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Study of Orbitally Excited $B_{(s)}$ Mesons and Evidence for a New $B\pi$ Resonance

GK-Workshop 2014 in Bad Liebenzell

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KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT)

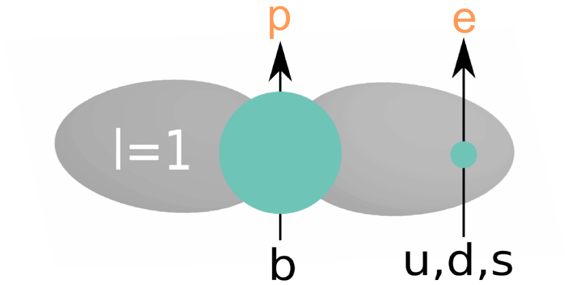
Why B-Meson Spectroscopy?

H atom:

- Heavy-light bound system
- Understanding of QED

B meson:

- Heavy-light bound system
- Study of QCD



Excitation with angular momentum $L = 1$ is called $B_{(s)}^{**}$ state

Phenomenology

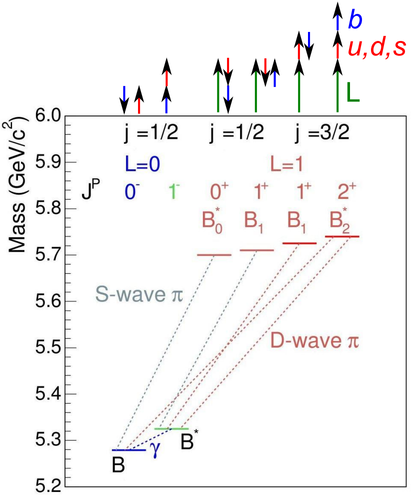
$L = 1$: Four states

- Fine splitting $\times$
  Hyperfine splitting = 4

Decay

- Strong interaction:

$$B^{**0}, B^{**+} \rightarrow B^{(*)}\pi$$
$$B_s^{**0} \rightarrow B^{(*)}K$$



Phenomenology

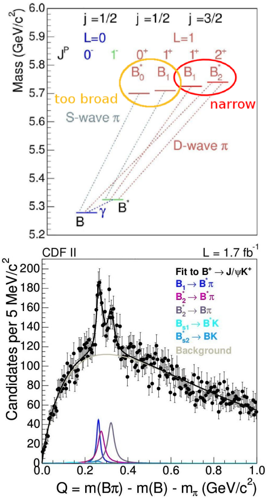
- Two narrow states
- Three observable decays per B meson flavor:

  $B_1 \to B^*\pi, \quad B_{s1} \to B^*K$

  $B_2^* \to B^*\pi, \quad B_{s2}^* \to B^*K$

  $B_2^* \to B\pi, \quad B_{s2}^* \to BK$

- Other two states too broad for CDF



PRL 102, 102003 (2009).

Heavy Quark Effective Theory

- Phenomenological models predict masses and widths
  - Relativistic and non-relativistic models
  - Lattice-gauge calculations
  - Potential models
- Covered range: 160 MeV/c^2 $\gg$ experimental uncertainty

Beyond B^{**}:

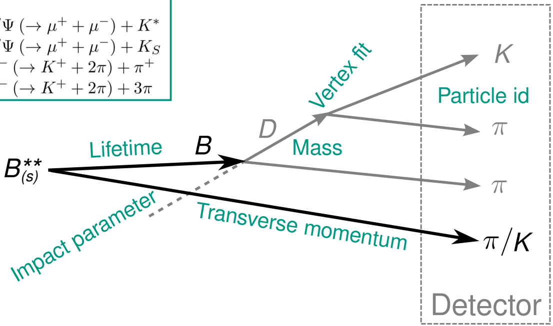
- $L \geq 2$ excitations and radial excitations
- A few such states observed for D mesons

