

Quarkonia and Heavy Flavours in CMS

Camelia Mironov
LLR/Ecole polytechnique
ERC QuarkGluonPlasmaCMS

on behalf of the
CMS Collaboration

Today

● Focus on the *beauty* in pp, pPb and PbPb CMS results

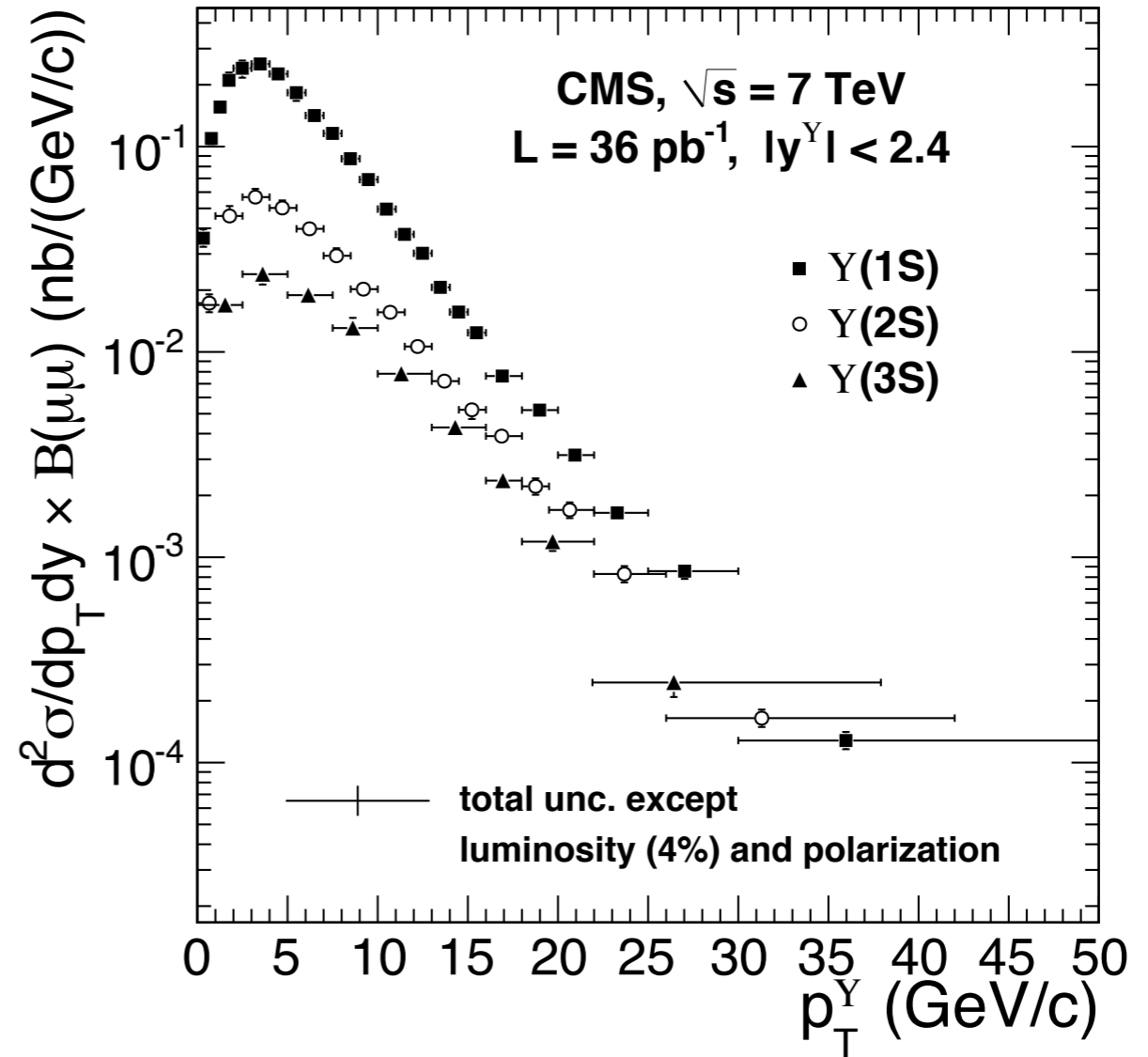
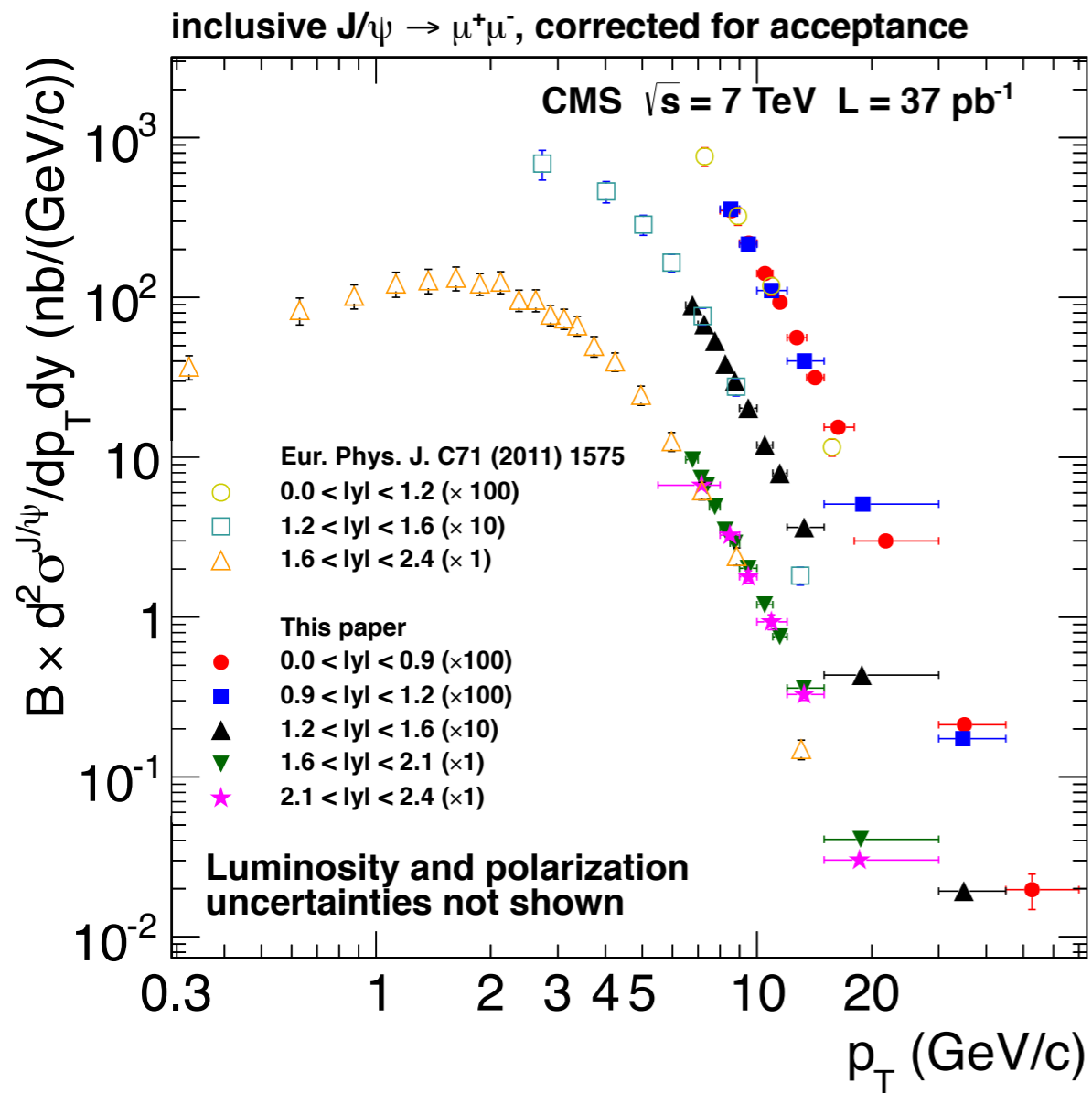
➔ B: PbPb (and pp) 2.76 TeV

➔ $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$: pp and PbPb 2.76 TeV, pPb 5.02 TeV

CμS : dimuon acceptance

Eur.Phys.J. C71 (2011) 1575
 JHEP 02 (2012) 011

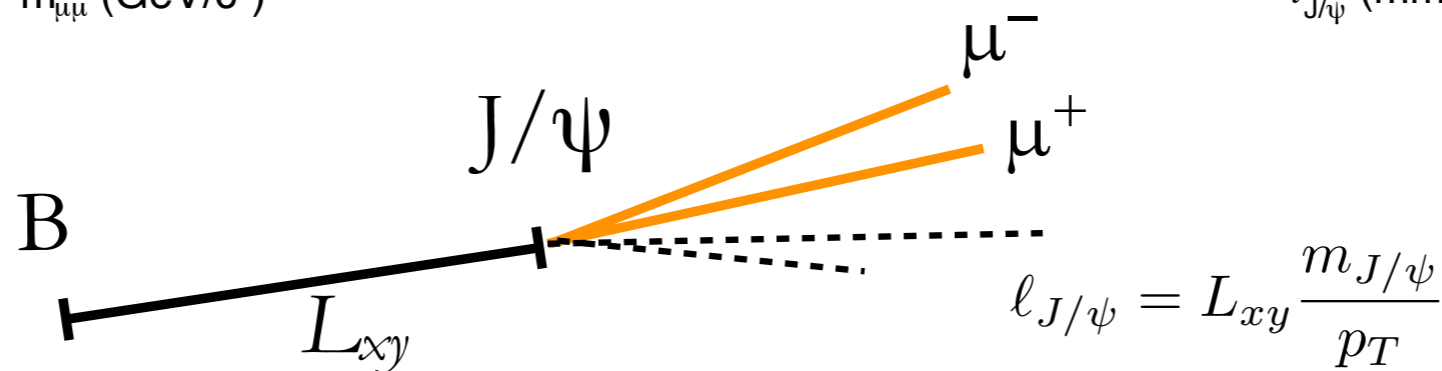
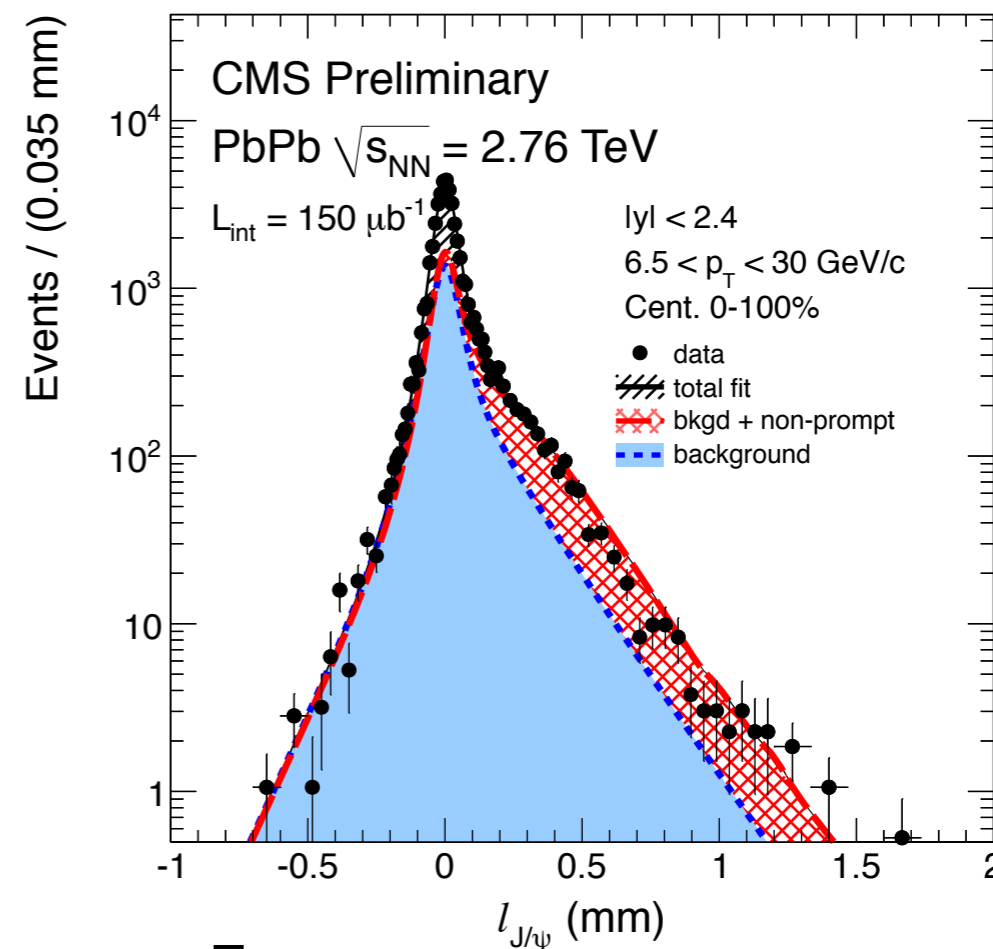
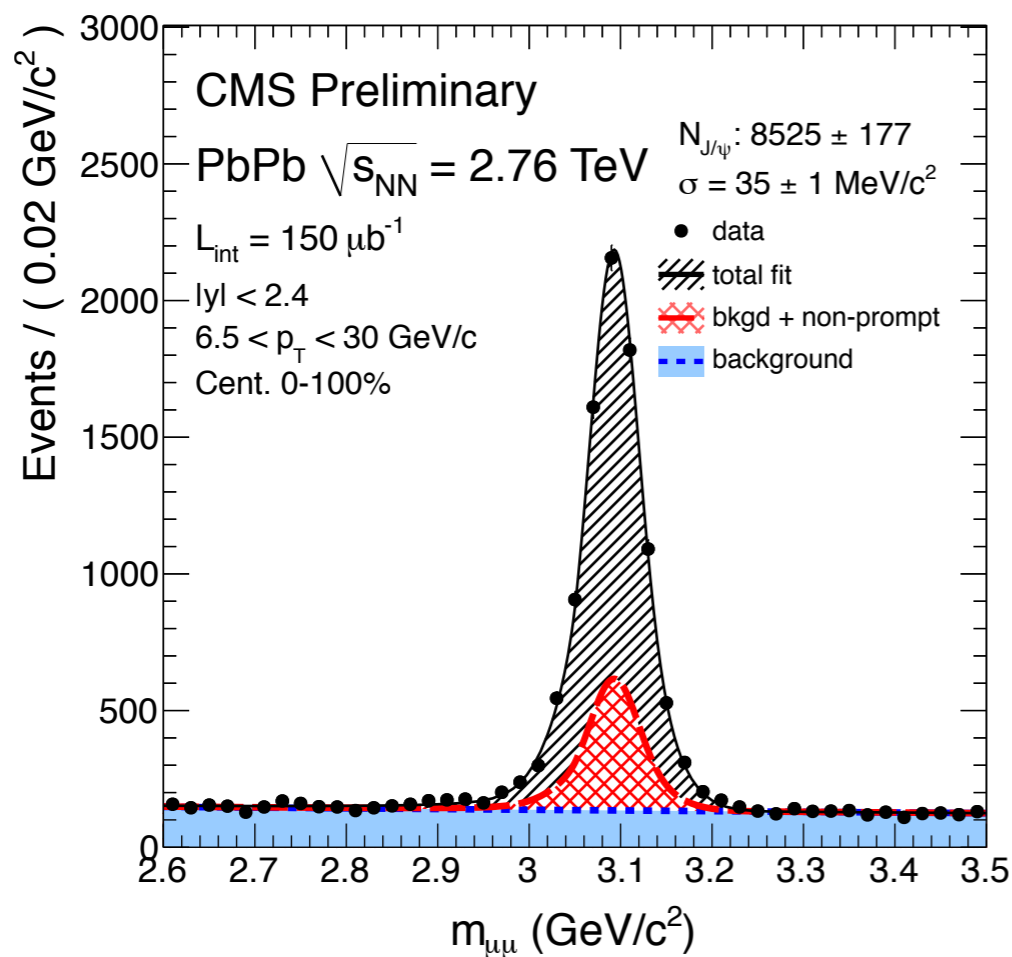
arXiv:1303.5900
 PLB accepted for pub.



