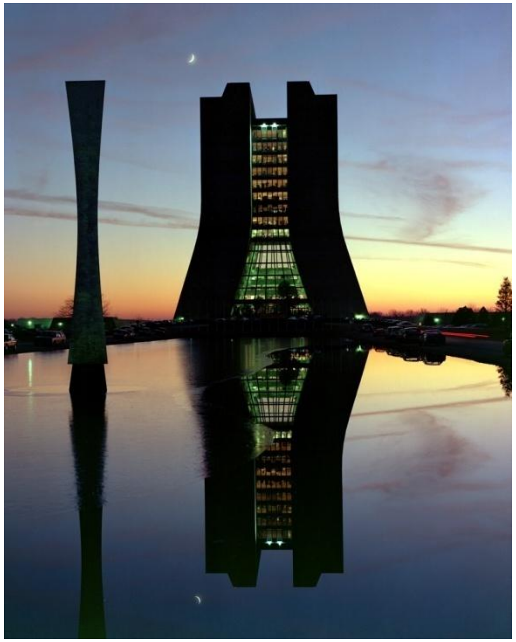


B- Hadron Spectroscopy and Lifetimes at the Tevatron

Penny Kasper (Fermilab)
for the CDF and D0 collaborations

OUTLINE

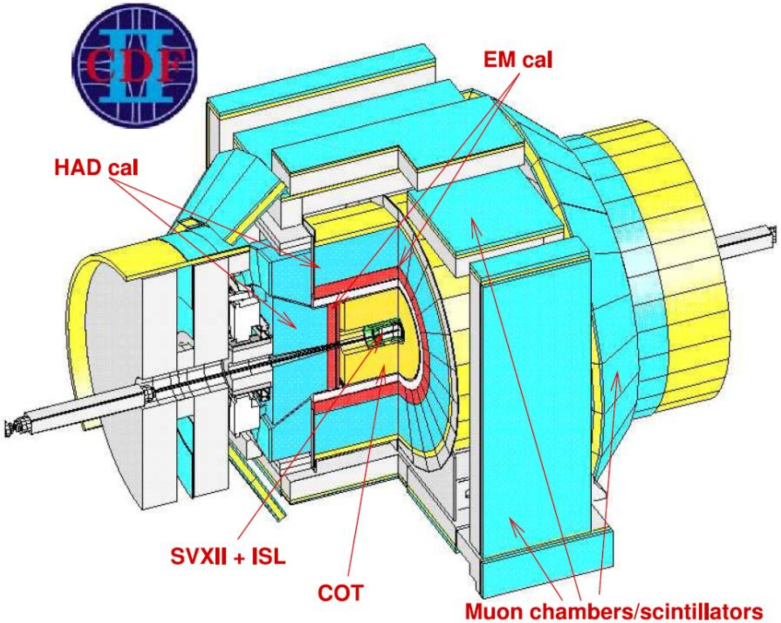
- Spectroscopy
  - B baryons Σ_b, Ξ_b, Ω_b
  - orbitally excited (L=1) B mesons
  - Charmonium-like states X(3872), Y(4140)

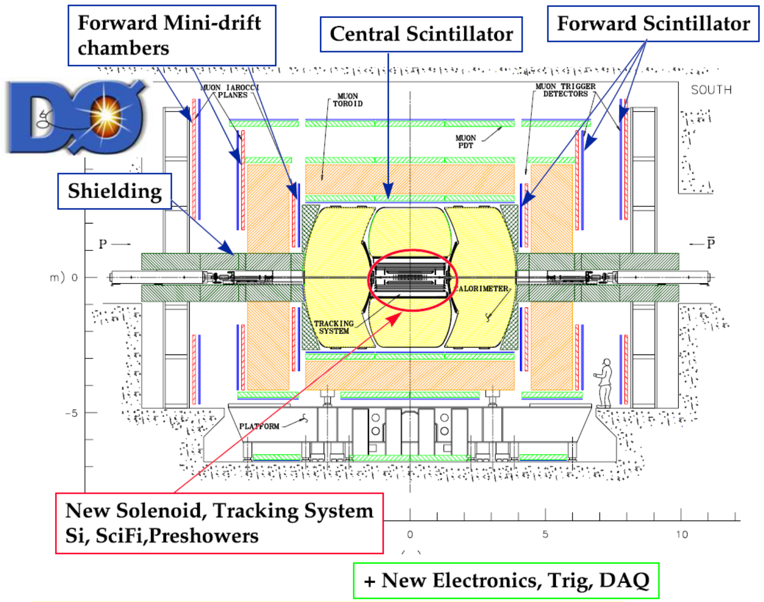
- Lifetimes
  - Λ_b

Detectors and Triggers

– CDF

- large central tracker
- Excellent momentum resolution
- particle ID (TOF & dE/dx)
- Displaced track trigger and di-muon triggers



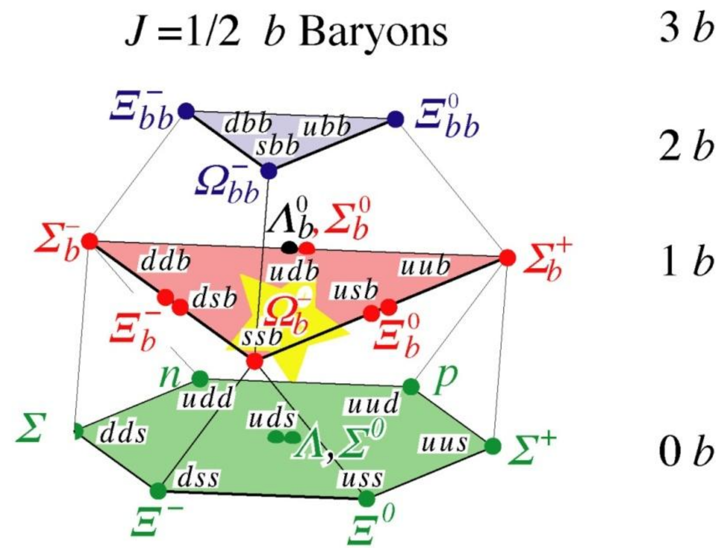


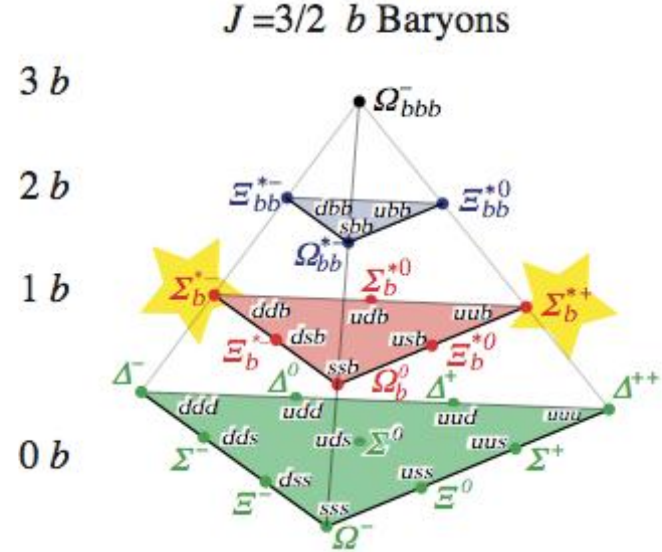
– D0

- large coverage of tracking and muon systems ($|\eta|<2$)
- New Layer 0 silicon (2006)
- High efficiency single and di-muon triggers

B-baryons

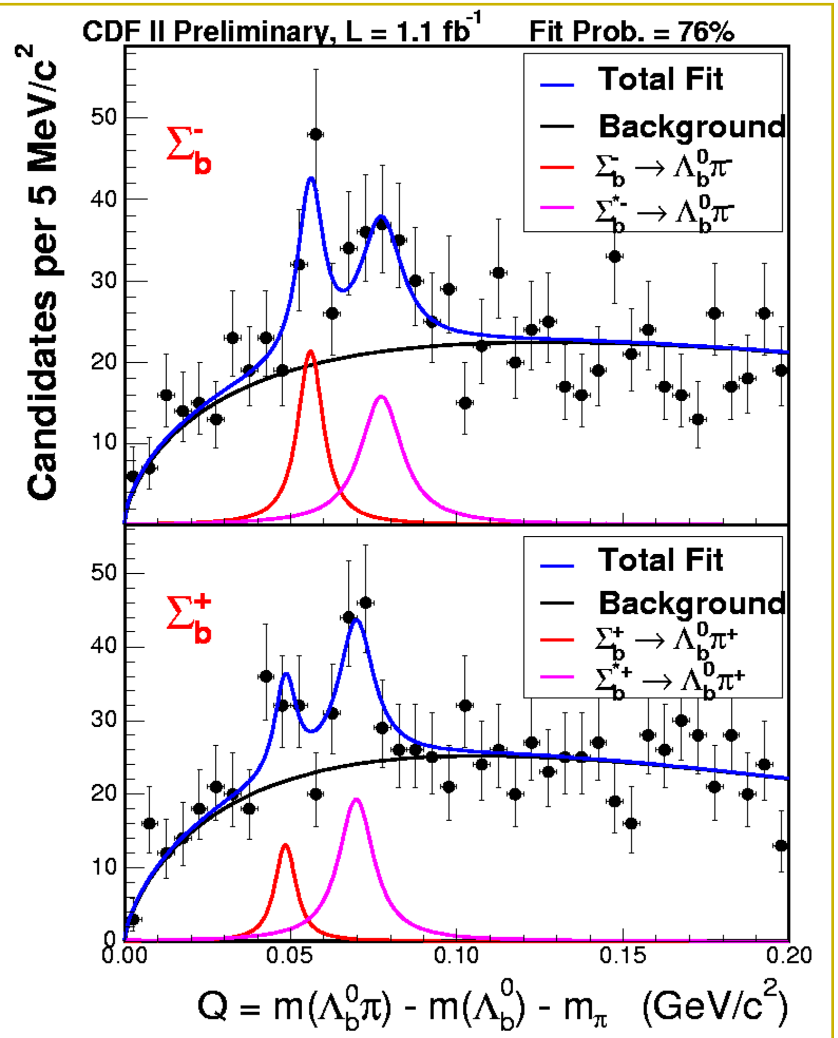
- Unique to Tevatron (not produced in B factories)
- B baryons produced copiously at the Tevatron
- Until 2006 only Λ_b was observed.
- Various mass predictions using different models.





Σ_b^- (bdd), Σ_b^+ (buu)

CDF



two-track trigger

$\Sigma_b^{(*)\pm} \to \Lambda_b \pi^\pm$,

$\Lambda_b \to \Lambda_c \pi^\pm$, $\Lambda_c \to p K \pi$

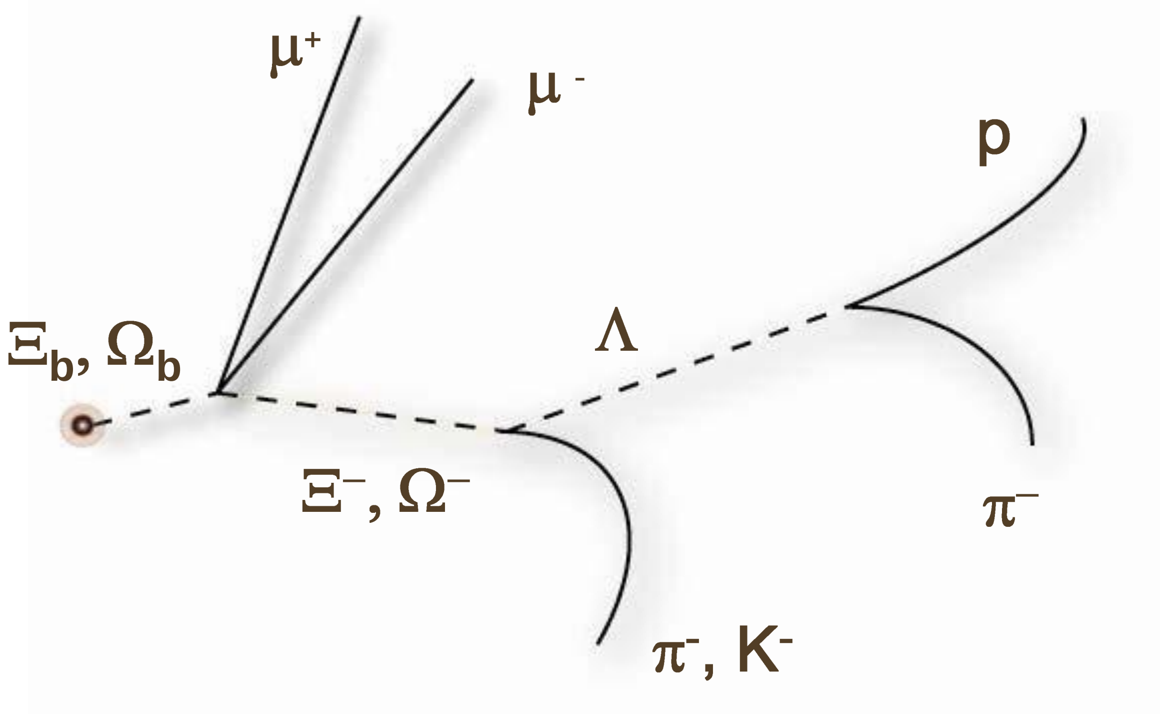
State	Yield	Q or $\Delta_{\Sigma_b^*}$ (MeV/c^2)	Mass (MeV/c^2)
Σ_b^+	32^{+13+5}_{-12-3}	$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$	$5807.8^{+2.0}_{-2.2} \pm 1.7$
Σ_b^-	59^{+15+9}_{-14-4}	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77^{+17+10}_{-16-6}	$\Delta_{\Sigma_b^*} = 21.2^{+2.0+0.4}_{-1.9-0.3}$	$5829.0^{+1.6+1.7}_{-1.8-1.8}$
Σ_b^{*-}	69^{+18+16}_{-17-5}		$5836.4 \pm 2.0^{+1.8}_{-1.7}$

