A panorama of bottomonium results

with focus on STAR and CMS.

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UCDAVIS

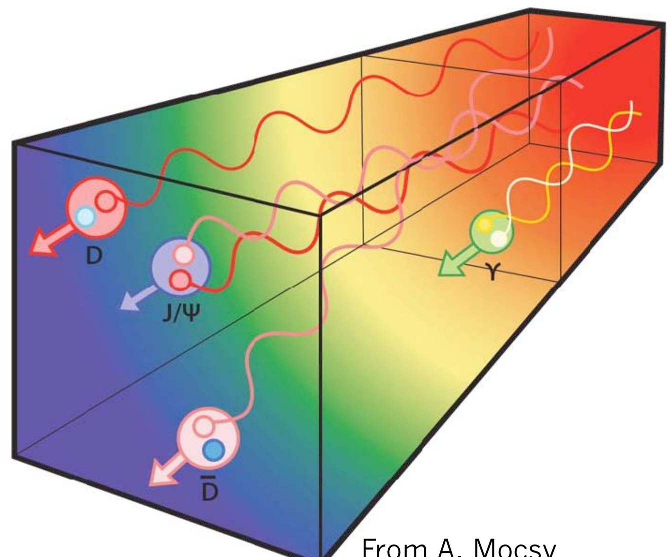
Outline

- Heavy Quarkonium
  - Υ production
    - pp, p(d)A collisions
      - RHIC & LHC
      - Comparison to models
      - Questions from trends in data
    - AA collisions
      - Ditto…

Two beautiful and massive objects that roam freely a colorful field.

Heavy Quarkonium: why?

- 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
  - Final state: energy loss, absorption
- Regeneration
  - Uncorrelated heavy-quarks can pair up
- Bottomonium: a cleaner probe than charmonium...
  - 3 states are accessible experimentally
  - expect small CNM effects
  - expect small regeneration effects

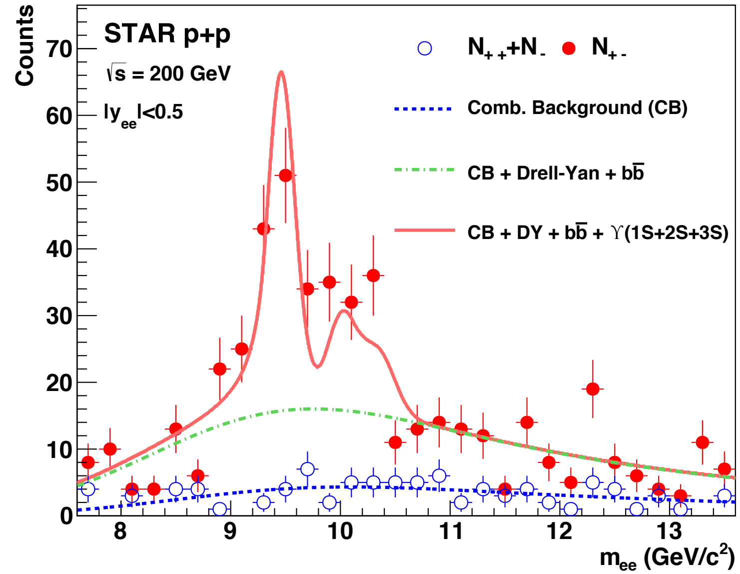


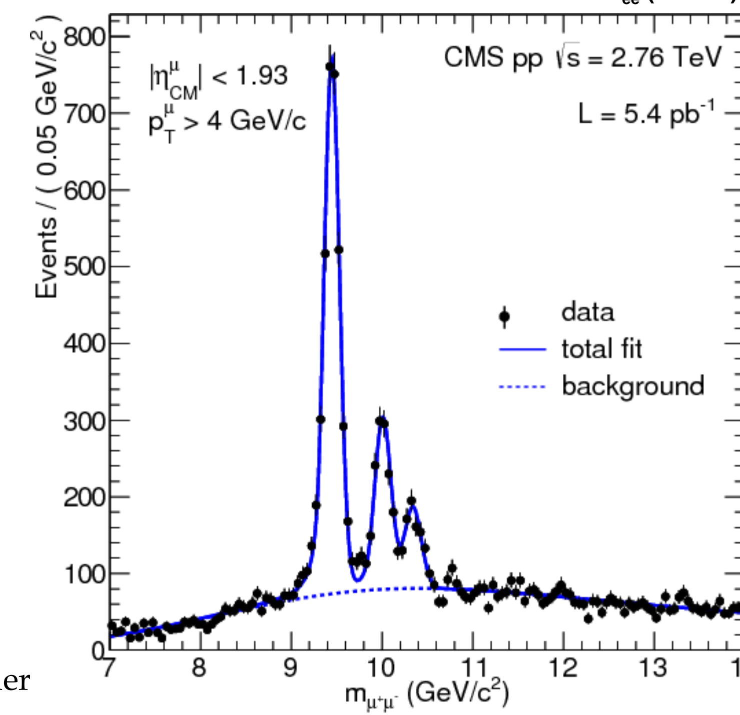
From A. Mocsy

Measuring Υ

- STAR: electron channel
- CMS, PHENIX, ALICE: dimuon channel

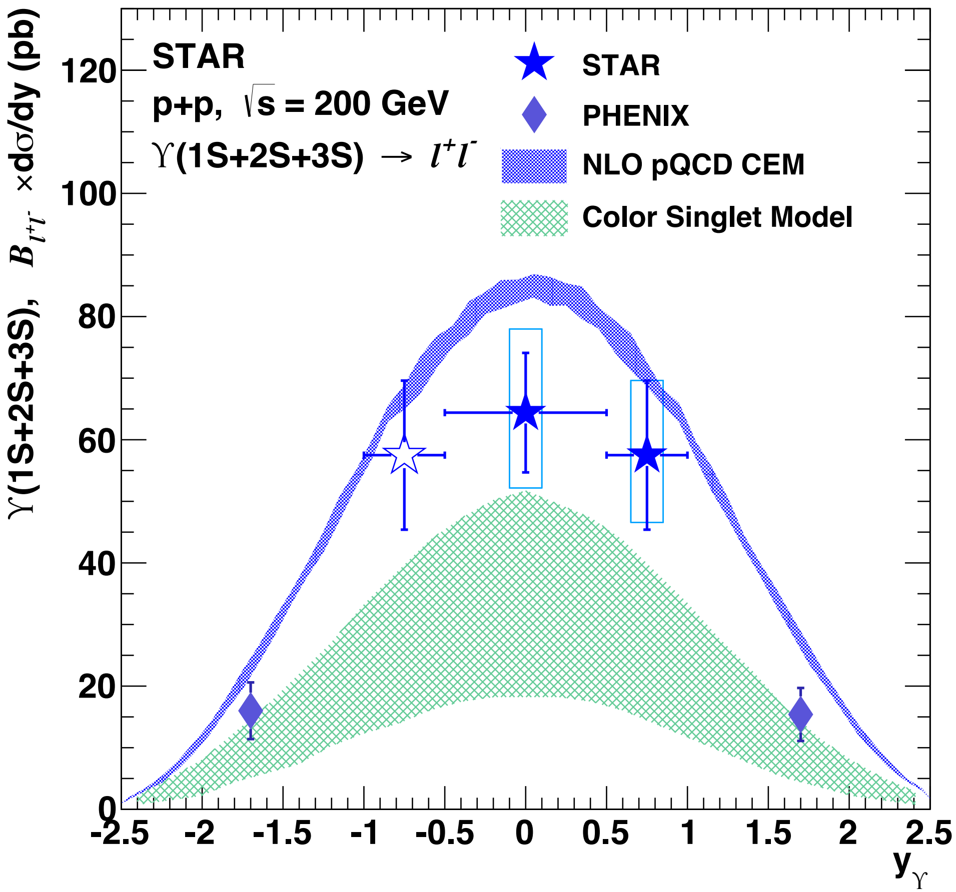
- Experimental Results:
  - STAR: PLB 735 (2014) 127
  - PHENIX: PRC 87, 044909 (2013)
  - CMS:
    - PRL 109 222301 (2012)
    - JHEP 04 103 (2014)
  - ALICE:
    - arXiv:1405.4493





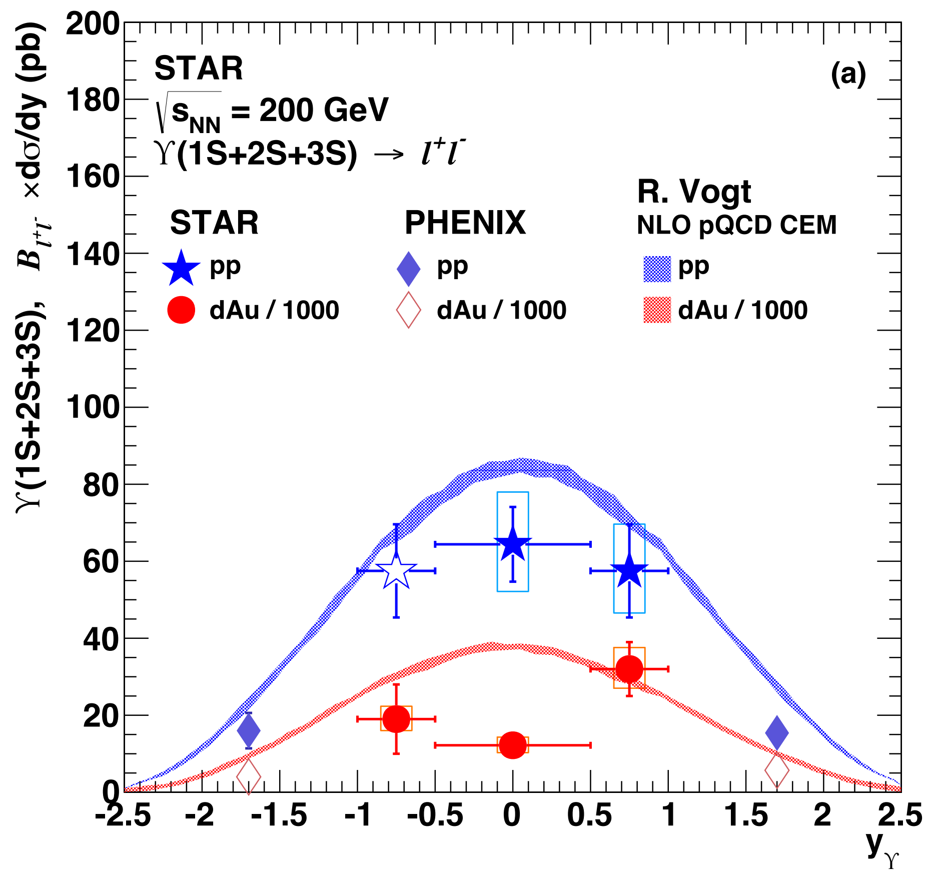
Υ in pp collisions at RHIC

- Results on cross sections
  - STAR: PLB 735 (2014) 127
  - PHENIX: PRC 87, 044909 (2013)
- STAR data:
  - 20 pb^{-1}, all from pp run 2009.
  - Improvement over 2006:
    - Less inner material
- Calculations:
  - CEM: R. Vogt
  - CSM: Lansberg & Brodsky
- Data ~ in between CEM and CSM predictions.



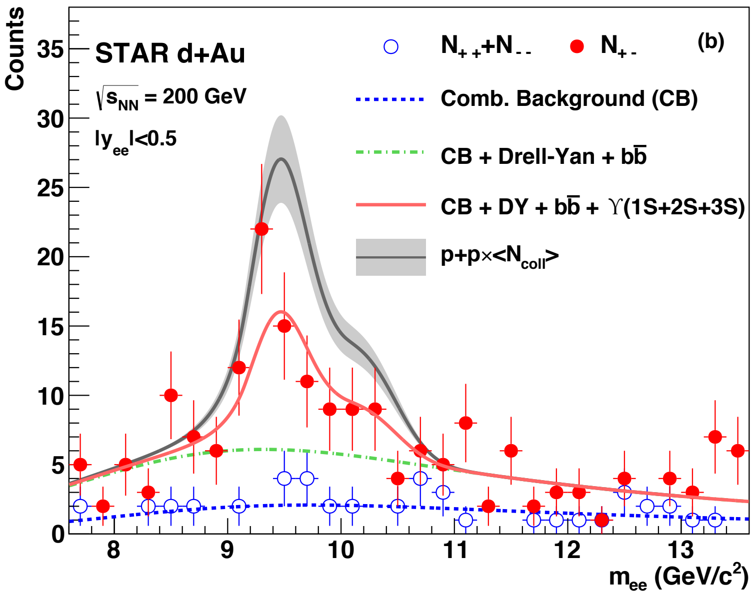
ϒ in d-Au at RHIC

- STAR dAu cross section
  - Note: Scaled by 10^3.
- Midrapidity point is lower than expectations from CEM.
  - Calculation includes shadowing
  - Does not include estimate of nuclear absorption
- pp data is also lower than prediction,
  - compare R_{dAu}, where many theoretical and experimental uncertainties cancel.

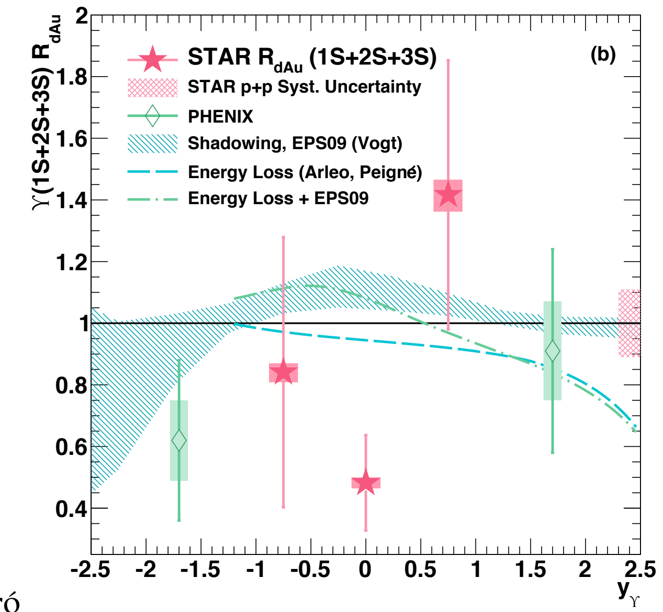


Υ R_{dAu} at RHIC, near y=0

- Invariant mass distribution in dAu at |y|<0.5
  - Scaled pp reference fit shown for comparison

