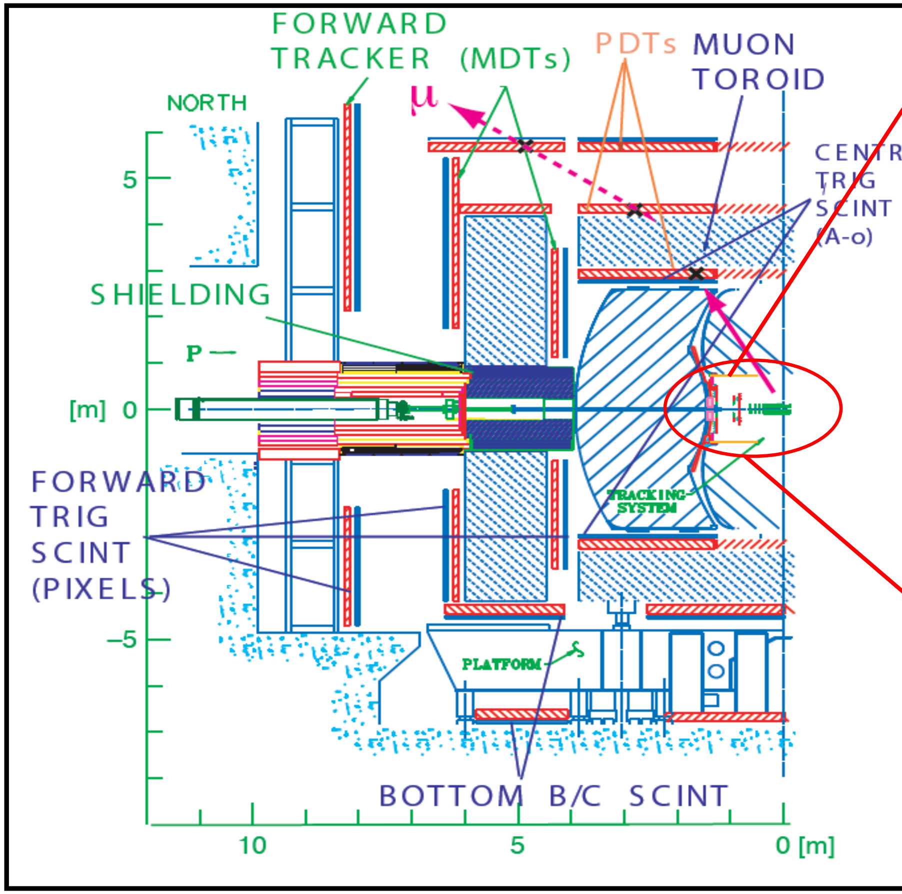
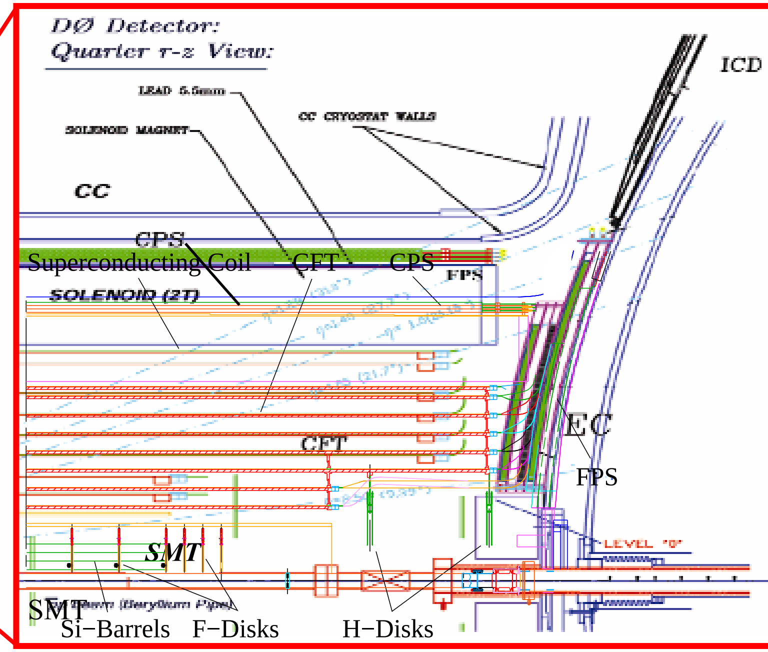
B Hadron Properties at D0

H. Eugene Fisk for the DØ Collaboration

- Introduction
- Orbitally Excited b-mesons
- Bc Mass and Lifetime
- Cascade B
- Conclusions

DØ Detector



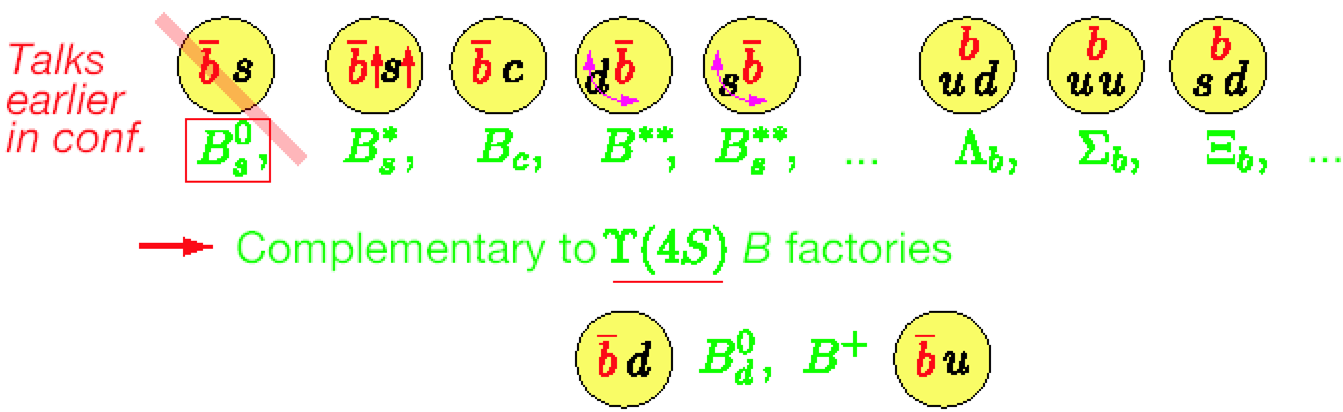


- General purpose detector
- Excellent coverage of Tracking and Muon Systems ($|\eta|<2$)
- Excellent vertex resolution
- 2T Solenoid

Why B spectroscopy?

