The 9th International Workshop on Heavy Quarkonium 2013 (Quarkonium 2013), IHEP, Beijing, China, 22-26 April, 2013

Υ(nS) Sequential Melting in Pb-Pb Collisions in CMS

Byungsik Hong
(Korea University)

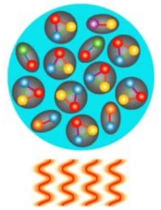
On behalf of the CMS Collaboration

Outline

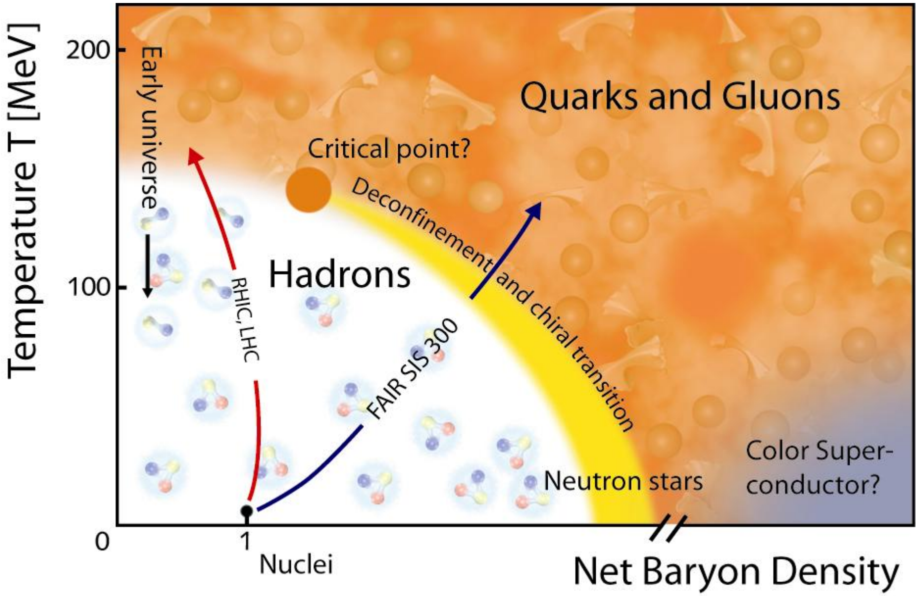
1. Introduction
   – Importance of quarkonia in heavy-ion collisions
   – Data-taking history for heavy-ion study in CMS
2. Experimental data at $\sqrt{s_{NN}}$=2.76 TeV
   – Υ(2S) & Υ(3S) suppressions relative to Υ(1S) in PbPb
   – Υ(nS) suppression in PbPb with respect to pp
   – Comparison to models
3. Summary

Introduction

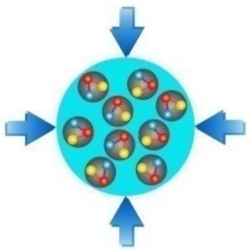
- Quark-gluon plasma (QGP)
  - Primordial matter existed a few μs after the Big Bang
  - $T \geq 170$ MeV, $\varepsilon_0 \geq 1$ GeV/fm^3
  - Critical to understand QCD at extreme conditions and nuclear phase diagram



Colliders
LHC/RHIC



Fixed Target
SIS100/300



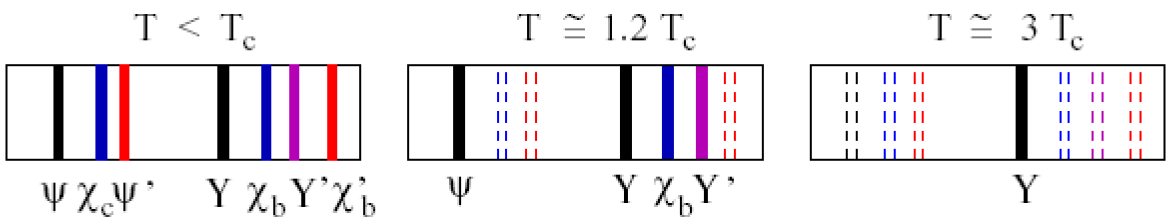
Quarkonium in Heavy Ions

- Powerful tool to probe QGP
  - Large mass: a large momentum transfer is required in hard gg scattering at early stage
  - Color Debye screening: various quarkonium states with different binding energies melt at different temperatures (Thermometer)

[Matsui & Satz, PLB 178, 416 (1986)]

State	J/ψ (1S)	χ_c (1P)	ψ' (2S)
m (GeV/c^2)	3.10	3.53	3.68
r_0 (fm)	0.50	0.72	0.90

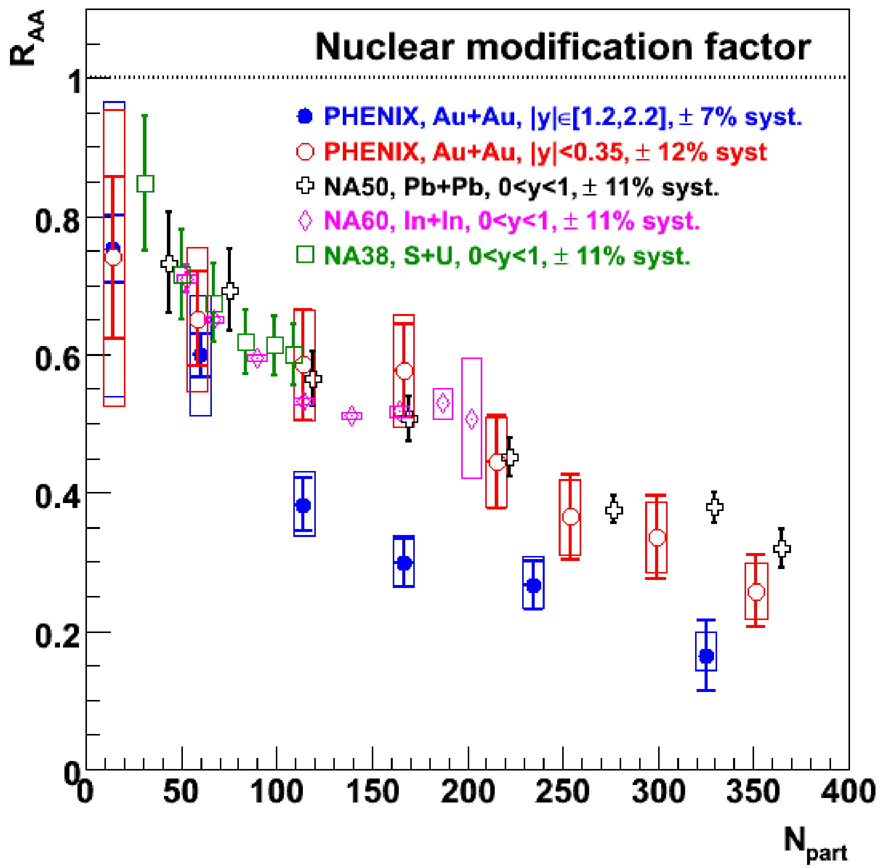
Υ (1S)	χ_b (1P)	Υ' (2S)	χ_b' (2P)	Υ'' (3S)
9.46	9.99	10.02	10.26	10.36
0.28	0.44	0.56	0.68	0.78



J/ψ at Lower Energies

- Two puzzles
  1) At mid-rapidity, similar suppression at RHIC & SPS (200 vs. 17 GeV), while density must be higher at RHIC.
  2) More suppression at forward rapidity where density must be lower.
- Possible explanations
  1) Cold: shadowing, saturation brings the forward yield down.
  2) Hot: recombination of uncorrelated $c\bar{c}$ brings the mid-rapidity yield up.

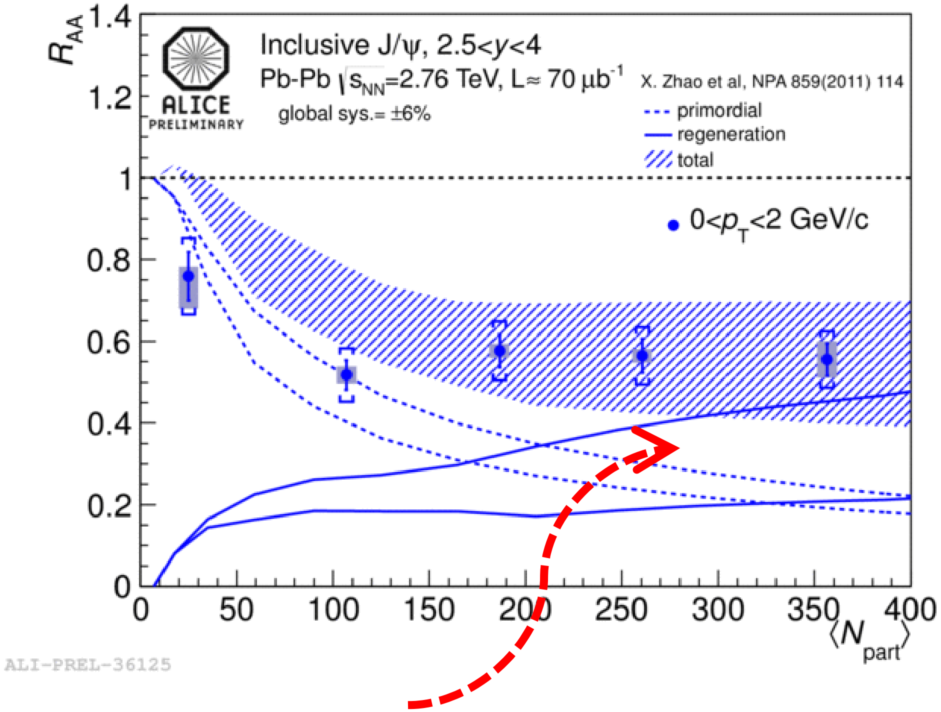
$$R_{AA}(p_T) = \frac{d^2N_{AA}/dp_T d\eta}{< T_{AA} > d^2\sigma_{NN}/dp_T d\eta}$$



Υ vs. J/Ψ at LHC

ALICE, PRL 109, 072301 (2012)

(p_T > 0 GeV, 2.5 < y < 4)



- Recombination is significant for J/ψ at low p_T.