- J/ψ
 - ▶ pp: $p_T > 0$ GeV/c ($1.6 < |y| < 2.4$), $p_T > 2$ GeV/c ($1.2 < |y| < 1.6$), $p_T > 6.5$ GeV/c ($|y| < 1.2$)
 - ▶ PbPb: $p_T > 3.5$ GeV/c ($1.6 < |y| < 2.4$), $p_T > 5.5$ GeV/c ($1.2 < |y| < 1.6$), $p_T > 6.5$ GeV/c ($|y| < 1.2$)
- Y
 - ▶ pp: $p_T > 0$ GeV/c

◎ Open beauty: $B \rightarrow J/\psi(\mu\mu) + X$

$B \rightarrow J/\psi \rightarrow \mu\mu$

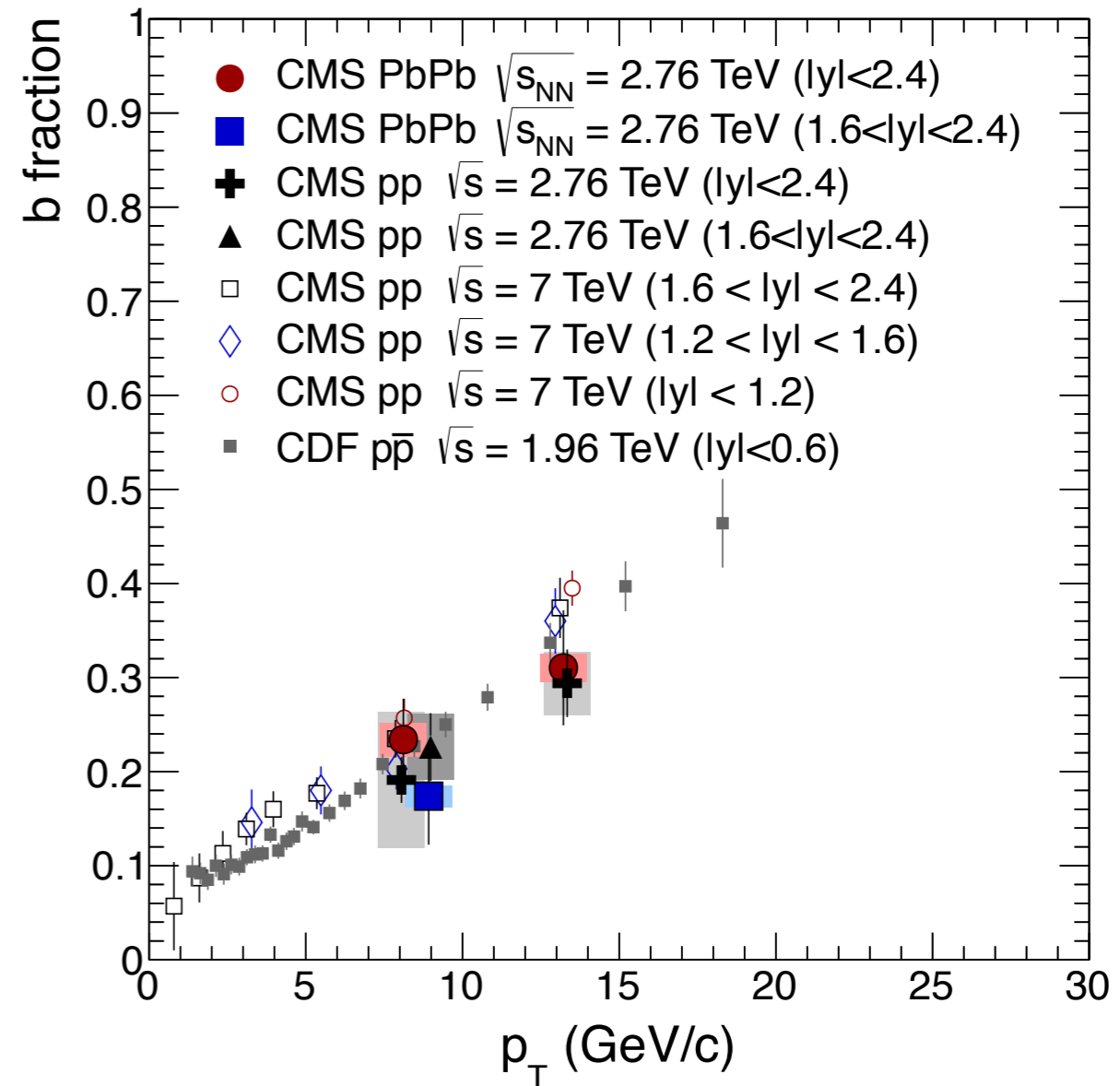
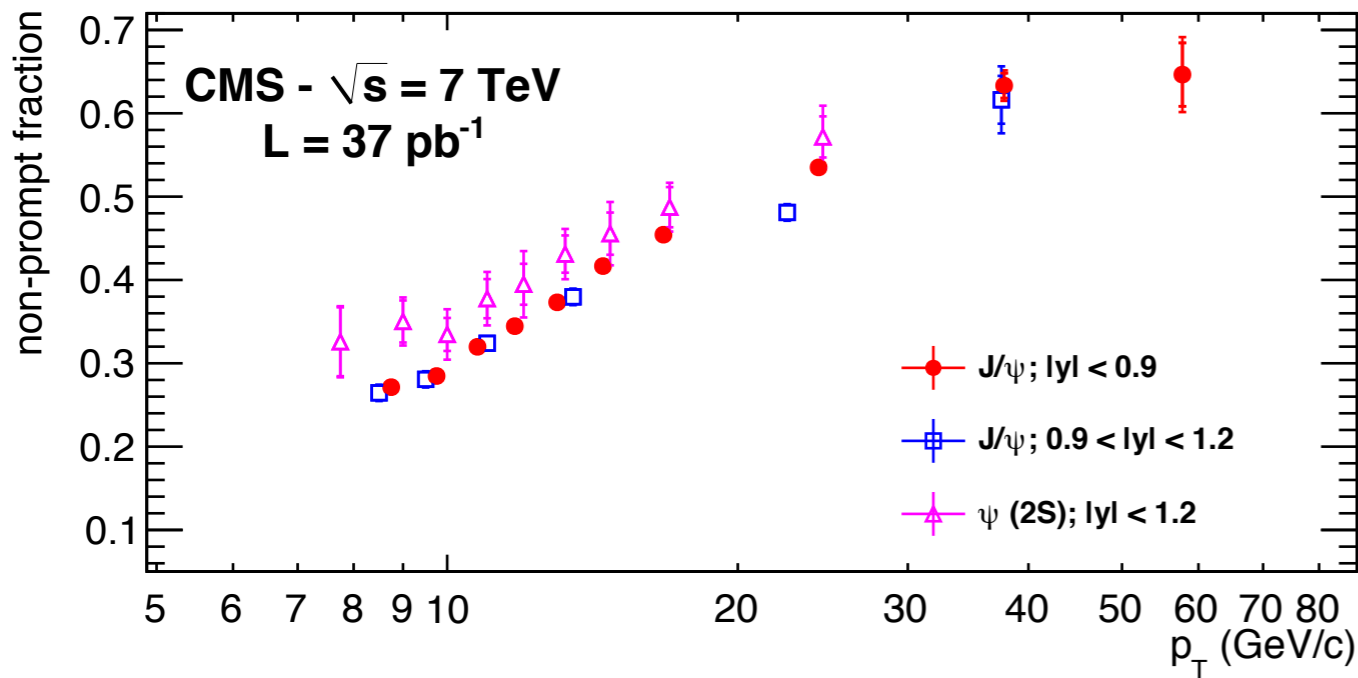


☉ Same procedure in both pp and PbPb:

➡ Reconstruct the $\mu^+\mu^-$ secondary vertex

➡ 2D fit of invariant mass and $l_{J/\psi} \rightarrow$ b-fraction in each p_T , y , centrality bin \rightarrow yields

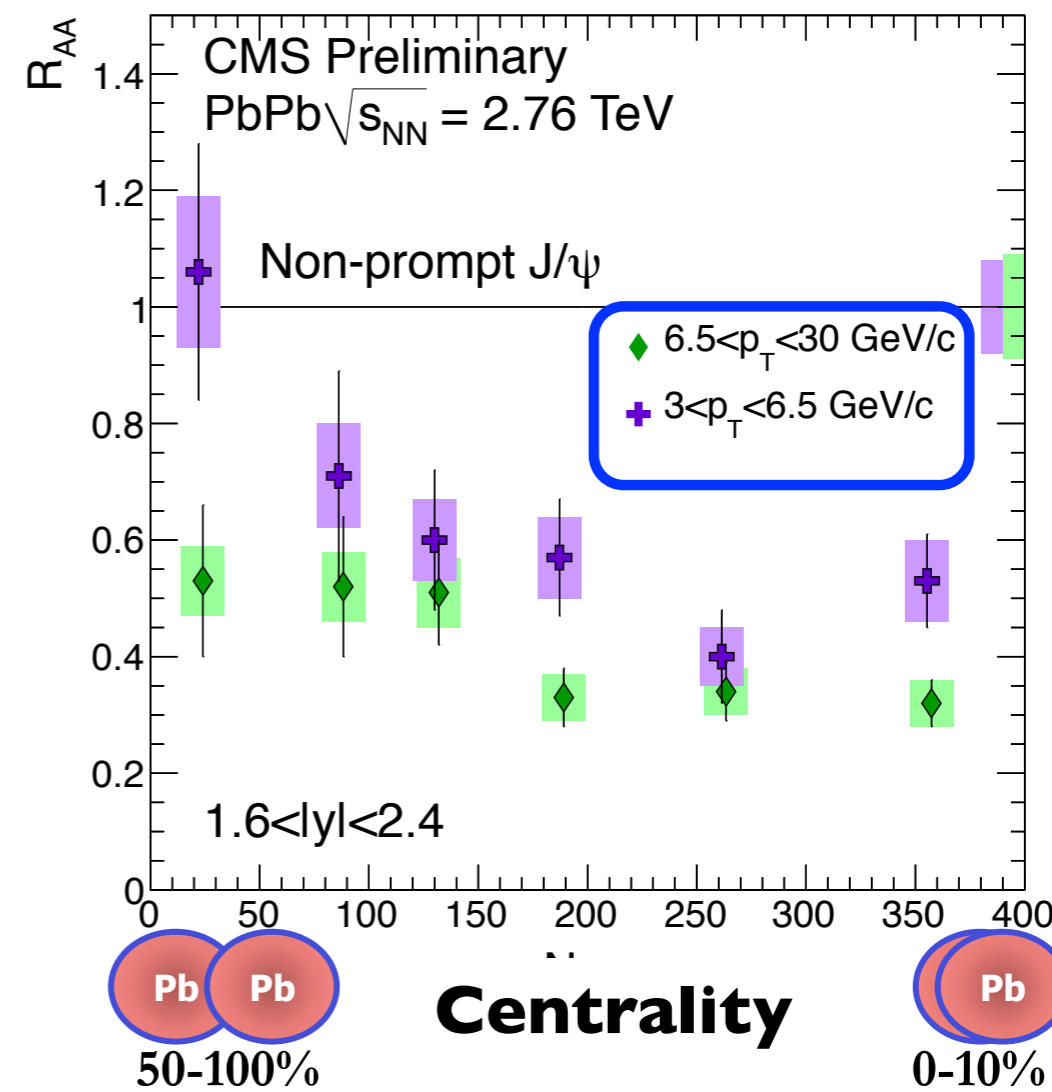
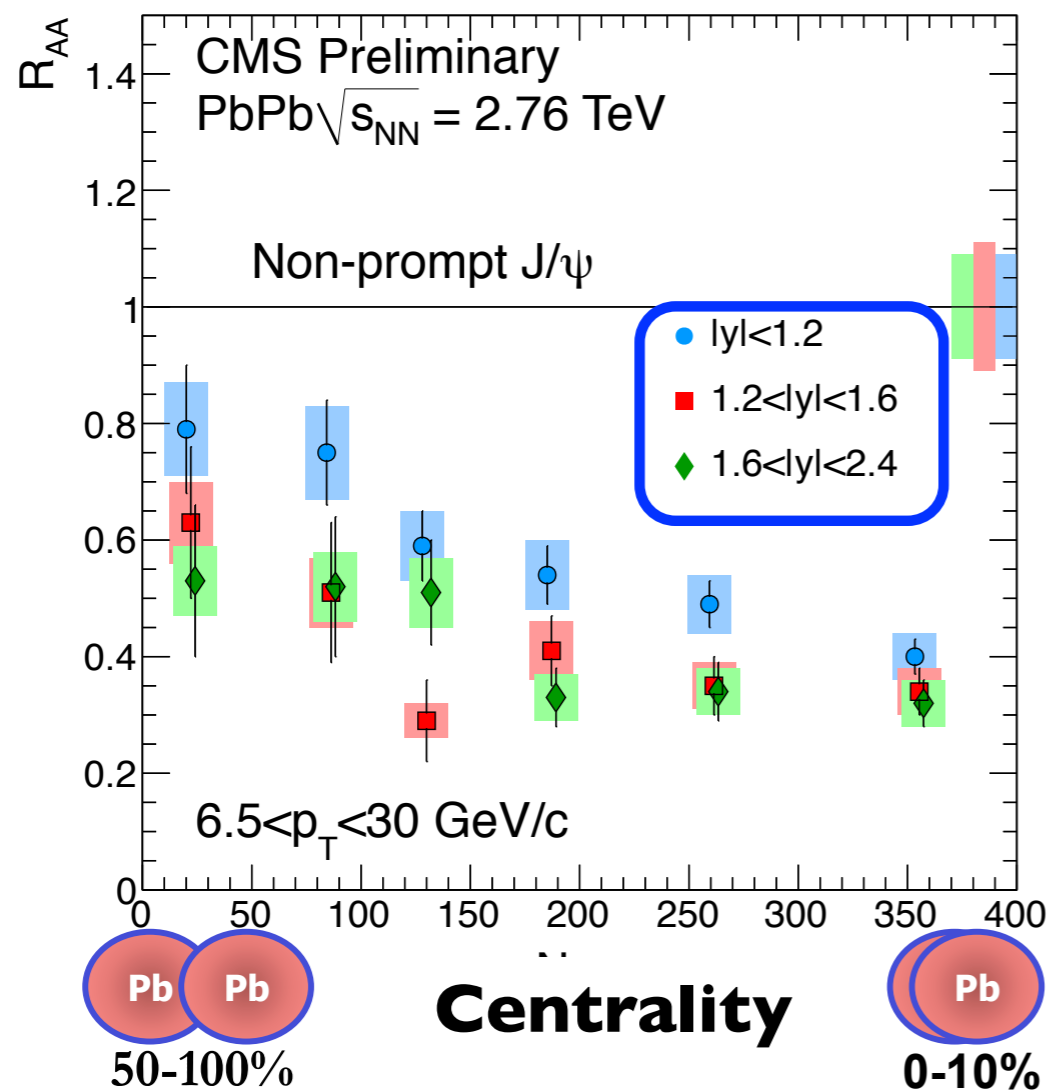
b-fraction = [non-prompt J/ψ] / [inclusive J/ψ]



