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

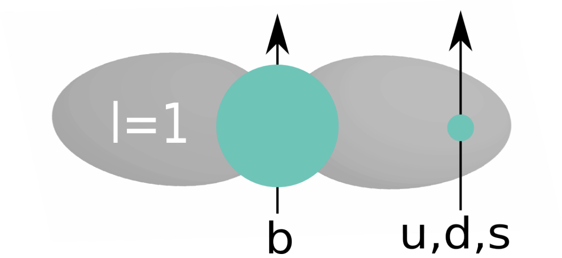
Rencontres de Physique de la Vallée d'Aoste

Manuel Kambeitz, on behalf of the CDF Collaboration | February 26, 2014

KARLSRUHE INSTITUTE OF TECHNOLOGY (KIT)

What do the hydrogen atom and the B meson have in common?

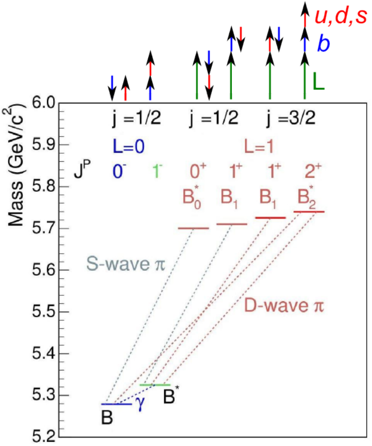
- Hydrogen atom: Heavy-light bound system, study led to understanding of QED
- B mesons are heavy-light systems of QCD
- Measure properties of excited B mesons to study quantum chromodynamics
- Excitation with angular momentum $L = 1$ is called $B^{**}_{(s)}$ state



Phenomenology

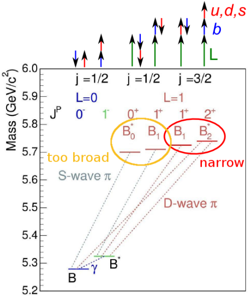
- Decay via strong interaction: $B^{**0,+} \to B^{(*)}\pi$ and $B_s^{**0} \to B^{(*)}K$

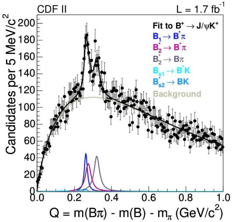
- Fine splitting: Light quark spin s couples with L to j of light quark
- Hyperfine splitting: j couples with spin of heavy quark to total angular momentum J



Phenomenology

- Parity and orbital angular momentum conservation make two of the states narrow
- We can observe three decays per B meson flavor:
  - $B_1 \to B^*\pi$, $B_{s1} \to B^*K$
  - $B_2^* \to B^*\pi$, $B_{s2}^* \to B^*K$
  - $B_2^* \to B\pi$, $B_{s2}^* \to BK$
- Other two states have predicted widths of 150 MeV/c^2
- Too broad for CDF





PRL 102, 102003 (2009).

Heavy Quark Effective Theory

- Various phenomenological models predict masses and widths
  - Relativistic and non-relativistic models
  - Lattice-gauge calculations
  - Potential models
- Predictions cover a range of 160 MeV/c^2 $\gg$ experimental uncertainty

Beyond B^{**}:

- Theory predicts $L \geq 2$ excitations and radial excitations
- A few such states have been found for D mesons

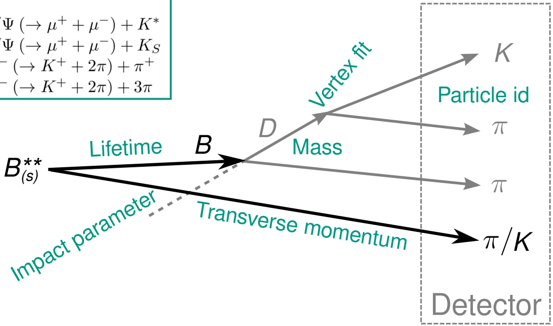
Goals of This Analysis

1. Measure properties of the narrow states B_1 and B_2^*:
   - Combined analysis of excited B^0, B^+ and B_s^0 mesons
   - First study of B^{**+}
   - Masses and widths
   - Production rates and branching fractions
   - Production rate relative to B meson production
2. Watch out for new excited B meson states.

