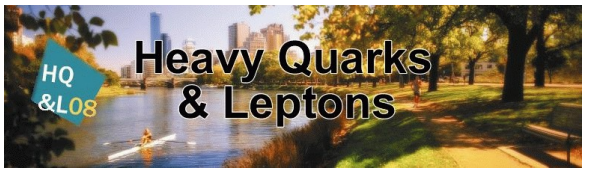
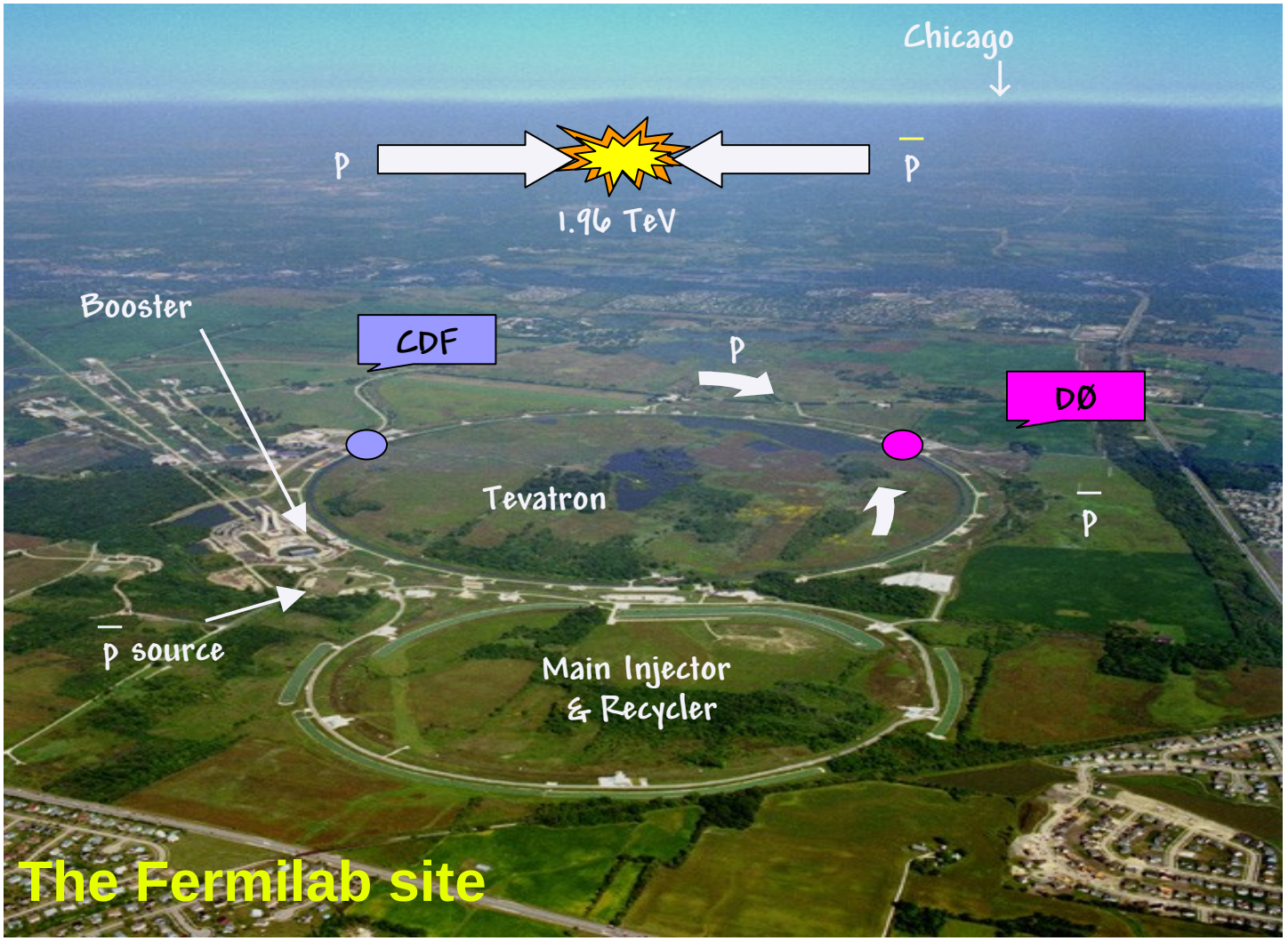
B States at the Tevatron



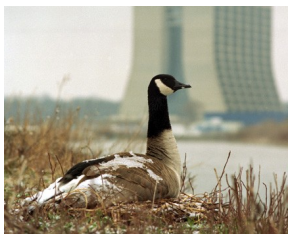
Manfred Paulini
Carnegie Mellon University
6 June 2008
HQL08 Conference
Melbourne, Australia

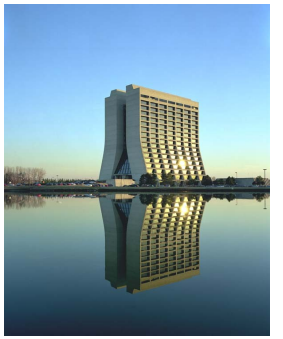
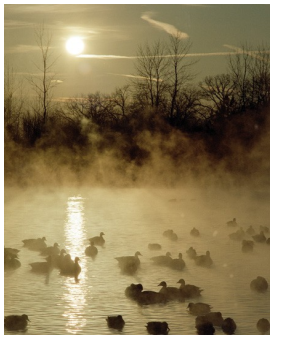
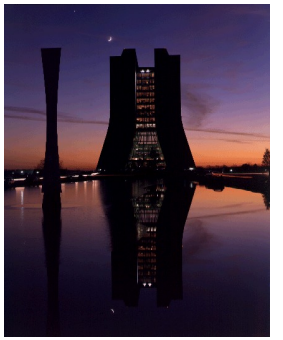
- Introduction
- Mesons
  - Excited B states: B^{**}, B_S^{**}
  - B_c mass
- Baryons
  - Σ_b states: masses
  - Ξ_b discovery
- Conclusion .....

Fermilab



The Fermilab site

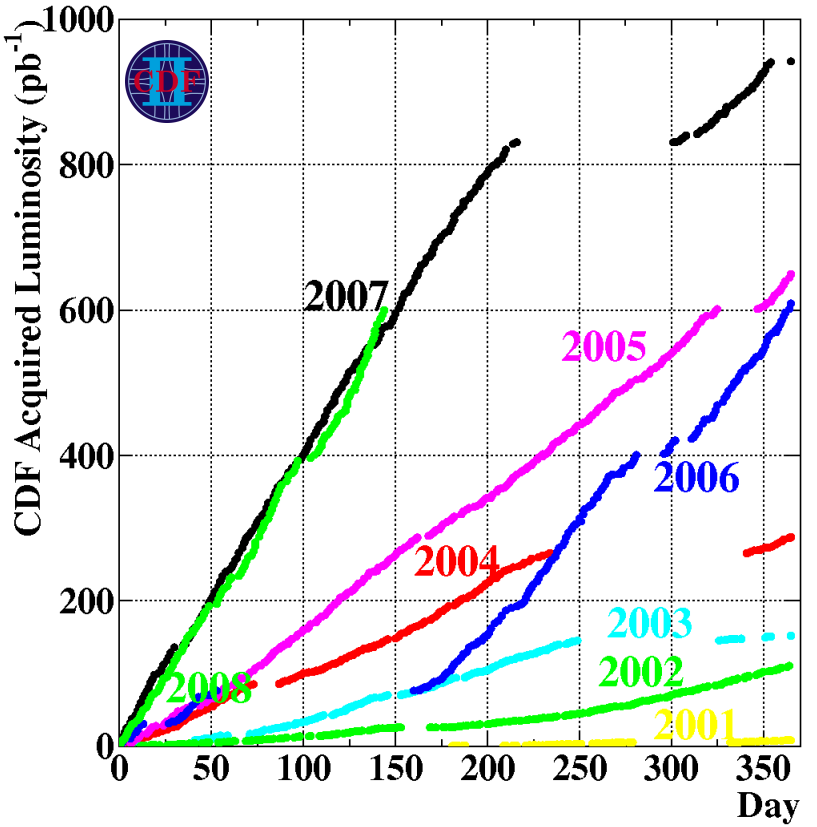


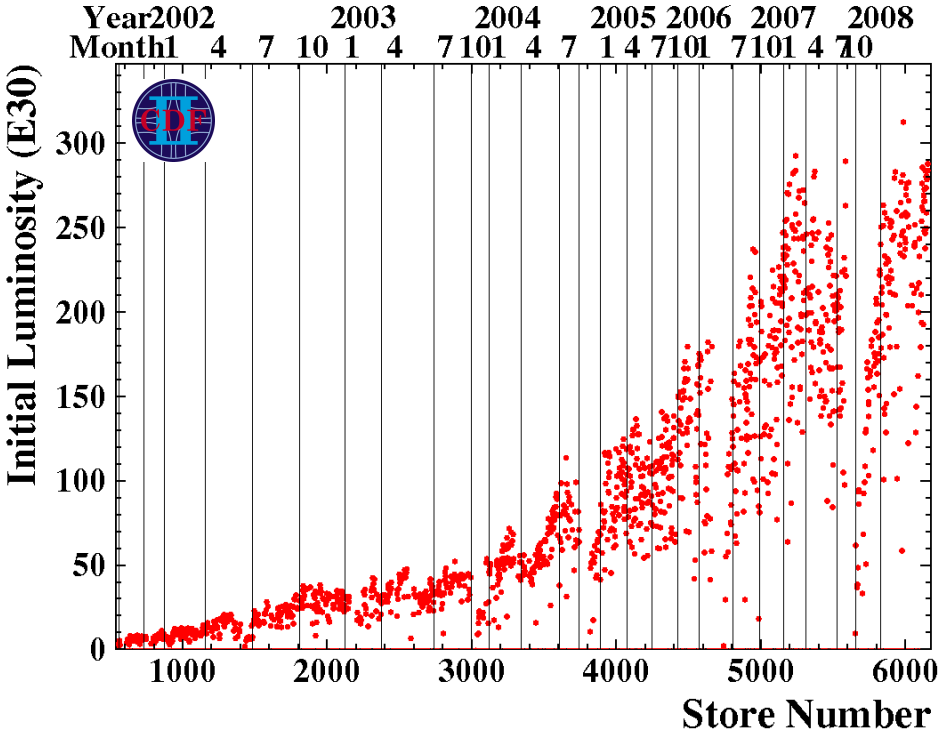




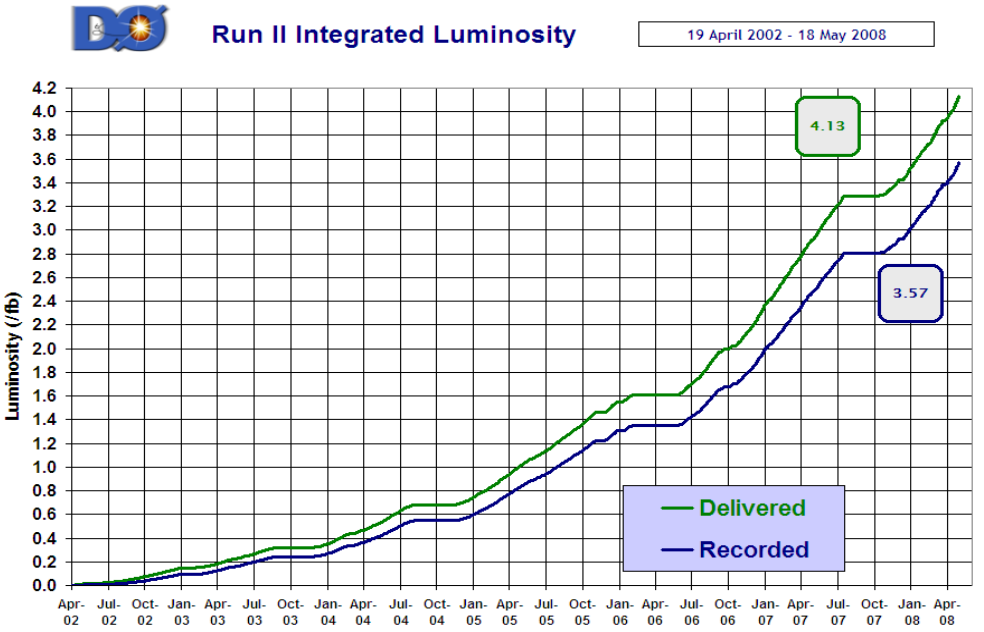
Tevatron Performance

Just keeps running well:

- Typical weekly int. lumi 30-40 pb^{-1}
- Record initial luminosity:
  $31.2 \times 10^{31}\ sec^{-1}\ cm^{-2}$ (03/08)
- ~3.5 fb^{-1} on tape (> 4.1 fb^{-1} deliv.)
- ~1-3 fb^{-1} used for analysis



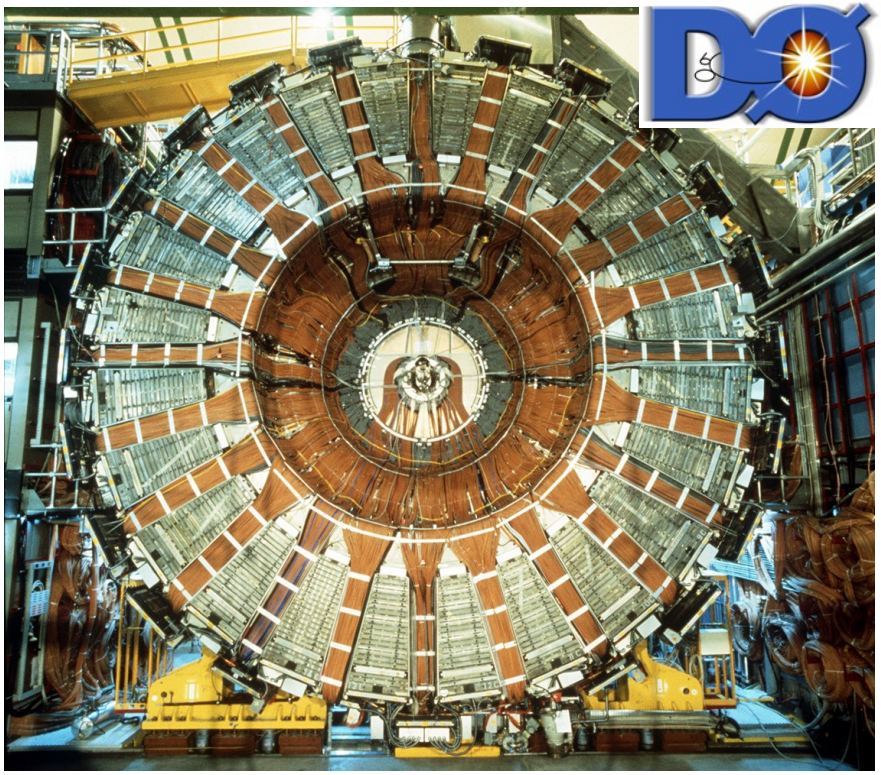




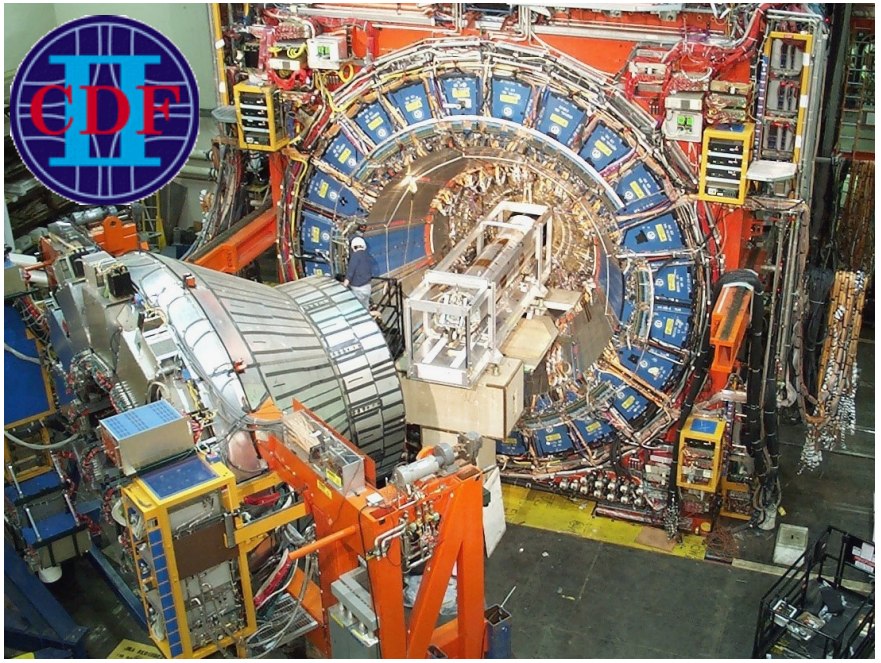
CDF & D0 Experiments

Strength of both Detectors:

- Silicon vertex trackers
- Central tracking in solenoid
- High rate trigger / DAQ
- Calorimeters and muon systems



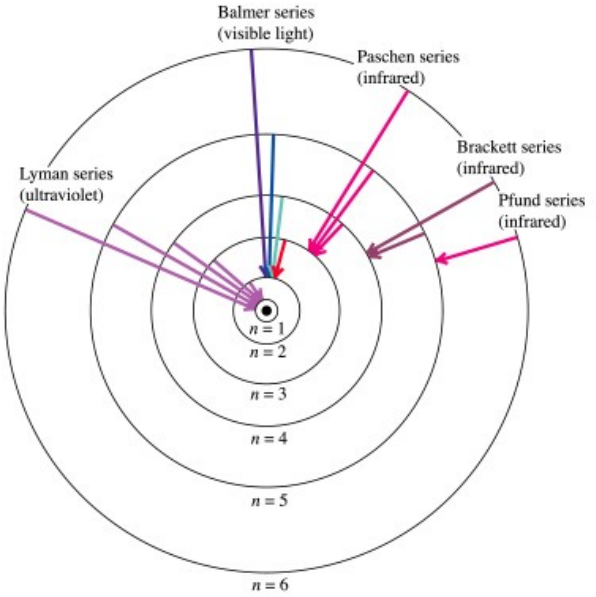
Good electron, muon ID and acceptance
Excellent tracking acceptance $|\eta| < 2\text{-}3$

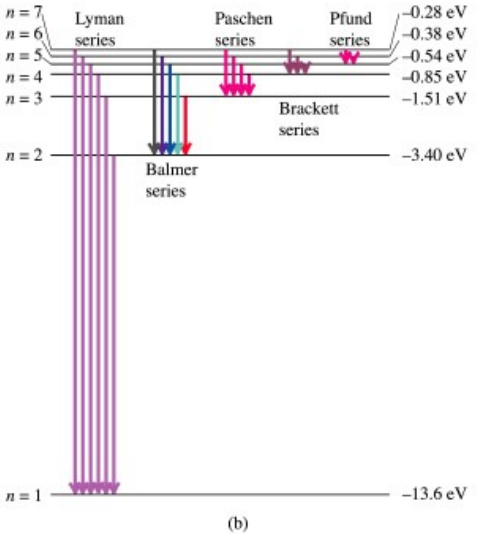


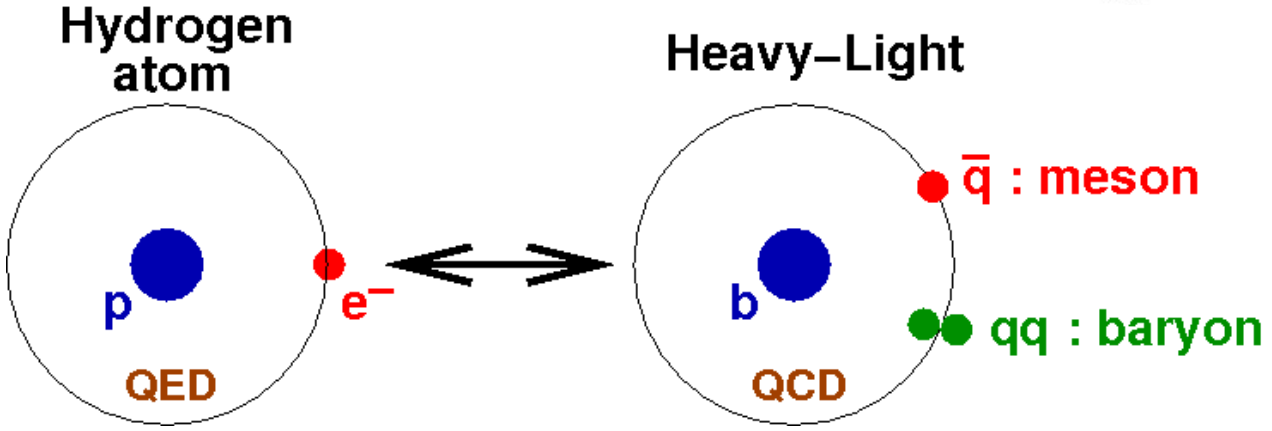
L2 trigger on displaced vertices
Excellent tracking resolution
Good low momentum PID

Motivation

From hydrogen atom
to B hadron spectroscopy



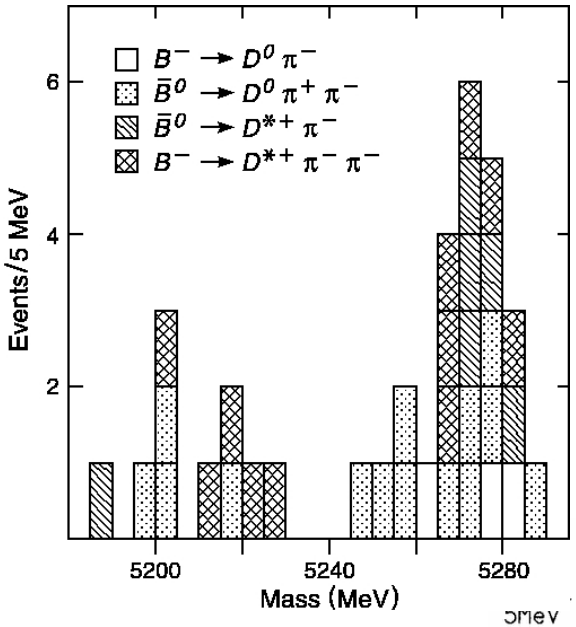




- **Heavy quark hadrons are the hydrogen atom of QCD**
  => study of B hadron states = study of (non-perturbative) QCD
- **Provide sensitive tests of potential models, HQET and all aspects of QCD including lattice gauge calculations**

How it all began ...