Reconstruction

Full CDF Run II data sample

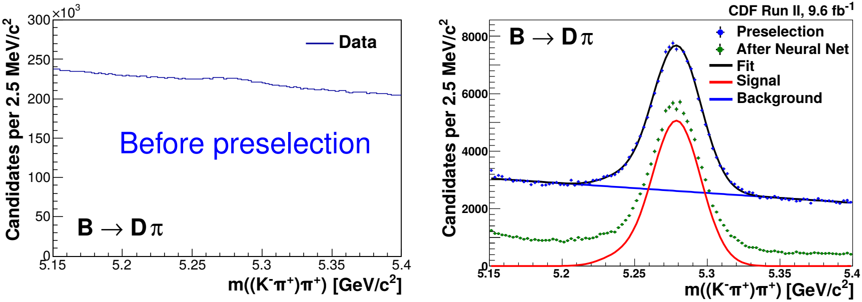
- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
- Int. luminosity: 9.6 fb^{-1}

$$
\begin{array}{ll}
B^+ & \to J/\Psi\,(\to \mu^+ + \mu^-) + K^+ \\
B^+ & \to \bar{D}^0\,(\to K^+ + \pi^-) + \pi^+ \\
B^+ & \to \bar{D}^0\,(\to K^+ + \pi^-) + 3\pi \\
 & \\
B^0 & \to J/\Psi\,(\to \mu^+ + \mu^-) + K^* \\
B^0 & \to J/\Psi\,(\to \mu^+ + \mu^-) + K_S \\
B^0 & \to D^-\,(\to K^+ + 2\pi) + \pi^+ \\
B^0 & \to D^-\,(\to K^+ + 2\pi) + 3\pi
\end{array}
$$



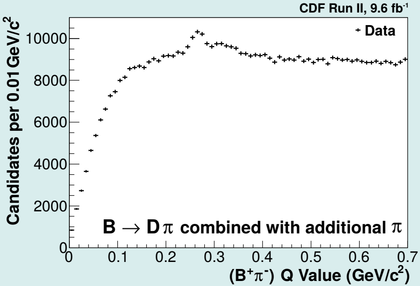
Preselection

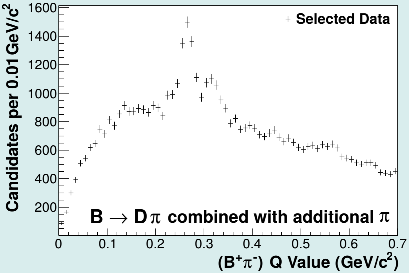
- Soft B meson preselection
- NeuroBayes ${}_s\mathcal{P}lot$ training to select B mesons



B^{**} Reconstruction and Selection

From $B\pi$ or BK combinations:





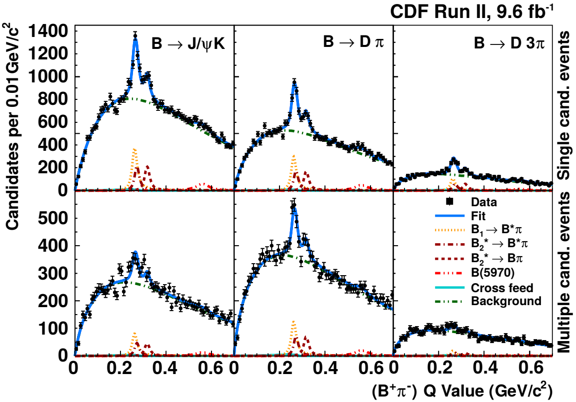
Selection

- Second NeuroBayes training using data and signal simulations
- Final cut

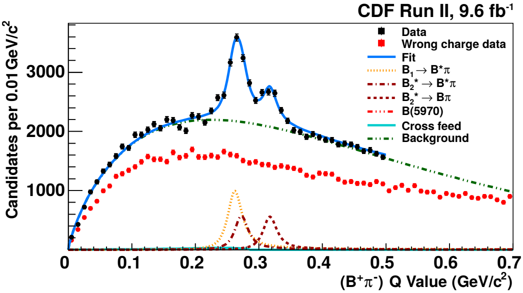
Fit Model

Unbinned simultaneous maximum likelihood fit

- Signal: Breit-Wigner $*$ double Gaussian (resolution)
- Phenomenological background function: Γ distribution or polynomial



