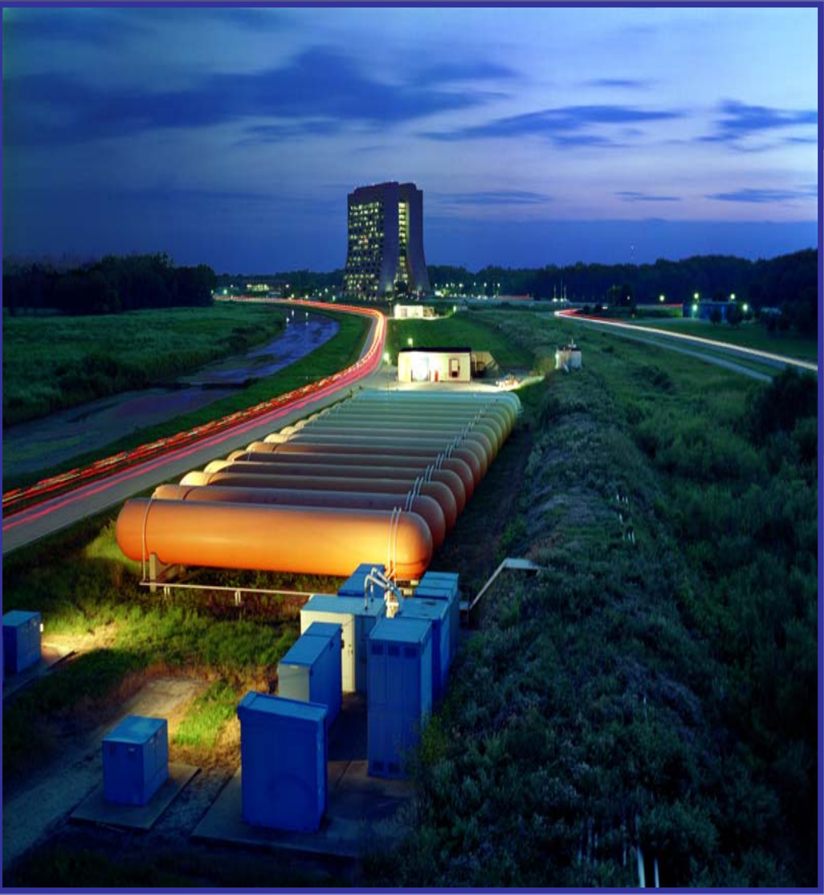
B spectroscopy at the Tevatron



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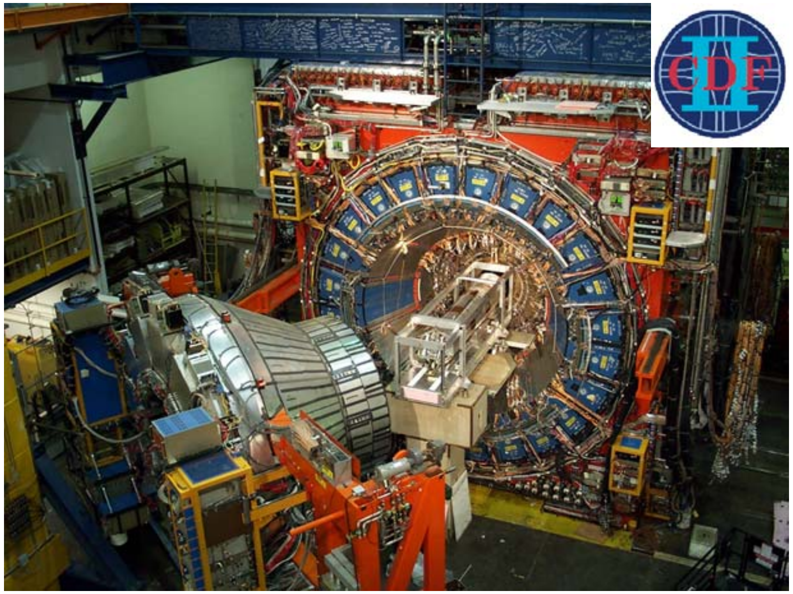
On behalf of the CDF and D0 collaboration

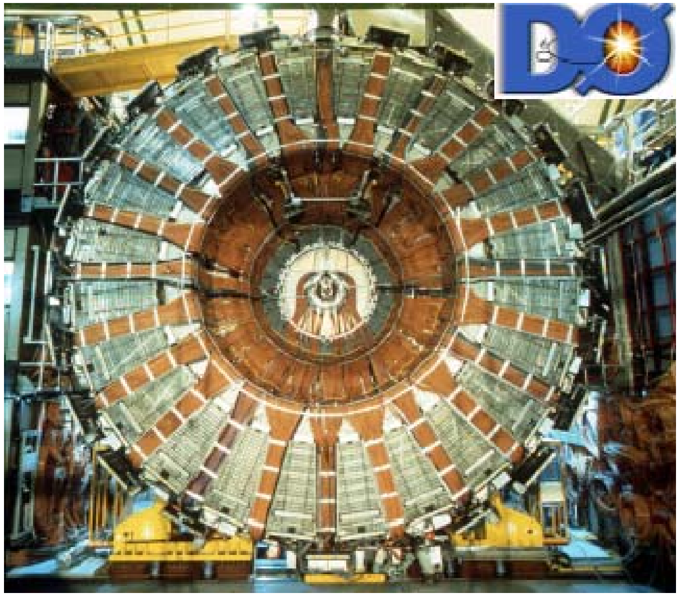
FPCP 2009, Lake Placid NY

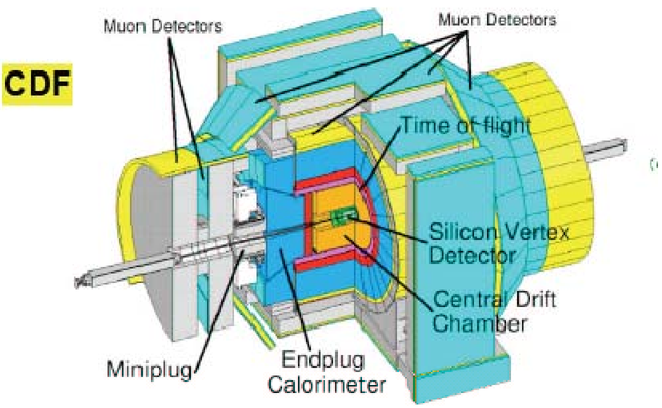
Outline:

- **CDF and DØ detectors**
- **B Physics @ Tevatron**
- **B_c mass measurement**
- **Excited Bs mesons**
- **Ξ_b and Ω_b observations**
- **Summary**

CDF and DØ detectors

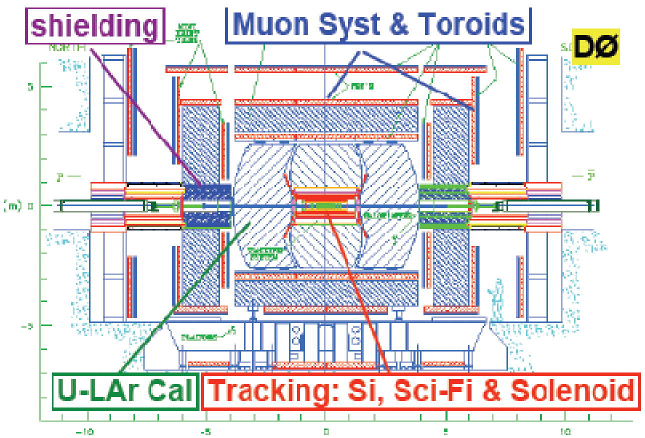




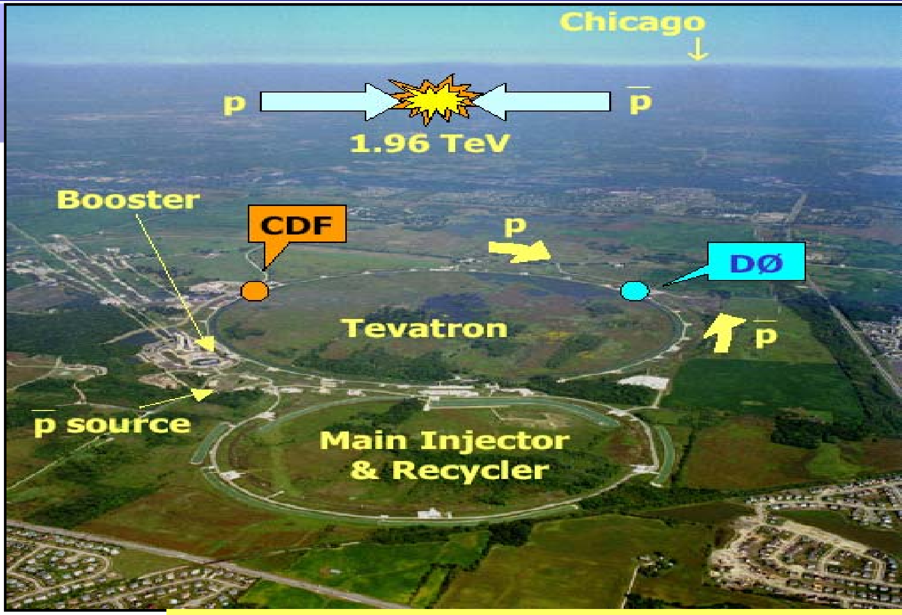


Important:

- Triggering
- Muons
- Tracking/vertexing



B Physics @ Tevatron



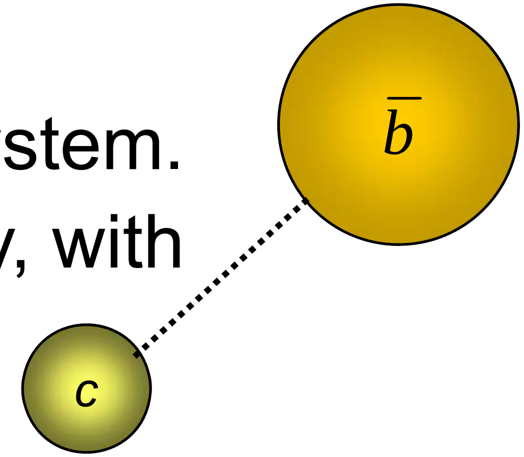
- Tevatron is an excellent place for B Physics
  - All B hadron species are produce: B^+,B^0,$\mathbf{B_s}$,$\mathbf{B_c}$, $\mathbf{\Lambda^0_b}$, **…**
  - Total inelastic cross section $\sigma(\text{total})/\sigma(b)>10^3$
  - Need of smart selection beginning from triggers

B spectroscopy status

- Mesons:
  - B^+, B^0, B_s, B_c^+ (established)
  - B* (established),
  - **B**(CDF & DØ)**
  - **B_s** (CDF & DØ)**
- Baryons
  - Λ_b (established)
  - **Σ_b^+, and Σ_b^{*+}(CDF)**
  - **Ξ_b^- , Ω_b^- (CDF & DØ)**

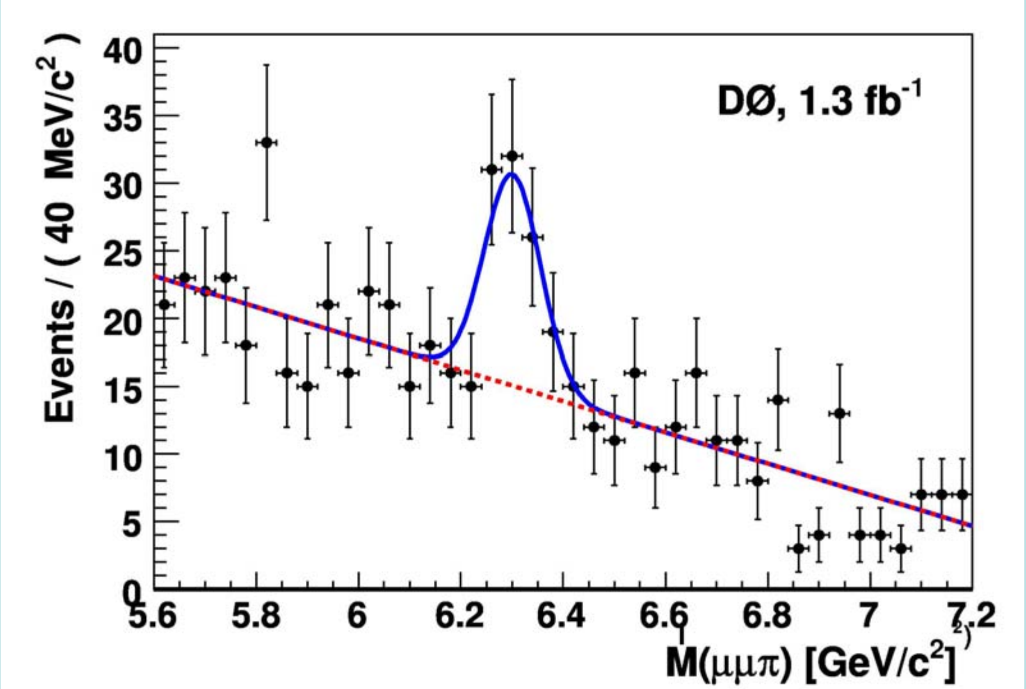
B_c system study

- B_c is not produced at b factories
- B_c is a unique (heavy-heavy, $\neq$q's) system.
- both *b* and *c* quark can decay weakly, with comparable probabilities
  - short (c-like) lifetimes observed
  - both DØ & CDF: τ~ 0:45 ps
- Experimentally challenging because of low production rate $f(b \to B_c) \sim 0.05\%$
- Observed and lifetime measured by DØ and CDF in $B_c \to J/\psi l \nu$ ($l=\mu,e$)



B_c mass measurement

- Exclusive reconstruction in $B_c^+ \to J/\psi\pi^+$
- Optimization in $B+ \to J/\psi K+$ and $B_c^+ \to J/\psi\pi^+$ Monte Carlo
- Data of 1.3 fb^{-1}integrated luminosity



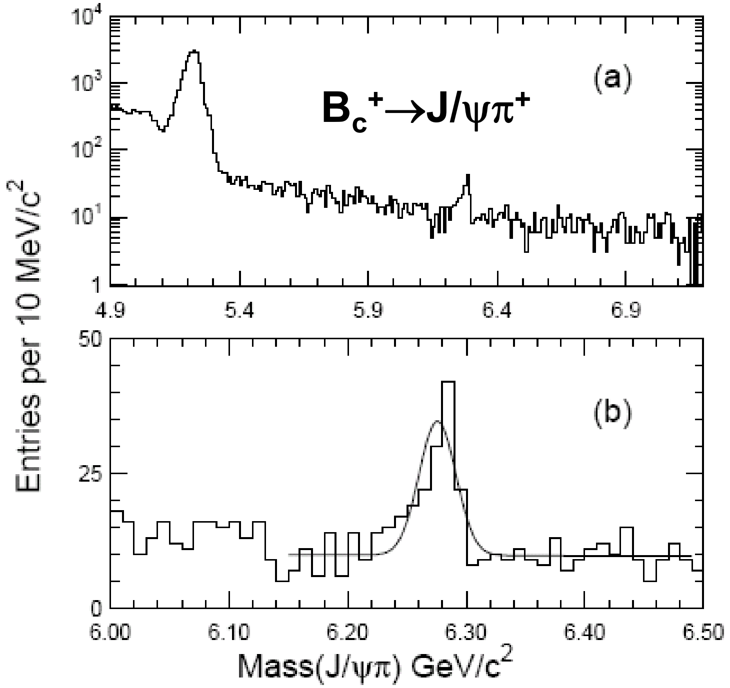
Signal significance > 5 σ

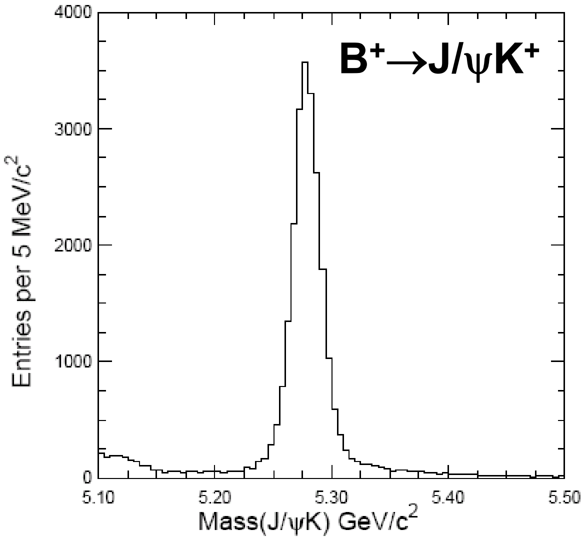
PRL 101, 012001 (2008)

$$M(B_c) = 6300 \pm 14\,(\mathrm{stat}) \pm 5\,(\mathrm{syst})\ \mathrm{MeV/c^2}$$

B_c mass measurement

- Exclusive reconstruction in $B_c^+ \to J/\psi \pi^+$
- Optimization in $B+ \to J/\psi K+$
- Data of 2.4 fb^{-1} integrated luminosity



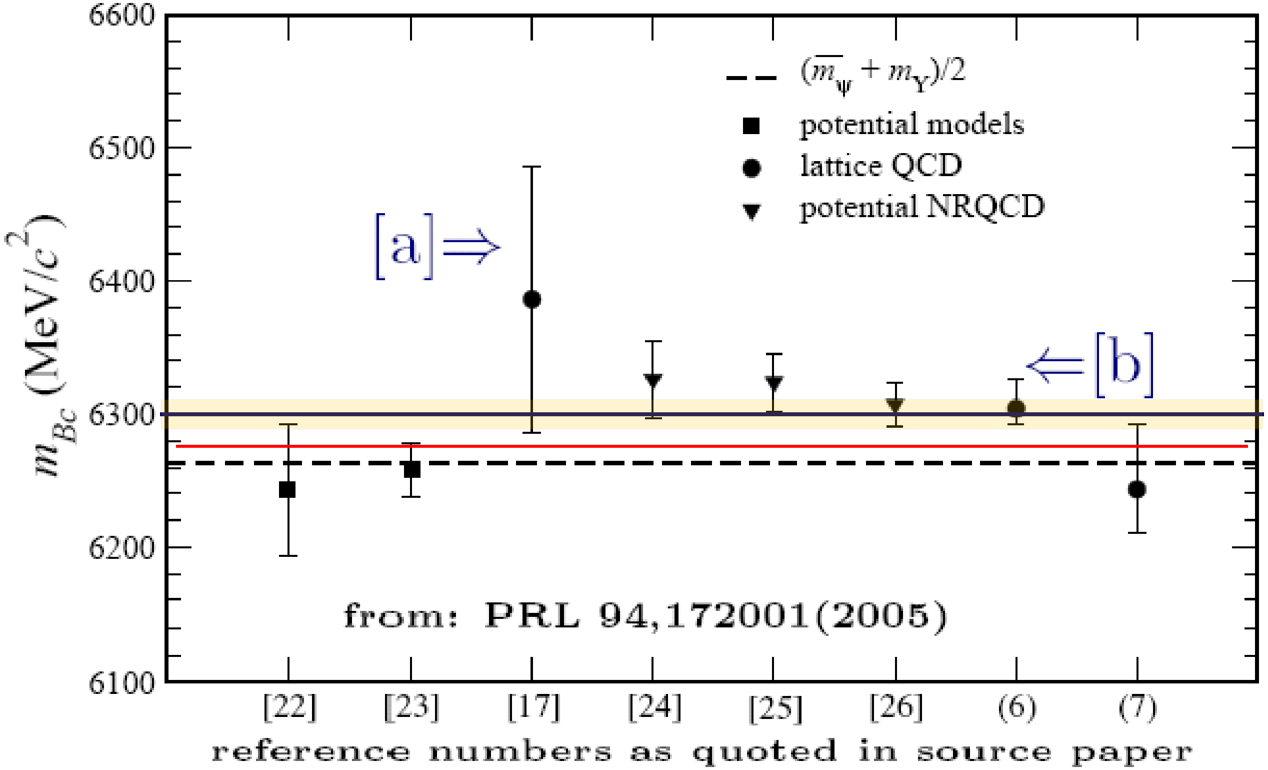


Signal significance > 8 σ

PRL 100, 182002 (2008)

$$M(B_c) = 6275.6 \pm 2.9\,(\text{stat}) \pm 2.5\,(\text{syst})\ \text{MeV/c}^2$$

