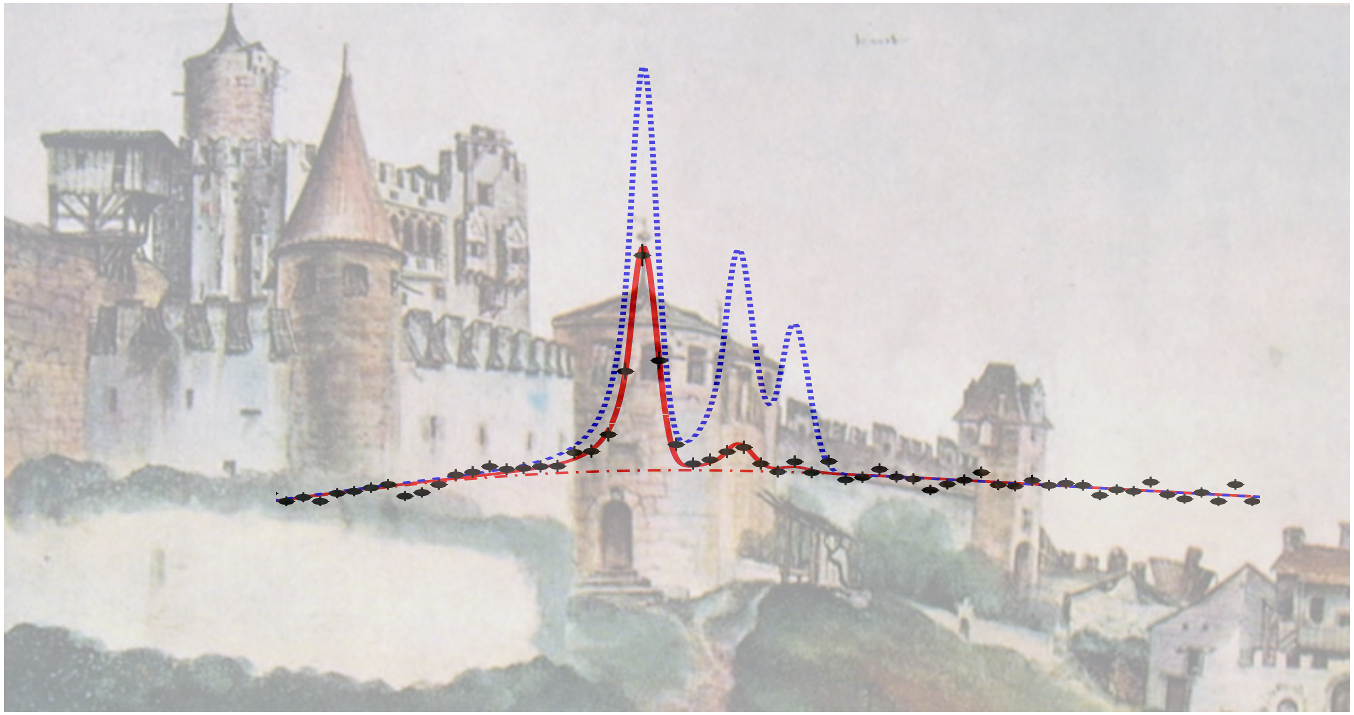
Υ production in pA and AA collisions from Fermilab, RHIC, and LHC



New Observables in Quarkonium Production
ECT* Workshop
1/March/2016

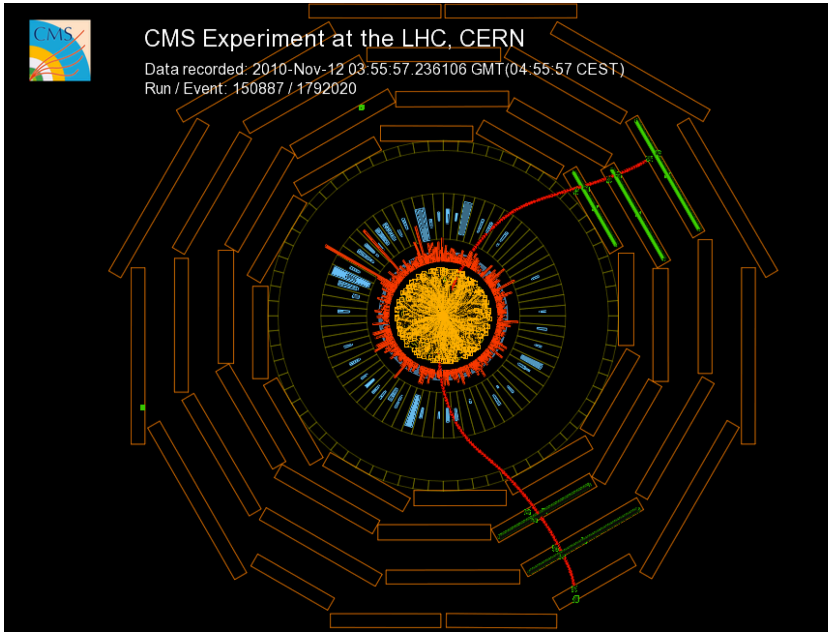
Manuel Calderón de la Barca Sánchez
UCDAVIS

Outline

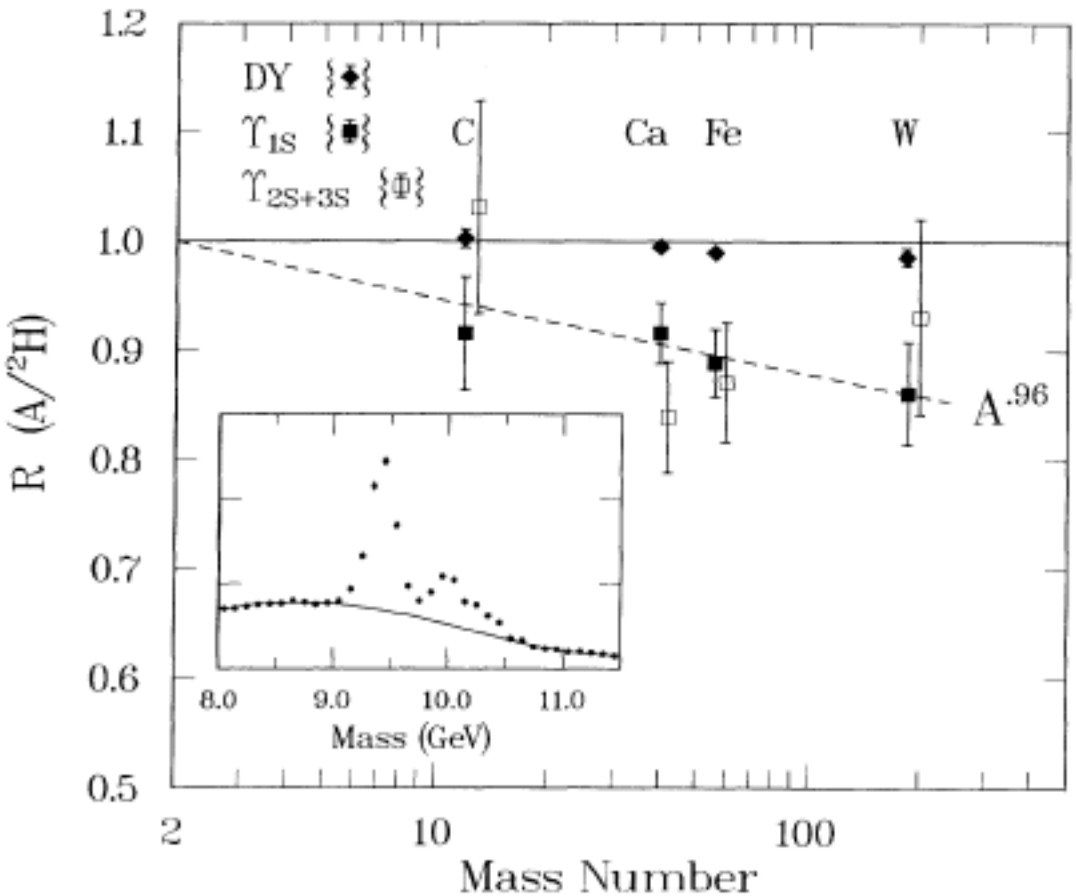
- Bottomonium Measurement in pA and AA collisions.
  - Emphasis on $\Upsilon(1S)$
    - Caveat: Many results include ground states.
    - Will be mentioned, but leave emphasis for session on excited states.
  - Fermilab pA
    - $\sqrt{s}$=40 GeV
  - RHIC dA, AA
    - $\sqrt{s}$=200 GeV
  - LHC pA, AA
  - $\sqrt{s}$=2.76, 5.02 TeV
- Summary

Bottomonium in pA and AA

- Υ in AA: a probe of color deconfinement
  - Suppression of yield: states do not form in a color deconfined medium
    - Color screening, gluodissociation, partonic breakup/Landau damping.
- Υ in pA: Production in Cold nuclear matter
  - Initial state effects: e.g. nPDF
  - Final state: energy loss, absorption
- Bottomonium: a cleaner probe than charmonium…
  - 3 states are accessible experimentally
  - Expect smaller recombination contribution compared to charmonium
    - $m_b \sim 3\ m_c$



E772 pA Υ measurement



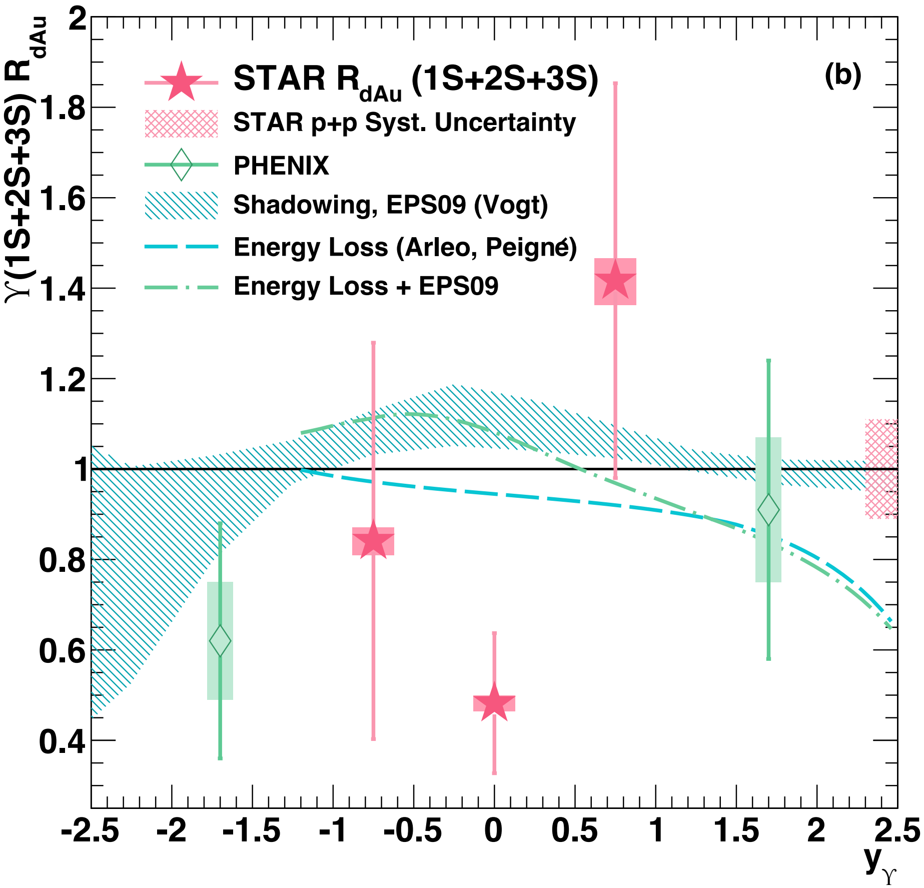
PRL 66 (1991) 2285

- Ratio of nuclear targets normalized to deuterium
- Suppression seen with increasing A.
- A dependence:

$$\alpha_{1S} = 0.962 \pm 0.006$$

$$\alpha_{2S+3S} = 0.948 \pm 0.012$$

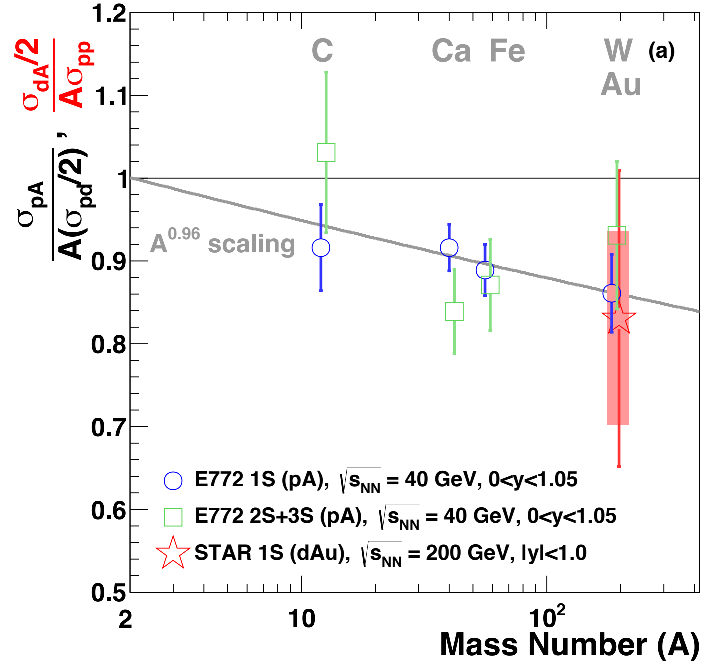
R_{dAu} at RHIC



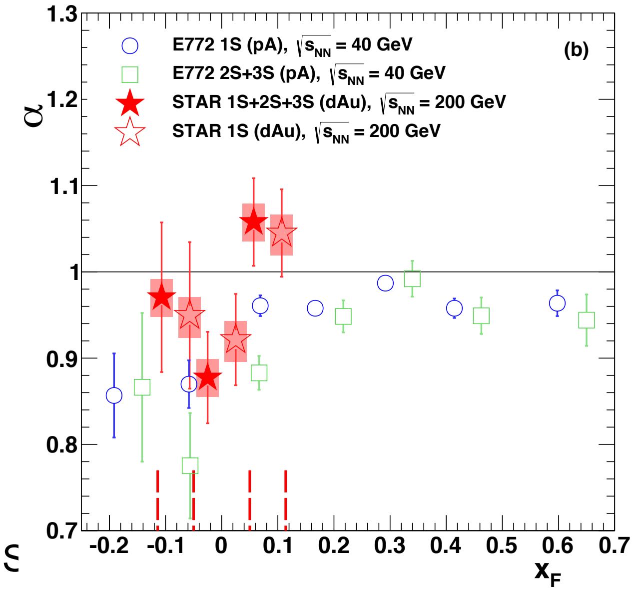
- R_{dAu} vs. y
  - Model comparison:
    - Shadowing, EPS09
      - R. Vogt
    - Energy loss
    - Energy loss + shadowing
  - y~0 is right in the middle of the antishadowing region
  - Expect R_{dAu} > 1 (small effect)
  - Observe R_{dAu} < 1

Comparison: STAR & E772

- For a similar comparison, separate $\Upsilon(1S)$ stat
  - Use |y|< 1, check A dependence.
- STAR result: consistent with trend vs. *A* from E772.

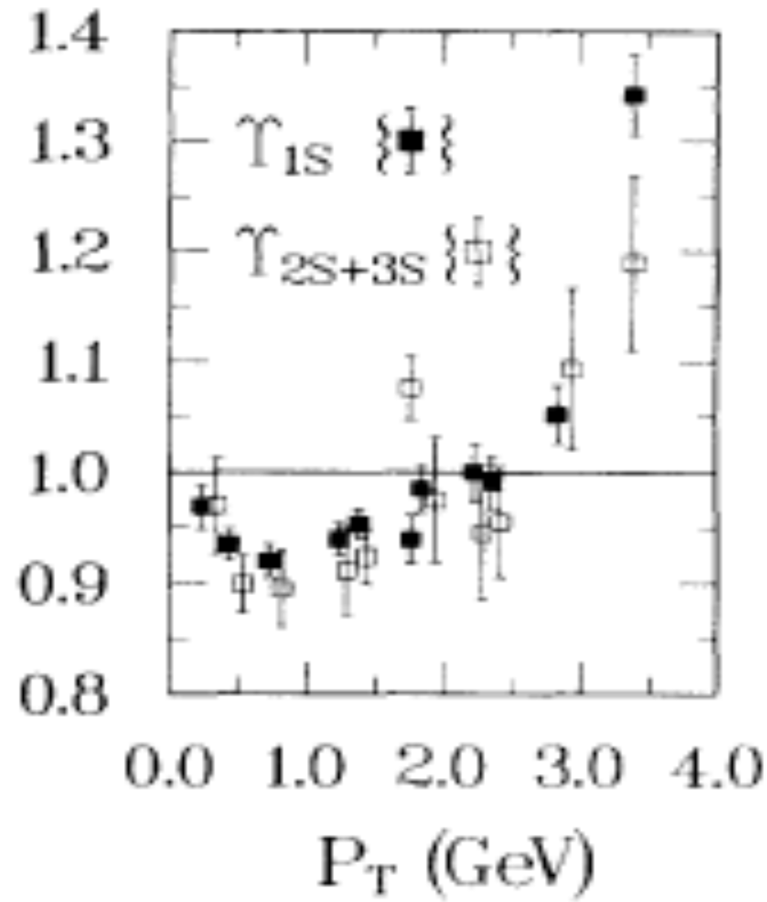


- Large suppression seen near xF~0 by E772, α~0.9.
  - Similar to STAR |y| <0.5 points.



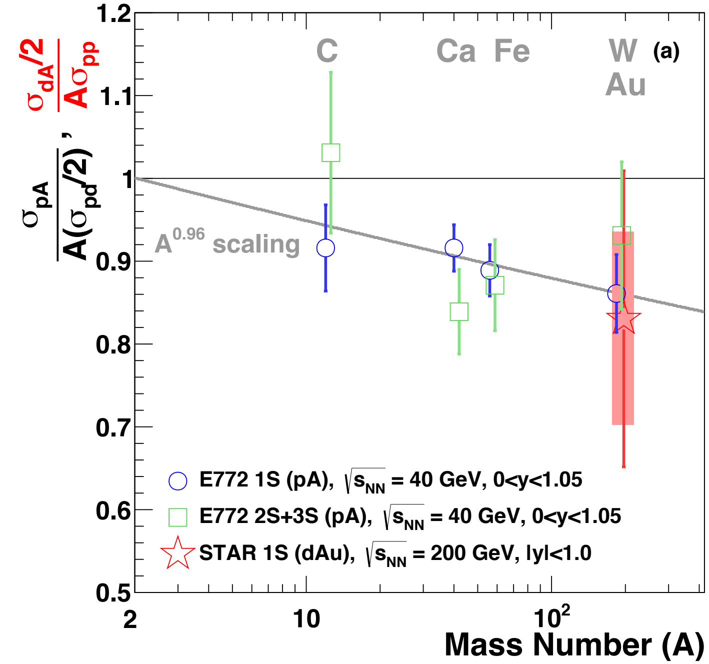
Note: p_T dependence of α in E772

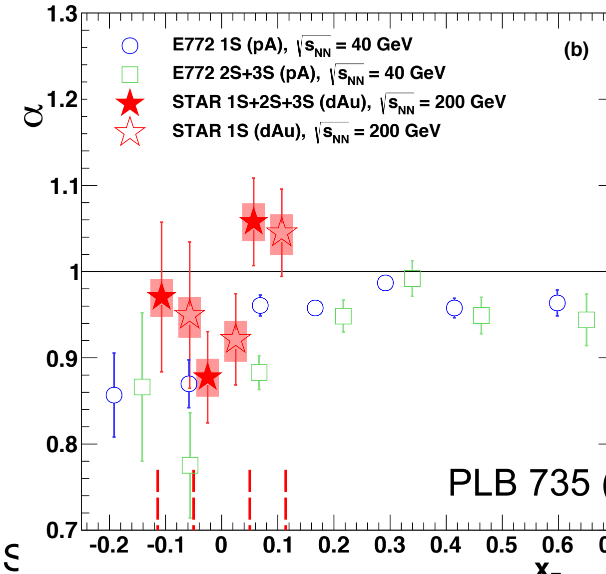
- Not trivial either.
  - Suppression largest at ~1 GeV
  - Large enhancement above 3 GeV
- No LHC measurements vs. p_T for pPb, yet.
  - pp reference at 5.02 TeV just taken



Comparison: STAR & E772

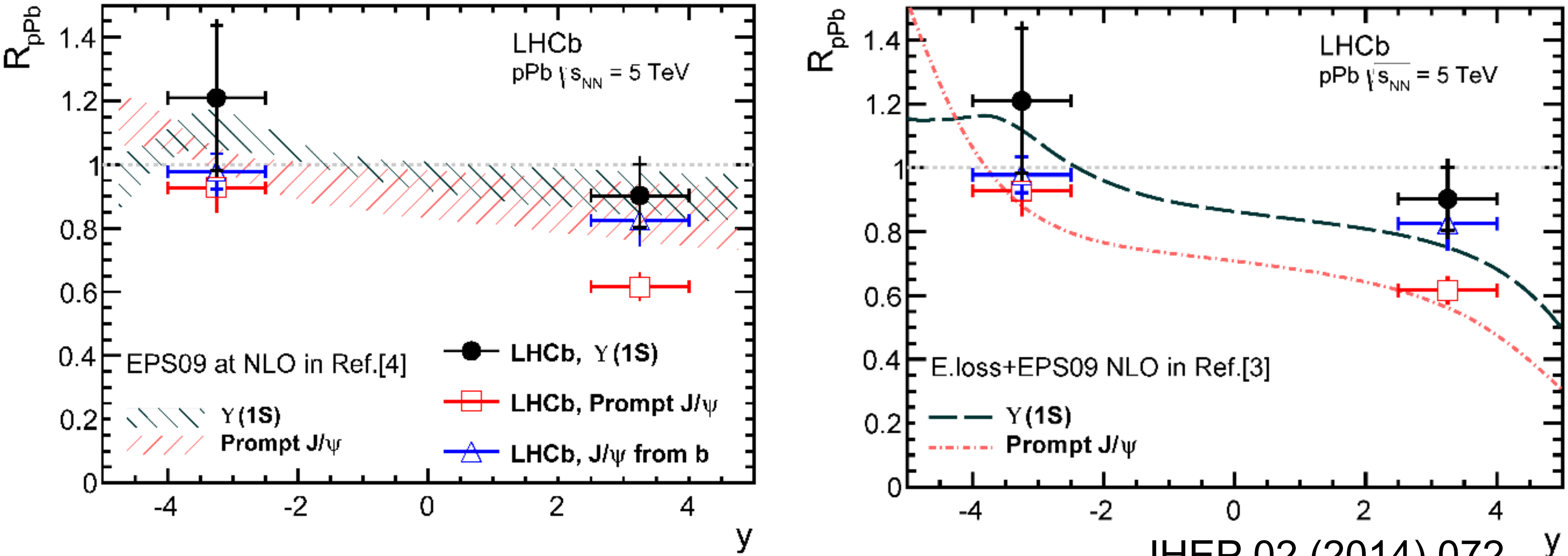
- For a similar comparison, separate $\Upsilon(1S)$ stat
  - Increases the statistical uncertainty compared to sum $\Upsilon(1S+2S+3S)$
  - Use $|y| < 1$, check A dependence.
  - Also compare y or x_F dependence.
- STAR result: consistent with A trend from E772.
- Large suppression seen near xF~0 by 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