Fit Model: Constraints

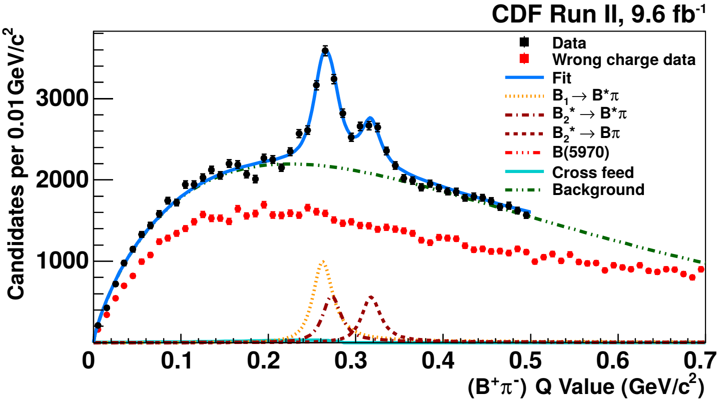


Due to overlap of the two left peaks

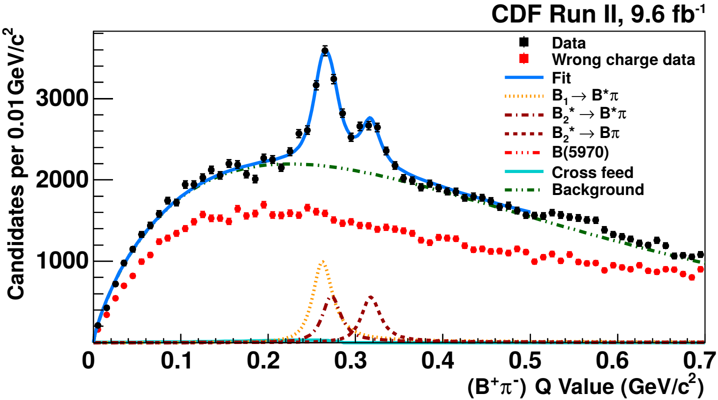
Constraints:

- $B^* \to B\gamma$ photon energy: about 45 MeV/c^2
- $B_2^{*0/+}$ branching ratio: $\mathcal{B}(B_2^* \to B\pi)/\mathcal{B}(B_2^* \to B^*\pi) = 1.02 \pm 0.24$

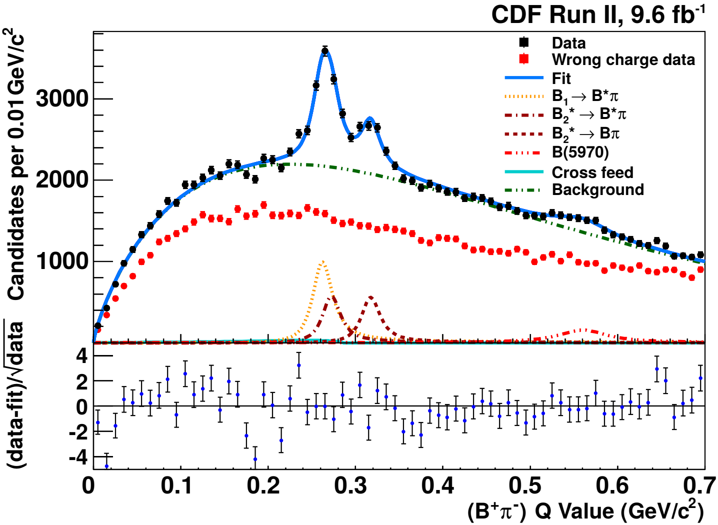
New Structure at Q = 0.55 GeV/c^2



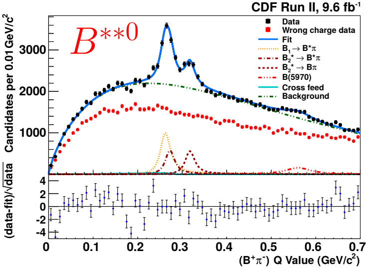
New Structure at Q = 0.55 GeV/c^2

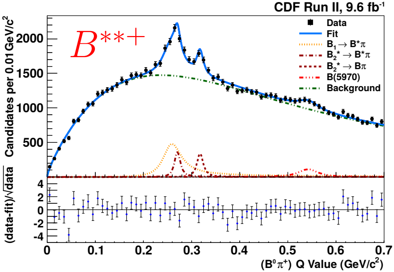


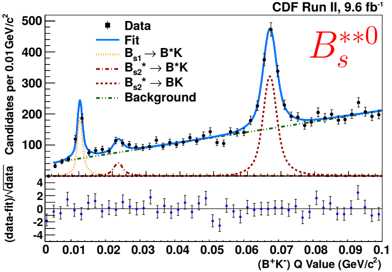
New Structure at Q = 0.55 GeV/c^2



All Analyzed Data







Dominant Systematic Uncertainties

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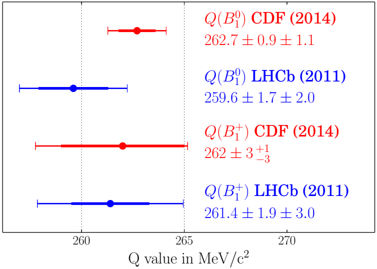
B^{**0} and B^{**+}

