Bottomonium production in pp, pPb, and PbPb collisions with CMS

Triggering Discoveries in High Energy Physics, 9-14 September 2013
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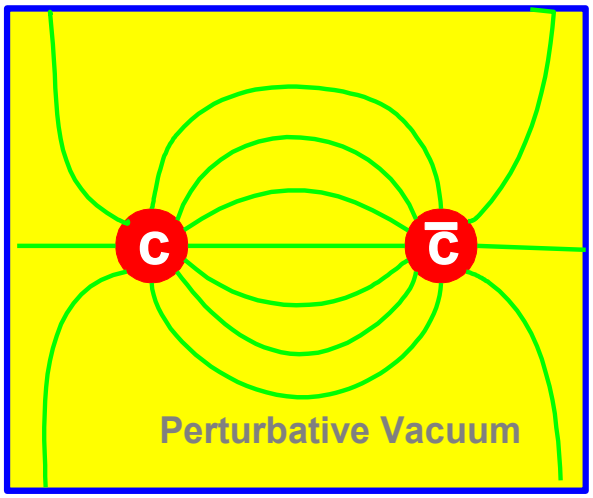
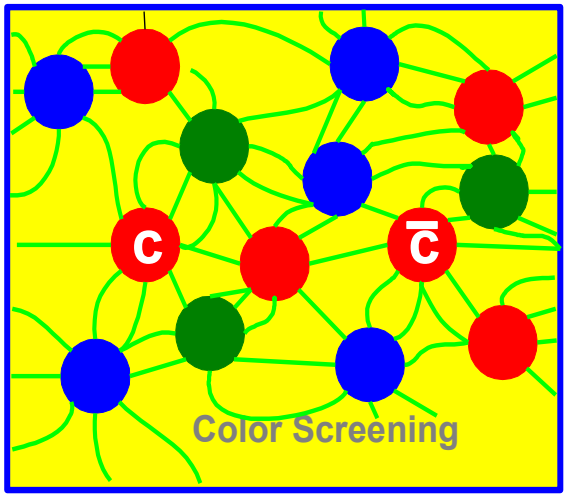
Outline

- Physics Motivation of quarkonium analyses in heavy ion collisions.
- Compact Muon Solenoid (CMS) at Large Hadron Collider (LHC).
- Υ measurements in Pb+Pb collisions.
- Υ measurements in p+Pb and p+p collisions.
- Summary and outlook.

QGP and Colour Screening of Quarkonia

- QCD Calculations indicate that, at a critical temperature around 170 MeV, strongly interacting matter undergoes a phase transition to a new state where the quarks and gluons are no longer confined in hadrons.
- Aim of Heavy Ion Collisions at high energies is to create, characterize and quantify the properties of QGP.



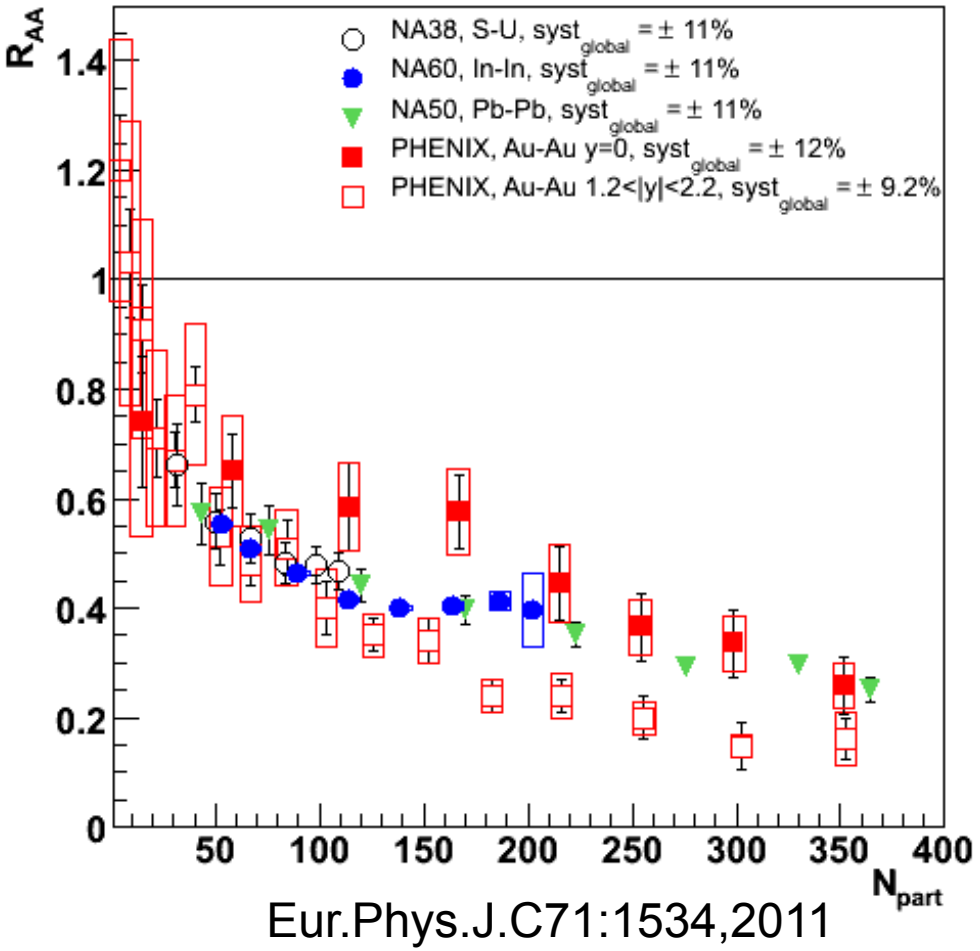


- Color screening in QGP is expected to prevent the formation of quarkonium states in deconfined matter
- Different quarkonium states J/ψ, ψ', χ_c, Υ(1S,2S,3S) are expected to dissociate at different temperatures, sequentially according to their radius.
- Measurement of a suppressed quarkonium yield may provide experimental sensitivity to the temperature of the medium created in high energy nuclear collisions.

Status of quarkonium measurements at lower energies

- Similar J/ψ suppression at the SPS and RHIC.
- More suppression in forward rapidity region at RHIC.
- But R_{AA} includes both hot and cold nuclear matter effects.
- **Hot Matter Effects**
  - color screening
- **Cold Nuclear Matter Effects**
  - Anything that can modify the production of heavy quarkonia in nucleus collisions (as opposed to p+p) in absence of a QGP.
  - To know the real effect of medium created in heavy ion collisions, measurements in pPb and pp collisions are essential.

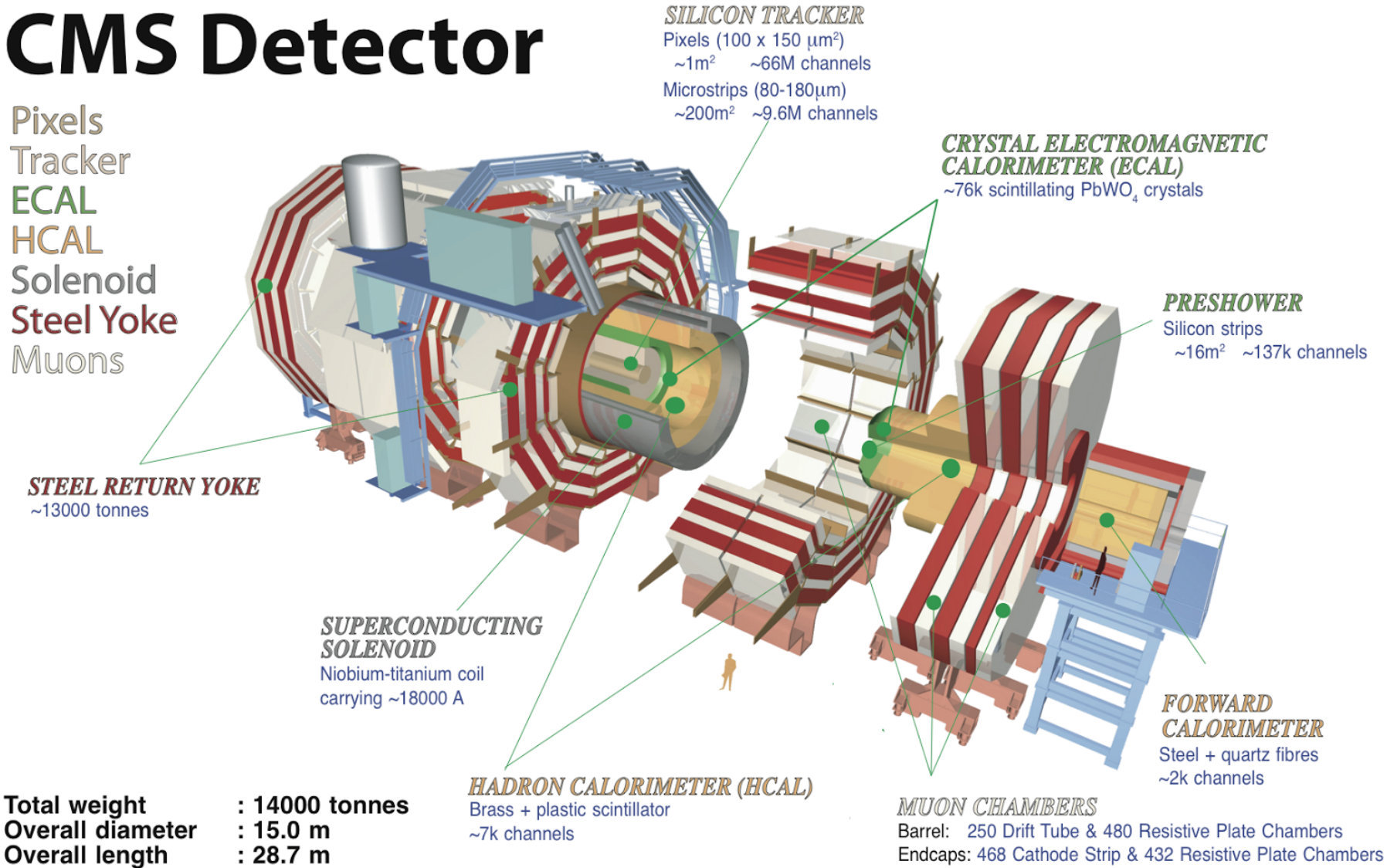
$$R_{AA} = \frac{N_{AA}}{N_{pp} \times N_{Coll}} \frac{\epsilon_{AA}}{\epsilon_{pp}}$$



