Spectroscopy and Decay of B Hadrons (TeV)

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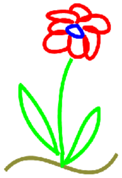
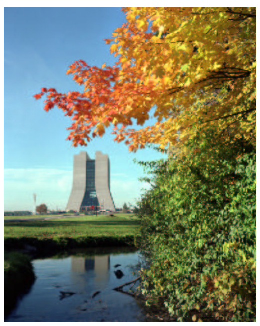
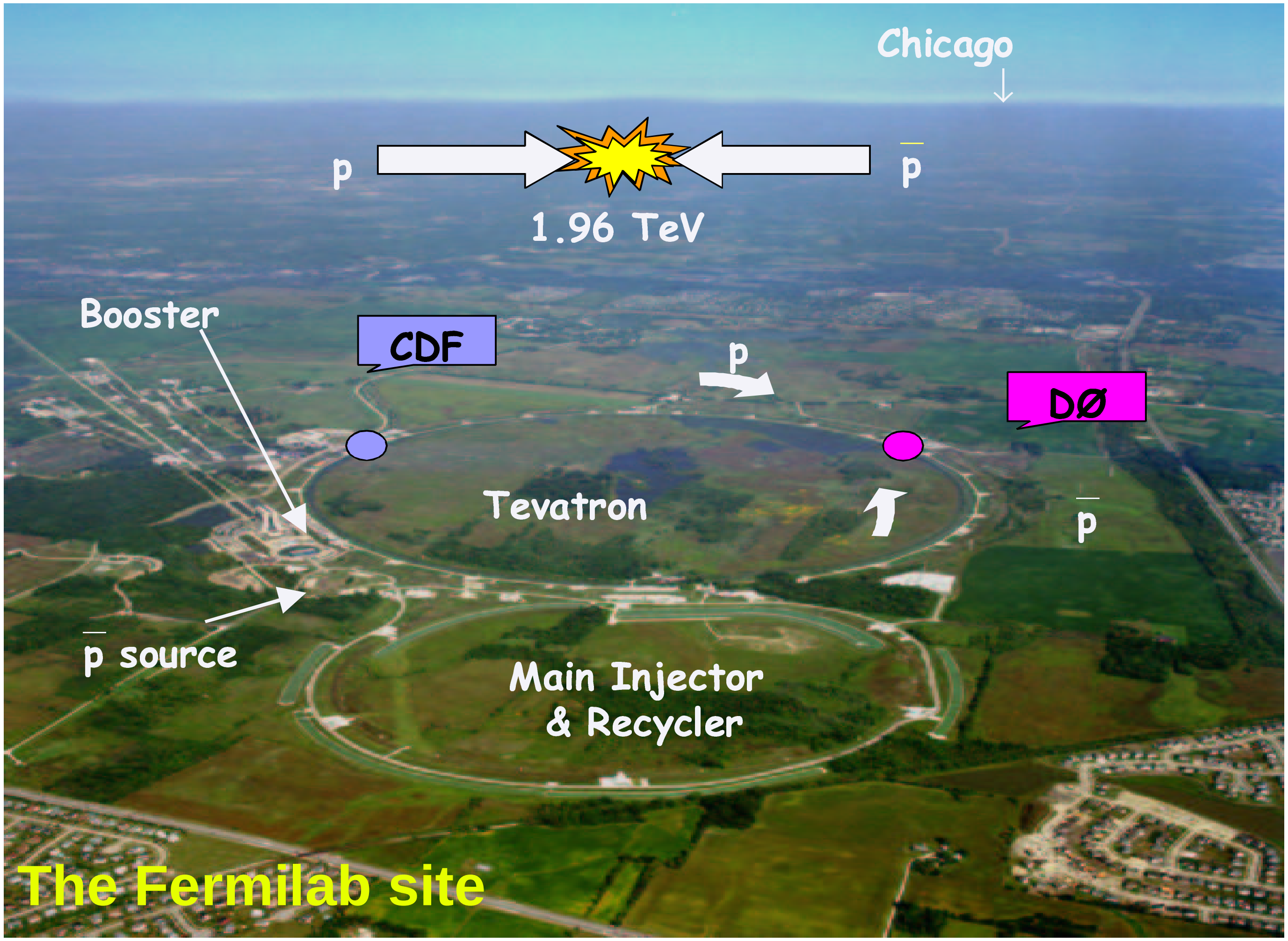
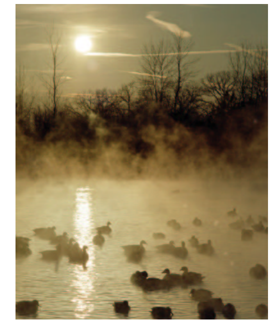
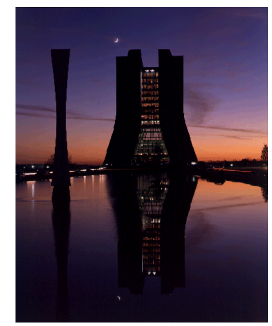
- **Introduction**
- **Spectroscopy**
  - Excited B states: B**, B_S**
  - Observation of Σ_b
  - Search for η_b
- **Decay of B Hadrons (Branching Fractions)**
  - B_S Decays
  - Charmless 2-body B -> hh
- **B Fragmentation Fractions**
- **Conclusion ....**



Fermilab

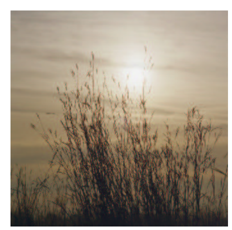





Chicago
p
$\bar{p}$
1.96 TeV
Booster
CDF
p
DØ
Tevatron
$\bar{p}$
$\bar{p}$ source
Main Injector
& Recycler
The Fermilab site