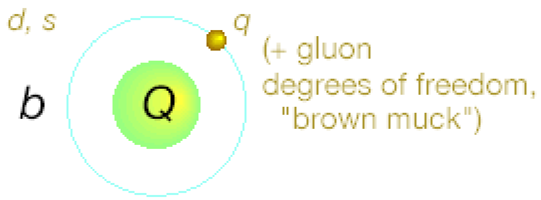
- b-quarks => heavy bound state mesons and baryons. The mesons serve as the "hydrogen atoms" of the quark world and the particle theorists love them because they can calculate!
- b-states measurements provide sensitive tests of potential models, heavy quark effective theory (HQET) and even tests of lattice gauge theory. Complementary to charm states.
- B-quark production cross-sections are large : ~1 μb for Pt > 5 GeV/c, can provide ~ 1200 events/day at L ~ 100 E30.
- Tevatron energy provides access to b-states that are not accessible at e+e- b-Factories.

Outline: *Heavy Mesons* *Heavy Baryons*



Orbitally-excited B mesons

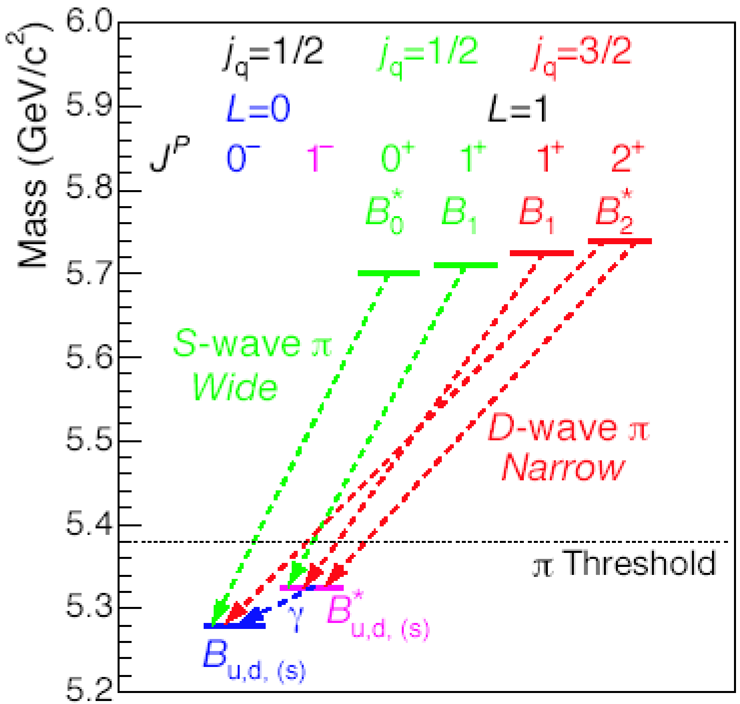
Hydrogen atom of strongly interacting systems



$L = 1$

$\vec{j}_q = \vec{s}_q + \vec{L}$	$\vec{J} = \vec{s}_Q + \vec{j}_q$		
$j_q = 1/2$	$J = 0, 1$	B_0^*, B_1'	B_{s0}^*, B_{s1}'
$j_q = 3/2$	$J = 1, 2$	B_1, B_2^*	B_{s1}, B_{s2}^*

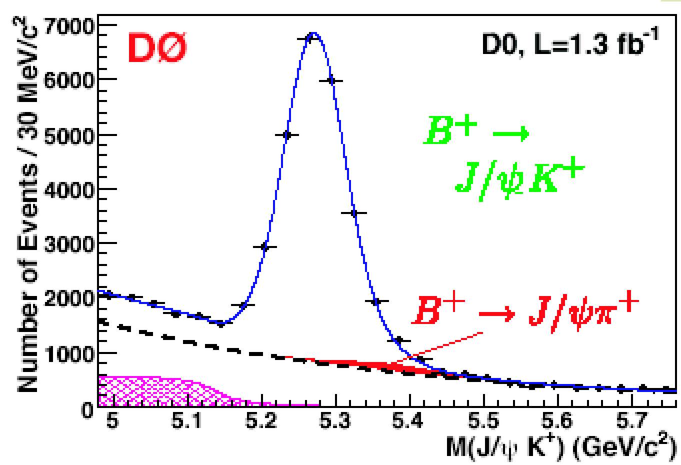
Collectively referred to as: B^{**}, B_J and B_s^{**}, B_{sJ}



B_1 or $B_2^* = B^{(*)+}\pi^- \Rightarrow J/\psi\, K^+ \pi^-$

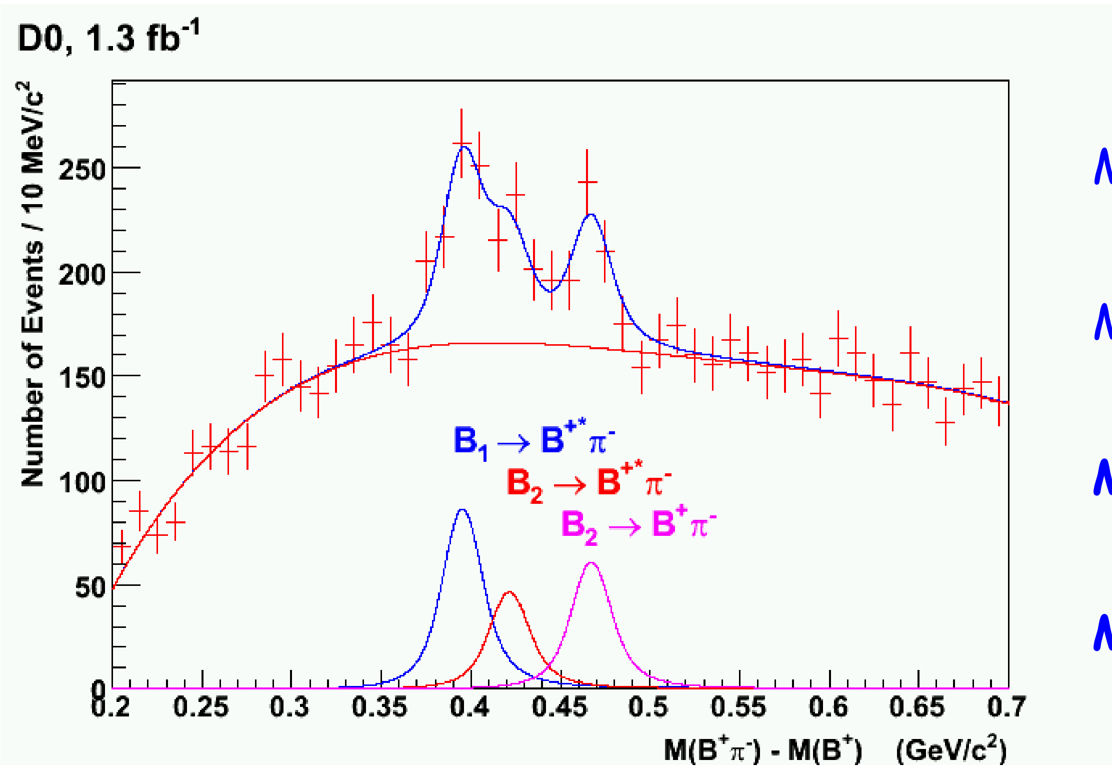
$J/\psi \Rightarrow \mu^+\mu^-$ and $B^* \Rightarrow B\gamma$

