Spectroscopy of Orbitally Excited B Mesons with the CDF II Detector

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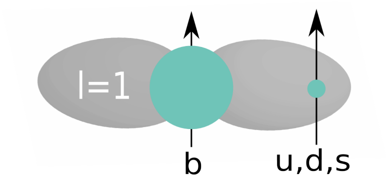
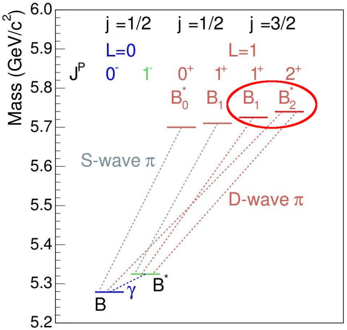
Motivation

- Study of heavy-light bound states led to understanding of QED: The hydrogen atom
- B mesons are heavy-light systems of QCD
- They are described by Heavy Quark Effective Theory (HQET)
- Recent discovery of the nonconventional $Z(3895)^{\pm}$ state (and others) shows our incomplete understanding of meson spectroscopy
- We are interested in orbital excitations of B mesons
- Angular momentum $L = 1$ between the two quarks: B^{**} mesons



Heavy Quark Effective Theory

- $m_b \gg \Lambda_{QCD}$ limit: Heavy quark is a quasistatic color source
- Orbital angular momentum L leads to excitation
- Fine splitting: Light quark spin s couples with L to j of light quark
- Parity and orbital angular momentum conservation make two of the states narrow
- Hyperfine splitting: j couples with spin of heavy quark to J
- We measure masses, widths and branching fractions



- In three decays $B_{(s)1} \to B^*\pi/K$, $B^*_{(s)2} \to B^*\pi/K$ and $B^*_{(s)2} \to B\pi/K$

Reconstruction and Preselection

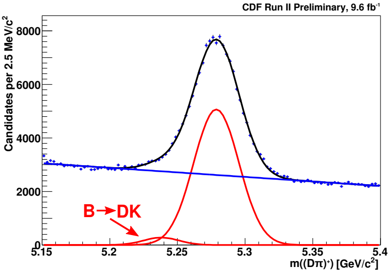
Reconstruction of B mesons:

- Full CDF II dataset of 9.6 fb^{-1}
- $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV
- Calculate topological, kinematic and particle identification quantities

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

Preselection:

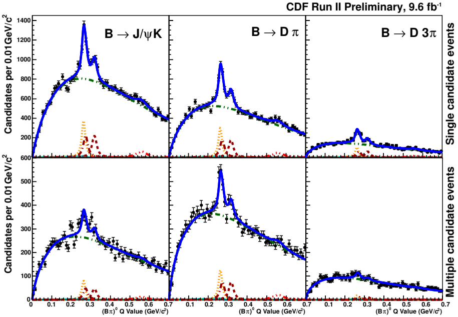
- Soft requirements on quantities with best separation power
- Mass peak of B mesons visible
- Train multivariate classifier NeuroBayes using ${}_s\mathcal{P}lot$ weights
- Training performed only using data and no simulations



Selection

B^{**} reconstruction and selection:

- Combine B candidates with additional pion or kaon
- Second NeuroBayes instance trained with signal simulations and background from data
- Simulations produced with same shape as background to avoid biasing the mass shape
- Final selection by requirement on NeuroBayes discriminant
- Split $B^{**0/+}$ by candidate multiplicity

