Charmonium and Bottomonium production at the LHC with the CMS experiment

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On behalf of the CMS Collaboration

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Outline

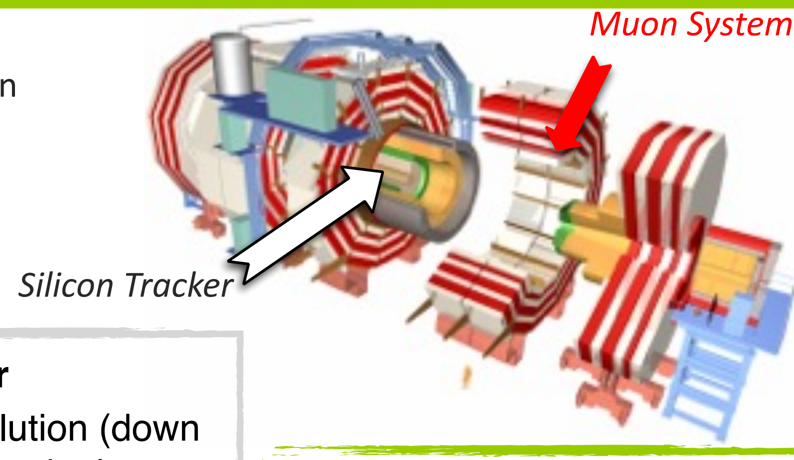
Recent quarkonium results at CMS:

- Quarkonium production cross sections at $\sqrt{s}$ = 13 TeV
- Double Quarkonium production
- Bottomonium production vs Charged Particles Multiplicity

New Preliminary Result!

The CMS Detector

- CMS is a general purpose detector optimized for **high-p_T** physics with a great potential in reconstructing charmonium in 2 muons final state.
- Collected **5.2 fb^{-1}** at 7 TeV, **20.1 fb^{-1}** at 8 TeV from 2010 to 2013, **2.7 fb^{-1}** 13 TeV in 2015, >**24 fb^{-1}** (ongoing) in 2016

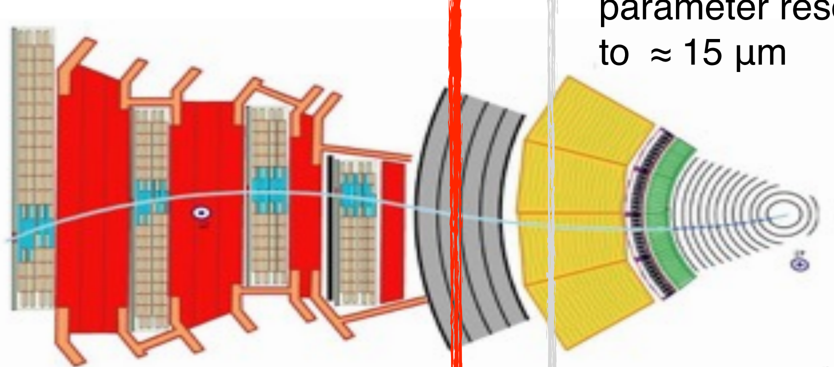


Silicon tracker

- Good p_T resolution (down to $\Delta p_T/p_T \simeq 1\%$ in the central region)
- Tracking efficiency >99% for muons
- Good vertex reconstruction and impact parameter resolution down to $\approx 15\ \mu m$

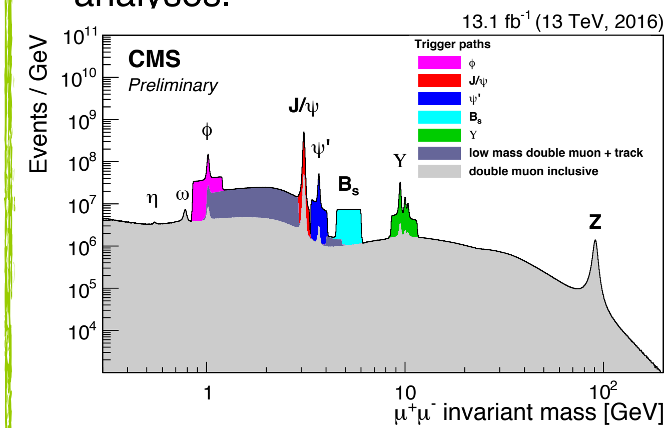
Muon System

- Redundant system with large rapidity coverage ($|\eta|<2.4$)
- Standalone $\Delta p_T/p_T \simeq 10\%$
- High-purity muon-ID: $\varepsilon(\mu \mid \pi,K,p) \leq (0.1\div0.2)\%$



Trigger

- Very efficient Hardware trigger
- Highly flexible High Level Trigger: paths dedicated to specific analyses.



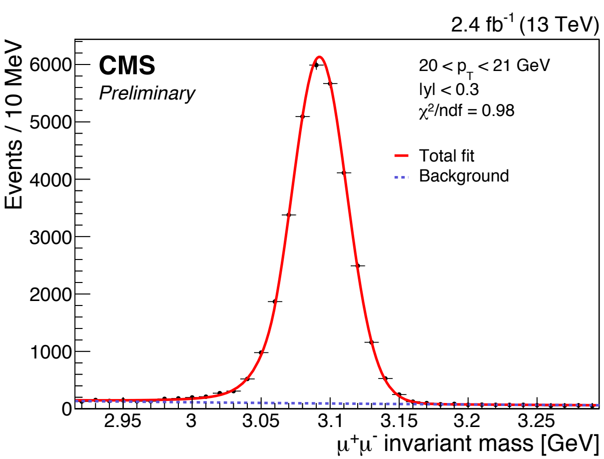
Quarkonium Cross Section at 13 TeV

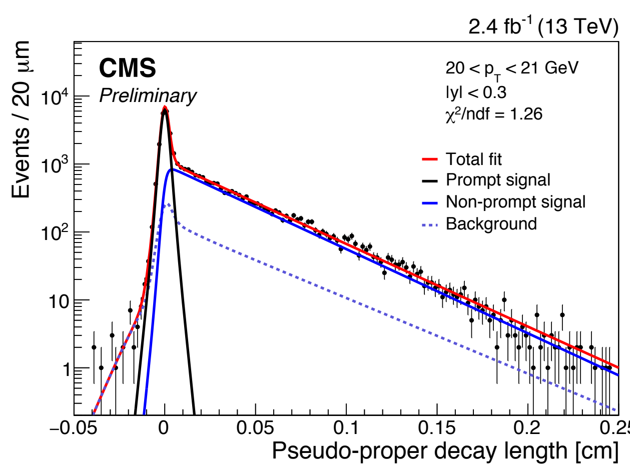
CMS-PAS-BPH-15-005

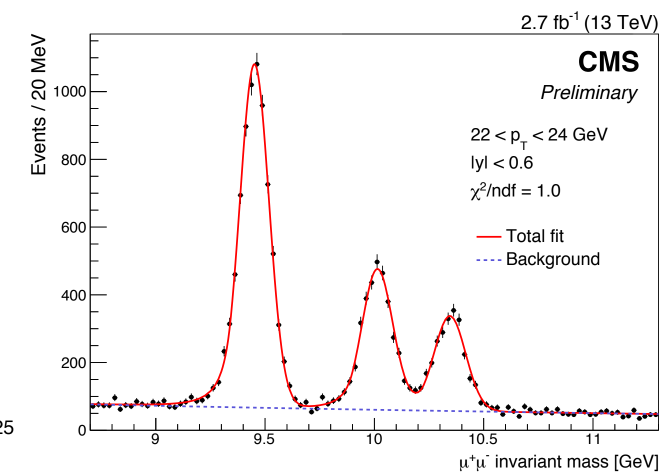
- Double differential cross section times branching ratio for quarkonium decaying in two muons:

$$BR(q\bar{q} \to \mu^+\mu^-) \times \frac{d^2\sigma^{q\bar{q}}}{dp_\mathrm{T}dy} = \frac{N^{q\bar{q}}(p_T, y)}{\mathcal{L}\Delta y \Delta p_\mathrm{T}} \cdot \langle \frac{1}{\epsilon(p_\mathrm{T}, y)\mathcal{A}(p_\mathrm{T}, y)} \rangle$$

  - Acceptance $\mathcal{A}$ calculated from simulations
  - Single muon and dimuon efficiency ε obtained from data
  - Signal yields N determined from unbinned maximum likelihood fits to dimuon mass and (in case of ψ(nS) states) pseudo-proper decay length distributions

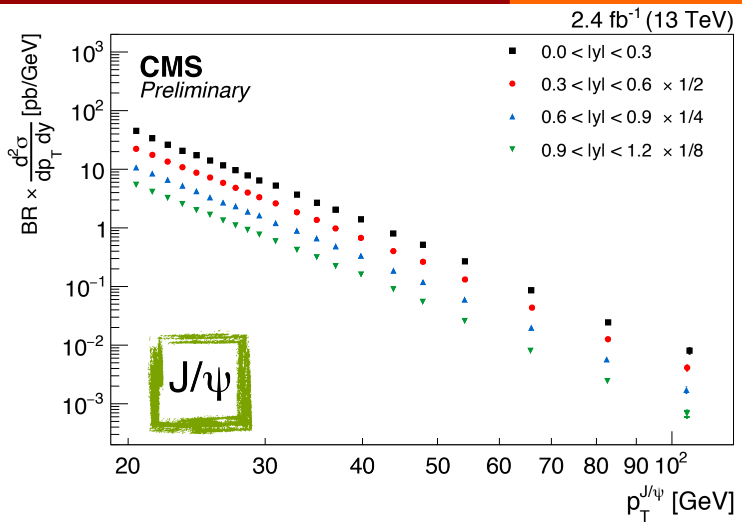


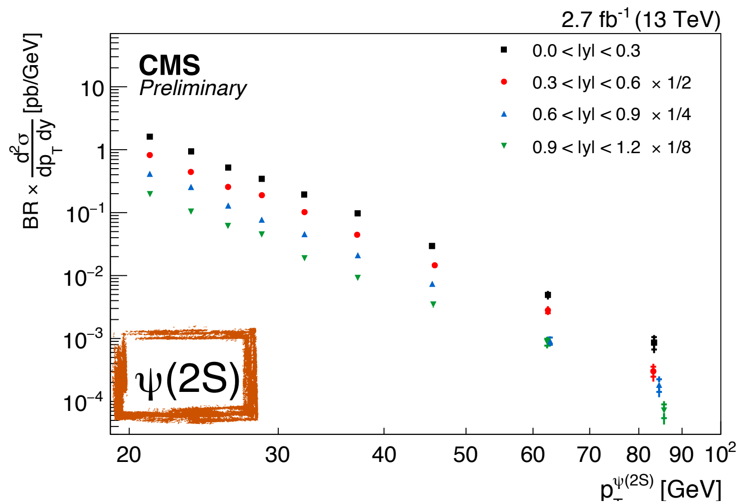


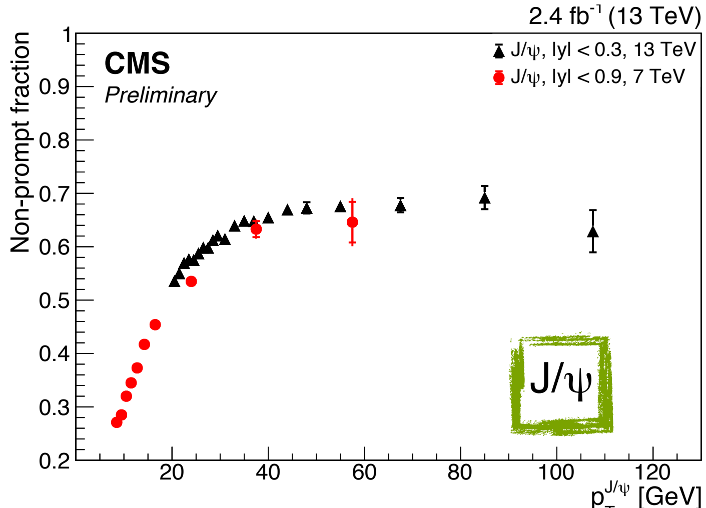


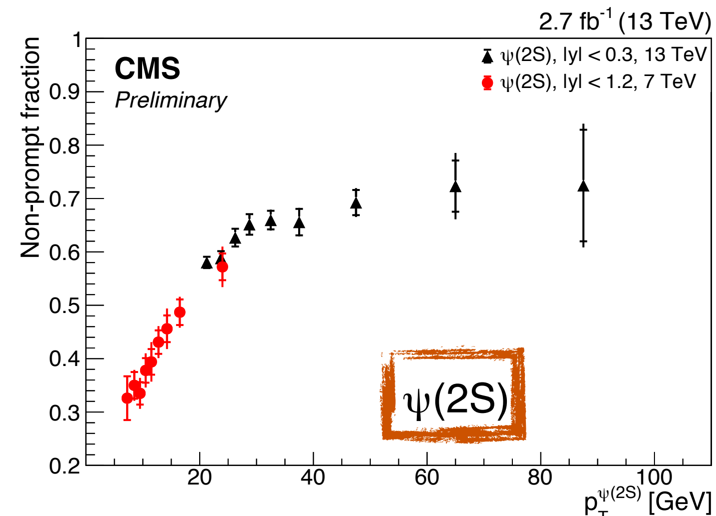
Charmonium prompt cross section

CMS-PAS-BPH-15-005





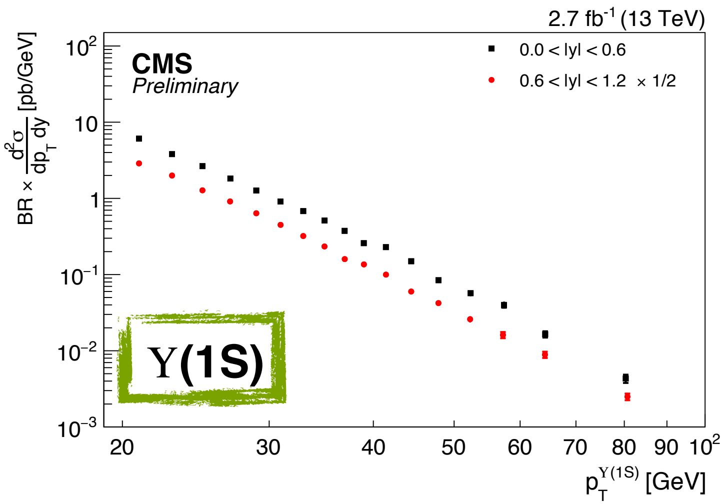


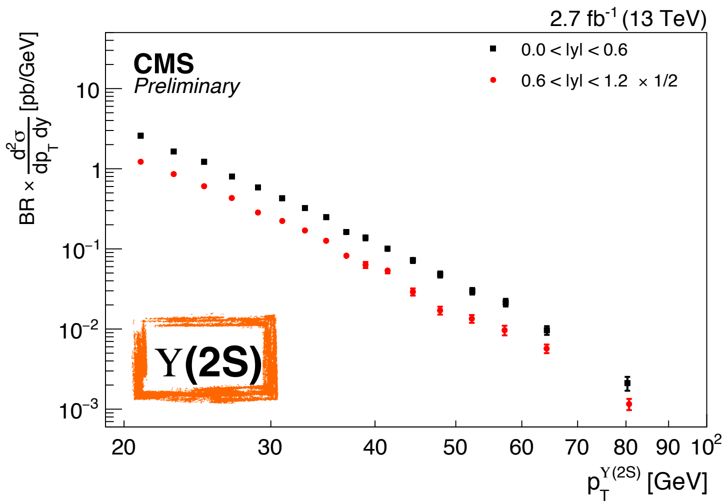


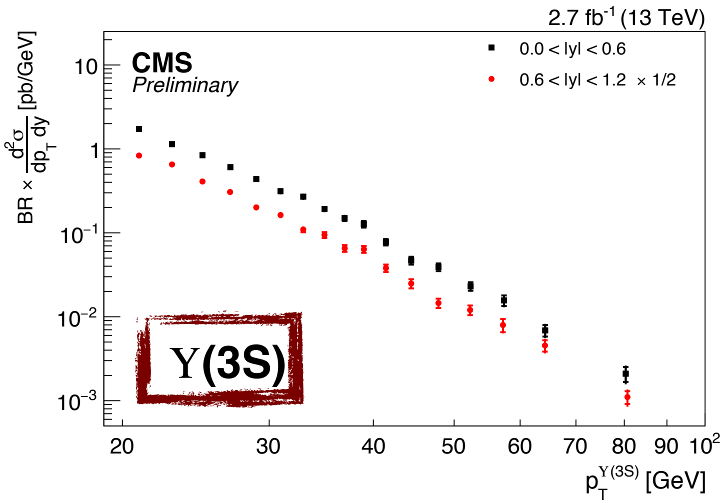
- Cross Section results given in bins of p_T in different rapidity ranges
- **High p_T reach**

