First Observation of the Excited Bs2* Meson at D0

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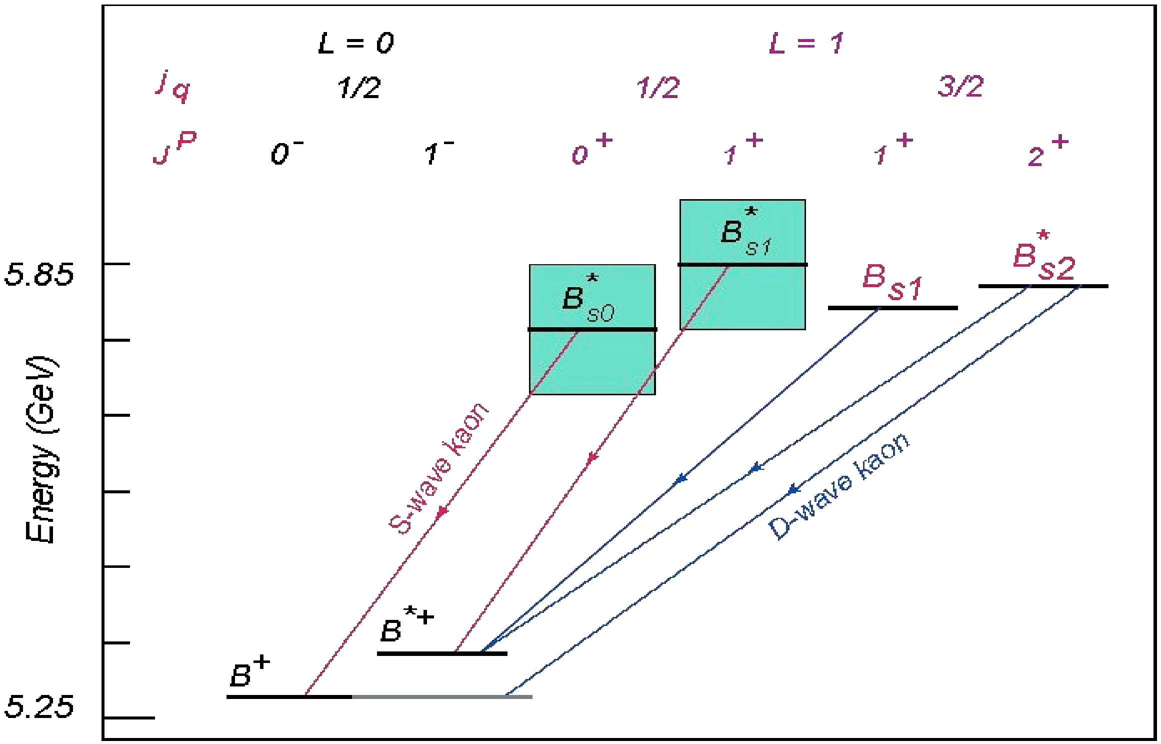
b-Meson Spectroscopy - Theory

The (bd), (bs) quark systems are well modeled by Heavy-Quark Effective Theory, since M(b) >> M(u,d,s). Theory predicts *four orbitally-excited L=1 states*, in addition to the well-measured ground state $B_{(s)}^{+}$, and singly-excited state $B_{(s)}^{+*}$.

- The two L=1, j_q=½ states are too wide (> 100 MeV) to be distinguished from background. Studies are therefore limited to the observation and measurement of the narrow states B_{s1} and B_{s2}^{*}, collectively denoted by B_{sJ} or B_{s}^{**}.

Dominant decay mode is $B_s^{**} \rightarrow B^+K^-$ since decays to $B_s^+\pi^-$ are forbidden by isospin conservation.

(Charge conjugated states are implied.)



b-Meson Spectroscopy – Theory (2)

- **By parity and angular momentum conservation, the B_{s1} decays 100% to B^{+*}.**