- Recombination is much smaller for Υ than J/ψ
  - $\sigma_{b\bar{b}}/\sigma_{c\bar{c}} \cong 1/20$
    $\sigma_{c\bar{c}} = 6.10 \pm 0.93$ mb
    in pp at 7 TeV

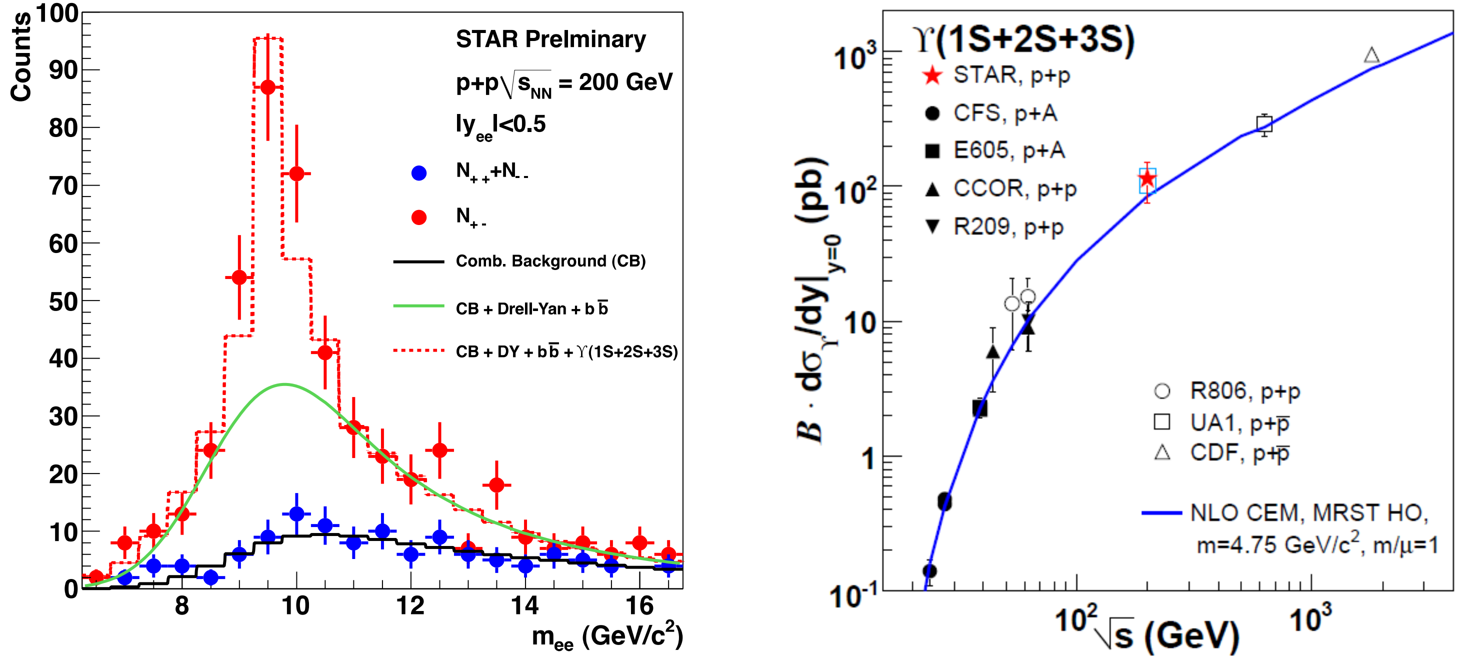
    [LHCb-CONF-2010-013]

- Co-mover absorption effect is smaller for Υ than J/ψ
  - $\sigma_{h-\Upsilon}$ is expected to be significantly (~5-10 times) smaller than $\sigma_{h-J/\psi}$
  - Absorption cross section $\sigma_{h-\Upsilon}$ ~ 0.2 mb at 150 MeV

    [Lin & Ko, PLB 503, 104 (2001)]

Υ at Lower Energy

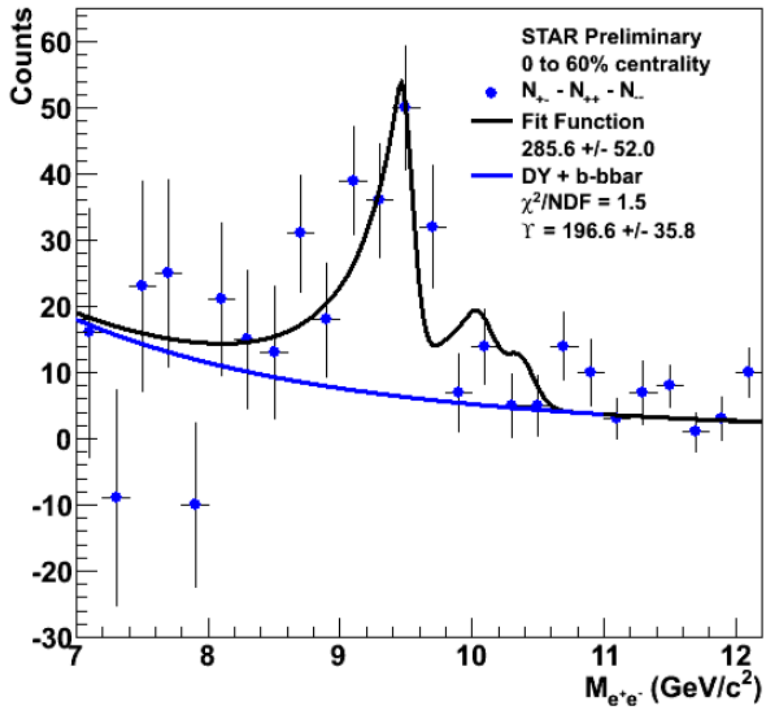
- Recent pp data at 200 GeV by dielectron channel at |y| < 0.5
- Consistent with the CEM calculations and world data trend



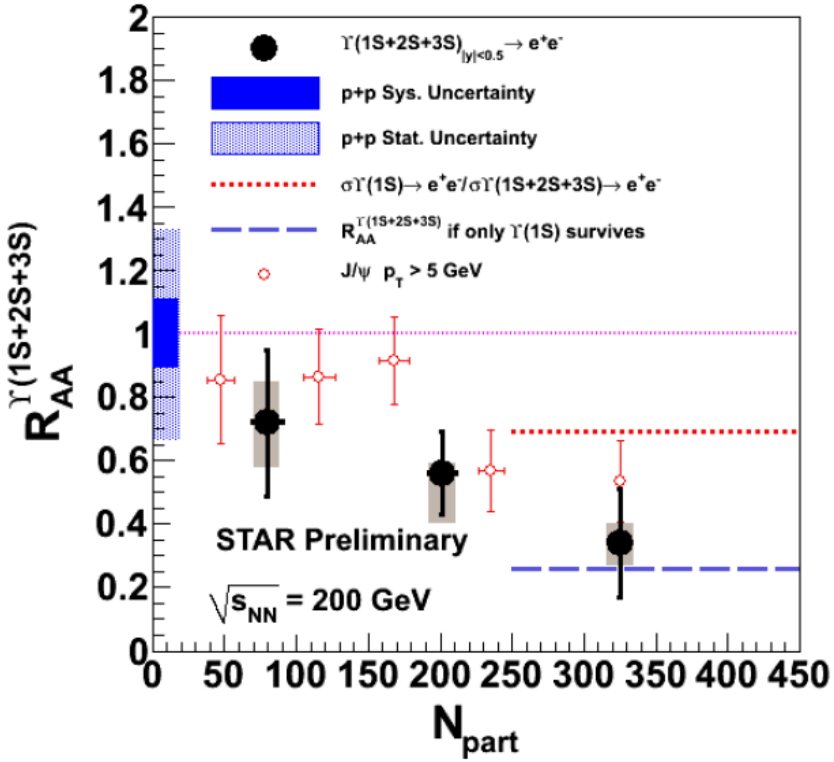
- Recent preliminary data presented by Manuel Calderon de la Barca Sanchez, 5th International Workshop on Heavy Quark Production in Heavy Ion Collisions (2012)
- Old data: PRD 82, 12004 (2010)

Υ at Lower Energy

First Υ data in AuAu from STAR,
arXiv:1109.3891



- Stronger suppression of Υ(1S+2S+3S) for more central collisions



To be compared with CMS data

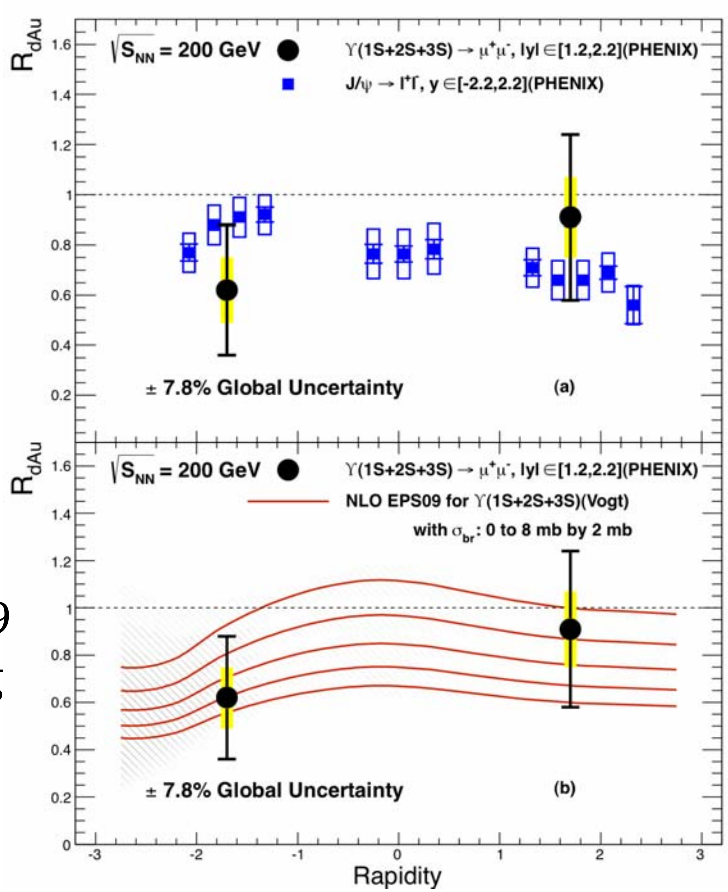
Υ at Lower Energy

pp and dAu at 200 GeV by dimuon channel (1.2<|y|<2.2)