● **pp**: strong increase with p_T (~30% at p_T~15 GeV/c) and as high as 60% at p_T=60 GeV/c

● **PbPb**: a different way of looking at the difference in en loss between c̄c̄ and b̄b̄

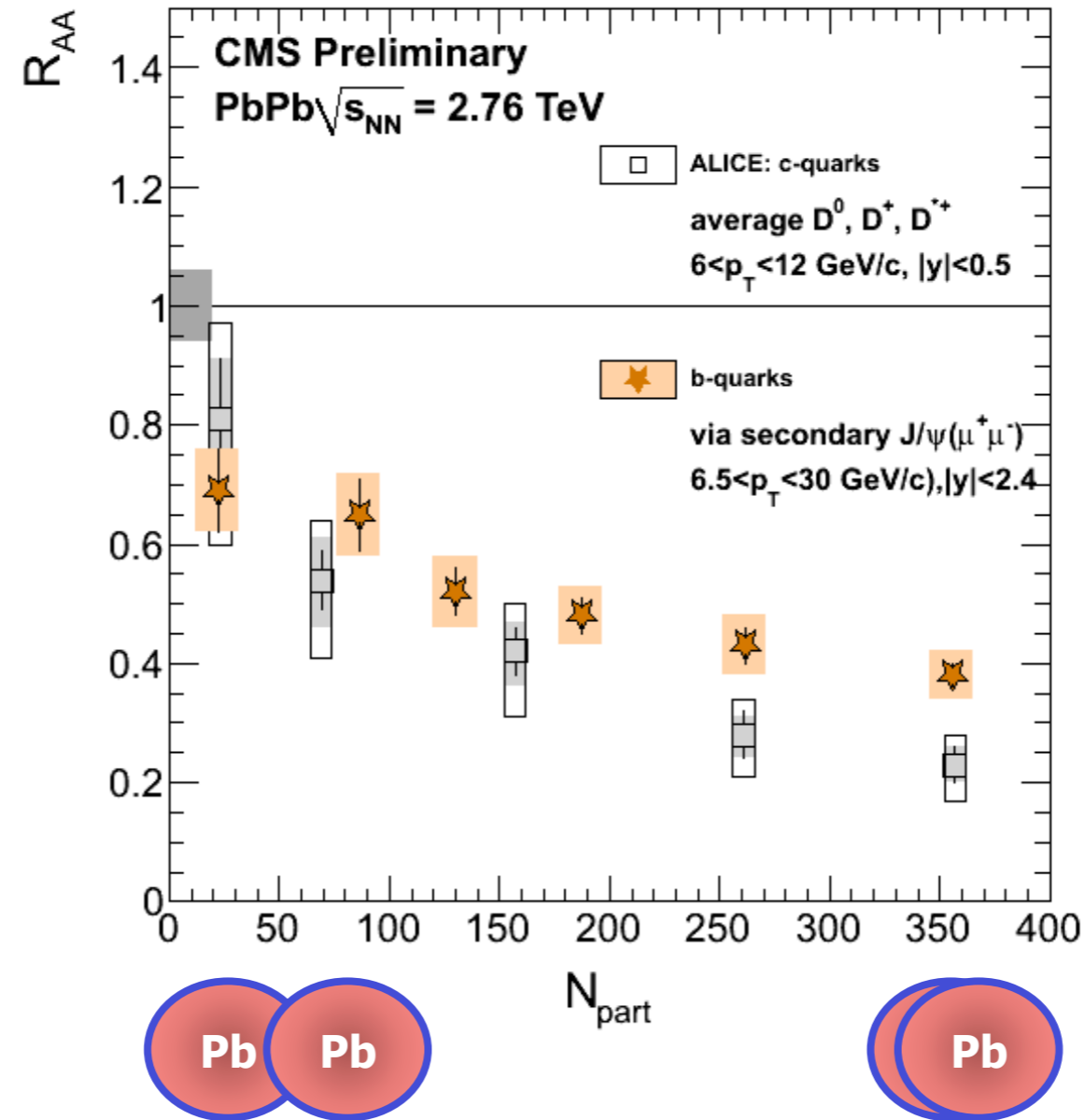
$b \rightarrow B \rightarrow J/\psi \rightarrow \mu\mu$ R_{AA}



⊙ high- p_T : $6.5 < p_T < 30$ GeV/c
 ➔ hints of less suppression at mid-rapidity

⊙ forward: $1.6 < |y| < 2.4$
 ➔ hints of less suppression at lower- p_T

Beauty vs Charm



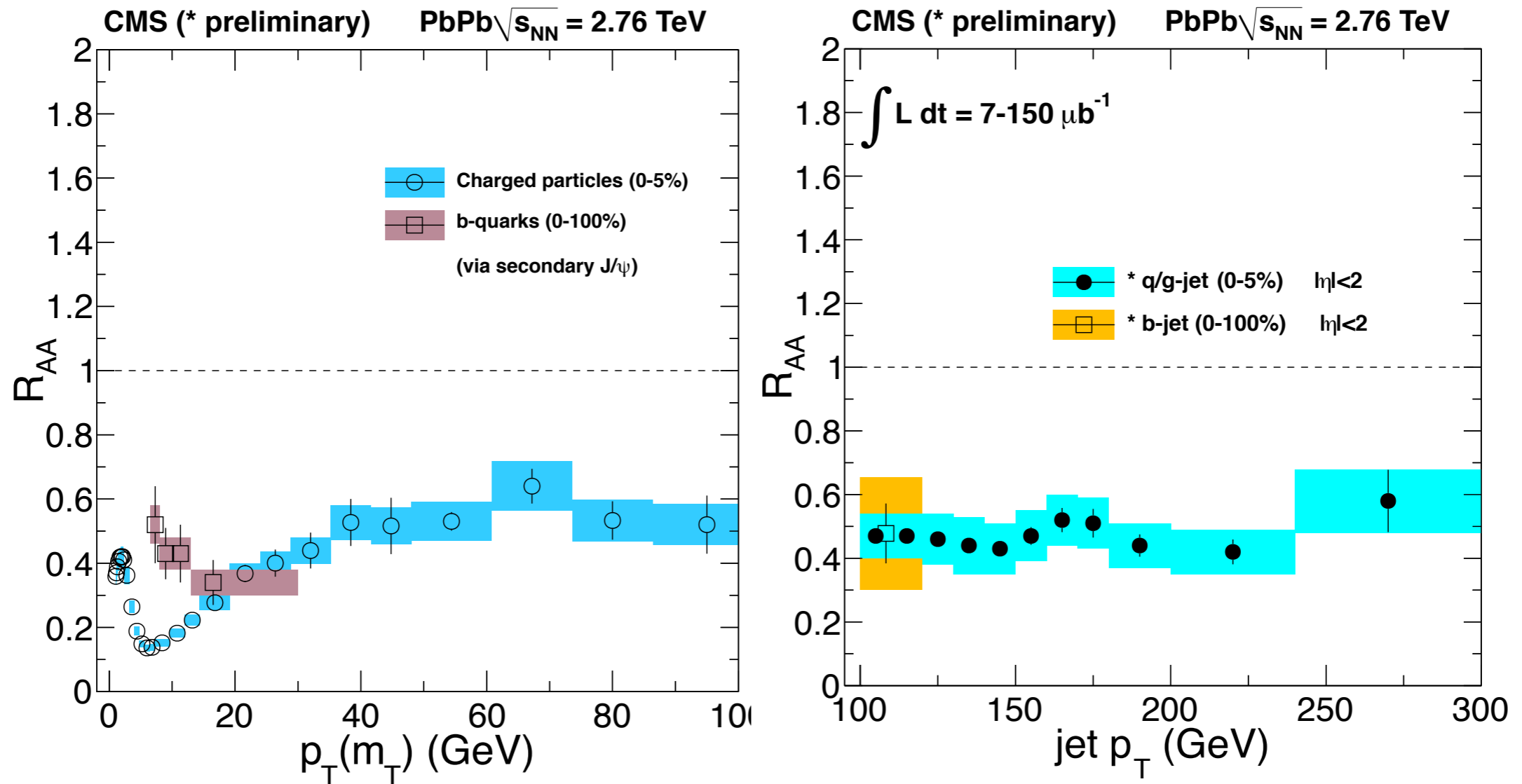
☉ **Centrality** (p_T, y integrated): slow decrease of suppression

➡ 50-100%: factor ~ 1.4

➡ 0-10%: factor 2.5

☉ **In central PbPb collisions, at the LHC: $R_{AA}^{charm} < R_{AA}^{beauty}$**

Heavy vs Light



⊙ At low- p_T ($B \rightarrow J/\psi$): different suppression pattern

⊙ At high- p_T (fully reconstructed b-jets): similar suppression

⊙ Note: gluon jets dominant at LHC --- energy loss gluon $>$ energy loss light quark --- not there yet for mass dependence of en loss

Summary I: Open Beauty $b \rightarrow B \rightarrow J/\psi$

- Hints of interesting (some unique) features in the p_T , y , and cent. dependence of R_{AA}
 - ➔ More statistics would be nice
 - ▶ pp: already on tape $\sim 20x$ more data (2013 pp run at 2.76 TeV)
 - ▶ 2011 PbPb re-processed : 40% more data (improved muon reconstruction algorithm in PbPb)
- There is something we predicted right: $R_{AA}^D < R_{AA}^B$ in central PbPb at the LHC

● Closed beauty: $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

$\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$

state	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$
Mass(GeV)	9.46	10.0	10.36
ΔE (GeV)	1.10	0.54	0.20
r_0 (fm)	0.28	0.56	0.78

◎ **Relatively close cross-section x branching ratios, close in mass**

- ➔ initial effects (before the hard-scattering that produced the bb) should be similar
 - ▶ nPDFs (shadowing, etc), initial parton energy loss

◎ **Different in size, binding energy (and formation time)**

- ➔ final effects of the medium on each state expected to be different (ordered/sequential)
 - ▶ after hard-scattering, before and after the bound state is formed
 - ▶ Debye screening, partonic and hadronic break-up, nuclear absorption

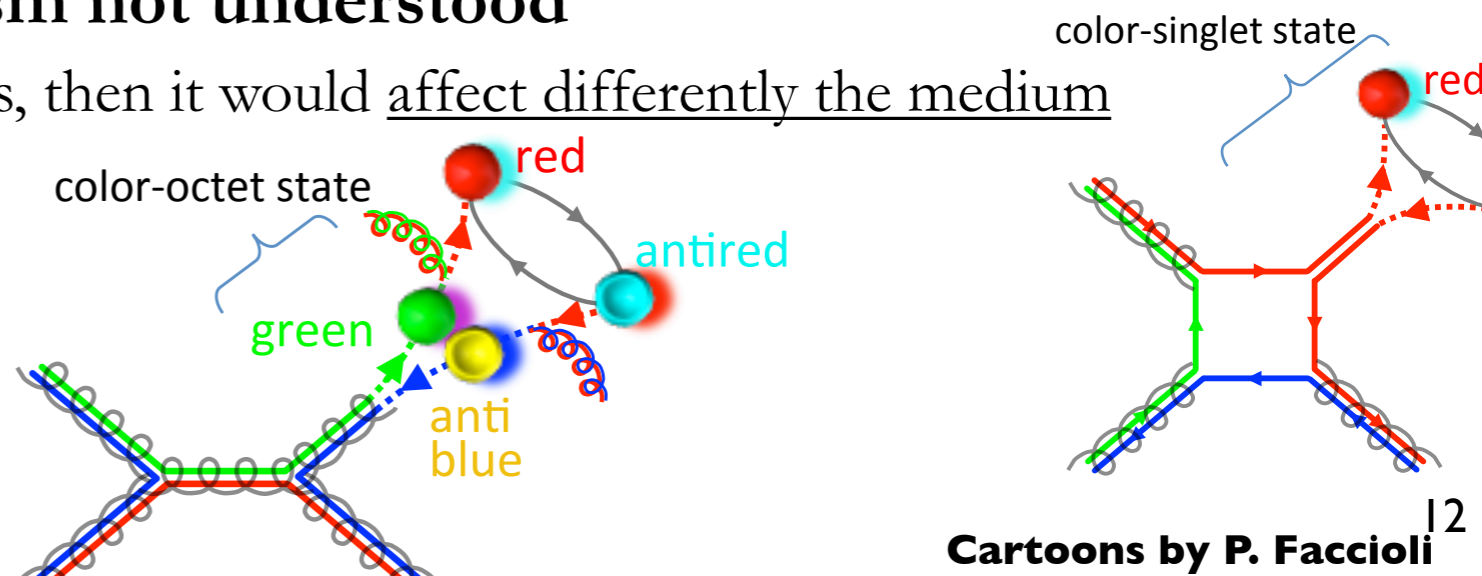
◎ **Different (and largely unknown) feed-down contributions**

