Detailed Measurements of Bottomonium Suppression in PbPb Collisions at 2.76 TeV with CMS

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for the CMS Collaboration

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Quarkonia

1. Quarkonia are very "unusual" hadrons

heavy quark ($Q\bar{Q}$) bound states stable under strong decay

- heavy: $\mathbf{m_c} \simeq 1.2 - 1.4$ GeV, $\mathbf{m_b} \simeq 4.6 - 4.9$ GeV
- stable: $\mathbf{M_{c\bar{c}}} - 2\mathbf{M_D} \mathbf{<< 0}$ and $\mathbf{M_{b\bar{b}}} - 2\mathbf{M_B} \mathbf{<< 0}$

What is "usual"?

- light quark ($q\bar{q}$) constituents
- loosely bound, $\mathbf{M}_\rho - 2\mathbf{M}_\pi \gg 0$, $\mathbf{M}_\Phi - 2\mathbf{M}_K \simeq 0$

- hadronic size ~ $1/\lambda_{QCD} \simeq 1$ fm, independent of mass

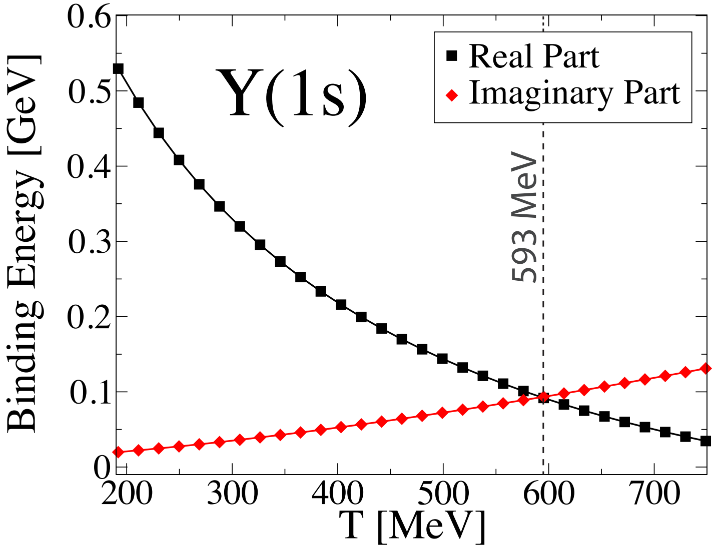
(At T = 0 Cornell potential gives full spectroscopy)

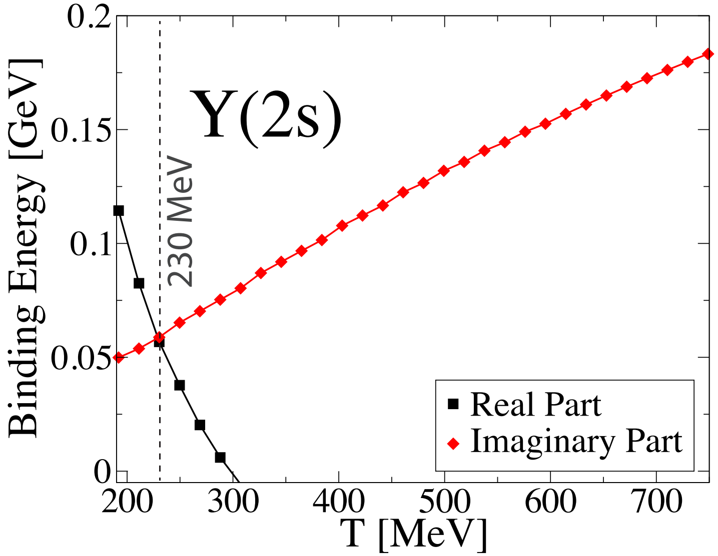
State	J/ψ	ψ′	Υ	Υ′	Υ′′
mass [GeV]	3.10	3.68	9.46	10.02	10.36
ΔE [GeV]	0.64	0.05	1.10	0.54	0.20
radius [fm]	0.25	0.45	0.14	0.28	0.39

Relativistic Heavy Ion Physics

By F Becattini, P Braun-Munzinger, Rainer Fries, C Gale, J. Schaffner-Bielich

Sequential Melting





Margotta et al. Phys. Rev. D 84, 069902(E) (2011)

✓ High temperature QGP: weaker color binding (Debye screening) (Phys. Lett. B178 (1986) 416)

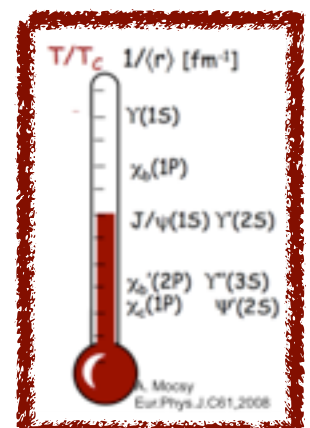
- Real V(T)

✓ Gluons collide with $Q\bar{Q}$ bound states:

- shorter lifetime ⇒ larger spectral widths (Landau Damping) (JHEP 0703:054,2007)
- Im V(T)

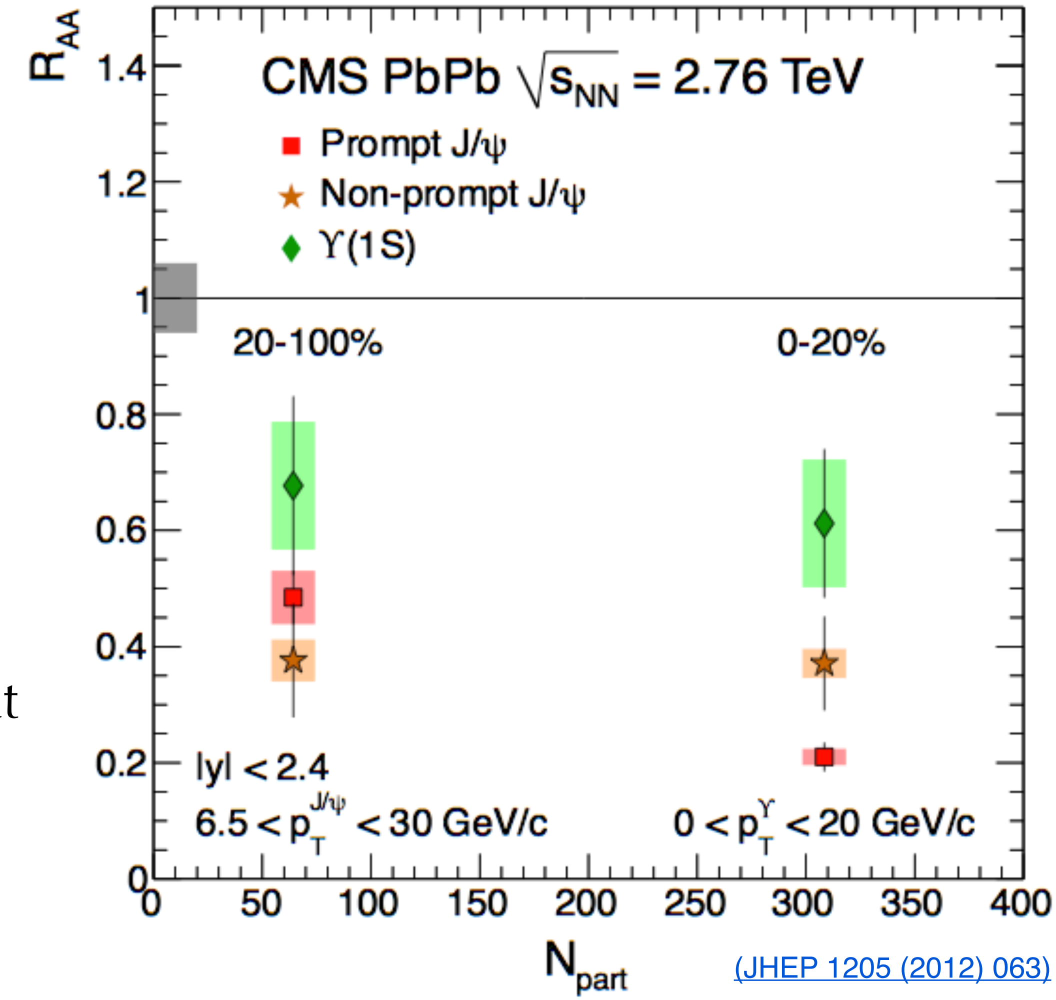
✓ Dissociation when Re V(T) ~ Im V(T)

✓ Quarkonia: help quantify medium properties (TEMPERATURE)



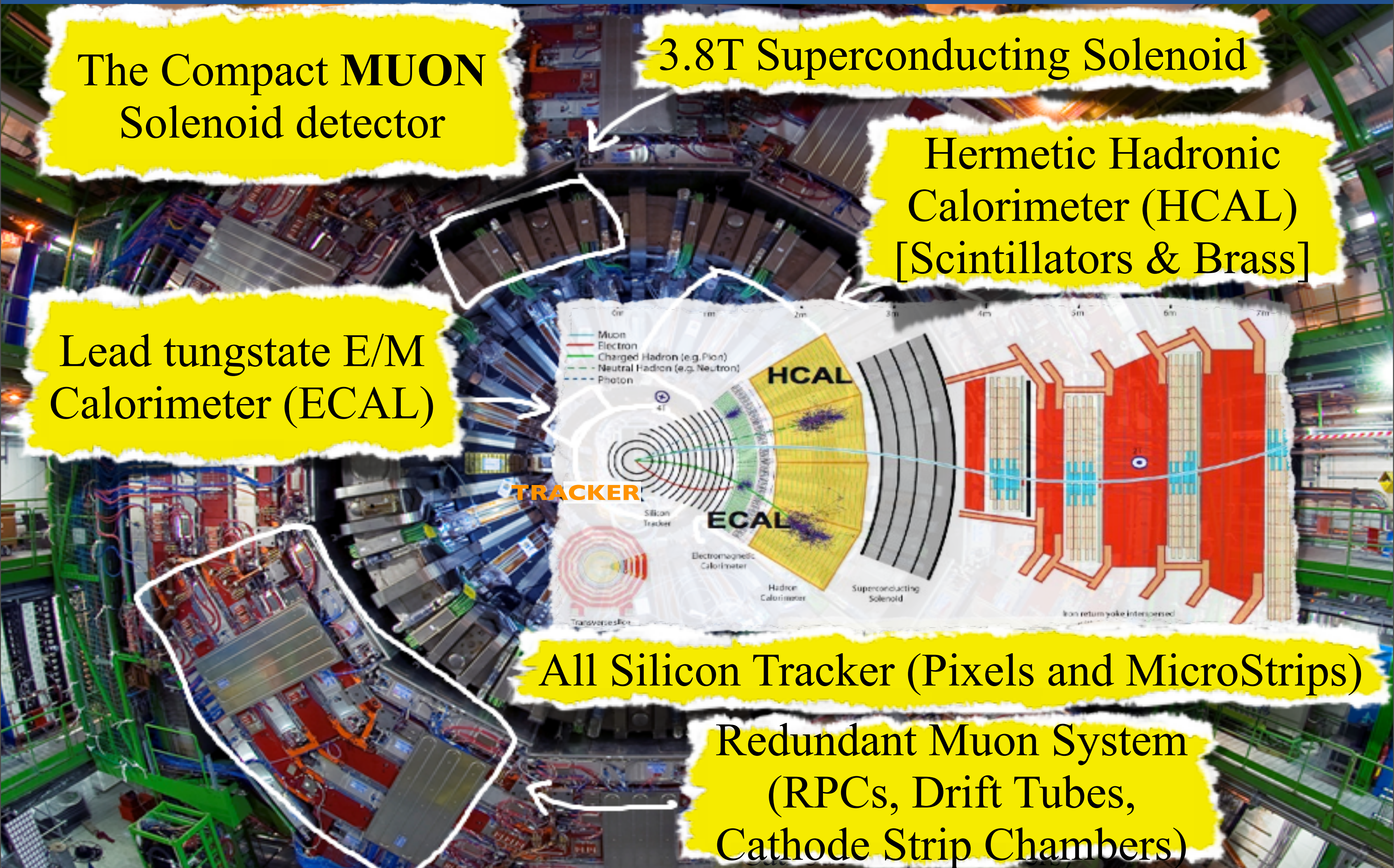
Bottomonium in Heavy Ions collisions

- ✓ Mass of the b-quark is large
- ✓ No B hadron feed down to Υ
- ✓ nPDF effects smaller
- ✓ The <u>relative</u> yields analysis of the excited states / ground state
  - – cancels cold nuclear matter effects
    - nPDFs (shadowing, etc)
    - initial parton energy loss
    - final state nuclear absorption (if negligible at LHC energies)
  - – carries only effects related to final (hot) medium
- ✓ Regeneration is smaller

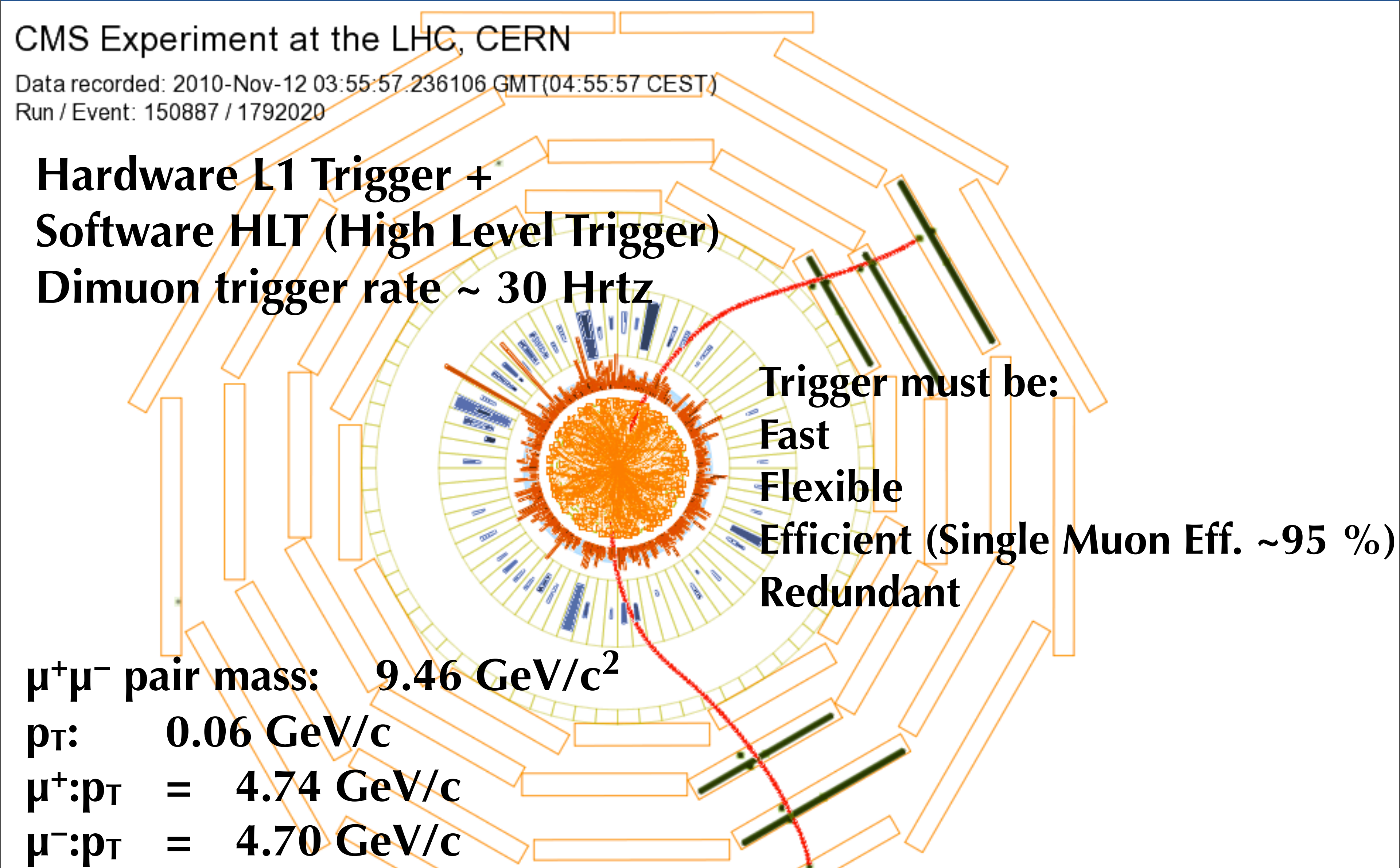


(JHEP 1205 (2012) 063)

