Exotic mesons and excited state spectroscopy at LHCb

Guy Wormser
On behalf of the LHCb Collaboration
LAL Orsay,
Université Paris Saclay
Talk Outline

• Exotic mesons spectroscopy
  – X3872 latest news
  – Z4430⁺ observation and demonstration of its resonance nature

• Excited states spectroscopy
  – Excited D**
    • Via direct D(∗)π combinations
    • Via B→DKπ Dalitz plot analysis (Recent paper arXiv:1503.02995)
  – Excited B** (Recent paper arXiv:1502.02638)

• Many other results could have presented (baryons spectroscopy, χ₃, etc...)
**LHCb** is a single-arm ($2 < \eta < 5$) spectrometer at the LHC

- $CP$ violation measurements, rare decays, **heavy flavor production**
- Exploits the correlated production of $b\bar{b}$ pairs in the LHC environment

- Time-dependent analyses require good time resolution: $\sim 40$ fs (VELO)
- Flavor tagging, final state discrimination needs excellent particle ID (RICH)
- Rare decays and extremely small asymmetries require pure data samples with high (and controlled) signal efficiency (Trigger)
Data set: $1 \text{ fb}^{-1}$ at $\sqrt{s} = 7 \text{ TeV}$

Prompt $D^+$, $D^0$ and $D^*$ yields:
- $D^+ \to K^- \pi^+ \pi^+ \quad 15.1 \times 10^6$
- $D^0 \to K^- \pi^+ \quad 20.4 \times 10^6$
- $D^{*+} \to D^0 \pi^+ \quad 6.4 \times 10^6$

Recalculate $m(D\pi)$

$$m(D^0\pi) = m(K^- \pi^+ \pi^+) - m(K^- \pi^+) + m_{D^0}$$

Combined with additional $\pi^+$

$p_t(D^{(*)}\pi) > 7.5 \text{GeV}$
- $D^{+}\pi^+ \quad 7.9 \times 10^6$

Yields:
- $D^0\pi^+ \quad 7.5 \times 10^6$
- $D^{*+}\pi^+ \quad 2.1 \times 10^6$
Charm Production at LHCb
Prompt Charm and Charm from Beauty

Beauty and charm hadron typical decay topologies:

**Beauty Hadrons**

- $B^{\pm}$ mass $\sim 5.28$ GeV, daughter $p_T \sim 0(1 \text{ GeV})$
- $\tau \sim 1.6$ ps, Flight distance $\sim 1$ cm
- Important signature: Detached muons from $B \to J/\psi X$, $J/\psi \to \mu\mu$

**Charm Hadrons**

- $D^0$ mass $\sim 1.86$ GeV, appreciable daughter $p_T$
- $\tau \sim 0.4$ ps, Flight distance $\sim 4$ mm
- Also produced as 'secondary' charm from $B$ decays.

**Trigger Strategy:**

- **Inclusive triggering** on displaced vertices with high-$p_T$ tracks and muons
- **Exclusive triggering** for anything else (Prompt Charm)
Charmonium spectroscopy \((c\bar{c})\)

- Simpler system to analyse since \(c\) quark is heavier
  - non-relativistic calculations
  - potential models
  - lattice QCD
- narrow, non-overlapping states below \(D\bar{D}\) threshold
- no mixing of \(c\bar{c}\) with lighter \(q\bar{q}\) states.

Classify using \(J^{PC}\)

- \(J = L \oplus S\)
- \(P = (-1)^{L+1}\)
- \(C = (-1)^{L+S}\)

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Exotic charmonium spectroscopy

- Many different exotic (XYZ) states have been seen.
  - BESIII, Belle/BaBar, CDF/D0
  - mass/width, decay, $J^P_C$
- Are these $[Qar{Q}][qar{q}]$ (tetraquarks), mesonic molecules, threshold effects, hybrids...?
- No clear pattern: need experimental, theoretical study to understand strong interaction dynamics that can cause their production and structure.

Lattice calculations begin to support existence of exotic charged states [arXiv:1405.7623v1]

A well known exotic meson: $X(3872)$

- Observed by 6 experiments, first by Belle
  [PRL 91 (2003) 262001 - 894 citations!]

- $B^+ \rightarrow X(3872)K^+, X(3872) \rightarrow J/\psi\pi^+\pi^-$

- Measured $J^{PC} = 1^{++}$ → unlikely to be conventional charmonium

- Exotic interpretation: $c\bar{c}u\bar{u}$ tetraquark, $D^0\bar{D}^{*0} = (c\bar{u})(\bar{c}u)$ molecule, $c\bar{c}g$

Γ_{X(3872)} < 1.2 MeV
$M_{X(3872)} = 3871.68 \pm 0.17$ MeV
$M_{D^0} + M_{\bar{D}^0} = 3871.85 \pm 0.20$ MeV

$X(3872)$ seen in $B$ decays and $pp, \bar{p}\bar{p}$ prompt production
Full Run1 X3872 sample

$B^+ \rightarrow X(3872)K^+$,
$X(3872) \rightarrow J/\psi \pi^+\pi^-$
$J/\psi \rightarrow \mu^+\mu^-$

LHCb-PAPER-2015-015

Candidates per 1 MeV

$M(\pi^+\pi^- J/\psi) - M(J/\psi)$ [MeV]

1011 $\pm$ 38 events

new
Previous determinations of $X(3872)$ $J^P$C

- $C=+$ since $X(3872) \rightarrow J/\psi \gamma$ (and $\psi(2S)\gamma$)

- Previous determinations of $J^P$ used $X(3872) \rightarrow \pi^+\pi^- J/\psi$
  - all assumed the lowest possible orbital angular momentum in this decays ($L_{\min}$ value depends on $J^P$).
  - CDF PRL 98(2007) 132002:
    - ruled out all but $1^{++}$ and $2^{-+}$
  - LHCb-PAPER-2013-001 (1 fb$^{-1}$) PRL 110 (2013) 222001:
    - ruled out $2^{-+}$
    - the data consistent with $1^{++}$ (and pure S-wave decay)

