Bottomonia in CMS

in pp, pPb and PbPb collisions

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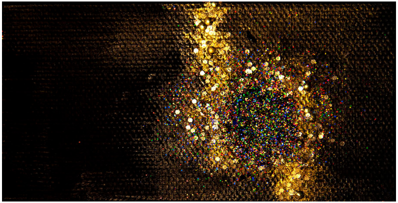
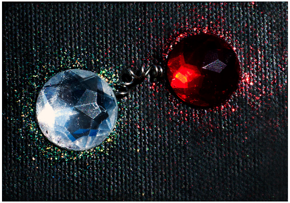
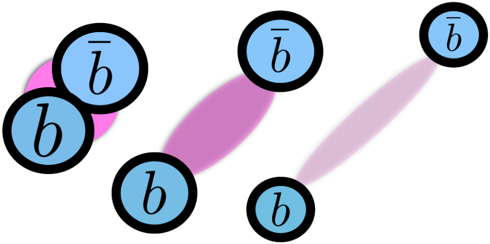




Sarah Szabo

- Quarkonia as good probes of the medium evolution.
- Two families (charmonia, bottomonia), several excited states: importance of quark mass, binding energy and size?
- pp collisions: production mechanism "in vacuum"
- pA collisions: cold nuclear matter effects
- AA collisions: quark gluon plasma

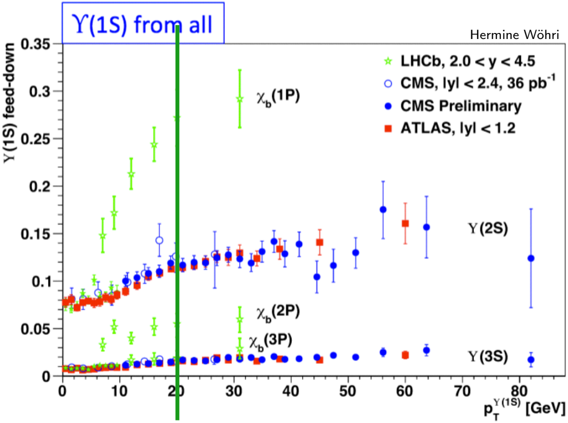
Bottomonia



Why study bottomonia?

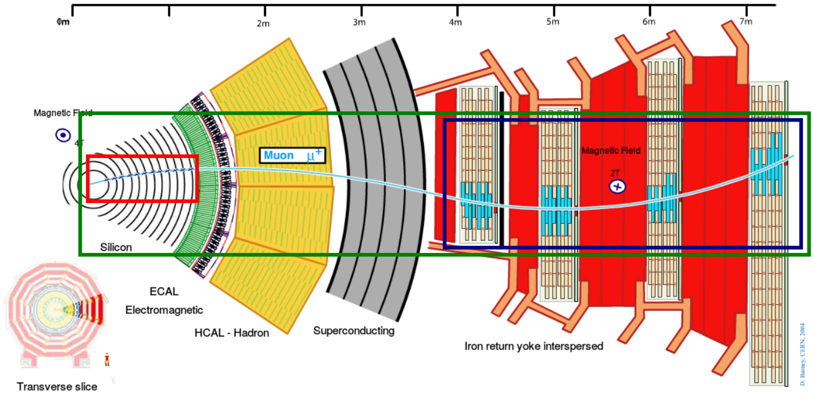
- Three states with similar production rate but different binding energy
- Higher mass than charmonia: better acceptance in CMS (down to 0 p_T)
- No non-prompt component
- Very high melting temperature for $\Upsilon(1S)$

Feed-down contribution to bottomonia production



Significant fraction of Υ coming from feed-down contributions (about $\sim 30-40\%$)

Muons in the CMS experiment

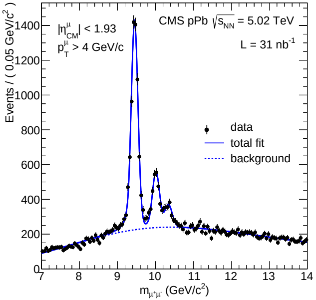


- *Muon reconstruction*: silicon tracker + muon sub-detectors
  - Tracker p_T resolution: 1-2% up to $p_T \sim 100\,\mathrm{GeV}/c$.
  - Excellent p_T resolution.
    - separation of quarkonium states
    - displaced tracks for heavy-flavour measurements