- ➔ different effects of the states on the medium

◎ **With vacuum production mechanism not understood**

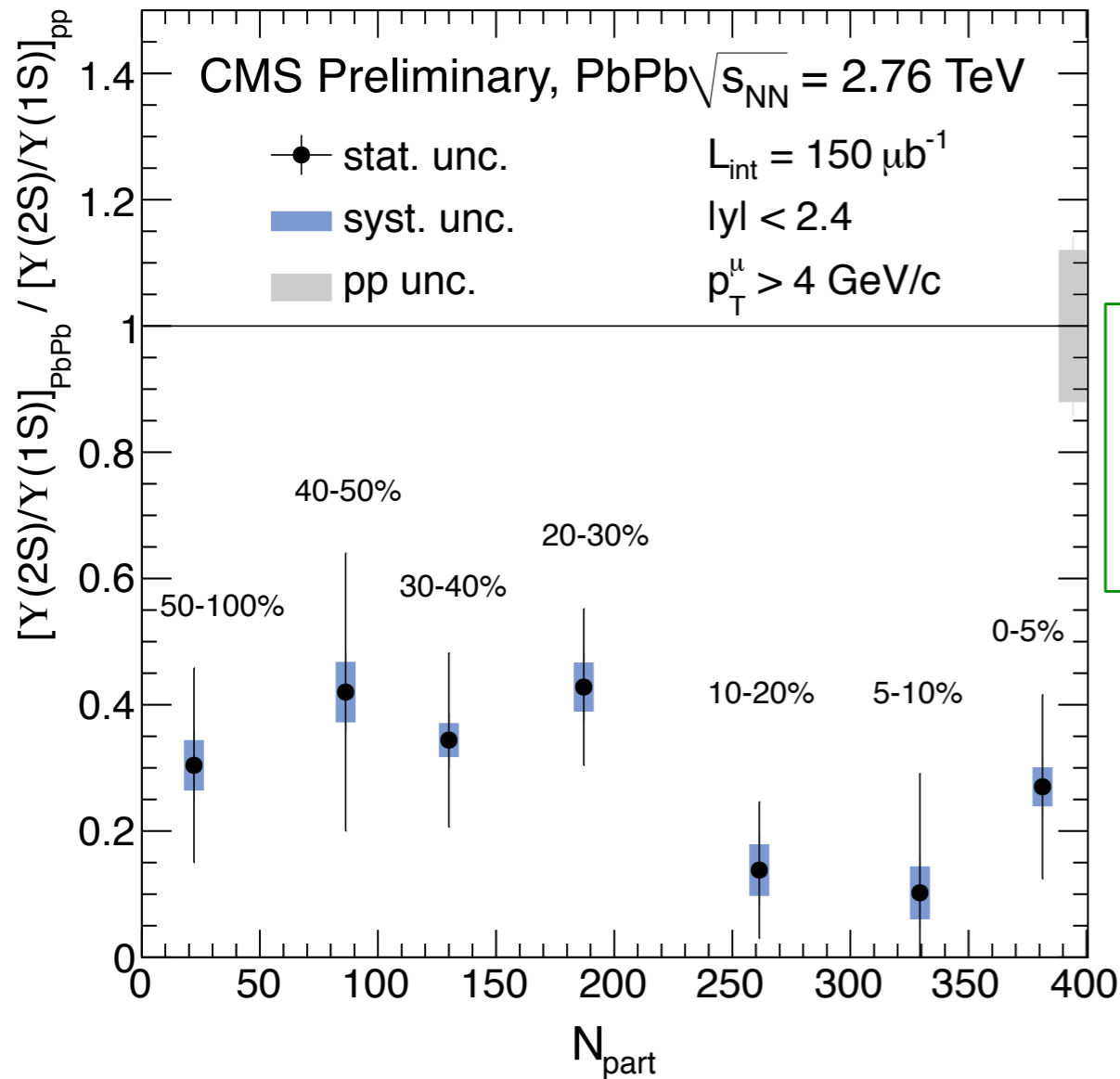
- ▶ if in any way different for the 3 states, then it would affect differently the medium

◎ **Or ...?**



Cartoons by P. Faccioli¹²

Double ratio

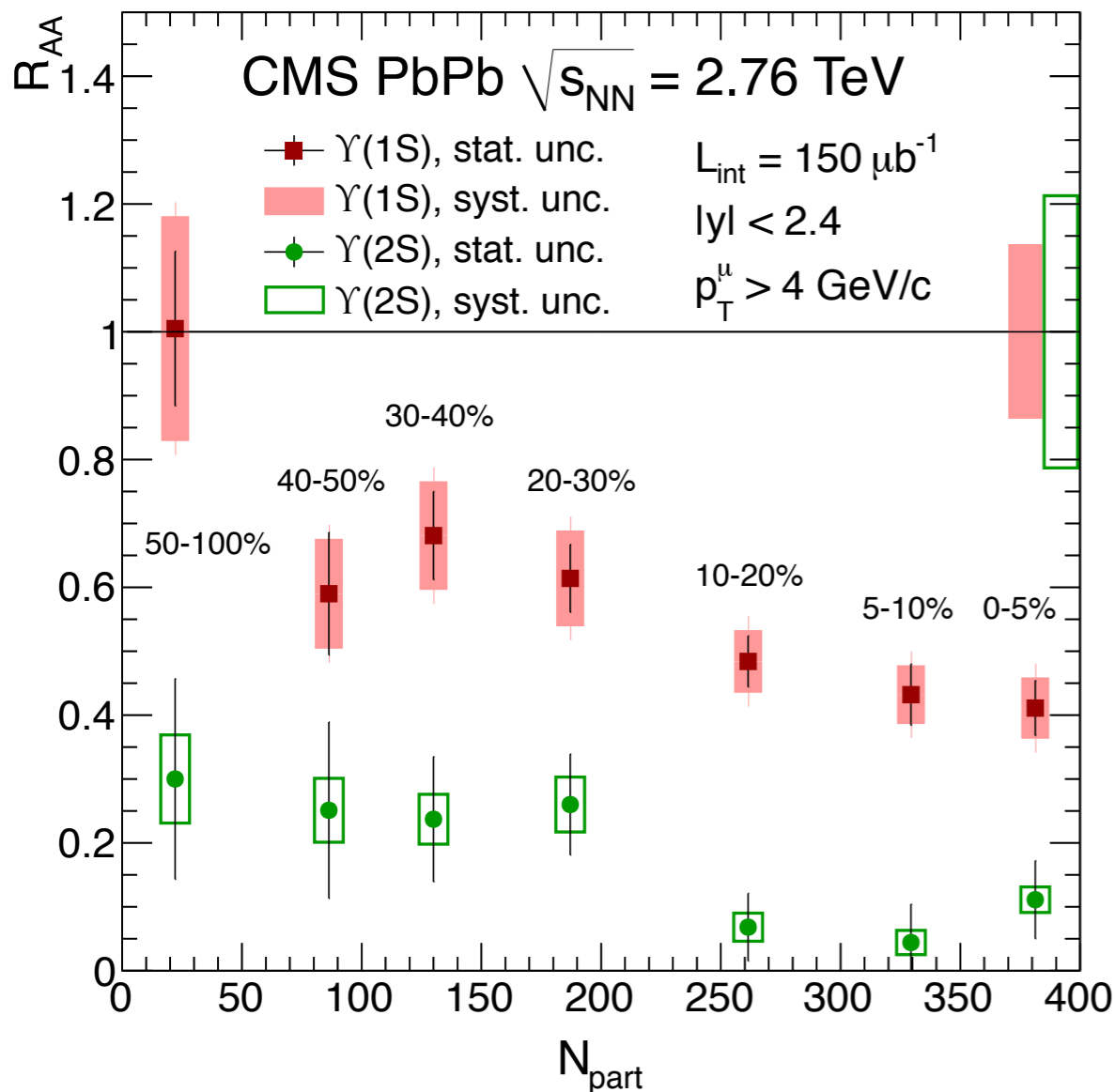


$$\frac{Y(2S)/Y(1S)|_{PbPb}}{Y(2S)/Y(1S)|_{pp}} = 0.21 \pm 0.07 \text{ (stat.)} \pm 0.02 \text{ (syst.)},$$

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

- The excited states, $\Upsilon(2S)$ and $\Upsilon(3S)$, are more suppressed than the ground state, $\Upsilon(1S)$
- But, in absence (by cancellation) of initial effects, the suppression due to the remaining final effects does not depend significantly on the event centrality.

➡ most 'peripheral': 50-100%



$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{Y(nS)|_{PbPb}}{Y(nS)|_{pp}} \frac{\epsilon_{pp}}{\epsilon_{PbPb}}$$

Centrality integrated R_{AA}

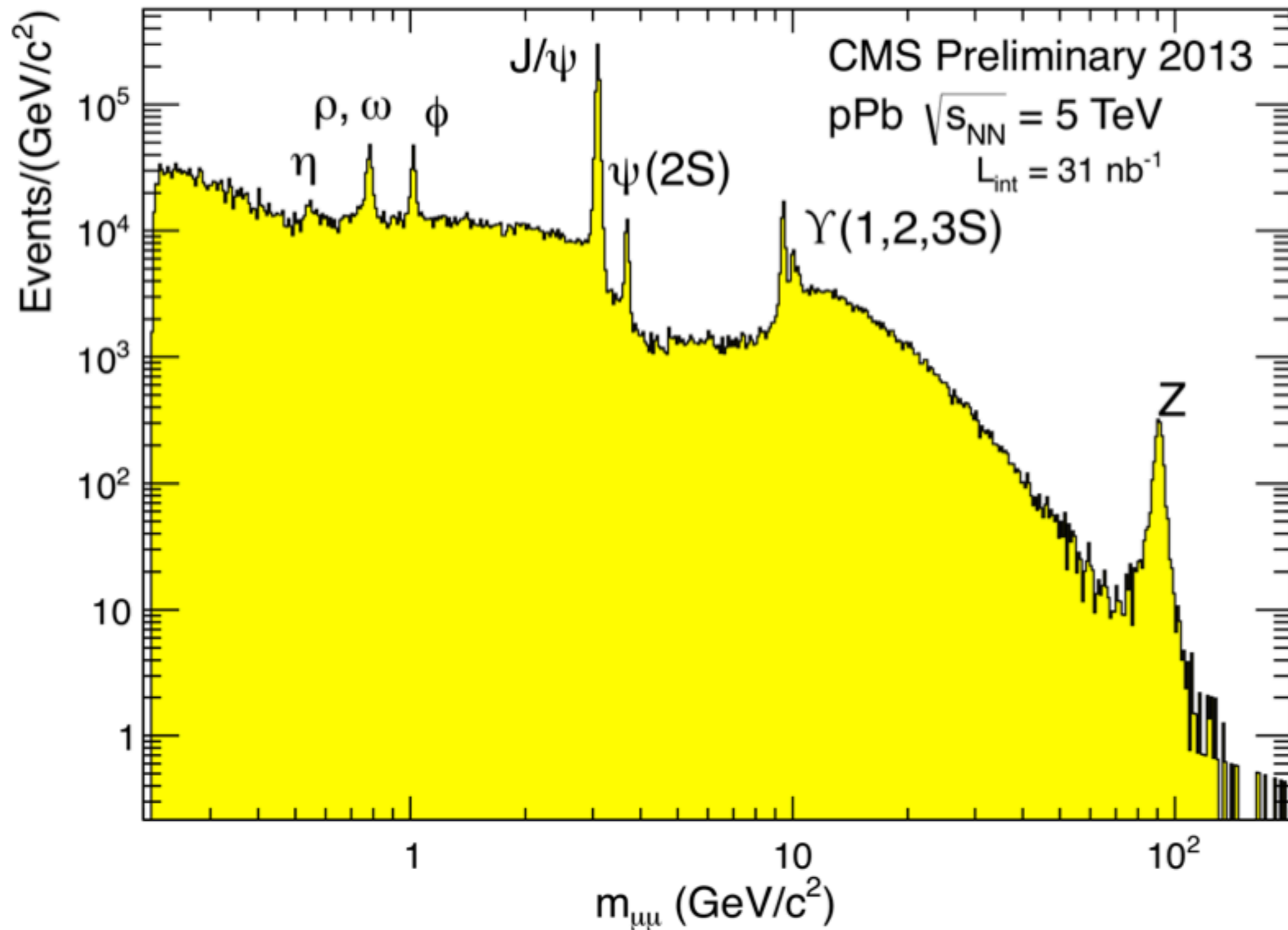
$Y(1S): 0.56 \pm 0.08 \pm 0.07$

$Y(2S): 0.12 \pm 0.04 \pm 0.02$

$Y(3S): < 0.1$ at 95% CL

- 2S more suppressed than 1S
- 1S suppression consistent with excited state suppression only ($\sim 50\%$)
- Ordering: $R_{AA}^{Y(3S)} < R_{AA}^{Y(2S)} < R_{AA}^{Y(1S)}$

pPb 2013, pp 2013



● pp: 5.4 pb⁻¹ (~20x more than pp 2011)

● pPb: 31 nb⁻¹

Introductory remarks

◎ pA asymmetric collisions (~ 0.47 rapidity boost):

➔ chose analysis cut so that $|\eta_{CM}^{\mu}| < 1.93 \rightarrow |y_{CM}^{\dimuon}| < 1.93$

▶ for p+ Pb: in LAB frame, $-2.4 < \eta < 1.47$

▶ for Pb+p: in LAB frame, $-1.47 < \eta < 2.4$

◎ pp: LAB=CM: $|\eta| < 1.93$

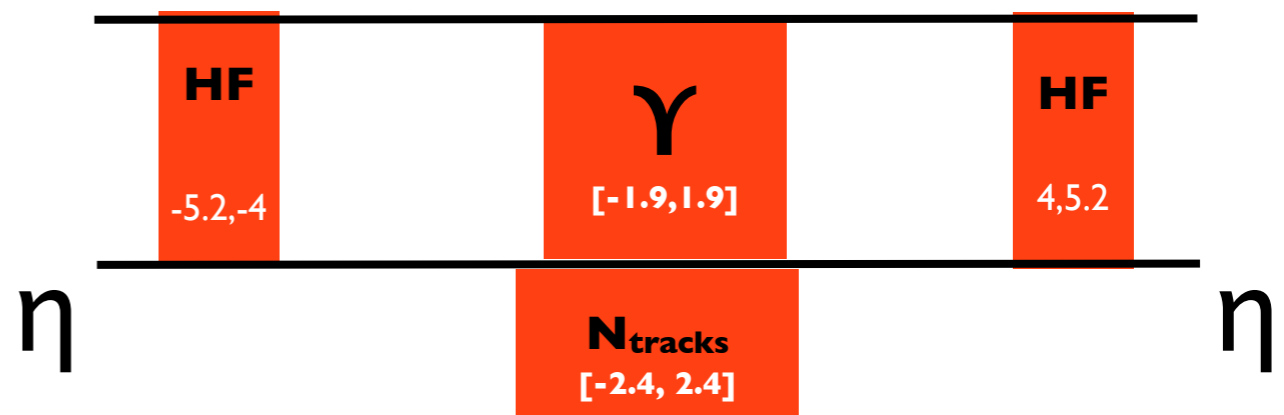
Ref. system	Pb+p			
LAB		-2.4	-0.47	1.47
COLLISION (CM)		-1.93	0	1.93