Reconstruction

$$B^+ \to J/\Psi\,(\to \mu^+ + \mu^-) + K^+$$
$$B^+ \to \bar{D}^0\,(\to K^+ + \pi^-) + \pi^+$$
$$B^+ \to \bar{D}^0\,(\to K^+ + \pi^-) + 3\pi$$

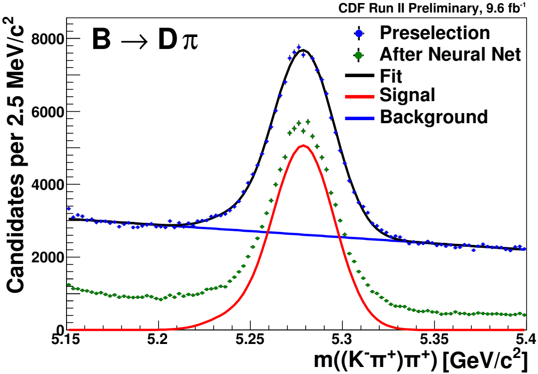
$$B^0 \to J/\Psi\,(\to \mu^+ + \mu^-) + K^*$$
$$B^0 \to J/\Psi\,(\to \mu^+ + \mu^-) + K_S$$
$$B^0 \to D^-\,(\to K^+ + 2\pi) + \pi^+$$
$$B^0 \to D^-\,(\to K^+ + 2\pi) + 3\pi$$



- Full CDF Run II data sample of $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
- Two different triggers: di-muon and displaced-track trigger
- Calculate topological, kinematic and particle identification quantities with significant signal-to-background separation

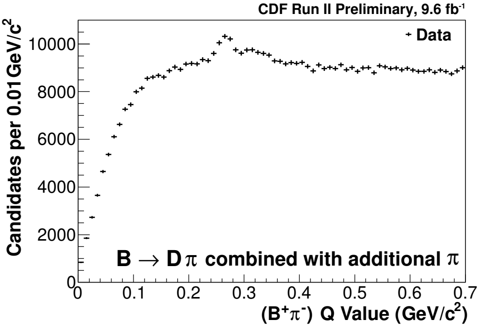
Preselection

- Mass peak of B mesons visible by soft selection requirements
- Train multivariate classifier NeuroBayes using ${}_s\mathcal{P}lot$ weights
- Training performed only using data
- Allows rejection of 74 % background while retaining 97% signal



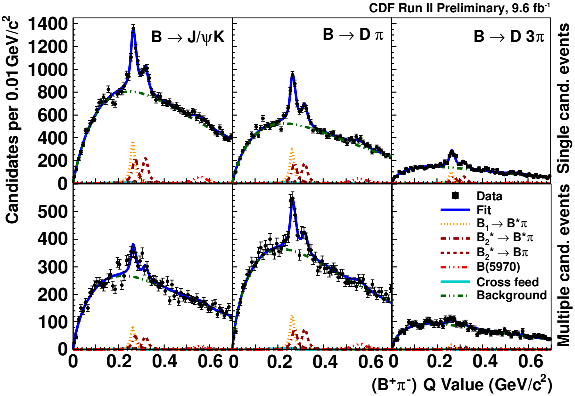
B^{**} Reconstruction and Selection

- Combine B candidates with additional pion or kaon



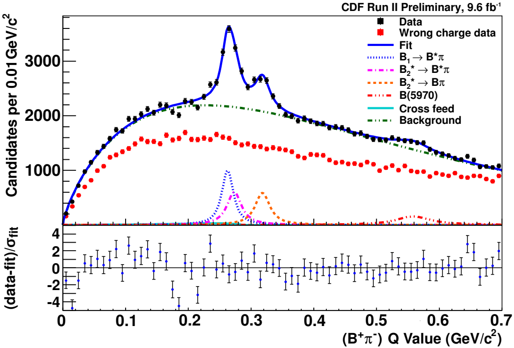
- Second NeuroBayes instance trained with non-peaking signal simulations and background from data
- Final selection by requirement (cut) on NeuroBayes discriminant

