Exotic quarkonium states in CMS

Leonardo Cristella (on behalf of the Collaboration)

UNIVERSITA’ DEGLI STUDI DI BARI “ALDO MORO” & I.N.F.N. SEZIONE DI BARI

25 – 29 January, 2016 / 54th International Winter Meeting on Nuclear Physics
**Compact Di-Muon Solenoid – $\mu$ reconstruction & triggers**

**Tracking system**
- Good $p_T$ resolution (down to $\Delta p_T/p_T \approx 1\%$ in barrel)
- Tracking efficiency $>99\%$ for central muons
- Good vertex reconstruction & impact parameter resolution down to $\approx 15\mu m$

**Muon system**
- Muon candidates by matching muon segments and a silicon track in a large rapidity coverage ($|\eta| < 2.4$)
- Good dimuon mass resolution (depending on $|y|$): $\Delta M/M \approx 0.6 \div 1.5\%$ (\(\rightarrow J/\psi : \approx (20 \div 70)MeV\))
- Excellent (high-purity) muon-ID: $\varepsilon(\mu | \pi, K, p) \leq (0.1 \div 0.2)\%$ [fake rates estimated in MC and data]
Compact Di-Muon Solenoid – \( \mu \) reconstruction & triggers

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**Trigger system**
- fast HW (Muon Detector based) triggers (L1)
  SW triggers with full tracking & vtx recon. (HLT)
- rare decays/quarkonia almost 100% BKG/Signal paths
- \( \sim 10\% \) of CMS bandwidth (\( \sim 10kHz \) @L1) to flavor physics
  Data Parking in 2012: clear benefits having \( \sim 120Hz \) on top of the 25-30Hz on prompt stream (@HLT)

**Data samples:**
- \( \sqrt{s} = 7 \text{ TeV}, \mathcal{L} = 5 \text{ fb}^{-1} \) (2011 run)
- \( \sqrt{s} = 8 \text{ TeV}, \mathcal{L} = 20 \text{ fb}^{-1} \) (2012 run)
The following “exotic” quarkonium-like states will be reviewed:

- $X(3872)$
- $Y(4140)$
$X(3872)$
The $X(3872)$ - I

- First exotic states discovered by Belle in 2003 in the decay $B \rightarrow K X(3872) \rightarrow K (J/\psi \pi^+ \pi^-)$:

- Quickly confirmed by CDF and D0 with inclusive $p\bar{p}$ collisions:

  - $p\bar{p} \rightarrow X(3872) + \text{anything}$
  - $p\bar{p} \rightarrow \psi(2S) + \text{anything}$

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Main hypothesis are:

- **Loosely bound molecular state**: suggested by proximity to \( D\bar{D}^{0*} \) threshold \( (J^{PC} = 0^{-+}, 1^{++}) \)

  The size of the \( X(3872) \) as a \( DD^* \) molecule is determined by its scattering length which in turn depends, by quantum mechanical considerations, upon the binding energy:

  \( X(3872) \) would be a large and fragile molecule with a miniscule binding energy

- **Tetraquark \( (J^{PC} = 1^{++}) \)**

  Conventional charmonium: assignments would be \( \chi_{c1}(2^3P_1) \) or \( \eta_{c2}(1^1D_2) \) and quantum numbers would be respectively \( J^{PC} = 1^{++} \) or \( 2^+ \)

  \( c\bar{c} \rightarrow \rho J/\psi \sim \) ruled out by the fact that should be a pure isoscalar state; \( X(3872) \) shows an equal amount of isospin components (\( I=0 \) & \( I=1 \)):

  \[
  \frac{BF(X \rightarrow J/\psi \pi^+\pi^-\pi^0)}{BF(X \rightarrow J/\psi \pi^+\pi^-)} = 0.8 \pm 0.3
  \]
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  $BF(X \rightarrow J/\psi \pi^+\pi^-\pi^0) / BF(X \rightarrow J/\psi \pi^+\pi^-) = 0.8 \pm 0.3$

- **LHCb made a sophisticated angular analysis** [PRL 110 (‘13) 222001 & PRL 92 (‘15) 011102] of the whole decay chain $B^+ \rightarrow K^+ X(3872) \rightarrow K^+ (J/\psi \pi^+\pi^-)$ dropping the assumption of lowest possible orbital angular momentum in the $X(3872)$ sub-decay and unambiguously determine the quantum numbers to be $J^{PC} = 1^{++}$ under more general conditions. No hints for a large size of $X(3872)$.