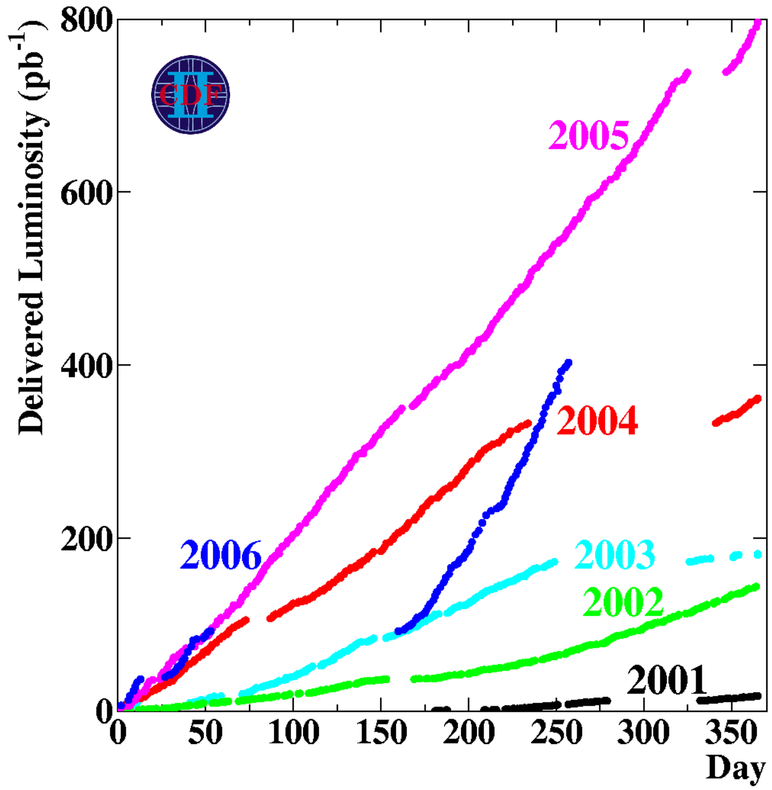


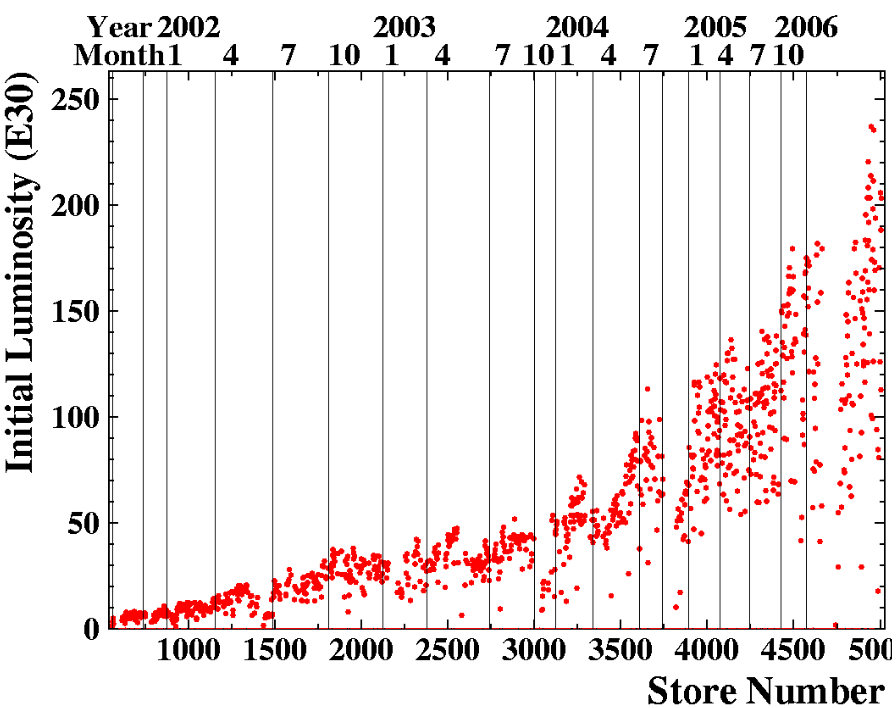


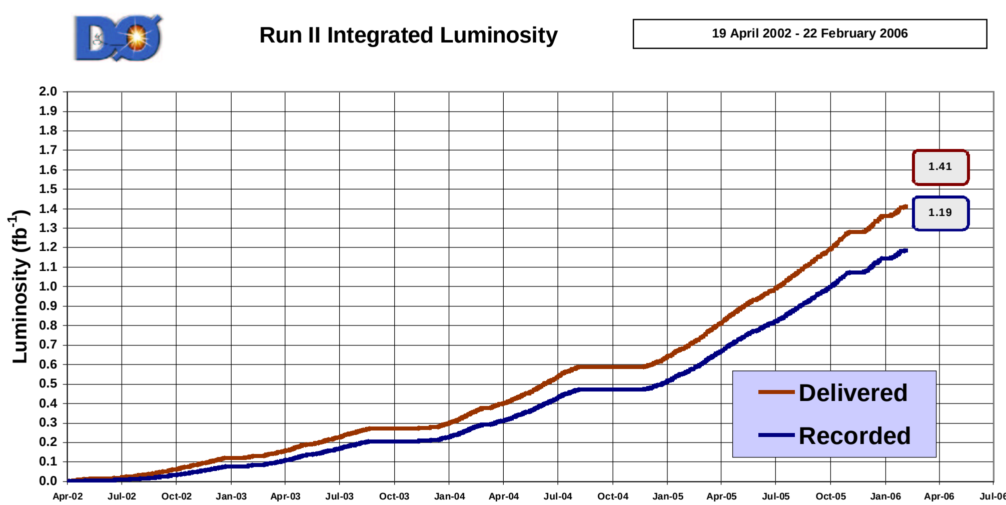

Tevatron Performance

From Record to Record

- Record weekly int. lumi > 30 pb^{-1}
- Record initial luminosity:
  23.6 x 10^{31} sec^{-1} cm^{-2} (Sep 10)
- >1.5 fb^{-1} on tape (> 1.9 fb^{-1} deliv.)
- ~1 fb^{-1} used for analysis

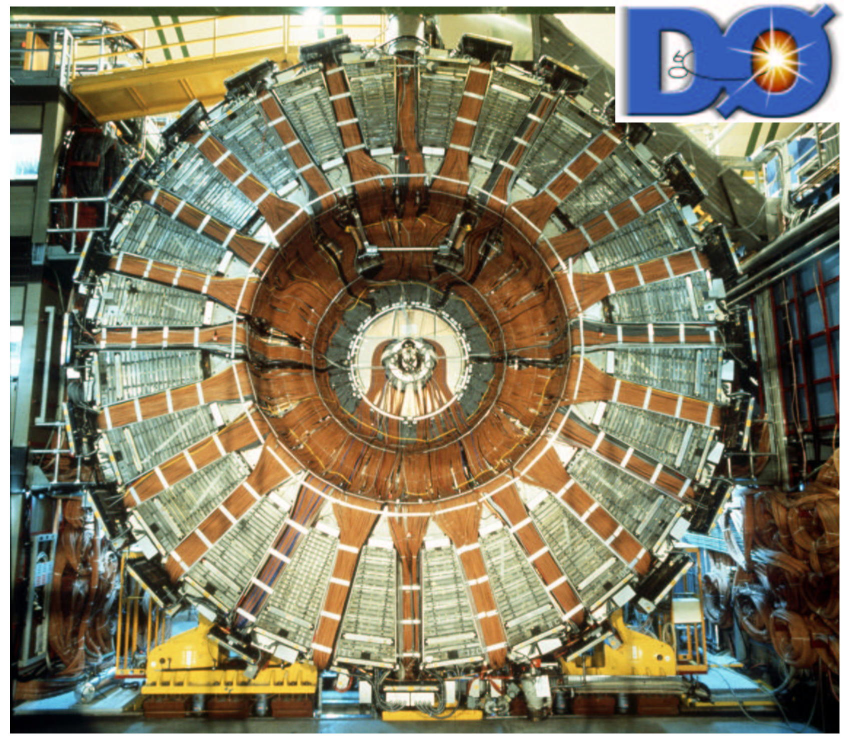


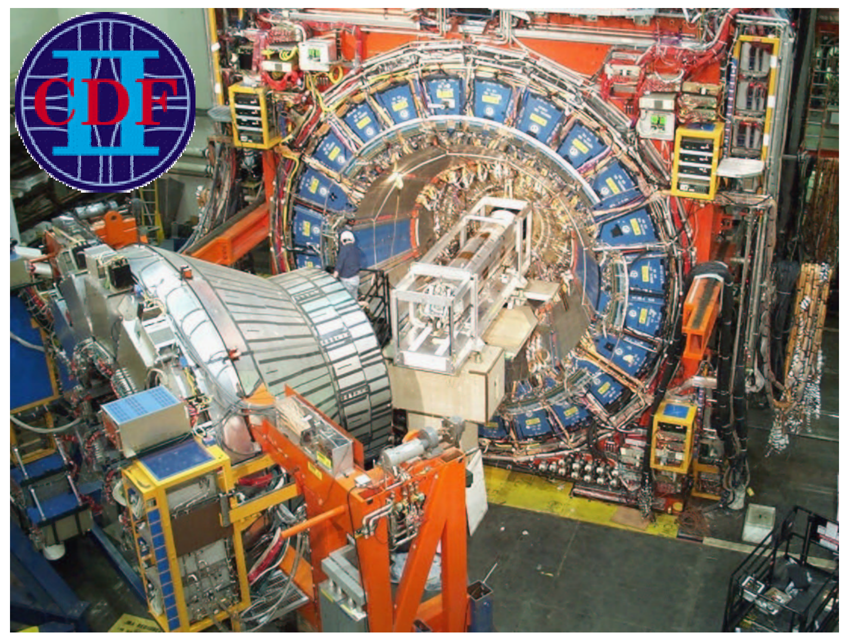




CDF & D0 Experiments

See also other TeV talks on B results by:
- Stephanie Menzemer
- Ay Cano





Both detectors

- Silicon microvertex tracker
- Central tracking in solenoid
- High rate trigger/DAQ
- Calorimeter and muons system

D0

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

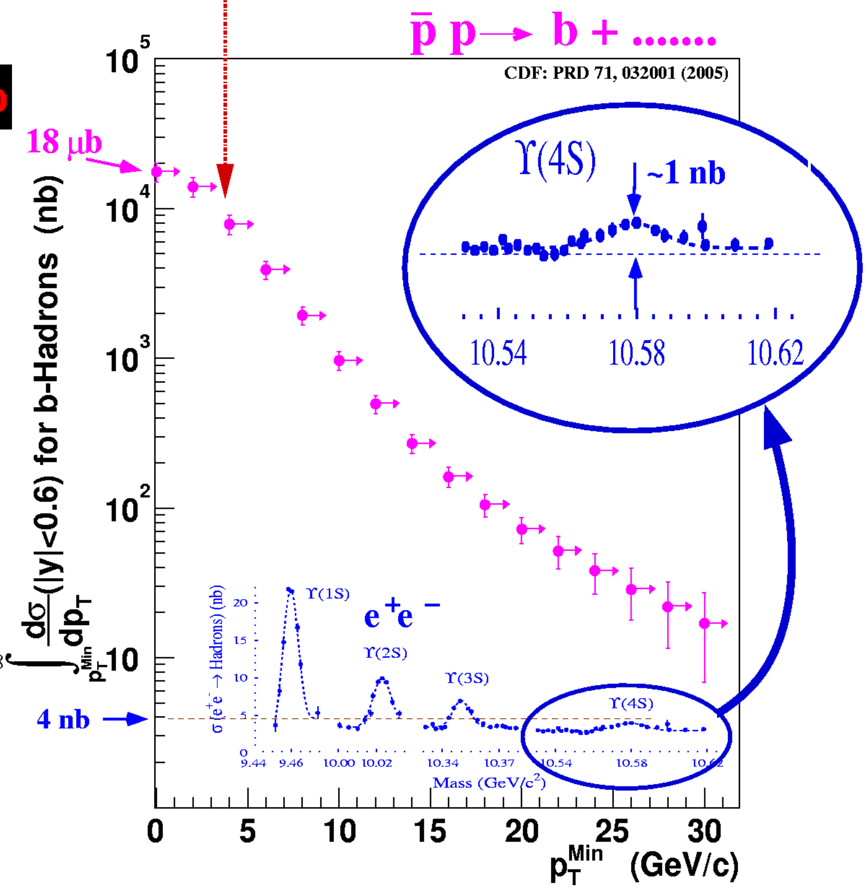
CDF II

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

B Physics at the Tevatron

Advantage of B Physics at the Tevatron:

- **All B hadrons are produced:**
  $B^0, B^+, B_s^+, B_c^+, \Lambda_b^0$
- **Enormous cross section:**
  - B Factory: $\sigma(\Upsilon(4S) \rightarrow B\bar{B}) \sim 1 \text{ nb}$
  - Tevatron:
    $\sigma(p\bar{p} \rightarrow b, |y| < 0.6) \sim 20\mu b$



However:

- **Total inelastic cross section:**
  $\sigma(\text{total})/\sigma(b) > 10^3$

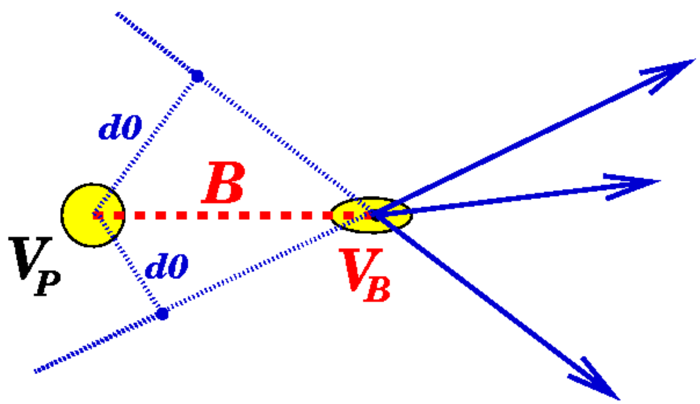
➔ Need to enrich events with B's

➔ It's all about the trigger!

Trigger for B Physics

- **Lepton Trigger:**
  - ➔ Dilepton trigger: J/ψ -> μ μ
  - ➔ Single lepton: Semileptonic B decays
  - ➔ Lepton+displaced track: Semilept. B's
- **Hadronic track trigger:** CDF (D0)

(exploit 'long' B lifetime)

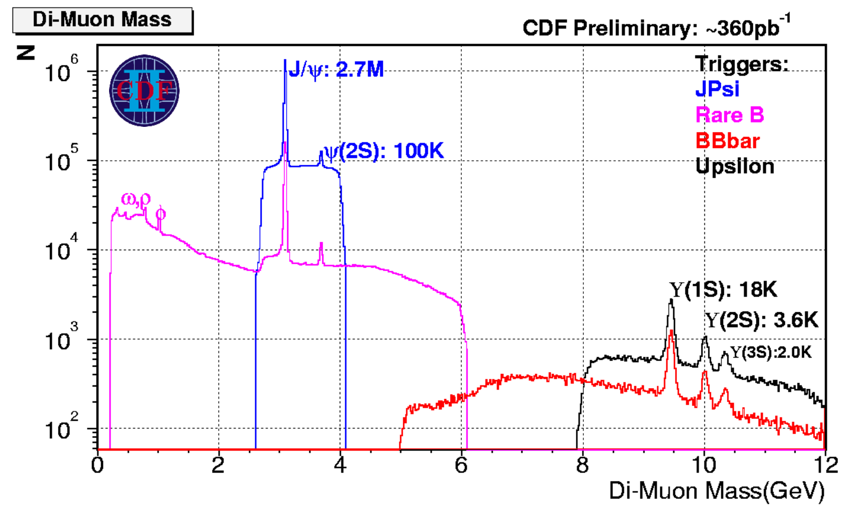


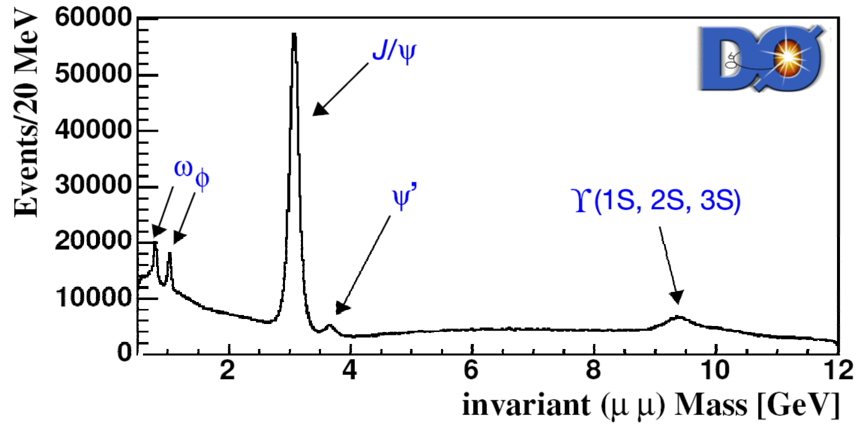
Level 1: Fast track trigger (XFT) finds charged track with p_T > 1.5 GeV/c

Level 2: Link tracks into silicon; require track impact parameter > 100 μm (SVT)

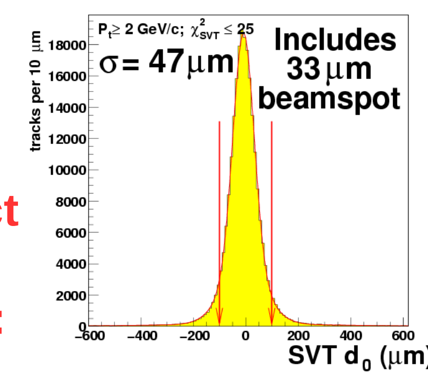
Access to hadronic B decay modes

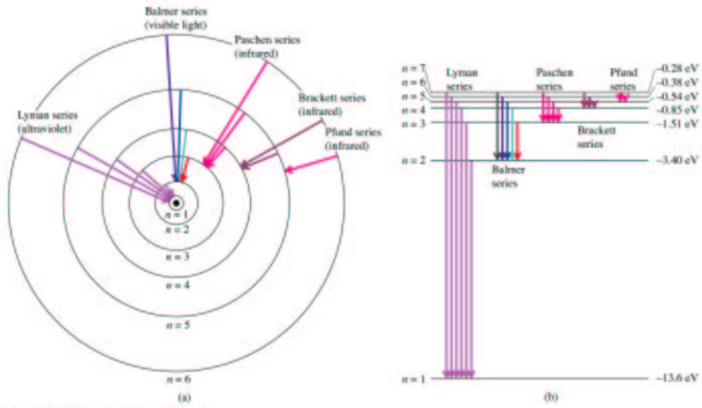
Dimuon trigger data

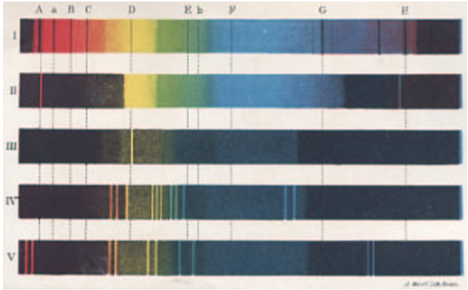




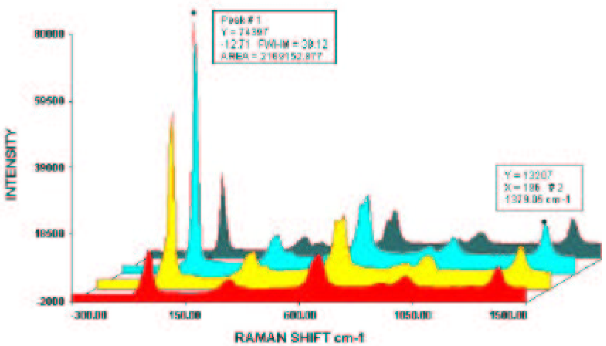
SVT impact parameter resolution:

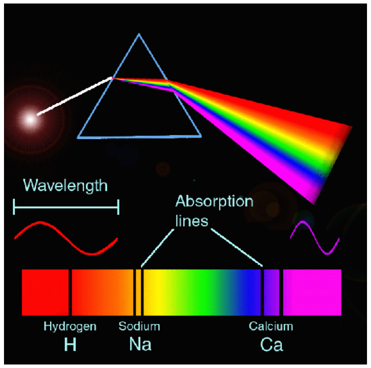






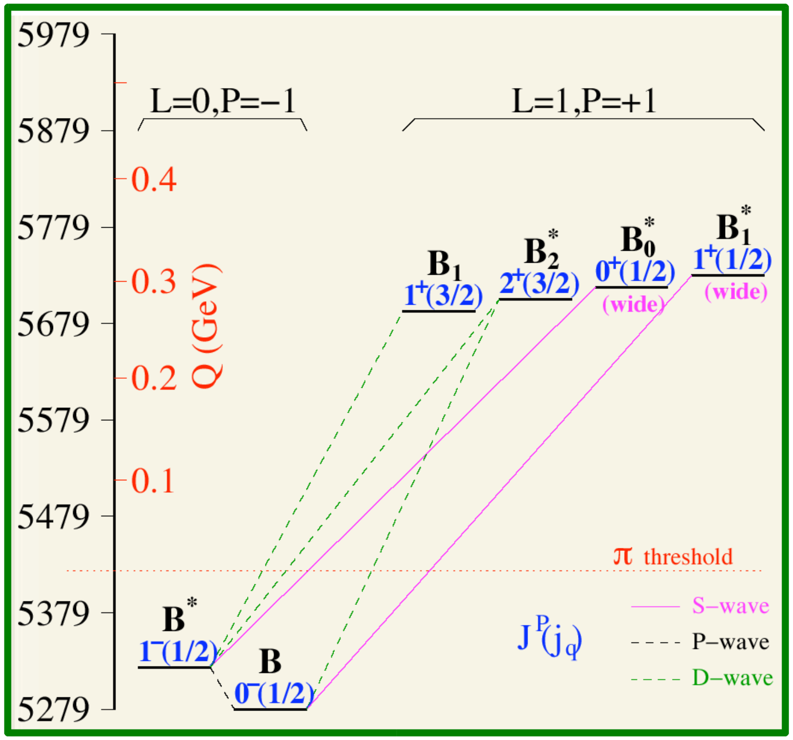
Spectroscopy: Excited B States

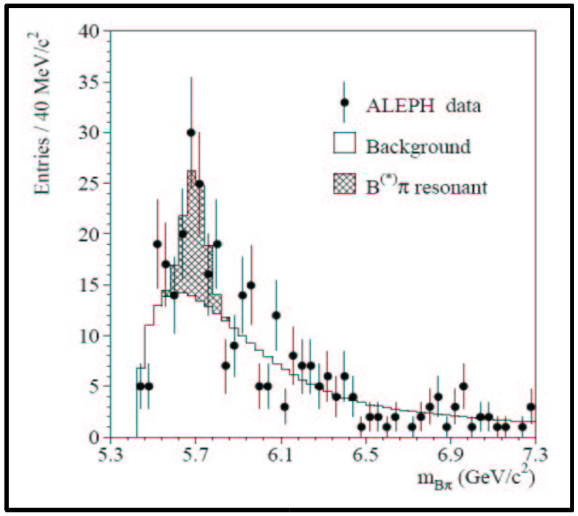


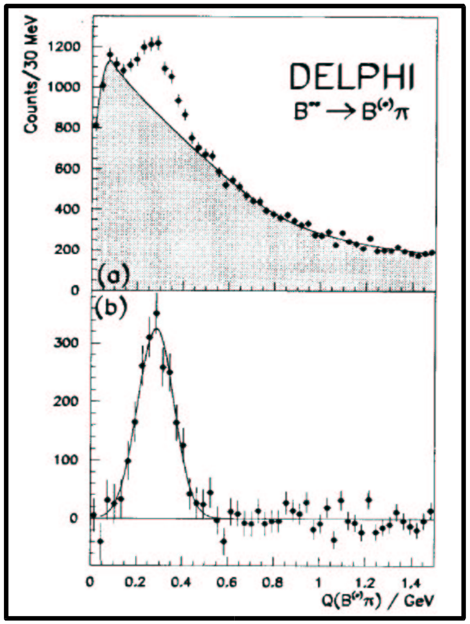


B Excited States

- Spectroscopy of |bq⟩ system not well studied
- Only ground states B^0, B^+, B_s or excited state B* established
- HQET predicts 4 P-wave states for the excited $B_{u/d}^{**}$ & B_s^{**}
  - Two decay via S-wave
    => wide states (~100 MeV)
  - Two decay via D wave
    => narrow states (~10 MeV)
- Experimental verification can give insight in quark interactions and verify precise predictions of masses, width and BR's





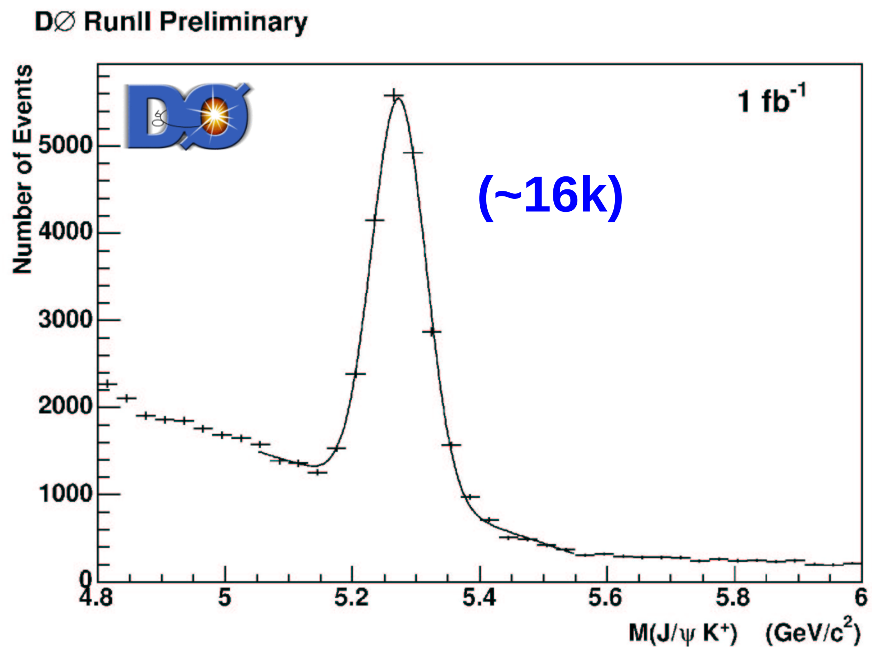


Previous results from LEP

Narrow B_d** States

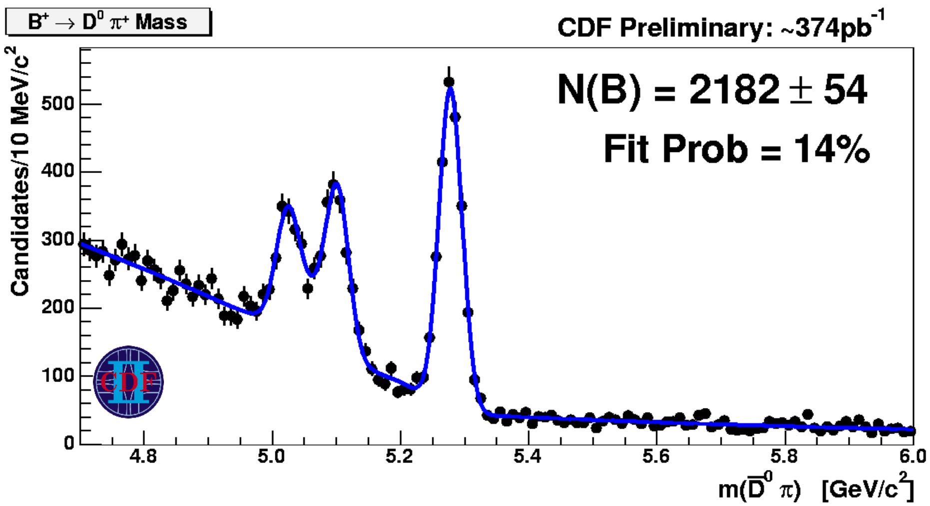
Reconstruct B in J/ψ and D⁰ modes

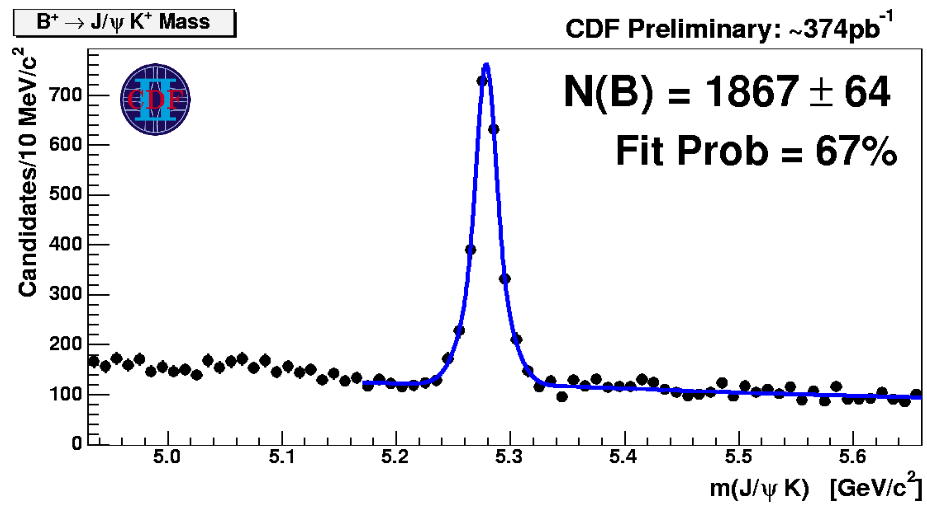
$$B_1^0 \rightarrow B^{*+}\pi^-;\ B^{*+} \rightarrow B^+\gamma$$
$$B_2^{*0} \rightarrow B^{*+}\pi^-;\ B^{*+} \rightarrow B^+\gamma$$
$$B_2^{*0} \rightarrow B^+\pi^-$$
$$B^+ \rightarrow J/\psi K^+ \qquad B^+ \rightarrow \bar{D}^0\pi^+$$
$$\hookrightarrow \mu^+\mu^-$$



