Bottomonium production in p+p, p+Pb and Pb+Pb collisions with CMS

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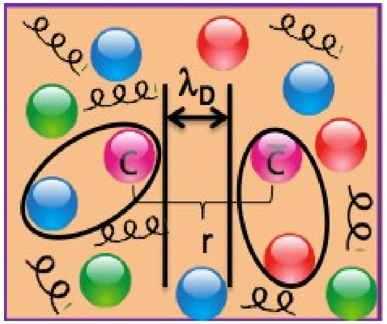
Quarkonia as probes of QGP

- **Quarkonia** (χ_c, ψ(1, 2S) and χ_b, Υ(1, 2, 3S)): Massive states
  - ➔ Produced at the early stage of the collision

State	Υ(1S)	Υ(2S)	Υ(3S)
Mass (GeV)	9.46	10.02	10.36
ΔE (GeV)	1.10	0.54	0.20
Radius r_0 (fm)	0.28	0.56	0.78

- **Sequential melting:** via Debye screening in QGP
  - ➔ Screening at different T for different states

    Matsui and Satz PLB 178 416 (1986), Digal PRD 64 0940150 (2001)

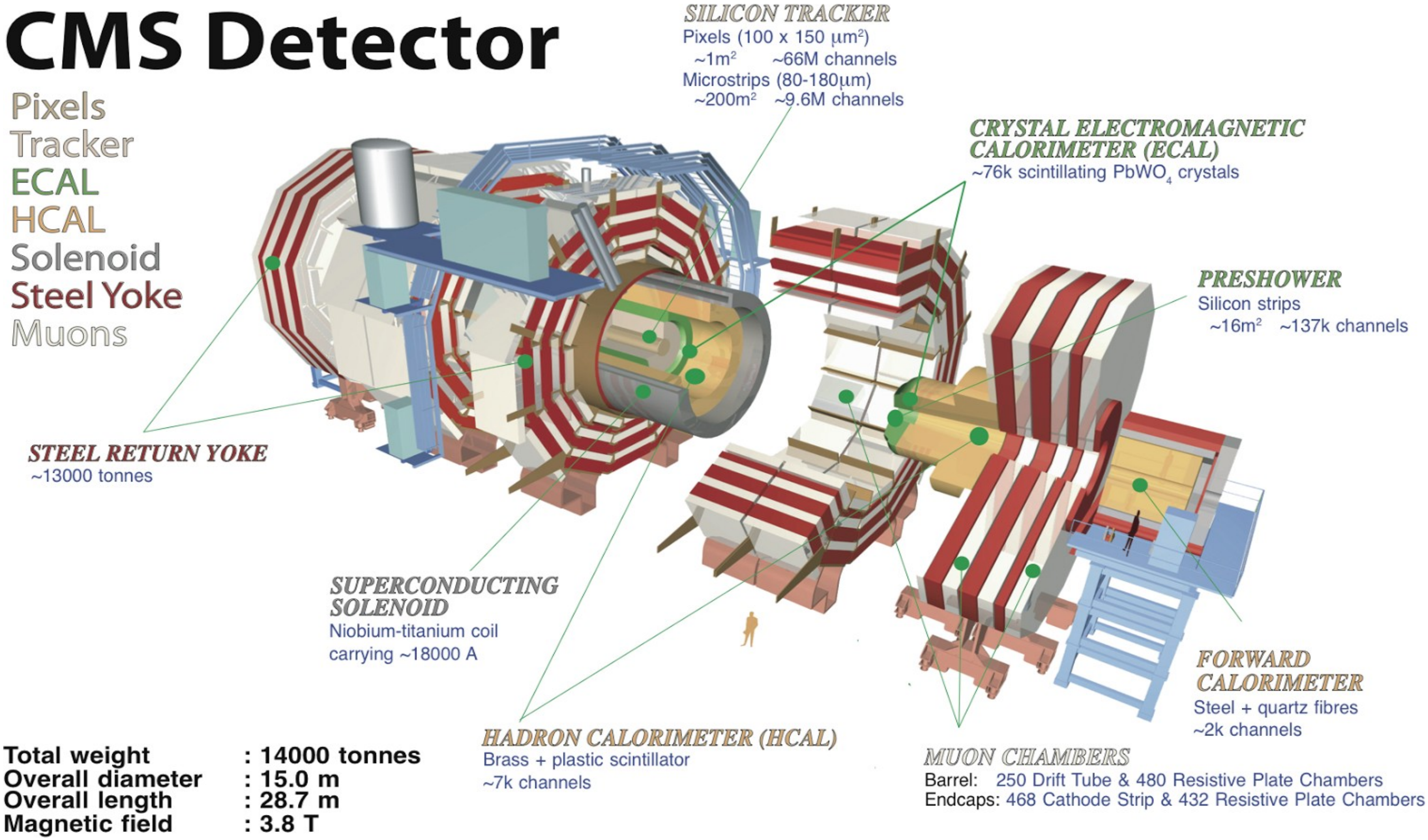


- **Cold Nuclear Matter Effects**:
  - ➔ Initial-state effects (eg: modification of nPDFs)
  - ➔ Final-state effects (eg: nuclear absorption, interactions with comovers)

- **Regeneration of quarkonia**:
  - ➔ From uncorrelated quarks and anti-quarks produced in bulk at LHC
    - ➢ Expected to be small for Υs as compared to J/ψ.

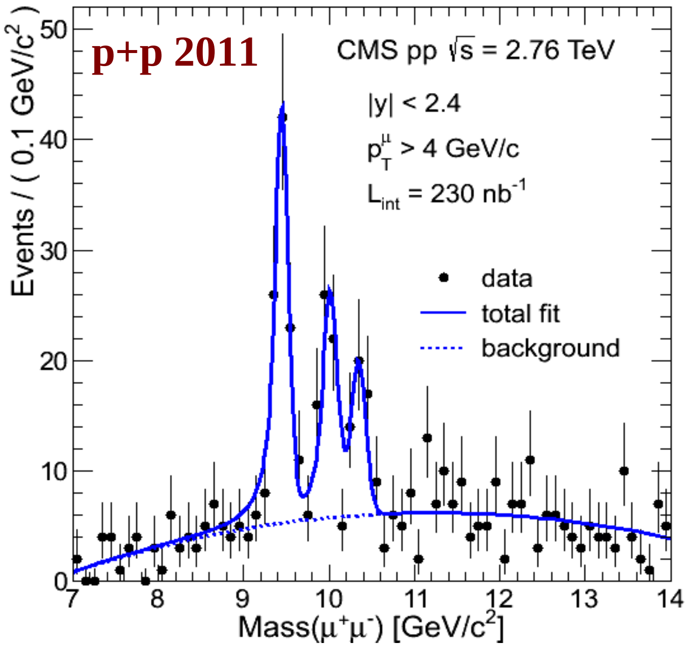
      R. L. Thews Phys. Rev. C63, 054905 (2001), Andronic PLB 571(2003) 36