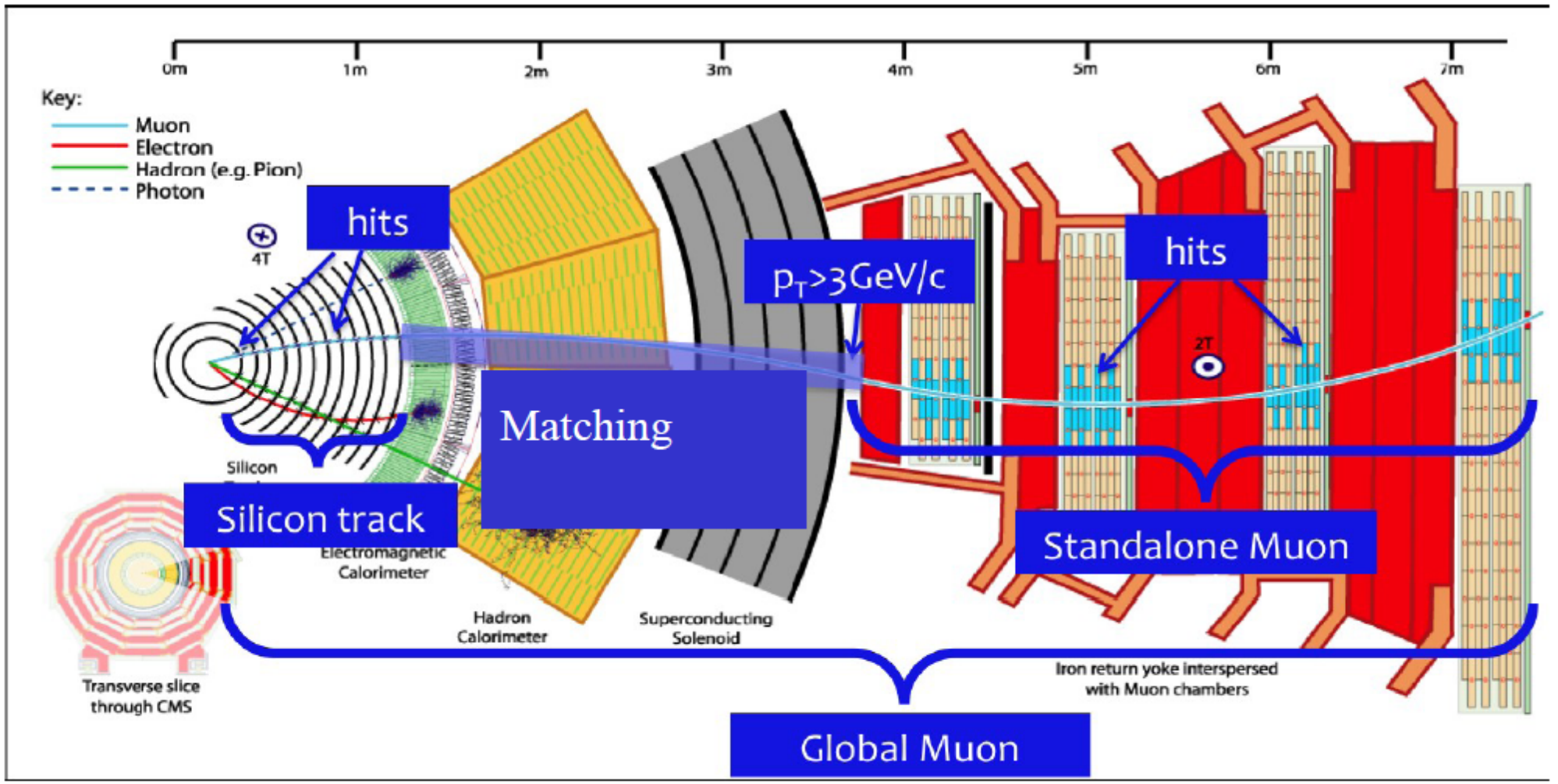
Eur.Phys.J.C71:1534,2011

CMS Detector at LHC

CMS at LHC


CMS Detector
Pixels
Tracker
ECAL
HCAL
Solenoid
Steel Yoke
Muons
SILICON TRACKER
Pixels (100 x 150 μm²)
~1m² ~66M channels
Microstrips (80-180μm)
~200m² ~9.6M channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76k scintillating PbWO4 crystals
PRESHOWER
Silicon strips
~16m² ~137k channels
STEEL RETURN YOKE
~13000 tonnes
SUPERCONDUCTING SOLENOID
Niobium-titanium coil
carrying ~18000 A
FORWARD CALORIMETER
Steel + quartz fibres
~2k channels
HADRON CALORIMETER (HCAL)
Brass + plastic scintillator
~7k channels
MUON CHAMBERS
Barrel: 250 Drift Tube & 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip & 432 Resistive Plate Chambers
Total weight : 14000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T

Muon reconstruction in CMS



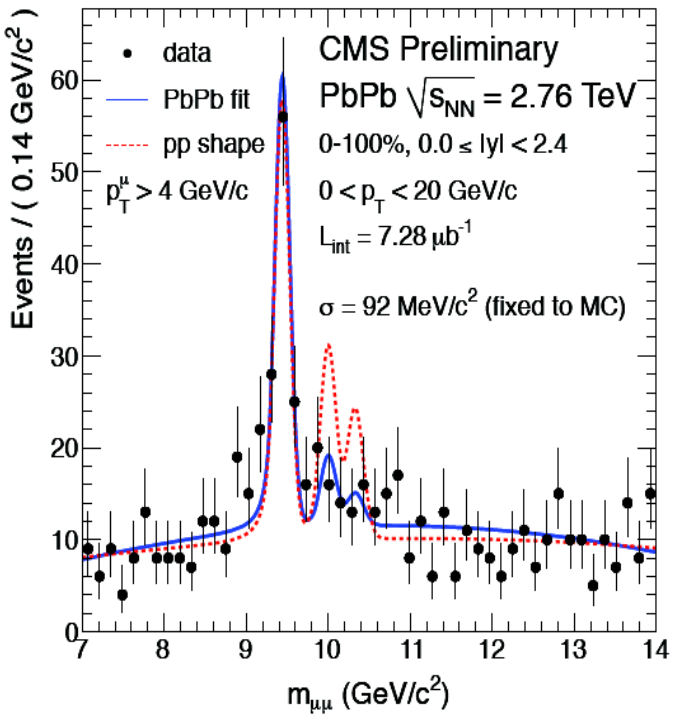
- Global Muons reconstructed with information from inner tracker and muon stations.
- StandAloneMuons in Muon chambers only.

LHC Runs of Heavy Ion Interest

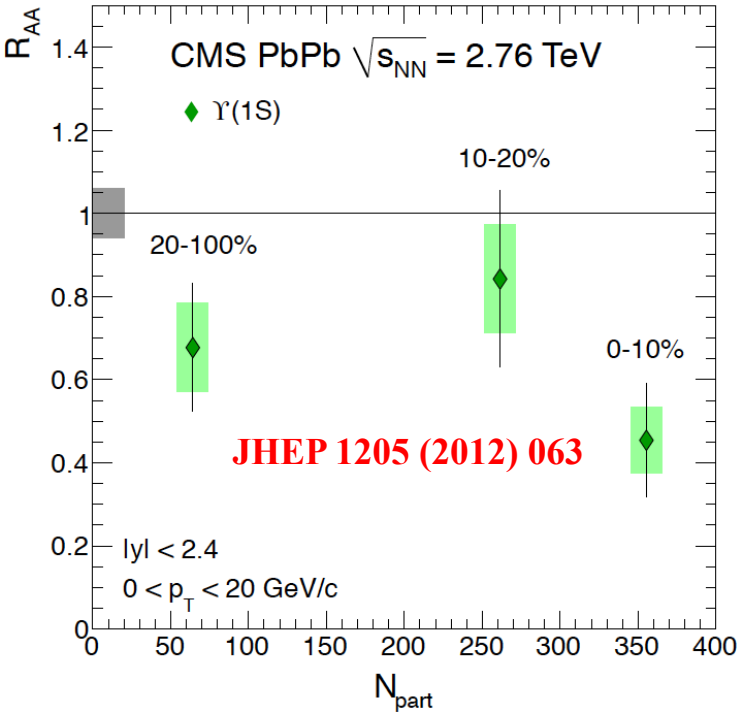
- 1st PbPb run at $\sqrt{s_{NN}}$ = 2.76 TeV (Nov-Dec 2010)
  - Recorded integrated luminosity: 7.3 μb^{-1}
- 2nd PbPb run at $\sqrt{s_{NN}}$ = 2.76 TeV (Nov-Dec 2011)
  - Recorded integrated luminosity: 150 μb^{-1}
- 1st pp run at $\sqrt{s}$ = 2.76 TeV (March 2011)
  - Recorded integrated luminosity: 230 nb^{-1}
- 1st pPb run at $\sqrt{s_{NN}}$ = 5.02 TeV (Jan-Feb 2013)
  - Recorded integrated luminosity: 31.7 nb^{-1}
- 2nd pp run at $\sqrt{s}$ = 2.76 TeV (Feb 2013)
  - Recorded integrated luminosity: 5.4 pb^{-1}
- Also high energy , high luminosity pp runs
- Our larger pp, pPb and PbPb data sets have roughly same N_{coll} scaled luminosities.