Ξ_b (bsd), Ω_b (bss)

$\Xi_b^- \rightarrow J/\psi\ \Xi^-$

$\Omega_b^- \rightarrow J/\psi\ \Omega^-$

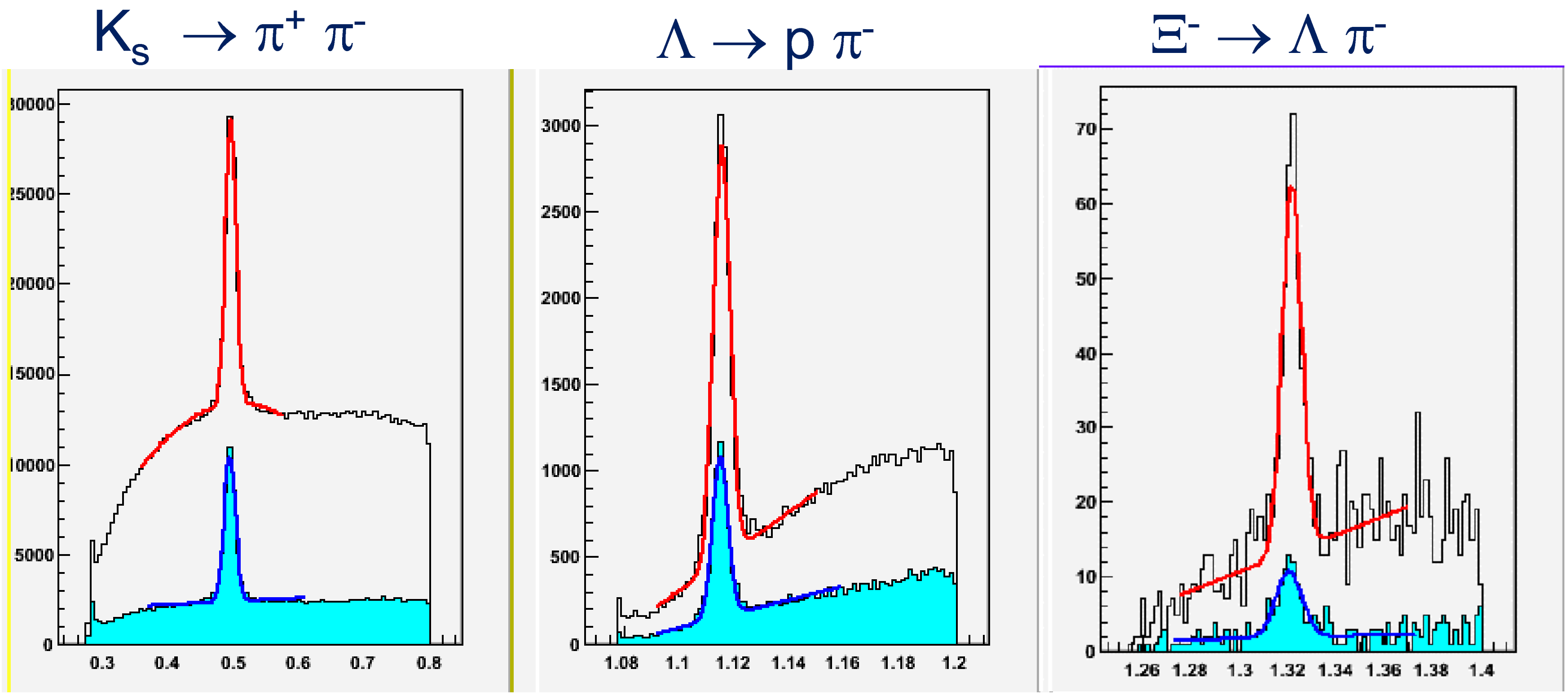
di-muon trigger



$c\tau\ (\Xi^-) = 4.9$ cm

$c\tau(\Omega^-) = 2.5$ cm

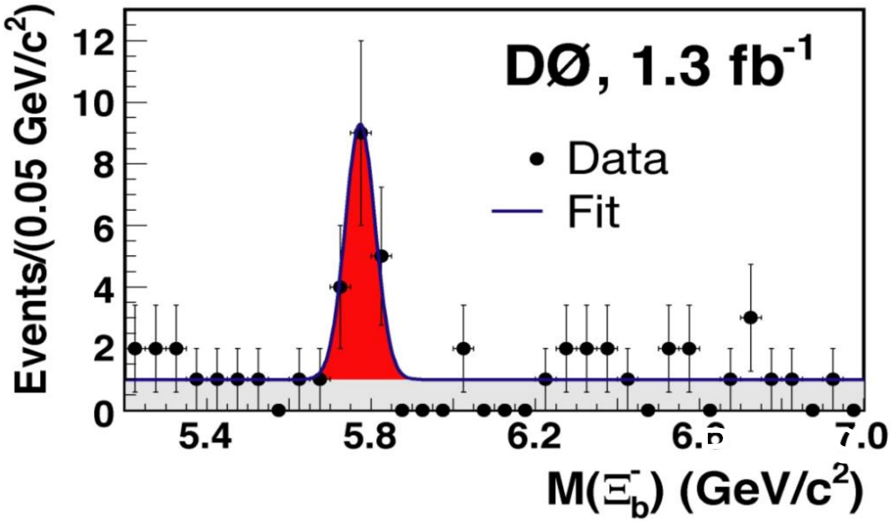
D0 data reprocessing



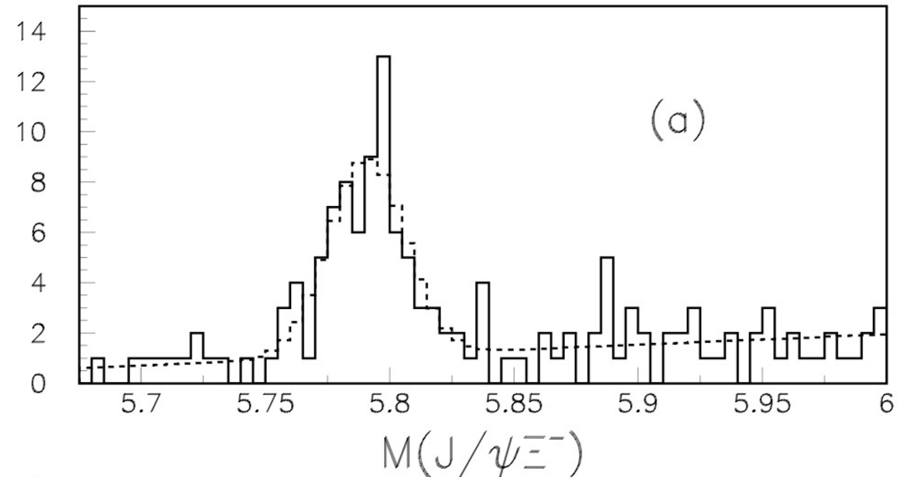
- events with J/ψ are reprocessed
- larger impact parameter, lower pT
- improve efficiency for tracks from long-lived particles.

Ξ_b Mass

PRL 99, 052001 (2007)



PR D 80, 072003 (2009)



Number of events: 15.2 ± 4.4

Mass: 5774 ±11(stat) MeV/c^2
significance > 5σ

Number of events 61 ± 10

m(Ξ_b) = 5790.9 ± 2.6 ± 0 .8 MeV/c^2

Ω_b (bss) → J/ψ Ω^-

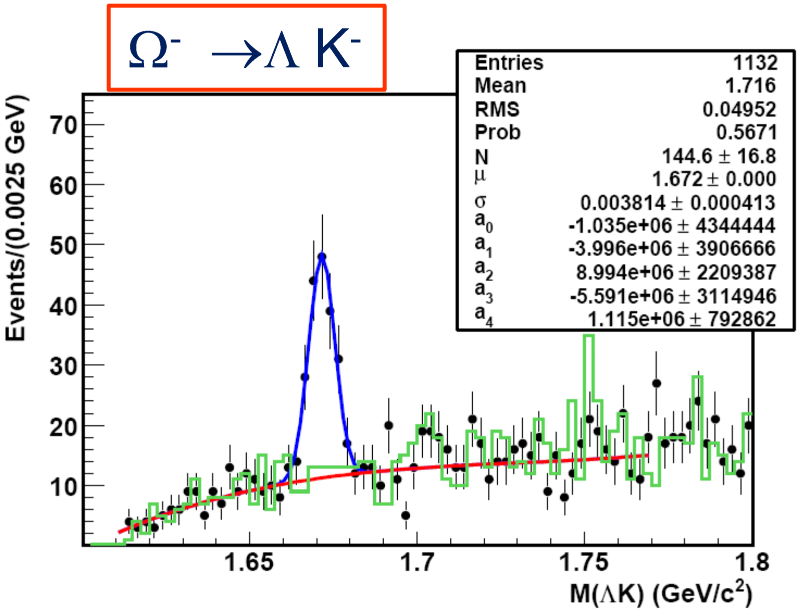
Decay length $\Lambda^0 > 10\sigma$

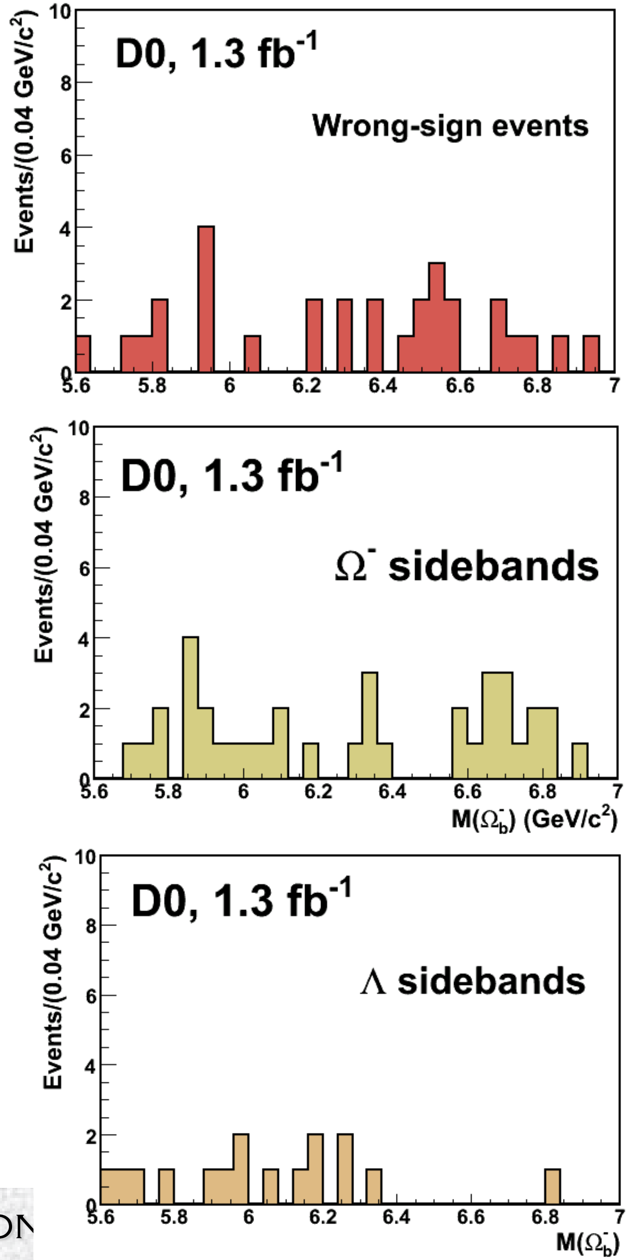
Optimize MC signal/wrong-sign BG from data