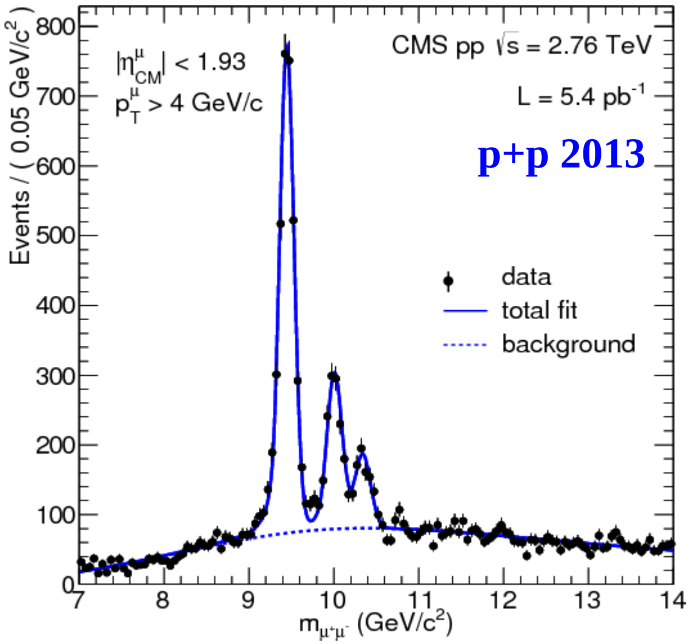
CMS at the LHC

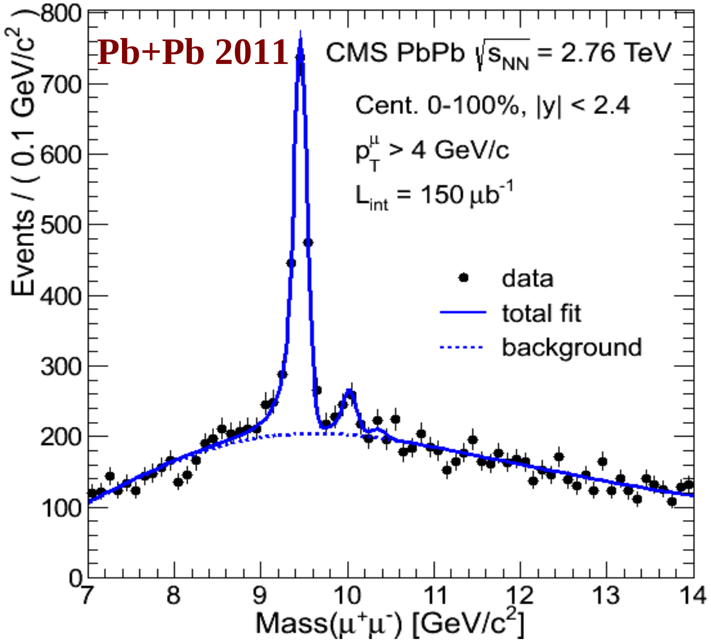


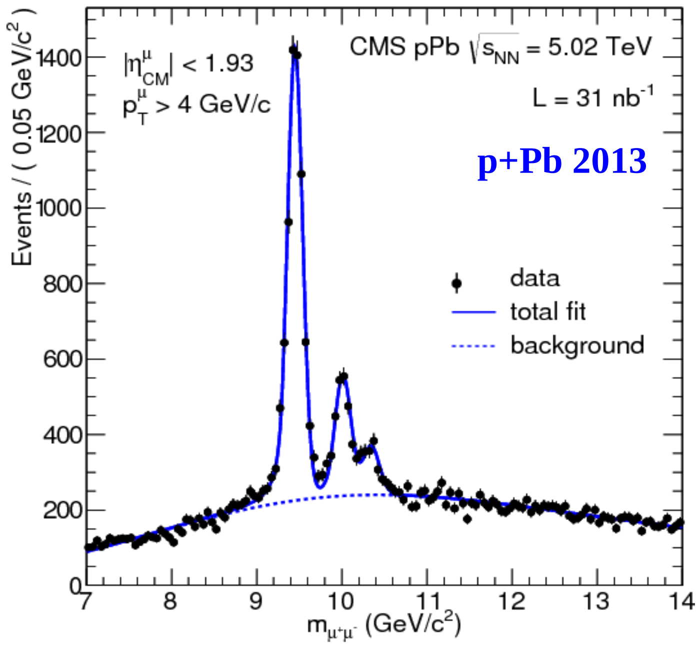
- **Muon reconstruction**: silicon tracker + muon sub detectors
- Silicon Tracker: p_T resolution 1-2% up to p_T ~ 100 GeV/c
  - ➔ Helpful to separate quarkonium states