CMS


The Compact **MUON** Solenoid detector
3.8T Superconducting Solenoid
Hermetic Hadronic Calorimeter (HCAL) [Scintillators & Brass]
Lead tungstate E/M Calorimeter (ECAL)
All Silicon Tracker (Pixels and MicroStrips)
Redundant Muon System (RPCs, Drift Tubes, Cathode Strip Chambers)
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
HCAL
ECAL
TRACKER
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed
Transverse slice

Υ candidate in PbPb at $\sqrt{s_{NN}} = 2.76$ TeV

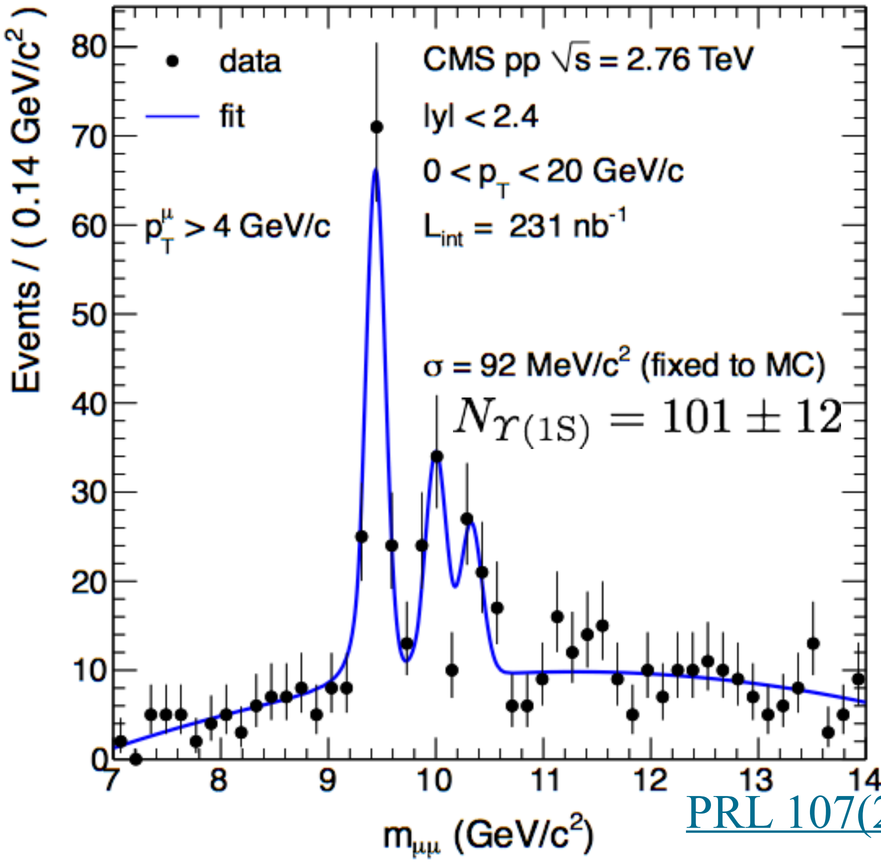


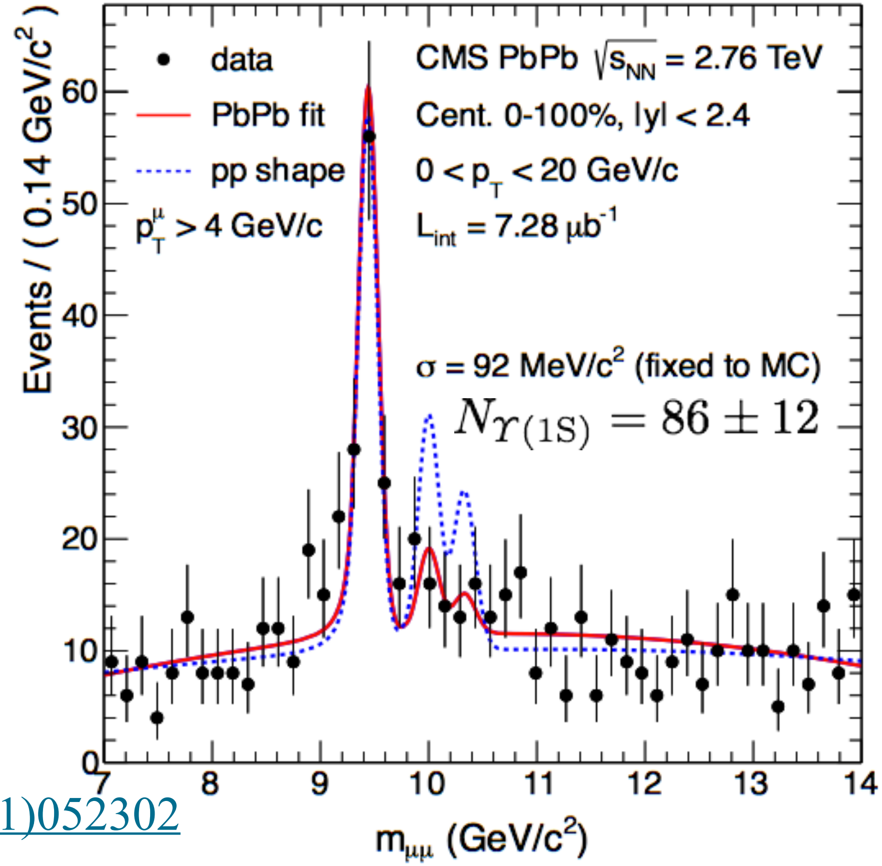
Hardware L1 Trigger +
Software HLT (High Level Trigger)
Dimuon trigger rate ~ 30 Hrtz

Trigger must be:
Fast
Flexible
Efficient (Single Muon Eff. ~95 %)
Redundant

$\mu^+\mu^-$ pair mass: 9.46 GeV/c^2
p_T: 0.06 GeV/c
μ^+:p_T = 4.74 GeV/c
μ^-:p_T = 4.70 GeV/c

Υ(2S+3S) Suppression in 2010





PRL 107(2011)052302

$\Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02$

$\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$

Measured Υ(2S+3S) production relative to Υ(1S)

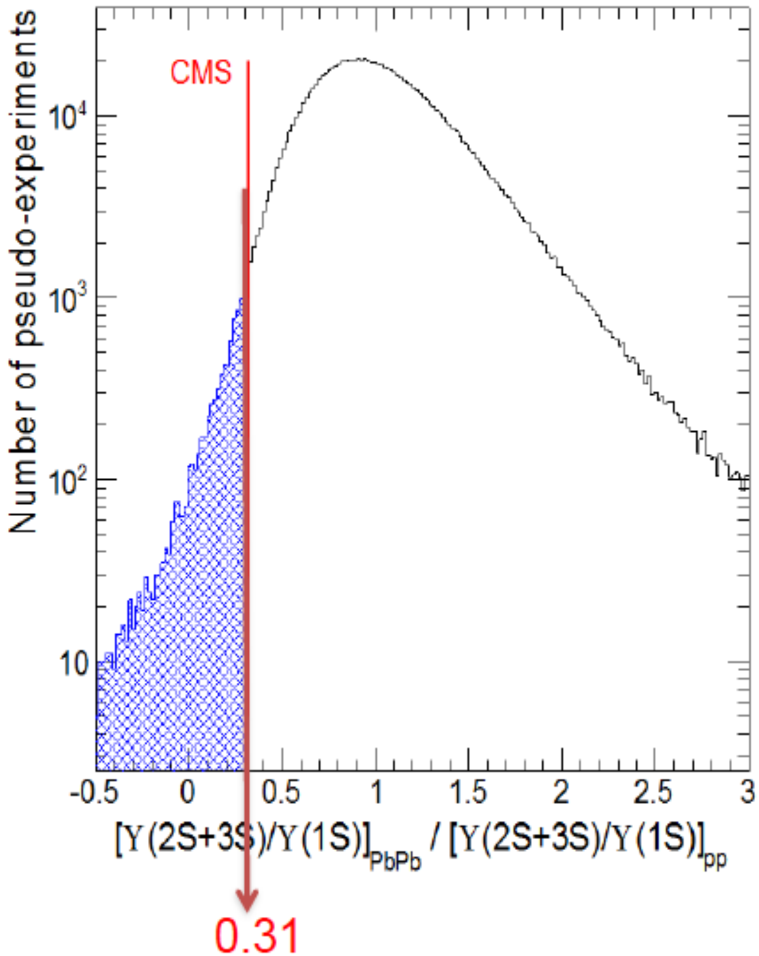
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

Indication of 2S+3S relative suppression
significance = 2.4 σ

Significance

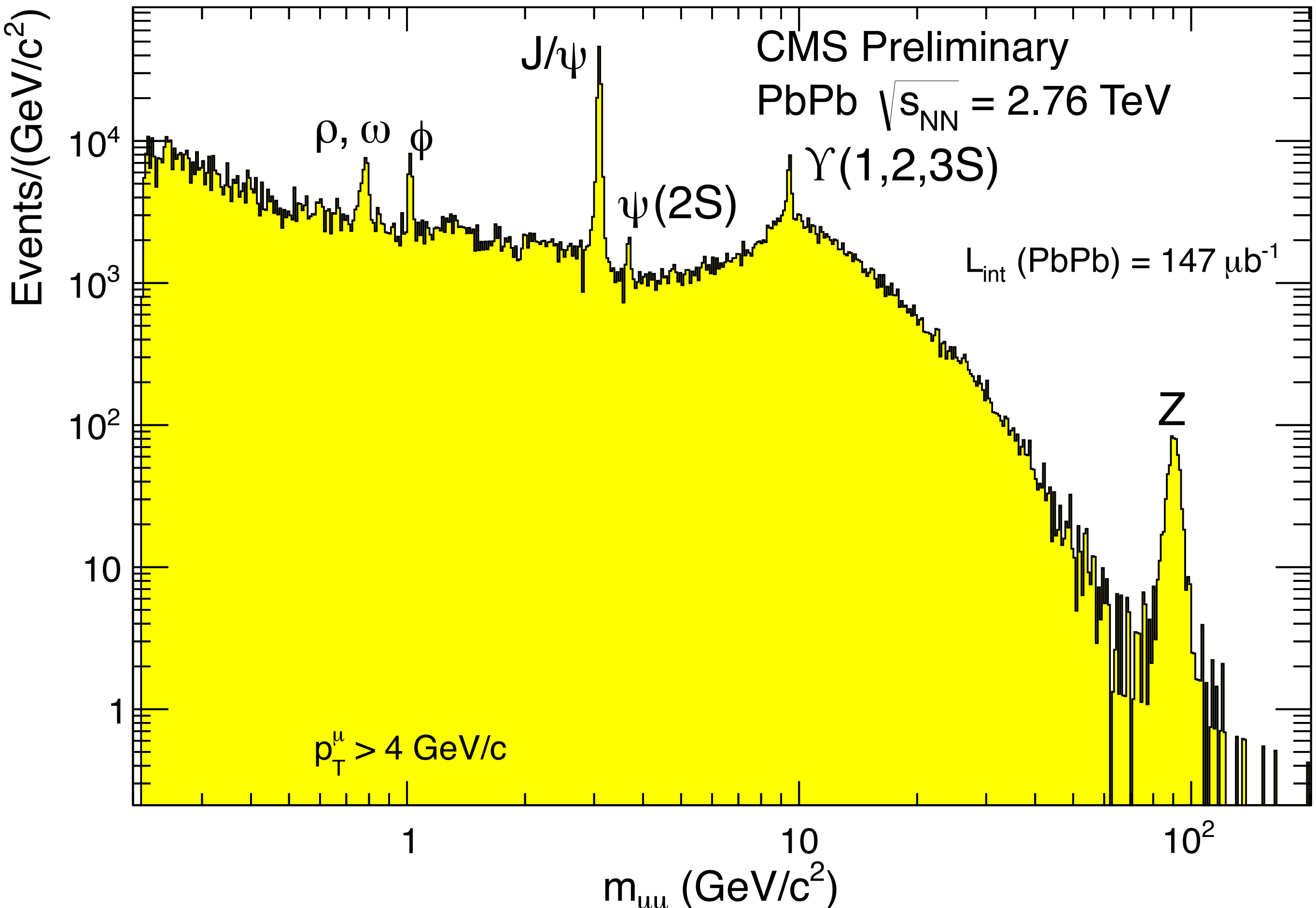
Could background fluctuation produce a result as extreme as observed in data?