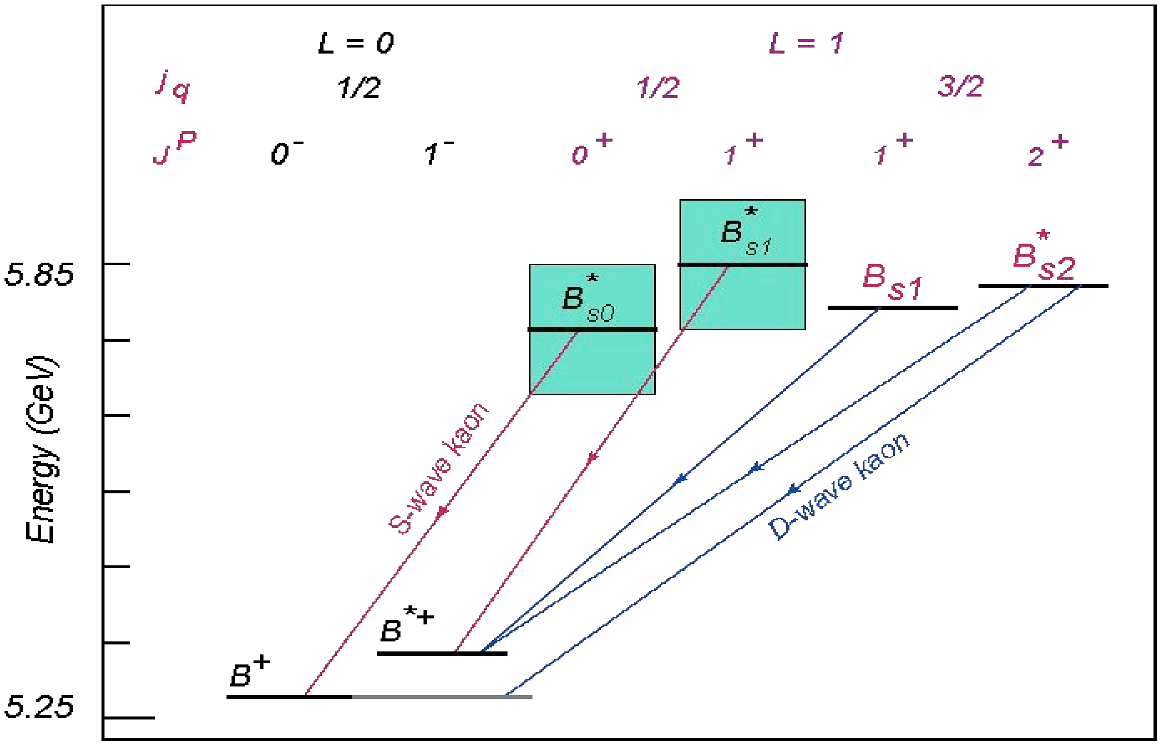
- **The B_{s2}^* can decay directly to the ground-state B^+, or via the intermediate state B^{+*}, with a branching ratio 1:1 predicted by theory.**

- **The B^{+*} decays ~100% to B^+ with the release of a photon of energy 45.78 ± 0.35 MeV.**

However...

Phase space factors can have a large effect on these relative decay rates, since they occur close to the production threshold:

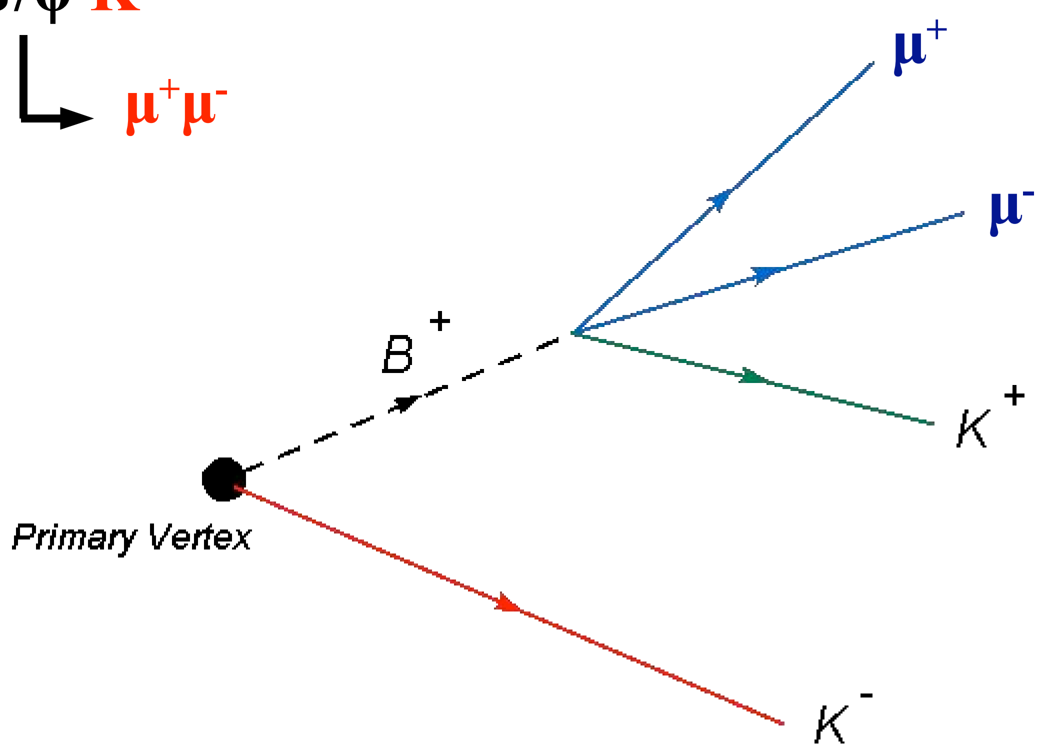
$$M(B^{**}) - M(B^+) - M(K^-) \approx 0$$



