New Results in b-hadron Spectroscopy at the Tevatron

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Hadron Collider Physics Symposium Isola d'Elba May 20-26.

This talk will cover:

* Orbitally excited B^0 mesons (L=1, B^{0**})

* Orbitally excited B^0_s mesons (L=1, B_s^{**})

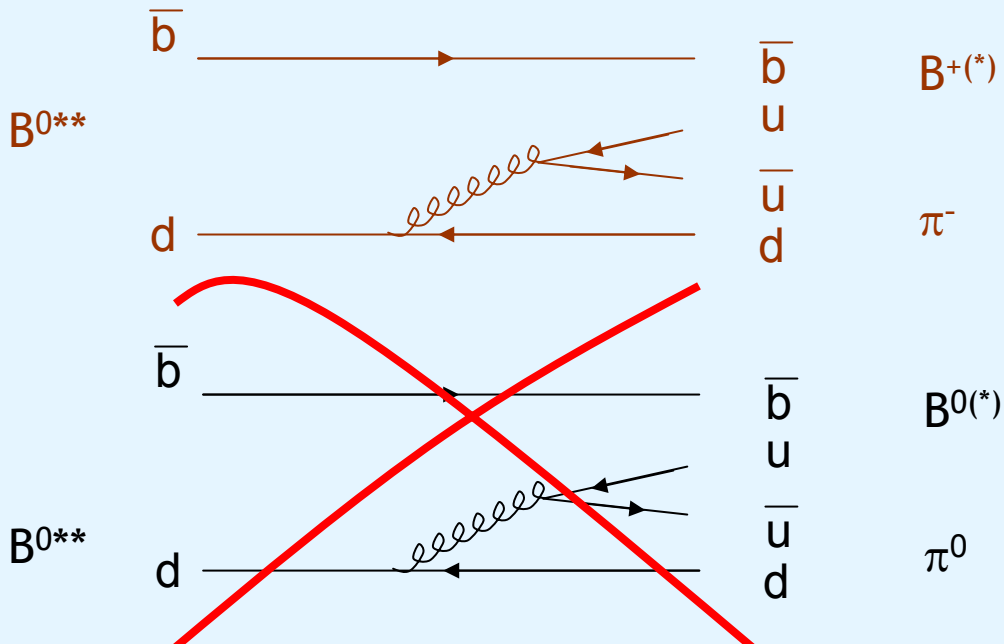
* New bottom baryons (buu and bdd), part of a new I-triplet Σ_b

B^{0**} is four states:

Name	J	J_q	Decay
B_0^*	0	½	$(B\pi)_{L=0}$
B_1^*	1	½	$(B^*\pi)_{L=0}$
B_1	1	3/2	$(B^*\pi)_{L=2}$
B_2^*	2	3/2	$(B\pi, B^*\pi)_{L=2}$

Width of the S-wave transitions:
~few hundred MeV.

Width of the D-wave transitions:
~ 10 MeV

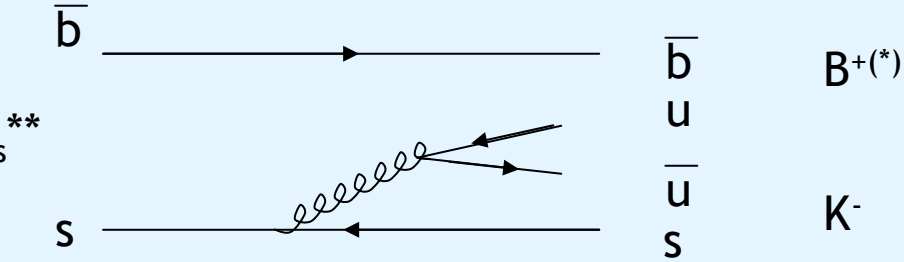


BR = 2/3

BR = 1/3

B_s^{**}, dominant mode is $B_s^{**} \rightarrow B^{(*)+} K^-$

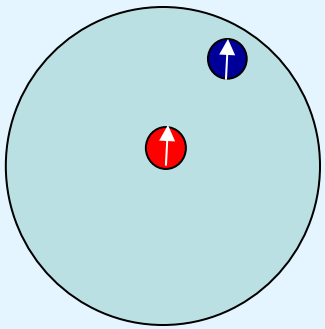
Q-Values for the decay are tens of MeV for the B_s^{**} and they are a few hundred MeV for the B_0^{**}



➔ Much narrower states (few MeV)

Name	J	J_q	Decay
B_{s0}^*	0	½	$(BK)_{L=0}$
B_{s1}^*	1	½	$(B^*K)_{L=0}$
B_{s1}	1	3/2	$(B^*K)_{L=2}$
B_{s2}^*	2	3/2	$(BK,B^*K)_{L=2}$

Why study the spectroscopy of heavy-light systems?

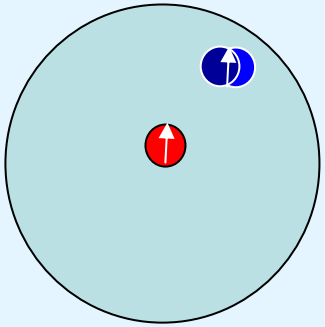


- They are like hydrogen atoms, bound by the strong interaction.

- Masses of the ** states are like the fine, hyperfine structure of hydrogen, except for QCD.

- B**'s and B_s**'s mesons probe the potential in a new regime.

- Flavor-tagging technology relies partially upon the B**'s



b-baryons: hyperfine structure generated by light diquark spi

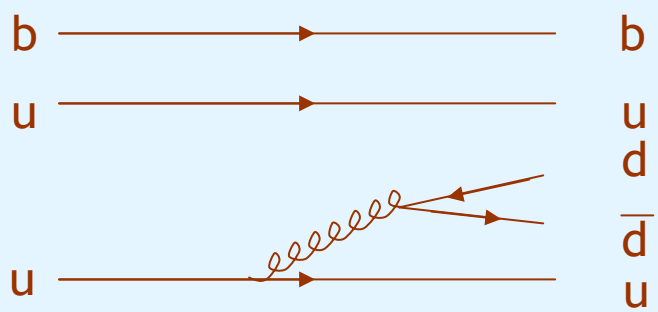
Λ_b: Light quark pair has spin-zero

ultiplets of b-baryons:

b	b(ud-du)	isospin singlet light quarks in a spin-0 state
$_b^+$ Σ_b^0 Σ_b^-	buu, b(ud+du), bdd	isospin triplet light quarks in a spin 1 state and J^P =1/
$_b^{*+}$ Σ_b^{*0} Σ_b^{*-}	buu, b(ud+du), bdd	isospin triplet light quarks in a spin 1 state and J^P =3/
$_b^0$, Ξ_b^-	bsu, bsd	isospin doublet of strange b-baryons, decay weakly
$_b$	bss	doubly strange b-baryon, decays weakly.. in detector.

The reaction $\Sigma_b^{(*)\pm} \rightarrow \Lambda_b\pi^\pm$ is strong decay in a P-wave: close to threshold, narrow.

$_b^{(*)+}$



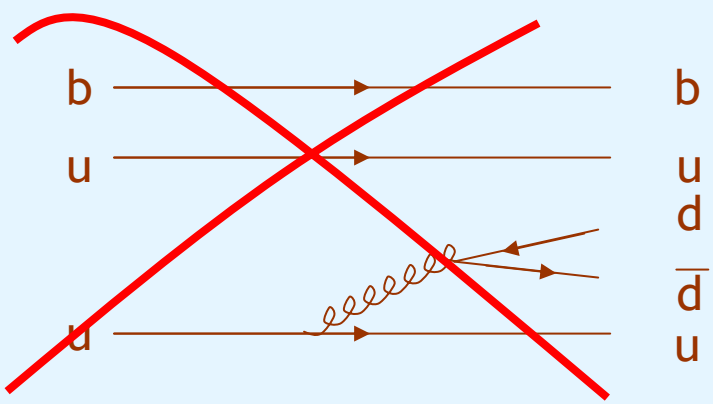
Λ_b

π^-

How close to threshold?

$M(\Sigma_b)-M(\Lambda_b) - M(\pi)$ ≈40-70 MeV
$M(\Sigma_b^*)-M(\Sigma_b)$ ≈10-40 MeV
$M(\Sigma_b^+)-M(\Sigma_b^-)$ ≈ 5-7 MeV

$\Sigma_b^{(*)0}$



Λ_b

π^0

How narrow?