B_c mass predictions



Lattice QCD:

- [a] Omitting sea quarks, (quenched approx.)
- [b] Add 2+1 sea flavors, u,d as light as possible, and strangeness mass

[a] PLB 455, 289 (1999)

$$M(B_c) = 6386 \pm 9 \pm 15 \pm 98 \text{ MeV}/c^2$$

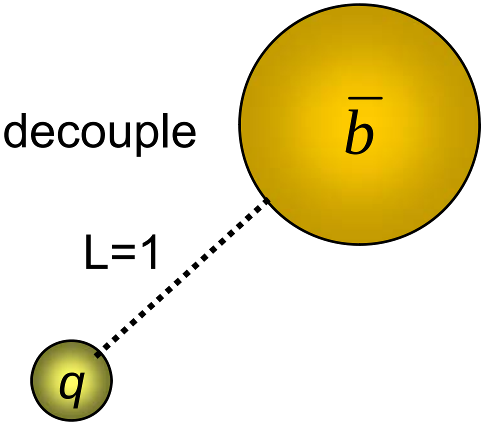
[b] PRL 94, 172001 (2005)

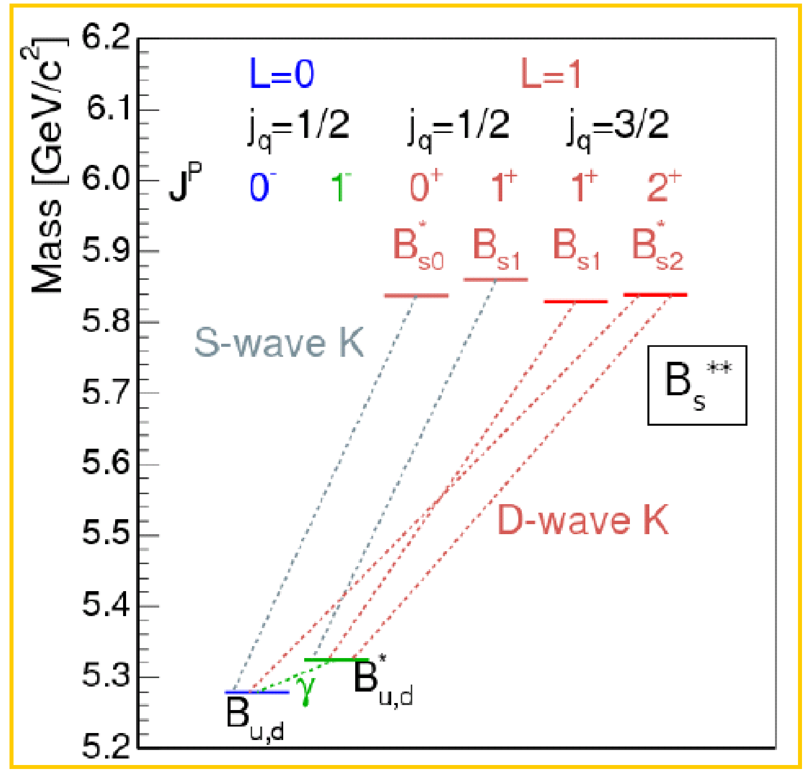
$$M(B_c) = 6304 \pm 4 \pm 11 \,^{+18}_{-0} \text{ MeV}/c^2$$

Excited (L=1) B_s mesons

HQET:

Spin of quarks decouple





j_q=1⊕1/2 — **1/2**, **3/2**

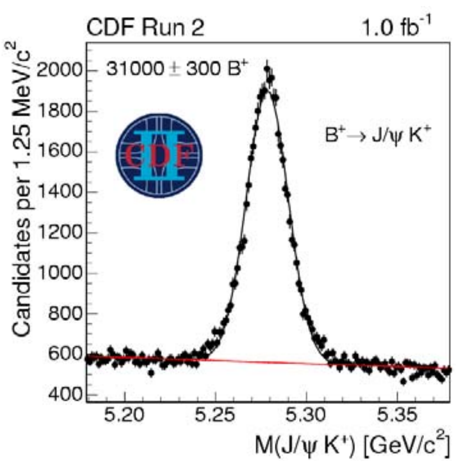
J=1/2⊕j_q — **1/2⊕1/2** → **1⁺**, **0⁺**; **1/2⊕3/2** → **2⁺**, **1⁺**

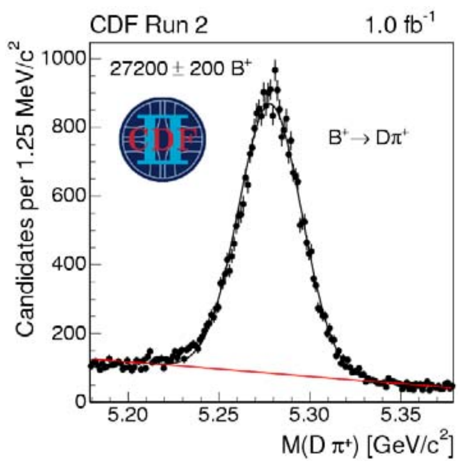
j_q=1/2 are wide states, we cannot observe them

j_q=3/2 are narrow states (we can look for them)

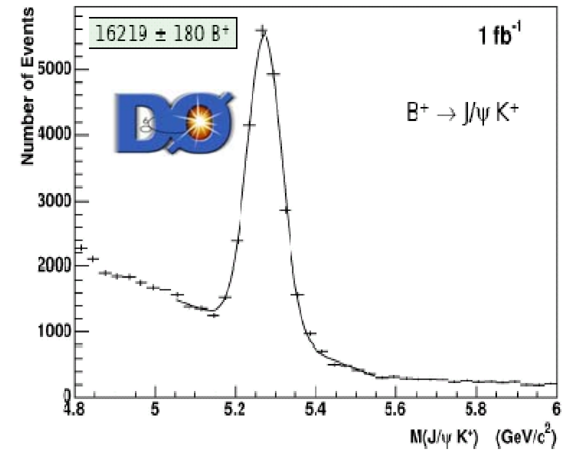
Search for narrow B_s^{**} mesons

- Reconstruct $B_s^{**} \rightarrow B^{(*)+}K^-$, $B^{*+} \rightarrow B^+\gamma$ (γ undetected), $B^+ \rightarrow J/\psi K^+$ (CDF & DØ) and $B^+ \rightarrow D^0\pi^+$ (CDF)

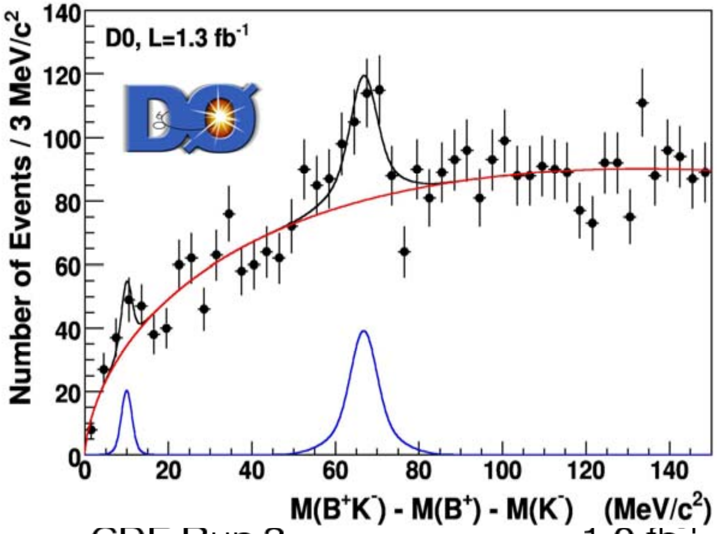




Use Neural Network to optimize both B^+ and B_s^{**}



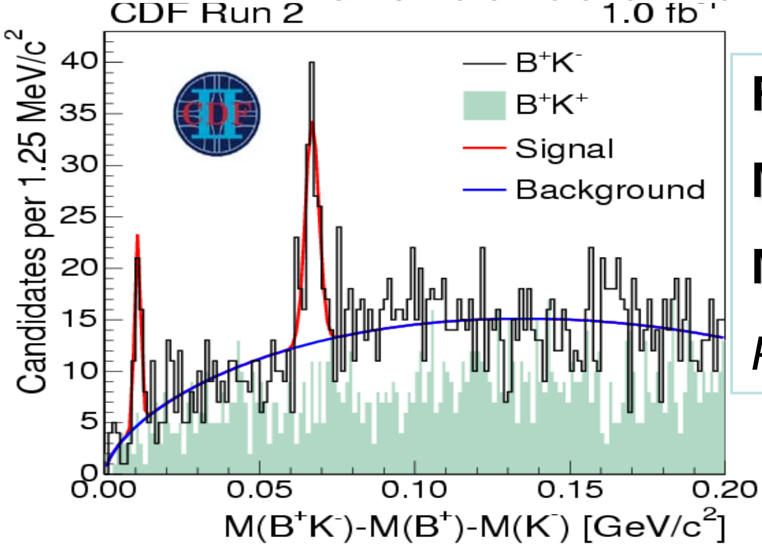
Excited (L=1) B_s mesons



First direct observation of B_{s2}^*

$M(B_{s2}^*) = 5839.6 \pm 1.1(stat) \pm 0.7\ (syst)\ GeV/c^2$

PRL ***100****, 082002 (2008)*



First observation of B_{s1}

$M(B_{s1}) = 5829.4 \pm 0.2 \pm 0.6\ GeV/c^2$

$M(B_{s2}^*) = 5839.6 \pm 0.4 \pm 0.5\ GeV/c^2$

PRL ***100****, 082001 (2008)*

B_{s1} signal significance > 5σ

When Tevatron Run II begun:

Notation	Quark content	J^P	SU(3)	(I,I_3)	S	Mass
Λ_b^0	**b[ud]**	**$1/2^+$**	**3***	**(0,0)**	**0**	**5619.7±1.2±1.2 MeV**
Ξ_b^0	b[su]	$1/2^+$	3*	(1/2,1/2)	-1	5.80 GeV
Ξ_b^-	b[sd]	$1/2^+$	3*	(1/2,-1/2)	-1	5.80 GeV
Σ_b^+	buu	$1/2^+$	6	(1,1)	0	5.82 GeV
Σ_b^0	b{ud}	$1/2^+$	6	(1,0)	0	5.82 GeV
Σ_b^-	bdd	$1/2^+$	6	(1,-1)	0	5.82 GeV
$\Xi_b^{0'}$	b{su}	$1/2^+$	6	(1/2,1/2)	-1	5.94 GeV
$\Xi_b^{-'}$	b{sd}	$1/2^+$	6	(1/2,-1/2)	-1	5.94 GeV
Ω_b^-	bss	$1/2^+$	6	(0,0)	-2	6.04 GeV
Σ_b^{*+}	buu	$3/2^+$	6	(1,1)	0	5.84 GeV
Σ_b^{*0}	bud	$3/2^+$	6	(1,0)	0	5.84 GeV
Σ_b^{*-}	bdd	$3/2^+$	6	(1,-1)	0	5.84 GeV
Ξ_b^{*0}	bus	$3/2^+$	6	(1/2,1/2)	-1	5.94 GeV
Ξ_b^{*-}	bds	$3/2^+$	6	(1/2,-1/2)	-1	5.94 GeV
Ω_b^{*-}	bss	$3/2^+$	6	(0,0)	-2	6.06 GeV

from hep-ph/9406359

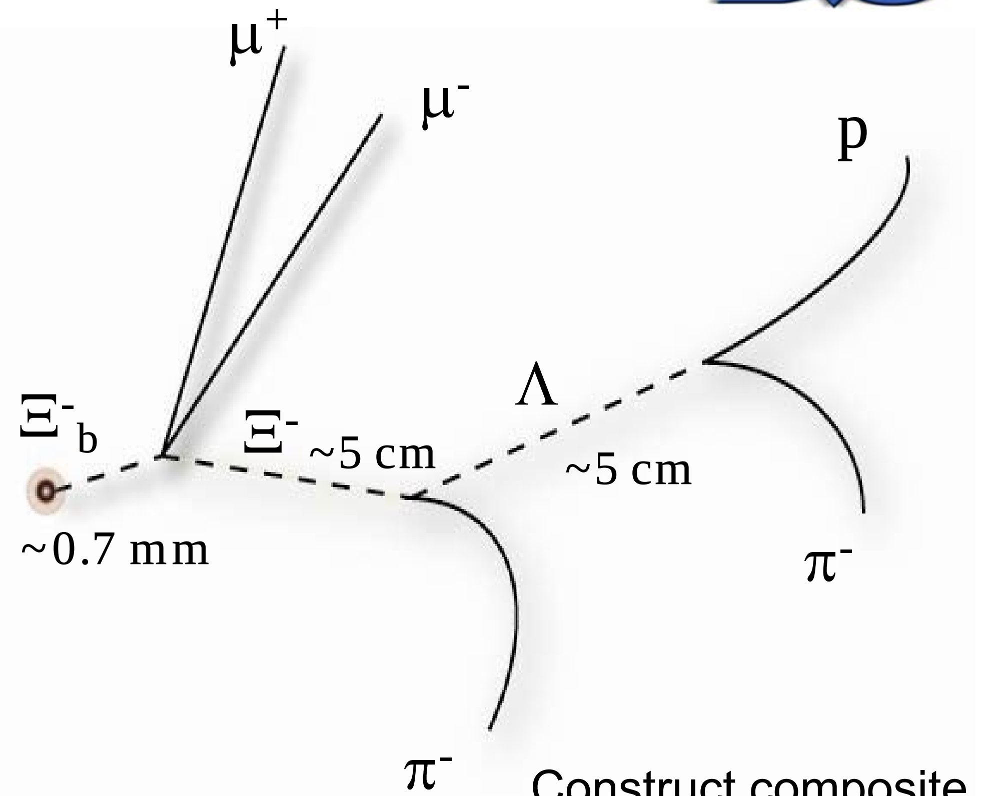
During Tevatron Run II

Notation	Quark content	J^P	SU(3)	(I,I_3)	S	Mass
Λ_b^0	b[ud]	$1/2^+$	3*	(0,0)	0	5620.2 ± 1.6 MeV
Ξ_b^0	b[su]	$1/2^+$	3*	(1/2,1/2)	-1	5.80 GeV
Ξ_b^-	b[sd]	$1/2^+$	3*	(1/2,-1/2)	-1	5792.4 ± 3.0 MeV
Σ_b^+	buu	$1/2^+$	6	(1,1)	0	5807.8 ± 2.7 MeV
Σ_b^0	b{ud}	$1/2^+$	6	(1,0)	0	5.82 GeV
Σ_b^-	bdd	$1/2^+$	6	(1,-1)	0	5815.2 ± 2.0 MeV
$\Xi_b^{0'}$	b{su}	$1/2^+$	6	(1/2,1/2)	-1	5.94 GeV
$\Xi_b^{-'}$	b{sd}	$1/2^+$	6	(1/2,-1/2)	-1	5.94 GeV
Ω_b^-	bss	$1/2^+$	6	(0,0)	-2	6.04 GeV
Σ_b^{*+}	buu	3/2+	6	(1,1)	0	5829.0 ± 3.4 MeV
Σ_b^{*0}	bud	$3/2^+$	6	(1,0)	0	5.84 GeV
Σ_b^{*-}	bdd	$3/2^+$	6	(1,-1)	0	5836.4 ± 2.8 MeV
Ξ_b^{*0}	bus	$3/2^+$	6	(1/2,1/2)	-1	5.94 GeV
Ξ_b^{*-}	bds	$3/2^+$	6	(1/2,-1/2)	-1	5.94 GeV
Ω_b^{*-}	bss	$3/2^+$	6	(0,0)	-2	6.06 GeV

Search for $\Xi_b^- \to J/\psi \Xi \to (\mu+\mu-)\Lambda\pi-$

Reconstruction procedure:

- Reconstruct $J/\psi \to \mu^+\mu^-$
- Reconstruct $\Lambda \to p\pi$
- Reconstruct $\Xi \to \Lambda + \pi$
- Combine $J/\psi + \Xi$
- Improve mass resolution by using an event-by-event mass difference correction
- **The optimization:**
  1. **$\Lambda_b \to J/\psi\Lambda$ decays in data**
  2. **$J/\psi + \Xi$(fake from $\Lambda(p\pi^-)\pi^+$)**
  3. **Monte Carlo simulation of $\Xi_b^- \to J/\psi + \Xi^-$**



Construct composite particle from $\Lambda\pi$.

Ξ_b^- Search optimization

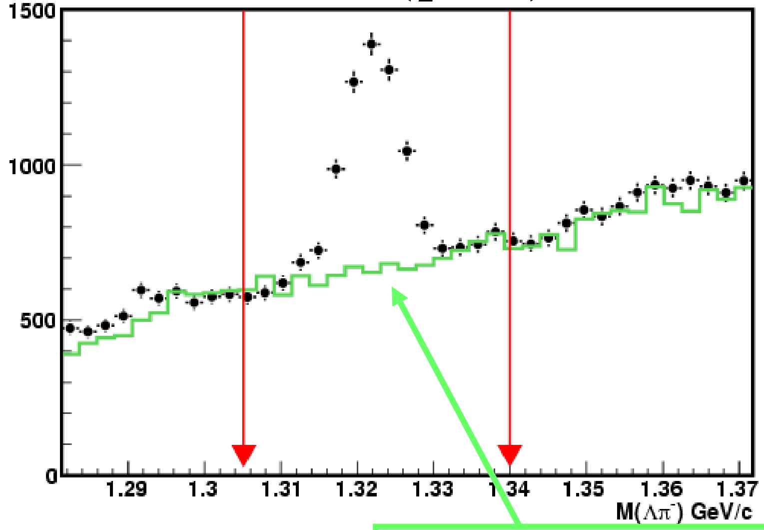
Final Ξ_b selection cuts:

- $\Lambda \to p\pi$ decays:
  - $p_T(p)>0.7$ GeV
  - $p_T(\pi)>0.3$ GeV
- $\Xi^- \to \Lambda\pi$ decays:
  - $p_T(\pi)>0.2$ GeV
  - Transverse decay length>0.5 cm
  - Collinearity>0.99
- Ξ^-_b particle:
  - Lifetime significance>2. (Lifetime divided by its error)

Based on:

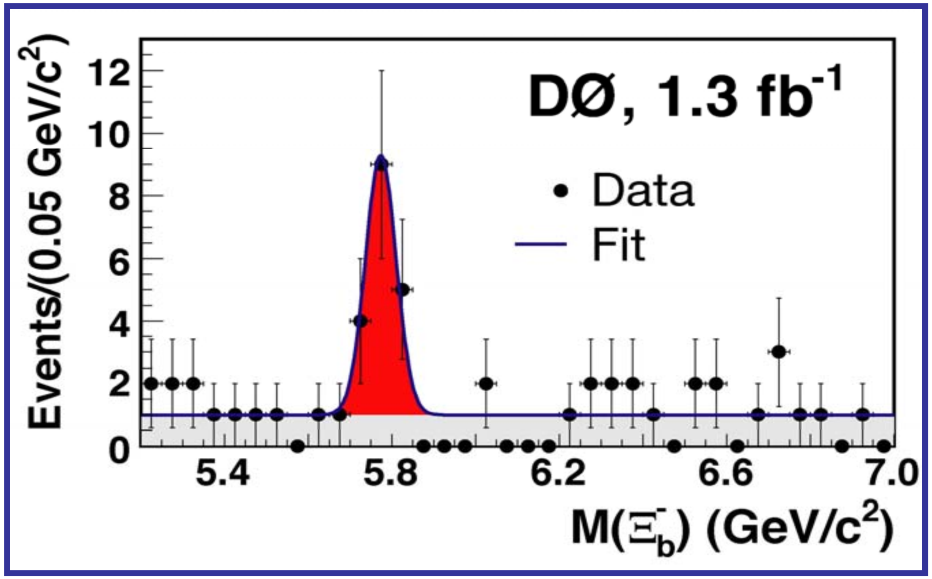
- $\Lambda_b \to J/\psi\Lambda$ decays in data
- J/ψ + Ξ(fake from $\Lambda(p\pi-)\pi+$)

$$\Xi^- \to \Lambda(p\pi^-)\pi^-$$



Background events from wrong-sign combinations ($\Lambda(p\pi^-)\ \pi^+$)

Ξ^-_b observation (DØ)



- Fit:
  - Unbinned extended log-likelihood fit
  - Gaussian signal, flat background
  - Number of background/signal events are floating parameters

Number of events: 15.2 ± 4.4

Mass: 5.774 ± 0.011(stat) GeV

Width: 0.037 ± 0.008 GeV

Signal Significance:

$$\sqrt{-2\Delta \ln L} = \sqrt{-2\ln\left(\frac{L_B}{L_{S+B}}\right)} = 5.5\sigma$$

We also measured:

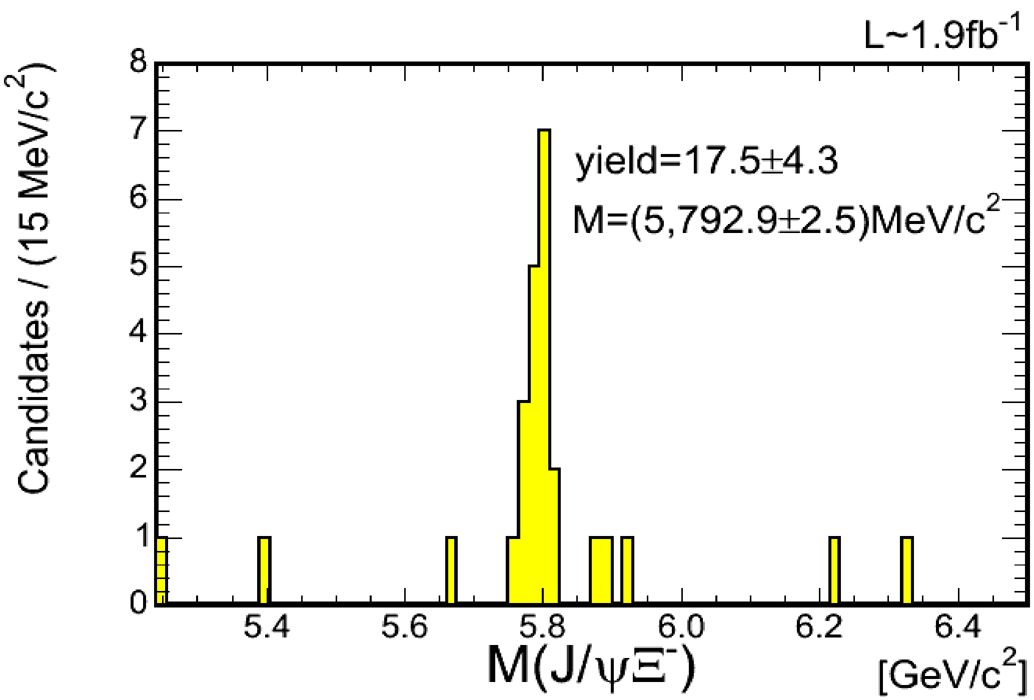
$$R = \frac{\sigma(\Xi_b^-)BR(\Xi_b^- \to J/\psi\ \Xi^-)}{\sigma(\Lambda_b)BR(\Lambda_b \to J/\psi\Lambda)}$$

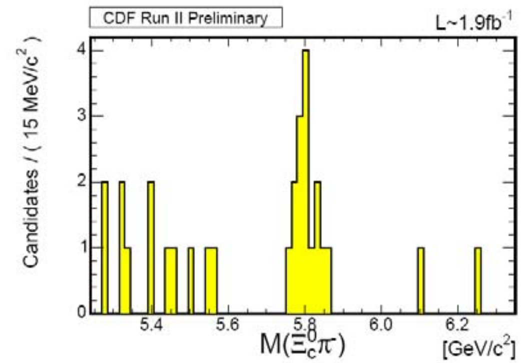
$$R = 0.28 \pm 0.09\ (\text{stat})\ {}^{+0.09}_{-0.08}\ (\text{syst})$$

$$M(\Xi_b^-) = 5.774 \pm 0.011\,(\text{stat}) \pm 0.015\,(\text{syst})$$

PRL 99, 052001 (2007)

Ξ^-_b observation (CDF)





Also searched for in $\Xi_b^- \rightarrow \Xi_c^0 \pi^-$

Error source	value
Tracking Momentum scale	$\delta m = \pm 0.4$ MeV/c^2
PDG Masses(J/ψ, Ξ, Λ)	$\delta m = \pm 0.14$ MeV/c^2
Mass scale calibration	$\delta m = \pm 0.6$ MeV/c^2
Fit model/resolution	$\delta m = \pm 1.5$ MeV/c^2
Total	$\delta m = \pm 1.7$ MeV/c^2

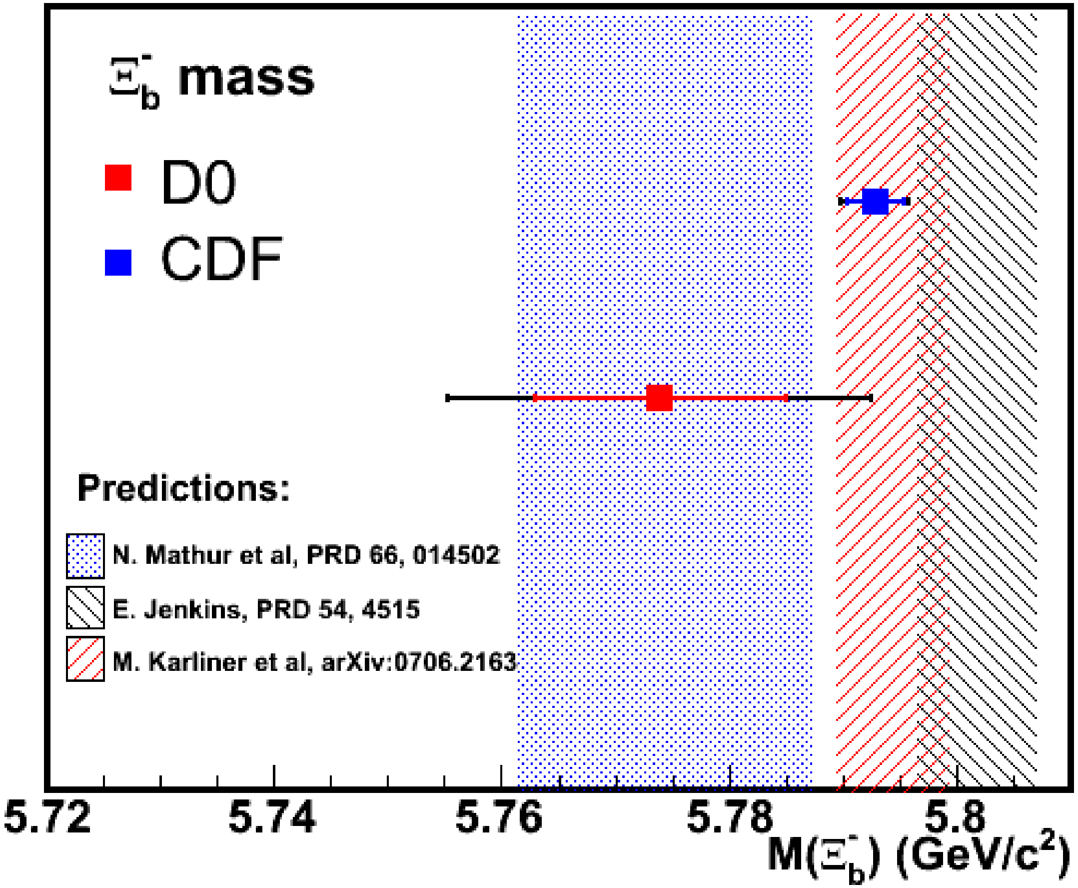
M(Ξ_b^-) = 5792.9 ± 2.5 (stat) ± 1.7 (syst) MeV/c^2

Signal significance = 7.8σ

Updated 2009 mass measurement in G.Punzi talk

PRL 99, 052002 (2007)