First fully reconstructed B hadron states:



CLEO 1983

PRL 50, 881 (1983)

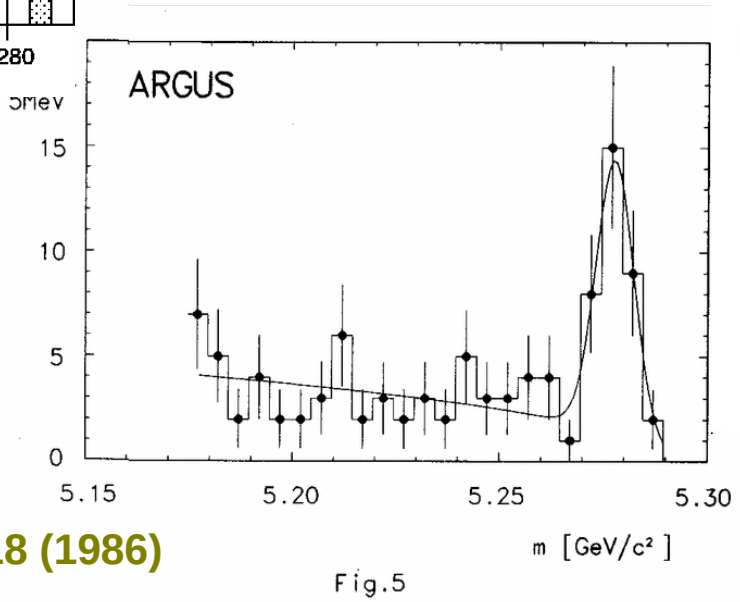


Fig.5

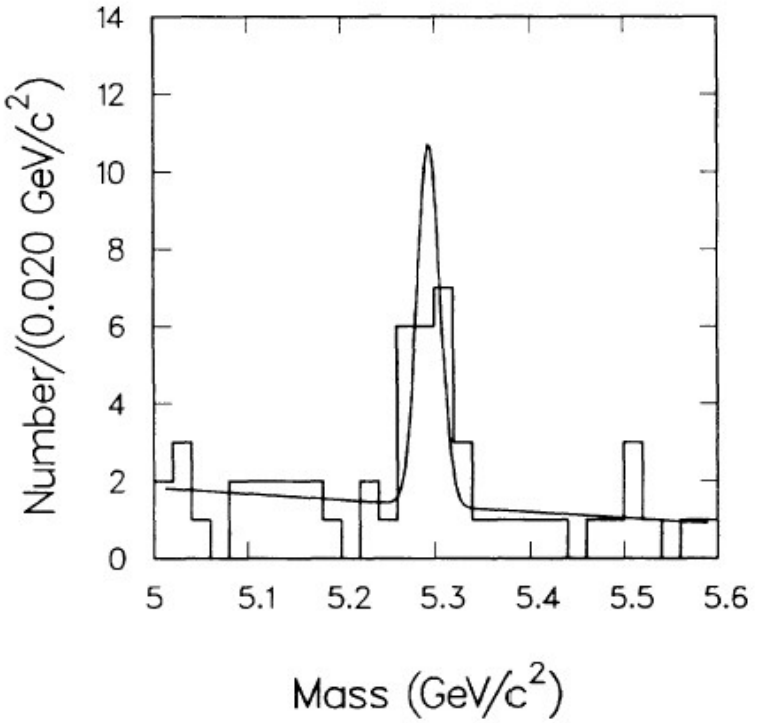
ARGUS 1986

Phys.Lett. B185, 218 (1986)

First fully reconstructed B mesons at a hadron collider:

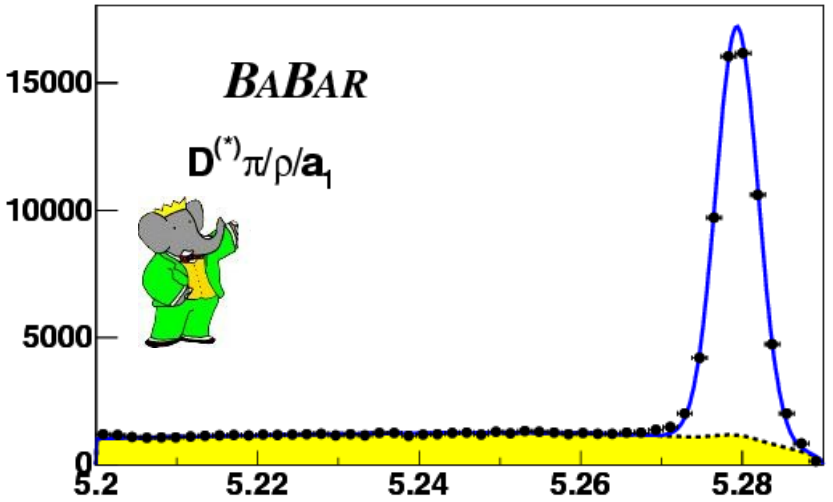
CDF 1992

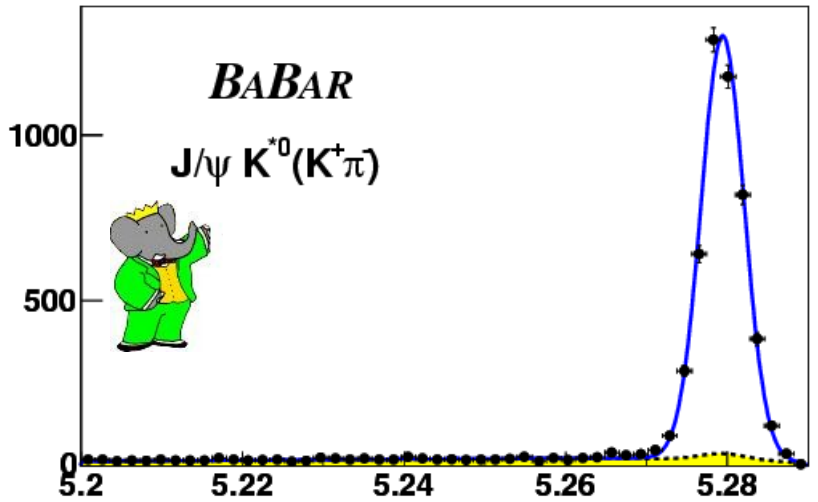
$B^+ \to J/\psi\ K^+$

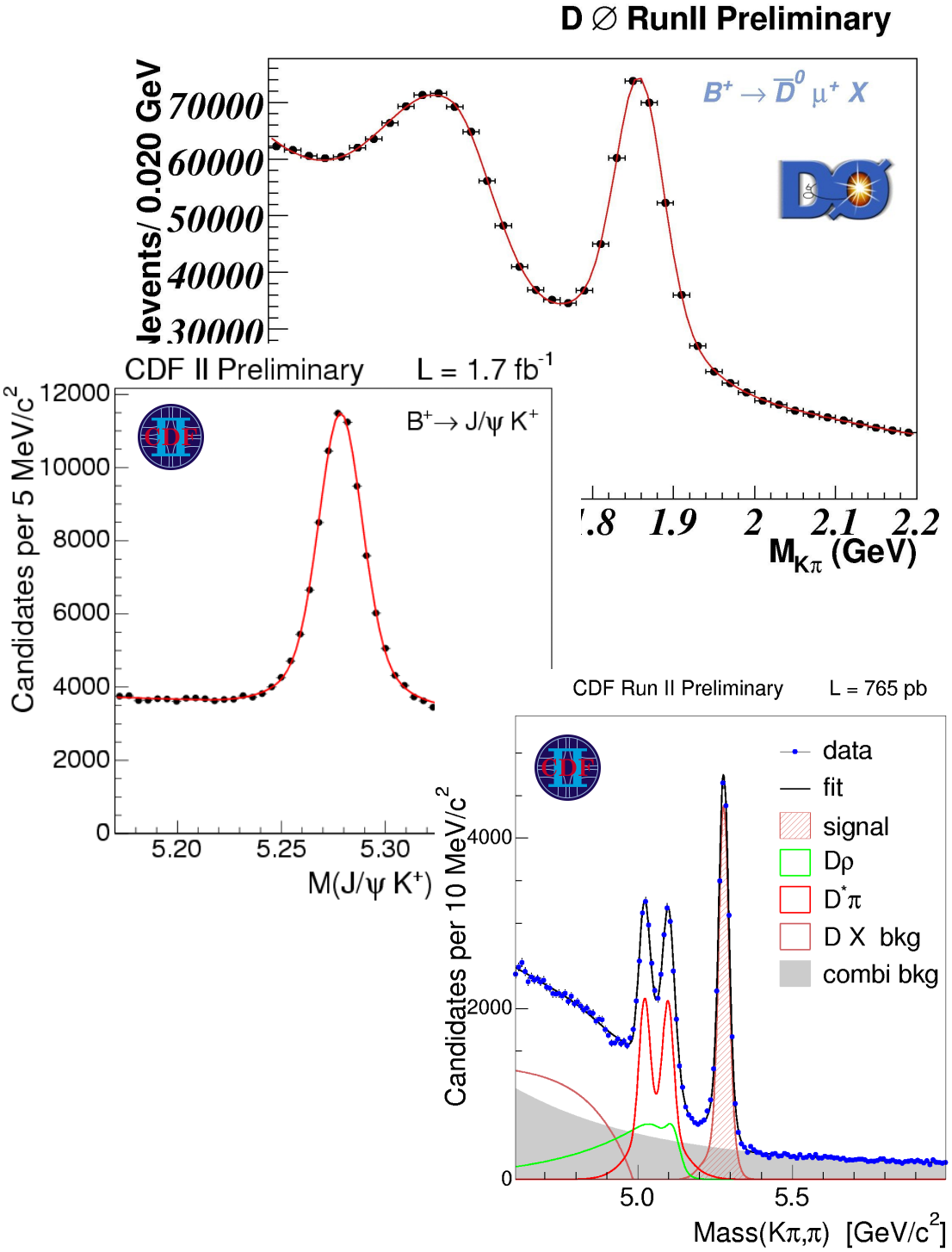


PRL 68, 3403 (1992)

Nowadays ...


BABAR
$D^{(*)}\pi/\rho/a_1$
15000
10000
5000
0
5.2
5.22
5.24
5.26
5.28


BABAR
$J/\psi\ K^{*0}(K^+\pi^-)$
1000
500
0
5.2
5.22
5.24
5.26
5.28


D ∅ RunII Preliminary
$B^+ \to \overline{D}^0 \mu^+ X$
Events/ 0.020 GeV
70000
60000
50000
40000
30000
1.8
1.9
2
2.1
2.2
$M_{K\pi}$ (GeV)
CDF II Preliminary
L = 1.7 fb^{-1}
$B^+ \to J/\psi\ K^+$
Candidates per 5 MeV/c^2
12000
10000
8000
6000
4000
2000
0
5.20
5.25
5.30
M(J/ψ K$^+$)
CDF Run II Preliminary
L = 765 pb
data
fit
signal
Dρ
D$^*\pi$
D X bkg
combi bkg
Candidates per 10 MeV/c^2
4000
2000
0
5.0
5.5
Mass(Kπ,π) [GeV/c^2]

