Spectroscopy of Exotic Hadrons

Sebastian Neubert

Heidelberg University

Confinement 2016, Aug 29th - Sept. 3rd, 2016, Thessaloniki
Experimental Efforts on Charmonium-like Exotics

Spectroscopy of Exotic Hadrons

Confinement 2016
Production Processes

- **B decays**

- **Initial state radiation/e^+e^-**

- **Double charmonium production**

- **γγ-fusion**

- **Decays of Y(4260) and higher charmonia**

- **p\bar{p} inclusive**

- **pp inclusive**

- **(virtual) photo production**
<table>
<thead>
<tr>
<th>Decay</th>
<th>States</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>X(3872)</td>
</tr>
<tr>
<td>$\psi (2S) \pi^+ \pi^-$</td>
<td>Y(4360) Y(4660)</td>
</tr>
<tr>
<td>$\Lambda_c^+ \Lambda_c$</td>
<td>Y(4630)</td>
</tr>
<tr>
<td>$J/\psi \gamma$</td>
<td>X(3872)</td>
</tr>
<tr>
<td>$\chi_{c1}(1P) \gamma$</td>
<td>X(3832)</td>
</tr>
<tr>
<td>$\chi_{c1}(1P) \omega$</td>
<td>Y(4220)</td>
</tr>
<tr>
<td>$J/\psi \omega$</td>
<td>X(3872) Y(3940) X(3915)</td>
</tr>
<tr>
<td>$J/\psi \phi$</td>
<td>X(4140) X(4274) X(4500) X(4700) X(4350)</td>
</tr>
<tr>
<td>$J/\psi \pi$</td>
<td>Z(4430) Z(4200) Z(4240)</td>
</tr>
<tr>
<td>$\psi (2S) \pi$</td>
<td>Z(4430)</td>
</tr>
<tr>
<td>$\chi_{c1}(1P) \pi$</td>
<td>Z(4051) Z(4248)</td>
</tr>
<tr>
<td>$h_{c}(1P) \pi$</td>
<td>Z(4020)</td>
</tr>
<tr>
<td>$D \bar{D}$</td>
<td>Z(3930)</td>
</tr>
<tr>
<td>$D \bar{D}^*$</td>
<td>X(3872) X(3940) Z(3885)</td>
</tr>
<tr>
<td>$D^* \bar{D}$</td>
<td>X(4160) Z(4025)</td>
</tr>
<tr>
<td>$J/\psi p$</td>
<td>$P_c(4380)$ $P_c(4430)$</td>
</tr>
<tr>
<td>$B_s^0 \pi$</td>
<td>X(5568) -</td>
</tr>
</tbody>
</table>
The $X(3872)$

- **Belle**
  - $B$ decays

- **BaBar**
  - $B$ decays

- **LHCb**
  - $\psi'$
  - $X(3872)$

- **CDF-II**
  - Inclusive
  - $\psi'$
  - $X(3872)$

- **D0**
  - Inclusive

- **CMS**
  - Inclusive
  - $\psi'$
  - $X(3872)$
Status of the $X(3872)$

- $J^{PC} = 1^{++}$ established
  

- Mass $m = 3871.69 \pm 0.17$ MeV (in $X(3872) \to J/\psi \ X$ decays)

- $D\bar{D}^*$ threshold: $3871.81 \pm 0.09$ MeV

- Mass difference $m_X - m_{J/\psi} = 775 \pm 4$ MeV

- Width $\Gamma < 1.2$ MeV Belle [PRD84(2011)052004]

- Mass and decay mode disfavor $c\bar{c}$ state.

- $J^{PC} = 1^{++}$: $D^0D^*$ molecule, Tetra-quark

- No charged partner, no $C = -1$ partner found
  
  - $X \to J/\psi \pi^+ \pi^0$ Belle[PRL111(2013)032001],BaBar[PRD71(2005)031501]
  
  - $X \to J/\psi \eta$ Belle[PTEP(2014)043C01],Belle[PRL111(2013)032001]
### X(3872) decays

#### Approx. product branching fractions

<table>
<thead>
<tr>
<th>Branching Fraction</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow D^+ D^-)$</td>
<td>$\sim 1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow J/\psi \pi \pi)$</td>
<td>$\sim 1 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow J/\psi \omega)$</td>
<td>$0.6 \times 10^{-5}$</td>
</tr>
<tr>
<td>$\mathcal{B}(B \rightarrow KX) \times \mathcal{B}(X \rightarrow J/\psi \gamma)$</td>
<td>$\sim 2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$\frac{\mathcal{B}(X \rightarrow \psi(2S) \gamma)}{\mathcal{B}(X \rightarrow J/\psi \gamma)}$</td>
<td>$\sim 2 - 3$</td>
</tr>
</tbody>
</table>