Widths can be predicted or
Scaled from Σ_c decay widths:

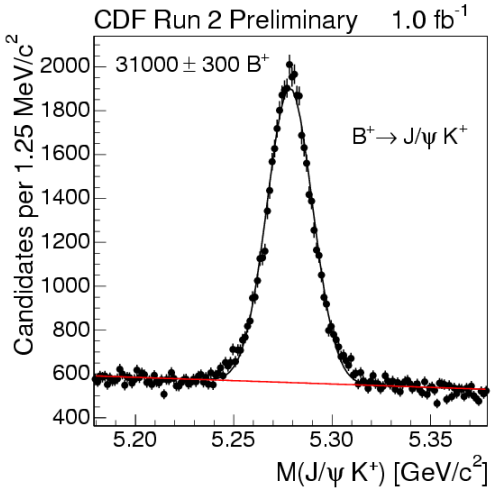
$\Gamma(\Sigma_b)$ ≈ 5 MeV
$\Gamma(\Sigma_b^*)$ ≈8 MeV

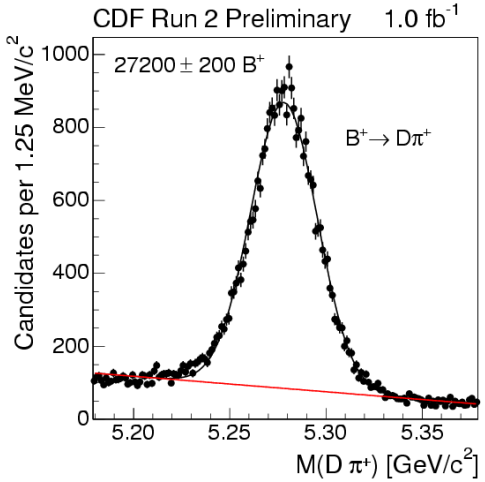
Hadron collider: large cross sections, large data sample, new B triggers:
SVT (CDF) collects practically as many reconstructed B decays as the J/ψ trigger.

J/ψ trigger

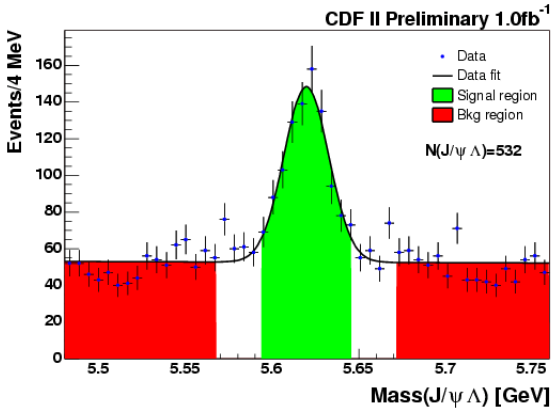
Hadronic B trigger

B^+ decays:

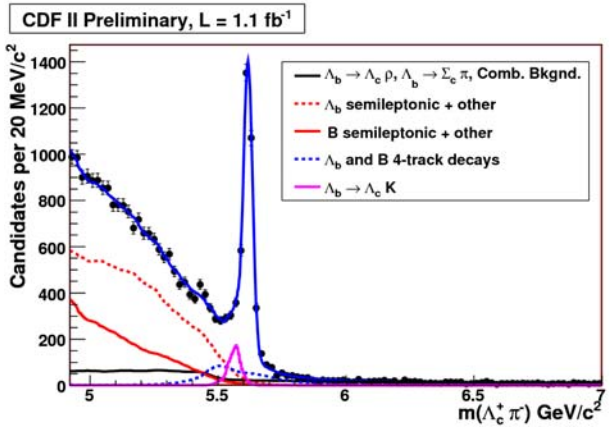




Λ_b decays



532 events (not used for Σ_b)
Λ_b-> J/ψ Λ

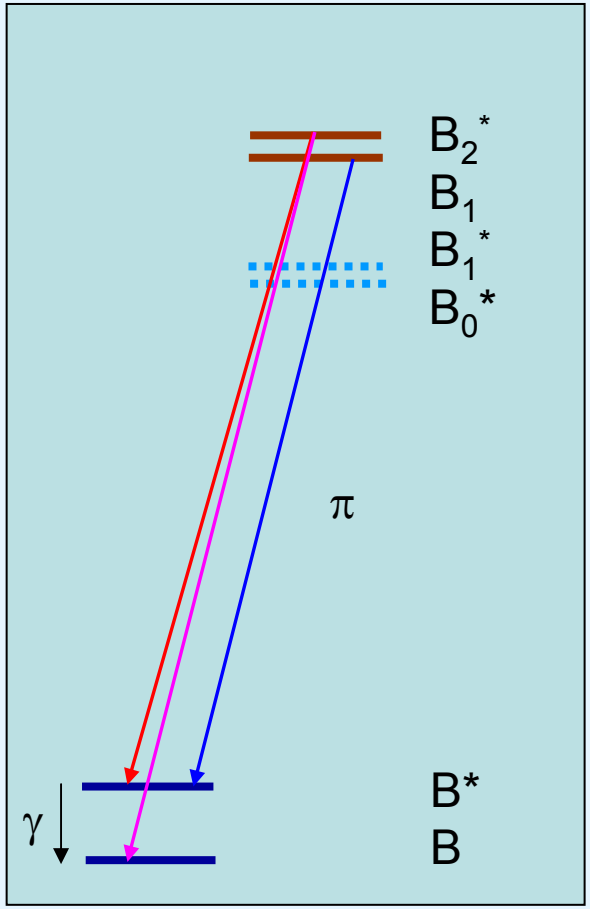


2.8 K events $\Lambda_b \to \Lambda_c\ \pi$

… basic analysis idea: add a "soft: pion.

B**

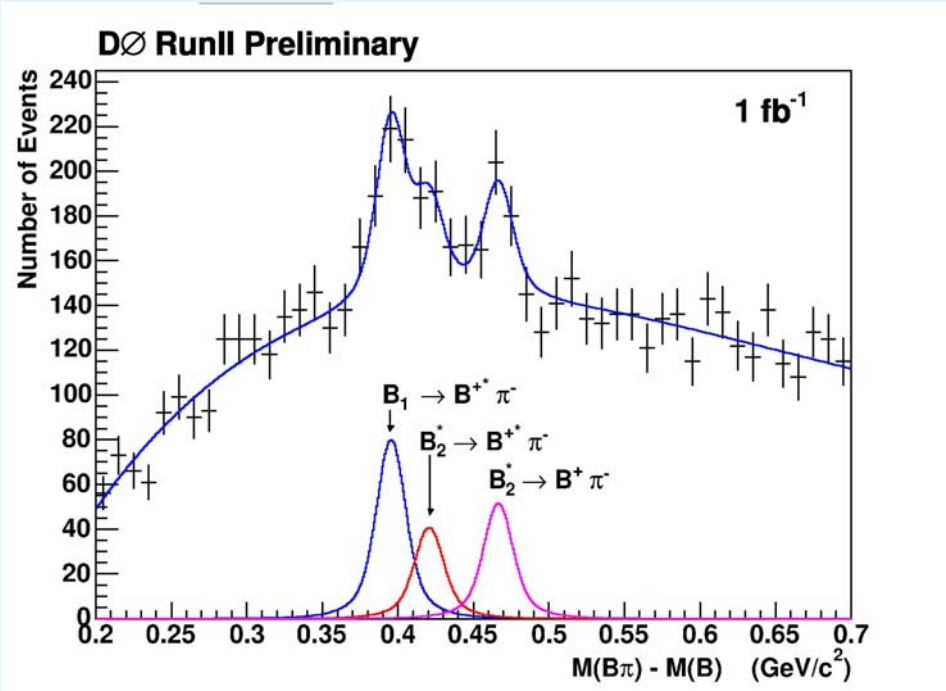
This is what is expected:



γ undetected

This is what is observed (D0):

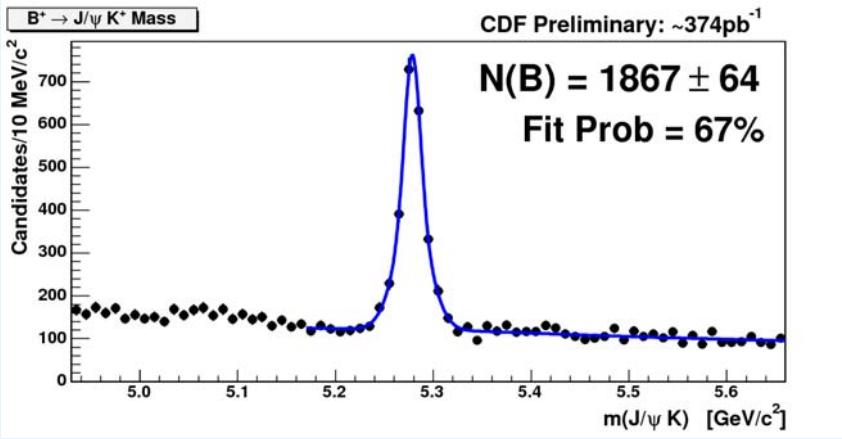
(soft pion added to B^+ candidate)