◎ Binning in 2 event-activity variables:

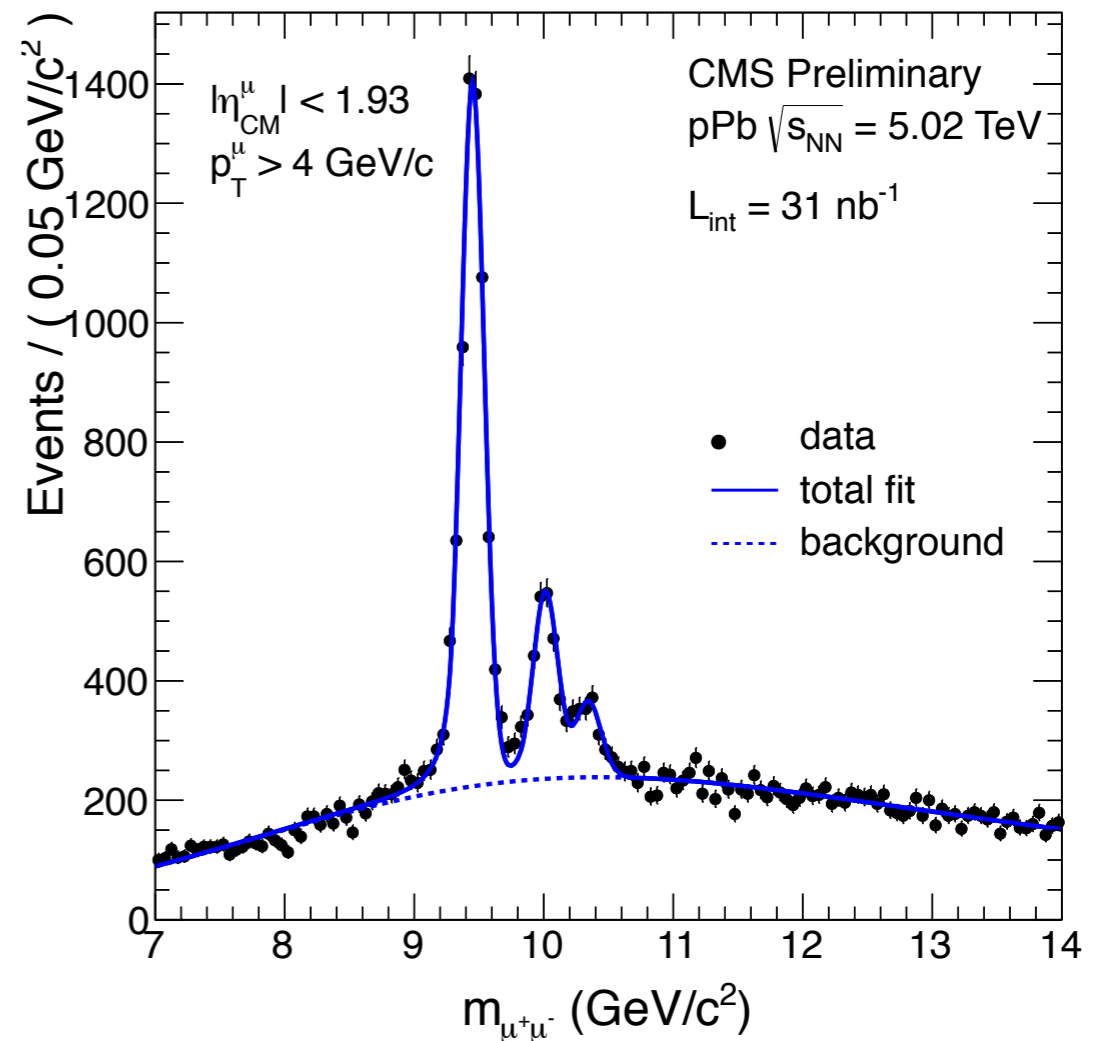
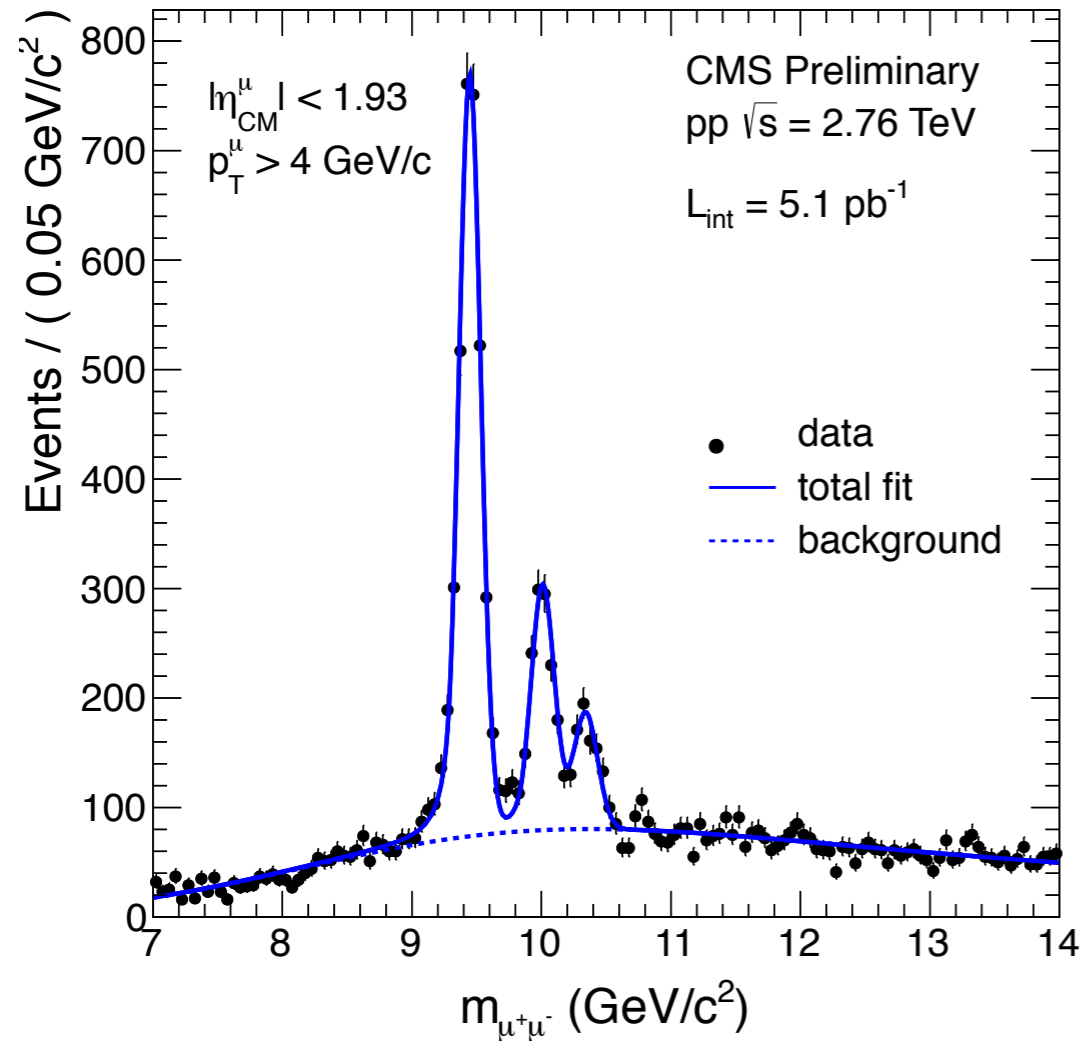
➔ corrected $N_{\text{track}}^{|\eta| < 2.4}$, $p_T > 400$ MeV/c

➔ raw transverse energy measured in HF, $E_T^{|\eta| > 4}$

➔ chose bin upper limits to be multiple of the average value measured in a minimum bias triggered sample (1 track with $p_T > 0.4$ GeV/c per pp or pPb bunch crossing).

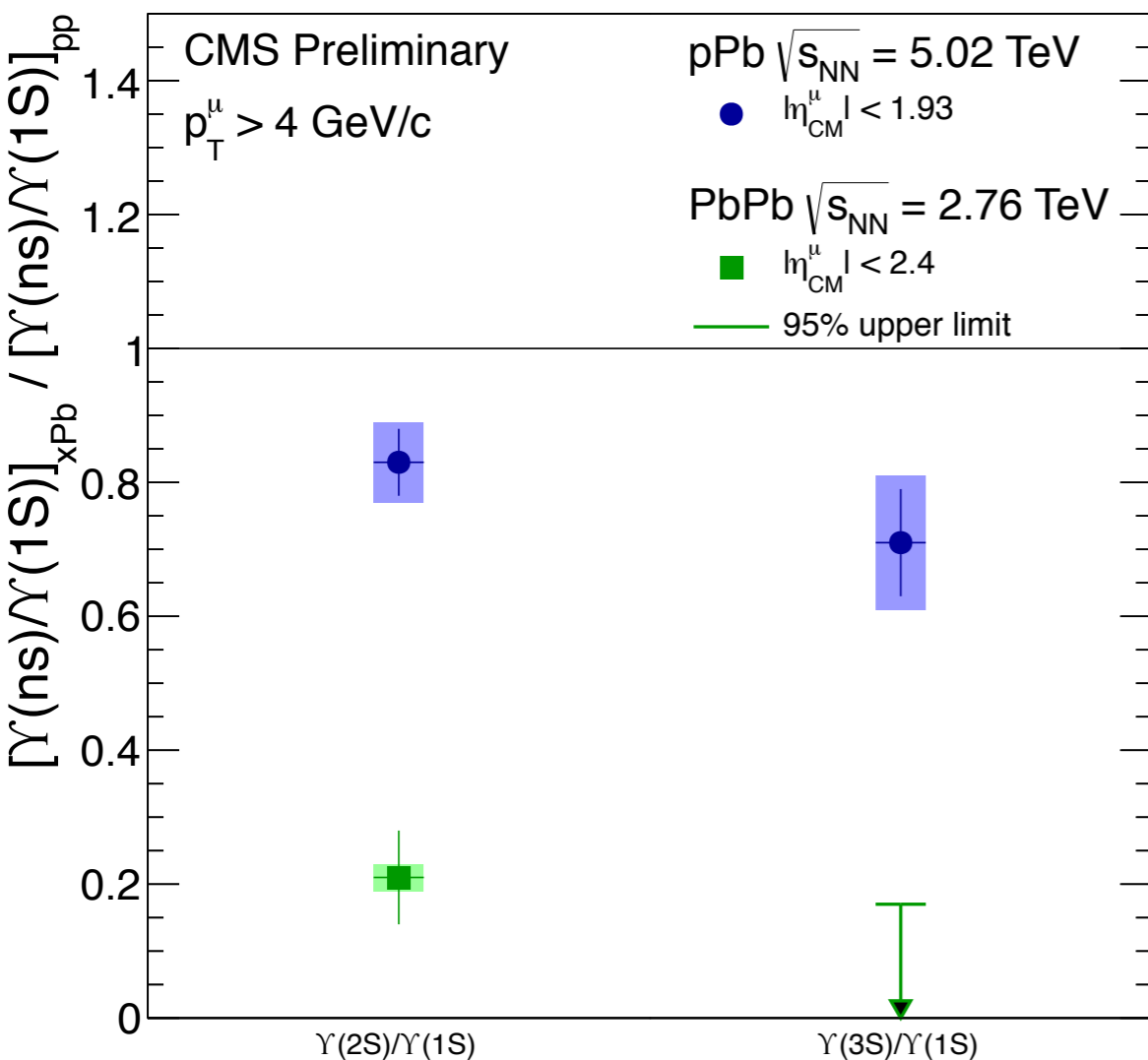


Invariant mass distributions



- ◎ Signal extraction in pp, pPb and PbPb same procedure
 - ➡ Unbinned maximum log likelihood with 1S, 2S/1S, 3S/1S variables in the fit
 - ▶ **Signal:** 3 Crystal-Ball functions (Gaussian with low-side tail replaced by a power-law)
 - ▶ **Background:** errorFunction * exponential (all background parameters free)

Integrated measurement: Double ratio



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

● **PbPb**: PRL 109 (2012)

➔ slightly different rapidity ($|y_{CM}| < 2.4$)

➔ 2011 pp dataset

● **pPb**

➔ systematic uncertainties from signal extraction and \sqrt{s} dependence of the pp reference

