

# Quarkonium and heavy flavour production in Run I and future prospects with the CMS experiment

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on behalf of the CMS Collaboration

LPCC Heavy Flavour Working Group  
10 November 2010



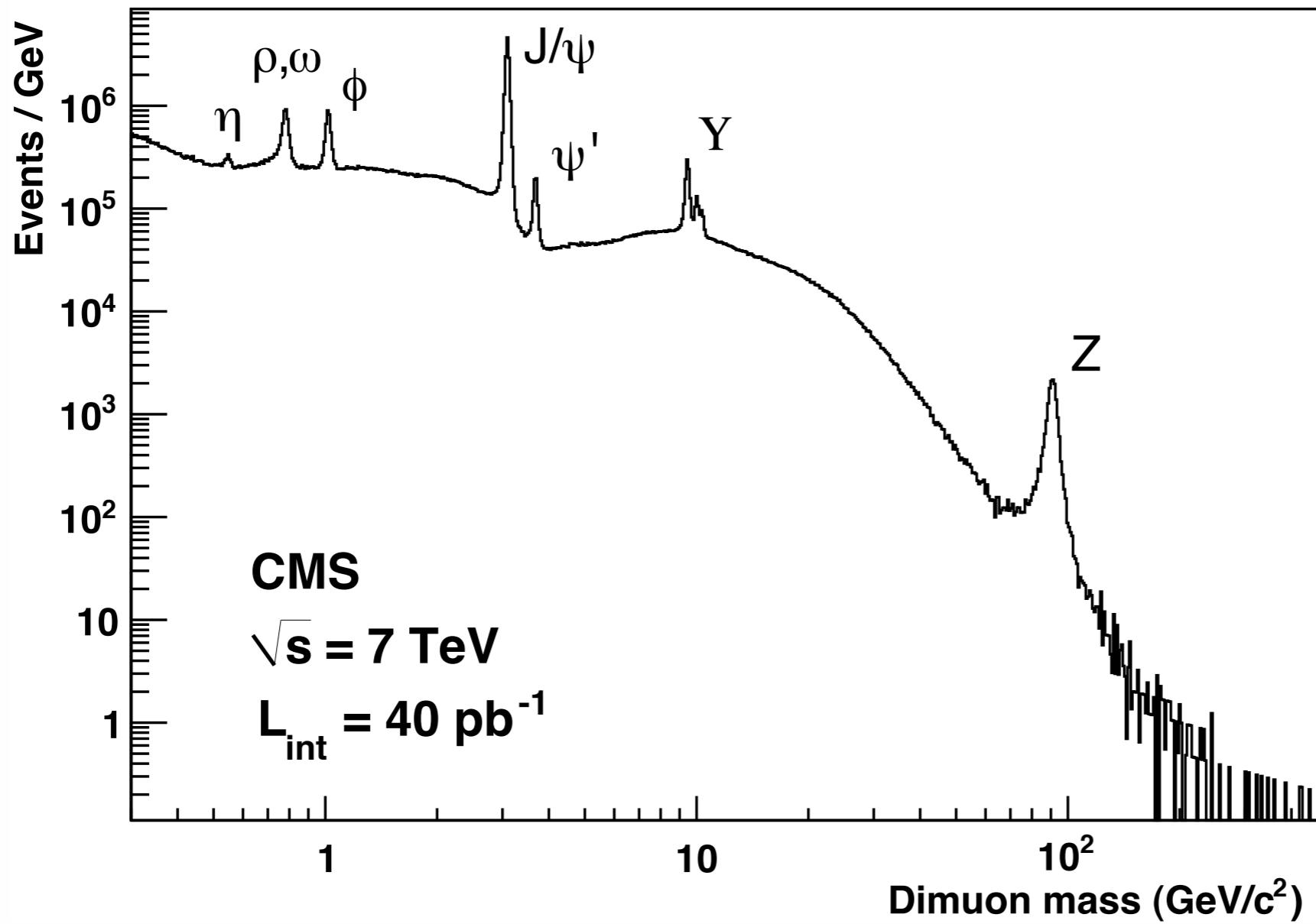
# Outline

- B hadron production results in Run I
- Quarkonium production results in Run I
- Future prospects and possibilities



# B hadron production in pp collisions

- Using 2010 pp collision data
- Trigger requiring two muons in a broad mass window
- Up to  $40 \text{ pb}^{-1}$  of integrated luminosity



# B hadron production measurements

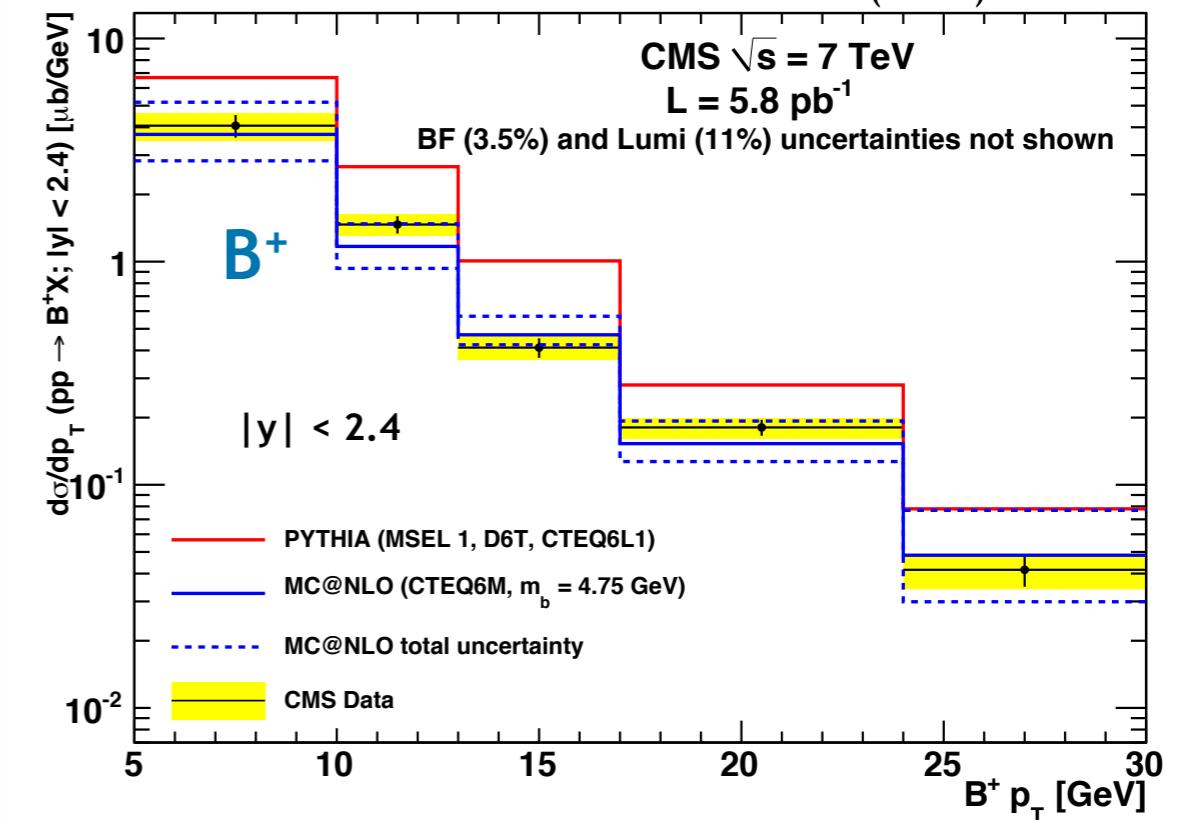
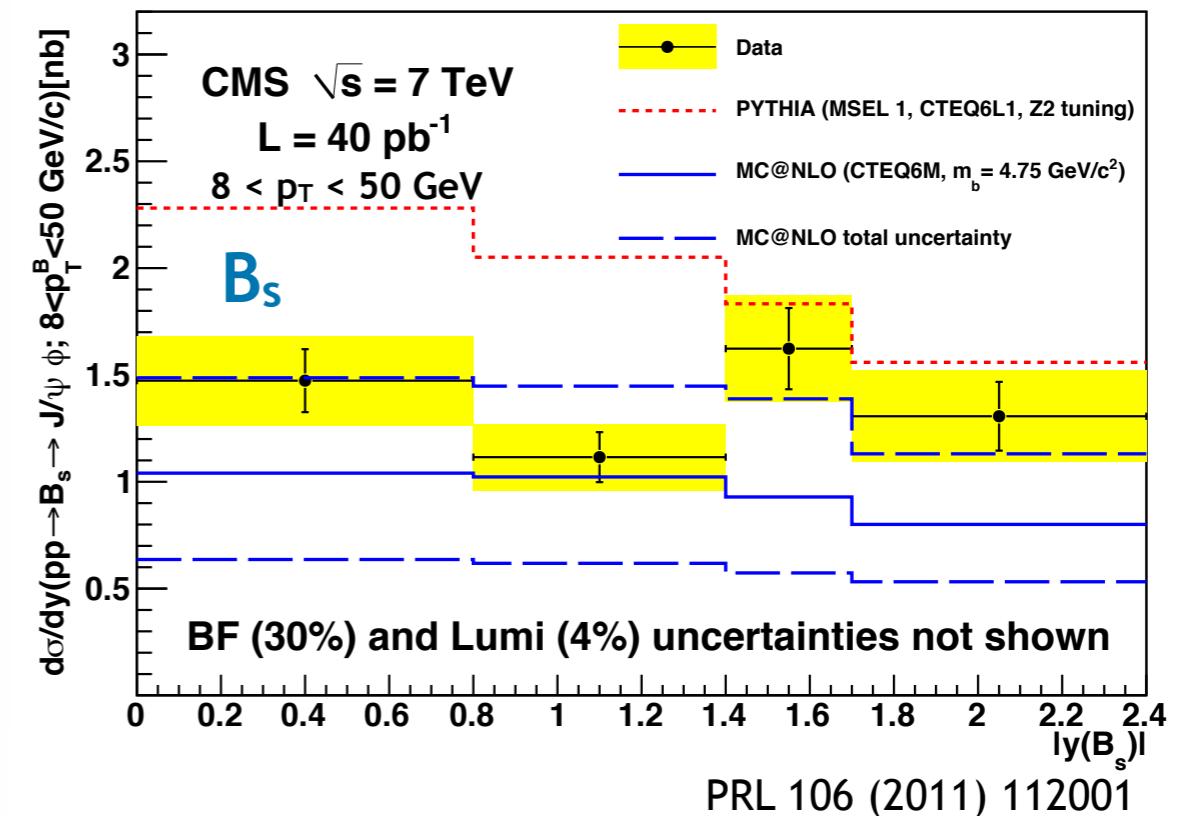
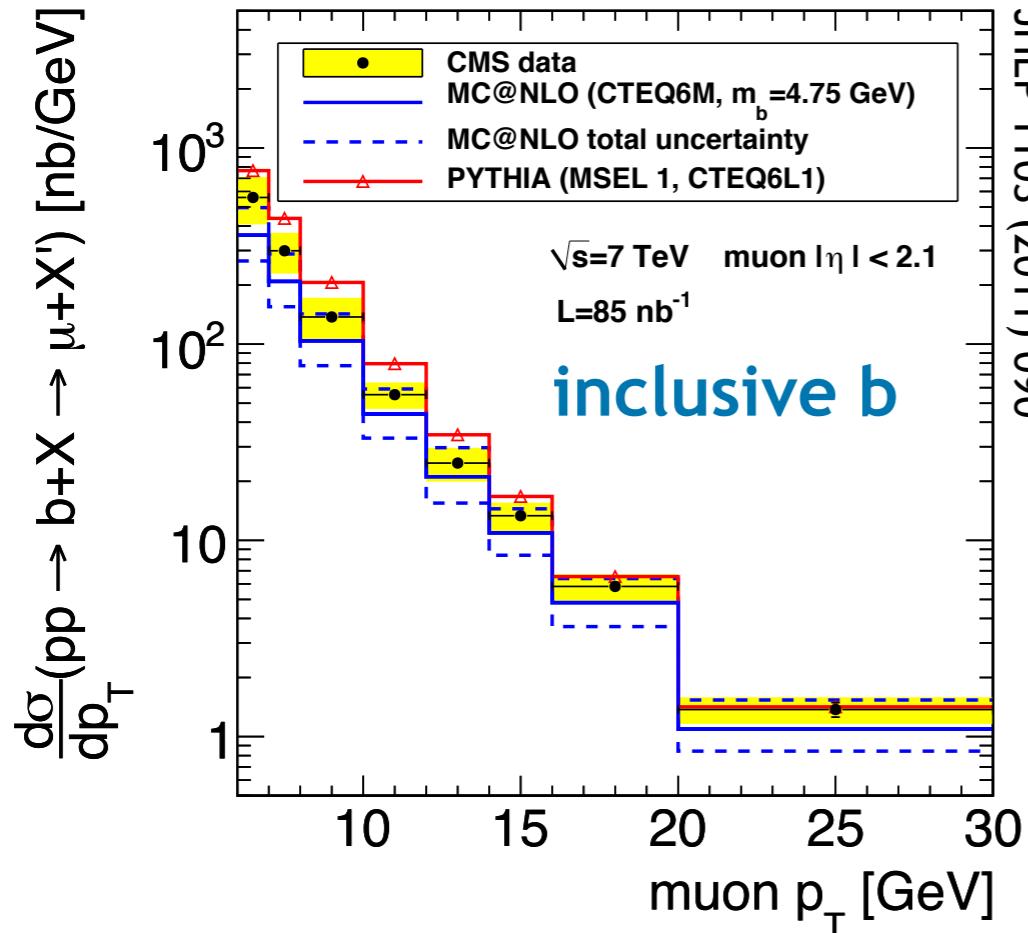
- $p_T$ -and  $|y|$ -differential cross sections:

- inclusive  $b\bar{b} + X$
- inclusive b hadrons with muons
  - using a low threshold single muon trigger
- inclusive b-jet
  - using minimum bias, single jet and
  - single muon triggers
- $B^+ \rightarrow J/\psi + K^+$
- $B^0 \rightarrow J/\psi + K_s^0$
- $B_s^0 \rightarrow J/\psi + \phi$
- $\Lambda_b \rightarrow J/\psi + \Lambda$ 
  - using 2011 dataset



