Search for Exotic Hadrons at D0

Peter H. Garbincius - Fermilab
August 1, 2017
DPF-2017

$X5568 \to B_s \pi$ via semileptonic decay $B_s \to \mu \nu D_s X$
and combination with $B_s \to J/\psi \phi$
and

Search for an exotic $J/\psi \Lambda$ resonance
Tevatron $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV
shutdown at end of September 2011 $\int \mathcal{L} dt = 10$ fb$^{-1}$

*FINAL* analyses based on Run II data sets 2001-2011

uniquely $p\bar{p}$!

**DØ:** excellent $\mu$-id and coverage
flip solenoid & toroid polarities for Asymmetry measurements
D0: Confirmation of the X(5568) with the semileptonic decay of $B_s^0$

D0 Note 6489-CONF – March 24, 2017
https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B68/B68.pdf

Last year D0 → Evidence for a new $X \rightarrow \pi B_s$ state with $B_s \rightarrow J/\psi \phi$


$\Delta R = \sqrt{\Delta \eta^2 + \Delta \varphi^2} < 0.3$ betw $\pi$ & $B_s$

fitted $M_X$ doesn’t vary with $\Delta R$ cut

$M_X = 5567.8 \pm 2.9$ (stat) $\pm 0.9$ $-1.6$ (syst) MeV

$\Gamma_X = 21.9 \pm 6.4 + 5.0 - 2.5$ MeV

global Significance including LEE & systematic uncertainty = 5.1 $\sigma$

$\rho = \sigma(X5568 \rightarrow Bs \pi)/\sigma(Bs) = [8.6 \pm 1.9 \pm 1.4]\%$
**D0: SL X5568 – prior result via Bs => J/ψ φ**

Also, in last year’s PRL without the ΔR cut:

\[ X \rightarrow π B_s \rightarrow J/ψ \ φ \]

with \( M_x \) and \( Γ_x \) fixed to same values as for analysis with ΔR cut,

Significance including LEE & syst. uncert. = 3.9 σ

LHCb and CMS have not observed this state in 7 & 8 TeV pp collisions

**D0: Evidence for an exotic $B_s^0 \pi^\pm$ $b$, $s$, $u$, $d$ state**

First observation of a state with **4 different quarks** for example, previous observed exotics are:

\[
X(3872) \rightarrow J/\psi \pi^+ \pi^- = c \bar{c} u \bar{u} + c \bar{c} d \bar{d}
\]

\[
Z^+(4430) \rightarrow \psi' \pi^+ = s \bar{s} u \bar{d}
\]

\[
Z_{b}^+(10610) \rightarrow \Upsilon(nS) \pi^+ = b \bar{b} u \bar{d}
\]

\[
Z_{b}^+(10650) \rightarrow \Upsilon(nS) \pi^+ = b \bar{b} u \bar{d}
\]

\[
P_c^+ \rightarrow J/\psi p = c \bar{c} u u d
\]

and many, many more

*see backup slides for a more extensive list of meson-like exotics*
D0: Evidence for an exotic $B_s^0\pi^\pm$ b, s, u, d state

$BK$ molecule is bound by colorless hadron and is expected to have mass near $BK$ threshold. $BK$ molecule is disfavored for $X(5568)$ since it would have $\sim 206$ MeV Binding Energy.

or the diquark + anti-diquark model by Maiani et al.

use new decay mode!

**use** $B^0_s \rightarrow \mu^+ \nu D_s^- X_{\text{anything}}$

**with** $D_s^- \rightarrow \phi \pi^-$ **then** $\phi \rightarrow K^+ K^-$

**complications due to missing** $\nu$

**requiring** $M(\mu D_s) > 4.5$ GeV

**limits missing** $\nu$ energy and

**thus improves mass resolution**

$X_{\text{anything}}$ mostly $\gamma$ (or $\pi^0$) from $D_s^*$ decays

add $\pi^\pm$ from primary vertex to form $X \rightarrow B_s^0 \pi^\pm$

estimate for invariant mass:

$$M(B_s^0 \pi^\pm) = M(\mu D_s \pi) - M(\mu D_s) + M_{PDG}(B_s^0)$$

Search for Exotic Hadrons @ D0 - Peter H. Garbincius - Fermilab - DPF 2017
D0: SL X5568