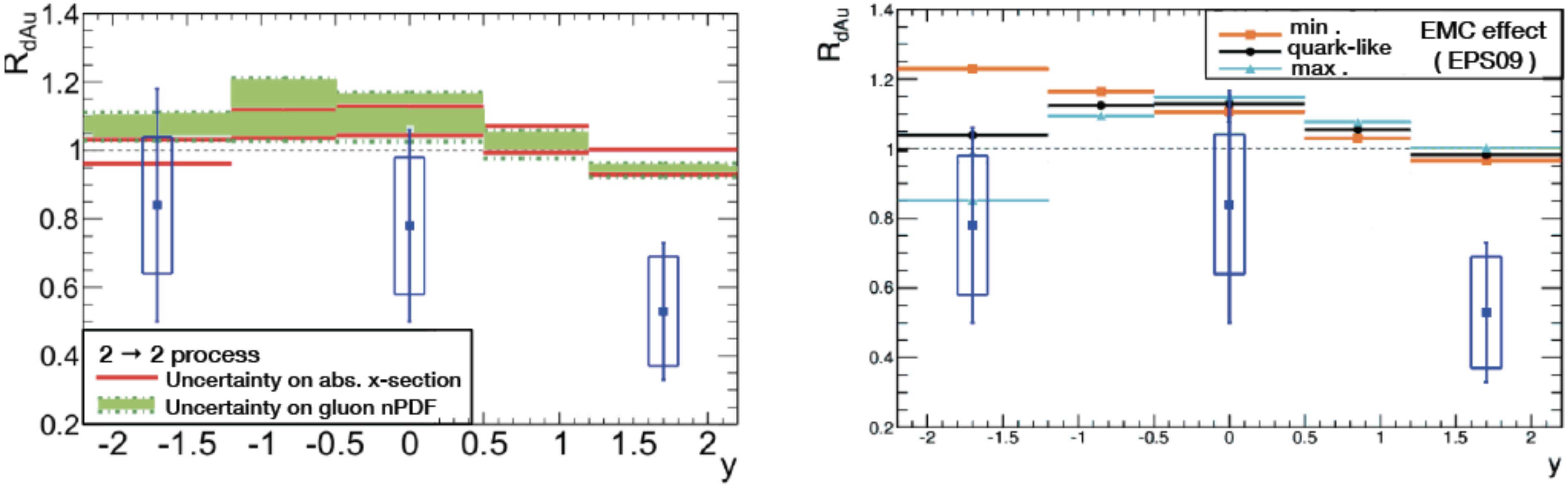


- RdAu vs. y
  - Model comparison:
    - Shadowing, EPS09
      - R. Vogt
    - Energy loss
    - Energy loss + shadowing
      - Arleo & Peigné



  - y~0 is right in the middle of the antishadowing region
  - Expect R_{dAu} > 1 (small effect)
  - Observe R_{dAu} < 1
  - Absorption seems to be important

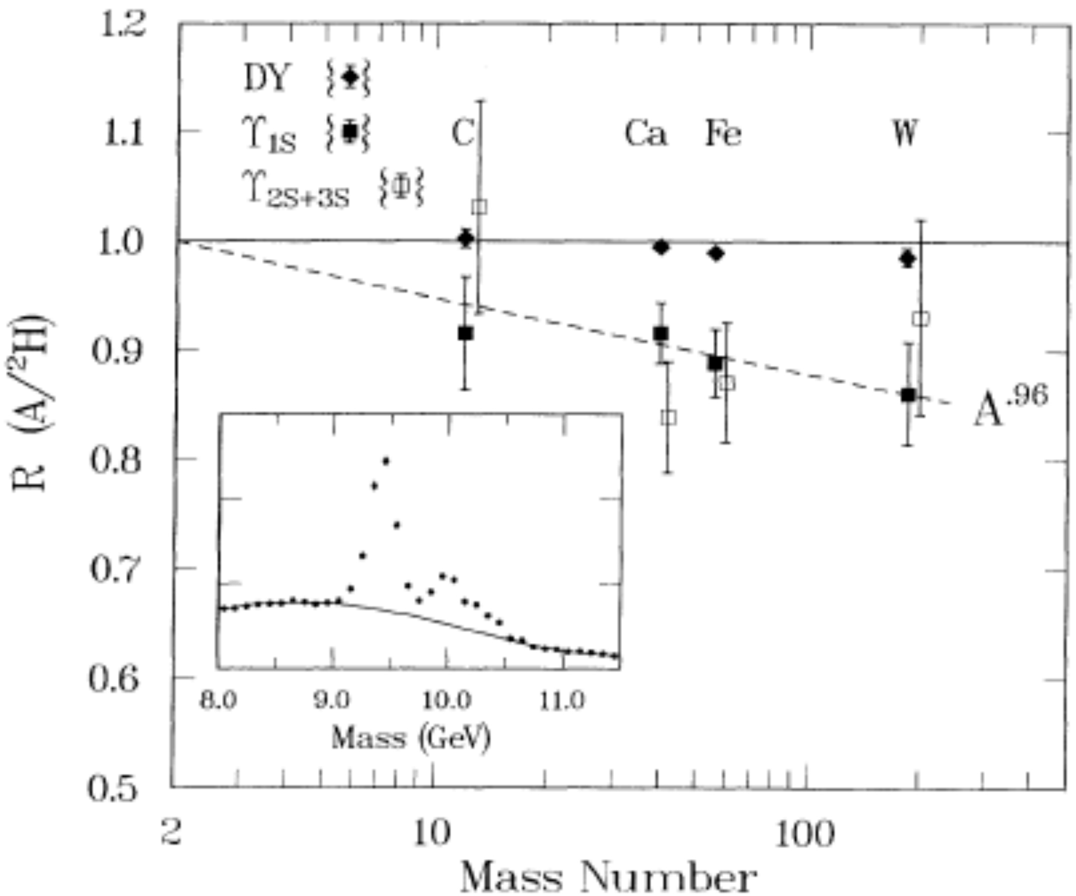
Model from A. Rakotozafindrabe, et al.



- **Shadowing/Antishadowing of gluon nPDF: green band**
  - Note: STAR data on plot were preliminary.
- EMC effect (right panel)
  - Also expects slight enhancement at mid-rapidity.
- Must include additional absorption (red lines)
  - Why does absorption still give R_{dAu}>1? : Heard that absorption in this calculation needed updating/revisiting.

A. Rakotozafindrabe,
E. Ferreiro,
F. Fleuret,
J.P. Lansberg,
N. Matagne,
arXiv:1207.3193

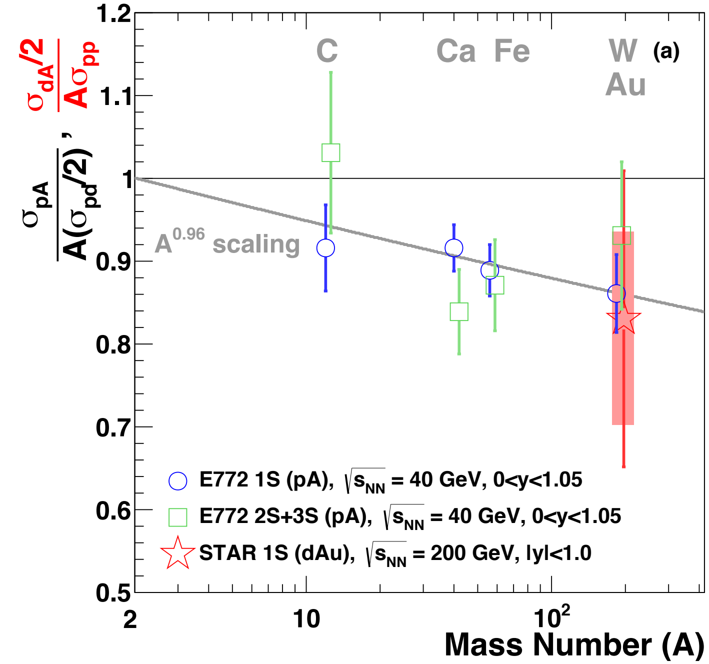
Yields vs. Mass Number in E772

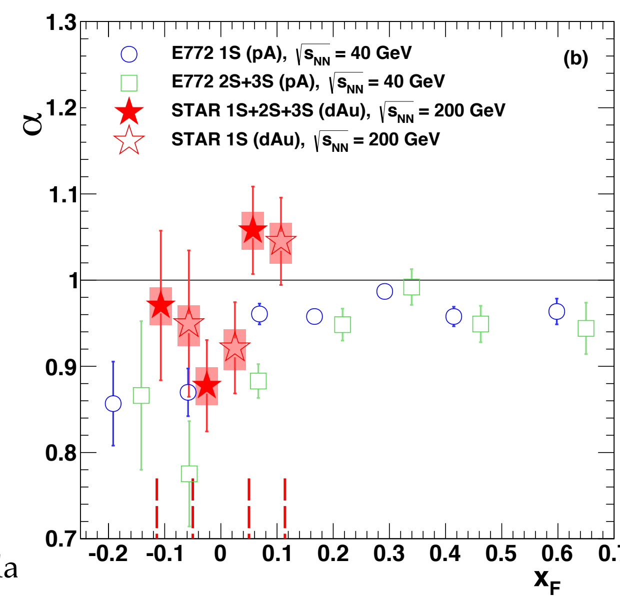


- Ratio of nuclear targets normalized to deuterium
- Suppression seen with increasing A.
- A dependence: $\sigma_{pA} = A^{\alpha}\sigma_{pp}$
  $\alpha_{1S} = 0.962 \pm 0.006$
  $\alpha_{2S+3S} = 0.948 \pm 0.012$
- **STAR result is in the same range**:
  - for $\sigma_{dAu} = (2\,A)^{\alpha}\sigma_{pp}$:
    - $\alpha = \ln(\sigma_{dAu} / \sigma_{pp}) / \ln(2A)$
    - $\alpha \sim 0.9$
- Suppression is the same for 1S and 2S+3S (within errors).
  - Drell-Yan is not suppressed, follows *A* scaling.
  - Suppression is not as large as for J/ψ (α=0.92±0.008)

Comparison: STAR & E772

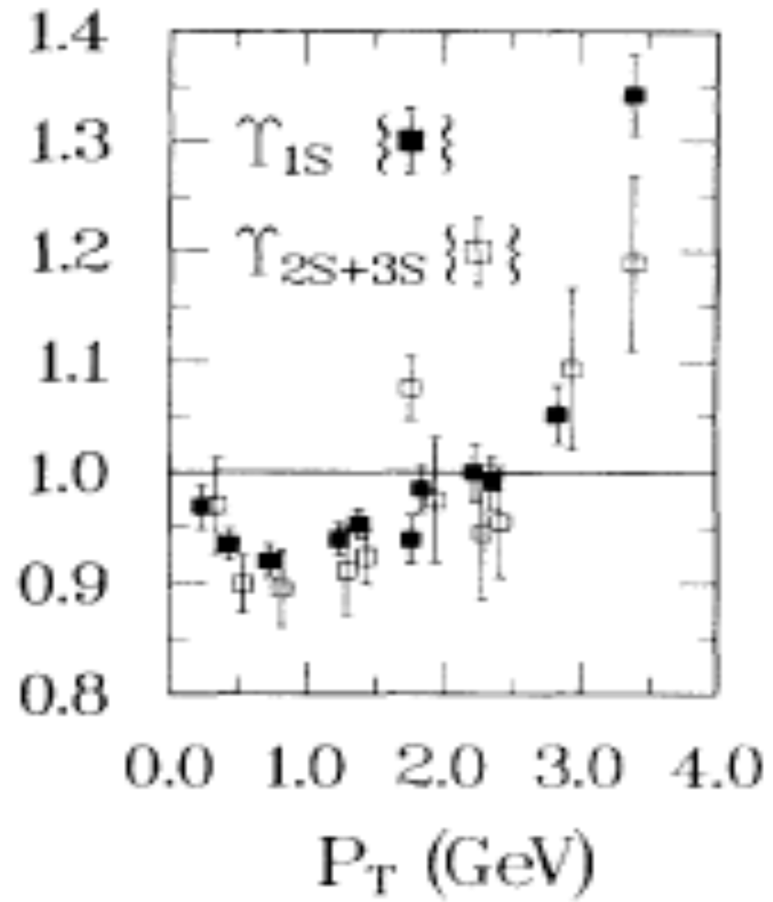
- For a similar comparison, separate ϒ(1S) stat
  - Increases the statistical uncertainty compared to sum ϒ(1S+2S+3S)
  - Use |y| < 1, check A dependence.
  - Also compare y or x_F dependence.
- STAR result: consistent with A trend from E772.
- Large suppression seen near xF~0 by E772, α~0.9.
  - Same as STAR |y|<0.5 points.
- Shadowing, or shadowing+E. Loss cannot explain suppression at y=0.
- Effect goes away in the forward y bins.
- A higher-statistics d+Au run would help.
  - Note: dAu 2008 run was first attempt at measuring bottomonium in cold nuclear matter, can revisit with higher statistics



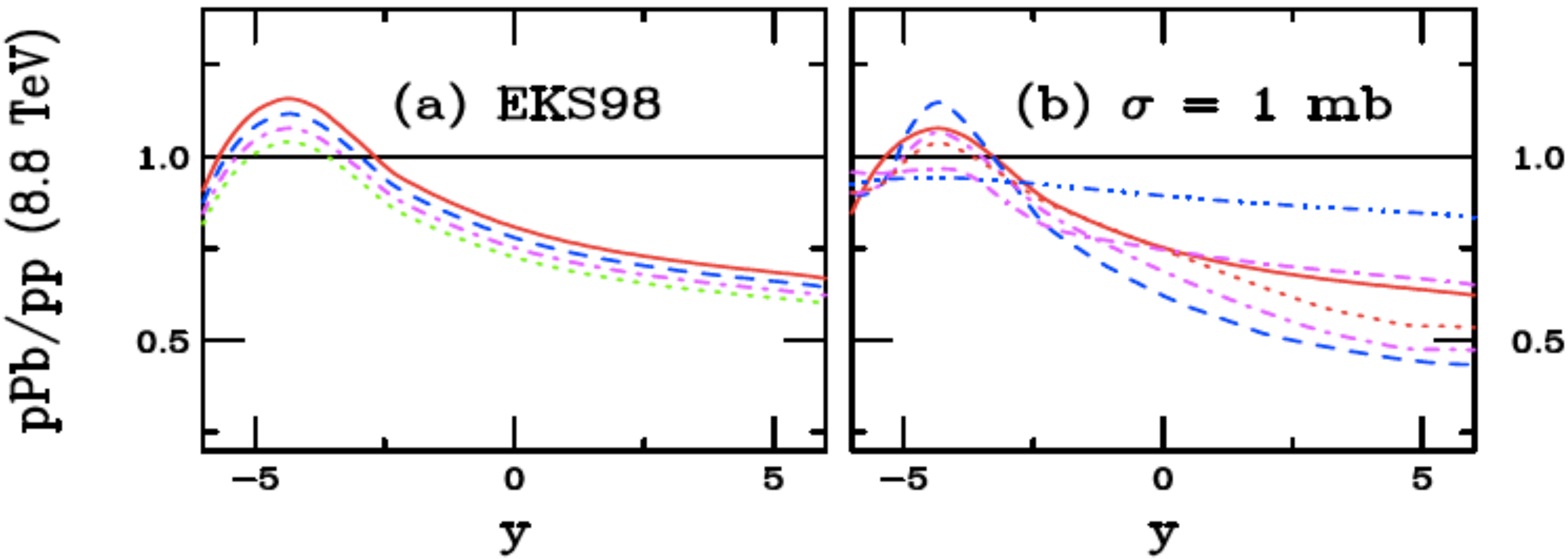


Note: p_T dependence in E772

- Not trivial either.
  - Suppression largest at ~1 GeV
  - Gives way to large enhancement above 3 GeV
- Might follow up later in STAR: but again, need more statistics.