45.8 MeV γ not observed



B** Mesons

$B_1 \Rightarrow B^{+*}\pi^-$ $B_2 \Rightarrow B^{+*}\pi^-$ $B_2 \Rightarrow B^{+}\pi^-$ $B^{+*} \Rightarrow B^{+}\gamma$



$M(B_1) - M(B^+) =$
$441.5 \pm 2.4 \pm 1.3$ MeV/c²

$M(B_2^*) - M(B1) =$
$26.2 \pm 3.1 \pm 0.9$ MeV/c²

$M(B_1) =$
$5720.6 \pm 2.4 \pm 1.4$ MeV/c²

$M(B_2^*) =$
$5746.8 \pm 2.4 \pm 1.7$ MeV/c²

N(B) =**
662 ± 91 ± 140 events

$\Delta_1 = M(B_1) - M(B^*)$,
$\Delta_2 = M(B_2^*) - M(B^*)$
$\Delta_3 = M(B_2^*) - M(B) = \Delta_2 + 45.8\text{MeV}$

B** Mass Fitting

$$F(\Delta M) = F_{sig}(\Delta M) + F_{bckg}(\Delta M)$$

$$F_{sig}(\Delta M) = N\{f_1 D(\Delta M, \Delta_1, \Gamma_1) + (1 - f_1)[f_2 D(\Delta M, \Delta_2, \Gamma_2) + (1 - f_2) D(\Delta M, \Delta_3, \Gamma_2)]\}$$

$F_{back}(\Delta M) = 4^{th}$ order polynomial. $D(x, xo, \Gamma)$ is the convol'n of a relativistic Breit-Wigner with Gaussian.

$M(B_1) = 5720.6 \pm 2.4 \pm 1.4$ Mev/c^2

$M(B_2^*) = 5746.8 \pm 2.4 \pm 1.7$ MeV/c^2

χ^2/d.o.f. = 33/40; w/o B_J signal χ^2/d.o.f. = 97/45.

Peak structure significance > 7σ.

Fitting with only one peak, χ^2/d.o.f. = 54/42 or 4σ.

With $B_2^* \Rightarrow B^*\pi$ removed, χ^2/d.o.f. = 41/41. Three peaks preferred, which agrees with theory, but statistically marginal.

Obs. of the Excited B_{s2} Meson ($b\bar{s}$)

Use the same events just discussed in the B_1 and B_2^* analysis, with the assignment of the charged track as a K meson. Look for:

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

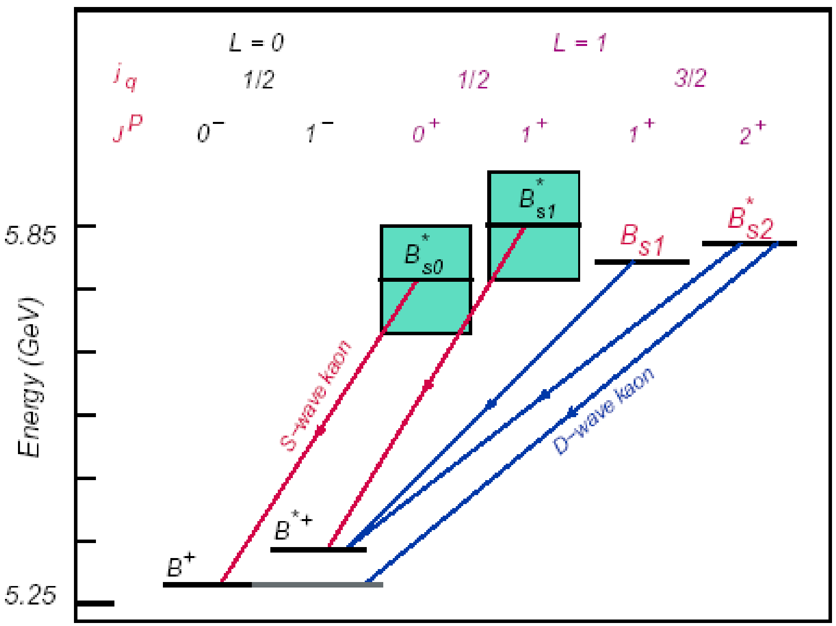
$B_{s2} \rightarrow B^{*+} K^-$, $B^{*+} \rightarrow B^+ \gamma$

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

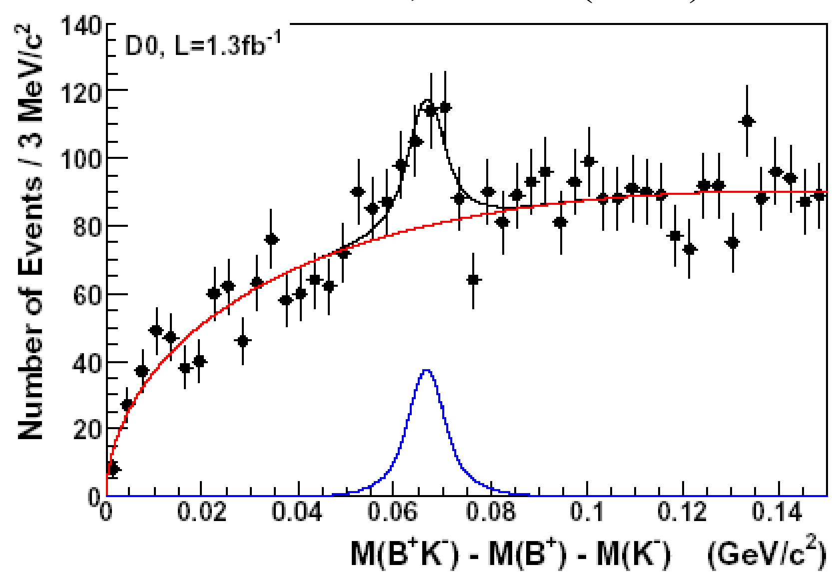
20,915 +/- 293 +/- 200 B+ candidates

Additional track p_t > 0.6 GeV/c w/charge opposite to the B charge.