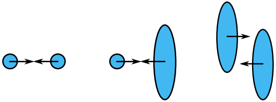
Outline

1. Υ in pPb
2. Υ polarisation vs multiplicity in pp
3. Υ in PbPb

Outline



CMS pPb $\sqrt{s_{NN}}$ = 5.02 TeV
L = 31 nb^{-1}
$|\eta^{\mu}_{CM}|$ < 1.93
p^{μ}_{T} > 4 GeV/c
data
total fit
background
Events / (0.05 GeV/c^2)
$m_{\mu^+\mu^-}$ (GeV/c^2)

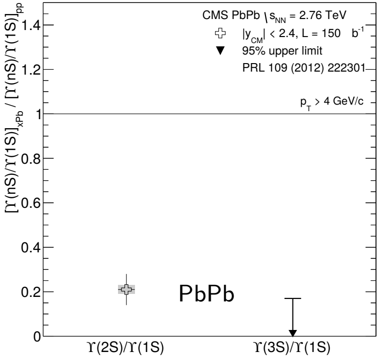


Double ratio

PRL 109 (2012) 222301

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

- Double ratio cancels initial state effects for excited ground states
    - Separating final state effects from initial state effects
- Binding energy dependence is observed.
- PbPb: factor > 5 more suppression of excited states compared to the ground state.

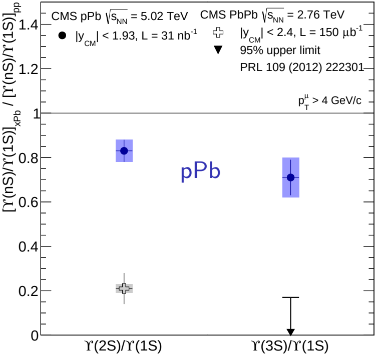


Double ratio

JHEP 04 (2014) 103

- Double ratio cancels initial state effects for excited ground states
  - Separating final state effects from initial state effects
- Binding energy dependence is observed.
- PbPb: factor > 5 more suppression of excited states compared to the ground state.
- pPb: much lower dependence on $\Upsilon(nS)$ states
  - Excited states also suffer more from CNM effects than the ground state.

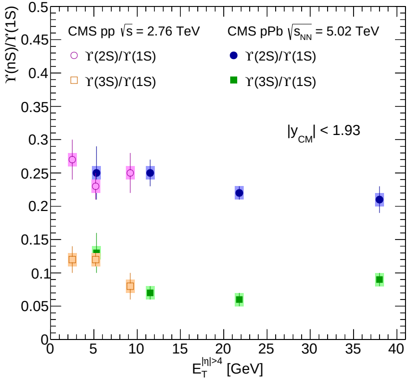
$$\frac{\left[\frac{\Upsilon(nS)}{\Upsilon(1S)}\right]_{\mathrm{pPb}}}{\left[\frac{\Upsilon(nS)}{\Upsilon(1S)}\right]_{\mathrm{pp}}} = \frac{R_{\mathrm{pPb}}(\Upsilon(nS))}{R_{\mathrm{pPb}}(\Upsilon(1S))}$$

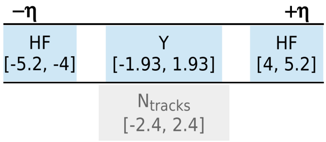


Single ratio of $nS/1S$ in pp and pPb

JHEP 04 (2014) 103

- Event activity is determined with transverse energy deposited in the forward hadronic calorimeter
- $\Upsilon(nS)/\Upsilon(1S)$ ratios fall with event activity
  - Is the multiplicity affecting the $\Upsilon(nS)$?
  - Are the $\Upsilon(nS)$ affecting the multiplicity?





Single ratio of $nS/1S$ in pp and pPb

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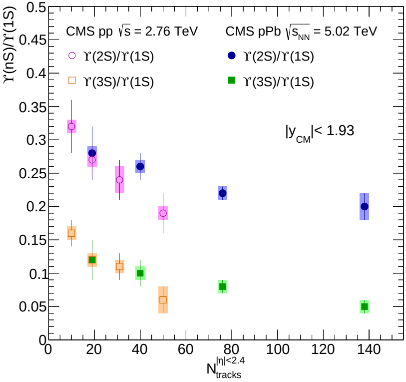
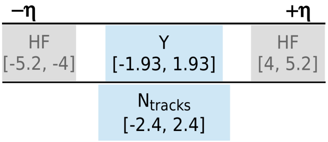
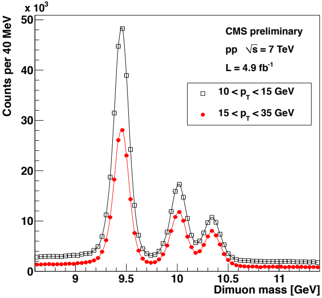
- Event activity is determined with number of tracks (charged particles) in the central detector
- $\Upsilon(nS)/\Upsilon(1S)$ ratios fall with event activity
  - Is the multiplicity affecting the $\Upsilon(nS)$?
  - Are the $\Upsilon(nS)$ affecting the multiplicity?
  - Effects become stronger with tracks nearby