# B hadron production results

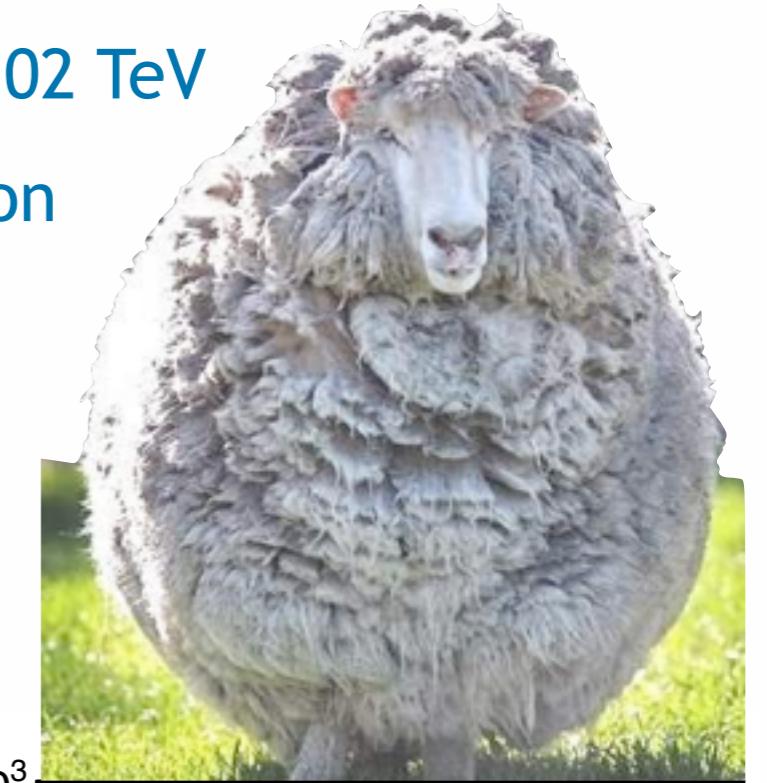
PRD 84 (2011) 052008



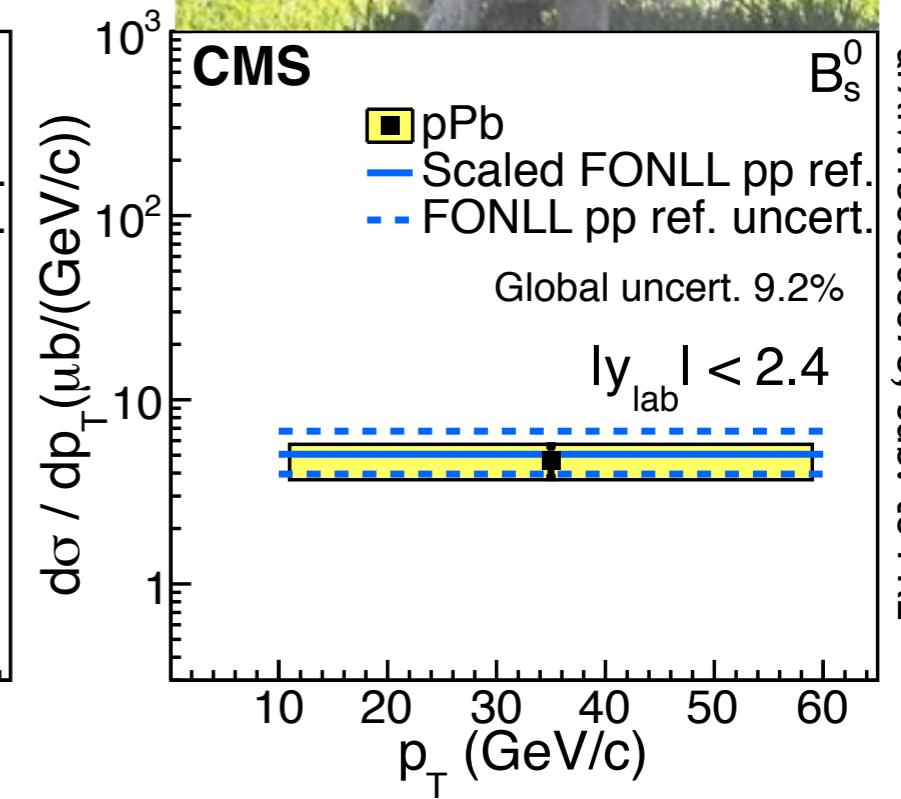
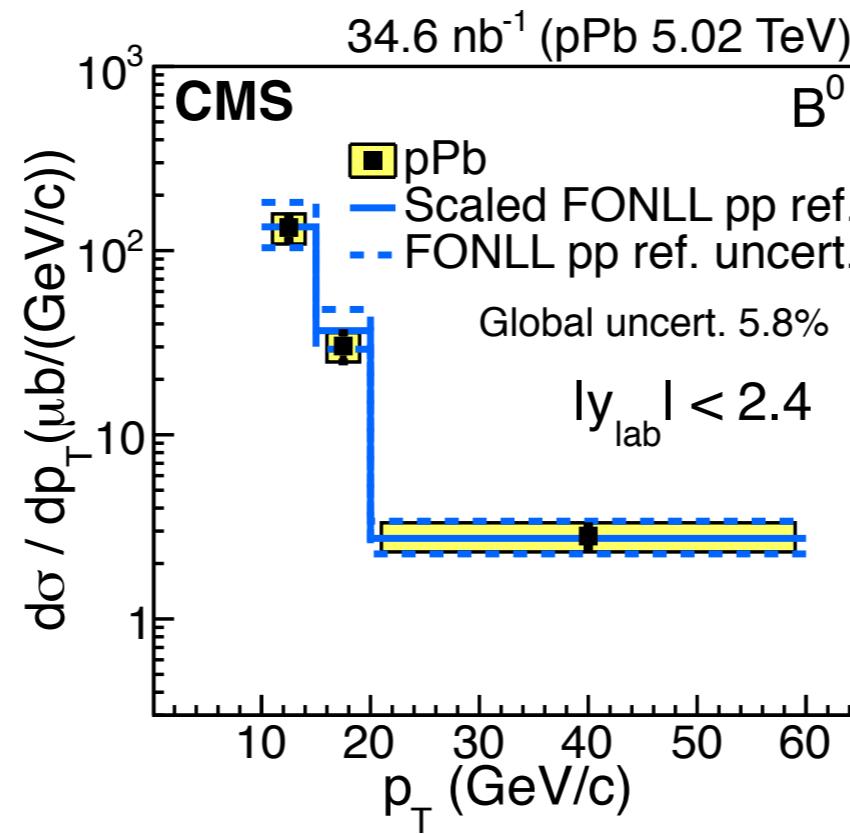
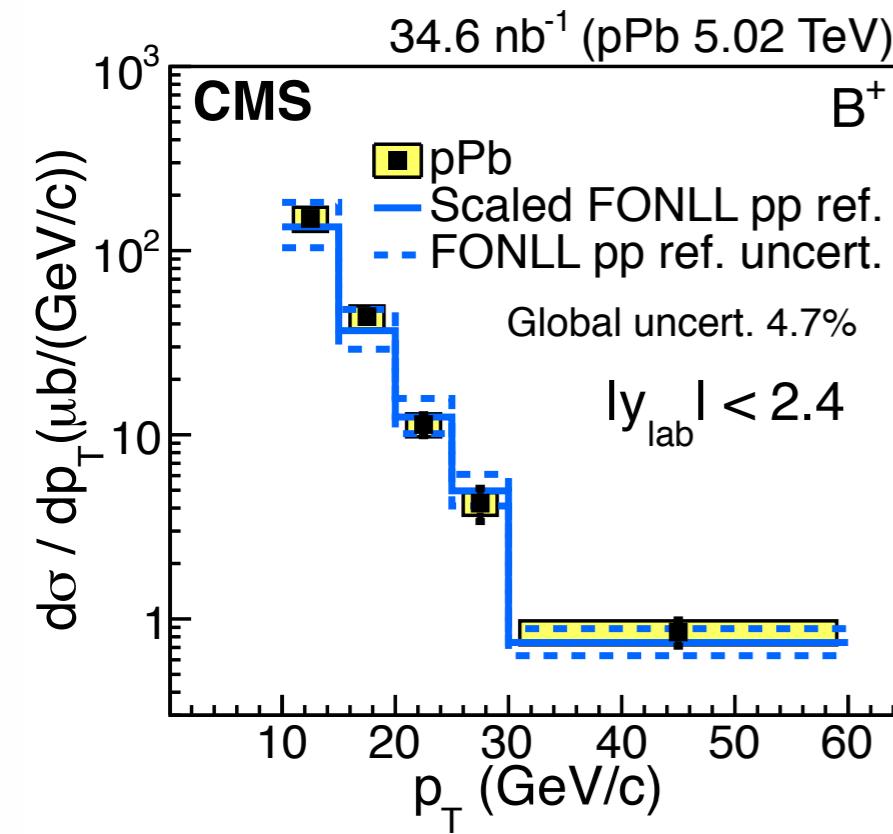
- Cross sections are in agreement with Pythia 6 and MC@NLO predictions within uncertainties for all measurements

# B hadron production in pPb collisions

- Trigger requiring a single muon with  $p_T > 3$  GeV
- Integrated luminosity of  $\sim 35 \text{ nb}^{-1}$  collected at  $\sqrt{s} = 5.02 \text{ TeV}$
- $p_T$ -differential cross sections and nuclear modification factors of
  - $B^+ \rightarrow J/\psi + K^+$
  - $B^0 \rightarrow J/\psi + K^*(892)$
  - $B_s^0 \rightarrow J/\psi + \phi$

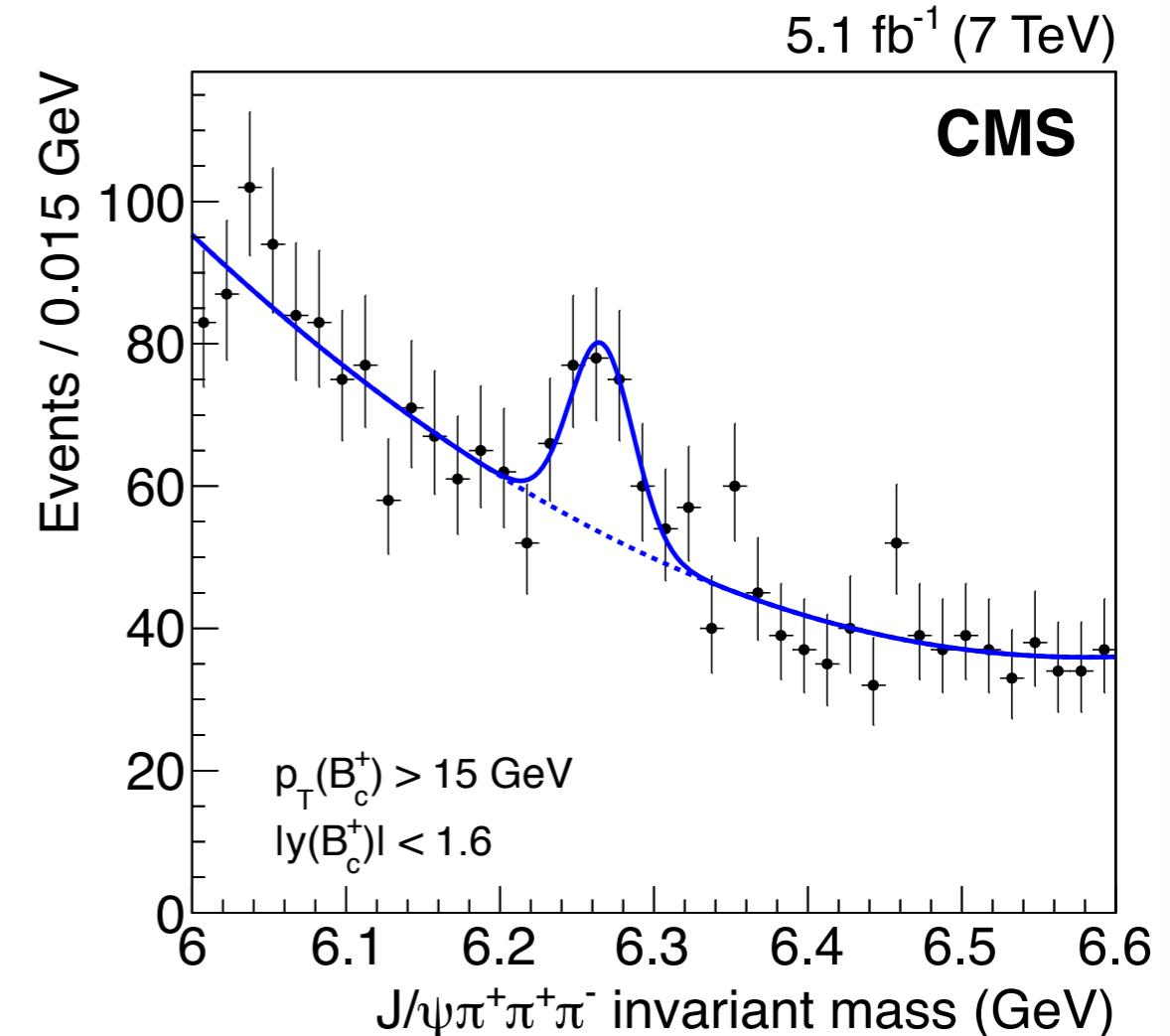
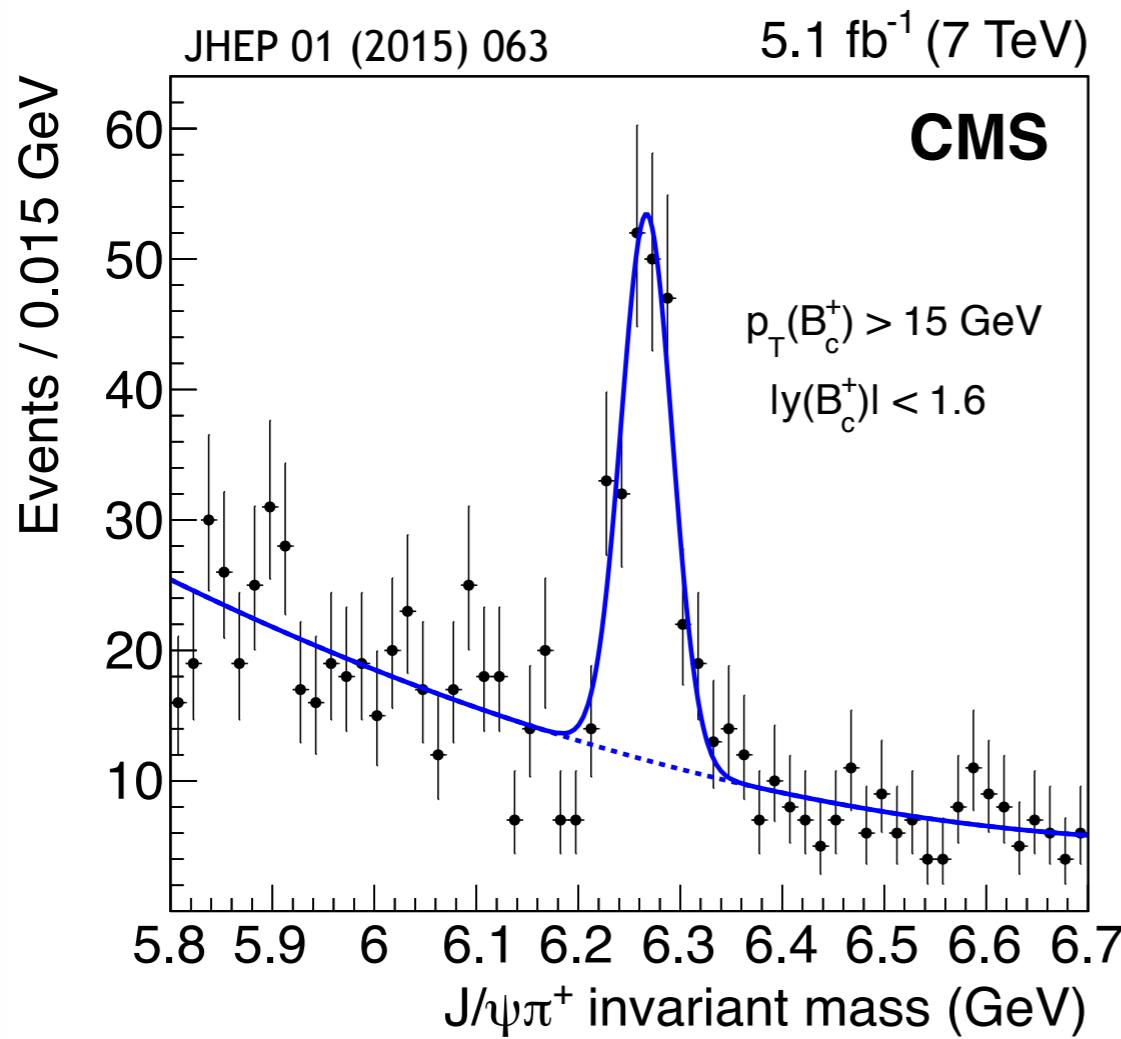


arXiv:1508.06678, sub. to PRL



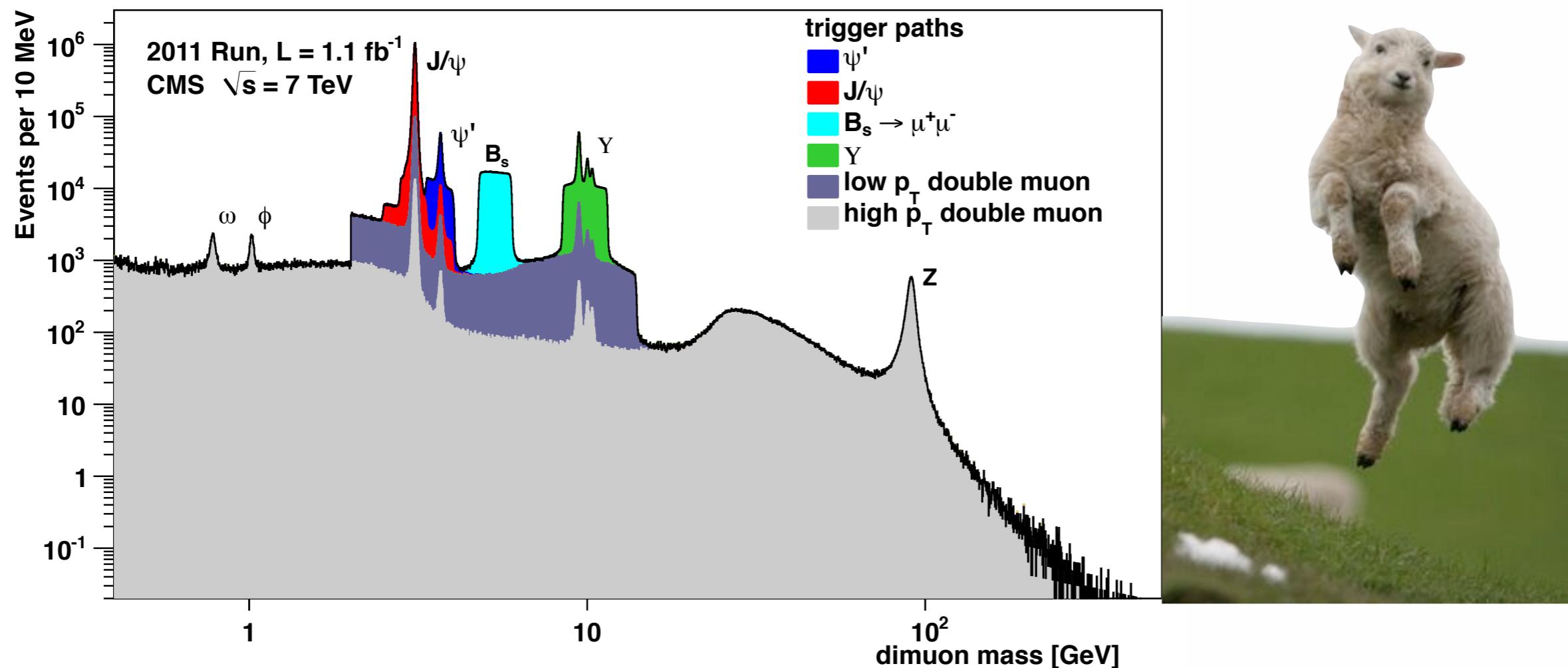
# $B_c$ production in pp collisions

- Using 2011 pp collision data
- Ratio of production cross section times branching ratio for  $B_c \rightarrow J/\psi + \pi$  over  $B^+ \rightarrow J/\psi + K$ :  $2.55 \pm 0.80(\text{stat.}) \pm 0.33(\text{syst.})^{+0.04}_{-0.01}(\tau_{B_c})$
- Relative branching fraction of  $B_c \rightarrow J/\psi + \pi\pi\pi$  over  $B_c \rightarrow J/\psi + \pi$ :  $(0.48 \pm 0.05(\text{stat.}) \pm 0.05(\text{syst.}) \pm 0.05(\tau_{B_c}))\%$