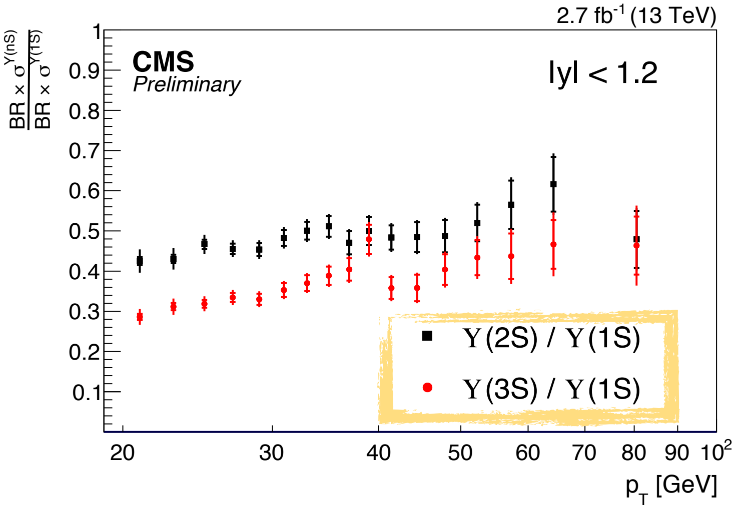
Bottomonium cross sections

CMS-PAS-BPH-15-005





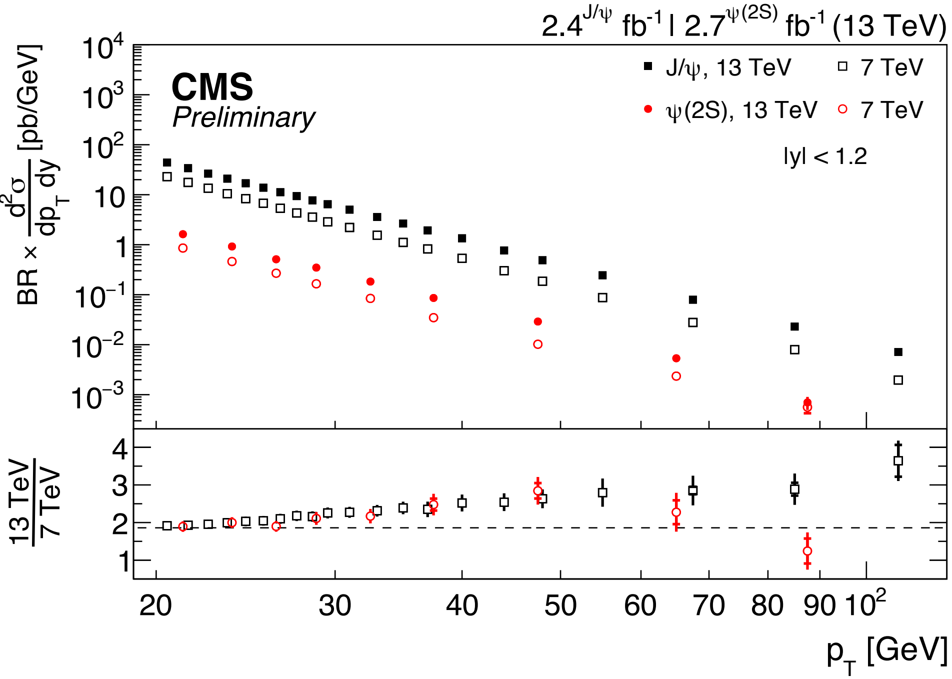


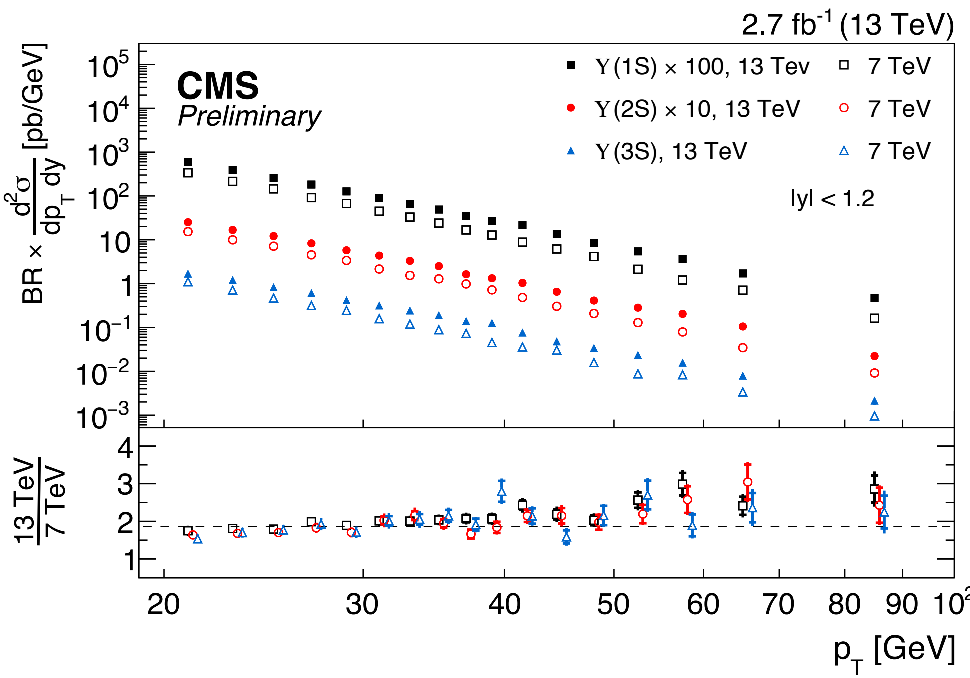


Comparison 13 TeV vs 7 TeV

CMS-PAS-BPH-15-005

- This comparison provides a good opportunity to test the factorization hypotheses of NRQCD.



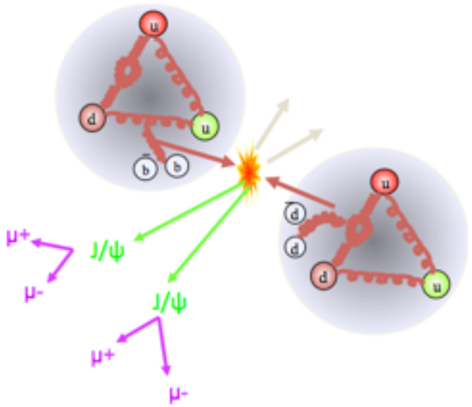


- All 13 TeV cross sections are factors of **2 to 3 larger than at 7 TeV**, changing slowly as a function of dimuon p_T.
- An increase of this order is expected from the evolution of parton distribution functions.
- A detailed comparison with theory **awaits an updated NRQCD** calculation for 13 TeV.