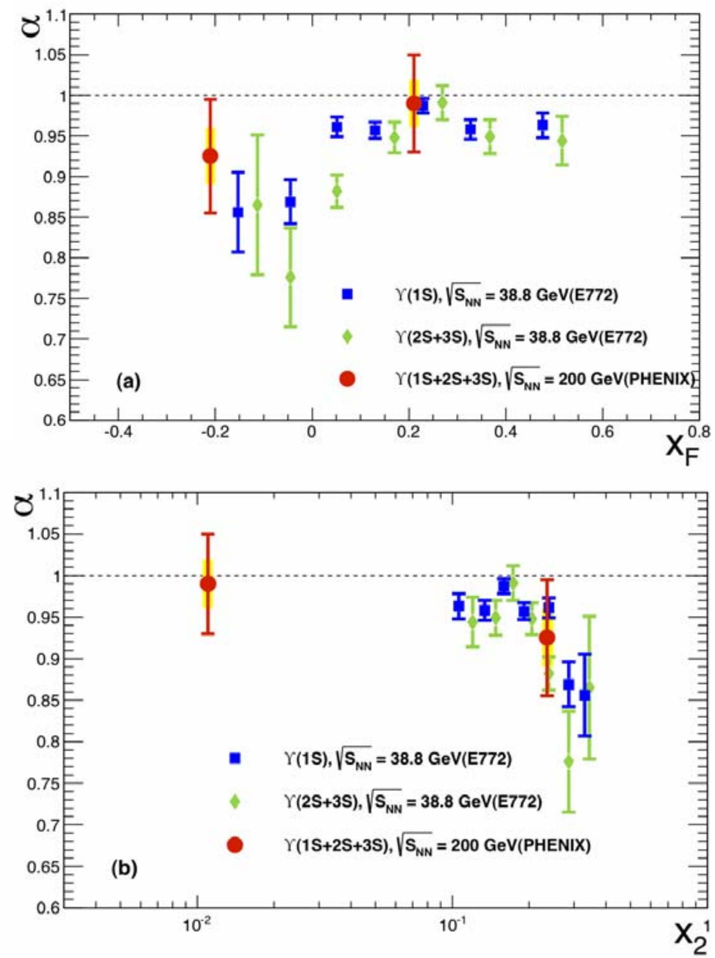
$\sigma_{\Upsilon}^{dAu} = \sigma_{\Upsilon}^{pp} \cdot (2A_{Au})^{\alpha}$

200 GeV vs. 38.8 GeV

Υ(1S+2S+3S) vs. J/ψ



Lines:
NLO EPS09 shadowing
$\sigma_{breakup} = 0\sim8$ mb

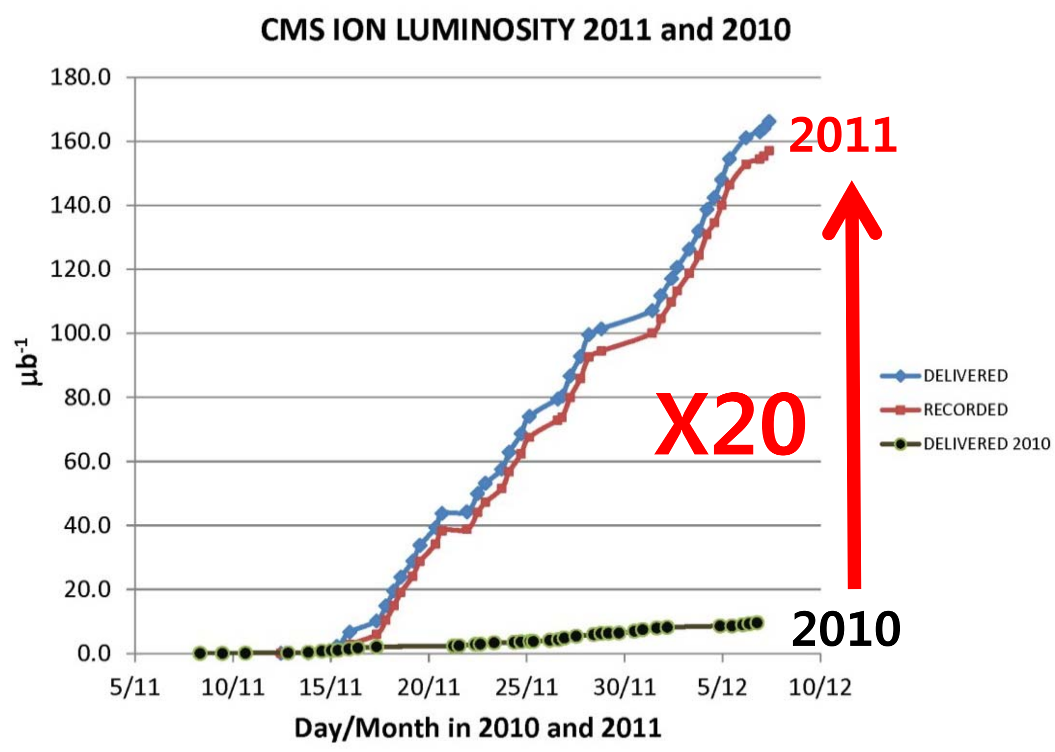


arXiv:1211.4017

Heavy-Ion Runs at LHC

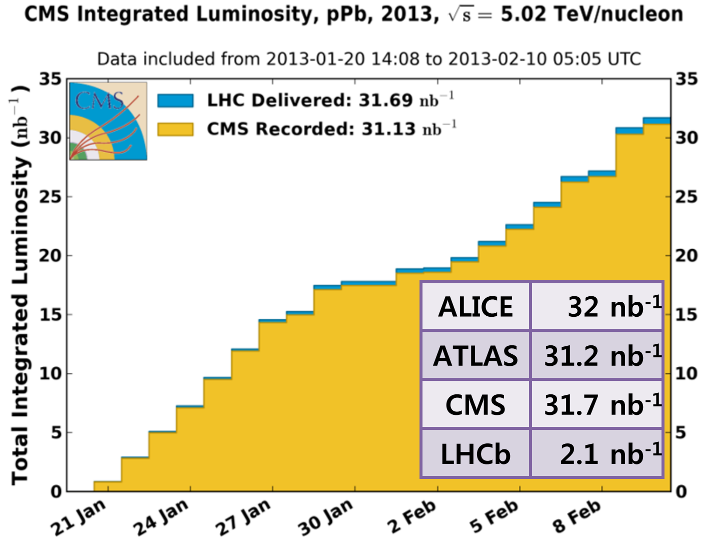
- 1st PbPb run @ $\sqrt{s_{NN}}$ = 2.76 TeV
  - November-December 2010
  - Recorded luminosity: 7.28 μb^{-1}

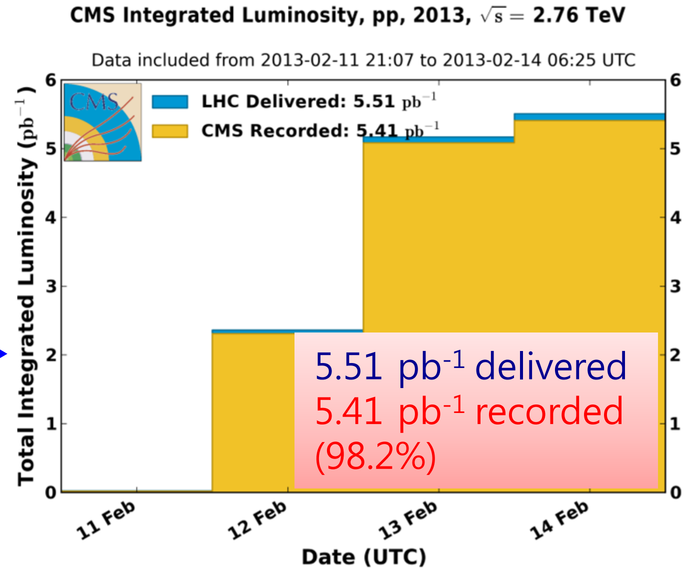
- 2nd PbPb run @ $\sqrt{s_{NN}}$ = 2.76 TeV
  - Nov.-Dec. 2011
  - Recorded luminosity: 150 μb^{-1}
    About 20 times more statistics than 2010 during similar beamtime



