Study of $Z_c(3900)$ Production in $p\bar{p}$ Collisions

P. Gutierrez

for the DØ Collaboration

Homer L. Dodge Department of Physics & Astronomy
University of Oklahoma

July 31, 2019
Charmonium $c\bar{c}$ states with radial & angular excitation.
Number of states discovered that don’t fit the charmonium model ($c\bar{c}$).

For example (state discussed in this presentation):

- $Z_c(3900)$ discovered by BELLE and BESII

\[
e^+e^- \rightarrow Y(4260) \\
Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^\mp \\
Z_c^{\pm}(3900) \rightarrow J/\psi\pi^\mp
\]


Decay is similar to a charmonium excited state for example: $\psi(2S) \rightarrow J/\psi\pi^+\pi^-$

- $Z_c(3900)$ cannot be charmonium since it is charged and decays via the strong interaction to charmonium.

- Minimum quark content $c\bar{c}u\bar{d}$. 
Models

Strongly bound:

Tetraquarks

\[ c\bar{c} - \text{gluon hybrid} \]

Weakly bound:

Hadroncharmonium

Color Singlet \( c\bar{c} \)

Hadroncharmonium

Color Octet \( c\bar{c} \)

Mesonic Molecule

\[ \pi, \sigma, \omega, \ldots \]

\[ \bar{D}^* \]
Charmonium & Charmonium-Like States

Rev. Mod. Phys 90 (2018)
Evidence for $H_b \rightarrow Z_c^{\pm}(3900)\pi^{\mp} + X$

**Introduction**

- DØ has performed a search for $Z_c(3900)$ from $b$ hadrons ($H_b$) decays at $\sqrt{s} = 1.96$ TeV using $\int L \, dt = 10.4 \text{ fb}^{-1}$
  

- Previous searches using exclusive hadronic decays proved inconclusive:
  - Belle – Not observed $\bar{B}^0 \rightarrow (J/\psi\pi^+)K^-$
  - LHCb – Not observed $B^0 \rightarrow (J/\psi\pi^+)\pi^-$
  - BaBar – Maybe observed $\bar{B}^0 \rightarrow J/\psi\pi\pi K$

- Since the process may be spread over many channels DØ used a semi-inclusive search $H_b \rightarrow Y(4260) + X$. 

---

P. Gutierrez (University of Oklahoma)
Evidence for $H_b \rightarrow Z_c^{\pm}(3900)\pi^{\mp} + X$

Search Strategy


- Search topology $Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp} \rightarrow (J/\psi\pi^{\pm})\pi^{\mp}$
  - Hence a secondary vertex comprised of $J/\psi \rightarrow \mu^+\mu^-$ plus 2 opposite sign charged particle tracks.

- Vertex requirements: secondary vertex pointing at primary vertex; impact parameter in added tracks.

- Invariant mass requirement
  $4.1 < M_{J/\psi\pi^{\pm}\pi^{\mp}} < 5.0$ GeV
  - Less than lowest $B$ meson mass
  - Includes $Y(4260)$

Transverse Decay Length

![Graph showing transverse decay length distribution](image)
Evidence for $H_b \rightarrow Z_c^\pm (3900) \pi^\mp + X$

$J/\psi \pi^+ \pi^- \text{ Invariant Mass}$

\[ 4.1 < M(J/\psi \pi^\pm \pi^\mp) < 4.2 \text{ GeV} \]
\[ 4.2 < M(J/\psi \pi^\pm \pi^\mp) < 4.25 \text{ GeV} \]
\[ 4.25 < M(J/\psi \pi^\pm \pi^\mp) < 4.3 \text{ GeV} \]
\[ 4.3 < M(J/\psi \pi^\pm \pi^\mp) < 4.4 \text{ GeV} \]
\[ 4.4 < M(J/\psi \pi^\pm \pi^\mp) < 4.7 \text{ GeV} \]
\[ 4.7 < M(J/\psi \pi^\pm \pi^\mp) < 5.0 \text{ GeV} \]
Evidence for $H_b \rightarrow Z_c^{\pm}(3900)\pi^{\mp} + X$

$Z_c(3900)$ Signal

- Signal at $M\left(J/\psi\pi^{\pm}\right) = 3895.0 \pm 5.2 \text{ (stat)}^{+4.0}_{-2.7} \text{ (syst)} \text{ MeV}$
- Significance of $4.6\sigma$ (with syst.)

