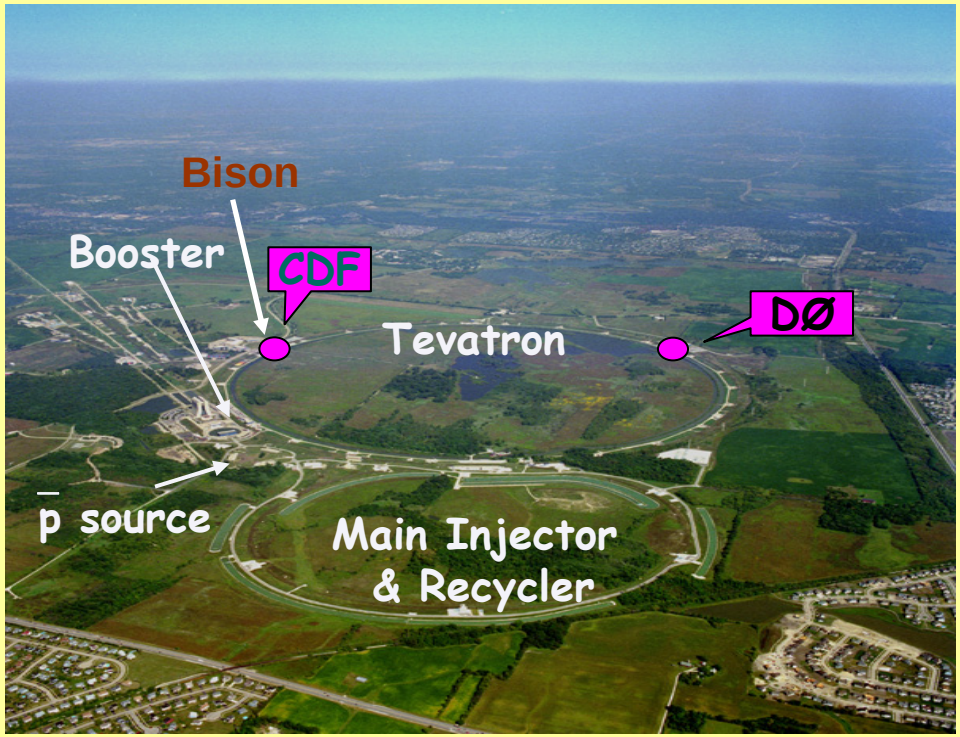
B-Hadron Properties at the Tevatron: Lifetimes, B_c, Excited States

Heather Gerberich
University of Illinois
(for the D0 and CDF experiments)

B-Hadron Properties

- Triggers
- Lifetimes
  - Λ_B
  - B_s



- B_c
  - Lifetime
  - Mass
  - Cross section
- Excited States
  - Masses, properties

Final States and Triggers

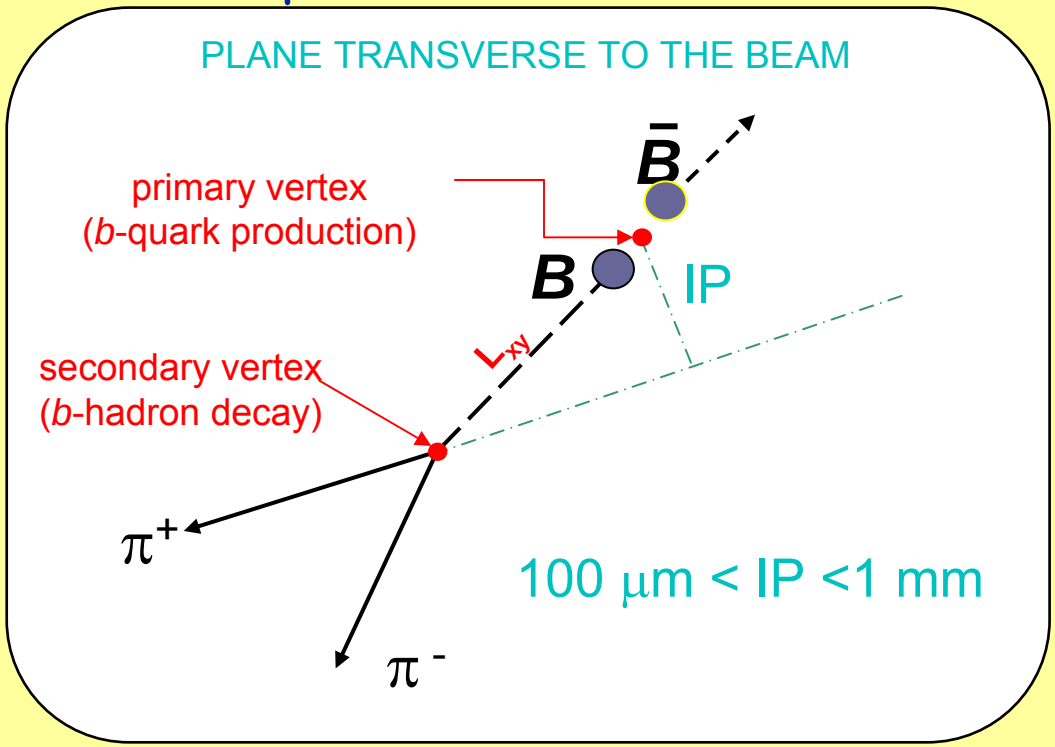
- Dimuon Final State
  - At least two muons in final state
  - **Dimuon trigger**
    - Typically used for signals with J/ψ in the final state
    - Require at least one track with matching muon segment along with another track (2 tracks required in total)
    - $p_T > 1.5$ GeV/c (CDF)
    - No lifetime bias from trigger

- Semileptonic Final States
  - At least one muon
  - **Single lepton trigger**
    - Require track with muon matching segment or calorimeter energy consistent with a MIP
    - $p_T > 2$ GeV
    - No lifetime bias from trigger

Final States and Triggers

- Hadronic final state
  - All or most final state particles are hadrons
- Trigger on displaced track vertices
  - Usually two tracks: **Two Track Trigger**
- At CDF, at Level 2, cut on SVT impact parameter: 100 – 1000 μm

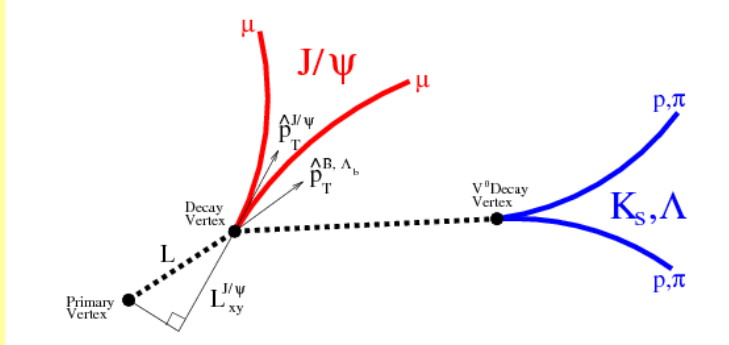
- Biases lifetime measurement
  - Bias accounted for using MC
- Increases statistics and allows measurements in different channels

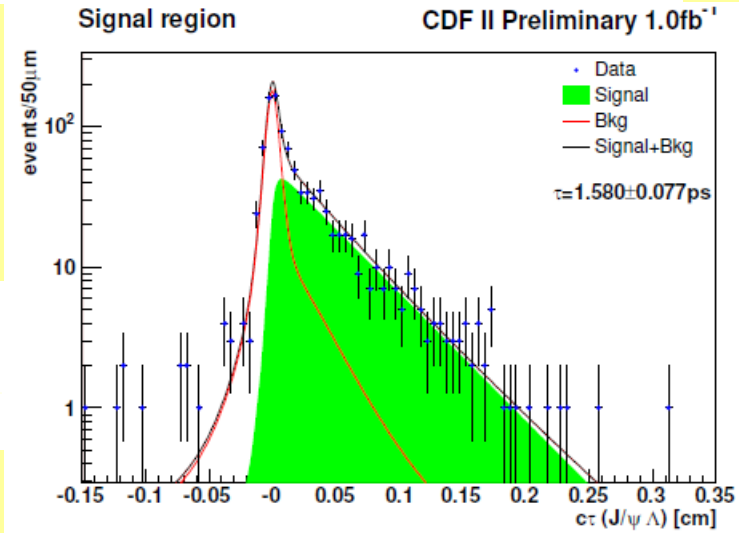


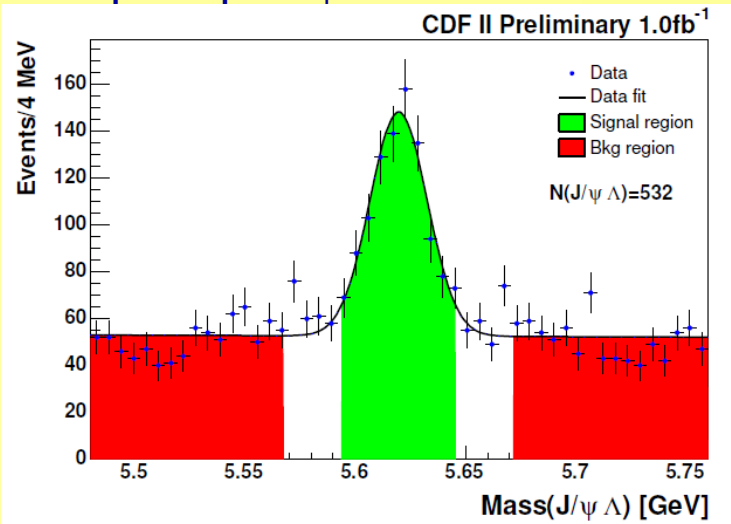
Λ_b Lifetime

Λ_b Lifetime: $\Lambda_b \rightarrow J/\psi\ \Lambda$, $\Lambda \rightarrow p\pi^-$