#### Isospin violation

- Allowed in molecule picture
  - [PLB742(2015)394]
  - [EPJ C75(2015)26]

#### NEW

- $1607.06446$

for a more details and precise values see the review [arXiv:1601.02092](https://arxiv.org/abs/1601.02092)
**X(3872) production**

- **Expectation:** Production of loosely bound hadronic molecules in high energy hadronic collisions suppressed [PRL103(2009)162001]

- **COMPASS** showed preliminary results for virtual photo production
  
  J. Bernhard, @ Baryon2016

---

See talks by F. Navarra, F. Carvalho and L. Cristello in Sec. C, Thur. afternoon
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- **Expectation:** Production of loosely bound hadronic molecules in high energy hadronic collisions suppressed [PRL103(2009)162001]

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**Graph Description:****

- **Deuteron @ALICE**
- **Helium-3 @ALICE** (rescaled from Pb-Pb)
- **X(3872) @CMS**
- **Hypertriton @ALICE** (rescaled from Pb-Pb)

**Plot Parameters:****

- **Legend:**
  - \( R_{AA} = 1 \)
  - \( R_{AA} = 5 \)

**Axes:**

- **Y-axis:** \( \frac{d\sigma}{dp_{\perp}} \) (nb/GeV)
- **X-axis:** \( p_{\perp} \) (GeV)

**Data Points:**

- Various experimental data points for different reactions.
Exotic vector mesons

Belle, BaBar
(running on $\Upsilon$ resonance)

BESIII
($\sqrt{s}$ scan)
<table>
<thead>
<tr>
<th>Resonance</th>
<th>p¯p incl.</th>
<th>pp incl.</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>X(3872)</td>
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</tr>
<tr>
<td>$\psi(2S) \pi^+ \pi^-$</td>
<td>Y(4260)</td>
<td>Y(4008)</td>
</tr>
<tr>
<td>$\Lambda_c \bar{\Lambda}_c$</td>
<td>Y(4630)</td>
<td></td>
</tr>
<tr>
<td>$\psi \gamma$</td>
<td>X(3872)</td>
<td></td>
</tr>
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<td>$X_{c1}(1P) \gamma$</td>
<td>X(3832)</td>
<td></td>
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<tr>
<td>$X_{c1}(1P) \omega$</td>
<td>Y(4220)</td>
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</tr>
<tr>
<td>$J/\psi \phi$</td>
<td>X(4140)</td>
<td>X(4350)</td>
</tr>
<tr>
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<td>Z(4430)</td>
<td>Z(3900)</td>
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<td>$\psi(2S) \pi$</td>
<td>Z(4420)</td>
<td></td>
</tr>
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<td>Z(4051)</td>
<td>Z(4020)</td>
</tr>
<tr>
<td>$h_{c}(1P) \pi$</td>
<td>Z(4248)</td>
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<td>$D \bar{D}$</td>
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<td>Z(3930)</td>
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<td>X(3940)</td>
</tr>
<tr>
<td>$D^+ \bar{D}^*$</td>
<td></td>
<td>X(4160)</td>
</tr>
<tr>
<td>$J/\psi p$</td>
<td>$P_c(4380)$</td>
<td></td>
</tr>
<tr>
<td>$B_s^0 \pi$</td>
<td></td>
<td>X(5568)</td>
</tr>
</tbody>
</table>
An overpopulation of $J^{PC} = 1^{--}$ states

- 7-9 vector states above $D\bar{D}$ threshold!
- $Y(4008)$ only seen by Belle
- All other states well established
- $Y(4260)$: no decay via $\psi' \pi \pi$
- $Y(4350)$: no decay via $J/\psi \pi \pi$
- $Y(4260)$ a source of exotic mesons (see later)
- Models: Tetraquark, Hadrocharmonium, Molecule, Hybrid

$Y(4630)$ in $\Lambda_c \bar{\Lambda}_c$
Charged exotic mesons - the Z states
<table>
<thead>
<tr>
<th>Charged exotic mesons</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>( J/\psi \pi^+ \pi^- )</td>
</tr>
<tr>
<td>( \psi(2S)\pi^+ \pi^- )</td>
</tr>
<tr>
<td>( \Lambda_c\Lambda_c )</td>
</tr>
<tr>
<td>( \psi \gamma )</td>
</tr>
<tr>
<td>( \chi_{c1}(1P)\gamma )</td>
</tr>
<tr>
<td>( \chi_{c1}(1P)\omega )</td>
</tr>
<tr>
<td>( J/\psi \omega )</td>
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</tr>
<tr>
<td>( D^{*}D )</td>
</tr>
<tr>
<td>( J/\psi P )</td>
</tr>
<tr>
<td>( B_{s}^{0}\pi )</td>
</tr>
</tbody>
</table>
The $Z(4430)^-$

