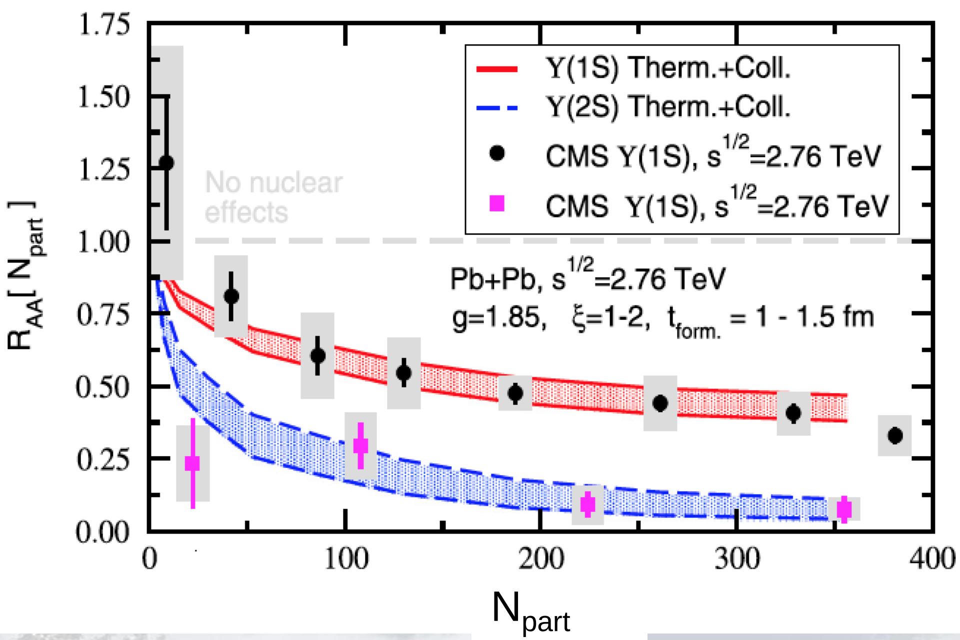


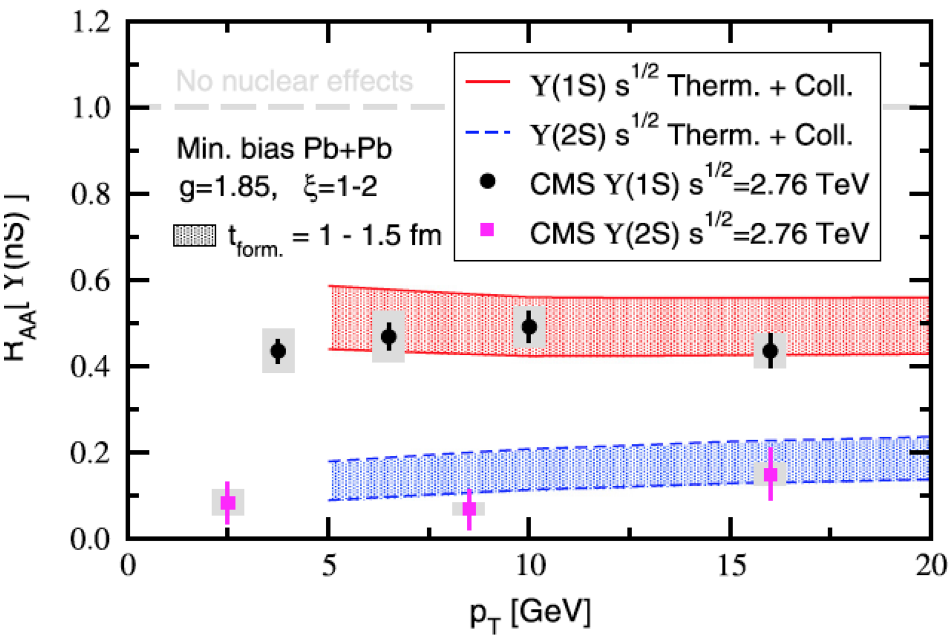




- Υ(nS): No significant dependence of R_{AA} on rapidity.
- y, Strickland Model: Modest increase of R_{AA} at higher rapidity. Consistent with data.