- $B^0 \rightarrow J/\psi\ K_s^0$, $B^0 \rightarrow J/\psi\ K^{*0}$, $B^+ \rightarrow J/\psi\ K^+$ measured to control systematics
- J/ψ trigger
- Rectangular cuts used to select J/ψ candidates and Λ (or K_s) candidates, avoiding bias from Λ lifetime
- Use J/ψ to determine decay vertex
- Use a prompt J/ψ sample to extract resolution function and apply to non-prompt J/ψ vertices







$$ct = L_{xy}\frac{M_B}{p_T}$$

$$c\tau(\Lambda_b) = 473.8 \pm 23.1(stat.) \pm 3.48(syst.)\mu m$$

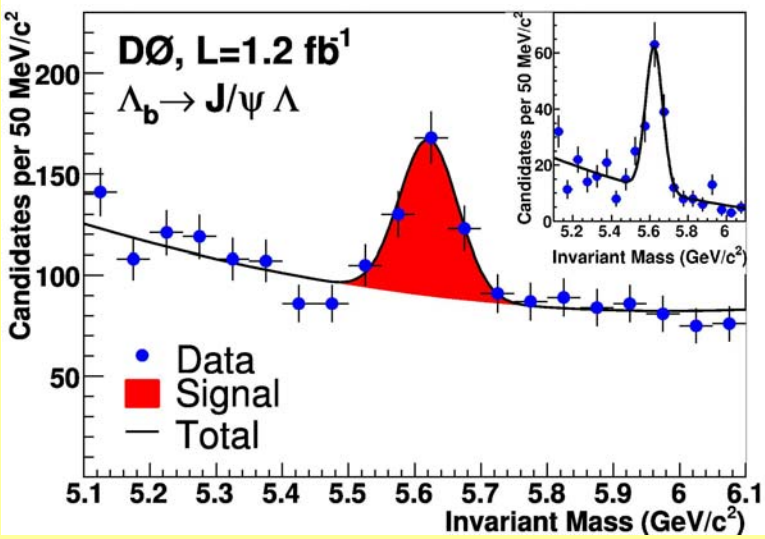
$$\tau(\Lambda_b) = 1.580 \pm 0.077\ (\text{stat.}) \pm 0.012\ (\text{syst.})\text{ps}$$

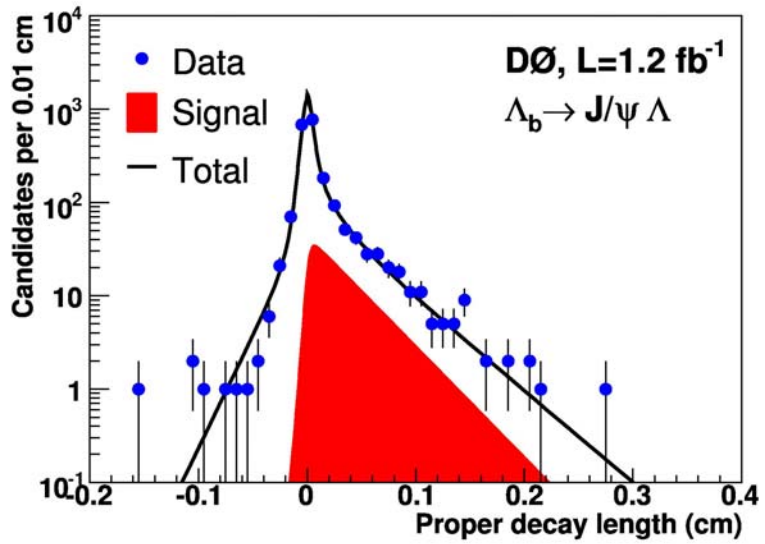
$$\tau(\Lambda_b)/\tau(B^0) = 1.018 \pm 0.062\ (\text{stat.}) \pm 0.007\ (\text{syst.})$$

http://www-cdf.fnal.gov/physics/new/bottom/061130.blessed-bh-lifetime_v2/

Λ_b Lifetime: $\Lambda_b \rightarrow J/\psi\ \Lambda$, $\Lambda \rightarrow p\pi^-$

PRL **99**, 142001 (2007)





- Triggers with no IP cuts; most are dimuon or single muon triggers
- Simultaneous unbinned maximum likelihood fit to the mass and PDL
- Systematic uncertainties from alignment, distribution models, long-lived components, and contamination
- Measure ratio w/r/t $B^0 \rightarrow J/\psi\ K^0_s$
  - Similar topology
  - Cross checks

$$c\tau(\Lambda_b) = 365.1^{+39.1}_{-34.7}(\text{stat}) \pm 12.7(\text{syst})\ \mu\text{m}$$

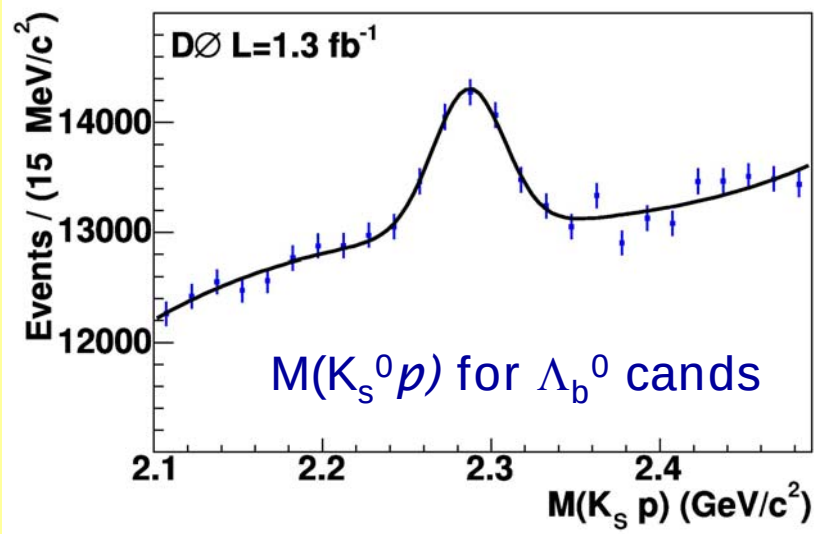
$$\tau(\Lambda_b) = 1.218^{+0.130}_{-0.115}(\text{stat}) \pm 0.042(\text{syst})\ \text{ps}$$

$$\frac{\tau(\Lambda_b)}{\tau(B^0)} = 0.811^{+0.096}_{-0.087}(\text{stat}) \pm 0.034(\text{syst})$$

Λ_b Lifetime: $\Lambda_b \rightarrow \mu\nu\Lambda_c^+X$, $\Lambda_c^+ \rightarrow K^0_s p$

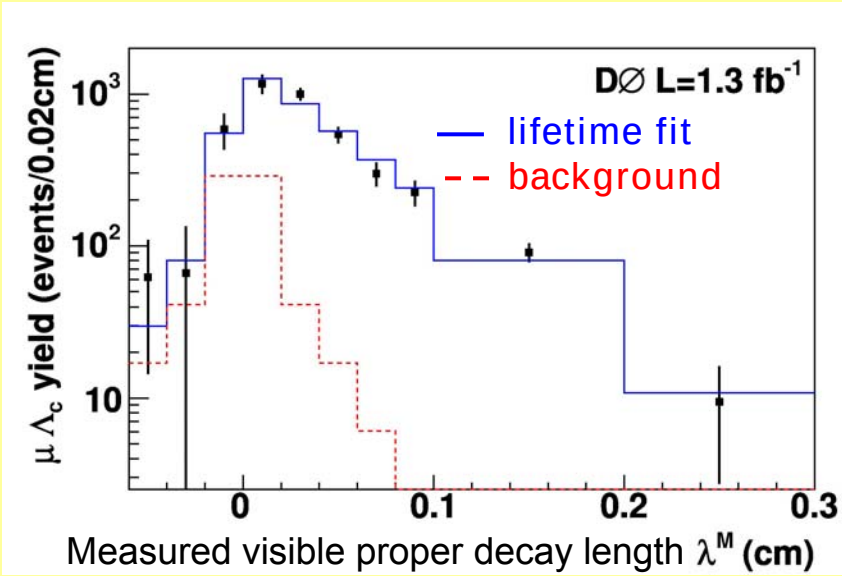
- Semileptonic Decay
- Inclusive single muon trigger
  - No impact parameter cuts
- MC used to correct for the unreconstructed neutrino
- Yield measured in bins of ct
- Yield: 4437±329(stat) candidates

PRL **99**, 182001 (2007)



$c\tau(\Lambda_b^0)=386.7^{+35.7}_{-32.9}(\text{stat})\,^{+26.1}_{-27.3}(\text{sys})\ \mu\text{m}$

$$\tau(\Lambda_b^0) = 1.290^{+0.119}_{-0.110}(\text{stat})^{+0.087}_{-0.091}(\text{syst})\ \text{ps}$$



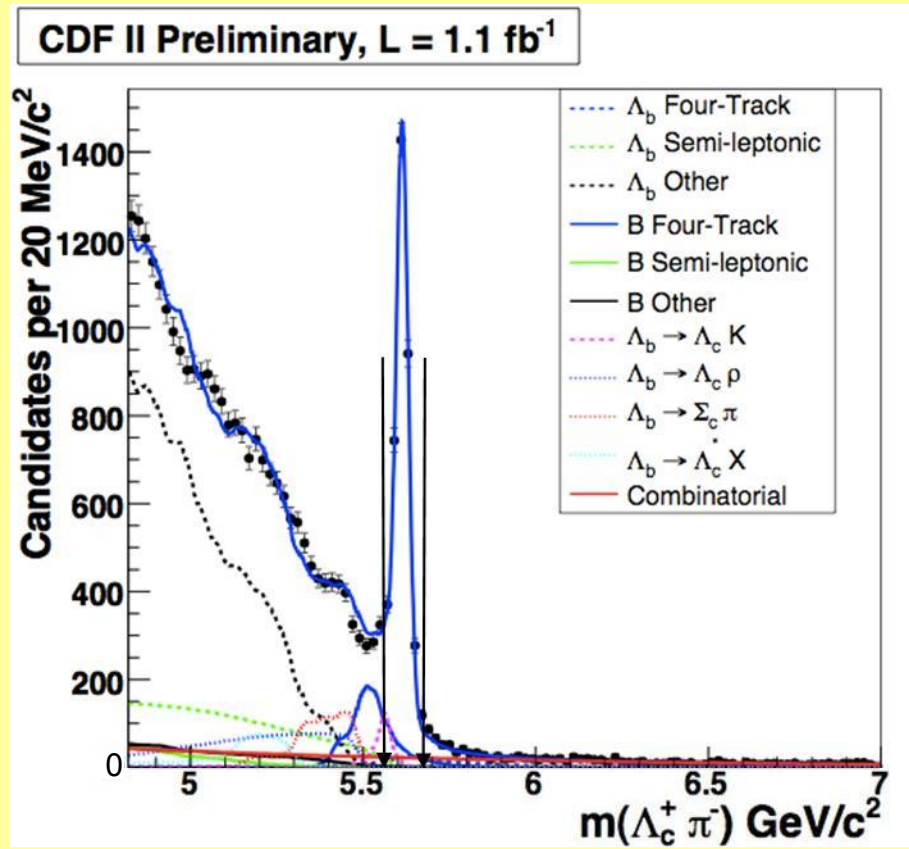
Combined result with D0 $\Lambda_b \rightarrow J/\psi\ \Lambda$:

$c\tau(\Lambda_b^0)=375.0^{+30.6}_{-28.8}\ \mu\text{m}$

$$\tau(\Lambda_b^0) = 1.251^{+0.102}_{-0.096}\ \text{ps}$$

Λ_b Lifetime: $\Lambda_b \rightarrow \Lambda_c \pi$, $\Lambda_c^+ \rightarrow p^+ K^- \pi^+$

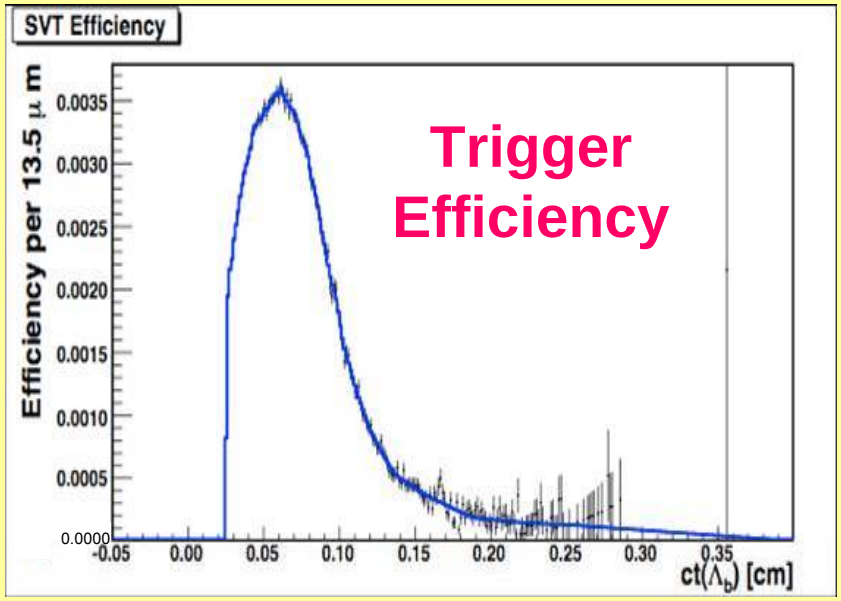
- Use large signal $\Lambda^0_b \rightarrow \Lambda^+_c \pi^-$ from the displaced vertex trigger
- $5.565 < M(\Lambda^+_c \pi^-) < 5.67$ GeV/c^2
- Λ^0_b yield: 2927 ± 58 events
- Take into account lifetime bias due to displaced vertex trigger



http://www-cdf.fnal.gov/physics/new/bottom/090416.blessed-lblcpi-ct/

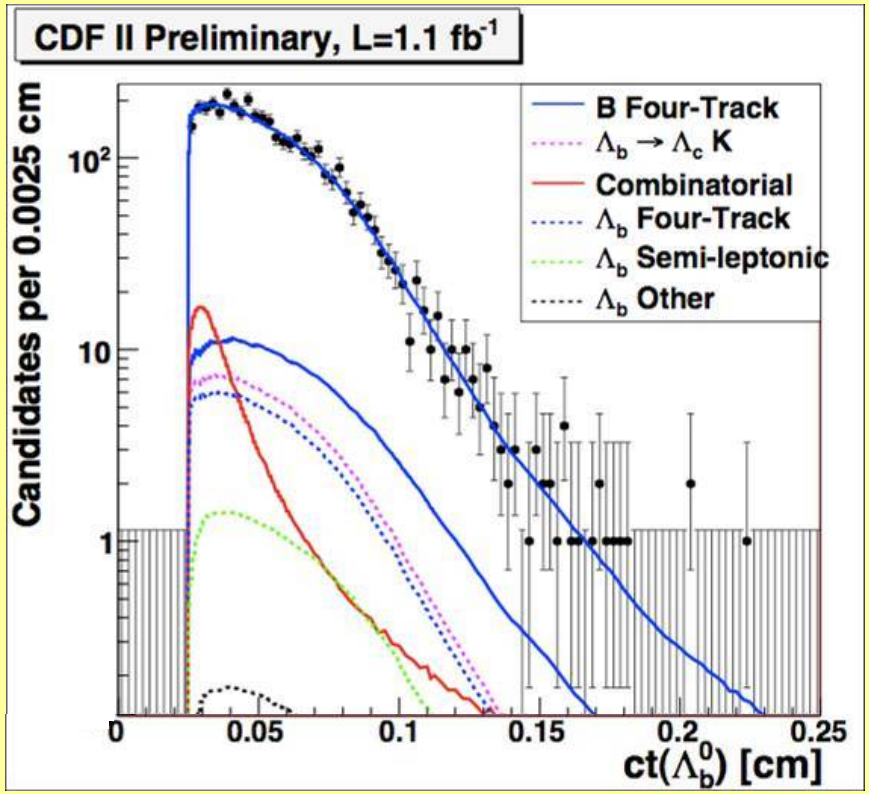
Λ_b Lifetime: $\Lambda_b \rightarrow \Lambda_c \pi$, $\Lambda_c \rightarrow p^+ K^- \pi^+$ (2)

- Use MC to extract trigger efficiency distribution



Systematics are dominated by MC model of trigger efficiency and decay

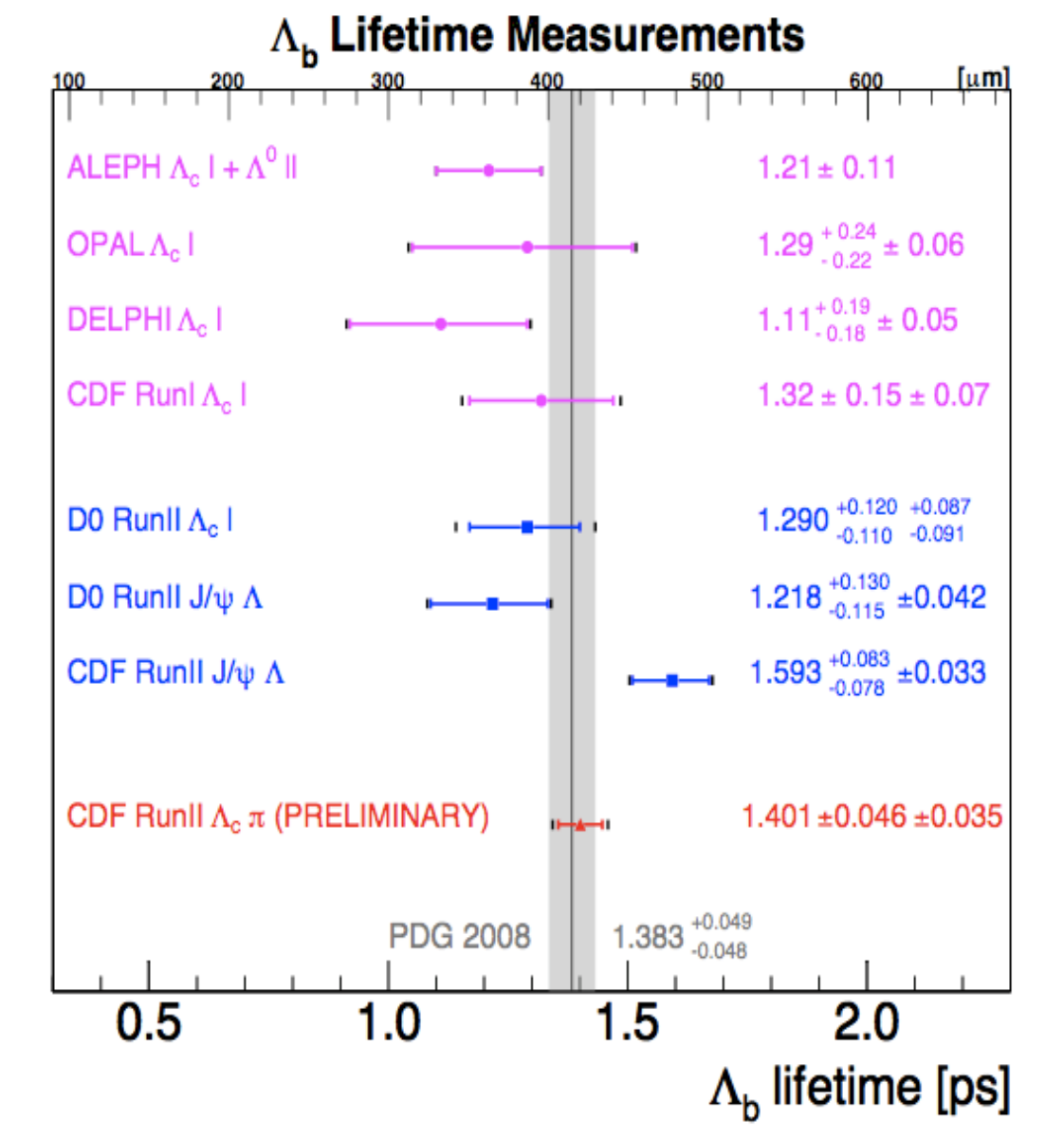
- Fit exponential convoluted with trigger efficiency and detector resolution function



$c\tau(\Lambda_b)$=420.0±13.8(stat)±10.5(syst) μm

$\tau(\Lambda_b^0) = 1.401 \pm 0.046\ (\text{stat}) \pm 0.035\ (\text{syst})$ ps

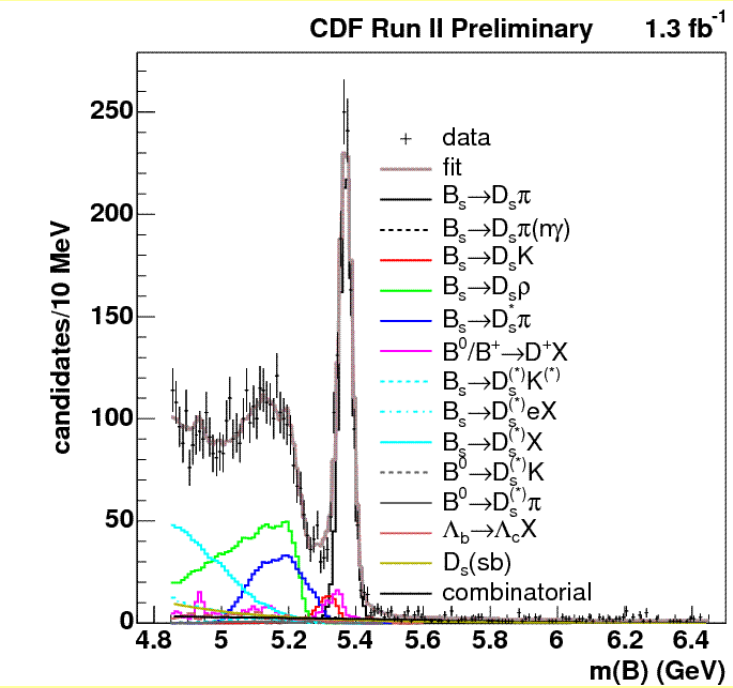
Comparison with other experiments



B_s Lifetime

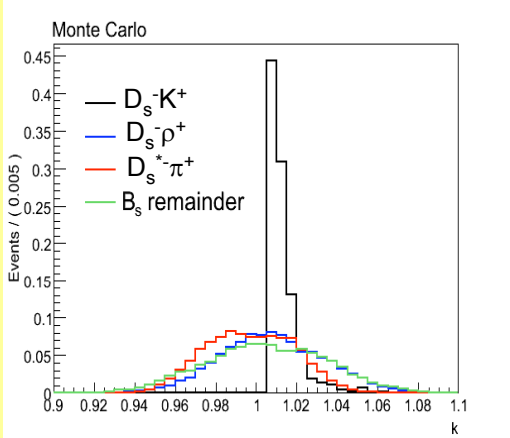
B_s Lifetime: Hadronic Modes

- Displaced track trigger
- Partially and Fully Reconstructed B_s Modes:
  - Fully: $B_s \rightarrow D_s^-(\phi\pi^-)\pi^+$
  - Partially: $B_s \rightarrow D_s^-\rho^+(\pi^+\pi^0)$; $B_s \rightarrow D_s^-K^+$; $B_s \rightarrow D_s^{*-}\pi^+$
    - Double statistics!