Υ measurement in Pb+Pb collisions

ϒ measurement with First Pb+Pb data at LHC



PRL. 107, 052302 (2011)



- First measurement of relative suppression of excited ϒ states.
- DR ($\Upsilon(2S+3S)/\Upsilon(1S)_{PbPb}/\Upsilon(2S+3S)/\Upsilon(1S)_{pp}$) = $0.31^{+0.19}_{-0.15}$ (stat.) ± 0.03 (syst.)

- Nuclear modification factor (R_{AA})

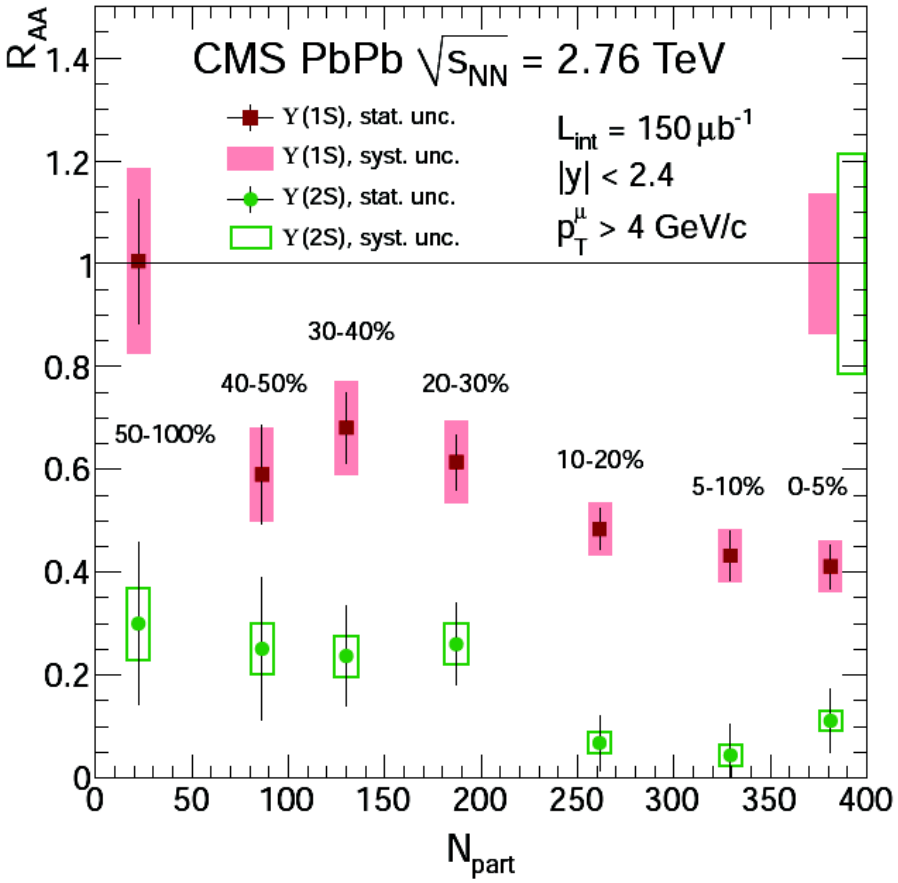
$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}(Q\bar{Q})}{N_{pp}(Q\bar{Q})} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}$$

- ϒ (1S) is suppressed in the most central collisions (0-10%)
  $R_{AA} = 0.45 \pm 0.14 \pm 0.08$

Υ measurement with second Pb+Pb run at LHC

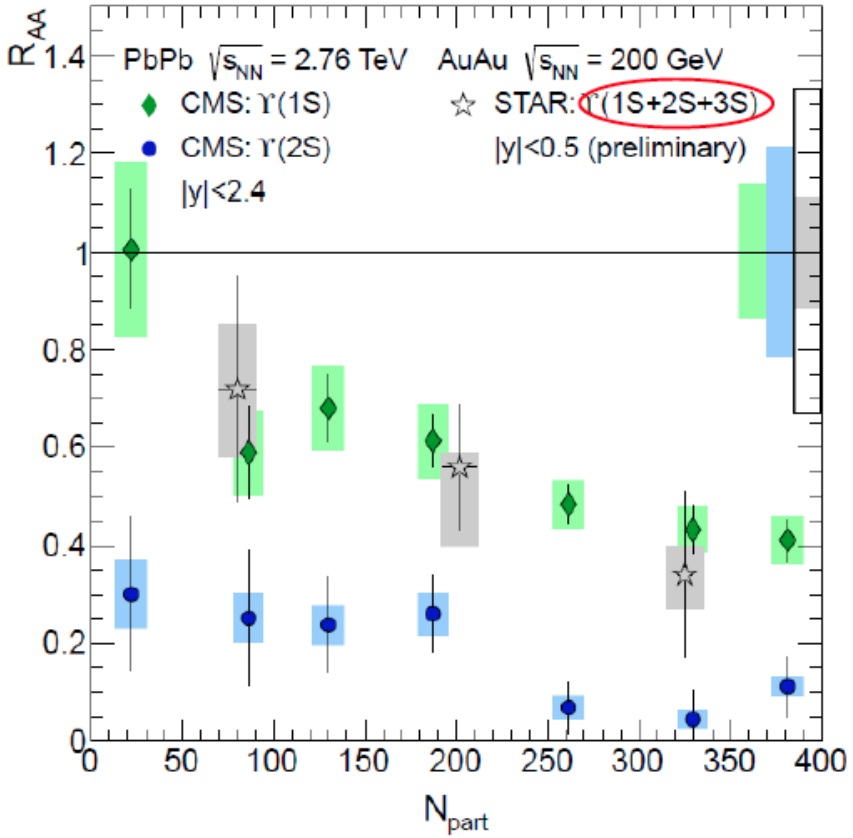
Nuclear Modification Factor as a function of event centrality

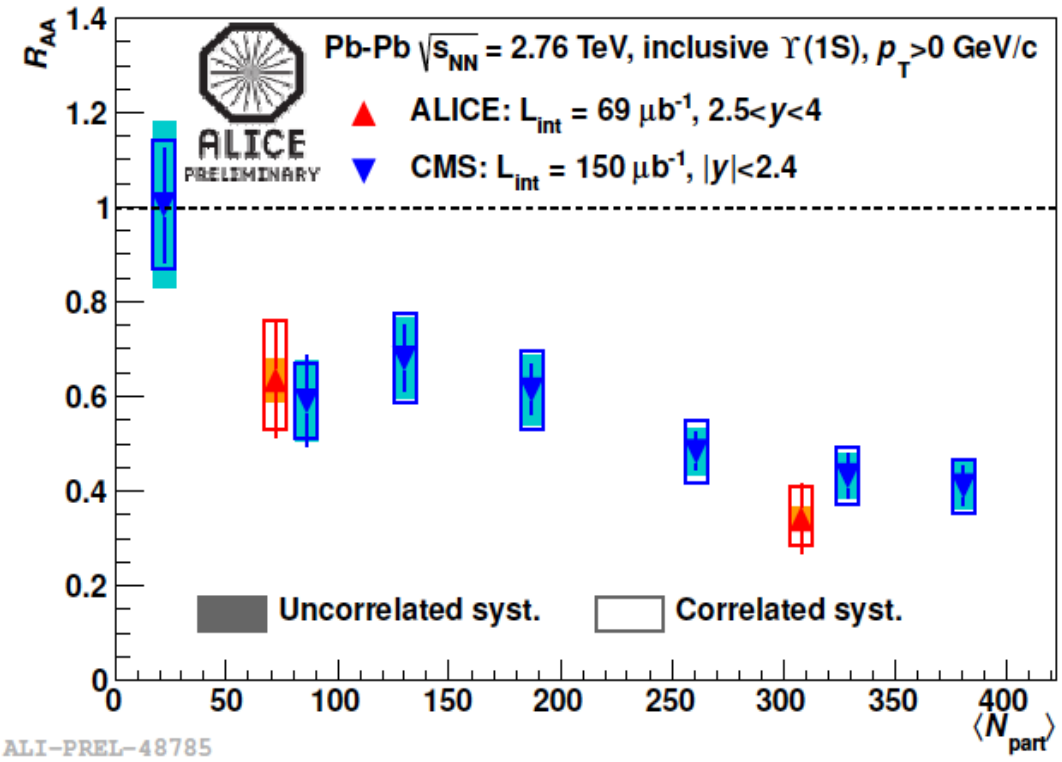
- Suppression of individual ϒ states as a function of centrality of event.
- ϒ(2S) more suppressed than ϒ(1S).
- ϒ(2S) still suppressed in most peripheral bin.
- ϒ(1S) : 0.41 ± 0.05 ± 0.04 (0-5%) → 1.01 ± 0.18 ± 0.12 (50-100%)
- ϒ(2S) : 0.11 ± 0.02 ± 0.06 (0-5%) → 0.30 ± 0.07 ± 0.16 (50-100%)



PRL. 109, 222301 (2012)