ϒ Collisional + Thermal dissociation model



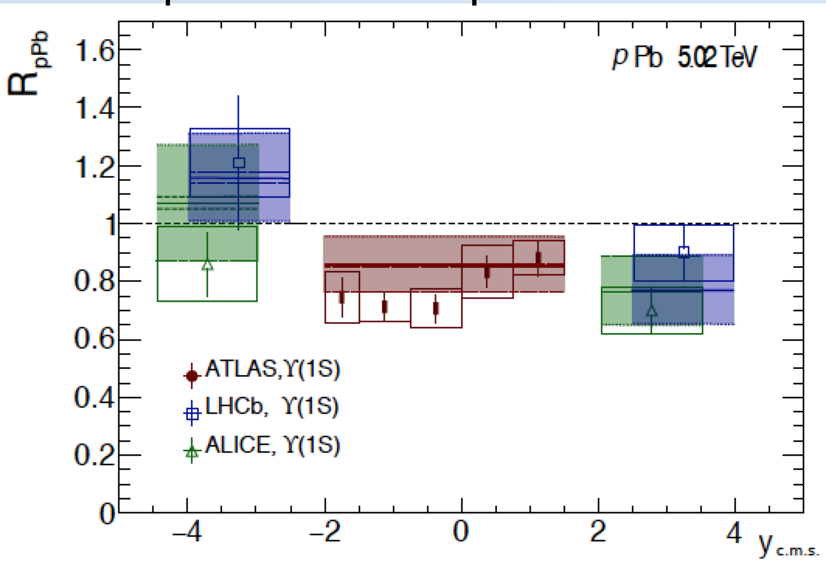


Aronson, Borras, Odegard, Sharma, Vitev, PLB 778 (2018) 384

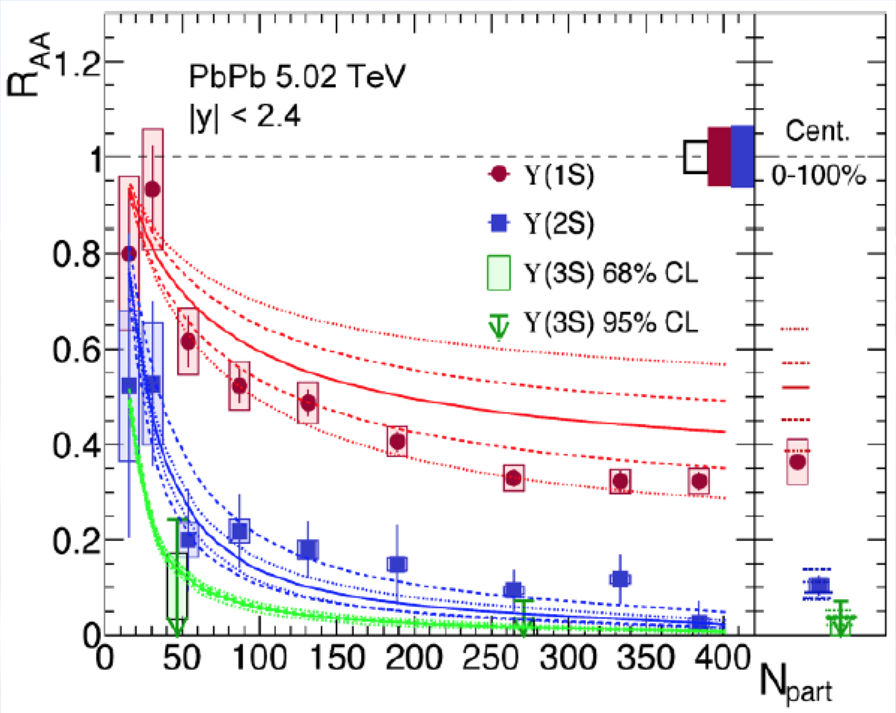
- Model:
  - $Q\bar{Q}$ proto-quarkonia state with formation time ~1 fm interacts via Debye screened potential.
    - Thermal screening dominates the suppression of excited states.
  - Broadening due to multiple scattering in QGP, controlled by ξ parameter.
    - Ground state is also dissociated due to collisional interactions.
  - Reproduce data at 2.76 TeV

ϒ in Co-mover Interaction Model

Fit dissociation cross section parameters in pA



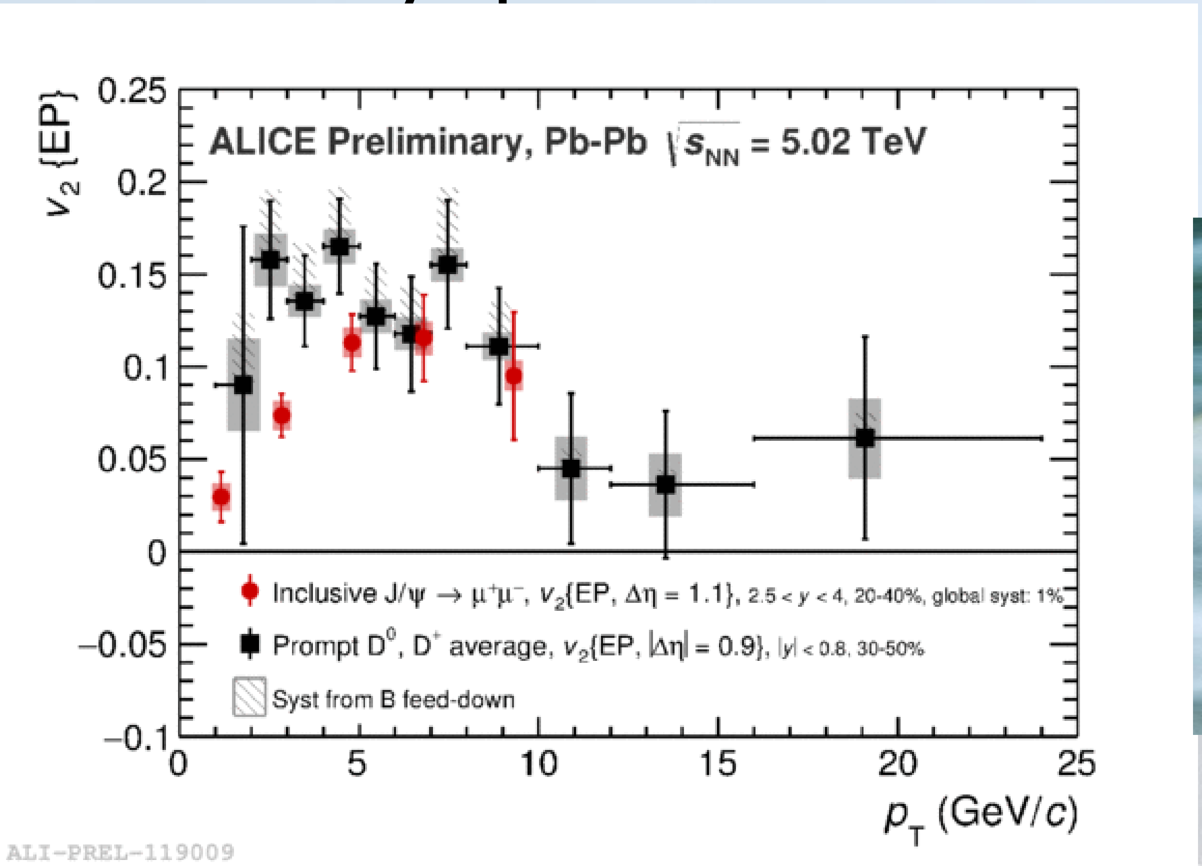
Extrapolate to AA using same parameters



- Same physics in pA and AA?
- Hadrons in pA vs gluons in AA? Same parameter for scattering strength in pp and AA…Coincidence?
- Do we agree these are gluons in all cases? QGP drop in pA? Is this a crude way to deal with gluodissociation?
- Note uncertainties from PDF: with reduced uncertainties, will this still work?