Fit mass difference

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

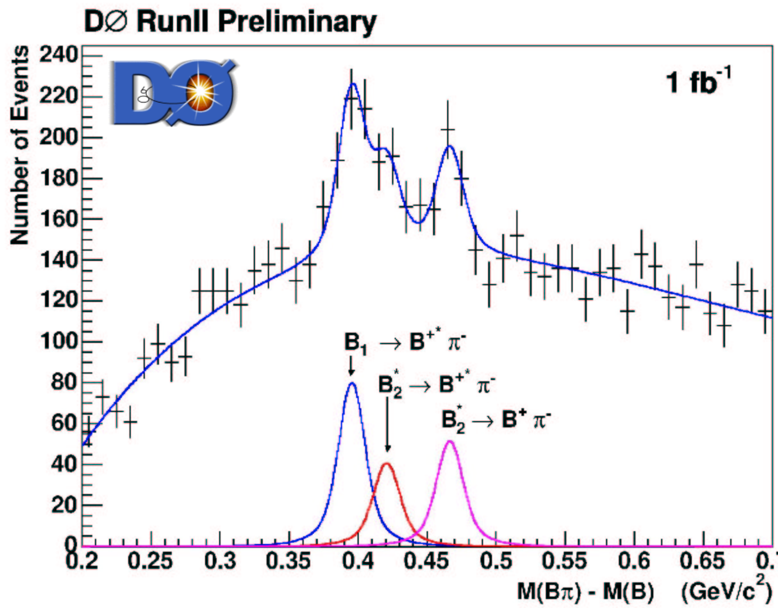


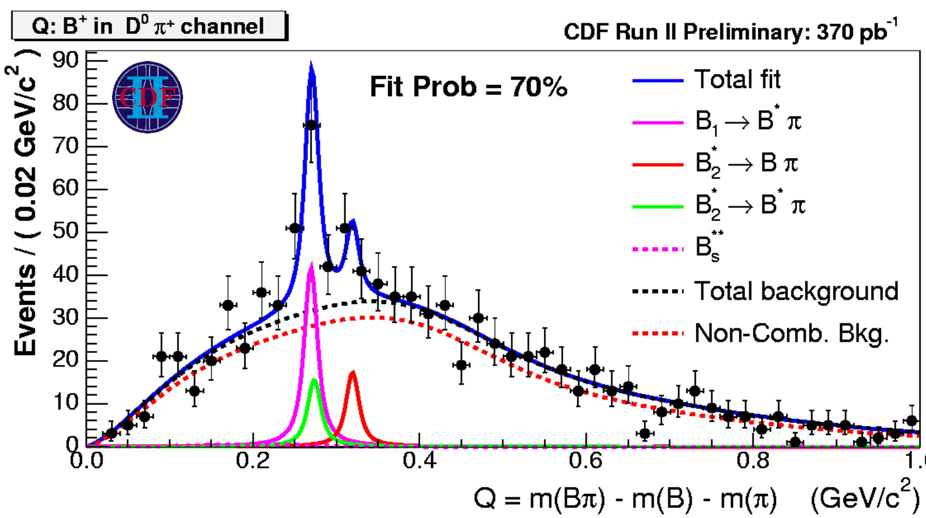


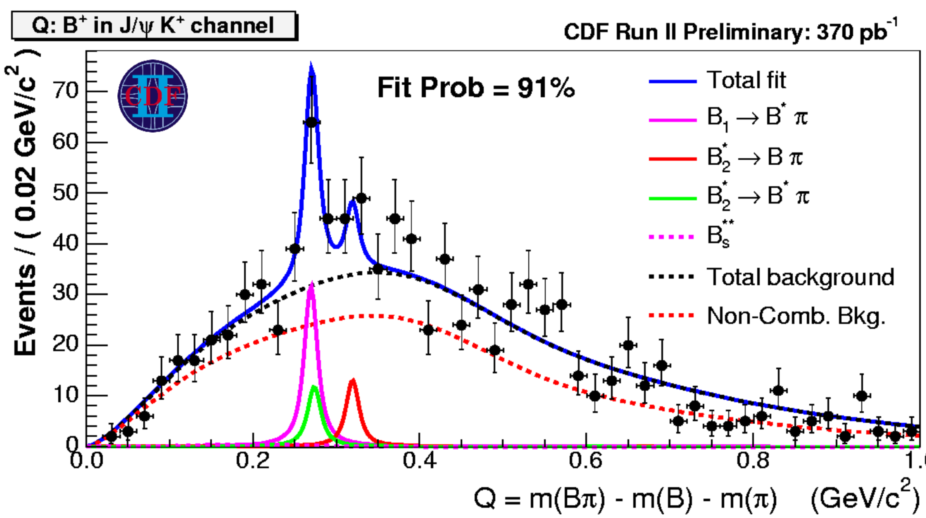
Narrow B_d** States

Results not in good agreement (CDF to update with 1 fb^{-1})

	CDF (370 pb^{-1})	DØ (1fb^{-1})
$m(B_1)$ [MeV/c^2]	5734±3±2	5720.8±2.5±5.3
$m(B^*_2)$ [MeV/c^2]	5738±5±1	5746.0±3.9±5.4
$m(B^*_2) - m(B_1)$ [MeV/c^2]	4±6±2	25.2±3.0±1.1
$\Gamma_1 = \Gamma_2$ [MeV/c^2]	16±6 (fixed)	6.6±5.3±4.2





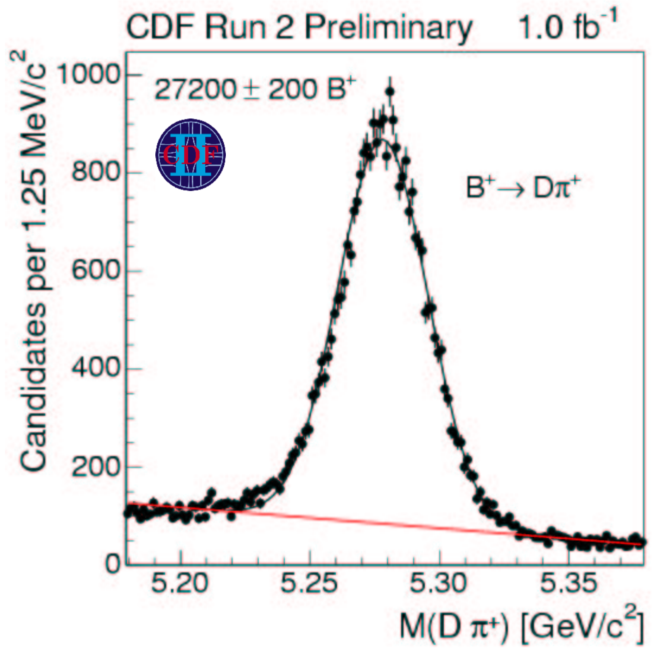


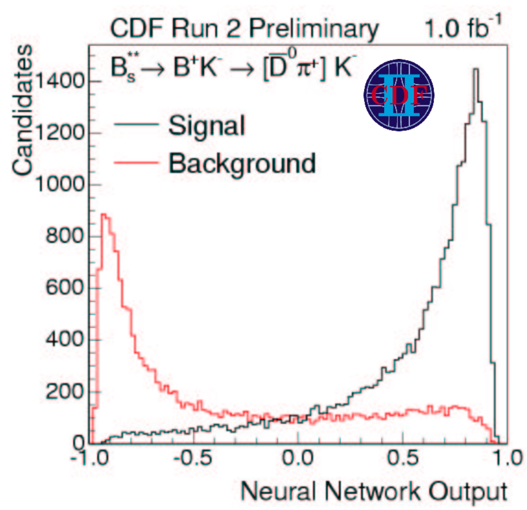
Narrow B_s^{**} States

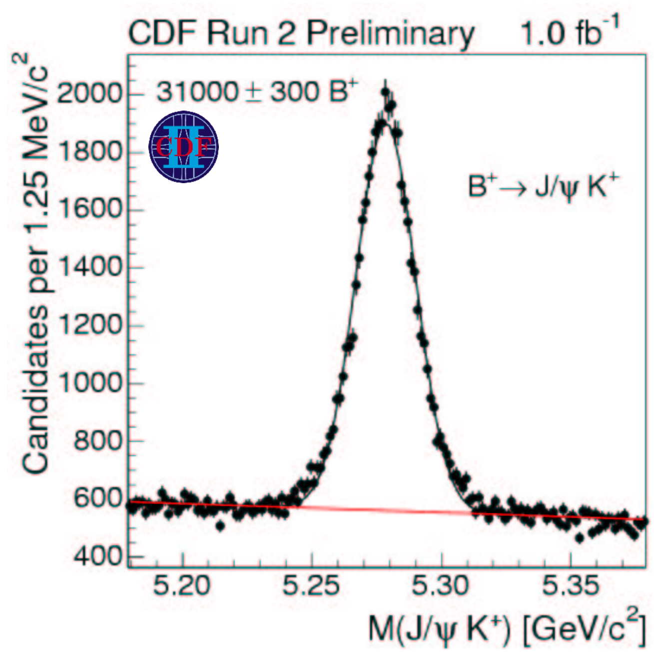
- Decay B_S^{**} to $B_S\,\pi$ isospin suppressed
- Reconstruct $B_S^{**} \to B^+K^-$
  with $B^+ \to J/\psi\, K^+$ & $B^+ \to D^0\pi^+$
- CDF uses neural network trained
  on MC to optimize $S^2/(S+B)$