Comparison with Other Experiments

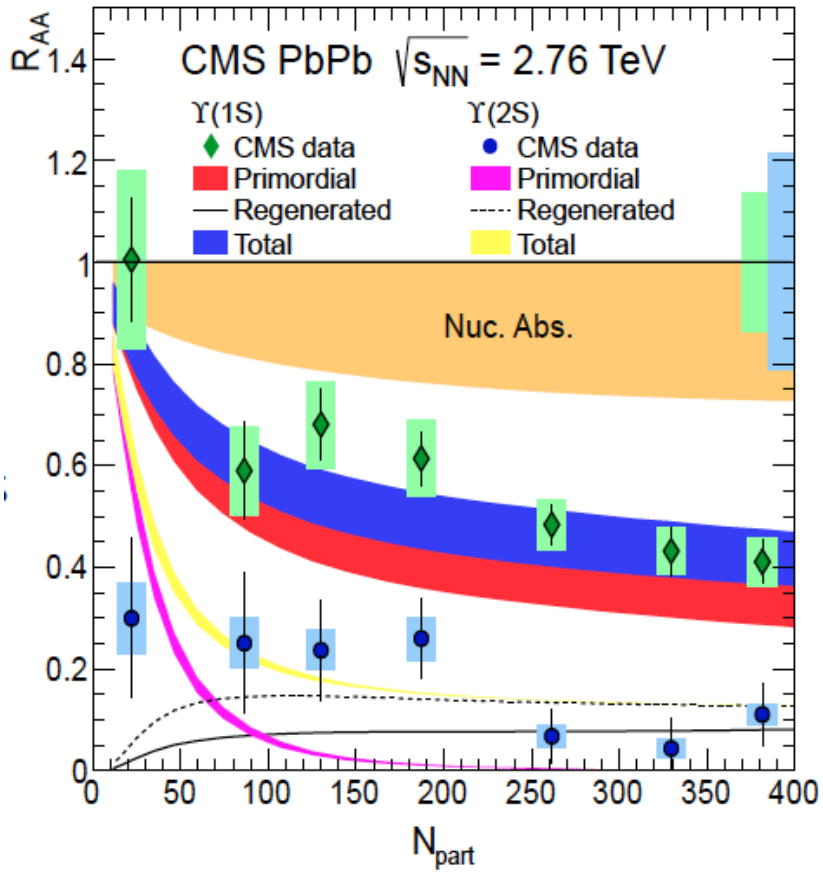




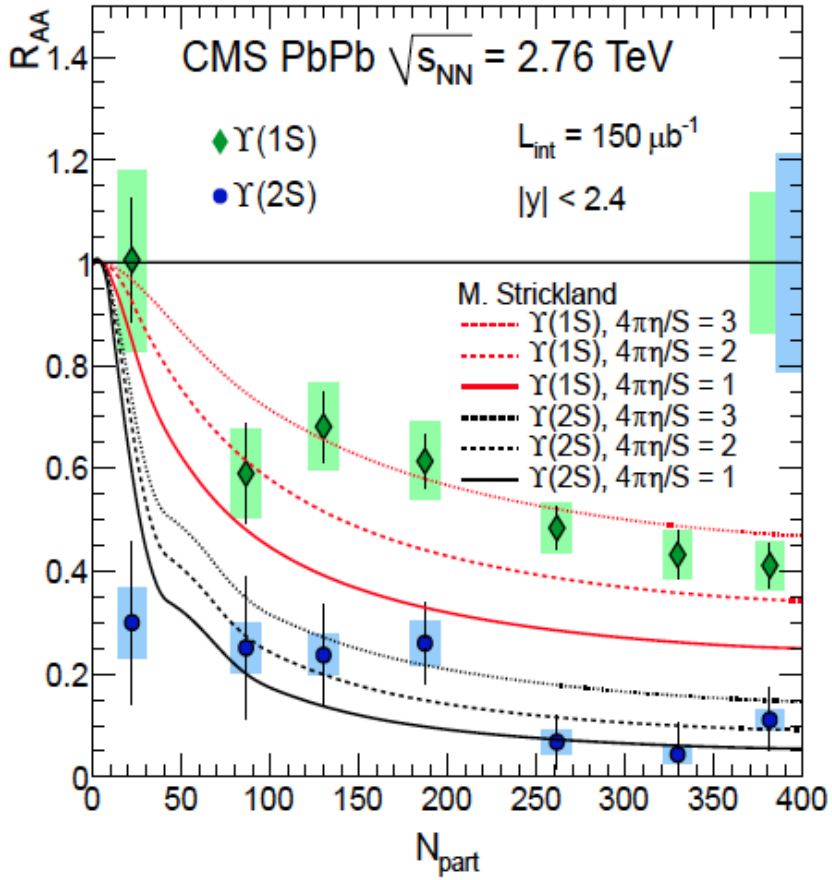
- STAR measurement for ϒ(1S+2S+3S)
- Qualitative agreement with CMS ϒ(1S) within uncertainty.

- ALICE measurement at forward rapidity
- ϒ(1S) suppression similar in magnitude as measured by CMS.

Comparison with Models



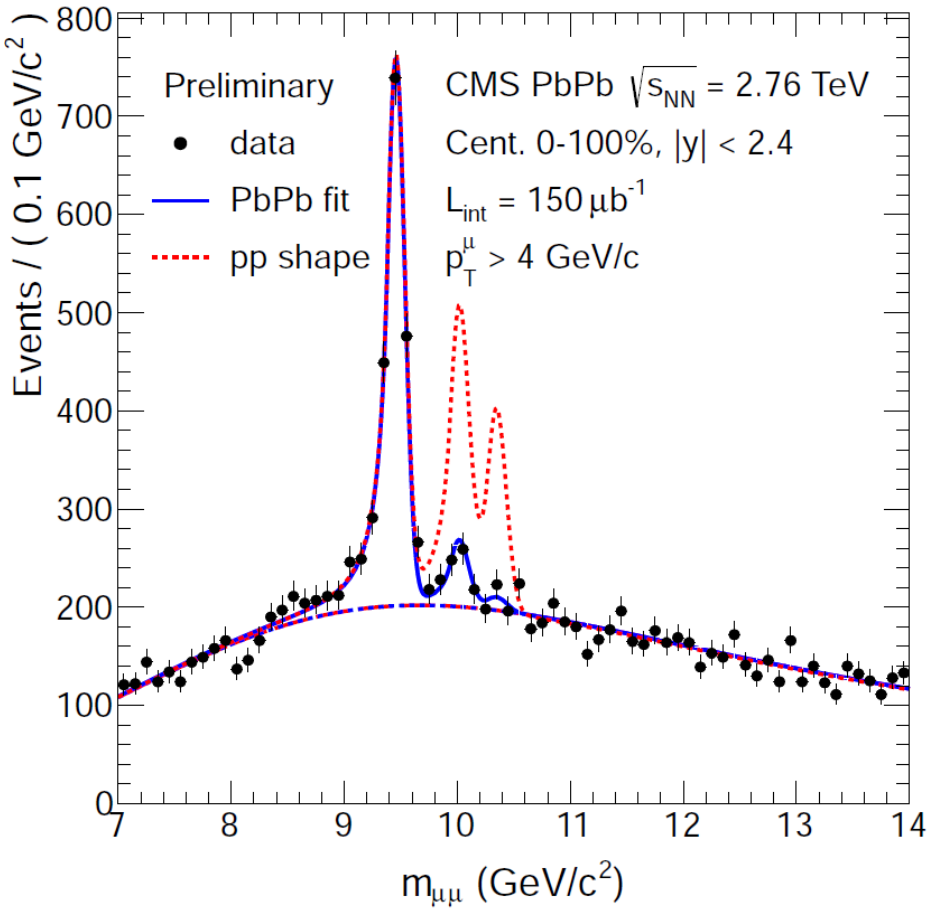
A. Emerick et al EPJA 48, 72 (2012)

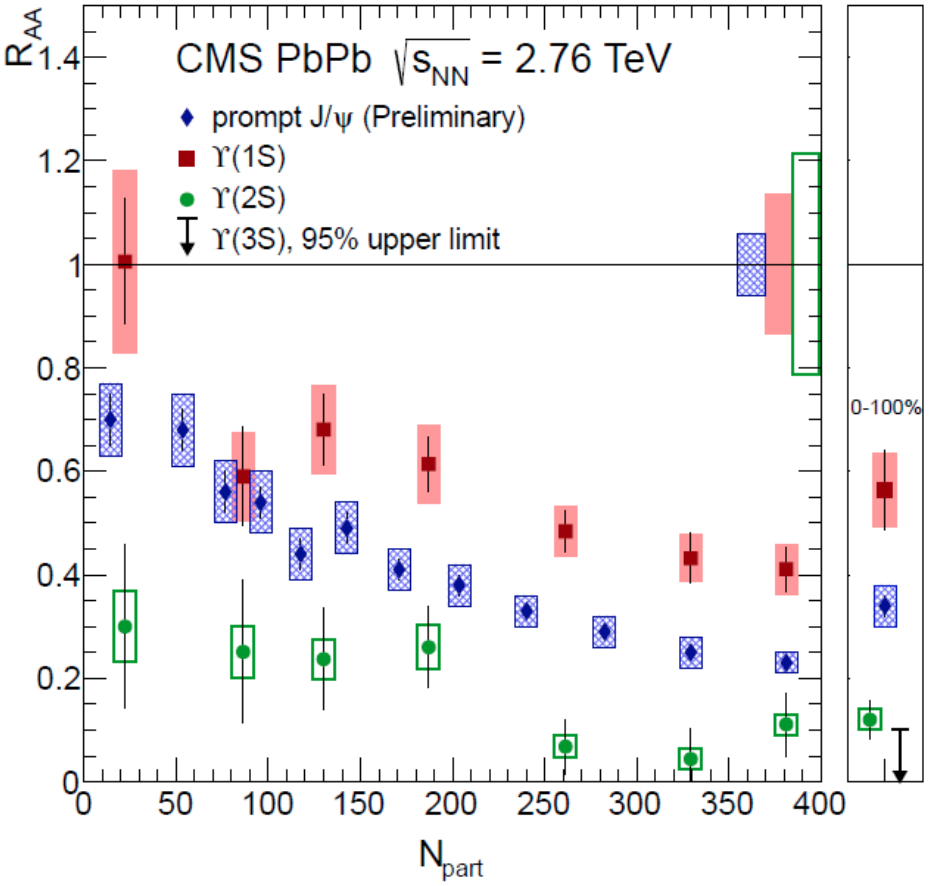


M. Strickland PRL 107, 132301 (2011)

- (Left) Kinetic equation approach assuming strong binding scenario.
  - Substantial regeneration for Υ(2S), Large uncertainty in nuclear absorption.
  - Mostly consistent with data.
- (Right) Calculate p_T dependent survival probability, incorporate lattice based potentials.
  - Anisotropic hydrodynamics for medium evolution.
  - Include sequential melting and feed-down contributions.