- Significant $L > L_{\min}$ could invalidate $J^P=1^+$ assignment and hint molecular structure of $X(3872)$
Determination of $X(3872)$ $J^P_C$: formalism

\[ M(\Omega|J_X) |^2 = \sum_{\Delta \lambda_\mu = -1,+1} \sum_{\lambda, \lambda_\mu} A_{\lambda, \lambda_\mu} \lambda_\rho \times D_{0, \lambda, \lambda_\mu}^{J_X}(0, \theta_X, 0)^* \times \]

\[ D_{\lambda_\rho, 0}^{J_X}((\Delta \phi_{X, \rho}; \theta, 0)^* \times D_{-\lambda_\rho, 0}^{J_X}((\Delta \phi_{X, \rho}; \theta, 0)^* \times \]}

\[ A_{\lambda, \lambda_\mu} = \sum L \sum S B_{LS} \times \left( \begin{array}{c} J_{\rho, \lambda_\mu} \\ \lambda \rho \\ \lambda_\mu \rho - \lambda_\rho \end{array} \right) \times \left( \begin{array}{c} L \\ 0 \\ \lambda_\mu - \lambda_\rho \end{array} \right) \]

\[ (-1)^L = (-1)^L \]

LHCb
this analysis

<table>
<thead>
<tr>
<th>$J^P_C$</th>
<th>all</th>
<th>$B_{LS}$ minimal $L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^+$</td>
<td>$B_{11}$</td>
<td>$B_{11}$</td>
</tr>
<tr>
<td>0$^+$</td>
<td>$B_{00}, B_{22}$</td>
<td>$B_{00}$</td>
</tr>
<tr>
<td>1$^-$</td>
<td>$B_{10}, B_{11}, B_{12}, B_{32}$</td>
<td>$B_{10}, B_{11}, B_{12}$</td>
</tr>
<tr>
<td>1$^+$</td>
<td>$B_{01}, B_{21}, B_{22}$</td>
<td>$B_{01}$</td>
</tr>
<tr>
<td>2$^+$</td>
<td>$B_{11}, B_{12}, B_{31}, B_{32}$</td>
<td>$B_{11}, B_{12}$</td>
</tr>
<tr>
<td>2$^+$</td>
<td>$B_{02}, B_{20}, B_{21}, B_{22}, B_{32}$</td>
<td>$B_{02}$</td>
</tr>
<tr>
<td>3$^+$</td>
<td>$B_{12}, B_{30}, B_{31}, B_{32}, B_{32}$</td>
<td>$B_{12}$</td>
</tr>
<tr>
<td>3$^+$</td>
<td>$B_{21}, B_{22}, B_{31}, B_{32}$</td>
<td>$B_{21}, B_{22}$</td>
</tr>
<tr>
<td>4$^+$</td>
<td>$B_{31}, B_{32}, B_{31}, B_{32}$</td>
<td>$B_{31}, B_{32}$</td>
</tr>
<tr>
<td>4$^+$</td>
<td>$B_{32}, B_{30}, B_{31}, B_{32}$</td>
<td>$B_{32}$</td>
</tr>
</tbody>
</table>

CDF 2007

LHCb 2013

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Data unambiguously prefers $1^{++}$ hypothesis (new: no assumptions about $L$)
Determination of D-wave fraction in $X(3872) \rightarrow \rho^0 J/\psi$ for $J^{PC}=1^{++}$

- Fit to the real data:
  $$\frac{|B_{21}|^2}{|B_{10}|^2} = 0.0018 \pm 0.0042 \quad \frac{|B_{22}|^2}{|B_{10}|^2} = 0.0066 \pm 0.0081$$

D-wave significance using Wilks theorem applied to the likelihood ratio with/without D: 0.8σ

D-wave amplitudes are consistent with zero.

$$f_D = \frac{\int |M(\Omega)_D|^2 d\Omega}{\int |M(\Omega)_{S+D}|^2 d\Omega}$$

- No hints for a large size of $X(3872)$ from the studies of the orbital angular momentum in $X(3872) \rightarrow \rho^0 J/\psi$ decays
- Also the observations of $X(3872)$ in prompt pp productions hints the typical charmonium size
A well known exotic meson: $X(3872)$

- LHCb has evidence for $X(3872)$ in decays of $B^+ \rightarrow \psi \gamma K^+$, $\psi \rightarrow \mu^+ \mu^-$
- Efficiency($\psi(2S)\gamma$) / Efficiency($J/\psi \gamma$) $\sim$ 0.2
- Detecting soft photons at hadronic collider is hard.
- Pure $D\bar{D}^*$ molecule interpretation disfavoured.

\[ R_{\psi \gamma} = \frac{B(X(3872) \rightarrow \psi(2S)\gamma)}{B(X(3872) \rightarrow J/\psi \gamma)} = 2.46 \pm 0.64 \pm 0.29. \]

Probe of internal structure of $X(3872)$
**History of the Z(4430)±**

- Belle observed Z(4430)± from sample of \( \sim 2k B^{+,0} \rightarrow \psi(2S)K^{+,0}\pi^- \)
- Charged state \( \Rightarrow \) minimal quark content of \( cc\bar{u}\bar{d} \)

\[
M = 4433 \pm 4 \pm 2 \text{ MeV}/c^2 \\
\Gamma = 45^{+18+30}_{-13-13} \text{ MeV}/c^2
\]

**BABAR Upper limits of BR 3 \(10^{-5}\) compatible with BELLE BR of 3 \(10^{-5}\)**
**History of the Z(4430)**

\[ M(D^*) + M(D^{**}) = 4472 \text{ MeV} \]

- **Belle** [PRL 100 (2008) 142001] 1D fit to \( m(\psi'\pi^-) \) 6.5\( \sigma \)
- **BaBar** [PRD 79 (2009) 112001] Not observed but does not contradict Belle!
- **Belle** [PRD 80 (2009) 031104] 2D amplitude fit to \( m(\psi'\pi^-) \) vs \( m(K^+\pi^-) \) 6.4\( \sigma \)
- **Belle** [PRD 88 (2013) 074026] 4D amplitude fit 6.4\( \sigma \)

\[ K^*(892)^0 \quad K_2^*(1430) \]

**K* veto region**

**With Z**

\[ M = 4485^{+22+28}_{-22-11} \text{ MeV}/c^2 \]

\[ \Gamma = 200^{+41+26}_{-46-35} \text{ MeV}/c^2 \]

**Without Z**

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4D “Dalitz plot” (scalar $\rightarrow$ vector scalar scalar)

- $\mathbf{B}^0 \rightarrow \psi'K^+\pi^-$, $\psi' \rightarrow \mu^+\mu^-$
- Must use the angular information, in addition to $m(\psi'\pi^-)^2$ vs $m(K^+\pi^-)^2$, to understand $|\mathcal{M}|^2$.

