The New Results from Multi-quark Exotic States Searches at DØ Experiment
~20 multi-quark states were observed since 2003 with high significance. Important examples of four-quark states:

- $X(3782) \rightarrow J/\psi \pi \pi$, $Z_c(4430) \rightarrow \psi(2S)\pi$, $X(4140) \rightarrow J/\psi \phi$;
- pentaquarks: $P_c(4380) \rightarrow J/\psi p$, $P_c(4450) \rightarrow J/\psi p$.

Recent review: *Olsen, Skwarnicki, Zieminska, Rev. Mod. Phys. 90, 015003 (2018)*

**Multi-quark States**

- **baryon**
- **meson**
- **Pentaquark**
- **tetraquark**
- **hybrid**
- **glueball**
- **molecule**

**Four-quark states**

- **Meson-meson molecule** – two white states loosely bound by a pion exchange.
- **Compact tetraquark** – diquark-antidiquark pair connected by color forces.
Evidence for $B_s\pi$ state, $B_s \rightarrow J/\psi \phi(1020)$


$X(5568)$

$M = 5567.8 \pm 2.9^{+0.9}_{-1.9} \text{(stat)}^{+0.9}_{-1.9} \text{(syst)} \text{MeV/c}^2$

$\Gamma = 21.9 \pm 6.4^{+5.0}_{-2.5} \text{(stat)}^{+5.0}_{-2.5} \text{(syst)} \text{MeV/c}^2$

$\rho(X(5568)/B_s) = 8.6 \pm 1.9^{\text{(stat)}} \pm 1.4^{\text{(syst)}} \text{%}$

Statistical significance (with systematics and LEE)

With $\Delta R = \sqrt{\Delta \eta(B_s, \pi) + \Delta \phi(B_s, \pi)} < 0.3$ cut: $5.1\sigma$

Without $\Delta R$ cut: $3.9\sigma$
X(5568)→B_sπ with semileptonic decays of the B_s mesons

Event reconstruction and selection

D0 Run II integrated luminosity 10.4 fb\(^{-1}\)

\[3 < p_T(\mu) < 25 \text{ GeV/c}; \quad p_T(K) > 1 \text{ GeV/c}; \]
\[1.012 < M(KK) < 1.03 \text{ GeV/c}^2\]
\[4.5 < M(D_s\mu) < M(B_s); \quad p_T(D_s\mu) > 10 \text{ GeV/c}\]

\[M(B_s\pi) = M(D_s\mu\pi) - M(D_s\mu) + M(B_s),\]
where \(M(B_s) = 5.3667 \text{ GeV/c}^2\)

\[5.506 < M(B_s\pi) < 5.906 \text{ GeV/c}^2\]
X(5568)→B_sπ with semileptonic decays of the B_s mesons

**Background parametrization**

\[ F_{\text{bgr}}(m) = (C_1 \cdot m + C_2 \cdot m^2 + C_3 \cdot m^3 + C_4 \cdot m^4) \times \exp(C_5 \cdot m + C_6 \cdot m^2) \]

where \( m = M - M_{\text{thr}} \)

**Fit to data**

\[ F_{\text{fit}}(m, M_x, \Gamma_x) = f_{\text{bgr}} \cdot F_{\text{bgr}}(m) + f_{\text{sig}} \cdot F_{\text{sig}}(m, M_x, \Gamma_x) \]

where \( F_{\text{sig}}(m, M_x, \Gamma_x) \) - S-wave BW function convoluted with resolution (including missing neutrino effect), \( f_{\text{bgr}}, f_{\text{sig}} \) - normalization coefficients.