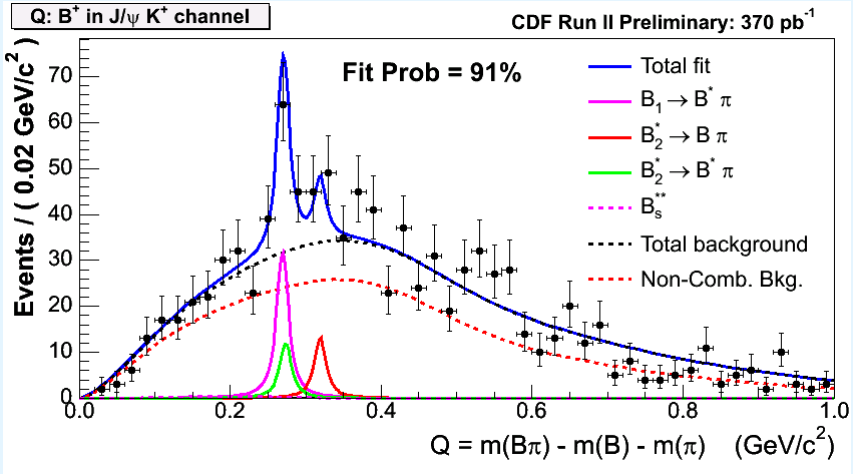


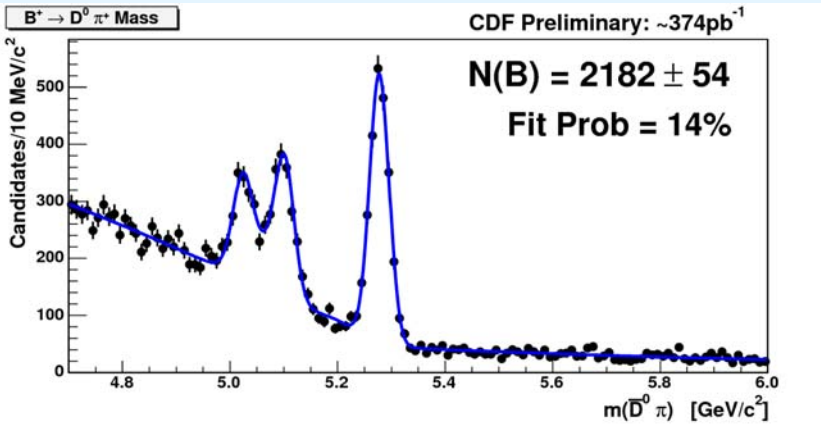
Observed widths dominated by detector resolution
Natural width extracted: $\Gamma = 6.6 \pm 5.3$ MeV

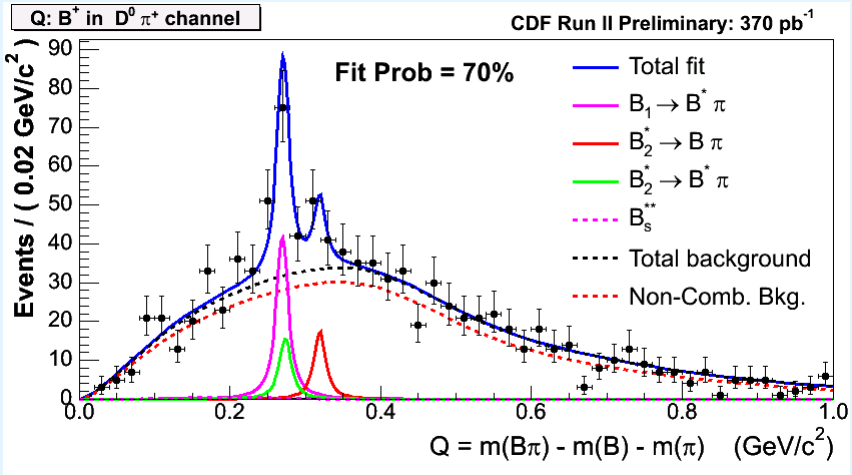
CDF has analyzed only 370 fb^{-1}, but includes a sample of $B^+ \rightarrow D^0\pi^+$ collected with the SVT:

Natural width fixed 16 MeV (theory)
Detector resolution ~ 3-4 MeV









Results from D0:

Mass:

$$M(B_1) = 5720.8 \pm 2.5\ (\text{stat}) \pm 5.3\ (\text{syst}) \quad \text{MeV/c}^2$$
$$M(B_2^*) - M(B_1) = 25.2 \pm 3.0\ (\text{stat}) \pm 1.1\ (\text{syst}) \quad \text{MeV/c}^2$$

CDF $M(B_1) = 5734 \pm 3 \pm 2$ MeV/c^2
$M(B_2^*) = 5738 \pm 4 \pm 1$ MeV/c^2

Width:

$$\Gamma_1 = \Gamma_2 = 6.6 \pm 5.3\ (\text{stat}) \pm 4.2\ (\text{syst}) \quad \text{MeV/c}^2$$

Branching fraction, B_2^*

$$\frac{Br(B_2^* \to B^*\pi)}{Br(B_2^* \to B^{(*)}\pi)} = 0.513 \pm 0.092\ (\text{stat}) \pm 0.115\ (\text{syst})$$

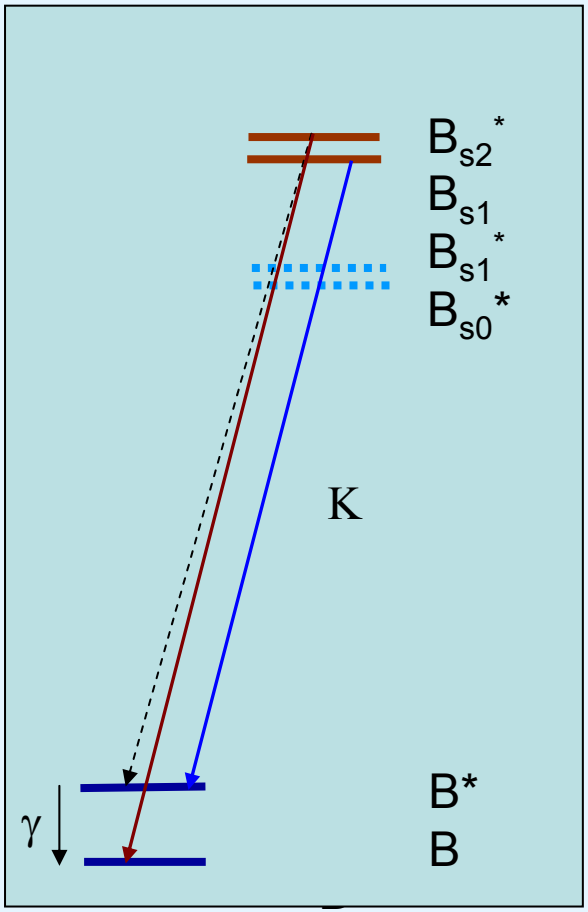
Sample composition:

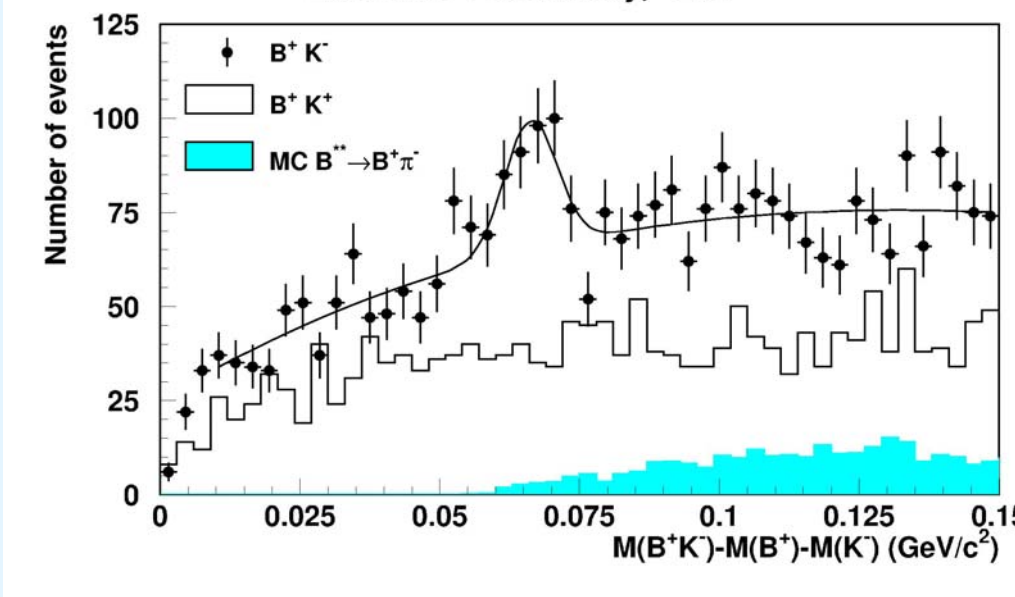
$$\frac{Br(B_1 \to B^{*+}\pi)}{Br(B_J \to B^{(*)}\pi)} = 0.545 \pm 0.064\ (\text{stat}) \pm 0.071\ (\text{syst})$$