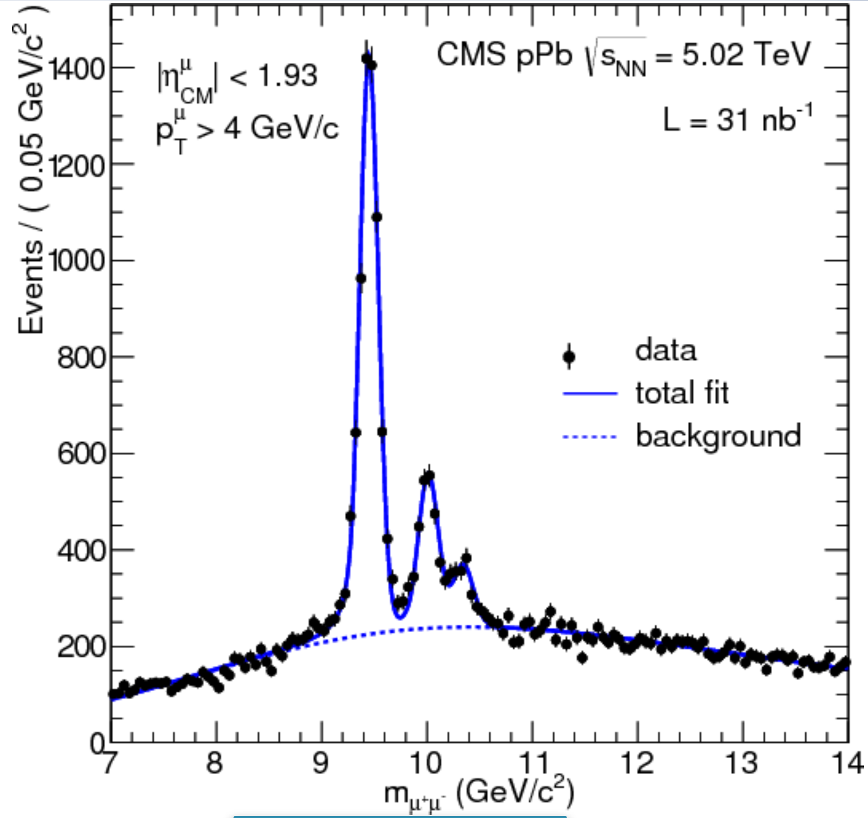
R_{pPb}: what to look for at LHC



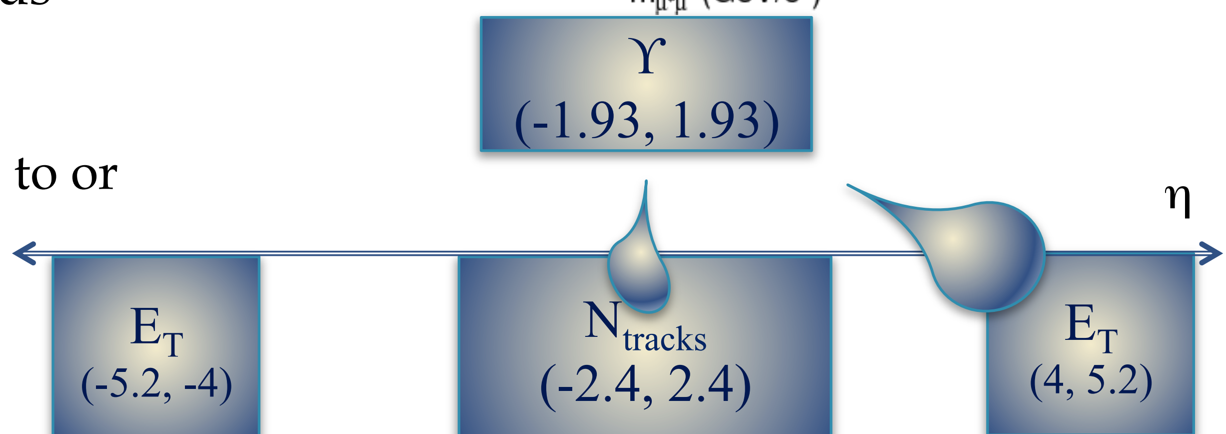
- Expectations From Ramona's calculations for LHC
- Left: fixed PDF, varying σ_{abs} : absorption has little effect
- Right: fixed σ_{abs}, vary the PDF : effect on pPb nPDF is large
- At LHC, kinematics of initial gluons different than at RHIC
  - Lower-x gluons: stronger shadowing.
    - Expect suppression at midrapidity at LHC from shadowing alone.
    - Larger uncertainty from gluon PDF than from absorption at LHC

ϒ in pPb at LHC with CMS

- CMS Upsilon dataset for pPb
  - 31 nb^{-1} @ $\sqrt{s_{NN}}$=5.02 TeV
    - From two datasets:
      - Pb+p, ~18 nb^{-1}
      - p+Pb, ~12 nb^{-1}
      - Energy of p beam: 4 TeV
        - Pb beam: 4 x Z/A = 1.58 eV



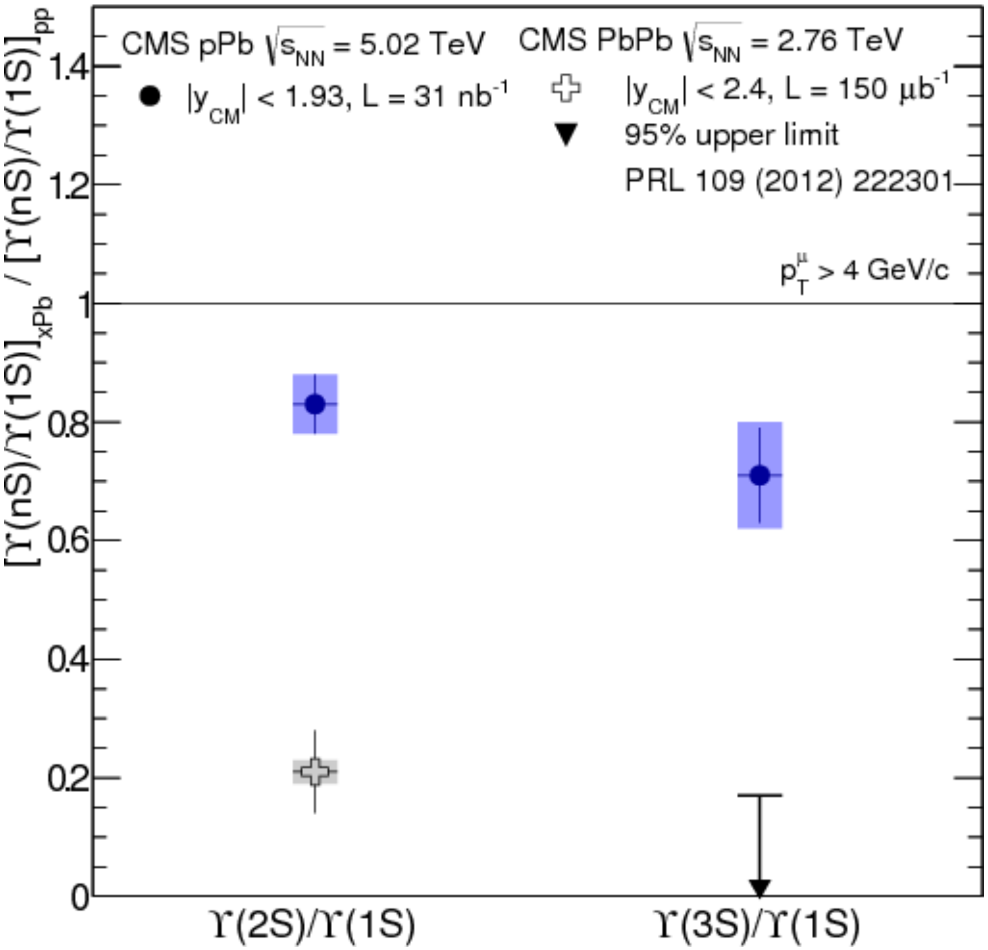
- Observables:
  - Double ratio, single ratio
  - "Self-normalized" yields
  - Study as a function of event activity
    - Look at activity close to or far from ϒ meson.
      - Close: N_{tracks}
      - Far: E_T



Υ Double ratio, pPb and pp

$$\frac{\left[\frac{\Upsilon(nS)}{\Upsilon(1S)}\right]_{pPb}}{\left[\frac{\Upsilon(nS)}{\Upsilon(1S)}\right]_{pp}} = \frac{R_{pPb}(\Upsilon(nS))}{R_{pPb}(\Upsilon(1S))}$$

- pp reference for single ratio:
  - No pp data at the same energy
  - Solution: use results from 1.9, 2.76, and 7 TeV
    - No significant dependence is observed vs. √s
- Key feature of double ratio:
  - All initial-state effects should cancel
    - e.g. shadowing affects excited and ground state in the same way
- Observation:
  - Double ratio < 1 in pPb
  - Double ratio in pPb higher than in PbPb
  - Similar for 2S than for 3S
- Implication: possible presence of final state effects in pPb which affect excited states more than ground state
  - Note: double ratio = 1 does not imply absence of final-state effects
  - They could modify excited and ground state equally



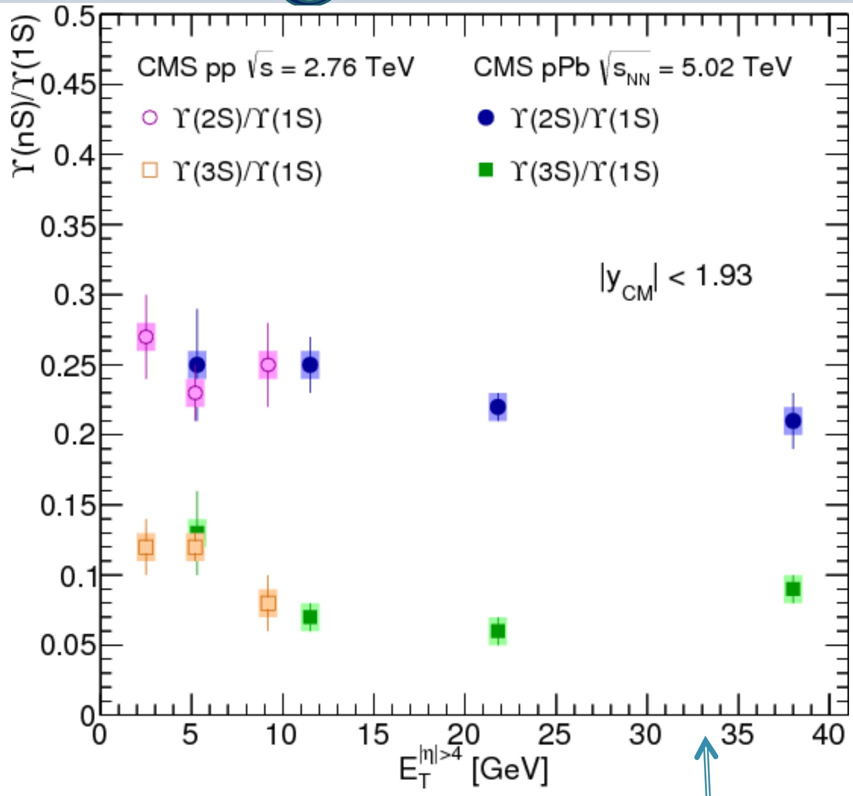
Expect small Υ absorption in hadronic matter

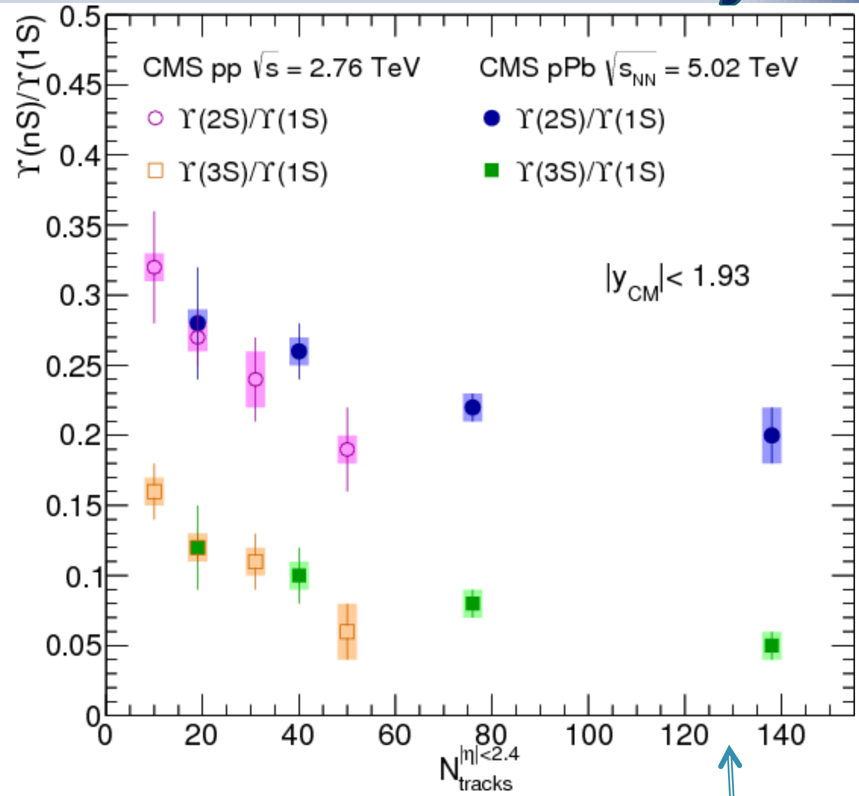
Lin & Ko, PLB 503 (2001) 104

Note: depends on radius.

Hence, larger absorption for 2S and 3S

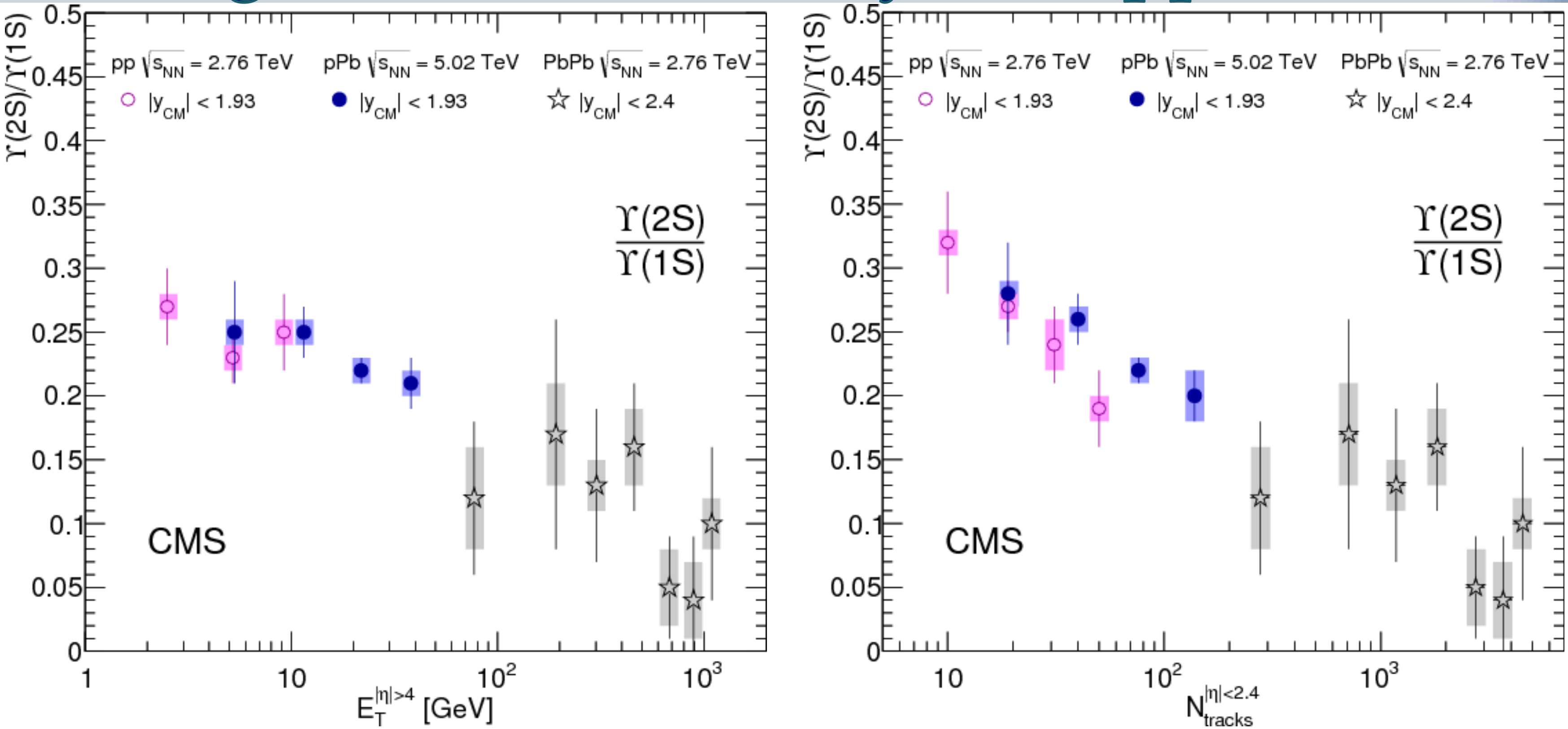
Single ratios vs. event activity





- $E_T^{|\eta|>4}$, Far activity:
  - Single ratios vary very little as the activity increases
- $N_{track}^{|\eta|<2.4}$, Near activity:
  - Single ratios decrease significantly with increasing activity
  - Interplay between produced and surrounding event, both in pp and pPb
    - Additional multiplicity produced with the ground state?
    - Final-state interactions breaking up the excited states?