Motivation

- Why study B hadron states at Tevatron?
- All B states are produced at Tevatron

separate talk
Joe Boudreau

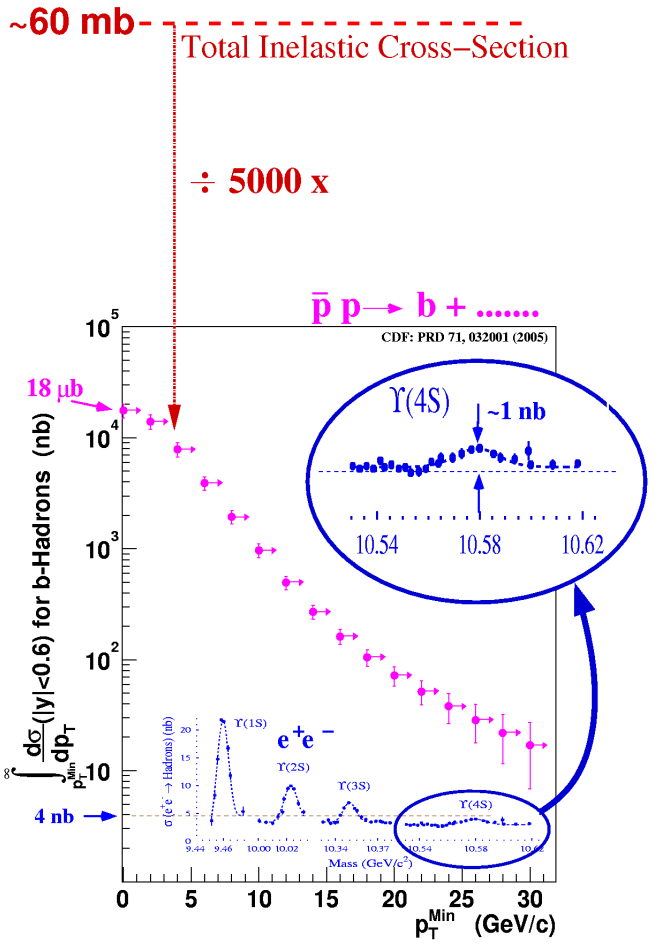
Mesons: $\bar{B}^0 = |b\,\bar{d}\rangle,\ B^- = |b\,\bar{u}\rangle,\ \bar{B}^0_S = |b\,\bar{s}\rangle,\ B^-_c = |b\,\bar{c}\rangle$

B factories

Excited Mesons: $B^{**}_{(S)} = |b\uparrow \bar{q}\uparrow\rangle$

Baryons: $\Lambda^0_b = |b\,d\,u\rangle,\ \Sigma^-_b = |b\,d\,d\rangle$

$\Xi^-_b = |b\,d\,s\rangle$



Other Bonus of B Physics at Tevatron:

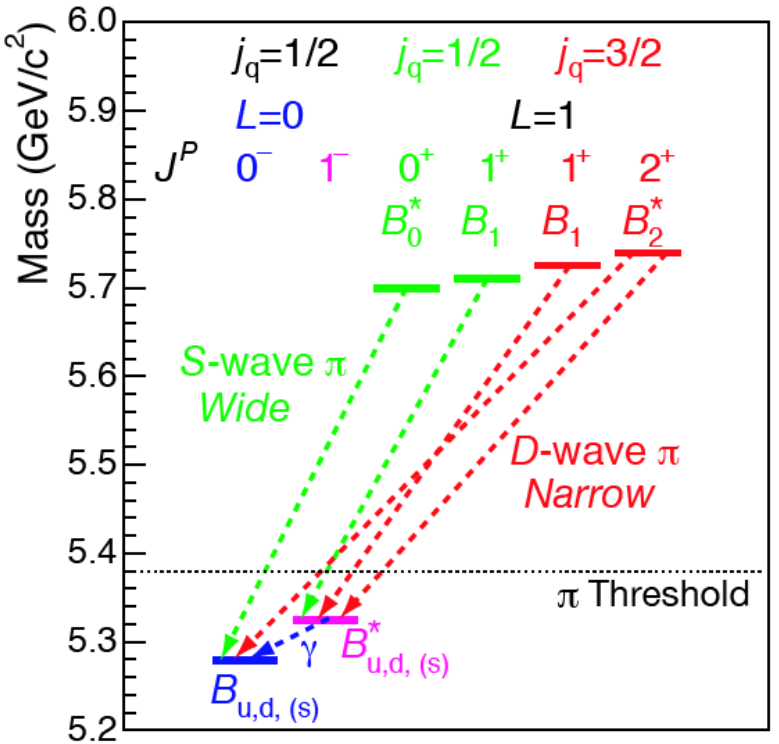
- Enormous cross section:
  - B Factory: $\sigma(\Upsilon(4S) \to B\bar{B}) \sim 1$ nb
  - Tevatron: $\sigma(p\bar{p} \to b, |y| < 0.6) \sim 20\mu b$

B Meson States

- B^{**}, B_s^{**}
- B_c

B Excited States

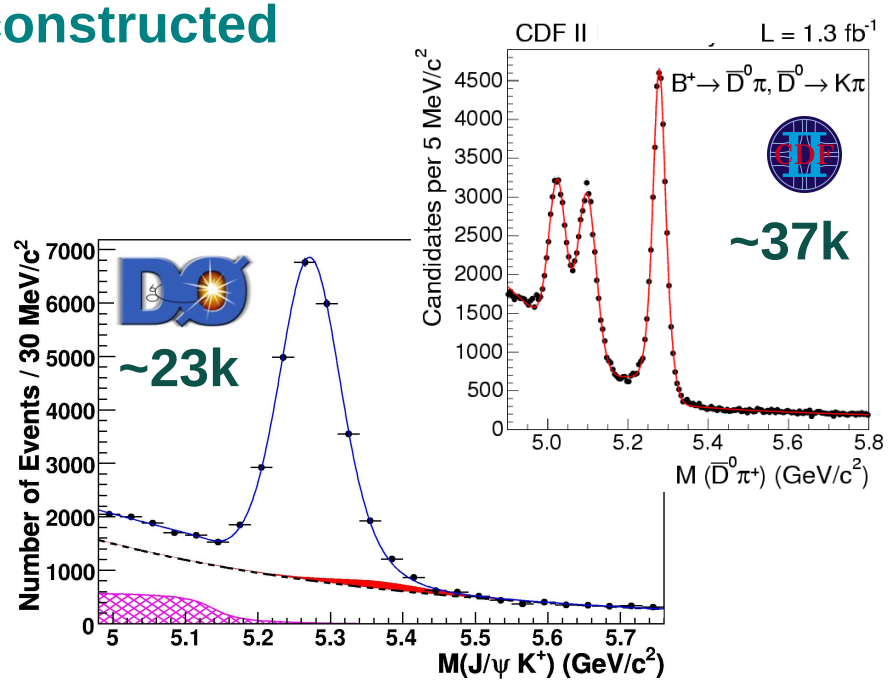
- Until recently only ground states B^0, B^+, B_s or excited state B* well established
- HQET predicts 4 P-wave states for the excited $B_{u/d}^{**}$ & B_s^{**}
  - Two decay via S-wave => wide (~100 MeV)
  - Two decay via D wave => narrow (~10 MeV)



Reconstruct B in J/ψ and D^0 modes and add pion

not reconstructed

$$B_1^0 \to B^{*+}\pi^-;\ B^{*+} \to B^+\gamma$$
$$B_2^{*0} \to B^{*+}\pi^-;\ B^{*+} \to B^+\gamma$$
$$B_2^{*0} \to B^+\pi^-$$
$$B^+ \to J/\psi K^+ \qquad B^+ \to \bar{D}^0\pi^+$$
$$\hookrightarrow \mu^+\mu^-$$

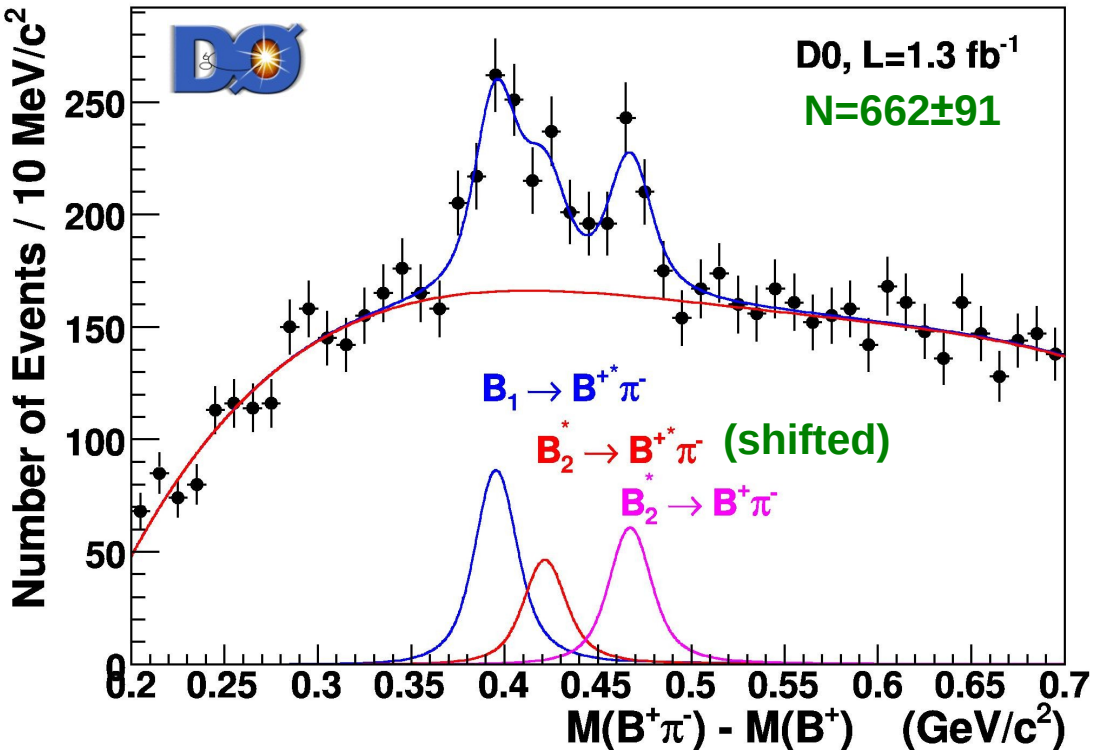


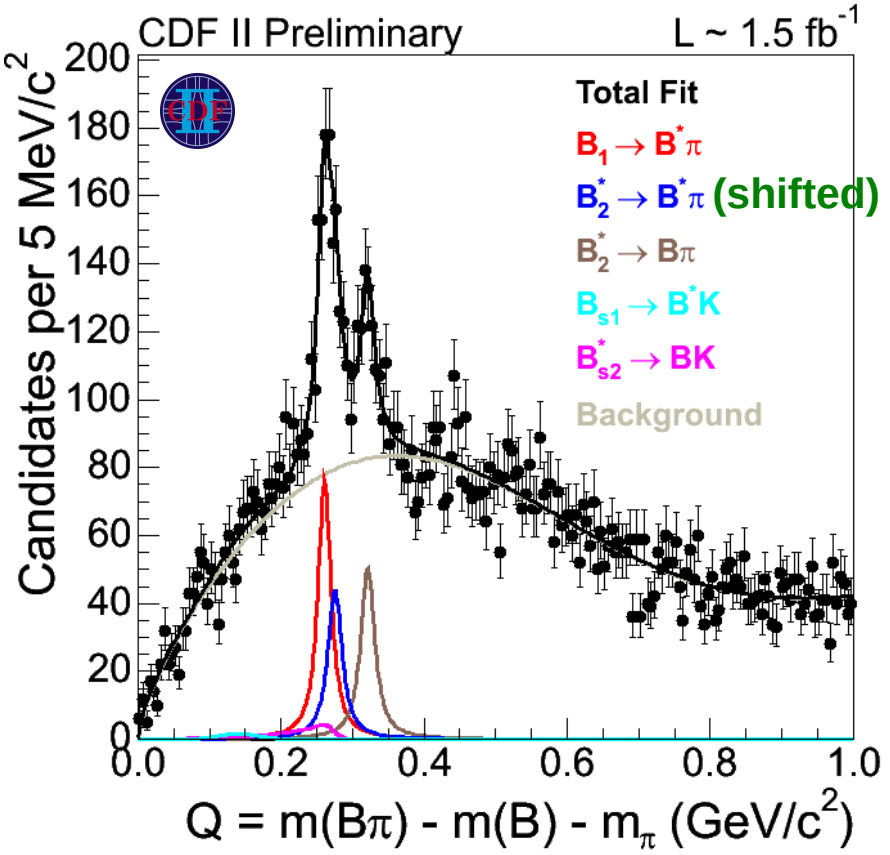
Fit mass difference

$$\Delta m(B^{**}) = m(B^{**}) - m(B) - m(\pi)$$

Narrow B_d^{**} States

Results:





$$M(B_1) = 5720.6 \pm 2.4 \pm 1.4 \text{ MeV}$$
$$M(B_2^*) = 5746.8 \pm 2.4 \pm 1.7 \text{ MeV}$$