<table>
<thead>
<tr>
<th>Constraints</th>
<th>Degrees of freedom</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 four-vectors</td>
<td>+12</td>
</tr>
<tr>
<td>All decay in same plane ($p_{i,z} = 0$)</td>
<td>-3</td>
</tr>
<tr>
<td>$E_i^2 = m_i^2 + p_i^2$</td>
<td>-3</td>
</tr>
<tr>
<td>Energy + momentum conservation</td>
<td>-3</td>
</tr>
<tr>
<td>Rotate system in plane</td>
<td>-1</td>
</tr>
<tr>
<td>Vector helicity</td>
<td>+2</td>
</tr>
<tr>
<td>Total</td>
<td>+4</td>
</tr>
</tbody>
</table>
Confirmation of the $Z(4430)^\pm$

- LHCb has sample of $>25k \, B^0 \rightarrow \psi' K^+ \pi^-$ candidates (x10 Belle/BaBar).
- Selection: most events come through dimuon trigger (eff~90%) $\psi' \rightarrow \mu^+ \mu^-$
- Typical $B^0$ pT $\sim 6$GeV, $\mu^+$ pT $\sim 2$GeV, $K^+$ pT $\sim 1$GeV.
- Use sidebands to build 4D model of combinatorial background.
  - Bkgs from mis-ID physics decays is small - excellent LHCb vertexing, PID!

![Graph showing data and analysis]
Amplitude model

- Use the Isobar approach.
- Build amplitude from sum of two-body decays: $B^0 \rightarrow \psi' \pi^- K^+$ and $B^0 \rightarrow Z(4430)^- K^+$
- Overlapping and interfering Breit-Wigner resonances.

Sum over the $k$ resonances

$$|\mathcal{M}|^2 = \sum_{\Delta \lambda_\mu = -1,1} \left| \sum_{\lambda_\psi = -1,0,1} \sum_k A_k, \lambda_\psi \left( m_{K\pi}, \Omega \mid m_{0k}, \Gamma_{0k} \right) \right|^2$$

In 4D fit, $\mu^+ \mu^-$ are final state particles so different dimuon helicity amplitudes are incoherent (cannot interfere)

Different $\psi'$ helicity amplitudes interfere

Complex amplitude that encodes the mass and angular dependence

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Which resonances should we add? [From PDG]

- $K^+ \pi^-$ spectrum contains many overlapping resonances.
- Each resonance has a complex amplitude for each helicity component.
- Measure all amplitudes relative to $K^*(892)$ helicity-0 component.

- Default result includes all resonances up to $K^*_{1}(1680)$ ($J \leq 2$).
- Main source of systematic uncertainties comes from varying model to include higher $K^+ \pi^-$ spin-states ($J = 3, 4, 5$).

Background from sidebands of B mass
Projections of 4D amplitude fit without Z(4430)

- Determine goodness-of-fit from 4D $\chi^2$.
- The $\chi^2$ p-value < $2 \times 10^{-6}$.
- The data cannot be adequately described only using $J \leq 3$ $K^*$ contributions.
- Other 3 dimensions not shown.
Projections of 4D amplitude fit with $Z(4430)$

Everything except the $Z \rightarrow$ large interference between $Z$ and $K^+\pi^-$ sector

$J^P = 1^+$ $Z$ component

- The 4D $\chi^2$ p-value = 12%.
- 4\% with no $K_1^*(1410)$, 12\% with $K_3^*(1780)$
- The data are well described when including a $J^P=1^+$ $Z(4430)$ in the fit.
Z(4430)$^{\pm}$ parameters from amplitude fit

<table>
<thead>
<tr>
<th></th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>$M(Z)$ [MeV]</strong></td>
<td>$4475 \pm 7^{+15}_{-25}$</td>
<td>$4485 \pm 22^{+28}_{-11}$</td>
</tr>
<tr>
<td><strong>$\Gamma(Z)$ [MeV]</strong></td>
<td>$172 \pm 13^{+37}_{-34}$</td>
<td>$200^{+41+26}_{-46-35}$</td>
</tr>
<tr>
<td><strong>$f_Z$ [%]</strong></td>
<td>$5.9 \pm 0.9^{+1.5}_{-3.3}$</td>
<td>$10.3^{+3.0+4.3}_{-3.5-2.3}$</td>
</tr>
<tr>
<td><strong>$f^I_Z$ [%]</strong></td>
<td>$16.7 \pm 1.6^{+2.6}_{-5.2}$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

Significance

- $f_Z$: New (large) systematic included
- $f^I_Z$: $> 13.9\sigma$
- $f_Z$: $> 5.2\sigma$
- $J^P$: $1^+$

Amplitude fractions [%]

<table>
<thead>
<tr>
<th>Contribution</th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-wave total</td>
<td>$10.8 \pm 1.3$</td>
<td>$0.3 \pm 0.8$</td>
</tr>
<tr>
<td>$K_0^*(800)$</td>
<td>$3.2 \pm 2.2$</td>
<td>$5.8 \pm 2.1$</td>
</tr>
<tr>
<td>$K_0^*(1430)$</td>
<td>$3.6 \pm 1.1$</td>
<td>$1.1 \pm 1.4$</td>
</tr>
<tr>
<td>$K^*(892)$</td>
<td>$59.1 \pm 0.9$</td>
<td>$63.8 \pm 2.6$</td>
</tr>
<tr>
<td>$K_2^*(1430)$</td>
<td>$7.0 \pm 0.4$</td>
<td>$4.5 \pm 1.0$</td>
</tr>
<tr>
<td>$K_1^*(1410)$</td>
<td>$1.7 \pm 0.8$</td>
<td>$4.3 \pm 2.3$</td>
</tr>
<tr>
<td>$K_1^*(1680)$</td>
<td>$4.0 \pm 1.5$</td>
<td>$4.4 \pm 1.9$</td>
</tr>
<tr>
<td>$Z(4430)^-$</td>
<td>$5.9 \pm 0.9$</td>
<td>$10.3^{+3.0}_{-3.5}$</td>
</tr>
</tbody>
</table>

Note: this corresponds to a BR of $3.6 \times 10^{-5}$

- Excellent agreement between LHCb and Belle.
- Large width - unlikely to be molecule?