- $Z(4430)^-$ has first been claimed by Belle in $B \to K(\pi^-\psi(2S))$
- Minimal quark content: $c\bar{c}d\bar{u}$
- BaBar could explain this through reflections of the $K\pi$ system ($K^*$)
- Amplitude analysis by Belle confirms new state (assuming a resonant shape)

Belle data

PRL 100(2008)142001
Charged exotic mesons

\[ B \rightarrow K \pi^- \psi(2S) \] at LHCb

Data sample:
- \( \sim 25,000 \ B \rightarrow K \pi^- \psi(2S) \) candidates
  in \( 3 \ fb^{-1} \) at LHCb

2 Analysis methods:
- 4D amplitude analysis a’la Belle
  extract resonant phase
  establish \( J^P = 1^+ \)
  [PRL112(2014)222002]

- Moments analysis a’la BaBar
  model independent
  confirms existence of \( \text{Z}(4430) \)
  [PRD92(2015)112009]
Charged exotic mesons

$\bar{B} \rightarrow K^- \pi^+ J/\psi$ at Belle

- $30,000 \bar{B} \rightarrow K^- \pi^+ J/\psi$ decays ($711 \text{ fb}^{-1}$)
- 4D amplitude analysis

- Adding $Z(4430)$ improves fit significance: $4.0\sigma$
- Adding $Z(4200)$ further improvement significance: $6.2\sigma$

- $Z(4430)$ with $J^P = 1^+$ confirmed
- $Z(4200)$ with $J^P = 1^+$ observed
Resonant nature established

\[
\begin{array}{c|c|c}
\text{Source} & M [\text{MeV}] & \Gamma [\text{MeV}] \\
\hline
\text{LHCb} & 4475 \pm 7^{+15}_{-25} & 172 \pm 13^{+37}_{-34} \\
\text{Belle} & 4485 \pm 22^{+28}_{-11} & 200^{+41}_{-46} \pm 26^{+37}_{-46} \\
\text{Belle} & 4196^{+30}_{-29} \pm 17 & 370^{+70}_{-70} \pm 172^{+37}_{-34} \\
\end{array}
\]

Both have \( J^P = 1^+ \)

- Positive parity rules out S-wave molecules
  - \( \bar{D}^*(2007)D_1^+(2420) \) and \( \bar{D}^*(2007)D_2^+(2460) \)

Candidate for a tetraquark

Rescattering effect?

**The \( Z(4240) \) at LHCb**

LHCb data can be fit including a second state with \( J^P = 0^- \) and \( M = 4239 \pm 18^{+45}_{-10} \) MeV

But in this fit \( \Gamma(Z(4430)) = 660 \pm 150 \) MeV

But: wrong sense of phasemotion

[PLB748(2015)183]
Charged exotic mesons

Charged exotics in $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1}(1P)$?

Belle \cite{PRD78(2008)072004}

with $Z(4051)$ and $Z(4248)$

BaBar \cite{PRD85(2012)052003}

No exotics needed
Charged exotic mesons

Charged exotics in $\bar{B}^0 \rightarrow K^- \pi^+ \chi_{c1}(1P)$?

Belle [PRD78(2008)072004]

with $Z(4051)$ and $Z(4248)$

BaBar [PRD85(2012)052003]

No exotics needed

Waiting for data

LHCb and BelleII
The Y(4260) as a source of exotic mesons at BESIII

MARK I, 1977
\[ e^+e^- \rightarrow \psi' \]
\[ \rightarrow J/\psi \pi^+ \pi^- \]
\[ \sqrt{s}=3868 \text{ MeV} \]

BESIII, 2013
\[ e^+e^- \rightarrow Y(4260) \]
\[ \rightarrow J/\psi \pi^+ \pi^- \]
\[ \sqrt{s}=4260 \text{ MeV} \]
Charged exotic mesons

**Z states in** $e^+e^- \rightarrow Y(4260) \rightarrow Z\pi$ decays at BES III

- $Z_c(3900)$
- $J/\psi\pi^\pm$
- $Z_c(3885)$
- $D^0D^{*-}$
- $Z_c(4020)$
- $h_c\pi^\pm$
- $Z_c(4025)$
- $D^{0*}D^{*-}$
**Z states in** $e^+e^- \rightarrow Y(4260) \rightarrow Z\pi$ **decays at BES III**

Are these one state?

- Masses / widths match
- Right above $DD^*$ threshold
- Decay into $D^0D^{*-}$ favoured
  
  \[ R = 6.2 \pm 1.1 \pm 2.7 \]
  
  similar to $X(3872)$

- Kinematic cusp effect?
  
  excluded due to signal in elastic channel [PRD91(2015)051504]
Are these one state?

- Masses / widths match
- Right above $D^*\overline{D}^*$ threshold
- Decay into $D^*\overline{D}^*$ favoured $R = 12 \pm 5$
- Kinematic cusp effect? excluded due to signal in elastic channel [PRD91(2015)051504]
There are neutral partners to the $Z_c$!