**Fit results without ΔR cut**

\[ M_x = 5566.7^{+3.6}_{-3.4} \text{ MeV/c}^2 \]
\[ \Gamma_x = 6.0^{+9.5}_{-6.0} \text{ MeV/c}^2, N_{\text{ev}} = 139^{+51}_{-63} \]
Local significance: 4.5σ

**Fit results with ΔR cut**

\[ M_x = 5566.4^{+3.4}_{-2.8} \text{ MeV/c}^2 \]
\[ \Gamma_x = 2.0^{+9.5}_{-2.0} \text{ MeV/c}^2, N_{\text{ev}} = 121^{+51}_{-34} \]
Local significance: 4.3σ

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ICPPA-2018

A. Popov (NRC “Kurchatov Institute” - IHEP, Protvino)
**X(5568) → B_sπ with semileptonic decays of the B_s mesons**

**Systematic uncertainties**
- Background shape description, background reweighting, B_s mass scale (MC and data), detector resolution and missing neutrino effect, P-wave Breit-Wigner.

**Significance with systematics**
- without ΔR cut: **3.4σ**
- with ΔR cut **3.2σ**

**Production ratio of X(5568) to B_s**
\[
\rho(X(5568)/B_s) = 7.3^{+2.8}_{-2.4}(\text{stat})^{+0.6}_{-1.7}(\text{syst})\%
\]

**Comparison with hadronic channel**

<table>
<thead>
<tr>
<th></th>
<th>Semileptonic</th>
<th>Hadronic (from Ref. [15])</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cone cut</td>
<td>No cone cut</td>
</tr>
<tr>
<td>Fitted mass, MeV/c²</td>
<td>5566.4±3.4 +1.5 -2.8 -0.6</td>
<td>5566.7±3.6 +1.0 -3.4 -1.0</td>
</tr>
<tr>
<td>Fitted width, MeV/c²</td>
<td>2.0±9.5 +2.8 -2.0 -2.0</td>
<td>6.0±9.5 +1.9 -6.0 -4.6</td>
</tr>
<tr>
<td>Fitted number of signal events</td>
<td>121±51 +9 -34 -28</td>
<td>139±51 +11 -63 -32</td>
</tr>
<tr>
<td>Local significance</td>
<td>4.3σ</td>
<td>4.5σ</td>
</tr>
<tr>
<td>Significance with systematics</td>
<td>3.2σ</td>
<td>3.4σ</td>
</tr>
<tr>
<td>Significance with LEE + systematics</td>
<td>...</td>
<td>...</td>
</tr>
</tbody>
</table>

**Results in semileptonic channel are compatible with those in hadronic channel within uncertainties.**
Simultaneous fit to hadronic and semileptonic channels

Fitted mass, MeV/c^2
Fitted width, MeV/c^2
Fitted number of hadronic signal events
Fitted number of semileptonic signal events
χ^2/ndf
p-value
Local significance
Significance with LEE
Significance with LEE + systematics

Cone cut
5566.9^{+3.2}_{-3.1} (stat) +0.6_{-1.2} (syst)
18.6^{+7.9}_{-6.1} (stat) +3.5_{-3.8} (syst)
131^{+37}_{-33} (stat) +15_{-14} (syst)
147^{+42}_{-37} (stat) +17_{-16} (syst)
94.7/(100 - 6)
2.2 \times 10^{-14}
7.6σ
6.9σ
6.7σ

No cone cut
5565.8^{+4.2}_{-4.0} (stat) +1.3_{-2.0} (syst)
16.3^{+9.8}_{-7.6} (stat) +4.2_{-6.5} (syst)
99^{+40}_{-34} (stat) +18_{-33} (syst)
111.7^{+46}_{-39} (stat) +20_{-38} (syst)
54.2/(50 - 6)
1.9 \times 10^{-8}
5.6σ
5.0σ
4.7σ

Significance increases with addition of semileptonic sample
X(5568)→B_sπ with semileptonic decays of the B_s mesons