D0 Run II, 10.4 fb$^{-1}$ preliminary

no $\Delta R$ cut

- $B_s \rightarrow \mu D_s \nu X$
- $B_s \rightarrow J/\psi \phi$
- X5568
D0: SL X5568 – data fit

\[ F = f_{\text{sig}} F_{\text{sig}}(m, M_X, \Gamma_X) + f_{\text{bgr}} F_{\text{bgr}}(m) \]

\[ BW(m) \propto \frac{M_X^2 \Gamma(m)}{(M_X^2 - m^2)^2 + M_X^2 \Gamma^2(m)} \]

S-wave relativistic Breit-Wigner

\[ \Gamma(m) = \Gamma_X \cdot \left( \frac{q_1}{q_0} \right) \]

convoluted with Gaussian resolution

nominal \( F_{\text{bgr}}(m) \) function A (above) fitted to re-weighted BKGD Monte Carlo agrees well with \( D_s \) sidebands & wrong-sign \( \mu^\pm \pi^\pm \) backgrounds

\[ \sigma_{\text{SL}} = \left[ 3.85 + 60.93(m - m_{\text{th}})^{0.85} \right] \text{MeV/c}^2 \]

4-track + missing \( \nu \) components

see D0: SL X5568 details in backup slides: re-weighting MC and compare data & MC backgrounds and for Alternative BKGD fits B & C
Local Significance = \sqrt{-2 \ln \left( \frac{\mathcal{L}_0}{\mathcal{L}_{\text{max}}} \right)} = 4.5 \sigma

where \( \mathcal{L}_0 \) is for fit to null hypothesis = BKGD only
and \( \mathcal{L}_{\text{max}} \) is for fit with Signal + BKGD

Including systematic uncertainties, Significance \rightarrow 3.2 \sigma
### D0: SL X5568 – systematics uncertainties

<table>
<thead>
<tr>
<th>Source</th>
<th>mass, MeV/c²</th>
<th>width, MeV/c²</th>
<th>event yield, events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Background shape description</td>
<td>+0.0 ; −0.7</td>
<td>+0.7 ; −2.5</td>
<td>+4.8 ; −28.0</td>
</tr>
<tr>
<td>Background reweighting</td>
<td>+0.1 ; −0.1</td>
<td>+0.7 ; −0.7</td>
<td>+5.0 ; −5.0</td>
</tr>
<tr>
<td>$B_s^0$ mass scale, MC and data</td>
<td>+0.3 ; −0.5</td>
<td>+1.0 ; −1.4</td>
<td>+7.5 ; −9.6</td>
</tr>
<tr>
<td>Detector resolution</td>
<td>+0.0 ; −0.5</td>
<td>+1.3 ; −2.6</td>
<td>+3.7 ; −6.4</td>
</tr>
<tr>
<td>$P$-wave Breit-Wigner</td>
<td>+0.0 ; −0.2</td>
<td>+0.0 ; −2.4</td>
<td>+0.0 ; −7.0</td>
</tr>
<tr>
<td>Missing neutrino effect</td>
<td>+1.0 ; −0.0</td>
<td>−</td>
<td>−</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>+1.0 ; −1.0</td>
<td>+1.9 ; −4.6</td>
<td>+10.9 ; −31.5</td>
</tr>
</tbody>
</table>

see **D0: SL X5568 specifics** in backup slides for studies of alternative background shapes
**D0: SL X5568 – combine with Bs → J/ψ φ**

<table>
<thead>
<tr>
<th></th>
<th>Semileptonic no cone cut</th>
<th>Hadronic, cone cut</th>
<th>Hadronic, no cone cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted mass, MeV/c^2</td>
<td>5566.7^{+3.6}<em>{-3.4}^{+1.0}</em>{-1.0}</td>
<td>5567.8 ± 2.9^{+0.9}_{-1.9}</td>
<td>5567.8</td>
</tr>
<tr>
<td>Fitted natural width, MeV/c^2</td>
<td>6.0^{+9.5}<em>{-6.0}^{+1.9}</em>{-4.6}</td>
<td>21.9 ± 6.4^{+5.0}_{-2.5}</td>
<td>21.9</td>
</tr>
<tr>
<td>Fitted number of signal events</td>
<td>139^{+51}<em>{-63}^{+10.9}</em>{-31.5}</td>
<td>133 ± 31 ± 15</td>
<td>106 ± 23</td>
</tr>
<tr>
<td>Local significance</td>
<td>4.5σ</td>
<td>6.6σ</td>
<td>4.8σ</td>
</tr>
<tr>
<td>Significance with systematics</td>
<td>3.2σ</td>
<td>5.6σ</td>
<td></td>
</tr>
<tr>
<td>Significance with LEE+systematics</td>
<td>-</td>
<td>5.1σ</td>
<td>3.9σ</td>
</tr>
</tbody>
</table>