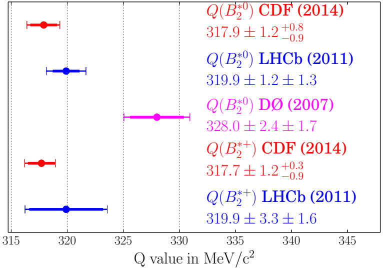
- Modeling of background shape
- Variation of external constraints in the fit model
- Possible influence of broad B^{**} states

B_s^{**0}

- Modeling of detector resolution
- Mass scale of the detector

Results $B^{**0/+}$





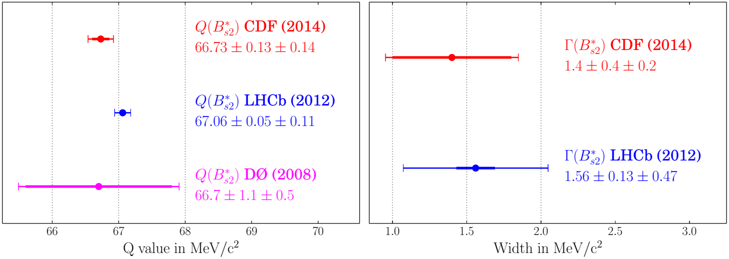
Relative production rate: $r_{\text{prod}} = \frac{\sigma(B_1)}{\sigma(B_2^*)} \cdot \frac{\mathcal{B}(B_1 \to B^* h)}{\mathcal{B}(B_2^* \to Bh) + \mathcal{B}(B_2^* \to B^* h)}$

- $r_{\text{prod}}(B^{**0}) = 0.66 \pm 0.12 \pm 0.51$
- $r_{\text{prod}}(B^{**+}) = 1.8 \pm 0.9 \pm 1.2$

B^{**} production rate relative to B production:

- $19 \pm 2 \pm 4\%$

Results B_s^{**}



Relative production rate:

- $r_{\text{prod}} = 0.25^{+0.07}_{-0.04} \pm 0.05$

Branching fraction:

- $\frac{\mathcal{B}(B_{s2}^* \to B^{*+}K^-)}{\mathcal{B}(B_{s2}^* \to B^+K^-)} = 0.10 \pm^{+0.03}_{-0.02} \pm 0.02$

The New Resonance

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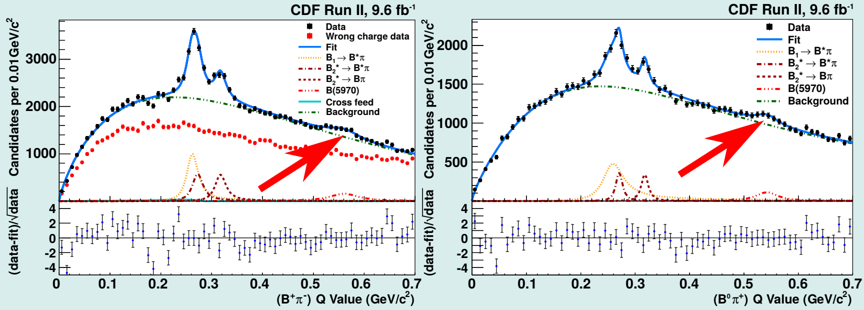
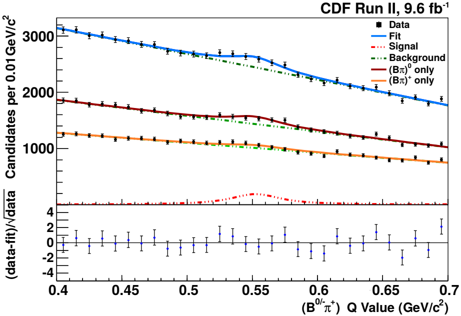
Sum of individual fits and samples:



- The structure is observed in excited B^0 and B^+ at the same position

Statistical Significance

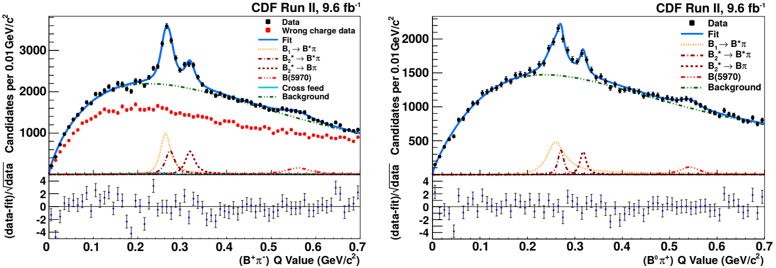
- $(B\pi)^{0,+}$ combined
- Unchanged selection
- Breit-Wigner $*$ single Gaussian
- Linear background
- Improvement of fit quality when signal peak is added
- p-value from background-only pseudoexperiments
- Search 0.45-0.65 GeV/c^2



We find

First evidence with 4.4σ significance

Additional Tests

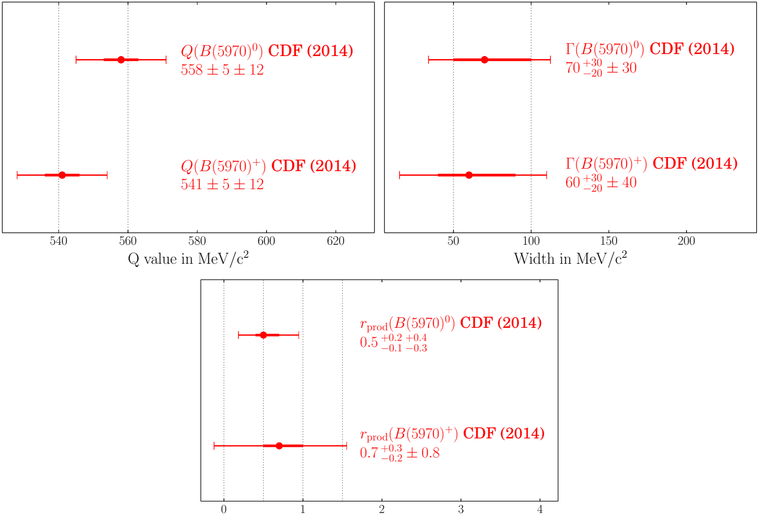


- Alternative method for significance determination: 5.6σ
- No signal in wrong charge $(B^+\pi^+)$ combinations
- Decide to provisionally call it $B(5970)$

Publication:

Phys. Rev. D **90**, 012013 – July 28, 2014

Results $B(5970)$

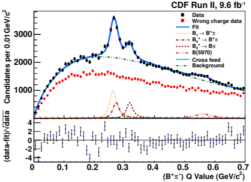


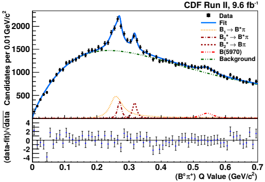
Systematic uncertainty mainly from modeling of the background

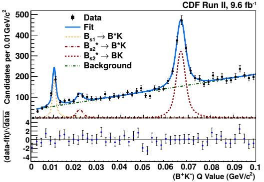
Conclusion

- Analysis of excited $B_{(s)}$ mesons on full CDF Run II dataset
- Study of QCD

- Masses, widths, production rates and branching fraction determined
- **First evidence and measurement of properties of $B(5970)$ with 4.4σ significance**
- Publication in Physical Review D





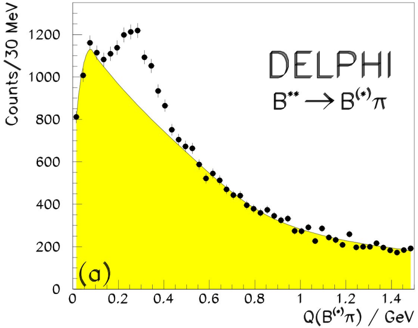


Supplemental Slides

Previous Results

- 1995: Observation of $B^{**}_{(s)}$ mesons at LEP

P. Abreu et al. (DELPHI Collaboration), Phys. Lett. B 345, 598 (1995).
R. Akers et al. (OPAL Collaboration), Z. Phys. C 66, 19 (1995).
D. Buskulic et al. (ALEPH Collaboration), Z. Phys. C 69, 393 (1996).
R. Barate et al. (ALEPH Collaboration), Phys. Lett. B 425, 215 (1998).



- 2004: Delphi separates B_1^0 and B_2^{*0} states and finds B_{s2}^{*0}

DELPHI Collaboration. Z. Albrecht et al. CONF 700. 2004-025.