Use Boosted Decision Tree (BDT)

to improve S/B for Ω^- signal

Remove events from Ξ^- reflection



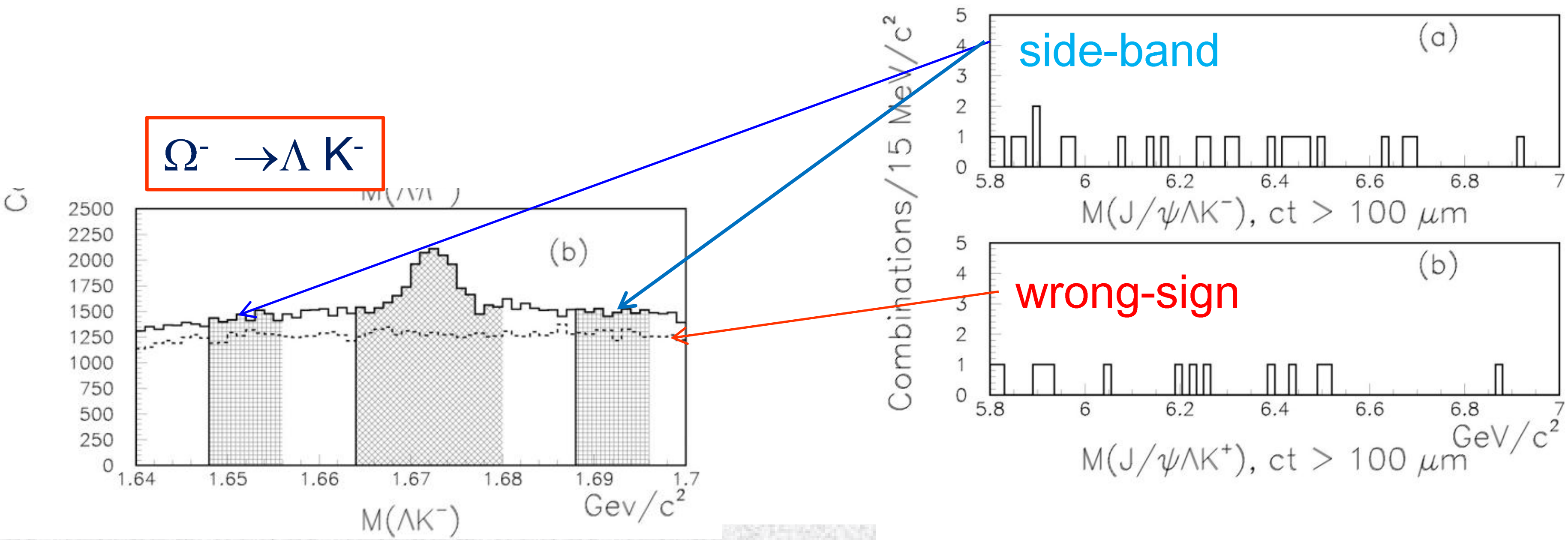


Background tests

Ω_b (bss)

- Flight distance of Λ^0 from primary vtx d > 1.0 cm
- Remove events from Ξ_b reflection
- Decay time of Ω_b ct > 100 um
- Ω^- constrained to J/ψ vertex
- Impact parameter of Ω_b wrt J/ψ vtx, and primary vtx < 3σ

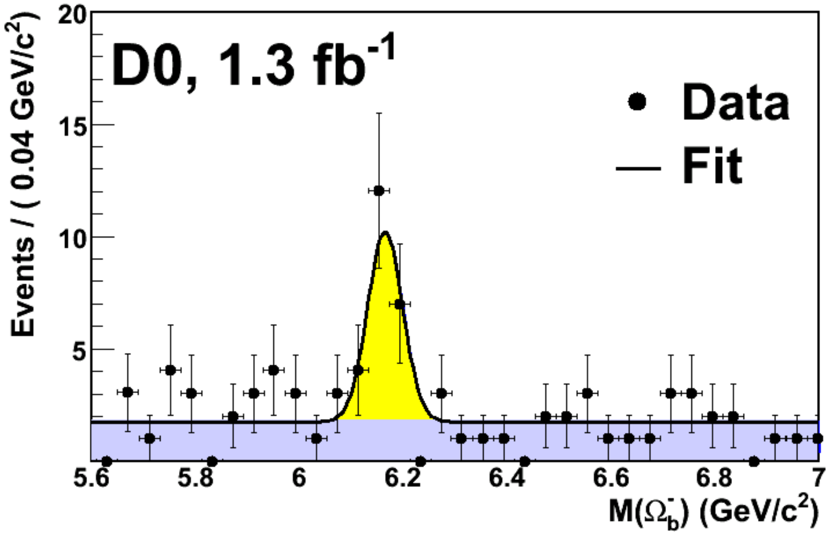
Ω_b background

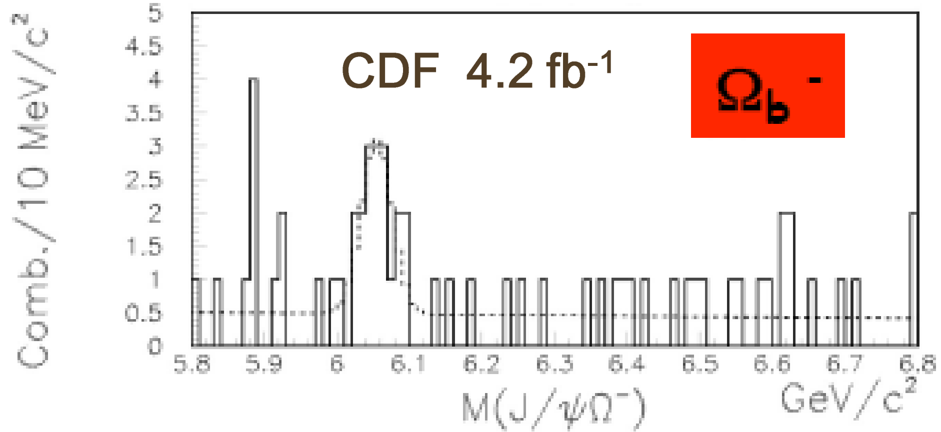


Ω_b MASS

PRL 101, 232002 (2008)

PRD 80,072003 (2009)





Number of events: 17.8 ±4.9
Mass: 6165 ±10 ±11 MeV/c^2

Number of events: 12 ± 4
Mass: 6054.4 ± 6.8 ± 0 .9 MeV/c^2

- unbinned max likelihood fit
- gaussian signal, flat BG
- significance 5.05 σ

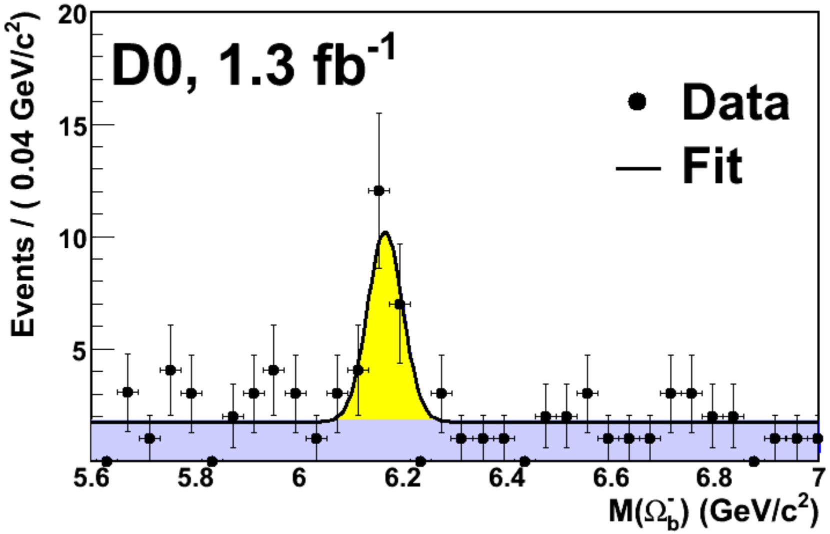
Mass fit : significance 4.9 σ

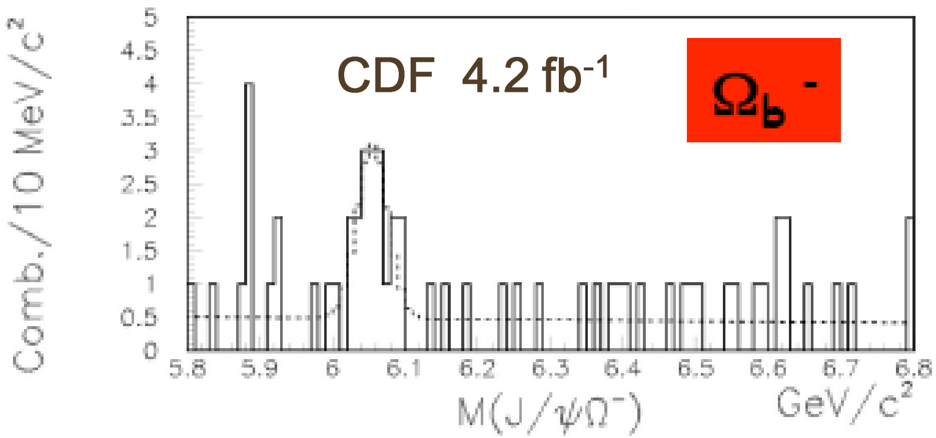
Combined mass and lifetime fit:
significance 5.5 σ

Ω_b MASS

PRL 101, 232002 (2008)

PRD 80,072003 (2009)





D0 : Λ_b mass OK

CDF: reconstructed B^0, Λ_b with similar cuts – OK

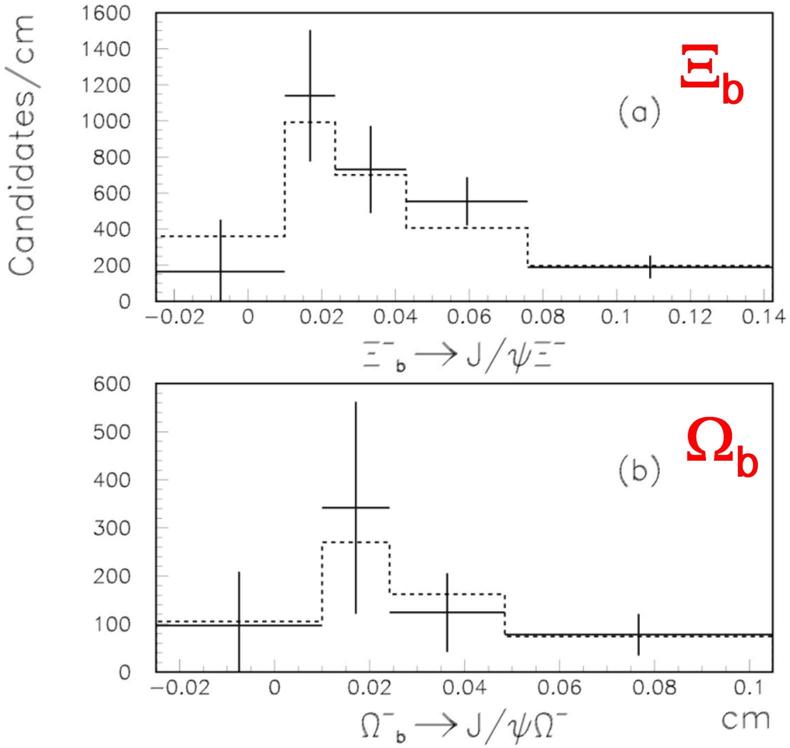
6σ difference in mass !
Not understood

M(Ξ_b) D0 < CDF
M(Ω_b) D0 > CDF

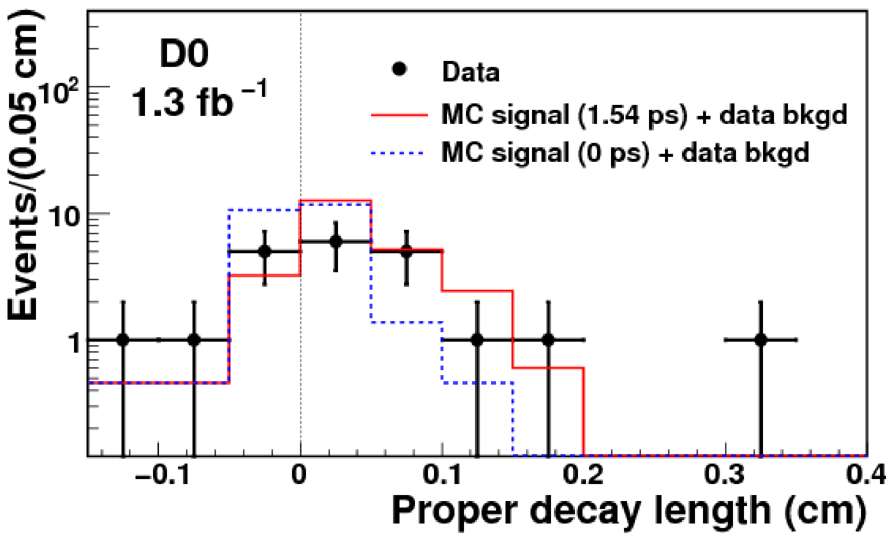
Updated D0 result in progress

Ξ_b, Ω_b Lifetime

CDF



Ω_b



consistent with weak decay

$$\tau(\Xi_b) = 1.56^{+0.27}_{-0.25}\ (\text{stat}) \pm 0.02 (\text{sys})\ \text{ps}$$

$$\tau(\Omega_b) = 1.13^{+0.53}_{-0.40}\ (\text{stat}) \pm 0.02 (\text{sys})\ \text{ps}$$