LHC Runs of Heavy Ion Interest



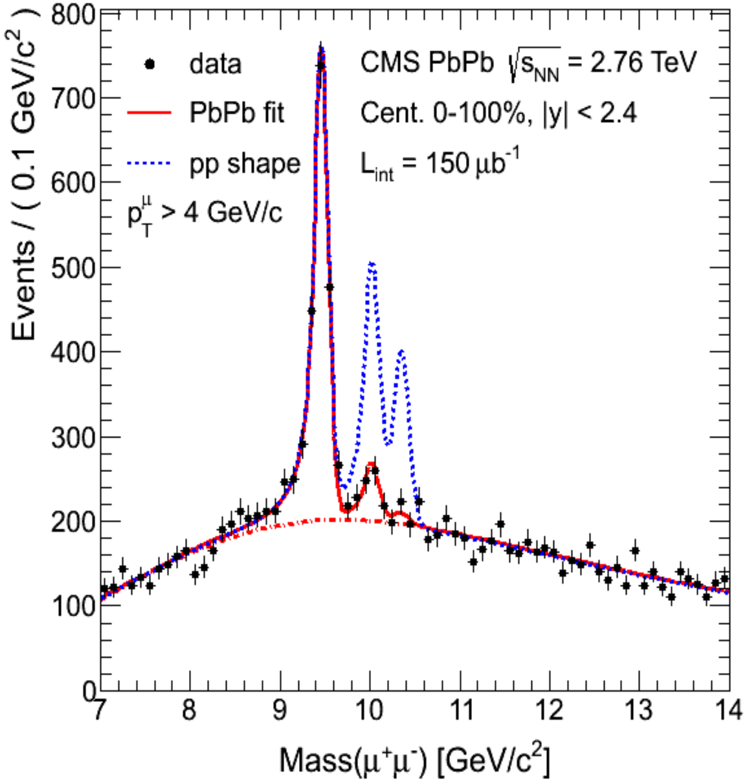


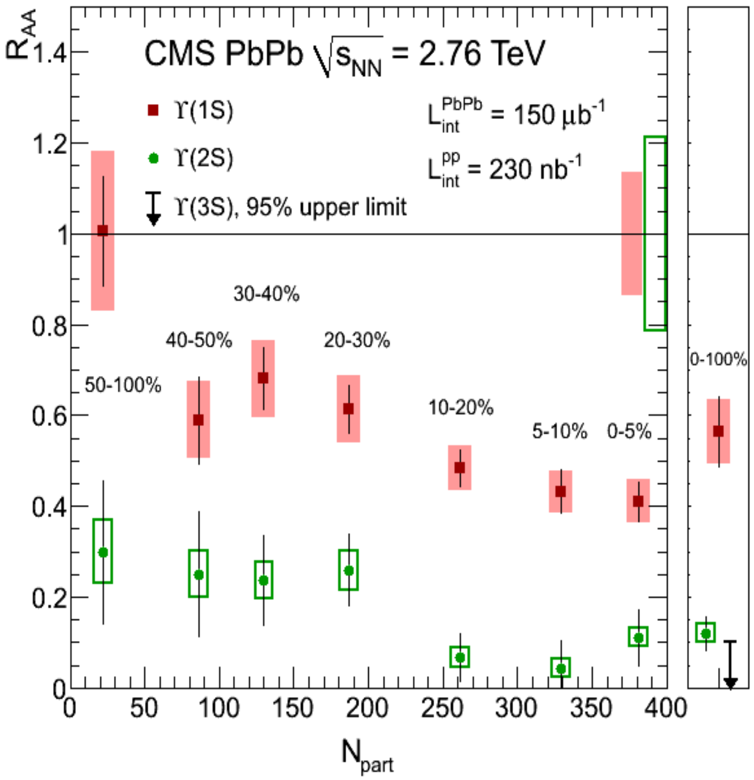




Υ measurement with ***Pb+Pb*** at LHC

R_{AA} with Pb+Pb





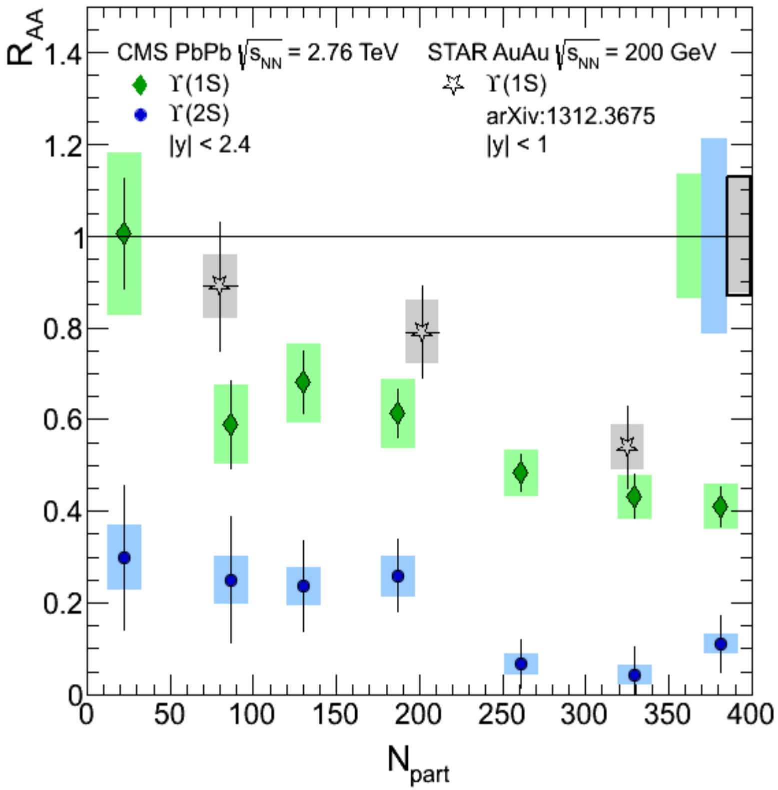
- The ϒs are identified through dimuon decay
- Clear suppression of excited states ϒ(2S, 3S)

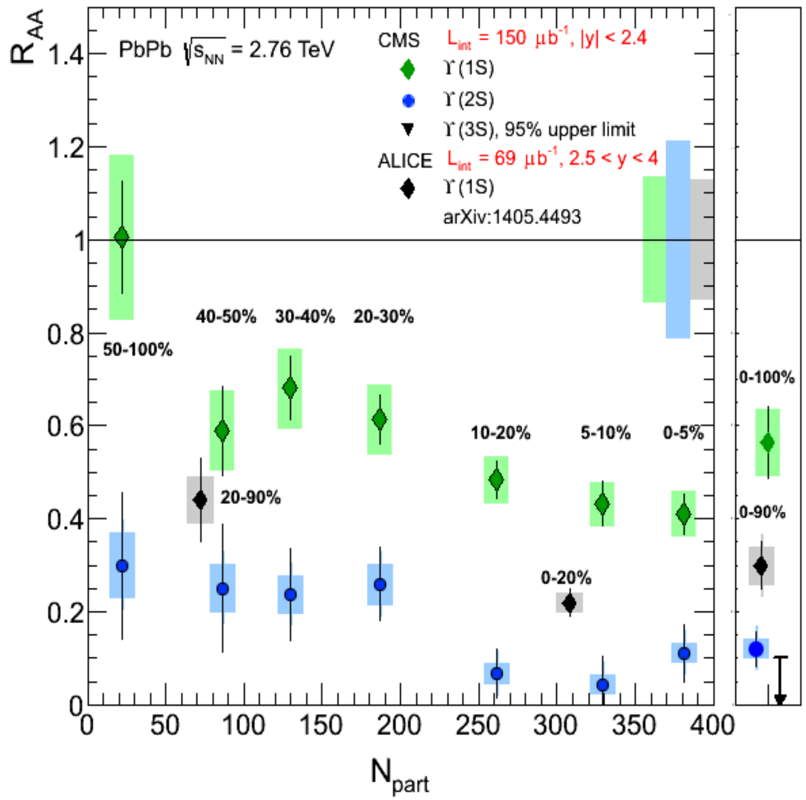
- **ϒ(1S)** : 0.56 ± 0.08 ± 0.07 **(0-100%)**
- **ϒ(2S)** : 0.12 ± 0.04 ± 0.02 **(0-100%)**
- **ϒ(3S) :** < 0.10 @ 95% CL **(0-100%)**

Sequence of suppression: $\mathbf{R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}}$

PRL 109 222301 (2012)