$Z_c(3900)^0$ \(J/\psi\pi^0\)

See talks in Sec. C.

by

B. Liu’s

F. Aceti

M. Albaladejo

F. K. Guo
Resonances decaying to $J/\psi \phi$
### Resonances in $J/\psi \phi$

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Symbols</th>
<th>Masses</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>$X(3872)$, $Y(4260)$, $Y(4008)$</td>
<td>$X(3872)$, $X(3872)$</td>
</tr>
<tr>
<td>$\psi(2S) \pi^+ \pi^-$</td>
<td>$Y(4360)$, $Y(4660)$</td>
<td></td>
</tr>
<tr>
<td>$\Lambda_c \bar{\Lambda}_c$</td>
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</tr>
<tr>
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<td>$X(3832)$</td>
<td></td>
</tr>
<tr>
<td>$X_{c1}(1P) \omega$</td>
<td></td>
<td>$Y(4220)$</td>
</tr>
<tr>
<td>$J/\psi \omega$</td>
<td>$X(3872)$, $Y(3940)$</td>
<td>$X(3915)$</td>
</tr>
<tr>
<td>$J/\psi \phi$</td>
<td>$X(4140)$, $X(4274)$, $X(4500)$, $X(4700)$</td>
<td>$X(4350)$</td>
</tr>
<tr>
<td>$J/\psi \pi$</td>
<td>$Z(4430)$, $Z(4200)$, $Z(4240)$</td>
<td>$Z(3900)$</td>
</tr>
<tr>
<td>$\psi(2S) \pi$</td>
<td>$Z(4430)$</td>
<td></td>
</tr>
<tr>
<td>$X_{c1}(1P) \pi$</td>
<td>$Z(4051)$, $Z(4248)$</td>
<td></td>
</tr>
<tr>
<td>$h_{c1}(1P) \pi$</td>
<td></td>
<td>$Z(4020)$</td>
</tr>
<tr>
<td>$D \bar{D}$</td>
<td></td>
<td>$Z(3930)$</td>
</tr>
<tr>
<td>$D \bar{D}^*$</td>
<td>$X(3872)$</td>
<td>$X(3940)$, $Z(3885)$</td>
</tr>
<tr>
<td>$D^* \bar{D}^*$</td>
<td></td>
<td>$Z(4025)$</td>
</tr>
<tr>
<td>$J/\psi p$</td>
<td>$P_c(4380)$, $P_c(4430)$</td>
<td></td>
</tr>
<tr>
<td>$B_{s0} \pi$</td>
<td></td>
<td>$X(5568)$, $-$</td>
</tr>
</tbody>
</table>

**Notes:**
- $\Lambda_c \bar{\Lambda}_c$ refers to the charm anticharm pair.
- $X(3872)$ and $X(4140)$ are known as charmonium resonances.
- $Z$-mesons are vector mesons.
- $D$ and $D^*$ are heavy quarkonia states.
- $B_{s0}$ is a bottom quarkonia state.
Narrow resonances in $J/\psi \phi$ (from B-decays)

- Narrow structures in $J/\psi \phi$ discovered by CDF in 2008
- Subsequent observations by D0 and CMS
- BaBar, Belle and LHCb ($0.37 \text{ fb}^{-1}$): no significant signal

[Averages]

<table>
<thead>
<tr>
<th></th>
<th>$M \text{ [MeV]}$</th>
<th>$\Gamma \text{ [MeV]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(4140)$</td>
<td>$4143.4 \pm 1.9$</td>
<td>$15.7 \pm 6.3$</td>
</tr>
<tr>
<td>$X(4274)$</td>
<td>$4293 \pm 20$</td>
<td>$35 \pm 16$</td>
</tr>
</tbody>
</table>

- No amplitude analysis so far
- CDF/CMS $X(4274)$ mass measurements disagree at $3.16\sigma$
A $J/\psi\phi$ resonance in $\gamma\gamma$ fusion

- Belle searched for the $X(4140)$ in $\gamma\gamma \to J/\psi\phi$
- No events were found close to threshold
- Instead a peak with $3.2\sigma$ significance at
  
  $$ m = 4350.6^{+4.6}_{-5.1} \pm 0.7 \text{ MeV} \quad \text{and} \quad \Gamma = 13^{+18}_{-9} \pm 4 \text{ MeV} $$

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$\Gamma_{\gamma\gamma}(X) \times B(X \to J/\psi\phi) \text{[eV]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^+$</td>
<td>$6.7^{+3.2}_{-2.4} \pm 1.1$</td>
</tr>
<tr>
<td>2$^+$</td>
<td>$1.5^{+0.7}_{-0.6} \pm 0.3$</td>
</tr>
</tbody>
</table>
Resonances in $J/\psi \phi$