- Pure molecular model is not supported by recent LHCb measurement [NPB 886 (2014) 665] of the radiative decay

Bormio 2016

Leonardo Cristella
CMS can easily reconstruct the $X(3872)$ in the decay channel $J/\psi(\rightarrow \mu \mu)\pi^+\pi^-$

With $4.8 fb^{-1}$ of data at 7 TeV reconstructed about 12,000 $X(3872)$ signal events

CMS studied:
- Cross section ratio w.r.t. $\psi(2S)$
- Non-prompt component vs $p_T$
- Prompt $X(3872)$ cross section
- Invariant mass distribution of the $\pi^+\pi^-$ system
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The $\pi^+\pi^-$ invariant mass distribution from $X(3872)$ decays to $J/\psi\pi^+\pi^-$ is measured in order to investigate the decay properties of the $X(3872)$

- Studies at CDF and Belle suggest that $X(3872)$ decays in $J/\psi$ and $\rho^0$

- The spectrum obtained from data is compared to simulations with and without an intermediate $\rho^0$ in the $J/\psi\pi^+\pi^-$ decay: the assumption of intermediate $\rho^0$ decay gives better agreement with data.
A ratio of the cross sections have been measured to cancel out many systematic sources:

\[
R \equiv \frac{\sigma(pp \rightarrow X(3872) + \text{anything}) \cdot B(X(3872) \rightarrow J/\psi \pi^+\pi^-)}{\sigma(pp \rightarrow \psi(2S) + \text{anything}) \cdot B(\psi(2S) \rightarrow J/\psi \pi^+\pi^-)} = \frac{N_{X(3872)} \cdot A_{\psi(2S)} \cdot \varepsilon_{\psi(2S)}}{N_{\psi(2S)} \cdot A_{X(3872)} \cdot \varepsilon_{X(3872)}}
\]

For 10 < \(p_T\) < 50 GeV & |y| < 1.2:

\[
R = 0.0656 \pm 0.0029 \text{ (stat.)} \pm 0.0065 \text{ (syst.)}
\]

The ratio shows no significant dependence on the \(p_T\) of the \(J/\psi\pi^+\pi^-\) system.
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The ratio shows no significant dependence on the \(p_T\) of the \(J/\psi \pi^+\pi^-\) system.

The \(X(3872)\) can be produced from decays of B hadrons in a secondary vertex related to the decay length \(l_{xy}\) of the B meson.

Events with \(X(3872)\) from B decays are selected by requiring \(l_{xy} > 100\mu m\):

\[
\text{non-prompt fraction} = \frac{\# \text{ of } X(3872) \text{ from } B}{\# \text{ of } X(3872)}
\]

The fraction of \(X(3872)\) produced from decay of \(B\) does not show a dependence on \(p_T(J/\psi \pi^+\pi^-)\).

For 10 < \(p_T\) < 50GeV & |y| < 1.2:
\[
X(3872) \text{ non prompt fraction} = 0.263 \pm 0.023 \text{ (stat.)} \pm 0.016 \text{ (syst.)}
\]
Putting together the previous measurements, the production of $X(3872)$ state is measured for the first time as a function of transverse momentum as:

$$\frac{\sigma_{\text{prompt}}^{\text{X(3872)}} \cdot \mathcal{B}(X(3872) \rightarrow J/\psi \pi^+ \pi^-)}{1 - f_{X(3872)}^B} = \frac{1}{R^1} \left( \frac{\sigma_{\psi(2S)}^{\text{prompt}} \cdot \mathcal{B}(\psi(2S) \rightarrow \mu^+ \mu^-)}{\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} \right) \cdot \frac{\mathcal{B}(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)}{\mathcal{B}(\psi(2S) \rightarrow \mu^+ \mu^-)}$$

- **Non-prompt fraction**
- **Cross sections ratio**
- **Measured by CMS in JHEP02 (2012) 011**
- **From PDG**
Putting together the previous measurements, the production of $X(3872)$ state is measured for the first time as a function of transverse momentum as:

$$\alpha_{X(3872)}^{\text{prompt}} \cdot B(X(3872) \to J/\psi \pi^+ \pi^-) \cdot \frac{1 + f_X^{\text{prompt}}}{1 + f_X^{\text{non-prompt}}} \cdot R \cdot \left( \frac{\sigma_{\psi(2S)}^{\text{prompt}} \cdot B(\psi(2S) \to \mu^+ \mu^-)}{\sigma_{\psi(2S)}^{\text{non-prompt}} \cdot B(\psi(2S) \to \mu^+ \mu^-)} \right)$$

Main systematic uncertainties are related to the measurements of $R$ and prompt $\psi(2S)$ cross section.