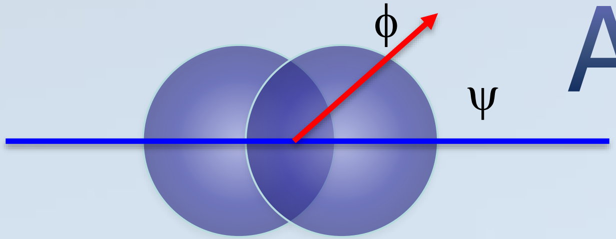
Next Υ measurements...

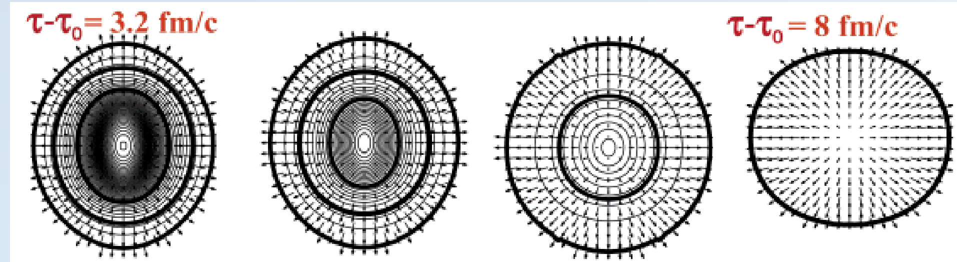
- Do heavy quarks flow?



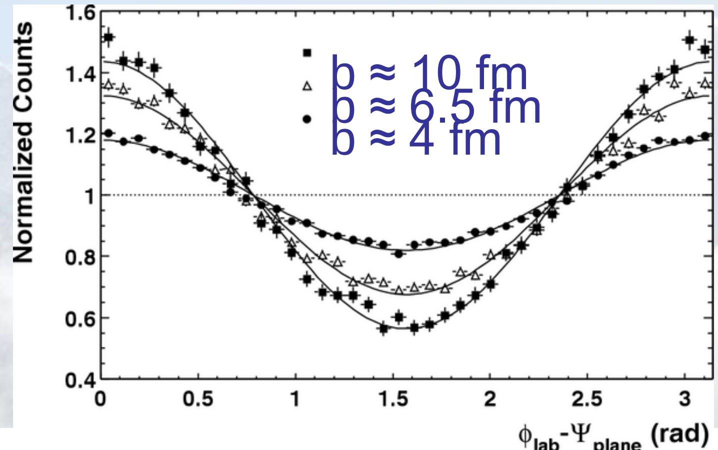
- J/ψ v_2 is large, and puzzling. Should heavy quarks flow? What will Υ do?