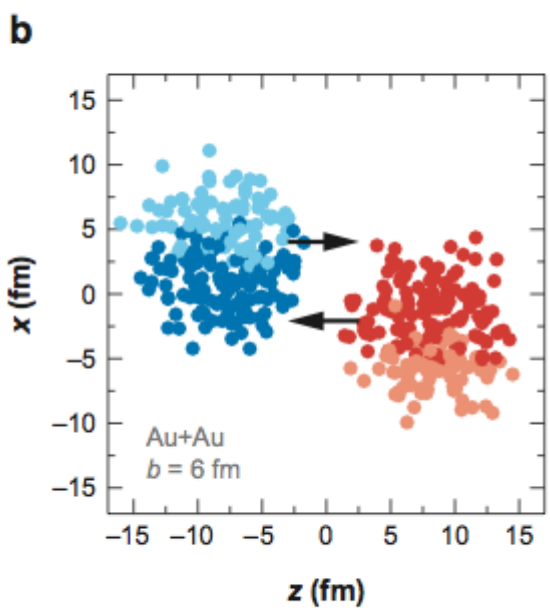
Single ratios vs. activity from pp to PbPb



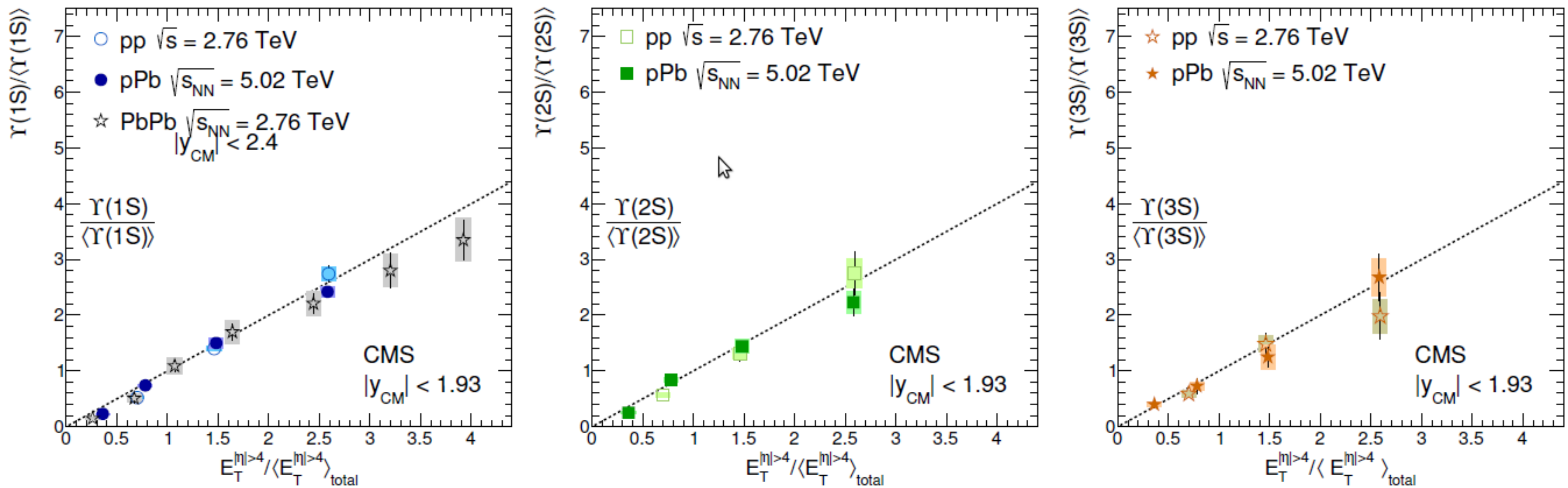
- Span large range in event activity variables, pp, pPb, PbPb
- Overlap is limited between pPb and PbPb
  - Need additional data to investigate the dependence in the three systems.

Self-normalized yield, motivation

- Allows us to look at scaling of cross section with activity
- In PbPb, activity connected to N_{coll} via Glauber model
- A simple binary-nucleon-nucleon collision ansatz:
  - In a given event, the yield of scales with binary collisions
  - In the same event, the activity of the event also scales with binary collisions
  - Leads to linear scaling of yields with activity, assuming no other effects
- Similar connection for pPb is also common paradigm: still deal with nucleon-nucleon collisons
- For pp, does this hold?



Self-normalized yields: Far

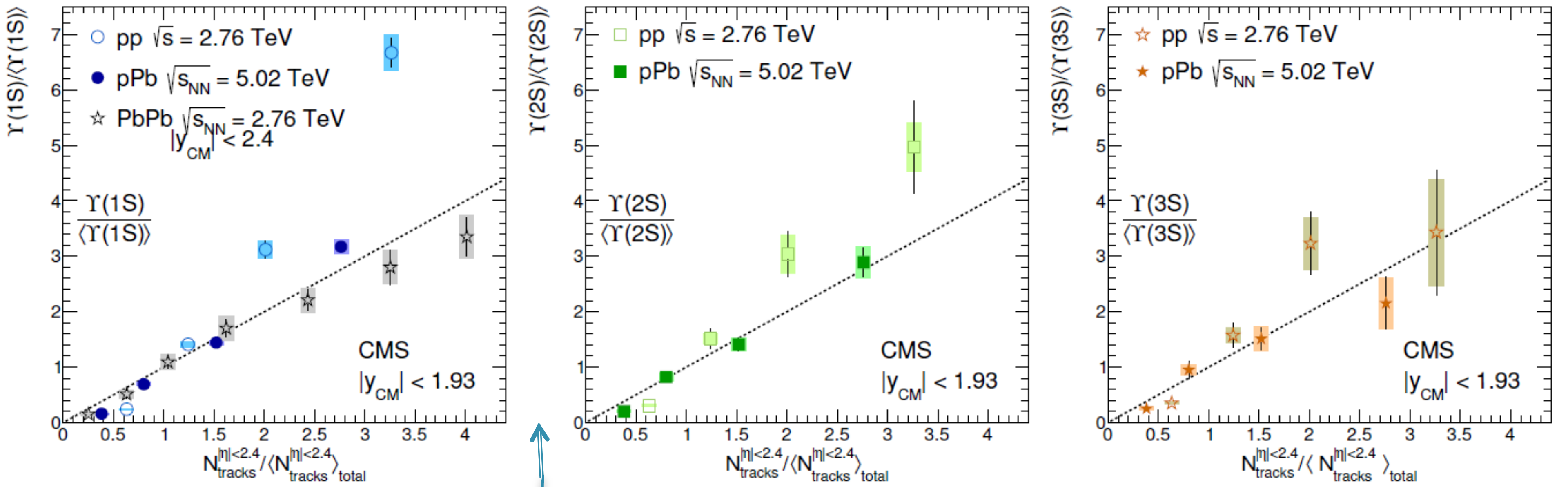


- E_T, Far activity

Note: x-axis is also self-normalized.

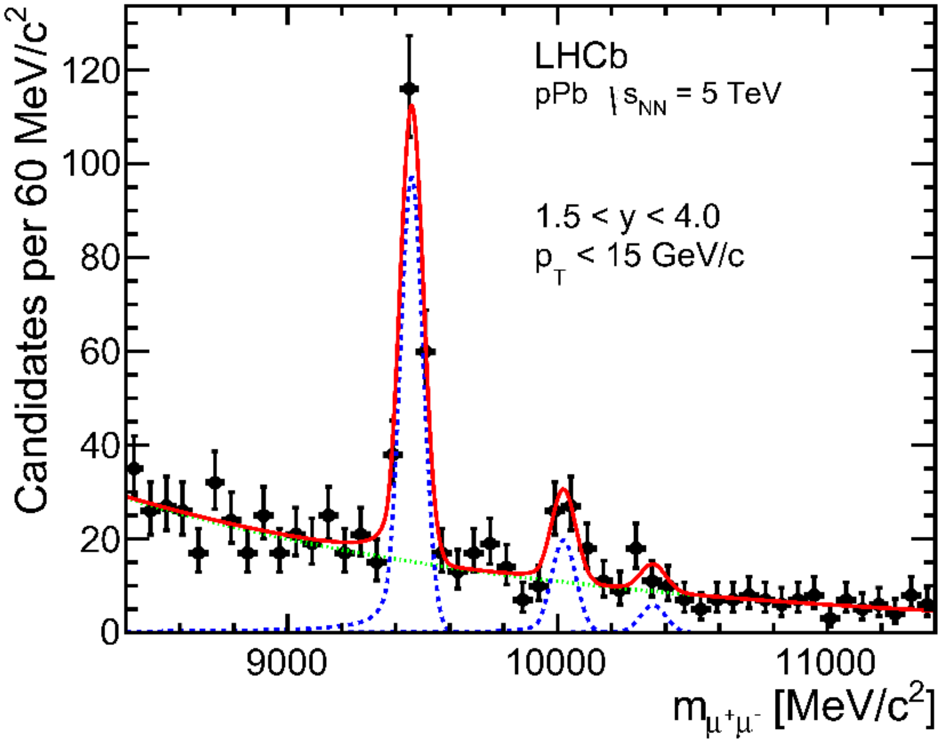
- Close to linear scaling is observed for all systems, all states.
  - Suppression in PbPb for high E_T: central events.
- pPb, pp follow very closely line with slope 1 (dashed line)
  - Fit gives slope consistent with 1 within errors.
  - All systems, all Υ states.

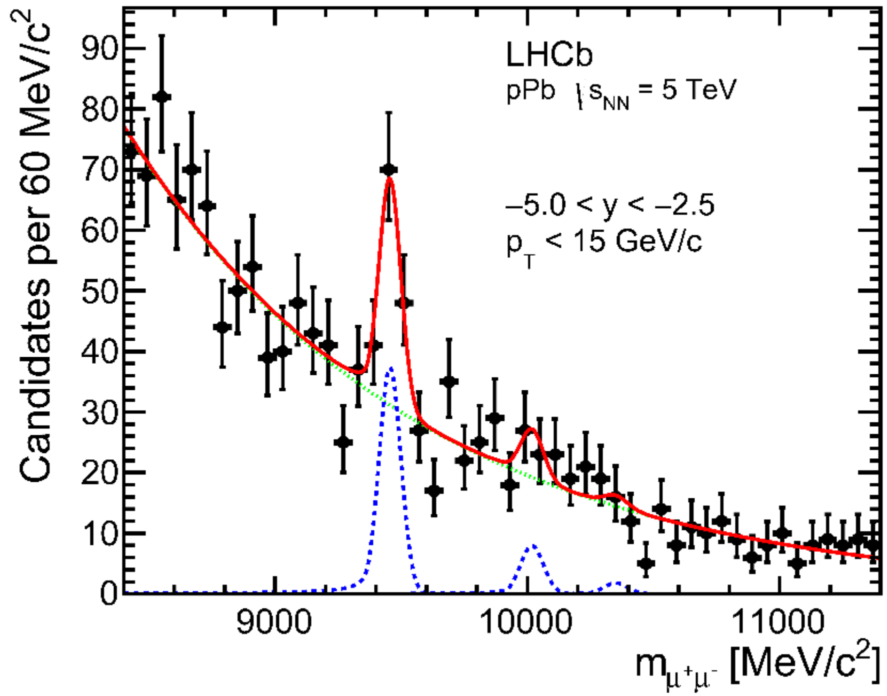
Self-normalized yields: Near



- N_{tracks}, Near activity
- Significant differences among systems and among states!
  - ϒ(1S) production scaling: stronger than linear in pp.
  - pp: indications that slope is smaller for 2S and for 3S.
- All states, even in pp, regardless of whether activity is far or near, show increase relative yield in higher activity events.
  - Number of parton-parton collision scaling? Multi-parton interactions in pp?