LHCb: $B^+ \to J/\psi \phi K^+$ amplitude analysis

- **3 fb$^{-1}$ yield** $4289 \pm 151$
- **7 $K^*$ resonances**
  + non-resonant $\phi K$ amplitude
- **4 exotic resonances in $J/\psi \phi$**
- Fit quality on Dalitz-Plot: $p_{2D} = 17\%$
- No $J/\psi K$ resonances needed
Results for $X(4140)$, $X(4274)$, $X(4500)$ & $X(4700)$

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>signi</th>
<th>$J^{PC}$</th>
<th>signi</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(4140)$</td>
<td>4146.5 ± 4.5$^{+4.6}_{-2.8}$</td>
<td>83 ± 21$^{+21}_{-14}$</td>
<td>8.4$\sigma$</td>
<td>1$^{++}$</td>
<td>5.7$\sigma$</td>
</tr>
<tr>
<td>$X(4274)$</td>
<td>4273.3 ± 8.3$^{+17.2}_{-3.6}$</td>
<td>56.2 ± 10.9$^{+8.4}_{-11.1}$</td>
<td>6.0$\sigma$</td>
<td>1$^{++}$</td>
<td>5.8$\sigma$</td>
</tr>
<tr>
<td>$X(4500)$</td>
<td>4506 ± 11$^{+12}_{-15}$</td>
<td>92 ± 21$^{+21}_{-20}$</td>
<td>6.1$\sigma$</td>
<td>0$^{++}$</td>
<td>4.0$\sigma$</td>
</tr>
<tr>
<td>$X(4700)$</td>
<td>4704 ± 10$^{+14}_{-24}$</td>
<td>120 ± 31$^{+42}_{-33}$</td>
<td>5.6$\sigma$</td>
<td>0$^{++}$</td>
<td>4.5$\sigma$</td>
</tr>
</tbody>
</table>

- $X(4140)$ & $X(4274)$ confirmed but with larger width than previous analyses
- First evidence of two new states $X(4500)$ and $X(4700)$
- Large contribution from $K^*$ resonances, including first observation of $K^*(1680) \rightarrow K^+ \phi$
- Non-resonant contribution in $0^{++}$ amplitude.
Resonances in $J/\psi \phi$

$D_s D_s^*$ cusp amplitudes

- $D_s^* D_s^*$ cusp-amplitudes included in fit
  - $X(4140)$ favours $D_s D_s^*$ cusp by $\Delta (-2 \ln \mathcal{L}) = 3.0^2$
  - $X(4274)$ resonance fav. over $J^P = 0^-$ cusp
  - Many cusps at higher masses, needs future investigation

[arXiv:1606.07898]
[arXiv:1606.07895]

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Status of $J/\psi \phi$ resonances

<table>
<thead>
<tr>
<th>State</th>
<th>$M$ [MeV]</th>
<th>$\Gamma$ [MeV]</th>
<th>$M_{LHCb}$ [MeV]</th>
<th>$\Gamma_{LHCb}$ [MeV]</th>
<th>$J^{PC}$</th>
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<td>$4146.5 \pm 4.5^{+4.6}_{-2.8}$</td>
<td>$83 \pm 21^{+21}_{-14}$</td>
<td>$1^{++}$</td>
</tr>
<tr>
<td>$X(4274)$</td>
<td>$4293 \pm 20$</td>
<td>$35 \pm 16$</td>
<td>$4273.3 \pm 8.3^{+17.2}_{-3.6}$</td>
<td>$56.2 \pm 10.9^{+8.4}_{-11.1}$</td>
<td>$1^{++}$</td>
</tr>
<tr>
<td>$X(4350)$</td>
<td>$4350.6^{+4.6}_{-5.1} \pm 0.7$</td>
<td>$13^{+18}_{-9} \pm 4$</td>
<td></td>
<td></td>
<td>$0^+$ or $2^+$</td>
</tr>
<tr>
<td>$X(4500)$</td>
<td></td>
<td></td>
<td>$4506 \pm 11^{+12}_{-15}$</td>
<td>$92 \pm 21^{+21}_{-20}$</td>
<td>$0^{++}$</td>
</tr>
<tr>
<td>$X(4700)$</td>
<td></td>
<td></td>
<td>$4704 \pm 10^{+14}_{-24}$</td>
<td>$120 \pm 31^{+42}_{-33}$</td>
<td>$0^{++}$</td>
</tr>
</tbody>
</table>

- $J^{PC} = 1^{++}$ assignment of $X(4140)$ and $X(4274)$ consistent with non-observation in $\gamma \gamma$ fusion
- Are $X(4350)$ and $X(4500)$ the same state? masses and widths don’t match well
- $X(4140)$ consistent with $D_s D_s^*$ cusp

