Evidence of X(3872) production in PbPb collisions at 5.02 TeV with CMS

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For the CMS Collaboration

Hard Probes 2020
International Conference on Hard and Electromagnetic Probes of High-Energy Nuclear Collisions

3 June 2020
Austin, TX (US)
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A new exotic particle Probe : High-Energy Nuclear Collisions

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Introduction: X(3872)

- 2003: X(3872), also known as $\chi_{c1}(3872)$, discovered by BELLE
  ➡ Charmonium state: Abandoned ← predict wrong mass

- 2013: Quantum number determined by LHCb data: $J^{PC}=1^{++}$

- Today: Internal structure is still under debate
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• 2013: Quantum number determined by LHCb data: $J^{PC}=1^{++}$

• Today: Internal structure is still under debate

  Remaining possibilities:
  ➡ Tetraquark (4q): Compact four quark state
  ➡ $D\bar{D}^*$ hadron molecule: mass $X(3872) \approx D(1875)\bar{D}^*(2007)$
  ➡ Hybrid: mixed molecule-charmonium state

• All can explain measured mass/decay width
  ⇒ Any way to distinguish those models?
X(3872) in Heavy-ion Collisions

- X(3872) production yield in QGP strongly reflects internal structure
  - Interact with other hadrons: produced + absorbed:
    \[ \pi X \rightleftharpoons D\bar{D}, D\bar{D}^*, \rho X \rightleftharpoons D\bar{D}, D\bar{D}^*, D^*\bar{D}^* \]
  - Different behaviors due to radius \( r_{4q} \ll r_{mol} \):
    - Molecule easier to be produced and destroyed than tetraquark
  - Help reveal the nature of X(3872)!

Tetraquark
- Small \( r_{4q} \approx r_{cc} \)
- \( \approx 0.3 \text{ fm} \)
- Tight bound

Hadron molecule
- Large \( r_{mol} \)
- \( \approx 5 \text{ fm} \)
- Loose bound

Hybrid

Jing Wang (MIT), X(3872) in PbPb with CMS detector, HP 2020 (Austin, TX)
X(3872) in Heavy-ion Collisions

- X(3872) production yield in QGP strongly reflects internal structure
  - **Interact** with other hadrons: produced + absorbed:
    \[
    \pi X \rightleftharpoons D\bar{D}, D\bar{D}^* \text{ and } pX \rightleftharpoons D\bar{D}, D\bar{D}^*, D^*\bar{D}^*
    \]
  - Different behaviors due to **radius** \( r_{4q} \ll r_{mol} \):
    - **Molecule** easier to be produced and destroyed than **tetraquark**
    - Help reveal the nature of X(3872)!

- Coalescence model [PRL 106 (2011) 212001]
  - Orders of yield difference

Tetraquark
- Small \( r_{4q} \approx r_{cc} \)
  - \( \approx 0.3 \text{ fm} \)
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Hadron molecule
- Large \( r_{mol} \)
  - \( \approx 5 \text{ fm} \)
- Loose bound

Hybrid

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X(3872) in Heavy-ion Collisions

- X(3872) production yield in QGP strongly reflects internal structure
  - Interact with other hadrons: produced + absorbed
    \[ \pi X \rightleftharpoons DD, DD^* \quad \text{and} \quad pX \rightleftharpoons D\bar{D}, D\bar{D}^*, D^*\bar{D}^* \]
  - Different behaviors due to radius \( r_{4q} \ll r_{mol} \)

Molecule easier to be produced and destroyed than tetraquark
⇒ Help reveal the nature of X(3872)!