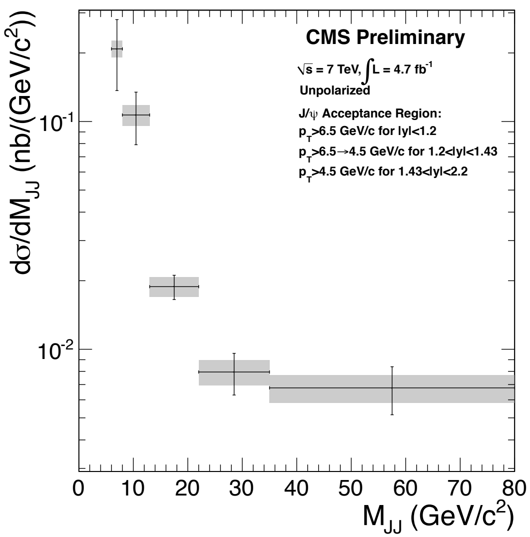
Quarkonium associated production

CMS-PAS-BPH-11-021

- Insight into particle production at LHC
  - **Single Parton Scattering** (SPS): Dominant →strongly correlated → small |Δy|
  - Double Parton Scattering (DPS):Difficult to calculate →less correlated → large |Δy|
- Color Singlet/Color Octect production of the J/ψ
- Search for ordinary or exotic resonances
- **First study in CMS was for J/ψ J/ψ production with 2011 data**

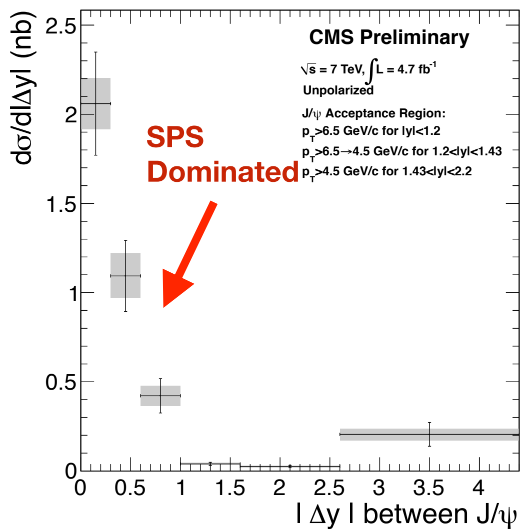


Differential vs total invariant mass



No evidence of resonant production

Differential vs rapidity difference



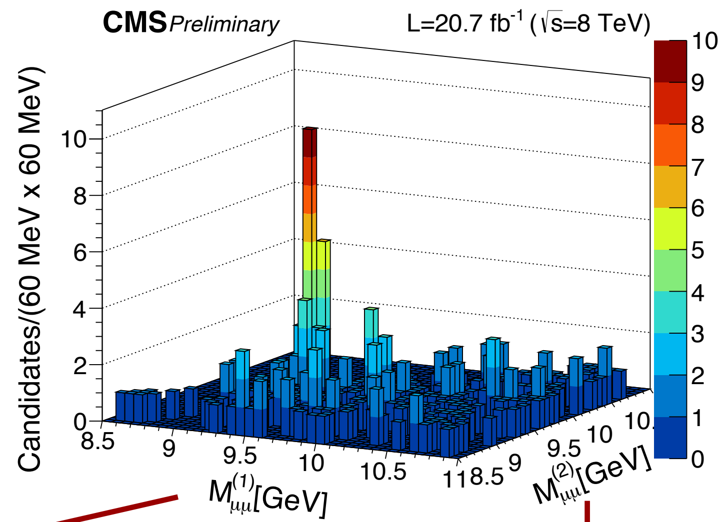
Excess found $|\Delta y| > 2.6$.