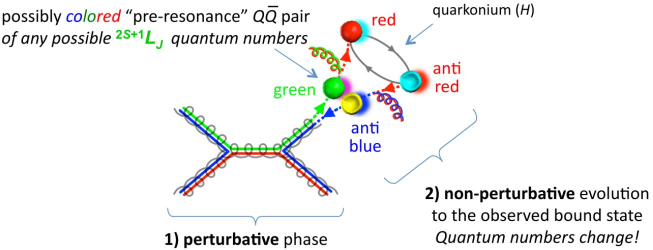
Outline



x 10^3
Counts per 40 MeV
CMS preliminary
pp √s = 7 TeV
L = 4.9 fb^-1
10 < p_T < 15 GeV
15 < p_T < 35 GeV
Dimuon mass [GeV]

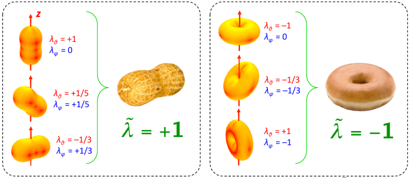
Quarkonium production

The non-relativistic QCD approach (factorisation):



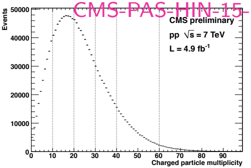
$$\sigma(A+B \to H+X) = \sigma(A+B \to ([Q\bar{Q}]+X) \otimes \mathcal{P}([Q\bar{Q}] \to H)$$

- Different long distance matrix elements (LDMEs) → different polarisations.
- Multiplicity dependence?

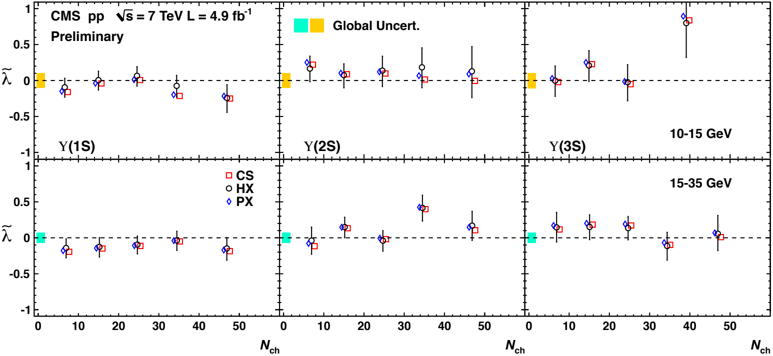


Upsilon polarisation vs multiplicity in pp

CMS-PAS-HIN-15-003

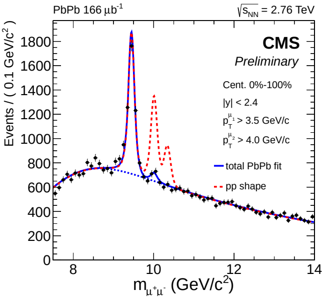


- The polarisation of ϒ states has been measured in pp collisions at $\sqrt{s} = 7$ TeV as a function of charged particle multiplicity
- Similar studies to come in heavy ion collisions

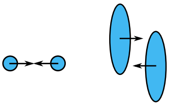


No strong change of ϒ polarisation with multiplicity

Outline



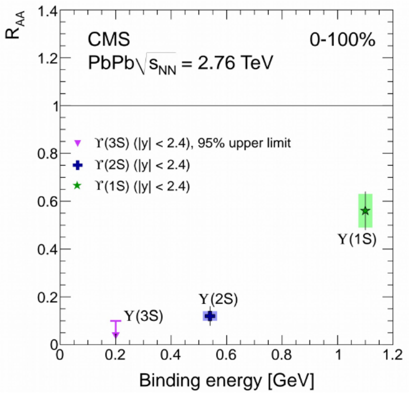
PbPb 166 μb-1
√sNN = 2.76 TeV
CMS
Preliminary
Cent. 0%-100%
|y| < 2.4
total PbPb fit
pp shape
Events / (0.1 GeV/c2)
mμ+μ- (GeV/c2)



Previous analyses

PRL 109 (2012) 222301

- $\Upsilon(nS)$ are suppressed in PbPb collisions
- Stronger suppression for excited states is observed
- Ordered with assumed binding energies
- New: larger pp reference at the same energy (2013 data)
  - Similar (N_{coll}-scaled) luminosity as 2011 PbPb data
  - More precise mapping of the kinematic of the suppression