R_{AA} : Comparison with Other Experiments



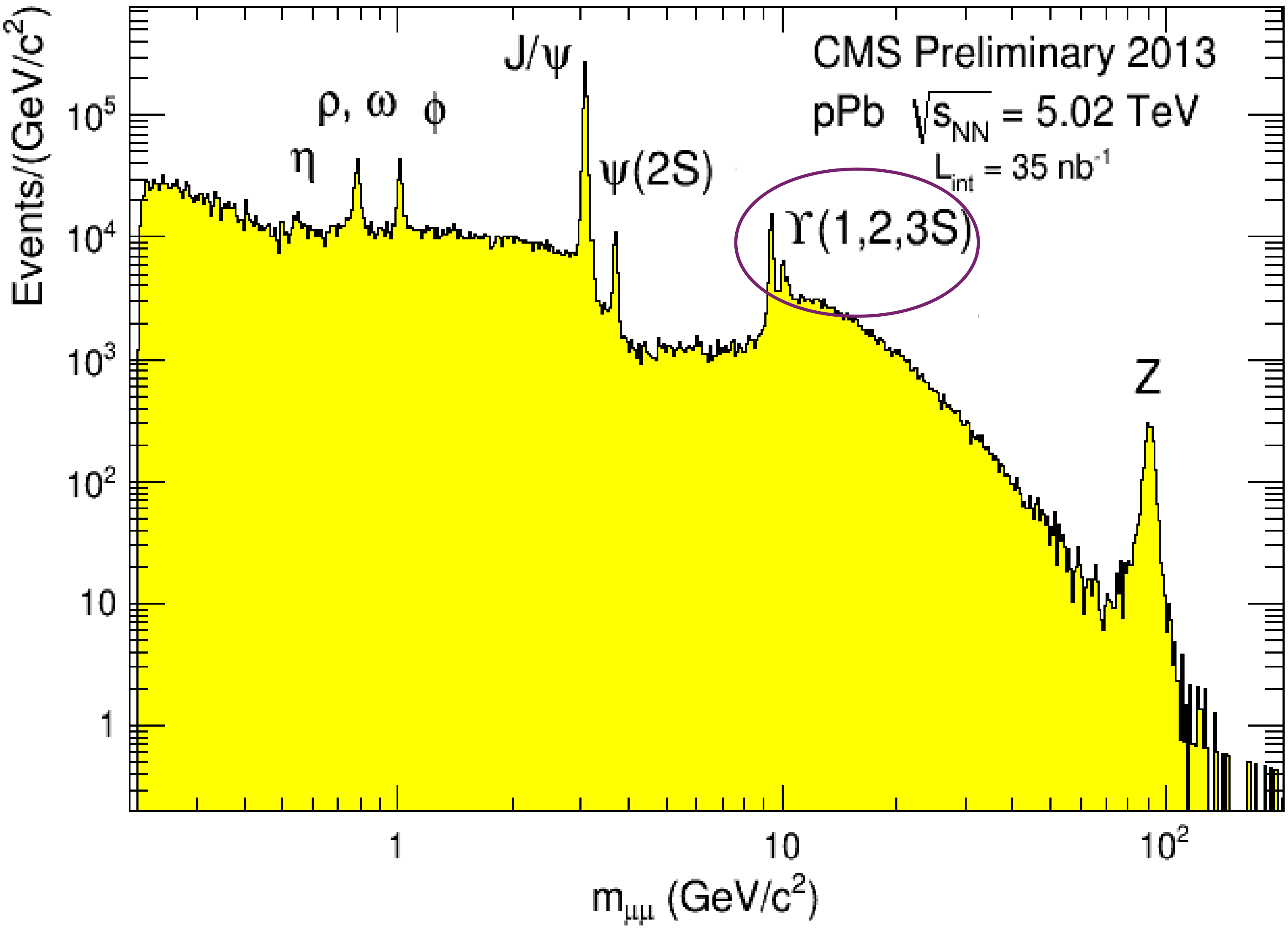


- STAR measurement for Υ(1S)
  - Centrality integrated : R_{AA} Υ(1S) = 0.71 ± 0.06 (stat) ± 0.06 (syst)
- CMS Centrality integrated: R_{AA} Υ(1S) = 0.56 ± 0.08 (stat) ± 0.07 (syst)
- More suppression at LHC as compared to RHIC **?**
- ALICE measurement at forward rapidity:
  - A stronger suppression is observed at forward rapidity than at mid-rapidity

https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsHIN11011

Υ measurement with *p+Pb* at LHC

Dimuon spectrum in 2013 p+Pb



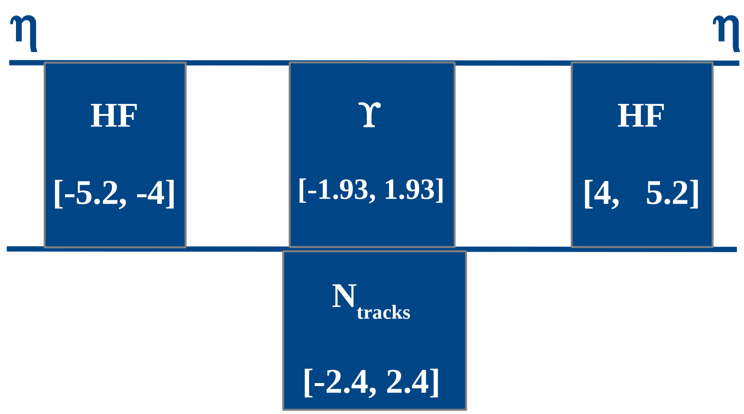
p+p : 5.4 pb^{-1} (~ 20 times more than p+p 2011)

p+Pb collisions

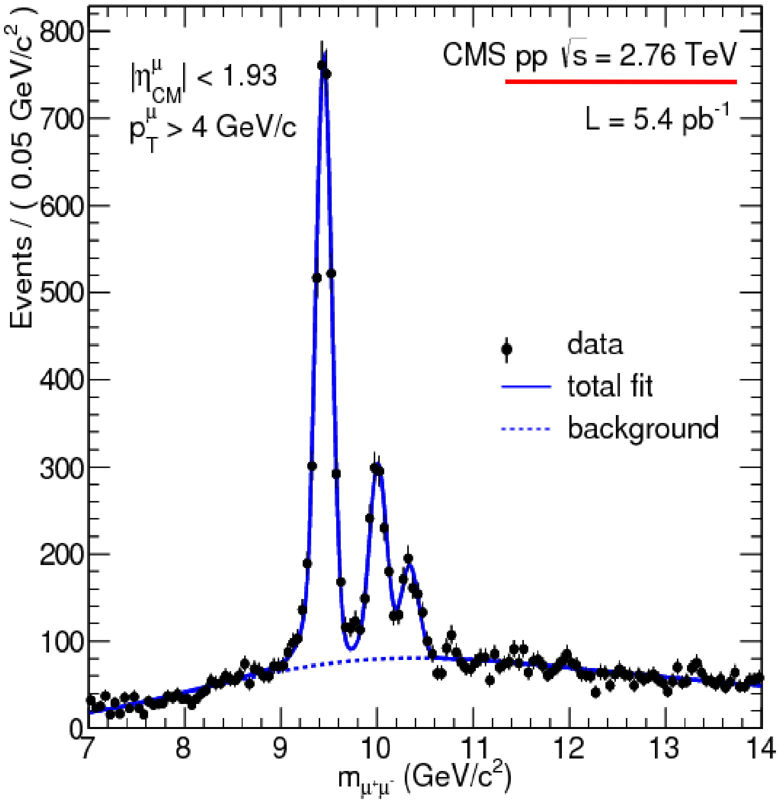
- **p+Pb asymmetric collisions (~0.47 rapidity boost)**
  - Integrated Luminosity Pb+p ~ 18 nb^{-1}, p+Pb ~12 nb^{-1}
  - Energy of p = 4 TeV, Energy of Pb = 4 x 82 / 208 = 1.58 A TeV
  - $\sqrt{s_{NN}} = \sqrt{(4 \times E_p \times E_{Pb})}$ = 5.02 TeV/ nucleon
  - Analysis cut: $|\eta^{\mu}_{CM}| < 1.93$, $p_T^{\mu} > 4$ GeV/c and $|y_{CM}| < 1.93$

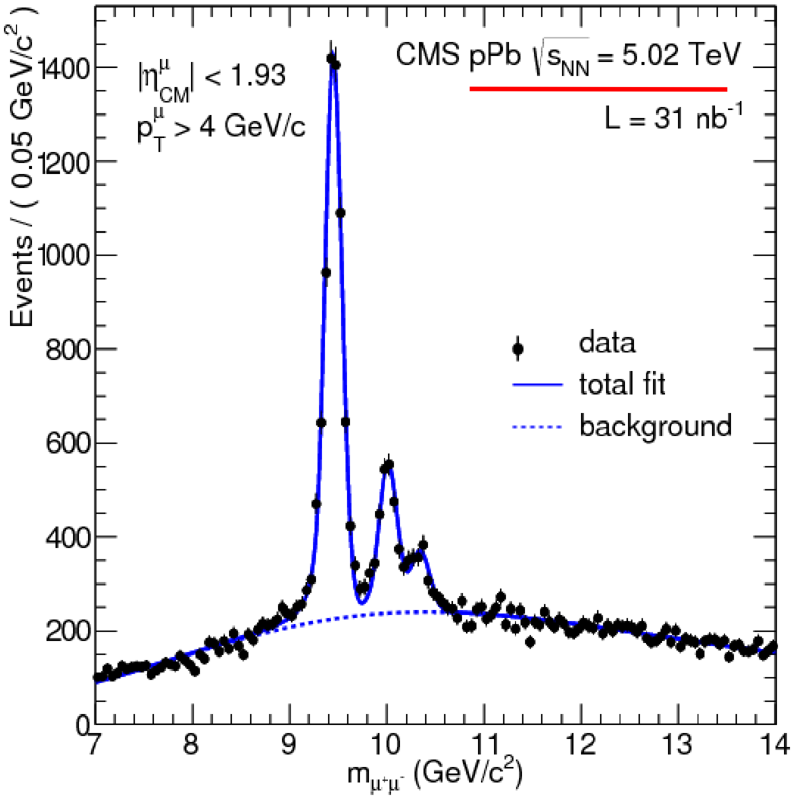
- **Ratio: Event activity integrated**
  - Similar method followed as in **PRL 109 222301 (2012)**