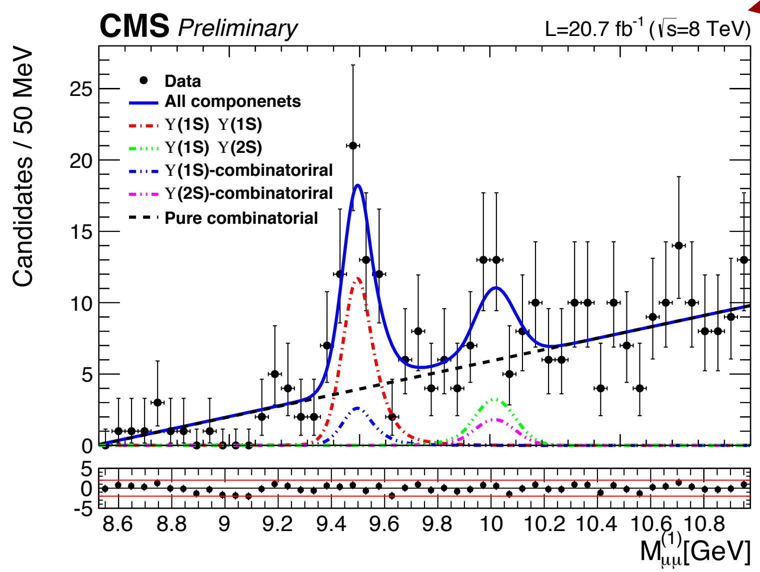
$$\sigma(pp \to J/\psi\, J/\psi + X) = 1.49 \pm 0.07 \pm 0.14 \text{ nb}$$

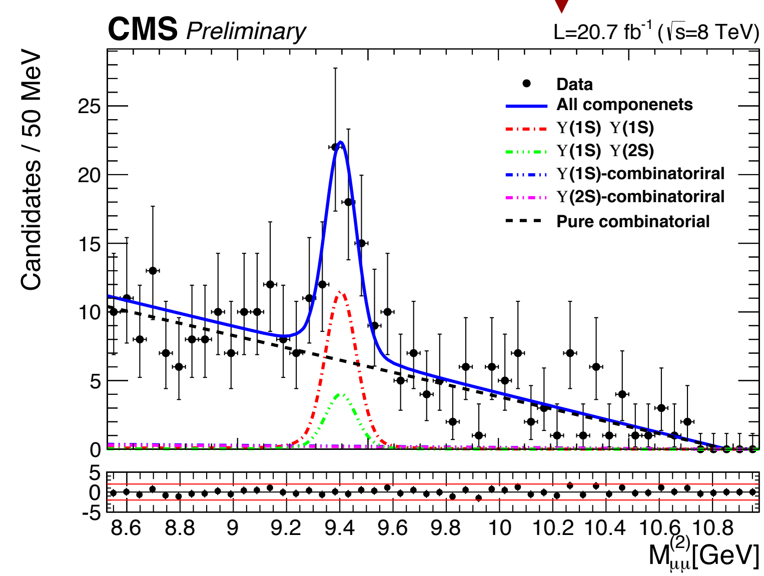
Y(1S) Pair Production

CMS PAS BPH-14-008

- New result for the Y(1S) pair production with 2012 Data
- Dataset taken at $\sqrt{s} = 8$ TeV corresponding to L = 20.7 fb^{-1}
- 38±7 Y(1S) pairs are observed for $p_T < 50$ GeV, |y| < 2







Υ(1S) Pair Production

CMS PAS BPH-14-008

- **First observation of Υ(1S) pair production with statistical significance well in excess of 5 σ**
- Systematics Uncertainties:

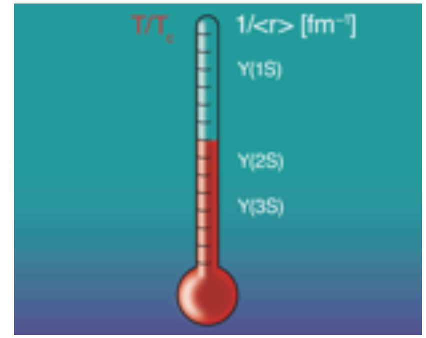
Component	Systematic Uncertainty
PDF Shape	7.9%
Simulation	4.9%
Efficiency	3.7%
Acceptance	2.8%
Integrated Luminosity	2.5%
Total Uncertainty	10.7%

- Total cross Section:

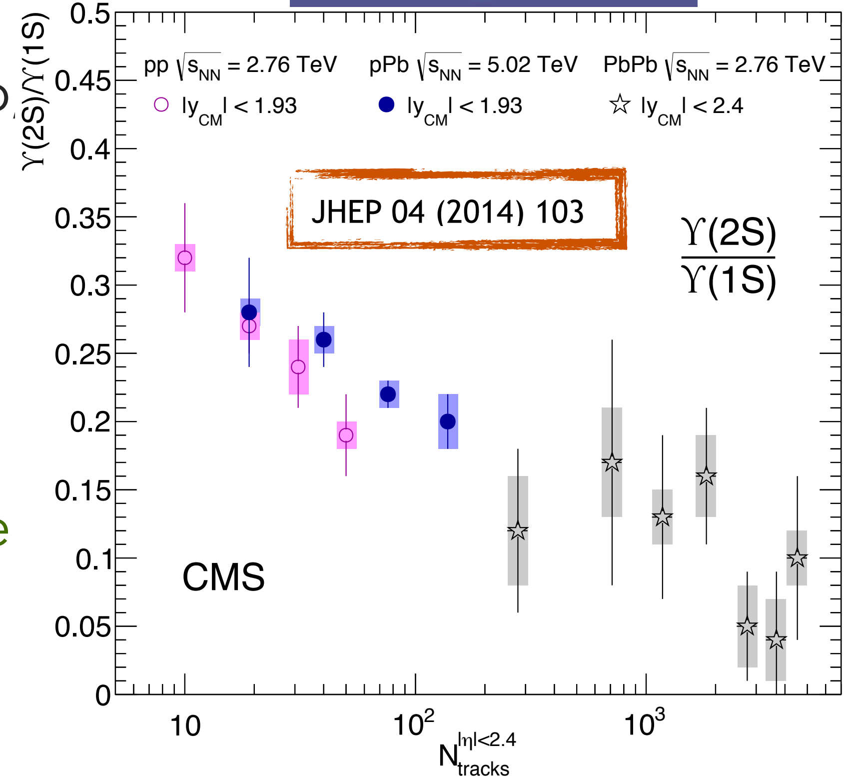
$$\sigma_T = 68.8 \pm 12.7(\text{stat.}) \pm 7.4\ (\text{syst.}) \pm 2.8\ (\text{BR})\ \text{pb}^{-1}$$