Reconstruction and Event Selection

B_{sJ} mesons reconstructed through final state $K^-K^+\mu^+\mu^-$:

- $B_{sJ} \rightarrow B^{+(*)}K^-$
  - $\rightarrow B^+\gamma$ (100%) (Photon not detected)
    - $\rightarrow J/\psi K^+$
      - $\rightarrow \mu^+\mu^-$



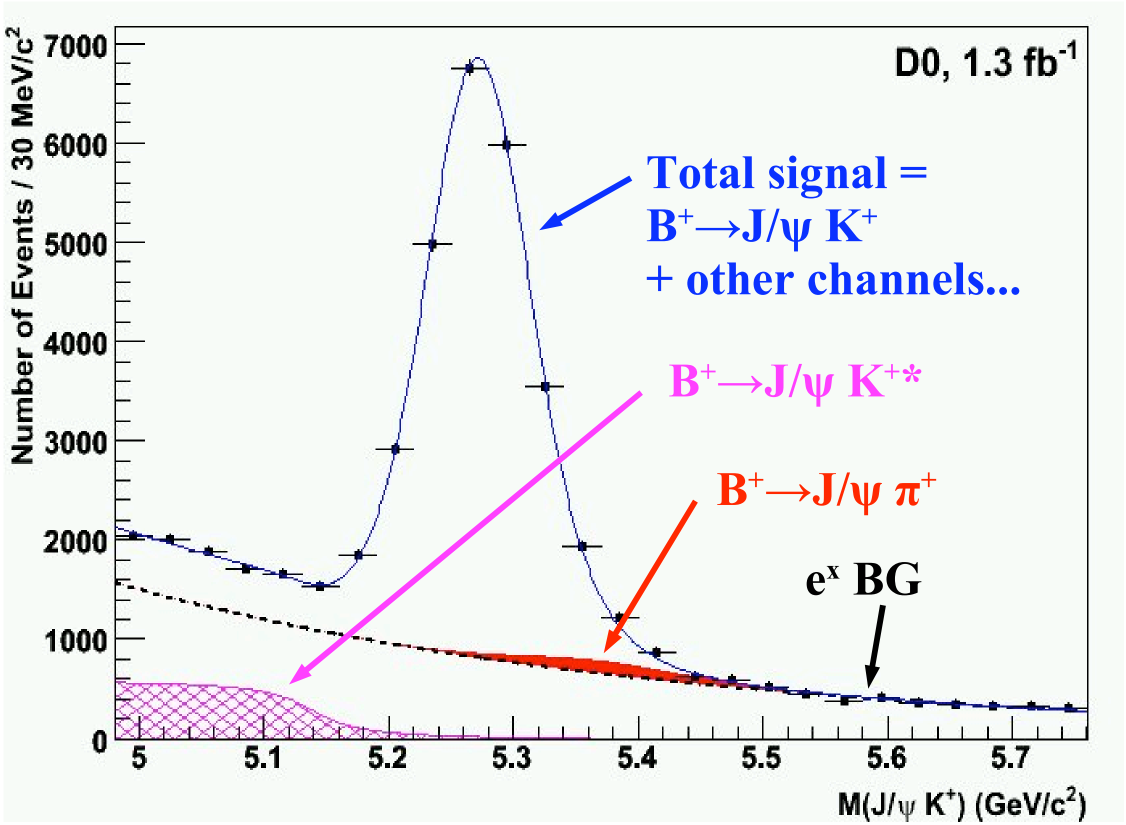
Reconstructing B^+ Candidates

B^+ candidates selected using a likelihood ratio method using several discriminating variables.