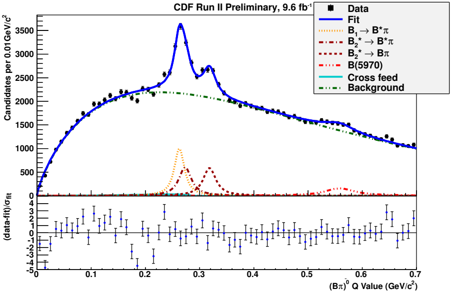


Consider Q value:

$$Q = M(B\pi/K) - M(B) - m_{\pi/K}$$

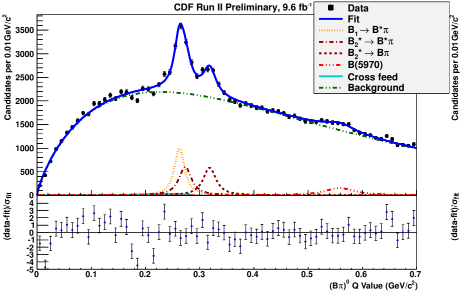
Fit Model

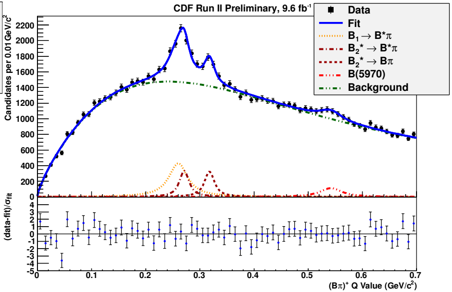
- Unbinned simultaneous maximum likelihood fit
- Signal: Breit-Wigner $*$ double Gaussian (resolution)
- Phenomenological smooth background function
- Photon from $B^* \to B\gamma$ not detected, constraint on photon energy
- Constraint on $B_2^{*0/+}$ branching ratios from D^{**}



- Excess seen at $Q = 550\mathrm{MeV/c^2}$
- We name it $B(5970)$
- Needs further investigation

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


CDF Run II Preliminary, 9.6 fb^{-1}
Data
Fit
$B_1 \to B^*\pi$
$B_2^* \to B^*\pi$
$B_2^* \to B\pi$
B(5970)
Cross feed
Background
Candidates per 0.01 GeV/c^2
(data-fit)/σ_{fit}
$(B\pi)^0$ Q Value (GeV/c^2)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B(5970)
Background
Candidates per 0.01 GeV/c^2
(data-fit)/σ_{fit}
$(B\pi)^+$ Q Value (GeV/c^2)

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

Quantity MeV/c^2	Value MeV/c^2	Stat. uncert. MeV/c^2	Syst. uncert. MeV/c^2
$Q(B_1^0)$	262.6	0.8	1.3
$Q(B_1^+)$	261.4	3.6	2.6
$Q(B_2^{*0})$	317.8	1.2	1.2
$Q(B_2^{*+})$	317.9	1.1	0.9
$\Gamma(B_1^0)$	20	2	5
$\Gamma(B_1^+)$	42	11	13
$\Gamma(B_2^{*0})$	26	3	3
$\Gamma(B_2^{*+})$	17	6	8

Relative production rate of B_1 and B_2^* $\times$ BR of observed decays:

- B^{**0}: $0.66 \pm 0.12\ \text{(stat.)} \pm 0.51\ \text{(syst.)}$
- B^{**+}: $1.8 \pm 0.9\ \text{(stat.)} \pm 1.2\ \text{(syst.)}$

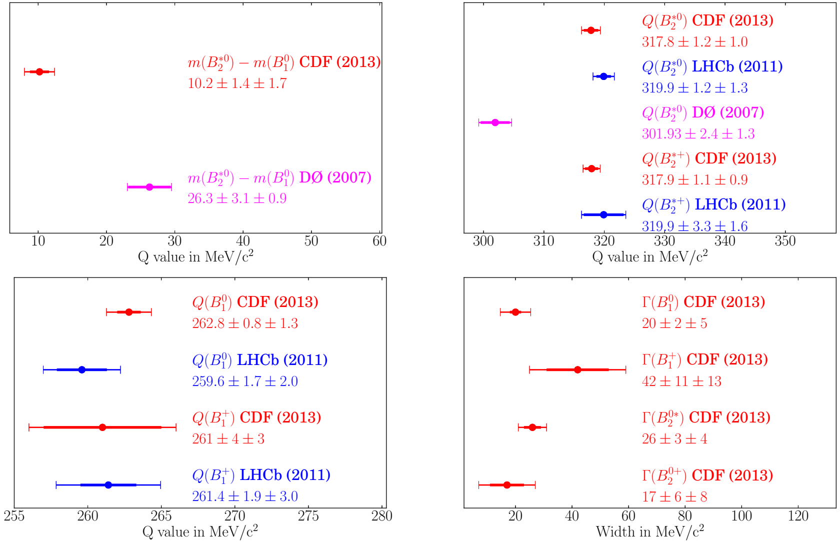
B^{**} production rate relative to B production:

- $(19 \pm 1.5(stat.) \pm 4(syst.))\%$

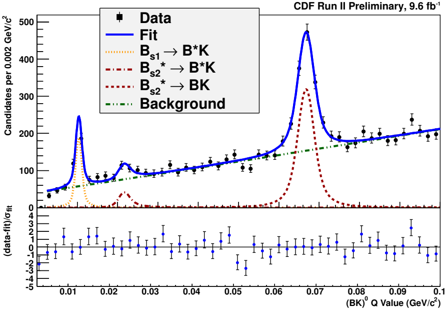
Considered sources of systematic uncertainties:

- Detector mass scale
- Detector resolution model
- Combinatorial background
- Broad B^{**} states
- Fit bias
- Fit constraints/form factors
- Relative acceptance
- Fit range
- Transverse momentum spectrum of B^{**} in simulations

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



Results B_s^{**}



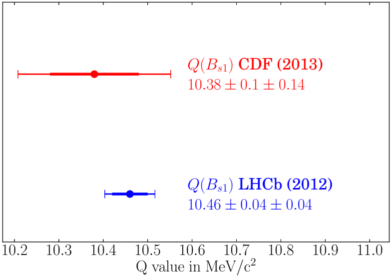
Quantity MeV/c^2	Value MeV/c^2	Stat. uncert. MeV/c^2	Syst. uncert. MeV/c^2
$Q(B_{s1})$	10.37	0.10	0.14
$Q(B_{s2}^*)$	66.75	0.13	0.14
$\Gamma(B_{s1})$	0.7	0.3	0.3
$\Gamma(B_{s2}^*)$	2.0	0.4	0.2

Relative production rate of B_1 and B_2^* $\times$ BR of observed decays:

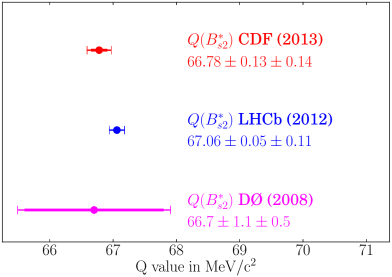
$$0.18 \pm 0.02\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$

$$\frac{BR(B_{s2}^* \to B^{*+}K^-)}{BR(B_{s2}^* \to B^+K^-)} = 0.11 \pm 0.03\,(\text{stat.}) \pm 0.02\,(\text{syst.})$$

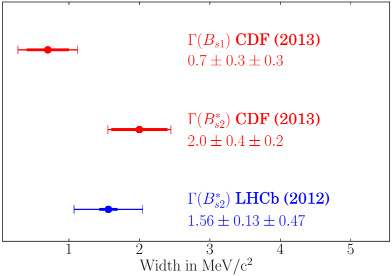
Results B_s^{**}



$Q(B_{s1})$ CDF (2013)
$10.38 \pm 0.1 \pm 0.14$
$Q(B_{s1})$ LHCb (2012)
$10.46 \pm 0.04 \pm 0.04$
10.2 10.3 10.4 10.5 10.6 10.7 10.8 10.9 11.0
Q value in MeV/c^2