pp and pPb Runs at LHC

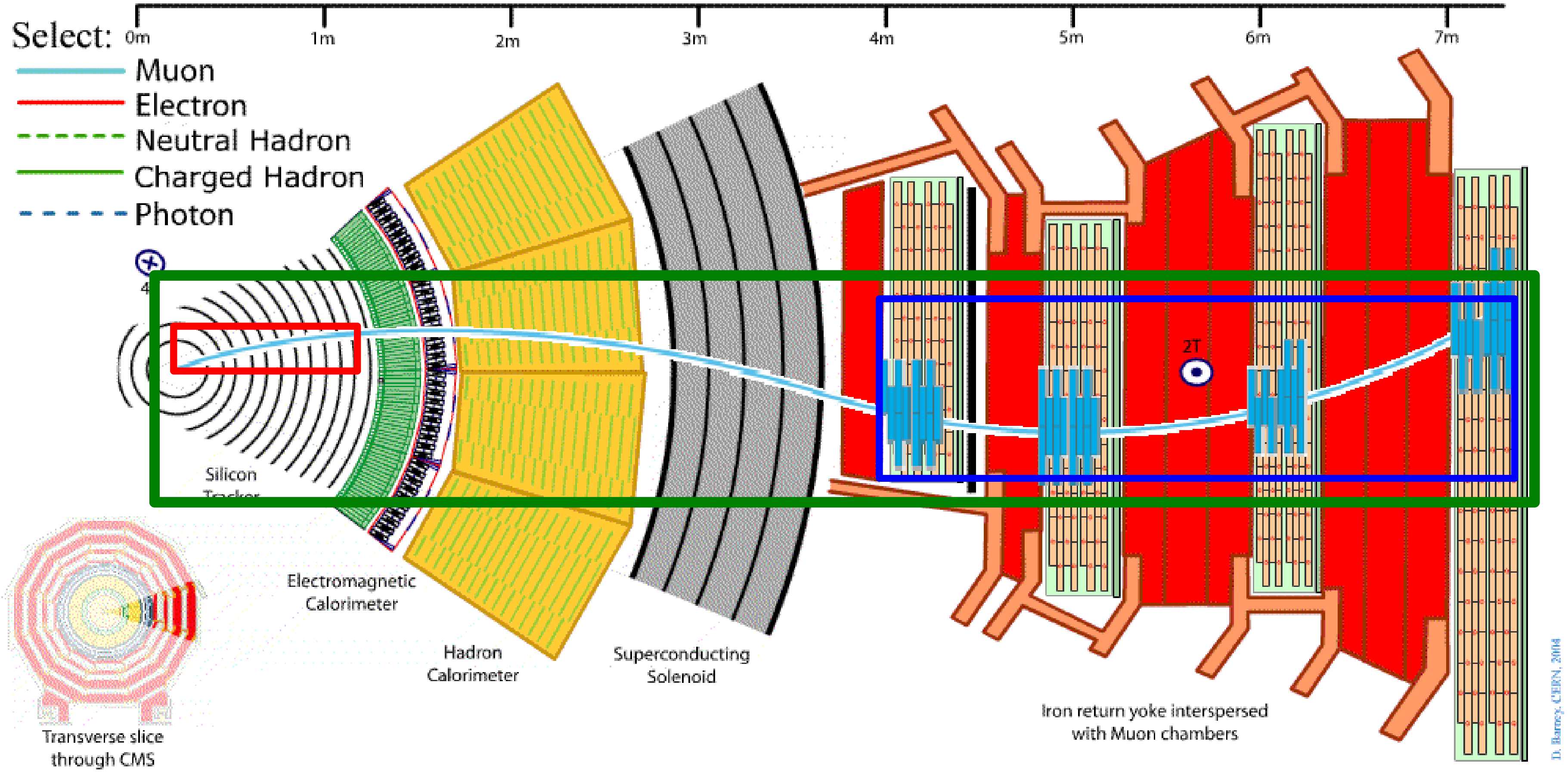
- 1^{st} pp run @ $\sqrt{s_{NN}}$ = 2.76 TeV
  - March 2011 (~1 week)
  - Rec. luminosity: 225 nb^{-1}
    - Equivalent to the number of hard probes in 2010 PbPb data
- pPb run @ $\sqrt{s_{NN}}$ = 5.02 TeV
  - January - February 2013
  - Rec. luminosity: 31.7 nb^{-1}
  - Cold nuclear matter effect
- 2^{nd} pp run @ $\sqrt{s_{NN}}$ = 2.76 TeV
  - February 2013 (3 days)
  - Rec. luminosity: 5.41 pb^{-1}
    About 24 times more statistics than the first pp run





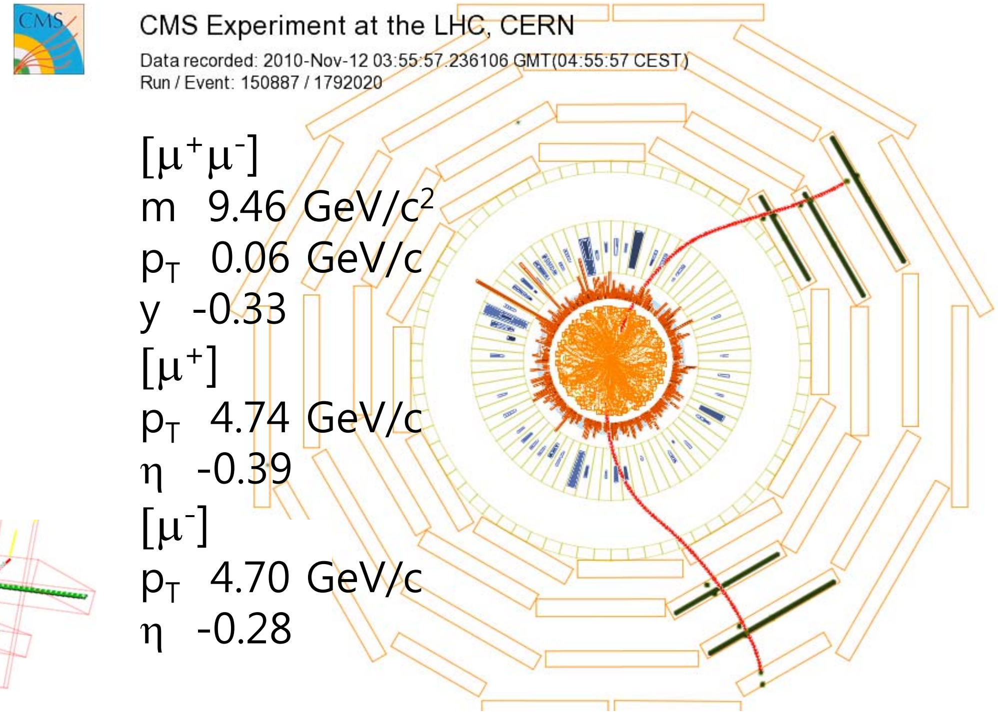
Muons in CMS

- Excellent muon ID and triggering in the muon system
- Excellent momentum resolution in tracker (overall ~1-2%)
- Global muons = Standalone muons x Tracker information

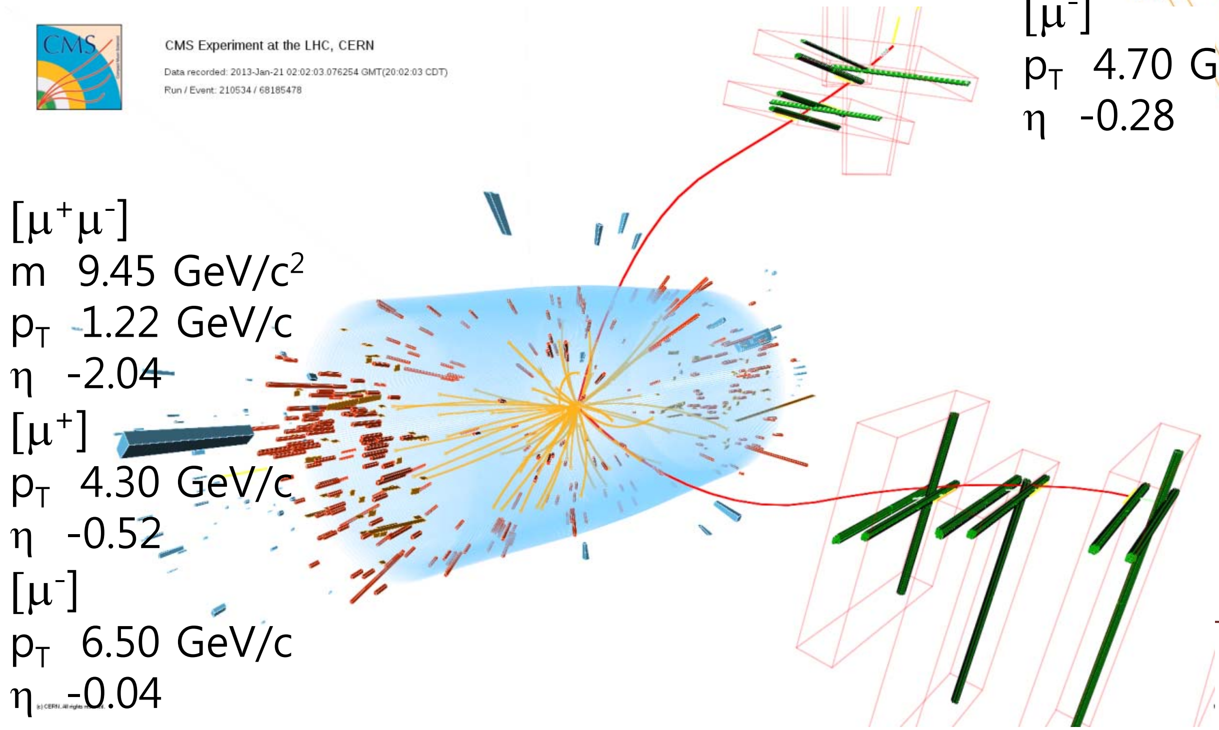


Υ(1S) Candidates in PbPb & pPb

PbPb



[$\mu^+\mu^-$]
m 9.46 GeV/c^2
p_T 0.06 GeV/c
y -0.33
[μ^+]
p_T 4.74 GeV/c
η -0.39
[μ^-]
p_T 4.70 GeV/c
η -0.28