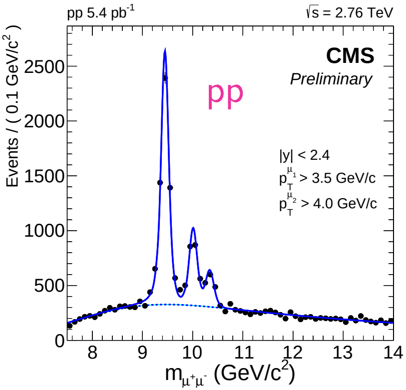


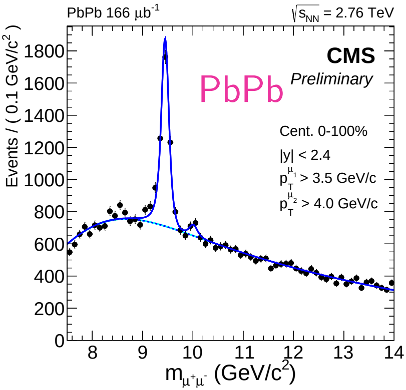
Signal extraction

CMS-PAS-HIN-15-001

Different single muon cuts for different states:

- $\Upsilon(1S)$: $p_T^{\mu 1} > 3.5\,\mathrm{GeV}$, $p_T^{\mu 2} > 4\,\mathrm{GeV}$
- $\Upsilon(2S,3S)$: $p_T^{\mu 1,2} > 4\,\mathrm{GeV}$





$\sim 5000\ \Upsilon(1S)$ in pp

$\sim 2500\ \Upsilon(1S)$ in PbPb

Analysis procedure and systematic uncertainties

CMS-PAS-HIN-15-001

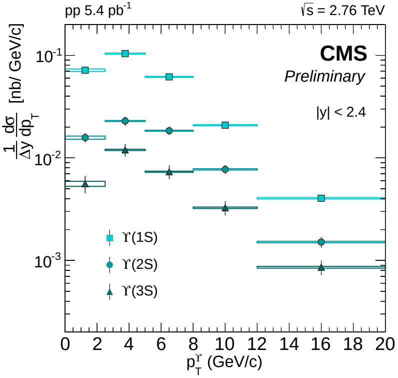
- Raw yields corrected for acceptance $\times$ efficiency
- Results given for $|y(\Upsilon)| < 2.4$, $0 < p_T(\Upsilon) < 20\,\text{GeV}$.
- Efficiency correction from simulation, corrected for data-MC differences using a tag and probe method.

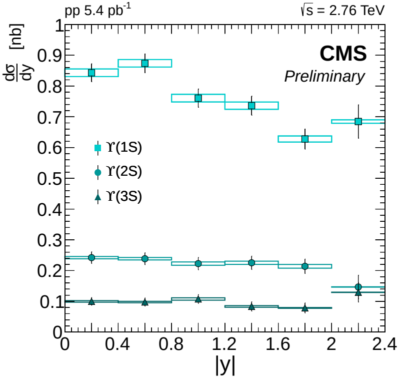
Systematic uncertainty	Magnitude	corr.
Signal extraction	$< 28\%$	no
Acceptance $\times$ efficiency	$\sim 2.5\%$ (pp), $\sim 8.2\%$ (PbPb)	no
Tag and probe: μID, trigger	0.4% – 17%	no
Tag and probe: inner tracking	3.4% (pp), 10% (PbPb)	yes
pp luminosity	3.7%	yes
Min. bias (PbPb norm.)	3%	yes
Overlap function T_{AA}	6.2%	yes (p_T, y)

Cross sections in pp

CMS-PAS-HIN-15-001

- Cross sections extracted for the three states.
- Important input to production models.