- Generate pseudo-experiments following the *null-hypothesis* (i.e. no suppression)
- Fit pseudo-data samples with nominal fit
- Count fraction of occurrences for which the ratio (taken as test statistic) is same or lower than observed:
  - p-value: 0.9%
  - 2.4σ (1-sided Gaussian test)



PRL 107 (2011) 052302

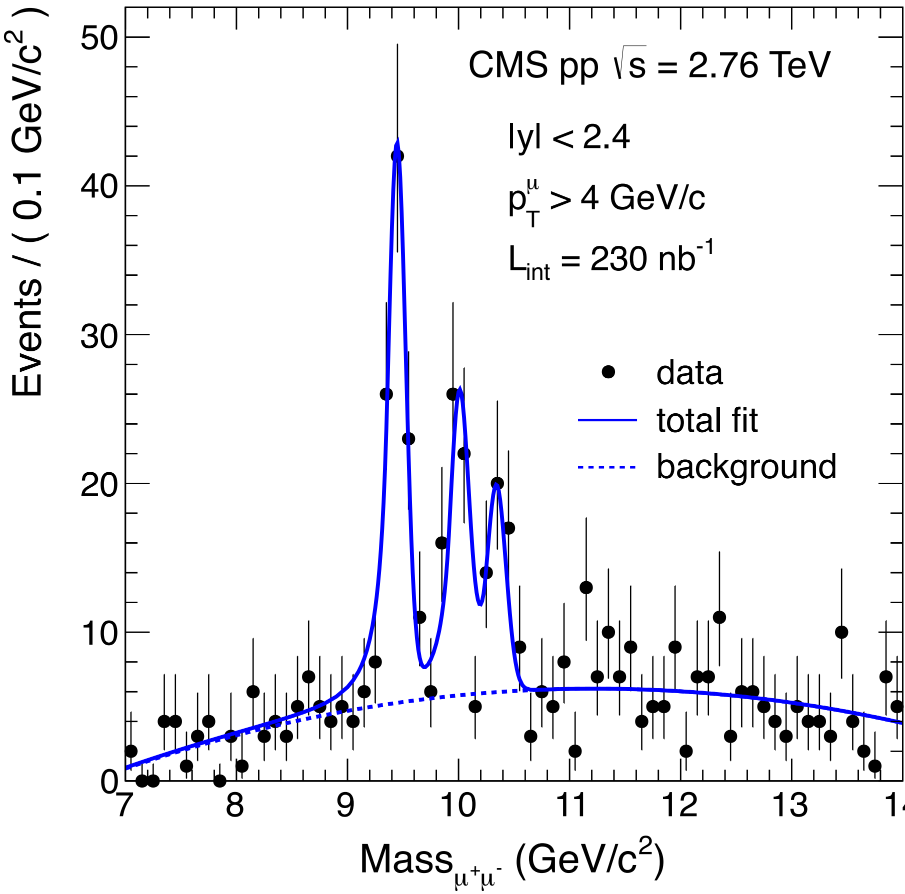
Muon pairs in PbPb at $\sqrt{s_{NN}}$ = 2.76 TeV

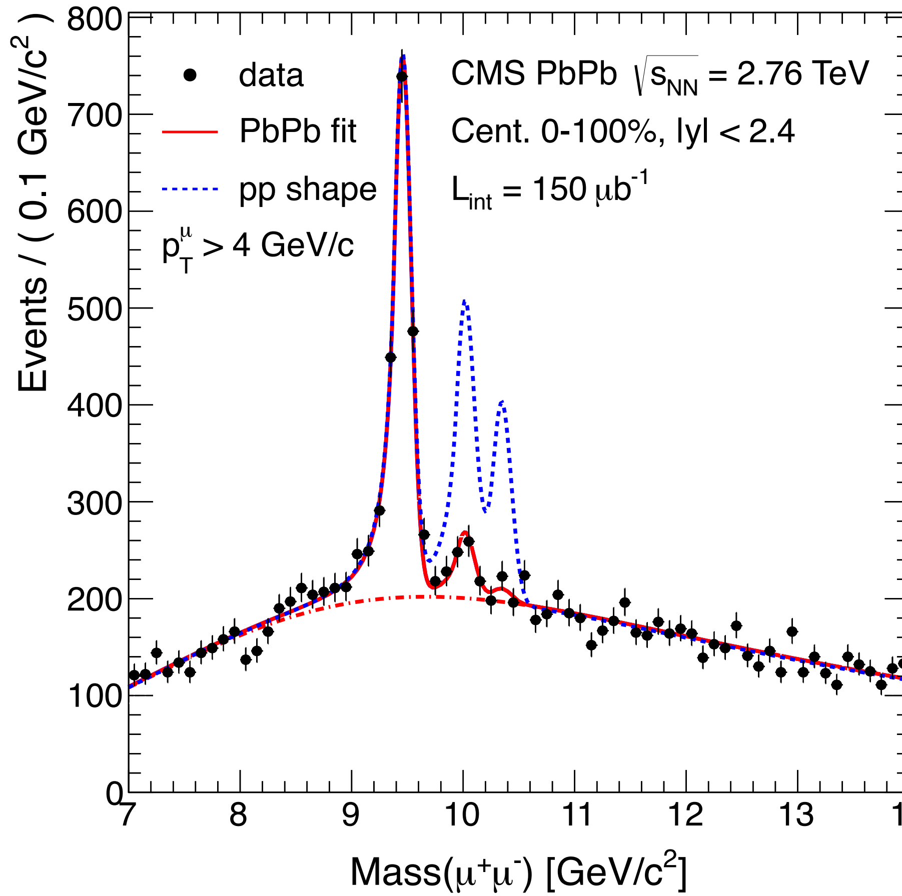


- ✓ Kinematic cuts applied to reduce background level
  - Single muon:
    $p_T^\mu > 4$ GeV/c, $|\eta^\mu| < 2.4$

✓ pp - PbPb
Same cuts, same reco. algorithm
Systematics cancel

Simultaneous Fit 2011





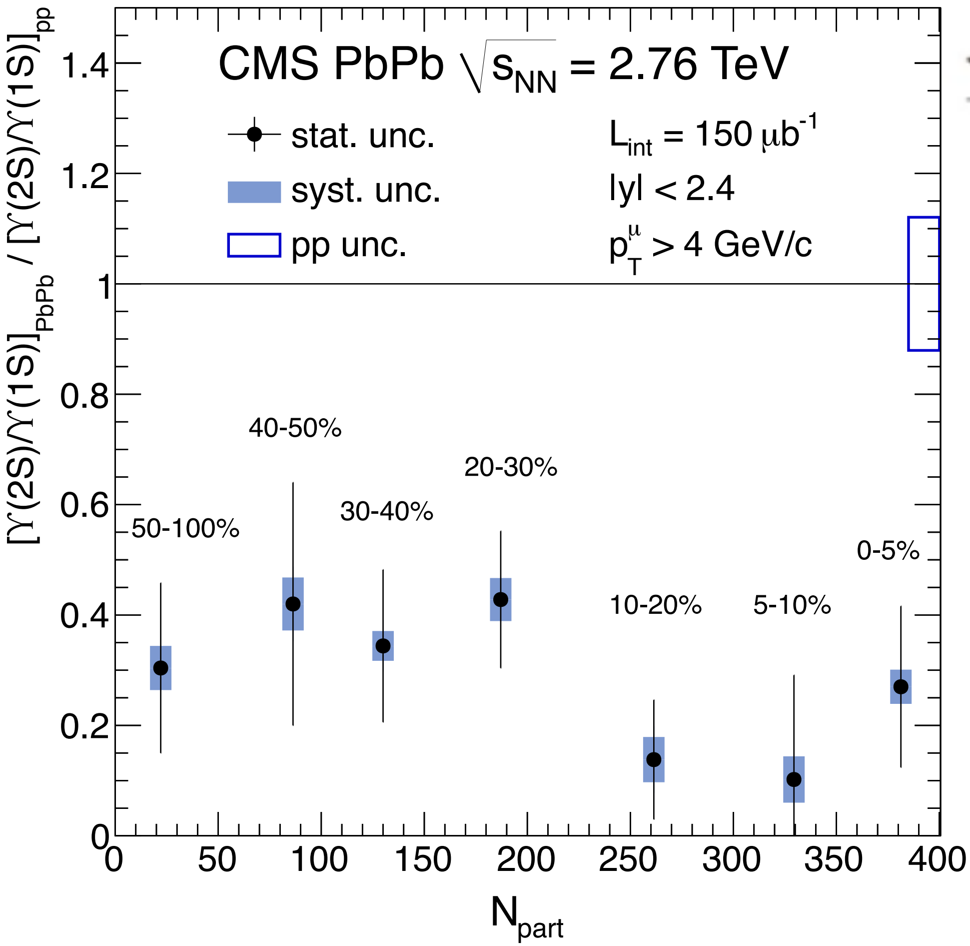
$\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb} / \Upsilon(2S+3S)/\Upsilon(1S)|_{pp} = 0.15 \pm 0.05 \pm 0.03$

Observation of 2S+3S relative suppression

(significance > 5 σ)

Υ(nS)/Υ(1S) Double ratio

Separated Υ(2S) and Υ(3S)



(0 - 100) % Centrality Integrated

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

$$\frac{\Upsilon(3S)/\Upsilon(1S)|_{PbPb}}{\Upsilon(3S)/\Upsilon(1S)|_{pp}} = 0.06 \pm 0.06\,(\text{stat.}) \pm 0.06\,(\text{syst.})$$

$$< 0.17 \quad (95\%\ \text{C.L.}).$$

Υ(2S) relative ratio to Υ(1S) in PbPb is suppressed compared to same ratio in pp

Systematics Uncertainties:

➡fitting (11%)

- Final state radiation modeling.
- Background modeling:

like-sign vs track-rotation

➡imperfect acceptance+efficiency cancellation: 1%

Υ(nS) Absolute Suppression

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\mathrm{MB}}} \frac{N_{\mathrm{PbPb}}(\Upsilon(1\mathrm{S}))}{N_{pp}(\Upsilon(1\mathrm{S}))} \frac{\varepsilon_{pp}}{\varepsilon_{\mathrm{PbPb(cent)}}}$$

First time the nuclear modification factors are measured for excited Υ states

$$\begin{aligned} R_{AA}(\Upsilon(1S)) &= 0.56 \pm 0.08\,(\text{stat.}) \pm 0.07\,(\text{syst.}) \\ R_{AA}(\Upsilon(2S)) &= 0.12 \pm 0.04\,(\text{stat.}) \pm 0.02\,(\text{syst.}) \\ R_{AA}(\Upsilon(3S)) &= 0.03 \pm 0.04\,(\text{stat.}) \pm 0.01\,(\text{syst.}) \\ &< 0.10 \quad (95\%\ \text{C.L.})\,. \end{aligned}$$

Υ states are suppressed sequentially:

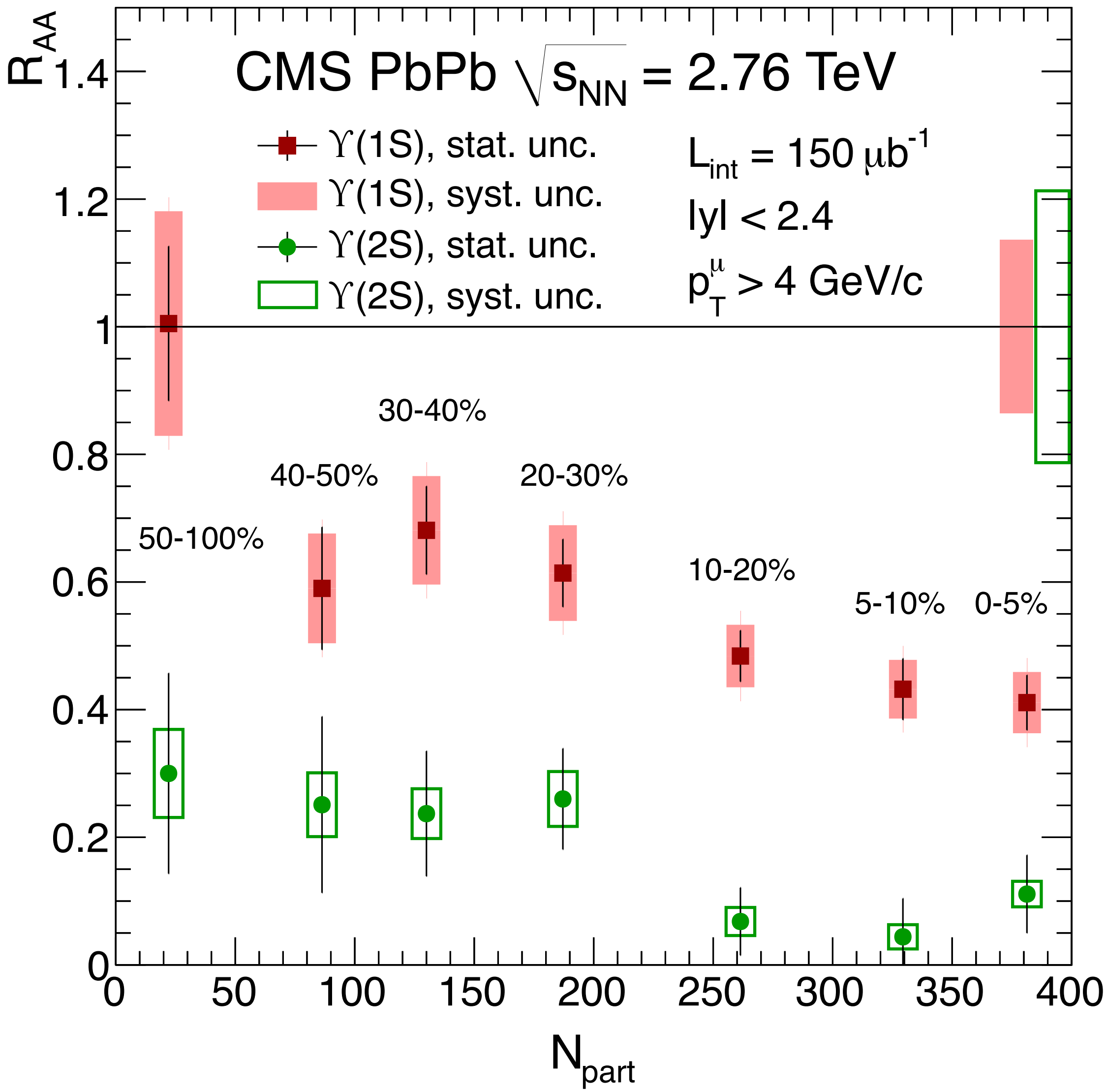
$R_{AA}\Upsilon(3S) < R_{AA}\Upsilon(2S) < R_{AA}\Upsilon(1S)$

✓Note: Inclusive measurement of Υ(1S) vs. direct production.

-R_{AA}(Υ(1S))-inclusive : Feed-down contributions (χ_b, Υ(2S), Υ(3S)).

-If feed-down ~50%, R_{AA}(Υ(1S))-inclusive is consistent with suppression of excited states only.