Highlights of Υ measurement in PbPb collisions

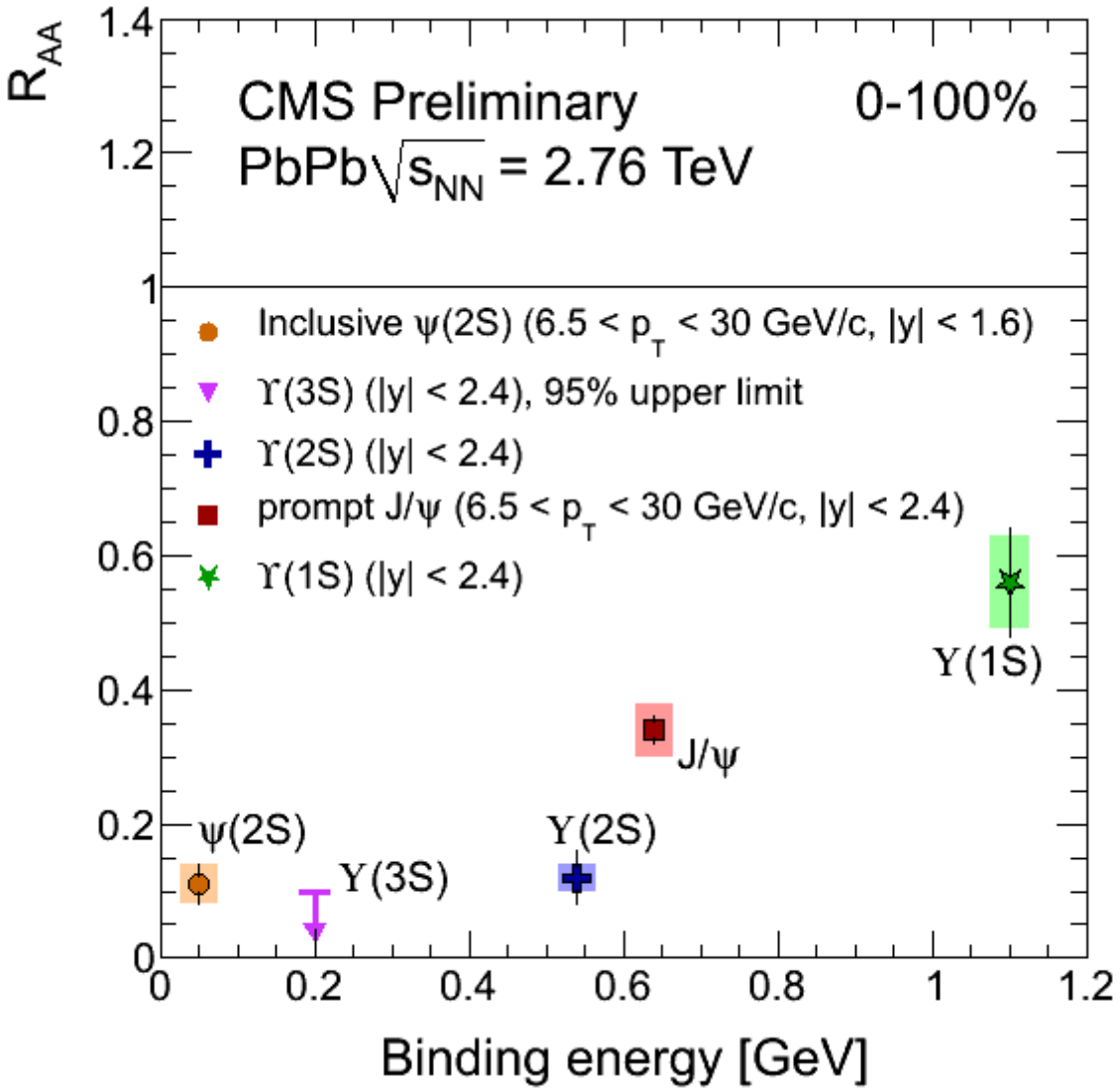




- First separate measurement, in HI collisions, of the relative suppression of Υ(2S) and Υ(3S) excited states wrt to the ground state.
- Suppression pattern as expected in the sequential melting scenario.
- Detailed study of suppression of individual Υ states as a function of centrality of event.
- Υ(2S) more suppressed than Υ(1S).
- Υ(2S) still suppressed in most peripheral bin.

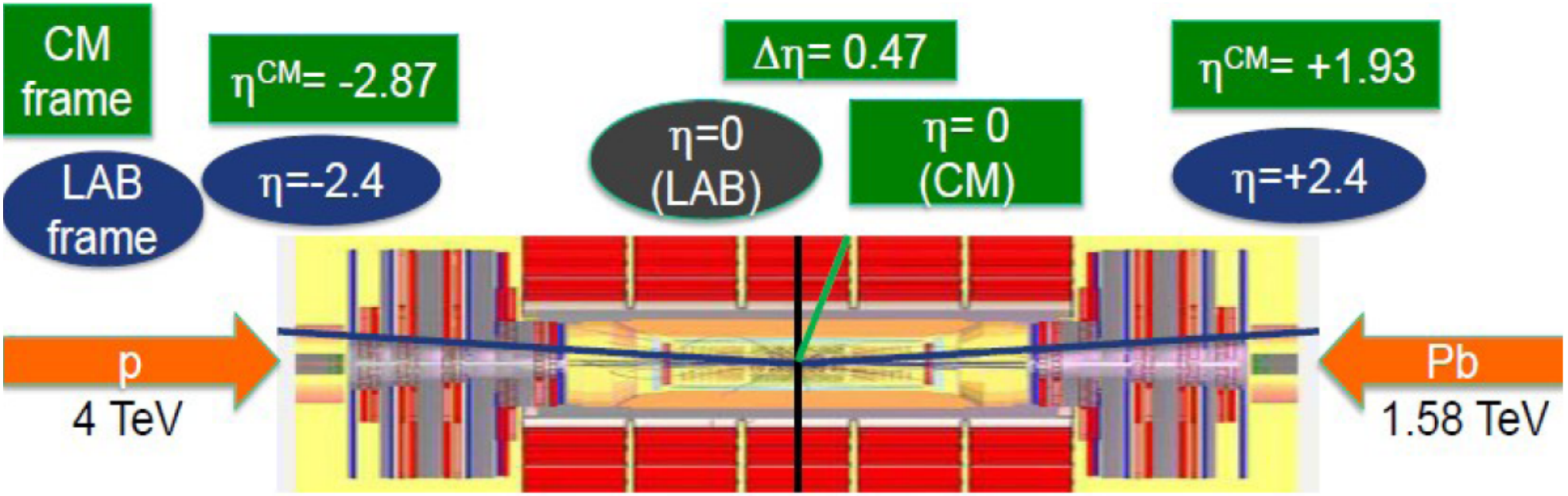
Highlight of Quarkonia measurement in PbPb collisions

- The sequential melting map is experimentally drawn for Υ.
- Staying away from the low p_T regeneration regime, the charmonia also fall well on this map.
- Looser bound states are more suppressed than the tighter bound states.
- Map includes: hot and cold effects(feed-down, nuclear absorption etc.).



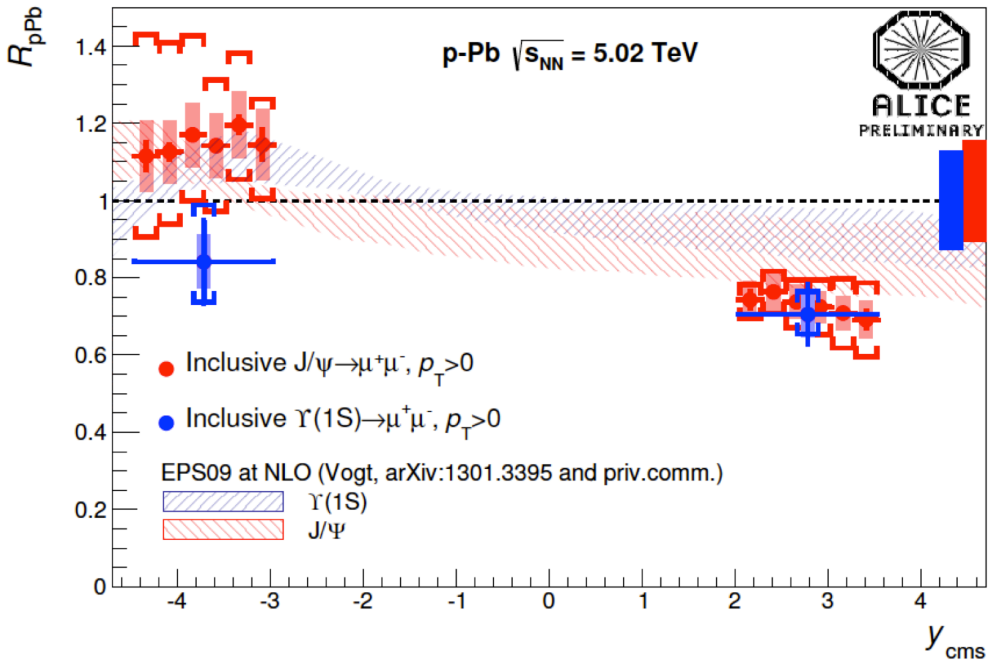
Quarkonia measurement in p+Pb collisions at LHC

