Observation of double \( \eta \) at CMS

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Outline

- CMS detectors & triggers
- Motivation
- Observation of double upsilon
  - Double J/ψ differential cross section
  - Double Upsilon observation
- Summary
CMS Detector

Key:
- **Muon**
- **Electron**
- **Charged Hadron** (e.g. Pion)
- **Neutral Hadron** (e.g. Neutron)
- **Photon**

Transverse slice through CMS

- **Silicon Tracker**
- **Electromagnetic Calorimeter**
- **Hadron Calorimeter**
- **Superconducting Solenoid**

Iron return yoke interspersed with Muon chambers

Tracker
CMS Detector Performance

Excellent muon/silicon detectors for quarkonium:

- Muon system
  - High-purity muon identification
  - Good dimu mass resolution ($\Delta m/m \sim 0.6\%$ for $J/\psi$)

- Silicon Tracking detector, $B=3.8T$
  - excellent track momentum resolution ($\Delta p_T/p_T \sim 1\%$)
  - excellent vertex reconstruction and impact parameter resolution

LHC luminosity and CMS trigger:

- collect data at increasing instantaneous luminosity
- Triggers are essential ingredients
  - Special trigger for different analyses
    combination of muon $p_T$, dimu $p_T$, dimu mass
displaced dimuon vertex, and dimu+additional muon
Discovery of X(3872) in 2003 revitalized the interest in exotic meson searches (PRL 91, 262001)

More than 20 new candidates have been observed since then, including penta-quark candidates.

CMS is a good place for this topic, and has made contributions to this topic, such as X(3872) production cross section measurement, confirmation of X(4140)

There are predictions of possible exotic meson candidates composed of all heavy quarks

**Motivation**


Phys.Rev. D19 (1979) 764-778

Table 1(a). The quantum numbers and masses for the (cc)^* - (QQ)^* states (without spin-dependent forces between two clusters)

<table>
<thead>
<tr>
<th>L</th>
<th>S</th>
<th>JPC</th>
<th>Mass (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0^-</td>
<td>6.55</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>0^-, 1^-, 2^-</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0^-, 1^-, 2^-, 3^-</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>0^-, 1^-, 2^-, 3^-, 4^-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>3^-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>2^-, 3^-, 4^-</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>1^-, 2^-, 3^-</td>
<td></td>
</tr>
</tbody>
</table>

5
Heavy tetra-quark bound states

- Heavy-quark tetra-quark states

--- No solid prediction for heavy quarks, but a few simple models, i.e.

\[c\bar{c}c\bar{c}\]

\begin{align*}
0^{++} & : M = 5.966 \text{ GeV}, \quad M - M_{th} = -228. \text{ MeV}, \\
1^{+-} & : M = 6.051 \text{ GeV}, \quad M - M_{th} = -142. \text{ MeV}, \\
2^{++} & : M = 6.223 \text{ GeV}, \quad M - M_{th} = 29.5 \text{ MeV}.
\end{align*}

Above double \(\eta_c\) threshold
Below double \(J/\psi\) threshold
Search via \(\eta_c\eta_c^?, J/\psi\mu^+\mu^-, J/\psi^*\)

\[b\bar{c}b\bar{c}\]

\begin{align*}
0^{++} & : M = 12.359 \text{ GeV}, \quad M - M_{th} = -191. \text{ MeV}, \\
0^{++} & : M = 12.471 \text{ GeV}, \quad M - M_{th} = -78.7 \text{ MeV}, \\
1^{+-} & : M = 12.424 \text{ GeV}, \quad M - M_{th} = -126. \text{ MeV}, \\
1^{++} & : M = 12.488 \text{ GeV}, \quad M - M_{th} = -62.5 \text{ MeV}, \\
1^{++} & : M = 12.485 \text{ GeV}, \quad M - M_{th} = -64.9 \text{ MeV}, \\
2^{++} & : M = 12.566 \text{ GeV}, \quad M - M_{th} = 16.1 \text{ MeV}.
\end{align*}

Below double \(B_c\) threshold
\(J/\psi\Upsilon(1S)\) threshold

\[b\bar{b}b\bar{b}\]

\begin{align*}
0^{++} & : M = 18.754 \text{ GeV}, \quad M - M_{th} = -544. \text{ MeV}, \\
1^{+-} & : M = 18.808 \text{ GeV}, \quad M - M_{th} = -490. \text{ MeV}, \\
2^{++} & : M = 18.916 \text{ GeV}, \quad M - M_{th} = -382. \text{ MeV}.
\end{align*}