* Combine SL & Hadronic modes

* This combination uses

\[ p = p_{HAD} * p_{SL} [1 - \ln (p_{HAD} * p_{SL})] \]

which applies since HAD and SL measurement are independent:
- different trigger conditions: HAD = 2 \( \mu \), SL = 1 \( \mu \)
- different \( B_s \) channel: HAD = J/ψ φ, SL = \( \mu \) ν \( D_s \) X

* no LEE applied for semileptonic channel because we already know where X5568 is

(Not quoted in PRL)
D0: SL X5568 – fraction of $B_s$ from X5568

Determine inclusive # $B_s$ by fitting the $M(\phi \pi)$ distribution and correct by removing the prompt and the same sign $\mu^\pm D_s^\pm$

\[
\text{for } p_T(\mu^+ D_s^-) > 10 \text{ GeV and } 4.5 \text{ GeV} < M(\mu^+ D_s^-) \\
X \rightarrow B_s \pi/B_s = \rho(\text{SL}) = [7.3^{+2.8}_{-2.4} \text{ (stat)}^{+0.6}_{-1.7} \text{ (syst)}]\
\]

\textit{consistent with} prior $p_T(J/\psi \phi) > 10 \text{ GeV}$

\[
X \rightarrow B_s \pi/B_s = \rho(\text{HAD}) = [8.6 \pm 1.9 \text{ (stat)} \pm 1.4 \text{ (syst)}]\
\]

$\rho(\text{LHCb}) < 2.4\% @ 95\% \text{ CL} \quad \rho(\text{CMS}) < 3.9\% @ 95\% \text{ CL}
We have presented the results of a search for the $X(5568) \rightarrow B_s^0 \pi^\pm$ with semileptonic decays of the $B_s^0$ meson.

There is an excess of events in the data consistent with the decay $X(5568) \rightarrow B_s^0 \pi^\pm$ with $B_s^0 \rightarrow J/\psi \phi$.

The mass, natural width, and production rates in the semileptonic and hadronic channels are consistent.

The signal p-value for the semileptonic channel is $6.4 \times 10^{-4}$ and the significance is 3.2 $\sigma$ when including systematic uncertainties, but not including Look Elsewhere Effect.

The combined p-value for the hadronic and semileptonic channels is $5.6 \times 10^{-9}$ with a corresponding significance of 5.7 $\sigma$. 

D0: Search for exotic baryons decaying into $J/\psi \Lambda$

D0 Note 6494-CONF – March 22, 2017

https://www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B69/B69.pdf

analog of $LHCb P_c^+ \rightarrow J/\psi p$ discovered by LHCb in $\Lambda_b$ decays; theoretically expect states within 500 MeV of threshold, we search:

under a magnifying glass

e.g. $\Xi_b^- \rightarrow J/\psi \Lambda K^-$
**D0: J/ψ Λ search**

- **Prompt**
  - No signal
  - D0 Run II, 10.4 fb⁻¹, Preliminary
  - Data: Prompt J/ψ

- **Non-Prompt**
  - A hint?
  - Search range to \( M_{\text{threshold}} + 500 \text{ MeV} \)
  - D0 Run II, 10.4 fb⁻¹, Preliminary
  - Data: Non-prompt J/ψ

**Signal Shape**
- Gaussian with free width
- \( \langle M \rangle = 4319.3 \pm 6.6 \text{ MeV} \)
- \( \sigma = 15.6 \pm 7.7 \text{ MeV} \)
- Resolution ~ 5 MeV

**Fit Results**
- \( \chi^2/\#\text{df} = 26/41 \)
- \( N_x = 142 \pm 66 \text{ events} \)
- \( \text{fit } 805 \pm 61 \Lambda_b \text{ decays} \)
Same as prior slide (for reference)

Scan $<M_x>$, fit signal width, & bkgd shape

max local Significance of 3.45 $\sigma$ @ $M_x = 4.32$ GeV

local Significance $= \sqrt{-2 \ln(\frac{L_0}{L_{max}})}$

where $L_{max}$ is for signal + bkgd fit

$L_0$ is null hypothesis for bkgd only

global Significance $= 2.8 \sigma$
alternative background shapes using \( J/\psi \) & \( \Lambda \) mass sidebands

Sideband shapes give larger Significance so using free background shape gives the minimum Significance in terms of systematic variations. Also investigated non-rel. BW signal and ARGUS bkgd shapes.