PLB 735 (2014) 127

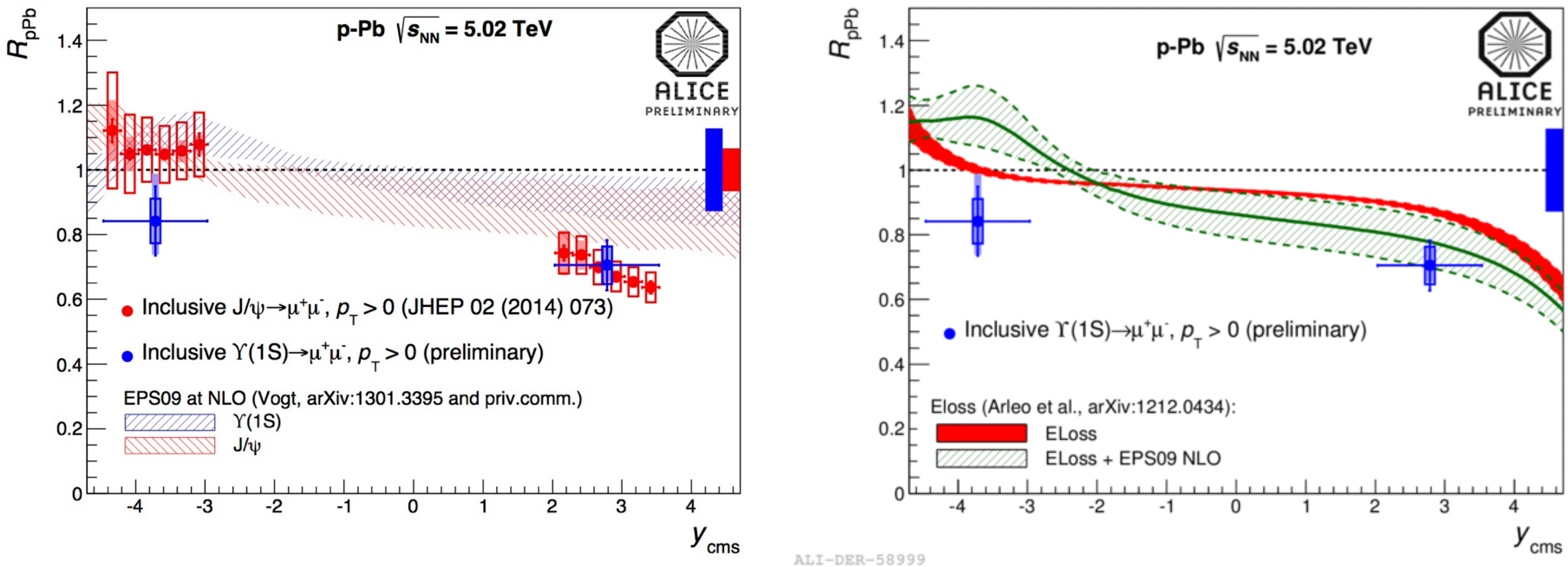
LHCb Υ results for R_{pPb}



JHEP 02 (2014) 072
JHEP 07 (2014) 094

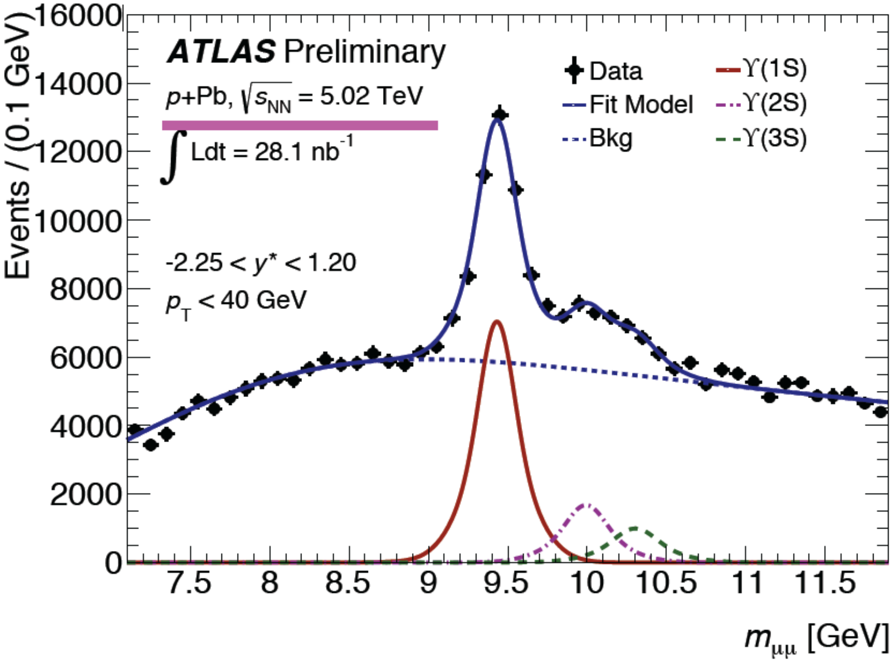
- Caveat emptor:
  - All LHC R_{pPb} results to date done without pp Reference at 5.02 TeV:
    - LHCb: Power-law interpolation: BR x s = 1.12 ± 0.11 nb
- Slight enhancement at negative rapidity, indication of antishadowing
- Slight suppression at forward rapidity
- Different theoretical models are consistent with data, within uncertainties
    - EPS09 NLO: IJMP E22 (2013) 1330007
    - E. loss : JHEP 03 (2013) 122

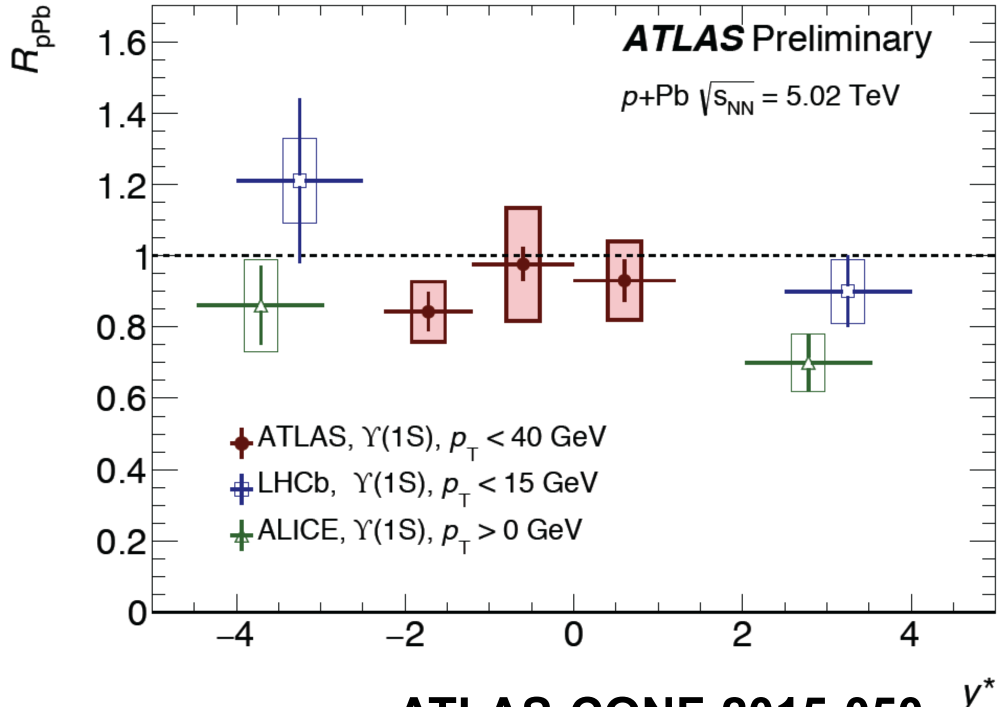
ALICE Υ results for R_{pPb}



- Backward rapidity: ALICE sees no enhancement, slight suppression.
  - EPS09 NLO: antishadowing in forward region. Enhancement remains when including ELoss + EPS09.
- 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.
- ALICE pp interpolation:
  - Used LHCb data (not in the same rapidity range).
    - Fit with CEM (15 different choices of scale, pdf), FONLL bare quark energy dependence; power-law, linear, exponential.
  - 1451 ± 114(syst) pb and 770 ± 87(syst) pb,

ATLAS LHC R_{pPb} Υ(1S)



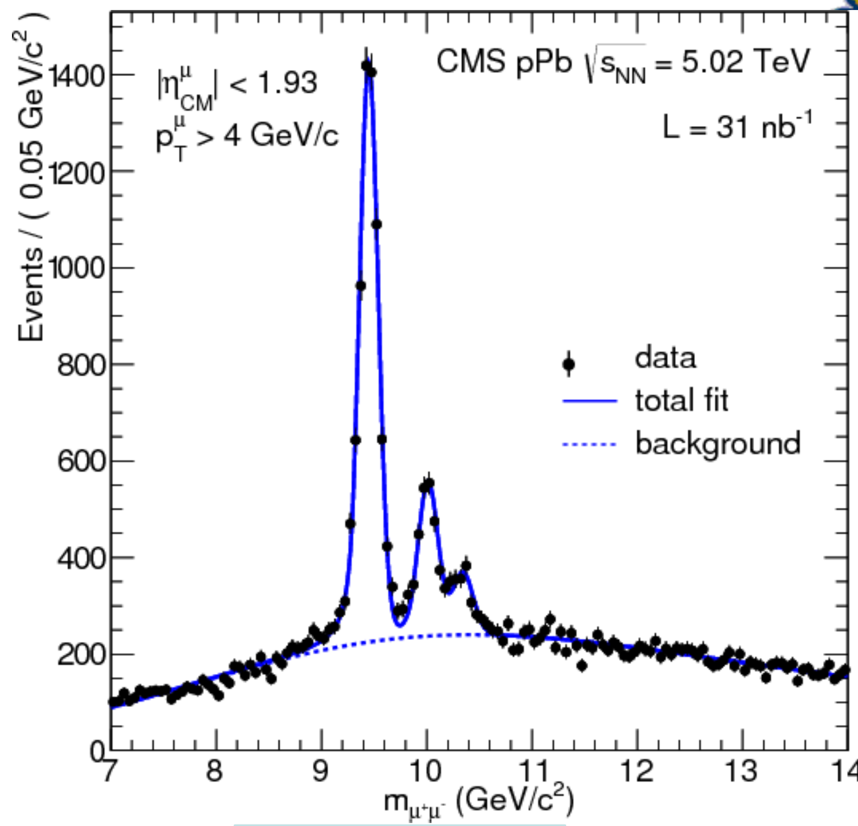


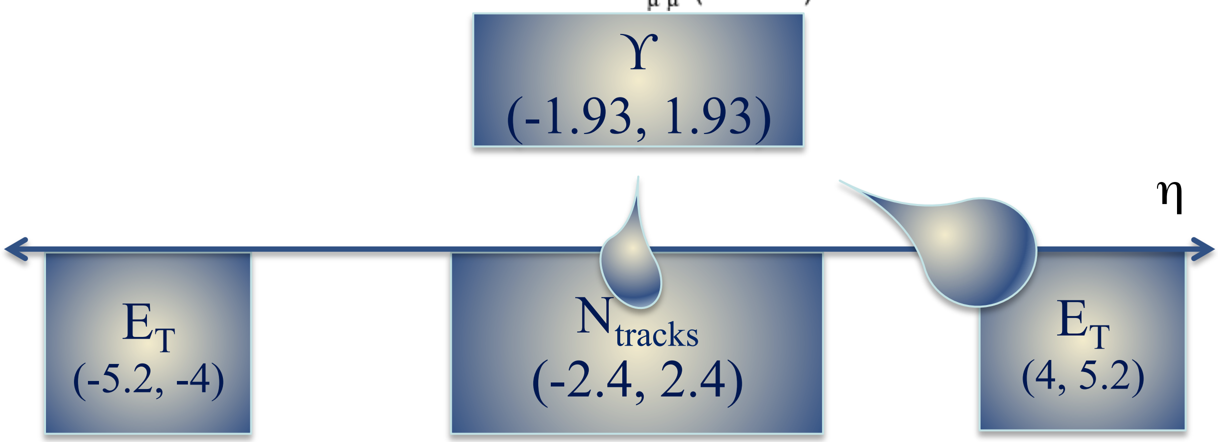
ATLAS-CONF-2015-050

- 1S in pPb, Little to no modification seen at midrapidity.
  - Contrast to E772 & STAR lower energy data for y~0.

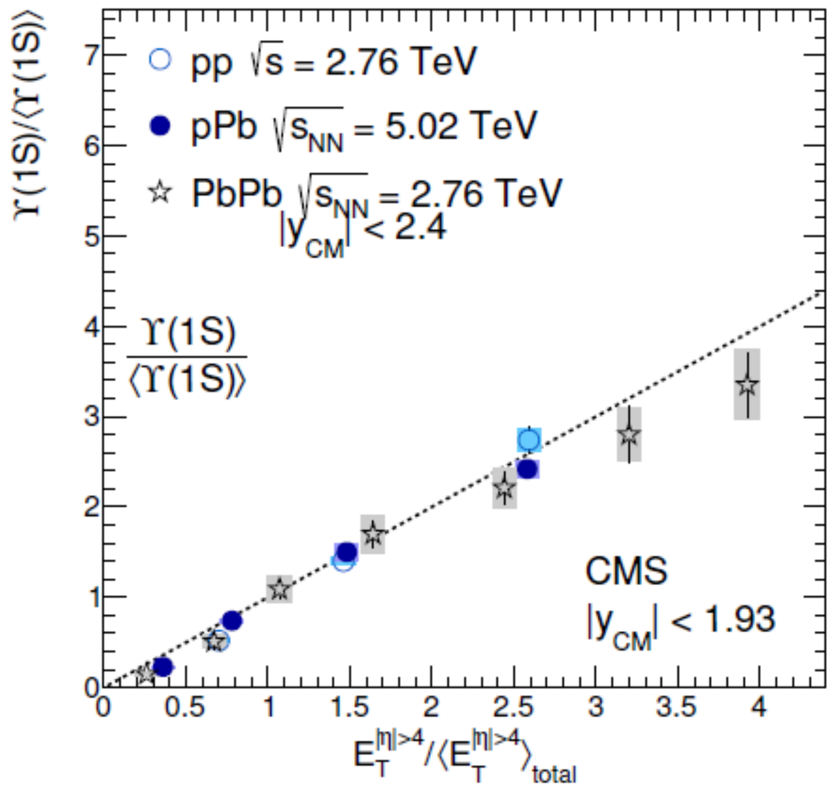
Υ in pPb at LHC with CMS

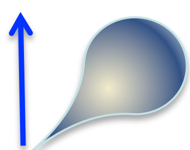
- Observables:
  - Double ratio, single ratio
  - "Self-normalized" yields
  - Study as a function of event activity
    - Look at activity close to or far from Υ meson.
      - Close: N_{tracks}
      - Far: E_T