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Spin determination

- Build different $|M|^2$ corresponding to different $J^P$ values.
- $J^P=1^+$ is favoured (confirms Belle).
- Rule out other $J^P$ with large significance.
- Quote exclusion based on asymptotic formula (lower bound).

$$\Delta (-2 \ln L) = [-2 \ln L(0^-)] - [-2 \ln L(1^+)]$$

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>LHCb</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0^-$</td>
<td>9.7$\sigma$</td>
<td>3.4$\sigma$</td>
</tr>
<tr>
<td>$1^-$</td>
<td>15.8$\sigma$</td>
<td>3.7$\sigma$</td>
</tr>
<tr>
<td>$2^+$</td>
<td>16.1$\sigma$</td>
<td>5.1$\sigma$</td>
</tr>
<tr>
<td>$2^-$</td>
<td>14.6$\sigma$</td>
<td>4.7$\sigma$</td>
</tr>
</tbody>
</table>

Resonant behaviour - a bound state?

Replace BW amplitude with 6 independent complex numbers in 6 bins of \( m(\psi'\pi) \) in region of \( Z(4430) \) mass peak.

Allows \( Z(4430) \) shape to be constrained only by amplitudes in \( K\pi \) sector.

Observe rapid change of phase near maximum of magnitude \( \Rightarrow \text{resonance!} \)
Systematics: second exotic Z?

- Fit confidence level increases to 26% with a second exotic ($J^P=0^-$) component, but...
  - No evidence for $Z_0$ in model independent approach.
  - Argand diagram for $Z_0$ is inconclusive.
  - Need larger samples to characterise this state.

\[
\begin{align*}
M_{Z_0} &= 4239 \pm 18^{+45}_{-10} \text{ MeV} \\
\Gamma_{Z_0} &= 220 \pm 47^{+108}_{-74} \text{ MeV} \\
f_{Z_0} &= (1.6 \pm 0.5^{+1.9}_{-0.4})\% 
\end{align*}
\]

- Same mass, width as $Z^0 \rightarrow \chi_{c1}\pi^-$ seen by Belle, but $J^P=0^-$ can't decay strongly to $\chi_{c1}\pi^-$. 
  
  [PRD 78 (2008) 072004]

- Many checks performed to determine stability of the result and evaluate systematic errors on $m_{Z}$, $\Gamma_{Z}$, $f_{Z}$.

- Main systematics come from assumption on $K^+\pi^-$ Isobar model, efficiency.
Summary

- LHCb has confirmed this existence and shown the resonant behaviour of the Z(4430)±.
- Minimal quark content of $c\bar{c}ud$.
- No clear picture of the complex system of charmonium-like exotic resonances.
- Further constraints will come from observing Z(4430)± and other exotics in alternative decay modes and/or production mechanisms.

- Interesting times ahead...
  - LHCb has large datasets of B decays containing $J/\psi$, $\psi(2S)$, $\chi_c$... where other exotics could live.
  - Look for synergies with the $s\bar{s}$ and $b\bar{b}$ sectors.
  - Data taking starts again in 2015, looking forward to collecting even higher statistics!

Z(4430) in the media: [http://www.phy.syr.edu/~tomasz/z4430.html](http://www.phy.syr.edu/~tomasz/z4430.html)
$D^+\pi^-$
- Strong $D_2^*(2460)^0$ signal
- Partially reconstructed cross-feed from $D_1(2420)^0 or D_2^*(2460)^0 \rightarrow \pi^- D^{*+}$
- Weak structures around 2600 and 2750 MeV

$D^0\pi^+$
- Strong $D_2^*(2460)^+$ signal
- Partially reconstructed cross-feed from $D_1(2420)^+ or D_2^*(2460)^+ \rightarrow \pi^+ D^{*0}$
- Wrong sign cross-feed: $D_1(2420)^0 or D_2^*(2460)^0 \rightarrow \pi^- D^{*+}(\rightarrow D^0\pi^+)$
- Weak structures around 2600 and 2750 MeV

$D^{*+}\pi^-$ both natural / unnatural parity
- $D_1(2420)^0$ and $D_2^*(2460)^0$ signals
- Broad structures around 2500 and 2800 MeV
Study of the $D^{*-+\pi^-}$ angular distributions.

- We divide the data into three samples:
  - $|\cos\theta_H| > 0.75$, Enhanced Unnatural Parity Sample. (0.55 x 10$^6$ events,
    Natural Parity suppressed by a factor 11.6)
  - $|\cos\theta_H| < 0.5$, Natural Parity Sample. (0.98 x 10$^6$ events,
    Natural Parity suppressed by a factor 1.5)
  - $|\cos\theta_H| > 0.5$, Unnatural Parity Sample. (1.06 x 10$^6$ events,
    Natural Parity suppressed by a factor 3.2)
Natural / unnatural parity differs in the helicity angle distribution (angle between $\pi^+$ and $\pi^-$ in $D^*\pi$ rest frame)

- Natural: $\propto \sin^2 \theta_H = 1 - \cos^2 \theta_H$
- Unnatural: $\propto (1 + h \cos^2 \theta_H)$

$\cos \theta_H > 0.75$
(enhanced unnatural parity)

$\cos \theta_H < 0.5$
(natural parity)
Resonance Parameters and Naturality

- Extract yields in bins of $\theta_H$
- Fit angular distribution
- Precise measurement of $D_1(2420)^0$ and $D_2^*(2460)^+$ parameters
- 2 additional natural parity states
- 3 additional unnatural parity states