Azimuthal anisotropy

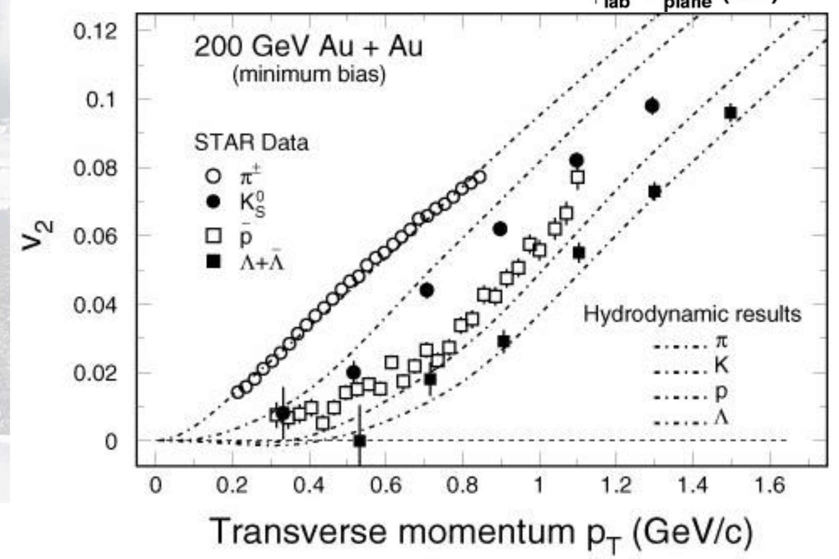




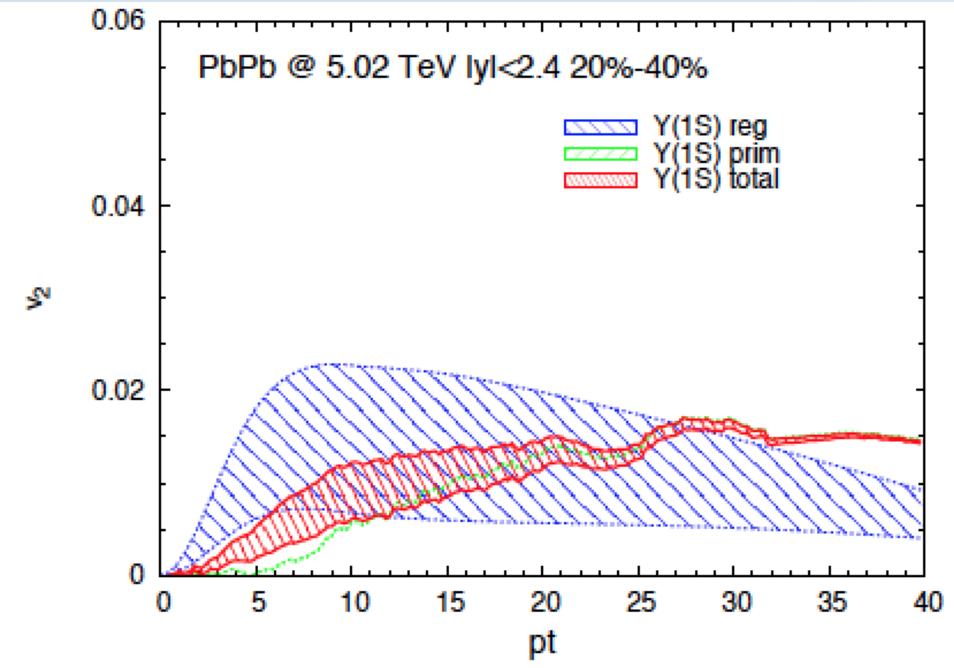
- Non-central collisions produce elliptical shape in transverse plane.
- Azimuthal distribution of particles around the reaction plane:
  - driven by large anisotropic pressure gradients in relativistic QGP fluid.
  - in-plane vs out-of plane difference
  - Characterized by Fourier series. 2nd coefficient: $v_2 \sim \langle 2\cos(2(\phi-\psi))\rangle$ called "elliptic flow".
- Low pt azimuthal anisotropy:

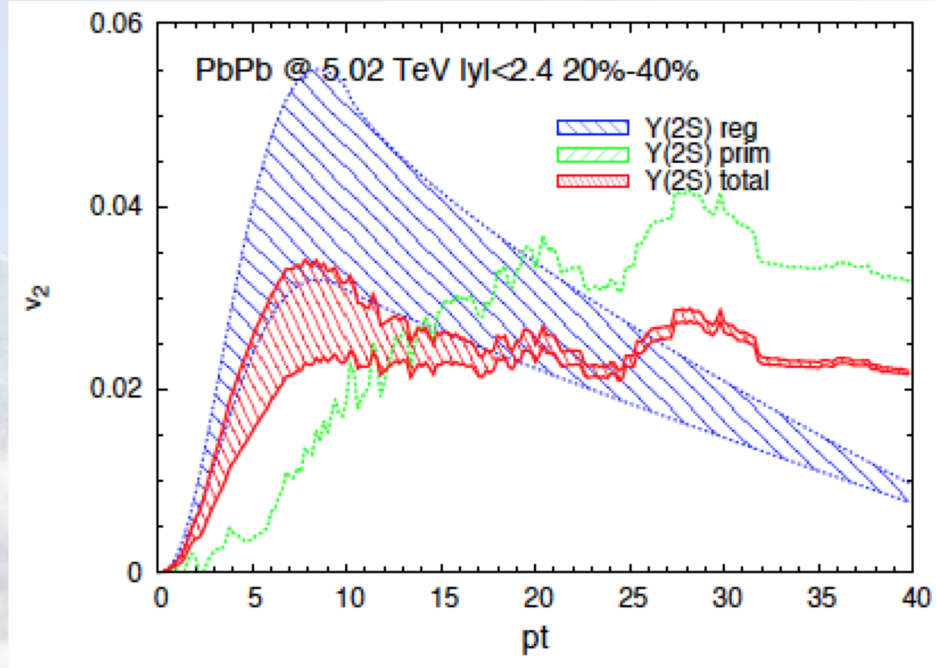


- Characteristic mass ordering vs p_T in Hydro
  - Same velocity, but different mass.