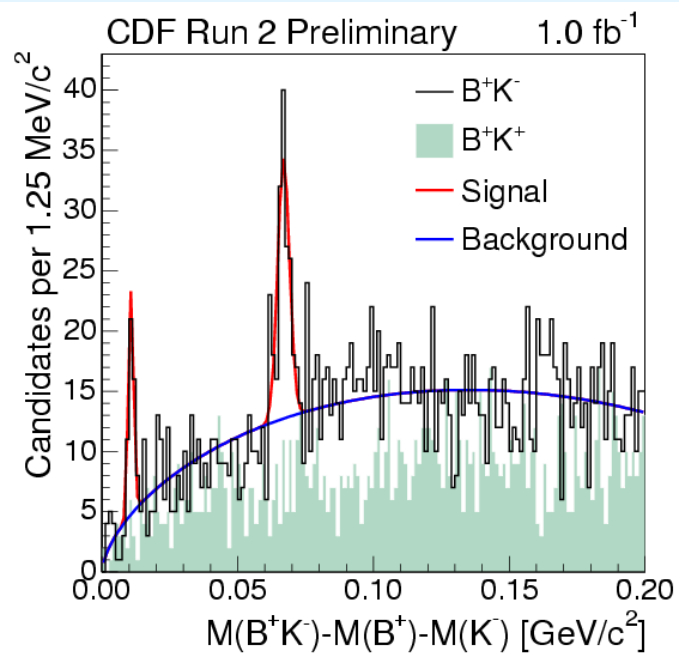
Production rates:

$$\frac{Br(b \to B_J^0 \to B\pi)}{Br(b \to B^+)} = 0.165 \pm 0.024\ (\text{stat}) \pm 0.028\ (\text{syst})$$

B_s : same transitions as for B^0
except substitute p→K. Expected:







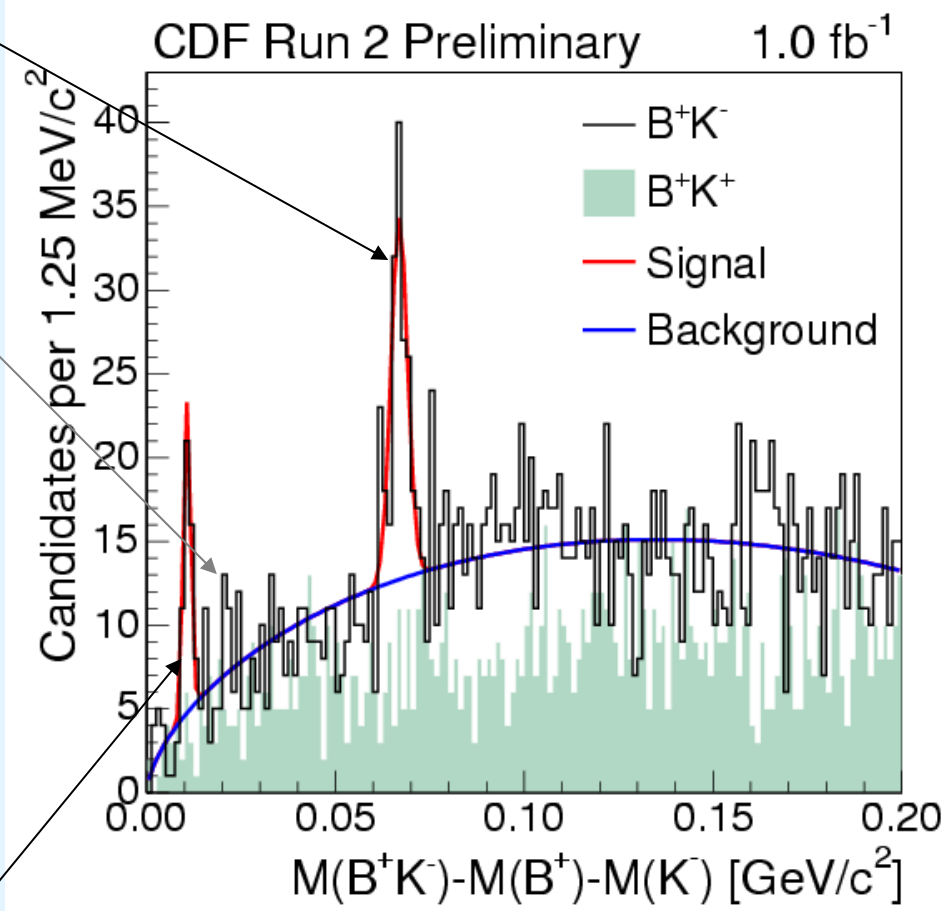
Q = 66.4 ± 1.4 ±1.5 MeV/c² (D0)
Q = 66.96 ± 0.39 ± 0.14 MeV/c² (CDF)
Q = 10.73 ± 0.21 ± 0.14/ MeV/c² (CDF)

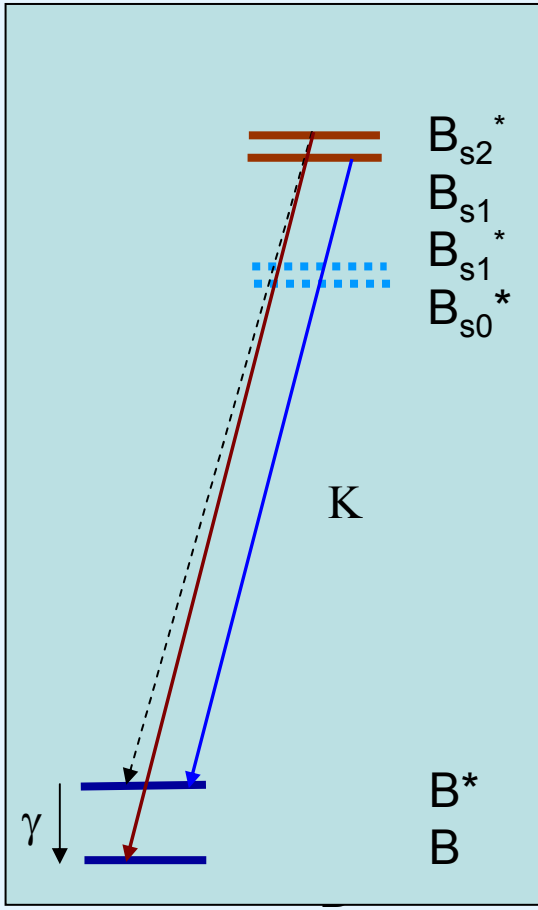
Interpretations

$B_{s2}^* \rightarrow B^+K^-$

$B_{s2}^* \rightarrow B^{*+}K^-$

Expected here
but rate would
be suppressed
by 12.0 ± 3.5)





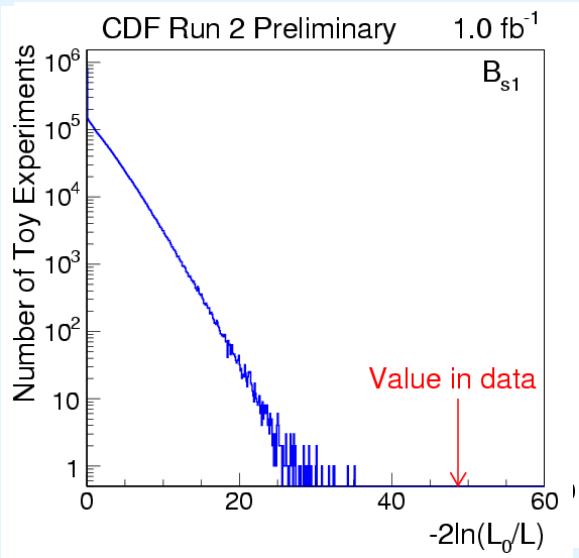
$B_{s1} \rightarrow B^+K^-$

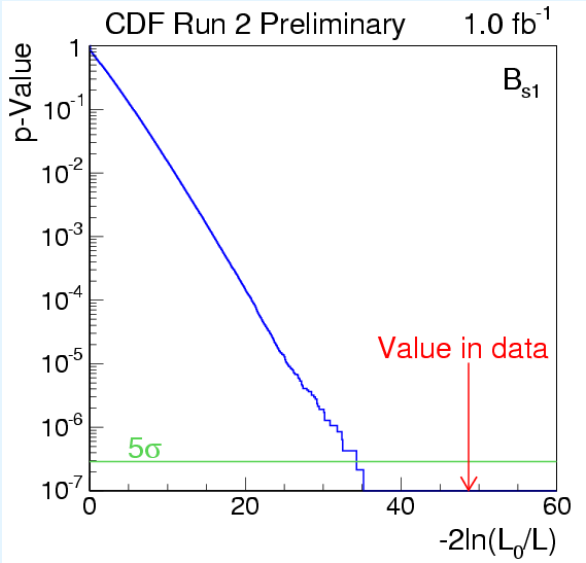
…. & natural widths would be few MeV for the B_{s2}^* and
< 1 MeV for the B_{s1}

$_{s2}$ observed by both experiments. B_{s1} only by CDF, so, is it real?