Again: Fit mass difference

$\Delta m(B_s^{**}) = m(BK) - m(B) - m(K)$

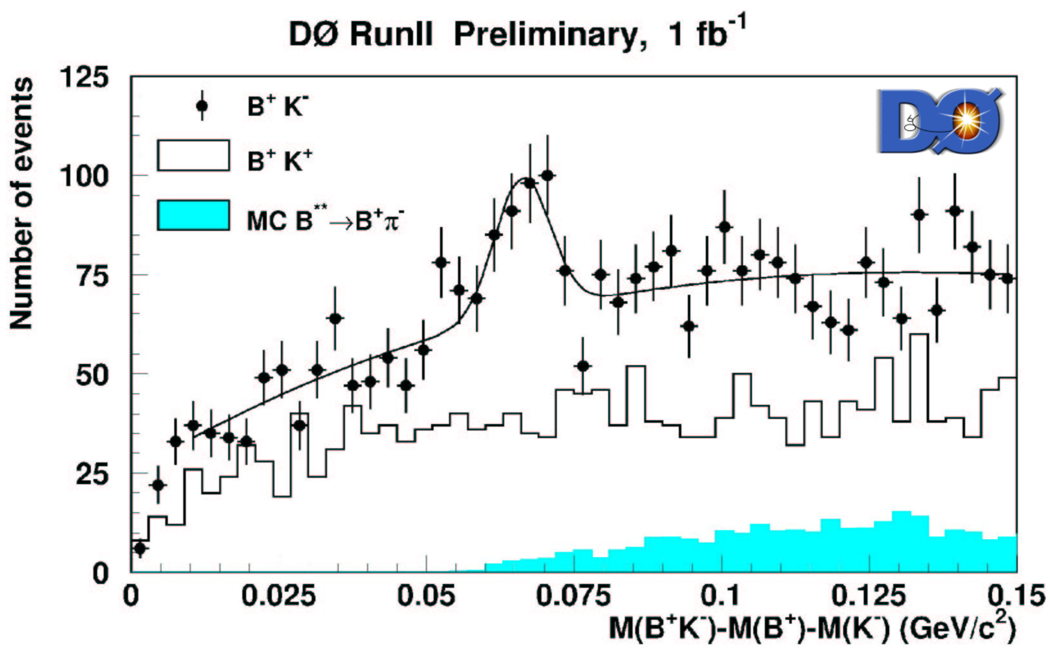


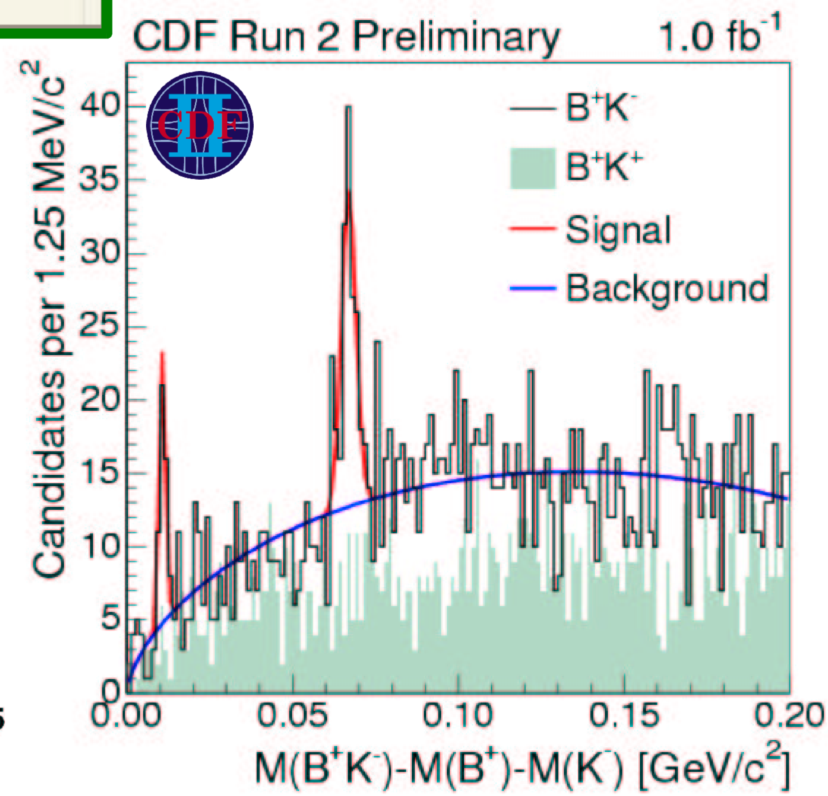




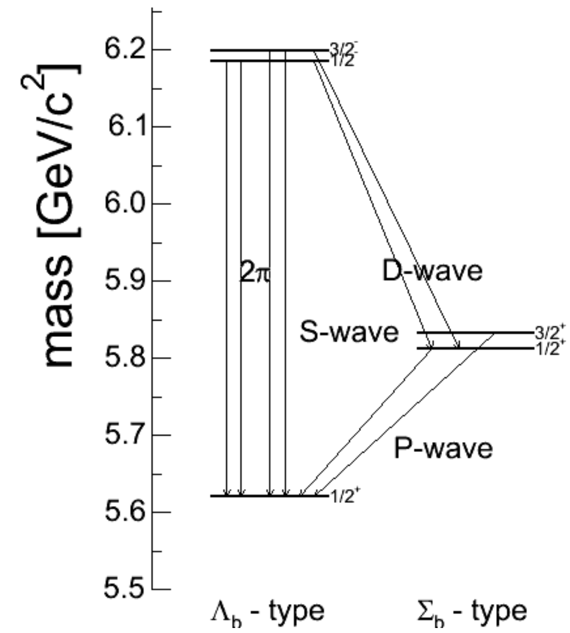
Narrow B_s** States

	CDF (1 fb^{-1})	DØ (1 fb^{-1})
$m(B_{s1})$ [MeV/c^2]	$5829.4 \pm 0.2 \pm 0.6$	–
$m(B^*_{s2})$ [MeV/c^2]	$5839.6 \pm 0.4 \pm 0.5$	$5839.1 \pm 1.4 \pm 1.5$
$m(B^*_{s2}) - m(B_{s1})$ [MeV/c^2]	$10.20 \pm 0.44 \pm 0.35$	–





Search for Σ_b Baryon



Motivation:

- Λ_b only established *B* baryon
- Next accessible baryons:

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

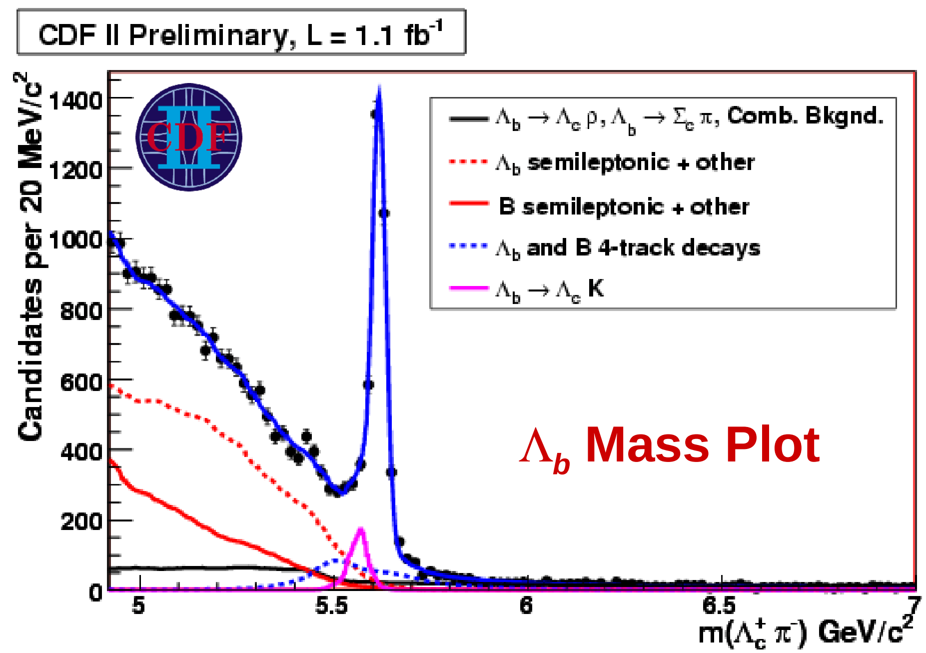
→ $= 3/2^+$ (Σ_b^*)