**D0: \( J/\psi \Lambda \) search**

global Significance is 2.8 \( \sigma \), so cannot claim any evidence for a non-prompt signal in \( J/\psi \Lambda \)

a starting point for other searches by other experiments
Many Thanks to all who supported the Tevatron program over parts of 5 decades (1970’s thru present)

Peter
LHCb & CMS searches for X5568 $\rightarrow B_s \pi$

LHCb produced similar analysis (Phys. Rev. Lett. 117, 152003 (2016))
- First (quick) analysis performed for Moriond QCD 2016
- Final analysis for ICHEP
- $J/\psi \phi$ and $D_s \pi$ channels
- No signal observed
- Yield relative to $B_s$ smaller than 2.4% at 95% CL (to be compared to D0 measurement of 8%)

CMS has produced similar analysis for ICHEP (CMS-PAS-BPH-16-002)
- No signal observed
- Yield relative to $B_s$ smaller than 3.9% at 95%CL

Mystery why nothing is seen at LHC
- Problem in D0 analysis?
- Different production modes for $X$ and/or $B_s$?
  - 2 TeV vs 8 TeV
  - pp vs pp
**D0: Observation of a new $B_s^0 \pi^{\pm}$ state**

-6 MeV \[ Q = m(B_d^0 \pi) - m(B_d^0) - m(\pi) \] 394 MeV

$\Delta R < 0.3$

$B_d^0 \pi^+; \quad B_d^0 \rightarrow J/\psi K^{*0}$;

$J/\psi \rightarrow \mu^+ \mu^-; \quad K^{*0} \rightarrow K^+ \pi^-$

Cuts are very similar to $B_s^0 \pi^+$ analysis identical topology

Cone cut does not produce peaks

60 MeV \[ Q = m(B^+ \pi^-) - m(B^+) - m(\pi^-) \] 560 MeV

$m(B^+ \pi^-)$ with $B^+ \rightarrow J/\psi K^+$

D0 published paper:


Search for Exotic Hadrons @ D0 - Peter H. Garbincius - Fermilab - DPF 2017
**D0: Observation of a new $B_s^0 \pi^\pm$ state**

\[ X \rightarrow B_s^0 \pi^\pm \]

\[ B_s^0 \rightarrow J/\psi \phi \]

\[ J/\psi \rightarrow \mu^+ \mu^- \]

\[ \phi \rightarrow K^+ K^- \]

without $b\bar{b}$ tagging, can’t tell $B_s^0$ from $\bar{B}_s^0$

also could have \[ X \rightarrow B_s^{*0} \pi^\pm \]

with $B_s^{*0} \rightarrow B_s^0 + \text{missing } \gamma$
D0: Confirmation of the $X(5568)$ with the semileptonic decay of $B_s^0$

2016 supplementary material associated w PRL: Evidence for a new $\pi B_s$ state with $B_s \rightarrow J/\psi \phi$

fitted $M_x$ doesn’t vary with $\Delta R$ cut
**D0: Evidence for an exotic $B_s^0 \pi^\pm$ state**