$4.2 < M(J/\psi\pi^{\pm}\pi^{\mp}) < 4.7 \text{ GeV}$

[Graphs showing data distribution and fit results]
Evidence for $H_b \rightarrow Z_c^\pm (3900) \pi^\mp + X$

**DØ Results**

- Rate relative to $B_d^0 \rightarrow J/\psi K^*$

\[
\frac{N \left[ H_b \rightarrow \left( Z_c^\pm (3900) \rightarrow J/\psi \pi^\pm \right) \pi^\mp + X \right]}{N \left[ B_d^0 \rightarrow J/\psi K^* \right]} = 0.085 \pm 0.019
\]

$B_d^0 \rightarrow J/\psi K^*$, $Z_c^\pm (3900) \rightarrow J/\psi \pi^\pm$

\[
\frac{N \left[ H_b \rightarrow \left( Z_c^\pm (3900) \rightarrow J/\psi \pi^\pm \right) K^\mp \right]}{N \left[ B_d^0 \rightarrow J/\psi K^* \right]} < 0.015 \text{ at 90\% C.L.}
\]
Prompt Production $Y(4260) \rightarrow Z_c^\pm (3900) \pi^\mp$

Outline

Phy. Rev. D 100 012005

- **Same channel** $Y(4260) \rightarrow \left( J/\psi \pi^\pm \right) \pi^\mp$.

- **Data is reprocessed to optimize low $p_T$ track reconstruction (50%) increase in sample.**

- **Split data into 2 non-overlapping subsets:**
  - Consistent with primary vertex.
  - Displaced vertex.
Prompt Production $Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}$

**Invariant Mass**

**Primary vertex**

\[4.1 < M(J/\psi \pi^{\pm} \pi^{\mp}) < 4.2 \text{ GeV}\]

\[4.2 < M(J/\psi \pi^{\pm} \pi^{\mp}) < 4.3 \text{ GeV}\]

\[4.3 < M(J/\psi \pi^{\pm} \pi^{\mp}) < 4.4 \text{ GeV}\]

**Displaced Vertex**

\[4.1 < M(J/\psi \pi^{\pm} \pi^{\mp}) < 4.2 \text{ GeV}\]

\[4.2 < M(J/\psi \pi^{\pm} \pi^{\mp}) < 4.3 \text{ GeV}\]

\[4.3 < M(J/\psi \pi^{\pm} \pi^{\mp}) < 4.4 \text{ GeV}\]
For the $Y(4260)$ displaced vertex mass range
$4.2 < M(J/\psi\pi^\pm\pi^\mp) < 4.3$ GeV

- Signal significance $5.4\sigma$
- $M = 3902.6 \pm 5.2$ (stat)$^{+3.4}_{-1.4}$ (syst) MeV
- $\Gamma = 32^{+28}_{-21}$ (stat)$^{+26}_{-7}$ (syst) MeV
Prompt Production $Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^\mp$

Results prompt production

<table>
<thead>
<tr>
<th>State</th>
<th>$N_{\text{prompt}}/N_{\text{non-prompt}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^\mp$</td>
<td>$&lt; 0.7$ at 95% C.L.</td>
</tr>
<tr>
<td>$X(3872) \rightarrow J/\psi\pi^\pm \pi^\mp$</td>
<td>$\approx 2.5$ CMS &amp; ATLAS</td>
</tr>
<tr>
<td>$X(4140) \rightarrow J/\psi\phi$</td>
<td>$\approx 1.5$ DØ</td>
</tr>
</tbody>
</table>

Displaced Vertex

Primary Vertex
Summary

- Measured the properties of the $Z_c(3900)$
- Observed $Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}$ in semi-inclusive $H_b$ decays.
  - But not in $B_d^0 \rightarrow J/\psi \pi^+ K^-$
- Prompt production of the $Y(4260) \rightarrow Z_c^{\pm}(3900)\pi^{\mp}$ is not observed.
  - Significantly less than $X(3872)$ abd $X(4140)$.

**Dø nabs $Z_c^*(3900)$**

Following first observations of the charmonium-like state $Z_c^*(3900)$ at $e^+e^-$ colliders in 2013, the Dø collaboration has published 5.4σ evidence for its presence in the decay chain of $b$-quarks in $p\bar{p}$ collisions.