● **pPb vs PbPb**: larger double ratios in pPb

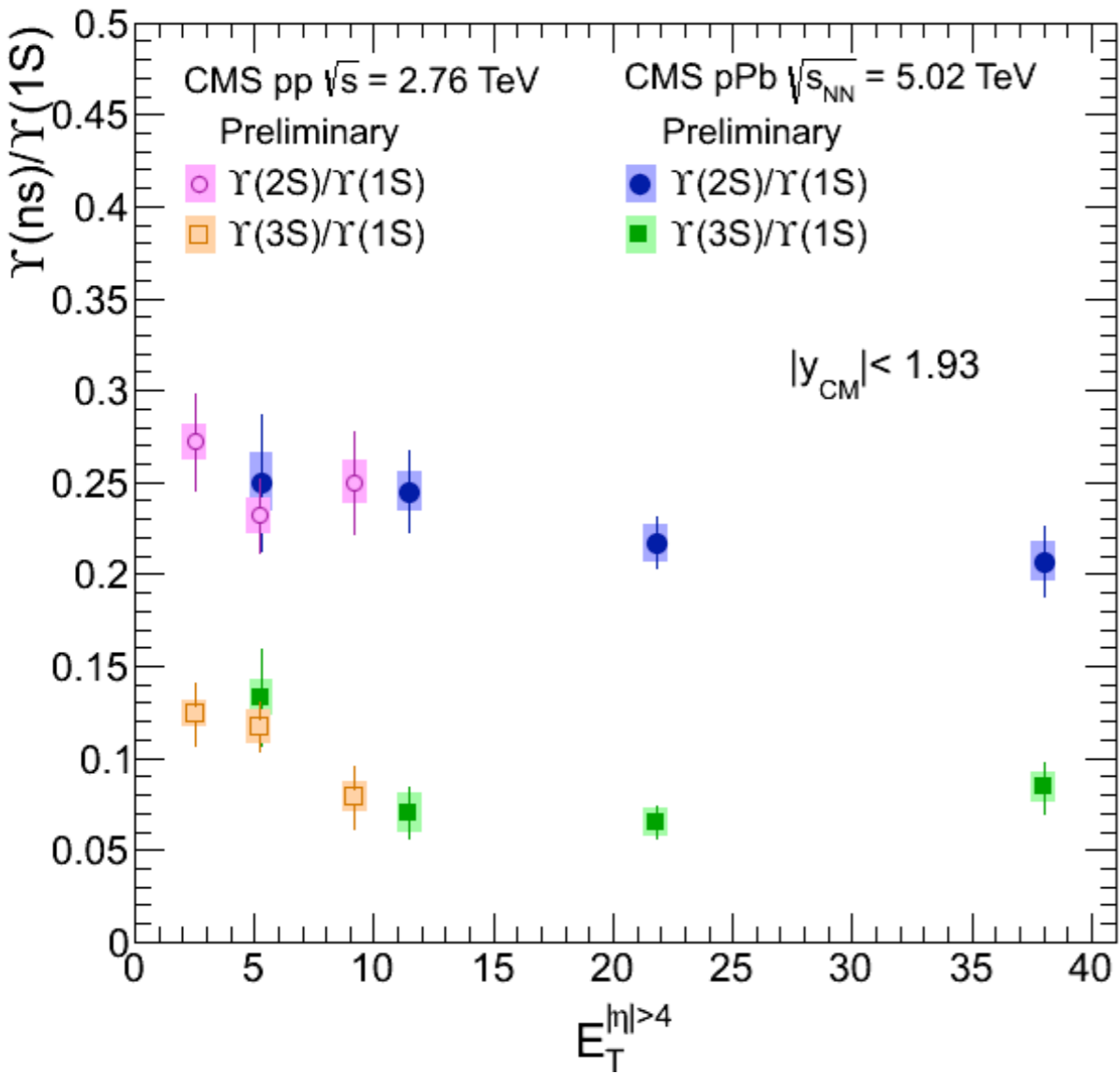
➔ suggest additional (and/or stronger) final effects in PbPb that affect more the excited states than the ground state

➔ but, theoretical modeling needed to extrapolate from pPb (1 Pb ion) to PbPb (2 Pb ions)

● **pPb vs pp**:

➔ excited states suppressed more than the ground state in pPb compared to pp collisions (significance $< 3\sigma$)

$\Upsilon(nS)/\Upsilon(1S)$ vs $E_T^{|\eta|>4}$

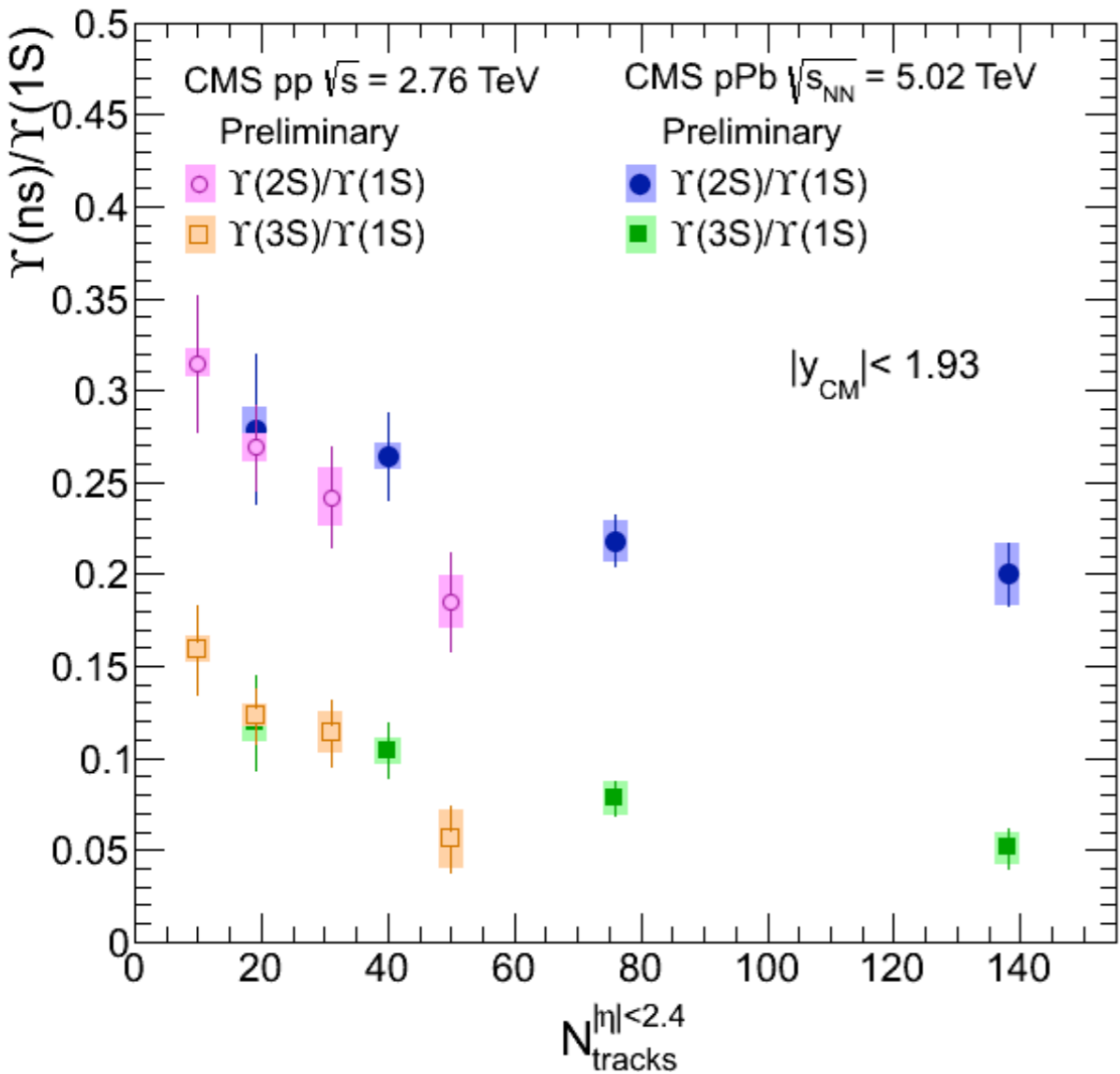
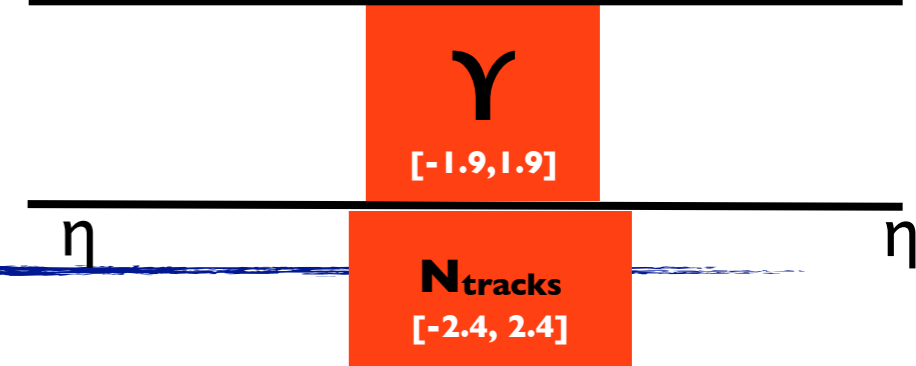


$$\left[\frac{\Upsilon(nS)}{\Upsilon(1S)} \right]_{pp,pPb}$$

- ⊙ Ratios corrected for acceptance and efficiency
- ⊙ Systematic uncertainties: from signal extraction
 ➔ additional 7-9% global uncertainties
- ⊙ Abscissae are the bin-average in the dimuon sample

- ⊙ Weak dependence of excited to the ground state ratio wrt $E_T^{|\eta|>4}$
 ➔ individual datasets consistent with being flat

$\Upsilon(nS)/\Upsilon(1S)$ vs $N_{\text{track}}^{|\eta|<2.4}$

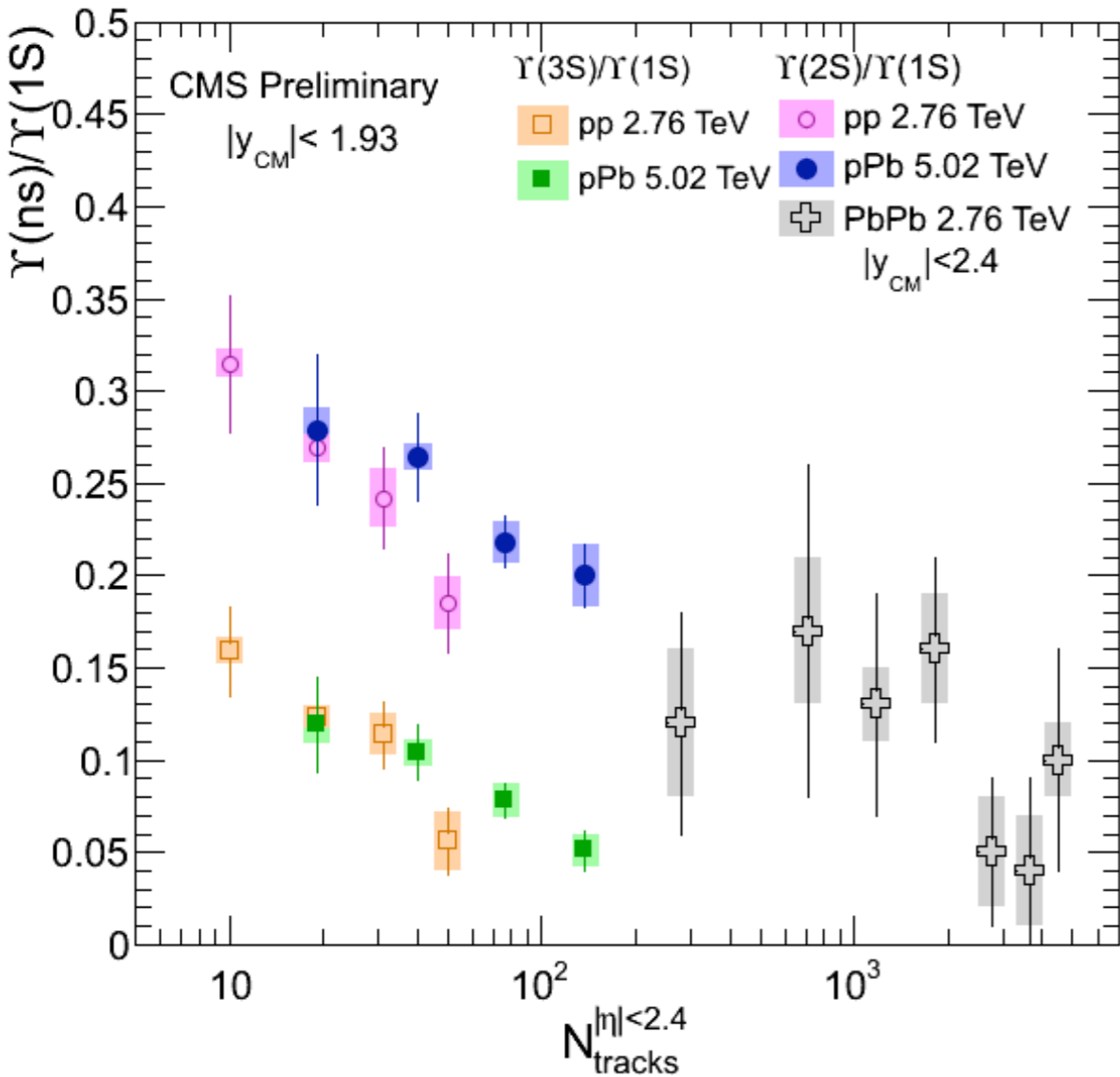


$$\left[\frac{\Upsilon(nS)}{\Upsilon(1S)} \right]_{pp, pPb}$$

- ⊙ Ratios corrected for acceptance and efficiency
- ⊙ Systematic uncertainties: from signal extraction
➔ additional 7-9% global uncertainties
- ⊙ Abscissae are the bin-average in the dimuon sample

- ⊙ Significant decrease of $\Upsilon(nS)/\Upsilon(1S)$ with increasing multiplicity, in pPb AND pp
- ⊙ Can think at 2 ways to produce this dependence, at play alone or together
 - ➔ Υ 'affects' the multiplicity
 - ▶ in both pp and pPb ~2 extra tracks in 1S events compared to 2S and 3S events
 - ➔ the multiplicity 'affects' the Υ
 - ▶ activity around the Υ breaks the states

$\Upsilon(nS)/\Upsilon(1S)$ compare PbPb



● 2011 PbPb single ratios $\Upsilon(2S)/\Upsilon(1S)$ corrected for acceptance and efficiency