Also baryonic pentaquarks

$P_c^+(4350)$ and $P_c^+(4450)$

$\rightarrow J/\psi \ p$

R. Aaij et al., (LHCb Collaboration)


---

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Process (decay mode)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>3871.68±0.17</td>
<td>&lt; 1.2</td>
<td>1++</td>
<td>$B \rightarrow K + (J/\psi \pi^+\pi^-)$</td>
<td>[32, 33, 34, 35]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$p\bar{p} \rightarrow (J/\psi \pi^+\pi^-) + ...$</td>
<td>[36, 37, 38, 39, 40]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K + (J/\psi \pi^+\pi^-)$</td>
<td>[41, 42]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K + (D^0\bar{D}^0\pi^0)$</td>
<td>[43, 44]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$B \rightarrow K + (J/\psi \gamma)$</td>
<td>[45, 46, 47]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\eta \rightarrow K + (\psi' \gamma)$</td>
<td>[45, 46, 47]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\eta \rightarrow K + (J/\psi \pi^+\pi^-)$</td>
<td>[48, 49]</td>
</tr>
<tr>
<td>$X(3915)$</td>
<td>3917.4±2.7</td>
<td>28^{+10}_{-9}</td>
<td>0++</td>
<td>$e^+e^- \rightarrow (J/\psi \omega)$</td>
<td>[50, 42]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$p\bar{p} \rightarrow (J/\psi \omega)$</td>
<td>[51, 52]</td>
</tr>
<tr>
<td>$X(3940)$</td>
<td>3942^{+3}_{-2}</td>
<td>37^{+7}_{-8}</td>
<td>0(?)+(?)</td>
<td>$e^+e^- \rightarrow (D^*D)$</td>
<td>[53]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow J/\psi$</td>
<td>[54]</td>
</tr>
<tr>
<td>$G(3900)$</td>
<td>3943±21</td>
<td>52±11</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma + (\omega)$</td>
<td>[55, 56]</td>
</tr>
<tr>
<td>$Y(4008)$</td>
<td>4008^{+49}_{-14}</td>
<td>226±97</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma + (J/\psi \phi)$</td>
<td>[57]</td>
</tr>
<tr>
<td>$Y(4140)$</td>
<td>4144±3</td>
<td>17±9</td>
<td>2?+</td>
<td>$B \rightarrow K + (J/\psi \phi)$</td>
<td>[58, 59, 60]</td>
</tr>
<tr>
<td>$X(4160)$</td>
<td>4156^{+29}_{-25}</td>
<td>139^{+13}_{-65}</td>
<td>0(?)+(?)</td>
<td>$e^+e^- \rightarrow J/\psi + (D^*D)$</td>
<td>[53]</td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>4263^{+8}_{-9}</td>
<td>95±14</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma + (J/\psi \pi^+\pi^-)$</td>
<td>[61, 62, 63, 57]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow (J/\psi \pi^+\pi^-)$</td>
<td>[64]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$e^+e^- \rightarrow (J/\psi \pi^+\pi^-)$</td>
<td>[65]</td>
</tr>
<tr>
<td>$Y(4360)$</td>
<td>4361±13</td>
<td>74±18</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma + (\psi' \pi^+\pi^-)$</td>
<td>[66]</td>
</tr>
<tr>
<td>$X(4630)$</td>
<td>4634^{+9}_{-11}</td>
<td>92^{+38}_{-22}</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma (\Lambda_c^+\Lambda_c^-)$</td>
<td>[67]</td>
</tr>
<tr>
<td>$Y(4660)$</td>
<td>4664±12</td>
<td>48±15</td>
<td>1--</td>
<td>$e^+e^- \rightarrow \gamma + (\psi' \pi^+\pi^-)$</td>
<td>[66]</td>
</tr>
<tr>
<td>$Z_c^+(3900)$</td>
<td>3890±3</td>
<td>33±10</td>
<td>1++</td>
<td>$Y(4260) \rightarrow \pi^- + (J/\psi \pi^+)$</td>
<td>[68, 69]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(4260) \rightarrow \pi^- + (D^*D)^+$</td>
<td>[70]</td>
</tr>
<tr>
<td>$Z_c^+(4020)$</td>
<td>4024±2</td>
<td>10±3</td>
<td>1(?)+(?)</td>
<td>$Y(4260) \rightarrow \pi^- + (h_c \pi^+)$</td>
<td>[71]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(4260) \rightarrow \pi^- + (D^*D)^+$</td>
<td>[72]</td>
</tr>
<tr>
<td>$Z_c^0(4020)$</td>
<td>4024±4</td>
<td>10±3</td>
<td>1(?)+(?)</td>
<td>$Y(4260) \rightarrow \pi^0 + (h_c \pi^0)$</td>
<td>[73]</td>
</tr>
<tr>
<td>$Z_c^+(4050)$</td>
<td>4051^{+24}_{-24}</td>
<td>82^{+51}_{-55}</td>
<td>2?+</td>
<td>$B \rightarrow K + (X_c1 \pi^+)$</td>
<td>[74, 75]</td>
</tr>
<tr>
<td>$Z_c^+(4200)$</td>
<td>4196^{+35}_{-32}</td>
<td>370^{+39}_{-49}</td>
<td>1++</td>
<td>$B \rightarrow K + (J/\psi \pi^+)$</td>
<td>[76]</td>
</tr>
<tr>
<td>$Z_c^+(4250)$</td>
<td>4248^{+35}_{-35}</td>
<td>177^{+21}_{-2}</td>
<td>2?+</td>
<td>$B \rightarrow K + (X_c1 \pi^+)$</td>
<td>[74, 75]</td>
</tr>
<tr>
<td>$Z_c^+(4430)$</td>
<td>4477±20</td>
<td>181±31</td>
<td>1++</td>
<td>$B \rightarrow K + (J/\psi \pi^+)$</td>
<td>[77, 78, 79, 80]</td>
</tr>
<tr>
<td>$Y_b(10890)$</td>
<td>10888.4±3.0</td>
<td>30.7^{+3.1}_{-2.7}</td>
<td>1--</td>
<td>$e^+e^- \rightarrow (\Upsilon(nS) \pi^+\pi^-)$</td>
<td>[81]</td>
</tr>
<tr>
<td>$Z_b^+(10610)$</td>
<td>10607.2±2.0</td>
<td>18.4±2.4</td>
<td>1++</td>
<td>$Y(5S) \rightarrow \pi^- + (\Upsilon(1,2,3S) \pi^+)$</td>
<td>[82, 83]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(5S) \rightarrow \pi^- + (h_b(1,2P) \pi^+)$</td>
<td>[82]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(5S) \rightarrow \pi^- + (B\bar{B}^*)^+$</td>
<td>[84]</td>
</tr>
<tr>
<td>$Z_b^0(10610)$</td>
<td>10609±6</td>
<td>1++</td>
<td></td>
<td>$Y(5S) \rightarrow \pi^0 + (\Upsilon(1,2,3S) \pi^0)$</td>
<td>[85]</td>
</tr>
<tr>
<td>$Z_b^+(10650)$</td>
<td>10652±1.5</td>
<td>11.5±2.2</td>
<td>1++</td>
<td>$Y(5S) \rightarrow \pi^- + (\Upsilon(1,2,3S) \pi^+)$</td>
<td>[82]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(5S) \rightarrow \pi^- + (h_b(1,2P) \pi^+)$</td>
<td>[82]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$Y(5S) \rightarrow \pi^- + (B\bar{B}^*)^+$</td>
<td>[84]</td>
</tr>
</tbody>
</table>