$X(4140)$ at CMS see L. Cristella, Sec. C, Thu. 17:40
The $B^0_s \pi^+$ System
A resonance in $B_s^0 \pi^+$ at DØ

Peaking structure found by DØ

Applying a cut $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$

- $5582 \pm 100 B_s^0 \rightarrow J/\psi \phi$ candidates
- significance: $3.9\sigma$ (incl. LEE)
A resonance in $B_s^0\pi^+$ at DØ

Peaking structure found by DØ

Applying a cut $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$

- $p_T > 10$ GeV

$\sigma$:

- $5582 \pm 100 B_s^0 \rightarrow J/\psi \phi$ candidates
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- $5.1\sigma$ significance after "cone"-cut
- $(8.6 \pm 1.9 \pm 1.4)$% of $B_s^0$ from X(5568)
A resonance in $B_s^0\pi^+$ at $D\phi$

Peaking structure found by $D\phi$

Applying a cut $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2} < 0.3$

$B_s^0\pi^+$

News at ICHEP

Similar result with $B_s^0 \to D_s\mu\nu$

consistent resonance parameters, rate awaiting publication

- $5582 \pm 100 \ B_s^0 \to J/\psi \phi$ candidates
- significance: $3.9\sigma$ (incl. LEE)
- $5.1\sigma$ significance after "cone"-cut
- $(8.6 \pm 1.9 \pm 1.4)\%$ of $B_s^0$ from $X(5568)$

$\rho_T > 10 \ GeV$
A four-flavour Tetraquark?

- Valence quark content $b\bar{s}u\bar{d}$

- How would such a state be generated/composed?
  - Tetraquark
  - $B_s^0\pi$, BK molecule
  - $B_s^*\pi$ cusp,
  - Nearest 2-body threshold: $B_s^*\pi$ @ 5555 MeV

- All models have troubles explaining the $X(5568)$
  [CTP65(2016)593][PLB760(2016)627]

- Can it be confirmed by other experiments?
Search for $X(5568)$ at the LHC

LHCb: $50k \, B_s^0 \rightarrow J/\psi \, \phi$ combined with $70k \, B_s^0 \rightarrow D_s \, \pi$ candidates

Limit on cross-section times branching fraction ratio at 90(95)% C.L.

$$\rho_X = \frac{\sigma(pp \rightarrow X + \text{anything}) \times B(X \rightarrow B_s^0 \pi^\pm)}{\sigma(pp \rightarrow B_s^0 + \text{anything})}$$

$$\rho_X^{\text{LHCb}}(p_T > 10 \, \text{GeV}) < 0.021(0.024)$$
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$$\rho_X^{LHCb}(p_T > 10 \, \text{GeV}) < 0.021(0.024)$$

News from CMS at ICHEP

$$\rho_X^{CMS} < 0.039 \quad @95\% \text{C.L.}$$

see L. Cristella, Sec. C, Thu. 17:40
X(5568) Experimental Status

- **Seen by D0 in** $p\bar{p} \to (B^0_s \pi) + \text{anything}$
  - with $B^0_s \to J/\psi \phi$
  - with $B^0_s \to D_s \mu \nu$
  - $\rho^{p\bar{p}}_X = (8.6 \pm 1.9 \pm 1.4)\%$

- **Not seen at the LHC** $pp \to (B^0_s \pi) + \text{anything}$
  - LHCb in $B^0_s \to J/\psi \phi$ and $B^0_s \to D_s \pi$
  - CMS in $B^0_s \to J/\psi \phi$
  - $\rho^{pp}_X < 2.4\% \ \@ 95\% \text{C.L. (LHCb)}$

- A word from CDF?
Baryon Resonances with Hidden Charm

\[ \Lambda_b \rightarrow J/\psi pK \]
Exotic Baryon Resonances

Discovery of $J/\psi p$ baryon resonances at LHCb

Three analyses performed:

- $\Lambda_b \rightarrow J/\psi p K$
  - 26,000 $\Lambda_b$ candidates
  - 6D amplitude analysis
    [PRL115(2015)072001]
  - moments analysis
    [PRL117(2016)082002]

- $\Lambda_b \rightarrow J/\psi p \pi$
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    [PRL117(2016)082003]
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    [PRL117(2016)082003]
Exotic Baryon Resonances

Amplitude Analysis of $\Lambda_b \to J/\psi \, p \, \pi^-$

Challenges:

- Cabibbo suppr.
  \[
  \frac{\mathcal{B}(\Lambda_b \to J/\psi p \pi^-)}{\mathcal{B}(\Lambda_b \to J/\psi p K)} \approx 8\%
  \]
  [JHEP 07(2014)103]

- Need to deal with $N^*$ resonances

- 6 $N^*$ states needed

- Up to 14 used for systematic studies

- Bonn-Gatchina model for systematics
  [EPJ A48(2012)15]