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



PRL **100**,082002 (2008)



B_{s1}, B_{s2}^* Search Results

Of the three decays through which the BsJ states can reach the ground state B+, one or more may be forbidden if the excited state mass is smaller than the mass of the decay products. One obvious bump at ΔM = 67 MeV/c². This is the highest energy transition: $B_{s2} \rightarrow B^+K^-$. Because this mass is close to threshold its width Γ is expected to be ~ 1MeV/c². The apparent width is due to our mass resolution, so Γ is fixed at 1 MeV/c². Fit to a single B-W with Gaussian expt'l resolution:

Single Peak Fit:

$\Delta_0 = M(B_{s2}^*)-M(B^+)-M(K^-)$

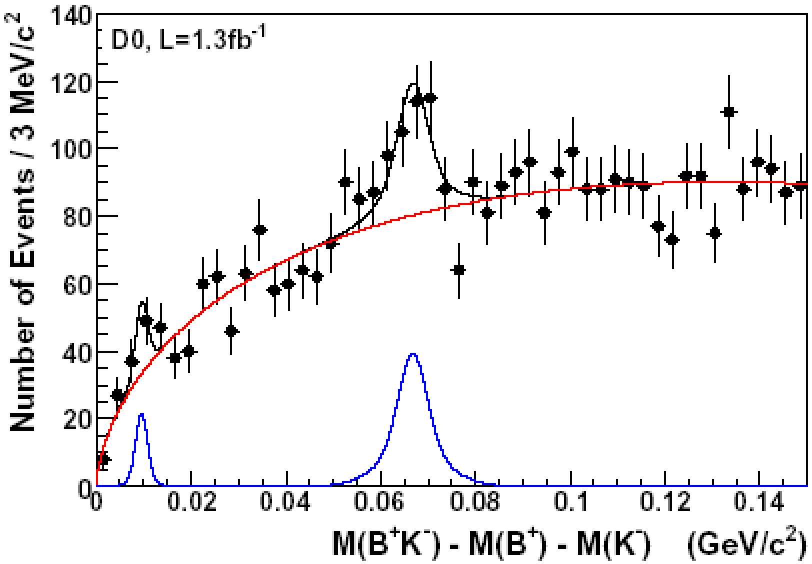
$= 66.7 \pm 1.1(stat)$ MeV/c².

w/o B_{s2} signal fit log L shows 4.8σ.

Double Peak Fit:

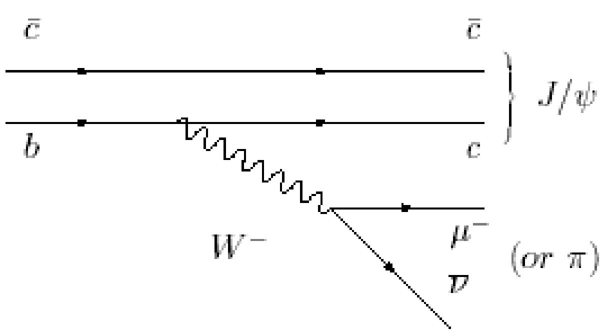
$\Delta M(B_{s1})=11.5 \pm 1.4(stat)$MeV/c².
w/o B_{s1} sig, log L shows a 2.7σ decrease so it is inconclusive.

Double Peak Fit

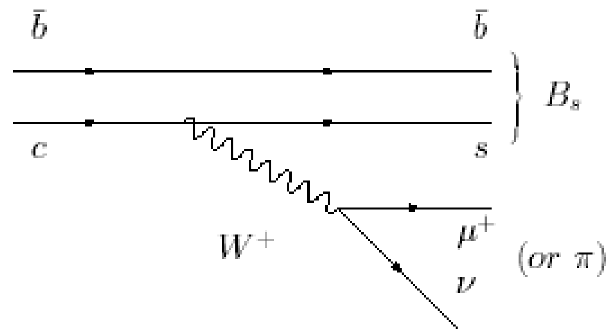


B_c Meson $(b, \bar{c})$: Mass and Lifetime

- Two heavy quarks; decays via b or c to W; also annihilation.



c as spectator (this talk)



b as spectator (not seen)

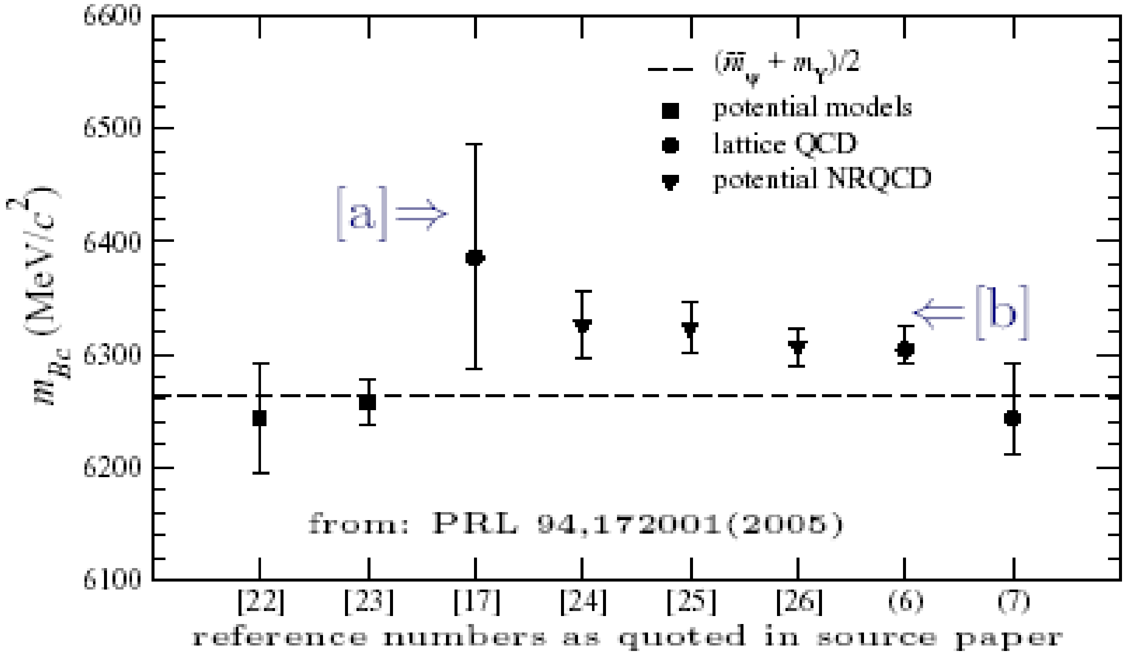
$J/\psi\ \mu\ \nu$ or $J/\psi\ \pi$

$B_s\ \pi$ or $B_s\ \mu\ \nu$

Expect the lifetime to be ~1/3 of other B-mesons.

For mass measurement $J/\psi\ \pi$ final state has no missing particles. Has di-muon plus charged pion vertex. Can tune up on a state with similar topology: $B^+ \rightarrow J/\psi\ K^+$.

B_c Mass Predictions



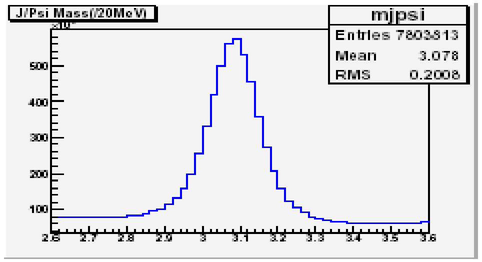
[a] Omitting sea quarks,
(quenched approx.).