Search for Exotic Hadrons @ D0 - Peter H. Garbincius - Fermilab - DPF 2017
How well does the estimate:

\[ M(B_s^0 \pi^\pm) = M(\mu D_s \pi) - M(\mu D_s) + M_{PDG}(B_s^0) \]

work?

full MC simulation for “heavy B-meson”
decaying into Bs π with
input M = 5568 MeV and \( \Gamma = 0 \)

MC gives reconstructed:
\[ \langle M \rangle = 5565 \pm 1 \text{ MeV} \]
and Gaussian
\[ \sigma = 11.1 \pm 0.5 \text{ MeV} \]

generate 100% \( X(\rightarrow B_s + \pi) + n \pi \),
but no “accidentals” \( B_s + m \pi \)
**D0: SL X5568 - background**

BKGD Model – re-weighted PYTHIA – EVTGEN MC

for data – MC agreement using $p_T(\mu)$ and $p_T(\mu D_s)$ see SL specifics 3,4

compare with $D_s$ wrong sign & sideband bkgds

**DATA**

MC shape reproduces both the sideband and same (wrong) sign backgrounds very well

$D^+$ peak is $\sim 10\%$ of total sidebands
D0: SL X5568 – signal injection closure test

Add MC signal of Nin events to MC background (scaled to bkgd level in data) and find that fitted $N_{OUT} = N_{IN}$ as expected

Signal Injection test

\[ N_{OUT} \]

\[ N_{IN} \]

D0 Simulation
**D0: SL X5568 specifics:**

- Optimize cuts to minimize effect of missing neutrino and reduce size of background
- $D_s \rightarrow \phi \pi$ with $\phi \rightarrow K^+ K^-$, $p_T(K^\pm) > 1$ GeV
- $1.012 \, M(K K) < 1.030$ GeV for $\phi$
- $1.92 < M(\phi \pi) < 2.02$ GeV, $\pi$ charge opposite to $\mu$
- $D_s$ decay vertex separated from primary vertex by at least 3 $\sigma$ in transverse plane
- Add $\mu$ inconsistent with PV which verticizes with $D_s$ flight path
- $p_T(\mu) > 3$ GeV
- $4.5 < M(\mu \, D_s) < 5.4$ GeV to minimize effect of $\nu$
D0: SL X5568 specifics (2):