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Final state</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Yields $\times 10^3$</th>
<th>Significance ($\sigma$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_1(2420)^0$</td>
<td>$D^{*-}\pi^-$</td>
<td>2419.6 ± 0.1 ± 0.7</td>
<td>35.2 ± 0.4 ± 0.9</td>
<td>210.2 ± 1.9 ± 0.7</td>
<td>24.5</td>
</tr>
<tr>
<td>$D_2^*(2460)^0$</td>
<td>$D^{*-}\pi^-$</td>
<td>2460.4 ± 0.4 ± 1.2</td>
<td>43.2 ± 1.2 ± 3.0</td>
<td>81.9 ± 1.2 ± 0.9</td>
<td>10.2</td>
</tr>
<tr>
<td>$D_1^*(2650)^0$</td>
<td>$D^{*-}\pi^-$</td>
<td>2649.2 ± 3.5 ± 3.5</td>
<td>140.2 ± 17.1 ± 18.6</td>
<td>50.7 ± 2.2 ± 2.3</td>
<td>18.8</td>
</tr>
<tr>
<td>$D_2^*(2760)^0$</td>
<td>$D^{*-}\pi^-$</td>
<td>2761.1 ± 5.1 ± 6.5</td>
<td>74.4 ± 3.4 ± 37.0</td>
<td>14.4 ± 1.7 ± 1.7</td>
<td>7.2</td>
</tr>
<tr>
<td>$D_3(2580)^0$</td>
<td>$D^{*-}\pi^-$</td>
<td>2579.5 ± 3.4 ± 5.5</td>
<td>177.5 ± 17.8 ± 46.0</td>
<td>60.3 ± 3.1 ± 3.4</td>
<td>9.0</td>
</tr>
<tr>
<td>$D_2(2740)^0$</td>
<td>$D^{*-}\pi^-$</td>
<td>2737.0 ± 3.5 ± 11.2</td>
<td>73.2 ± 13.4 ± 25.0</td>
<td>7.7 ± 1.1 ± 1.2</td>
<td>9.9</td>
</tr>
<tr>
<td>$D_3(3000)^0$</td>
<td>$D^{*-}\pi^-$</td>
<td>2971.8 ± 8.7</td>
<td>188.1 ± 44.8</td>
<td>9.5 ± 1.1</td>
<td>9.0</td>
</tr>
<tr>
<td>$D_2^*(2460)^0$</td>
<td>$D^{+}\pi^-$</td>
<td>2460.4 ± 0.1 ± 0.1</td>
<td>45.6 ± 0.4 ± 1.1</td>
<td>675.0 ± 9.0 ± 1.3</td>
<td>17.3</td>
</tr>
<tr>
<td>$D_1^*(2760)^0$</td>
<td>$D^{+}\pi^-$</td>
<td>2760.1 ± 1.1 ± 3.7</td>
<td>74.4 ± 3.4 ± 19.1</td>
<td>55.8 ± 1.3 ± 10.0</td>
<td>21.2</td>
</tr>
<tr>
<td>$D_2^*(3000)^0$</td>
<td>$D^{+}\pi^-$</td>
<td>3008.1 ± 4.0</td>
<td>110.5 ± 11.5</td>
<td>17.6 ± 1.1</td>
<td>18.8</td>
</tr>
<tr>
<td>$D_2^*(2460)^+$</td>
<td>$D^0\pi^+$</td>
<td>2463.1 ± 0.2 ± 0.6</td>
<td>48.6 ± 1.3 ± 1.9</td>
<td>341.6 ± 22.0 ± 2.0</td>
<td>6.6</td>
</tr>
<tr>
<td>$D_1^*(2760)^+$</td>
<td>$D^0\pi^+$</td>
<td>2771.7 ± 1.7 ± 3.8</td>
<td>66.7 ± 6.6 ± 10.5</td>
<td>20.1 ± 2.2 ± 1.0</td>
<td>6.6</td>
</tr>
<tr>
<td>$D_2^*(3000)^+$</td>
<td>$D^0\pi^+$</td>
<td>3008.1 (fixed)</td>
<td>110.5 (fixed)</td>
<td>7.6 ± 1.2</td>
<td>6.6</td>
</tr>
</tbody>
</table>

St Goar conference, March 24-27, 2015
Fit to the $D^+\pi^-$ and $D^0\pi^+$ mass spectra.

- Cross-feeds (in red) produce a distortion of the $D_2^*(2460)$ and $D^*_J(2650)$ lineshapes.

- For $D^*_J(2650)$ we rely on the results obtained from the $D^{*+}\pi^-$ mass analysis.
- We observe the $D^{*_J}(2760)$.
- The fits require the presence of a broad structure around 3.0 GeV which we label $D^{*_J}(3000)$.
The $D_J^*(2650)^0$ resonance could be identified as a $J^P = 1^-$ state ($2S$ $D_1^*(2618)$).

The $D_J^*(2760)^0$ could be identified as a $J^P = 1^-$ state ($1D$ $D_1^*(2796)$).

The $D_J(2580)^0$ could be identified with the ($2S$ $D_0(2558)$) state, although $J^P = 0^-$ does not fit well the data.

The $D_J(2740)^0$ could be identified as the $J^P = 2^-$ ($1D$ $D_2(2801)$) resonance.

Broad structures are observed around 3.0 GeV in the $D^{*+}\pi^-$ and $D\pi$ mass spectra. They could be superpositions of several states.
Introduction and overview

- **New results** on $D^{**}$ states from $B^{-} \rightarrow D^{+}K^{-}\pi^{-}$
  - First observation of decay mode
  - Resonant structure studied with a Dalitz plot analysis
  - Observed spin-1 resonance $D_{1}^{*}(2760)$

- **New results** on $B^{**}$ states in $B^{+}\pi^{-}$ and $B^{0}\pi^{+}$ spectra
  - Low mass states precisely measured
  - Structures observed at higher mass
  - $B_{2}^{*}(5747)$ and $B_{1}(5721)$ states observed

*arXiv:1503.02995* to be submitted to PRD

*arXiv:1502.02638* submitted to JHEP
\( D^{**} \) Spectroscopy with \( B^- \rightarrow D^+ K^- \pi^- \)

- Spectrum can be studied with a Dalitz plot analysis of \( B^- \rightarrow D^+ K^- \pi^- \)
- Only states with **natural spin-parity** \( (J^P) \) can decay to \( D^+ \pi^- \)
- \( D_0^*(2400)^0 \), \( D_2^*(2460)^0 \) and higher mass states expected to contribute
- Amplitude analysis techniques give spin-parity information

Evidence for several high mass states but no spin-parity information yet

\( D_2^*(2460)^0 \)
\( D_0^*(2400)^0 \)
Branching fraction measurement

Events selected with loose cuts and neural network used to reduce backgrounds


$\sim 2000 \, B^- \rightarrow D^+ K^- \pi^- \,$ candidate events ($> 60 \sigma$ observation!)