Signal and physics backgrounds modeled by sum of 3 functions:

- **A Gaussian $B^+ \to J/\psi K^+$ peak.**
- **$B^+ \to J/\psi\ \pi^+$ contamination.**
- **A contribution from partially reconstructed decays $B^+ \to J/\psi K^{+*}$, where $K^{+*} \to K\pi$ (MC simulation).**

Combinatorial background parameterised by an exponential function.



- M(J/ψ K^+): **5271.6 ± 0.4 MeV/c^2**
- N(B^+) with $5.19 < M(B+) < 5.36$: **20,915 ± 293 Candidates**

B_{sJ} Reconstruction and Selection

For each B^+ meson reconstructed, an additional track (K) is required, which must pass the following selection criteria:

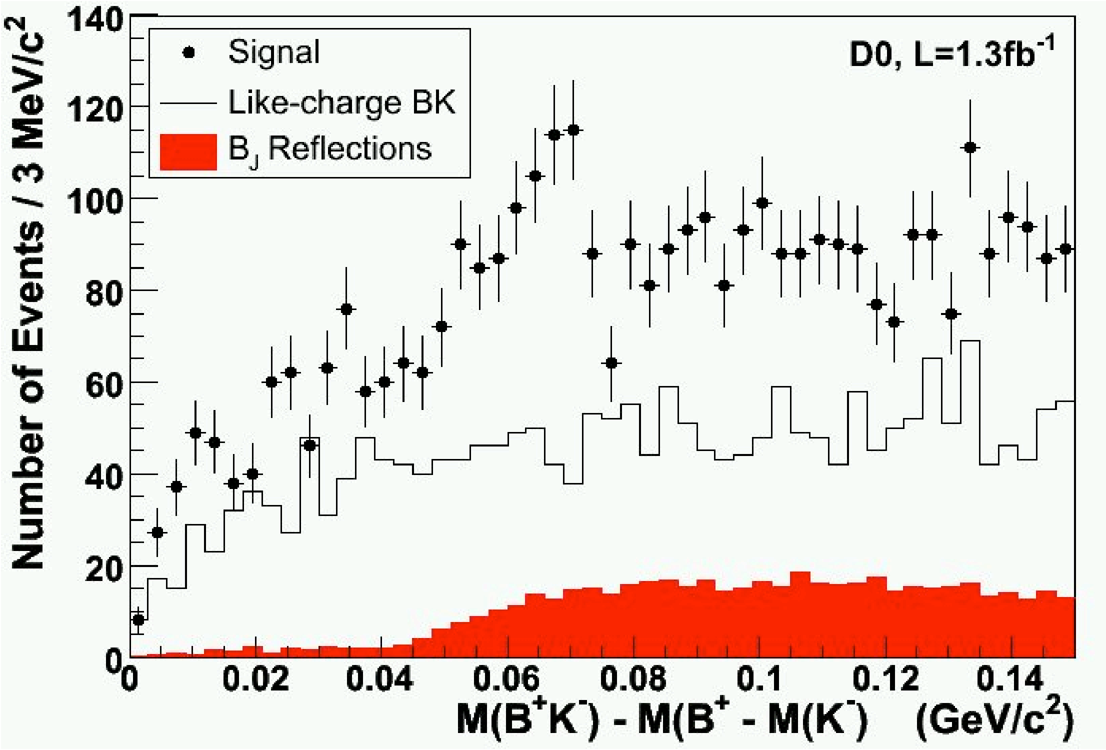
- $\geq$ 2 hits in silicon tracker
- $\geq$ 2 hits in central fiber tracker
- Transverse momentum $\geq$ 0.60 GeV/c
- Correct charge correlation (i.e. B^+K^- or B^-K^+ combinations only)
- 2σ B^+ mass window: $5.19 \leq M(B^+) \leq 5.36$ GeV/c^2
- $S_{PV} \leq \sqrt{6}$ (Impact parameter significance – i.e. originates at PV)

This particle is assigned the kaon mass, and used to reconstruct the invariant mass $M(B^+K^-)$. **For each track in an event satisfying the above selections, the mass difference is computed:**

$$\Delta M = M(B^+K^-) - M(B^+) - M(K^-)$$

B_{sJ} Mass Distribution

- The ΔM distribution is well modelled by a smooth, broad background, except in region ($0.05 < \Delta M < 0.075$) GeV/c^2, where there is an excess of events.
- This is interpreted as the signature of $B_{s2}^{*} \rightarrow B^{+}K^{-}$ transitions, since this is the highest energy of the three possible B_{sJ} decays.
- Our primary fit hypothesis then assumes that the lower-energy decays are suppressed by phase-space factors – we fit with just one signal peak.
- Alternative fit hypotheses are tested later...



