Charmonium and Bottomonium production at the LHC with the CMS experiment

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On behalf of the CMS Collaboration
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, \(\geq 24\) fb\(^{-1}\) (ongoing) in 2016.

Muon System

- Redundant system with large rapidity coverage (\(|\eta|<2.4\))
- Standalone \(\Delta p_T/p_T = 10\%\)
- High-purity muon-ID: \(\varepsilon(\mu | \pi,K,p) \leq (0.1 \div 0.2)\%\)

Silicon tracker

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

Trigger

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

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**Event Distribution**

- CMS Preliminary
- Trigger paths: \(\phi, J/\psi, B_s, \gamma, \) low mass double muon + track double muon inclusive.
- \(13.1\) fb\(^{-1}\) (13 TeV, 2016)

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**Invariant Mass Spectrum**

- Dimuon + invariant mass spectrum for ICHEP2016.
Double differential cross section times branching ratio for quarkonium decaying in two muons:

$$BR(q\bar{q} \rightarrow \mu^+\mu^-) \times \frac{d^2\sigma_{q\bar{q}}}{dp_Tdy} = \frac{N_{q\bar{q}}(p_T,y)}{\mathcal{L}\Delta y\Delta p_T} \cdot \left\langle \frac{1}{\varepsilon(p_T,y)\mathcal{A}(p_T,y)} \right\rangle$$

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

Cross Section results given in bins of $p_T$ in different rapidity ranges

High $p_T$ reach
Bottomonium cross sections

**Y(1S)**

![Graph of Y(1S) cross section vs. PT](image)

**Y(2S)**

![Graph of Y(2S) cross section vs. PT](image)

**Y(3S)**

![Graph of Y(3S) cross section vs. PT](image)
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

- Insight into particle production at LHC
  - **Single Parton Scattering** (SPS): Dominant $\rightarrow$ strongly correlated $\rightarrow$ small $|\Delta y|$
  - **Double Parton Scattering** (DPS): Difficult to calculate $\rightarrow$ less correlated $\rightarrow$ large $|\Delta y|$

- Color Singlet/Color Octect production of the $J/\psi$

- Search for ordinary or exotic resonances

- **First study in CMS was for $J/\psi J/\psi$ production with 2011 data**

**Differential vs total invariant mass**

- No evidence of resonant production

**Differential vs rapidity difference**

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

\(\sigma(pp \rightarrow J/\psi J/\psi + X) = 1.49 \pm 0.07 \pm 0.14 \text{ nb}\)
New result for the $Y(1S)$ pair production with 2012 Data

Dataset taken at $\sqrt{s} = 8$ TeV corresponding to $L = 20.7$ fb$^{-1}$

$38\pm7$ $Y(1S)$ pairs are observed for $p_T < 50$ GeV, $|y| < 2$
First observation of $\Upsilon(1S)$ pair production with statistical significance well in excess of 5 $\sigma$

Systematics Uncertainties:

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<th>Component</th>
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<tr>
<td>Total Uncertainty</td>
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</table>

Total cross Section:

$$\sigma_T = 68.8 \pm 12.7\,\text{(stat.)} \pm 7.4\,\text{(syst.)} \pm 2.8\,\text{(BR)}\,\text{pb}^{-1}$$
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
Used 2011 Dataset, for 4.8 fb$^{-1}$

- Mean PileUp $\sim$7 collisions for Bunch Crossing

Y(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 Y(3S)/Y(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 $p_T$

- 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 $\sim 20$ GeV
Y(nS) ratio and Underlying event

Y(nS) ratios vs charged particle in different $\Phi$ regions w.r.t. the Y(nS)

Y(nS) ratios for different number of tracks along Y(nS) direction

Y(nS) ratios for different Underlying Event sphericity

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

CMS Preliminary 4.8 fb$^{-1}$ (7 TeV)
Polarization is measured through the average angular decay distribution:

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

where \( \lambda_\theta, \lambda_\varphi, \lambda_{\theta\varphi} \) are the polarization parameters.

The shape of the function is invariant and can be characterized in every frame by an invariant parameter.
Y(nS) polarization vs $N_{ch}$

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

**Y(2S) and Y(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

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CMS 4.9 fb$^{-1}$ (7 TeV)
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 $J/\psi$ and Double $Y(1S)$ 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.