- Signals are observed in both channels with sharp well-defined likelihood curves.
- Significance evaluated using ratio L/L_0 (L_0 = likelihood with no signal in model)

Significance 6.3 σ





Additional check: toy Monte Carlo is run to see how often a background fluctuation could generate L/L_0 as high as that seen in the data… that's converted to a p-value

answer: well above the 5σ level

Summary of B_s^{**}

CDF

$M(B_{s1}) = 5829.41 \pm 0.21$ (stat) ± 0.14 (syst) ± 0.6 (PDG) MeV/c^2
$M(B_{s2}^*) = 5839.64 \pm 0.39$ (stat) ± 0.14 (syst) ± 0.5 (PDG) MeV/c^2

$DM(B_{s2}^*, B_{s1}) = 10.20 \pm 0.39$ (stat) ± 0.44 (syst) ± 0.35 (PDG) MeV/c^2

D0

$M(B_{s2}^*) = 5839.1 \pm 1.4$(stat) ± 1.5 (syst) MeV/c^2

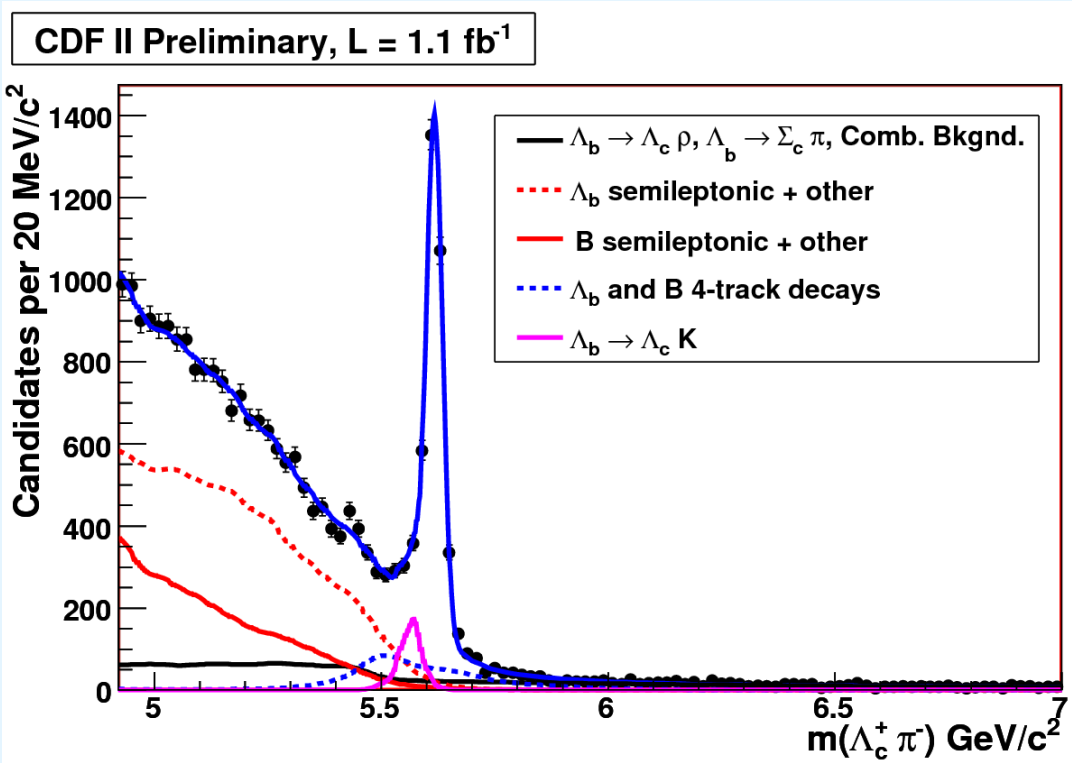
$\Sigma_b^{(*)\pm}$ (four particles)

Let's return to those 2.8K events $\Lambda_b \rightarrow \Lambda^+_c \pi^-$ $\Lambda^+_c \rightarrow pK^-\pi^+$ in the hadronic trigger.

The plot shows a fit to the Λ_b mass in this sample, together with predicted backgrounds.

Σ_b candidates are formed by adding a "soft" $\pi^{\pm}$.

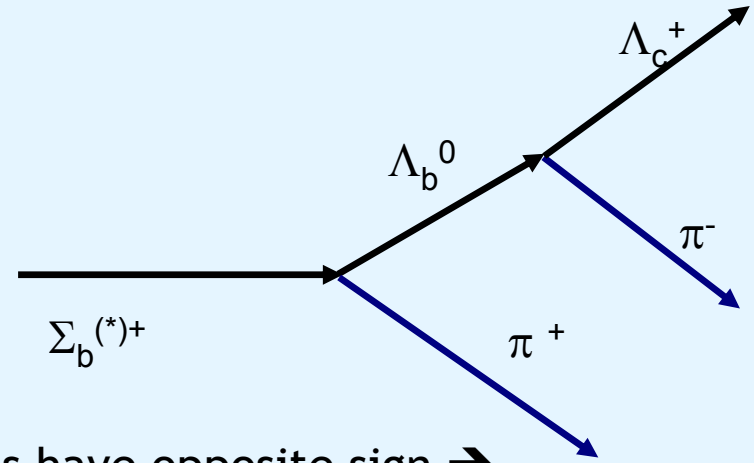
(no p_T cut) .



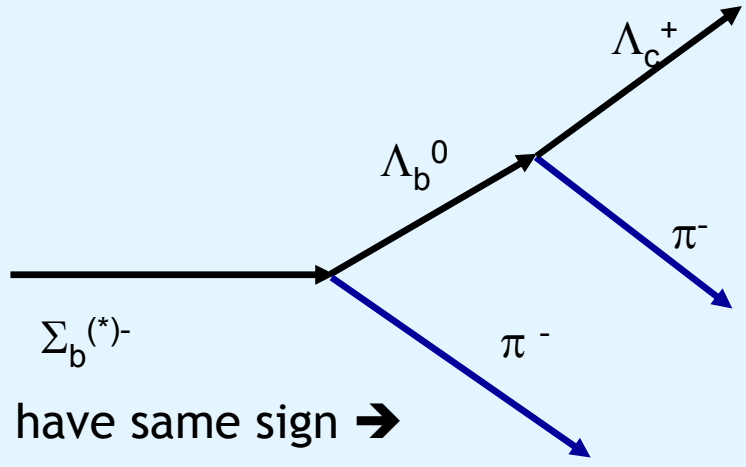
Σ_b^+ (buu) $\rightarrow \Lambda_b \pi^+$
Σ_b^- (bdd) $\rightarrow \Lambda_b \pi^-$

I-spin partners, not antiparticles!

$\bar{\Sigma}_b^+ (\bar{b}\bar{u}\bar{u}) \rightarrow \bar{\Lambda}_b \pi^-$
$\bar{\Sigma}_b^- (\bar{b}\bar{d}\bar{d}) \rightarrow \bar{\Lambda}_b \pi^+$



Pions have opposite sign ➔
$\Sigma_b^{(*)+}$



Pions have same sign ➔
$\Sigma_b^{(*)-}$

Region 30 < Q < 100 MeV/c^2 is kept blind in this analysis. Monte Carlo and Sidebands used to optimize impact parameter significance cuts on the soft pion, cosq* (π_s) cuts, and p_T (Σ_b)

MC used to evaluate the ΔM resolution (checked with D*)

Sources of background are:

- Λ_b^0 hadronization and underlying event (largest background)

  Size and shape taken from Monte Carlo after a careful comparison of this Monte Carlo with data.