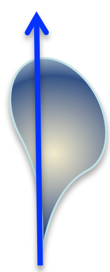
Υ Self-normalized yields: Far activity

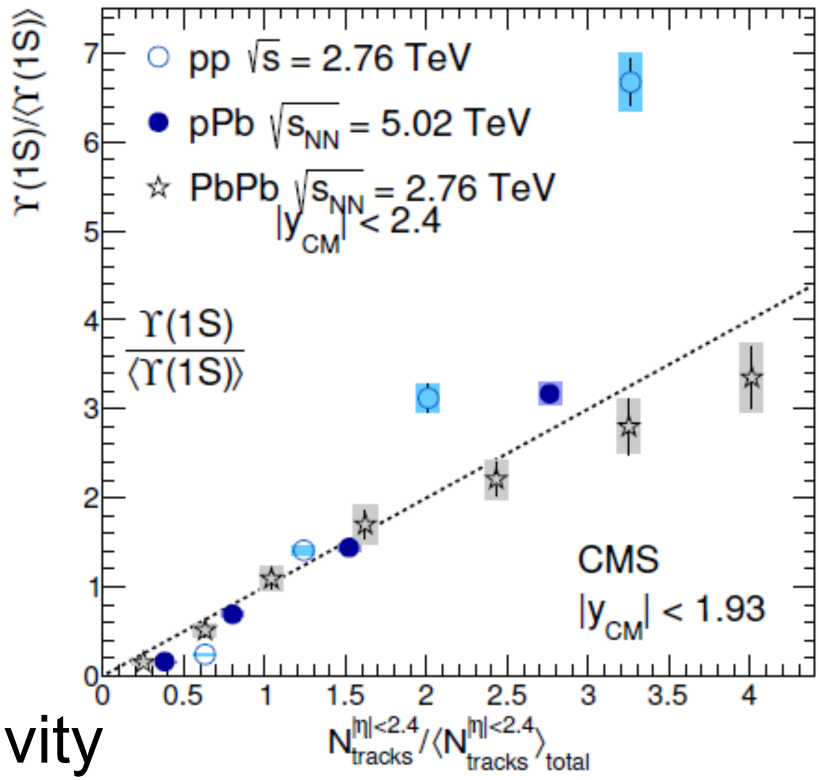




- E_T, Far activity
- Close to linear scaling is observed for all systems.
  - Suppression in PbPb for high E_T: central events.
- pPb, pp follow very closely line with slope 1 (dashed line)
  - Fit gives slope consistent with 1 within errors.
  - All systems, all Υ states.

Υ Self-normalized yields: Near activity

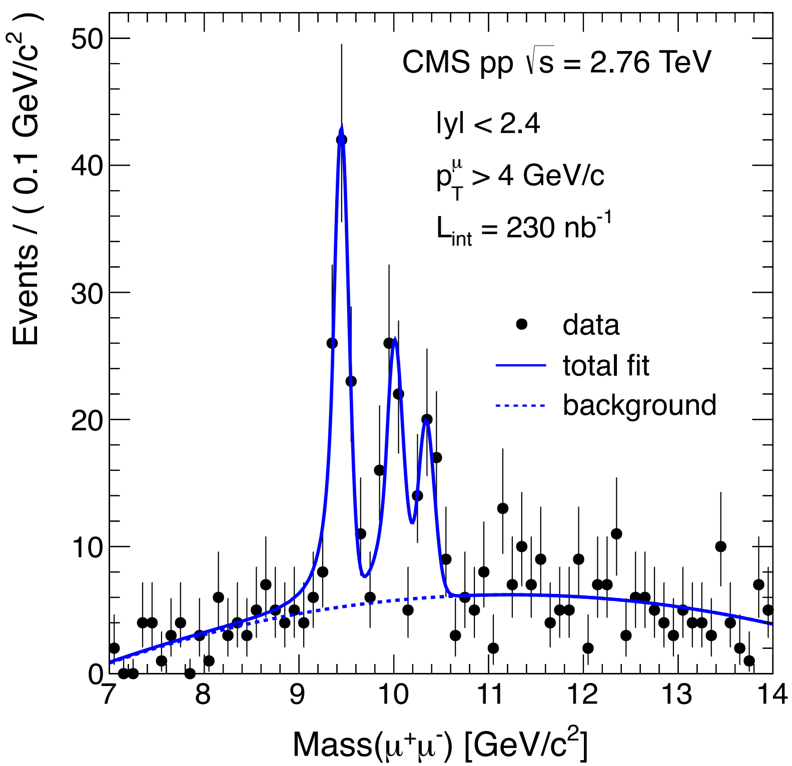


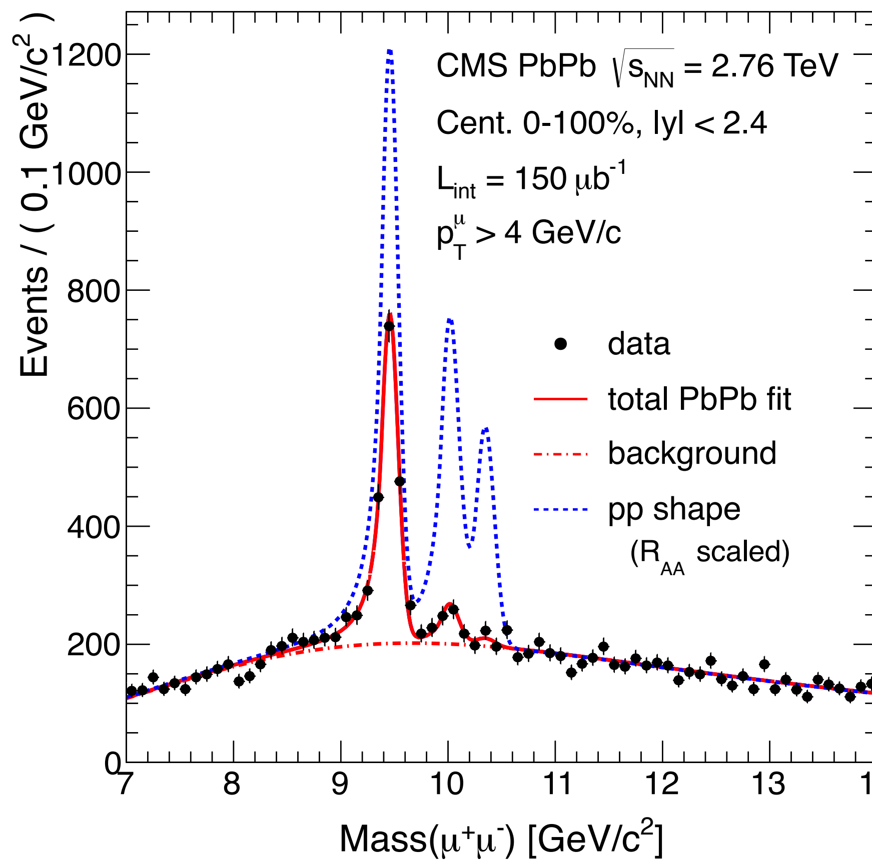


- N_{tracks}, Near activity
- Significant differences among systems and among states!
  - Υ(1S) production scaling: stronger than linear in pp.

- All states, even in pp, regardless of whether activity is far or near, show increasing relative yield in higher activity events.
  - Multi-parton interactions in pp?

Υ in CMS PbPb

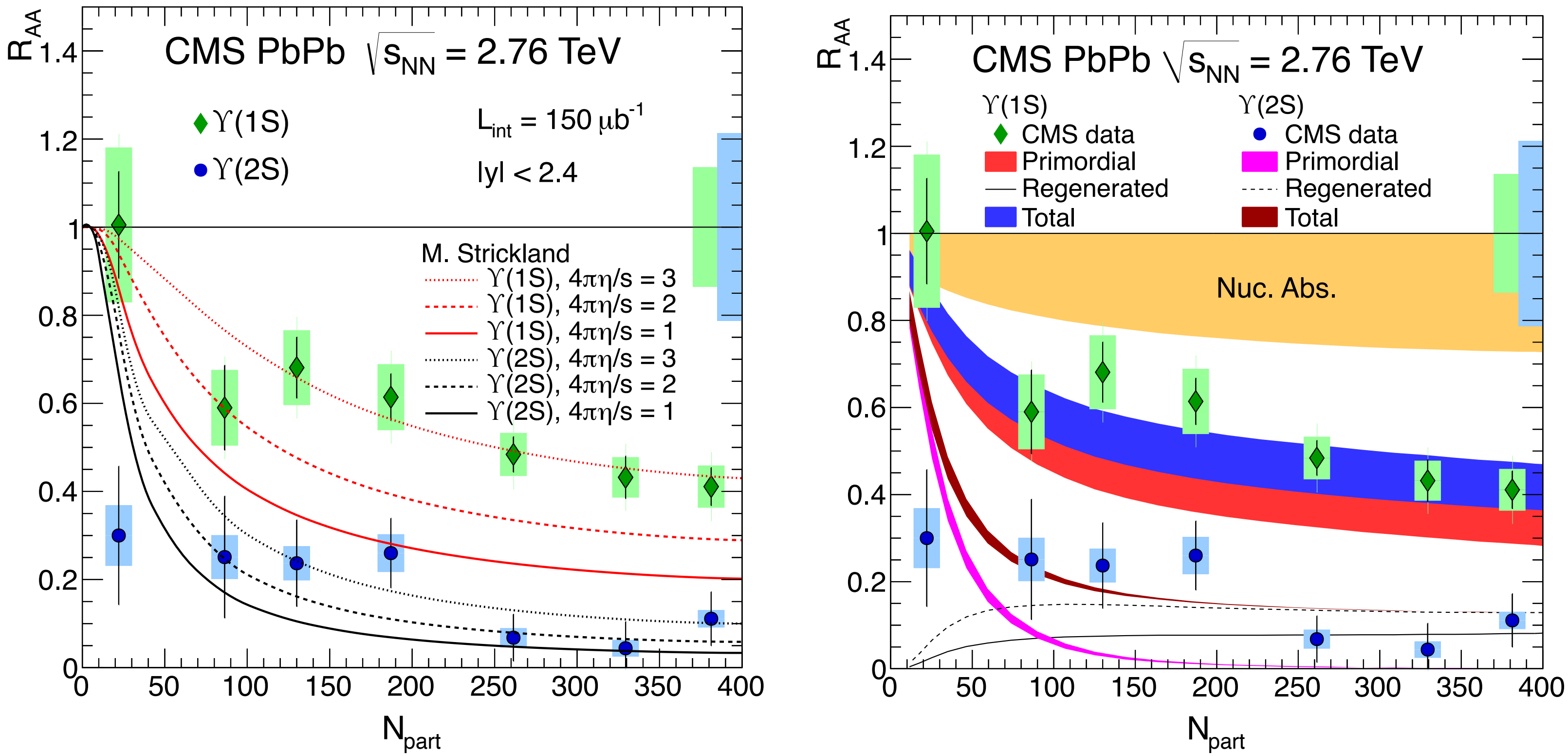




CMS: PRL 109 222301 (2012)

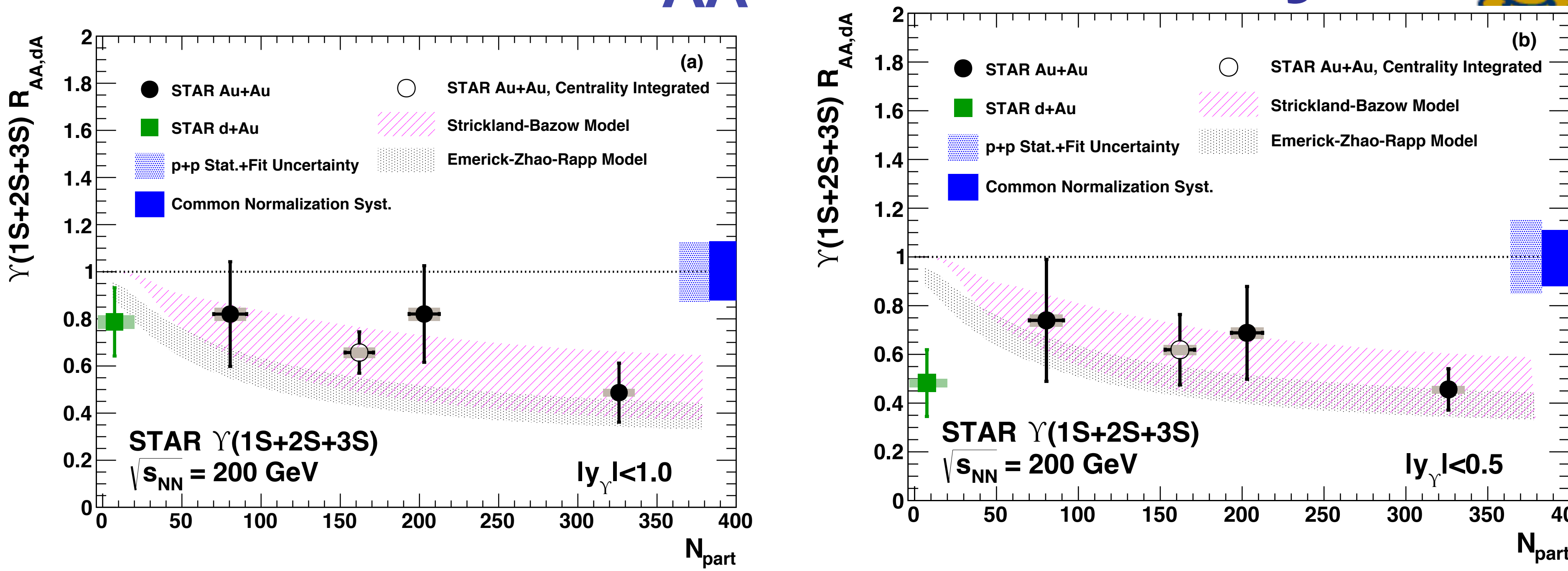
- CMS:Clear suppression of all states in PbPb compared to pp.