Y(nS) ratios vs Multiplicity

- Quarkonia production is extensively studied in Heavy Ions collision
  - **Suppression of exited states expected in QGP formation**
- CMS studied Y(nS) production in PbPb pPb collisions, finding evidence of suppression
  - **A small sample of pp collisions at 2.76 TeV was used as reference**
  - This sample also shows a decrease of the ratios at high multiplicities

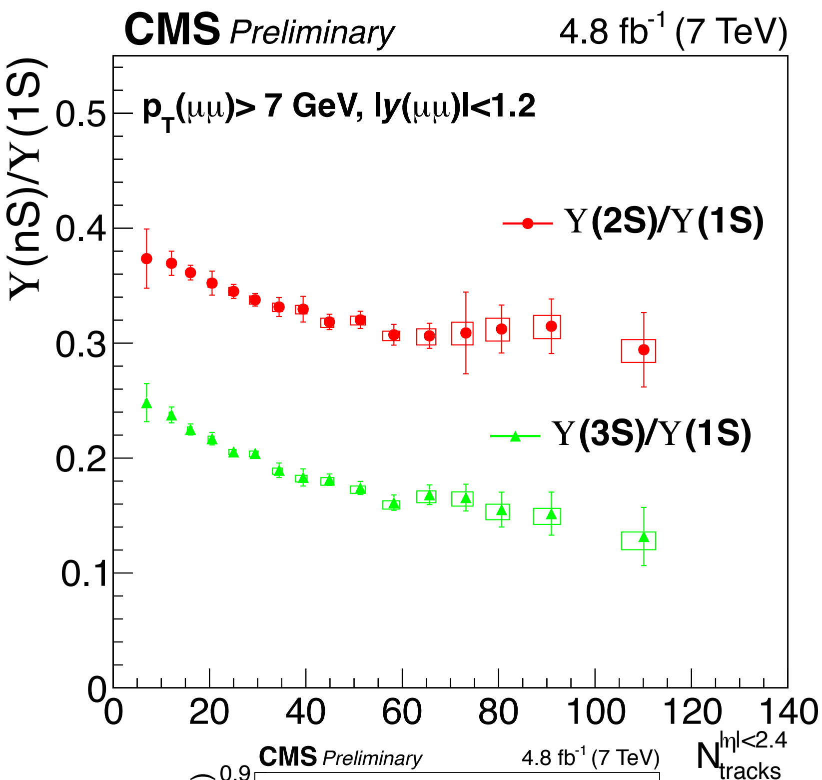


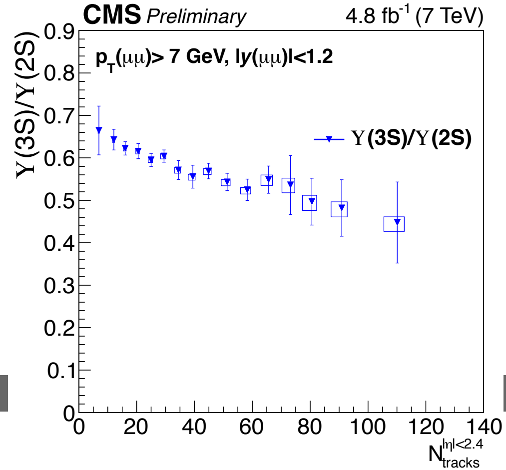
A. Mocsy, Eur. Phys. J. C 61, 705 (2009)



Υ(nS) ratio vs Multiplicity in pp collision at 7 TeV

- Used **2011 Dataset**, for 4.8 fb^{-1}
  - Mean PileUp ~7 collisions for Bunch Crossing
- **Υ(nS) kinematic region**
  - $|y| < 1.2$ and $p_T > 7$ GeV
  - Applied reconstruction efficiencies and **unpolarized** acceptance correction
- **Charged Track Selection**
  - $|y| < 2.4$ and $p_T > 0.4$ GeV
  - Applied reconstruction efficiencies correction
- **A decrease of the ratio is found up to 45% for Υ(3S)/Υ(1S)**
- Dominant source of systematics comes from the bin migration due merging of pileup vertices
  - Events at low multiplicity are moved to higher multiplicity bins