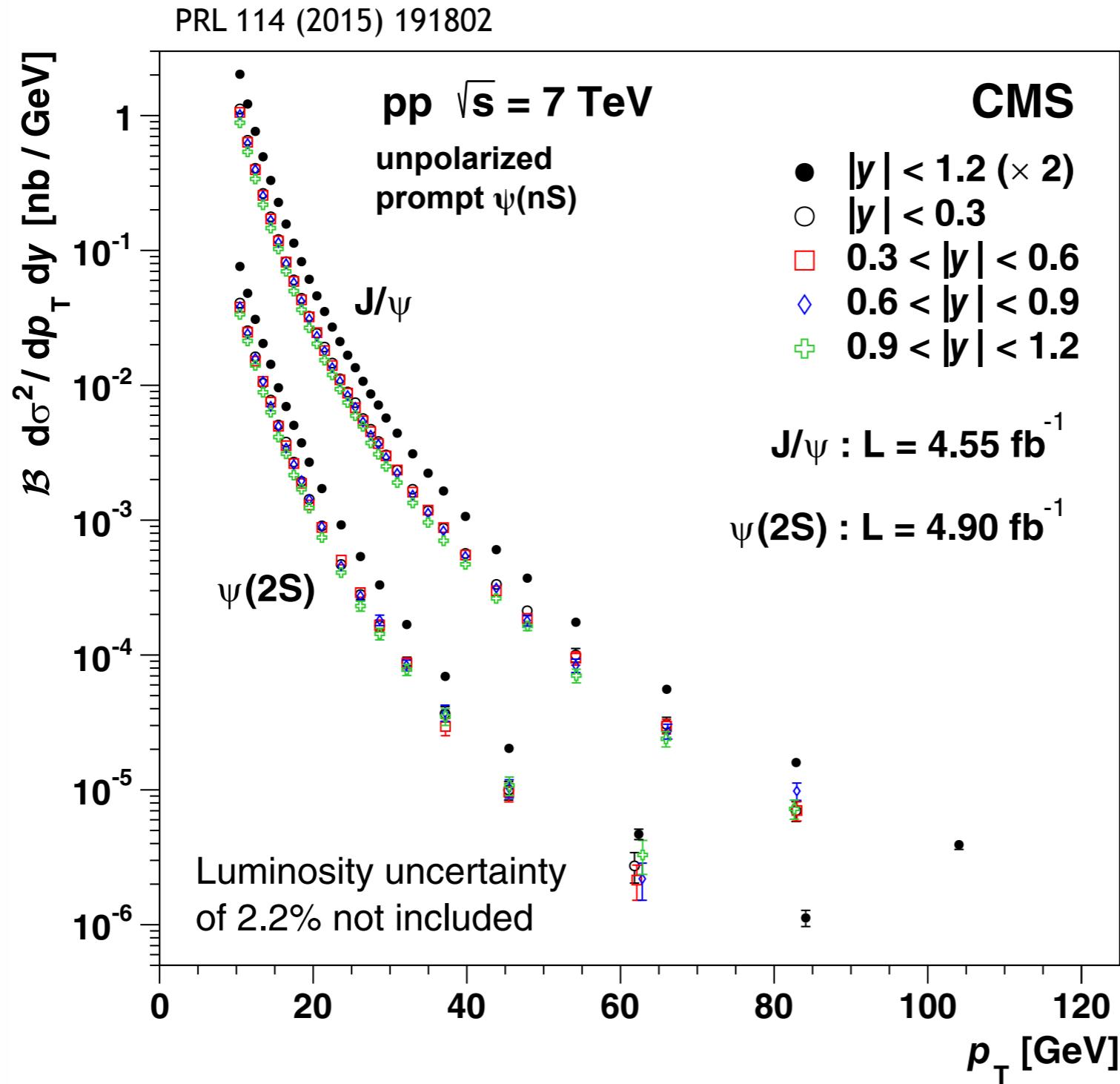
# S-wave quarkonium production in pp collisions

- Using 2011 pp collision data
- Trigger requiring two muons from the same vertex in different mass windows with conditions on the dimuon  $p_T$  and  $y$
- Dedicated triggers with displaced vertices in the  $J/\psi$  mass window
- Total integrated luminosity of  $\sim 5 \text{ fb}^{-1}$



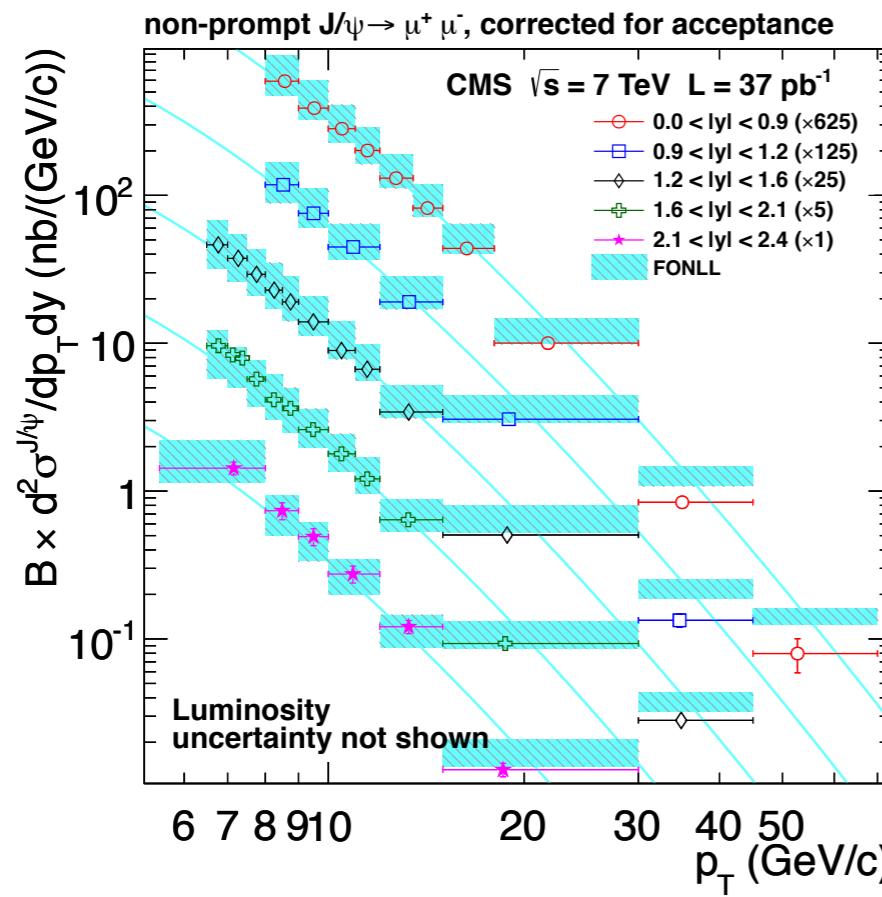
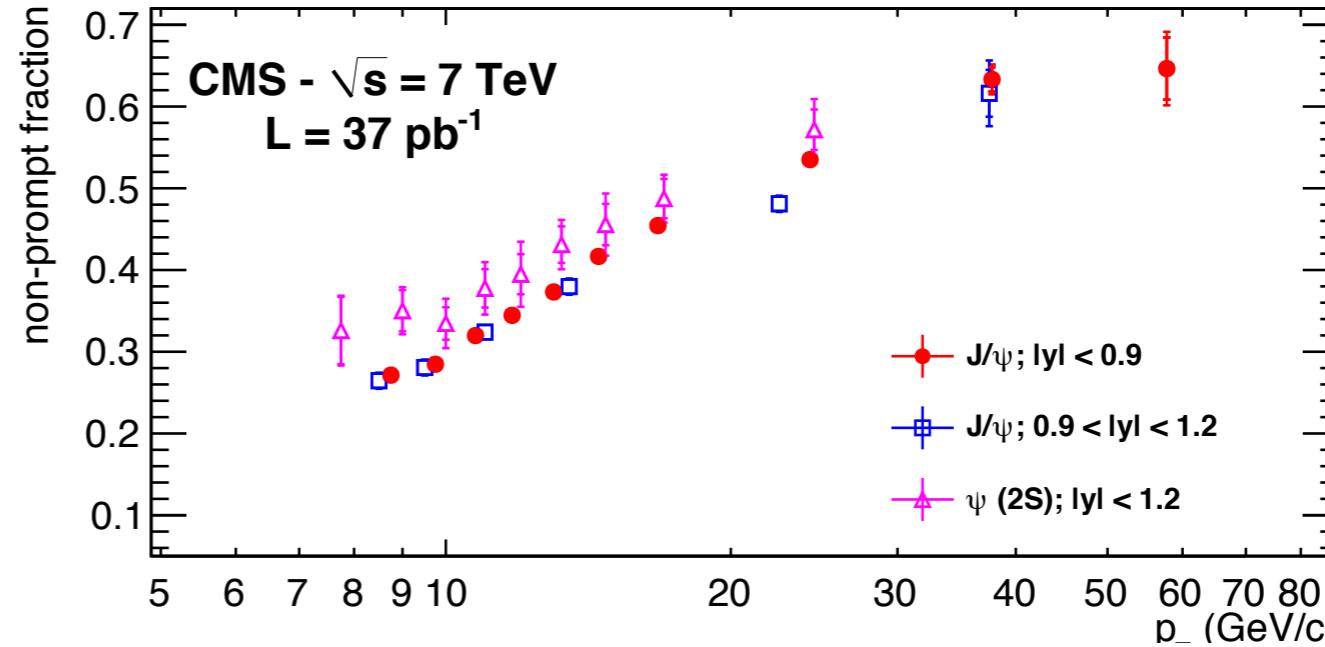
# S-wave quarkonium cross sections measurements

- Prompt  $\psi(nS)$   $p_T$ - and  $|y|$ -differential cross sections

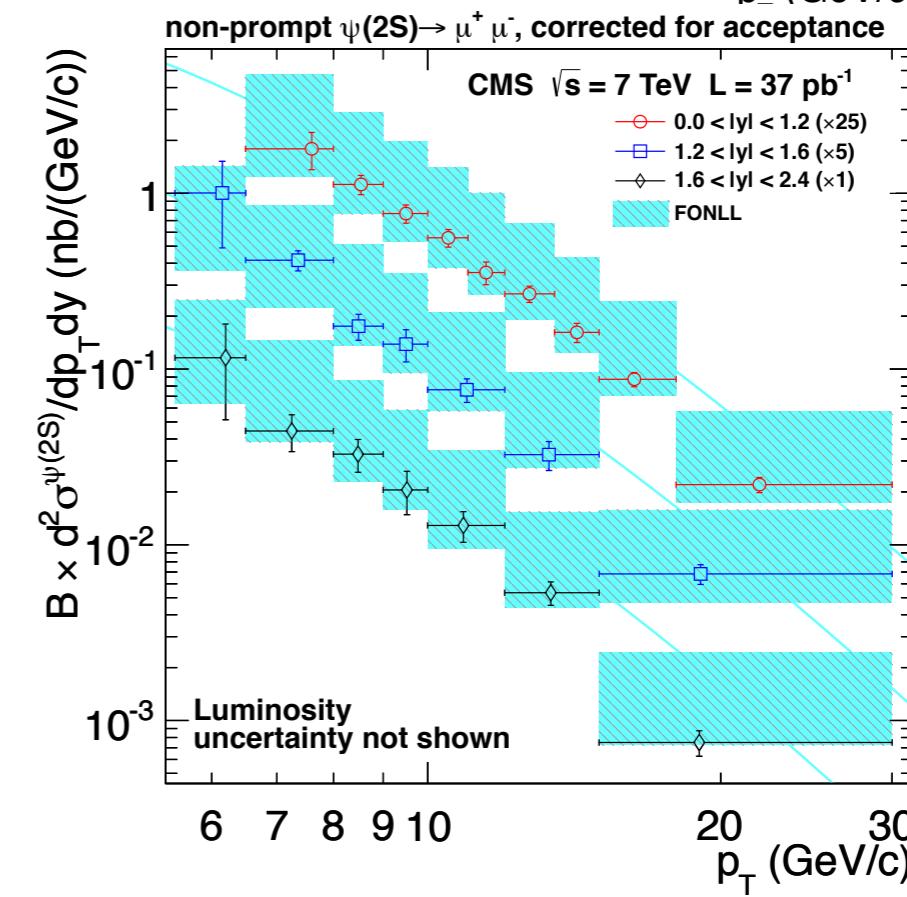


# S-wave quarkonium cross sections measurements

- Non prompt  $\psi(nS)$   $p_T$  and  $|y|$ -differential cross sections using 2010 data