CMS Υ R_{AA} in PbPb and models



- Strickland et al. : Nucl. Phys. A 879 (2012) 25
  - Incorporate Re and Im Potential, insert into hydrodynamic expansion, include feed-down contributions.
- Emerick et al. : EPJ A (2012) 48:72
  - Attempt to model binding behavior, test strong/weak binding, kinetic transport model, includes production of Upsilon via "regeneration" of uncorrelated bottom quarks, cold-nuclear-matter aborption.
- Both models consistent with data.
  - But now we have more information, e.g. feeddown contribution is not 50%. What does this do to R_{AA} in models?

STAR Υ R_{AA} vs. Centrality

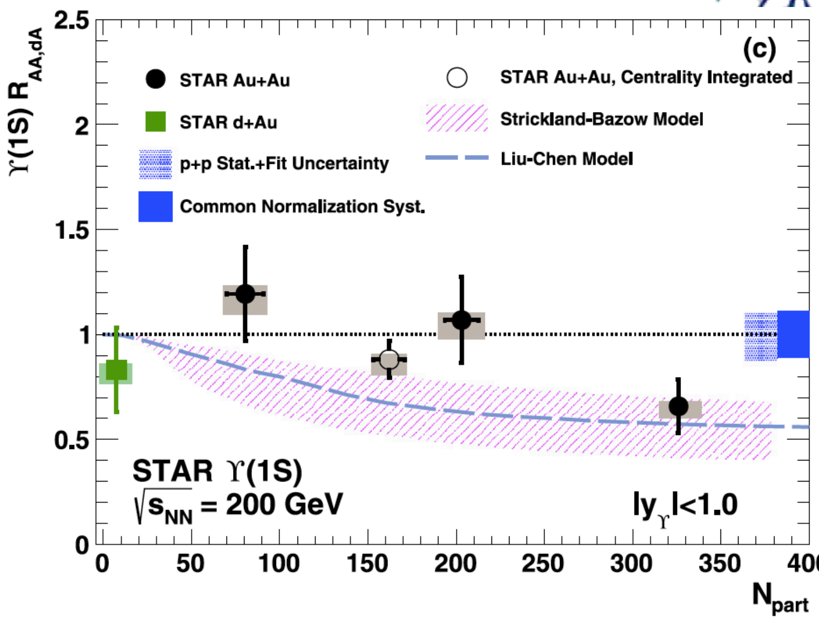


PLB 735 (2014) 127

- Left: 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…
- Right: 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.
    - Eur. Phys. J. A (2012) 48: 72

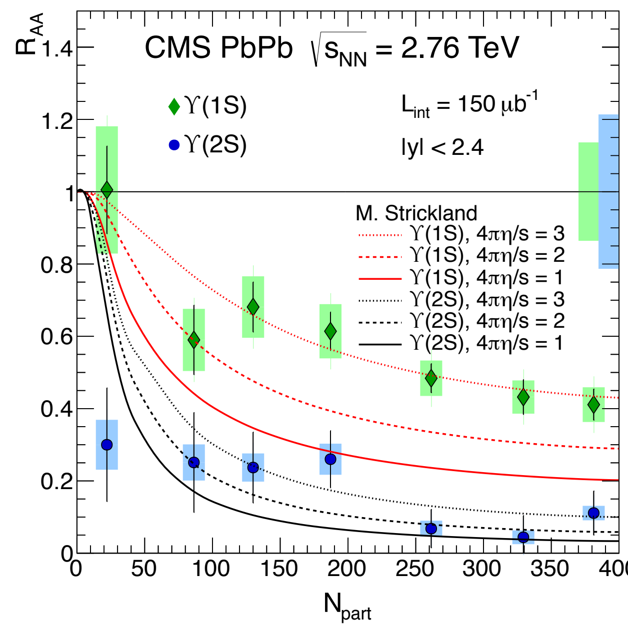
STAR & CMS data and model parameters

- Strickland & Bazow:
- Incorporating lattice-based potentials,
  - including real and imaginary parts
- Includes sequential melting and feed-down contributions
  - Used: ~50% feed-down (what was known at the time)
- Dynamical expansion, variations in initial conditions (T_0, η/S)
  - Data indicate:
    - $428 < T_0 < 442$ MeV at RHIC
    - $552 < T_0 < 580$ MeV at LHC
    - for $3 > 4\pi\eta/S > 1$



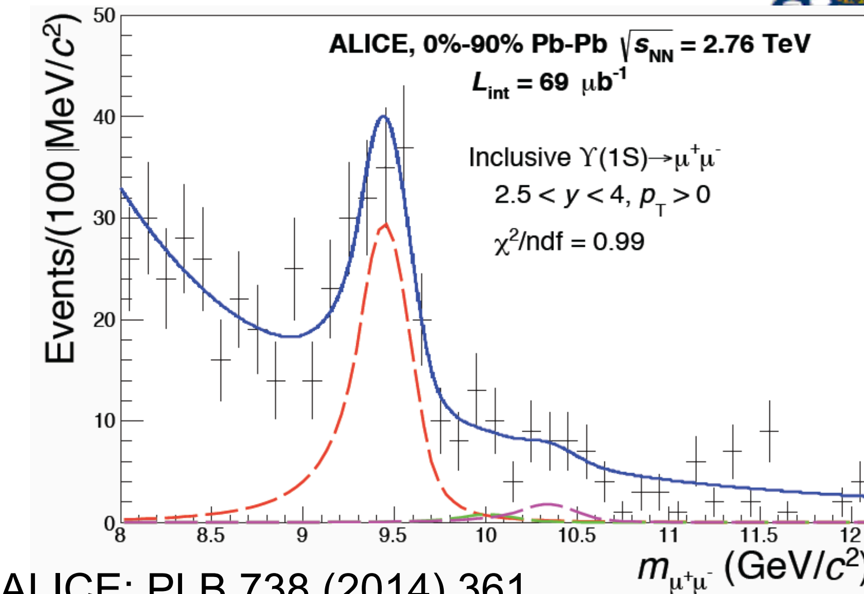
- Emerick, Zhao, Rapp:
- Kinetic Theory Model
  - Rate Equation: dissociation + regeneration
  - Fireball model: T evolution.
    - $T_0 \sim 300$ MeV at RHIC
    - $T_0 \sim 600$ MeV at LHC

- All models have T_0 well above $T_c \sim$ 150-160 MeV

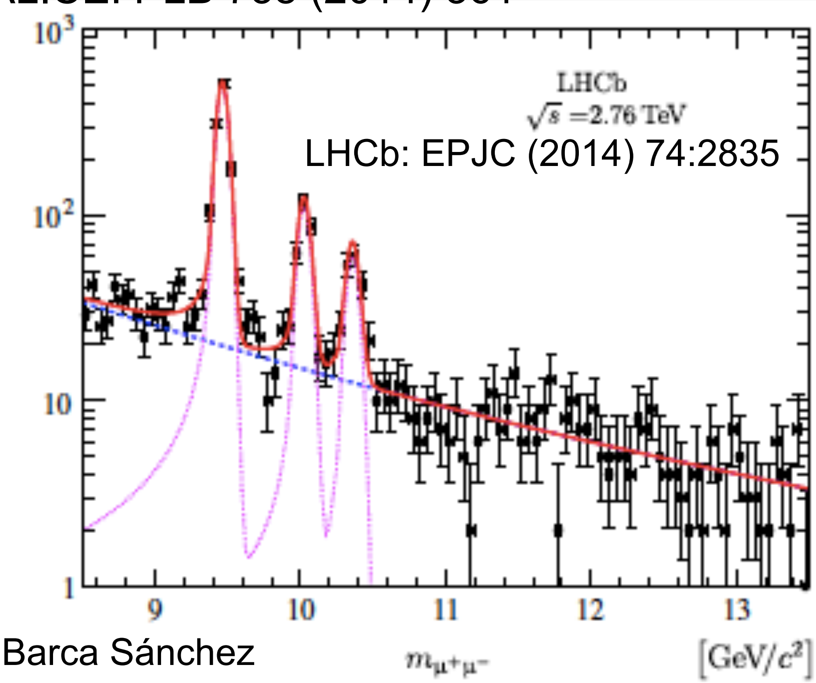


ALICE, LHCb: Υ R_{AA} forward

- 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
- pp Reference: LHCb
  - 2.0 < y < 4.5