Υ v_2 predictions, Transport Model



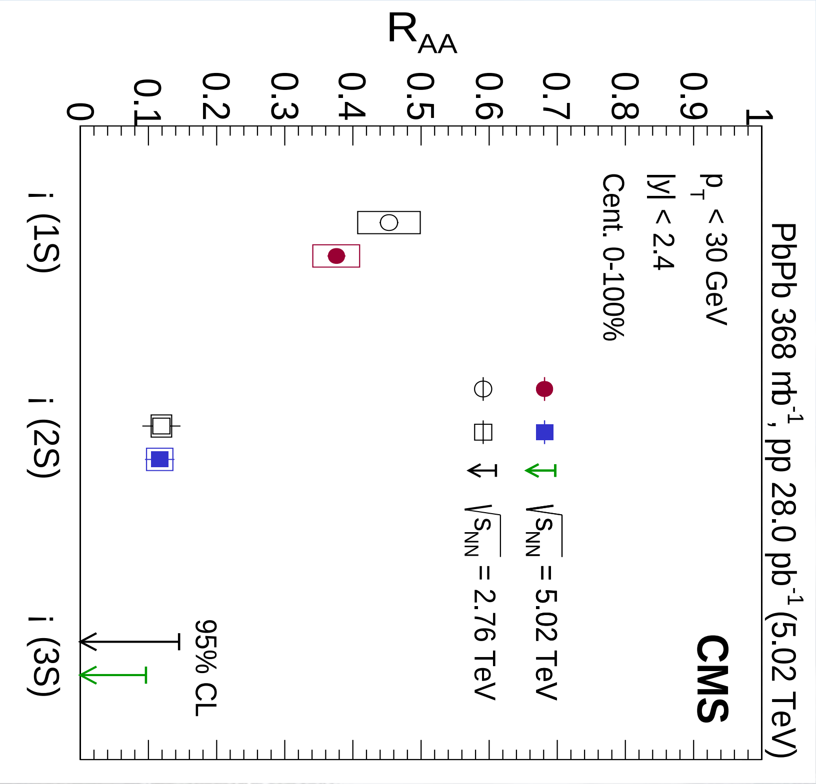


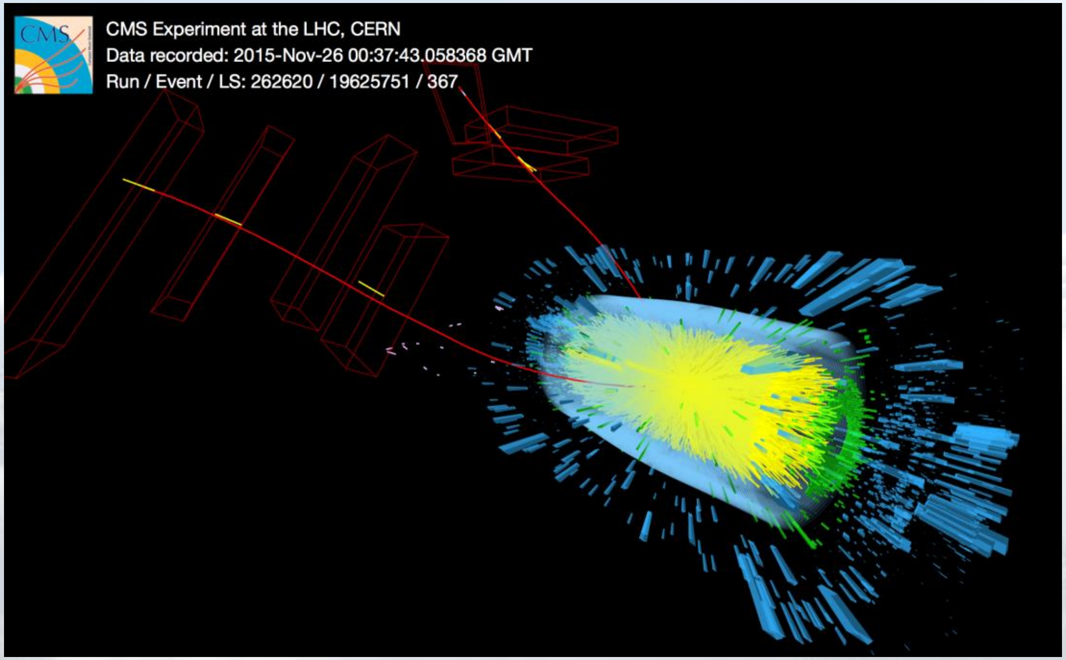
Du, He, Rapp, PRC96 (2017) 054901

- Expect small (< 2%) v_2 for 1S (with reg). Otherwise ~ 0 up to 10 GeV/c.
  - Also expected small v_2 for J/ψ… didn't happen. Attempt Υ v_2 with 2018 data.
- Test of regeneration: $v_2(2S) \sim 2\, v_2(1S)$
  - Will need higher luminosity, more data for $v_2(2S)$.
- Toward correlating Υ with activity in azimuth in AA.

UCDAVIS

Summary





Bottomonia: essential to quantitatively explore the temperature and color deconfinement properties of the Quark Gluon Plasma.

1S: Direct ~67%, RAA ~0.4, how much suppression from CNM?

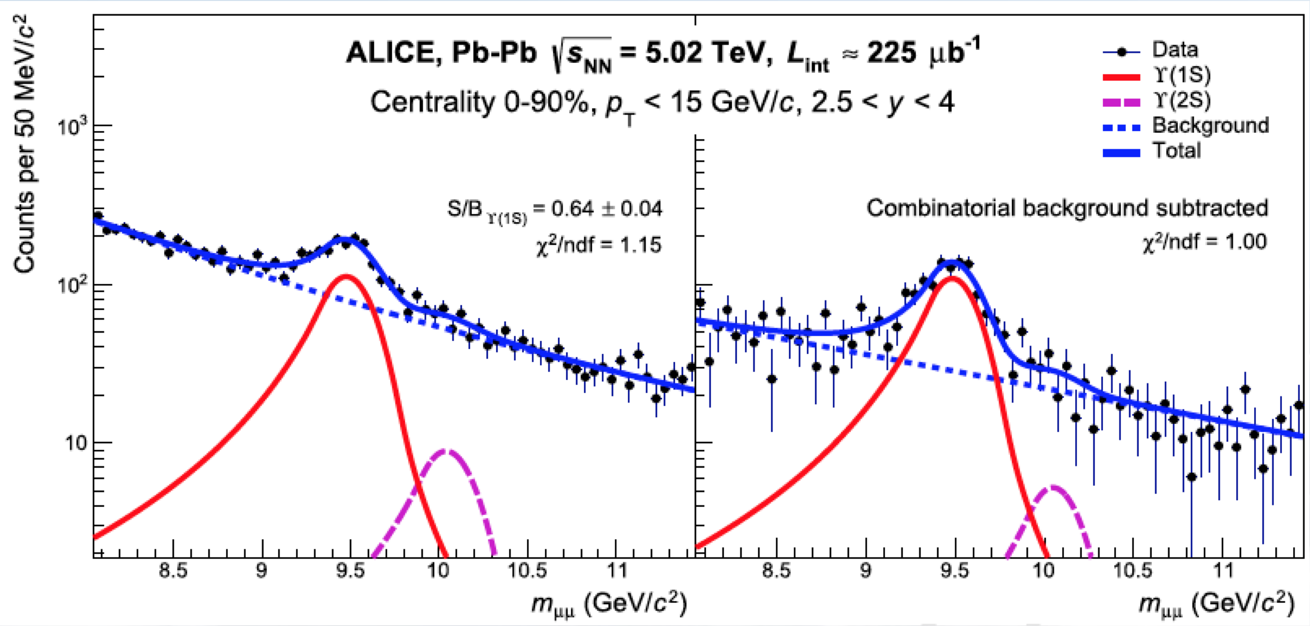
2S: Dominated by regeneration? Not all models include it.

3S: Fully melted?!