Branching fraction measured wrt to $B^- \rightarrow D^+ \pi^- \pi^-$

$$B(B^- \rightarrow D^+ K^- \pi^-) = (7.92 \pm 0.23 \pm 0.24 \pm 0.42) \times 10^{-5}$$

Uncertainties are statistical, systematic and due to PDG uncertainty on $B^- \rightarrow D^+ \pi^- \pi^- \,$ BF

arXiv:1503.02995
### Dalitz plot model

Efficiency and background distributions studied and used as input

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Spin</th>
<th>DP axis</th>
<th>Model</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D_0^*(2400)^0$</td>
<td>0</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>$m = 2318 \pm 29$ MeV/$c^2$, $\Gamma = 267 \pm 40$ MeV</td>
</tr>
<tr>
<td>$D_2^*(2460)^0$</td>
<td>2</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>Floated</td>
</tr>
<tr>
<td>$D_j^*(2760)^0$</td>
<td>1</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>Floated</td>
</tr>
<tr>
<td>Nonresonant</td>
<td>0</td>
<td>$m^2(D\pi)$</td>
<td>EFF</td>
<td>Floated</td>
</tr>
<tr>
<td>Nonresonant</td>
<td>1</td>
<td>$m^2(D\pi)$</td>
<td>EFF</td>
<td>Floated</td>
</tr>
<tr>
<td>$D_{K}^*(2007)^0$</td>
<td>1</td>
<td>$m^2(D\pi)$</td>
<td>RBW</td>
<td>$m = 2006.98 \pm 0.15$ MeV/$c^2$, $\Gamma = 2.1$ MeV</td>
</tr>
<tr>
<td>$B_{K}^*$</td>
<td>1</td>
<td>$m^2(DK)$</td>
<td>RBW</td>
<td>$m = 5325.2 \pm 0.4$ MeV/$c^2$, $\Gamma = 0.0$ MeV</td>
</tr>
</tbody>
</table>

$D_0^*(2400)^0$ and $D_2^*(2460)^0$ states expected
High mass $D_j^*(2760)^0$ state included, previously unknown spin
Two virtual states

Relativistic Breit-Wigner shape used to model resonances

Two non-resonant components (S-wave and P-wave), exponential model
- Model independent tests support need for both

arXiv:1503.02995
Dalitz plot fit

arXiv:1503.02995
Dalitz plot fit

- (Right) helicity angle distributions for (left) interesting $m(D^+\pi^-)$ regions

![Graphs showing Dalitz plots with data and fits for $m(D^+\pi^-)$ and cos $\theta(D^+\pi^-)$ distributions.](image-url)
Dalitz plot analysis results

- $D_1^*(2760)^0$ determined to have spin-1
  - Other hypotheses rejected with high significance

- Masses and widths of $D_2^*(2460)^0$ and $D_1^*(2760)^0$ reported:

  \[
  \begin{align*}
  m(D_2^*(2460)^0) &= (2464.0 \pm 1.4 \pm 0.5 \pm 0.2) \text{ MeV/c}^2 \\
  \Gamma(D_2^*(2460)^0) &= (43.8 \pm 2.9 \pm 1.7 \pm 0.6) \text{ MeV} \\
  m(D_1^*(2760)^0) &= (2781 \pm 18 \pm 11 \pm 6) \text{ MeV/c}^2 \\
  \Gamma(D_1^*(2760)^0) &= (177 \pm 32 \pm 20 \pm 7) \text{ MeV}
  \end{align*}
  \]

  Uncertainties are statistical, experimental systematic and model uncertainties

- Product branching fractions ($\times 10^{-4}$) measured:

  \[
  \begin{array}{|c|c|}
  \hline
  \text{Resonance} & \text{Branching fraction} \\
  \hline
  D_0^*(2400)^0 & 6.6 \pm 2.1 \pm 0.5 \pm 1.5 \pm 0.4 \\
  D_2^*(2460)^0 & 25.2 \pm 1.2 \pm 0.7 \pm 1.1 \pm 1.7 \\
  D_1^*(2760)^0 & 3.9 \pm 1.0 \pm 0.3 \pm 0.7 \pm 0.3 \\
  \text{S-wave nonresonant} & 30.1 \pm 5.9 \pm 1.2 \pm 8.6 \pm 2.0 \\
  \text{P-wave nonresonant} & 18.9 \pm 4.4 \pm 1.6 \pm 2.9 \pm 1.3 \\
  D^*_v(2007)^0 & 6.0 \pm 1.8 \pm 1.0 \pm 1.2 \pm 0.4 \\
  B^*_v & 2.9 \pm 1.5 \pm 0.7 \pm 1.3 \pm 0.2 \\
  \hline
  \end{array}
  \]

  Final errors due to uncertainty on $DK\pi$ BF result
**B****S** Spectroscopy

- Heavy Quark Effective Theory predicts spectrum of excited B states
  - Spectrum should be almost identical for charged and neutral B**S** states
  - Higher excitations decay to B/B* plus π

- Current knowledge is limited

- Broad B* 0 and B 1 states predicted

- Evidence for higher mass states from CDF [Phys.Rev. D90 (2014) 1, 012013]
Inclusive Study of the B⁺π⁻ and B⁰π⁺ Mass Spectra

Analysis strategy

- 2011+2012 data sample corresponding to \( \mathcal{L} = 3.0 \text{ fb}^{-1} \)
- Selection of a high purity \( B^+ \) and \( B^0 \) samples
- The \( B^+ (B^0) \) candidates combined with \( \pi (\pi^+) \) originating from the interaction point
- Analysis carried out by fitting the Q distributions:

\[ Q \equiv m(B\pi) - m(B) - m(\pi) \]
Nominal Fit Results

Candidates integrated over the 3 $p_T$ bins

$B^+\pi^-$  $B^0\pi^+$

St Goar conference, March 24-27, 2015
**Fit Model**

Associated Production
(Broad resonances + correlated nonresonant production of $B$ and $\pi$ in the fragmentation chain)

$B_1(5721) \rightarrow B^*\pi$

feed-down

$B_2^*(5747) \rightarrow B^*\pi$

feed-down

$B_2^*(5747) \rightarrow B\pi$

Broad structures $B_J(5840)$ and $B_J(5960)$

**Empirical Model ≡ Minimal choice**

Combintorial background (i.e. WS)

Alternative fit models (≡ Quark Model) consider the two broad states belonging to the same doublet. Then an extra fit function is added for the $B_J \rightarrow B^*\pi$ feed-down.
Nominal Fit Results by $p_T$ Bin

$0.5 < p_T < 1$ GeV

$1 < p_T < 2$ GeV

$p_T > 2$ GeV

$B^+\pi^-$

$B^0\pi^+$
Nominal Fit Results

Candidates integrated over the $3 \, p_T$ bins

$B^+\pi^-$  $B^0\pi^+$

**Final Results:**

$B_1(5721)^0, +$ and $B_2^*(5747)^0, +$

$Q$ values converted into absolute masses by adding the known $B, \pi$ and $B-B^*$ masses