➔ log-x axis to plot all samples on the same figure

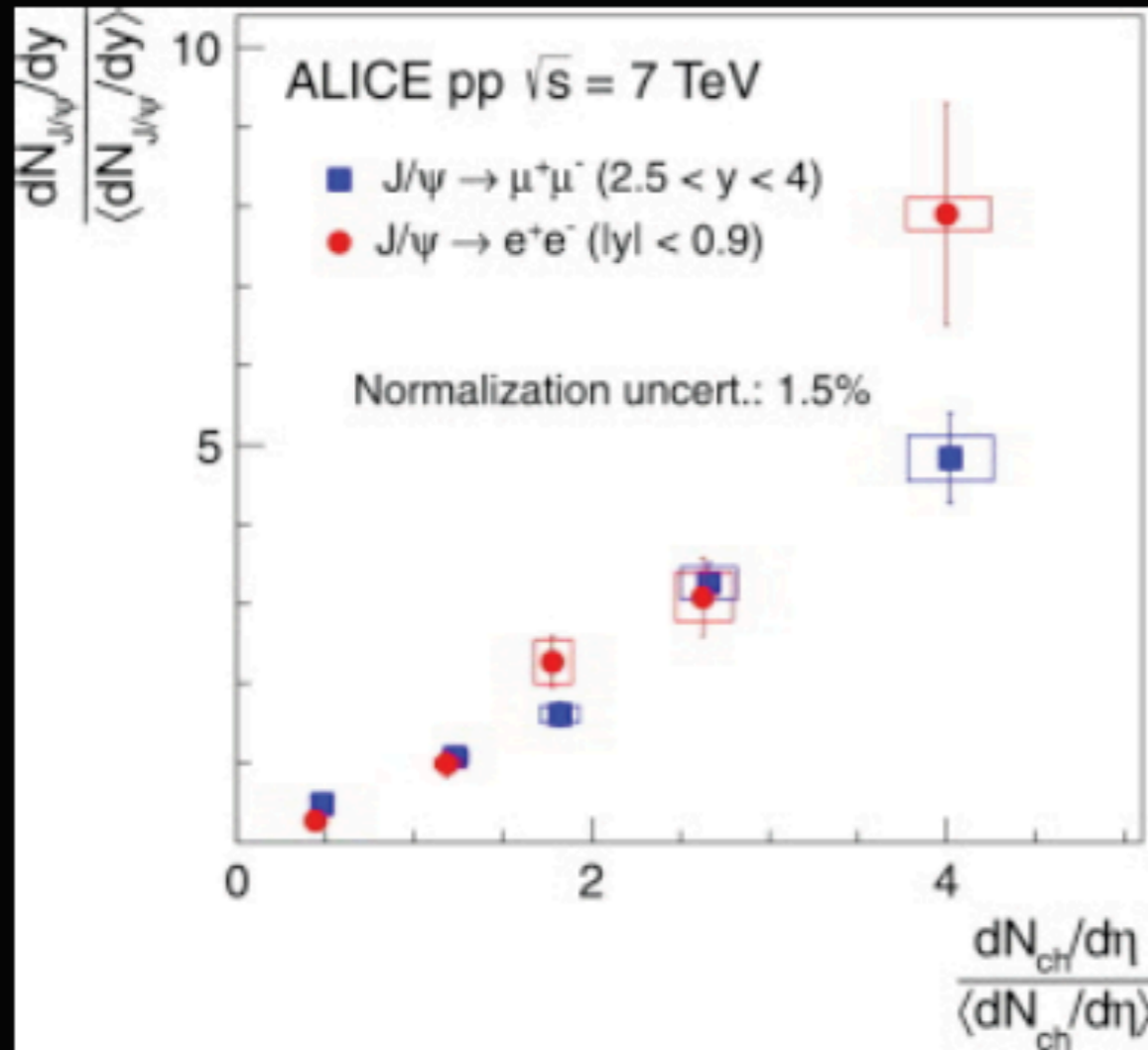
➔ small overlap between most 'central' pPb and most peripheral PbPb (50-100%)

● PbPb: no significant dependence on N_{tracks} , but large uncertainties (need more PbPb!!!)

● The PbPb points are below all the pPb data points, but uncertainties too big to tell if already in most central pPb the level of suppression is the same as in PbPb peripheral

Quarkonia yield and event activity

ALICE
Phys.Lett. B712 (2012) 165-175



Similar to dijets, strong correlation of hard probe and event activity

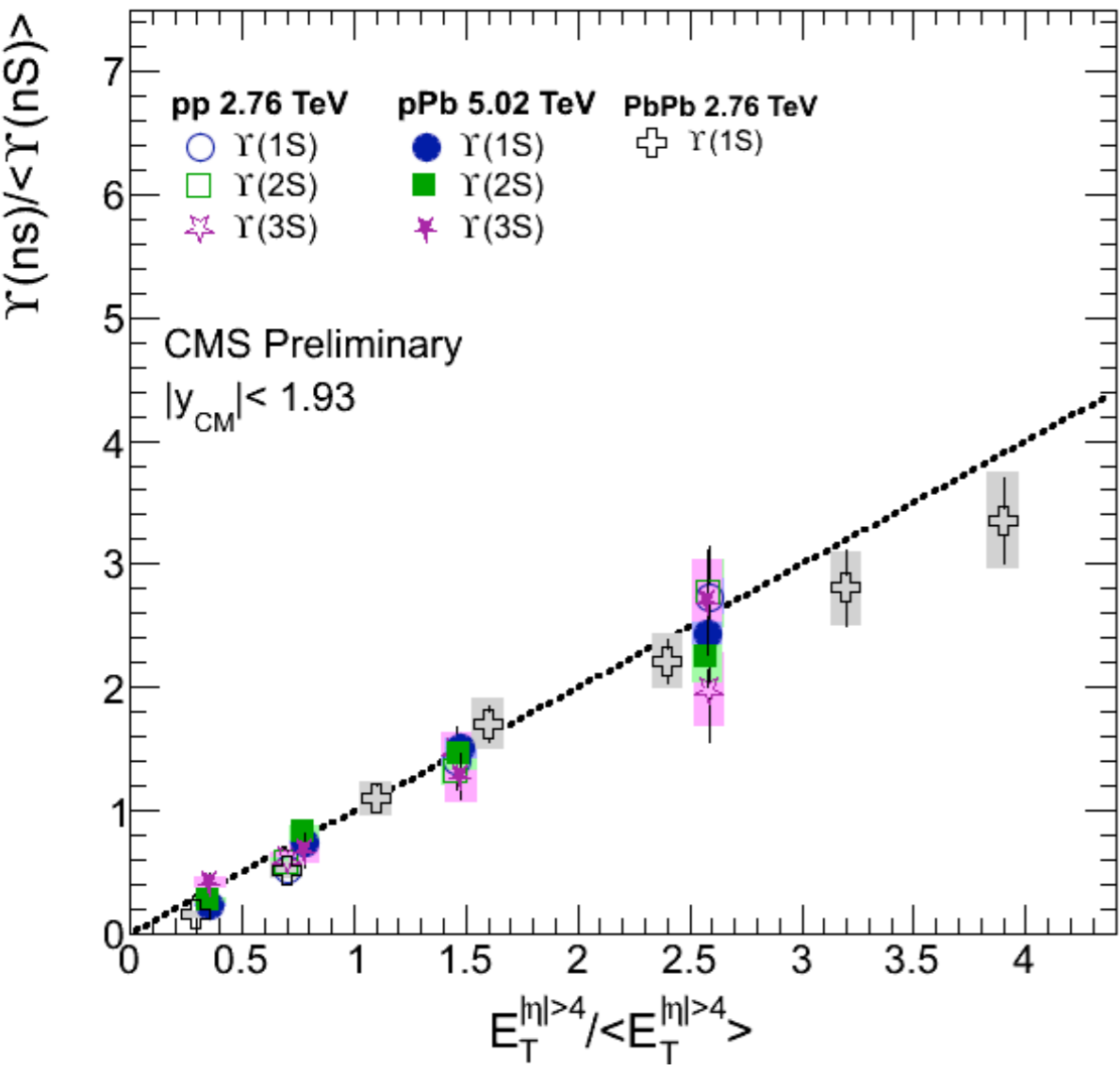
Self-normalized ratios: $\Upsilon(nS)/\langle\Upsilon(nS)\rangle$

- Yield versus event-activity, both normalized to their average
- Access to individual-state variations (as opposed to excited states relative to the ground state)
 - ➔ a replacement of the R_{pA} , R_{AA} type of measurements; it can be done also for pp

- Note: PbPb from PRL 109 (2012), derived from ratios of the R_{AA} -s

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{Y(nS)|_{PbPb}}{Y(nS)|_{pp}} \frac{\epsilon_{pp}}{\epsilon_{PbPb}} \rightarrow \frac{R_{AA}^i}{R_{AA}} = \frac{T_{AA}}{T_{AA}^i} * \frac{\Upsilon(nS)^i}{\langle\Upsilon(nS)\rangle} * \frac{\epsilon}{\epsilon^i}$$

Self-normalized ratios: $\Upsilon(nS) / \langle \Upsilon(nS) \rangle_n$



$$\frac{\Upsilon(nS)}{\langle \Upsilon(nS) \rangle}$$

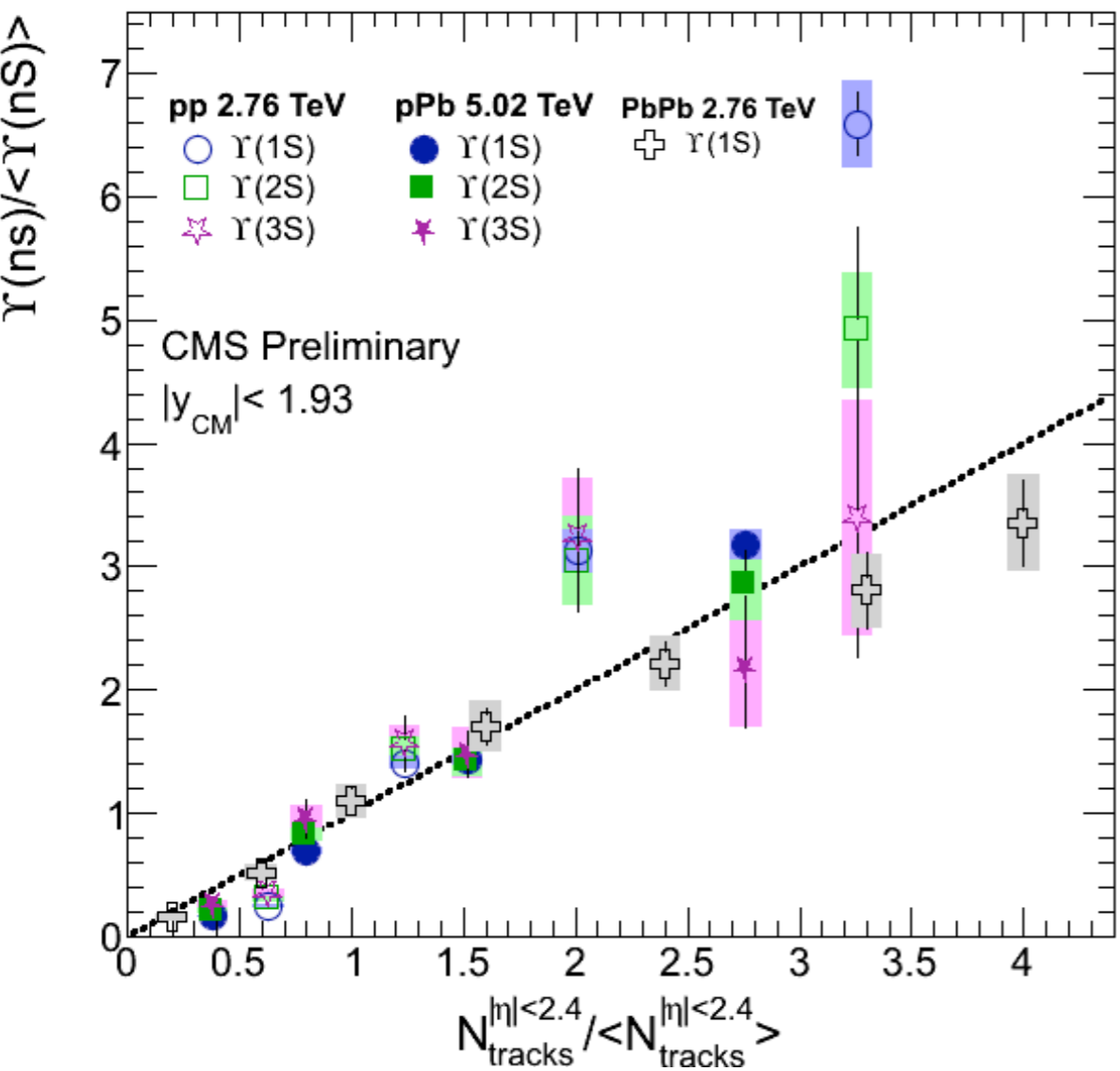
- Yield versus event-activity, both normalized to average
- ➔ more upsilons in events with higher-event activity
- Corrected ratios (multiplicity dependence of the reconstruction efficiency)

- E_T : all slopes consistent with 1
- ➔ very different $\langle E_T \rangle$: 3.5 (pp), 14.7 (pPb), 760 GeV (PbPb)

Self-normalized ratios: $\Upsilon(nS) / \langle \Upsilon(nS) \rangle$

Υ
[-1.9, 1.9]

N_{tracks}
[-2.4, 2.4]



$$\frac{\Upsilon(nS)}{\langle \Upsilon(nS) \rangle}$$

- Yield versus event-activity, both normalized to average
- ➔ more upsilons in events with higher-event activity
- Corrected ratios (multiplicity dependence of the reconstruction efficiency)

● N_{track} : less coherent behaviour (related to the $\Upsilon(nS) / \Upsilon(1S)$ variations)

● More or less surprising:

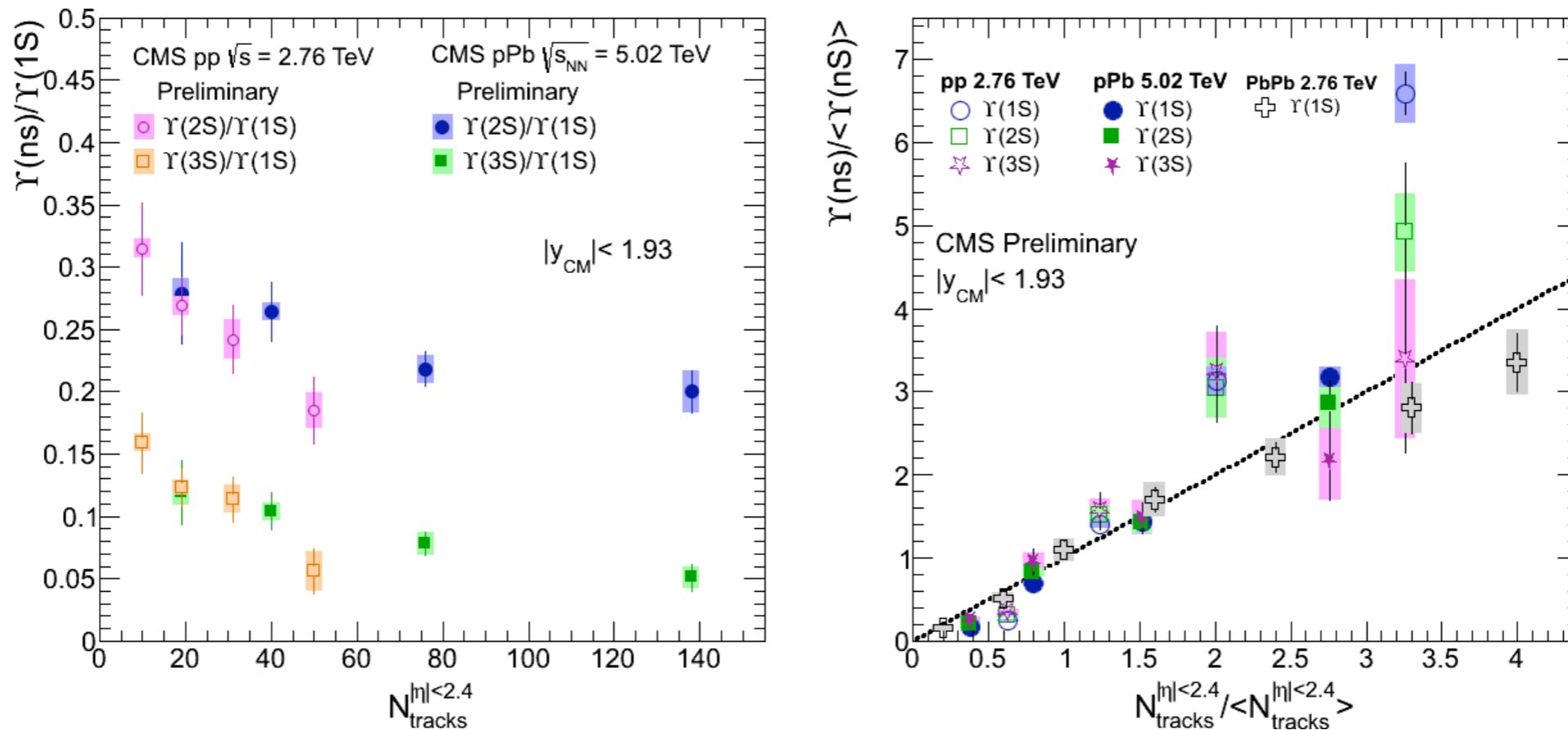
➔ pPb and PbPb: N_{coll} scaling

➔ pp: multi parton interaction

▶ should have the same effect on 1S, 2S and 3S

▶ 'most central' pp shows differences ... need more data (7, 8 TeV ?)