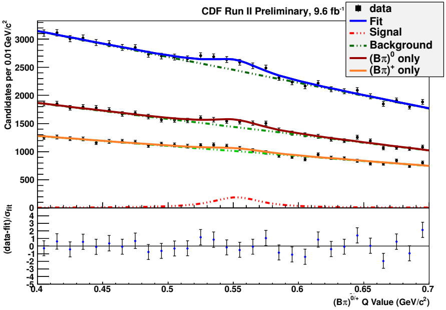
$Q(B_{s2}^*)$ CDF (2013)
$66.78 \pm 0.13 \pm 0.14$
$Q(B_{s2}^*)$ LHCb (2012)
$67.06 \pm 0.05 \pm 0.11$
$Q(B_{s2}^*)$ DØ (2008)
$66.7 \pm 1.1 \pm 0.5$
66 67 68 69 70 71
Q value in MeV/c^2

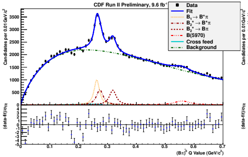


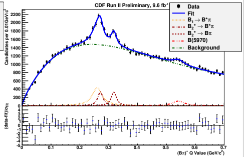
$\Gamma(B_{s1})$ CDF (2013)
$0.7 \pm 0.3 \pm 0.3$
$\Gamma(B_{s2}^*)$ CDF (2013)
$2.0 \pm 0.4 \pm 0.2$
$\Gamma(B_{s2}^*)$ LHCb (2012)
$1.56 \pm 0.13 \pm 0.47$
1 2 3 4 5
Width in MeV/c^2

Test of Significance of the $B(5970)$

- Breit-Wigner $*$ single Gaussian
- Linear background
- $(B\pi)^{0/+}$ combined
- Search $450 - 650 \mathrm{MeV/c^2}$
- Consider improvement of minimal log-likelihood against background only fit on data
- Fit background only samples in pseudo experiments
- Calculate p-value







Results $B(5970)$

Karlsruhe Institute of Technology

First evidence with 4.4σ significance.

Consistent with the hypothesis of a radial excitation decaying to $B^*\pi$ with a missing photon from B^*.

Quantity MeV/c^2	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	3
$\Gamma(B(5970)^0)$	70	18	31
$\Gamma(B(5970)^+)$	60	20	40

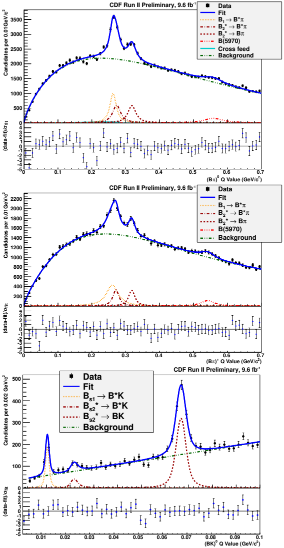
Production rate relative to $B_2^* \to B\pi$:

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

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

Conclusion

- Update of B^{**} analysis with full CDF Run II dataset
- All nine narrow transitions measured
- Masses, widths, production rates and branching fraction determined
- Broad B^{**} states remain difficult to find
- First evidence and measurement of $B(5970)$ with 4.4σ significance
- Further analysis is required to establish exact properties of the $B(5970)$ state



Backup Slides

Previous Results

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

OPAL Collaboration R. Akers et al. Z. Phys. C C66:19 (1995).
ALEPH Collaboration. Contribution to the International Euro-physics Conference on High Energy Physics, Brussels (1995).
DELPHI Collaboration. DELPHI 95-105 PHYS 540 (1995).

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

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

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

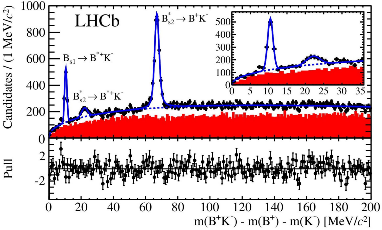
T. Aaltonen et al. Phys.Rev.Lett. 102 (2009).
T. Aaltonen et al. Phys.Rev.Lett. 100 (2008).
V.M. Abazov et al. Phys.Rev.Lett. 99 (2007).
V.M. Abazov et al. Phys.Rev.Lett. 100 (2008).