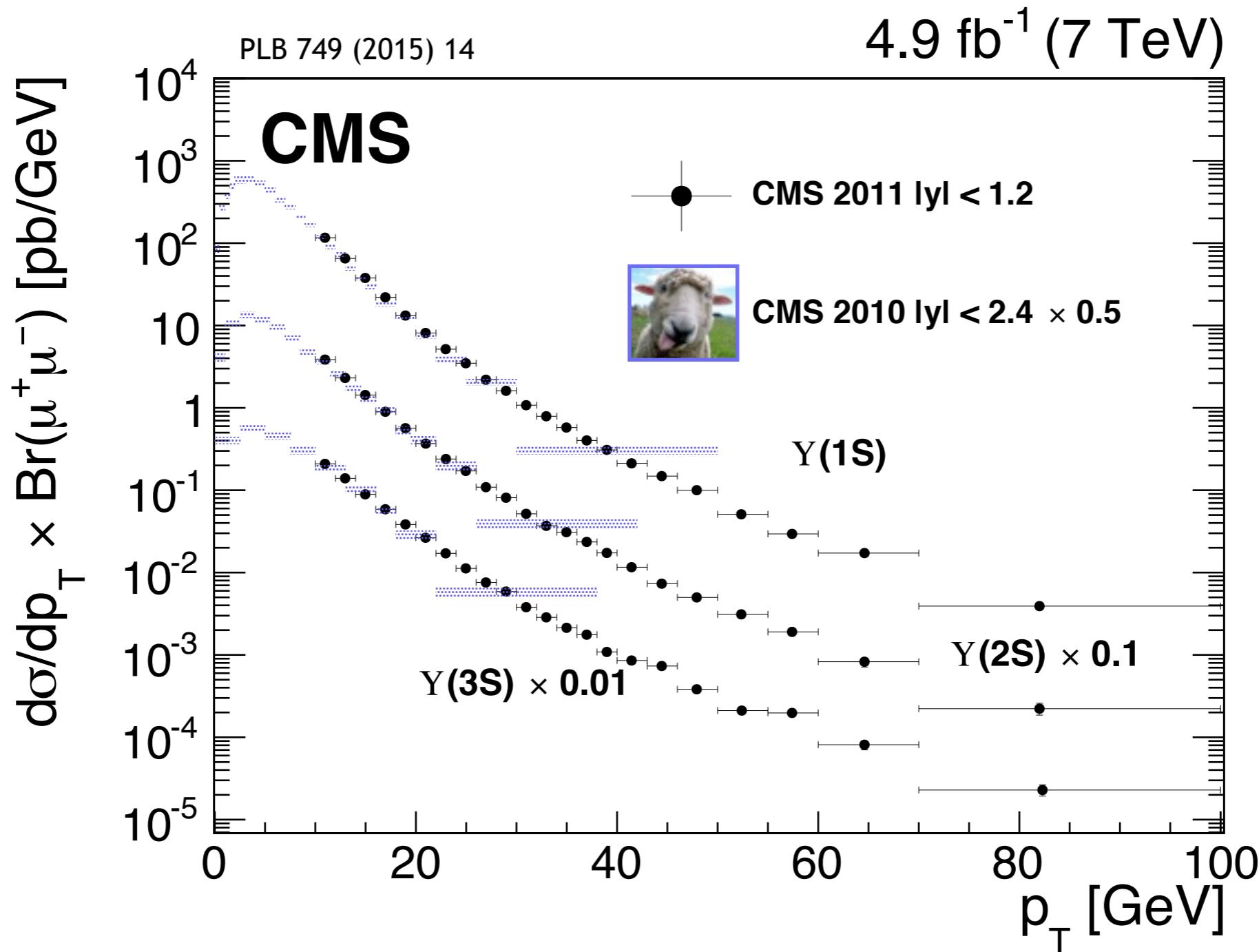


JHEP 02 (2012) 011



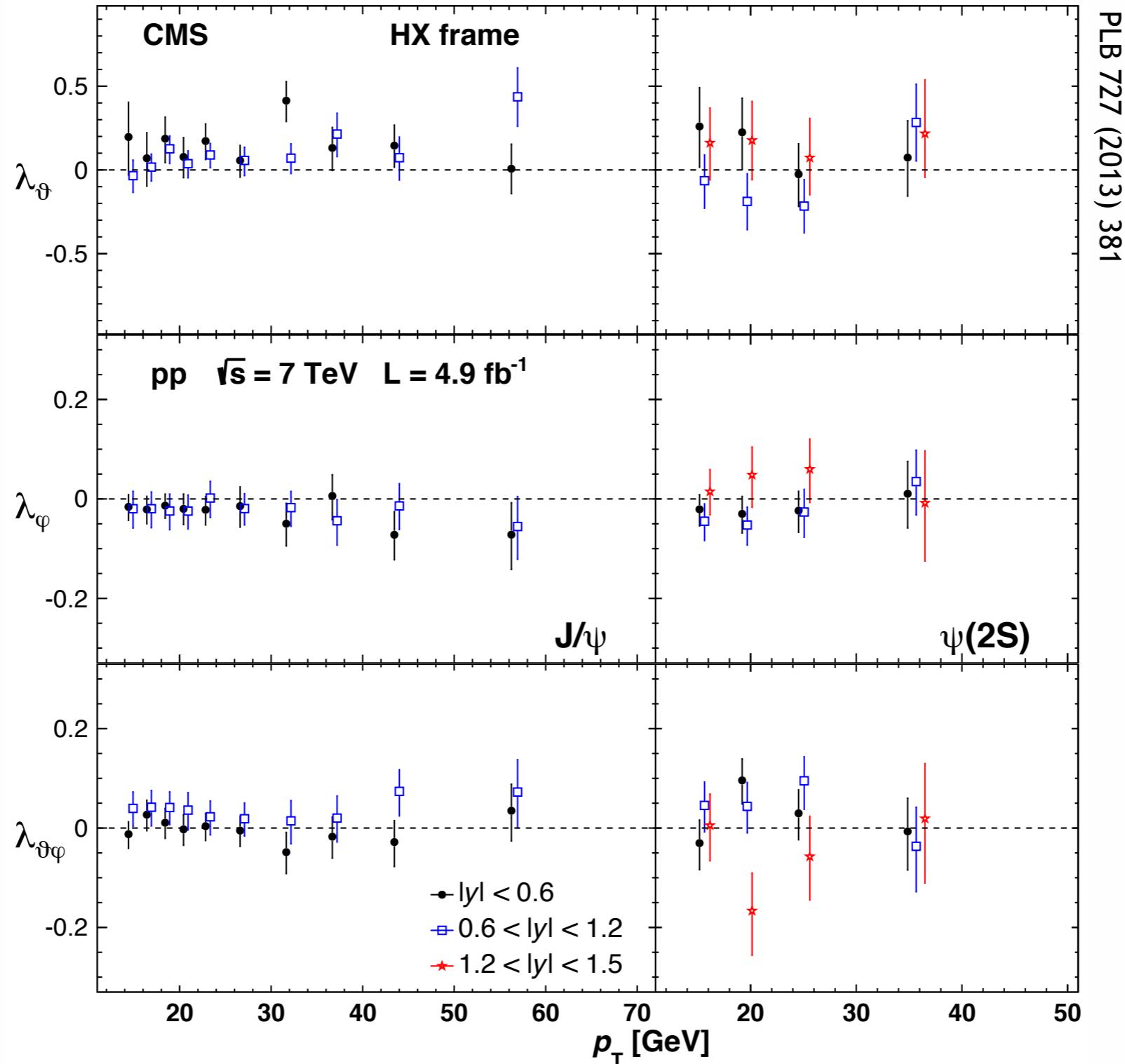
# S-wave quarkonium cross sections measurements

- $\Upsilon(nS)$   $p_T$ -differential cross sections in  $|y| < 1.2$



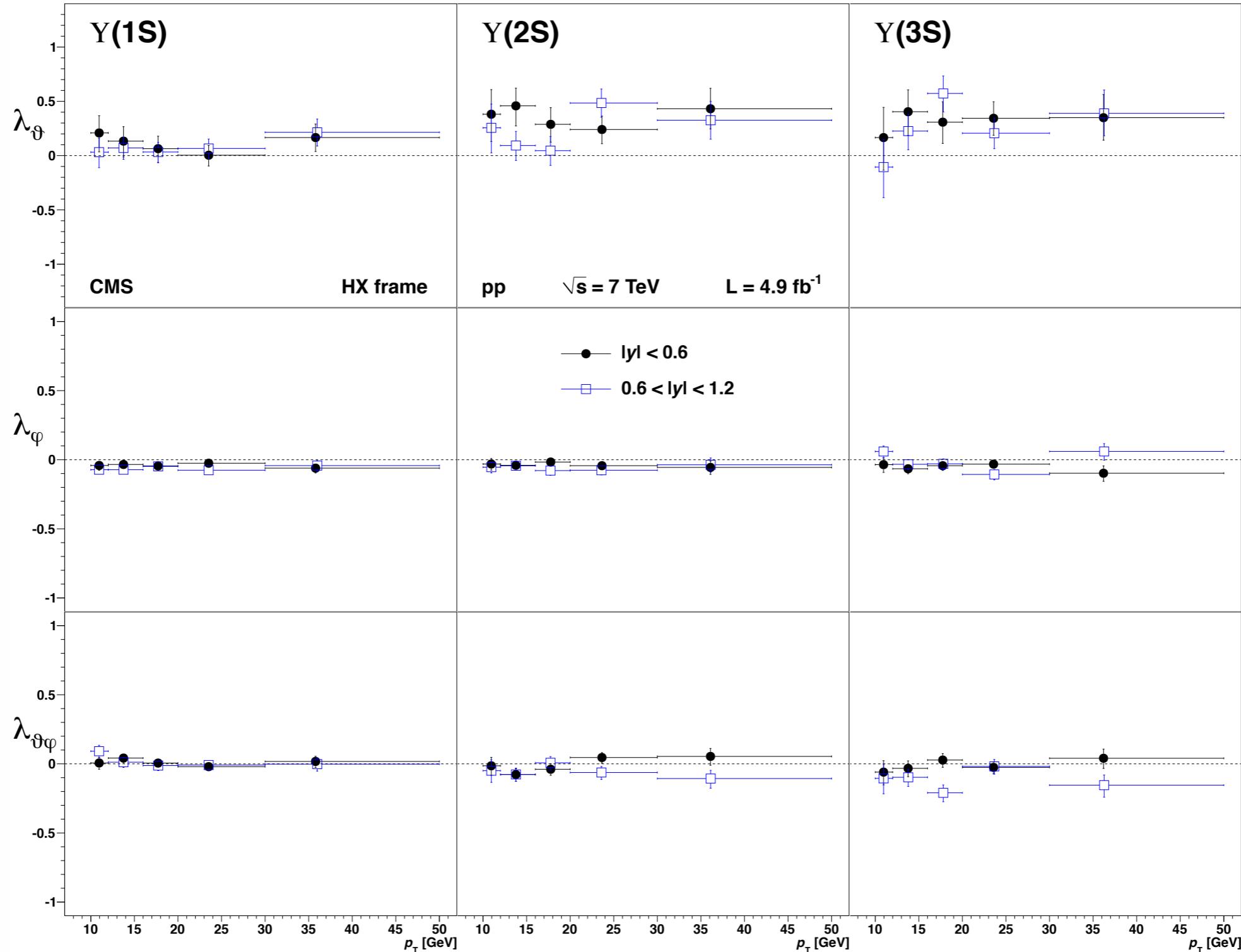
# S-wave quarkonium polarization measurements

- Prompt  $\psi(nS)$  polarizations measured as function of  $p_T$  and  $|y|$



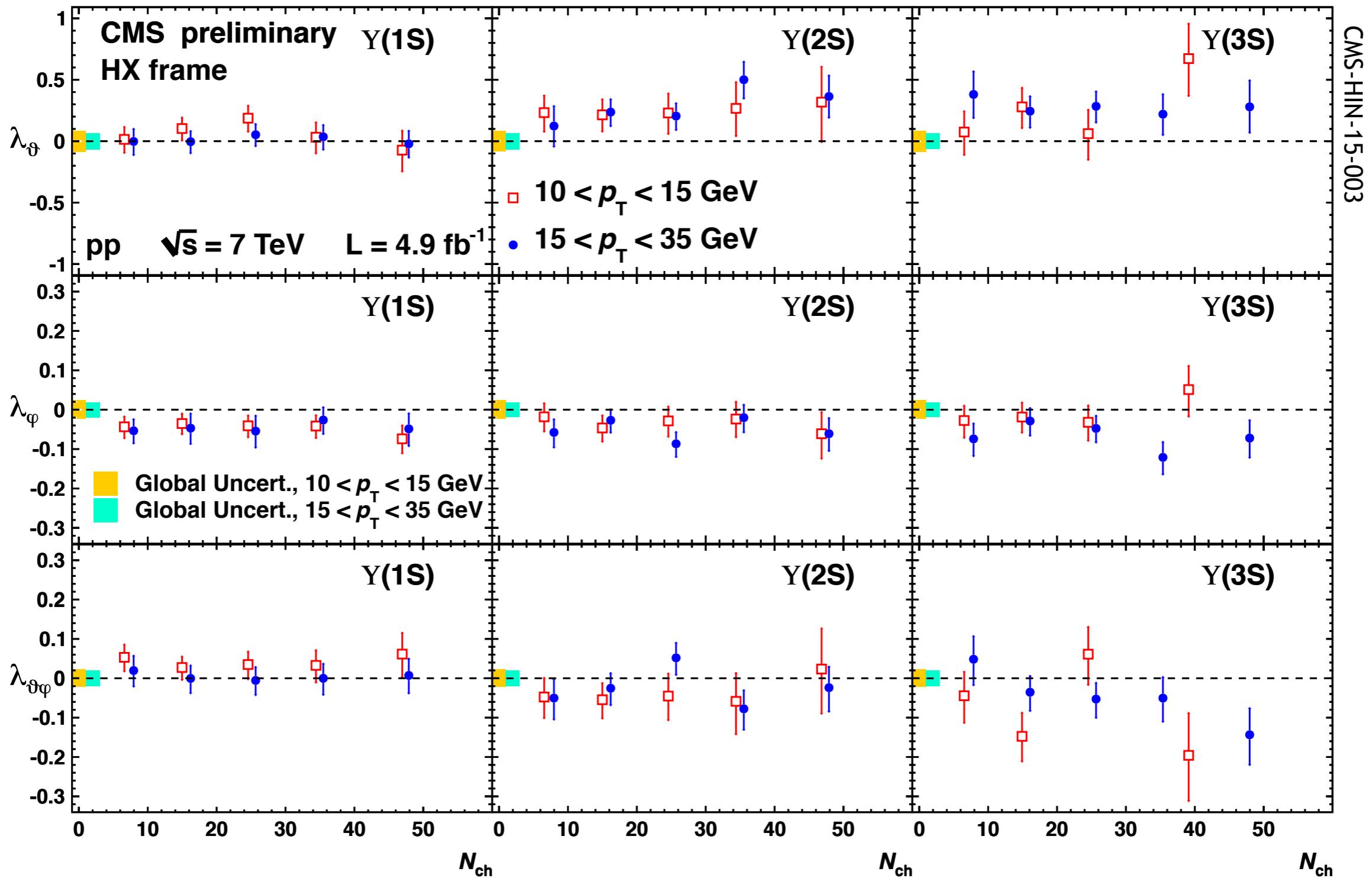
# S-wave quarkonium polarization measurements

- $\Upsilon(nS)$  polarizations measured as function of  $p_T$  and rapidity,  $|y|$



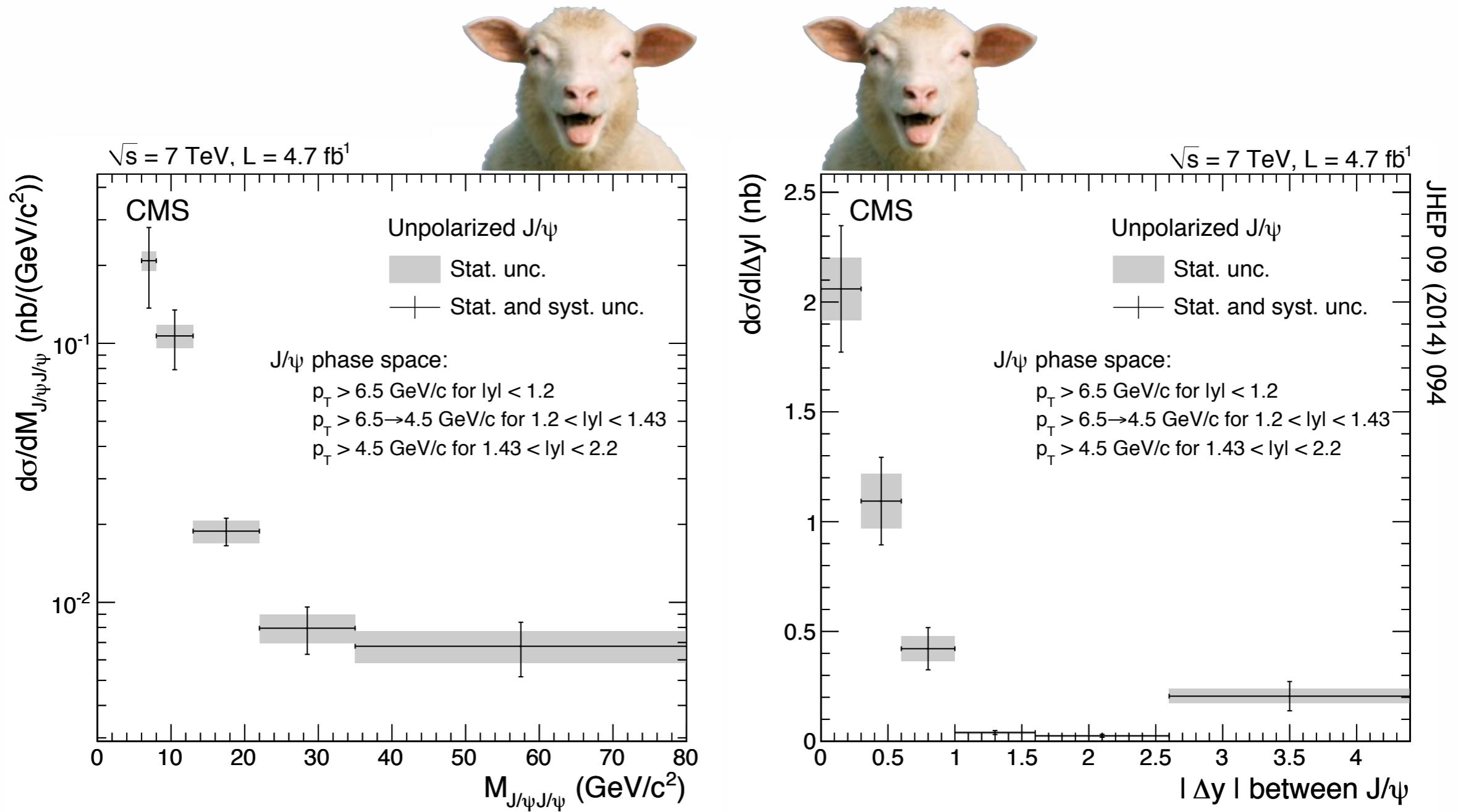
# S-wave quarkonium polarization measurements