Open questions: Feed-down, suppression mechanisms, energy dependence, pA to AA…

Backup Material

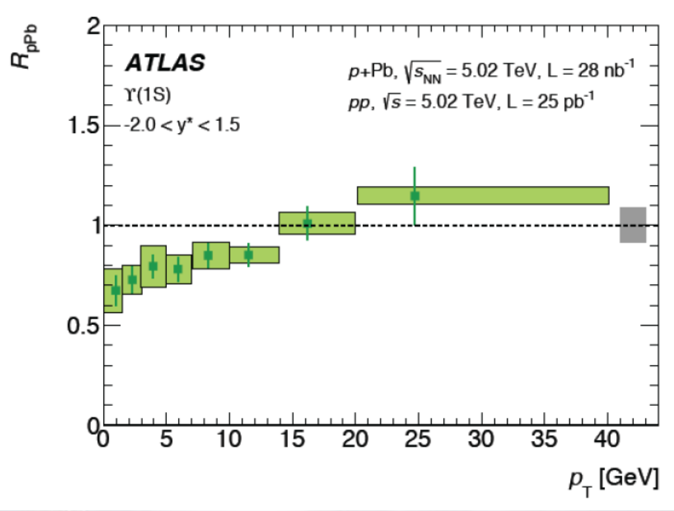
ALICE signal

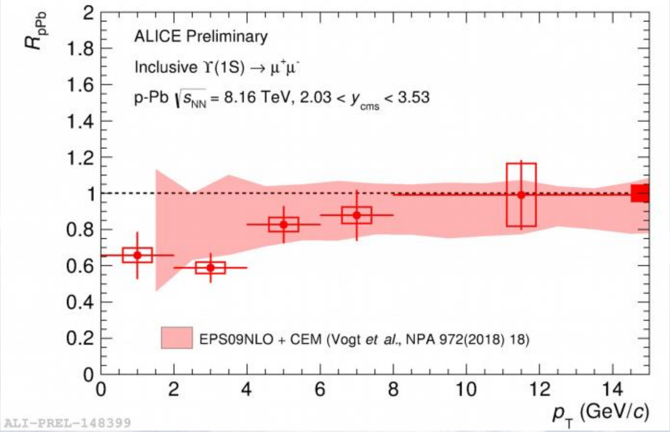


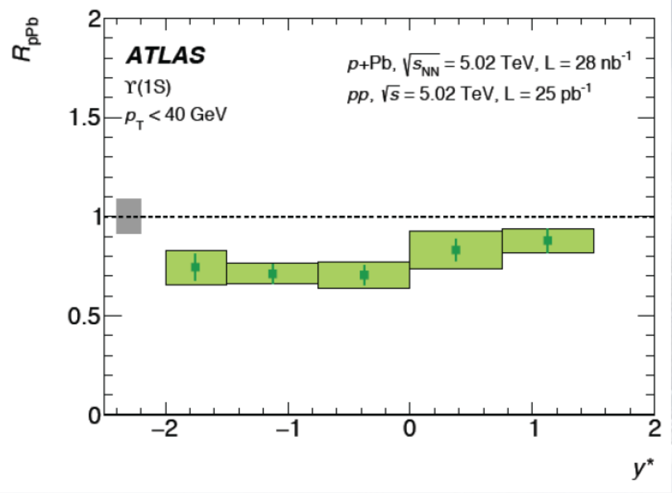
- 1S and 2S observed. 3S consistent with zero.