- 2007–2009: CDF and DØ measure neutral and strange B_1 and B_2^* states

T. Aaltonen et al. Phys.Rev.Lett. 102 (2009).
T. Aaltonen et al. Phys.Rev.Lett. 100 (2008).
V.M. Abazov et al. Phys.Rev.Lett. 99 (2007).
V.M. Abazov et al. Phys.Rev.Lett. 100 (2008).

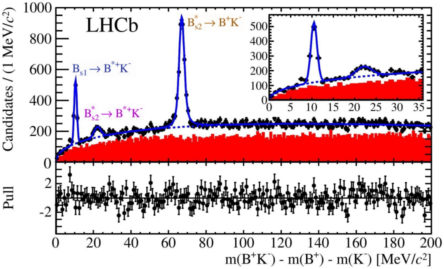
Previous Results

- 2011: LHCb shows measurement of all narrow states

The LHCb Collaboration. LHCb-CONF-2011-053.

- 2012: LHCb measures B_s^{**0} and observes $B_{s2}^{*0} \to B^* K$

The LHCb Collaboration. Phys.Rev.Lett. 110, 151803 (2013)



Measured Masses

	m (MeV$/c^2$)
B_1^0	$5726.6 \pm 0.9\ ^{+1.1}_{-1.2} \pm 0.4$
B_2^{*0}	$5736.7 \pm 1.2\ ^{+0.8}_{-0.9} \pm 0.2$
B_1^+	$5727 \pm 3\ ^{+1}_{-3} \pm 2$
B_2^{*+}	$5736.9 \pm 1.2\ ^{+0.3}_{-0.9} \pm 0.2$
B_{s1}^0	$5828.3 \pm 0.1 \pm 0.2 \pm 0.4$
B_{s2}^{*0}	$5839.7 \pm 0.1 \pm 0.1 \pm 0.2$
$B(5970)^0$	$5978 \pm 5 \pm 12$
$B(5970)^+$	$5961 \pm 5 \pm 12$

Systematic Uncertainties B^{**0}

	Q (MeV/c^2) B_1	Q (MeV/c^2) B_2^*	Γ (MeV/c^2) B_1	Γ (MeV/c^2) B_2^*	Δm (MeV/c^2)	r_{prod}
Mass scale	0.2	0.2	-	-	0.0	-
Resolution	0.0	0.0	0.3	0.2	0.0	0.0
Signal Model	0.0	0.1	0.7	0.7	0.1	0.1
Backgr. model	0.0	0.7	3.2	3.6	0.7	0.3
Broad B^{**0} states	$^{+0.1}_{-0.3}$	$^{+0.0}_{-0.4}$	$^{+0.1}_{-2.1}$	$^{+0.0}_{-3.9}$	$^{+0.3}_{-0.4}$	$^{+0.3}_{-0.0}$
Fit bias	-	-	-	0.3	-	$^{+0.0}_{-0.1}$
Fit constraints	1.1	$^{+0.3}_{-0.2}$	$^{+1.5}_{-1.6}$	0.4	0.9	$^{+0.2}_{-0.3}$
Acceptance	-	$^{+0.0}_{-0.3}$	$^{+0.6}_{-0.0}$	-	$^{+0.3}_{-0.0}$	$^{+0.1}_{-0.2}$
Total systematic	$^{+1.1}_{-1.2}$	$^{+0.8}_{-0.9}$	4	$^{+4}_{-5}$	1.2	0.5
Statistical	0.9	1.2	3	$^{+3}_{-2}$	1.7	$^{+0.2}_{-0.4}$

$$r_{\text{prod}} = \frac{\sigma(B_1)}{\sigma(B_2^*)} \cdot \frac{\mathcal{B}(B_1 \to B^* h)}{\mathcal{B}(B_2^* \to Bh) + \mathcal{B}(B_2^* \to B^* h)}$$

$$r_{\text{dec}} = \frac{\mathcal{B}(B_{s2}^* \to B^{*+} K^-)}{\mathcal{B}(B_{s2}^* \to B^+ K^-)}$$