<table>
<thead>
<tr>
<th>Mass</th>
<th>stat.</th>
<th>syst.</th>
<th>B mass</th>
<th>$B^*-B$ mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_{B_1(5721)^0}$</td>
<td>$5727.7 \pm 0.7 \pm 1.4 \pm 0.17 \pm 0.4$</td>
<td>MeV,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_2^*(5747)^0}$</td>
<td>$5739.44 \pm 0.37 \pm 0.33 \pm 0.17$</td>
<td>MeV,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_1(5721)^+}$</td>
<td>$5725.1 \pm 1.8 \pm 3.1 \pm 0.17 \pm 0.4$</td>
<td>MeV,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_2^*(5747)^+}$</td>
<td>$5737.20 \pm 0.72 \pm 0.40 \pm 0.17$</td>
<td>MeV,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_1(5721)^0}$</td>
<td>$30.1 \pm 1.5 \pm 3.5$</td>
<td>MeV,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_2^*(5747)^0}$</td>
<td>$24.5 \pm 1.0 \pm 1.5$</td>
<td>MeV,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_1(5721)^+}$</td>
<td>$29.1 \pm 3.6 \pm 4.3$</td>
<td>MeV,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_2^*(5747)^+}$</td>
<td>$23.6 \pm 2.0 \pm 2.1$</td>
<td>MeV,</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Most precise measurements of the $B_1(5721)$ and $B_2^*(5747)$ masses and widths

$$\frac{B(B_2^*(5747)^0 \rightarrow B^+\pi^-)}{B(B_2^*(5747)^0 \rightarrow B^+\pi^-)} = 0.71 \pm 0.14 \pm 0.30,$$

$$\frac{B(B_2^*(5747)^+ \rightarrow B^{0}\pi^+)}{B(B_2^*(5747)^+ \rightarrow B^{0}\pi^+)} = 1.0 \pm 0.5 \pm 0.8,$$

First evidence of the $B_2^*(5747)^0 \rightarrow B^{*+}\pi$ (3.7σ)!
**Final Results:**

$B_J(5840)^{0,+}$ and $B_J(5960)^{0,+}$

The properties of the $B_J(5960)^{0,+}$ states are consistent with and more precise than those obtained by the CDF collaboration when assuming decay only to $B\pi$.

If the $B_J(5840)^{0,+}$ and $B_J(5960)^{0,+}$ states are considered under the quark model hypothesis, their properties are consistent with those expected for the $B(2S)$ and $B^*(2S)$ radially excited states.
### Detailed table of $B(5840)$ and $B(5960)$

<table>
<thead>
<tr>
<th></th>
<th>stat.</th>
<th>syst.</th>
<th>B mass</th>
<th>$B^*-B$ mass</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Empirical model</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5840)}^0$</td>
<td>5862.9 ± 5.0</td>
<td>6.7 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5840)}$</td>
<td>127.4 ± 16.7</td>
<td>34.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5960)}^0$</td>
<td>5969.2 ± 2.9</td>
<td>5.1 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5960)}$</td>
<td>82.3 ± 7.7</td>
<td>9.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5840)}^{+}$</td>
<td>5850.3 ± 12.7</td>
<td>13.7 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5840)}^{+}$</td>
<td>224.4 ± 23.9</td>
<td>79.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5960)}^{+}$</td>
<td>5964.9 ± 4.1</td>
<td>2.5 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5960)}^{+}$</td>
<td>63.0 ± 14.5</td>
<td>17.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Quark model, $B_J(5840)^{0,+}$ natural</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5840)}^0$</td>
<td>5889.7 ± 22.2</td>
<td>6.7 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5840)}$</td>
<td>107.0 ± 19.6</td>
<td>34.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5960)}^0$</td>
<td>6015.9 ± 3.7</td>
<td>5.1 ± 0.2</td>
<td>0.2 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5960)}$</td>
<td>81.6 ± 9.9</td>
<td>9.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5840)}^{+}$</td>
<td>5874.5 ± 25.7</td>
<td>13.7 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5840)}^{+}$</td>
<td>214.6 ± 26.7</td>
<td>79.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5960)}^{+}$</td>
<td>6010.6 ± 4.0</td>
<td>2.5 ± 0.2</td>
<td>0.2 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5960)}^{+}$</td>
<td>61.4 ± 14.5</td>
<td>17.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Quark model, $B_J(5960)^{0,+}$ natural</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5840)}^0$</td>
<td>5907.8 ± 4.7</td>
<td>6.7 ± 0.2</td>
<td>0.2 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5840)}$</td>
<td>119.4 ± 17.2</td>
<td>34.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5960)}^0$</td>
<td>5993.6 ± 6.4</td>
<td>5.1 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5960)}$</td>
<td>55.9 ± 6.6</td>
<td>9.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5840)}^{+}$</td>
<td>5889.3 ± 15.0</td>
<td>13.7 ± 0.2</td>
<td>0.2 ± 0.4</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5840)}^{+}$</td>
<td>229.3 ± 26.9</td>
<td>79.8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{B_J(5960)}^{+}$</td>
<td>5966.4 ± 4.5</td>
<td>2.5 ± 0.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{B_J(5960)}^{+}$</td>
<td>60.8 ± 14.0</td>
<td>17.2</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
**THE EXCITED $B_s$ STATES**

- LHCb has reported the first observation of $B_{s2}^* \to B^*K$ decay $\Rightarrow (B_{s1}, B_{s2}^*)$
- $L=1$, $j_q=3/2$ doublet
- Masses, widths, BR’s well consistent with theory

---

**The two $B_{s1}/B_{s2}^* \to B^*K$ signals peak in the BK spectrum as well shifted by the $B^{*+} - B^+$ mass difference ($\sim 45$ MeV) due to missing momentum of $\gamma$**

---

**Table**

<table>
<thead>
<tr>
<th>$(j_q, J^P)$</th>
<th>Allowed decay mode</th>
<th>$B^{+}K^-$</th>
<th>$B^{*+}K^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(1/2, 0^+)$</td>
<td>yes</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>$(1/2, 1^+)$</td>
<td>no</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>$(3/2, 1^+)$</td>
<td>no</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>$(3/2, 2^+)$</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
</tbody>
</table>

**[LHCb: PRL 113, 162001 (2014)]**
Many new results from LHCb regarding spectroscopy! 😊

- Exotic mesons:
  - X3872: radiative decay in $\psi'\gamma$, disfavoring a pure DD* molecule interpretation
  - X3872 new spin assignment without min L assumption
  - Z4430: resonance nature established!