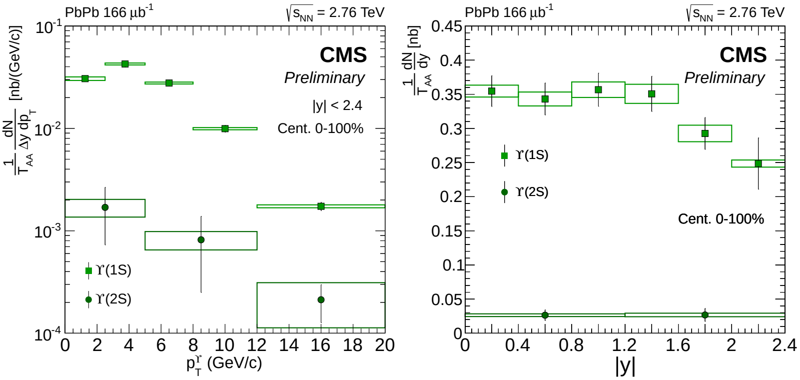




Cross sections in PbPb

CMS-PAS-HIN-15-001

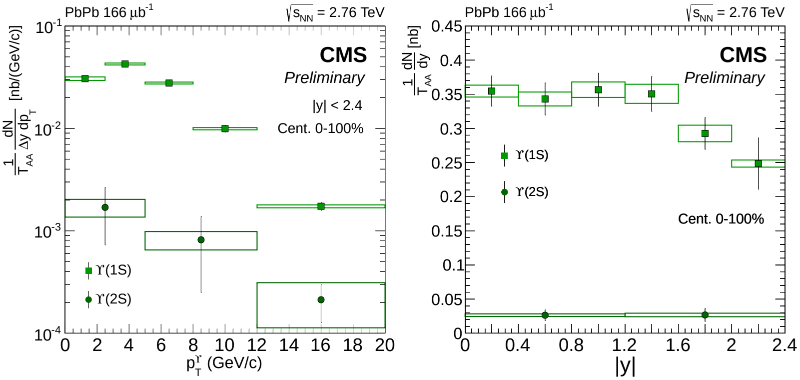
- First measurement of the kinematic dependence of $\Upsilon(2S)$ production in AA.



Cross sections in PbPb

CMS-PAS-HIN-15-001

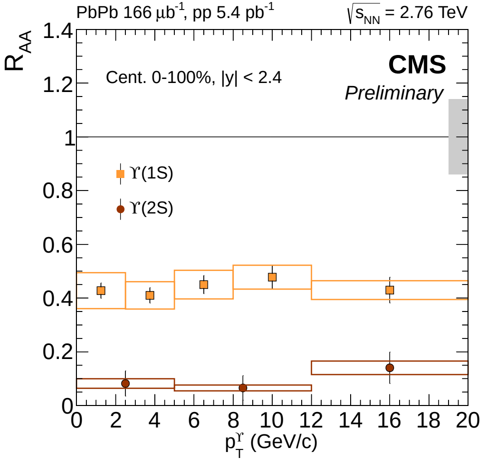
- First measurement of the kinematic dependence of $\Upsilon(2S)$ production in AA.
- Let's compare pp to AA: nuclear modification factors (R_{AA}).



R_{AA}: p_T dependence

CMS-PAS-HIN-15-001

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{AA}}{N_{pp}} \frac{\epsilon_{pp}}{\epsilon_{AA}}$$



Υ production is suppressed in PbPb, with binding energy ordering.
Integrated results (Min. bias):

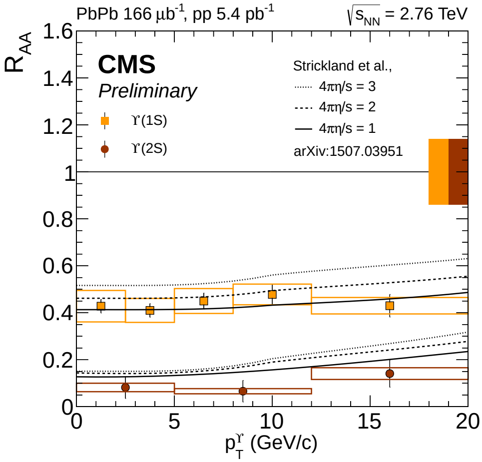
- $R_{AA}(\Upsilon(1S)) = 0.43 \pm 0.03 \pm 0.07$
- $R_{AA}(\Upsilon(2S)) = 0.12 \pm 0.03 \pm 0.02$
- $R_{AA}(\Upsilon(3S)) < 0.14$ at 95% C.L.

- No significant p_T dependence over the measured range.

R_{AA}: p_T dependence

CMS-PAS-HIN-15-001

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{AA}}{N_{pp}} \frac{\epsilon_{pp}}{\epsilon_{AA}}$$



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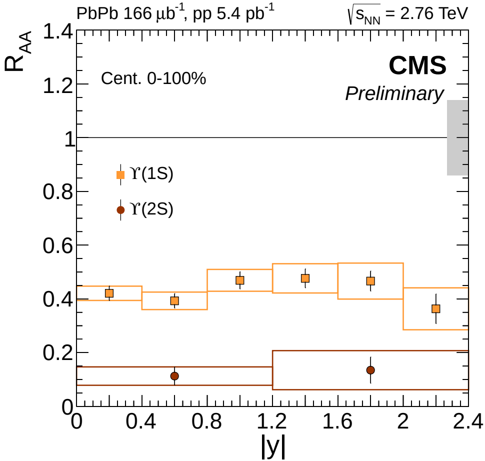
- $R_{AA}(\Upsilon(3S)) < 0.14$ at 95% C.L.