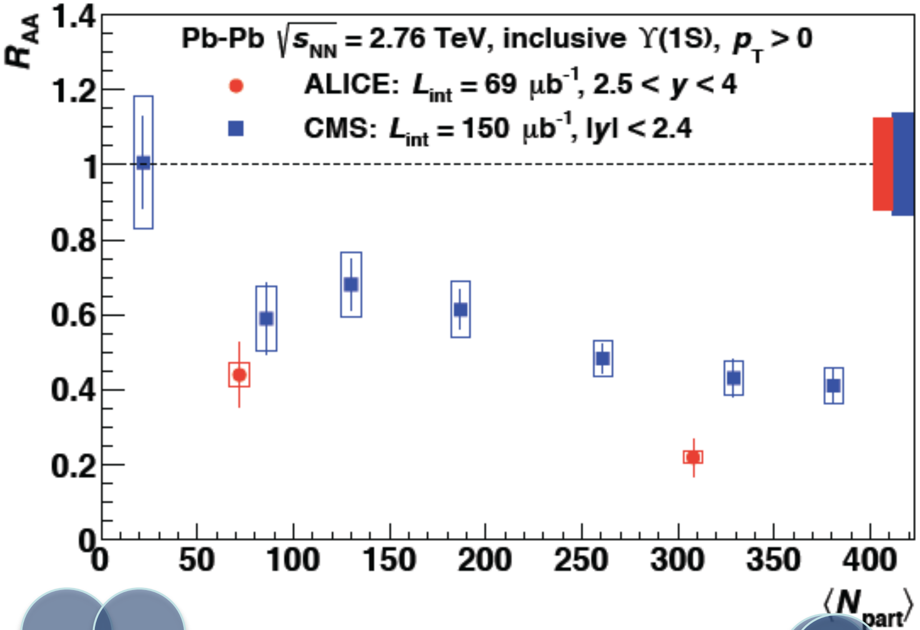


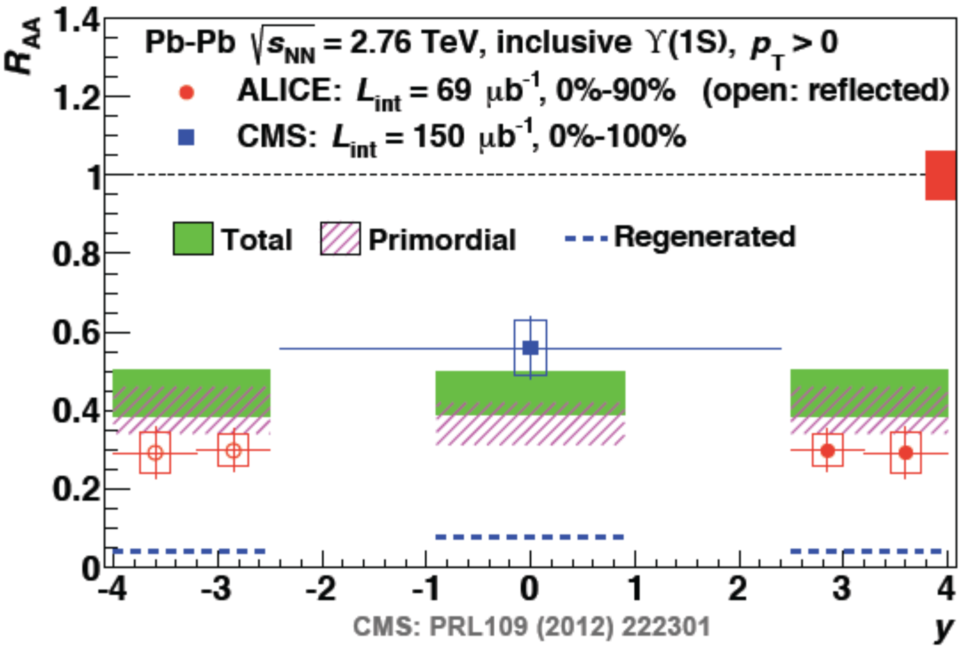
ALICE: PLB 738 (2014) 361



LHCb: EPJC (2014) 74:2835

Υ R_{AA} at forward y



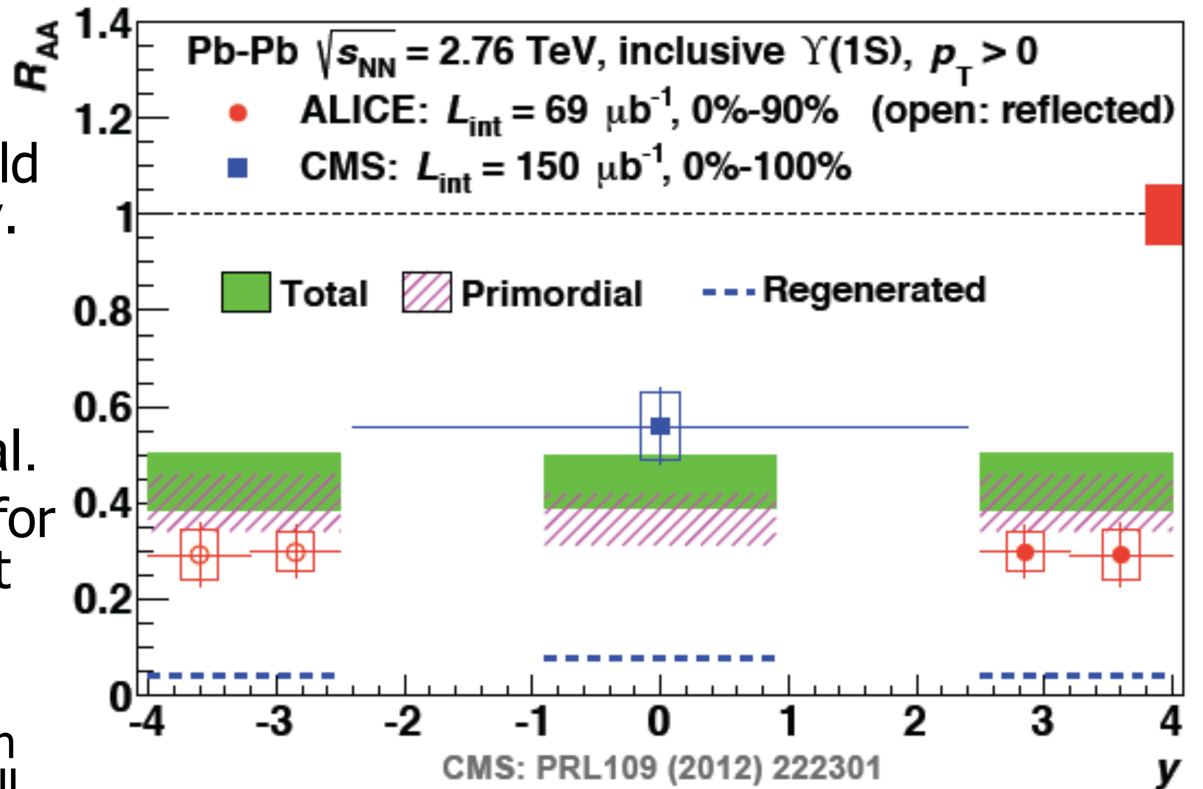


ALICE: PLB 738 (2014) 361

- Comparison between CMS and ALICE/LHCb
  - Υ R_{AA}: more suppression at forward rapidities!
    - Energy density, T should be smaller at forward y.
      - Argues for less suppression, not more.

Comparison to transport/regeneration

- More suppression at forward rapidity.
  - Energy density, T should be smaller at forward y.
    - Argues for less suppression, not more.
- Model from Emerick et al.
  - Model cannot account for stronger suppression at forward rapidity
    - Includes a regeneration component, albeit small
    - Includes absorption component

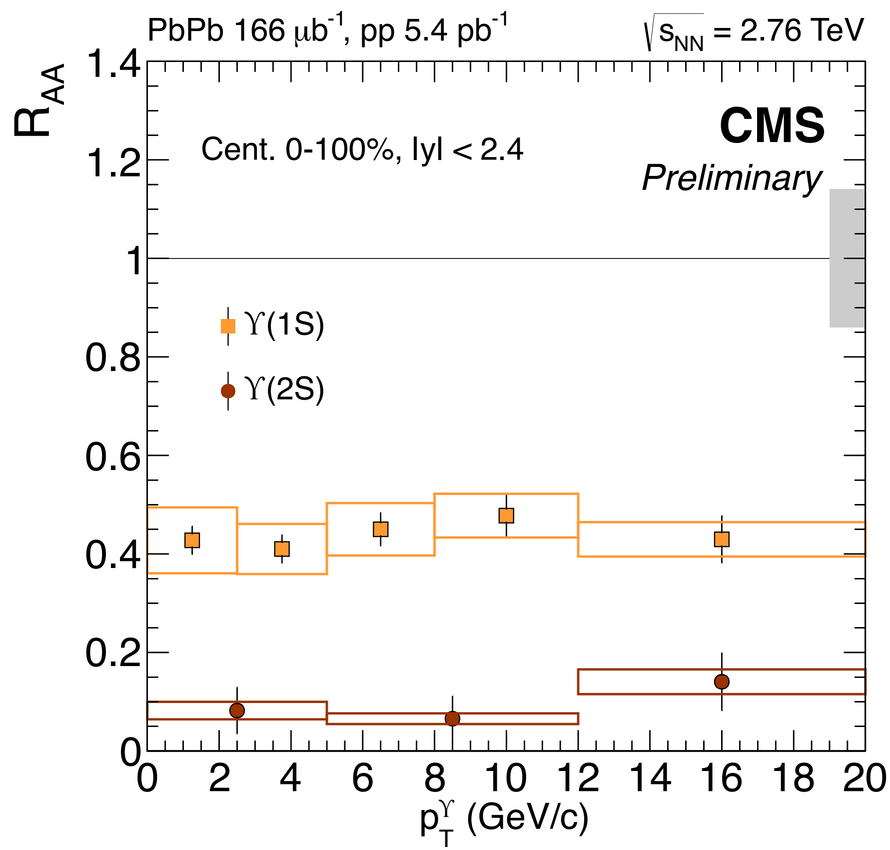


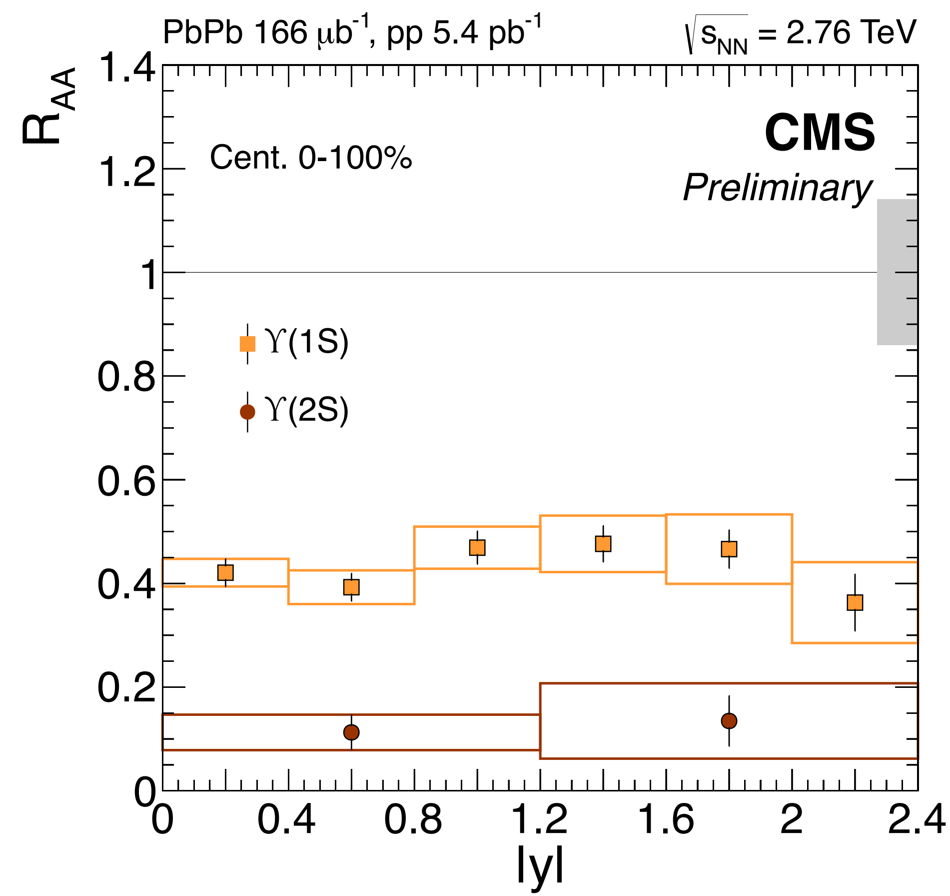
CMS: PRL109 (2012) 222301
ALICE: PLB 738 (2014) 361

CMS: Kinematic dependence of R_{AA}

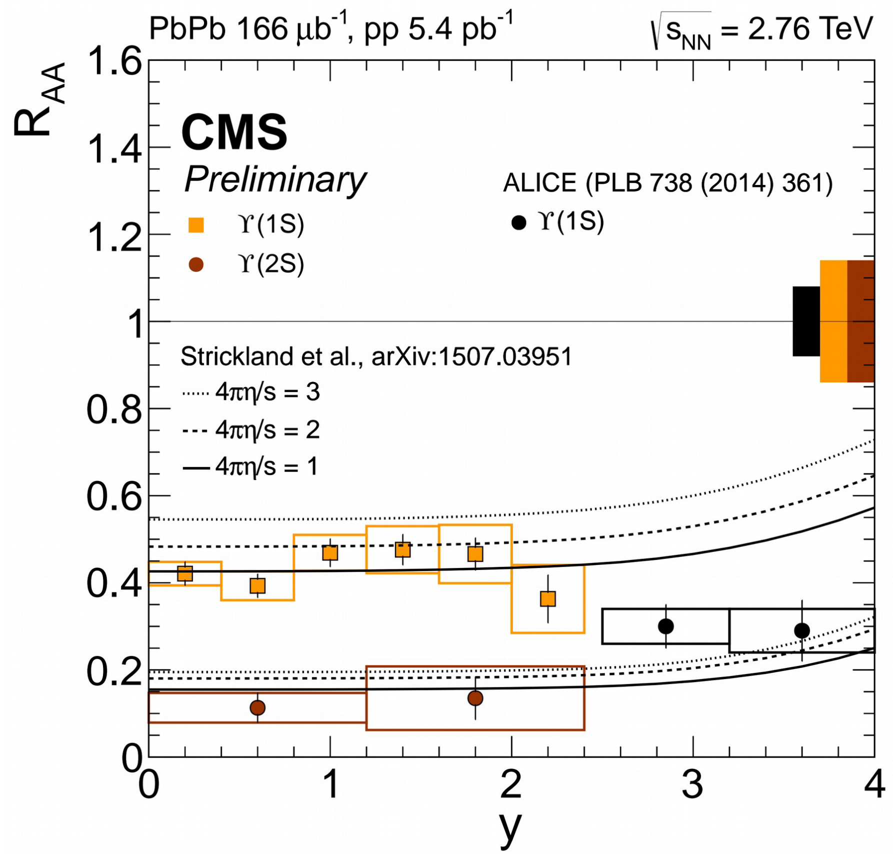
- Higher stats. for pp @ 2.76 allow finer bins in p_T and y