p+Pb collisions at LHC

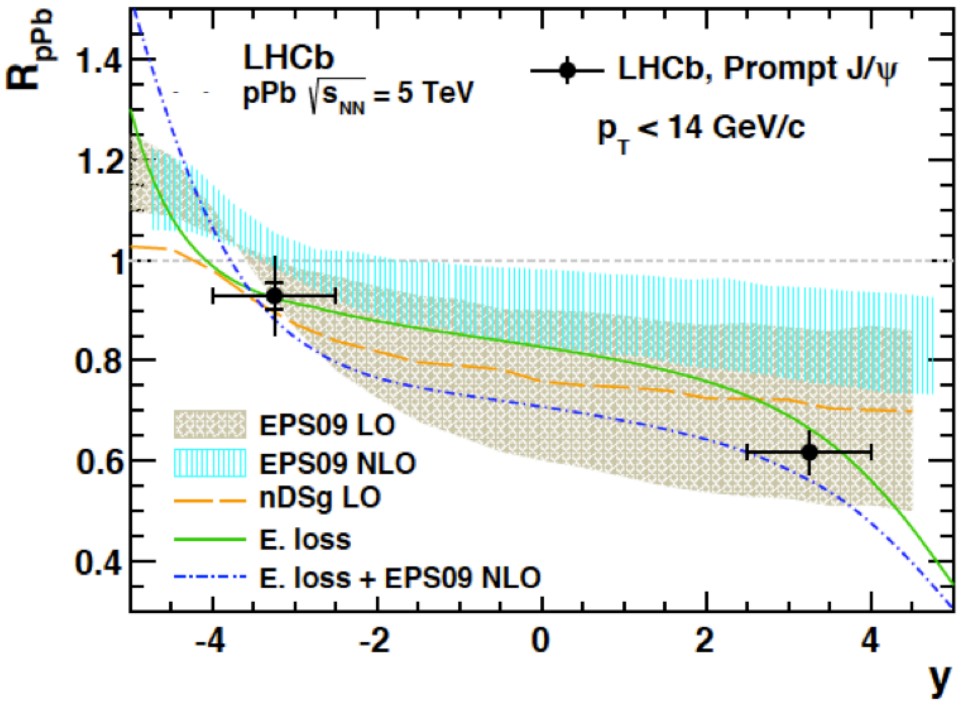


- Integrated Luminosity Pb+p ~18 nb^{-1} , p+Pb ~12 nb^{-1}
- Rapidity shift 0.465
- Energy of p = 4 TeV, Energy of Pb = 4 x 82 / 208 = 1.58 ATeV.
- $\sqrt{s_{NN}} = \sqrt{(4 \times E_p \times E_{Pb})}$ = 5.02 TeV/ nucleon.

Quarkonia measurement in p+Pb collisions



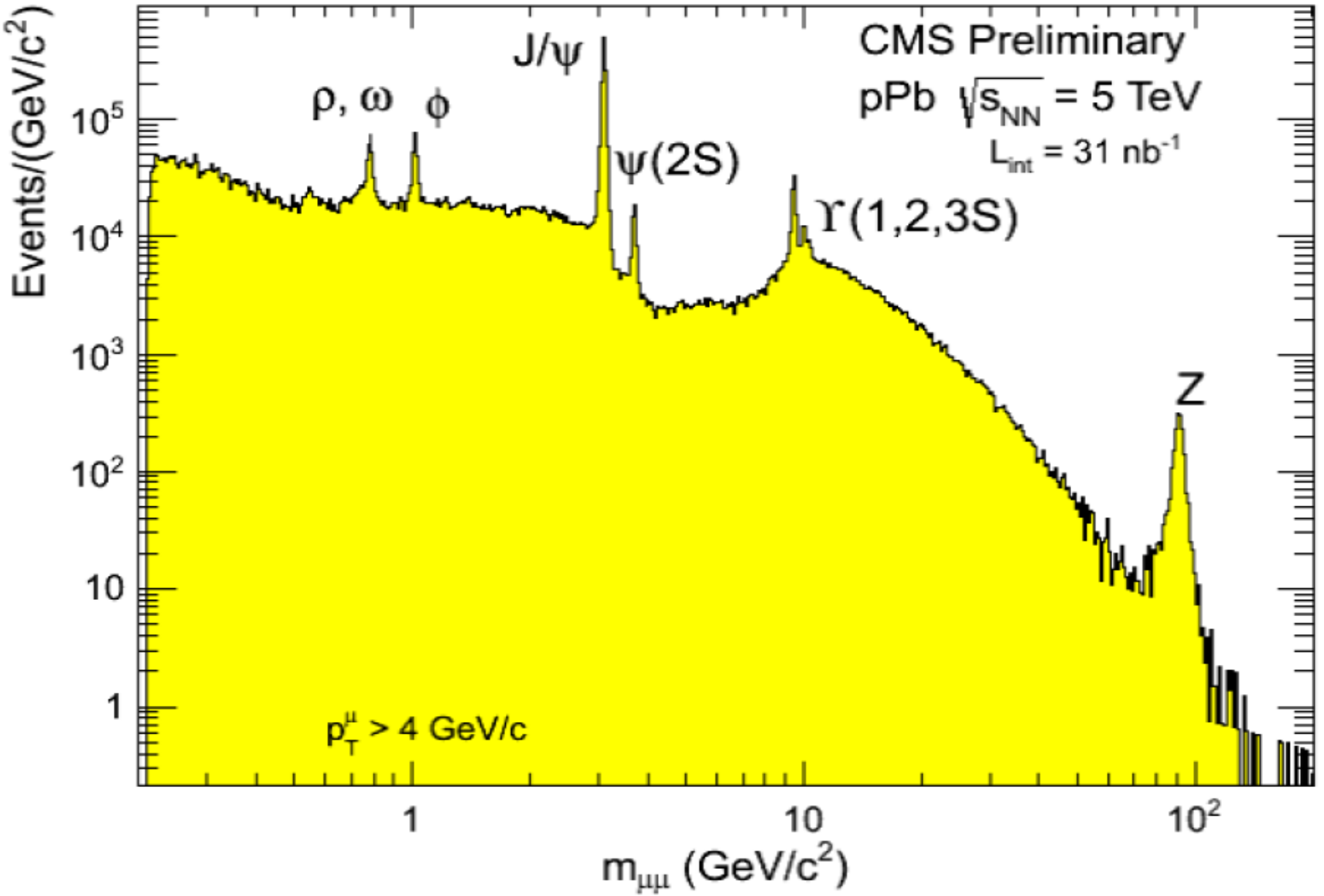
ALICE Collaboration hep-ex:1308.6726



LHCb Collaboration hep-ex:1308.6729

- ALICE measured inclusive J/ψ and ϒ in forward and backward rapidity regions.
- LHCb measure prompt J/ψ.
- J/ψ production decreases with respect to pp collisions from backward to forward rapidity.
- The ϒ(1S) and the J/ψ suppression are similar at positive rapidity
- Only shadowing is not sufficient to reproduce data.

Dimuons in p+Pb collisions at CMS



Υ measurement in p+p and p+Pb collisions : CMS

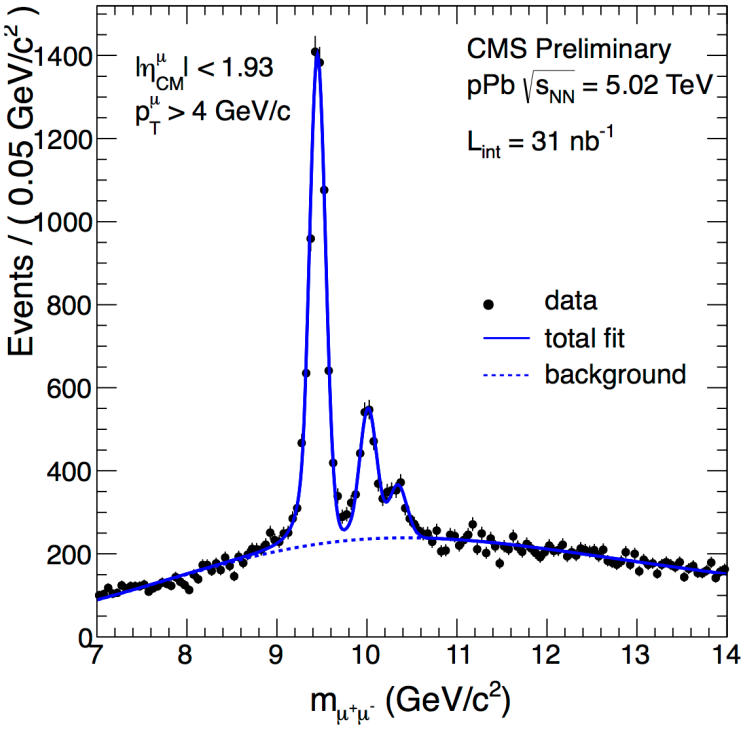
https://twiki.cern.ch/twiki/bin/view/CMS/FiguresHIN13003

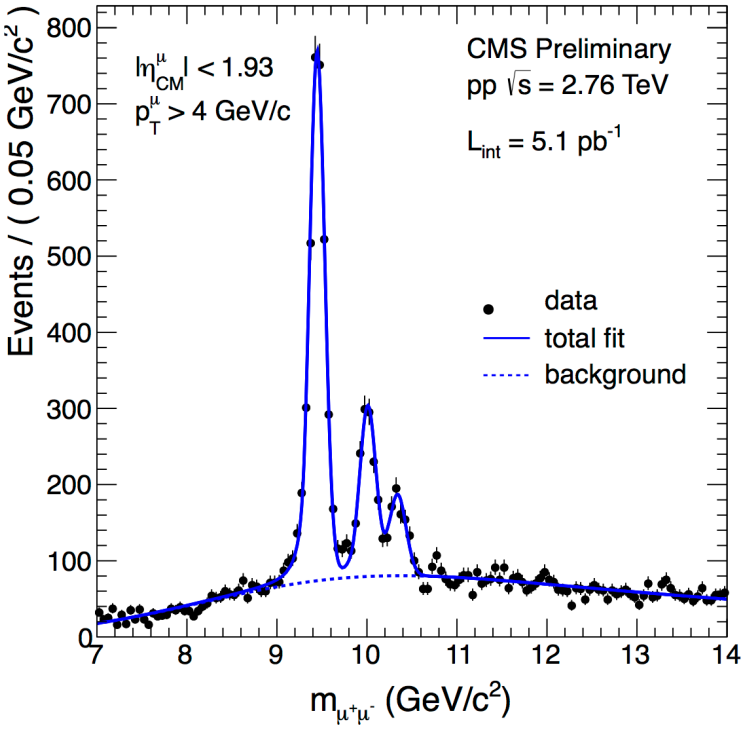
Υ in p+Pb collisions : Event Selection

- Online Selection
  - Hadronic p+Pb Collision Selection
    - At least one track with $p_T > 400$ MeV/c in the pixel tracker.
    - Bunch crossing identified by the Beam Pick-up Timing Experiment Detectors (BPTX)
  - Muon Trigger
    - Trigger requires two muon candidates in muon detectors.
    - No explicit p_T or rapidity cut

- Offline Selection
  - Coincidence of at least one HF calorimeter tower with more than 3 GeV of total energy in each of the HF detectors.
  - Selection of two-track (at least) fitted vertex
- Muon Selection
  - $|\eta^{\mu}|_{CM} < 1.93$.
  - $p_T^{\mu} > 4.0$ GeV/c.
  - Global muons with several quality cuts
- Same selection criteria is applied for both pp and pPb.