- $\Upsilon(nS)$  polarizations measured as function of charged particle multiplicity



# Prompt J/ $\psi$ pair production measurement

- Trigger requires at least 3 muons with two oppositely charged muons within the J/ $\psi$  mass window
- Cross sections as function of  $p_T$ ,  $|\Delta y|$  and mass



# S-wave quarkonium production in PbPb collisions

- Using 2011 PbPb and pp datasets collected at  $\sqrt{s} = 2.76$  TeV
- Hardware based trigger requiring two muons
- Integrated luminosities of  $\sim 150 \mu\text{b}^{-1}$  (PbPb) and  $\sim 5.4 \text{ pb}^{-1}$  (pp)

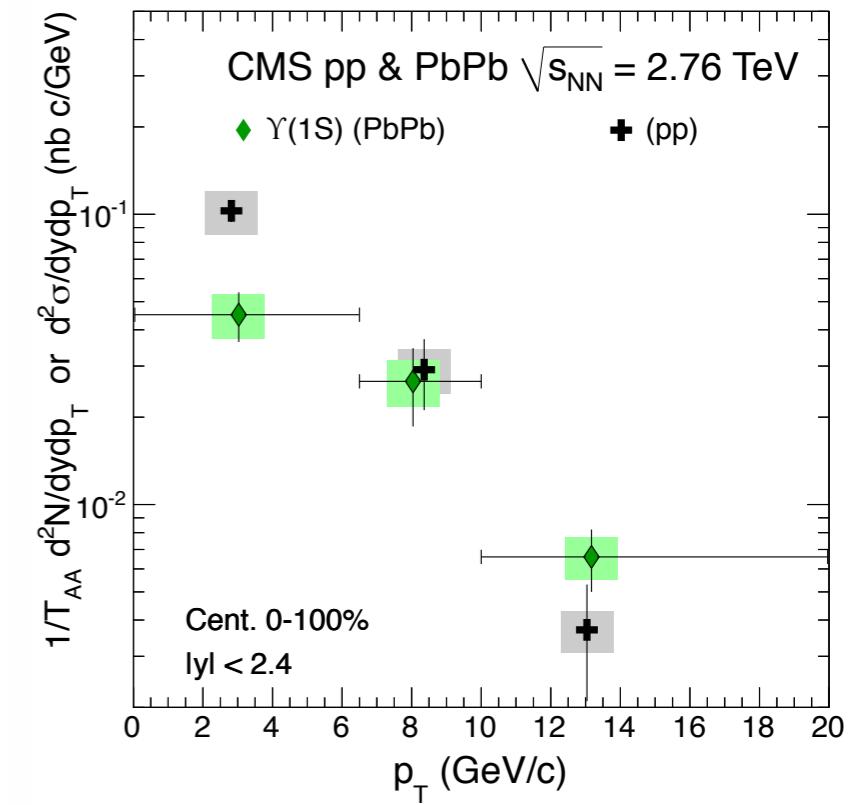
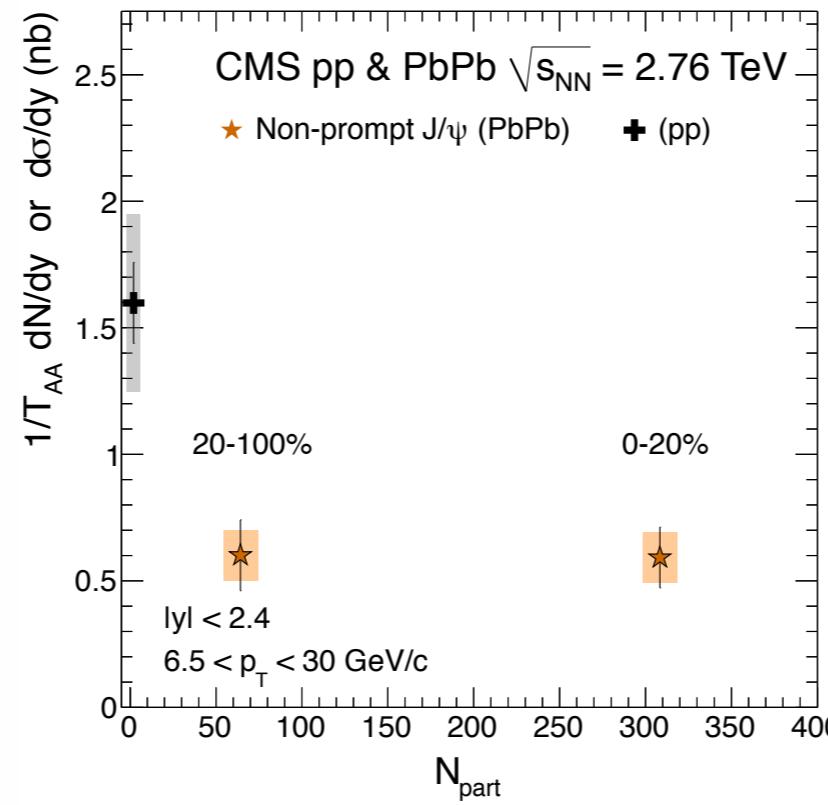
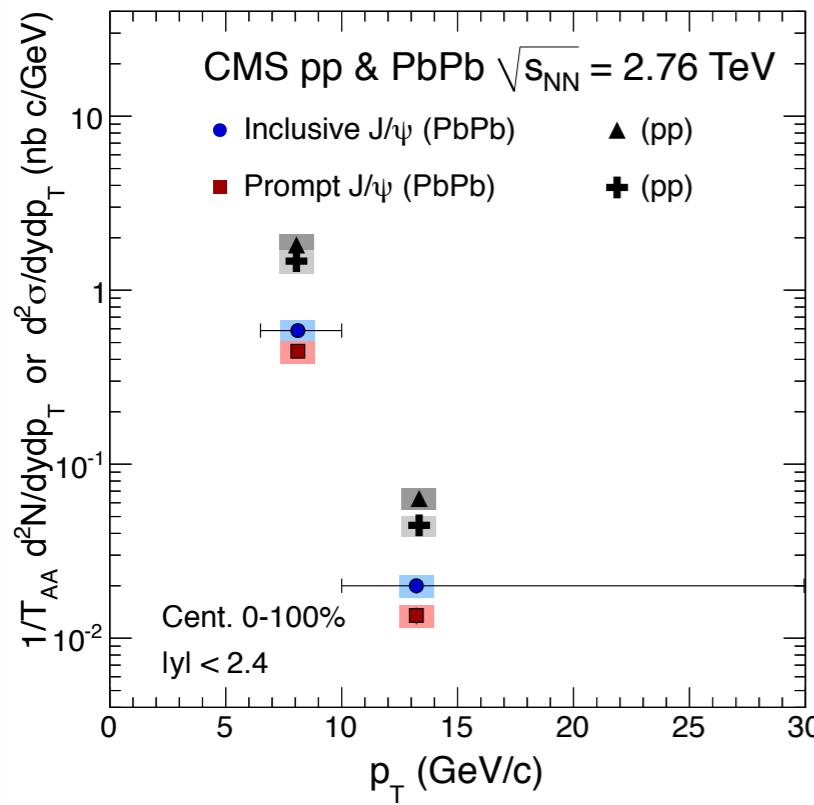


# S-wave quarkonium production measurements

- Cross sections and nuclear modification factors as function of  $p_T$ ,  $|y|$  and centrality for
  - prompt  $J/\psi$
  - non prompt  $J/\psi$
  - $\Upsilon(1S)$

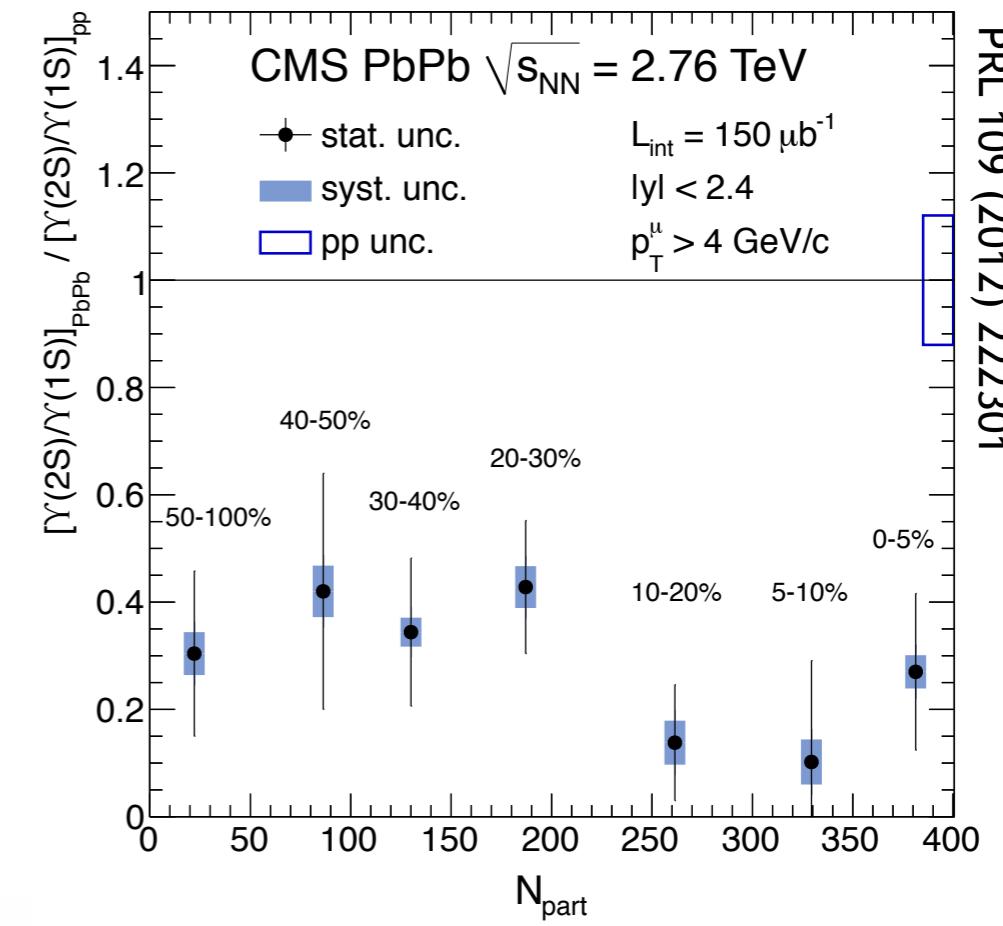
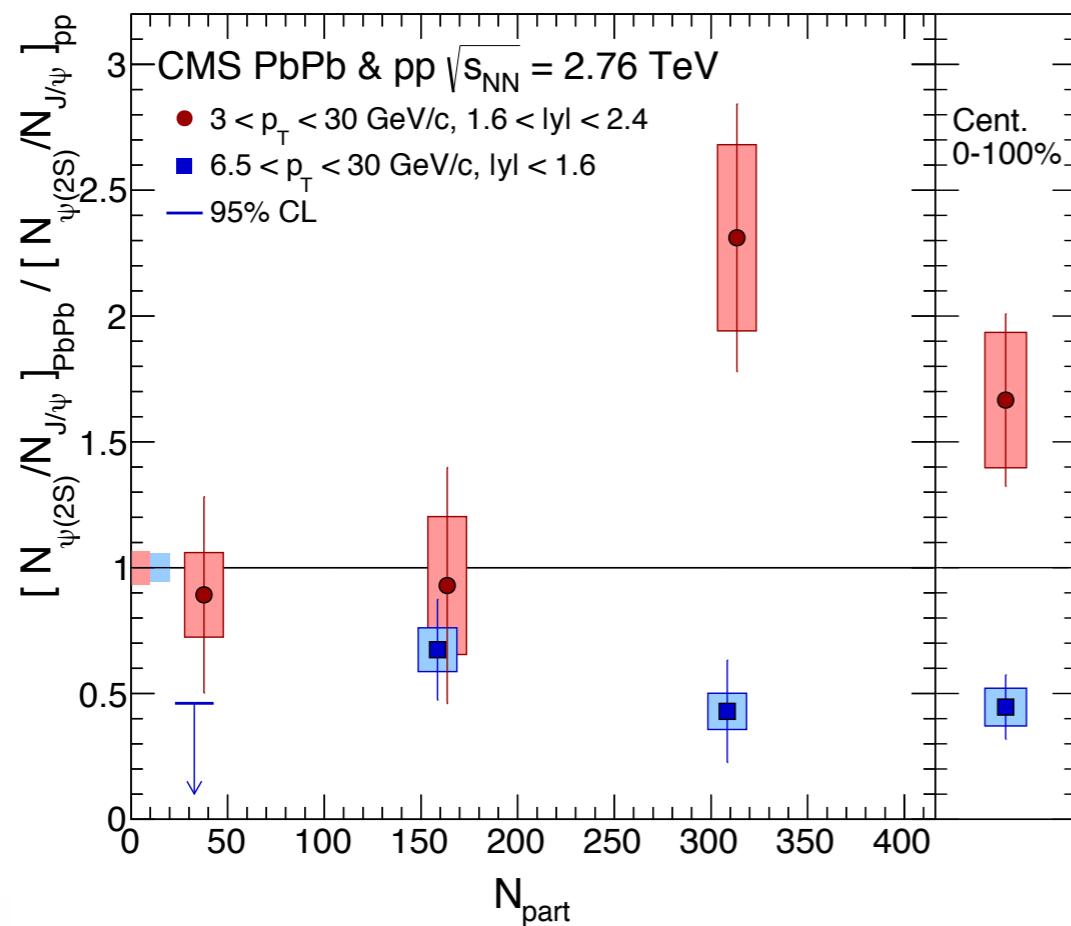


JHEP 05 (2012) 063



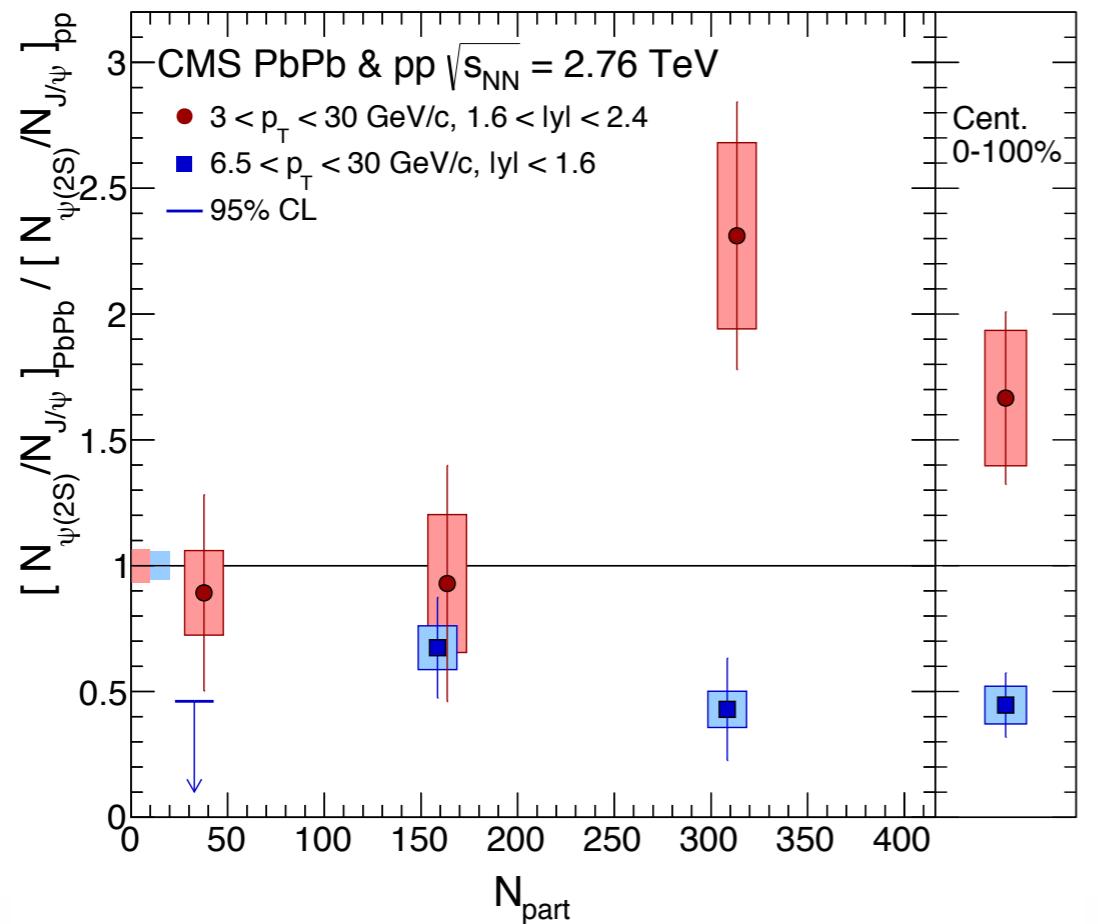
# S-wave quarkonium production measurements