- No significant p_T dependence over the measured range.
- $\Upsilon(1S)$ well described, some tension for $\Upsilon(2S)$

R_{AA}: rapidity dependence

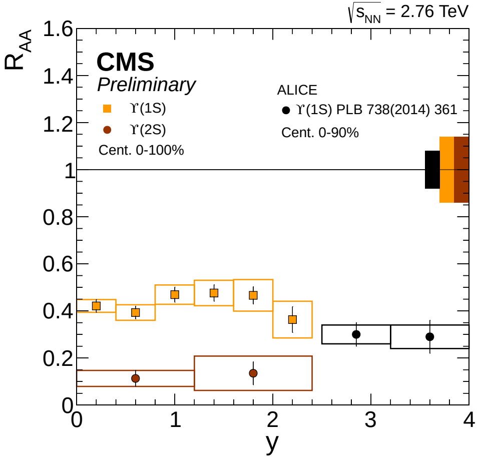
CMS-PAS-HIN-15-001



- No significant y dependence over the measured range

R_{AA}: rapidity dependence

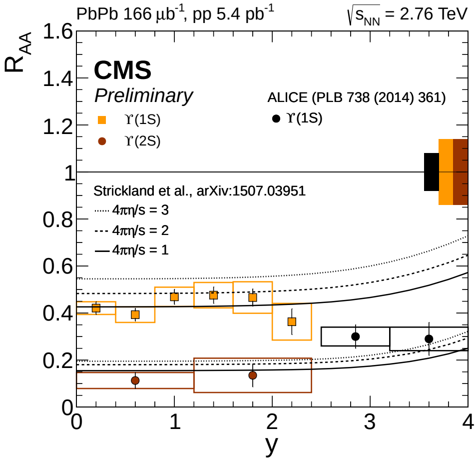
CMS-PAS-HIN-15-001



- No significant y dependence over the measured range
- Similar $1S$ suppression in the ALICE rapidity range

R_{AA}: rapidity dependence

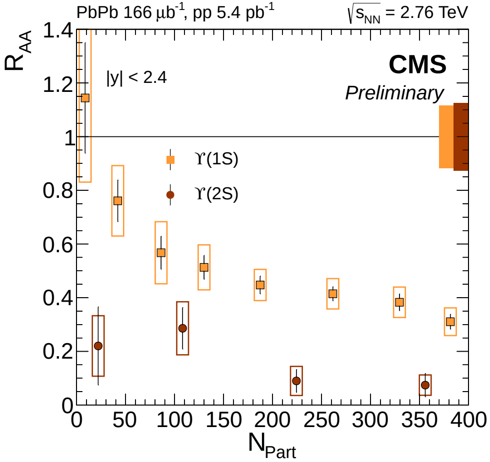
CMS-PAS-HIN-15-001



- No significant y dependence over the measured range
- Similar 1S suppression in the ALICE rapidity range
- Good description in the model, at mid-rapidity only

R_{AA}: centrality dependence

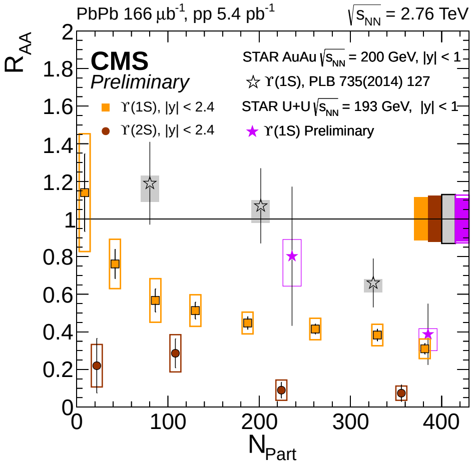
CMS-PAS-HIN-15-001



- Stronger suppression in central events
- Significant $\Upsilon(2S)$ suppression in peripheral events

R_{AA}: centrality dependence

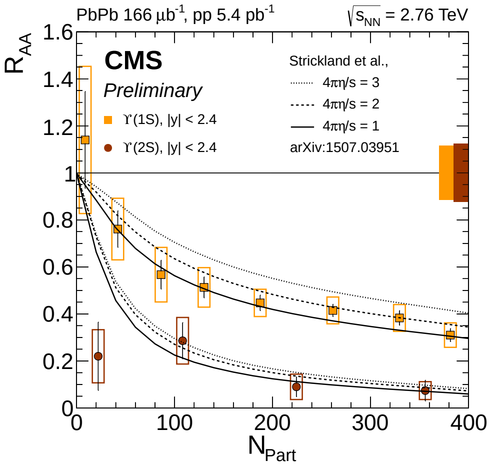
CMS-PAS-HIN-15-001



- Stronger suppression in central events
- Significant $\Upsilon(2S)$ suppression in peripheral events
- Comparison with STAR ($|y| < 1$, $\sqrt{s_{NN}} = 200\,\text{GeV}$ (AuAu) or $193\,\text{GeV}$ (UU):
  - No significant modification in peripheral events
  - Strong suppression in central events