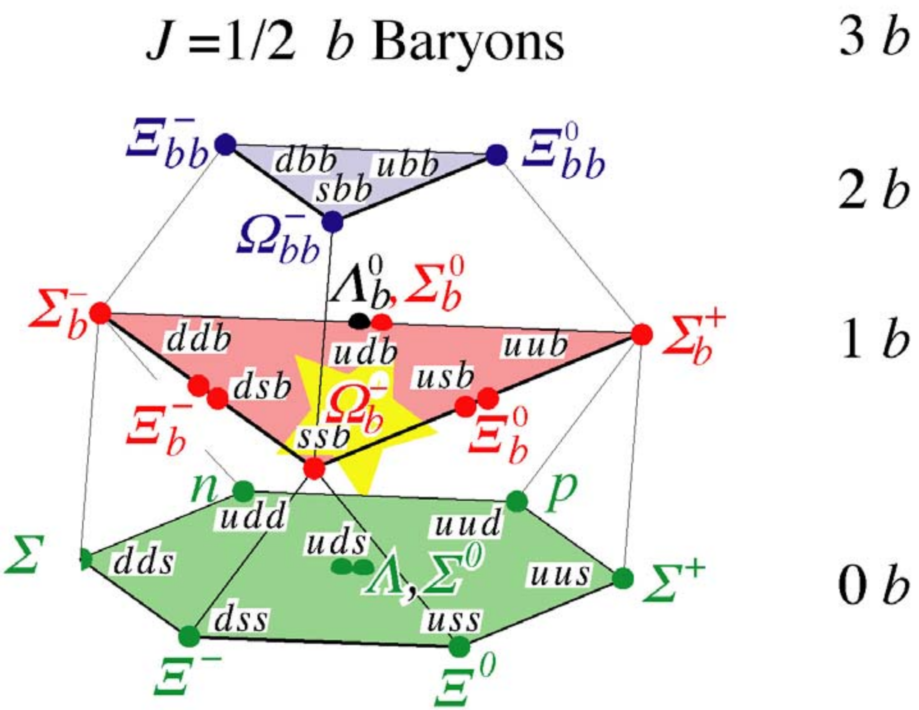
Comparison: Experiment/Theory



DØ PRL 99, 052001 (2007)

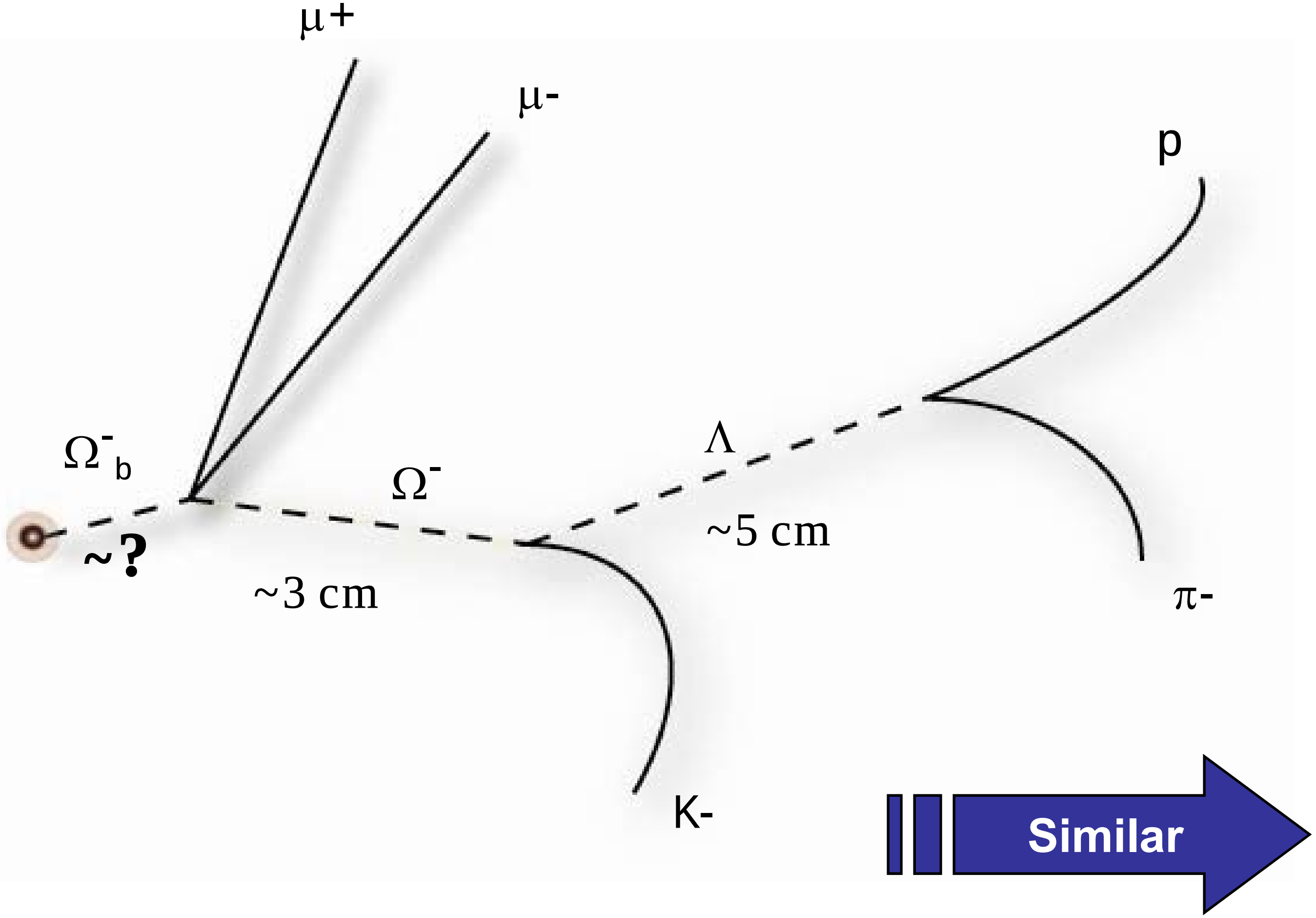
CDF PRL 99, 052002 (2007)

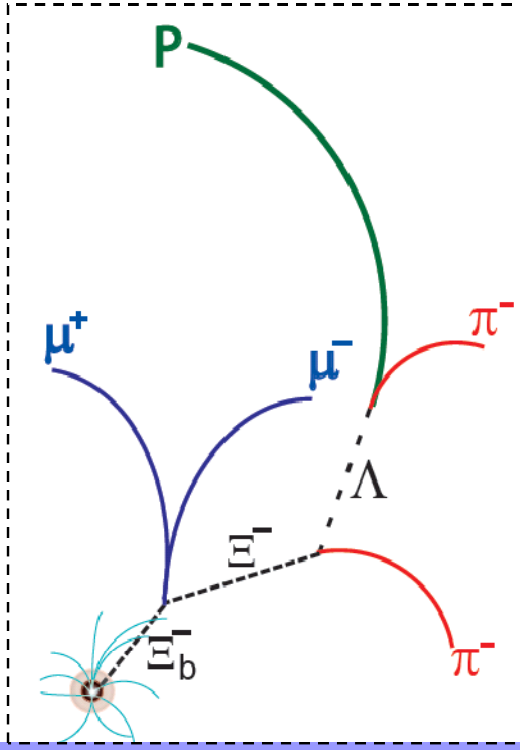
Search for the Ω^-_b(bss)



- *bss* quarks combination
- Mass is predicted to be 5.94 - 6.12 GeV
- $M(\Omega^-_b) > M(\Lambda_b)$
- Lifetime is predicted to be $0.83<\tau(\Omega^-_b)<1.67$ ps

How do we look for it?

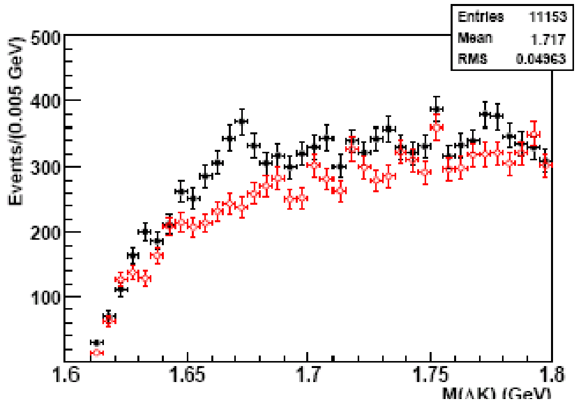


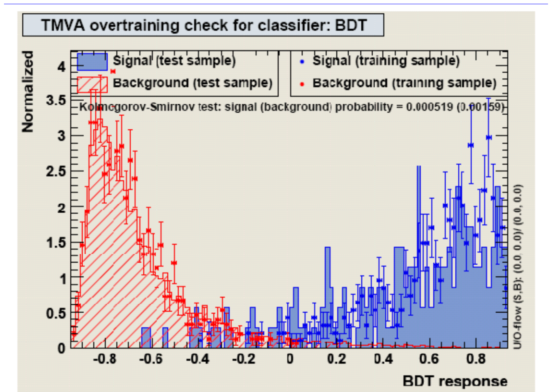


Analysis strategy

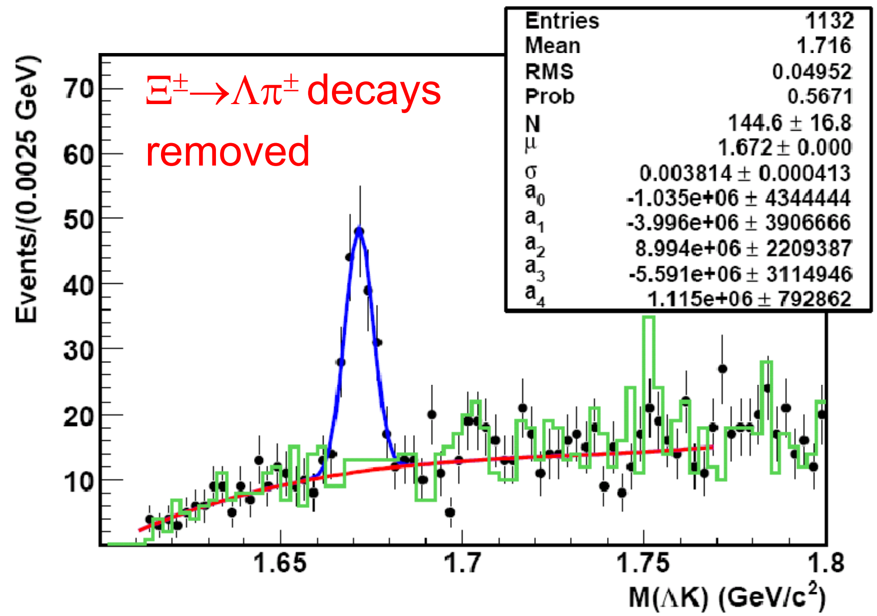
Select J/ψ candidates	Events are reprocessed to increase reconstruction efficiency of long-lived particles.
Select $\Lambda \rightarrow p\pi$	Yield is optimized by using proper decay length significance cuts.
Reconstruction of $\Omega \rightarrow \Lambda + K$	Optimize yield by using multivariate techniques
Combine $J/\psi + (\Lambda K^+)$	Keep blinded $J/\psi + \Omega$ combinations and optimize on $J/\psi + (\Lambda K^+)$
Event per event mass correction	Improve mass resolution from 80 MeV to 34 MeV
Fix selection criteria and then apply them to $J/\psi + \Omega$	Perform as many test as possible in different background samples