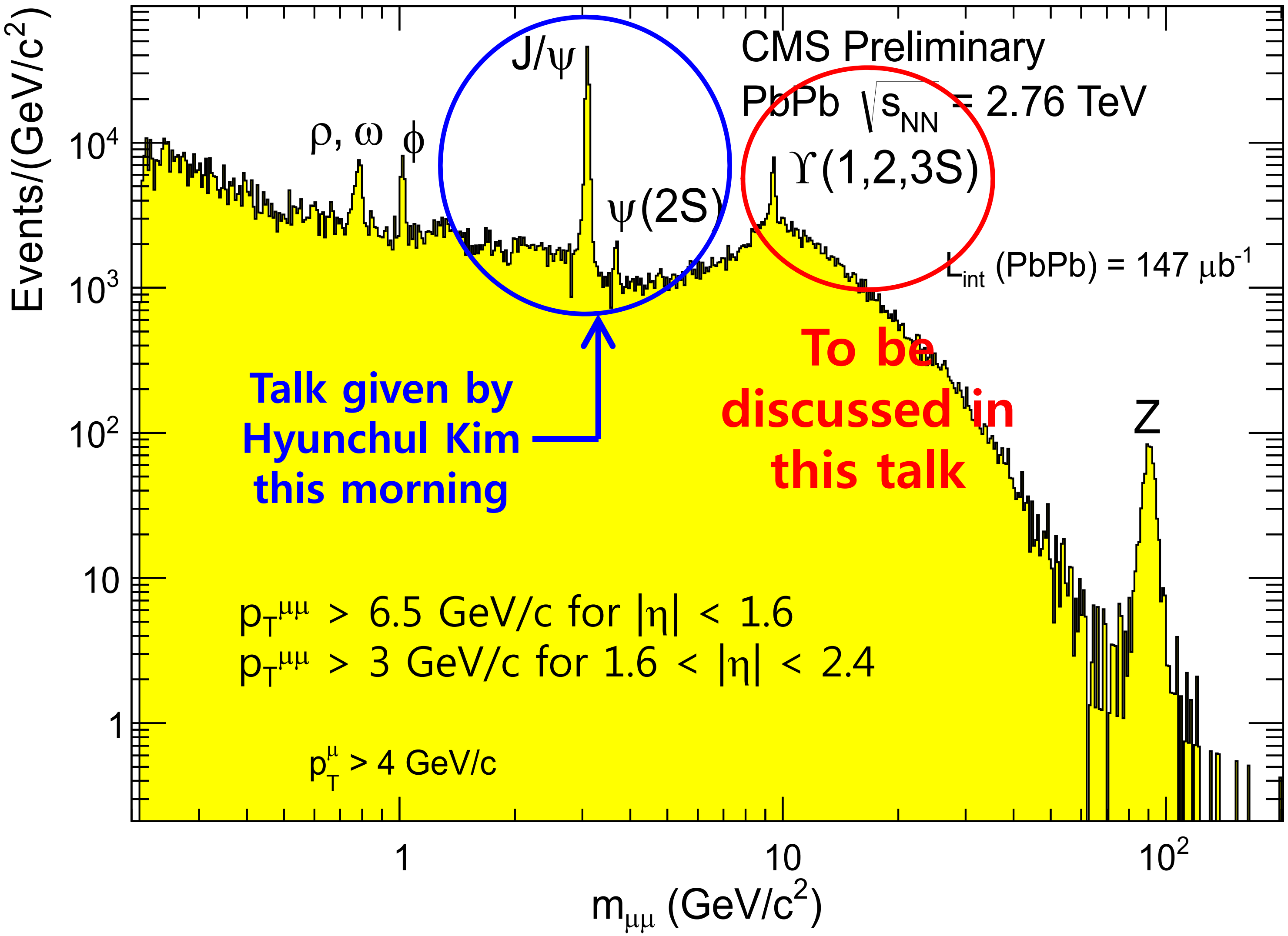


[$\mu^+\mu^-$]
m 9.45 GeV/c^2
p_T 1.22 GeV/c
η -2.04
[μ^+]
p_T 4.30 GeV/c
η -0.52
[μ^-]
p_T 6.50 GeV/c
η -0.04

pPb

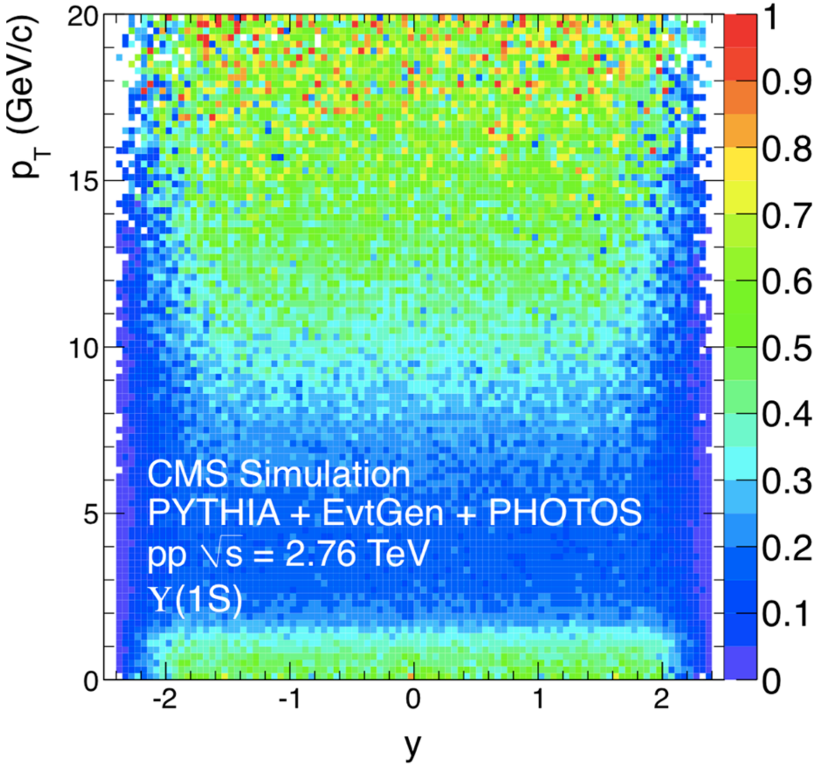
CMS DP-2013-001

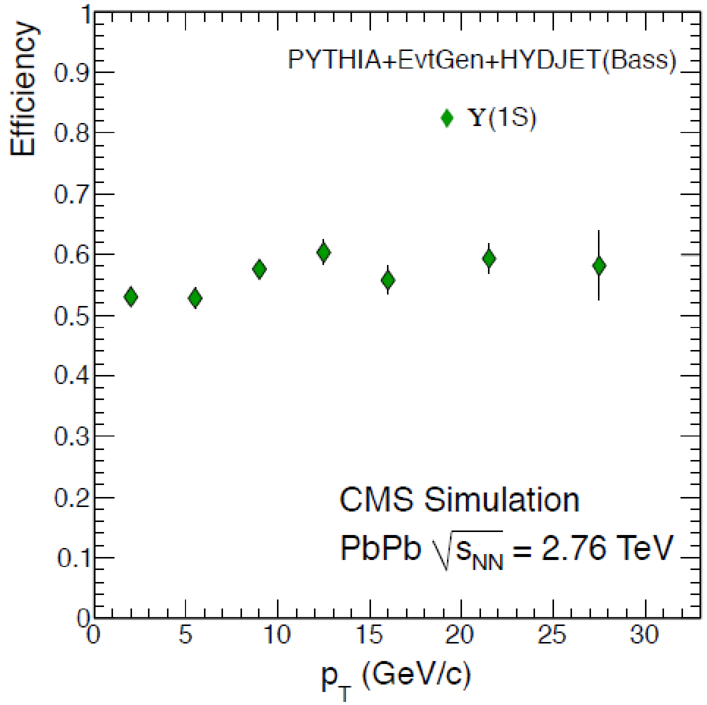
$\mu^-\mu^+$ Invariant Mass in 2011



Acceptance & Efficiency for Υ(1S)

- Acceptance
  $p_T > 0$ for $|y| < 2.4$

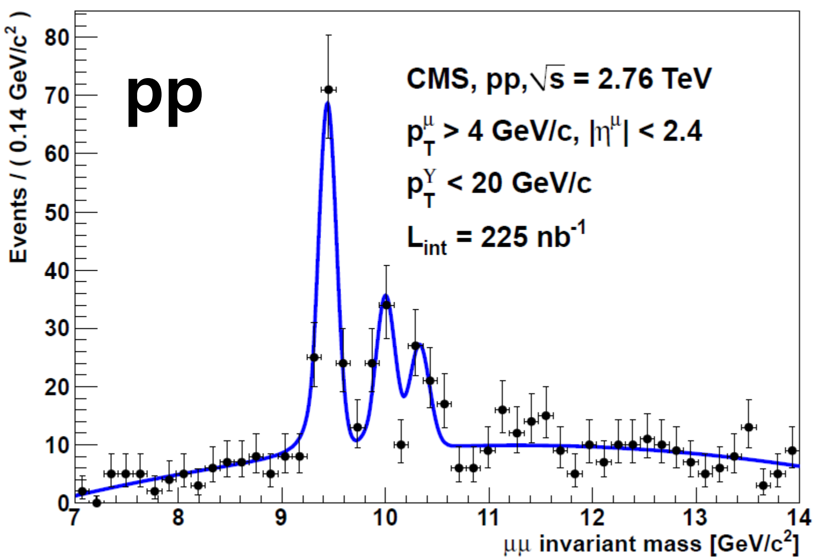


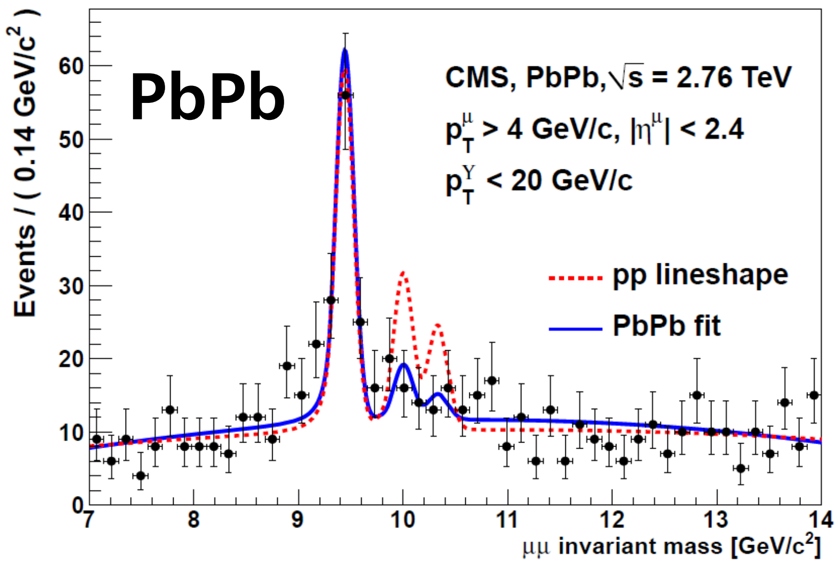


- Efficiency
  - Estimated from MC
  - Validated by data driven method (Tag & Probe)