Fit Model



- Unbinned simultaneous maximum likelihood fit
- Signal: Breit-Wigner $*$ double Gaussian (resolution)
- Phenomenological smooth background function: Γ distribution or polynomial

Fit Model: Constraints

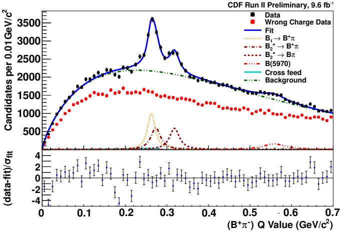


- Overlap of $B_1 \to B^*\pi$ and $B_2^* \to B^*\pi$ peaks
- Photon from $B^* \to B\gamma$ not reconstructed, constraint on photon energy from world average value

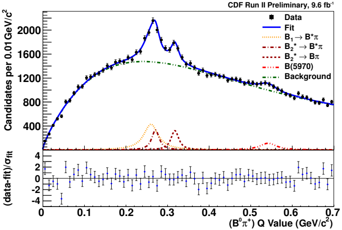
- Constraint on $B_2^{*0/+}$ branching ratio from extrapolation of measurement of D^{**} considering phase space:
  - From $\mathcal{B}(D_2^* \to D\pi)/\mathcal{B}(D_2^* \to D^*\pi) = F_c \left(\frac{k_D}{k_{D^*}}\right)^5 = 1.56 \pm 0.16$
  - Follows $\mathcal{B}(B_2^* \to B\pi)/\mathcal{B}(B_2^* \to B^*\pi) = F_b \left(\frac{k_B}{k_{B^*}}\right)^5 = 1.02 \pm 0.24$

Sum of individual fits and samples

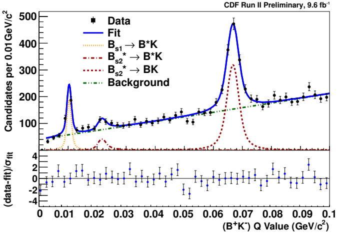
Neutral bottom



Charged bottom



Strange bottom



- Structure seen at $Q = 550\mathrm{MeV}/c^2$
- See later

Dominant Systematic Uncertainties

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

- Modeling of background shape
  - Fit with alternative background model
- Variation of external constraints in the fit model
- Possible influence of broad B^{**} states
  - Evaluate influence of additional broad structures at various positions on fit results

B_s^{**0}

- Modeling of detector resolution
  - Correct for discrepancy between data and simulations and vary correction factor
- Mass scale of the detector

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

	Q (MeV/c^2)	Γ (MeV/c^2)	Number of candidates
B_1^0	$262.6 \pm 0.8 \pm 1.3$	$20 \pm 2 \pm 5$	3400 ± 400
B_1^+	$261 \pm 4 \pm 3$	$42 \pm 11 \pm 13$	1300 ± 300
B_2^{*0}	$317.8 \pm 1.2 \pm 1.2$	$26 \pm 3 \pm 3$	5000 ± 200
B_2^{*+}	$317.9 \pm 1.1 \pm 0.9$	$17 \pm 6 \pm 8$	2000 ± 200

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

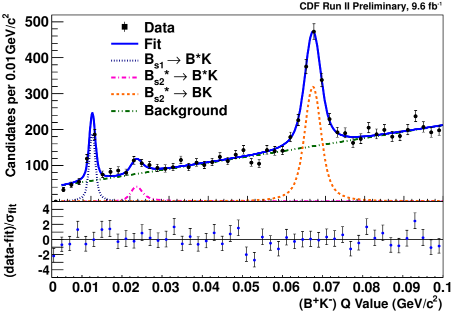
- $r_{\text{prod}}(B^{**0}) = 0.66 \pm 0.12 \pm 0.51$
- $r_{\text{prod}}(B^{**+}) = 1.8 \pm 0.9 \pm 1.2$