LHC pPb Results

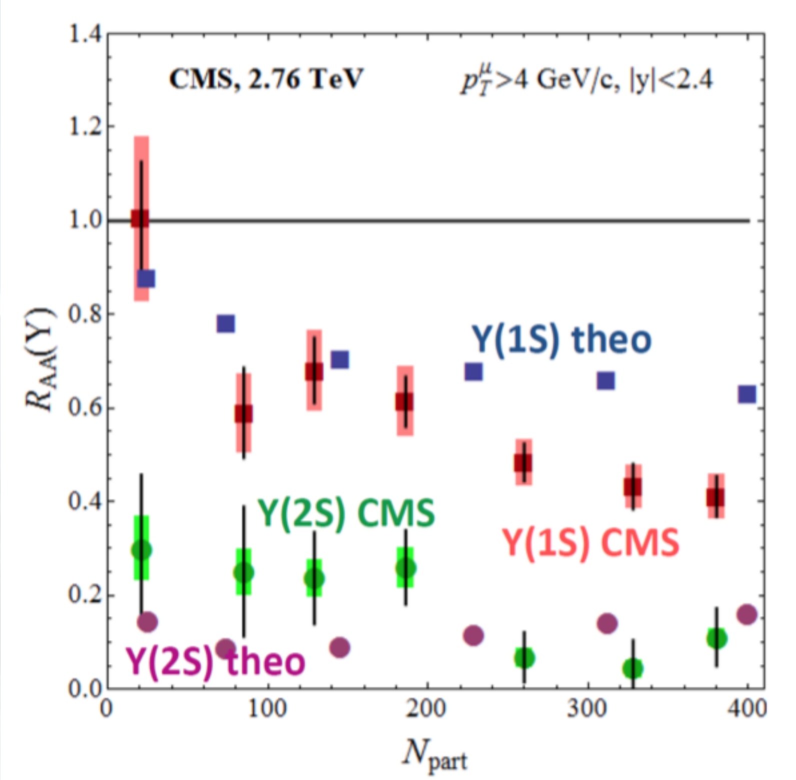
- ATLAS, ALICE, LHCb







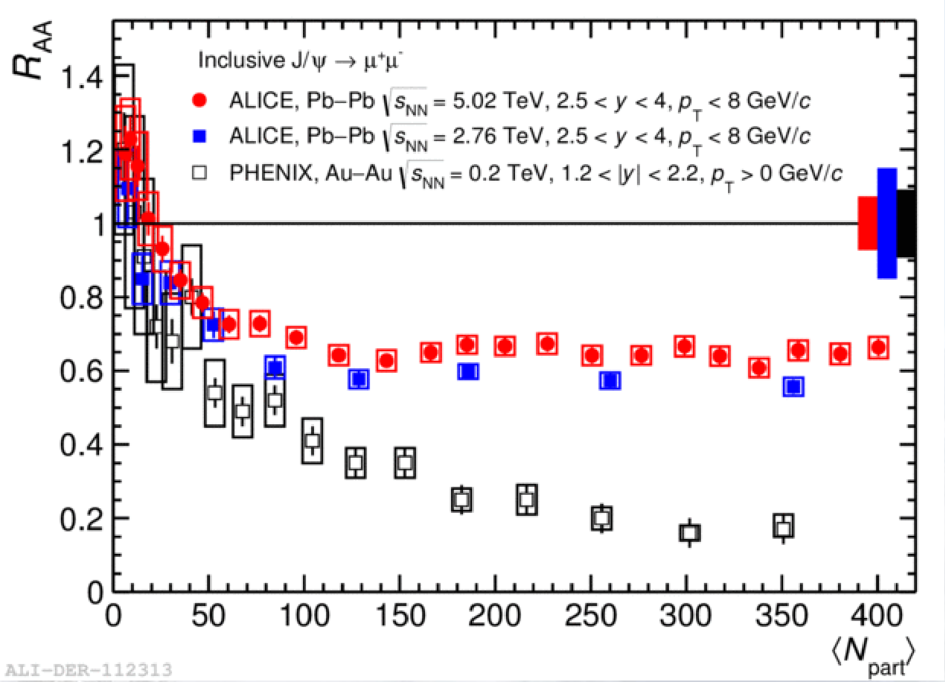
Schrödinger-Langevin Approach

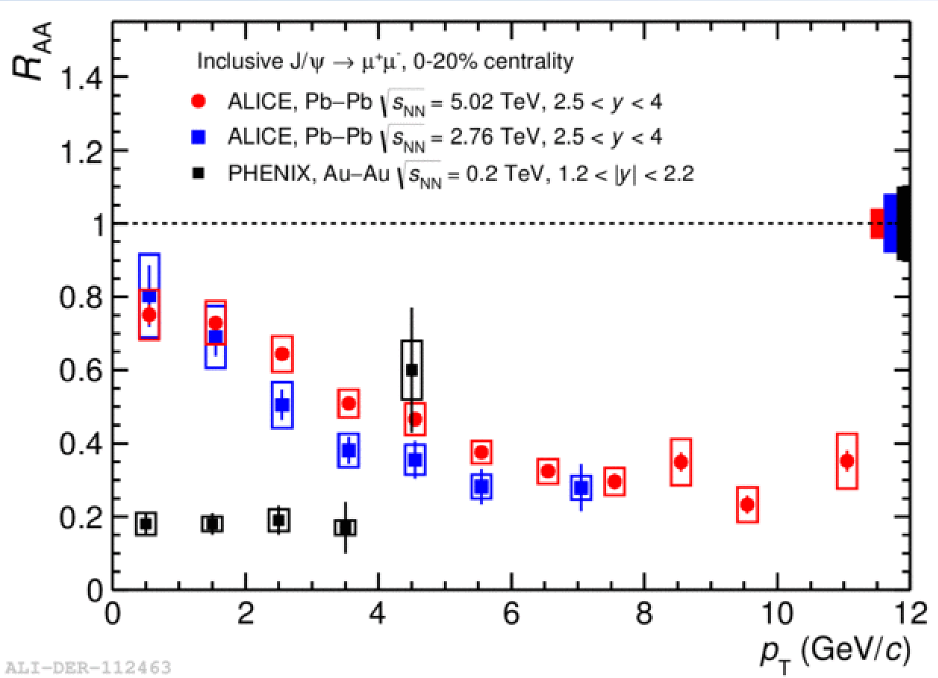


Gossiaux and Katz
[arXiv:1611.06499]

- Central collisions: 1S states survive more in Model.
  - P →S transitions, not fully compensated by suppression of feed-down from higher excited states.
  - Need to include CNM effects in model.