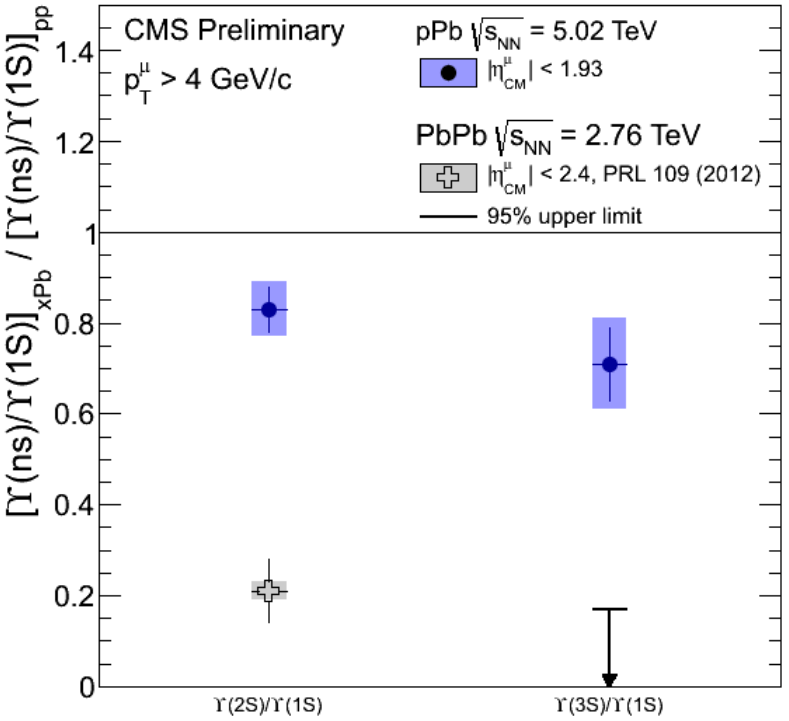
Yield extraction

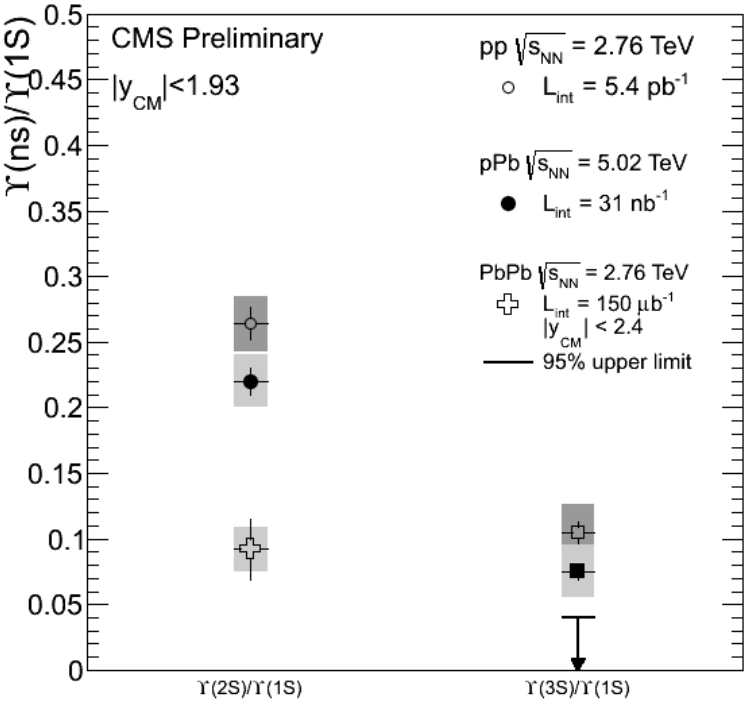




- Unbinned maximum likelihood fit
- **Signal:**
  - Three resonances modeled by crystal-ball function: Gaussian resolution and FSR power-law low mass tail
- **Background :**
  - exponential x error function
- Variations of the models checked as systematics.

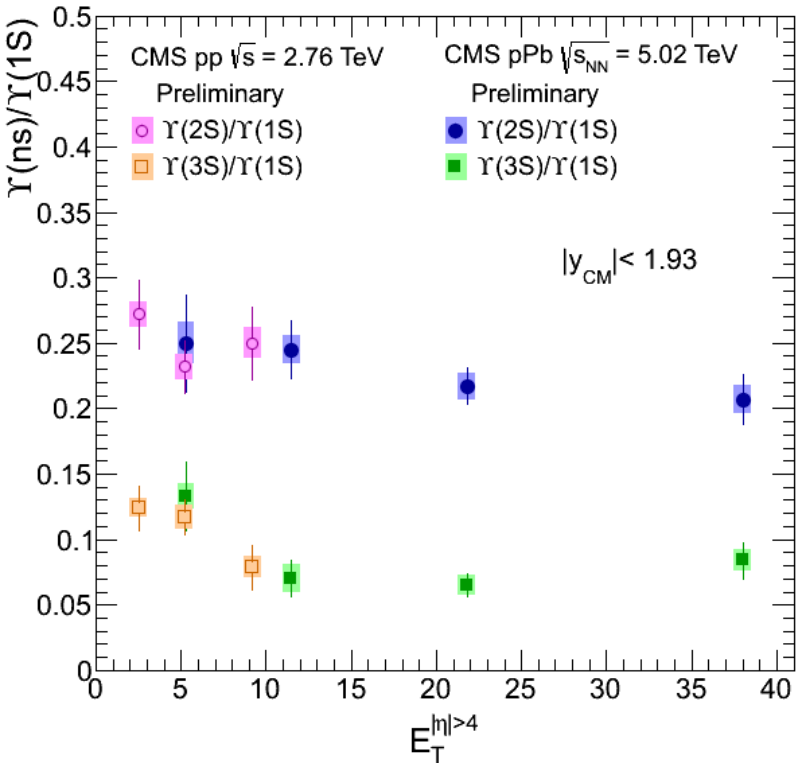
Relative yields

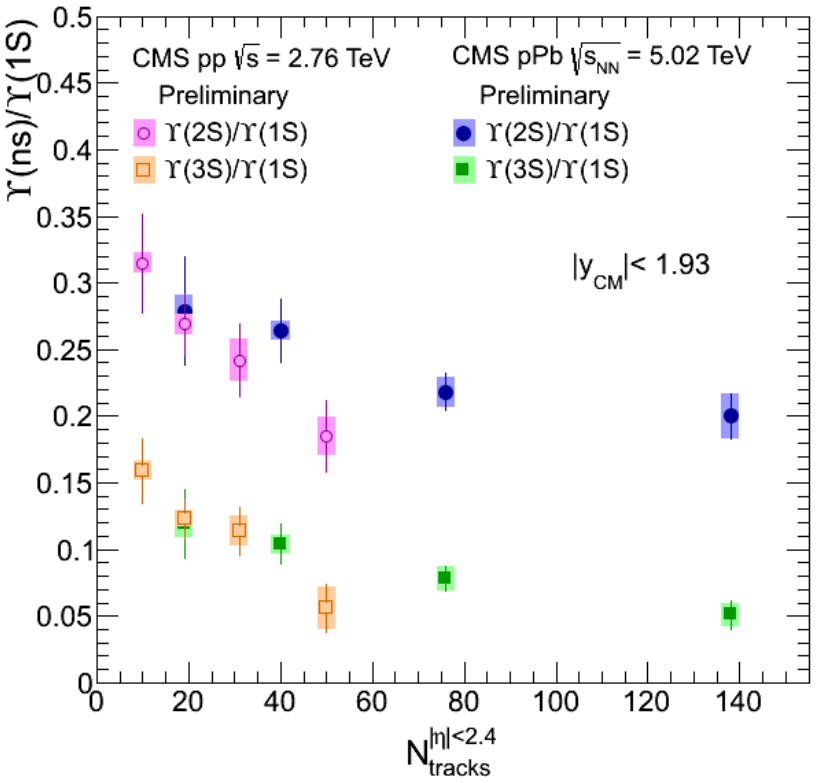




- In Double Ratio (DR) initial state effects cancel to first approximation.
- DR suggest presence of final state effects in pPb collisions compared to pp collisions.
- Affect ground state and excited states differently.
- The single ratios also signal the presence of different effects acting on excited states compared to ground state.