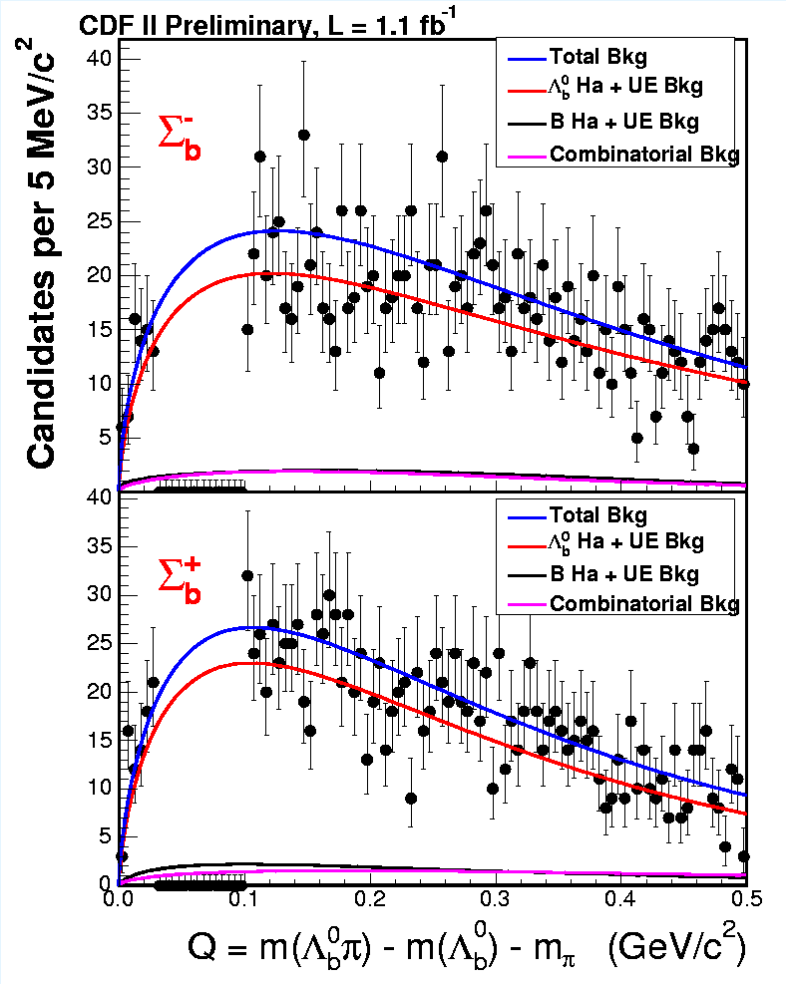
  MC reweighted to bring $p_T(\Lambda_b)$ & p_T(track) into agreement with data.

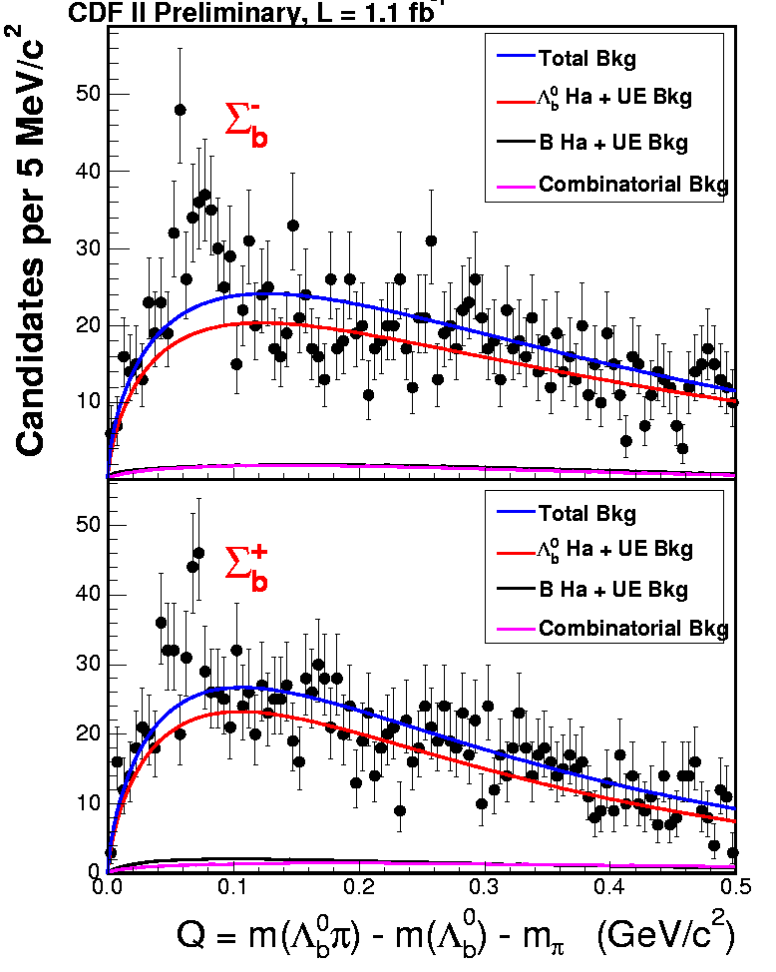
- Hadronization and underlying event of the physics backgrounds to the Λ_b (reflections)

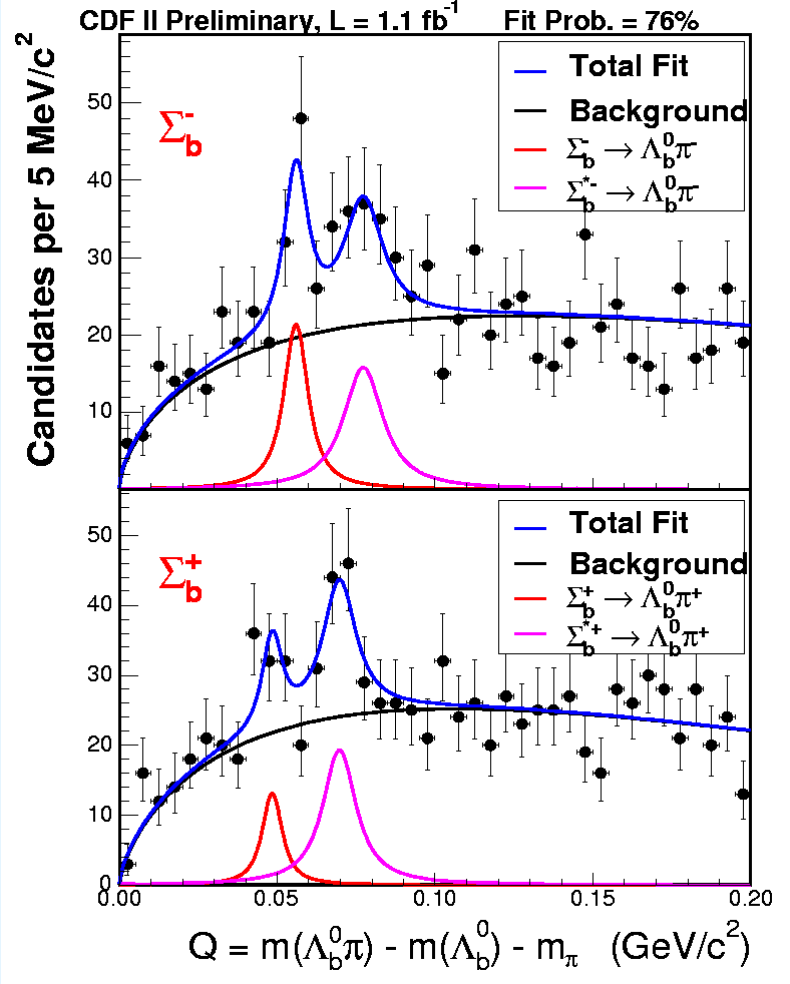
  Shape taken from $B^0 \rightarrow D^- \pi^+$ data reconstructed as Λ_b. Normalization from Λ_b sidebands

*Combinatorial background to the Λ_b

  Size and shape taken from Λ_b mass fit (sidebands)







In the fit: Breit-Wigners (with predicted widths) are convolved with detector resolution from Monte Carlo.

The significance of the results is evaluated by taking the ratio LR of the likelihood of the fit:

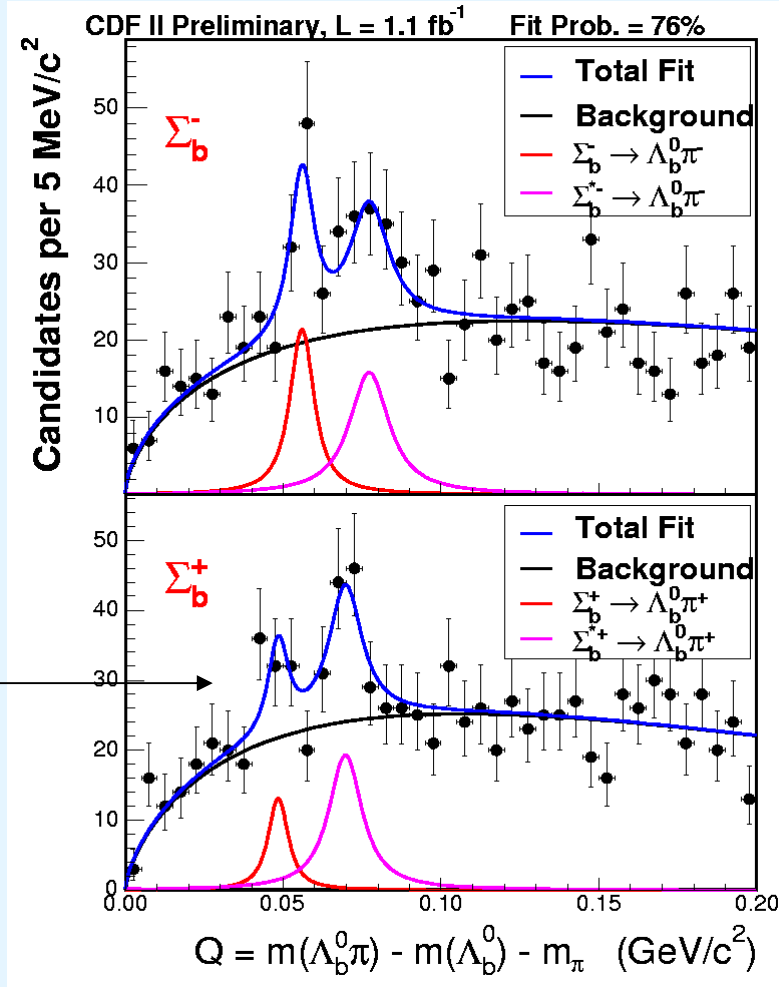
- With four peaks

  to

- Alternate hypothesis

Hypothesis	$\Delta(-\ln(L))$	LR
Null	44.7	2.6×10^{19}
Two Σ_b states	14.3	1.6×10^{6}
No Σ_b^- signal	10.4	3.3×10^{4}
No Σ_b^+ signal	1.1	3
No Σ_b^{*-} signal	10.1	2.4×10^{4}
No Σ_b^{*+} signal	9.8	1.8×10^{4}

weakest



- p-value for the four-peak fit to be due to a deviation of NULL hypothesis corresponds to a significance > 5.2 σ