Υ(2S+3S) Suppression in 2010

PRL 107, 052302 (2011), PbPb MinBias, L_{int} = 7.28 μb[-1]



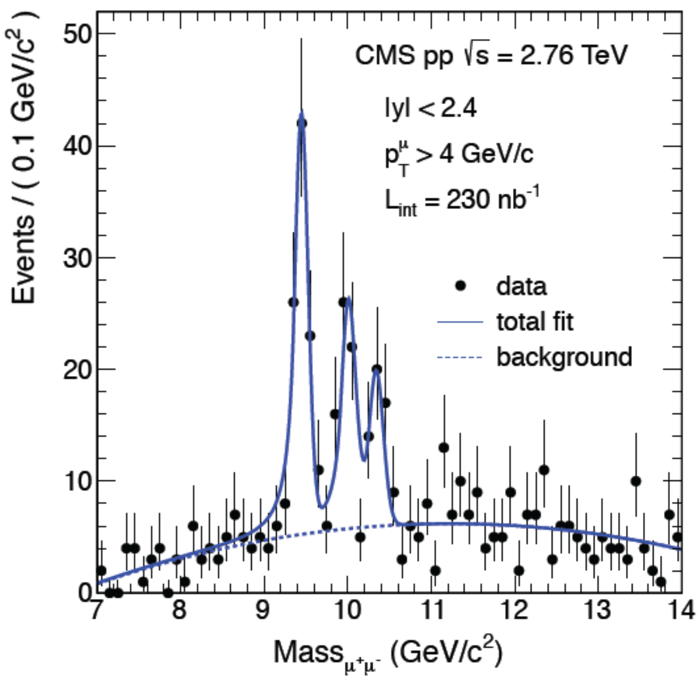


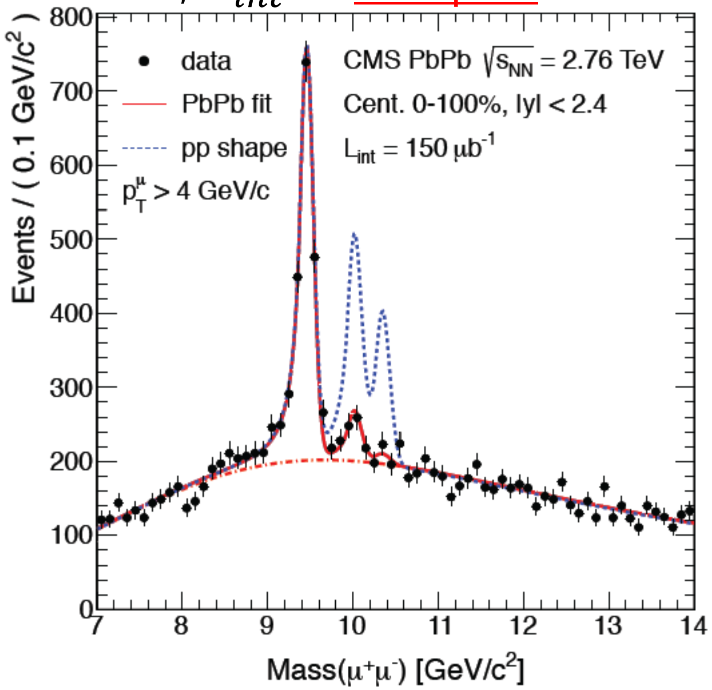
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Probability to obtain the measured value, or lower, from the background fluctuation is 0.9% (2.4σ effect)

Υ(2S+3S) Suppression in 2011

PRL 109, 222301 (2012), PbPb MinBias, L_{int} = 150 μb^{-1}





$\Upsilon(2S)/\Upsilon(1S)\,|_{pp} = 0.56 \pm 0.13 \pm 0.02$

$\Upsilon(3S)/\Upsilon(1S)\,|_{pp} = 0.41 \pm 0.11 \pm 0.04$

$\Upsilon(2S)/\Upsilon(1S)\,|_{PbPb} = 0.12 \pm 0.03 \pm 0.02$

$\Upsilon(3S)/\Upsilon(1S)\,|_{PbPb} = 0.02 \pm 0.02 \pm 0.02$

(< 0.07 at 95% CL)

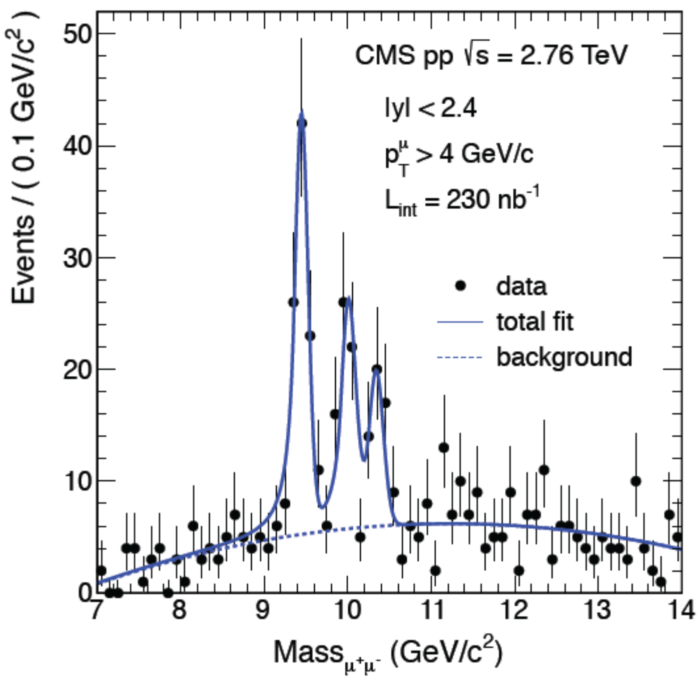
Ratios not corrected for acceptance and efficiency

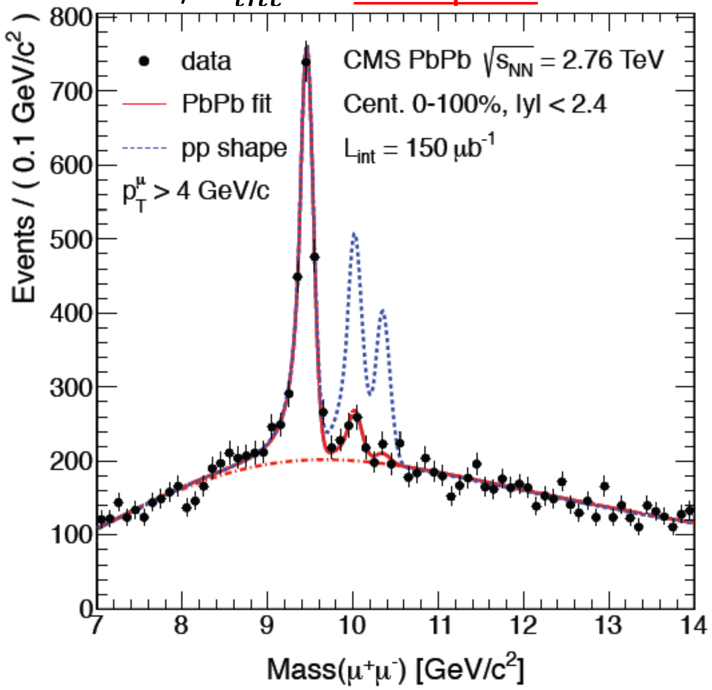
	pp	PbPb
$\Upsilon(1S)$	88±11	1317±73
$\Upsilon(2S)$	49±10	156±38