**World comparison**

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Production ratio ( B_s / X(5568) )</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>D0 (J/ψ φ)</td>
<td>8.6 ± 1.9 ± 1.4%</td>
<td>PRL 117,022003(2016)</td>
</tr>
<tr>
<td>D0 (μ D_s)</td>
<td>7.3^{+2.8}<em>{-2.4}^{+0.6}</em>{-1.7} %</td>
<td>PRD 97, 092004 (2018)</td>
</tr>
<tr>
<td>LHCb</td>
<td>&lt; 2.4% (p_T(B_s^0) &gt; 10 GeV)</td>
<td>PRL 117,152003 (2016)</td>
</tr>
<tr>
<td>CMS</td>
<td>&lt; 1.1% (p_T(B_s^0) &gt; 10 GeV)</td>
<td>PRL 120, 202005 (2018)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>&lt; 1.5% (p_T(B_s^0) &gt; 10 GeV)</td>
<td>PRL 120, 202007 (2018)</td>
</tr>
<tr>
<td>CDF</td>
<td>&lt; 6.7% (2.3 ± 1.9 ± 0.9%)</td>
<td>PRL 120, 202006 (2018)</td>
</tr>
</tbody>
</table>

LHC experiments do not observe X(5568), but CM energy is rather different. CDF results is in ~2σ tension with DØ, kinematic selections vary substantially. Without theoretical model for X(5568) production and decays it is hard to compare various experiments quantitatively.
A search for $Z_c(3900)$ at DØ experiment

$Z_c^{\pm}(3900)$ was discovered in 2013 by Belle and BESIII in the process:

$$e^+e^- \rightarrow Y(4260) \rightarrow Z_c^{\pm}(3900) \pi^\mp,$$

$$Z_c^{\pm}(3900) \rightarrow J/\psi \pi^\pm.$$

$Y(4260)$: two interfering resonances $\psi(4260)$ and $\psi(4360)$ (BESIII).

- Which component decays to $Z_c^{\pm}(3900)$?
- Are there decays $H_b \rightarrow Y(4260) \rightarrow Z_c^{\pm}(3900) \pi^\mp + \text{anything}$?

$H_b \rightarrow Y(4260) + \text{anything}, Y(4260) \rightarrow Z_c^{\pm}(3900) \pi^\mp, Z_c^{\pm}(3900) \rightarrow J/\psi \pi^\pm$

- 10.4 fb$^{-1}$ of $p\bar{p}$ data at 1.96 TeV.
- $J/\psi + 2$ tracks, $p_T^1 > 1$ GeV, $p_T^2 > 0.8$ GeV, opposite charge.
- Veto $K^* \rightarrow K\pi(\pi K), \phi \rightarrow KK, \gamma$ conversion.
- Displaced vertex: $L_{xy}(J/\psi \pi^\pm)/\sigma(L_{xy}) > 5, IP_{xy}(\pi^\pm)/\sigma(IP) > 2$

- Vertex fits: $J/\psi \pi^\pm \chi^2 < 10$, adding extra pion $\delta\chi^2 < 6$.
- Select events with displaced $J/\psi \pi^+\pi^-$ vertices, $L_{xy}$ distribution has a slope consistent with $B$ hadron decays lifetime.
- $4.1 < M(J/\psi \pi^+\pi^-) < 5.0$ GeV.
A search for $Z_c(3900)$ at DØ experiment

**Fit to data**

- **Background parametrization:** Chebyshev polynomials.
- **Signal parametrization:** S-wave Breit-Wigner smeared with resolution (17 MeV).
- $\Gamma$ fixed to PDG value (28.2 MeV).
- $4.2 < M(J/\psi \pi^+ \pi^-) < 4.7$ GeV.

**Systematic uncertainties:**

- Mass calibration, mass resolution, background shape (different degrees of Chebyshev polynomials), bin size, signal model (different Breit-Wigner forms), natural width variations.

**Results**

- $M_x = 3895.0 \pm 5.2^{+4.0}_{-2.7}(syst)$ MeV,
- $N_{ev} = 505 \pm 92^{(stat)} \pm 64^{(syst)}$.
- Local significance: 5.6$\sigma$.
- Significance with systematics: 4.6$\sigma$.
A search for $Z_c(3900)$ at DØ experiment
A search for $Z_c(3900)$ at DØ experiment

Since $Z_c(3900) \rightarrow J/\psi \pi$ and $B^0_d \rightarrow J/\psi K^*$ have the similar topology and efficiencies, they are cancel out in the ratio

$$\frac{N(Z_c(3900) \rightarrow J/\psi \pi)}{N(B^0_d \rightarrow J/\psi K^*)} = 0.085 \pm 0.019$$