- **Binning in 2 event-activity variables**
  - $N_{tracks}^{|\eta| < 2.4}$ Number of charged particles
  - $E_T^{|\eta| > 4}$ Raw transverse energy measured in hadron forward calorimeter (HF)



Invariant mass distributions

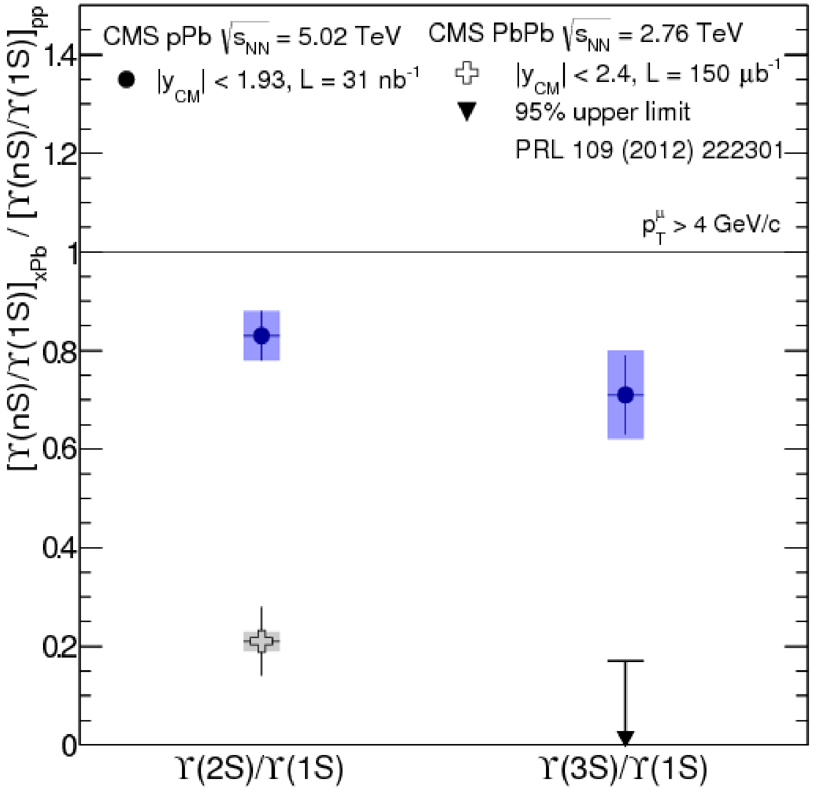




- Signal extraction: Same procedure in pp, pPb and PbPb
- Unbinned maximum log likelihood fit with 1S, 2S/1S, 3S/1S variables
  - ➔ Signal: 3 Crystal-Ball functions
  - ➔ Background: ErrorFunction * exponential (all background parameters free)

JHEP 04 103 (2014)

Double ratio (DR) : Event activity integrated



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

- **pPb DR :** √s dependence of the single ratio in pp : (7, 1.9 and 2.76 TeV)
  - ➔ No significant difference is found within the systematic and statistical uncertainties
- In Double Ratio initial state effects likely to cancel in p+Pb and Pb+Pb collisions.
  - ➔ Suggesting presence of final state effects in p+Pb and Pb+Pb
  - ➔ Affecting more strongly excited states ϒ(2S) and ϒ(3S) than ϒ(1S).

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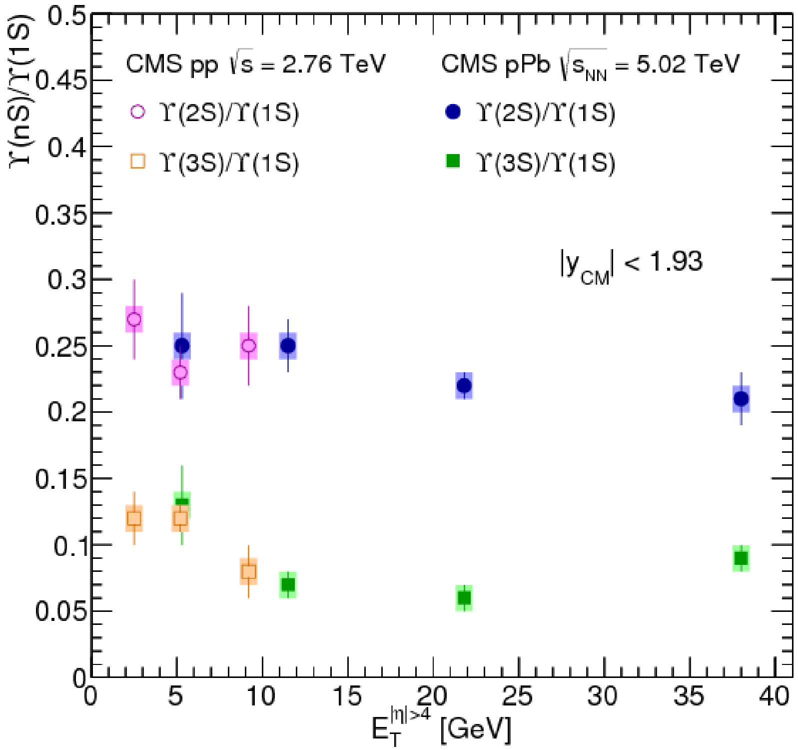
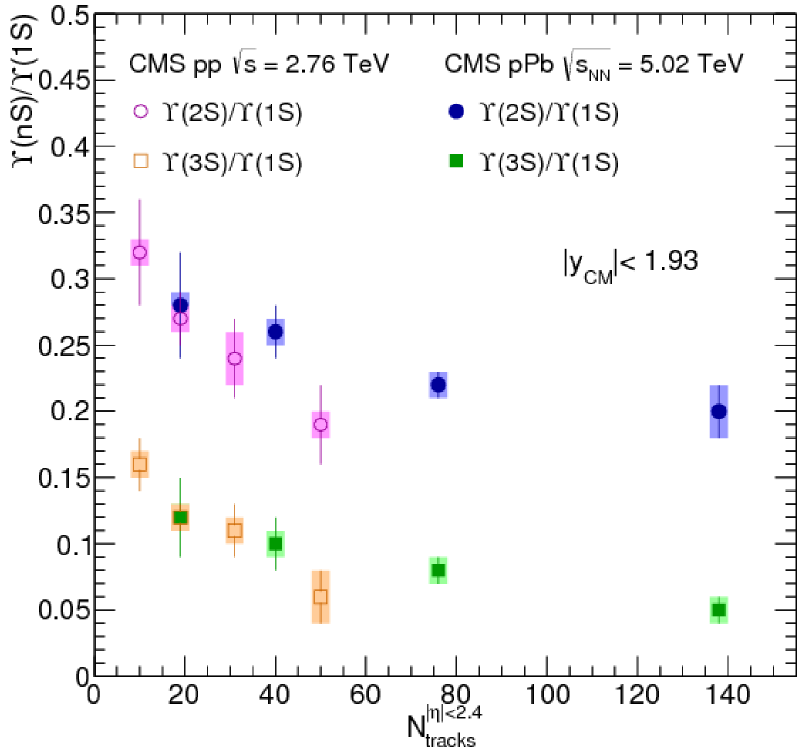
Single ratios Vs Event activity





- $E_T^{|\eta|>4}$ Transverse energy deposited in HF
  - Single ratios are varying weakly as a function of $E_T^{|\eta|>4}$
- $N_{tracks}^{|\eta|<2.4}$ Number of charged particles reconstructed in tracker, p_T > 400 MeV/c
  - Single ratios exhibit a significant decrease with increasing multiplicity
    - Υ(1S) is produced with more charged particles than the excited Υ states
    - Υ(nS) are affected by final-state interaction (*Possible explanations*)