R_{AA}: centrality dependence

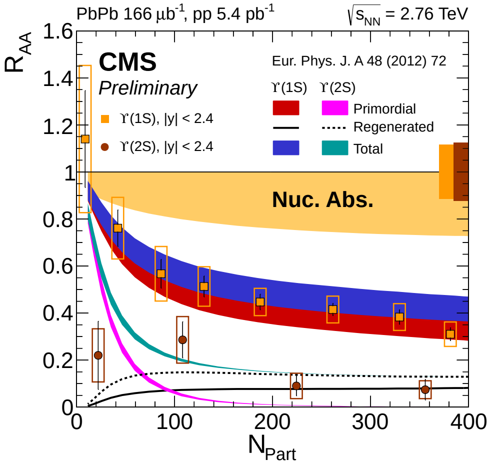
CMS-PAS-HIN-15-001



- Strickland: thermal suppression in QGP, satisfactory description

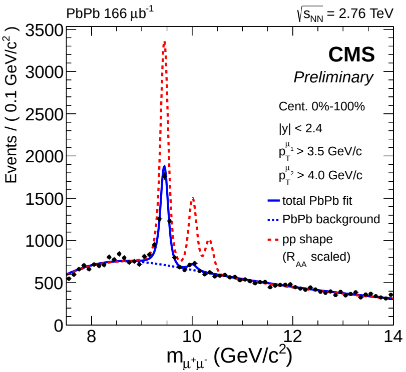
R_{AA}: centrality dependence

CMS-PAS-HIN-15-001



- Strickland: thermal suppression in QGP, satisfactory description
- TAMU: also includes CNM and regeneration effects
  - Regeneration dominates for ϒ(2*S*) in central events

Summary



Comprehensive study of Υ production in pp, pPb and PbPb collisions.

- Larger suppression of excited Υ states in PbPb than in pPb, with respect to pp
- Different $\Upsilon(nS)/\Upsilon(1S)$ depending on event activity
- No evidence for different production mechanisms vs. multiplicity
- Suppression in PbPb: stronger for excited states, stronger in central events, flat in p_T and y.

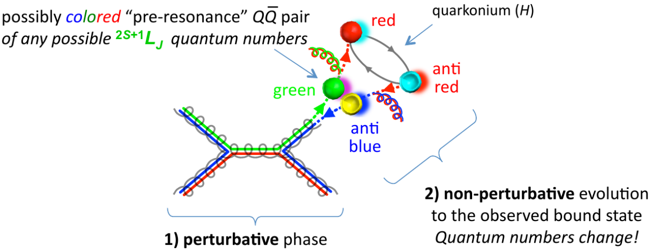
2015 PbPb data ($\sqrt{s_{NN}} = 5.02\,\text{TeV}$)

- $\sqrt{s_{NN}}$ dependence of $\Upsilon(1S)$ suppression?
- How suppressed really are $\Upsilon(3S)$?

Additional material

Quarkonium production

The non-relativistic QCD approach:



$$\sigma(A + B \to H + X) = \sigma(A + B \to ([Q\bar{Q}] + X) \otimes \mathcal{P}([Q\bar{Q}] \to H)$$

- $\sigma(A + B \to ([Q\bar{Q}] + X)$ (short-distance coefficients, SDCs): perturbative
- $\mathcal{P}([Q\bar{Q}] \to H)$ (long-distance matrix elements, LDMEs): non-perturbative, dependent on the $Q\bar{Q}$ quantum numbers (colour, spin, orbital momentum), constant and universal

- Are LDMEs really universal?
- Dependence with charged particle multiplicity, pp vs pPb vs PbPb...?