Belle Collaboration did not see a significant signal from $Z_c(3900)$ in $\bar{B}^0_d \rightarrow J/\psi \pi^+K^-$. In our case the mass spectrum for $J/\psi \pi^+$ also show no indication of the $Z_c(3900)$ ($5.15 < M(J/\psi \pi^+K^-) < 5.4 \text{ GeV}$, no $K^*$)

Upper limit on the ratio to the $B^0_d \rightarrow J/\psi K^*$ process of 0.015 (at 90% CL) is obtained.
Conclusion

• We confirm production of $X(5568)$ state in proton-antiproton collisions at 1.96 TeV with an independent data set with semileptonic decay of $B^0_S$ meson.

• $X(5568)$ properties in hadronic and semileptonic channels are consistent.

• Combined significance of $X(5568)$ state observation in these two channels is $6.7\sigma$.

• DØ observed $Z_c^{\pm}(3900)$ exotic state decaying to $J/\psi \, \pi^{\pm}$ in proton-antiproton collisions at 1.96 TeV with $4.6\sigma$ significance.

• Measured mass of $Z_c^{\pm}(3900)$ is $M_x = 3895.0 \pm 5.2 (\text{stat})^{+4.0}_{-2.7} (\text{syst})$ MeV consistent with Belle and BESIII measurements.

• Ratio $\frac{N(Z_c(3900)\rightarrow J/\psi \, \pi)}{N(B^0_d \rightarrow J/\psi \, K^*)} = 8.5 \pm 1.9 \%$.

• Published in *Phys. Rev. D98, 052010 (2018)*.
Backup slides
X(5568)→B_sπ with semileptonic decays of the B_s mesons

Background parametrization

Background distribution is obtained from MC and reweighted to data.

\[ F_{\text{bgr}}(m) = (C_1 \cdot m + C_2 \cdot m^2 + C_3 \cdot m^3 + C_4 \cdot m^4) \times \exp(C_5 \cdot m + C_6 \cdot m^2), \]

where \( m = M - M_{\text{thr}} \).

Several alternative parametrizations of the background were used to model the background for background shape systematics estimation.

Alternative parametrizations

1. \( F_{\text{bgr}}(M) = (C_1 + C_2 \cdot m^2 + C_3 \cdot m^3 + C_4 \cdot m^4) \times \exp(C_5 \cdot m + C_6 \cdot m^2), \)

where \( m = M - \Delta, \Delta = 5.5 \text{ GeV/c}^2 \).

2. \( F_{\text{bgr}}(M) = M \cdot \left( \frac{M^2}{M_{\text{thr}}^2} - 1 \right) C_1 \times \exp(C_2 \cdot M), \)

where \( M_{\text{thr}} \) is a \( B_s\pi \) threshold.

3. Histogram smoothing (one iteration of 353QH algorithm).

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![Graph](graph.png)

(a) D0 Background Model

\[ \Delta R < 0.3 \]