In summary two charged Σ_b's have been discovered at CDF, plus their Isospin partners and here is their measured Q-values and mass splittings:

- $m(\Sigma_b^-) - m(\Lambda_b^0) - m(\pi) = 55.9^{+1.0}_{-1.0}$ (stat) ± 0.1 (syst) MeV/c^2
- $m(\Sigma_b^+) - m(\Lambda_b^0) - m(\pi) = 48.4^{+2.0}_{-2.3}$ (stat) ± 0.1 (syst) MeV/c^2
- $m(\Sigma_b^{*-}) - m(\Sigma_b^-) = m(\Sigma_b^{*+}) - m(\Sigma_b^+) = 21.3^{+2.0}_{-1.9}$ (stat) $^{+0.4}_{-0.2}$ (syst) MeV/c^2

From which we can derive measured masses of these new heavy baryons and their yields:

- $m(\Sigma_b^-) = 5816^{+1.0}_{-1.0}$ (stat) ± 1.7 (syst) MeV/c^2, $N(\Sigma_b^-) = 60^{+14.8}_{-13.8}$ (stat) $^{+8.4}_{-4.0}$ (syst)
- $m(\Sigma_b^+) = 5808^{+2.0}_{-2.3}$ (stat) ± 1.7 (syst) MeV/c^2, $N(\Sigma_b^+) = 29^{+12.4}_{-11.6}$ (stat) $^{+5.0}_{-3.4}$ (syst)
- $m(\Sigma_b^{*-}) = 5837^{+2.1}_{-1.9}$ (stat) ± 1.7 (syst) MeV/c^2, $N(\Sigma_b^{*-}) = 74^{+18.2}_{-17.4}$ (stat) $^{+15.6}_{-5.0}$ (syst)
- $m(\Sigma_b^{*+}) = 5829^{+1.6}_{-1.8}$ (stat) ± 1.7 (syst) MeV/c^2, $N(\Sigma_b^{*+}) = 74^{+17.2}_{-16.3}$ (stat) $^{+10.3}_{-5.7}$ (syst)

All errors in mass difference are dominated by statistical errors.

In conclusion there is a lot of new information on new B hadrons and excited B hadrons coming from the Tevatron experiments:

B_{s2}^{**} seen in both experiments, with the same mass.
Four new heavy baryons seen at CDF

But:

The B_{s1} state seen by CDF has not been confirmed by D0.
CDF & D0 measurements of $M(B_2^*)$-$M(B_1)$ are discrepant

Intrigue:

Will the B_s^{**} "broad" states be narrow?

- $B_{s(0,1)}^* \rightarrow B_s K$ may be below threshold
- $B_{s(0,1)}^* \rightarrow B_s \pi$ suppressed by I-spin conservation
- $B_{s(0,1)}^* \rightarrow B_s \pi\pi$ suppressed by phase space.
- $B_{s(0,1)}^* \rightarrow B_s \gamma$ is an EM decay..

Will the rest of the b-baryons be seen at the Tevatron?

A continued analysis effort in this sector is warranted.

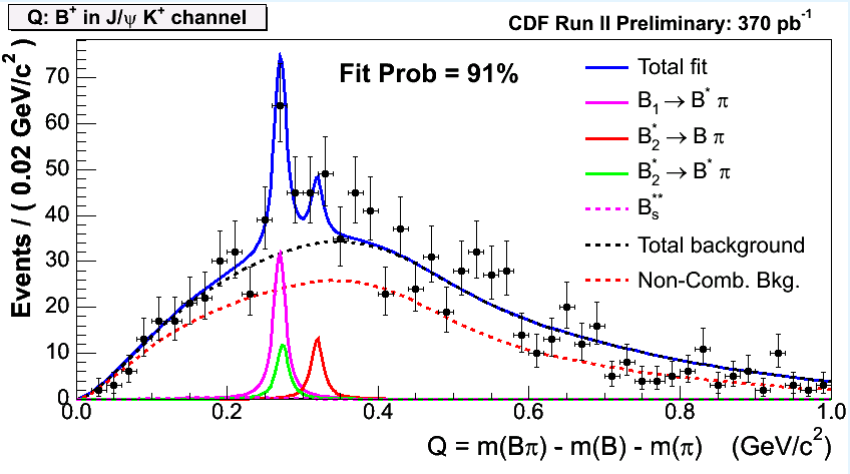
FIN

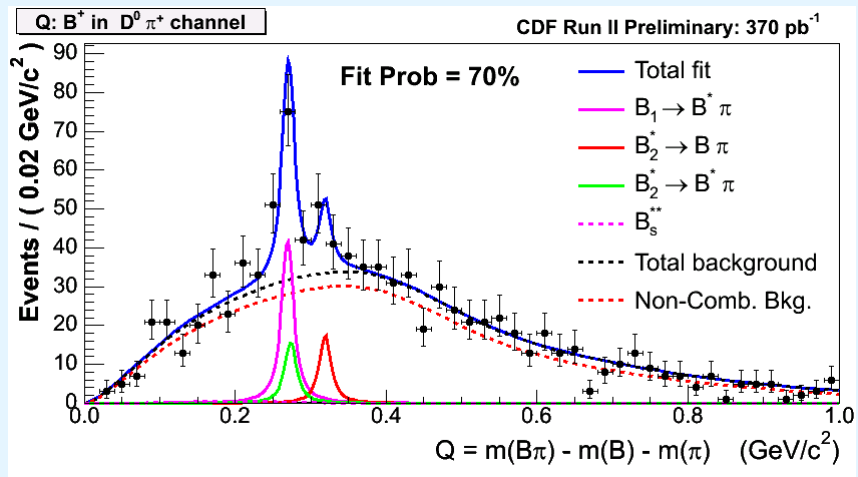
Table of systematic errors for the Sigma B Mass Measurements:

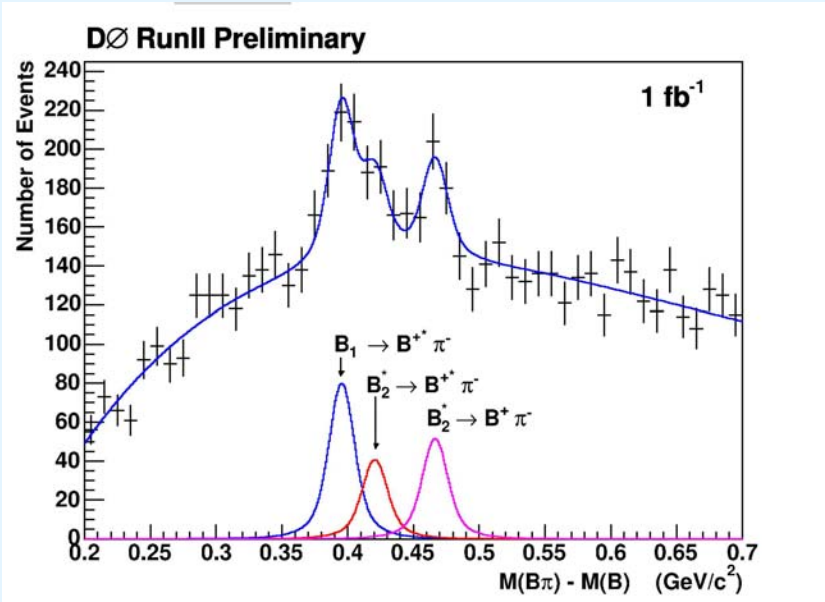
Parameter	Tracking	Λ_b^0 Comp.	Λ_b^0 Norm.	Λ_b^0 Shape	Reweight	Reso.	Σ_b Width	Total
Σ_b^- Q (MeV/c^2)	0.06 -0.06	0.0 -0.03	0.009 -0.002	0.0 -0.011	0.04 -0.0004	0.0 -0.011	0.009 -0.005	0.07 -0.07
Σ_b^- events	0.0 0.0	0.7 0.0	2.2 -2.2	0.3 0.0	7.4 0.0	0.3 0.0	3.4 -3.4	8.5 -4.0
Σ_b^+ Q (MeV/c^2)	0.06 -0.06	0.03 0.0	0.013 -0.013	0.013 0.0	0.0 -0.11	0.0 -0.014	0.01 -0.02	0.07 -0.13
Σ_b^+ events	0.0 0.0	3.3 0.0	2.1 -2.1	1.2 0.0	2.3 -1.8	0.3 0.0	1.8 -2.0	5.0 -3.4
Σ_b^{*-} events	0.0 0.0	0.4 0.0	4.8 -4.7	0.3 0.0	14.7 0.0	0.1 0.0	1.7 -1.7	15.6 -5.0
Σ_b^{*+} events	0.0 0.0	7.3 0.0	4.8 -4.8	2.8 0.0	4.6 -2.9	0.2 0.0	0.8 -0.8	10.3 -5.7
Σ_b^* - Σ_b Q (MeV/c^2)	0.06 -0.06	0.05 0.0	0.14 -0.13	0.04 0.0	0.32 0.0	0.02 0.0	0.07 -0.07	0.37 -0.16
Σ_b^{*-} Q (MeV/c^2)	0.06 -0.06	0.02 0.0	0.13 -0.13	0.03 0.0	0.32 0.0	0.003 0.0	0.08 -0.07	0.36 -0.16
Σ_b^{*+} Q (MeV/c^2)	0.06 -0.06	0.09 0.0	0.12 -0.13	0.05 0.0	0.17 0.0	0.001 0.0	0.05 -0.06	0.24 -0.16