Background Contribution in ΔM

- Background is dominated by combinatorial background. The contribution from this source is determined by examining the like-charge BK sample, which has the shape:

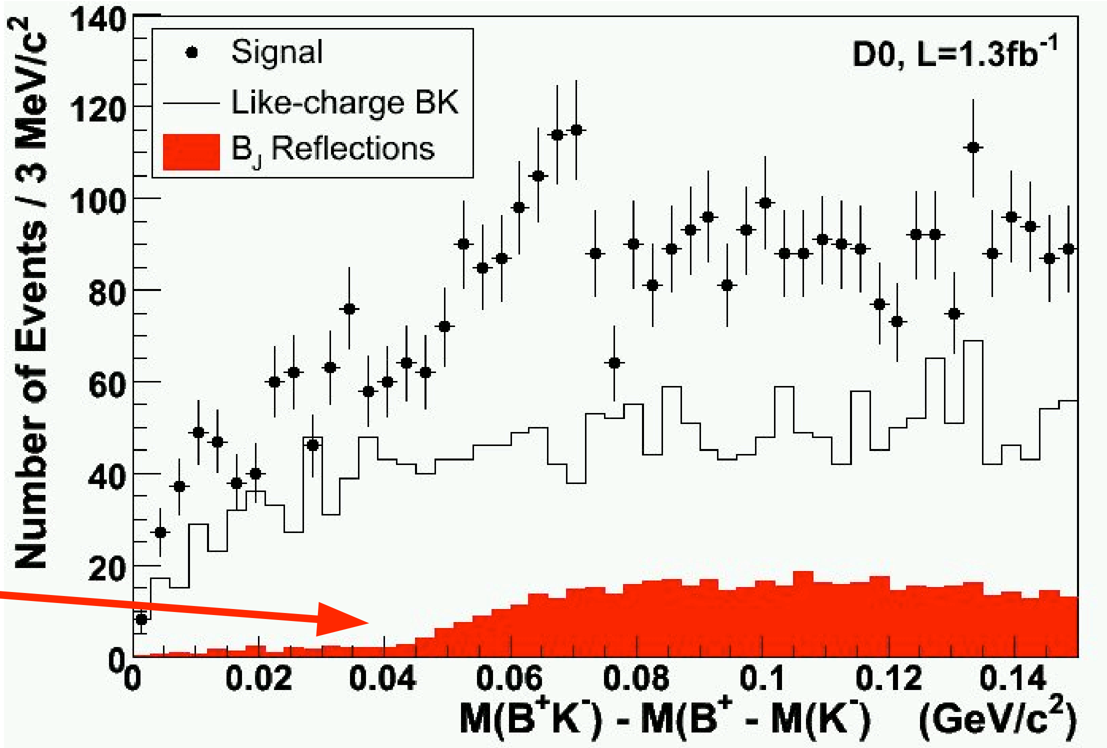
$$f_{bckg}(\Delta M) = c(\Delta M)^k + d(\Delta M)$$

In the final fit, c, d and k are kept as free parameters to account for other broad backgrounds:

- Non-resonant production,
- B^{**} reflections,
- Contribution from broad B_{sJ} states.

- B^{**} reflections occur when pions in the decays $B^{**} \rightarrow B^+\pi^-$ are mis-identified as kaons.

The effects are modelled from MC simulation, with input parameters from the recent B^{**} analysis by D0.