Ξ_b , Ω_b production rates

D0

$$\frac{\sigma(\Xi_b)\,BR(\Xi_b \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b)\,BR(\Lambda_b \to J/\psi\,\Lambda)} = 0.28 \pm 0.09 \pm 0.09$$

$$\frac{f(b \to \Omega_b)\,BR(\Omega_b \to J/\psi\,\Omega^-)}{f(b \to \Xi_b)\,BR(\Xi_b \to J/\psi\,\Xi^-)} = 0.80 \pm 0.32 \pm 20$$

using $\frac{\Gamma(\Omega_b \to J/\psi\,\Omega^-)}{\Gamma(\Xi_b \to J/\psi\,\Xi^-)} = 9.8$, and estimates for $\tau(\Xi_b)$, $\tau(\Omega_b)$

$$\frac{f(b \to \Omega_b)}{f(b \to \Xi_b)} \approx 0.07 - 0.14$$

CDF

$$\frac{\sigma(\Xi_b)\,BR(\Xi_b \to J/\psi\,\Xi^-)}{\sigma(\Lambda_b)\,BR(\Lambda_b \to J/\psi\,\Lambda)} = 0.167^{+0.037}_{-0.025}$$

$$\frac{\sigma(\Omega_b)\,BR(\Xi_b \to J/\psi\,\Omega^-)}{\sigma(\Lambda_b)\,BR(\Lambda_b \to J/\psi\,\Lambda)} = 0.045^{+0.017}_{-0.012}$$

Excited (L=1) B Mesons

- Heavy-light quark mesons ~ hydrogen atom
- The heavy quark acts as a static source of charge and color and the meson's properties are governed by the dynamics of the light quark
- good approx as $m_b >> \Lambda_{QCD}$

For L=1 mesons, energy levels characterized by

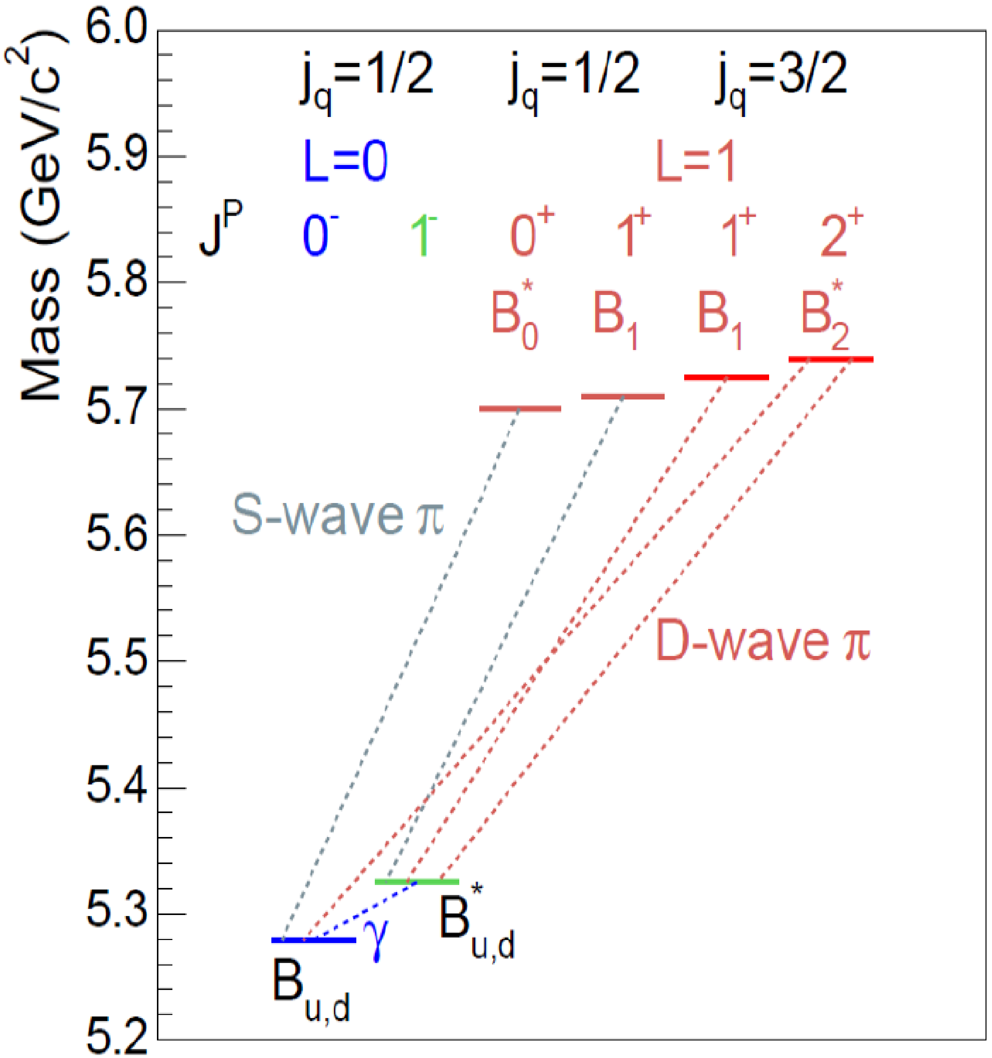
$j=L+S_q$ total angular momentum of light quark

2 degenerate doublets

j=1/2 (0+, 1+) S-wave decay , broad Γ ~O(100MeV)

j=3/2 (1+, 2+) D-wave decay, narrow Γ~O(10MeV)

Excited (L=1) Mesons

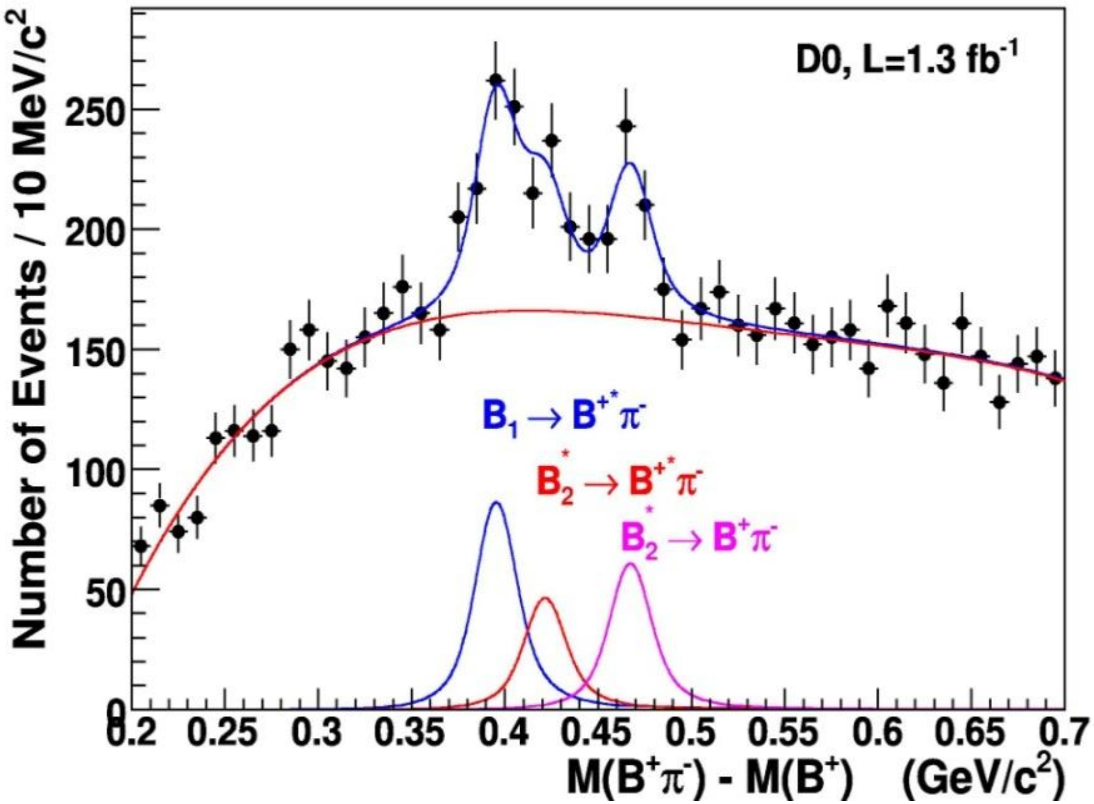


L=1 mesons B_1, B_2^*

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

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

di-muon trigger



$m(B_1) = 5720.6 \pm 2.4 \pm 1.4\ MeV/c^2$

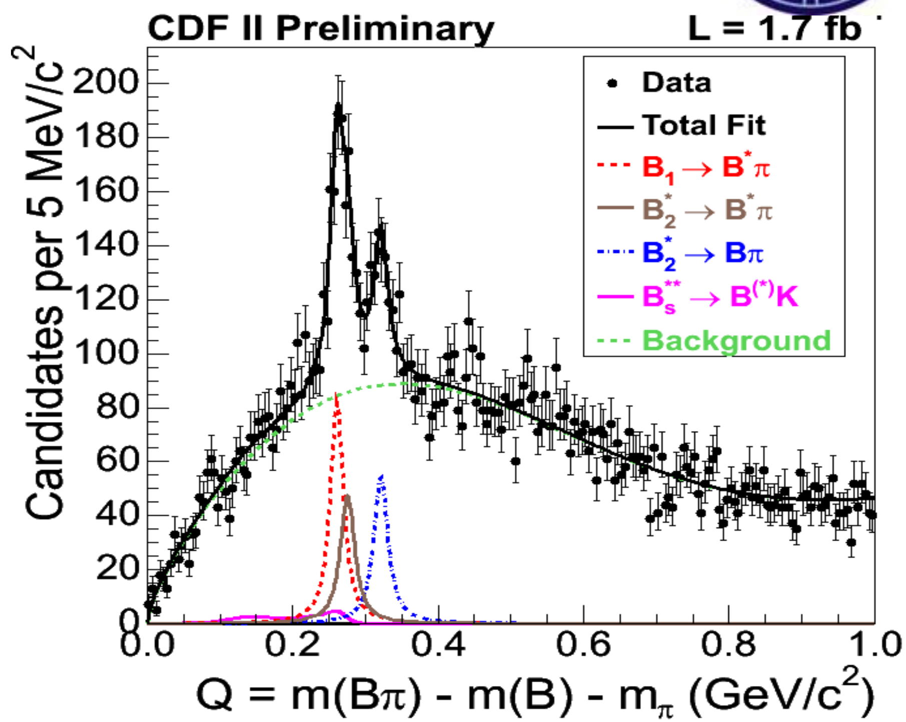
$m(B_2^*) = 5746.8 \pm 2.4 \pm 1.7\ MeV/c^2$

L=1 mesons B_1, B_2^*

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

$B^+ \to J/\psi K^+$, $J/\psi \to \mu^+\mu^-$
di-muon trigger

$B^+ \to D^0(3)\pi^+$, $D^0 \to K^+\pi^-$
Two Track Trigger



Most precise mass measurement

First measurement of B_2^* width

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

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

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

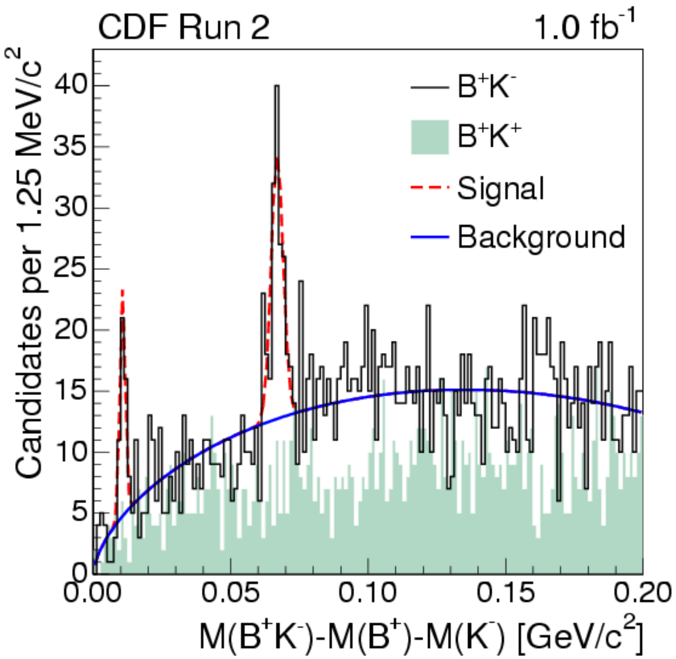
PRL 102, 102003(2009)