[b] Add 2+1 sea flavors,
u, d as light as possible,
and strangeness mass.

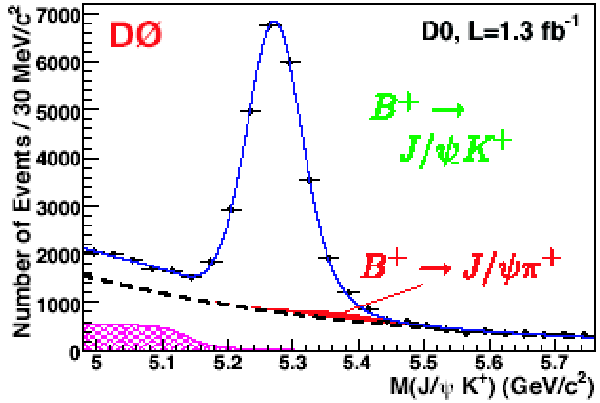
[a] H.P. Shanahan, P. Boyle, C.H.T. Davies, H. Newton
PLB 453, 289 (1999) 6386 +/- 9 +/- 15 +/- 98 MeV/c^2

[b] I.F. Allison, C.T.H. Davies, A. Gray, A.S. Kronfeld, P. B. Mackenzie, J.N. Simone
PRL 94, 172001 (2005) 6304 +/- 4 +/- 11 (+18/-0) MeV/c^2

Data Cuts: Learn on $B^+ \to J/\psi\ K^+$ signal and sidebands

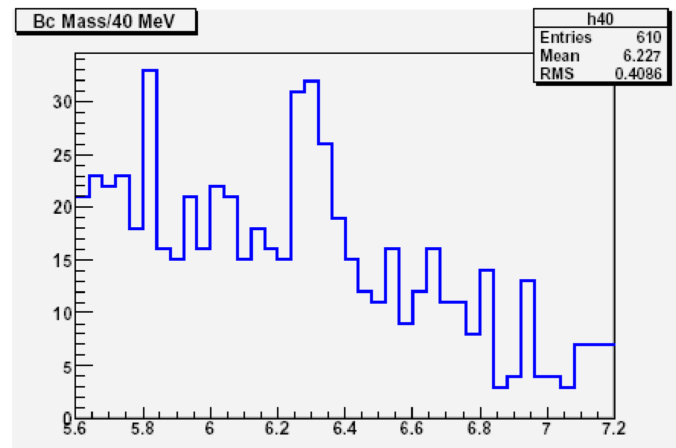


$J/\psi \to \mu^+\mu^-$
7.6M events

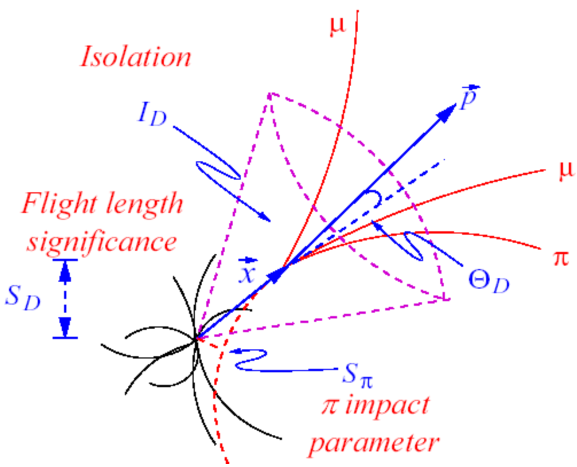


$(J/\psi\ K^+)$ Mass
37K events

Pre-selection Cuts:
- $P_T\ J/\psi > 4$ GeV/c
- P_T 3rd particle > 1.5 GeV/c
- $P_T(B) > 5$ GeV/c



$J/\psi\ \pi$ Mass

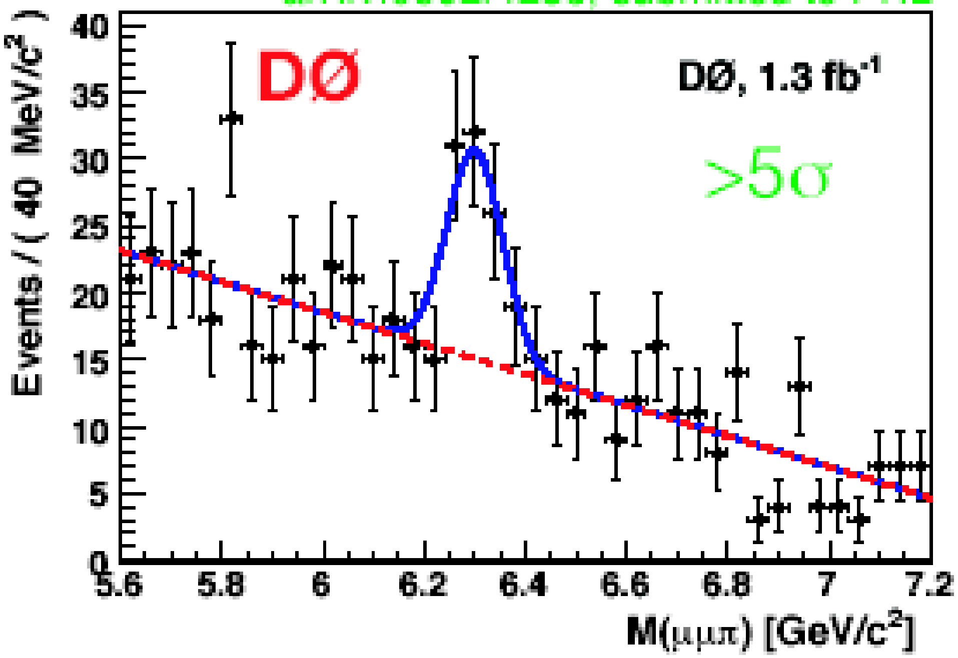


Data based cuts:
- IPsigB: 3-D Impact Par Signif of B wrt PV;
- IPsig3: 3-D Impact parameter - third track;
- χ^2: formation of the 3 particle vertex;
- Sxy: 2-D Decay length Significance;
- Cxy: 2-D point cos for the B cand w.r.t. PV

B_c Mass

accepted by

arXiv:0802.4258, ~~submitted to~~ PRL



$$m(B_c^+) = 6300 \pm 14 \pm 5\,\mathrm{MeV}$$

$B_c \Rightarrow J/\psi\ \mu + X$ Lifetime Measurement I

arXiv:0805.2614v1 [hep-ex]

- Integrated Luminosity of ~1.3 fb^{-1}.
- Decay length from primary vertex to $J/\psi\ \mu$ vertex.
- The B_c signal is established by using mass fits following decay length requirements.
- MC samples of signal and backgrounds are used to model mass and decay length distributions.
- J/ψ sample from reconstructed opposite sign μ's w/pt > 1.5 GeV/c and di-muon mass in the range 2.90 to 3.26 GeV/c^2
- Add a third muon whose track forms a good vertex with the J/ψ.
- Find 14,753 events with $J/\psi\ \mu$ masses between 3 and 10 GeV/c^2.