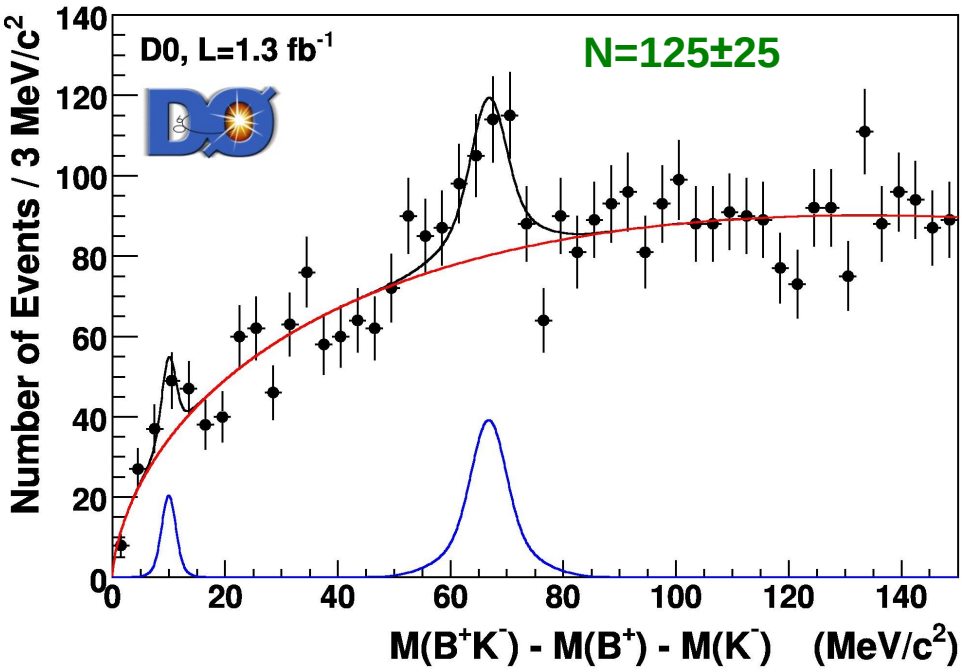
PRL 99, 172001 (2007)

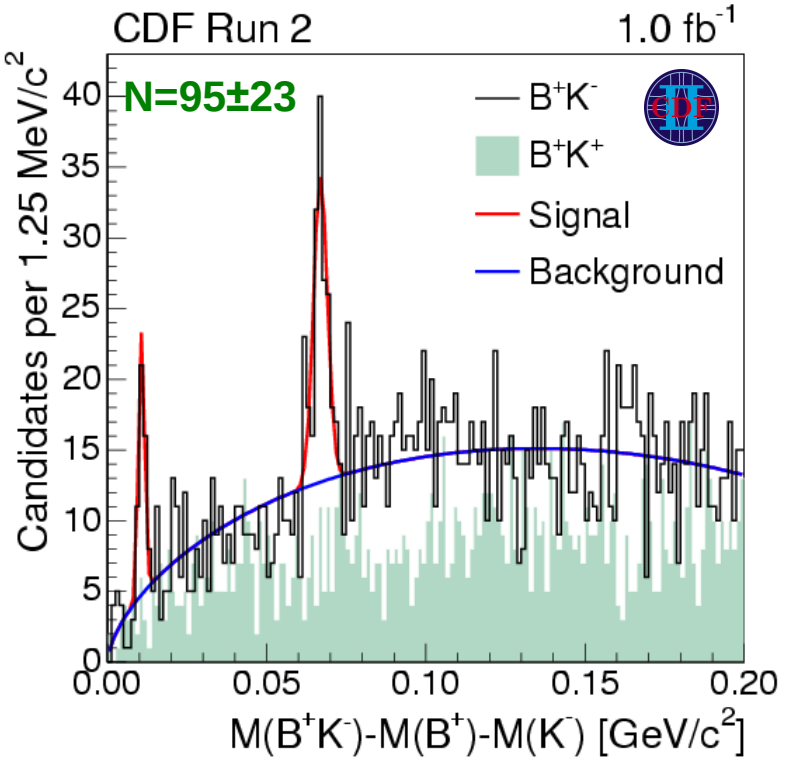
$$M(B_1^0) = 5725.3^{+1.6+0.8}_{-2.1-1.1} \text{ MeV}$$
$$M(B_2^{*0}) = 5739.9^{+1.7+0.5}_{-1.8-0.6} \text{ MeV}$$

Measurements in agreement

Narrow B_s^{**} States

- Decay B_S^{**} to $B_S\,\pi$ isospin suppressed
- Reconstruct B_S^{**} --> B^+K^- with B^+ --> $J/\psi\,K^+$ & B^+ --> $D^0\pi^+$





$$M(B_{s2}^*) = 5839.6 \pm 1.1 \pm 0.7\,\mathrm{MeV}$$

(B_{s1} not significant enough, < 3 σ)

PRL 100, 082002 (2008)

$$M(B_{s1}) = 5829.4 \pm 0.21 \pm 0.14 \pm 0.6\,(\mathrm{PDG})\,\mathrm{MeV}$$

$$M(B_{s2}^*) = 5839.6 \pm 0.39 \pm 0.14 \pm 0.5\,(\mathrm{PDG})\,\mathrm{MeV}$$

PRL 100, 082001 (2008)

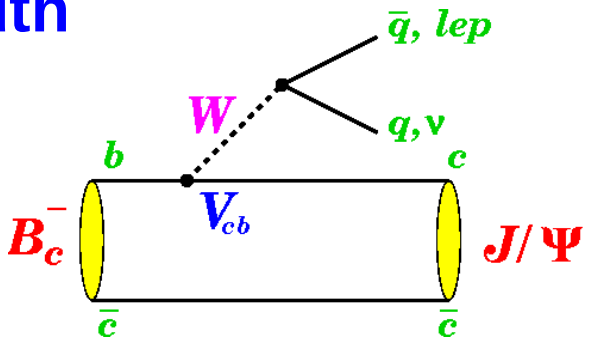
B_c Meson $B_c^- = |b\,\bar{c}\rangle$

- Unique particle as it contains 2 heavy quarks
- Mass measurement tests potential models & lattice QCD
- Decay: Both quarks contribute to decay width

  - via b quark:

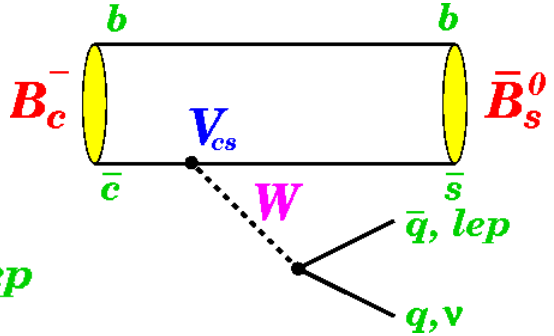
    discovery mode

    $B_c^- \to J/\psi X \quad (J/\psi\pi^-, J/\psi\ell^-\nu)$



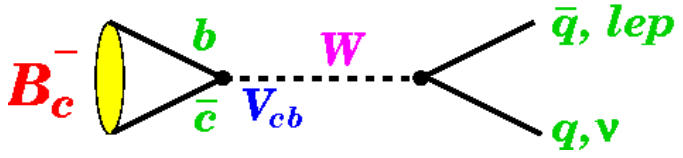
  - via c quark:

    $B_c^- \to \bar{B}_s^0 X \quad (\bar{B}_s^0\pi^-,\ \bar{B}_s^0\ell^-\nu)$



  - via annihilation:

    $B_c^- \to \ell^-\nu/q\bar{q}X$

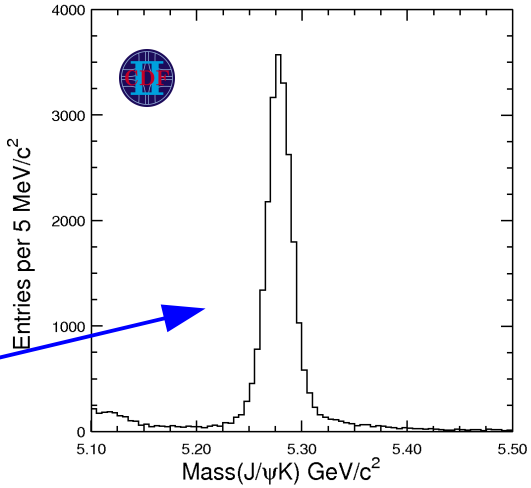


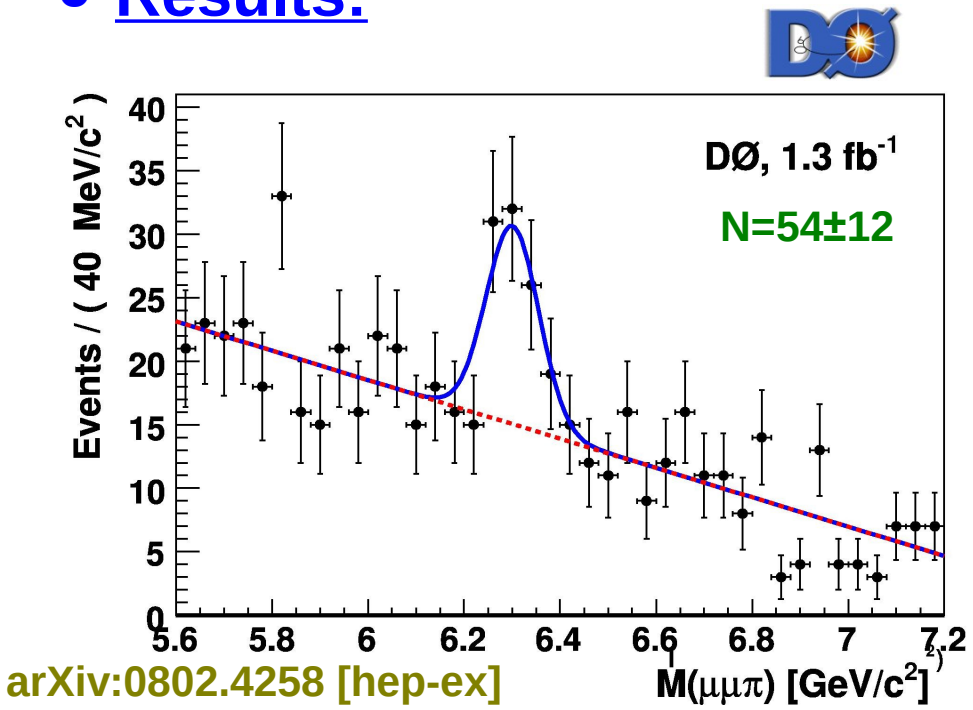
- Theory predicts lifetime of ~0.5 ps

(for lifetimes see talk Hal Evans)