- X(3872)/\( \psi(2S) \) vs. multiplicity in pp

![Graph showing the relationship between X(3872)/\( \psi(2S) \) and multiplicity in pp](image)

**Tetraquark**
- Small \( r_{4q} \approx r_{c\bar{c}} \)
  ≈ 0.3 fm
- Tight bound

**Hadron molecule**
- Large \( r_{mol} \)
  ≈ 5 fm
- Loose bound

**Hybrid**

- Destroyed by interactions with other hadrons due to smaller binding energy?
X(3872) in Heavy-ion Collisions

- **X(3872) production yield in QGP strongly reflects internal structure**
  - **Interact** with other hadrons: produced + absorbed
  \[ \pi X \Rightarrow D\bar{D}, D\bar{D}^* \quad \& \quad pX \Rightarrow D\bar{D}, D\bar{D}^*, D^*\bar{D}^* \]
  - Different behaviors due to **radius** \( r_{4q} \ll r_{mol} \)
  - Molecule easier to be produced and destroyed than tetraquark
  - Help reveal the nature of X(3872)!

- **X(3872)/\psi(2S) vs. multiplicity in pp**

![Graph showing BR(\chi_{c1}(3872) \rightarrow J/\psi \pi^+ \pi^-) and BR(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-) vs. N_{tracks}]

What will happen in even larger systems?

- **Tetraquark**
  - Small \( r_{4q} \approx r_{c\bar{c}} \)
  - \( \approx 0.3 \text{ fm} \)
  - Tight bound

- **Hadron molecule**
  - Large \( r_{mol} \)
  - \( \approx 5 \text{ fm} \)
  - Loose bound

- **Hybrid**
  - ?
  - C

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Jing Wang (MIT), X(3872) in PbPb with CMS detector, HP 2020 (Austin, TX)
X(3872) and ψ(2S) Reconstruction

- Di-muon trigger sample in PbPb collisions at 5 TeV (LHC 2018 Run)
- X(3872) and ψ(2S) fully reconstructed with same hadronic decay chain J/ψ(μμ)π+π−
- No constraints on invariant mass m(π+π−)

Observable: \( R = \frac{N^{(\text{Corr})}_{X(3872)}}{N^{(\text{Corr})}_{\psi(2S)}} \),

\[
N^{(\text{Corr})} = N^{(\text{Raw})} \times f_{\text{prompt}} / \left( \alpha \times \epsilon_{\text{reco}} \times \epsilon_{\text{sel}} \right)_{\text{prompt}}
\]
Monte-Carlo Simulation

- Di-muon trigger sample in PbPb collisions at 5 TeV (LHC 2018 Run)
- $X(3872)$ and $\psi(2S)$ fully reconstructed with same hadronic decay chain $J/\psi(\mu\mu)\pi^+\pi^-$
- No constraints on invariant mass $m(\pi^+\pi^-)$

**Observable:**

$$R = \frac{N_{X(3872)}^{(Corr)}}{N_{\psi(2S)}^{(Corr)}} / \frac{N_{X(3872)}^{(Raw)} \times f_{\text{prompt}}}{\alpha \times e_{\text{reco}} \times e_{\text{sel}}}$$

- **PYTHIA8** simulation embedded in HYDJET PbPb events used for acceptance and efficiency correction
- Simulation: $X(3872) \rightarrow \rho(\pi\pi)J/\psi(\mu\mu)$
  - $m(\pi^+\pi^-)$ distribution from simulation w/ $\rho$ resonance agrees better to pp data
  - Cross-check with non-resonance simulation
Combinatorial Background Suppression

- A boosted decision tree (BDT) algorithm used to suppress the combinatorial background

- 5 variables input to BDT
  - Secondary vertex probability
  - $\pi p_T$ imbalance
  - Slow $\pi p_T$
  - Opening angle between $J/\psi$ and $\pi$: $\Delta R_1, \Delta R_2$

- Additional cut on $Q = m_{\mu\mu\pi\pi} - m_{\mu\mu} - m_{\pi\pi}$

Observable: $R = \frac{N^{(\text{Corr})}_{X(3872)}}{N^{(\text{Corr})}_{\psi(2S)}}$, \[ N^{(\text{Corr})} = \frac{N^{(\text{Raw})}}{f_{\text{prompt}}} \times \frac{1}{(\alpha \times \epsilon_{\text{reco}} \times \epsilon_{\text{sel}})} \times f_{\text{prompt}} \]
Raw Yield Extraction