Υ(nS) R_{AA} vs Centrality



Suppression observed to increase with centrality of the collisions

Υ(2S)

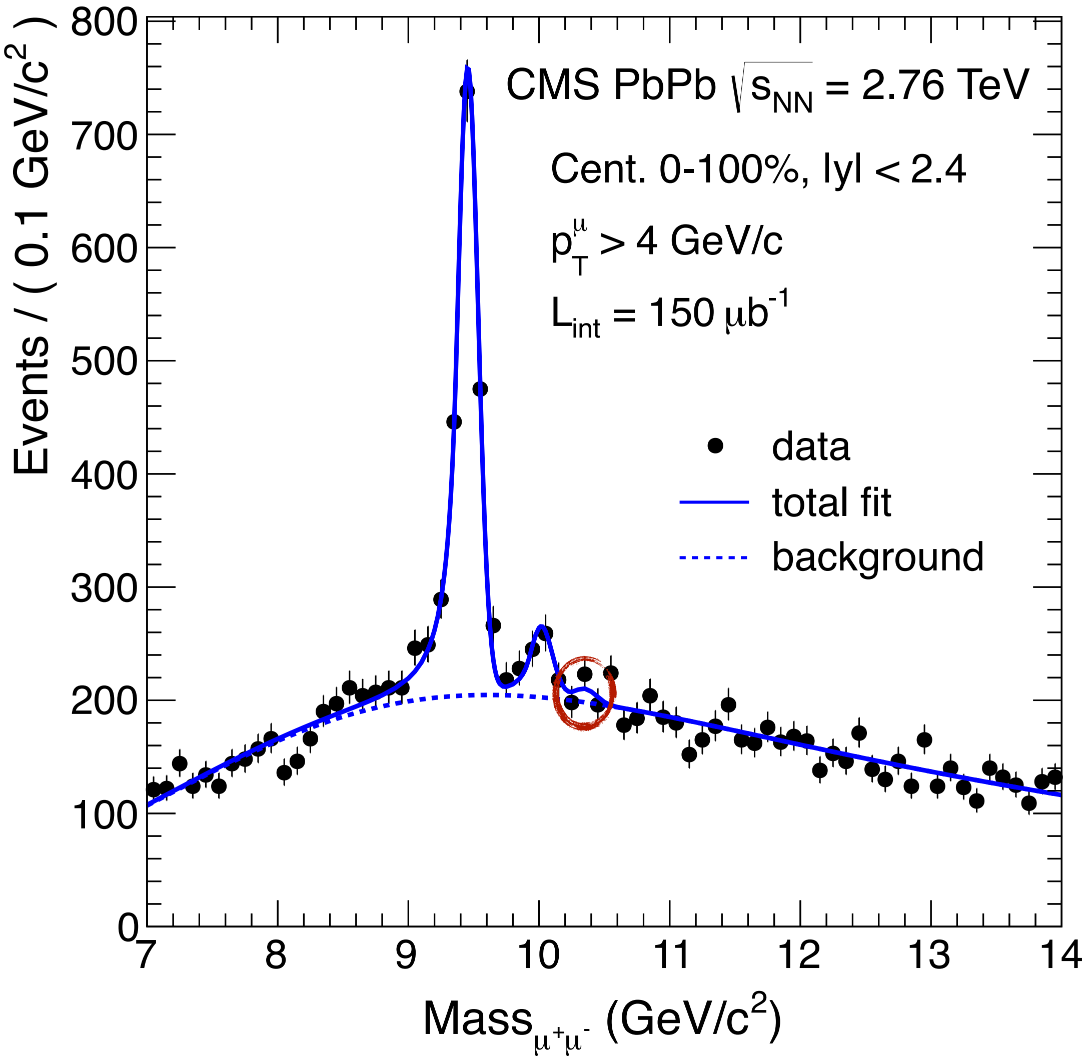
- ✓ Always more suppressed that Υ(1S)
- ✓ Still suppressed in the most peripheral bin (50-100%)

Global Uncertainties lumi pp & fittting pp:

14% Υ(1S)

21% Υ(2S)

Υ(3S) Upper Limit



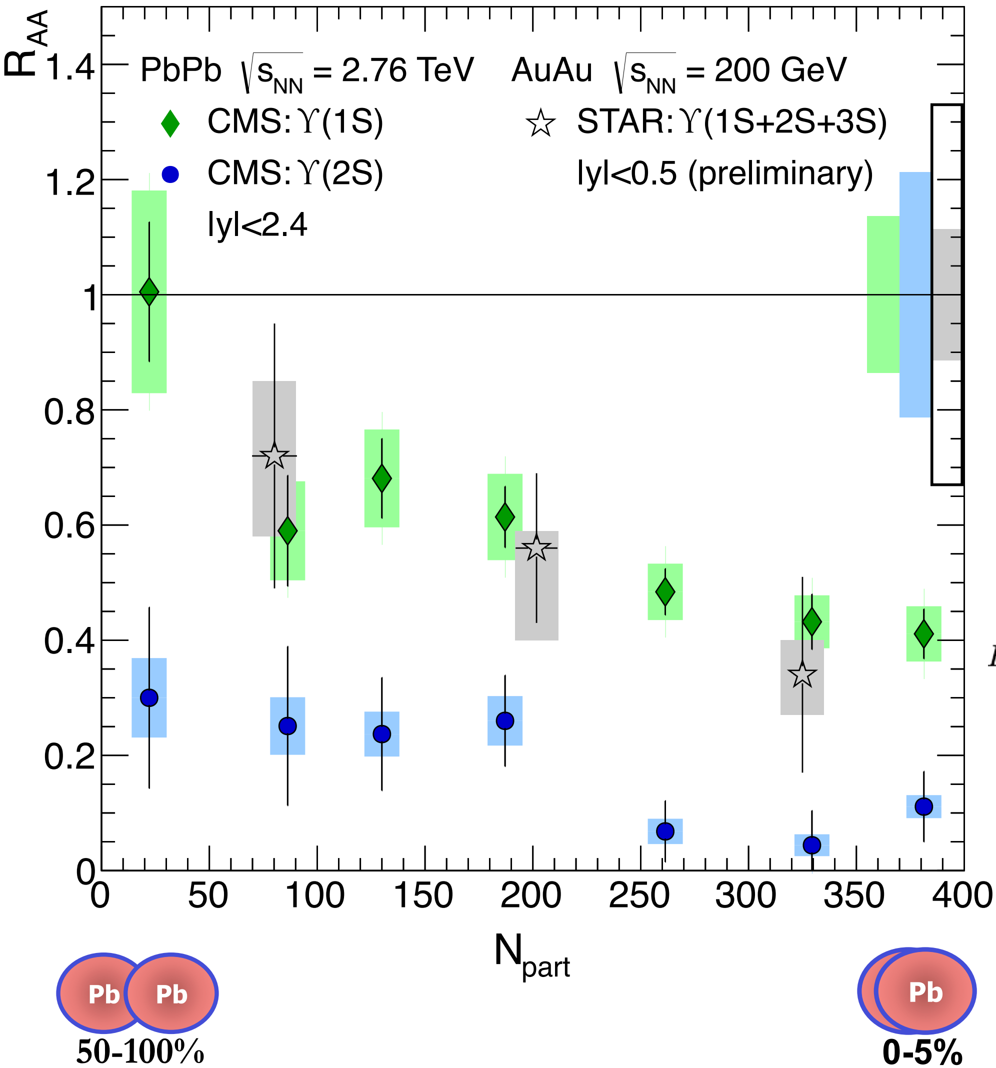
The Υ(3S) peak is barely visible in the PbPb data.

Set upper limits at 95% C.L. using the Feldman Cousins technique. (arXiv:physics/9711021v2)

$R_{AA}^{\Upsilon(3S)} < 0.1$

(0 - 100) % Centrality Integrated

Experimental Comparisons



✓STAR measured R_{AA} of ϒ(1S+2S+3S) combined

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

(arXiv:1109.3891v1)

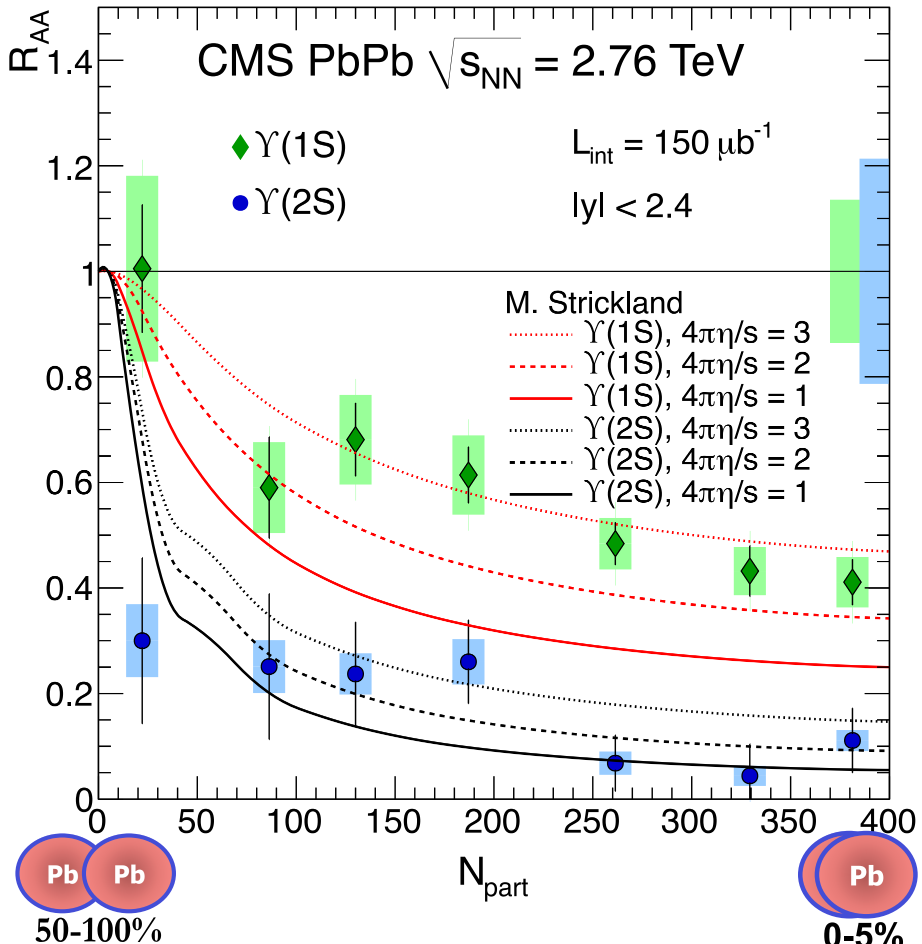
✓CMS: separate R_{AA} for ϒ(1S) and ϒ(2S) can calculate R_{AA} of ϒ(1S+2S+3S):

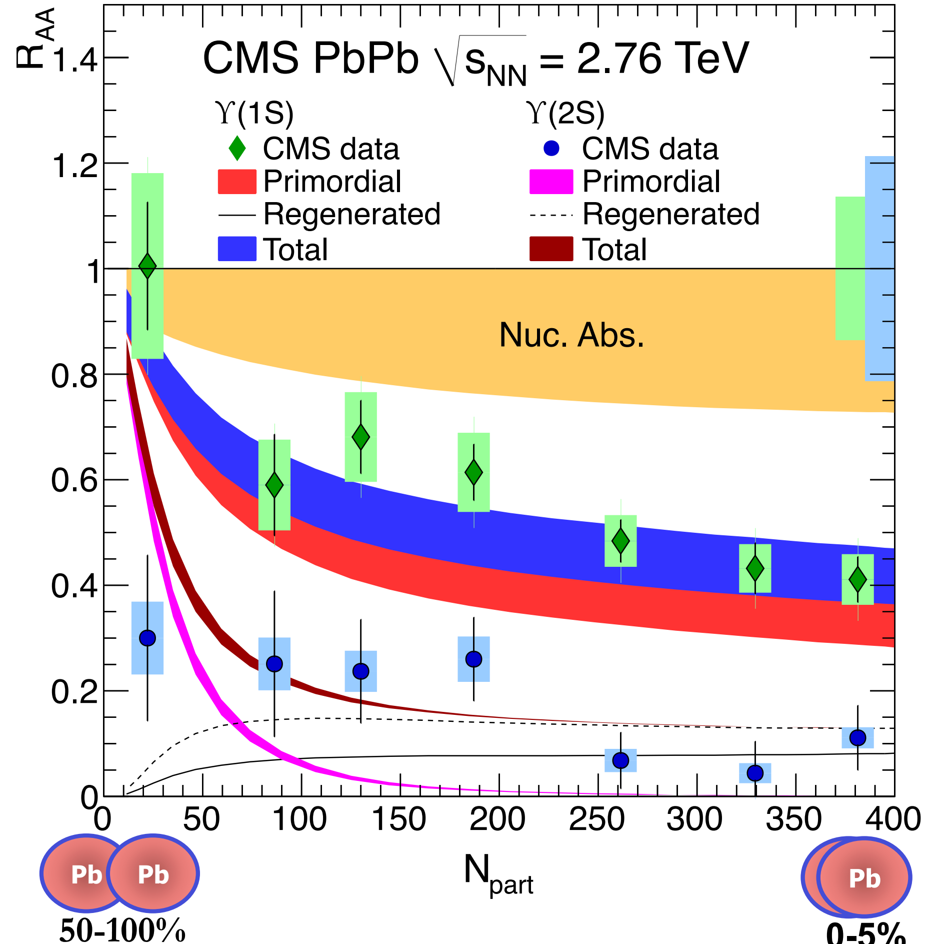
$$R_{AA}(\Upsilon(1S+2S+3S)) = R_{AA}(\Upsilon(1S)) \times \frac{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{PbPb}}{1+\Upsilon(2S+3S)/\Upsilon(1S)|_{pp}}$$

$$R_{AA}\,(\Upsilon(1S+2S+3S)) \sim 0.32$$

✓Similar Suppression Pattern

Theoretical Comparisons

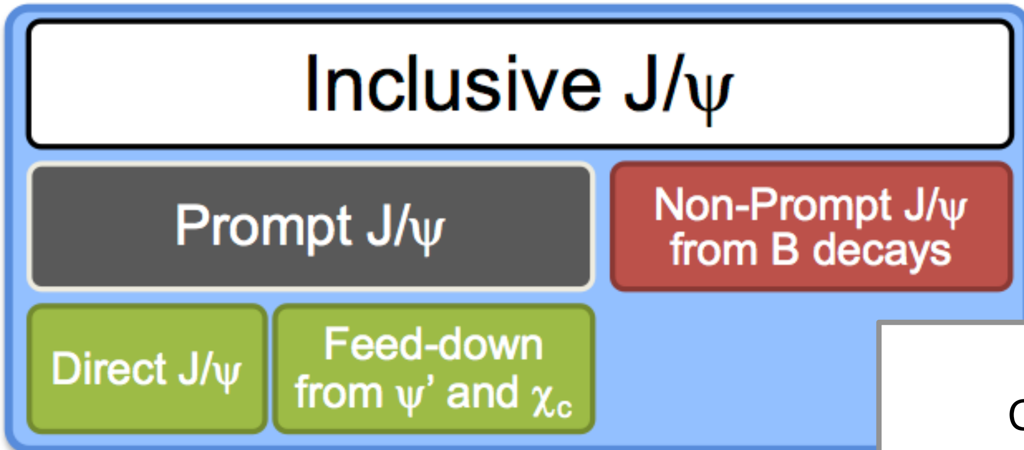


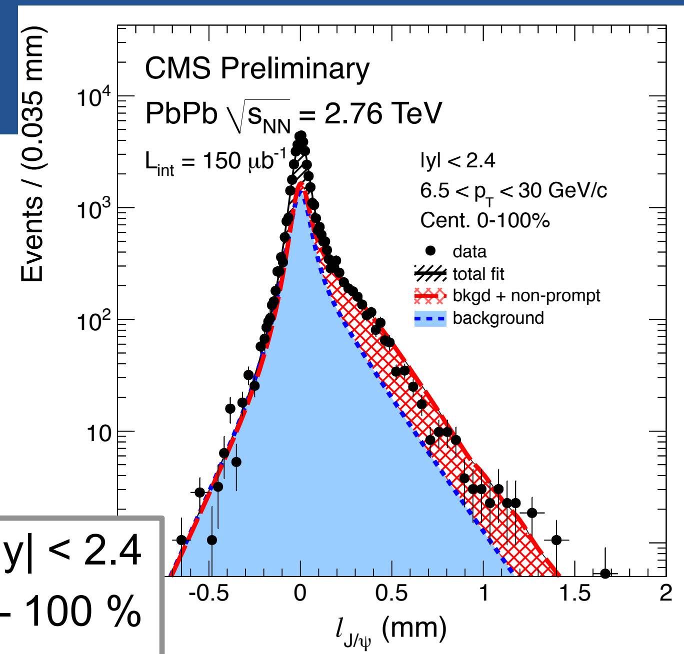


CMS data consistent within uncertainties with range of suppression predicted for both ϒ(1S) and ϒ(2S).