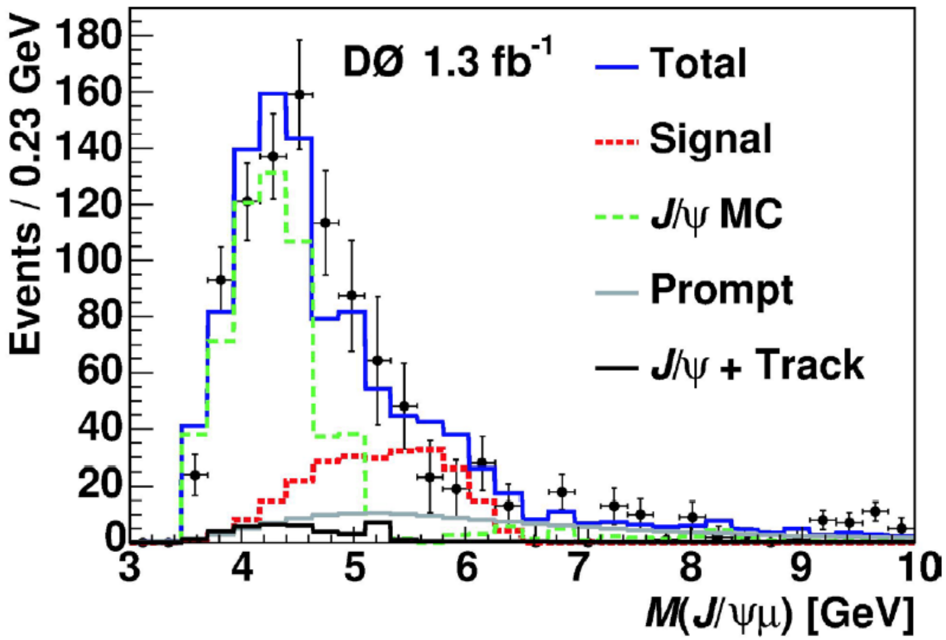
The $J/\psi\ \mu$ mass can be used to characterize the components that make up the sample:
(1) Signal - SI
(2) Real J/ψ with a "fake" muon due to a track – JT (small component)
(3) Fake J/ψ from combinatorial background – CB
(4) Real muon forms a vertex with a real J/ψ, neither from a B_c – JM
(5) $B^+ \rightarrow J/\psi\ K^+$ with $K \Rightarrow \mu\ \nu$ in flight – DK
(6) c pair where a prompt J/ψ is associated with a muon - PR

The $J/\psi\ \mu$ invariant mass is used to model the six components. And the decay length is also a parameter. The lifetime of the B_c is not measured because of the missing ν.

B_c => $J/\psi\ \mu$ Lifetime Measurement (2)

Use the Visible-Proper Decay Length (VPDL) = $L_{xy} \dfrac{m(B_c^{\pm})}{p_T(J/\psi\mu)} = \dfrac{c\tau}{K}$

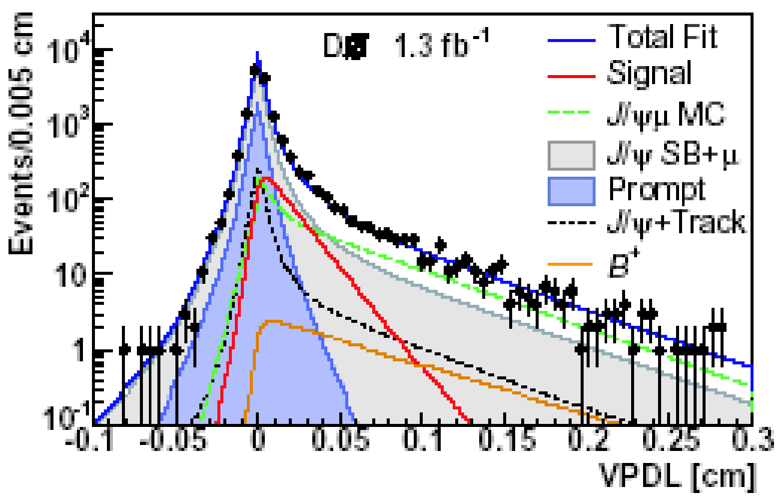
to define the K factor distribution that is then applied statistically when extracting the $c\tau(B_c)$.



Fit to the $J/\psi + \mu$ vertex with the J/ψ mass sideband and B^+ components subtracted and decay length significance $L_{xy}/\sigma(L_{xy}) > 4$ required.

$B_c \Rightarrow J/\psi\ \mu$ Lifetime Measurement (3)

- Both the $M(J/\psi\ \mu)$ and VPDL distributions can be fitted simultaneously after the various components of backgrounds are established.