CMS HIN-15-001





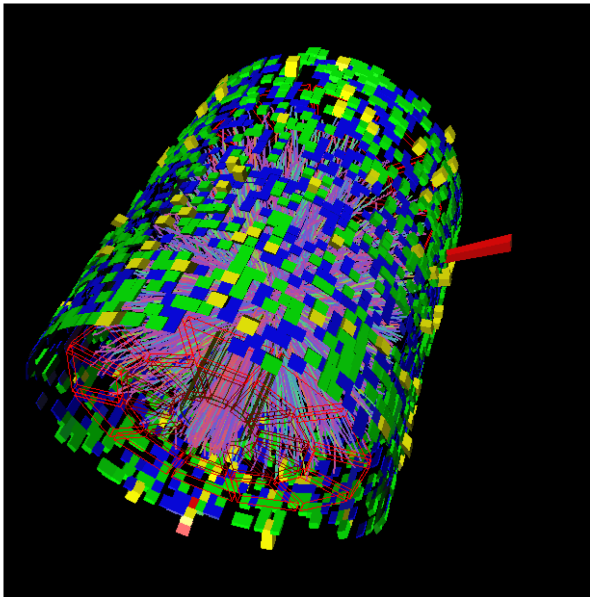
CMS and ALICE: Υ rapidity dependence

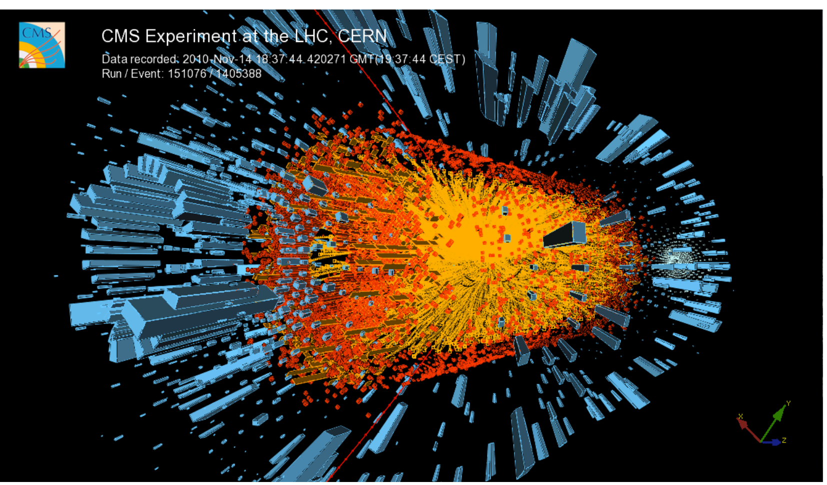


ALICE:
Phys. Lett. B 738 (2014) 361
CMS Preliminary:
CMS-PAS-HIN-15-001

- CMS and ALICE data are consistent near their acceptance limits.
  - Observe a flat or falling rapidity dependence of Upsilon suppression.
- Comparison to Strickland & Bazow model, with Re & Im V(T) + hydro:
  - R_{AA} increases at forward rapidities. (Lower energy density/Temperature)

The bottom line...





- pA collisions:
  - Modifications of production compared to pp observed.
  - Shadowing effects, E.Loss.
    - But not consistent with all data
      - dAu RHIC, LHCb vs. ALICE pPb.
- AA collisions:
  - Large suppression of Upsilon production seen.
  - Need quantitative comparisons pA vs. AA to shed disentangle hot vs. cold nuclear matter.
    - Rapidity dependence: not expected.
  - Goal: Pinning down the medium properties, e.g. Temperature.

Results/References

- Fermilab
  - E772, pA: PRL 66 (1991) 2285
- RHIC
  - STAR, pp, dAu, AuAu: PLB 735 (2014) 127
  - PHENIX: PRC 87, 044909 (2013)
- LHC
  - LHCb, pPb: JHEP 07 (2014) 094
  - ATLAS pPb: ATLAS-CONF-2015-050
  - ALICE pPb: PLB 740 (2015) 105
  - CMS pPb: JHEP 04 103 (2014)

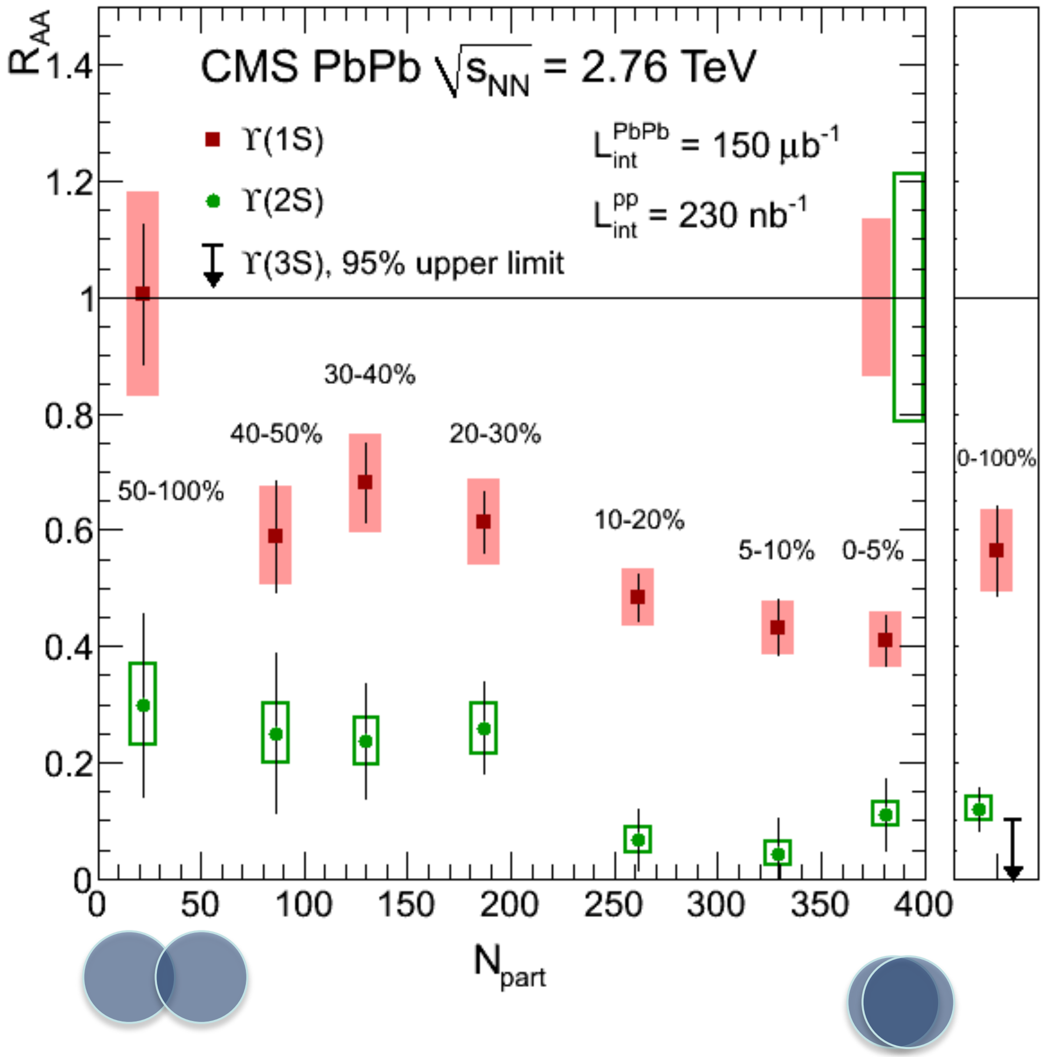
  - ALICE PbPb: PLB 738 (2014) 361
  - CMS PbPb: PRL 109 222301 (2012)

Backup

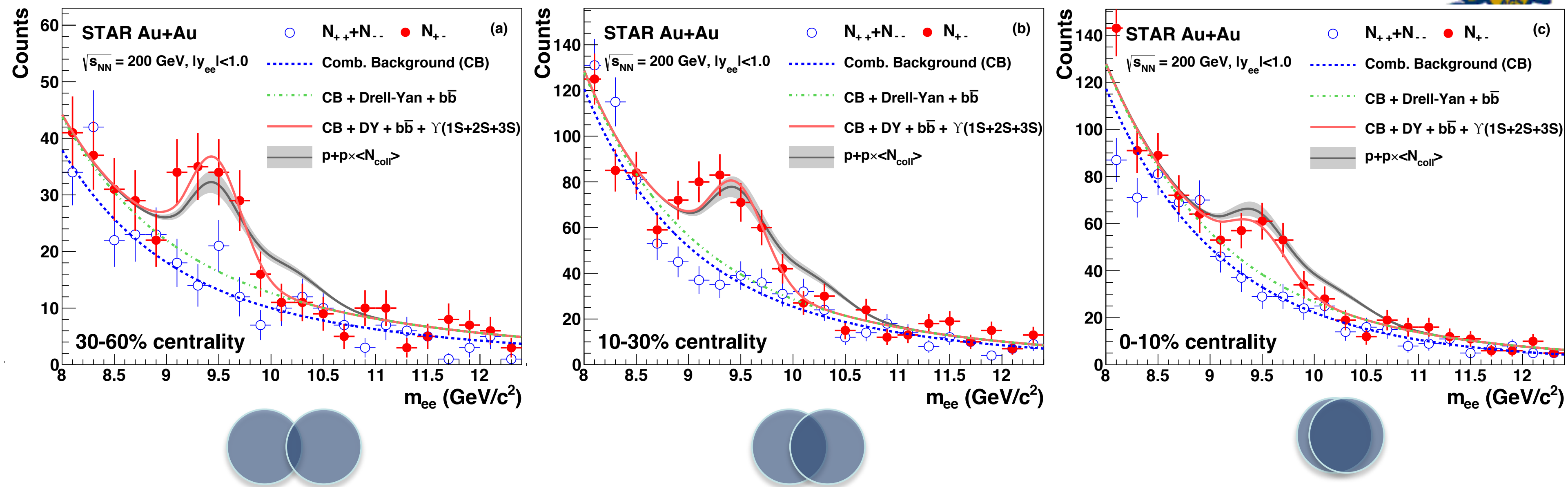
CMS Υ R_{AA} vs. Centrality

- 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

PRL 109 222301 (2012)



Υ in STAR, AuAu

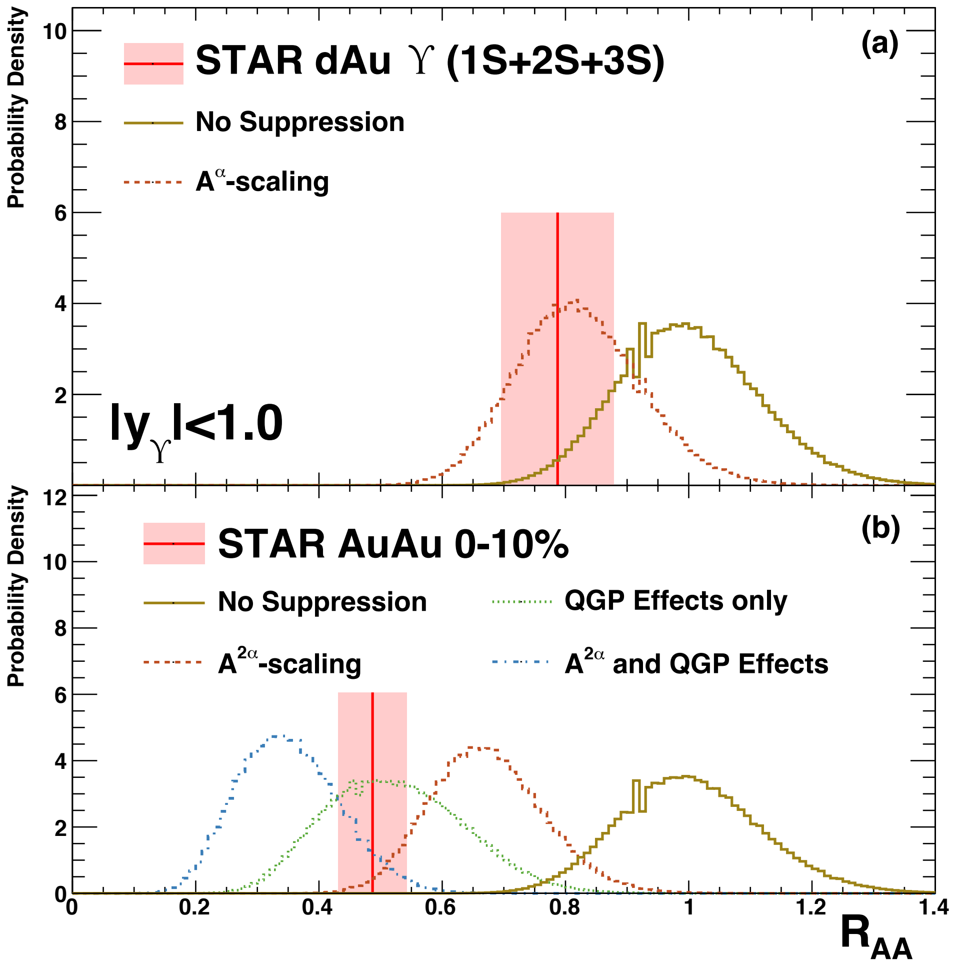


STAR: PLB 735 (2014) 127

- Invariant mass distributions in 3 centrality bins
- Comparison to N_{coll}-scaled pp reference:
  - Clear suppression of excited states.
    - Report results for sum of 3 states, and for ground state.