→ $= 1/2^+$ (Σ_b)

- HQET well tested for meson systems; check predictions for *Qqq* systems

- Baryon spectroscopy tests Lattice QCD & potential quark models

CDF with 1.1 fb^{-1}, world's largest sample of Λ_b: ~3000



Search for Σ_b Baryon

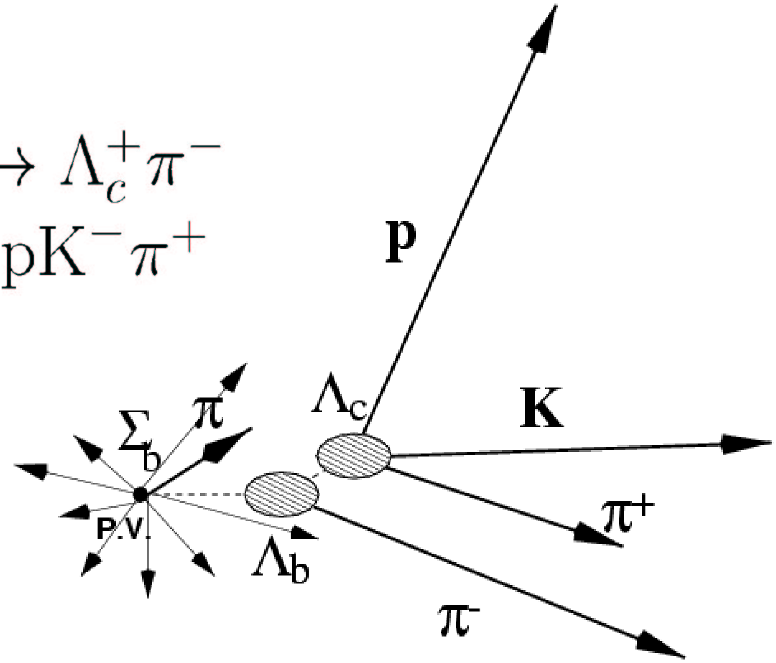
Search Strategy:

Use 2 track trigger to reconstruct: $\Lambda_b^0 \rightarrow \Lambda_c^+ \pi^-$

$\Lambda_c^+ \rightarrow pK^- \pi^+$

- 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^+:

$$\Sigma_b^{(*)-} \rightarrow \Lambda_b^0 \pi^- \rightarrow \Lambda_c^+ \pi^- \pi^-$$
$$\Sigma_b^{(*)+} \rightarrow \Lambda_b^0 \pi^+ \rightarrow \Lambda_c^+ \pi^- \pi^+$$



- Search for resonances in mass diff.:

$$Q = m(\Lambda_b \pi) - m(\Lambda_b) - m_\pi$$

- Optimize Σ_b cuts with Σ_b signal region blinded: $30 < Q < 100$ MeV/c^2

Σ_b backgrounds:

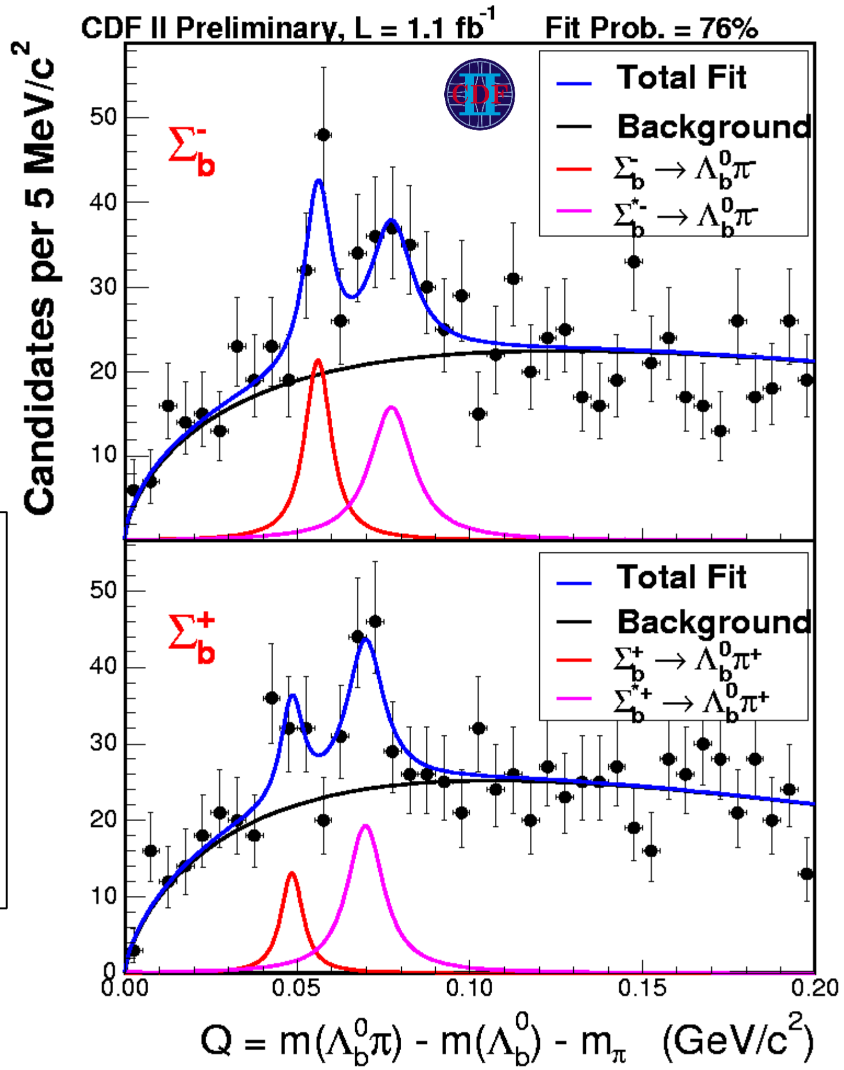
- Λ_b Hadronization + Underlying Event – Dominant!
- *B* meson Hadronization
- Combinatorial background

Fix background contributions from data or PYTHIA MC

Observation of Σ_b Baryon

- **Observe signals consistent with lowest lying charged Σ_b states**
- **With unbinned likelihood fit, measure number of events**

$$N(\Sigma_b^-) = 60^{+14.8}_{-13.8}\ (\text{stat})\ ^{+8.4}_{-4.0}\ (\text{syst})$$
$$N(\Sigma_b^+) = 29^{+12.4}_{-11.6}\ (\text{stat})\ ^{+5.0}_{-3.4}\ (\text{syst})$$
$$N(\Sigma_b^{*-}) = 74^{+18.2}_{-17.4}\ (\text{stat})\ ^{+15.6}_{-5.0}\ (\text{syst})$$
$$N(\Sigma_b^{*+}) = 74^{+17.2}_{-16.3}\ (\text{stat})\ ^{+10.3}_{-5.7}\ (\text{syst})$$



Determine mass difference values:

$$m(\Sigma_b^-) - m(\Lambda_b^0) - m_\pi = 55.9^{+1.0}_{-1.0}\ (\text{stat}) \pm 0.1\ (\text{syst})\ \text{MeV}/c^2$$
$$m(\Sigma_b^+) - m(\Lambda_b^0) - m_\pi = 48.4^{+2.0}_{-2.3}\ (\text{stat}) \pm 0.1\ (\text{syst})\ \text{MeV}/c^2$$
$$m(\Sigma_b^*) - m(\Sigma_b) = 21.3^{+2.0}_{-1.9}\ (\text{stat})\ ^{+0.4}_{-0.2}\ (\text{syst})\ \text{MeV}/c^2$$