B_c Mass

- Use fully reconstructed
  $B_c^- \to J/\psi(\to \mu^+\mu^-)\ \pi^-$
  for precise mass measurement
- Optimize selection criteria on $B^+ \to J/\psi\ K^+$, apply to $B_c \to J/\psi\ \pi$
- Results:

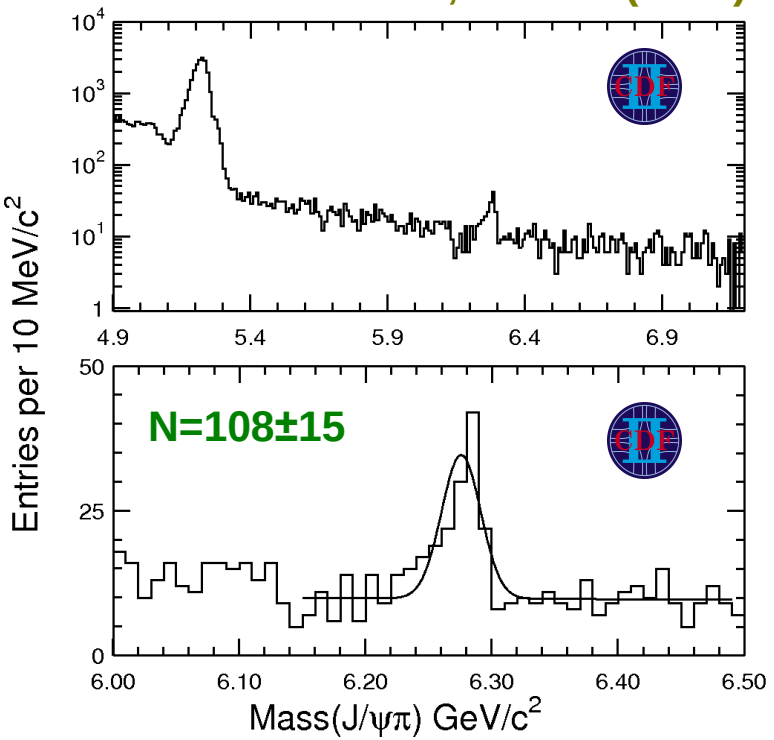




arXiv:0802.4258 [hep-ex]

$M(B_c) = (6300 \pm 14 \pm 5)$ MeV/c²

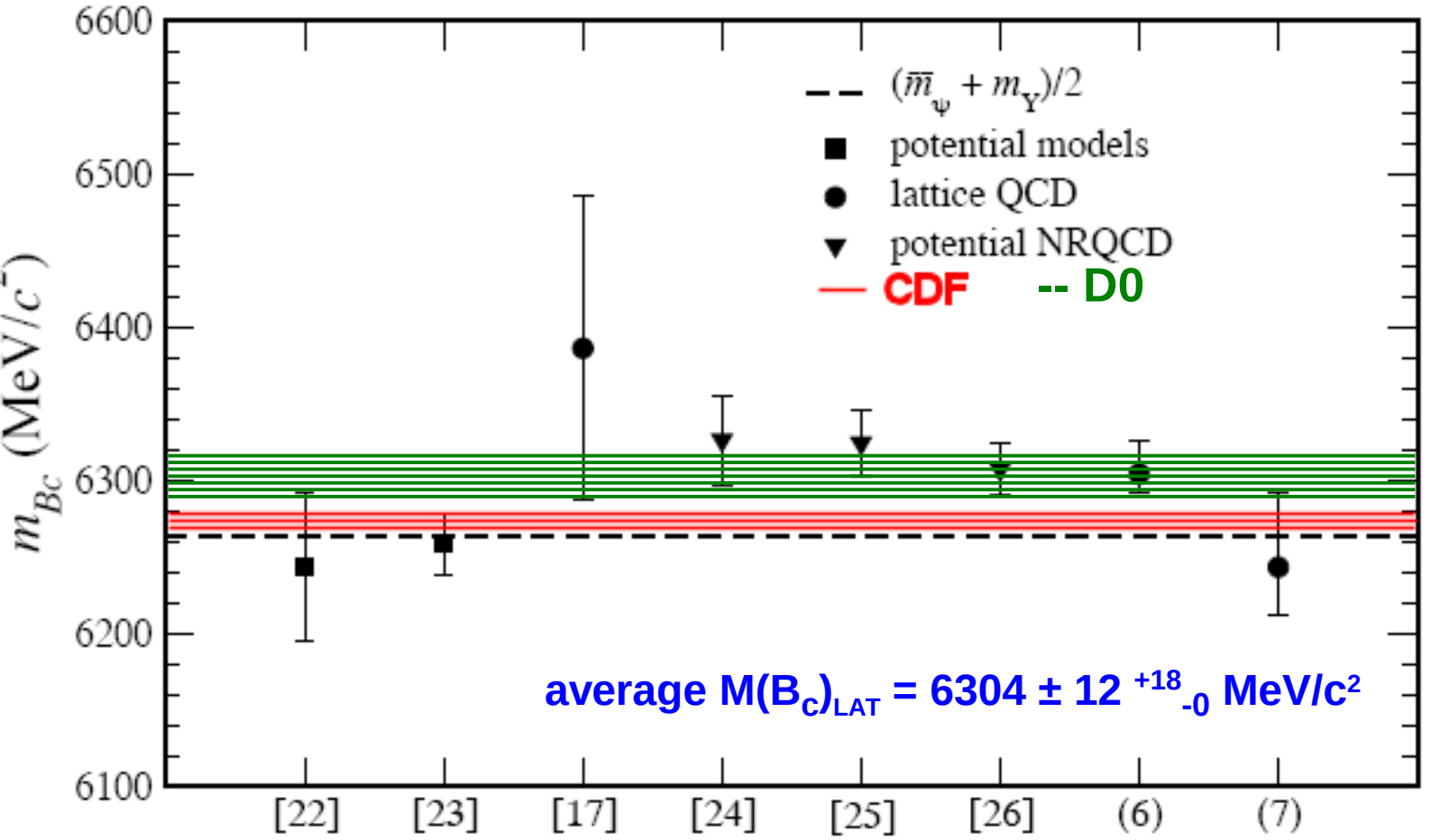
PRL 100, 182002 (2008)



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

B_c Mass

Comparison to predictions:



Experimental measurements with small uncertainties challenge theoretical models and Lattice techniques

B Baryon States

- Σ_b
- Ξ_b

Heavy B Baryons

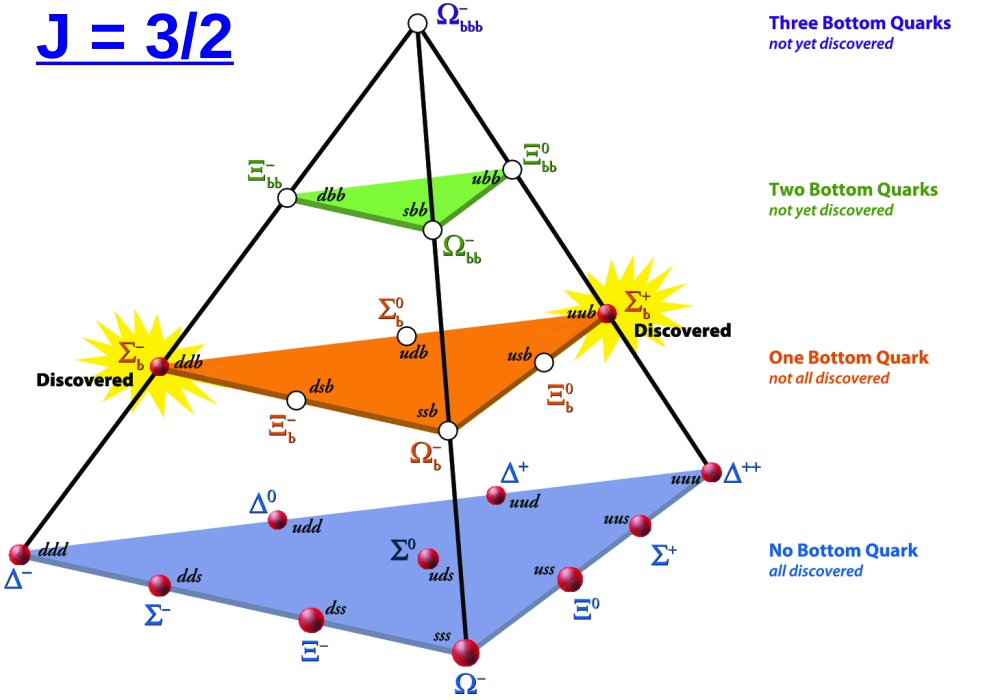
Motivation:

Until 2006 $\Lambda_b^0 = |b\,d\,u\rangle$ was only established *B* baryon

=> Search for

$$\Sigma_b^{(*)+} = |b\,u\,u\rangle \quad \Xi_b^- = |b\,d\,s\rangle$$
$$\Sigma_b^{(*)-} = |b\,d\,d\rangle \quad \Xi_b^0 = |b\,u\,s\rangle$$

Baryons with Up, Down, Strange and Bottom Quarks and Highest Spin (J = 3/2)



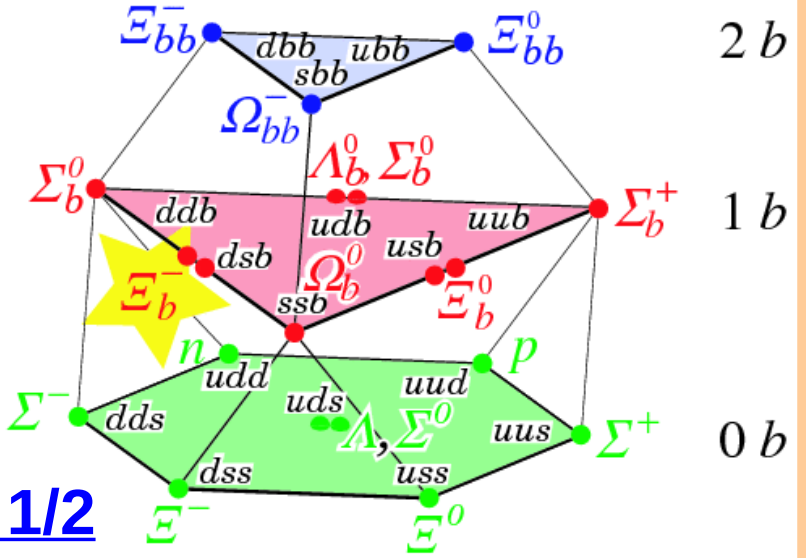
Example: Σ_b

Σ_b: $b\{qq\}$, $q = u,d$; $J^P = S_Q + s_{qq}$

$= 3/2^+$ (Σ_b*)

$= 1/2^+$ (Σ_b)

H-atom: spin-spin interaction
= hyperfine splitting



Σ_b Baryon

Searching for: $\Sigma_b^{(*)+} = |b\,u\,u\rangle$ $\Sigma_b^{(*)-} = |b\,d\,d\rangle$