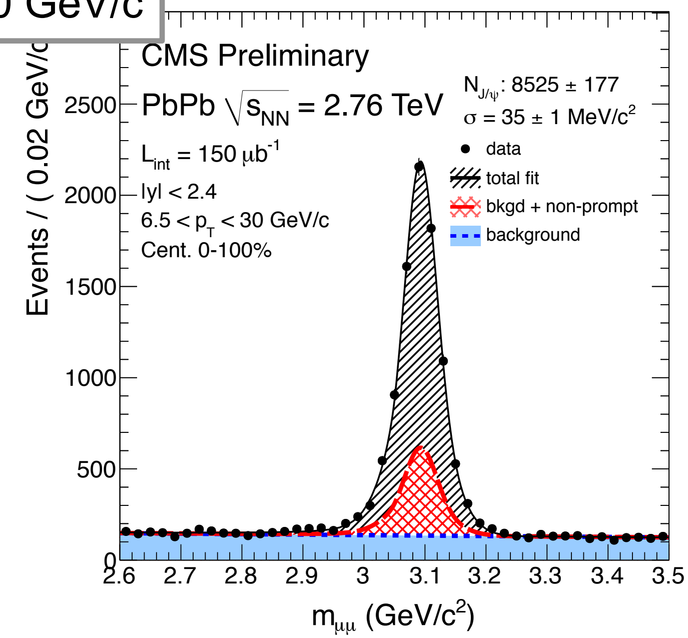
Strickland and D. Bazow (PRL 107 (2011) 132301) Emerick, X.Zhao, R.Rapp (Eur. Phys. J. A48 (2012) 72)

Prompt/non-prompt J/ψ



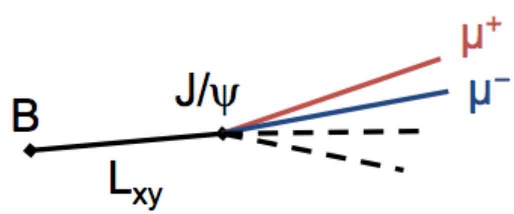


|y| < 2.4
Cent. 0 – 100 %
6.5 < < p_T < 30 GeV/c



- Reconstruct opposite sign muon vertex
- 2-D unbinned maximum likelihood fit of dimuon mass and pseudo-proper decay length ($l_{J/\psi}$)

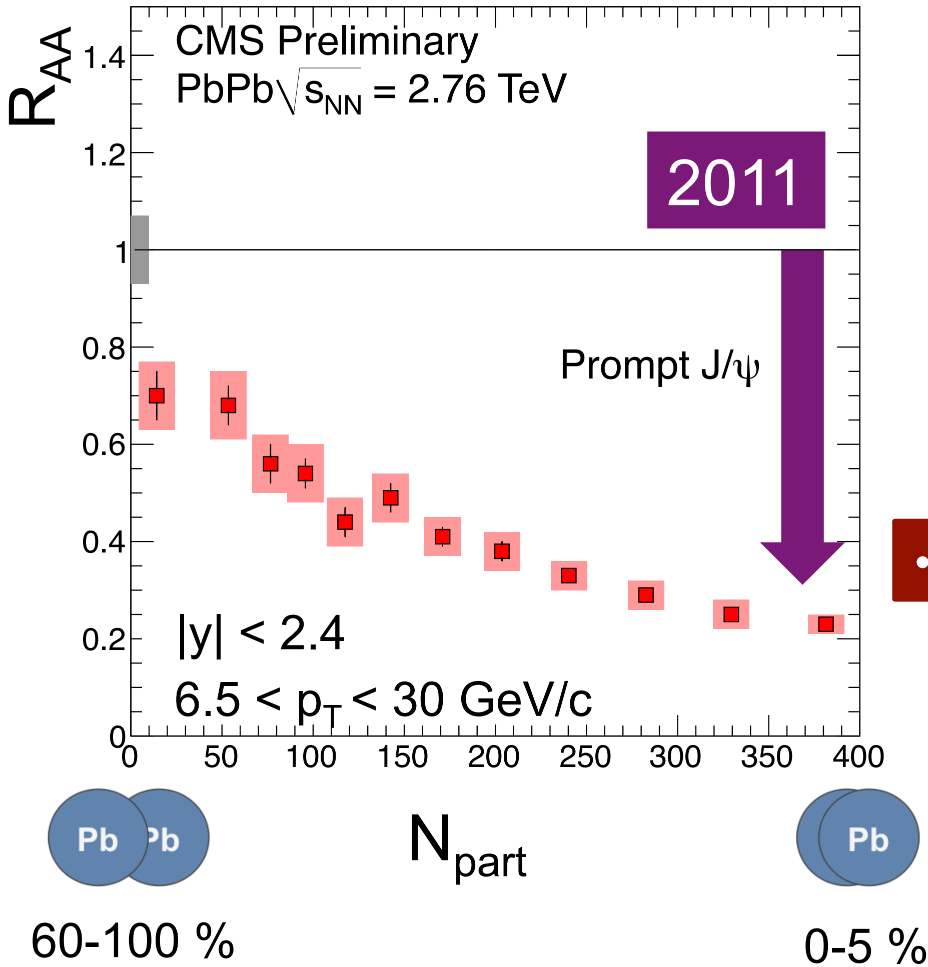
$$\ell_{J/\psi} = L_{xy} \frac{m_{J/\psi}}{p_T}$$



R_{AA} of prompt J/ψ vs N_{part}

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{\rm MB}} \frac{N_{\rm PbPb}(J/\psi)}{N_{pp}(J/\psi)} \frac{\varepsilon_{pp}}{\varepsilon_{\rm PbPb}(\rm cent)}$$

PAS CMS-HIN-12-014

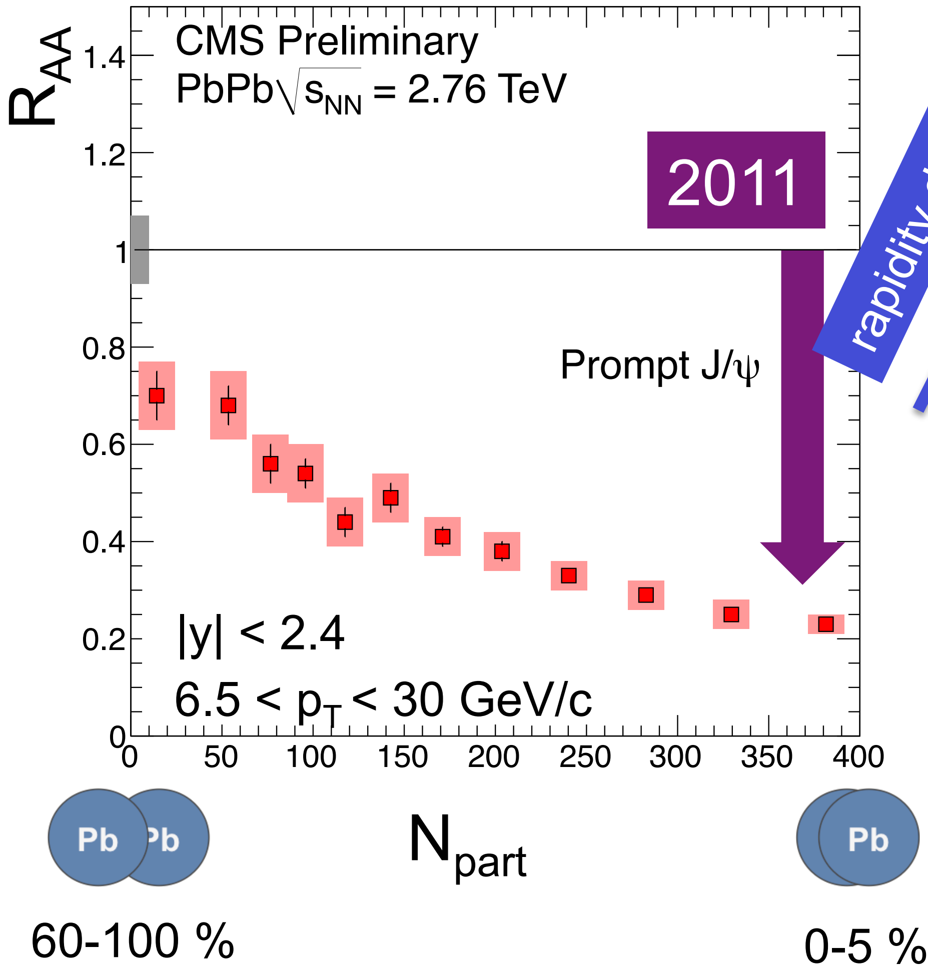


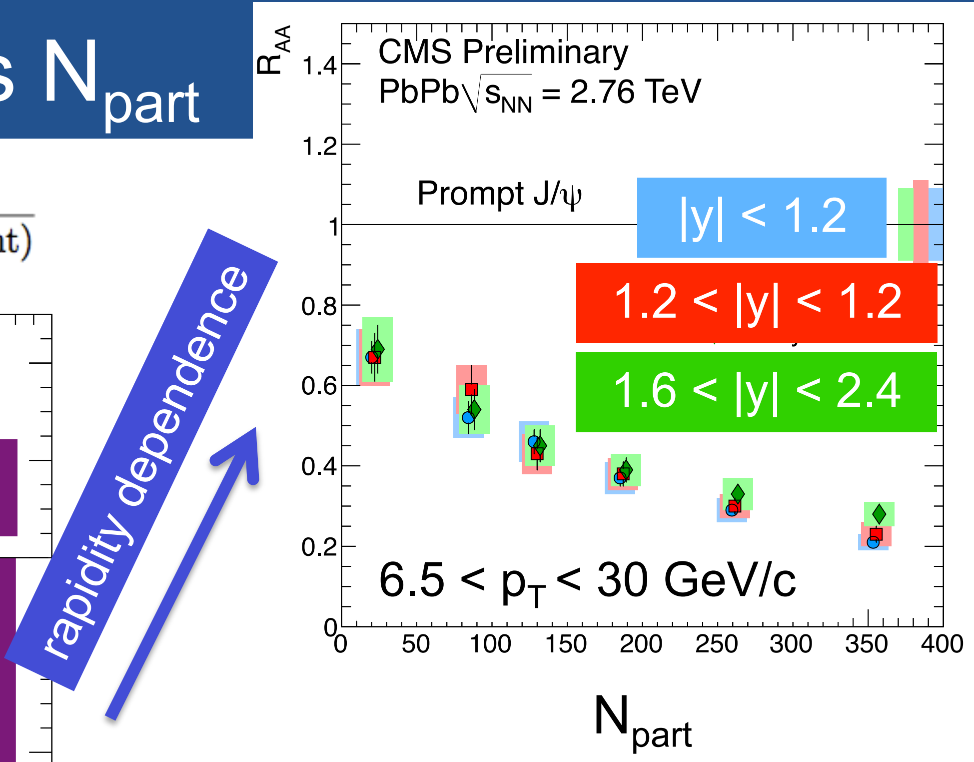
- Suppressed by factor 5 in most central

R_{AA} of prompt J/ψ vs N_{part}

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}(J/\psi)}{N_{pp}(J/\psi)} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}(cent)}$$