- MC used to quantify the effect of partially reconstructed modes
  - "K" factor accounts for missing momentum and mass:

$$ct \equiv \frac{L_{xy} \cdot m_B^{rec}}{p_{T_B}} \cdot K$$

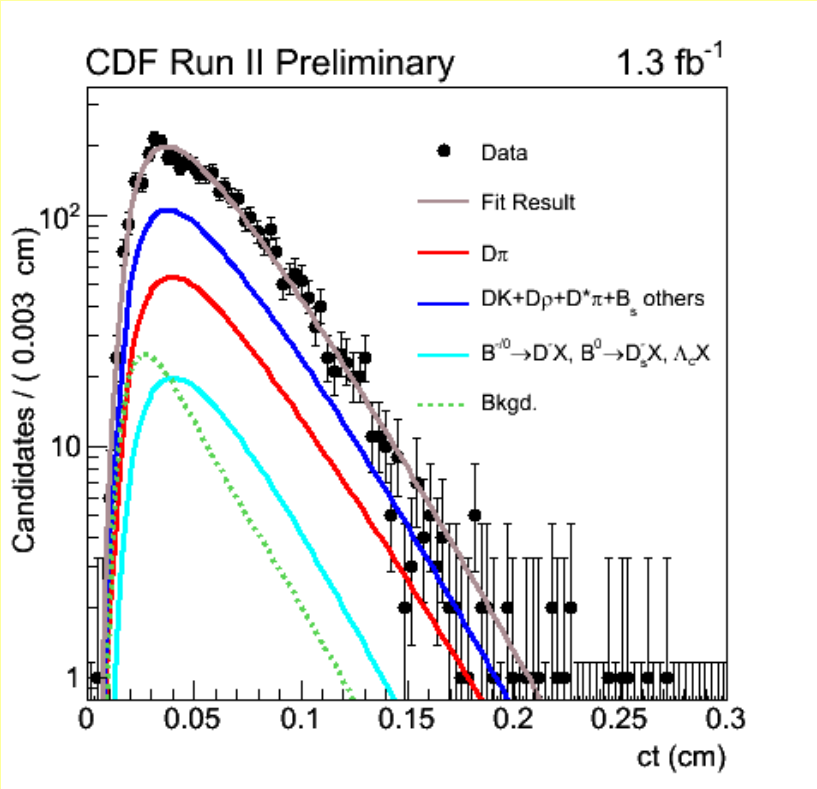


- Several control samples used for lifetime validation and calibration
  - $B^0 \rightarrow D^-(K^+\pi^-\pi^-)\pi^+$
  - $B^0 \rightarrow D^{*-}[D^0(K^+\pi^-)\pi^-]\pi^+$
  - $B^+ \rightarrow D^0(K^+\pi^-)\pi^+$

http://www-cdf.fnal.gov/physics/new/bottom/080207.blessed-bs-lifetime/

B_s Lifetime: Hadronic Modes (2)

- Effect of trigger on ct distribution is evident
- The effect of the displace vertex trigger is taken into account using "trigger efficiency" curve from MC



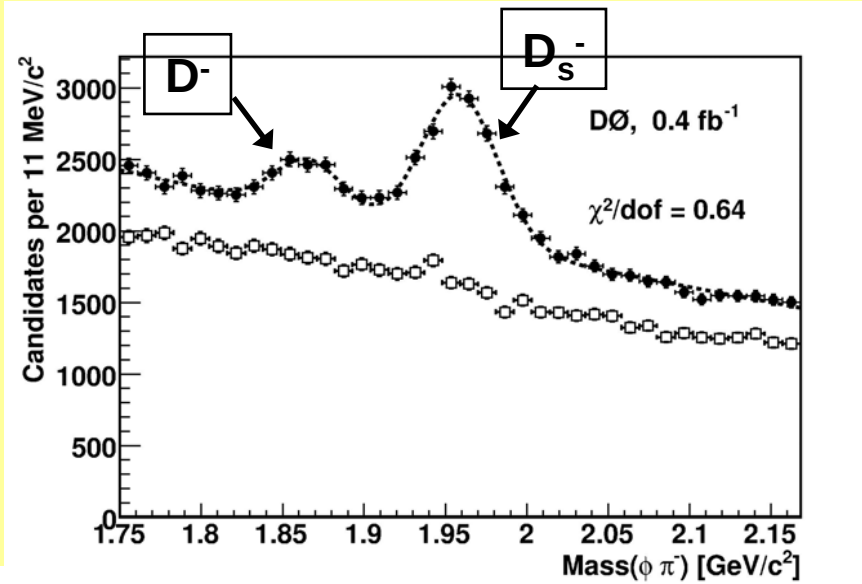
$$c\tau(B_s \to D_s^-(\phi\pi^-)\pi^+) = 455.0 \pm 12.2(\text{stat.}) \pm 8.2(\text{syst.})\ \mu\text{m}$$

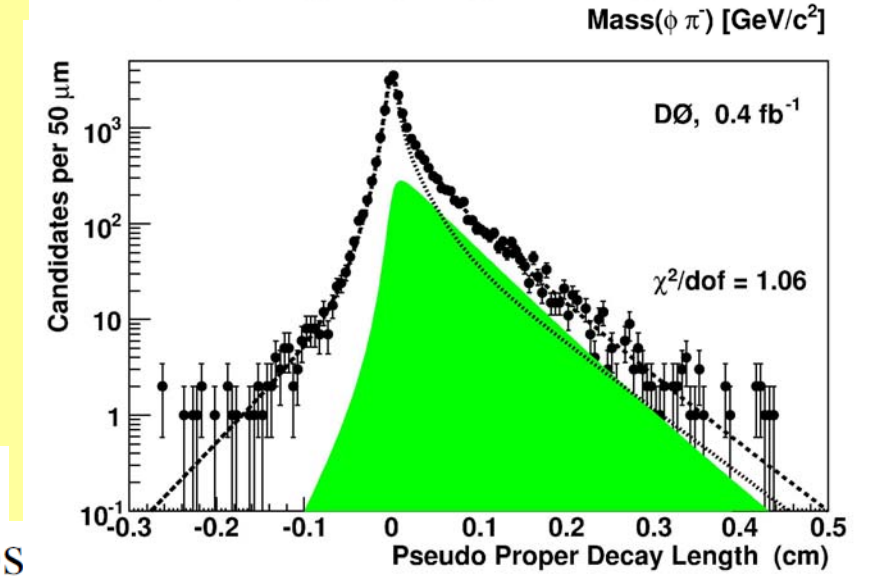
$\tau(B_s^0 \rightarrow D_s^-(\phi\pi^-)\pi^+)$=1.52± 0.04(stat)± 0.03(syst) ps

http://www-cdf.fnal.gov/physics/new/bottom/080207.blessed-bs-lifetime/

B_s Lifetime: $B_s^0 \rightarrow D_s^- \mu^+ \nu X$, $D_s^- \rightarrow \phi \pi^-$

- Semileptonic final state
- Partially reconstructed
- Inclusive single muon trigger
  - No impact parameter cuts
- Monte Carlo used to determine K-factor to correct for the unreconstructed neutrino: $K = p_T(D_s^- \mu^+)/p_T(B_s^0)$





$c\tau(B_s^0) = 419.1 \pm 13.2\,(\text{stat})\,^{+8.4}_{-7.5}\,(\text{syst})\ \mu\text{m}$

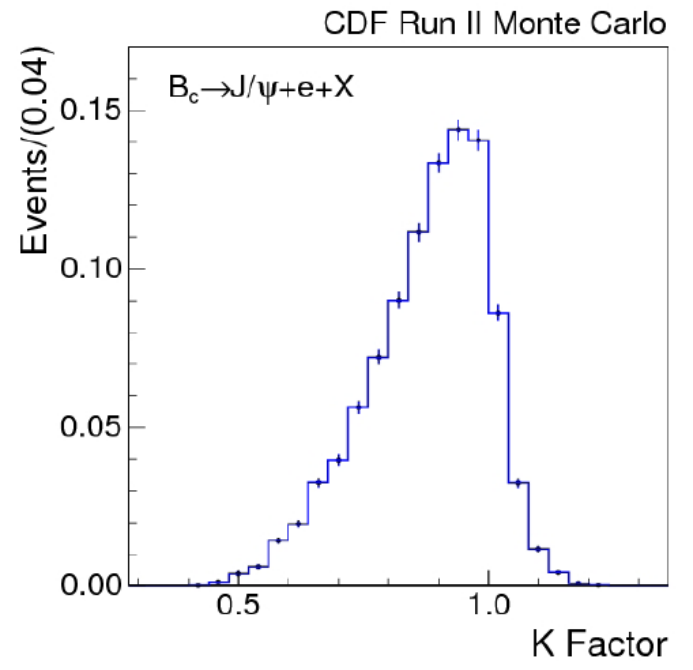
$\tau(B_s^0) = 1.398 \pm 0.044(\text{stat})^{+0.028}_{-0.025}(\text{syst})\ \text{ps}$

PRL **97**, 241801 (2006)