B_{s1} B_{s2}^*

$B_{s1} \to B^{*+} K^-$, $B^{*+} \to B^+ \gamma$
$B_{s2}^* \to B^+ K^-$,
$B_{s2}^* \to B^{*+} K^-$, $B^{*+} \to B^+ \gamma$

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

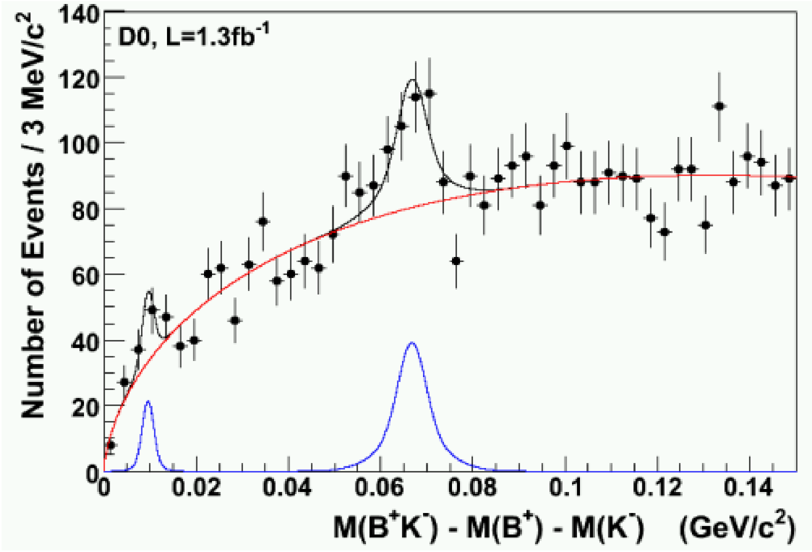
$B^+ \to D0\ \pi^+$, $D0 \to K^+\pi^-$



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

PRL 100, 082001(2008)

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



$M(B_{s2}^*) = 5839.6 \pm 0.7$ MeV/c^2

Test for B_{s1} signal - fit ΔM with two-peak hypothesis -- second peak $<3\sigma$ significance

PRL 100, 082002(2008)

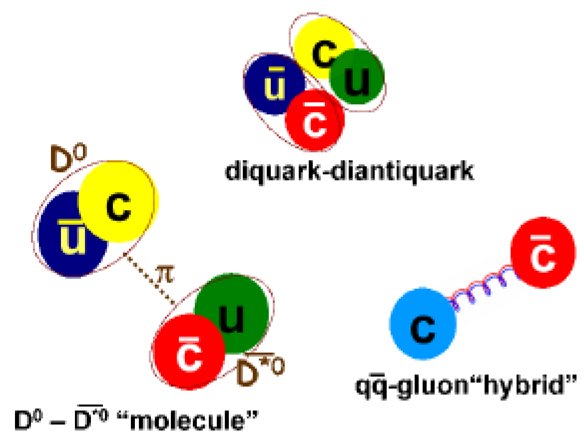
Charmonium-like states

Large number of candidates for charmonium and charmonium-like states

Many not easily accomodated by theoretical expectations for $c\bar{c}$ mesons

Several models proposed:

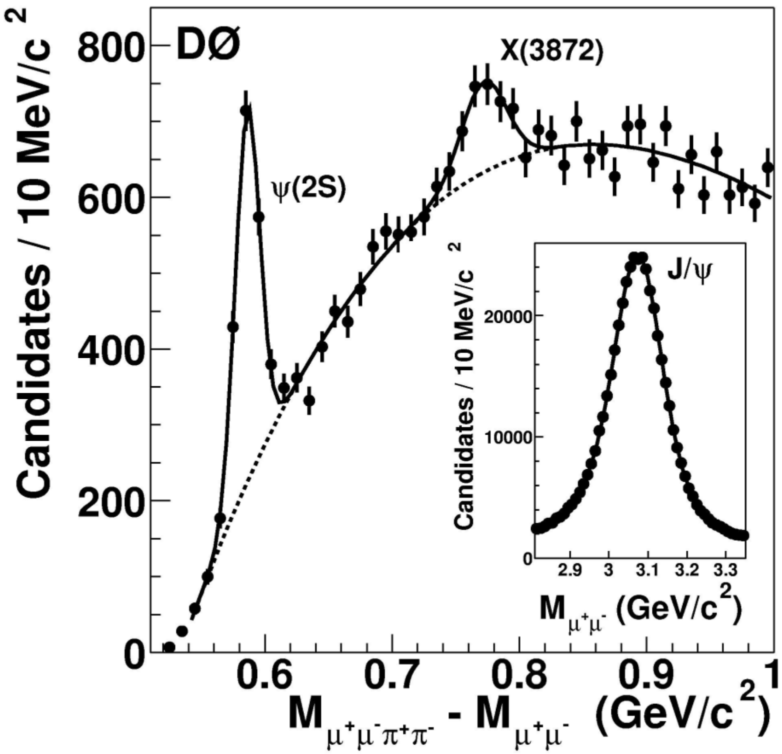
- Meson-antimeson molecules
- diquark-antidiquark bound states
- $c\bar{c}$-gluon hybrids
- threshold effects



X(3872)

- Discovered Belle(2003)
- Seen at CDF, D0, BaBar
- $J^{PC} = 1^{++}$ or 2^{-+}
- available charmonium states are not expected to have large BF to $J/\psi\ \rho$.
- D^0D^{*0} molecule? close to threshold.
- Tetraquark? Maiani predicts another state very close in mass ~8 MeV/c^2
  Maiani, PRD71,014028(2005)

D0



mass $3871.8 \pm 3.1 \pm 3.0$ MeV

$X(3872) \rightarrow J/\psi\, \pi^+ \pi^-$

New CDF result

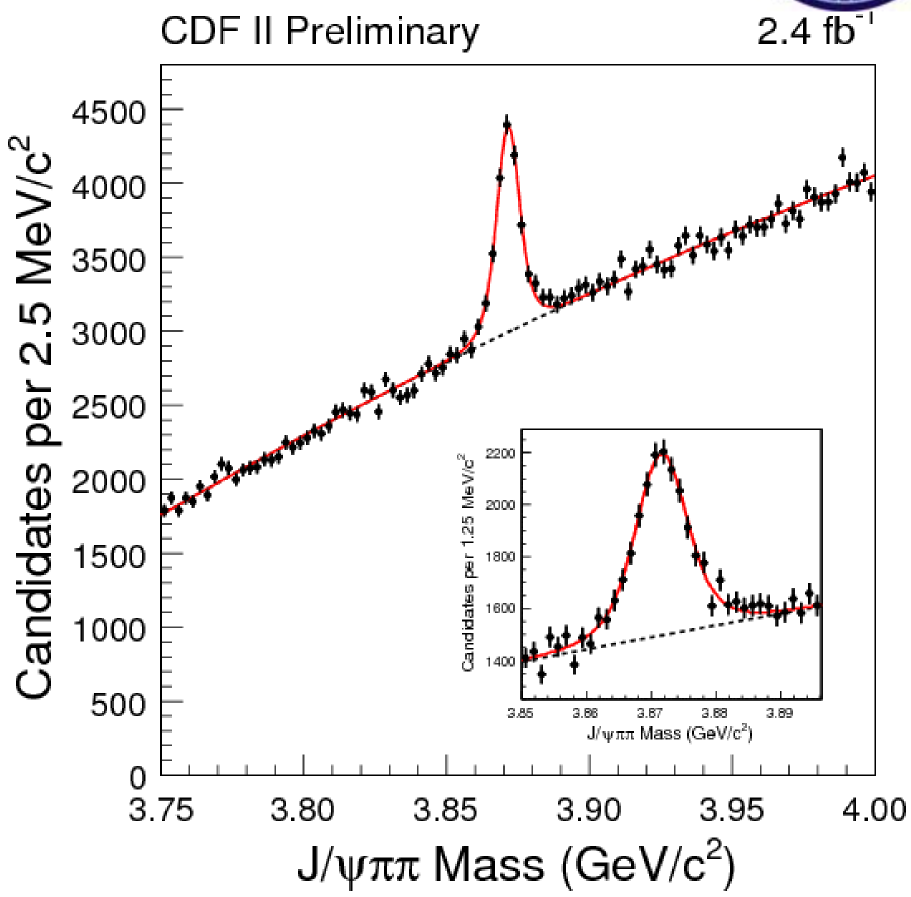
Neural net to optimize S/B

most precise mass measurement
$3871.61 \pm 0.16 \pm 0.19$ MeV/c^2

No evidence for 2 states

Just below $D^0 D^{*0}$ threshold
3871.80 ± 0.35 MeV/c^2

Possibly a $D^0 D^{*0}$ molecule

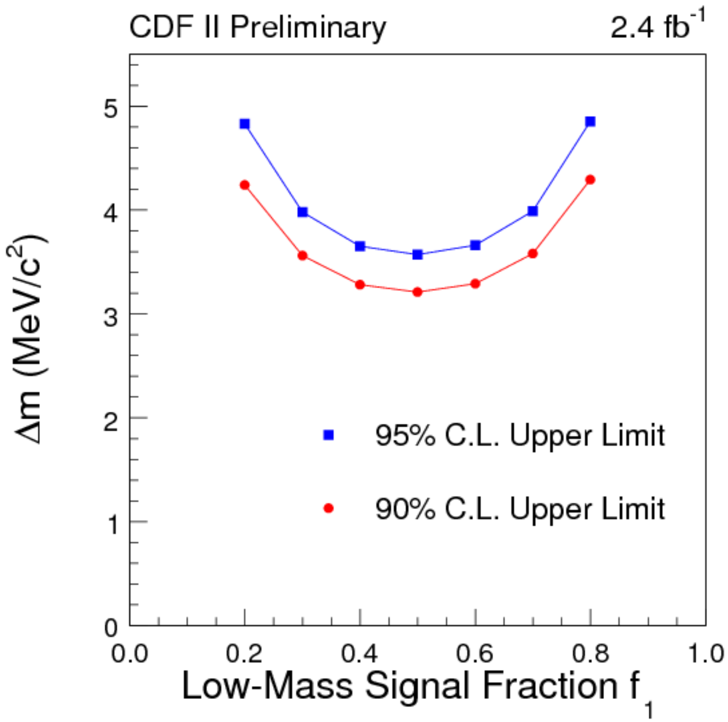


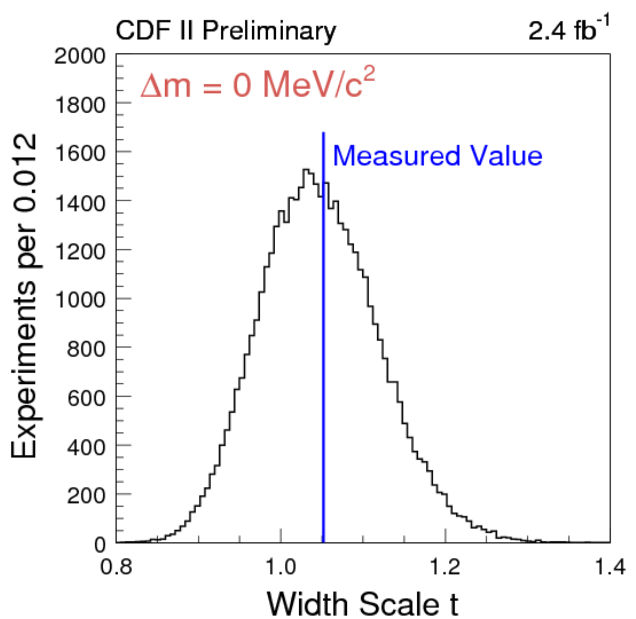
PRL 103, 152001 (2009)

X(3872) TWO STATES?