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

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

Results B_s^{**}

	Q (MeV/c^2)	Γ (MeV/c^2)	Number of candidates
B_{s1}^0	$10.37 \pm 0.10 \pm 0.14$	$0.7 \pm 0.3 \pm 0.3$	188 ± 18
B_{s2}^{*0}	$66.75 \pm 0.13 \pm 0.14$	$2.0 \pm 0.4 \pm 0.2$	1160 ± 70



Relative production rate:

$$r_{\text{prod}}(B_s^{**0}) = 0.18 \pm 0.02 \pm 0.02$$

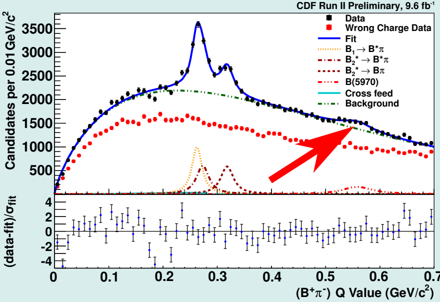
Branching fraction:

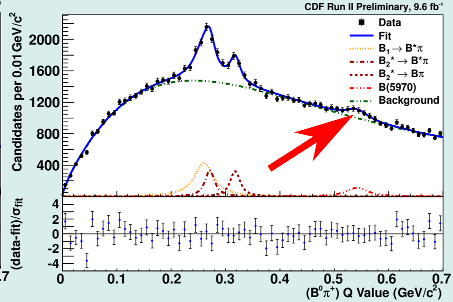
$$\frac{\mathcal{B}(B_{s2}^* \to B^{*+}K^-)}{\mathcal{B}(B_{s2}^* \to B^+K^-)} = 0.11 \pm 0.03 \pm 0.02$$

Consistent with prediction for $B^{**0/+}$ when considering difference in phase space

The New Resonance

Sum of individual fits and samples:

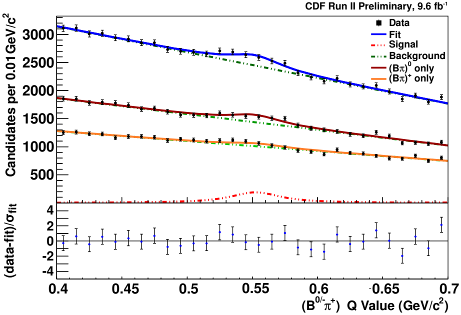




- The structure is observed in excited B^0 and B^+ at the same position

Statistical Significance

- $(B\pi)^{0,+}$ combined
- Keep selection from B^{**} analysis unchanged
- Breit-Wigner $*$ single Gaussian
- Linear background
- Consider improvement of minimal log-likelihood against background only fit on data
- Fit background only samples in pseudoexperiments
- Search $450 - 650\mathrm{MeV}/\mathrm{c}^2$



We find

First evidence with 4.4σ significance in the range $450 - 650\mathrm{MeV}/\mathrm{c}^2$.

Additional Tests

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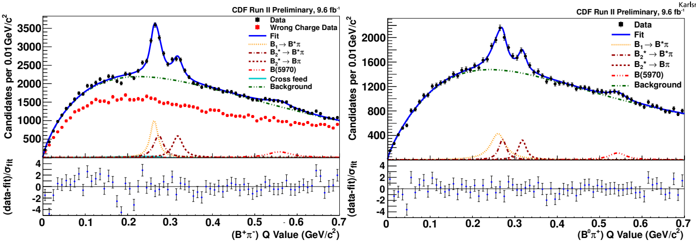

- Alternative method for significance determination:
  - Calculate p-value with the full Q range fit model
  - Determine significance for $B^+\pi^-$ and $B^0\pi^+$ separately
  - Difference due to different background description
  - Combination results in even 5.6σ significance
- No signal in wrong charge $(B^+\pi^+)$ combinations, behaves like B meson
- Decide to provisionally call it $B(5970)$

Results $B(5970)$

Separate measurement of charged and neutral state:

Quantity	Value MeV/c^2	Stat. uncert. MeV/c^2	Syst. uncert. MeV/c^2
$Q(B(5970)^0)$	558	5	12
$Q(B(5970)^+)$	541	5	12
$\Gamma(B(5970)^0)$	70	18	31
$\Gamma(B(5970)^+)$	60	20	40

Production rate relative to $B_2^* \to B\pi$:

$$r_{prod}(B(5970)^0) = 0.52 \pm 0.14\ (\text{stat.}) \pm 0.34\ (\text{syst.})$$

$$r_{prod}(B(5970)^+) = 0.7 \pm 0.2\ (\text{stat.}) \pm 0.8\ (\text{syst.})$$

Systematic uncertainty mainly from modeling of the background

Conclusion

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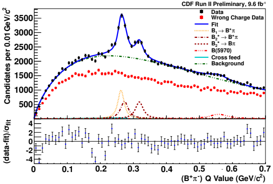
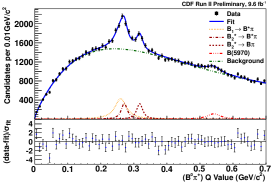
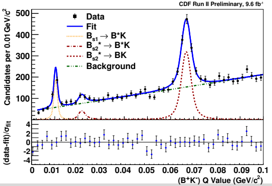
- Update of several B^{**} analysis on full CDF Run II dataset
- All nine narrow transitions observed
- B^{**+} observed for the first time
- Masses, widths, production rates and branching fraction determined
- **First evidence and measurement of properties of $B(5970)$ with 4.4σ significance**







Supplemental Slides

Measured Masses

	m (MeV/c^2)
B_1^0	$5726.4 \pm 0.8 \pm 1.3 \pm 0.4$
B_2^{*0}	$5736.6 \pm 1.2 \pm 1.2 \pm 0.2$
B_1^+	$5726 \pm 4 \pm 3 \pm 2$
B_2^{*+}	$5737.1 \pm 1.1 \pm 0.9 \pm 0.2$
B_{s1}^0	$5828.3 \pm 0.1 \pm 0.1 \pm 0.4$
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)		Γ (MeV/c^2)		Δm	r_{prod}
	B_1^0	B_2^*	B_1^0	B_2^*	(MeV/c^2)	
Mass scale	0.2	0.2	-	-	<0.1	-
Resolution	<0.1	<0.1	<1	<1	<0.1	<0.01
Backgr. model	<0.1	0.7	3	1	0.6	0.13
Broad B^{**} states	0.3	0.6	2	4	0.4	0.20
Fit bias	-	-	-	1	0.6	0.02
Fit constraints	1.2	0.3	3	<1	1.4	0.45
Acceptance	-	-	-	-	-	0.07
Total systematic	1.3	1.0	5	4	1.7	0.51
Statistical	0.8	1.2	2	3	1.4	0.12

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

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

Systematic Uncertainties B^{**+}

	Q (MeV/c^2)		Γ (MeV/c^2)		Δm	$r_{\rm prod}$
	B_1^0	B_2^*	B_1^0	B_2^*	(MeV/c^2)	
Mass scale	<1	0.2	-	-	<1	-
Resolution	<1	<0.1	<1	<1	<1	<0.1
Backgr. model	1	0.5	10	6	<1	0.5
Broad B^{**} states	1	0.2	3	5	1	0.7
Fit bias	1	0.3	-	1	1	0.4
Fit constraints	2	0.7	8	3	3	0.8
Acceptance	-	-	-	-	-	0.2
Total systematic	3	0.9	13	8	3	1.2
Statistical	4	1.1	11	6	4	0.9

Systematic Uncertainties B_s^{**}

	Q (MeV/c^2)		Γ (MeV/c^2)		Δm	r_{prod}	r_{dec}
	B_{s1}	B_{s2}^*	B_{s1}	B_{s2}^*	(MeV/c^2)		
Mass scale	0.14	0.14	-	-	$<$0.01	-	-
Resolution	$<$0.01	$<$0.01	0.1	0.2	$<$0.01	$<$0.01	$<$0.01
Bkg. model	$<$0.01	$<$0.01	$<$0.1	0.1	$<$0.01	$<$0.01	0.01
Fit range	0.01	$<$0.01	0.3	$<$0.1	0.01	0.02	0.02
Fit constr.	$<$0.01	0.03	$<$0.1	0.1	0.03	$<$0.01	0.01
Fit bias	-	-	0.1	-	-	-	-
Acceptance	-	-	-	-	-	0.01	0.01
Total syst	0.14	0.14	0.3	0.2	0.03	0.02	0.02
Statistical	0.10	0.13	0.3	0.4	0.16	0.02	0.03