LHCb Υ results for pPb

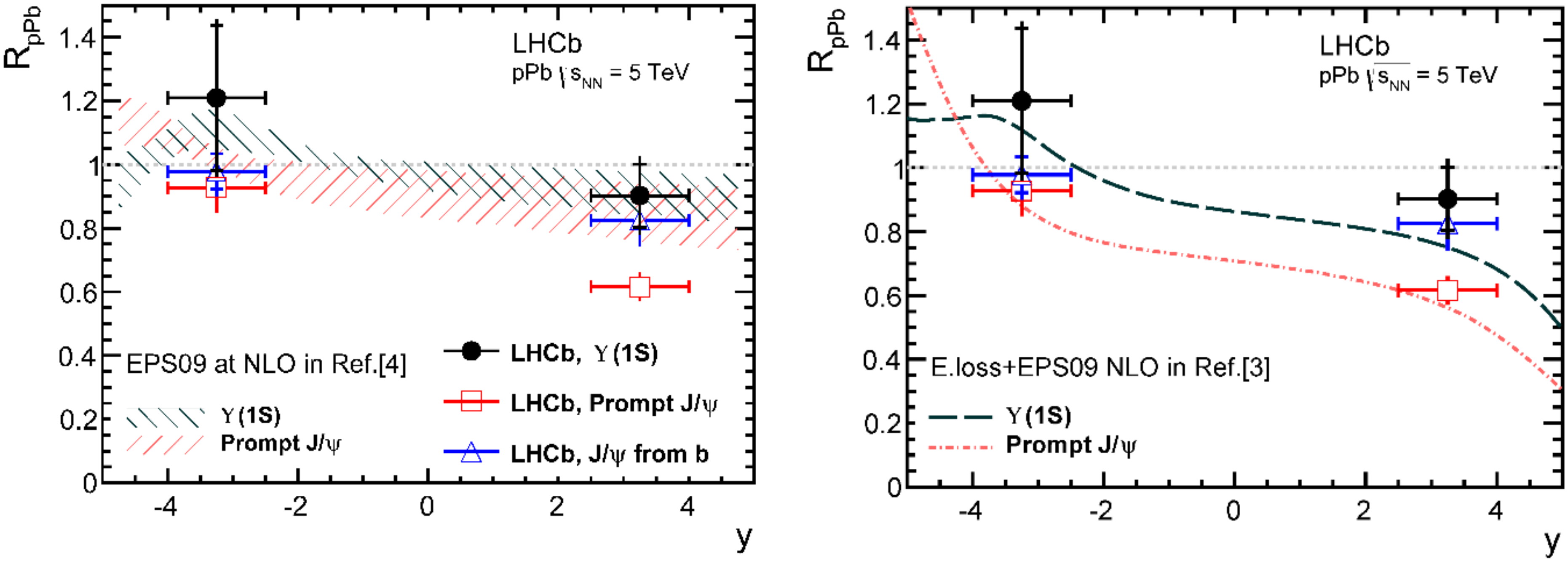




- arXiv:1405.5152
- Signal seen in LHCb

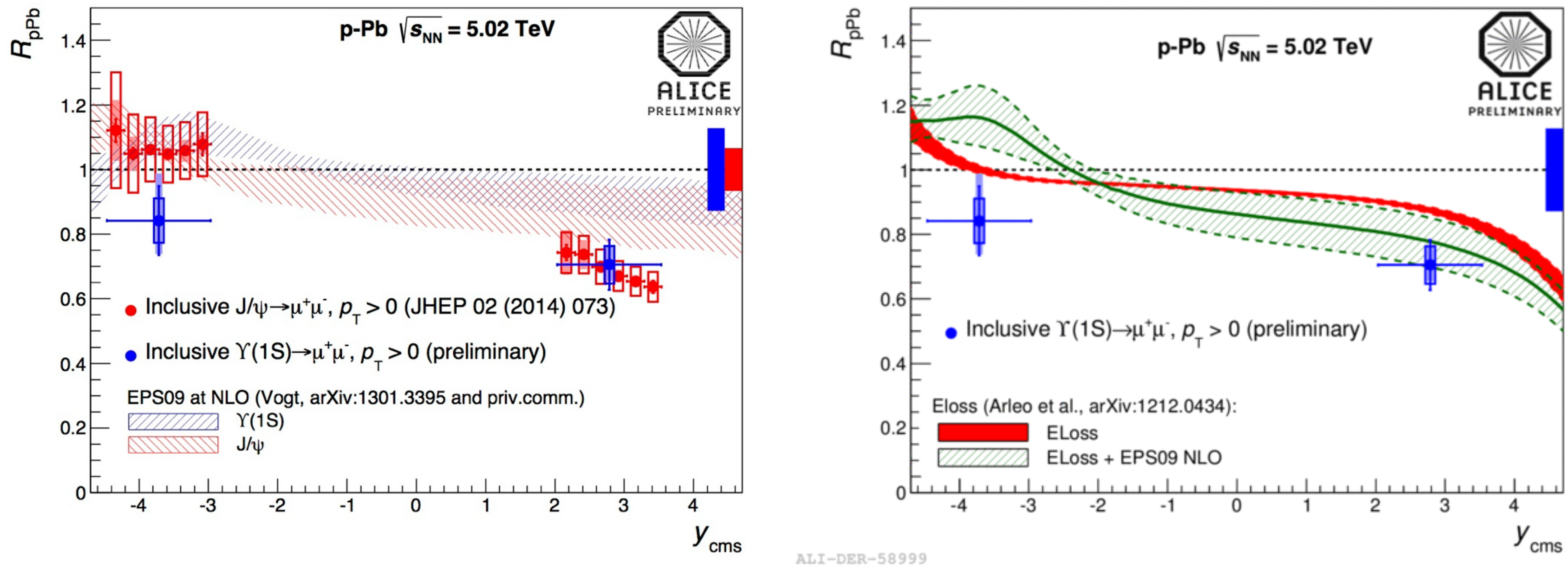
Signal yield	Forward (pPb)	Backward (Pbp)
Υ(1S)	189±16	72±14
Υ(2S)	41±9	17±10
Υ(3S)	13±7	4±8

LHCb Υ results for R_{pPb}



- Used interpolated pp reference
- Slight enhancement at negative rapidity, indication of antishadowing
- Slight suppression at forward rapidity
- Different theoretical models are consistent with data, within uncertainties
  - EPS09 NLO: IJMP E22 (2013) 1330007
  - E. loss : JHEP 03 (2013) 122

ALICE Υ results for R_{pPb}



- ALICE sees no enhancement at backward rapidity, slight suppression.
  - EPS09 NLO expects antishadowing. ELoss + EPS09 also expects enhancement.
- Forward rapidity data:
  - EPS09 NLO expects only modest suppression
  - Including E. Loss lowers R_{pPb}, data near lower end of prediction
- Note: ALICE data in both cases lower than LHCb data.

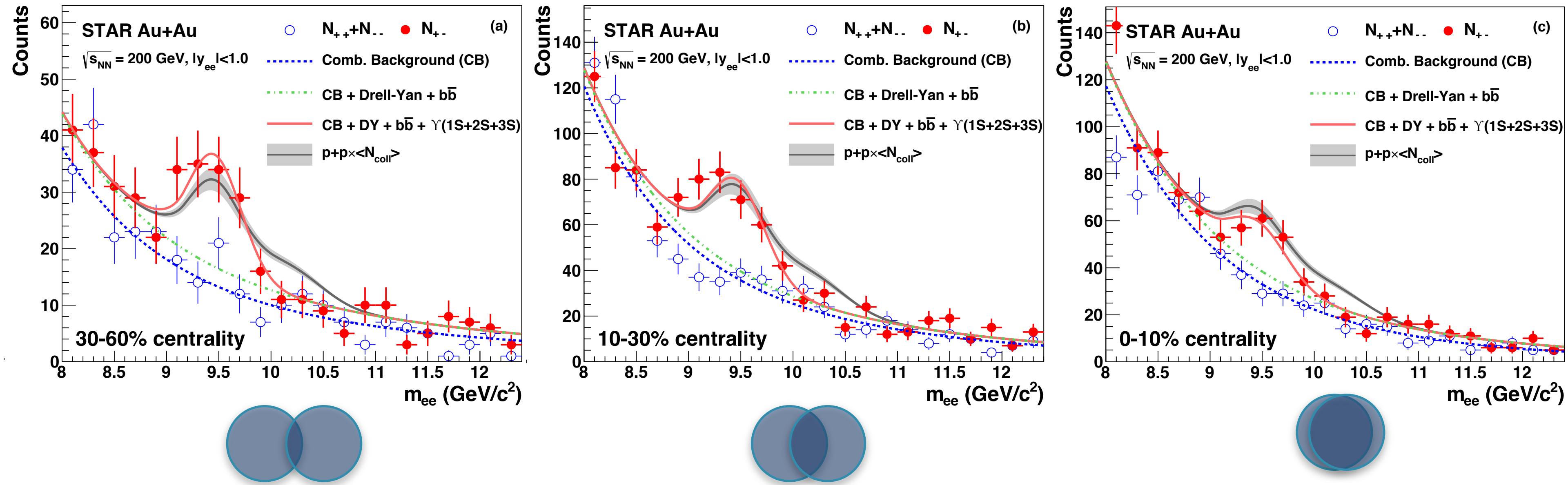
dAu, pPb Summary

- Cold Nuclear Matter effects are important
- STAR dAu results show suppression at y=0
  - Not expected from shadowing
  - Absorption seems to be needed
  - Similar effect seen in E772
- CMS pPb results:
  - Evidence for final state effects in pPb: suppress excited states relative to ground state
- CMS event activity study:
  - single ratios affected by nearby activity
    - final-state breakup of excited state?
  - self-normalized yields increase vs. activity
    - multi-parton interactions in pp?

Bottomonium in Hot Matter

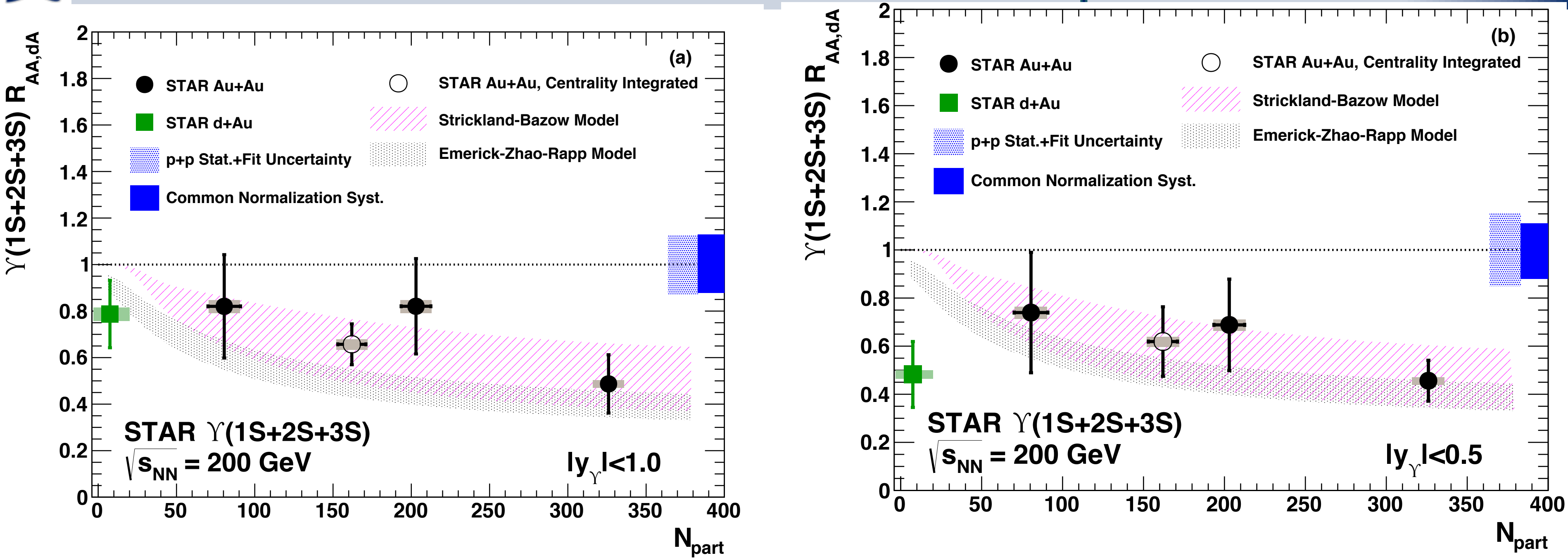
- "Morning glory" pool: a hot spring with a balmy temperature of 70 C.

Υ in STAR, AuAu



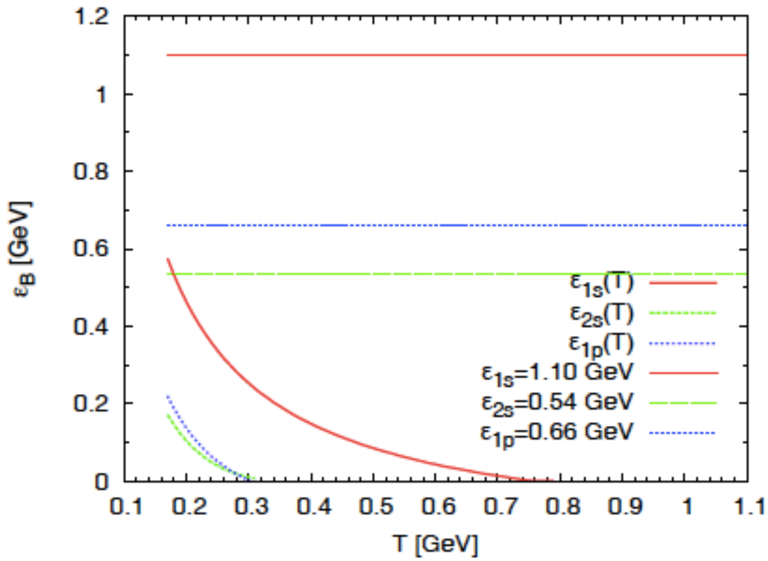
- Invariant mass distributions in 3 centrality bins
- Possible to separate ground state.
- Comparison to N_{coll}-scaled pp reference:
  - Clear suppression of excited states.
  - Suppression of ground state in most central bin.

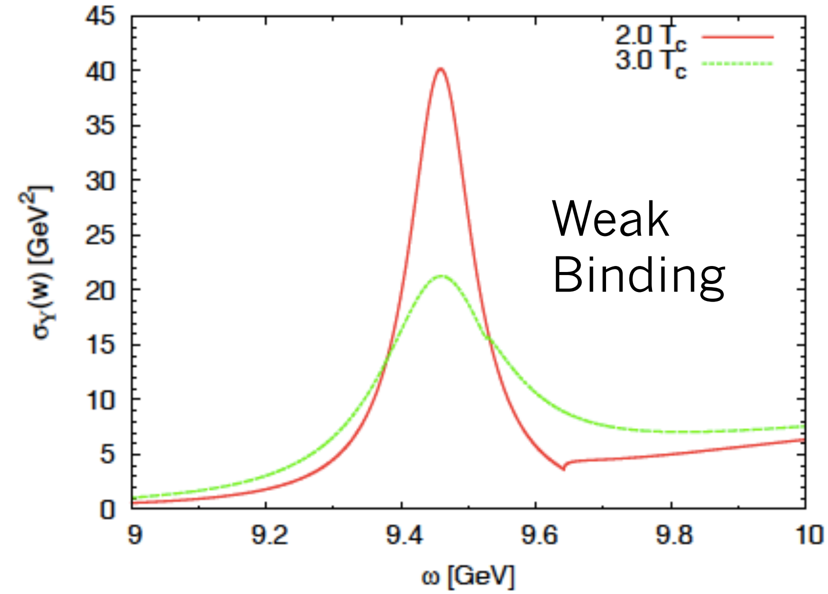
STAR ϒ R_{AA} vs. N_{part}



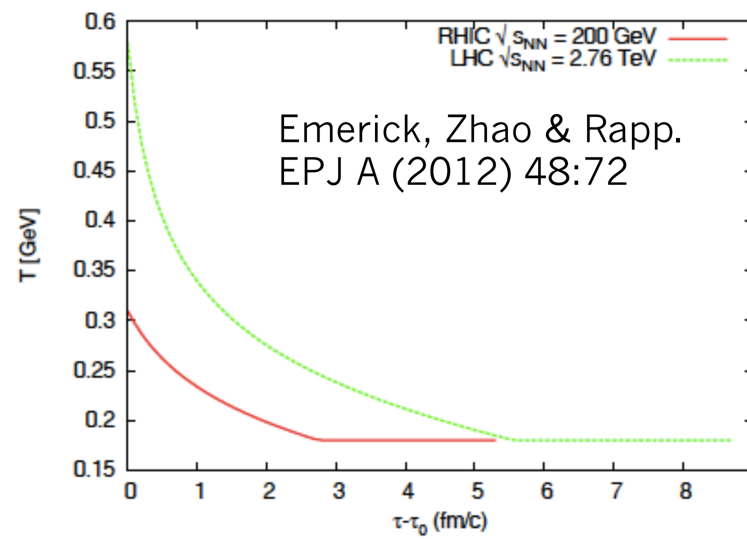
- Right panel: all data in STAR acceptance |y|<1
  - dAu, and two most peripheral bins: consistent with no suppression
  - Suppression most central Au+Au: Consistent with expectations for hot & cold nuclear matter, however…
- Left panel: bin closest to midrapidity, |y|<0.5
  - dAu suppression is of the same magnitude as central AuAu: Important to understand dAu system
- Calculations:
  - Strickland & Bazow: Includes estimate of heavy quarkonium potential, Re and Im. Models evolution through anisotropic hydro. (Nucl. Phys. A 879 (2012) 25)
  - Emerick, Zhao & Rapp: attempt to include both Hot & Cold nuclear effects