B_c Lifetime, Mass, Cross section

B_c Lifetime: $B_c \rightarrow J/\psi\mu+X$ and $B_c \rightarrow J/\psi e+X$

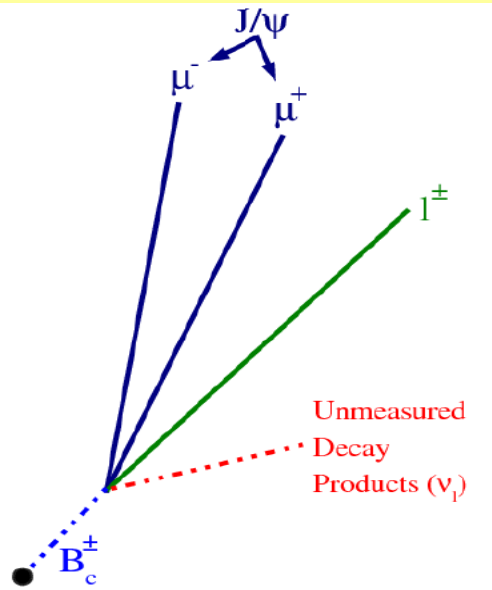
- J/ψ trigger (semileptonic decay)
- Scale K factor determined by MC to account for unreconstructed particles – missing momentum, correct pseudo-lifetime



$$ct = \mathbf{K} \times ct^*$$

$$ct^* = \frac{M(B_c)\, L_{xy}(J/\psi + l)}{p_T(J/\psi + l)}$$

$$\mathbf{K} = p_T(J/\psi\ l) / p_T(B_c)$$

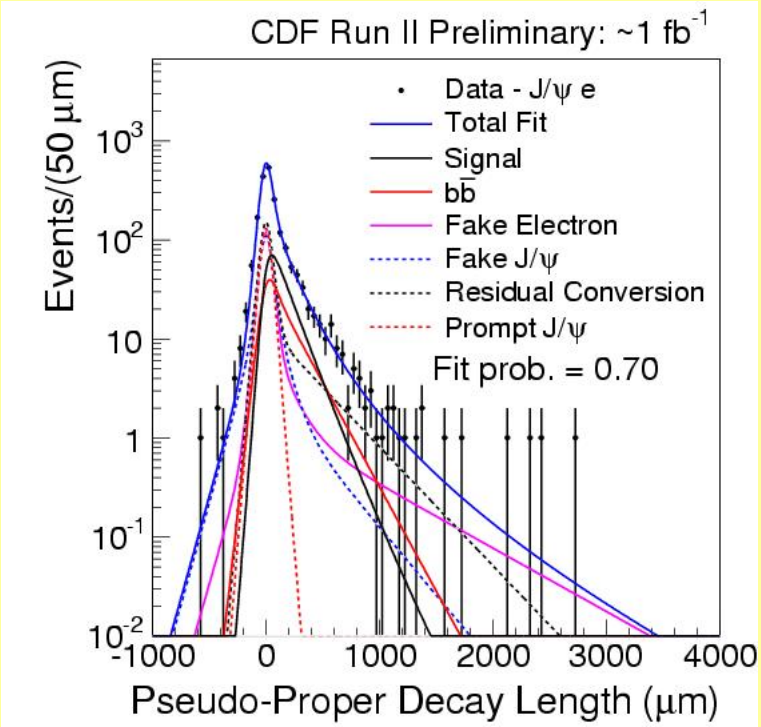


Main challenge is multiple backgrounds:

- real J/Ψ + fake lepton / fake J/Ψ + real lepton
- real J/Ψ + real lepton → from bb events
- prompt J/Ψ + lepton
- residual conversion (J/ψ+e only)

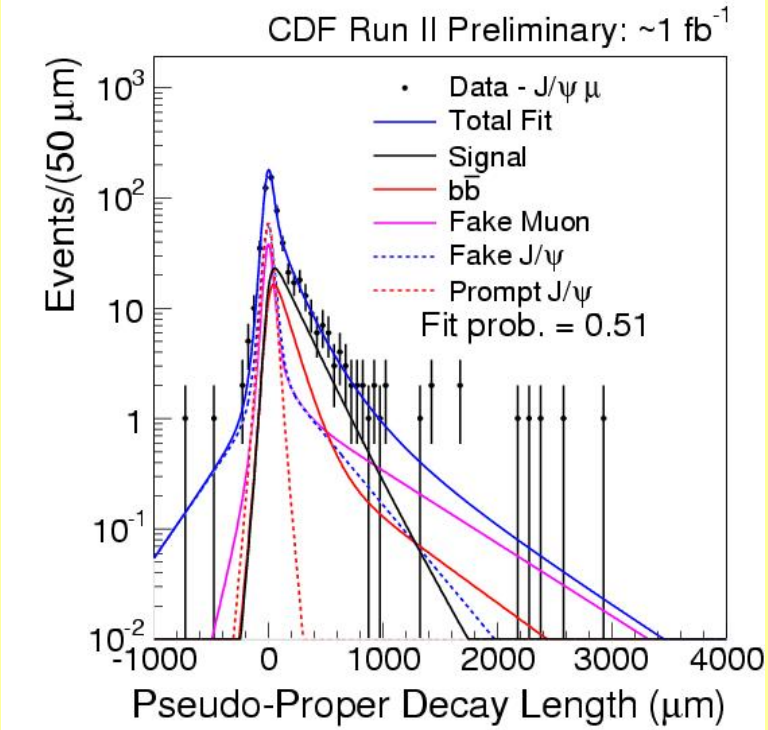
http://www-cdf.fnal.gov/physics/new/bottom/080327.blessed-BC_LT_SemiLeptonic/

B_c Lifetime: $B_c \rightarrow J/\psi\mu + X$ and $B_c \rightarrow J/\psi e + X$ (2)



Electron Channel

$$c\tau_e = 121.7^{+18.0}_{-16.3}\ (\text{stat.})\ \mu\text{m}$$



Muon Channel

$$c\tau_\mu = 179.1^{+32.6}_{-27.2}\ (\text{stat.})\ \mu\text{m}$$

Combined measurement using likelihood:

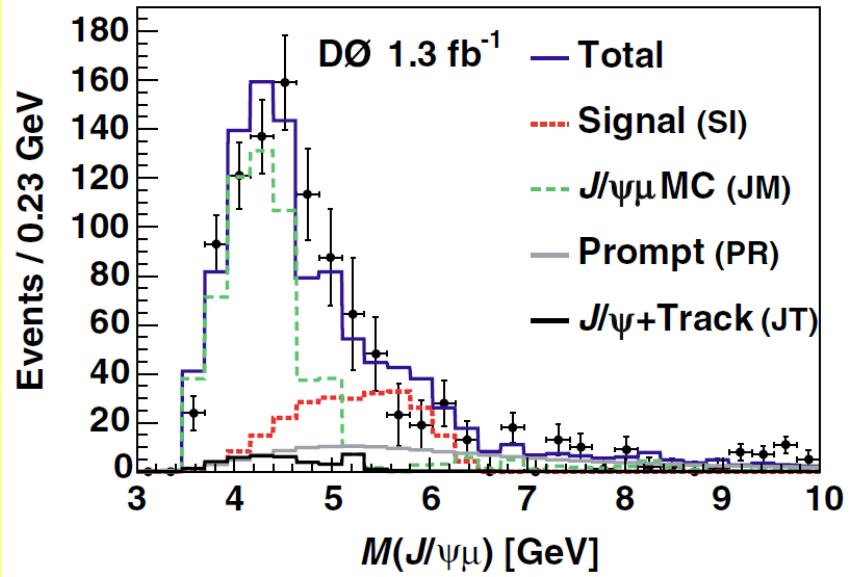
$$c\tau = 142.5^{+15.8}_{-14.8}\ (\text{stat.}) \pm 5.5\ (\text{syst.})\ \mu\text{m}$$

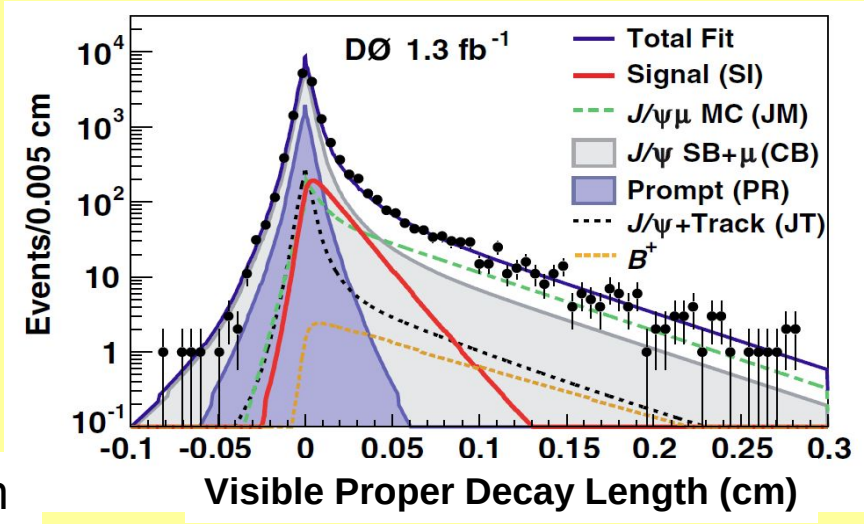
$\tau = 0.475^{+0.053}_{-0.050}$ (stat) ± 0.018 (syst) ps

http://www-cdf.fnal.gov/physics/new/bottom/080327.blessed-BC_LT_SemiLeptonic/

B_c Lifetime: $B_c \rightarrow J/\psi\mu + X$

- Semileptonic decay
- Single muon trigger – no IP cut
- K factor distribution from MC used to correct for unreconstructed particle
- Mass – lifetime simultaneous fit used to extract the small B_c signal among large fractions of backgrounds
- Yield: 881 ± 80 (stat)





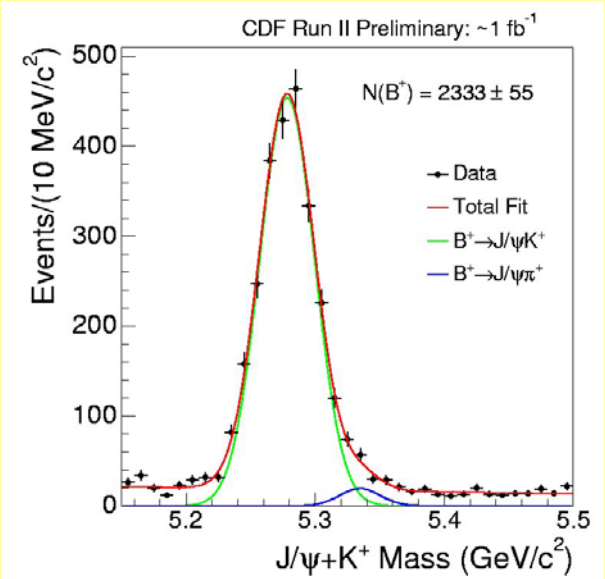
$c\tau(B_c) = 134.3\ ^{+11.4}_{-10.8}(\text{stat}) \pm 9.59\ (\text{syst})\ \mu\text{m}$

$$\tau(B_c^{\pm}) = 0.448^{+0.038}_{-0.036}(\text{stat}) \pm 0.032(\text{syst})\ \text{ps}$$