$X(3872)$ and $\psi(2S)$ are assumed to be unpolarized.

Results are compared with a theoretical prediction based on NRQCD factorization approach by Artoisenet & Brateen [PhysRevD.81.114018] with calculations normalized using Tevatron results, modified by the authors to match the phase-space of the CMS measurement.

The shape is reasonably well described by the theory while the predicted cross section is overestimated by over $3\sigma$.
Putting together the previous measurements, the production of $X(3872)$ state is measured for the first time as a function of transverse momentum as:

$$\sigma_{X(3872)}^{\text{prompt}} \cdot \mathcal{B}(X(3872) \to J/\psi \pi^+ \pi^-) = \frac{1 - f_X^{\text{B}}(3872)}{1 - f_{\psi(2S)}^{\text{B}}} \left( R \cdot \frac{\sigma_{\psi(2S)}^{\text{prompt}} \cdot \mathcal{B}(\psi(2S) \to \mu^+ \mu^-)}{\mathcal{B}(\psi(2S) \to J/\psi \pi^+ \pi^-)} \right)$$

where $R$ is the ratio of prompt to non-prompt production cross sections.

Main systematic uncertainties are related to the measurements of $R$ and prompt $\psi(2S)$ cross section. $X(3872)$ and $\psi(2S)$ are assumed to be unpolarized.

Predictions by Artoisenet & Brateen assume, within an S-wave molecular model, the relative momentum of the mesons being bound by an upper limit of 400 MeV which is quite high for a loosely bound molecule, but they assume it is possible as a result of rescattering effects.

On the other hand, an upper limit lower of one order of magnitude would imply lower prompt production rates of few orders of magnitude [Bignamini et al., PRL 2009, 103(16)]
Run-II data taking started last year at $\sqrt{s} = 13\text{TeV}$ with the first bunch of data recorded in July.

The plot shows the invariant mass of $J/\psi \pi^+\pi^-$ where is visible the $X(3872)$ signal beyond the $\psi(2S)$ one:
Search for $X_b$ [beauty partner of the $X(3872)$]

HQ symmetry suggests an $X_b$ analogous of $X_c$. Molecular model suggests to search it close to $B\bar{B}$ threshold (Swanson, 2004).

CMS looked for $X_b \rightarrow \Upsilon(1S)\pi^+\pi^-$ decay seemingly analogous to $X(3872) \rightarrow J/\psi \pi^+\pi^-$

Analysis strategy: search for a peak other than known $\Upsilon(2S)$ & $\Upsilon(3S)$ in the $\Upsilon(1S)\pi^+\pi^-$ spectrum within 10-11GeV

95% CL upper limits set on the ratio $R$ of the inclusive production Xsections times BFs to $\Upsilon(1S)\pi^+\pi^-$ (the one for $X_b$ is unknown):

$$R \equiv \frac{\sigma(pp \rightarrow X_b \rightarrow \Upsilon(1S)\pi^+\pi^-)}{\sigma(pp \rightarrow \Upsilon(2S) \rightarrow \Upsilon(1S)\pi^+\pi^-)}$$

Observed UL range: 0.9% to 5.4% (similar result by ATLAS)
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> According to Karliner & Rosner [PRD91 (2015) 014014], this decay should be forbidden by G-parity conservation; while for the $X(3872)$ the isospin-conserving decay to $\omega J/\psi$ was kinematically suppressed, the same is not true for a bottomonium-like $J^{PC} = 1^{++}$ counterpart. The strategy for $X_b$ observation should include search of $X_b \rightarrow \Upsilon(1S) \omega(\rightarrow \pi^+\pi^-\pi^0)$, $X_b \rightarrow X_{b1}(1P) (\rightarrow \Upsilon(1S)\gamma) \pi^+\pi^-$, $X_b \rightarrow \Upsilon(3S)\gamma$ (not easy: for Run-II)
$Y(4140)$

PLB 734 (2014) 261
CDF (2009) reported evidence (@3.8σ) for narrow peak in $J/\psi \phi$ mass spectrum, close to the kinematical threshold, in decays $B^+ \rightarrow J/\psi \phi K^+$

CDF (2011) presents update analysis with larger dataset, (6.0fb$^{-1}$ vs 2.7fb$^{-1}$) observing the so called $Y(4140)$ state:

Belle (2009) searched and did not find this state in the same decay

LHCb (2012) has searched for these two states reconstructing 383 ±22 $B^+ \rightarrow J/\psi \phi K^+$ candidates