- Possibility in $J/\psi \pi$:
  $Z(4200)$
Amplitude Analysis of $\Lambda_b \rightarrow J/\psi \ p \ \pi^-$

Challenges:

- Cabibbo suppr. 
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  [JHEP 07(2014)103]

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  [EPJ A48(2012)15]

- Possibility in $J/\psi \pi$: $Z(4200)$

---

**plot fit results for $m(p\pi) > 1.8 \text{ GeV}$**

(b) LHCb

- $N^* + 2P_c + Z$
- $N^*$ only

- $Z(4200)$

---

Exotic Baryon Resonances
Amplitude Analysis of $\Lambda_b \to J/\psi \ p \ \pi^-$

Challenges:
- Cabibbo suppr.
  \[
  \frac{\mathcal{B}(\Lambda_b \to J/\psi p \pi)}{\mathcal{B}(\Lambda_b \to J/\psi pK)} \approx 8\%
  \]  
  [JHEP 07(2014)103]
- Need to deal with $N^*$ resonances
- 6 $N^*$ states needed
- Up to 14 used for systematic studies
- Bonn-Gatchina model for systematics  
  [EPJ A48(2012)15]
- Possibility in $J/\psi \pi$: $Z(4200)$

Both types of exotics: significance $3.1\sigma$
- Two $P_c$ have a significance of $3.3\sigma$
  Assuming $Z(4200)$ negligible
- Exotic contributions needed, can’t distinguish scenarios
Exotic Baryon Resonances

Parameters from $\Lambda_b \to J/\psi pK$ amplitude analysis

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_c(4380)^+$</td>
<td>$4380 \pm 8 \pm 29$</td>
<td>$205 \pm 18 \pm 86$</td>
<td>$3/2^-$</td>
<td>$(8.4 \pm 0.7 \pm 4.2)%$</td>
<td>$9\sigma$</td>
</tr>
<tr>
<td>$P_c(4450)^+$</td>
<td>$4449.8 \pm 1.7 \pm 2.5$</td>
<td>$39 \pm 5 \pm 19$</td>
<td>$5/2^+$</td>
<td>$(4.1 \pm 0.5 \pm 1.1)%$</td>
<td>$12\sigma$</td>
</tr>
</tbody>
</table>

- Interference of two states of **opposite parity** required by forward-backward asymmetry in $P_c$ helicity angle

- Spin-parity assignment not conclusive:

<table>
<thead>
<tr>
<th>Fit</th>
<th>$\Delta(-2 \ln \mathcal{L})$</th>
<th>$P_c$ (Low) Mass</th>
<th>$P_c$ (Low) $\Gamma$</th>
<th>$P_c$ (High) Mass</th>
<th>$P_c$ (High) $\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$3/2^-, 5/2^+$</td>
<td>$0$</td>
<td>$4.3799 \pm 0.0064$</td>
<td>$0.205 \pm 0.011$</td>
<td>$4.4498 \pm 0.0017$</td>
<td>$0.0387 \pm 0.0037$</td>
</tr>
<tr>
<td>$3/2^+, 5/2^-$</td>
<td>$0.9^2$</td>
<td>$4.3696 \pm 0.0063$</td>
<td>$0.211 \pm 0.012$</td>
<td>$4.4504 \pm 0.0017$</td>
<td>$0.0492 \pm 0.0040$</td>
</tr>
<tr>
<td>$5/2^+, 3/2^-$</td>
<td>$2.3^2$</td>
<td>$4.3770 \pm 0.0098$</td>
<td>$0.239 \pm 0.024$</td>
<td>$4.4486 \pm 0.0018$</td>
<td>$0.0444 \pm 0.0053$</td>
</tr>
</tbody>
</table>


Valence quark content: $uudc\bar{c}$

What are the relevant degrees of freedom?

Are there more of their kind?

Challenges to theory:

Why two states with opposite parity?

Small mass gap $\approx 100$ MeV

Narrow width of $P_c(4450)$
Proximity of 2-body thresholds
→ need to be taken into account

<table>
<thead>
<tr>
<th></th>
<th>( P_c(4380)^+ )</th>
<th>( P_c(4450)^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>( 4380 \pm 8 \pm 29 )</td>
<td>( 4449.8 \pm 1.7 \pm 2.5 )</td>
</tr>
<tr>
<td>( \Sigma_c^+D^0 )</td>
<td>( 4382.3 \pm 2.4 )</td>
<td>[ \text{MeV} ]</td>
</tr>
<tr>
<td>( \chi_{c1}(1P)p )</td>
<td>[ \text{MeV} ]</td>
<td>( 4448.93 \pm 0.07 )</td>
</tr>
<tr>
<td>( \Lambda_c^{+*} \bar{D}^0 )</td>
<td>[ \text{MeV} ]</td>
<td>( 4457.09 \pm 0.35 )</td>
</tr>
<tr>
<td>( \Sigma_c \bar{D}^0^* )</td>
<td>[ \text{MeV} ]</td>
<td>( 4459.9 \pm 0.5 )</td>
</tr>
<tr>
<td>( \Sigma_c \bar{D}^0 \pi^0 )</td>
<td>[ \text{MeV} ]</td>
<td>( 4452.7 \pm 0.5 )</td>
</tr>
</tbody>
</table>