- Trajectories of $\mu$ and $D_s$ must be consistent with coming from common $B_s$ decay vertex
- Cosine of angle between $p(\mu D_s)$ and vector from primary vertex to $B_s$ decay vertex > 0.95
- $B_s$ decay vertex – primary vertex separation > 4 $\sigma$
- $p_T(\mu D_s)$ > 10 GeV
- $4.5 < M(\mu D_s) < 5.4$ GeV to minimize effect of $\nu$
- Impact parameters with respect to primary vertex:
  - 2D IP of $\mu \pi$ (from $D_s$) > 50 $\mu$m each
  - 3D IP of $\mu K^+ K^- \pi$ (from $D_s$) < 2 cm each
**D0: SL X5568 specifics (3):**

- Add $\pi^\pm$ from primary interaction vertex
- Form common $\pi^\pm B_s$ vertex consistent w PV
- Impact Parameters wrt primary vertex for $\pi^\pm$
  
  - 2D IP < 20 $\mu$m and 3D IP < 0.12 cm
- $p_T(\pi) > 0.5$ GeV for this $\pi^\pm$
- Reject events with > 20 $B_s$ $\pi$ candidates (light cut)
- Same cuts on this $\pi^\pm$ as for $X \rightarrow \pi B_s (\rightarrow J/\psi \ \phi)$
- model the X5568 as a heavy spin-0 $B$-meson in PYTHIA.
- re-weight MC to better agree with data
- Exclude signal region $5.55 < M(B_s \pi) < 5.60$ GeV in fit for Data/MC re-weighting ratio
- Weight($p_T(\mu)$, $p_T(\mu \ D_s)$) accounts for trigger and reconstruction efficiencies
**D0: SL X5568 specifics (4):**

re-weighting MC BKGD simulation:

- using $p_T(\mu)$ and $p_T(\mu D_s)$
- example of most extensive reweighting

reweighting brings data and MC into better agreement low $M(B_s \pi)$

![Graph showing $p_T(B_s \pi)$ and $M(B_s \pi)$ distributions with data and MC curves](image-url)
D0: SL X5568 specifics (5):

Parameterizations of shape of MC Background

A: *nominal* – goes to zero at threshold

\[
F_{bgr}(m) = (C_1m_0 + C_2m_0^2 + C_3m_0^3 + C_4m_0^4) \exp(C_5m_0 + C_7m_0^2)
\]

\[m_0 = m(B_s \pi) - 5.506 \text{ GeV}\]

B: same as used in \(X \to \pi B_s (B_s \to J/\psi \phi)\) PRL

\[
F_{bgr}(m) = (C_1 + C_2m_\Delta^2 + C_3m_\Delta^3 + C_4m_\Delta^4) \exp(C_5 + C_6m_\Delta + C_7m_\Delta^2)
\]

\[m_\Delta = m(B_s \pi) - 5.500 \text{ GeV}\]

C: ARGUS – for behavior near mass threshold

\[
F_{bgr}(m) = m \left( \frac{m^2}{m_{th}^2} - 1 \right)^{C_1} \exp(C_2m)
\]

D: use *smoothed* MC histogram shape directly

\[N_i^{smooth} = 0.25 \ N_{i-1} + 0.5 \ N_i + 0.25 \ N_{i+1}\]
**D0: SL X5568 (6): MC BKGD shape fit**

A: nominal

B: prior PRL shape

C: ARGUS

A: 

\[ F_{bgr}(m) = \left( C_1 m_0 + C_2 m_0^2 + C_3 m_0^3 + C_4 m_0^4 \right) \exp \left( C_5 m_0 + C_7 m_0^2 \right) \]

\[ m_0 = m(B_s \pi) - 5.506 \text{ GeV} \]

D: smoothed MC

Search for Exotic Hadrons @ D0 - Peter H. Garbincius - Fermilab - DPF 2017
**D0: SL X5568 (7): check various fits**

TABLE V. Fit results for Parametrization (6), the nominal fit, with all parameters free and the mass and width fixed to those of the hadronic channel.