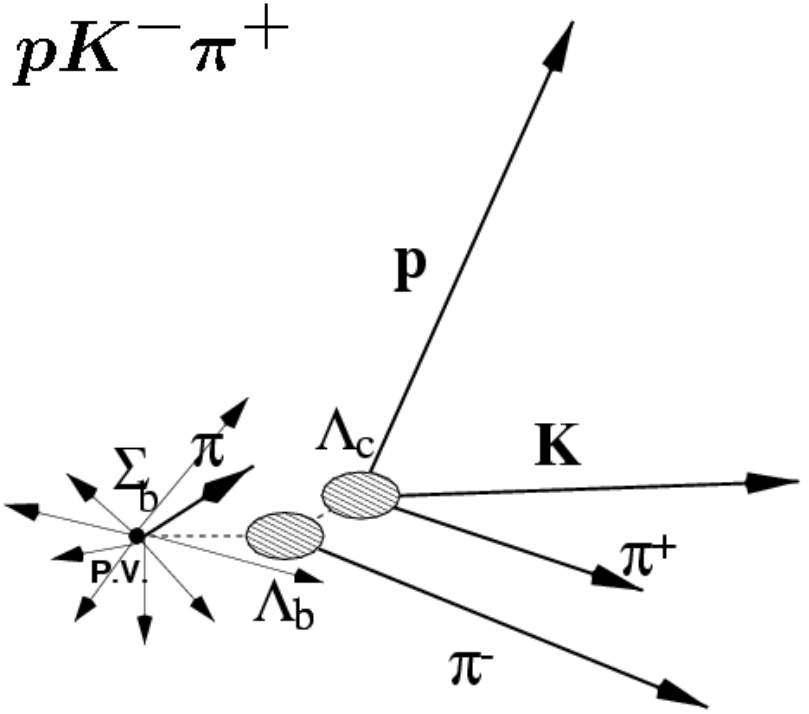
$\Sigma_b^{(*)0} = |b\,u\,d\rangle$ $\Sigma_b^{(*)0} \to \Lambda_b^0\,\pi^0$ ← difficult for CDF & D0

Search Strategy:

Use CDF two-track trigger to reconstruct:

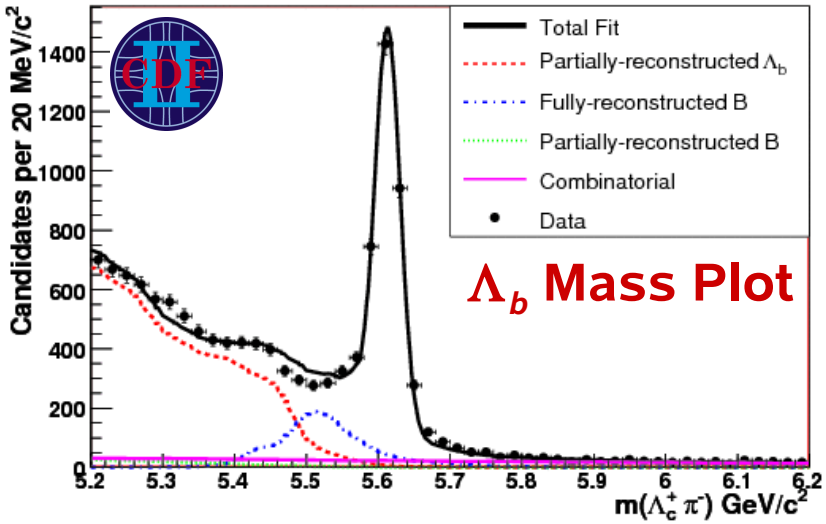
$$\Sigma_b^{(*)\pm} \to \Lambda_b^0\,\pi^\pm$$
$$\hookrightarrow \Lambda_c^+\pi^-; \quad \Lambda_c^+ \to pK^-\pi^+$$

- Σ_b decays at primary vertex
- Combine Λ_b with a prompt track to form a Σ_b candidate
- Separate Σ_b^- and Σ_b^+

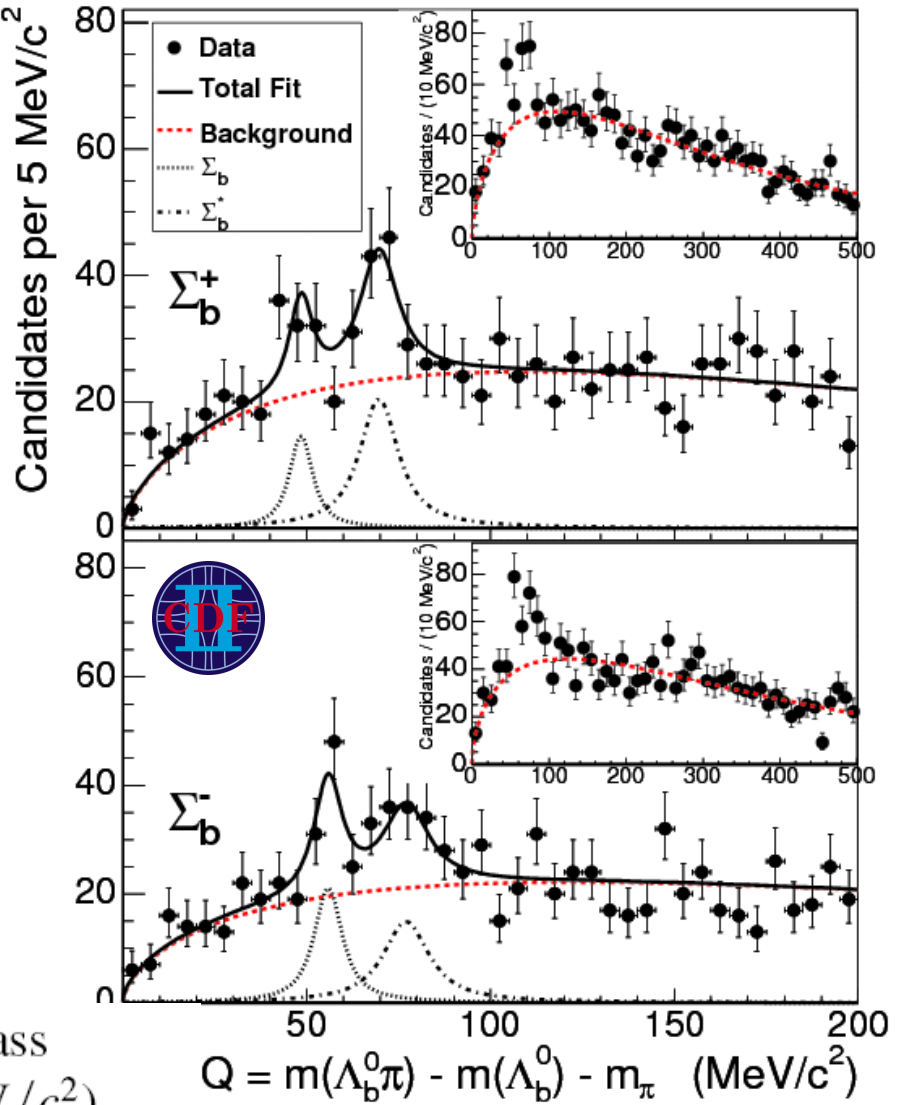


Σ_b Baryon

Use large sample of Λ_b: ~3000



Λ_b Mass Plot



Observe peaks with >5σ w.r.t. no signal

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}		$5836.4 \pm 2.0^{+1.8}_{-1.7}$

PRL 99, 202001 (2007)

Ξ_b Baryon

difficult for CDF & D0

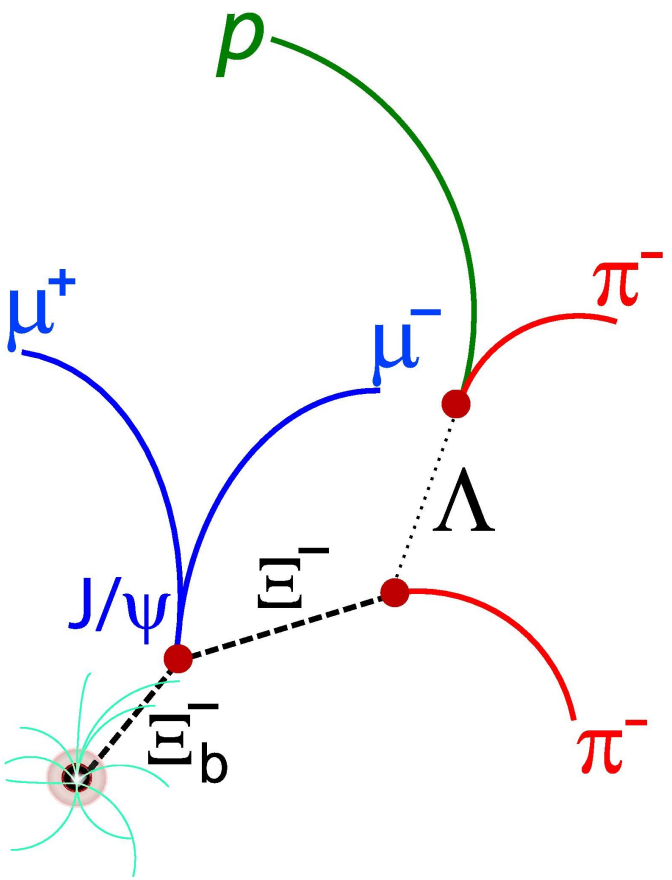
Possible decay modes:

$$\Xi_b^- = |b\,d\,s\rangle \quad \Xi_b^- \to J/\psi\Xi^-$$
$$\Xi_b^0 = |b\,u\,s\rangle \quad \Xi_b^0 \to \Xi_c^0\pi^0, \quad J/\psi\Xi^0\,(\Lambda\pi^0)$$

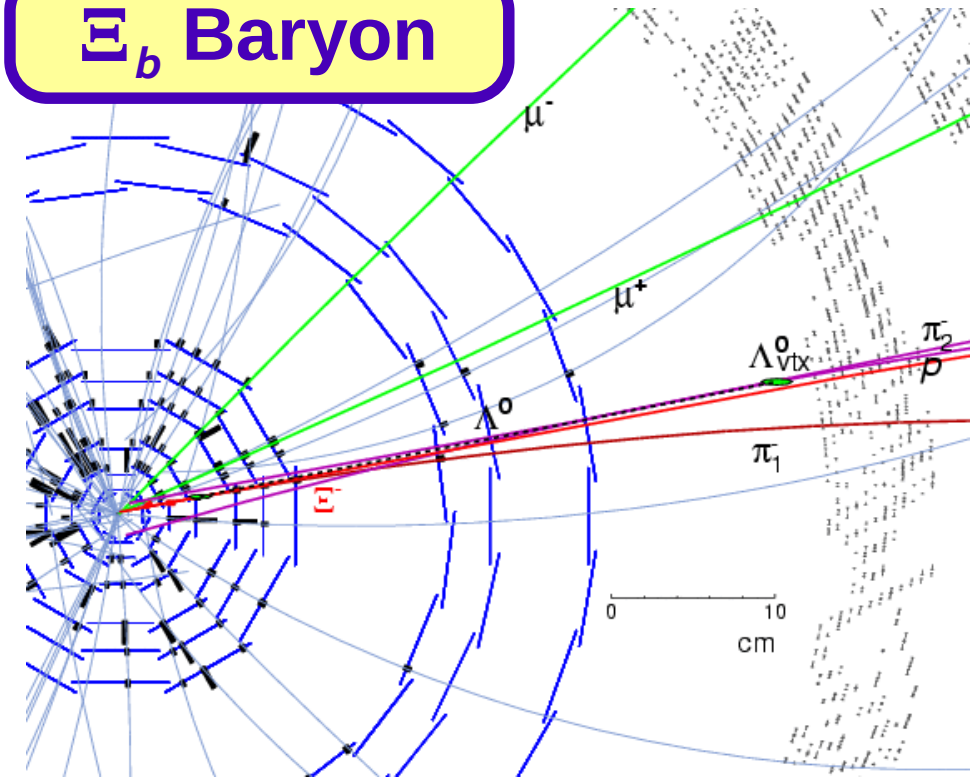
Search for Ξ_b:

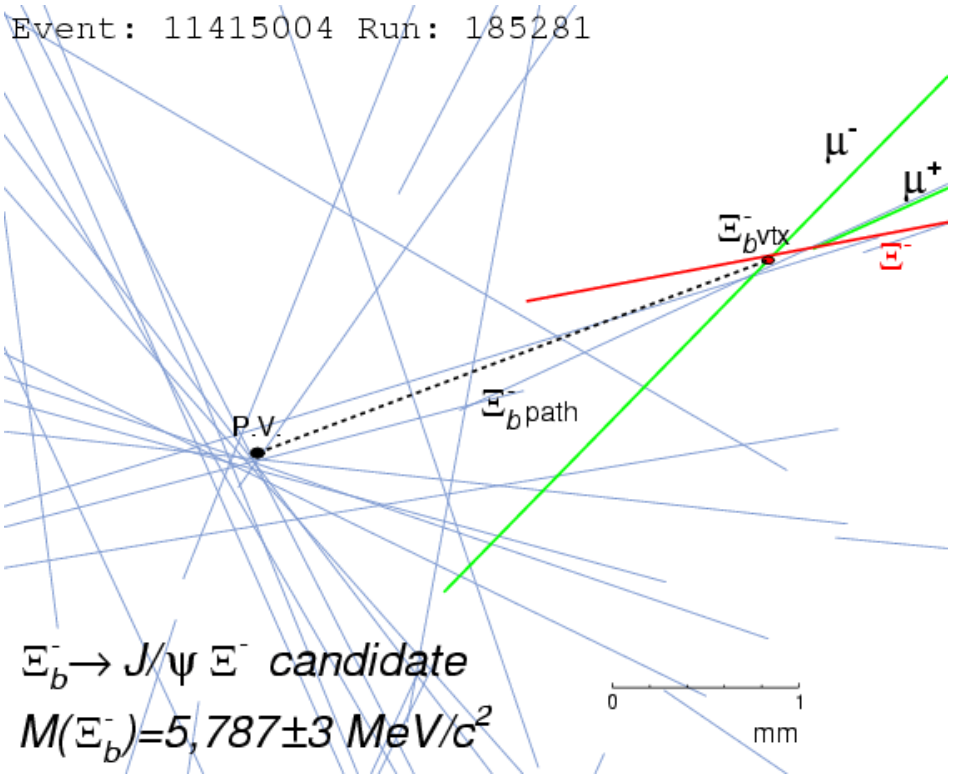
- Decays weakly through b-quark decay
  Expect lifetime similar to B lifetime
  (DELPHI: 1.4 ± 0.3 ps)
- Reconstruct

$$\Xi_b^- \to J/\psi\ \Xi^- \hookrightarrow \Lambda\pi^- \hookrightarrow p\pi^-$$



Ξ_b Baryon



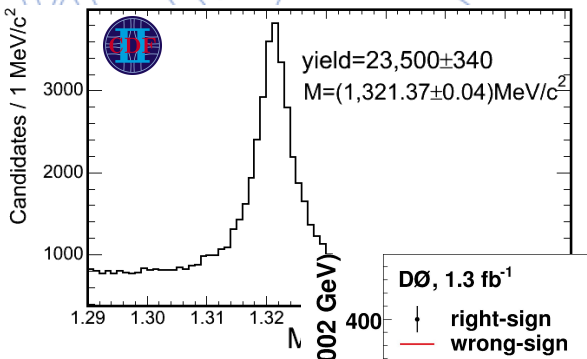


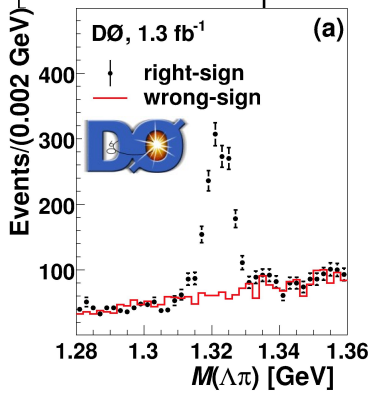
$\Xi_b^- \rightarrow J/\psi\, \Xi^-$ *candidate*

$M(\Xi_b^-) = 5,787 \pm 3$ MeV/c^2

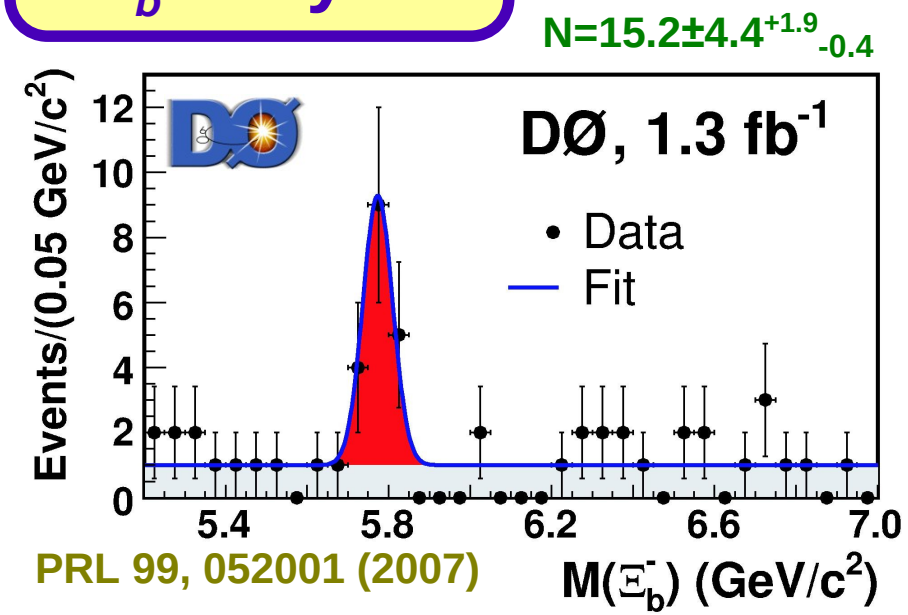
Challenging track reconstruction for Ξ_b:

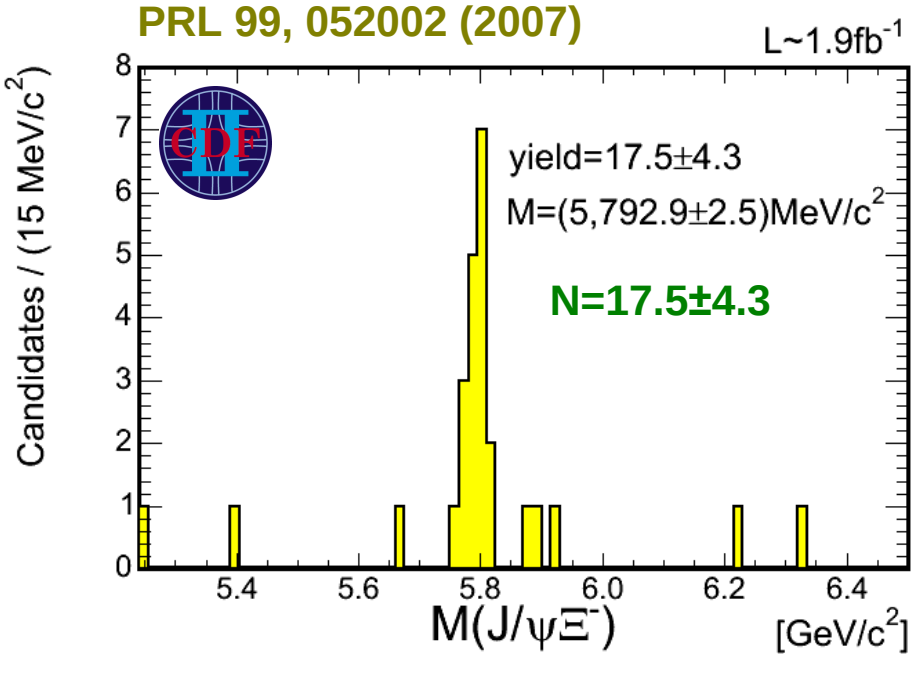
- D0: Special data reprocessing to improve
- efficiency for high impact parameter tracks
- CDF: Dedicated Si-only tracking algorithm to reconstruct Ξ in Si-detector
- D0: Analysis based on wrong-sign data and MC
- CDF: Analysis uses B -> J/ψ K as control sample; replace K with Ξ





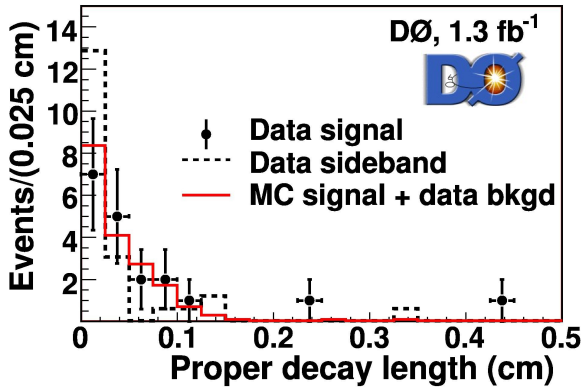
Ξ_b Baryon

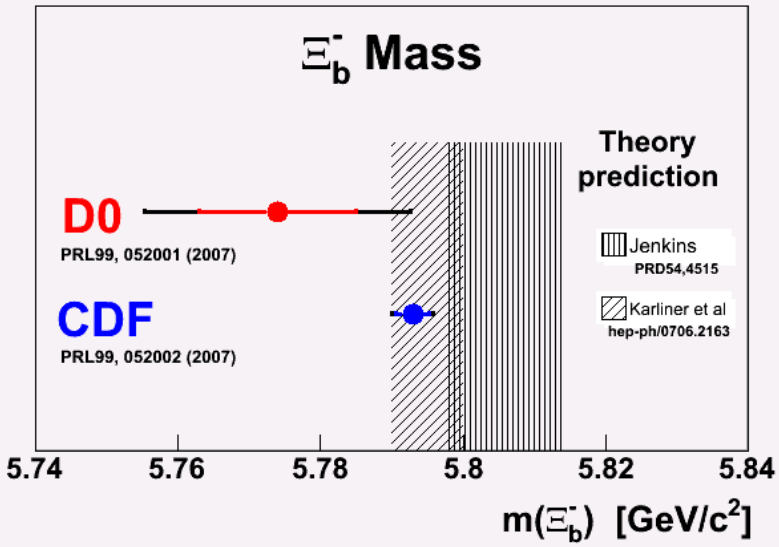




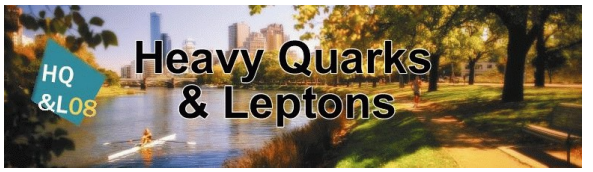
Both experiments see significant Ξ_b signals (D0: 5.5σ, CDF: 7.7σ)

- **CDF: M(Ξ_b) = (5792.9 ± 2.5 ± 1.7) MeV/c^2**
- **D0: M(Ξ_b) = (5774 ± 11 ± 15) MeV/c^2**
- **D0: Lifetime consistent with expectations**





Conclusions



- **Tevatron offers rich heavy flavour program**
- **Many result about properties of B states:**
  - $B_{(S)}^{**}$, B_c, Σ_b, Ξ_b
- **Tevatron will accumulate much more data with many more results to come before LHC(b) results**
  - **Next discoveries:** Ω_b, Ξ_{bc}, ... ???
- **Coming up or down under ?**