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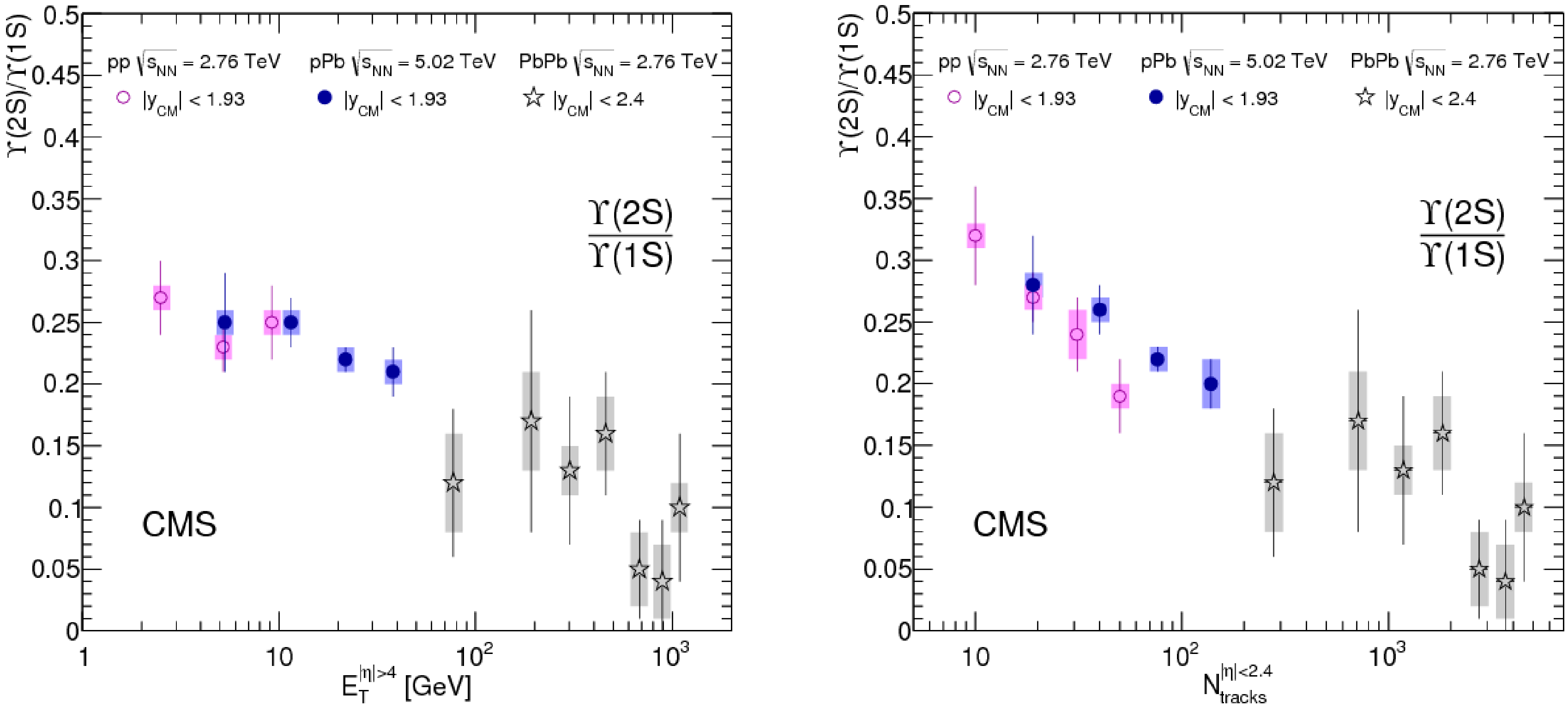
Single ratios Vs Event activity



- Single Ratios, $\Upsilon(nS)/\Upsilon(1S)$ are compared for all three collision systems p+p, p+Pb and Pb+Pb
- Little overlap between most peripheral (50–100%) PbPb bin and high-multiplicity pPb bin
- PbPb ratios are below the pPb ratios, with large uncertainties:
  - ➔ More Pb+Pb data are needed to investigate the dependence in three systems

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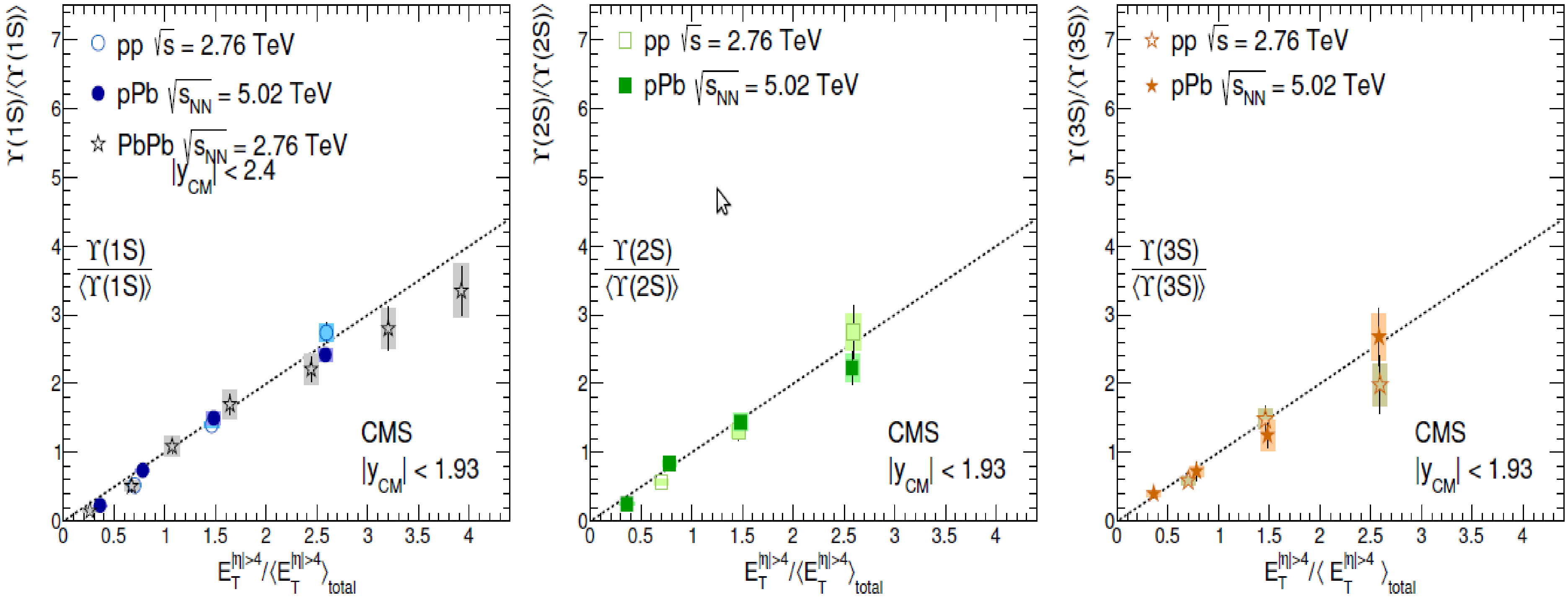
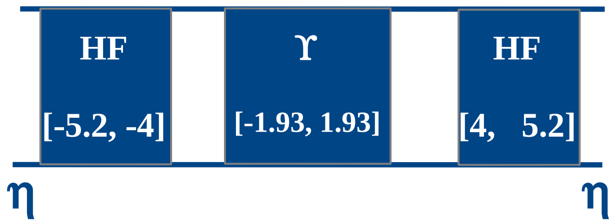
Self-normalized Yields: $\Upsilon(nS)/\langle\Upsilon(nS)\rangle$ Vs E_T