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	-	-	10	10	-	-
Acceptance	-	-	-	-	0.1	0.1
Total syst	12	12	31	40	0.3	0.8
Statistical	5	5	18	20	0.1	0.2

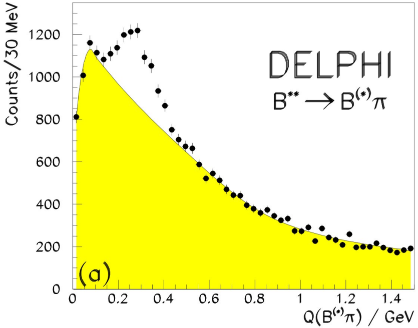
Fit Model: Constraints

- 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
  - 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

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).

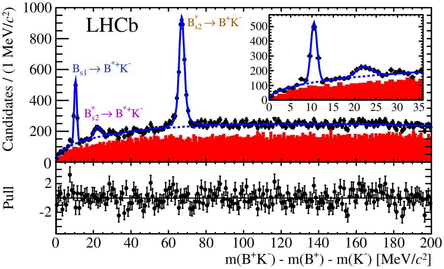
Previous Results

- 2011: LHCb shows measurement of all narrow states

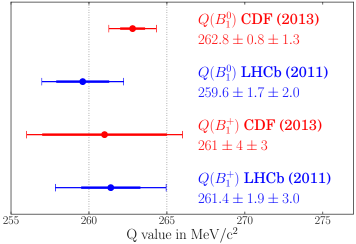
The LHCb Collaboration. LHCb-CONF-2011-053.

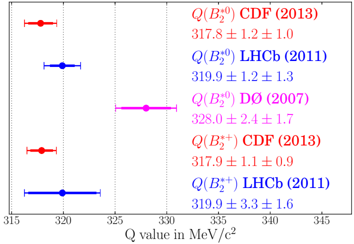
- 2012: LHCb measures B_s^{**0} and observes $B_{s2}^{*0} \to B^* K$

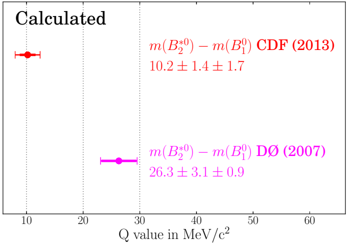
The LHCb Collaboration. Phys.Rev.Lett. 110, 151803 (2013)

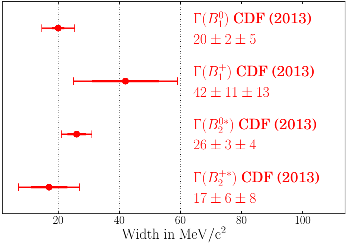


Comparison $B^{**0/+}$



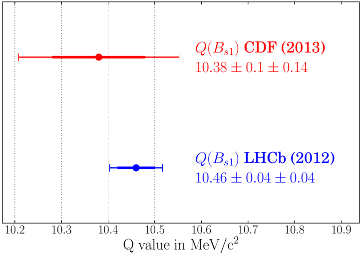


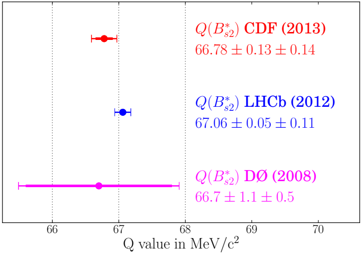




PRL 99, 172001 (2007). LHCb-CONF-2011-053. PRELIMINARY.

Results B_s^{**}





PRL 100, 082002 (2008).
PRL 110, 151803 (2013).