Υ in Emerick, Zhao, Rapp model



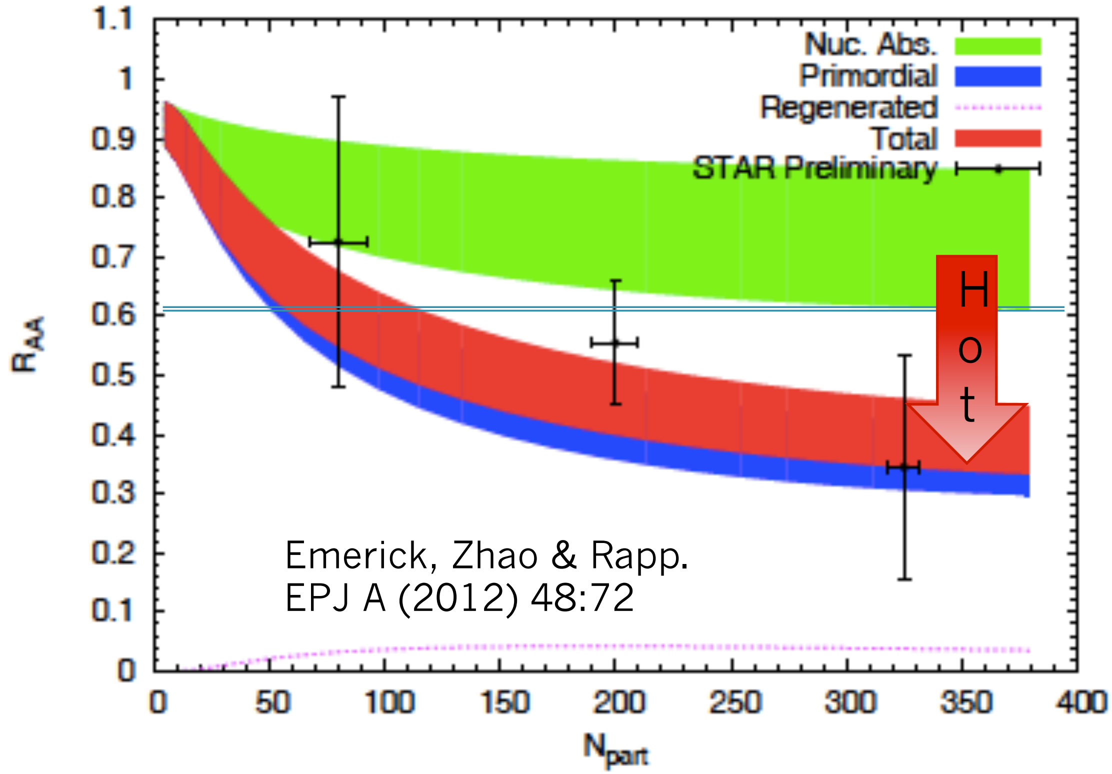


- Weak vs. Strong Binding
  - Binding energy changes (or not) with T.
  - Narrower spectral functions for "Strong" case
  - Ratios of correlators compared to Lattice: favor "Strong" binding case
- Kinetic Theory Model
  - Rate Equation: dissociation + regeneration
  - Fireball model: T evolution.
    - T ~ 300 MeV @ RHIC
    - T ~ 600 MeV @ LHC



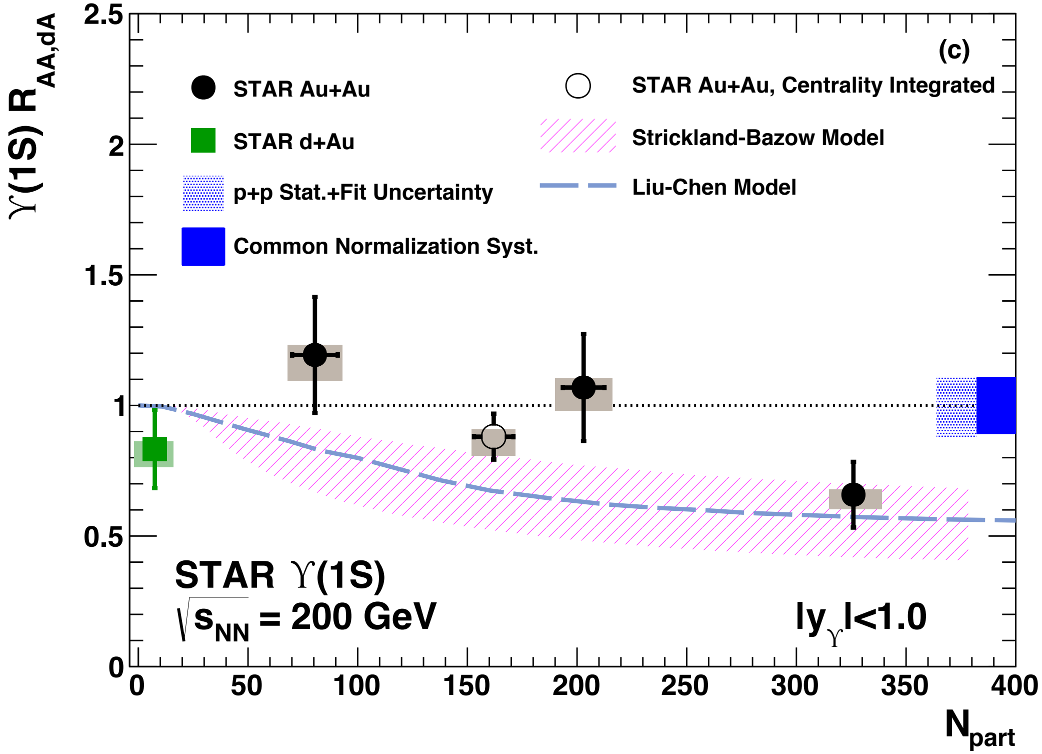
Υ in Emerick, Zhao, Rapp model

- Comparison to data:
  - Mostly consistent with data
  - Little regeneration: Final result ~ Primordial suppression
  - **Large uncertainty in nuclear absorption. Need dAu, pPb.**
    - **Based on our preliminary result R_{dAu}=0.78**
    - **σ_{abs} ~ 1 – 3.1 mb**



Suppression due to **cold** nuclear matter: can bring R_{AA} down to ~0.6 (most central, lower edge of green band).
Additional suppression needed to bring R_{AA} down to ~0.4 : **hot** nuclear effects

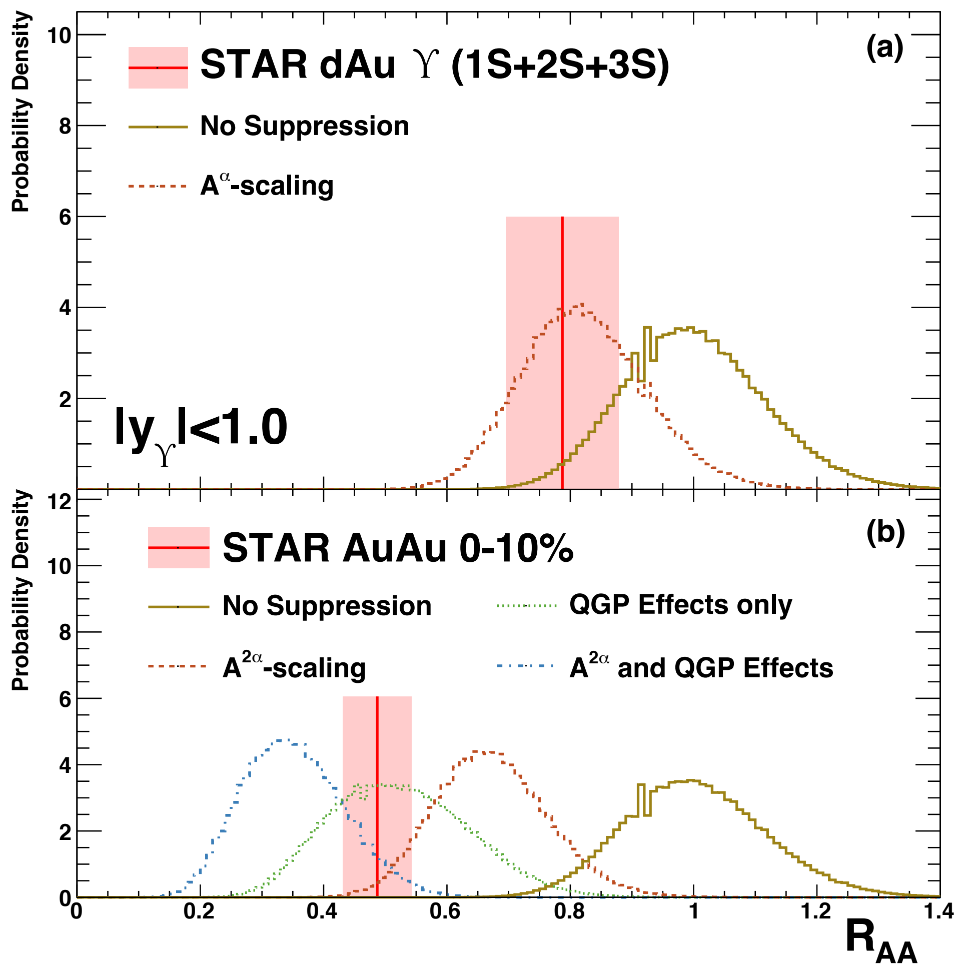
Υ Ground state R_{AA} in STAR



- Consistent with no suppression in dAu and peripheral AuAu
- Suppression in most central collisions
  - $R_{AA}(1S) = 0.66 \pm 0.13(\text{Au}+\text{Au stat.}) \pm 0.10(p+p \text{ stat.})^{+0.02}_{-0.05}(\text{Au}+\text{Au syst.}) \pm 0.08(p+p \text{ syst.})$.
  - Models from Strickland et al., and Liu et al. consistent with central suppression
    - However, neither model includes any CNM effects.

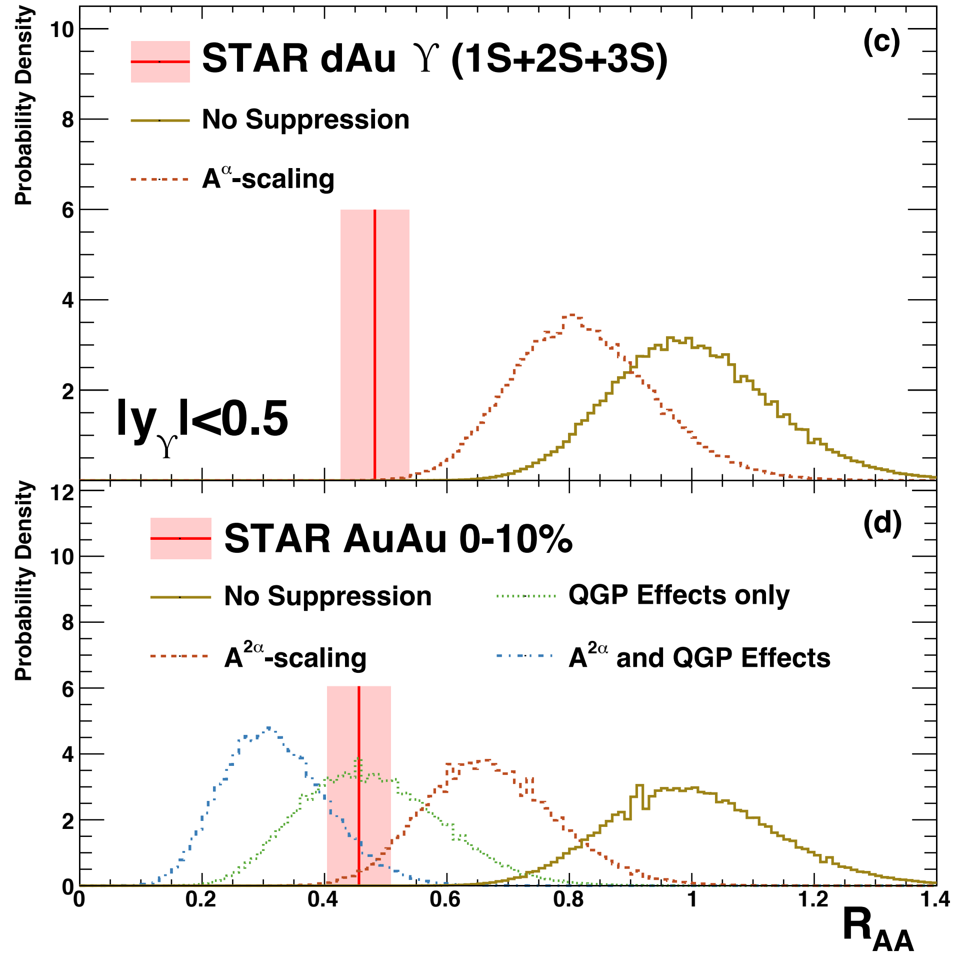
Hypothesis testing, |y|<1

- Measurements: vertical line
  - R_{dAu}
  - R_{AA}, 0-10% most central
    - pink band: syst. unc.
- Hypothesis test:
  - Run pseudoexperiments for various scenarios
  - Stat. unc.: width of distributions
    - No suppression: RAA=1
    - A^{α} scaling for dAu (CNM effect)
      - $A^{2\alpha}$ for AuAu
    - QGP effects only
      - Based on Strickland et al.
    - QGP effects + A^{α} scaling
- A^{α} scaling: consistent with dAu data
- QGP+A^{α} scaling: consistent with AuAu data
- Other scenarios are disfavored.

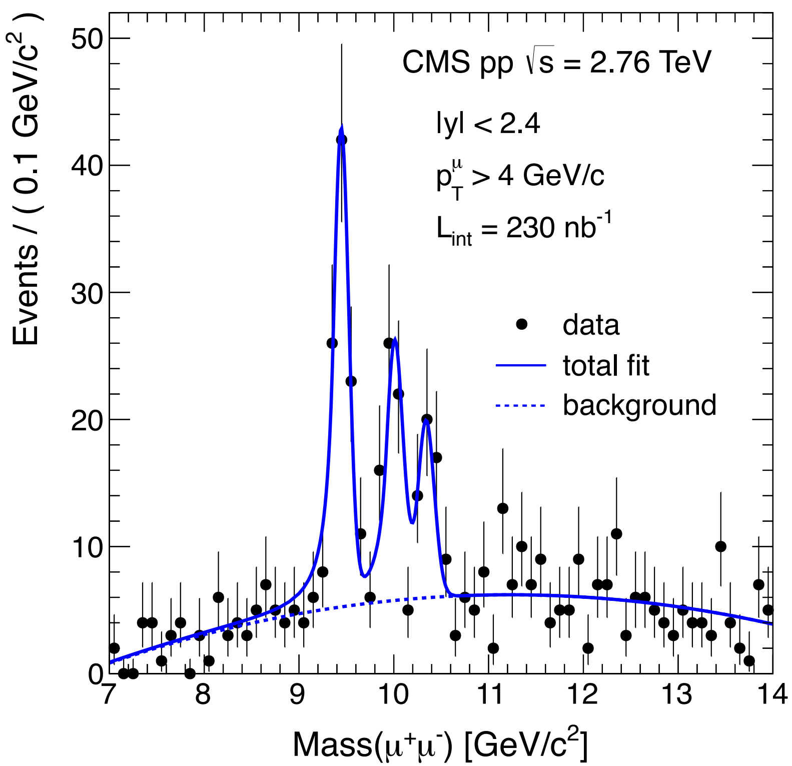


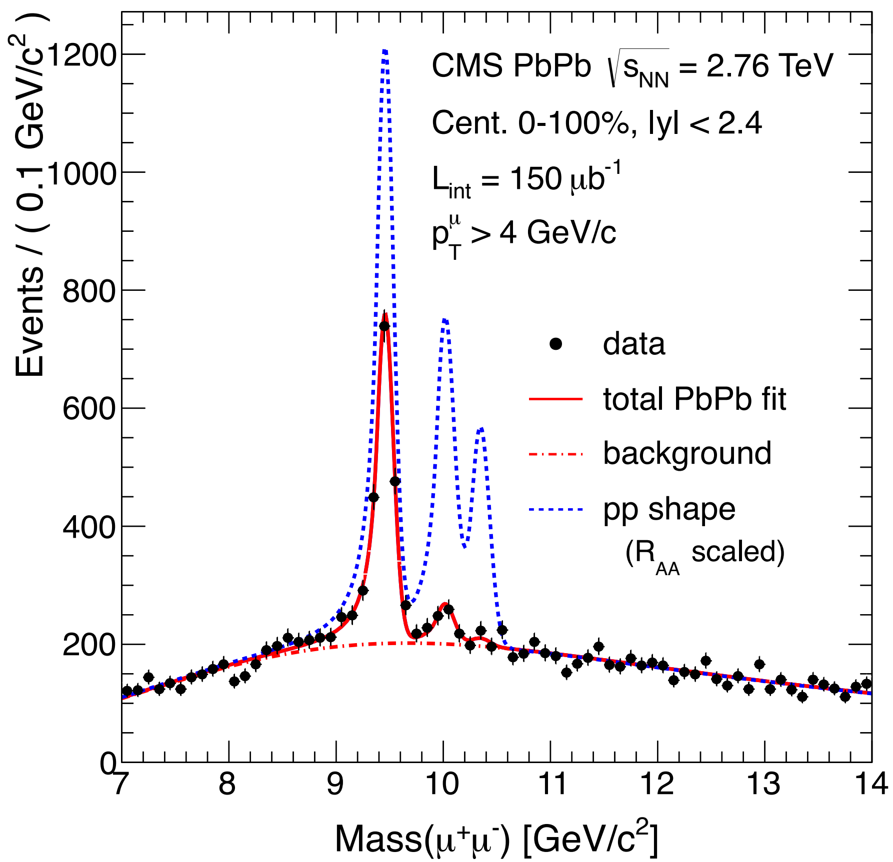
Hypothesis testing, |y|<0.5

- Hypothesis tests:
  - No suppression: RAA=1
  - A^{α} scaling for dAu (CNM effect)
    - $A^{2\alpha}$ for AuAu
  - QGP effects only
    - Based on Strickland et al.
  - QGP effects + A^{α} scaling
- Clear that |y|<0.5 shows large suppression in dAu.
  - Comparable to central AuAu
  - No particular scenario is favored.
    - Additional statistics in dAu would be beneficial.