- Width of BW and gaussian resolution fixed to expected values
- Introduce width scale factor t
- Compare measured value of t with toy MC
- Data consistent with single state

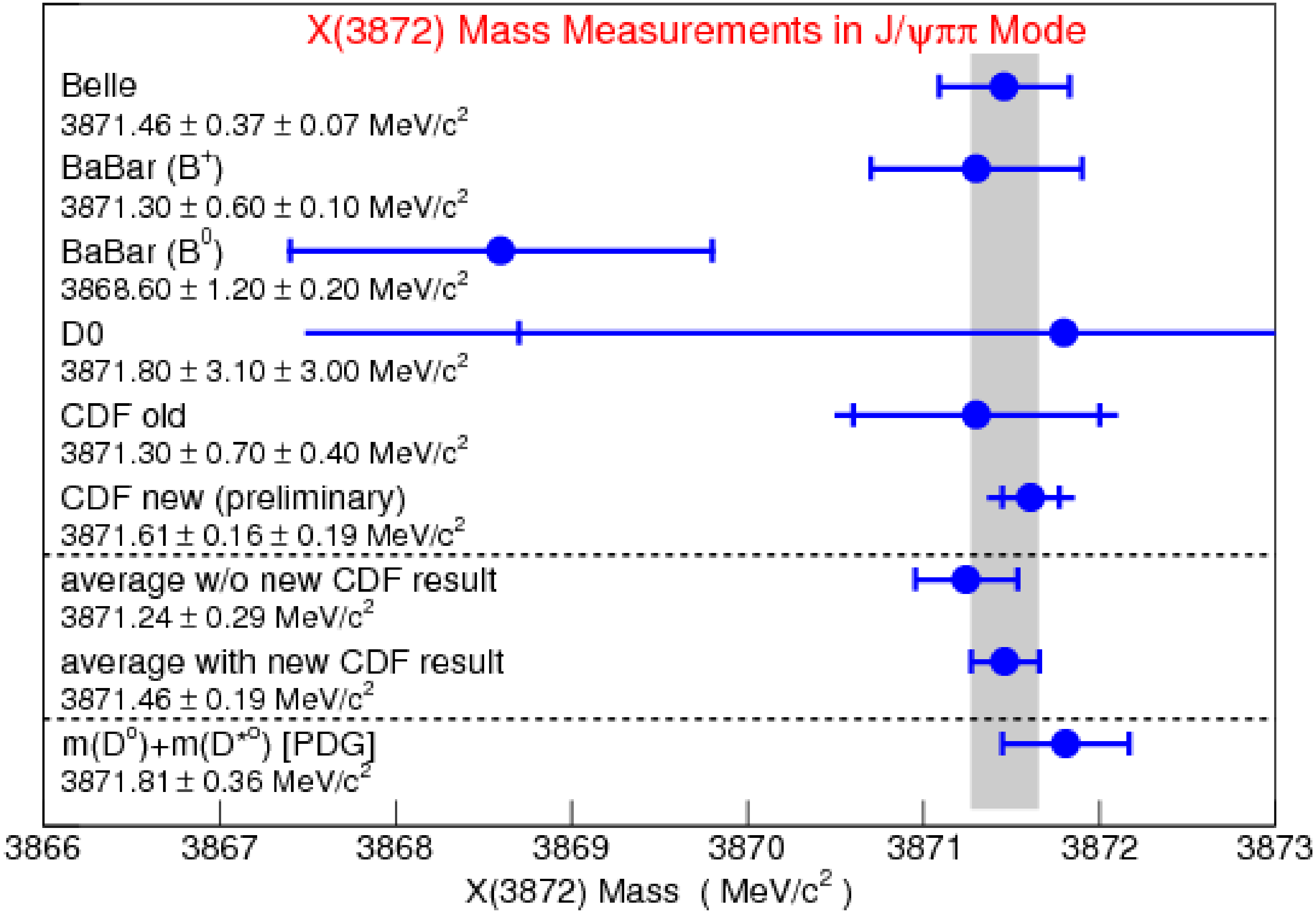
- Generate t for simulated mass differences
- Find upper limit as function of fraction of lower-lying state





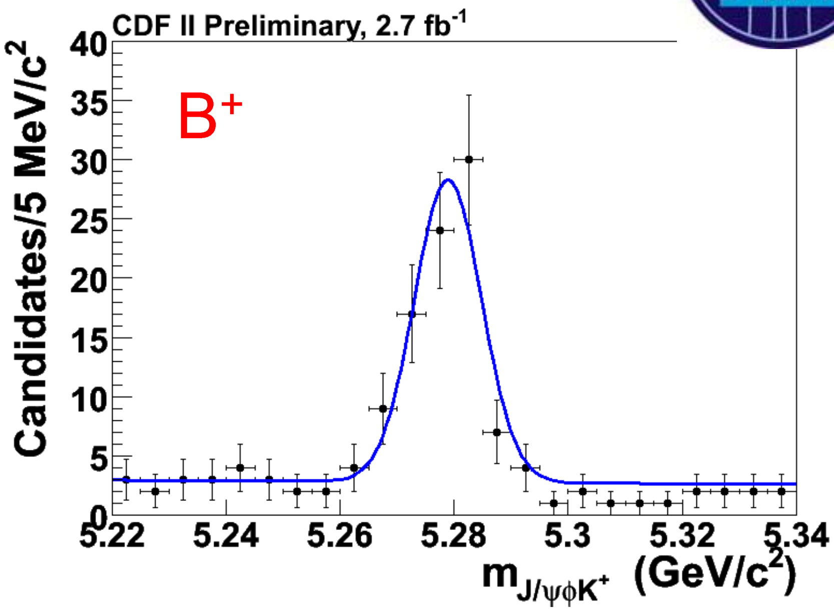
Upper limit on mass difference assuming equal mix:
3.6 MeV/c^2 at 95% cl

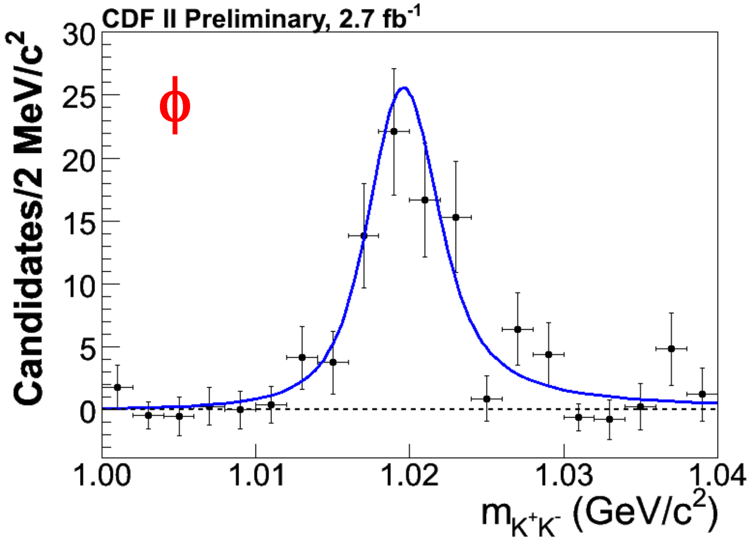
X(3872)


X(3872) Mass Measurements in J/ψππ Mode
Belle
3871.46 ± 0.37 ± 0.07 MeV/c²
BaBar (B⁺)
3871.30 ± 0.60 ± 0.10 MeV/c²
BaBar (B⁰)
3868.60 ± 1.20 ± 0.20 MeV/c²
D0
3871.80 ± 3.10 ± 3.00 MeV/c²
CDF old
3871.30 ± 0.70 ± 0.40 MeV/c²
CDF new (preliminary)
3871.61 ± 0.16 ± 0.19 MeV/c²
average w/o new CDF result
3871.24 ± 0.29 MeV/c²
average with new CDF result
3871.46 ± 0.19 MeV/c²
m(D⁰)+m(D*⁰) [PDG]
3871.81 ± 0.36 MeV/c²
3866
3867
3868
3869
3870
3871
3872
3873
X(3872) Mass (MeV/c²)

Evidence for Y(4140)

- J/ψ φ - observation of Y(3930) near J/ψ ω threshold motivates search for similar states near **J/ψ φ** threshold
- use $B^+ \to J/\psi\ \phi\ K^+$ to reduce background
- di-muon trigger
- dE/dx and TOF to identify kaons





Evidence for Y(4140)

$\Delta M = m(\mu\mu KK) - m(\mu\mu)$

- unbinned likelihood fit
- Signal: relativistic BW convoluted with gaussian
- BG: 3-body phase space

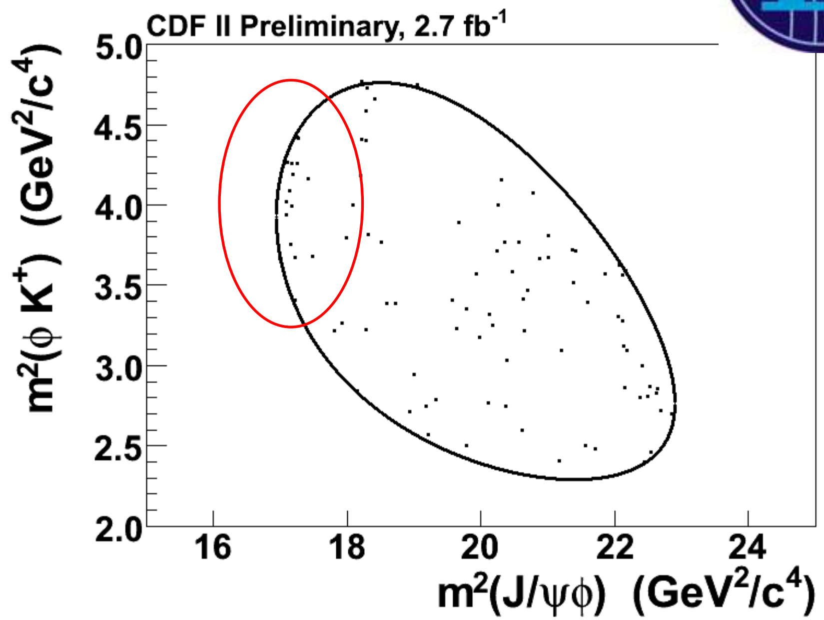
14 ± 5 signal events
m = 4143 ± 2.9 ± 1.2 MeV/c^2

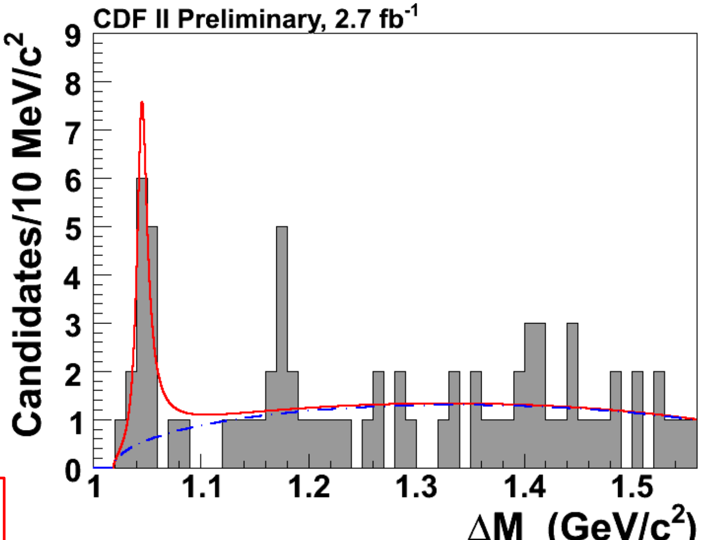
$$\Gamma = 11.7^{+8.3}_{-5.0} \pm 3.7 \ \text{MeV}/c^2$$

significance 3.8σ

Not seen by Belle

PRL 102, 242000(2009)





B Lifetimes

- Weak decays of hadrons with one heavy quark are dominated by the decay of the heavy quark
- In limit $m_b \to \infty$ all b hadrons have same lifetime, differences due to spectator quarks.