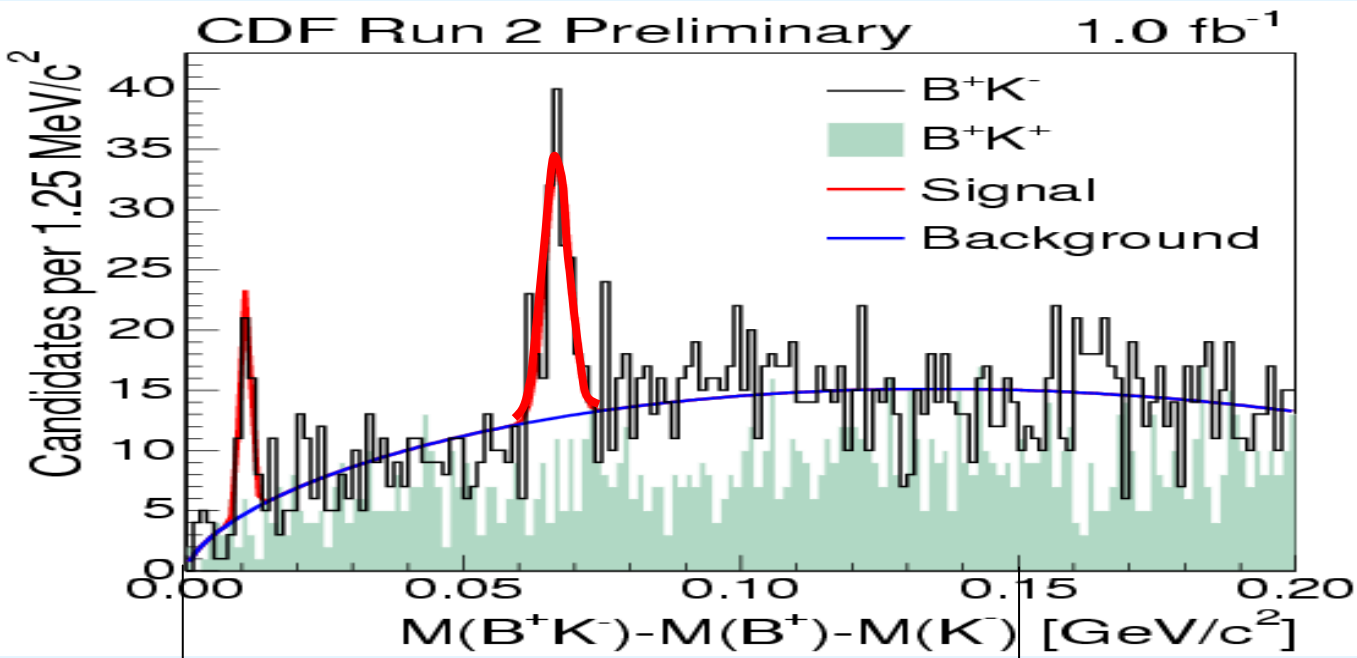
D* Λ_b fit MC Uncertainty D* Theory

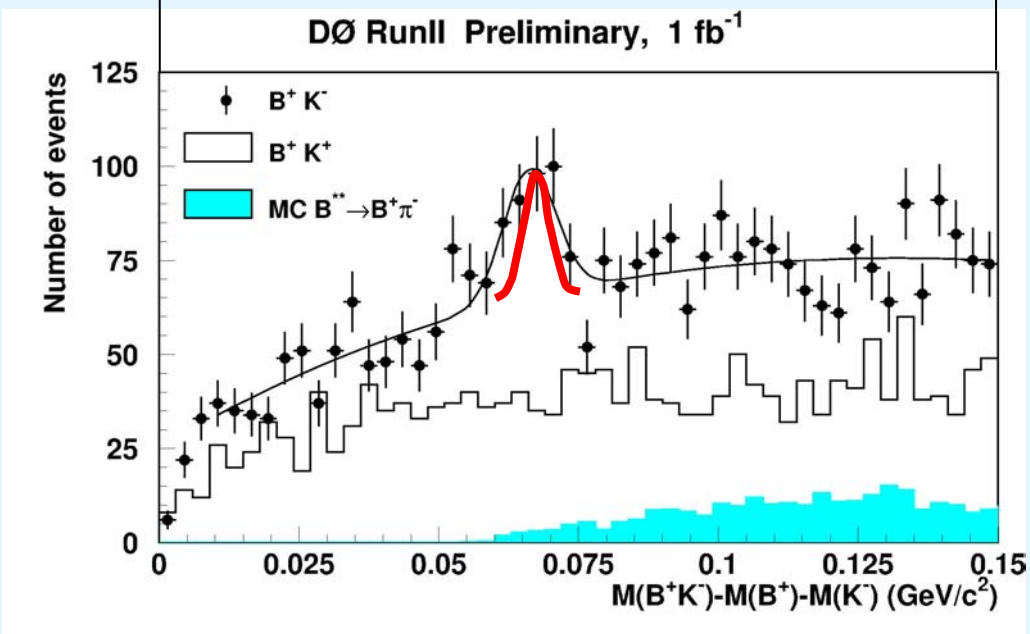
Let's compare the CDF & D0 fits by eye before looking at the numbers:











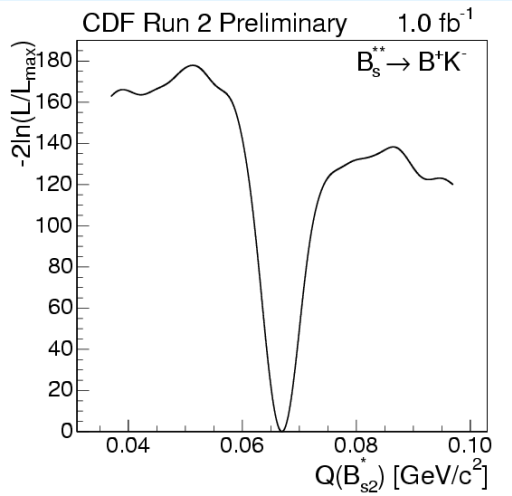
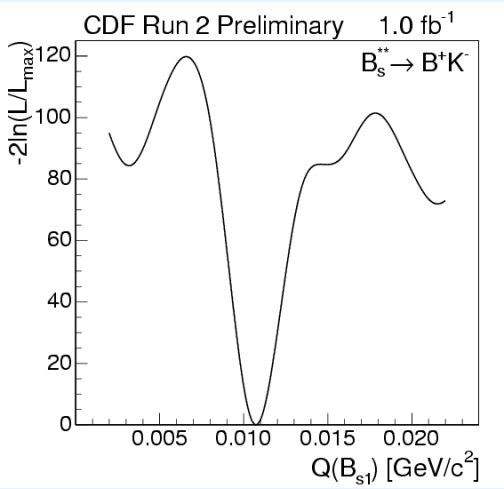
D0 Resolution:

4.6 ± 0.2 MeV/c^2 Q=66MeV/c^2

CDF Resolution:

< 2 MeV @ Q=66 MeV/c^2
< 1 MeV @ Q=11 MeV/c^2

-2Ln(L) scan for the B_{s1} peak at Q=10.73 MeV/c^2



-2Ln(L) scan for the B_{s2}^* peak at Q=66.96 MeV/c^2