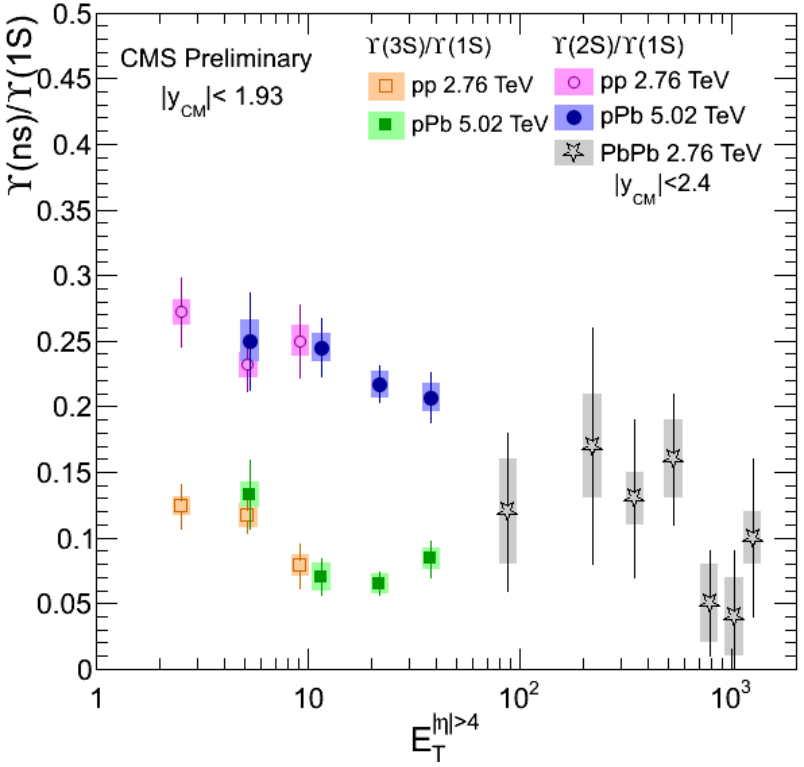
Ratios versus Event activity

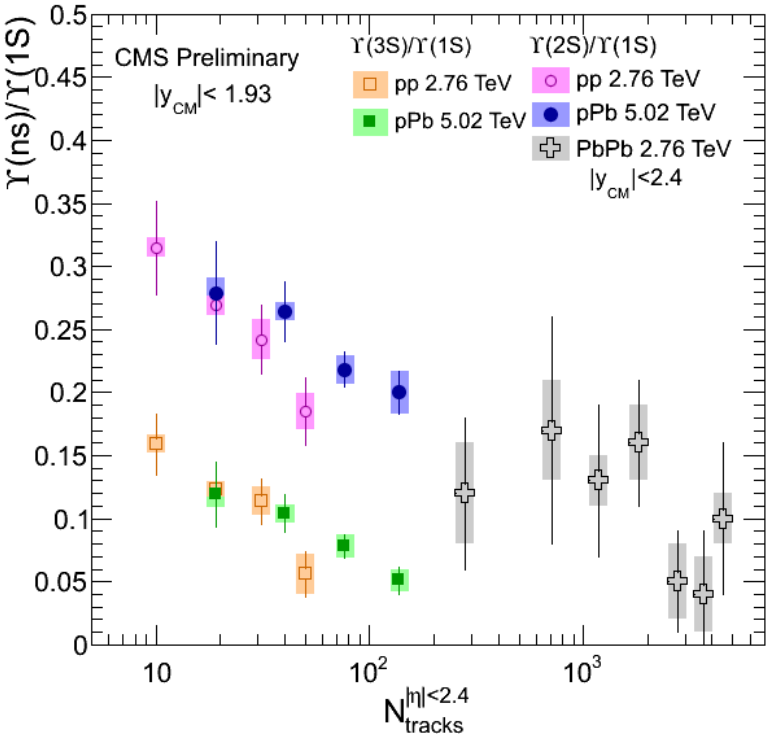




- Single Ratio (SR) as a function of two event activity variables
  - The transverse energy deposited in most forward part of HF calorimeters ($E_T^{|\eta|>4}$).
  - The number of charged particles reconstructed in tracker ($N_{tracks}^{|\eta| < 2.4}$).
- Single Ratios are consistent with being flat as a function of $E_T^{|\eta|>4}$.
- Present a significant decrease with increasing multiplicity in mid-rapidity.
  - ϒ affecting multiplicity or multiplicity affecting ϒ ?

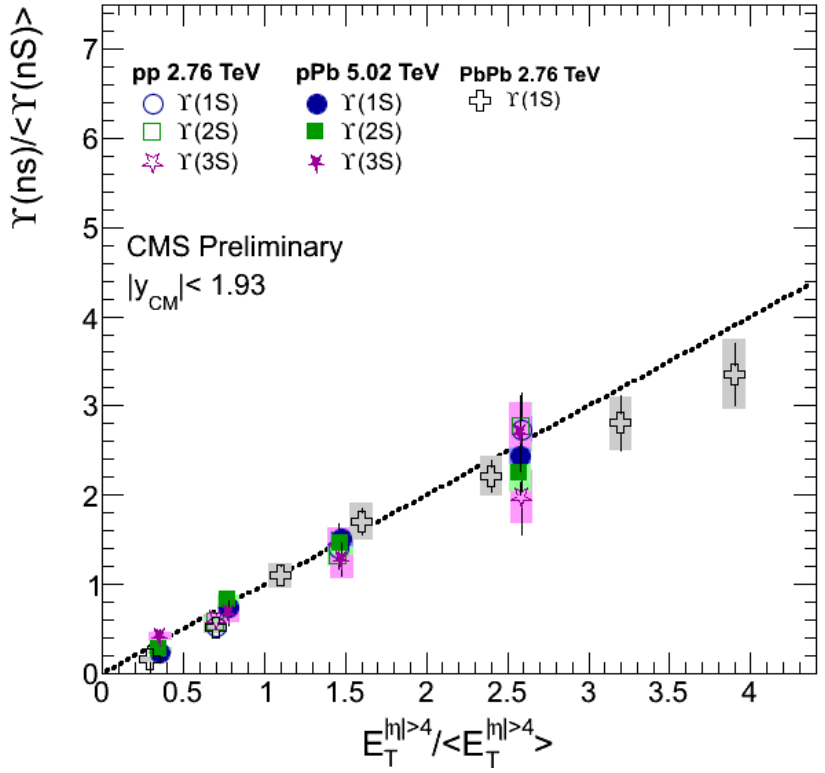
Ratios versus Event activity

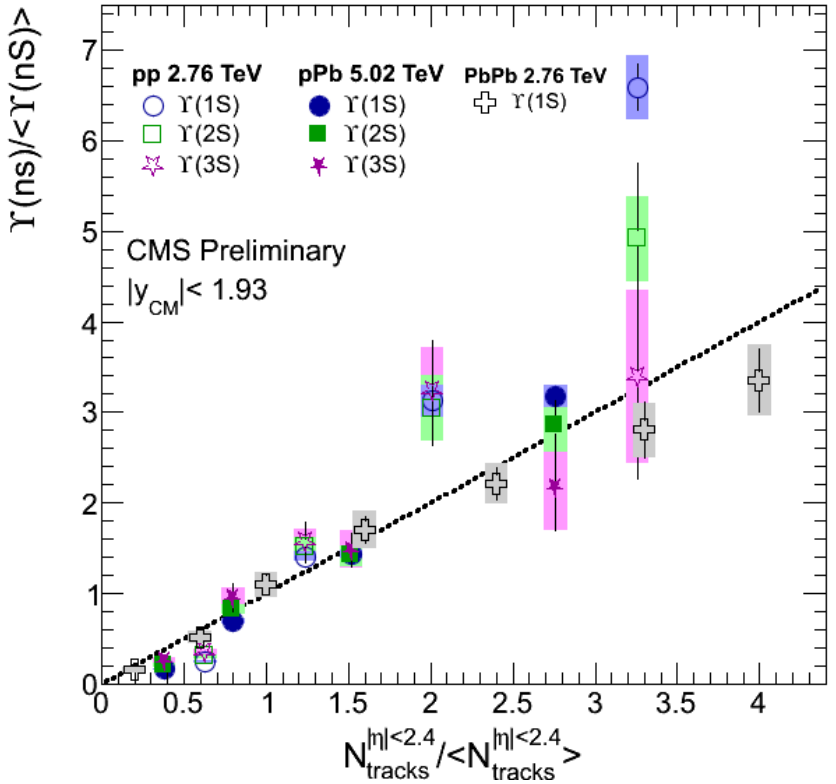




- Single Ratios are compared for all three collision systems.
- Within uncertainties no centrality dependence in PbPb collisions.
- All pp and pPb ratios are far above the PbPb activity-integrated ratios.
- Ratio seems to be constantly decreasing with increasing mid rapidity multiplicity.
- More data are needed to investigate the dependence in three systems and their possible relation.

Self Normalized yields versus Event activity





- Individual Υ(ns) yields, self normalized to their event activity integrated values are computed.
- All ratios present an increasing trend with increasing event activity.
- For pPb and PbPb it can arise from the increase in the number of nucleon-nucleon collisions, for pp results however are unexpected.
- ALICE measured similar increase in J/ψ yield with multiplicity. (hep:ex:1202.2816)
- Multi-parton scattering ?

Summary and Outlook

- CMS measures bottomonia in all three (pp, pPb and PbPb) collision systems.

- **PbPb collisions**
  - CMS shows first separate measurement, in PbPb collisions, of the relative suppression of $\Upsilon(2S)$ and $\Upsilon(3S)$ excited states wrt to the ground state.
  - $\Upsilon(2S)$ five times more suppressed than $\Upsilon(1S)$ in PbPb collisions.
  - Detailed study of centrality dependence of suppression patterns for individual Υ states.
  - Results compatible with other experiments and theoretical models.

- **pPb and pp collisions**
  - CMS measures relative production of three Υ states in the pPb and pp collisions.
  - Self-normalized yields increase with event activity.
  - Ratios of excited to ground states decrease with increasing charged particle multiplicity in mid rapidity region.
  - Dependence is less pronounced with transverse energy deposited in forward region.
  - Event activity integrated double ratios in pPb are found to be less than one but higher than those measured in PbPb collisions.
  - ALICE and LHCb show an increasing suppression of the J/ψ yield towards forward rapidity.

- A global understanding of effects at play in pp, pPb and PbPb collisions calls for more activity-related study of Υ yields in pp collisions.
- More PbPb data is required for finer investigation of most peripheral events.