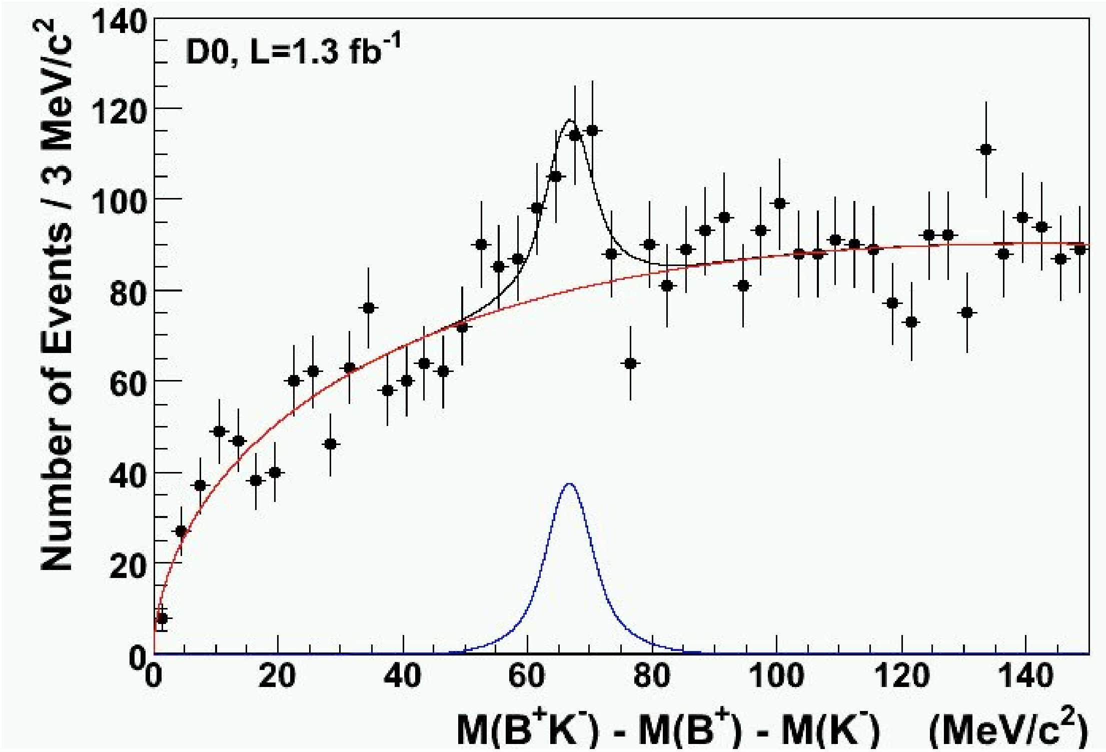
ΔM Distribution: B_{s2}^* Fit

- B_{s2}^* signal peak parameterised by convolution of a relativistic Breit-Wigner function (actual physical 'shape' of resonance), with a double-Gaussian function (smearing due to limited detector resolution).
- Physical width is fixed at 1.0 MeV/c^2 (from theory)
- Binned Maximum-Likelihood fit is performed...

- $\Delta M(B_{s2}^*) = 66.7 \pm 1.1$ MeV/c^2
- $N(B_{s2}^*) = 125 \pm 25$ events

Combining with PDG masses:
- $M(B_{s2}^*) = 5839.6 \pm 1.1$ MeV/c^2

- Fit Significance: 5σ
(comparing values of -log(L) with and without signal contribution)



Interpretation: Where are the other peaks??

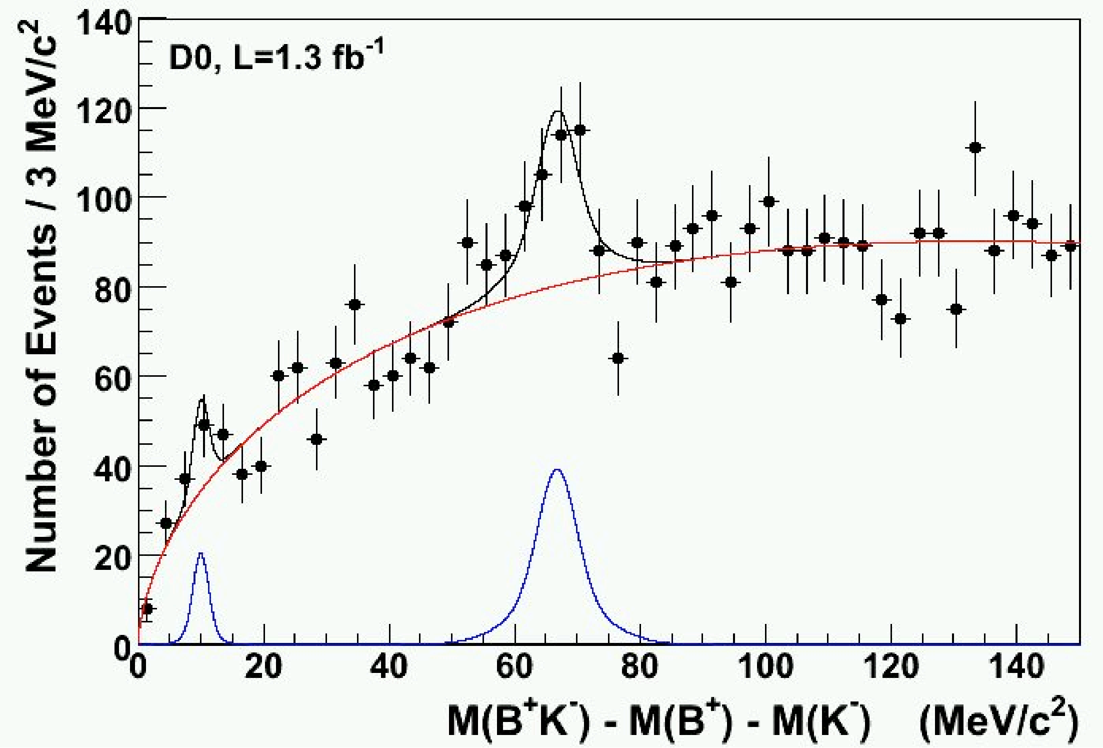
- The B_{s2}^* should decay equally into (B^+K^-) and $(B^{+*}K^-)$ channels – why don't we see any excess at $\Delta M = 66.7 - 45.78 \approx 21$ MeV/c^2 ?
  - Answer: Decay is suppressed by a factor ~14 due to the reduced phase space.