Systematic Uncertainties B^{**+}

	Q (MeV/c^2)		Γ (MeV/c^2)		Δm	r_{prod}
	B_1	B_2^*	B_1	B_2^*	(MeV/c^2)	
Mass scale	0.2	0.2	-	-	0.0	-
Resolution	0.0	0.0	0.1	0.2	0.0	0.0
Signal Model	0.3	0.0	1.0	0.7	0.3	0.2
Backgr. model	0.4	0.1	2.1	1.6	0.5	0.5
Broad B^{**+} states	$^{+0.2}_{-1.3}$	$^{+0.1}_{-0.0}$	$^{+0.0}_{-9.9}$	$^{+0.0}_{-3.2}$	$^{+1.3}_{-0.0}$	$^{+0.5}_{-0.2}$
Fit bias	-	-	$^{+0.0}_{-1.9}$	-	-	$^{+0.0}_{-0.4}$
Fit constraints	$^{+1.0}_{-2.2}$	$^{+0.2}_{-0.9}$	$^{+0.0}_{-7.4}$	$^{+2.8}_{-1.4}$	$^{+1.5}_{-0.8}$	$^{+0.5}_{-0.8}$
Acceptance	-	0.0	$^{+0.0}_{-3.8}$	$^{+1.0}_{-0.0}$	0.0	$^{+0.3}_{-0.5}$
Total systematic	$^{+1}_{-3}$	$^{+0.3}_{-0.9}$	$^{+2}_{-13}$	$^{+3}_{-4}$	$^{+2}_{-1}$	$^{+0.9}_{-1.2}$
Statistical	3	1.2	$^{+12}_{-10}$	$^{+4}_{-3}$	3	$^{+1.6}_{-1.0}$

Systematic Uncertainties B_s^{**}

	Q (MeV/c^2)		Γ (MeV/c^2)		Δm	$r_{\rm prod}$	$r_{\rm dec}$
	B_{s1}	B_{s2}^*	B_{s1}	B_{s2}^*	(MeV/c^2)		
Mass scale	0.14	0.14	-	-	0.01	-	-
Resolution	0.00	0.00	0.06	0.19	0.00	0.00	0.00
Signal Model	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Bkg. model	0.00	0.01	0.02	0.05	0.01	0.00	0.01
Fit range	0.04	0.01	0.26	0.02	0.03	0.04	0.01
Fit bias	-	-	0.02	0.02	-	$^{+0.00}_{-0.01}$	-
Fit constr.	0.00	0.02	0.01	0.04	0.02	0.00	0.00
Acceptance	-	-	-	-	-	0.01	0.01
Total syst.	0.15	0.14	0.3	0.2	0.04	0.04	0.02
Statistical	0.12	0.13	0.3	0.4	0.18	$^{+0.07}_{-0.05}$	$^{+0.03}_{-0.02}$

Systematic Uncertainties $B(5970)$

	Q (MeV/c^2)		Γ (MeV/c^2)		Rel. yield	
	Neutr.	Char.	Neutr.	Char.	Neutr.	Char.
Bkg. model	12	12	30	40	0.3	0.8
Fit bias	-	-	$^{+0}_{-10}$	$^{+0}_{-10}$	-	-
Acceptance	-	$^{+1}_{-0}$	3	-	$^{+0.2}_{-0.1}$	$^{+0.2}_{-0.1}$
Total syst.	12	12	30	40	$^{+0.4}_{-0.3}$	0.8
Statistical	5	5	$^{+30}_{-20}$	$^{+30}_{-20}$	$^{+0.2}_{-0.1}$	$^{+0.3}_{-0.2}$

Fit Model: Constraints

- Constraint on $B_2^{*0/+}$ branching ratio from extrapolation of measurement of D^{**}:
  - From $\mathcal{B}(D_2^* \to D\pi)/\mathcal{B}(D_2^* \to D^*\pi) = F_c \left(\frac{k_D}{k_{D^*}}\right)^5 = 1.56 \pm 0.16$
  - Calculate form factor F_c
  - F_c determines properties of initial state
  - Kinematic term characterizes final state, $k_{D^{(*)}}$ = momentum of decay product in the rest frame of mother particle
  - Assume $F_b = F_c$ due to heavy quark symmetry
  - Calculate $\mathcal{B}(B_2^* \to B\pi)/\mathcal{B}(B_2^* \to B^*\pi) = F_b \left(\frac{k_B}{k_{B^*}}\right)^5 = 1.02 \pm 0.24$
  - Uncertainty whether Blatt-Weisskopf form factor should be multiplied as additional kinematic term
  - So we apply it in a second calculation and obtain deviation by 0.24