- Double ratio of
  - prompt  $\psi(2S)$  over  $J/\psi$
  - $\Upsilon(2S)$  over  $\Upsilon(1S)$
  - $\Upsilon(3S)$  over  $\Upsilon(1S)$  (statistically not significant)
- In PbPb and pp collisions
- As function of centrality

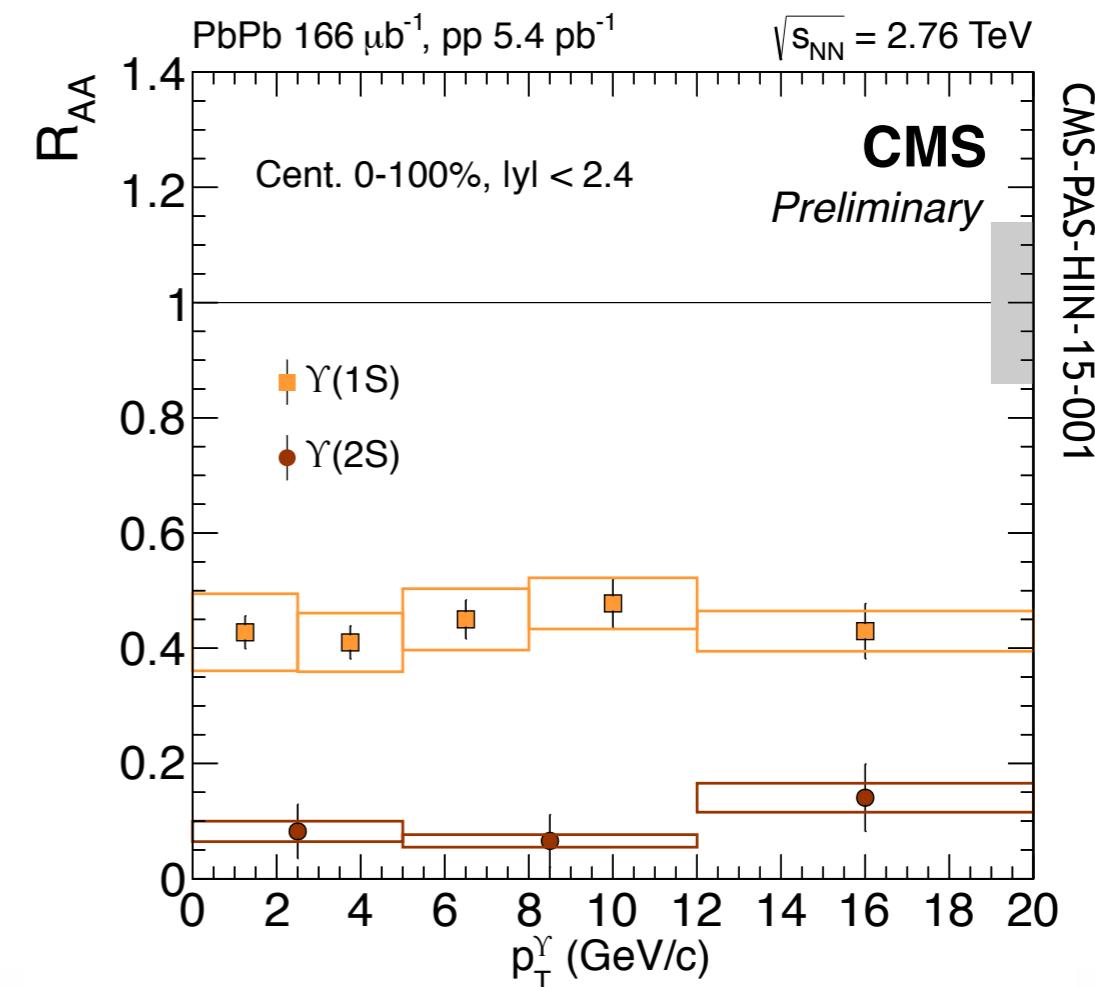


# S-wave quarkonium production measurements

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  - $\Upsilon(2S)$  over  $\Upsilon(1S)$
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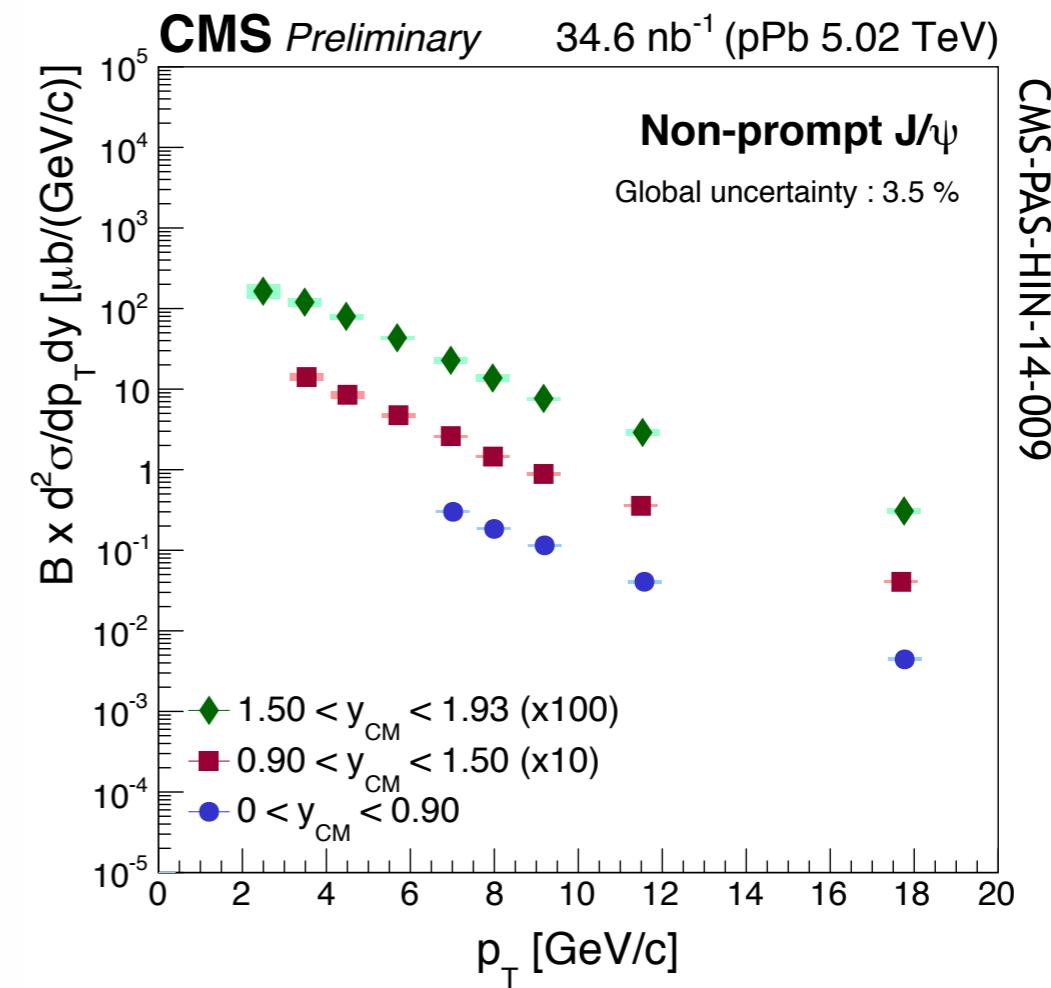
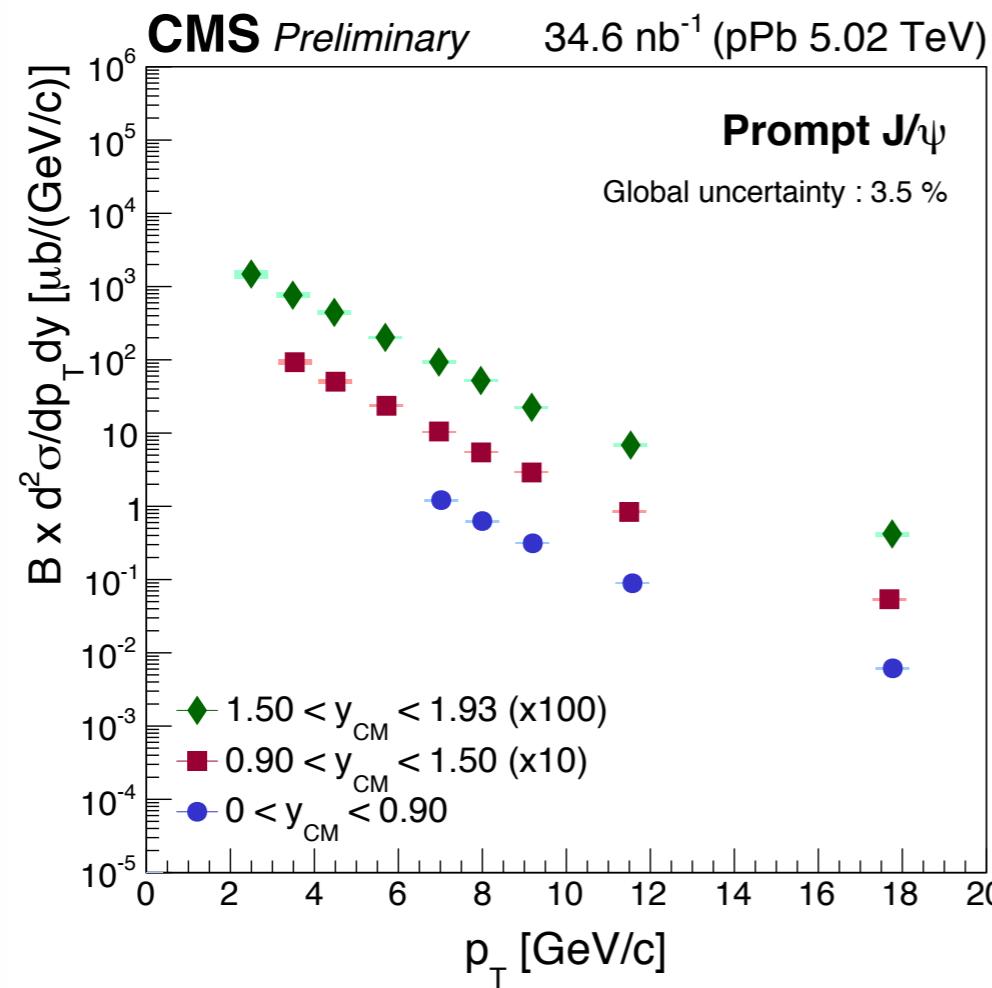


- Improved data reconstruction increases yields
- Nuclear modification factor for  $\Upsilon(1S)$  and  $\Upsilon(2S)$  as function of  $p_T$ ,  $|y|$  and centrality



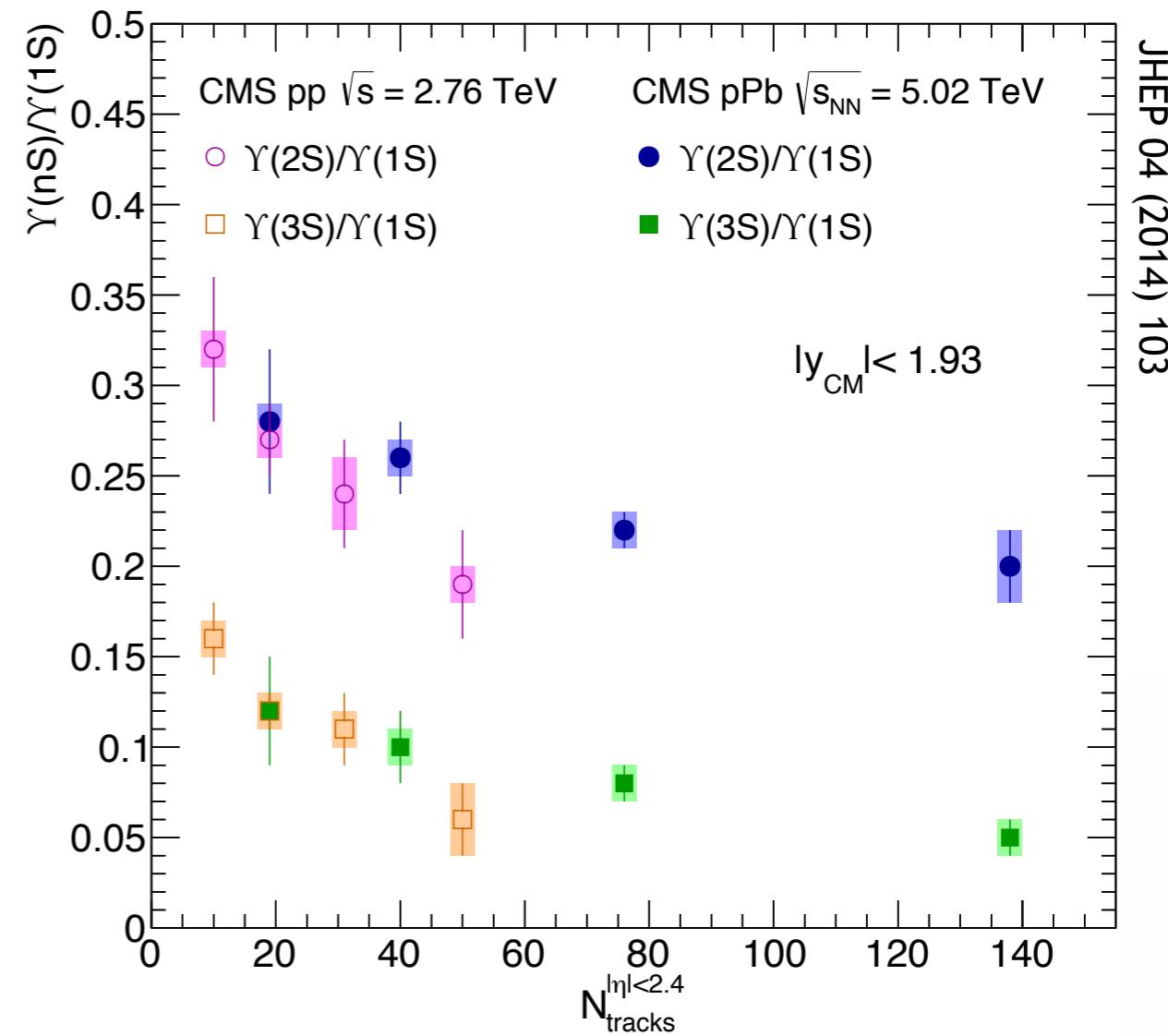
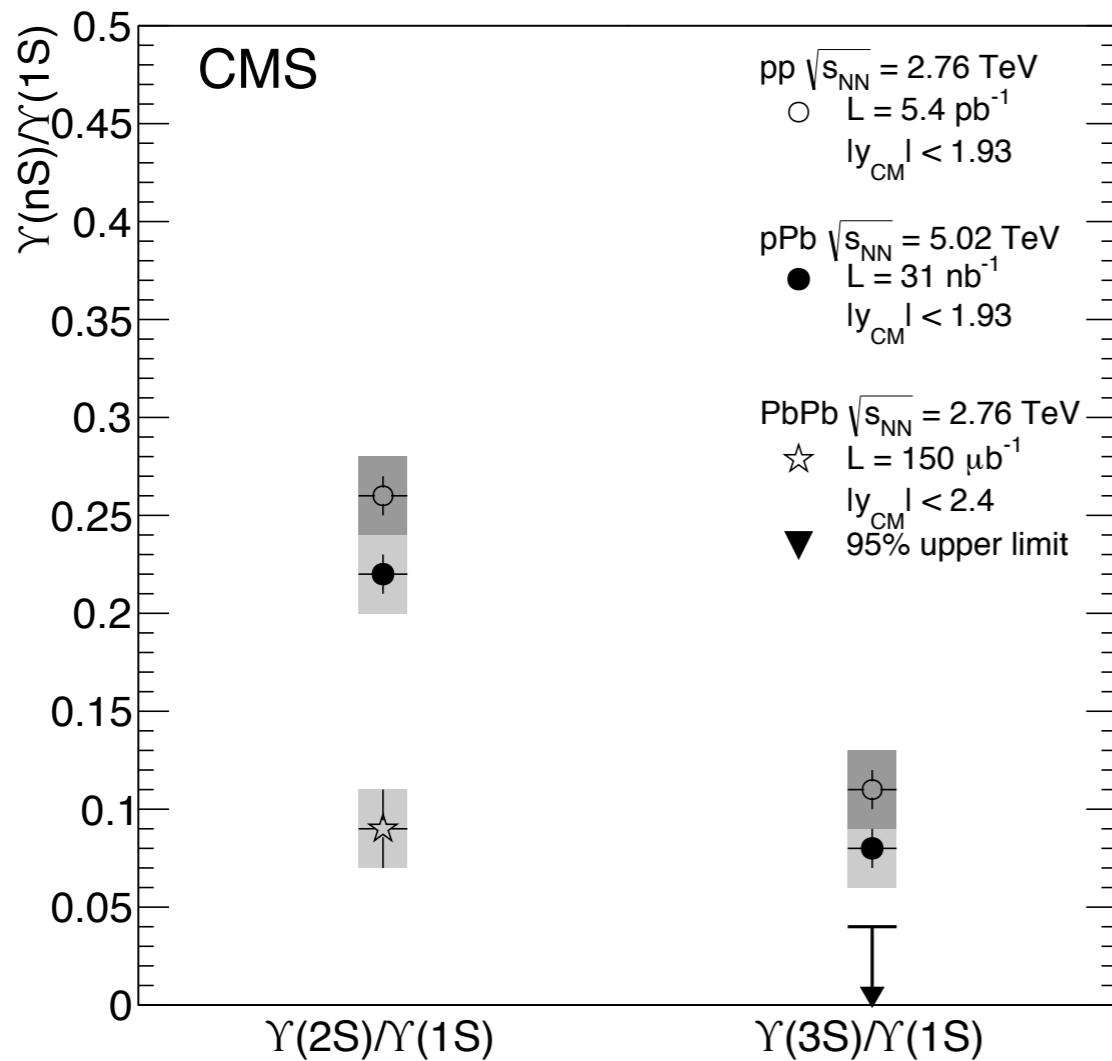
# S-wave quarkonia production in pPb collisions