Above double \(B_c\) threshold
\(J/\psi\Upsilon(1S)\) threshold
Search via \(\Upsilon(1S)\mu^+\mu^-\)

Below double \(\Upsilon(1S)\) threshold
Search via \(\Upsilon(1S)\mu^+\mu^-\)

Will be a breakthrough for exotic meson if established
Arguable to call below \(J/\psi\) mass events as \(J/\psi^*\) since \(J/\psi\) is very narrow, same for \(\Upsilon^*\)
Motivation

- The production of $J/\psi J/\psi$, $YJ/\psi$, $YY$ are the benchmark measurements to evaluate the sensitivity of possible tetra-quark states composed of all heavy quarks at LHC.

- On the other hand, the measurement of quarkonium and double quarkonium provide insight to the production mechanism.
  - Single Parton Scattering (SPS)
  - Double Parton Scattering (DPS)

- DPS production is expected to be significant at LHC.

- Only SPS is relevant to the production of exotic mesons, DPS contributes as background events.
**Double $J/\psi$ cross section**

\[ \sigma_{\text{tot}} = 1.49 \pm 0.07(\text{stat}) \pm 0.13(\text{syst}) \text{ nb, prompt component} \]

We have observed double $J/\psi$ events and measured its production cross section dominated by SPS, hint of DPS.

How about an upsilon pair?
Observation of $Y(1S)Y(1S)$

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Motivation:
--Investigate the production mechanism: SPS vs DPS
--Benchmark measurement for 4b bound state searches

Main selections:
--muon $p_T > 3.5$ GeV, pseudorapidity within 2.4
--Upsilon pseudorapidity within 2.0
--four-muons come from the same vertex: vertex-probability $> 5\%$
Two-dimensional scatter plot

Two-dimensional scatter plot of selected events, Striking peaks at 9.5 GeV from both dimensions.
**Main selections:** Yield extraction from maximizing 2D likelihood PDF
--signal is modeled by two Crystal-ball functions
--background is modeled as 1st order polynomial

Number of $Y(1S)Y(1S)$: $38 \pm 7$

Significance: $>>5\sigma$

Also see a hint of $(Y(1S)Y(2S))$

First time observation in the world
**Y(1S)Y(1S) Cross section @ 8 TeV**

Assuming unpolarized production of $Y(1S)$ meson, the cross section of $Y(1S)Y(1S)$ with pseudorapidity within 2.0 for each $Y(1S)$, and $p_T$ less than 50 GeV at 8 TeV is measured as:

$$\sigma(pp \to YY) = 68.8 \pm 12.7\,(\text{stat}) \pm 7.4\,(\text{syst}) \pm 2.8\,(\text{BR})\,pb$$

Different assumptions of $Y(1S)$ polarization gives the total cross section uncertainty between -38% and 36%.

No enough statistics to separate SPS and DPS fractions.

The effective cross section can be calculated by:

$$\sigma_{\text{eff}} = \frac{[\sigma(Y)]^2}{2 f_{\text{DPS}} \sigma_{\text{fid}} [\mathcal{B}(Y(1S) \to \mu^+\mu^-)]^2}$$

The effective cross section is between 6.6 and 1.32 mb assuming 10%-50% $f_{\text{DPS}}$. 
Comparison with other channels

- effective cross section from various channels at different experiments
- relatively small for quarkonium pair
- provide insight information for DPS

CMS Y+Y @8TeV
**Y(1S)Y(1S) SPS Cross section @ 8 TeV**

Assuming $f_{DPS}$ to be 10%-50%, the SPS cross section @8 TeV in CMS can be as large as [34,62] pb

CMS will be sensitive if tetra-quark state cross section is close to pb level @CMS.

LHCb limit


No upsilon pair cross section reported from LHCb yet
Summary

• CMS observed the upsilon pair production for the first time

• The fiducial cross section is measured as:
  \[ \sigma(pp \rightarrow YY) = 68.8 \pm 12.7\,\text{(stat)} \pm 7.4\,\text{(syst)} \pm 2.8\,(BR)\,pb \]

• provide insight to upsilon pair production mechanism

• The SPS cross section can be as large as 34-62 pb

Stay tuned!