PAS CMS-HIN-12-014



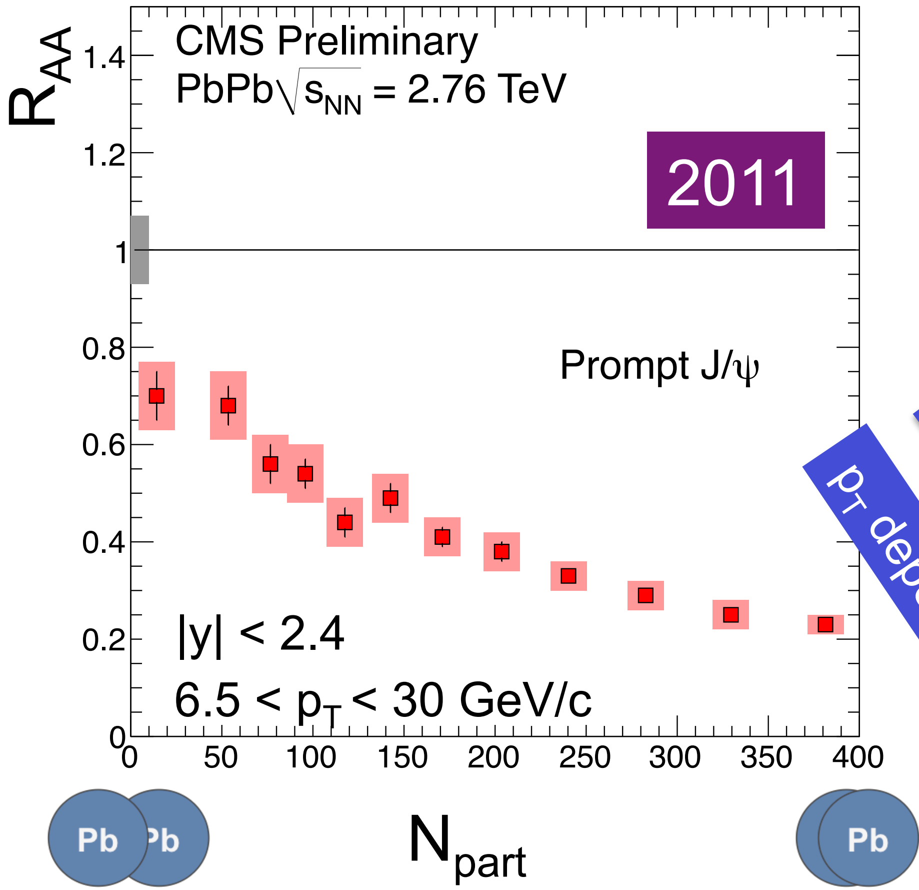


- No strong dependence on rapidity

R_{AA} of prompt J/ψ vs N_{part}

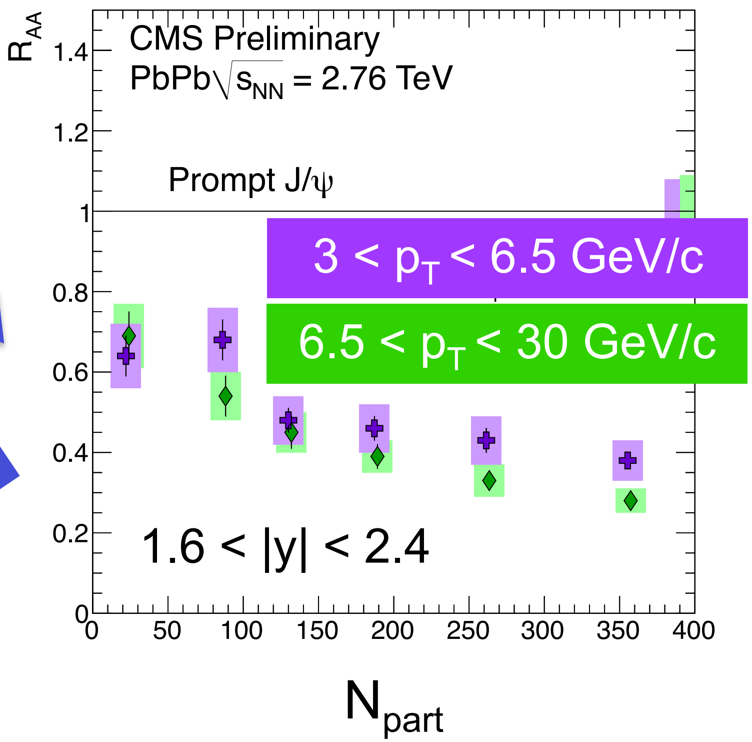
$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}(J/\psi)}{N_{pp}(J/\psi)} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}(\text{cent})}$$

PAS CMS-HIN-12-014

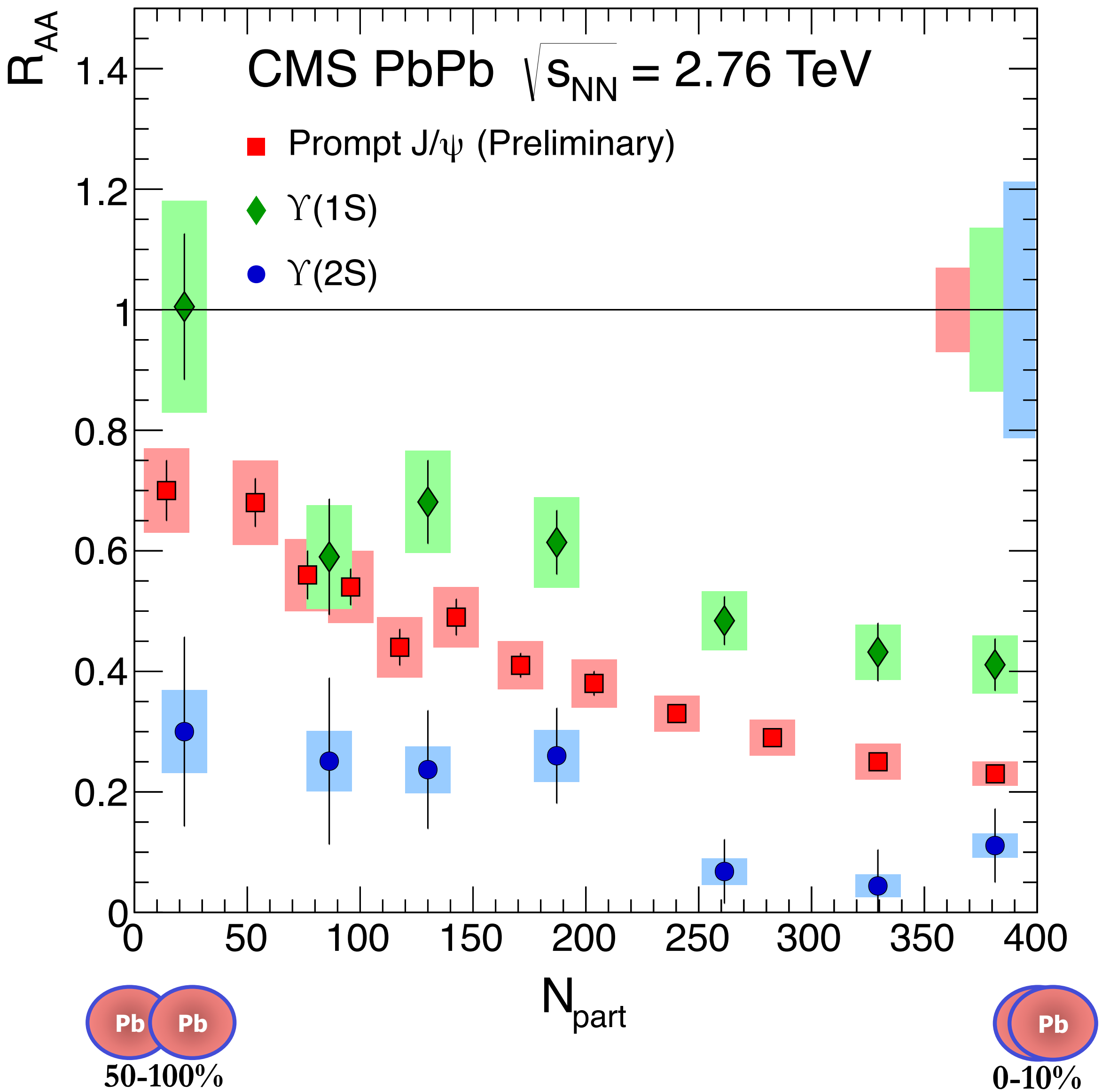


- Hint of less suppression at lower p_T

pT dependence

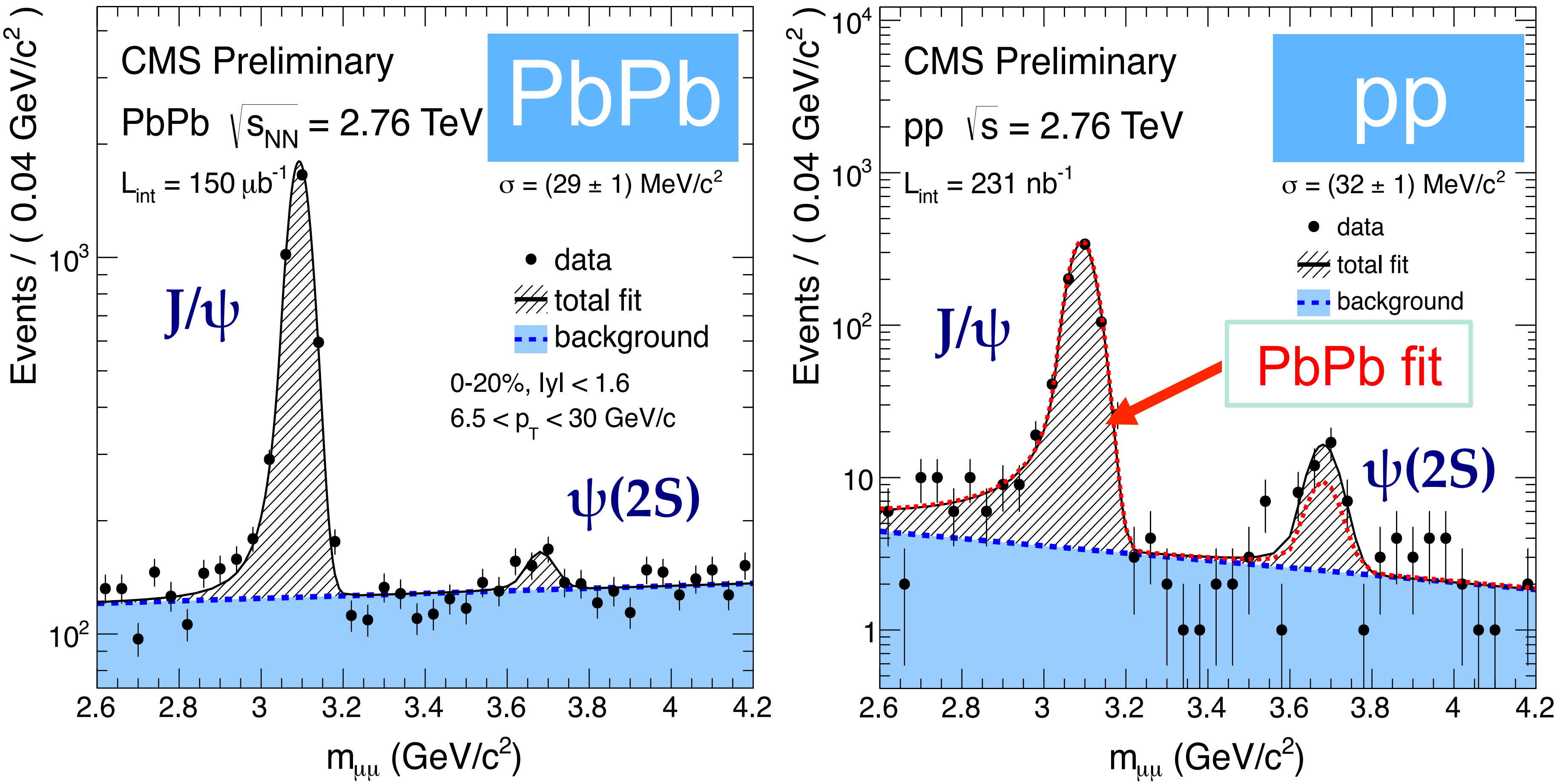


Charmonia Comparisons



ψ(2S) PbPb and pp

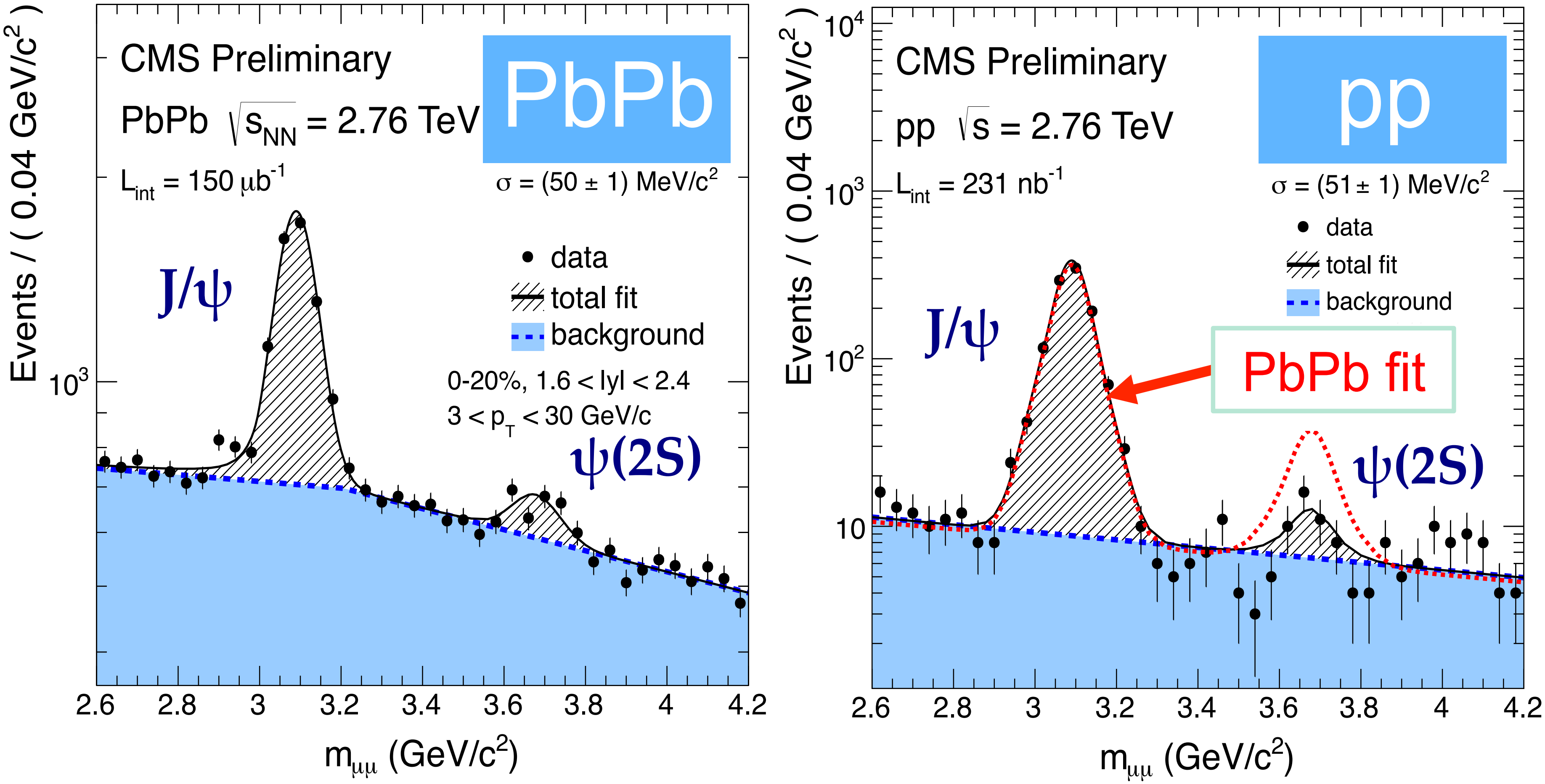
$|y| < 1.6$ and $6.5 < p_T < 30$ GeV/c



Raw yields ratio (ψ(2S) / J/ψ) in PbPb is ~2 times smaller than pp.