- Theoretical predictions:
  - $\tau(B^+) > \tau(B_d) \sim \tau(B_s) > \tau(\Lambda_b) >> \tau(B_c)$
  - $\tau(B^+)/\tau(B_d) = 1.06 \pm 0.02$
  - $\tau(B_s)/\tau(B_d) = 1.00 \pm 0.01$
  - $\tau(\Lambda_b)/\tau(B_d) = 0.88 \pm 0.05$ Tarantino (arXiv hep-ph/0310241)

Λ_b Lifetime: $\Lambda_b \to J/\psi\ \Lambda$

- di-muon trigger
- compare with $B^0 \to J/\psi\ K_s$ which is topolgically similar

CDF

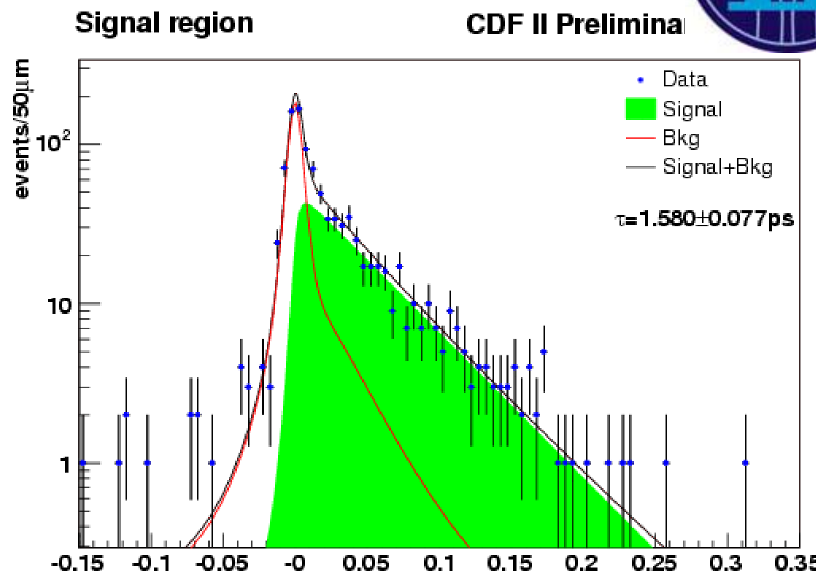
$\tau(\Lambda_b) = 1.580 \pm 0.077 \pm 0.012$ ps

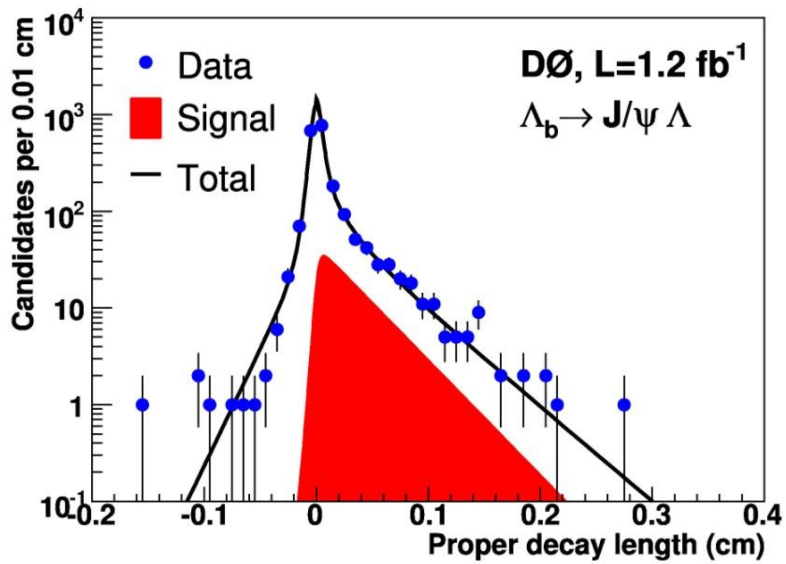
$\tau(\Lambda_b)/\tau(B^0) = 1.018 \pm 0.062 \pm 0.007$

D0

$\tau(\Lambda_b) = 1.218 \pm 0.12 \pm 0.042$ ps

$\tau(\Lambda_b)/\tau(B^0) = 0.811 \pm 0.09 \pm 0.034$





$\Lambda_b \to \mu\nu\Lambda_c X$, $\Lambda_c \to K_s\, p$

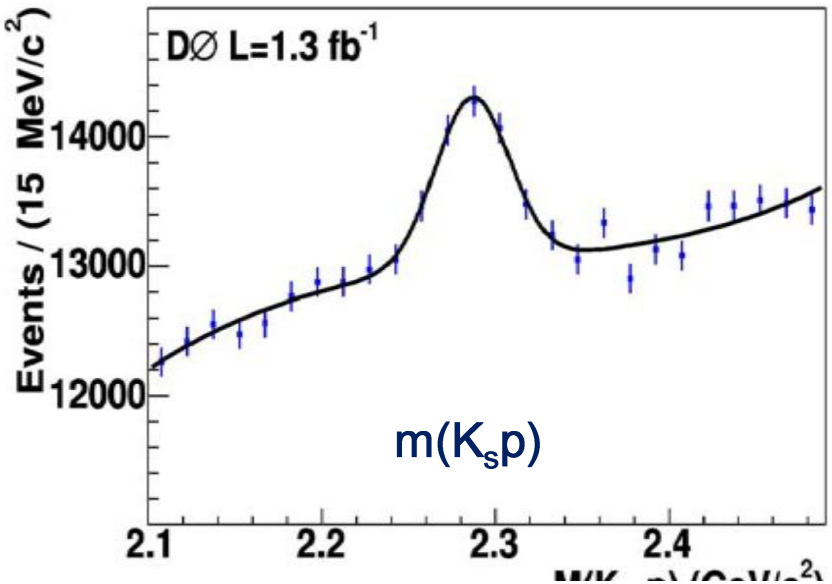
- Semileptonic decay
- Single muon trigger without impact parameter cuts
- MC used to correct for missing ν

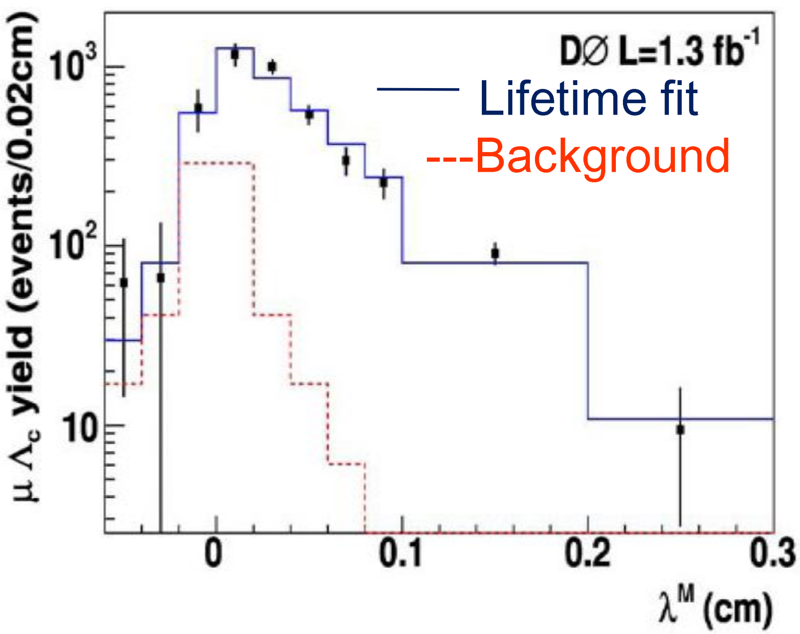
- Yield measured in bins of Visible proper decay length

$\tau(\Lambda_b) = 1.29 \pm 0.11 \pm 0.09$ ps

combined with $J/\psi\ \Lambda$ results
$\tau(\Lambda_b) = 1.25 \pm 0.10$ ps

PRL 99,182001(2007)

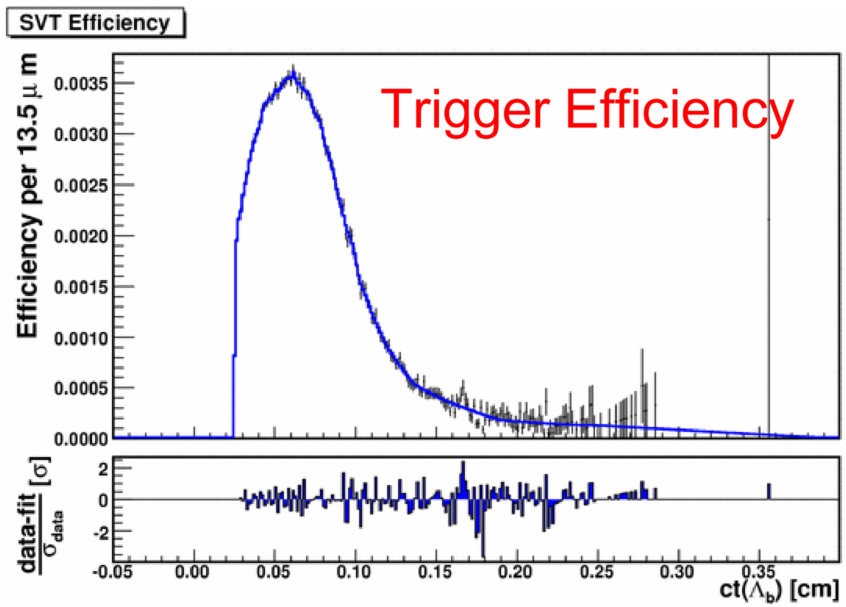


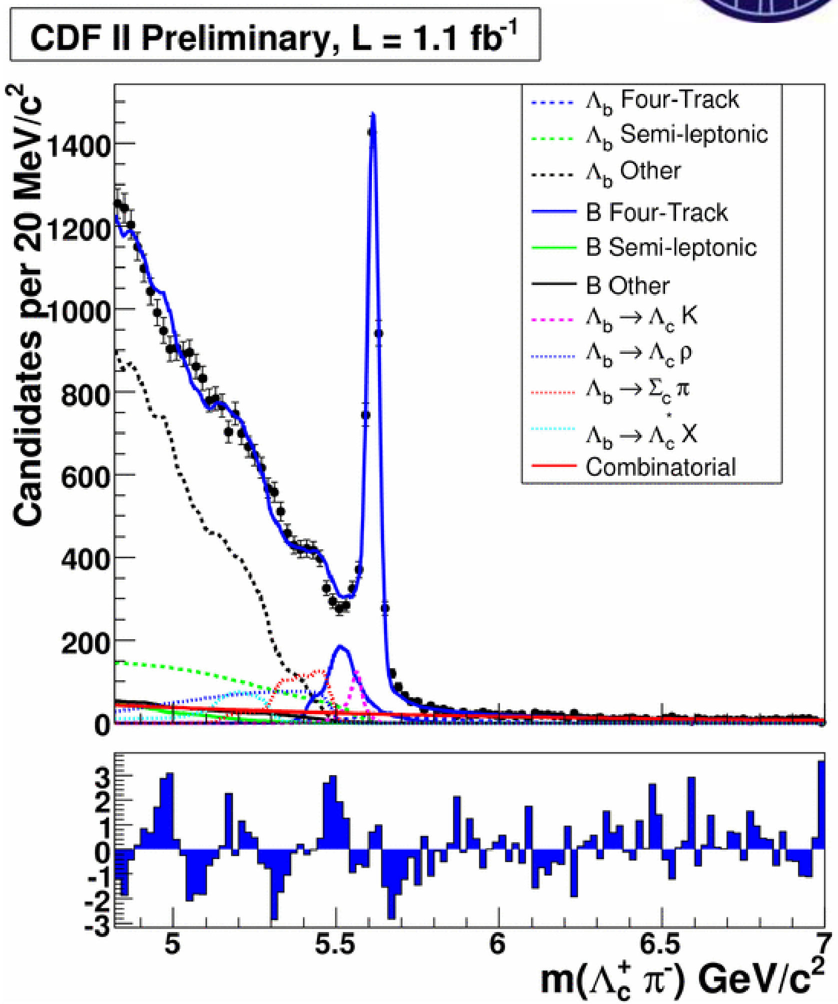


Λ_b Lifetime: $\Lambda_b \to \Lambda_c \pi$, $\Lambda_c \to pK\pi$

- Clean high statistics sample from Two displaced track trigger (TTT)