PRL **102**, 092001 (2009)

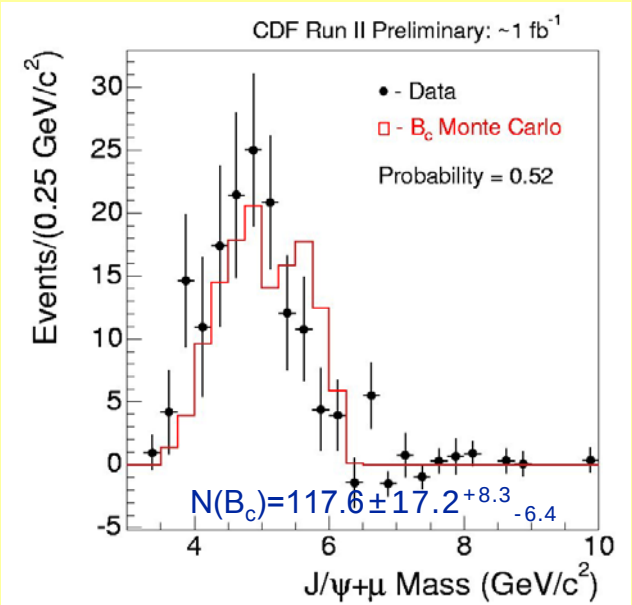
$B^+_c \rightarrow J/\psi\mu+\nu$ Cross section

$$\frac{\sigma(B_c^+)\cdot BR(B_c^+ \rightarrow J/\psi+\mu^+ +\nu)}{\sigma(B^+)\cdot BR(B^+ \rightarrow J/\psi+K^+)} = \frac{N_{B_c^+}}{N_{B^+}} \times \epsilon_{rel}$$



Need to model B^+, B^+_c p_T spectra to calculate relative efficiency between decays

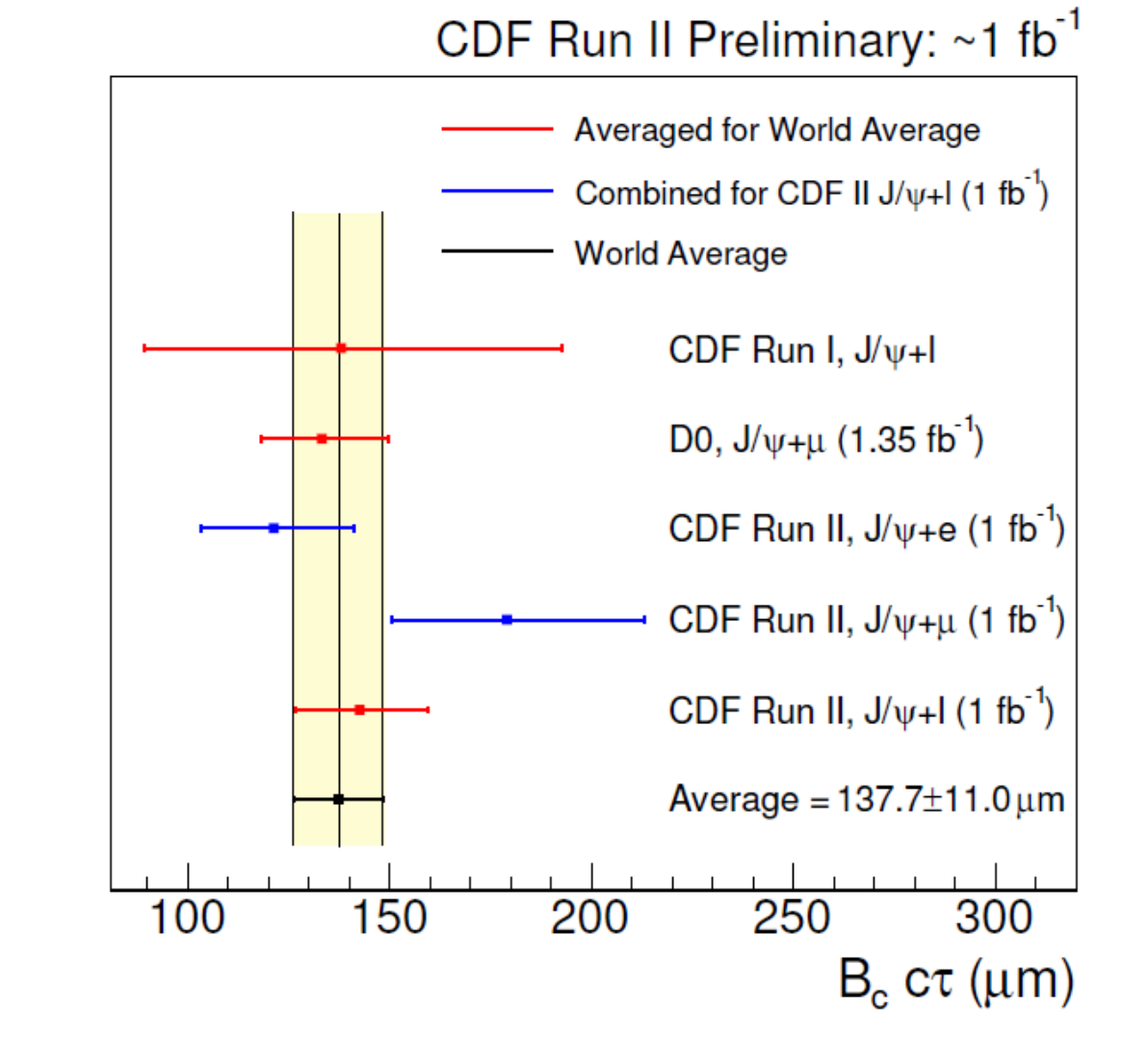
Backgrounds:
- Misidentified J/ψ
- Misidentified muons
- bb background
- other b hadrons



$p_T(B)$ value	$R = \frac{\sigma(B_c^+)\cdot BR(B_c^+ \rightarrow J/\psi+\mu^+ +\nu)}{\sigma(B^+)\cdot BR(B^+ \rightarrow J/\psi+K^+)}$
$p_T(B) > 4\ GeV/c$	$0.295 \pm 0.040(\text{stat})^{+0.033}_{-0.026}(\text{sys}) \pm 0.036(p_T \text{ spectrum})$
$p_T(B) > 6\ GeV/c$	$0.227 \pm 0.033(\text{stat})^{+0.024}_{-0.017}(\text{sys}) \pm 0.014(p_T \text{ spectrum})$

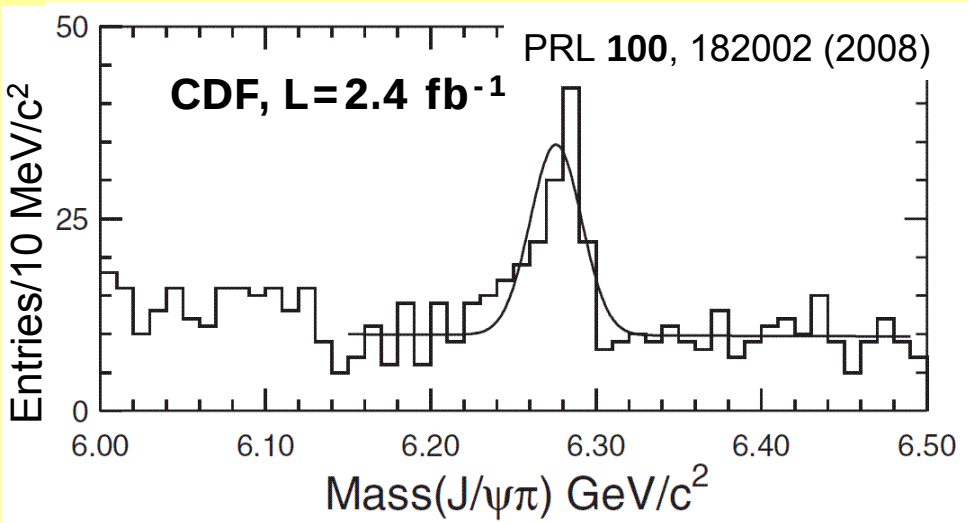
http://www-cdf.fnal.gov/physics/new/bottom/090305.blessed-bc-slXsec/