- First evidence of \( X(3872) \) production in heavy ion collisions!
  - Statistical significance > 3\( \sigma \)
- Clear \( \psi(2S) \) signal is also observed under same selections
- Raw yield extracted with unbinned likelihood fit of invariant mass spectra

**Observable:** \( R = \frac{N^{(\text{Corr})}_{X(3872)}}{N^{(\text{Corr})}_{\psi(2S)}} \),

\[
N^{(\text{Corr})} = \frac{N^{(\text{Raw})}}{f_{\text{prompt}}/\left(\alpha \times \epsilon_{\text{reco}} \times \epsilon_{\text{sel}}\right)_{\text{prompt}}}
\]
Separation of Nonprompt Component

- **Inclusive:**
  - ✔ **Prompt**: c-quark fragmentation
  - ✗ **Nonprompt**: b-hadron decays

- **Pseudo-proper decay length** $l_{xy}$
  \[
  l_{xy} = \frac{L_{xy} \cdot m}{| \vec{p}_T |}
  \]

- **Separate nonprompt with** $l_{xy}$

**Observable:**
\[
R = \frac{N_{X(3872)}^{(Corr)}}{N_{\psi(2S)}^{(Corr)}},
N_{X(3872)}^{(Corr)} = N_{X(3872)}^{(Raw)} \times f_{\text{prompt}} \times (\alpha \times \epsilon_{\text{reco}} \times \epsilon_{\text{sel}})^{\text{prompt}}
\]
**I_{xy} Distribution in Simulation**

**Nonprompt**

- Inclusive:
  - ✔ Prompt: c-quark fragmentation
  - ✗ Nonprompt: b-hadron decays

- B-enriched sample:
  - Prompt component strongly suppressed in |l_{xy}| > 0.1mm

**Prompt**

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  - ✔ Prompt: c-quark fragmentation
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---

Observable: \[ R = \frac{N^{(\text{Corr})}_{X(3872)}}{N^{(\text{Corr})}_{\psi(2S)}} \]

\[ N^{(\text{Corr})} = N^{(\text{Raw})} \times f_{\text{prompt}} \times \left( \alpha \times \epsilon_{\text{reco}} \times \epsilon_{\text{sel}} \right)_{\text{prompt}} \]
Yield Extraction in B-enriched Sample

• **B-enriched: pure nonprompt**

**Prompt fraction:**

\[
f_{\text{prompt}} = 1 - \frac{N_{\text{data}}}{N_{\text{Prompt MC}} \cdot N_{\text{Inclusive}}}\]

**Cross-check with \(l_{xy}\) template fit method**

**Observable:**

\[
R = \frac{N^{(\text{Corr})}_{\psi(2S)}}{N^{(\text{Corr})}_{X(3872)}} = \frac{N^{(\text{Raw})}}{f_{\text{prompt}} \times (\alpha \times \epsilon_{\text{reco}} \times \epsilon_{\text{sel}})_{\text{prompt}}} \]

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Jing Wang (MIT), X(3872) in PbPb with CMS detector, HP 2020 (Austin, TX)
Result: $X(3872)/\psi(2S)$ Ratio in PbPb

- In PbPb collisions
  \[ R = 1.10 \pm 0.51 \text{ (stat.)} \pm 0.53 \text{ (syst.)} \]

- Indication of \textbf{R enhancement in PbPb} collisions with respect to pp at 8 TeV
  \[ R(\text{pp}) \sim 0.04-0.1 \]