BDT to select $\Omega^- \to \Lambda K$ decays



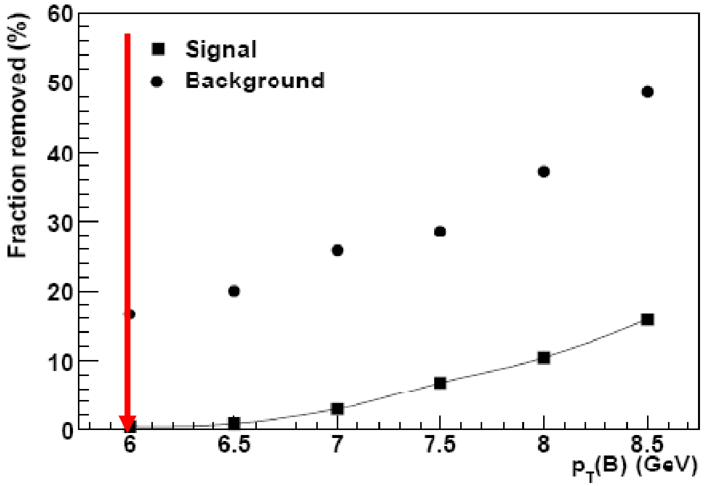


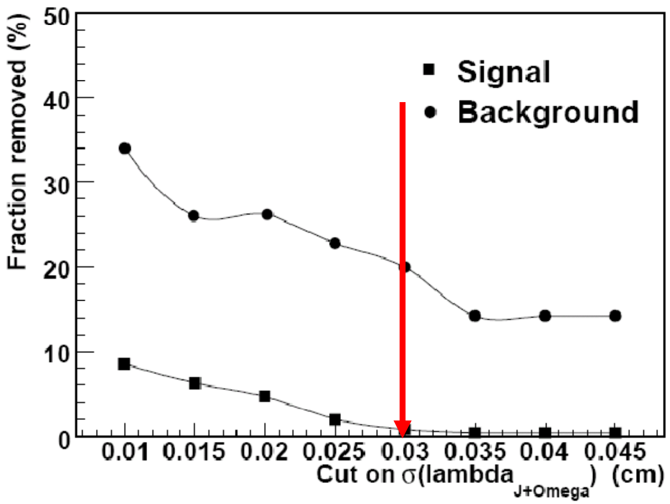
Variable description
Λ vertex χ^2
Λ collinearity
Λ lifetime significance
p track (from Λ) χ^2
p (from Λ) combined impact parameter significance
p track SMT hits
p track CFT hits
π track (from Λ) χ^2
π (from Λ) combined impact parameter significance
π track SMT hits
π track CFT hits
p (from Λ) p_T
π (from Λ) p_T
Λ transverse decay length
Error on Λ transverse decay length
Error on Ω^- transverse decay length
Ω^- transverse decay length
Ω^- collinearity
K^- (from Ω^-) p_T
K^- (from Ω^-) combined impact parameter significance



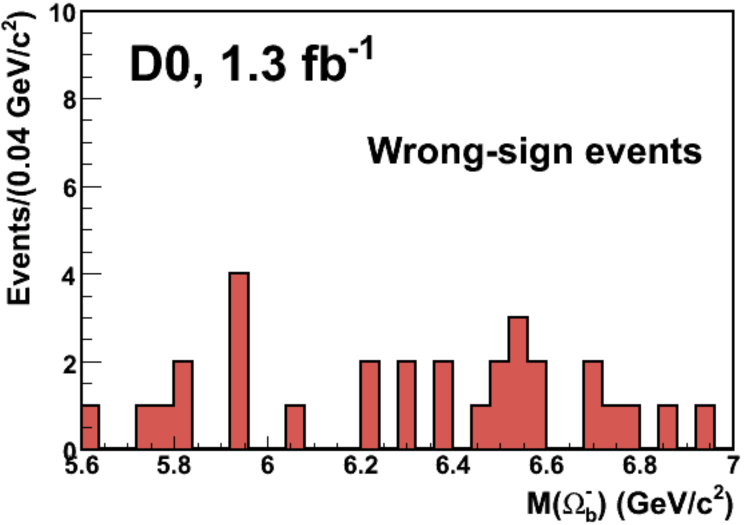
Final optimization

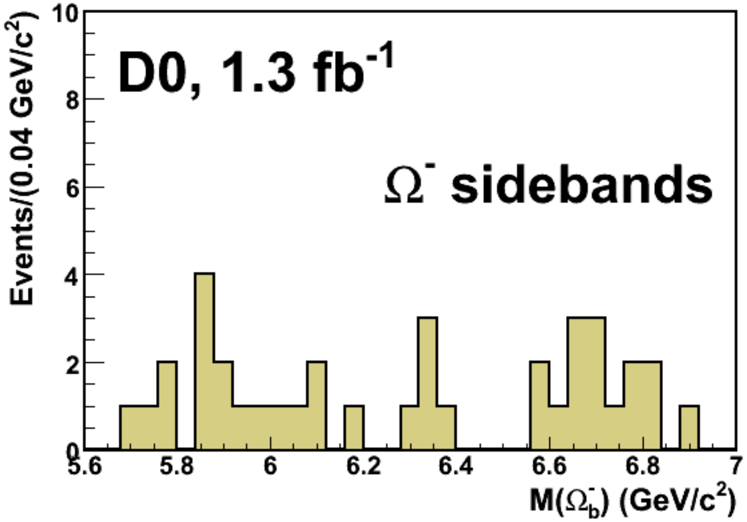
- We compare MC signal vs wrong-sign background events.

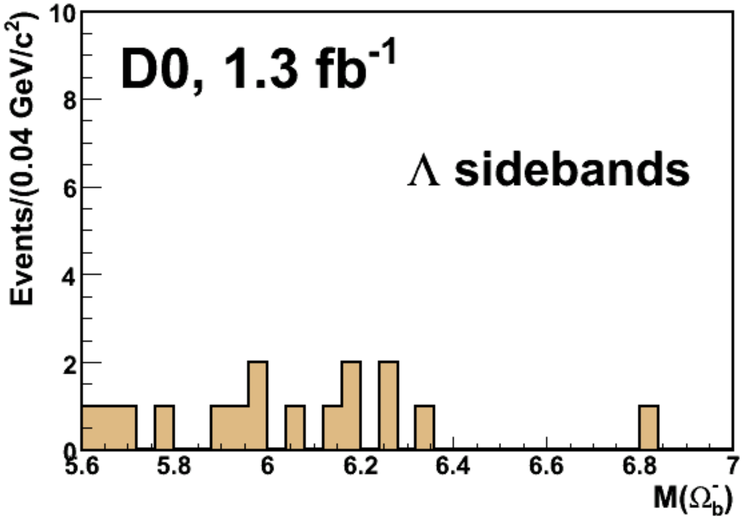




Nothing where nothing should be







We check also high statistics MC samples

$$\Lambda_b \to J/\psi\Lambda \to (\mu^+\mu^-)(p\pi^-)$$

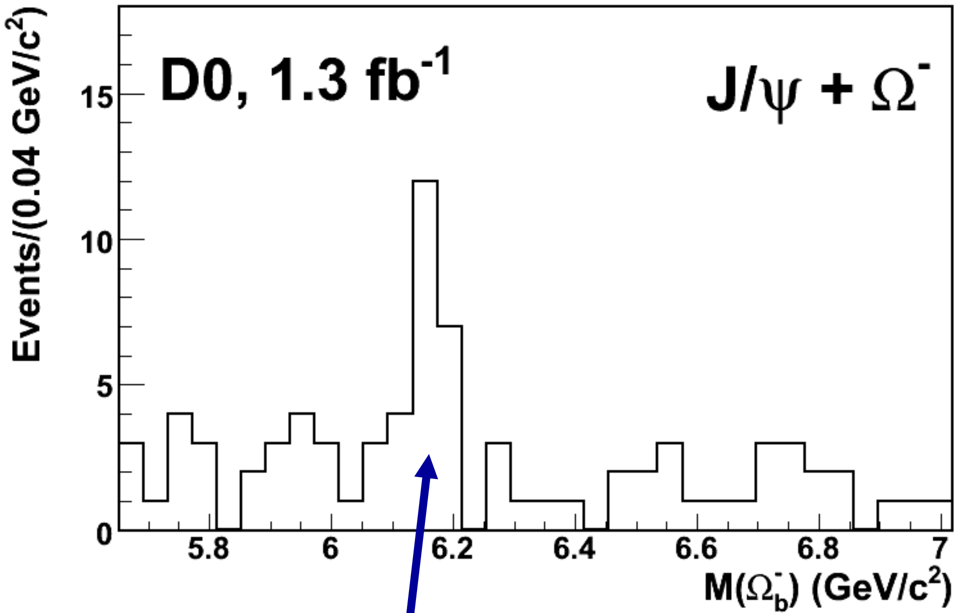
$$B^- \to J/\psi K^{*-} \to (\mu^+\mu^-)(K_S^0\pi^-) \to (\mu^+\mu^-)((\pi^+\pi^-)\pi^-)$$

$$\Xi_b^- \to J/\psi\Xi^- \to (\mu^+\mu^-)(\Lambda\pi^-) \to (\mu^+\mu^-)((p\pi^-)\pi^-)$$

No excess is observed in any control samples after selection criteria is applied to them.