- 2011: LHCb shows measurement of all narrow states

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

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

The LHCb Collaboration. arXiv:1211.5994.



Systematic Uncertainties B^{**0}

	Q_{B_1} MeV/c^2	Γ_{B_1} MeV/c^2	$Q_{B_2^*}$ MeV/c^2	$\Gamma_{B_2^*}$ MeV/c^2	$Q_{B_2^*} - Q_{B_1}$ MeV/c^2	r_{prod} -
Mass scale	0.2	-	0.2	-	0.003	-
Resolution	0.01	0.2	0.03	0.19	0.02	0.002
Comb. background	0.03	3	0.7	0.9	0.6	0.13
Broad B^{**} states	0.3	2	0.6	4	0.4	0.20
Fit bias	-	-	-	0.6	0.6	0.017
Form factors	1.2	3	0.3	0.4	1.4	0.45
Relative acceptance	-	-	-	-	-	0.07
Total systematic	1.3	5	1.0	4	1.7	0.51
Statistical	0.8	2	1.2	3	1.4	0.12

Systematic Uncertainties B^{**+}

	Q_{B_1} MeV/c^2	Γ_{B_1} MeV/c^2	$Q_{B_2^*}$ MeV/c^2	$\Gamma_{B_2^*}$ MeV/c^2	$Q_{B_2^*} - Q_{B_1}$ MeV/c^2	r_{prod} -
Mass scale	0.2	-	0.2	-	0.003	-
Resolution	0.01	0.10	0.01	0.11	0.02	0.012
Comb. background	0.8	10	0.5	6	0.3	0.5
Broad B^{**} states	1.0	3	0.15	5	1.2	0.7
Fit bias	1.0	-	0.3	0.9	1.0	0.4
Form factors	2	8	0.7	3	2.5	0.8
Relative acceptance	-	-	-	-	-	0.18
Total systematic	2.6	13	0.9	8	3	1.2
Statistical	3.6	11	1.1	6	4	0.9

Systematic Uncertainties B_s^{**}

	Q_{B_1} MeV/c^2	Γ_{B_1} MeV/c^2	$Q_{B_2^*}$ MeV/c^2	$\Gamma_{B_2^*}$ MeV/c^2	$Q_{B_2^*} - Q_{B_1}$ MeV /c^2	r_{prod} -	r_{dec} -
Mass scale	0.14	-	0.14	-	0.003	-	-
Resolution	0.002	0.07	0.0010	0.17	0.001	0.001	0.004
Comb. background	0.002	0.008	0.0012	0.07	0.003	0.0014	0.005
Form factors	0.0010	0.014	0.03	0.05	0.03	0.0017	0.011
Fit Range	0.009	0.3	0.0010	0.03	0.010	0.02	0.02
Fit Bias	-	0.05	-	-	-	-	-
Relative acceptance	-	-	-	-	-	0.009	0.006
Total systematic	0.14	0.3	0.14	0.2	0.03	0.02	0.02
Statistical	0.10	0.3	0.13	0.4	0.16	0.02	0.03

Systematic Uncertainties $B(5970)$

	$Q(B(5970)^0)$ MeV/c^2	Γ MeV/c^2	rel yield	$Q(B(5970)^+)$ MeV/c^2	Γ MeV/c^2	rel yield
Resolution	0.01	0.8	0.001	0.01	0.8	0.001
Comb. background	12	30	0.34	3	40	0.8
Fit bias	-	7	-	-	5	-
Relative acceptance	-	-	0.05	-	-	0.07
Total systematic	12	31	0.34	3	40	0.8
Statistical	5	18	0.14	5	20	0.2