◀ Limited by pp statistics! Large statistics 2013 pp data available

Υ(2S+3S) Suppression in 2011

PRL 109, 222301 (2012), PbPb MinBias, L_{int} = 150 μb^{-1}



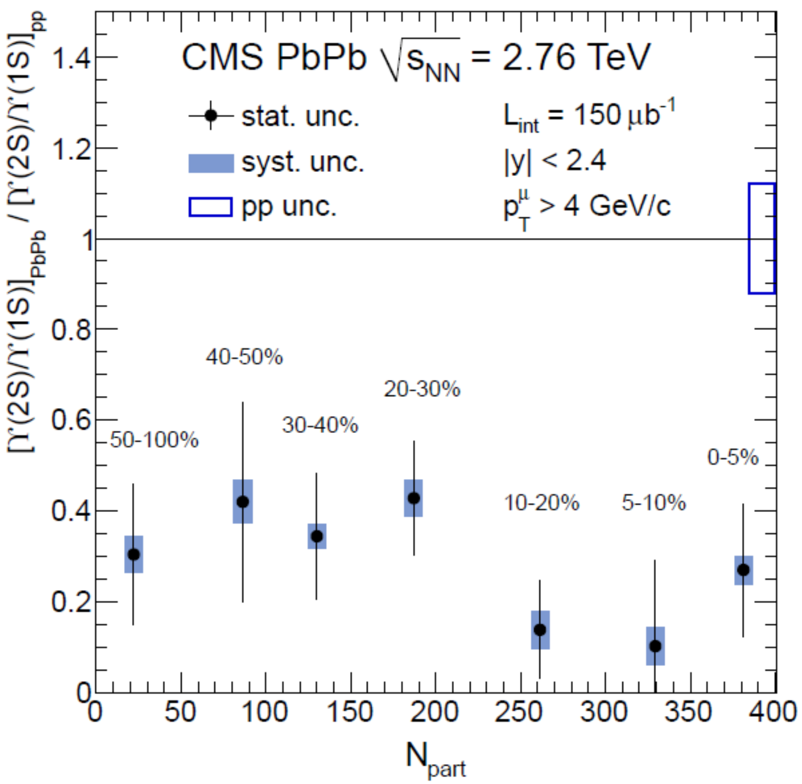


$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.15 \pm 0.05 \pm 0.03$$

- Observation of Υ(2S+3S) relative suppression (>5σ effect)

Υ(2S) and Υ(3S) Suppressions

PRL 109, 222301 (2012)



- Centrality integrated

$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07 \pm 0.02$$

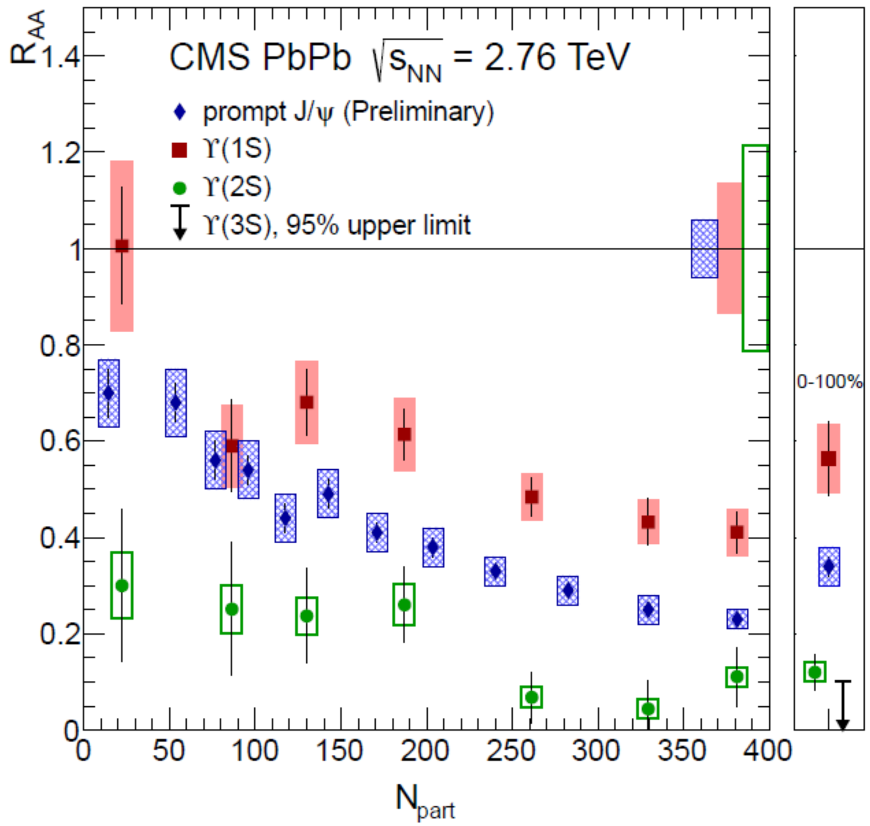
$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} = 0.06 \pm 0.06 \pm 0.06$$
$$(< 0.17 \text{ at } 95\% \text{ CL})$$

- **Υ states are suppressed sequentially**

  $R_{AA}[\Upsilon(3S)] < R_{AA}[\Upsilon(2S)] < R_{AA}[\Upsilon(1S)]$
- Υ(2S) is suppressed even in the most peripheral bin.

Υ(1S), Υ(2S) and Υ(3S) R_{AA}

PRL 109, 222301 (2012)



Υ(1S)

J/ψ (prompt)

Υ(2S)

Υ(3S)

- Centrality integrated results

$$R_{AA}[\Upsilon(1S)] = 0.56 \pm 0.08 \pm 0.07$$
$$R_{AA}[\Upsilon(2S)] = 0.12 \pm 0.04 \pm 0.02$$
$$R_{AA}[\Upsilon(3S)] = 0.03 \pm 0.04 \pm 0.01$$
$$(<0.10 \text{ at } 95\% \text{ CL})$$

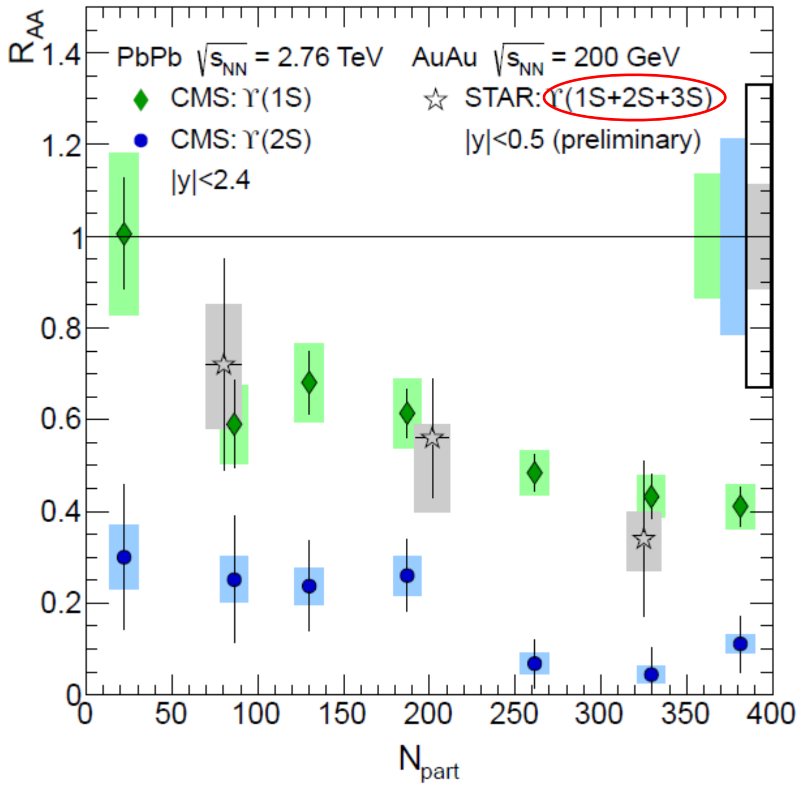
[Note] If the feed-down contribution ~50%, Υ(1S) suppression is consistent with the suppression of the excited states only.

- **Υ states are suppressed sequentially**

$$R_{AA}[\Upsilon(3S)] < R_{AA}[\Upsilon(2S)] < R_{AA}[\Upsilon(1S)]$$

- Υ(1S) is not suppressed in the most peripheral bin.

Comparison to RHIC for Υ



- STAR data for Υ(1S+2S+3S) in AuAu at 200 GeV integrated for centrality

$$R_{AA}[\Upsilon(1S+2S+3S)] = 0.56 \pm 0.21^{+0.08}_{-0.16}$$

arXiv:1109.3891

PRL 109, 222301 (2012)

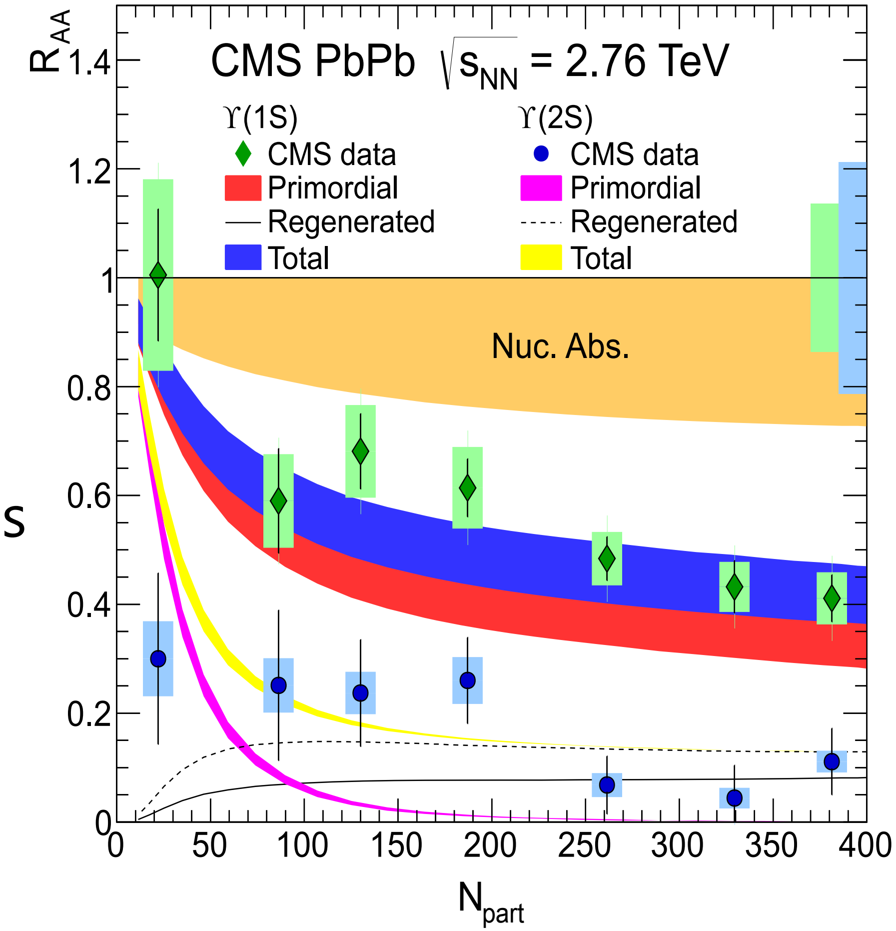
- CMS data for Υ(1S+2S+3S) integrated for centrality

$$R_{AA}[\Upsilon(1S+2S+3S)] = \frac{\Upsilon(1S+2S+3S)|_{PbPb}}{\Upsilon(1S+2S+3S)|_{pp}}$$

$$= \frac{\Upsilon(1S)|_{PbPb}}{\Upsilon(1S)|_{pp}} \times \frac{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.56 \times \frac{1+0.14}{1+0.97} \approx 0.32$$