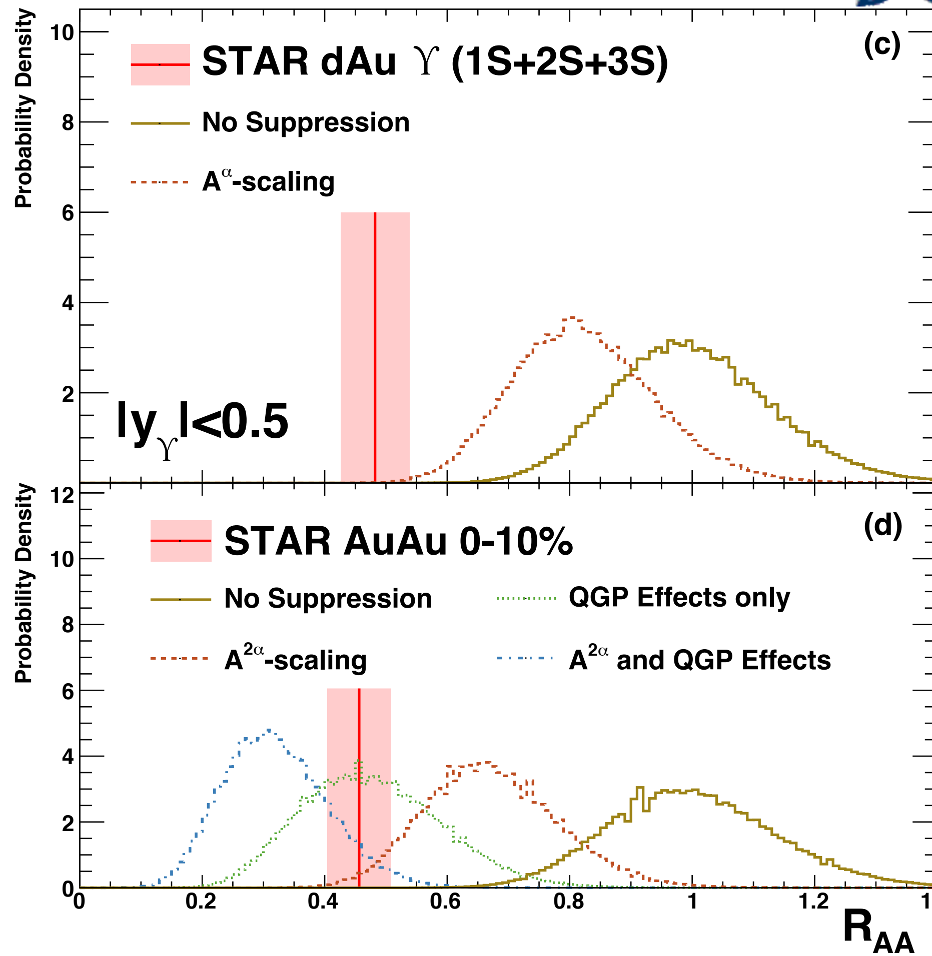
STAR Hypothesis testing, |y|<1

- 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)
      - As seen by E776 at Fermilab
      - $A^{2\alpha}$ 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.

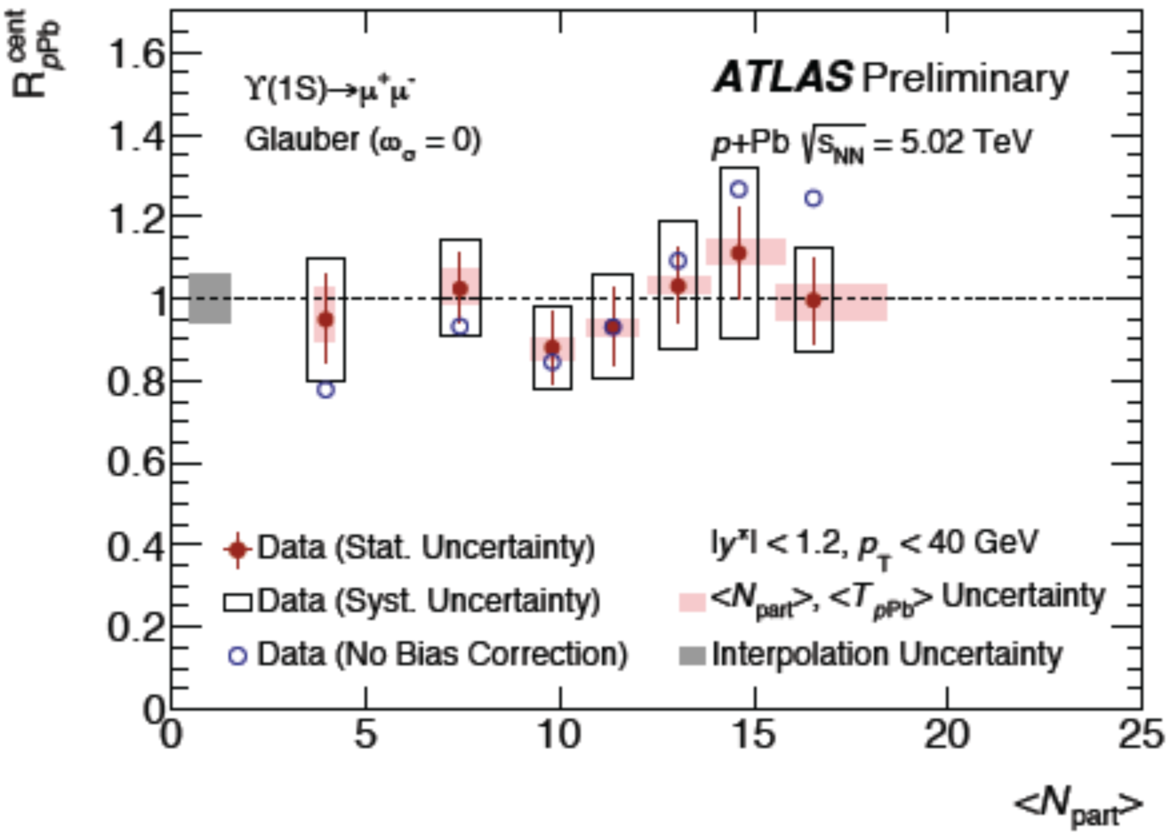


STAR Hypothesis testing, |y|<0.5

- 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: |y|<0.5 shows large suppression in dAu.
  - Comparable to central AuAu!
  - No particular scenario is favored.
    - pAu run at RHIC from 2015, stay tuned!



ATLAS, RpPb Υ(1S) vs. N_{part}

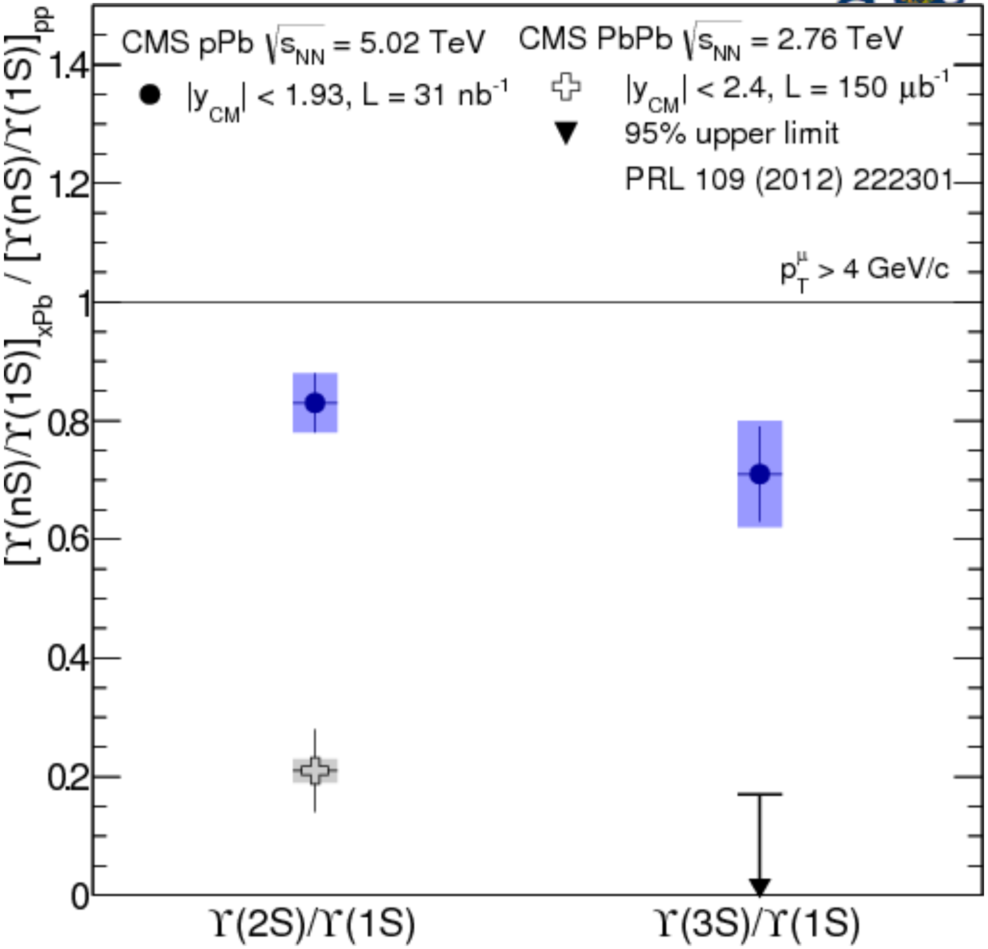


- Υ(1S): No modification seen vs. N_{part} in pPb.
- ATLAS and ALICE do a “bias correction”.

Υ Double ratio, pPb and pp

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

- Key feature of double ratio:
  - All initial-state effects should cancel
    - e.g. shadowing modifies 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



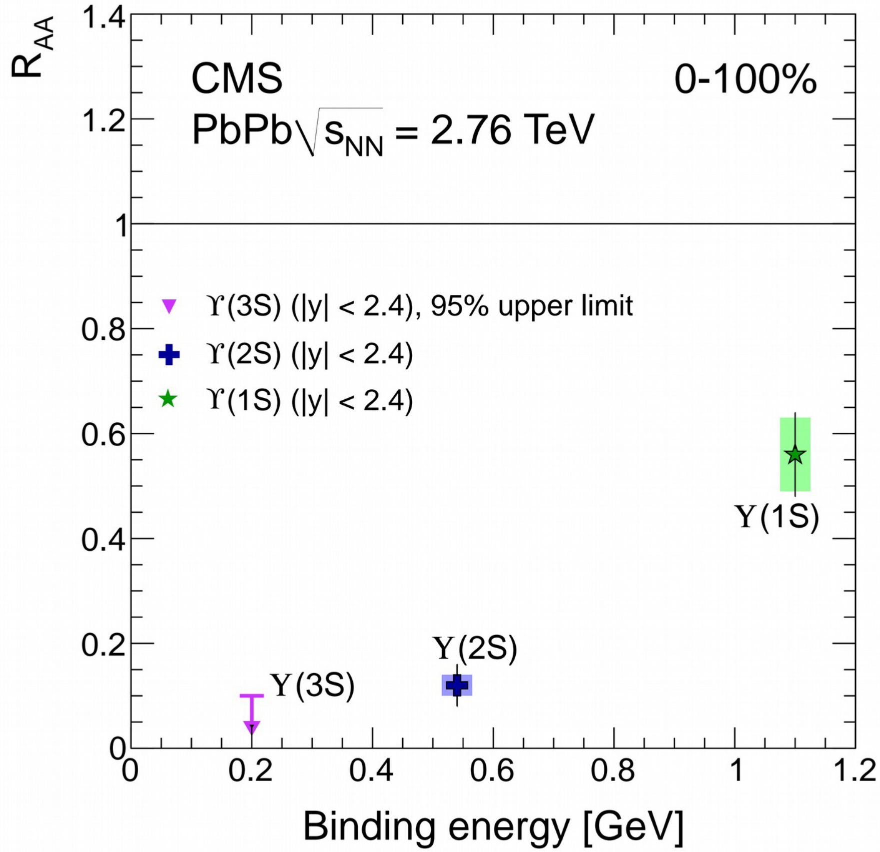
Expect small Υ absorption in hadronic matter

Lin & Ko, PLB 503 (2001) 104

But absorption depends on radius:

Larger absorption for 2S and 3S

ϒ Summary plot vs. binding energy



- Overall pattern of sequential suppression is observed.
  - But there are important details that indicate additional physics...