- What about the B_{s1} meson? If it is produced at sufficient rate, there should be a second peak below $\Delta M \approx 21$ MeV/c^2 : try fitting a second peak to the mass distribution...

- $\Delta M(B_{s1}) = 11.5 \pm 1.4$ MeV/c^2
- $N(B_{s1}) = 25 \pm 10$ events

- Fit Significance: $< 3\sigma$ (comparing values of -log(L) with and without signal contribution)

⇒Not a statistically significant signal (yet!), although CDF also see a signal here.



Systematic Uncertainties

The effect of various sources of systematic error were measured:

Source	$\delta M(B_{s2}^*)$ (MeV/c2)	δN
parameterization	0.0	3
Bin widths/positions	0.3	7
Value of Γ	0.3	5
PDG mass uncertainties	0.5	0
Momentum scale uncertainty	0.1	0
Mass Resolution Uncertainty	0.1	3
Total	0.7	10

Scale factor 'k' fixed at like-charge value

Assumption $\Gamma(B_{s2}^*) = 1.0$ tested by using a number of small widths in the fit

Uncertainties quoted on the PDG errors of B^+ and K^- are included as systematic errors on the absolute B_{s2}^* mass.

A 100% systematic uncertainty is assigned to the upward shift of the Bs2* mass, used to correct of the effect of the D0 momentum scale issue.

The fit is repeated without the 10% increase in the Gaussian widths σ(wide) and σ(narrow), to test the effect of the correction of data/MC disagreement. A 100% systematic uncertainty is assigned to the effect of this refit on the parameters.

$$M(B_{s2}^*) = 5839.6 \pm 1.1 \text{ (stat.)} \pm 0.7 \text{ (syst.) MeV}/c^2$$
$$N(B_{s2}^*) = 125 \pm 25 \text{ (stat.)} \pm 10 \text{ (syst.)}$$

B_{s2}^{*} Relative Production Rate

From the relative B_{s2}^{*}/B^{+} detection efficiency (measured from Simulation), and the number of B^{+} and B_{s2}^{*} events detected, a measurement is made of the relative production rate:

- $N(B_{s2}^{*}) = 125 \pm 25$ (stat.) ± 10 (syst.)
- $N(B^{+}) = 20915 \pm 293$ (stat.) ± 200 (syst.)
- $Eff(B_{s2}^{*}) / Eff(B^{+}) = (51.8 \pm 4.4)$ %

Thus relative production rate of B_{s2}^{*} mesons into *charged* kaon channels is:

- **$R(b \rightarrow B_{s2}^{*} \rightarrow B^{+}K^{-}) / R(b \rightarrow B^{+}) = [1.15 \pm 0.23$ (stat) ± 0.13 (syst)$]$ %**

This is the first (and currently only) measurement of the production rate of the B_{s2}^{*}. Aside from its inherent value as a test of theoretical predictions, it is valuable in understanding B^{+} composition in future mixing studies.

Summary

• The orbitally-excited B_{s2}^* meson has been observed for the first time, simultaneously by D0 and CDF. This follows last year's first observations of B_2^* and B_1 (the equivalent states in the (bd) quark system) by D0.