Comparison to Model for Υ

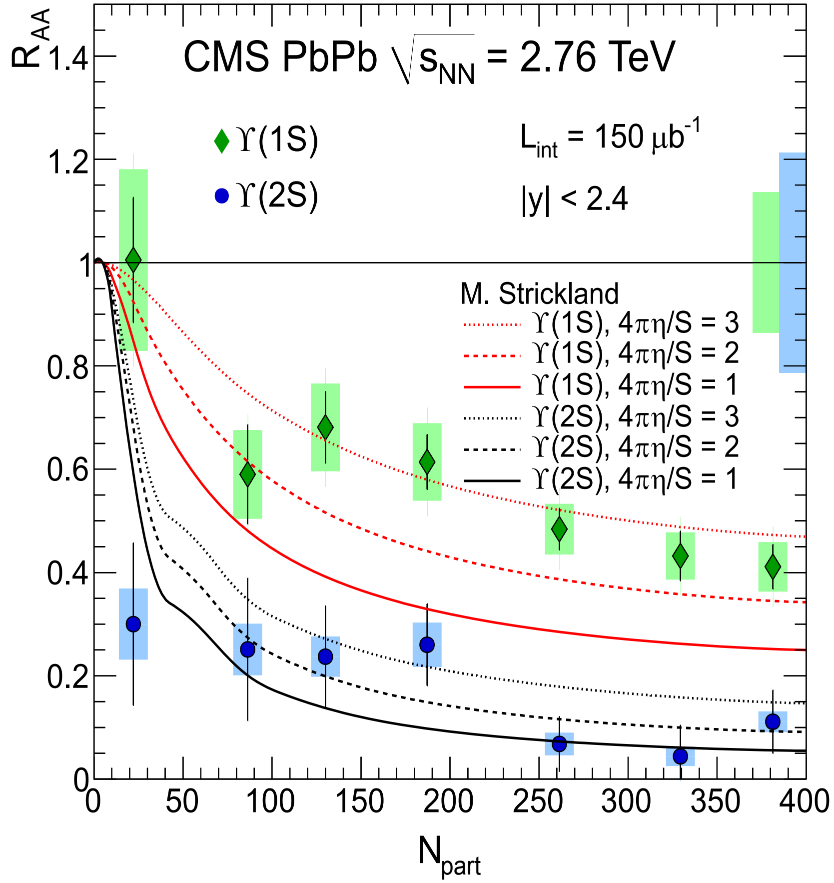
- Strong Υ binding scenario
  - ⇒ Mostly consistent with data
  - ⇒ Υ(1S): Small regeneration indicates the suppression is mostly primordial.
  - ⇒ Υ(2S): Regeneration is dominant in central collisions
  - ⇒ Large uncertainty in nuclear absorption: pPb will help!
  - ⇒ T ≈ 610 MeV in this calculation
    - Are there any sensitivity to initial temperature?



Model calculations:
A. Emerick, X. Zhao & R. Rapp, EPJA 48, 72 (2012)

Comparison to Model for ϒ

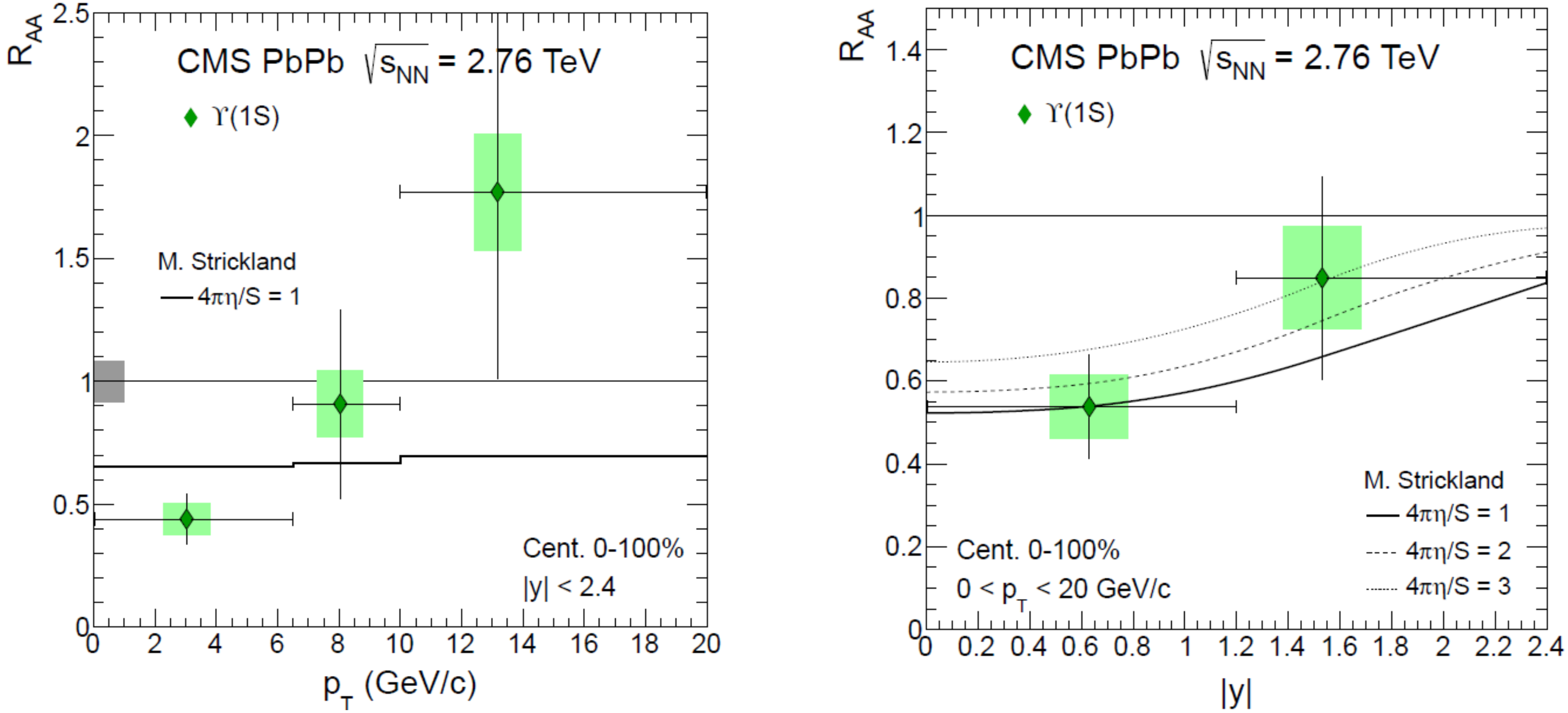
- AHYDRO: Anisotropic hydrodynamics model
- Incorporating lattice-based potentials, including Re and Im parts
- Includes sequential melting and feed-down contributions
  $\Rightarrow$ ~50% feed-down from χ_b
- Dynamical expansion with variations in initial conditions for T_0 and η/S: data indicates
  $\Rightarrow$ $552 < T_0 < 580$ MeV
  $\Rightarrow$ $1 < 4\pi\eta/s < 3$



Model calculations:
M. Strickland and D. Bazow, NPA 879, 25 (2012)
M. Strickland, PRL 107, 132301 (2011)

Υ(1S) R_{AA} vs. p_T and y

Data: JHEP 05, 063 (2012), Model: M. Strickland, PRL 107, 132301 (2011)



- Obtained with 2010 PbPb (7.28 μb^{-1}) and 2011 pp (225 nb^{-1})
  - Clear suppression at low p_T
- High-statistics data sets: 2011 PbPb (150 μb^{-1}) and 2013 pp (5.41 pb^{-1})
  - The accuracy of the results will be greatly improved in the future.

Summary

1. Available CMS heavy-ion data sets
   - PbPb @ $\sqrt{s_{NN}}$ = 2.76 TeV: 7.28 μb^{-1} + 150 μb^{-1}
   - pp @ $\sqrt{s_{NN}}$ = 2.76 TeV: 225 nb^{-1} + 5.41 pb^{-1}
   - pPb @ $\sqrt{s_{NN}}$ = 5.02 TeV: 31.7 nb^{-1}
2. Experimental results on Upsilons
   - Υ(2S) and Υ(3S) are suppressed relative to Υ(1S) in PbPb.
   - Υ(1S), Υ(2S) and Υ(3S) in PbPb are suppressed relative to those in pp
   - Sequential melting is observed in the Upsilon states

$$R_{AA}[\Upsilon(3S)] < R_{AA}[\Upsilon(2S)] < R_{AA}[\Upsilon(1S)]$$

3. Prospects
   - Initial state effect will be investigated using the pPb data.
   - Large statistics pp data will improve the accuracy of the data.