- Yield versus Transverse energy, normalized to their average
- Linear Fit: all slopes consistent with unity
  - No significant difference between three Υ states
  - Very different $\langle E_T \rangle$ GeV: 3.5 (pp), 14.7 (pPb), 765 (PbPb)



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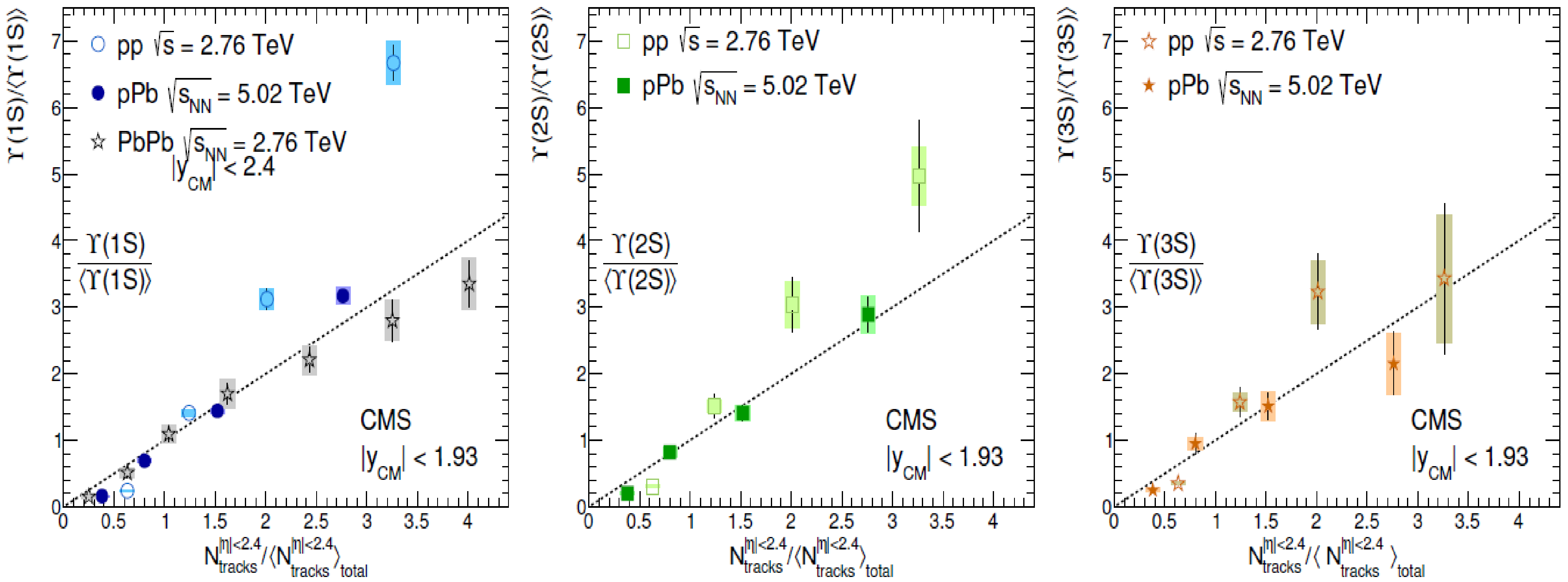
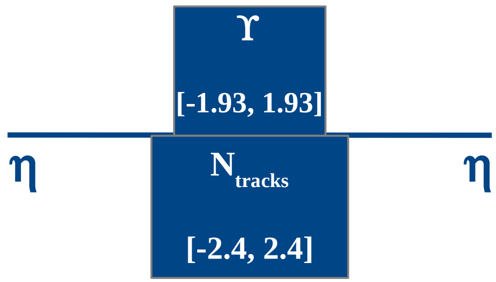
Self-normalized Yields: $\Upsilon(nS)/<\Upsilon(nS)>$ Vs N_{tracks}



- Yield versus N_{tracks}, normalized to their average
- Shows difference between three Υ states
  - Fastest rise of Υ(1S) in p+p collisions



- All ratios present an increasing trend with increasing event activity (E_T and N_{tracks})
  - In pPb and PbPb : more nucleon-nucleon collisions
  - In pp : multiple parton-parton interactions (*Possible explanation*)

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Summary

Pb+Pb

- We observed sequential suppression of three Υ states at LHC
  - ➔ $R_{AA}^{\Upsilon(3S)} < R_{AA}^{\Upsilon(2S)} < R_{AA}^{\Upsilon(1S)}$

- Υ analysis will be updated with new p+p data recorded in 2013 and with Pb+Pb data reconstructed more efficiently

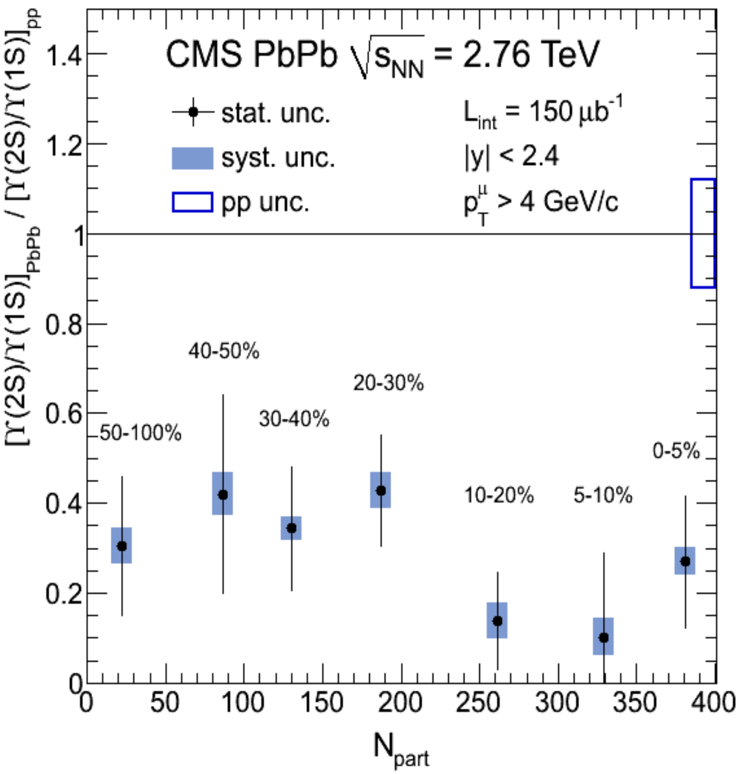
p+Pb

- Double Ratio: Suggest the presence of final state effects in p+Pb collisions
  - ➔ Υ(2S) and Υ(3S) are more affected than Υ(1S)
- Binned in Event activity: Υ(nS)/Υ(1S)
  - ➔ Single ratios are varying weakly as a function of $E_T^{|\eta| > 4}$
  - ➔ Single ratios are decreasing with increasing $N_{tracks}^{|\eta| < 2.4}$
- Self normalised ratio: Υ(nS)/<Υ(nS)>
- All ratios present an increasing trend with increasing event activity
  - ➔ $\mathbf{E_T}$ **:** Slopes are consistent with unity for all states
    - ➢ no significant difference between three Υ states
  - ➔ $\mathbf{N_{track}}$ **:** Shows difference between the Υ states