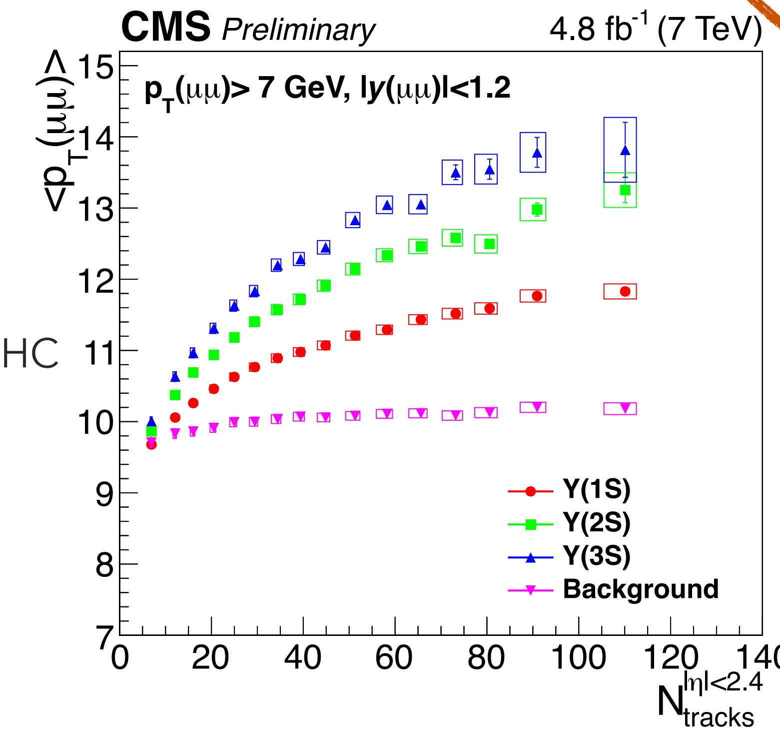


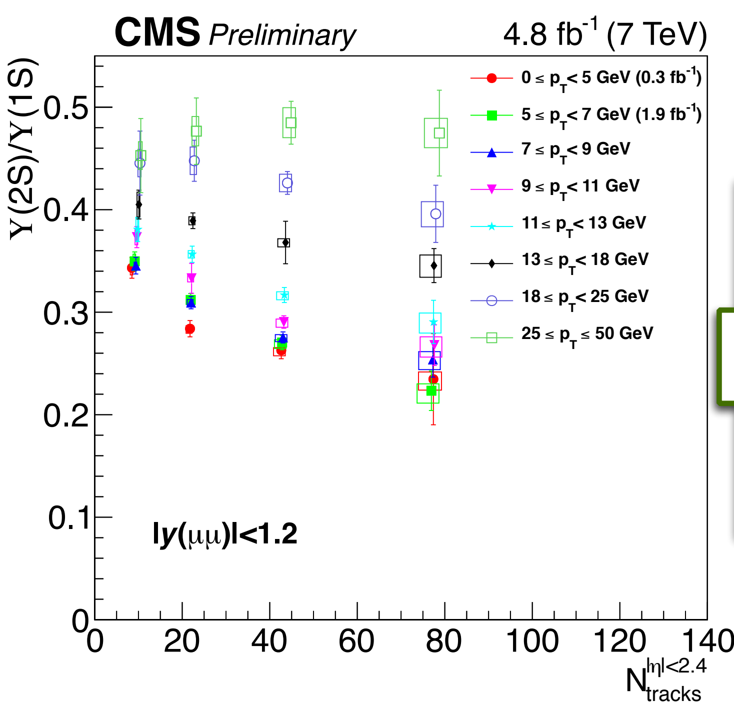


Multiplicity and p_T

CMS PAS BPH-14-009

- Mean p_T vs multiplicity for Y(nS) with **|y|< 1.2 and p_T>7 GeV**
- **It increases with multiplicity**
- The **increase is stronger for higher mass state**
  - **Hierarchical structure** as a function of mass observed also for pions, kaons and proton at LHC (doi:10.1140/epjc/s10052-012-2164-1)
- The sideband background remains flat.

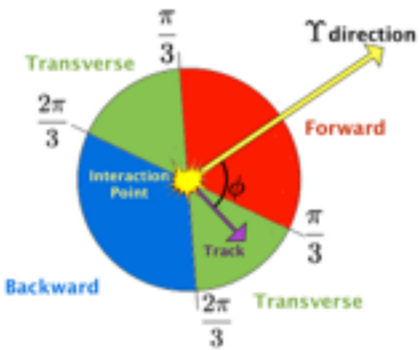


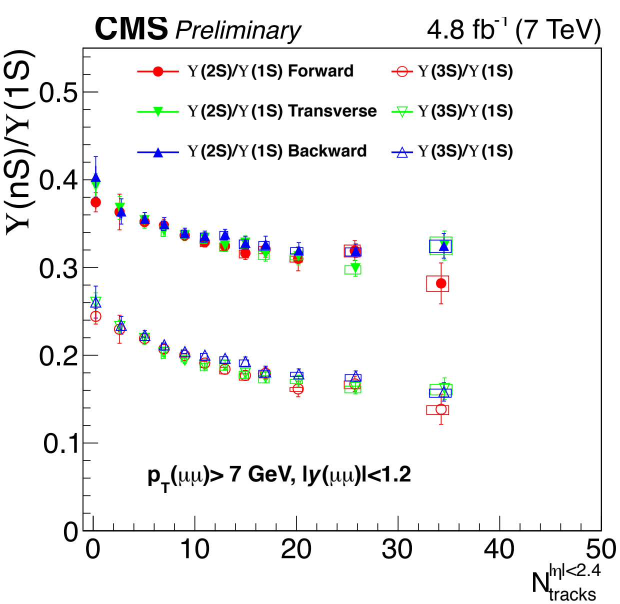


- Y(2S)/Y(1S) ratio vs multiplicity **in regions of p_T**
- Used early data at low luminosity for low-p_T bins
- **The ratio decrease stronger at lower p_T**
- **Flattening appears around ~20 GeV**

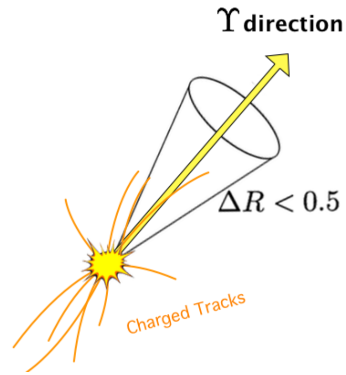
Υ(nS) ratio and Underlying event

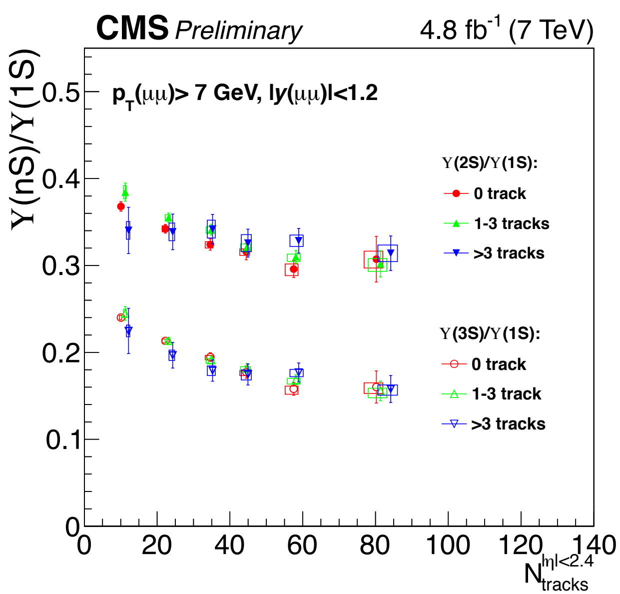
- Υ(nS) ratios vs charged particle in **different Φ regions w.r.t. the Υ(nS)**





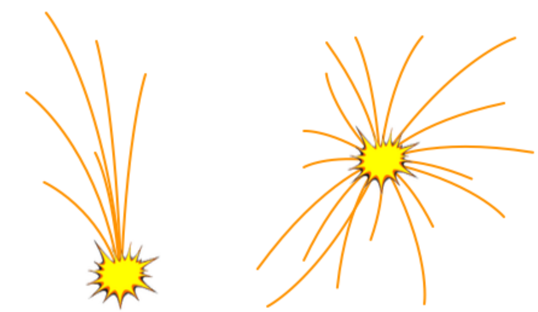
- Υ(nS) ratios for different number of **tracks along Υ(nS) direction**