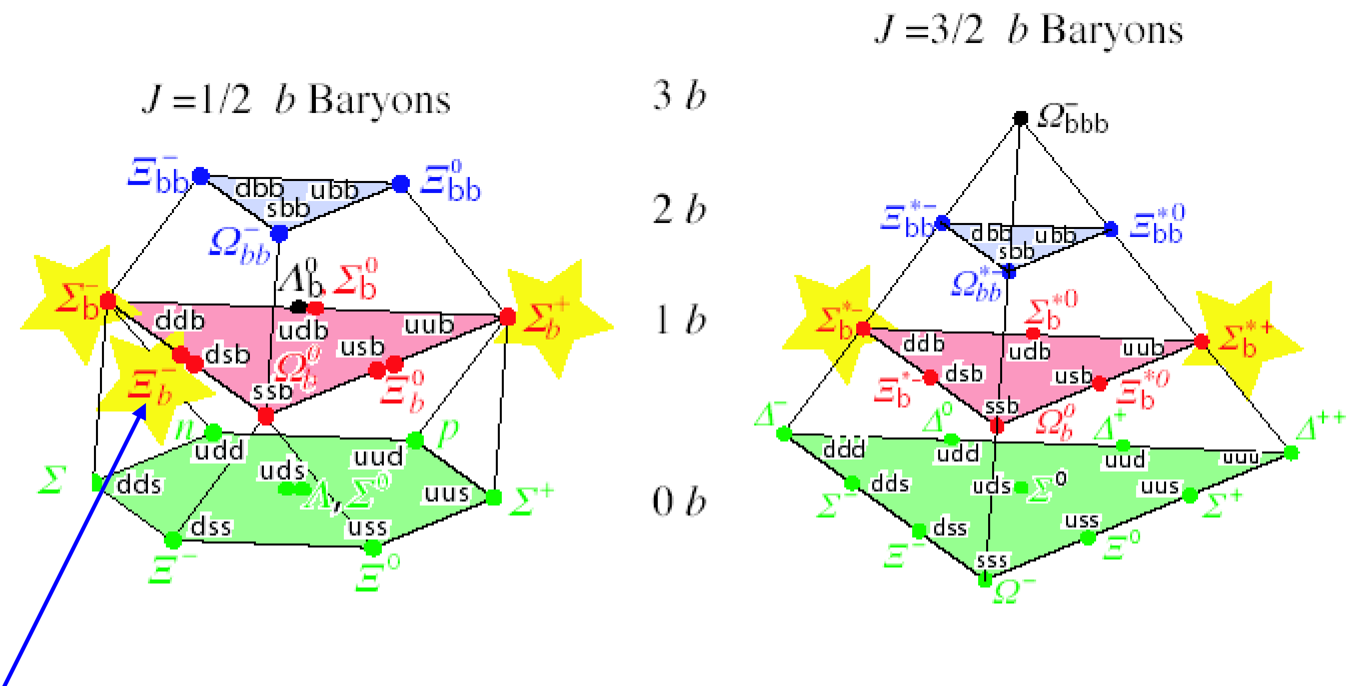


Summary of estimated systematics	
Systematic Source	$\Delta\tau$ (ps)
Mass model uncertainty	±0.021
Lifetime model uncertainty	±0.022
Signal feed-down fraction	±0.005
Alignment	±0.006
Total	±0.032

World's best!

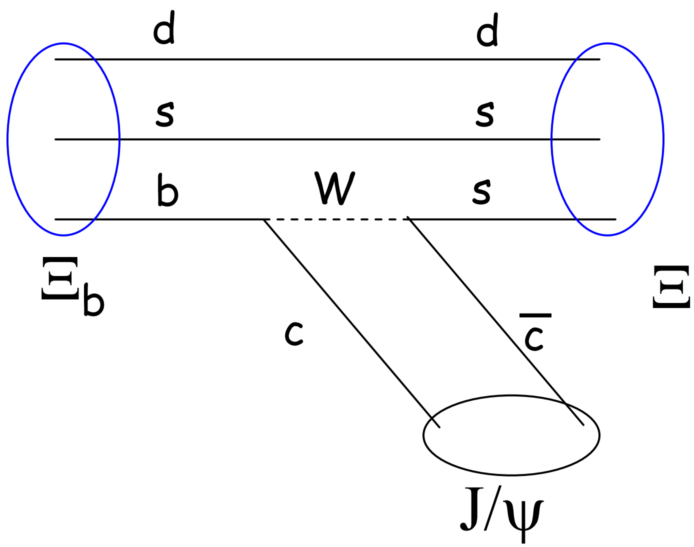
$\tau(B_c) = 0.448\ {+0.038/-0.036}(\text{stat}) \pm 0.032(\text{sys})$ ps

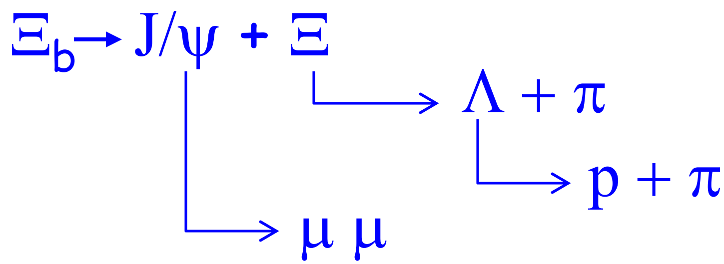
b Baryons: Where are they?

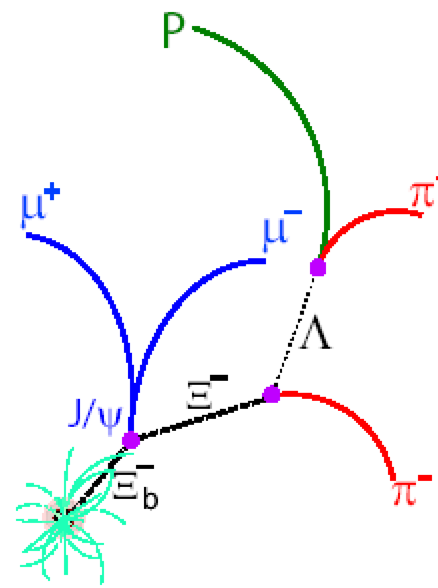


Search for the Cascade b

Cascade b: (d, s, b) or Ξ_b







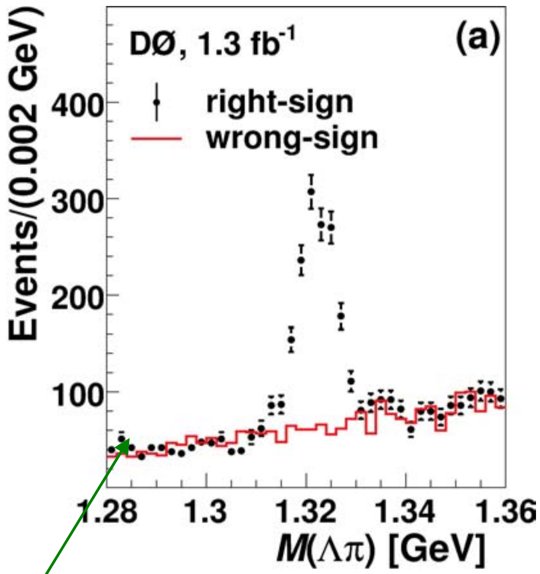
Challenging to connect all the dots!
Start with di-muons, then developed downstream search for Λ search.
Kinematics constraints were then applied.

Ξ_b Candidate Selection

J/ψ requirements:
- Opposite sign μ's w/common origin;
- Matching μ track in CT and μ PDTs;
- P_t (μ) > 1.5 GeV/c;
- 2.5 < M(μ,μ) < 3.6 Gev/c;
- If more than one cand., take closest.