<table>
<thead>
<tr>
<th></th>
<th>Nominal Fit</th>
<th>All Parameters free</th>
<th>Mass and Width Fixed to Hadronic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fitted mass, MeV/c^2</td>
<td>5566.7±3.6</td>
<td>5566.6 ± 3.5</td>
<td>5567.8</td>
</tr>
<tr>
<td>Fitted width, MeV/c^2</td>
<td>6.0±0.5</td>
<td>8.4 ± 14.5</td>
<td>21.9</td>
</tr>
<tr>
<td>Fitted number of signal events</td>
<td>138.6±50.8</td>
<td>143.7 ± 101.1</td>
<td>168 ± 42</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>30.4/(50 − 4)</td>
<td>27.4/(50 − 10)</td>
<td>32.8/(50 − 2)</td>
</tr>
<tr>
<td>Local significance</td>
<td>4.5(\sigma)</td>
<td>4.4(\sigma)</td>
<td>4.2(\sigma)</td>
</tr>
</tbody>
</table>

**FIG. 32.** or Parametrization (6), the nominal fit, (a) with all parameters free and (b) the mass and width fixed to those of the hadronic channel.
**D0: J/ψ Λ search specifics (1):**

- LHCb discovered two $P_c^+(J/ψ p)$ resonances in $Λ_b \rightarrow J/ψ p K^-$ decays, at 4380 and 4450 MeV, interpreted as (c c-bar u d s) Pentaquarks.
- D0 used both single- and di-muon triggers.
- Muons: $p_T(μ) > 1.0$ GeV/c, $2.92 < M(μμ) < 3.25$ GeV.
- Lambda: assume lower $p_T$ particle is $π$.
  - "extended tracking" to increase $Λ$ acceptance
    - $p_T(π) > 0.15$ GeV (usually $0.5$ GeV)
    - $p_T(Λ) > 0.7$ GeV (usually $1.8$ GeV)
    - $|η(Λ)| < 2.5$
**D0: J/ψ Λ search specifics (2):**

- Lowered pT(Λ) cut increases backgrounds due to $\gamma \rightarrow e^+ e^-$ conversions in material, cut by require KE released in decay $Q > 0.07$ GeV

- To reduce random backgrounds, require Λ decay vertex to be 0.5-30 cm from J/ψ vertex and point back to J/ψ vertex with cosine of pointing angle $> 0.9999$
Accept J/ψ if $2.92 < M(\mu\mu) < 3.25$ GeV
Accept Λ if $1.110 < M(p\pi) < 1.122$ GeV
Reject Λ candidates if $0.48 < M(\pi\pi) < 0.52$ GeV
\[ N(X_{4320}) = \sigma^*B(X_{4320} \rightarrow J/\psi \Lambda) \times \epsilon_{\text{eff}}(M < 4.7 \text{ GeV}) \]
\[ N(\Lambda_{b}^0) = \sigma^*B(\Lambda_{b}^0 \rightarrow J/\psi \Lambda) \times \epsilon_{\text{eff}}(M(\Lambda_{b}^0 )) \]
\[ \sigma^*B(X_{4320} \rightarrow J/\psi \Lambda) = \frac{N(X_{4320})}{\epsilon_{\text{eff}}(M < 4.7 \text{ GeV})} \]
\[ \sigma^*B(\Lambda_{b}^0 \rightarrow J/\psi \Lambda) = \frac{N(\Lambda_{b}^0)}{\epsilon_{\text{eff}}(M(\Lambda_{b}^0 ))} \]

\[ N(X_{4320}) = 142 \pm 66 \]
\[ N(\Lambda_{b}^0) = 805 \pm 61 \]
\[ \epsilon_{\text{eff}}(M < 4.7 \text{ GeV})/\epsilon_{\text{eff}}(M(\Lambda_{b}^0 )) = 1.0 \pm 0.1 \]
\[ \sigma^*B(X_{4320} \rightarrow J/\psi \Lambda) = 17.5\% \pm 8.4\% \]
\[ \sigma^*B(\Lambda_{b}^0 \rightarrow J/\psi \Lambda) \]

Combining the \( \Lambda \) and \( J/\psi \) efficiencies, we estimate the ratio of detection efficiency of the \( J/\psi \Lambda \) system in the search region of \( M < 4.7 \text{ GeV} \) and at \( M = M_{\Lambda} \) to be \( 1.0 \pm 0.1 \).