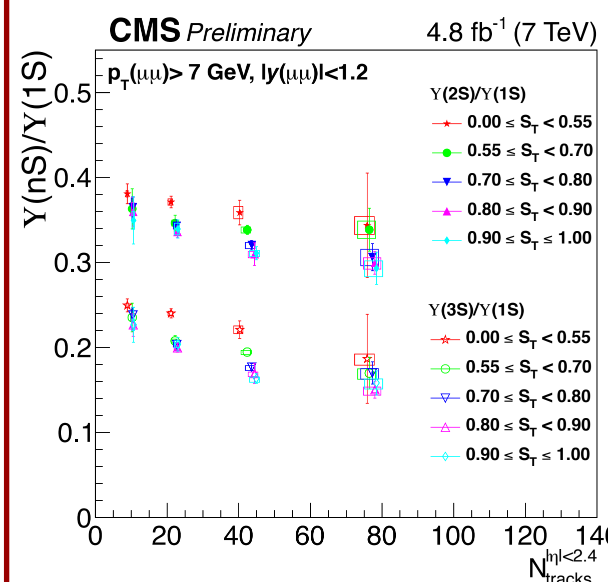




- Υ(nS) ratios for different **Underlying Event sphericity**

Sphericity→0 **Sphericity→1**





No correlations found with the observed decrease
Cause of the decrease appears linked to the Underlying Event

Y(nS) polarization vs N_{ch}

PLB 761 (2016) 31

Polarization is measured through the average angular decay distribution:

$$W(\cos\vartheta,\varphi|\vec{\lambda}) = \frac{3/(4\pi)}{(3+\lambda_\vartheta)}(1+\lambda_\vartheta\cos^2\vartheta+\lambda_\varphi\sin^2\vartheta\cos 2\varphi+\lambda_{\vartheta\varphi}\sin 2\vartheta\cos\varphi)$$

where λ_θ, λ_φ, $\lambda_{\theta\varphi}$ are the polarization parameters

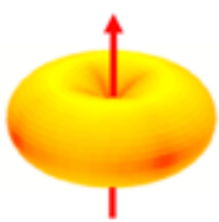
Extreme decay distributions:

Longitudinal polarization

$\lambda_\vartheta = -1$

$\lambda_\varphi = 0$

$\lambda_{\vartheta\varphi} = 0$



$\tilde{\lambda} = -1$

Transverse polarization

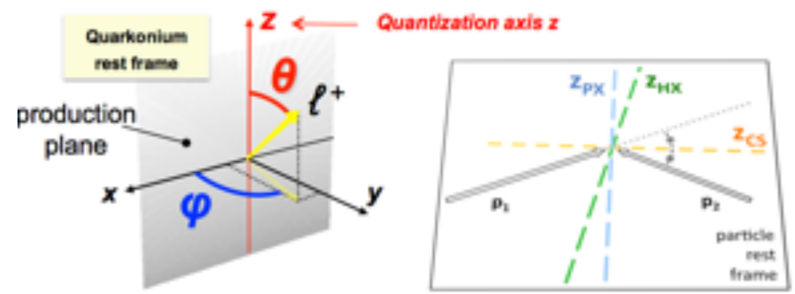
$\lambda_\vartheta = +1$

$\lambda_\varphi = 0$

$\lambda_{\vartheta\varphi} = 0$

$\tilde{\lambda} = +1$

Reference frames:



Helicity axis (HX): direction of quarkonium momentum

Collins-Soper axis (CS): direction of relative velocity of colliding particles (p_1, p_2)

Perpendicular helicity axis (PX): perpendicular to CS

$$\tilde{\lambda} = \frac{\lambda_\vartheta + 3\,\lambda_\varphi}{1-\lambda_\varphi}$$

The shape of the function is invariant and can be characterized in every frame by an invariant parameter.

Υ(nS) polarization vs N_{ch}

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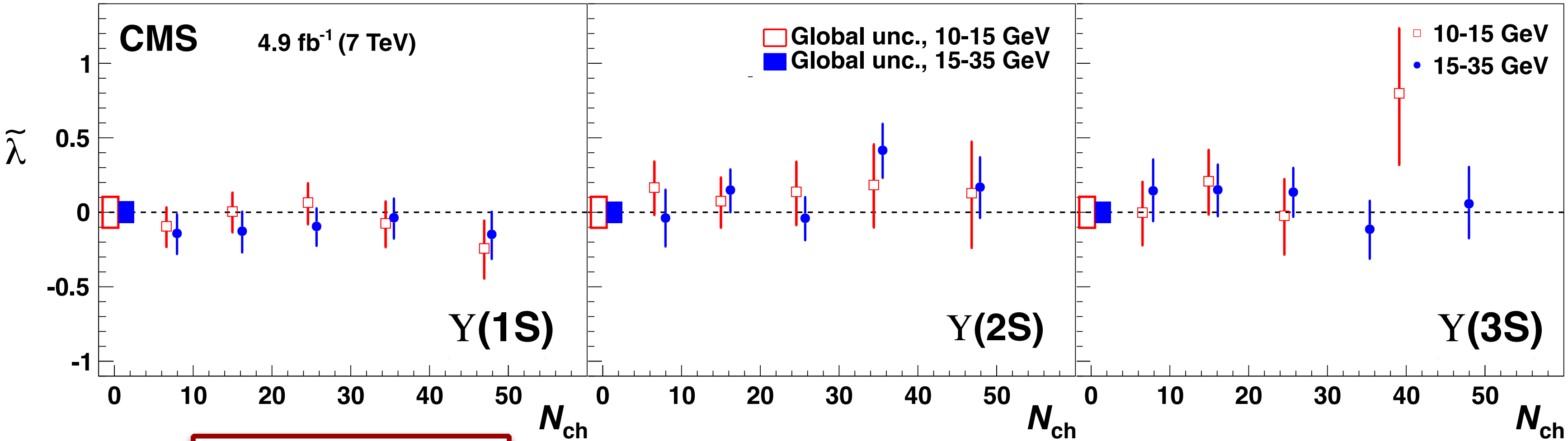

- **Υ(1S):**
  - λ parameters close to 0
  - Unpolarized production
  - Compatible with a dominant production through $^1S_0^{[8]}$ octet state
  - No dependence with N_{ch}

- **Υ(2S) and Υ(3S):**
  - Production compatible with non-negligible fraction of produced via the transversely polarized $^3S_1^{[8]}$ octet term.
  - Large uncertainties prevent us from giving a conclusive result on the N_{ch} dependence

Summary

- CMS has a wide program for studying quarkonium production
  - New LHC collision energy allow for new high precision results to be compared with theoretical predictions
  - Large statistic collected allows us to look for double production of quarkonia
    - Observation of Double J/ψ and Double Υ(1S) production
    - Input for DPS models
  - Large interest in production vs Multiplicity in pp collision
    - Reference for Heavy Ions results
    - **A significant decrease of the excited over ground state ratio for Bottomonium was observed in pp with 2011 CMS data.**
      - For this **new preliminary results** public documentation will be available soon.