(b) D0 Background Model

No \( \Delta R \)
X(5568)→$B_s\pi$ with semileptonic decays of the $B_s$ mesons

### Systematic uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>Mass, MeV/c^2</th>
<th>Width, MeV/c^2</th>
<th>Event yield, events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cone cut</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(i) Background shape description</td>
<td>+0.7; −0.3</td>
<td>+0.0; −1.0</td>
<td>+0.0; −26.6</td>
</tr>
<tr>
<td>(ii) Background reweighting</td>
<td>+0.1; −0.1</td>
<td>+0.4; −0.4</td>
<td>+3.9; −4.2</td>
</tr>
<tr>
<td>(iii) $B_s^0$ mass scale, MC simulation and data</td>
<td>+0.1; −0.3</td>
<td>+0.8; −1.0</td>
<td>+5.1; −7.8</td>
</tr>
<tr>
<td>(iv) Detector resolution</td>
<td>+0.9; −0.0</td>
<td>+2.7; −1.0</td>
<td>+6.5; −0.0</td>
</tr>
<tr>
<td>(v) $P$-wave Breit-Wigner</td>
<td>+0.0; −0.4</td>
<td>+0.0; −1.0</td>
<td>+0.0; −3.7</td>
</tr>
<tr>
<td>(vi) Missing neutrino effect</td>
<td>+1.0; −0.0</td>
<td>…</td>
<td>…</td>
</tr>
<tr>
<td>Total</td>
<td>+1.5; −0.6</td>
<td>+2.8; −2.0</td>
<td>+9.1; −28.3</td>
</tr>
<tr>
<td>No cone cut</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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<td>+0.0; −0.7</td>
<td>+0.7; −2.5</td>
<td>+4.8; −28.0</td>
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<tr>
<td>(ii) Background reweighting</td>
<td>+0.1; −0.1</td>
<td>+0.7; −0.7</td>
<td>+5.0; −5.0</td>
</tr>
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<td>(iii) $B_s^0$ mass scale, MC simulation and data</td>
<td>+0.3; −0.5</td>
<td>+1.0; −1.4</td>
<td>+7.5; −9.6</td>
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<td>(iv) Detector resolution</td>
<td>+0.0; −0.5</td>
<td>+1.3; −2.6</td>
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<td>+1.0; −0.0</td>
<td>…</td>
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</tr>
<tr>
<td>Total</td>
<td>+1.0; −1.0</td>
<td>+1.9; −4.6</td>
<td>+10.9; −31.5</td>
</tr>
</tbody>
</table>
A search for $Z_c(3900)$ at DØ experiment

Systematic uncertainties

<table>
<thead>
<tr>
<th>Systematic uncertainty</th>
<th>Mass (MeV)</th>
<th>Yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass calibration</td>
<td>$+3_{-0}$</td>
<td>$&lt; 1$</td>
</tr>
<tr>
<td>Mass resolution</td>
<td>$&lt; 0.1$</td>
<td>$\pm 27$</td>
</tr>
<tr>
<td>Background shape</td>
<td>$\pm 0.4$</td>
<td>$\pm 53$</td>
</tr>
<tr>
<td>Bin size</td>
<td>$\pm 1.1$</td>
<td>$\pm 9$</td>
</tr>
<tr>
<td>Signal model</td>
<td>$\pm 2.4$</td>
<td>$\pm 3$</td>
</tr>
<tr>
<td>Natural width variation</td>
<td>$&lt; 0.1$</td>
<td>$\pm 23$</td>
</tr>
<tr>
<td>Total (sum in quadrature)</td>
<td>$-2.7, +4.0$</td>
<td>$\pm 64$</td>
</tr>
</tbody>
</table>
A search for $Z_c(3900)$ at DØ experiment

Cross-checks

- Two ranges of $p_T(\pi)$ from $J/\psi \pi$ system ($>1.5$ or $<1.5$ GeV).
- Three pseudorapidity ranges ($|\eta|<0.9$, $0.9<|\eta|<1.3$, $1.3<|\eta|<2.0$).
- $Z_c^+$ and $Z_c^-$.
- Events in the high $\chi^2$ tail.
- Various Run II periods.
- $J/\psi$ mass window and sidebands.
- $M(\pi^+\pi^-)$ from $J/\psi \pi^+\pi^-$ system ($>1.0$ or $<1.0$ GeV).
- Reversed IP cut on second track (to show predominant non-prompt production).
- Same sign pion pairs from $J/\psi \pi\pi$ system.

All cross-checks provided expected results.
A search for $Z_c(3900)$ at DØ experiment

The $L_{xy}$ distribution was fitted with $\sim e^{-L_{xy}/\Lambda}$

$Z_c(3900)\rightarrow J/\psi \pi$: $\Lambda = 0.098 \pm 0.030$;

$B^0\rightarrow J/\psi K^*$: $\Lambda = 0.130 \pm 0.004$. Consistent with each other.

The two $p_T$ distributions are also similar.