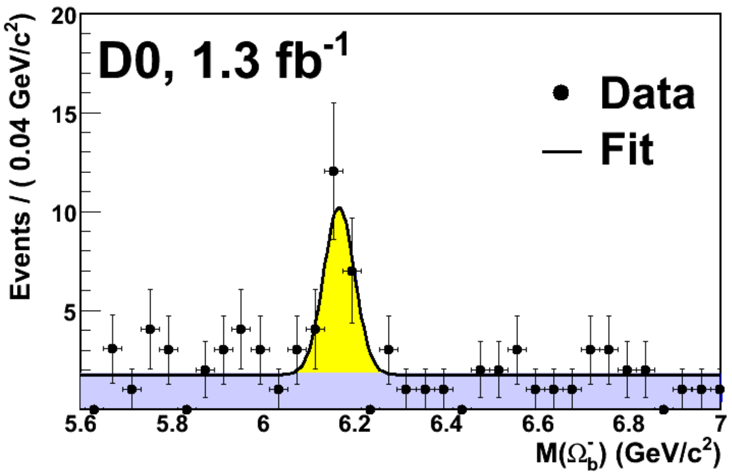
Looking at right-sign combinations

- After optimization:
  - σ_λ<0.03 cm
  - J/ψ and Ω in the same hemisphere
  - $p_T(J/\psi+\Omega)$>6 GeV
- Mass window for the search: 5.6 - 7 GeV



Clear excess of events near 6.2 GeV

Ω_b^- mass measurement



- Fit:
  - Unbinned extended log-likelihood fit
  - Gaussian signal, flat background
  - Number of background/signal events are floating parameters

N= 17.8 ± 4.9 (stat) ± 0.8(syst)

Mass: 6.165 ± 0.010(stat) ± 0.013(syst) GeV

Width fixed (MC): 0.034 GeV

$$\sqrt{-2\Delta \ln L} = \sqrt{-2\ln\left(\frac{L_B}{L_{S+B}}\right)} = 5.4\sigma$$

$$M(\Omega_b^-) = 6.165 \pm 0.010(\text{stat}) \pm 0.013(\text{syst})\ \text{GeV}$$

$$R = \frac{f(b \to \Omega_b^-) Br(\Omega_b^- \to J/\psi\ \Omega^-)}{f(b \to \Xi_b^-) Br(\Xi_b^- \to J/\psi\ \Xi^-)}$$

$$R = 0.80 \pm 0.32(stat)^{+0.14}_{-0.22}(syst)$$

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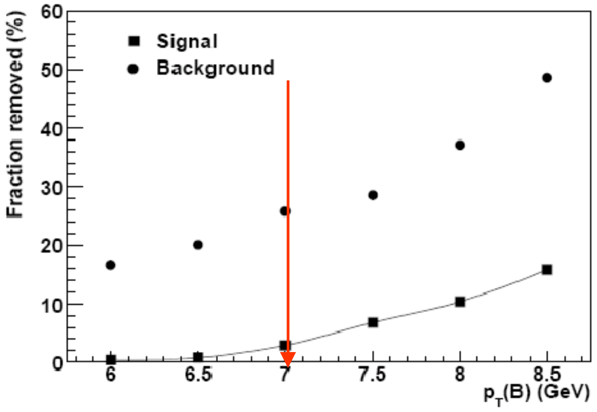
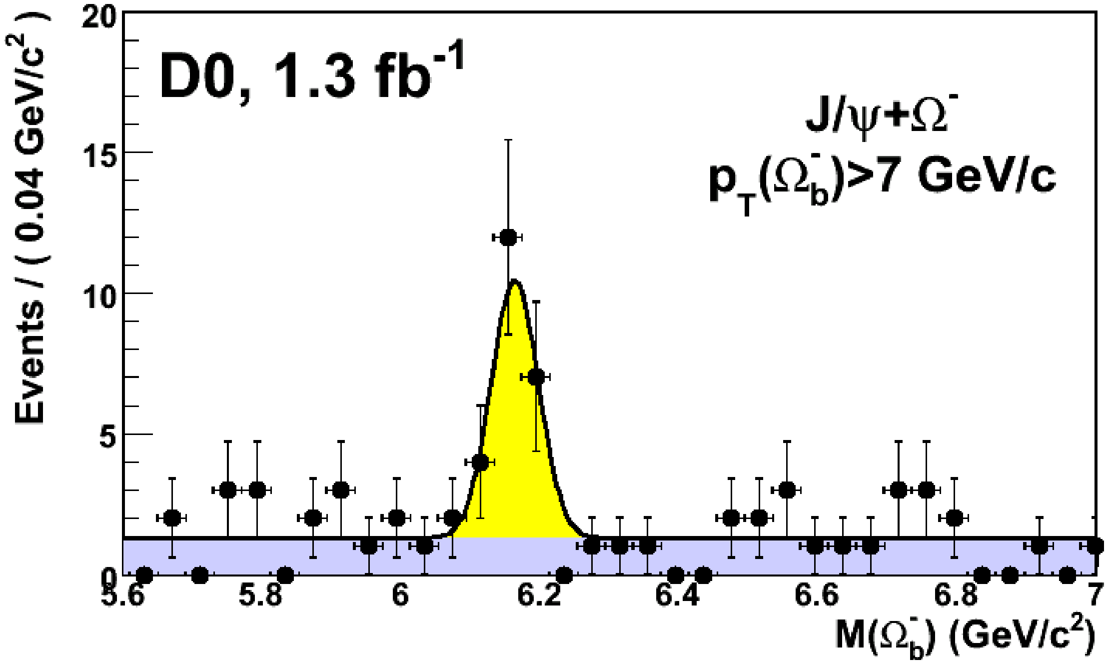
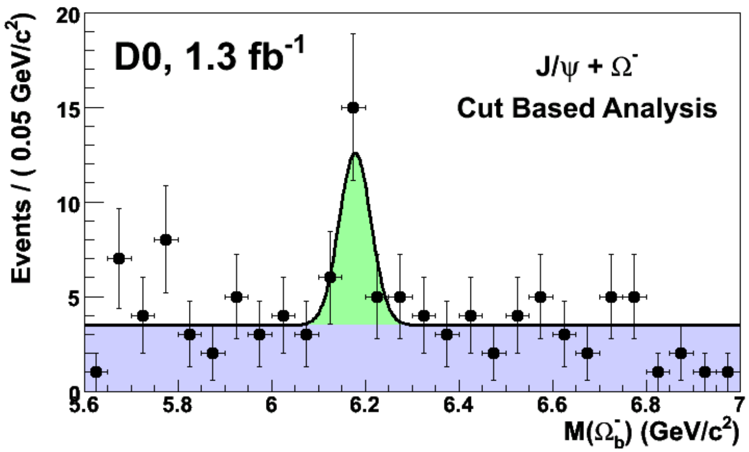
Consistency check: Increase $p_T(B)$





Significance >6

Cut Based Analysis (CBA)



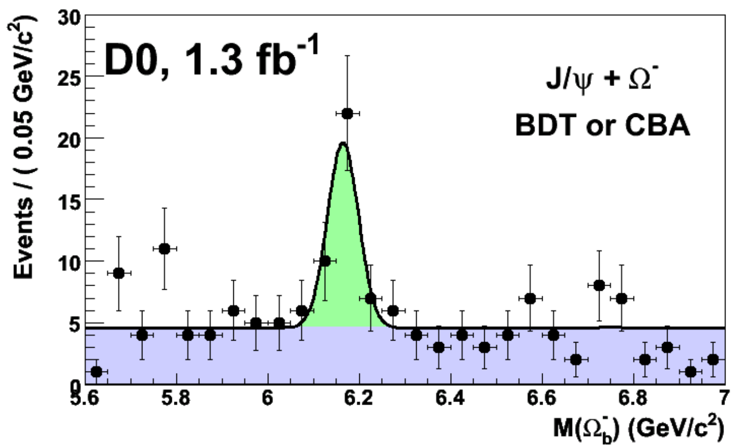
Variable	BDT	CBA
$p_T(\pi)$ (GeV)	>0.2 and input to BDT	>0.2
$p_T(p)$ (GeV)	>0.2 and input to BDT	>0.7
$p_T(K)$ (GeV)	input to BDT	>0.3
Ω^- collinearity	input to BDT	>0.99
Ω^- transverse decay length (cm)	input to BDT	>0.5
Proper decay length uncertainty (cm)	<0.3	<0.3

Number of signal events: 15.7 ± 5.3

Mean : 6.177 ± 0.015(stat) GeV

Width fixed (MC): 0.034 GeV

Signal significance: 3.9σ



- After remove duplicate events, we observe 25.5 ± 6.5 events.
- Significance: 5.4σ

Summary

Many unique results coming from Tevatron:

- First direct observation of B_{s1} and B_{s2}^*
- Precise measurement of the B_c mass.
- First observation of Ξ_b^- and Ω_b^- baryons
- Not shown here:
  - Precise B** mass measurement
  - First observation of Σ_b^- and Σ_b^{*-} baryons
  - Limits in η_b production
  - And many more results …

http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm
http://www-cdf.fnal.gov/physics/new/bottom/bottom.html