Thank you

Extra slides

Υ Double Ratio with Pb+Pb



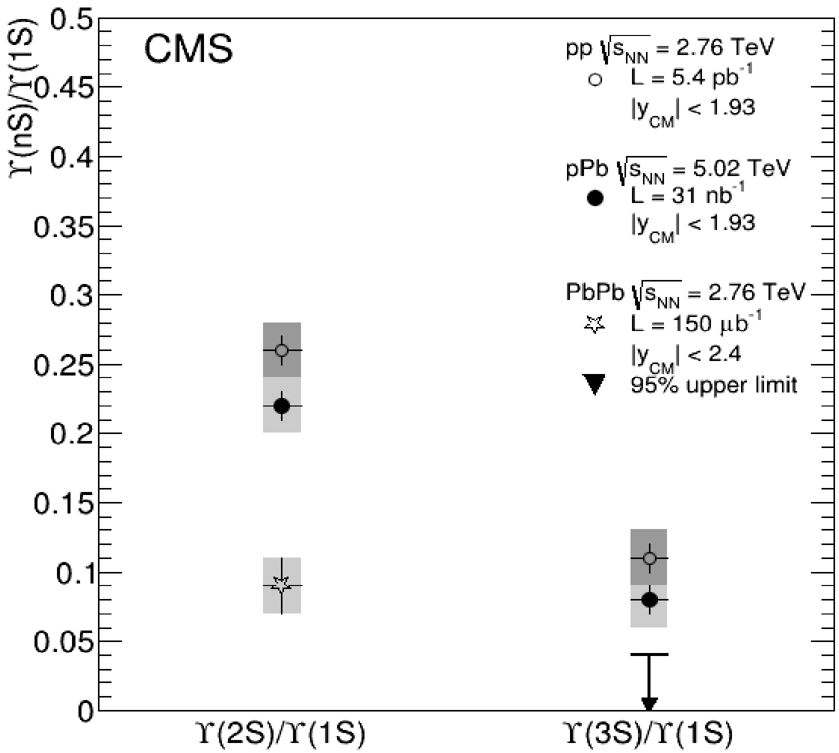
$$\frac{\Upsilon(2S)/\Upsilon(1S)|_{\mathrm{PbPb}}}{\Upsilon(2S)/\Upsilon(1S)|_{pp}} = 0.21 \pm 0.07(\mathrm{stat}) \pm 0.02(\mathrm{syst}),$$

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

$$< 0.17(95\%\mathrm{CL}).$$

- Double ratio of Υ(nS)/Υ(1S) with Pb+Pb at 2.76 TeV
- The ratios are less than one in all centrality region in |y| < 2.4
- More suppression of Υ(2S) w.r.t Υ(1S)

Single ratios



Data	Rapidity	$\frac{\Upsilon(2S)}{\Upsilon(1S)}$	$\frac{\Upsilon(3S)}{\Upsilon(1S)}$
pp $\sqrt{s} = 2.76$ TeV	$\lvert y_{CM} \rvert < 1.93$	$0.26 \pm 0.01 \pm 0.01 \pm 0.02$	$0.11 \pm 0.01 \pm 0.01 \pm 0.01$
pPb $\sqrt{s_{NN}} = 5.02$ TeV	$\lvert y_{CM} \rvert < 1.93$	$0.22 \pm 0.01 \pm 0.01 \pm 0.02$	$0.08 \pm 0.01 \pm 0.01 \pm 0.01$
PbPb $\sqrt{s_{NN}} = 2.76$ TeV	$\lvert y_{CM} \rvert < 2.4$	$0.09 \pm 0.02 \pm 0.02 \pm 0.01$	<0.04 (at 95% confidence level)

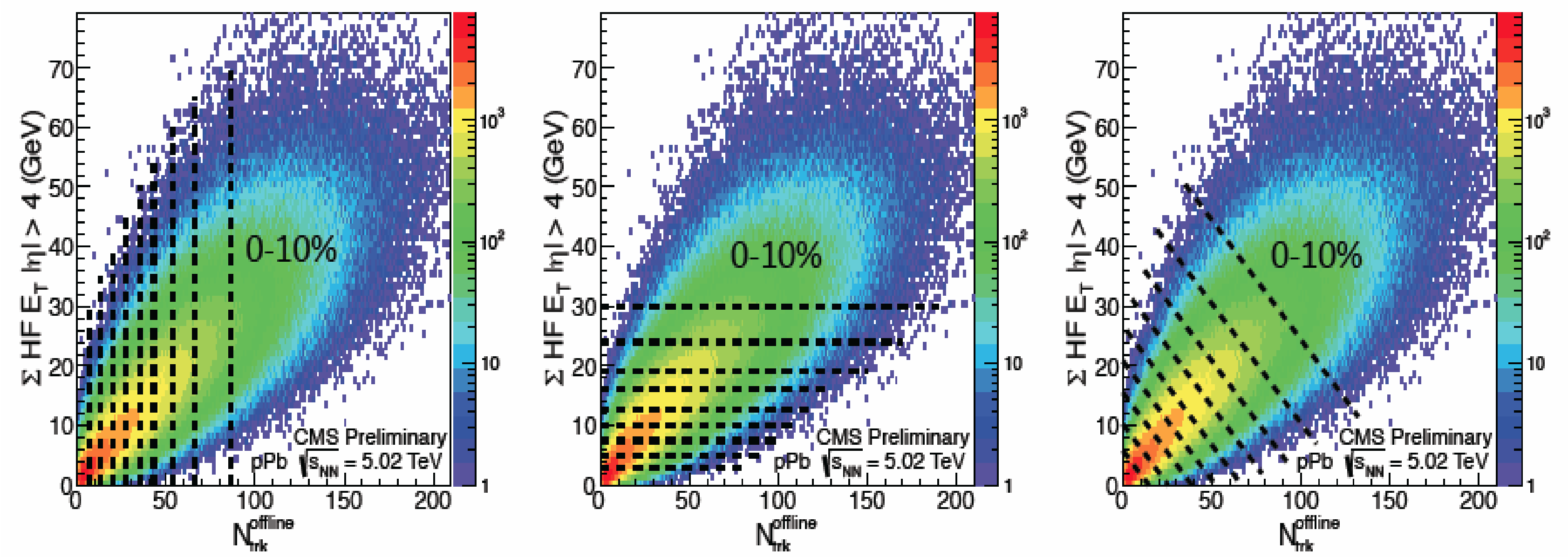
$\sqrt{s}$ dependence of single ratio in pp

Data	p_{T} [GeV/c]	Rapidity	$\frac{\Upsilon(2S)}{\Upsilon(1S)}$ total	$\frac{\Upsilon(3S)}{\Upsilon(1S)}$ total
CMS pp $\sqrt{s} = 2.76$ TeV	0–40	$\lvert y\rvert < 1.93$	0.26 ± 0.02	0.11 ± 0.02
CMS pp $\sqrt{s} = 7$ TeV [33]	0–38	$\lvert y\rvert < 2.4$	0.26 ± 0.03	0.13 ± 0.02
CDF p$\overline{\mathrm{p}}$ $\sqrt{s} = 1.9$ TeV [34]	1–10	$\lvert y\rvert < 0.4$	0.28 ± 0.05	0.16 ± 0.03

Table 1. The $\sqrt{s}$ dependence of the excited-to-ground-state cross section ratios, $\frac{\Upsilon(\mathrm{nS})}{\Upsilon(1\mathrm{S})}$, in pp and p$\overline{\mathrm{p}}$ collisions. The total quoted uncertainties represent the quadratic sum of the statistical, systematic, and global uncertainties. Listed also are the Υ rapidity and transverse momentum ranges for which each measurement is reported.

<N_{coll}> from different methods agree well

Defining centrality from different methods:



- Slicing multiplicity and ΣHF E_T |η|>4 means selecting very different events (e.g. 0-10% in the plots), but <N_{coll}> are the same
- The real difficulties of centrality determination are about how to define centrality in real data (which η range to use?) for an analysis and study possible biases