LHCb observed no signals; this measured UL implies a 2.4σ tension with CDF

Y(4140) $[> 5\sigma]$  
Y(4274) $[> 3.1\sigma]$
The \textit{Y(4140): another long story...}

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  \[ \text{Y(4274)} \text{ [} > 3.1\sigma \text{]} \]

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**Interpretations**

- Masses are well above 3770MeV open charm threshold; the conventional charmonium should decay into $D\bar{D}$, with tiny B.F. to $J/\psi\phi$ (OZI-suppressed)

- For the \textit{Y(4140)} decaying several interpretations have been proposed:
  - $D^*_s\bar{D}^*_s$ molecule, that is the molecular strange partner of the \textit{Y(3940)}
  - $c\bar{s}\bar{c}s$ tetraquark
  - threshold kinematic effect
  - hybrid charmonium
  - weak transition with $D_s\bar{D}_s$ rescattering
CMS search for $Y(4140)$

- Search performed with 5.2 fb$^{-1}$ of collision at 7 TeV
- 2480 ± 160 $B^+$ events
- Largest $B^+$ sample to date:
  - 20 times CDF
  - 7 times LHCb

$m(J/\psi KKK) \in [m(B^\pm) - 3\sigma, m(B^\pm) + 3\sigma]$
CMS search for $Y(4140)$

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**Signal extraction:**
- $p_T > 1 GeV$ for any kaon
- Selection on common vertex probability and angular separation between $J/\psi$ and kaons
- $p_T (J/\psi) > 7 GeV$
- Transverse $B^+$ flight length significance $> 3$

- The $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ spectrum is considered till 1.568 GeV to avoid reflections from $B_s \rightarrow \psi(2S)\phi \rightarrow J/\psi\pi^+\pi^-\phi$
  (but whole spectrum also investigated)

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$m(J/\psi KKK) \in [m(B^+) - 3\sigma, m(B^+) + 3\sigma]$
The $\Delta m = m(\mu^+\mu^-K^+K^-) - m(\mu^+\mu^-)$ spectrum is obtained:

- dividing the dataset in $20\text{MeV}$ $\Delta m$ bins
- fitting every bin with:
  - Signal PDF: S-wave relativistic Breit-Wigner (BW) convoluted with mass resolution
  - Background PDF: 3-body Phase Space Shape (PS)
  - **1-D Fit**: Binned $\chi^2$ fit to the extracted $\Delta m$ spectrum using the BW and PS shape.
  - **Global 2-D Fit**: simultaneous fit of $m(B^+)$ and $\Delta m$ with implicit background subtraction

- extracting the number of $B^+$ signal in each $\Delta m$ bin by fitting the spectrum
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<table>
<thead>
<tr>
<th>Yield</th>
<th>Mass [MeV]</th>
<th>$\Gamma$ [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>310 ± 70</td>
<td>$4148.0 \pm 2.4$ (stat) $\pm 6.3$ (syst)</td>
<td>$28^{+15}_{-11}$ (stat) $\pm 19$ (syst)</td>
</tr>
<tr>
<td>418 ± 170</td>
<td>$4313.8 \pm 5.3$ (stat) $\pm 7.3$ (syst)</td>
<td>$38^{+30}_{-15}$ (stat) $\pm 16$ (syst)</td>
</tr>
</tbody>
</table>

First structure is consistent with $Y(4140)$ of CDF observed with a stat. significance > 5$\sigma$!
There is evidence for a second structure in the same mass spectrum

Naïve yields’ ratio estimate: $\frac{BR(Y(4140))}{BR(J/\psi\phi K^\pm)} \approx 0.10 \pm 0.03\%$ consistent with CDF and LHCb UL
Understanding the nature of both structures needs further investigation.

The $\phi K^*$ mass distribution shows an excess w.r.t. PHSP profile in the region where large resonances [$K_2(1770)$ & $K_2(1820)$] may appear; reflections studies are carried out.
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Understanding the nature of both structures needs further investigation & requires a full amplitude analysis (not easy task: 2 vectors in the final state!).

It is suitable for CMS adding Run-II data to extract an enough pure $B^+$ sample with enough statistics.

**Next steps for $Y(4140)$**

$Y(4140)$ appears to be uncorrelated to $\phi K^+$ resonances

Additional peak may be affected by them
Although designed for high-$p_T$ physics ...
... CMS is an exceptional apparatus for dealing with flavor physics topics!