B_c Lifetime Summary

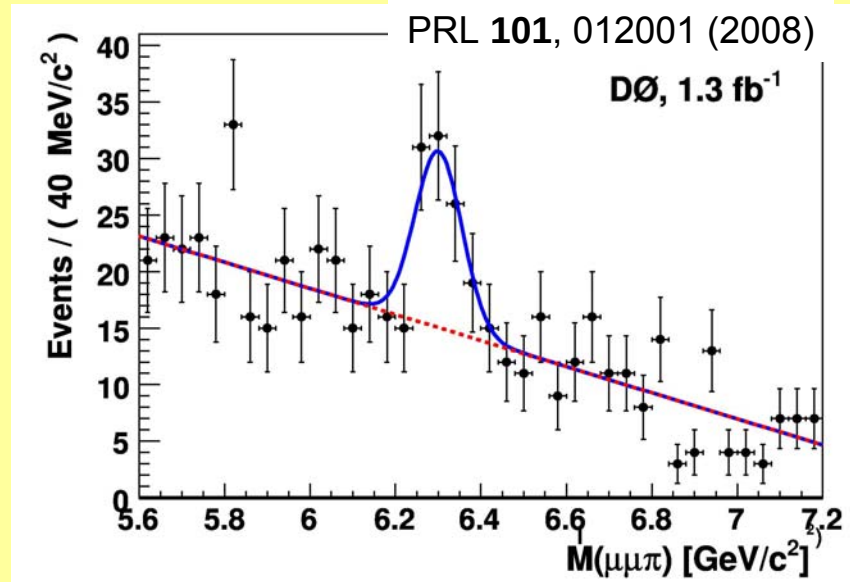


B^+_c Mass using $B_c \rightarrow J/\psi\ \pi$

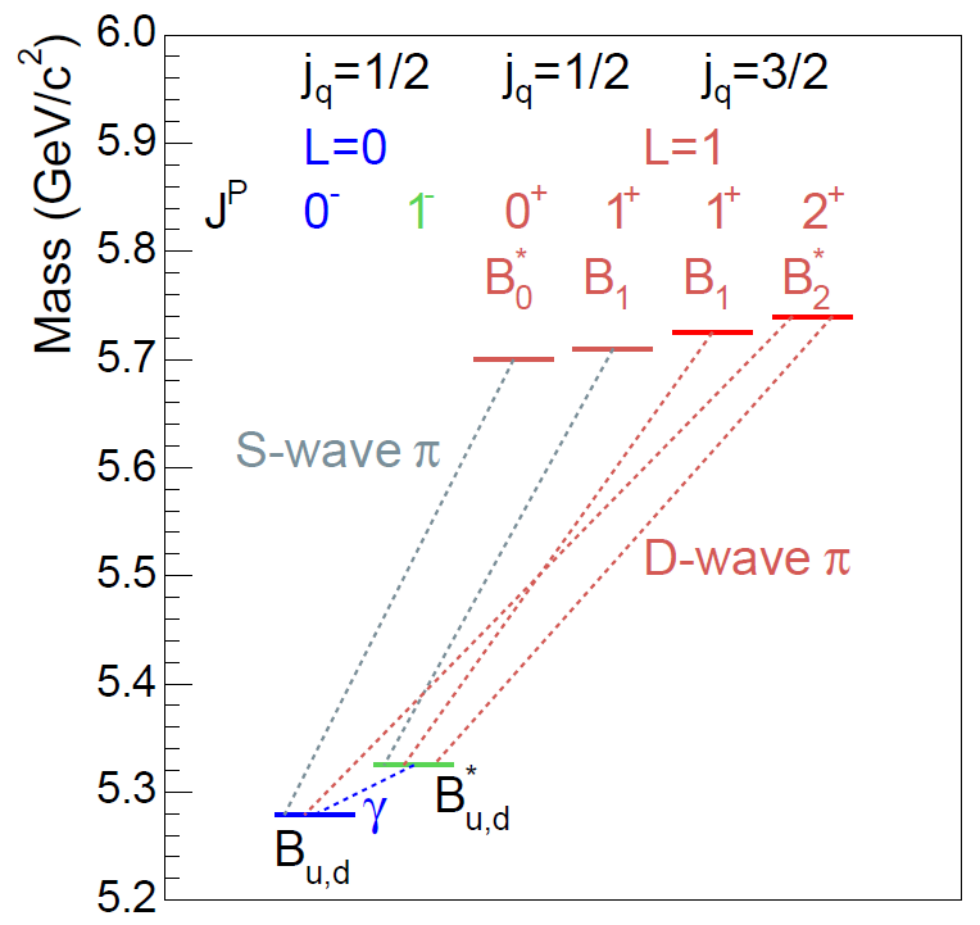
- Cuts optimized for $B^+ \rightarrow J/\psi K^+$ selection
- Backgrounds:
  - Combinatorial
  - Cabibbo-suppressed $B^+_c \rightarrow J/\psi K^+$
- $80 < ct < 300\ \mu m$
- Signal of 108 ± 15 B_c candidates with significance of 8σ
- First Observation in this mode



$M(B_c)=6275.6 \pm 2.9(stat) \pm 2.5(syst)$ MeV/c²



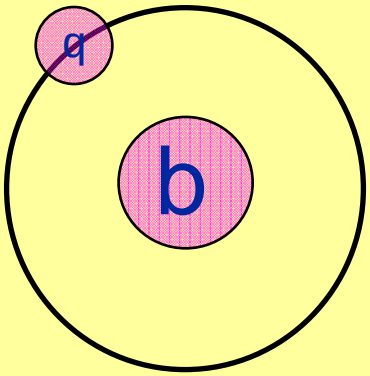
- All muon triggers considered
- Rectangular cuts
- Unbinned log likelihood fit
- Signal of 54 ± 12 Candidates with a significance of 5.2σ
- $M(B_c)=6300 \pm 14(stat) \pm 5(syst)$ MeV/c²
- Primary systematic from selection criteria – mostly π kinematic cut



Excited States

Orbitally (L=1) Excited B^0 Mesons

Heavy-light quark meson is similar to the hydrogen atom in understanding QED



Spin of b quark: $j_b=1/2$

j_q=1/2 states		
Particle Name	**J**	**Decay Mode(s)**
B_0^*	0	Broad Resonance
B_1'	1	Broad Resonance
j_q=3/2 states		
B_1	1	$B_1 \to B^{*+}\pi^-$, $B^{*+} \to B^+\gamma$
B_2^*	2	$B_2^* \to B^+\pi^-$ $B_2^* \to B^{*+}\pi^-$, $B^{*+} \to B^+\gamma$

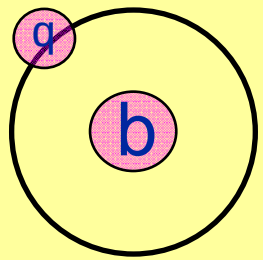
S-wave decay

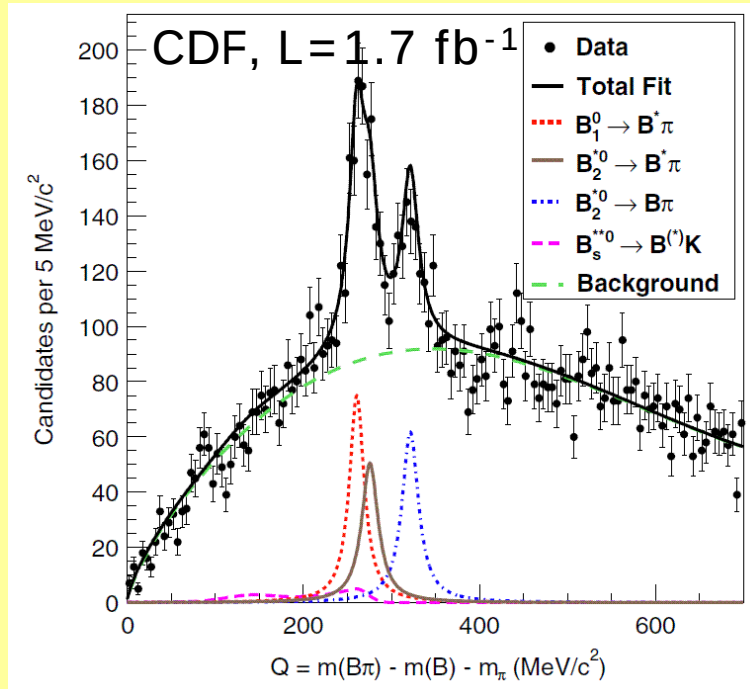
Narrow Resonances
D-wave decay

(γ not reconstructed in $B^* \to B\gamma$ decay)

Orbitally Excited (L=1) B^0 Mesons

j_q=3/2 states		
Particle Name	**J**	**Decay Mode(s)**
B_1	1	$B_1 \to B^{*+}\pi^-$, $B^{*+} \to B^+\gamma$
B_2^*	2	$B_2^* \to B^+\pi^-$ $B_2^* \to B^{*+}\pi^-$, $B^{*+} \to B^+\gamma$





- $B^+ \to J/\psi K^+$, $J/\psi \to \mu\mu$
  - Dimuon trigger
- $B^+ \to D^0(3)\pi^+$, $D^0 \to K^+\pi^-$
  - Two track Trigger
- B^+ selection based on Neural Network which combines topological, kinematic, and particle identification
- B** candidates are selected using additional Neural Networks

$$N(B_2^{*0} \to B^+\pi^-) = 385^{+48}_{-45}\ (\text{stat.})$$

$$N(B_2^{*0} \to B^{*+}\pi^-) = 351^{+48}_{-45}\ (\text{stat.})$$

$$N(B_1^0 \to B^*\pi) = 503^{+75}_{-68}\ (\text{stat.})$$

$$m(B_1^0) = 5725.3^{+1.6}_{-2.2}\ (\text{stat.})\ ^{+1.4}_{-1.5}\ (\text{syst.})\ \text{MeV/c}^2$$

$$m(B_2^{*0}) = 5740.2^{+1.7}_{-1.8}\ (\text{stat.})\ ^{+0.9}_{-0.8}\ (\text{syst.})\ \text{MeV/c}^2$$

$$\Gamma(B_2^{*0}) = 22.7^{+3.8}_{-3.2}\ (\text{stat.})\ ^{+3.2}_{-10.2}\ (\text{syst.})\ \text{MeV/c}^2$$

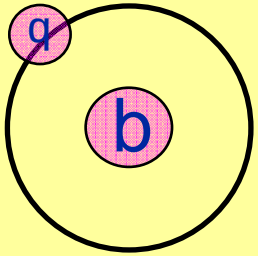
Most precise mass measurements of these states

First measurement of B_2^{*0} width

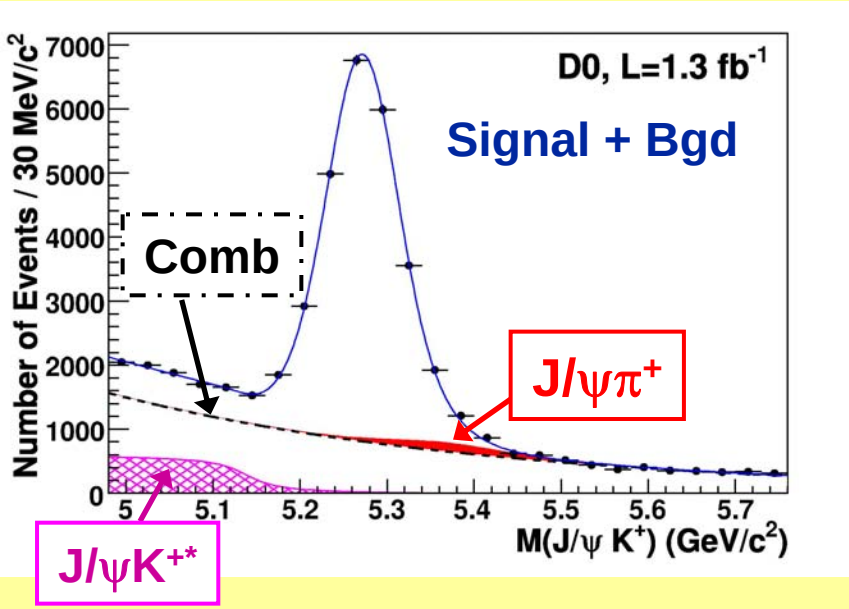
PRL 102, 102003 (2009)