ψ(2S) PbPb and pp

$1.6 < |y| < 2.4$ and $3 < p_T < 30$ GeV/c



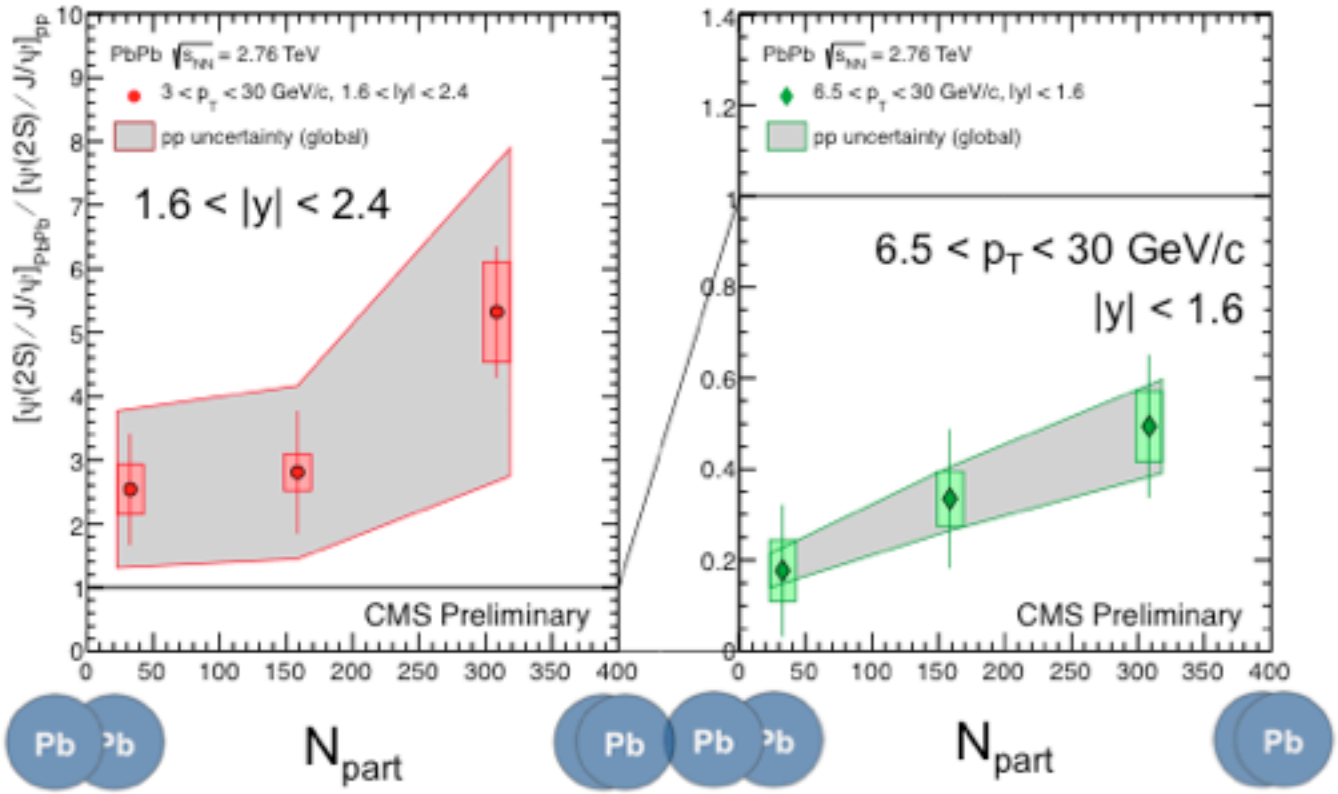
Raw ratio (ψ(2S) / J/ψ) in PbPb is ~5 times larger than pp.

Double Ratio ψ(2S) / J/ψ

3 < p_T < 30 GeV/c

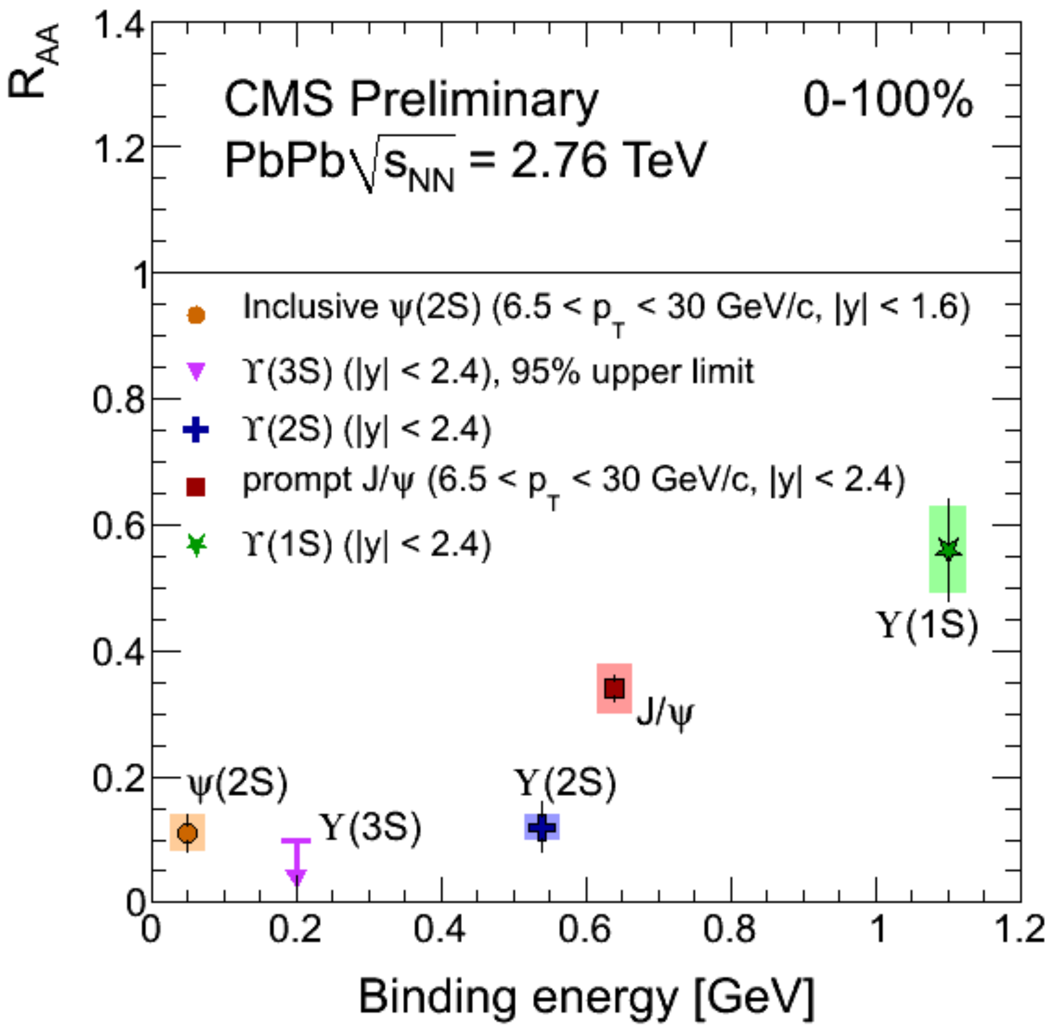
$$\frac{R^{\mathrm{PbPb}}_{\psi(2S)}}{R^{\mathrm{pp}}_{\psi(2S)}} = \left[\frac{N_{\psi(2S)}}{N_{J/\psi}}\right]_{\mathrm{PbPb}} \Big/ \left[\frac{N_{\psi(2S)}}{N_{J/\psi}}\right]_{\mathrm{pp}}$$

PAS CMS-HIN-12-007



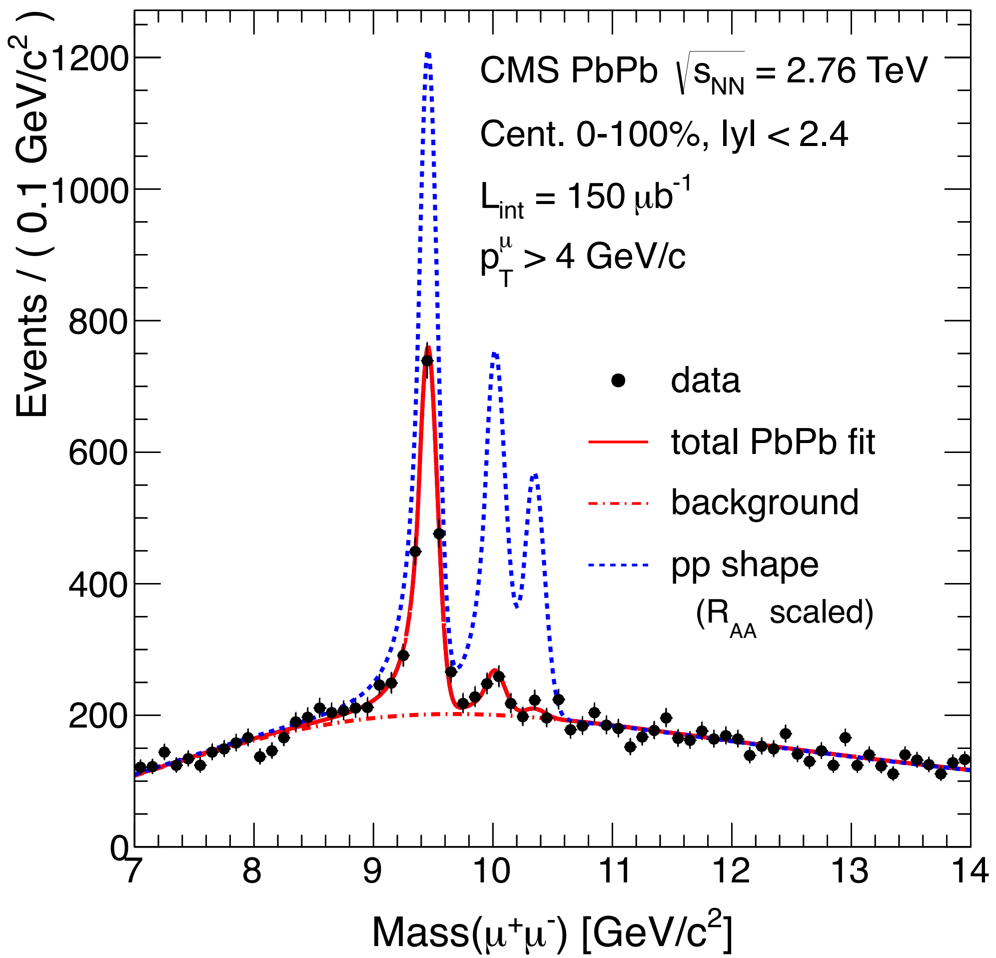
For p_T > 6.5 GeV/c, ψ(2S) are more suppressed than J/ψ.
Indication that ψ(2S) less suppressed than J/ψ for p_T > 3 GeV/c.
(not more than 2σ significance, limited by pp statistics)

Putting it all together



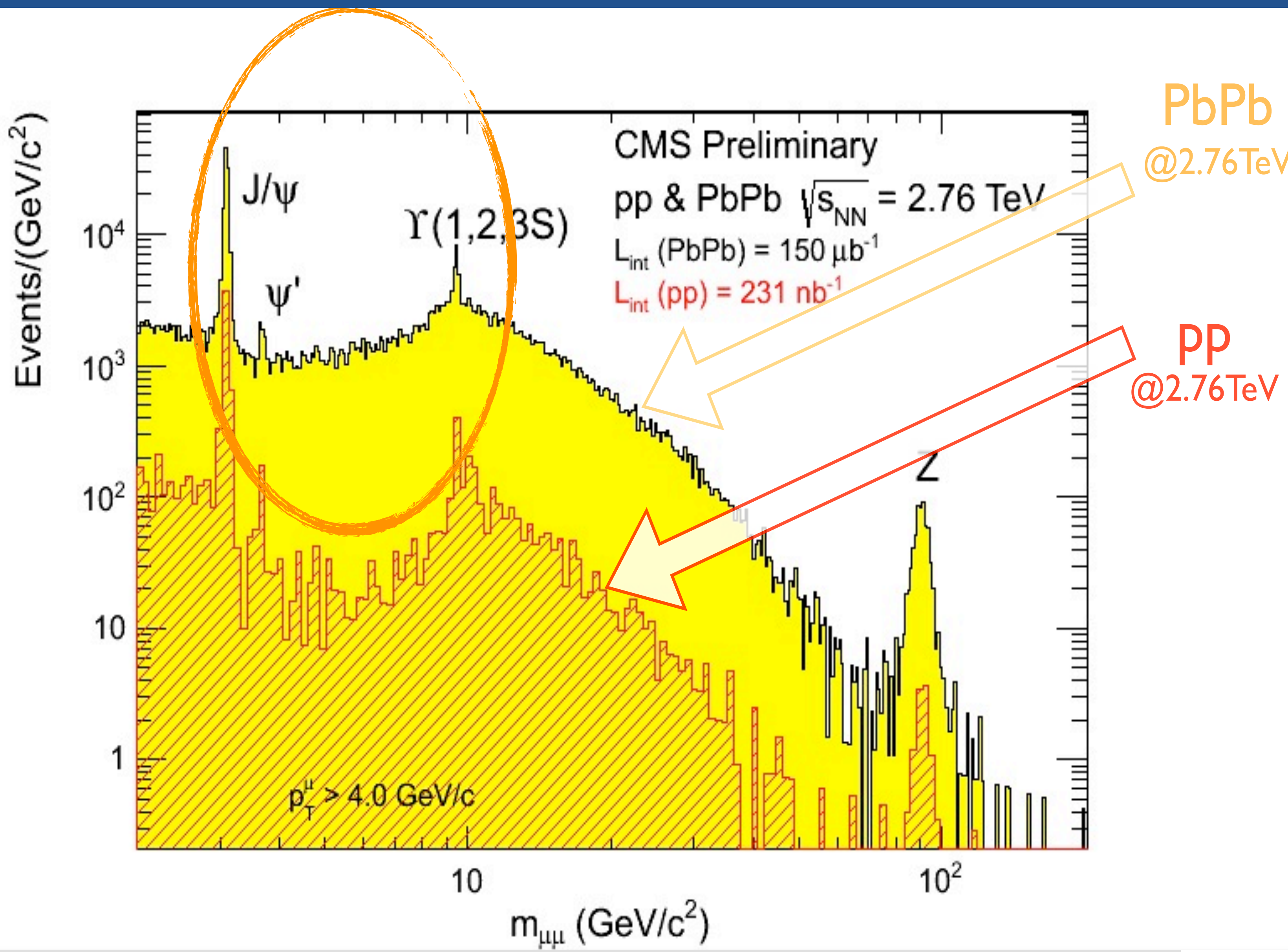
Summary

- ✓ First measurements of the excited Υ states in heavy-ions.
- ✓ Υ (1S) suppression consistent with melting of excited states only.
- ✓ Suppression pattern (sequential "melting") has been established.
- ✓ Set upper limits for the Υ (3S) state for the first time.