Υ in CMS PbPb

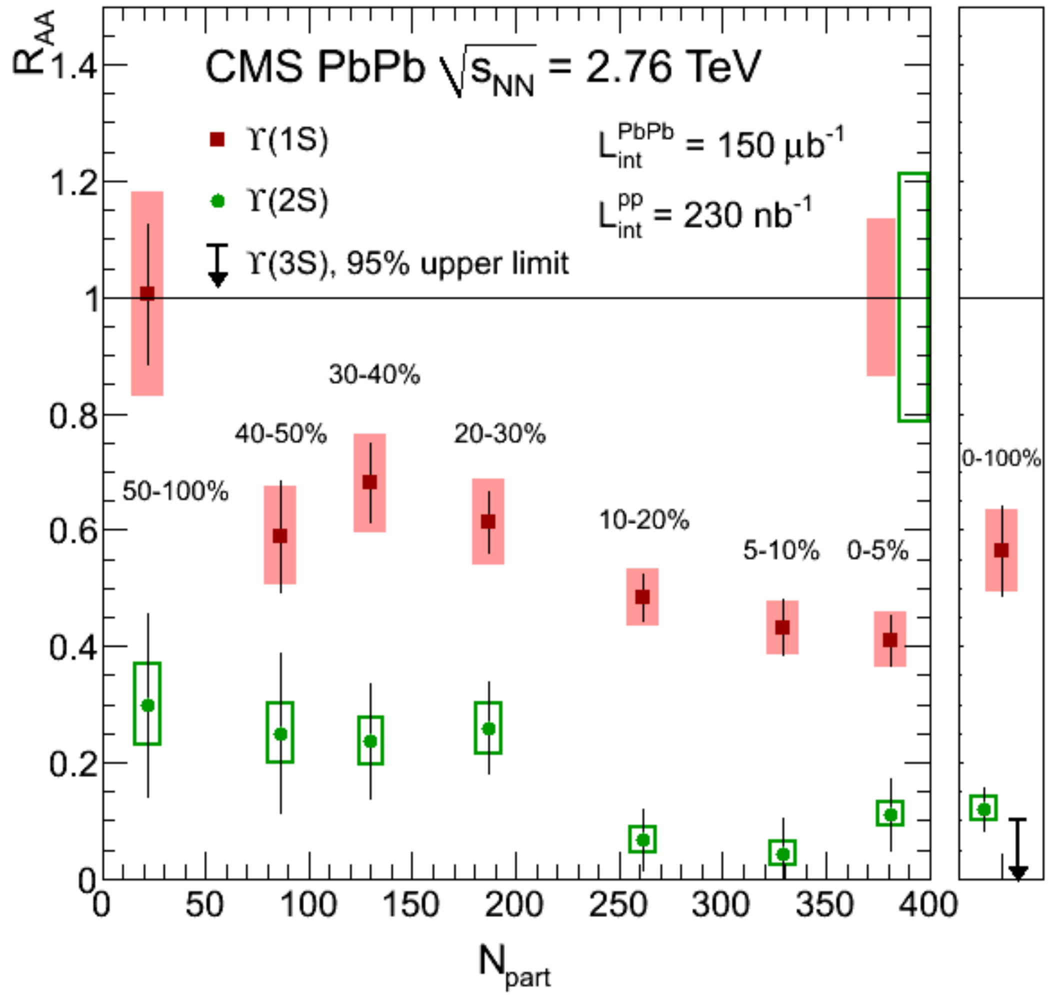




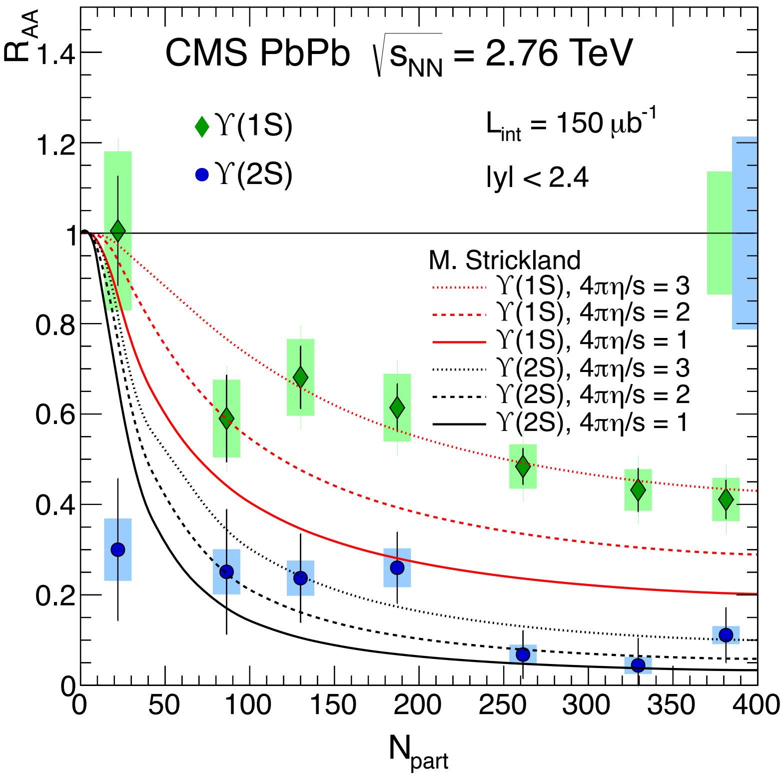
- Clear suppression of all states in PbPb.

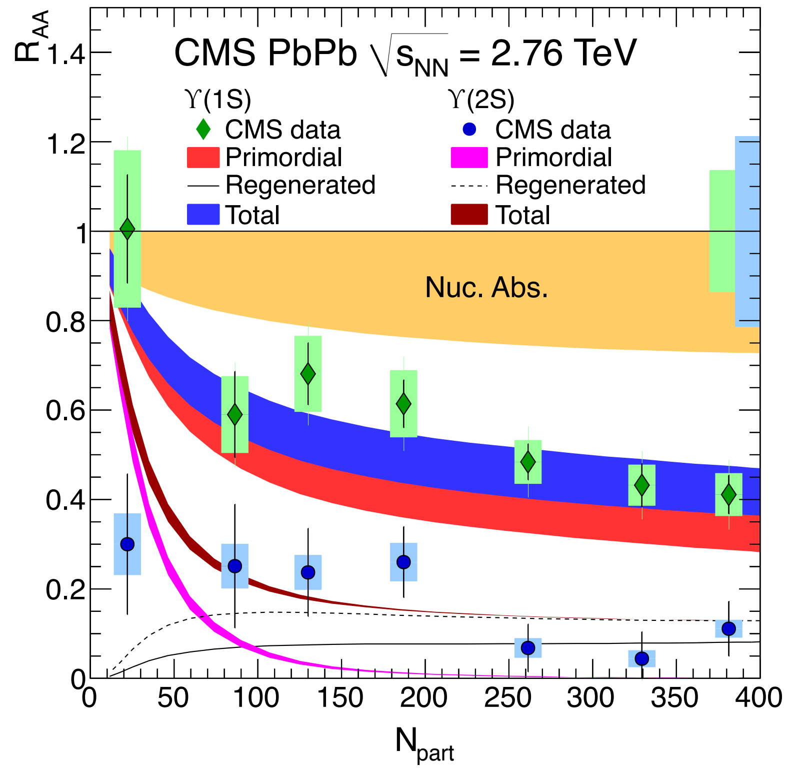
CMS Υ R_{AA} vs. N_{part}

- Centrality integrated:
  - Υ(1S) : 0.56 ± 0.08 ± 0.07
  - Υ(2S) : 0.12 ± 0.04 ± 0.02
  - **Υ(3S) : < 0.10 @ 95% CL**
- Observation of sequential suppression.
- Comparison to STAR R_{AA} Υ(1S), |y|<1 :
  - $0.88 \pm 0.09 \pm 0.13^{+0.03}_{-0.07} \pm 0.11$
  - More suppression at LHC compared to RHIC
- If directly produced fraction is ~51%: result consistent with suppression of excited states only.



CMS PbPb and models





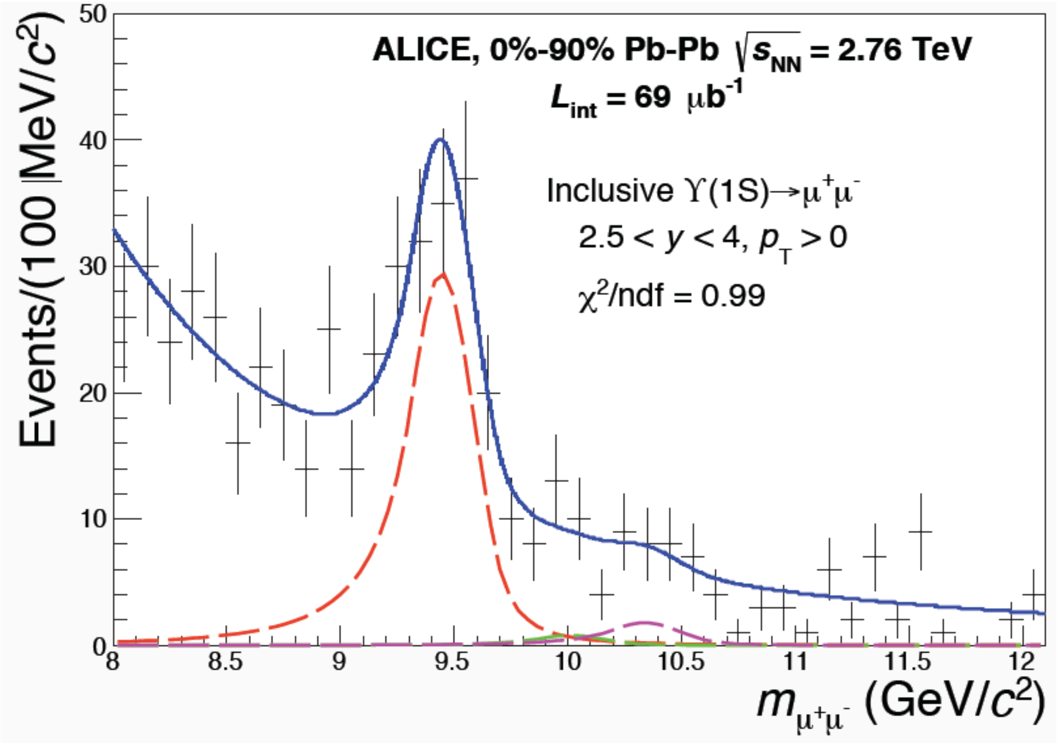
- Models from Strickland et al. and Emerick et al. consistent with data.
  - Suppression level is similar in both models
  - EZR model: Regeneration component is small for ϒ.

LHC results…

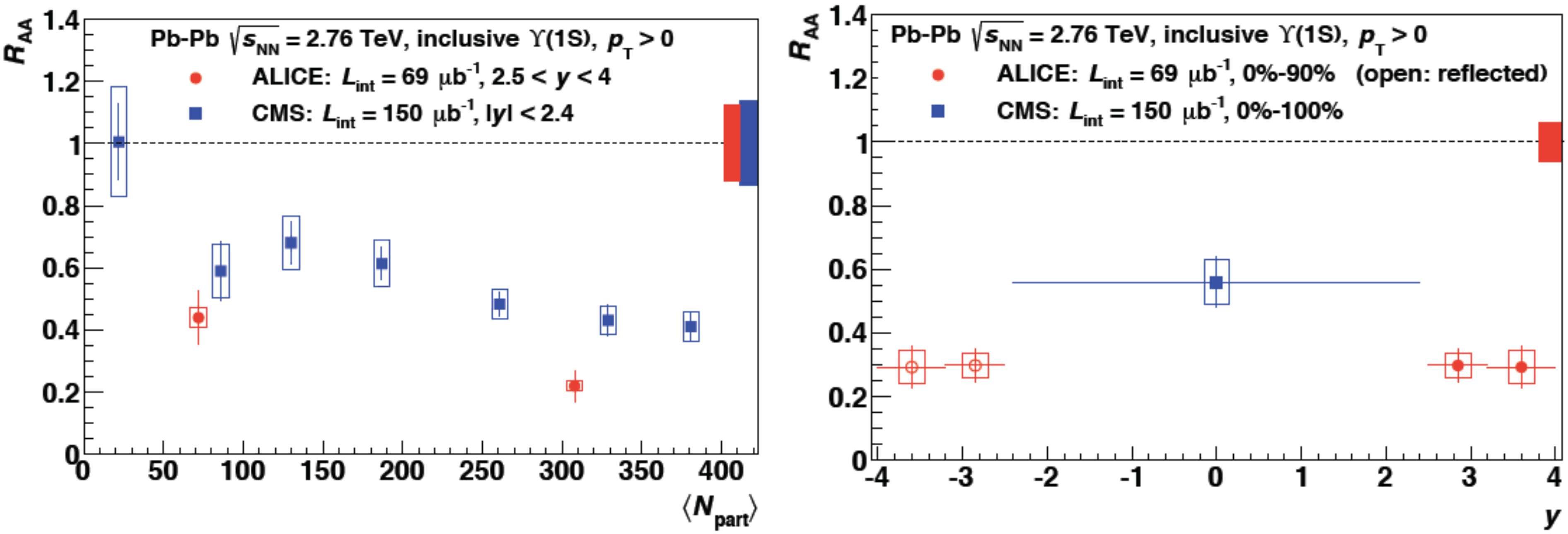
- CMS showed sequential suppression
  - Models are consistent with this picture
- LHCb shows results consistent with shadowing, can also have some E. loss, but both ok within uncertainties
- The beauty peaks were painting a compelling picture.
- … but then things got murky…

arXiv:1405.4493

- ALICE Measures ϒ in PbPb
  - Forward rapidity region
    - $2.5 < y < 4$
    - Note: CMS, $|y|<2.4$
- Fit to 1S to extract yield in PbPb
- Uses LHCb pp for reference