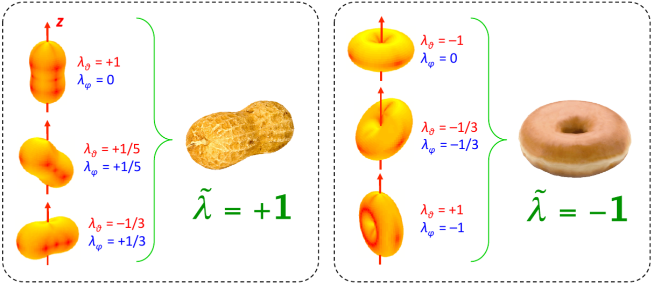
Quarkonium polarisation

- The polarisation information is stored in the angular distribution of the particle decay:

$$W(\cos\theta, \phi|\vec{\lambda}) = 1 + \lambda_\theta \cos^2\theta + \lambda_\phi \sin\theta \cos 2\phi + \lambda_{\theta\phi} \sin 2\theta \cos\phi$$

- The polarisation parameters $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})$ depend on the choice of reference frame.
- A frame-independent approach:

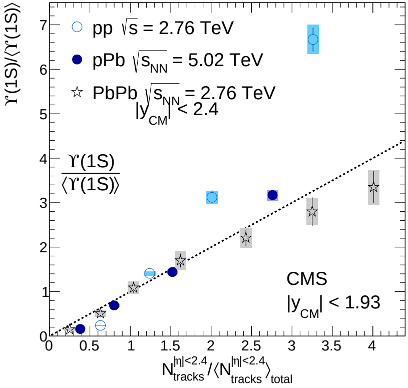
$$\tilde{\lambda} = \frac{\lambda_\theta + 3\lambda_\phi}{1 - \lambda_\phi}$$

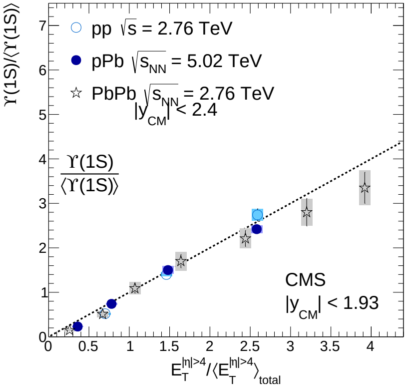


Event activity dependence for $\Upsilon(1S)$

JHEP 04 (2014) 103

Goal: measure self-normalised cross sections as a function of multiplicity.

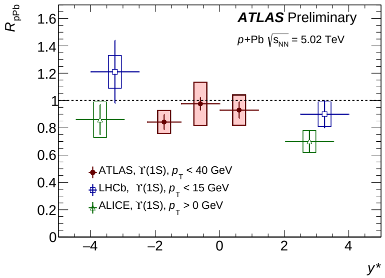


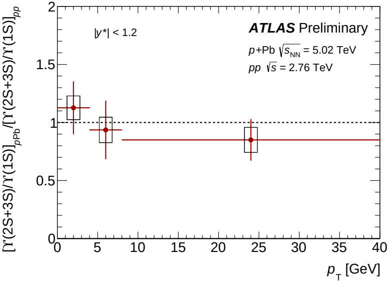


Positive correlation in pp, small negative correlation in PbPb (suppression).

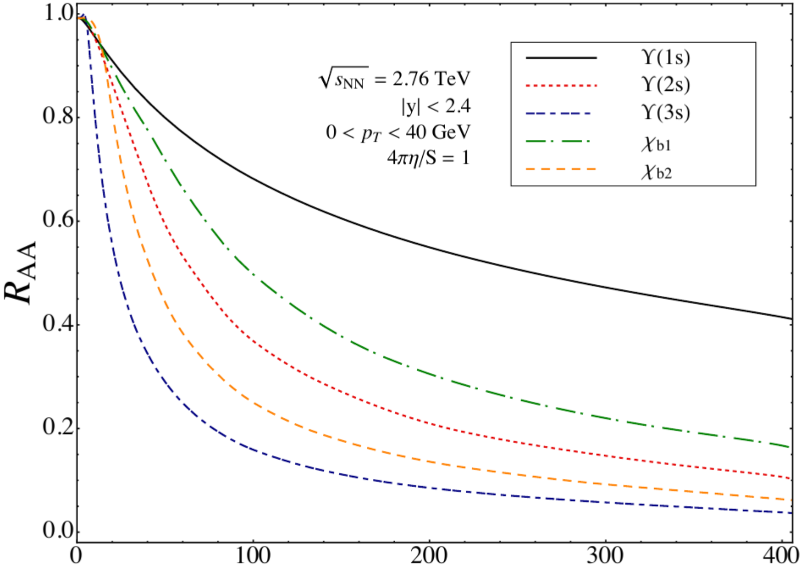
Unit slope in pp and pPb.

R_{pA} of Υ from other LHC experiments





Raw R_{AA} (Strickland, 1507.03951)



Feed down contributions (LHCb, EPJC 74 (2014) 3092