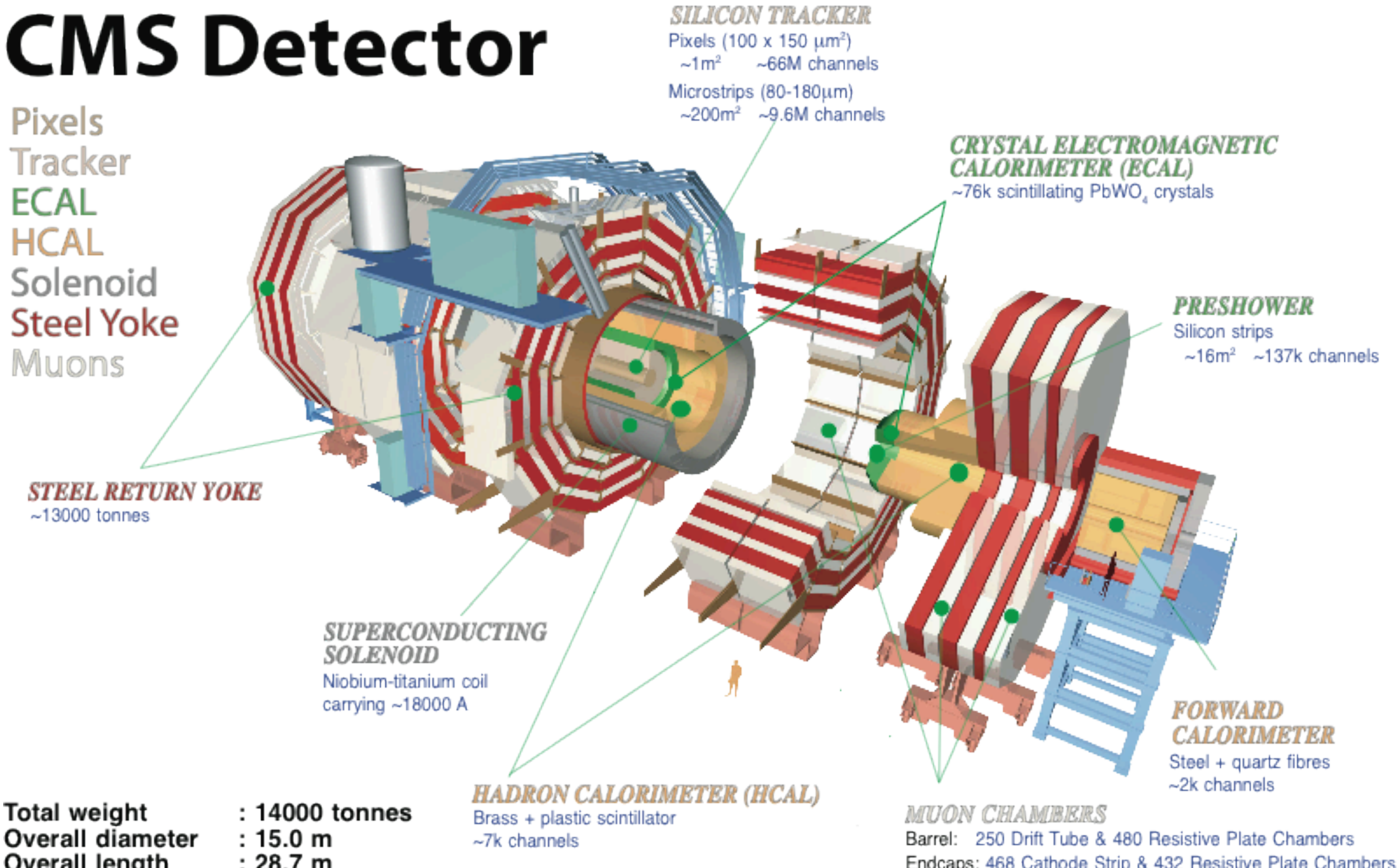


Back-up

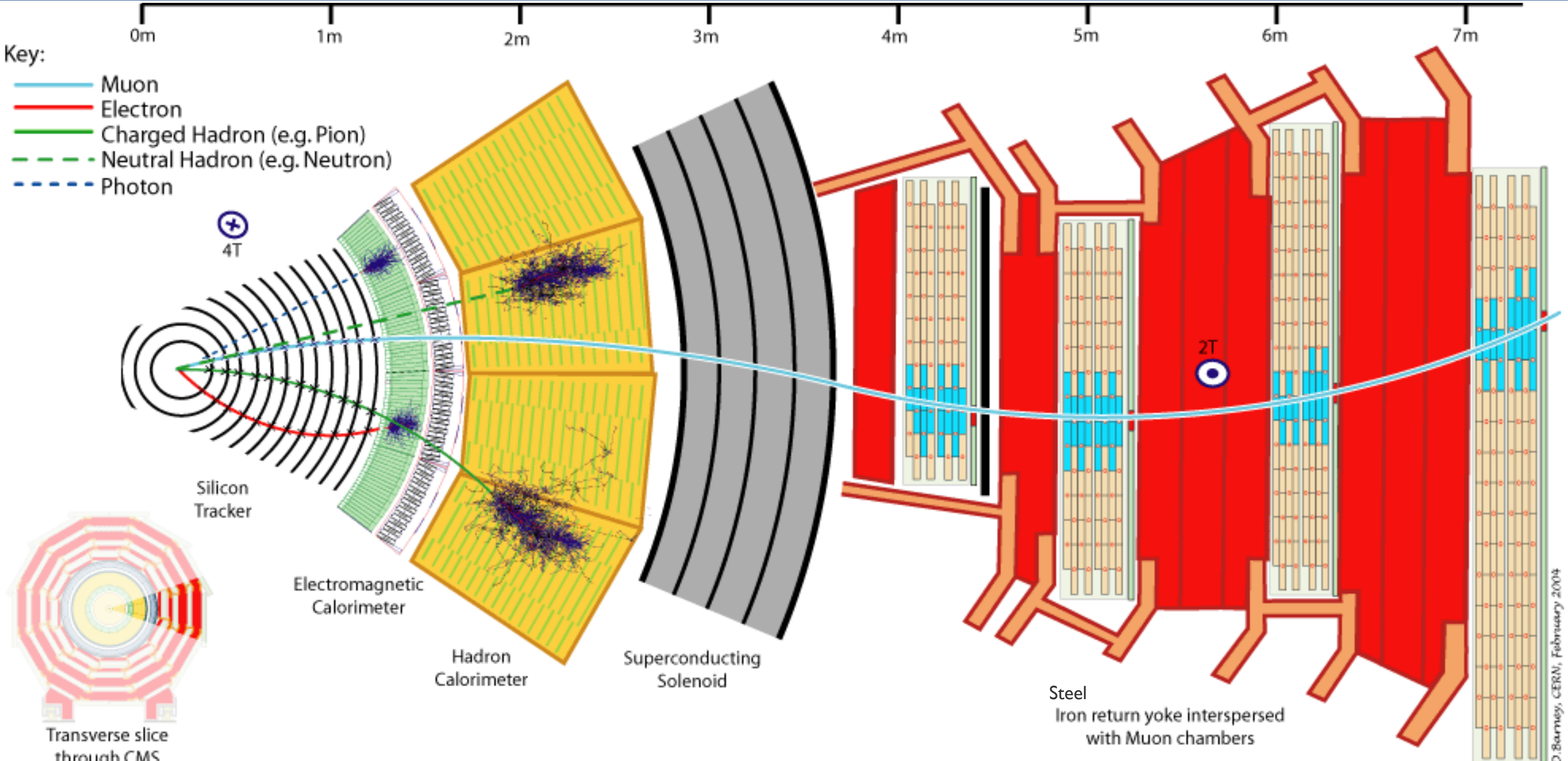
Muon pairs in PbPb and pp at √s$_{NN}$ = 2.76 TeV



The Compact Muon Solenoid



Muon reconstruction in CMS



Global muons reconstructed with information from tracker and muon stations

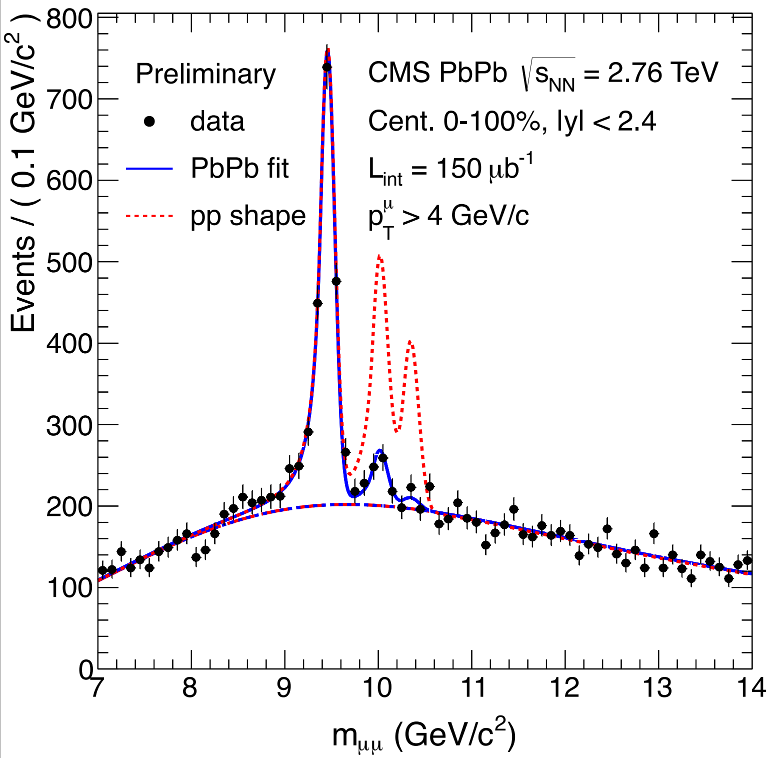
Muons need to overcome the magnetic field and energy loss in the absorber → need a minimum momentum of p~3–5 GeV/c to reach the muon stations

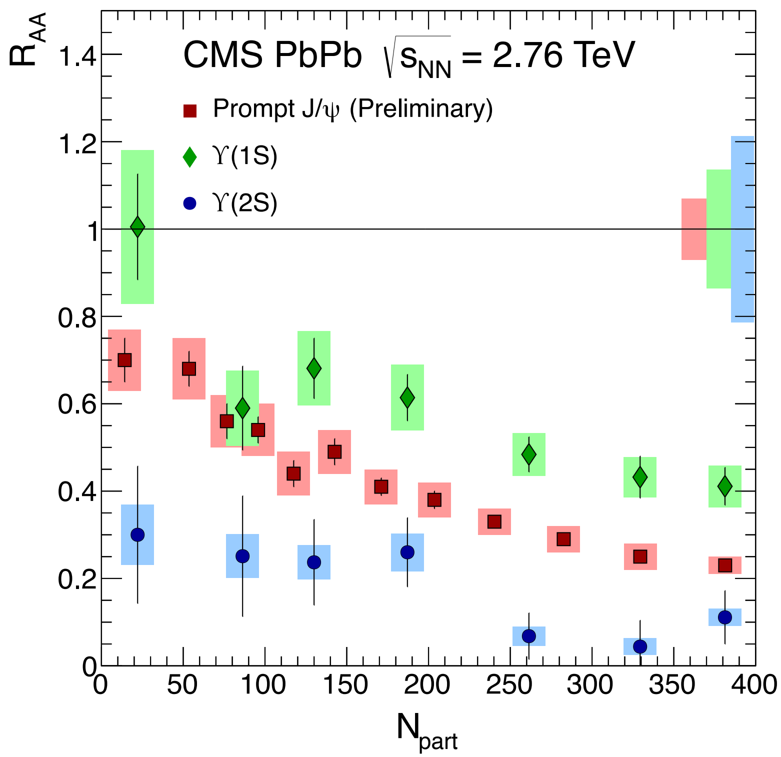
Further muon ID based on track quality (χ^2, # hits,...)

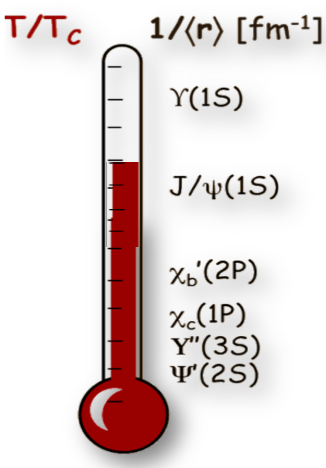
Quarkonia Suppression

We have established the suppression pattern pinning down medium properties.

We have measured the Quarkonia sequential suppression

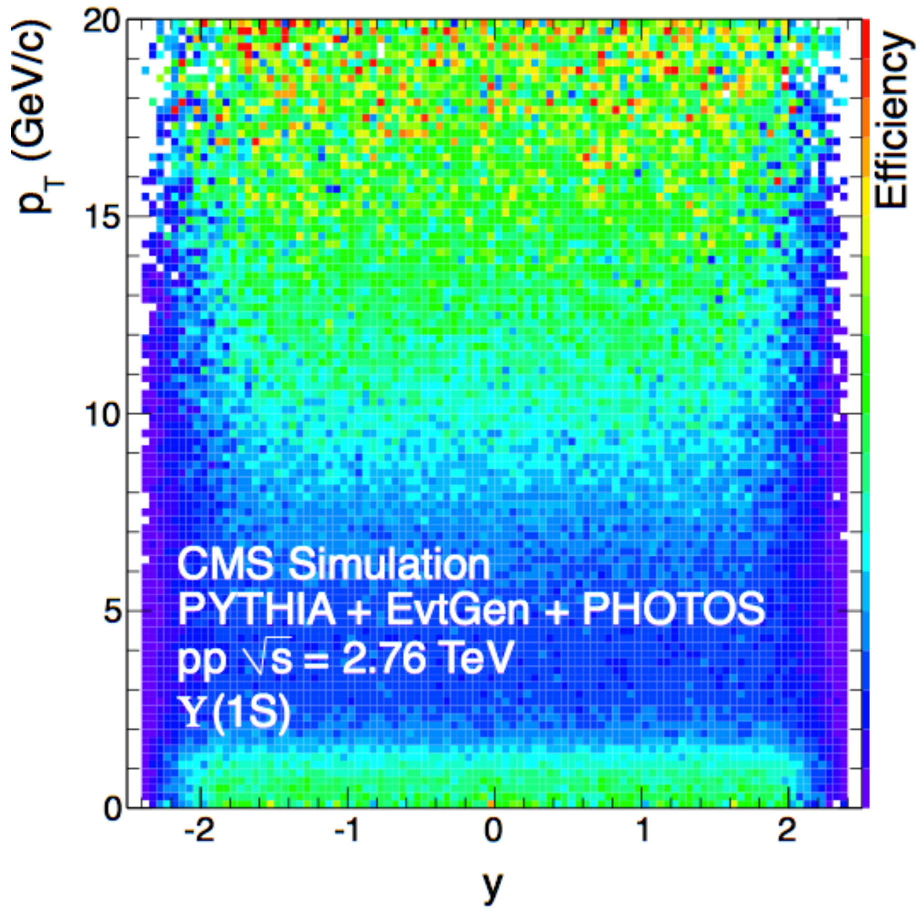






Acceptance/Efficiency

Acceptance



Efficiency