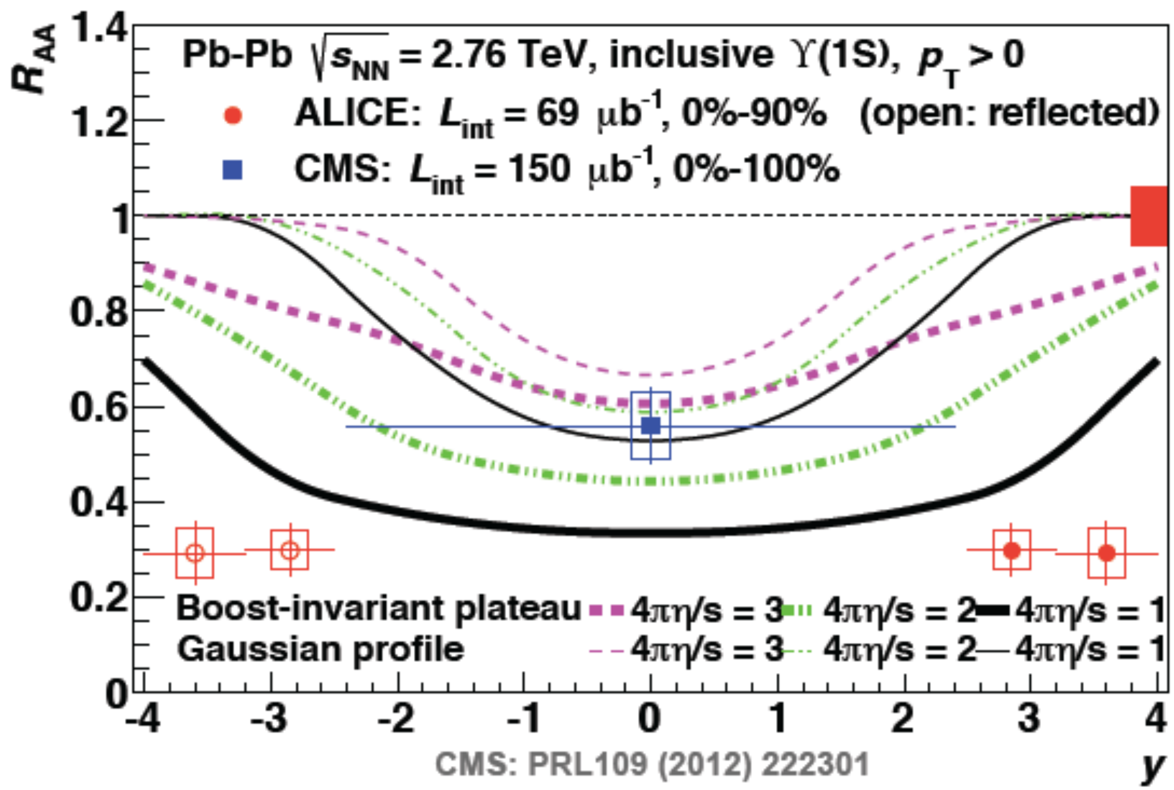
Υ R_{AA} vs. Npart, forward y



- Comparison between CMS and ALICE
  - Υ R_{AA}: more suppression at forward rapidities!
    - Energy density, T should be smaller at forward y. What gives?

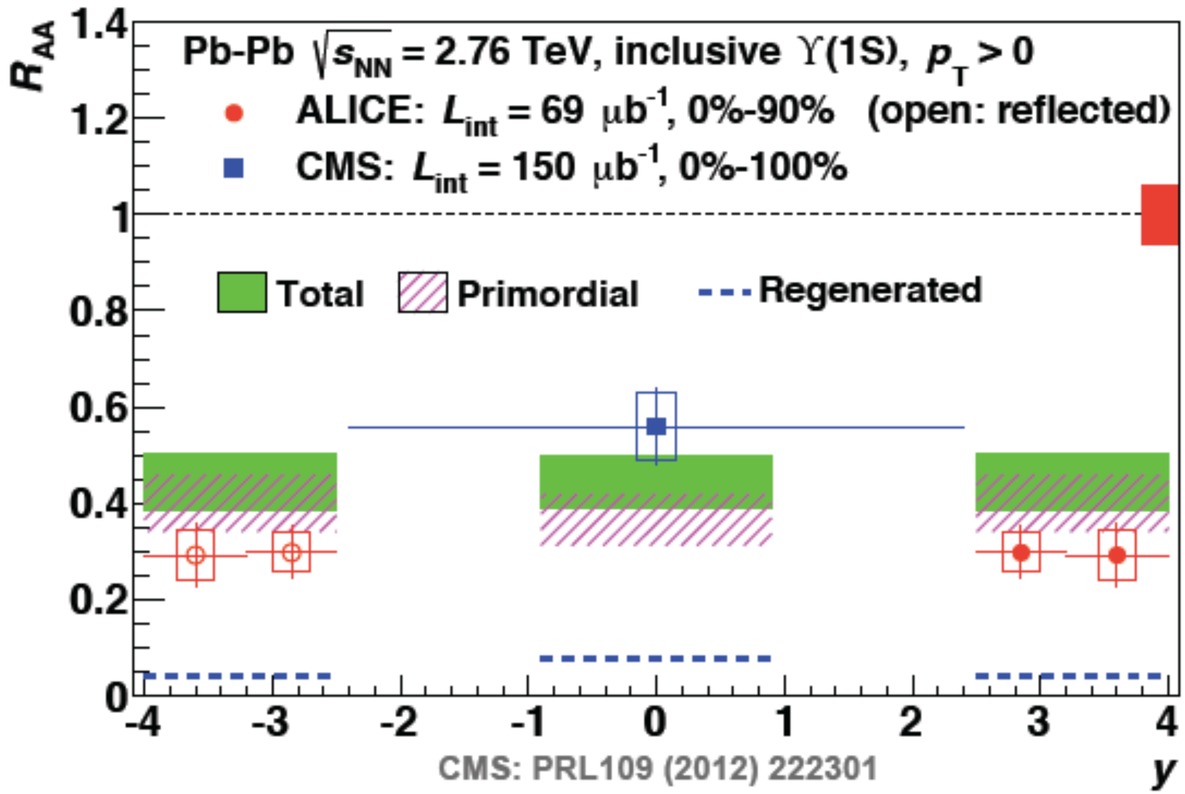
Comparison to dynamical model

- Model from Strickland et al.
  - Expect largest suppressio "dip" at y=0.
  - Changing model parameters does not change this feature.
    - Change in T profile
      - Gaussian profile
      - Boost invariant profile
      - Widens/narrows dip, bu dip remains
    - Change in shear viscosity (and therefore initial T)
      - Increases/Decreases R_{AA} scale, but dip remains
  - Most (all?) models on the market have this behavior.
    - Note: this model does not have regeneration…

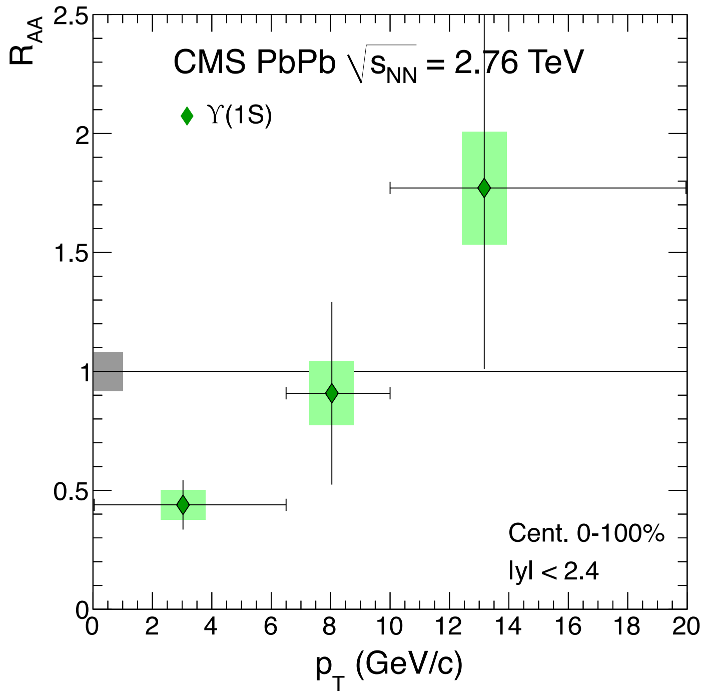


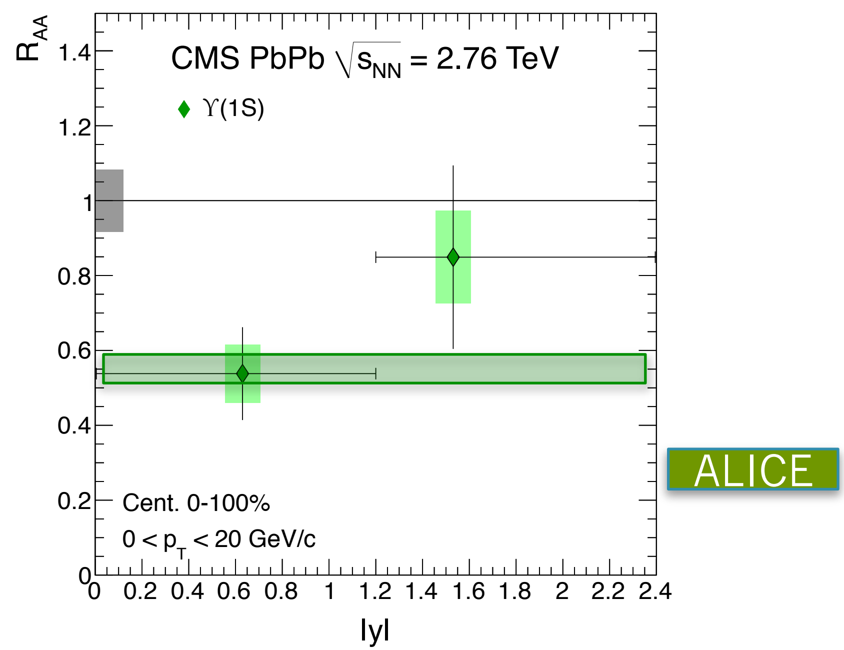
Comparison to transport/regeneration

- Model from Emerick et al.
  - Includes a regeneration component, albeit small
  - Includes absorption component
  - Yet, model cannot account for stronger suppression at forward rapidity



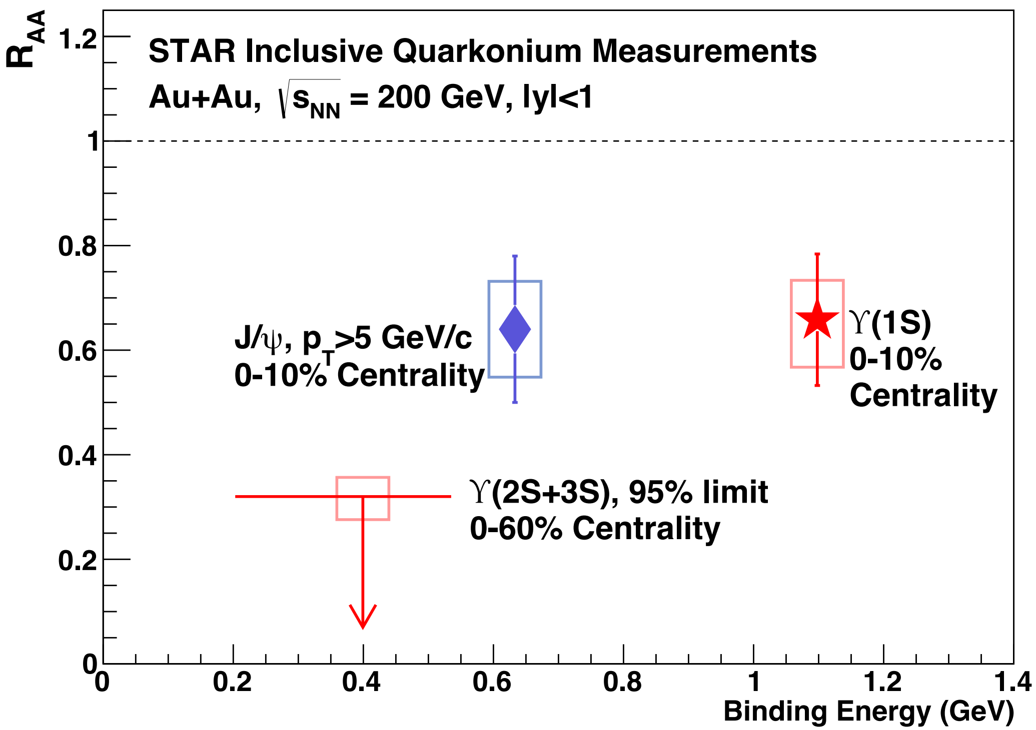
In the works, p_T and y

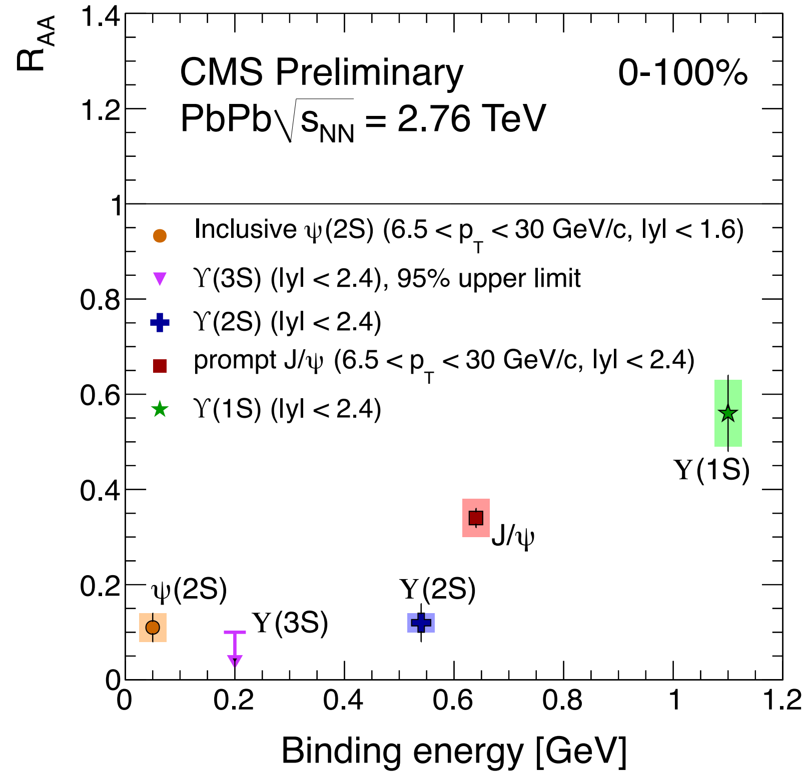




- CMS results on R_{AA} vs. p_T and y with first PbPb run, limited statistics
  - JHEP 1205 (2012) 063
  - No indication of smaller R_{AA} at higher y.
- In progress, p_T and y dependence with higher statistics and finer bins.
  - 150 μb^{-1}, compared to 7.3 μb^{-1}

Summary plots vs. binding energy





- Overall pattern of sequential suppression is observed.
  - But there are important details that do not fit.

Conclusions

- Υ: an observable that is throwing surprises!
- dAu, pPb data are now showing intriguing features
  - Possible large suppression at y=0 at RHIC
  - Final state modifications of excited state compared to ground state
    - Double ratio < 1 in pPb
- pp data vs. event activity:
  - single ratios decrease when activity is near Υ:
    - breakup of excited states? higher multiplicity when ground state is produced?
  - Increase of self-normalized yield: multi-parton interactions?
- AuAu data: The first results from STAR and CMS looked very consistent with sequential suppression picture.
  - But forward rapidity data challenges our closely held beliefs!

Thanks!

- Here's to the continued exploration of beautiful peaks, and that we find a crisp, clear vista of the QCD landscape