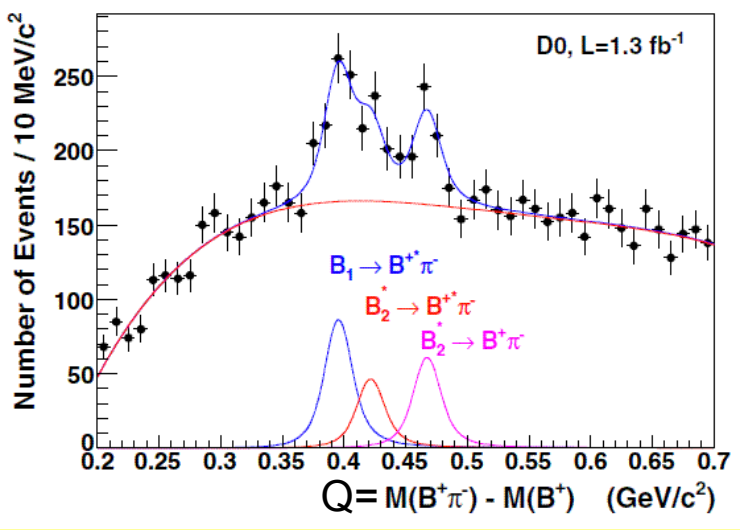
Orbitally Excited (L=1) B^0 Mesons

j_q=3/2 states		
Particle Name	**J**	**Decay Mode(s)**
B_1	1	$B_1 \to B^{*+}\pi^-$, $B^{*+} \to B^+\gamma$
B_2^*	2	$B_2^* \to B^+\pi^-$ $B_2^* \to B^{*+}\pi^-$, $B^{*+} \to B^+\gamma$



- B^+ is reconstructed in the exclusive decay $B^+ \to J/\psi K^+$, $J/\psi \to \mu\mu$
- Backgrounds:
  - $B^+ \to J/\psi\pi^+$, $B^+ \to J/\psi K^{+*}$
  - Combinatorial





$$M(B_1) = 5720.6 \pm 2.4 \pm 1.4 \text{ MeV}/c^2$$

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

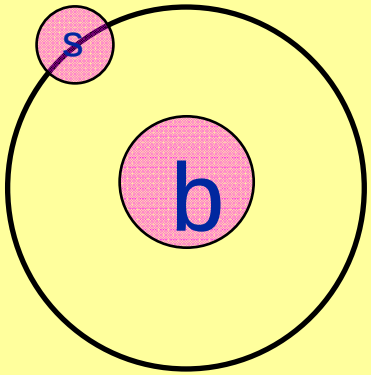
PRL 99, 172001 (2007)

B_1 and B_2^* production rate is (13.9±1.9±3.2)% the production rate of B^+ meson

Orbitally (L=1) Excited B_s Mesons

Spin of b quark: j_b=1/2

Spin of s quark: j_s=1/2, 3/2



j_s=1/2 states		
Particle Name	**J**	**Decay Mode(s)**
B_0^*	0	Broad Resonance
B_1'	1	Broad Resonance
j_s=3/2 states		
B_{s1}	1	$B_{s1} \to B^{*+}K^-$, $B^{*+} \to B^+\gamma$
B_{s2}^*	2	$B_{s2}^* \to B^+K^-$ $B_{s2}^* \to B^{*+}K^-$, $B^{*+} \to B^+\gamma$

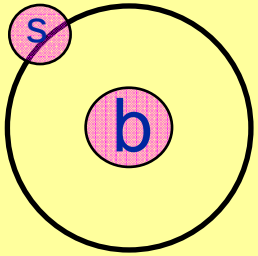
S-wave decay

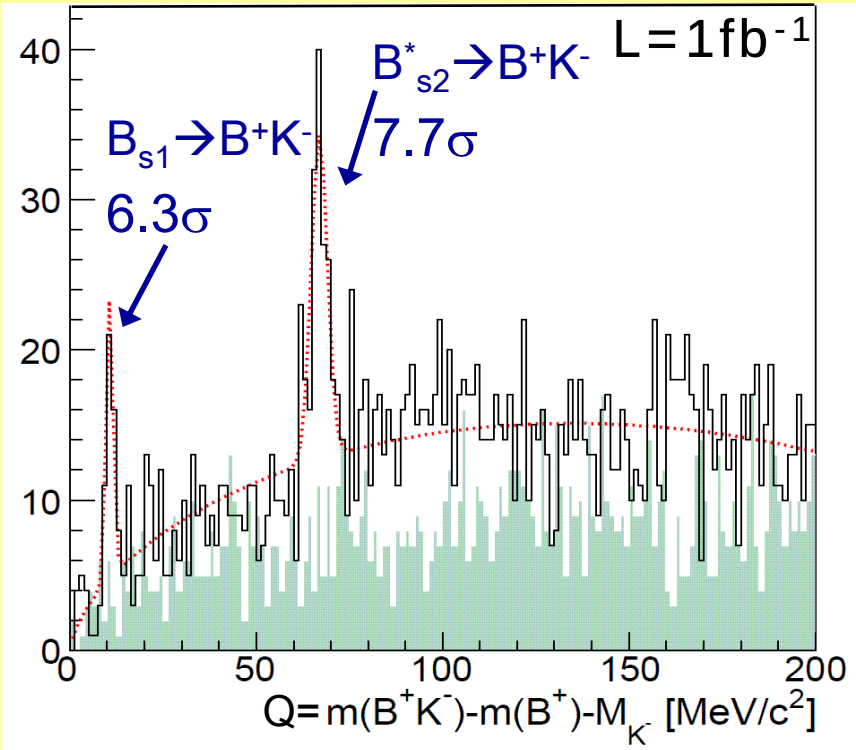
Narrow Resonances
D-wave decay

(γ not reconstructed in $B^* \to B\gamma$ decay)

Orbitally Excited (L=1) B_s Mesons

j_s=3/2 states		
Particle Name	**J**	**Decay Mode(s)**
B_{s1}	1	$B_{s1} \to B^{*+}K^-$, $B^{*+} \to B^+\gamma$
B_{s2}^*	2	$B_{s2}^* \to B^+K^-$ $B_{s2}^* \to B^{*+}K^-$, $B^{*+} \to B^+\gamma$





- B^+ is reconstructed in
  - $B^+ \to J/\psi K^+$, $J/\psi \to \mu\mu$
    - J/ψ trigger
  - $B^+ \to D^0\pi^+$, $D^0 \to K^+p^-$
    - Displaced vertex trigger
- B^+ and B_s^{**} selection based on Neural Network which combines topological, kinematic, and particle identification

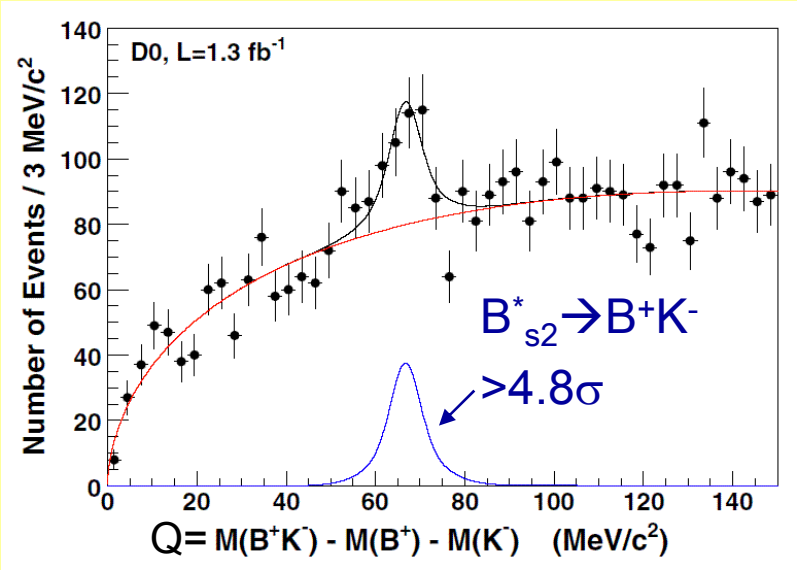
$$m(B_{s1}) = 5829.4 \pm 0.7\,\mathrm{MeV}/c^2$$
$$m(B_{s2}^*) = 5839.6 \pm 0.7\,\mathrm{MeV}/c^2$$

PRL 100, 082001 (2008)

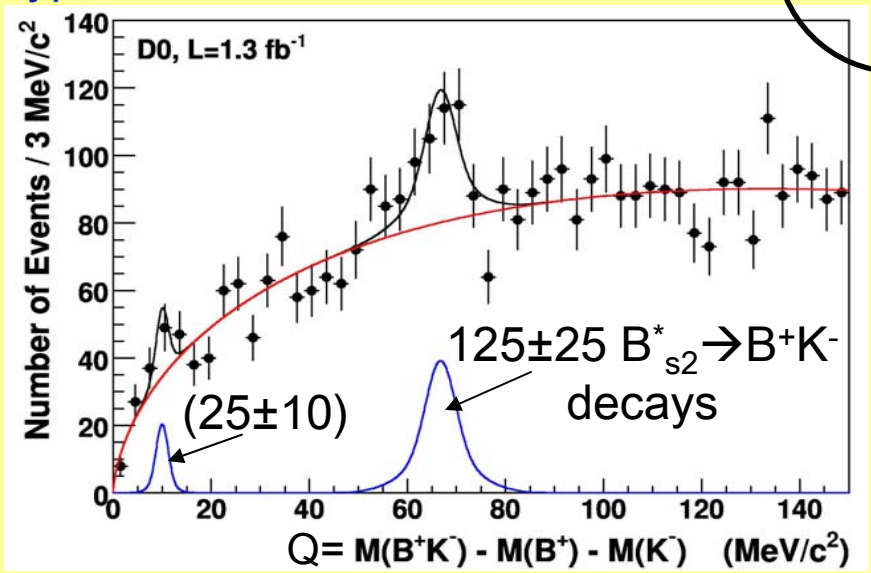
Orbitally (L=1) Excited B_s Mesons

j_s=3/2 states		
Particle Name	**J**	**Decay Mode(s)**
B_{s1}	1	$B_{s1} \to B^{*+}K^-$, $B^{*+} \to B^+\gamma$
B_{s2}^*	2	$B_{s2}^* \to B^+K^-$ $B_{s2}^* \to B^{*+}K^-$, $B^{*+} \to B^+\gamma$

- B^+ is reconstructed in
  - $B^+ \to J/\psi K^+$, $J/\psi \to \mu\mu$



To check for the presence of a B_{s1} signal, fit ΔM with two mass hypothesis



- Peak around Q=11.5±1.4(stat) MeV/c^2 has statistical significance less than 3σ

$$M(B^*_{s2}) = 5839.6 \pm 1.1 \pm 0.7 \text{ MeV}/c^2$$

B_{s2}^* production rate is (1.15±0.23±0.13)% the production rate of B^+ meson

PRL **100**, 082002 (2008)

Summary

- D0 and CDF have made lifetime measurements of the B_s, Λ_b, and B_c particles
- D0 and CDF have made measurements of the B_c mass
- D0 and CDF have observed B and B_s excited states

- We aren't done!
- We have more data on the way
- We are using more sophisticated techniques (hardware and analysis) to squeeze out as much signal from the data as we can

- Look forward to new and improved results soon!