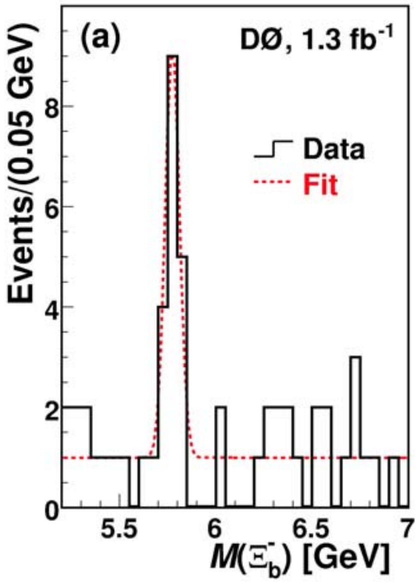
Other requirements:
- Primary vertex;
- Reprocess evts using improved eff. for finding downstream vertices/tracks.
- For Λ candidates assume the high p_t track is a proton (MC says ~100% OK)
- $1.105 < M(p,\pi^-) < 1.125$ GeV/c;

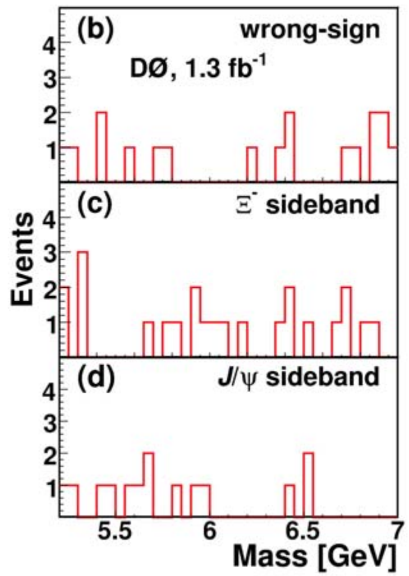
Ξ^- and additional π^- requirements:
- Λ and π common upst. vertex; IP reqs
- Same charge sign for π_Λ and the other π;
- Wrong sign π_Λ and other π → bckgd level.



$\Xi_b \rightarrow J/\psi\ \Xi$ Conditions:
- For p(Λ): p_t > 0.7 GeV/c
- B decays suppressed l_Ξ >5mm (avg l_Ξ in MC is 4.8cm)
- $\cos(\theta_{col})$ > 0.99 (MC studies) (Reduce Bkgd 56%; -1.7% Sig)
- $l_{\Xi b}$ DK length sig > 2 ($l_{\Xi b}$ MC)

$M(\Xi_b)$ Mass: 1st Observation





$M(J/\psi\ \Lambda\ \pi^+)$ Wrong sign π

$M(J/\psi\ \Lambda\ \pi^-)$ in Ξ^- sidebands
i.e. $1.28 < M(\Lambda\pi^-) < 1.36$ GeV/c^2 but
excluding $1.305 < M_\Xi < 1.340$ GeV/c^2

$M(J/\psi\ \Lambda\ \pi^-)$ in J/ψ Lower Sideband
Avoid upper sideband because of ψ'.
$2.5 < M(\mu^+\mu^-) < 2.7$ GeV/c^2

$M(\Xi_b) = M(J/\psi\ \Xi^-) - M(\mu^+\mu^-) - M(\Lambda\pi^-) +$
$M_{PDG}(J/\psi) + M_{PDG}(\Xi^-)$

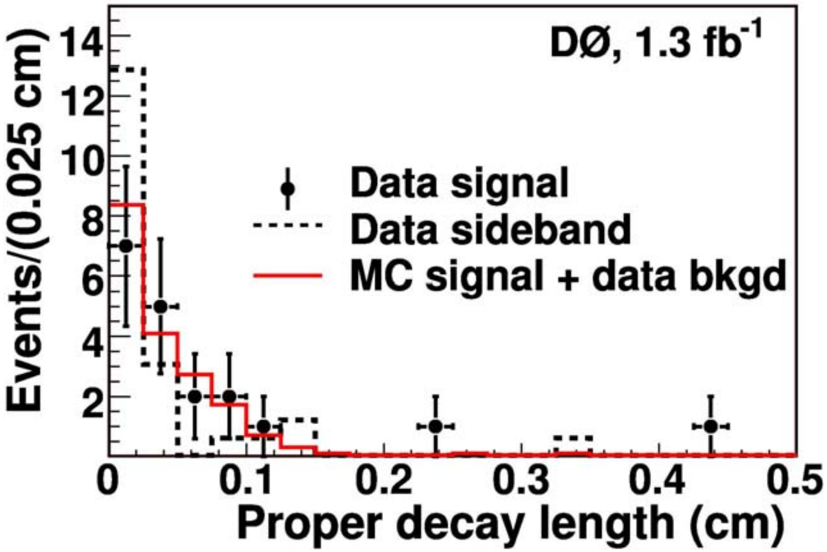
Unbinned Likelihood fit gives:
$= 5.774 \pm 0.011(\text{stat}) \pm 0.015(\text{syst})$ GeV/c^2

19 Candidate Events fitted with a Gaussian + flat background yields a signal/bkgd of 15.2/4.4 events.
Log likelihood ratio $\sqrt{2\ln(L_{(s+b)}/L_b)}$
$\rightarrow 5.5\sigma$, thus the probability of the signal being a bckg fluctuation is $3.3\text{X}10^{-8}$,
=> $2.2 \text{ X } 10^{-7}$ with all errors included.

Systematic Errors:
Event selection – Using multivariate technique using different variables for event selection leads to a conservative ±0.015 GeV/c^2 syst in the Ξ_b mass.
Signal & Background Models – Using the world average masses (PDG) shows a weak dependence on the track momentum scale. Verified with $\Lambda_b \rightarrow J/\psi\ \Lambda$ and $B^0 \rightarrow J/\psi\ K_s$ implies a mass uncertainty of ±0.002 GeV/c^2.

CDF's $M(\Xi_b)$ measurement is:
$5.792 \pm 0.0025 \pm 0.0017$ GeV/c^2

Ξ_b Proper Decay Length Distribution



19 candidate events in the $M_{\Xi b} \pm 2.5\sigma$ window and sideband events, defined to be 5σ away from the fitted mass, scaled to the number of events in the signal mass window, are included.

The expected distribution for 14.8 MC Ξ_b events and 3.6 background events are also shown.

K-S tests indicate that the distribution of signal events is favored over that of the sideband events, when compared to the MC generated Xb events, by 5 to 1 odds.

Ξ_b (σ X $\mathcal{B}$) Relative to Λ_b

$$\frac{\sigma(\Xi_b^-)\times B(\Xi_b^- \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b)\times B(\Lambda_b \to J/\psi\,\Lambda)} = \frac{\varepsilon(\Lambda_b \to J/\psi\,\Lambda)}{\varepsilon(\Xi_b^- \to J/\psi\,\Xi^-)}\frac{N_{\Xi_b^-}}{N_{\Lambda_b}}$$

$N(\Xi_b) = 15.2 \pm 4.4 +1.9/-0.4$

$N(\Lambda_b) = 240 \pm 30 \pm 12$

Efficiency ratio (MC) = 4.4 ± 1.3

$$\frac{\sigma(\Xi_b^-)\times B(\Xi_b^- \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b)\times B(\Lambda_b \to J/\psi\,\Lambda)} = \quad 0.28 \pm 0.09(\text{stat}) +0.09/-0.08$$

Summary/Conclusions

B hadron properties are being understood with data from the Tevatron on many fronts:

- New states that excite us: e.g. Ξ_b
- Orbitally excited mesons; we are making theorists happy.
- b-state lifetimes for previously unmeasured states, B_c;
- We're testing lots of b-physics predictions like lattice gauge.
- The Fermilab collider is supplying much data for us. That's great! Our thanks to all who have done so well.