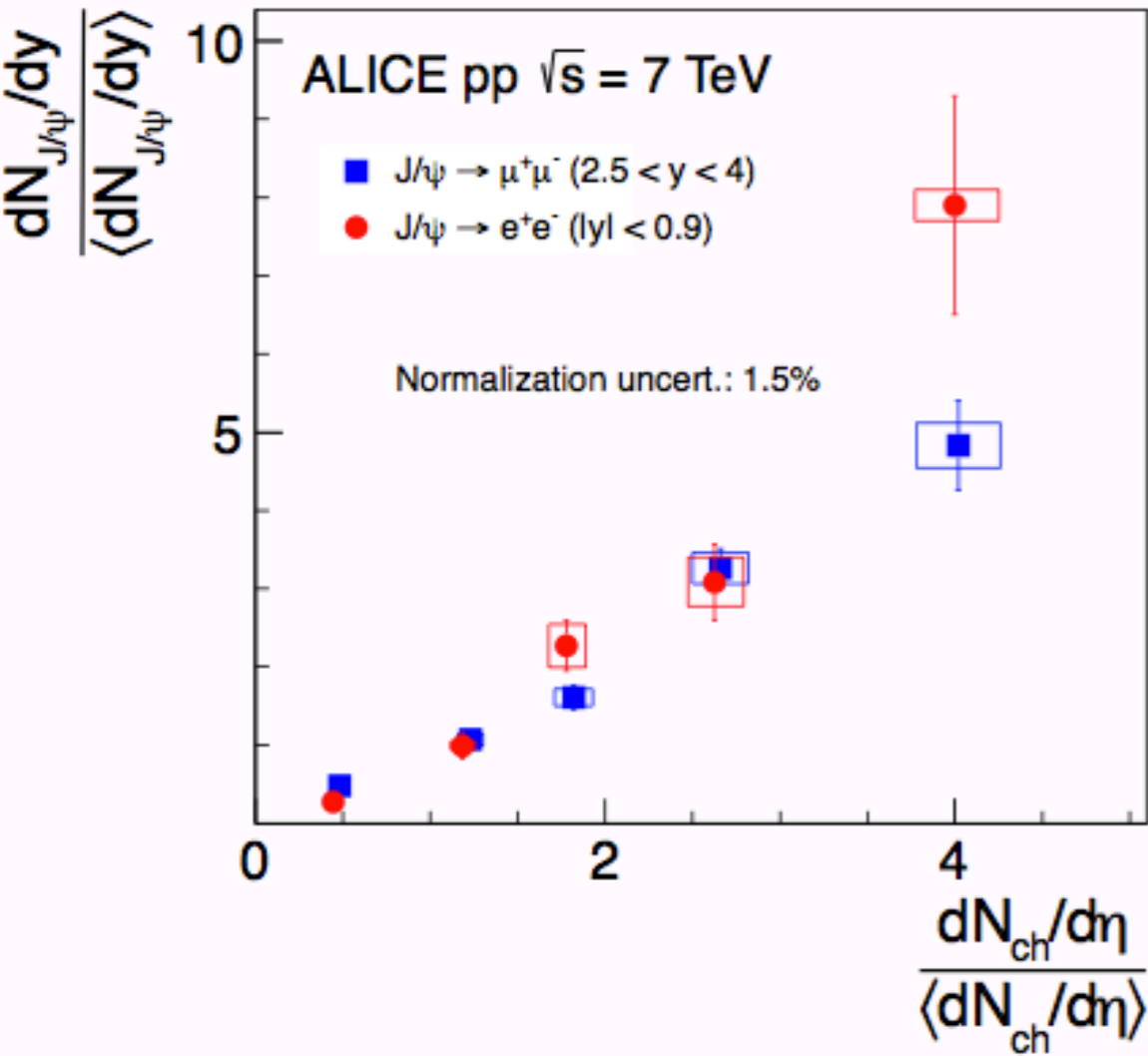
Summary II: Closed beauty $\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$



- **PbPb**: sequential suppression in order of binding energy of the bottomonium states
- **pPb**: double ratios $[\Upsilon(nS)/\Upsilon(1S)]_{\text{pPb}} / [\Upsilon(nS)/\Upsilon(1S)]_{\text{pp}}$
 - ▶ higher than measured PbPb
 - ▶ hinting to the presence of additional effects in pPb than in pp, different for 1S and (2S, 3S)
- $Y(nS)/Y(1S)$: decrease with increase of charged-particle multiplicity in both pp and pPb (less pronounced when measured versus energy deposited at large pseudorapidity)
 - ▶ reflect an influence of the particles on the Y and/or
 - ▶ reflect a different multiplicity associated with the Y states production
- $Y(nS)/\langle Y(nS) \rangle$: increase with increasing event activity in pp, pPb and PbPb

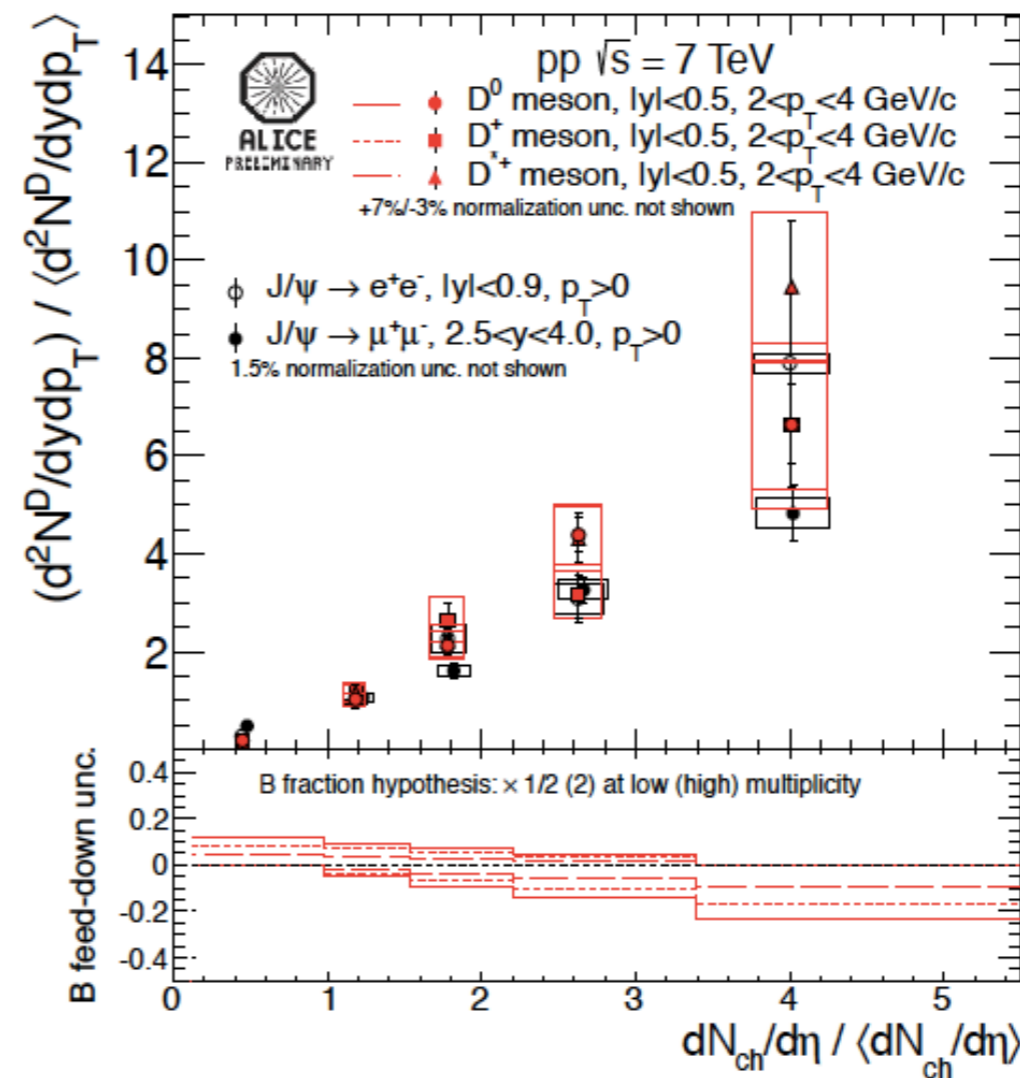
Extra

Multiplicity binning (x-axis)

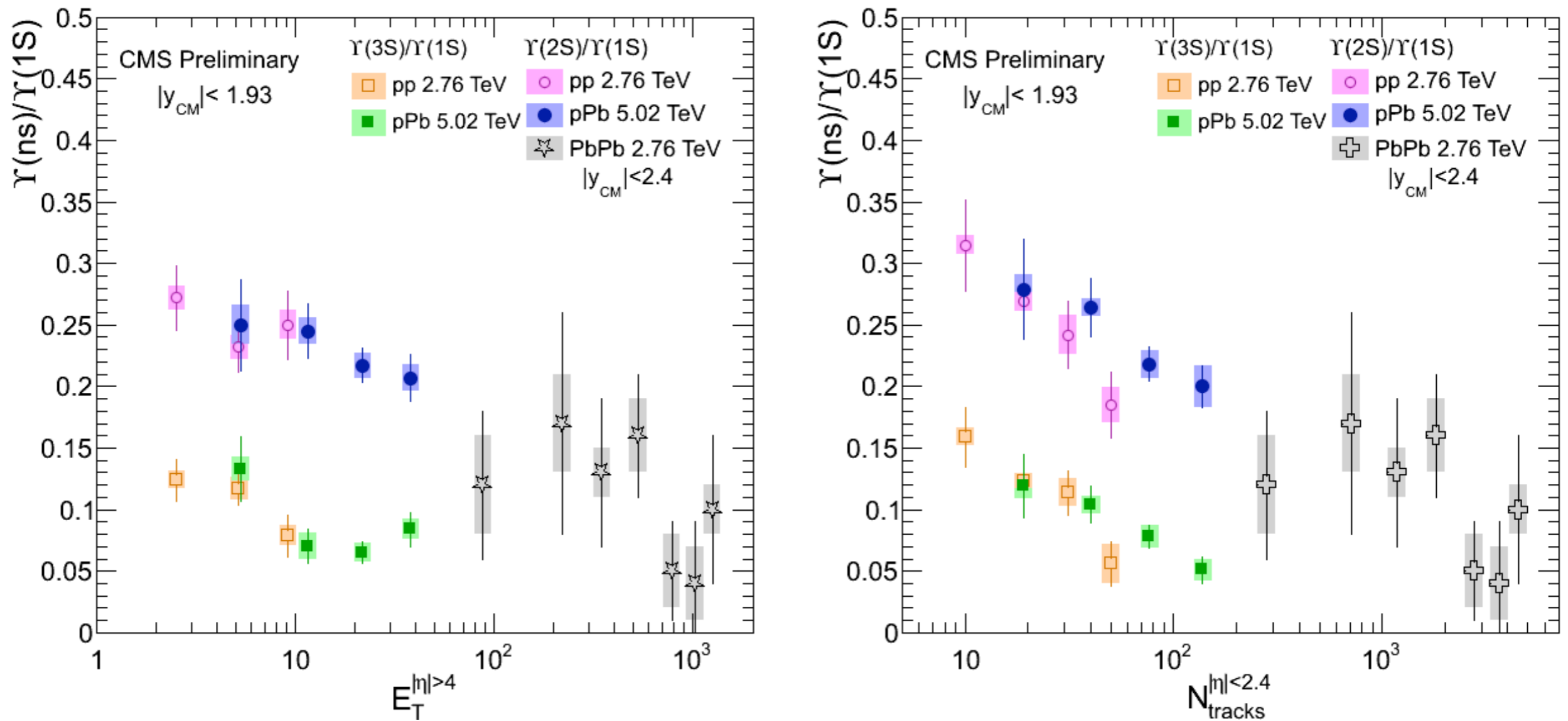


J/ψ yield $dN_{J/\psi}/dy$ as a function of the charged particle multiplicity densities at mid-rapidity $dN_{ch}/d\eta$. The data points are normalized by the corresponding value for minimum bias pp collisions ($\langle dN_{J/\psi}/dy \rangle$, $\langle dN_{ch}/d\eta \rangle$). The measurements at forward rapidities ($J/\psi \rightarrow \mu^+\mu^-$, $2.5 < y < 4$) and at mid-rapidity ($J/\psi \rightarrow e^+e^-$, $|y| < 0.9$) are shown. The error bars represent the statistical uncertainty on the J/ψ yields, while the quadratic sum of the point systematic uncertainties on the J/ψ yield as well as on $dN_{ch}/d\eta$ is depicted as boxes.

J/ψ : PLB712 (2012) 165
Charm: preliminary



$\Upsilon(nS)/\Upsilon(1S)$ compare PbPb



● 2011 PbPb single ratios $\Upsilon(2S)/\Upsilon(1S)$ corrected for acceptance and efficiency

➡ log-x axis to be able to plot all samples on the same figure

➡ small overlap between most 'central' pPb and most peripheral PbPb (50-100%)

● PbPb: large uncertainties (dependence on N_{tracks}/E_T is not pronounced)

● The PbPb points are below all the pPb data points, but uncertainties too big to tell if already in most central pPb the level of suppression is the same as in PbPb peripheral

PbPb 2011, pp 2011