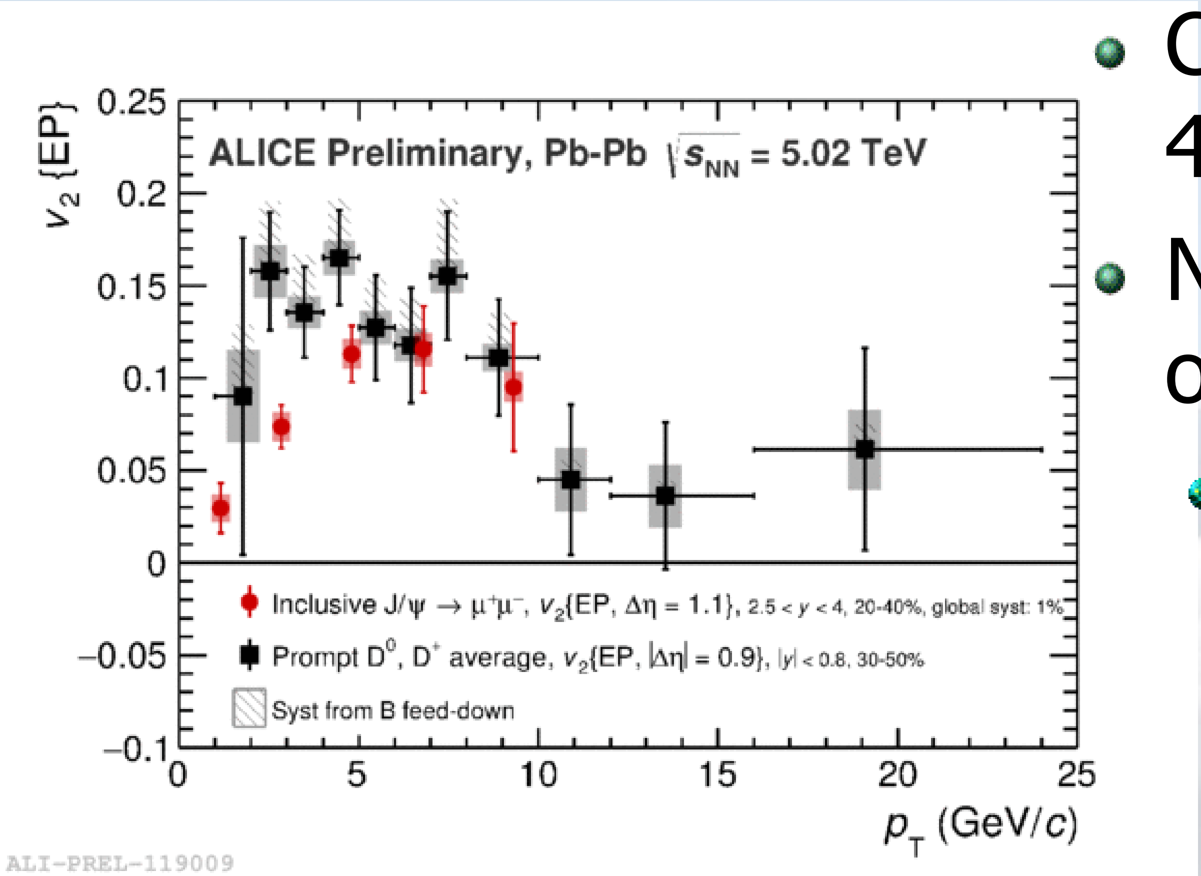
J/ψ Forward, ALICE & PHENIX





- p_T-integrated R_{AA} : systematically larger at LHC than at RHIC.
  - 5.02 TeV RAA > than at 2.76 TeV
- Excess seen at LHC from low-p_T J/ψ.
  - Theoretical interpretation: screening + regeneration

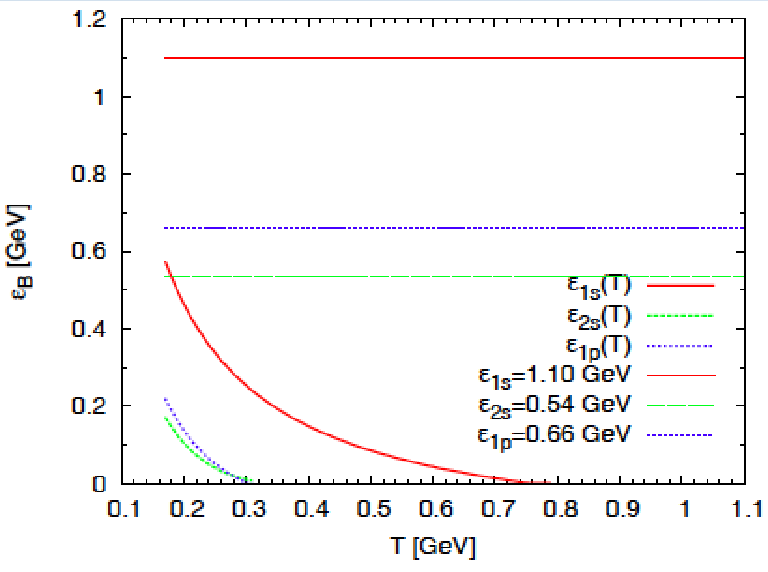
J/ψ v_2: recombination signal

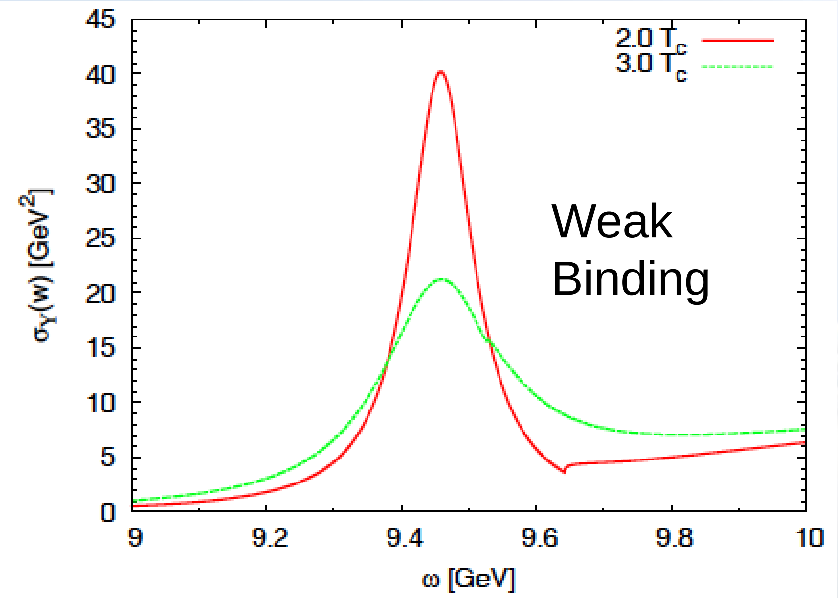


- Centrality 20-40%
- Non-zero v_2 observed!!
  - Effect is 5-7σ for some p_T bins.

- Supports the idea that charm quarks thermalize in the QGP
  - If so, expect D meson v_2 to be similar, but maybe a little higher.

Υ R_{AA} Model II





- Weak vs. Strong Binding
  - Narrower spectral functions for "Strong" case
  - Ratios of correlators compared to Lattice: favor "Strong" binding case
- Kinetic Theory Model
  - Rate Equation: dissociation + regeneration
  - Fireball model: T evolution. T_0 ~ 300 MeV