- Using 2013 pPb dataset collected at  $\sqrt{s} = 5.02$  TeV
- Hardware based trigger requiring two muons
- Cross sections and nuclear modification factors as function of  $p_T$ ,  $|y|$  and centrality for
  - prompt  $J/\psi$
  - non prompt  $J/\psi$



# S-wave quarkonia production in pPb collisions

- Using 2013 pPb dataset collected at  $\sqrt{s} = 5.02$  TeV
- Hardware based trigger requiring two muons
- Double ratios and single cross section ratios as function of charged particle multiplicity and transverse energy for  $\Upsilon(nS)$  states



# P-wave quarkonium production in pp collisions

- Using 2011 and 2012 pp collision data
- Trigger strategy in 2012 similar to 2011
- Total integrated luminosity of  $\sim 20 \text{ fb}^{-1}$  collected in 2012



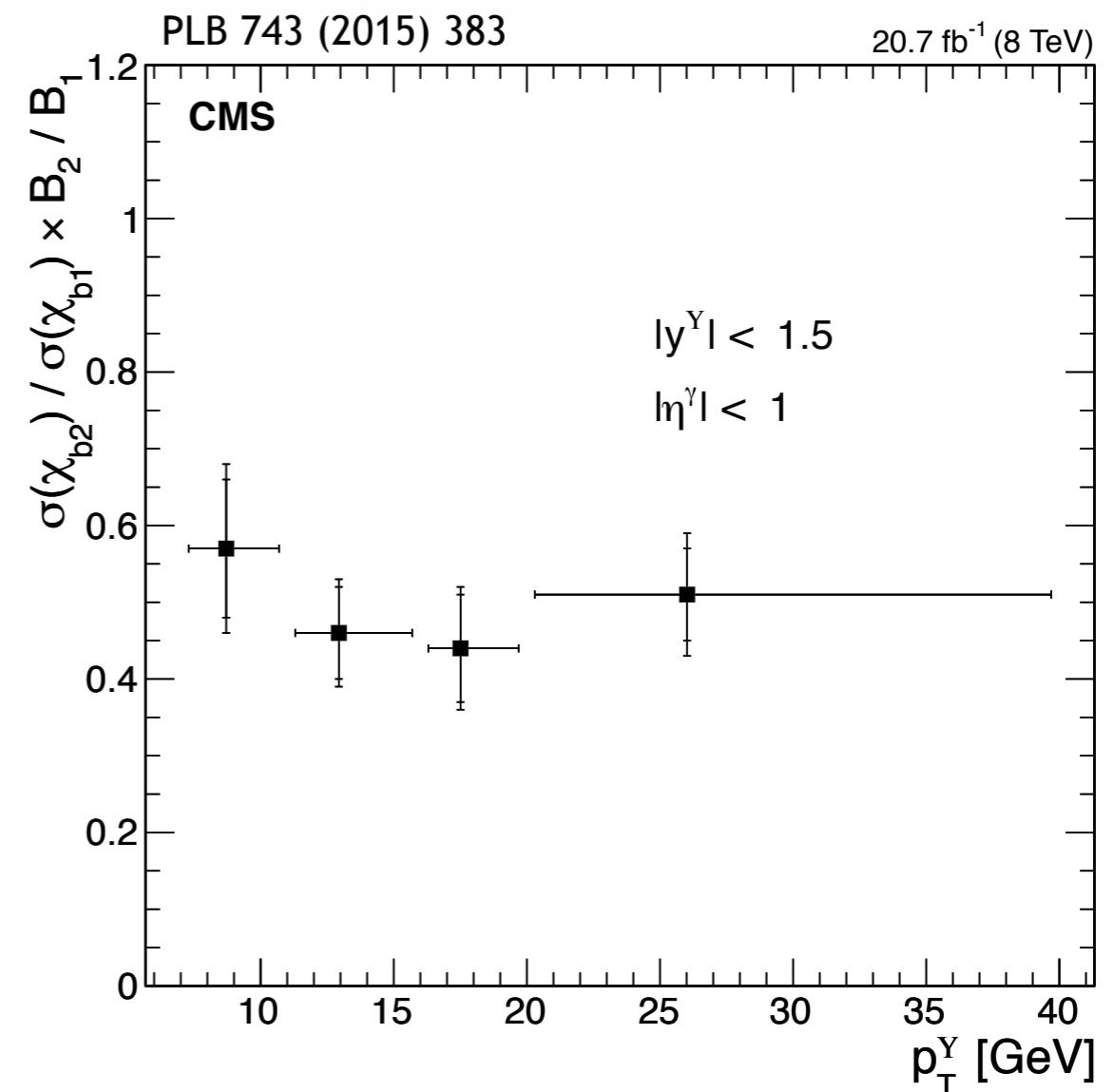
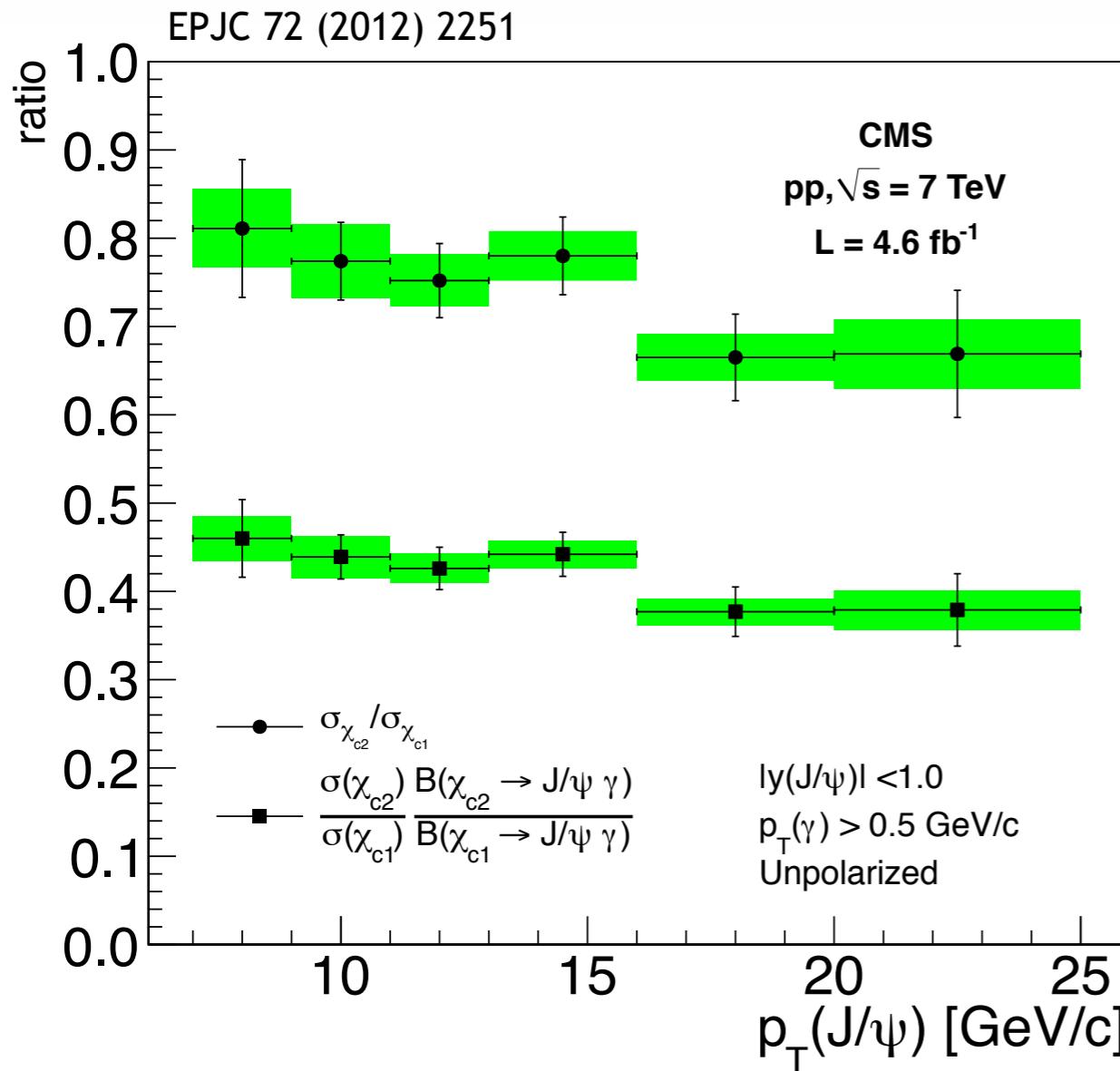
# P-wave quarkonium cross section ratio measurements

- Detection via radiative decays using converted photons

$$\chi_c \rightarrow J/\psi + \gamma$$

$$\chi_b(1P) \rightarrow Y(1S) + \gamma$$

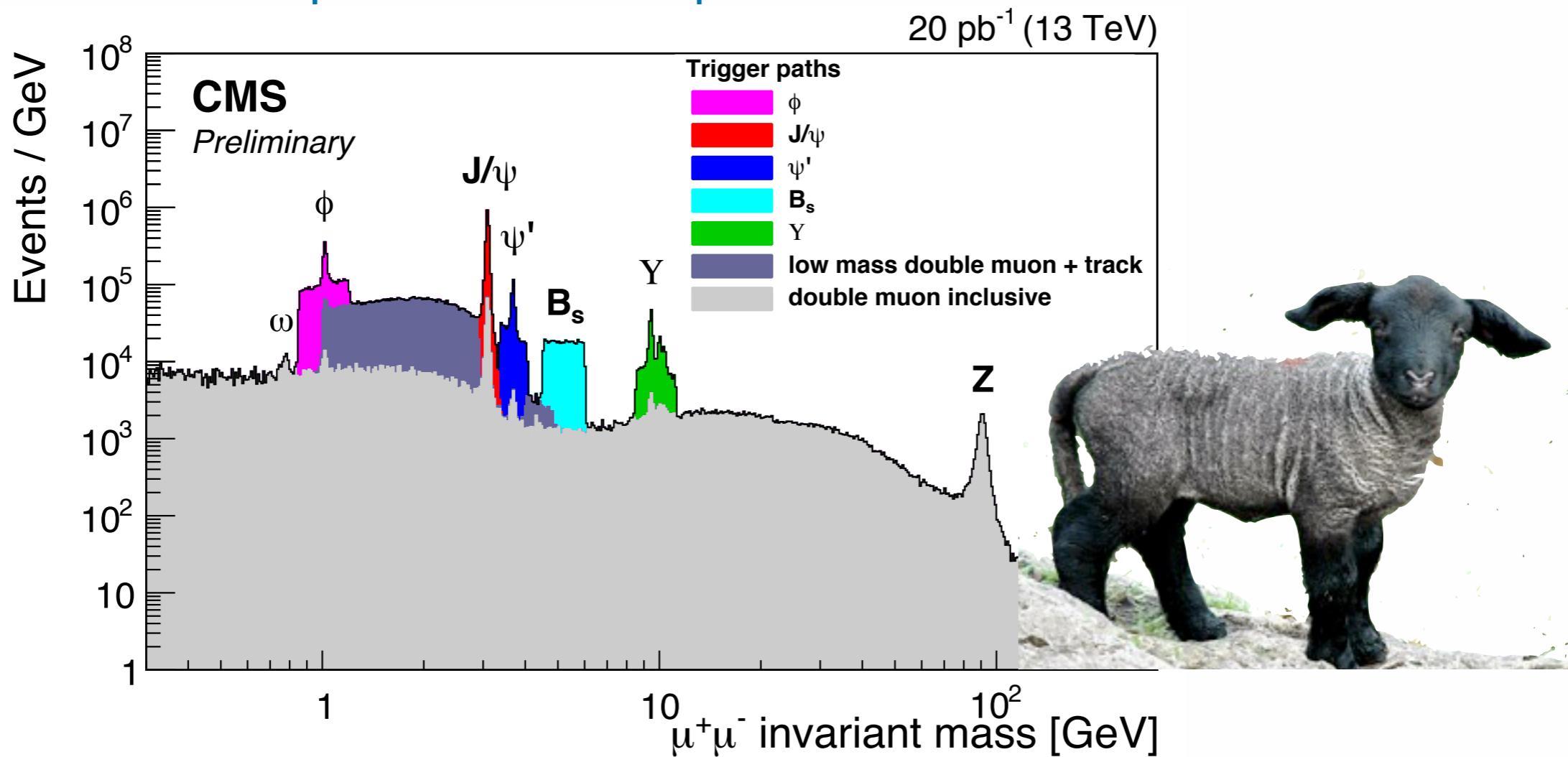
- Ratios of cross sections of prompt  $\chi_{c2}(1P)/\chi_{c1}(1P)$  and  $\chi_{b2}(1P)/\chi_{b1}(1P)$