- D**: New Dalitz-based analysis using $B \rightarrow DK\pi$ channel
  - Spin parity of D* (2760)$^0$ determined to be spin 1

- B**: 2 new structures: $B^*(5840)^{0,+}$ and $B^*(5960)^{0,+}$

- One narrow $B_s^{**}$ decaying to BK: can be useful for analysis involving partial reconstruction and kinematical fits
Backups
### Systematics Uncertainties

<table>
<thead>
<tr>
<th>Source (μ and Γ in MeV)</th>
<th>$B_1(5721)^0$</th>
<th>$B_2^*(5747)^0$</th>
<th>$B_J(5840)^0$</th>
<th>$B_J(5960)^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μ</td>
<td>Γ</td>
<td>BF ratio</td>
<td>μ</td>
</tr>
<tr>
<td>Total statistical</td>
<td>0.72</td>
<td>1.52</td>
<td>0.14</td>
<td>0.37</td>
</tr>
<tr>
<td>Fit range (high)</td>
<td>0.33</td>
<td>1.30</td>
<td>0.06</td>
<td>0.08</td>
</tr>
<tr>
<td>Fit range (low)</td>
<td>0.04</td>
<td>0.11</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>2 MeV bins</td>
<td>0.02</td>
<td>0.14</td>
<td>0.00</td>
<td>0.04</td>
</tr>
<tr>
<td>Spline knots</td>
<td>0.11</td>
<td>0.01</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Float AP</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
</tr>
<tr>
<td>$B_2^*(5747)^0$ rel. eff., low $p_T$</td>
<td>0.56</td>
<td>0.91</td>
<td>0.15</td>
<td>0.08</td>
</tr>
<tr>
<td>$B_2^*(5747)^0$ rel. eff., mid $p_T$</td>
<td>0.64</td>
<td>1.01</td>
<td>0.05</td>
<td>0.09</td>
</tr>
<tr>
<td>$B_2^*(5747)^0$ rel. eff., high $p_T$</td>
<td>0.20</td>
<td>0.37</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>Eff. variation with $Q$ value</td>
<td>0.13</td>
<td>0.33</td>
<td>0.02</td>
<td>0.04</td>
</tr>
<tr>
<td>Data-simulation reweighting</td>
<td>0.07</td>
<td>0.38</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>$B$ $p_T$ cut</td>
<td>0.02</td>
<td>0.20</td>
<td>0.01</td>
<td>0.24</td>
</tr>
<tr>
<td>$p_T$ binning</td>
<td>0.90</td>
<td>2.45</td>
<td>0.24</td>
<td>0.06</td>
</tr>
<tr>
<td>Fit bias</td>
<td>0.06</td>
<td>0.17</td>
<td>0.01</td>
<td>0.00</td>
</tr>
<tr>
<td>Spin</td>
<td>0.02</td>
<td>0.06</td>
<td>0.01</td>
<td>0.06</td>
</tr>
<tr>
<td>Effective radius</td>
<td>0.33</td>
<td>1.44</td>
<td>0.02</td>
<td>0.12</td>
</tr>
<tr>
<td>$B^* - B$ mass</td>
<td>0.10</td>
<td>0.11</td>
<td>0.03</td>
<td>0.02</td>
</tr>
<tr>
<td>$B_J(5840)^0$ $J^P$</td>
<td>0.01</td>
<td>0.04</td>
<td>0.00</td>
<td>0.01</td>
</tr>
<tr>
<td>$B_J(5960)^0$ $J^P$</td>
<td>0.01</td>
<td>0.20</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Extra state</td>
<td>0.00</td>
<td>0.26</td>
<td>0.00</td>
<td>0.04</td>
</tr>
<tr>
<td>Total systematic</td>
<td>1.36</td>
<td>3.49</td>
<td>0.30</td>
<td>0.33</td>
</tr>
</tbody>
</table>

St Goar conference, March 24-27, 2015
Ds spectroscopy

Puzzle: Excited Ds Mesons: L=1, j_q = 1/2(?)

Inclusive studies of Ds(π^0)π^0
[BaBar, PRL90, 242001][CLEO, PRD68, 032002]

<table>
<thead>
<tr>
<th>PDG</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ds0^*(2317)±</td>
<td>2317.7 ± 0.6</td>
<td>&lt; 3.8</td>
</tr>
<tr>
<td>Ds1(2460)±</td>
<td>2459.5 ± 0.6</td>
<td>&lt; 3.5</td>
</tr>
</tbody>
</table>

Surprisingly narrow!
PUZZLE: EXCITED $D_s$ MESONS: $L=1, j_q = 1/2(?)$

- Spin-Parity $J^P = (0^+, 1^+)$ as expected for the $L=1, j_q=1/2$ states
- $B \rightarrow DD_{s0}^*$ branching ratios below expectations (i.e. $\sim 1$) for a $q\bar{q}$ state [PLB572, 164 (2003)] [PRD69, 054002 (2004)]

$$\frac{\mathcal{B}(B^+ \rightarrow D^0 D_{s0}^{*+})}{\mathcal{B}(B^+ \rightarrow D^0 D_{s0}^{*+})} = 0.081^{+0.032}_{-0.025}$$
$$\frac{\mathcal{B}(B^0 \rightarrow D^- D_{s0}^{*+})}{\mathcal{B}(B^0 \rightarrow D^- D_{s0}^{*+})} = 0.13 \pm 0.04$$

- Many alternative interpretations:
  - DK or $D_s \pi$ molecule, $q\bar{q} +$ tetraquark/DK mixing

No $D_s^{\pm}\pi^\pm$ partners have been observed in inclusive studies [BaBar: PRD74 (2006) 032007] or in $B$ decays [Belle: R.Chistov@ EPS-HEP, Stockholm, Sweden (18 July 2013)]
SEARCH FOR \textquotedblleft D_{s0}^* \textquotedblright \ IN B_s DECAYS

If the D_{s0}^*(2317) is not the L=1, j_g=1/2 excited D_s state, then a broad D_{s0}^* state above the DK threshold should appear in B_s decays.

-Amplitude analysis of B_s \rightarrow D^0 K^- \pi^+

No evidence for such a broad D_{s0}^* state.

[LHCb: PRL 113, 162001 (2014)]
[LHCb: PRD 90, 072003 (2014)]