- Better precision needed to draw conclusion

\[
R = \frac{N_{X(3872)}}{N_{\psi(2S)}}
\]

\[
N_{X(3872)}^{\text{(Corr)}} = N_{X(3872)}^{\text{(Raw)}} \times f_{\text{prompt}} (\alpha \times \epsilon_{\text{reco}} \times \epsilon_{\text{sel}})_{\text{prompt}}
\]

\[
N_{\psi(2S)}^{\text{(Corr)}} = N_{\psi(2S)}^{\text{(Raw)}}
\]
Result: $X(3872)/\psi(2S)$ Ratio in PbPb

- $\psi(2S)$ as reference suppressed in PbPb
  $\Rightarrow R_{AA}(\psi(2S)) \sim 0.1$

- $R$ enhancement:
  $\Rightarrow X(3872)$ less suppressed than $\psi(2S)$
Result: $X(3872)/\psi(2S)$ Ratio in PbPb

- From low to high-multiplicity pp:
  $\rightarrow$ $X(3872)$ more suppressed than $\psi(2S)$

- From pp to PbPb:
  $\rightarrow$ $X(3872)$ less suppressed than $\psi(2S)$
Summary

- First evidence of \textbf{X(3872)} production in heavy ion collisions!

- Indication of prompt X(3872) to \(\psi(2S)\) ratio enhancement in PbPb
  \(\Rightarrow R_{\text{PbPb}} = 1.10 \pm 0.51 \text{ (stat.)} \pm 0.53 \text{ (syst.)}\)
  \(\Rightarrow (R_{\text{pp}} \sim 0.04-0.1)\)

- Potential new constraints on the inner structure of X(3872)!

\[\mathcal{B}(\mathcal{B} \to \psi(2S) X(3872)) \times \sigma(\mathcal{B} \to X(3872)) \times \rho(\psi(2S) \to \mu^+\mu^-) \times \mathcal{B}(\mu^+\mu^- \to \mu^+\mu^-) = 1.7 \text{ nb}^{-1} \]
Thanks for your attention!
Back up

Thanks for your attention!
Combinatorial Background Suppression

- Large combinatorial background in PbPb collisions

![Graph showing before and after BDT cut for X(3872) in PbPb collisions with CMS detector.](image)
ρ(ππ) Resonance

\[ JHEP 04 (2013) 154 \]
## Heavy-ion data in CMS

<table>
<thead>
<tr>
<th>Collision System</th>
<th>Energy</th>
<th>LHC Delivered</th>
<th>CMS Recorded</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Run 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011 Pb-Pb</td>
<td>2.76 TeV</td>
<td>184.1 μb⁻¹</td>
<td>174.3 μb⁻¹</td>
</tr>
<tr>
<td>2013 p-Pb</td>
<td>5.02 TeV</td>
<td>36.1 nb⁻¹</td>
<td>35.5 nb⁻¹</td>
</tr>
<tr>
<td><strong>Run 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2015 p-p</td>
<td>5.02 TeV</td>
<td>28.8 pb⁻¹</td>
<td>28.1 pb⁻¹</td>
</tr>
<tr>
<td>2015 Pb-Pb</td>
<td>5.02 TeV</td>
<td>0.60 nb⁻¹</td>
<td>0.55 nb⁻¹</td>
</tr>
<tr>
<td>2016 p-Pb</td>
<td>8.16 TeV</td>
<td>188.3 nb⁻¹</td>
<td>180.2 nb⁻¹</td>
</tr>
<tr>
<td>2017 Xe+Xe</td>
<td>5.44 TeV</td>
<td>6.3 μb⁻¹</td>
<td>6.0 μb⁻¹</td>
</tr>
<tr>
<td>2017 p-p</td>
<td>5.02 TeV</td>
<td>334.3 pb⁻¹</td>
<td>316.3 pb⁻¹</td>
</tr>
<tr>
<td>2018 Pb-Pb</td>
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<td>1.80 nb⁻¹</td>
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X(3872)/ψ(2S) Ratio vs. Theory

- Coalescence ➔ PRL 106 (2011) 212001
- TAMU model

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