# Production in pp collisions in 2015

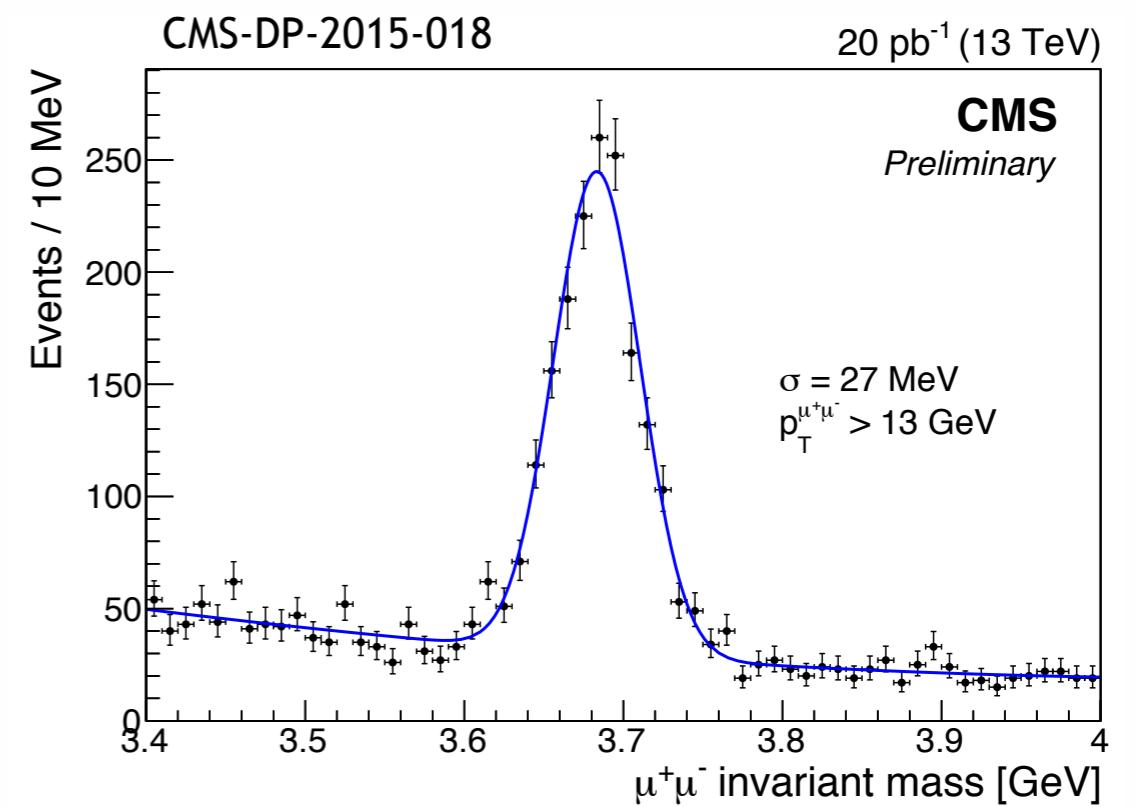
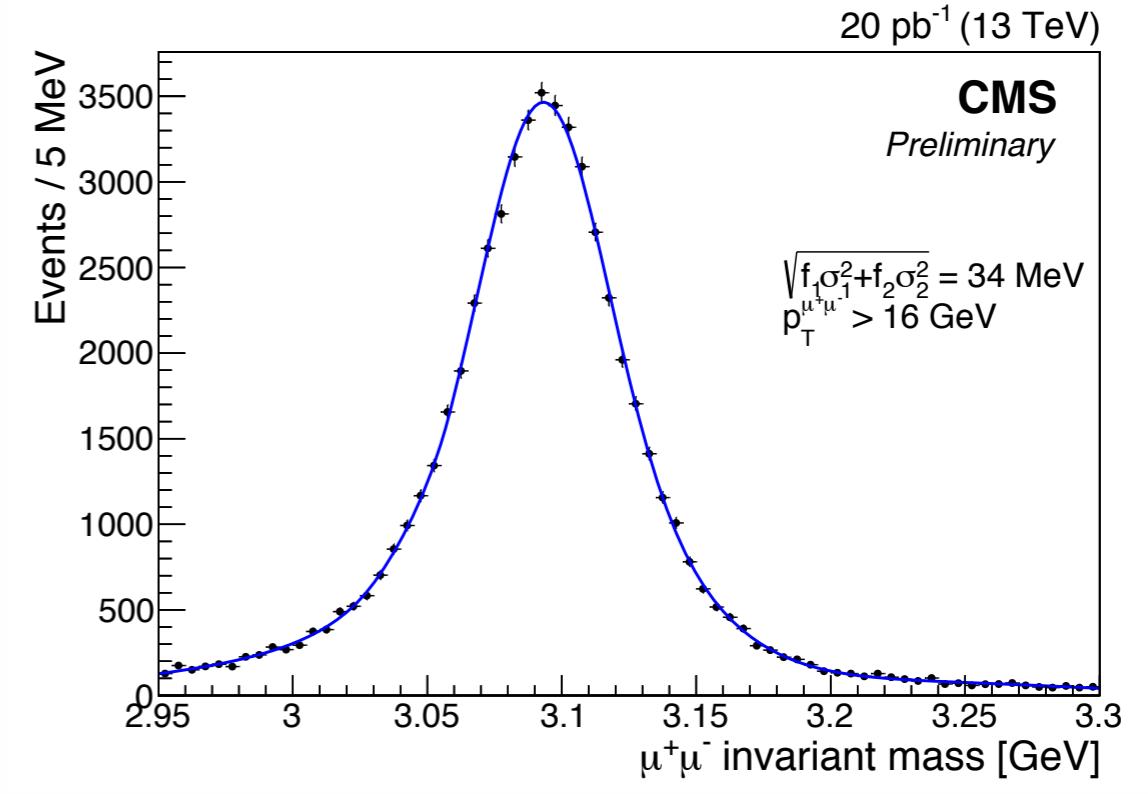
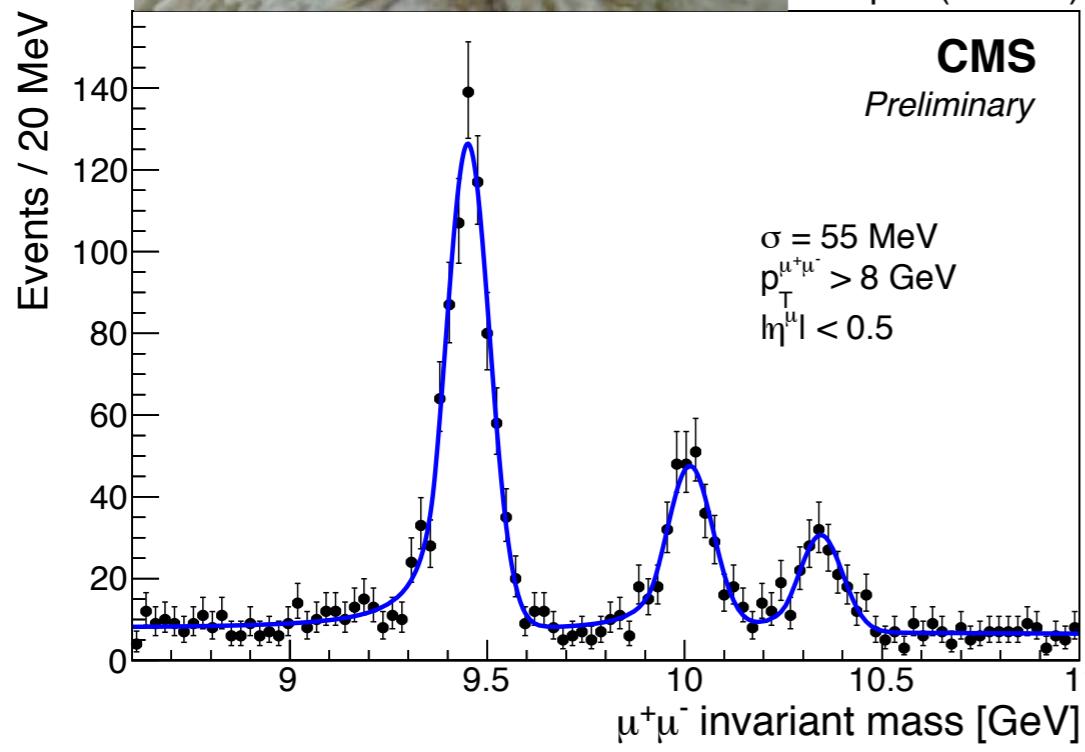
## Trigger

- Requiring two muons coming from the same vertex
- In different mass windows
- With conditions on dimuon  $p_T$  and  $y$  and partly on single muon  $p_T$
- Some with displaced vertex requirement



# Analyses with early 2015 pp collision data coming soon

- Double-differential cross sections of
  - all five S-wave quarkonia
  - $B^+$  decaying to  $J/\psi + K^+$



## Future possibilities

- High luminosity in Run I pp collisions compensates for high energy in Run II so far
- ➡ Possibility to fully exploit 2012 dataset
- Previous measurements can be extended to higher  $p_T$  with increased  $\sqrt{s}$  and increased statistics



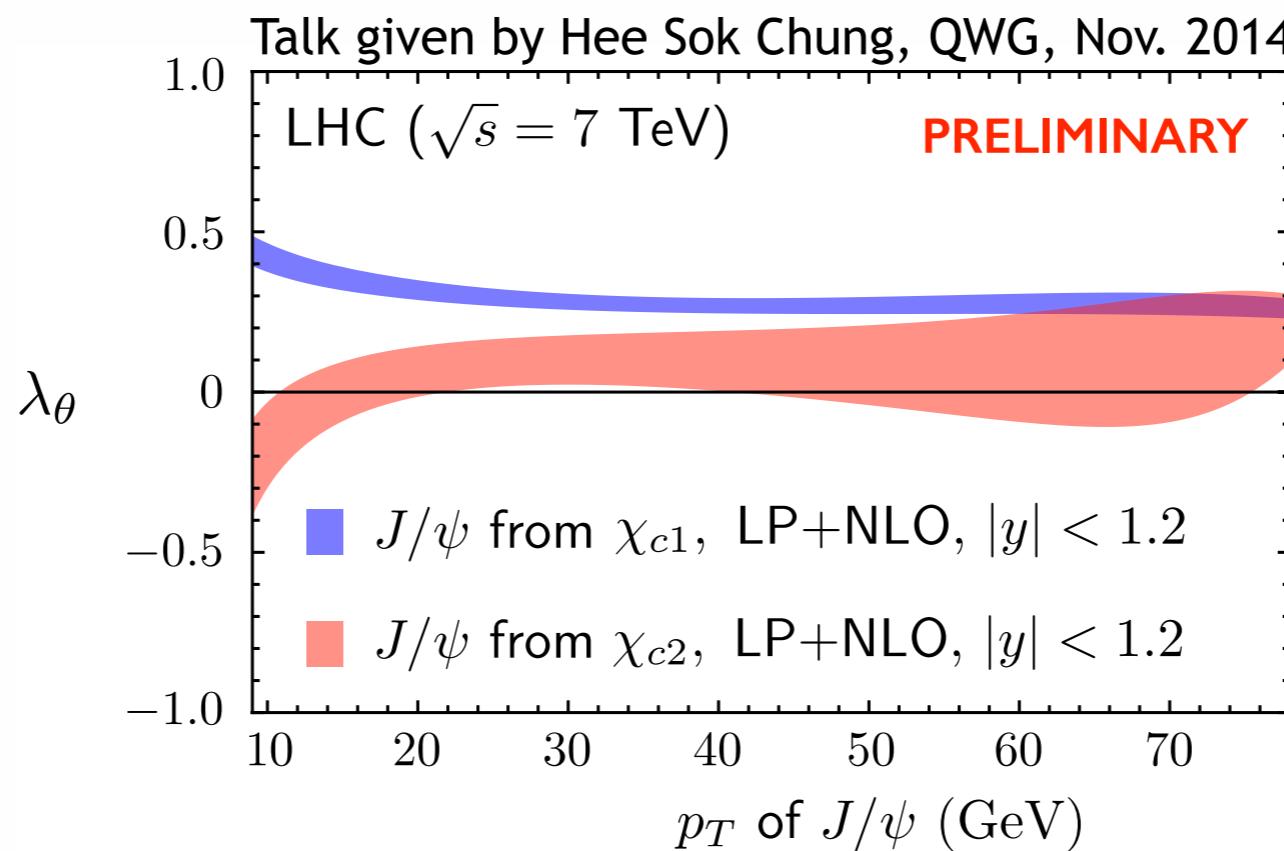
# Future possibilities: S-wave quarkonia

- Extend polarization measurement as function of  $N_{ch}$  to pPb and PbPb collisions to test universality (process independence) of long distance strong force
- Study suppression patterns in heavy ions with increased statistics
- Production of quarkonia in association with W and Z bosons, other quarkonia, jets, photons...



# Future possibilities: P-wave quarkonia

- Absolute cross sections and feed-down fractions:
  - Experimental challenge: determining photon efficiencies using  $B^+ \rightarrow J/\psi + K^+$  and  $B^+ \rightarrow \chi_{c1} + K^+ \rightarrow J/\psi + \gamma + K^+$
- $\chi_c$  and  $\chi_b(1P)$  polarizations:
  - Measurement through the angular distributions of  $J/\psi$  and  $\Upsilon(1S)$  decaying into two muons  
(P. Faccioli, et al. PRD 83 (2011) 096001)
  - Crucial to understand polarization of S-wave quarkonium states



## Summary and conclusions

- Numerous results on quarkonium and heavy flavour production already published

<http://cms-results.web.cern.ch/cms-results/public-results/publications/BPH/index.html>

<http://cms-results.web.cern.ch/cms-results/public-results/publications/HIN/index.html>

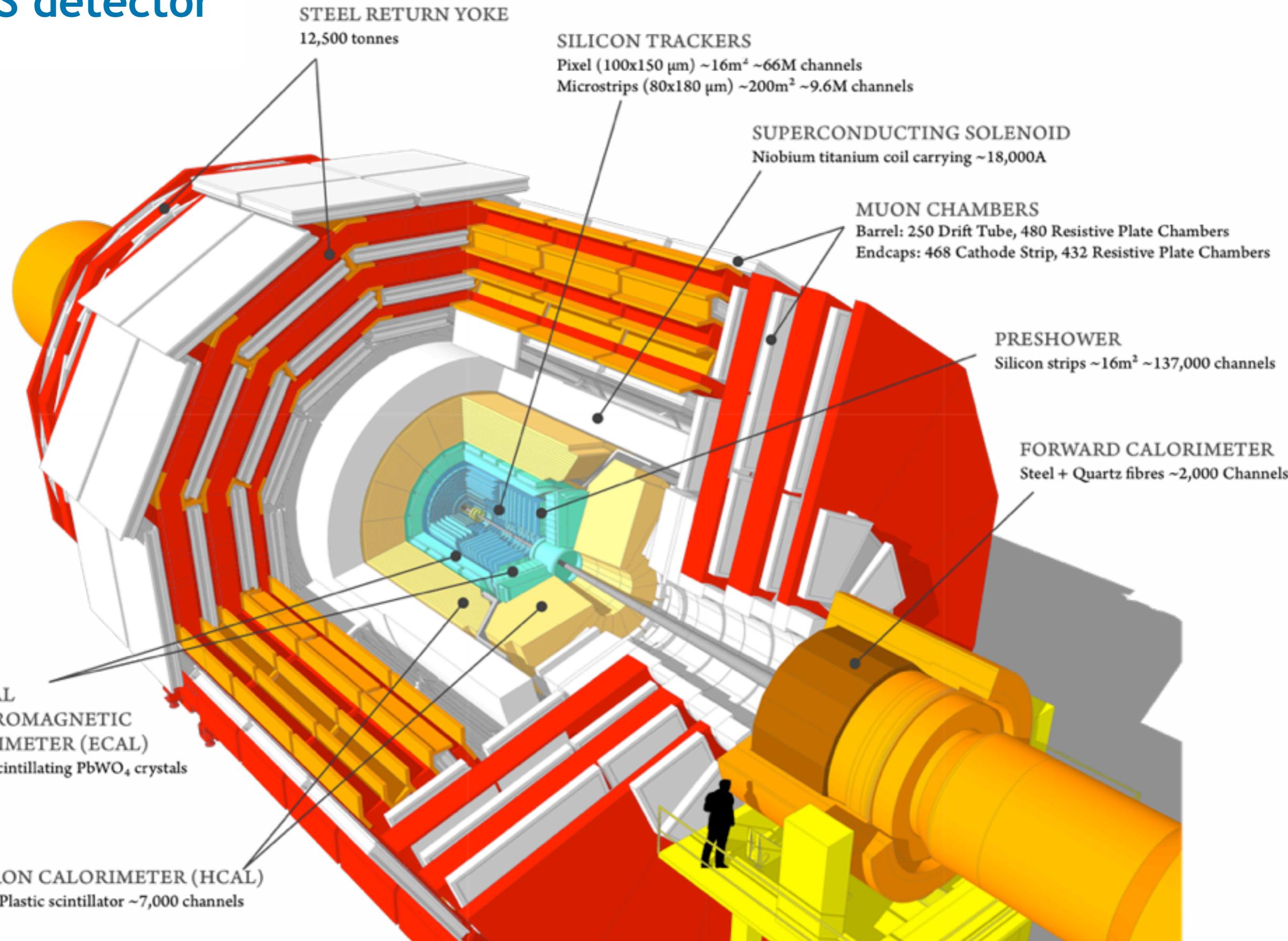
- Many possibilities for future analyses with 2012 and forthcoming datasets



**BACKUP**



# CMS detector



# $\Upsilon(nS)$ suppression