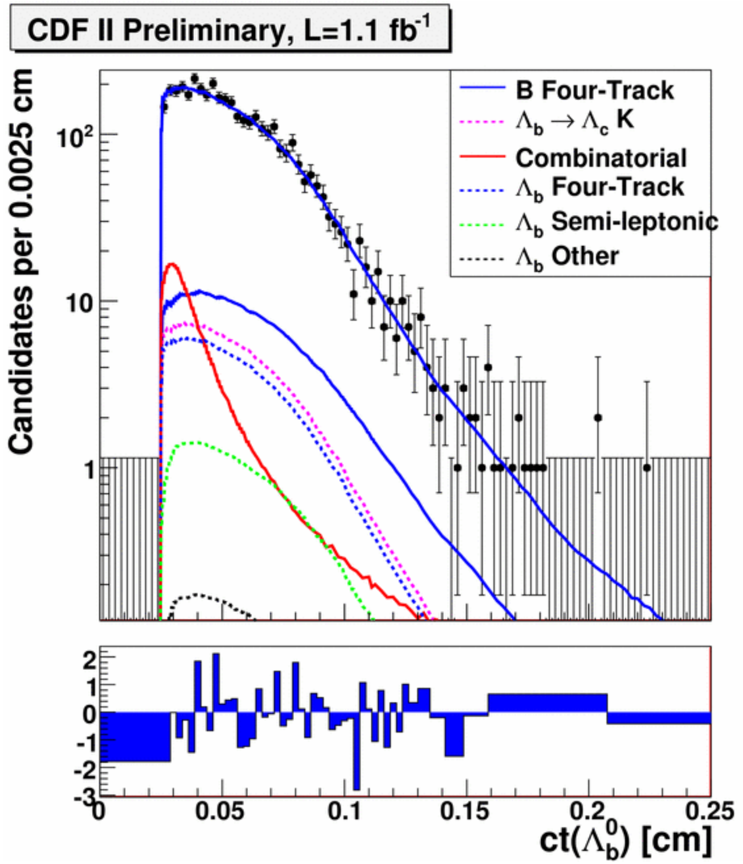
- TTT has lifetime bias, correct with MC





wwwcdf.fnal.gov/physics/new/bottom/090416.blessed-lblcpi-ct

Λ_b Lifetime: $\Lambda_b \to \Lambda_c \pi$, $\Lambda_c \to pK\pi$

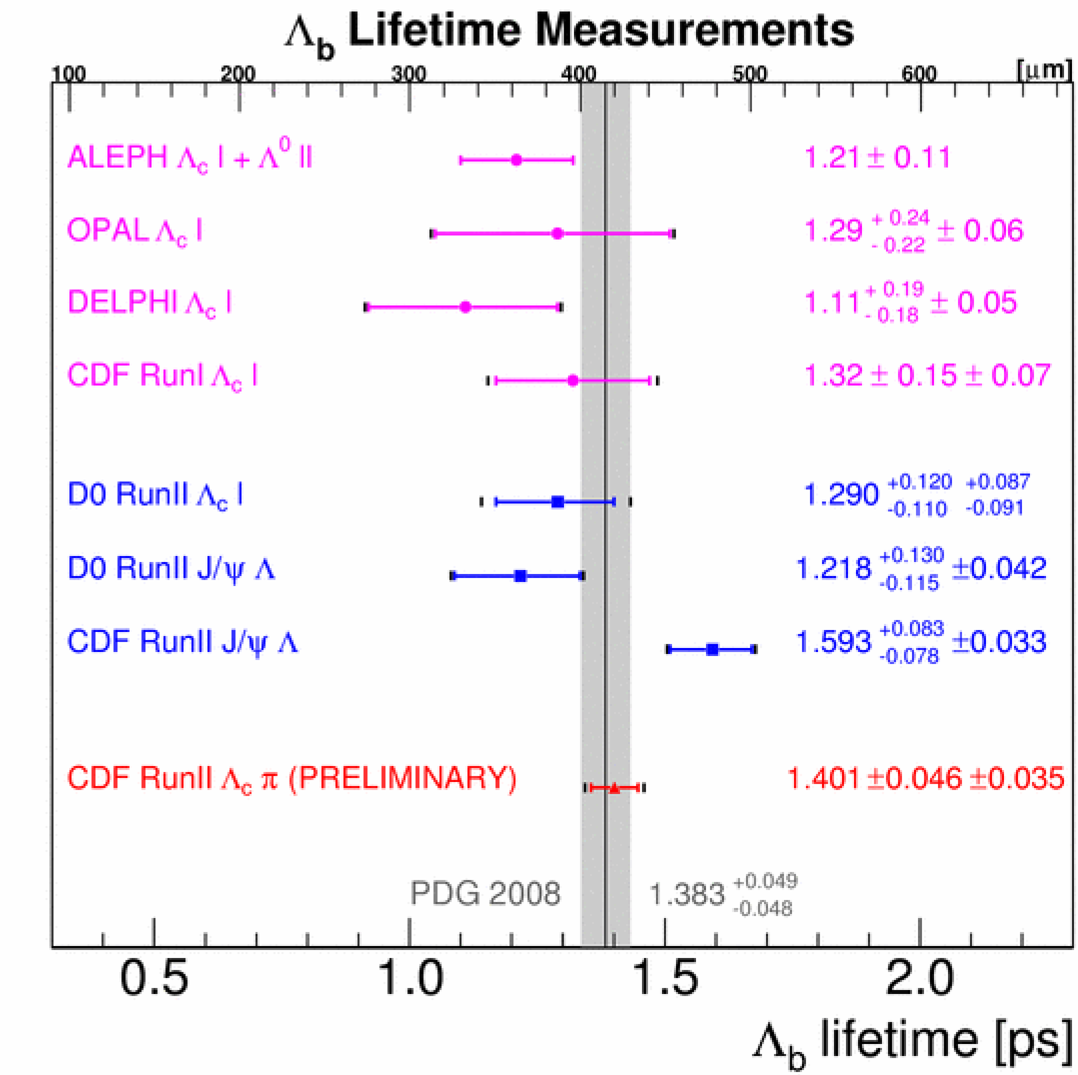


- Fit mass distribution to find sample composition of signal region
- unbinned likelihood fit - exponential convoluted with trigger efficiency and detector resolution

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

wwwcdf.fnal.gov/physics/new/bottom/090416.blessed-lblcpi-ct

Λ_b Lifetime



Summary

- Tevatron is an ideal place to study b-physics
  - production of B baryons, B_c and excited mesons not produced at B factories

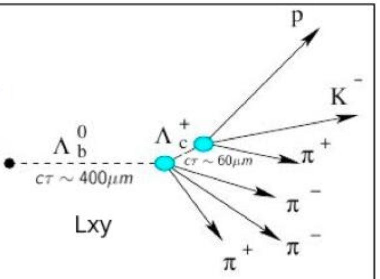
- CDF and D0 have made many important measurements
  - Many results presented here use < 2 fb^{-1} data
  - Tevatron has delivered >7 fb^{-1}, and more on the way
  - Looking forward to new and higher precision results from data already on tape.

Observation of resonances in $\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^-\pi^+$ final states and measurement of the relative BRs

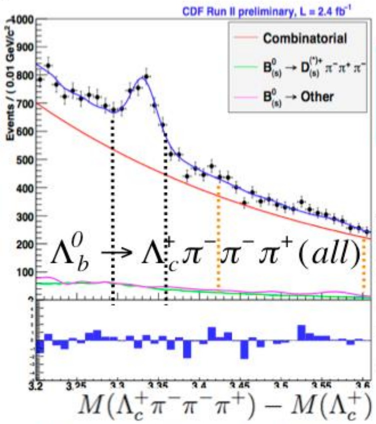
CDF

Why? New possible measurements of relative and absolute BRs allowing test of HQET

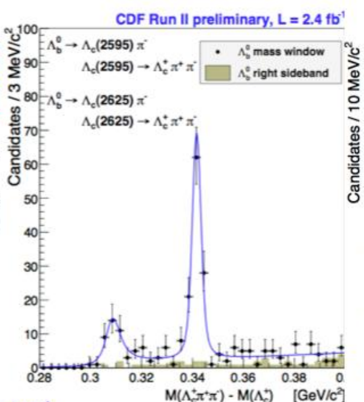
$$\Lambda_b^0 \to \Lambda_c^+\pi^+\pi^-\pi^-$$
$$\to \Lambda_c^*(2593)^+\pi^-, \quad \Lambda_c^*(2593)^+ \to \Lambda_c^+\pi^+\pi^-$$
$$\to \Lambda_c^*(2625)^+\pi^-, \quad \Lambda_c^*(2625)^+ \to \Lambda_c^+\pi^+\pi^-$$
$$\to \Sigma_c^{++}\pi^-\pi^-, \quad \Sigma_c^{++} \to \Lambda_c^+\pi^+$$
$$\to \Sigma_c^0\pi^-\pi^+, \quad \Sigma_c^0 \to \Lambda_c^+\pi^-$$
$$\to \Lambda_c^+\rho^0\pi^-$$

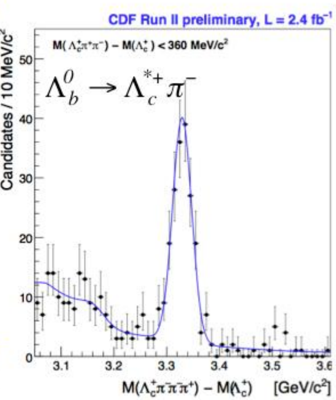


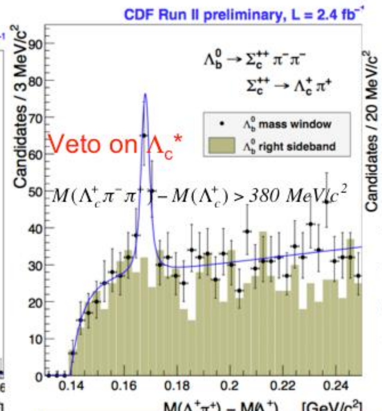
CDF observed same resonances in SL $\Lambda_b^0 \to \Lambda_c^+\mu^-\bar{\nu}_\mu\pi^-\pi^+$ final states (PR D79, 032001 (2009)).

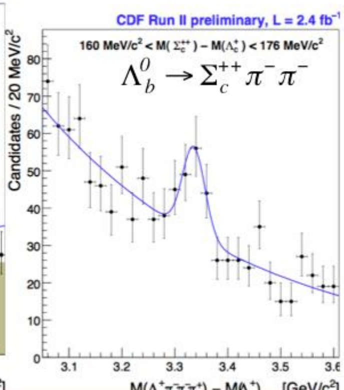


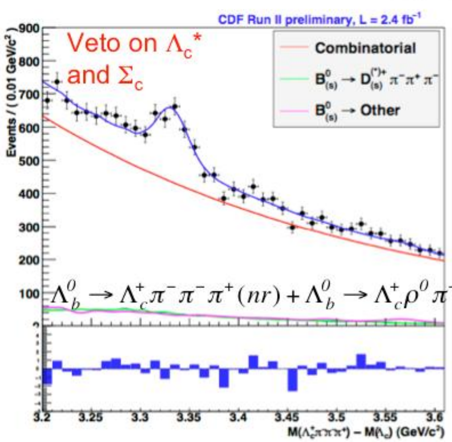
Events collected by TTT B_CHARM_SCENA and B_CHARM_LOWPT











$\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^-\pi^+$ final states	Yields from fit
$\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^-\pi^+(all)$	848±93
$\Lambda_b^0 \to \Lambda_c(2595)^+\pi^-$	47±10
$\Lambda_b^0 \to \Lambda_c(2625)^+\pi^-$	114±13
$\Lambda_b^0 \to \Sigma_c^{++}\pi^-\pi^-$	81±15
$\Lambda_b^0 \to \Sigma_c^0\pi^-\pi^+$	42±9
$\Lambda_b^0 \to \Lambda_c^+\pi^-\pi^-\pi^+(nr) + \Lambda_b^0 \to \Lambda_c^+\rho^0\pi^-$	610±88

$$\frac{BR(\Lambda_b^0\to\Lambda_c(2595)^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c^+\pi^-\pi^+\pi^-(all))} = (2.5 \pm 0.6(stat.) \pm 0.5(syst.)) \times 10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Lambda_c(2625)^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c^+\pi^-\pi^+\pi^-(all))} = (6.2 \pm 1.0(stat.)^{+1.0}_{-0.9}(syst.)) \times 10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Sigma_c(2455)^{++}\pi^-\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c^+\pi^-\pi^+\pi^-(all))} = (5.2 \pm 1.1(stat.) \pm 0.8(syst.)) \times 10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Sigma_c(2455)^0\pi^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c^+\pi^-\pi^+\pi^-(all))} = (8.9 \pm 2.1(stat.)^{+1.2}_{-1.0}(syst.)) \times 10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Lambda_c^+\rho^0\pi^- + \Lambda_c^+3\pi(nr)\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c^+\pi^-\pi^+\pi^-(all))} = (77.3 \pm 3.1(stat)^{+3.0}_{-3.3}(syst)) \cdot 10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Lambda_c(2595)^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Lambda_c(2625)^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)} = (40.3 \pm 9.8(stat)^{+2.3}_{-1.8}(syst)) \cdot 10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Sigma_c(2455)^{++}\pi^-\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Sigma_c(2455)^0\pi^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)} = (58.1 \pm 16.9(stat)^{+6.3}_{-9.1}(syst)) \cdot 10^{-2}$$

$$\frac{BR(\Lambda_b^0\to\Lambda_c(2625)^+\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)}{BR(\Lambda_b^0\to\Sigma_c(2455)^{++}\pi^-\pi^-\to\Lambda_c^+\pi^-\pi^+\pi^-)} = (119.7 \pm 26.0(stat)^{+4.7}_{-9.1}(syst)) \cdot 10^{-2}$$