• The mass and production rate are calculated to be:

- **$M(B_{s2}^*) = 5839.6 \pm 1.1$ (stat.) ± 0.7 (syst.) MeV/c^2**
- **$R(b \rightarrow B_{s2}^* \rightarrow B^+K^-) = [1.15 \pm 0.23$ (stat) ± 0.13 (syst)$]^* R(b \rightarrow B^+)$ %**

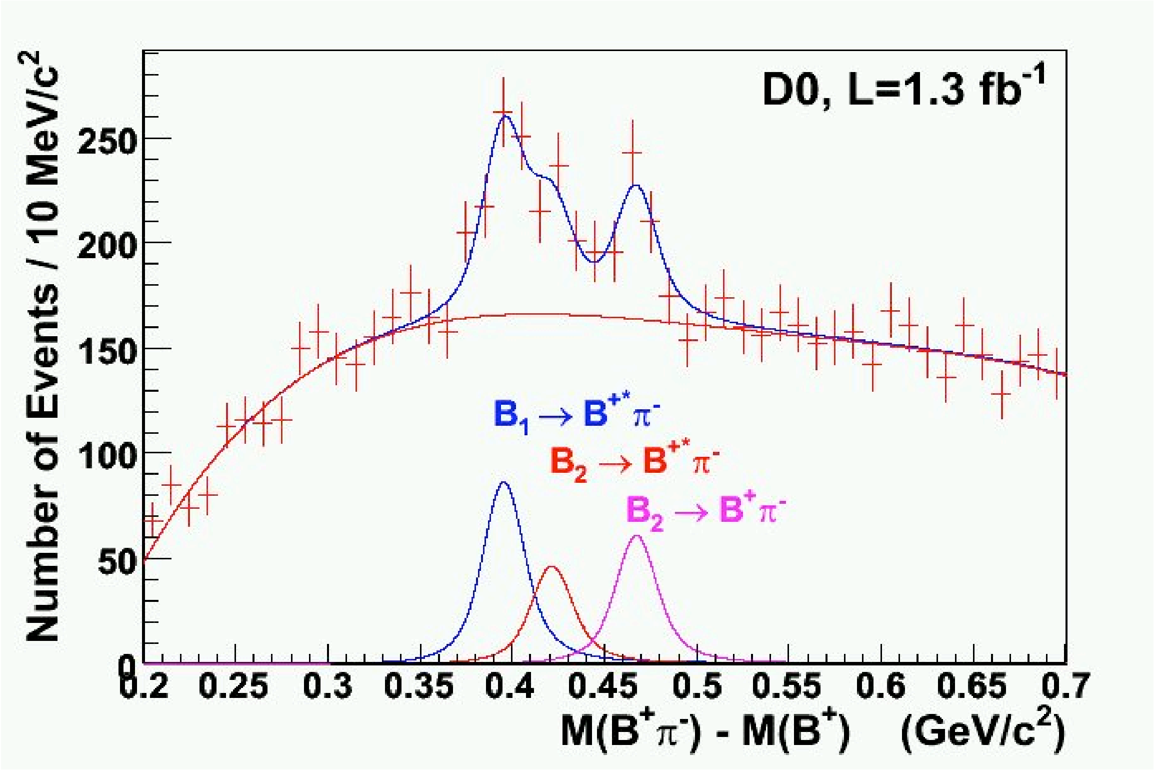
• No conclusive evidence is found for the presence or absence of a B_{s1} signal, although CDF recently reported strong evidence of a resonance at the same mass.

• This analysis was published in Phys. Rev. Lett. (Vol. 100, No. 8) on 28th February 2008:

http://link.aip.org/link?prl/100/082002

Thanks for listening!

Comparison with B** states:



- N = 662 ± 91 Events
- Γ = 10 MeV/c^2 *fixed*

Masses and width:

- $M(B_1)$ = 5720.6 ± 2.4 (stat) ± 1.3 (syst) MeV/c^2
- $M(B_2^*)$ = 5746.8 ± 3.1 (stat) ± 0.9 (syst) MeV/c^2

Branching ratios and relative production rate:

- $Br(B_1^* \to B^*\pi) / Br(B_J \to B^{(*)}\pi)$ = 0.477 ± 0.069 (stat) ± 0.062 (syst)
- $Br(B_2^* \to B^*\pi) / Br(B_2^* \to B^{(*)}\pi)$ = 0.475 ± 0.095 (stat) ± 0.069 (syst)
- $R(b \to B^0_J \to B^{(*)}\pi)/R(b \to B^+)$ = 13.9 ± 1.9 (stat) ± 3.2 (syst) %