- Guo et al [PRD92(2015)071502]
- can explain \( P_c(4450) \) phase motion
  But \( P_c(4380) \)?
- Rescattering would not explain a narrow enhancement in \( \chi_{c1}(1P)p \) ← can be checked at LHCb
### Exotic Baryon Resonances

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Decay Modes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>$X(3872)$, $Y(4260)$, $Y(4008)$</td>
</tr>
<tr>
<td>$\psi(2S)\pi^+ \pi^-$</td>
<td>$Y(4360)$, $Y(4660)$</td>
</tr>
<tr>
<td>$\Lambda_c \bar{\Lambda}_c$</td>
<td>$Y(4630)$</td>
</tr>
<tr>
<td>$\psi \gamma$</td>
<td>$X(3872)$</td>
</tr>
<tr>
<td>$X_{c1}(1P)\gamma$</td>
<td>$X(3832)$</td>
</tr>
<tr>
<td>$X_{c1}(1P)\omega$</td>
<td>$Y(4220)$</td>
</tr>
<tr>
<td>$J/\psi \omega$</td>
<td>$X(3872)$, $Y(3940)$, $X(3915)$</td>
</tr>
<tr>
<td>$J/\psi \phi$</td>
<td>$X(4140)$, $X(4274)$, $X(4500)$, $X(4700)$, $X(4350)$</td>
</tr>
<tr>
<td>$J/\psi \pi$</td>
<td>$Z(4430)$, $Z(4200)$, $Z(4240)$, $Z(3900)$</td>
</tr>
<tr>
<td>$\psi(2S)\pi$</td>
<td>$Z(4430)$</td>
</tr>
<tr>
<td>$X_{c1}(1P)\pi$</td>
<td>$Z(4051)$, $Z(4248)$</td>
</tr>
<tr>
<td>$h_{c}(1P)\pi$</td>
<td>$Z(4020)$, $Z(3930)$</td>
</tr>
<tr>
<td>$D\bar{D}$</td>
<td>$Z(3930)$</td>
</tr>
<tr>
<td>$D\bar{D}^*$</td>
<td>$X(3872)$, $X(3940)$, $Z(3885)$</td>
</tr>
<tr>
<td>$D^*\bar{D}$</td>
<td>$X(4160)$, $Z(4025)$</td>
</tr>
<tr>
<td>$J/\psi p$</td>
<td>$P_c(3800)$, $P_c(4430)$</td>
</tr>
<tr>
<td>$B_{s \pi}$</td>
<td>$X(5568)$, $-$</td>
</tr>
</tbody>
</table>
Conclusion

- Patterns among the XYZ are getting clearer
- Unified description of phenomena lacking
- Case-to-case treatment of kinematic and coupled-channel effects
- More data in the analysis pipelines
- Exotics with hidden charm in the baryon sector!
- There is more! Sorry if I left out your favourite topic.

Very useful review article: arXiv:1601.02092
Many thanks to Soeren Lange for inspiration!
Backup
Model-independent analysis of $\Lambda_b \rightarrow J/\psi pK$

Legendre-moments of $pK$ decay angle distribution

From moments construct toy MC: Reflections of $pK$-system into $J/\psi p$

- Hypo "only $\Lambda^*$" rejected with $> 9\sigma$
- Confirms findings of amplitude analysis

assume: at low mass only low-spin $\Lambda^*$
Model-independent analysis of $\Lambda_b \rightarrow J/\psi pK$

- Observation of the $P_c(4380)$ and $P_c(4450)$ used a model for the decay matrix element
- $\Lambda^*$ spectrum biggest uncertainty

In bins of $m(pK)$: decompose decay-angle distribution into Legendre-moments

Only low-spin states at low masses
Model-independent analysis of $\Lambda_b \rightarrow J/\psi pK$

Construct $\ell_{\text{max}}$-filtered toy MC:

Reflections of $pK$-system into $J/\psi$

- $pK$-reflections cannot explain the narrow structure in $J/\psi$.

Testing sensitivity on MC for various models:

- Hypothesis "only $\Lambda^*$" rejected with $>9\sigma$
- Confirms findings of amplitude analysis
The peaking structure in \( m_{J/\psi p} \) is asymmetric as a function of \( m_{Kp} \) (or \( \cos \theta_{Pc} \)).

This can be explained by interference of two states with opposing parity.