CMS has greatly contributed to the **study of exotic states**: 
- $X(3872)$ prompt cross section 
- Search for $X_b$ 
- $Y(4140)$ confirmation

Their actual nature is still a challenge. 
Moreover **many final states still to be explored**!
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Run-II just started

CMS will record much larger integrated luminosity than LHCb, in an harsher environment

Dedicated triggers developed for the most important analyses
Backup slides / Additional material
Signal extraction:

- 2 $\mu$ with $p_T > 4$GeV coming from $J/\psi$ in the central region of the detector ($|y(\mu^+\mu^-)| < 1.25$)
- 2 tracks with opposite charge and $p_T > 600$MeV
- combination of these four tracks with constraint on common vertex
- selection on common vertex probability, angular distance between $J/\psi$ and $\pi$, $Q$ value $[m(\mu\mu\pi\pi) - m(J/\psi_{PDG}) - m(\pi\pi)]$.

Non-prompt fraction:

<table>
<thead>
<tr>
<th>Source</th>
<th>Relative uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertex estimation</td>
<td>1</td>
</tr>
<tr>
<td>Background parametrization</td>
<td>2-3</td>
</tr>
<tr>
<td>Efficiency</td>
<td>3-8</td>
</tr>
<tr>
<td>Decay length resolution</td>
<td>4</td>
</tr>
<tr>
<td>Pileup</td>
<td>2</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>6-10</strong></td>
</tr>
</tbody>
</table>
Systematic uncertainties

\[
R \equiv \frac{\sigma(pp \to X(3872) + \text{anything}) \cdot B(X(3872) \to J/\psi \pi^+\pi^-)}{\sigma(pp \to \psi(2S) + \text{anything}) \cdot B(\psi(2S) \to J/\psi \pi^+\pi^-)} = \frac{N_{X(3872)} \cdot A_{\psi(2S)} \cdot \varepsilon_{\psi(2S)}}{N_{\psi(2S)} \cdot A_{X(3872)} \cdot \varepsilon_{X(3872)}}
\]

<table>
<thead>
<tr>
<th>Source</th>
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</tr>
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<tbody>
<tr>
<td>Fit functions</td>
<td>1-2</td>
</tr>
<tr>
<td>(\varepsilon(\mu^+\mu^-))</td>
<td>&lt; 1</td>
</tr>
<tr>
<td>(\varepsilon(\pi^+\pi^-))</td>
<td>1-5</td>
</tr>
<tr>
<td>Efficiency statistical precision</td>
<td>1-3</td>
</tr>
<tr>
<td>(X(3872) p_T) spectrum</td>
<td>1-11</td>
</tr>
<tr>
<td>(\psi(2S) p_T) spectrum</td>
<td>1–4</td>
</tr>
<tr>
<td>(m(\pi^+\pi^-)) spectrum</td>
<td>1–2</td>
</tr>
<tr>
<td>Acceptance statistical precision</td>
<td>1–3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>5–13</strong></td>
</tr>
</tbody>
</table>
More stringent quality and kinematic cuts are used to produce a cleaner sample

- 40% of the defaults $B$ signal
- 10 times less background

Found structure can be clearly seen also with this selection
Invesigation of the whole \( \Delta m \) region

- Check the events with \( \Delta m \) larger than 1.568\( GeV \) (eliminated from the analysis) to ensure that they could not cause reflections in the low-\( \Delta m \) region.

- The \( \Delta m \) spectrum after subtracting \( B^0_s \) contribution but including non-\( B \) events within 1.5 \( \sigma \) of the B mass.

- The extension of \( \Delta m \) spectrum after subtracting non-\( B \) background, to the full phase space.

The events in the cutoff region are consistent with phase space.

**The absence of strong activity in the high-\( \Delta m \) region reinforces our conclusion that the near-threshold narrow structure is not due to a reflection of other resonances.**
## Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>$m_1$ (MeV)</th>
<th>$\Gamma_1$ (MeV)</th>
<th>$\Gamma_2$ (MeV)</th>
<th>$m_1$ (MeV)</th>
</tr>
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<tbody>
<tr>
<td>$B^+$ background PDF</td>
<td>0.8</td>
<td>7.4</td>
<td>2.6</td>
<td>9.9</td>
</tr>
<tr>
<td>$B^+$ signal PDF</td>
<td>0.2</td>
<td>3.6</td>
<td>2.7</td>
<td>0.2</td>
</tr>
<tr>
<td>Relative efficiency</td>
<td>4.8</td>
<td>6.0</td>
<td>0.9</td>
<td>10.0</td>
</tr>
<tr>
<td>$\Delta m$ binning</td>
<td>3.7</td>
<td>1.5</td>
<td>2.7</td>
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