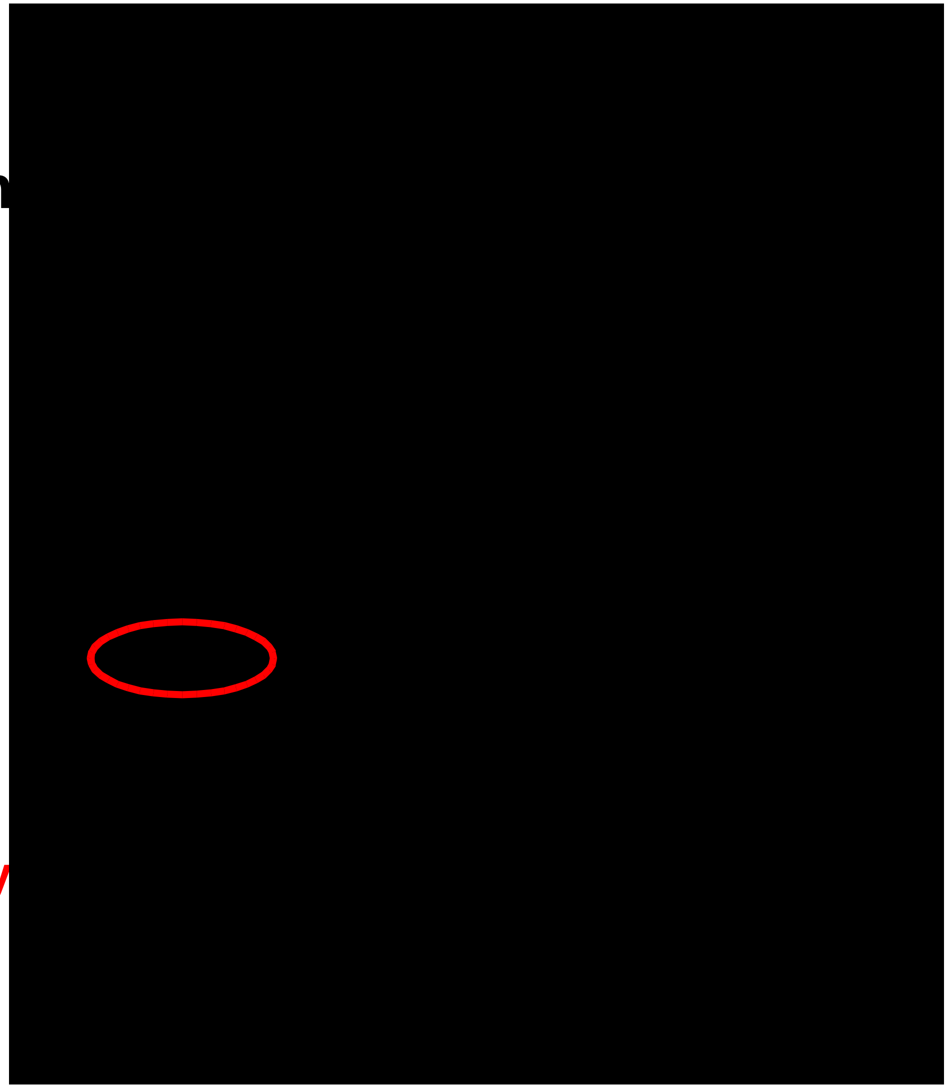
Search for η_b

- Spin-singlet $b\bar{b}$ bound state

  η_b yet to be observed
- $\sigma(p\bar{p} \to \eta_b X) \sim \mu b$ at Tevatron energy scale
- Look for η_b decay in

  $\eta_b \to J/\psi\ J/\psi$ in 1.1 fb^{-1}
  - Expect between 0.2 and 20 events with both J/ψ decaying to $\mu^+ \mu^-$
  - Reconstruct as 3μ + track
  - Use $B_s \to J/\psi\ \phi$ as a consistency check

Bottomium spectrum

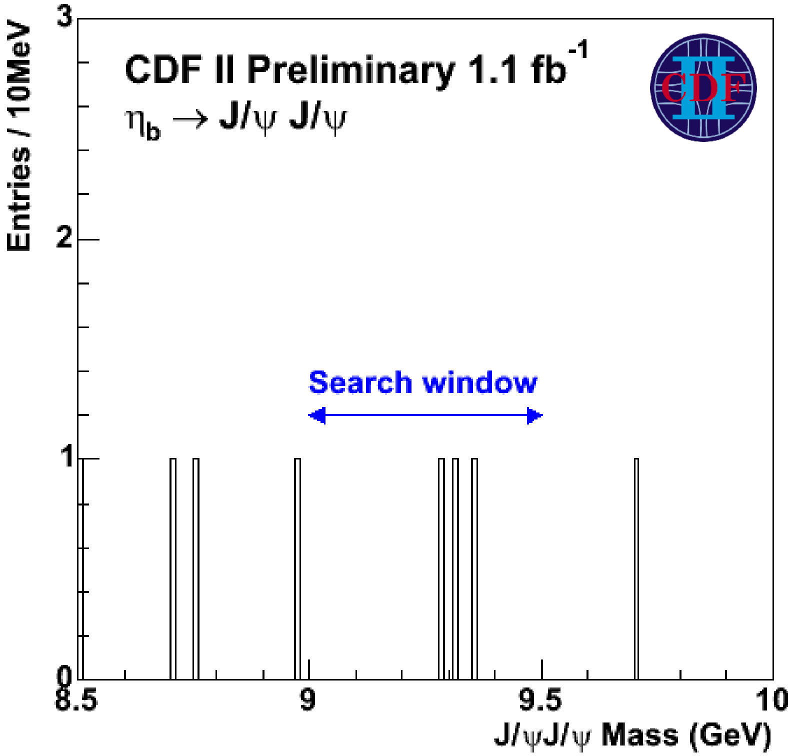


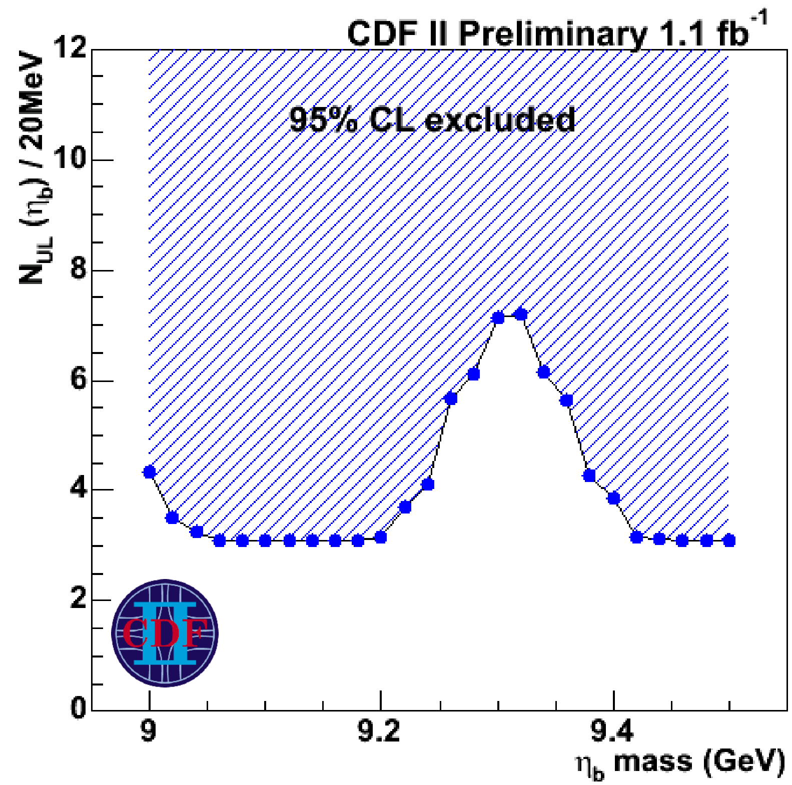
Search for η_b

- **Expected 3.6 bkg events; observe 3 events**
- **Set upper limit for production cross section:**

$$\frac{\sigma(p\bar{p} \to \eta_b X; |y(\eta_b)| < 0.6, p_T(\eta_b) > 3.0GeV) \cdot Br(\eta_b \to J/\psi J/\psi)}{\sigma(p\bar{p} \to H_b \to J/\psi X); |y(J/\psi)| < 0.6, p_T(J/\psi) > 3.0GeV)} < 5.0 \times 10^{-3}$$

$$\sigma(p\bar{p} \to \eta_b X, |y(\eta_b)| < 0.6, p_T(\eta_b) > 3GeV) \cdot Br(\eta_b \to J/\psi J/\psi) \cdot [Br(J/\psi \to \mu\mu)]^2 < 2.6 \text{ pb}$$





Decay of B Hadrons: Branching Fractions

BR(B_S -> $D_S^{(*)}$ $D_S^{(*)}$)

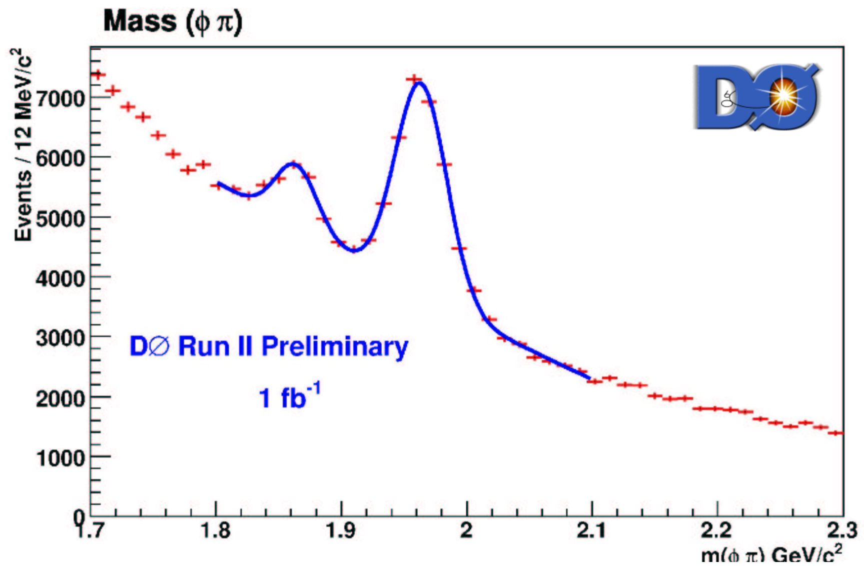
Reconstruct
$D_s \to \phi\pi$, $D_s \to \phi\mu\nu$, ($\phi \to K^+ K^-$)

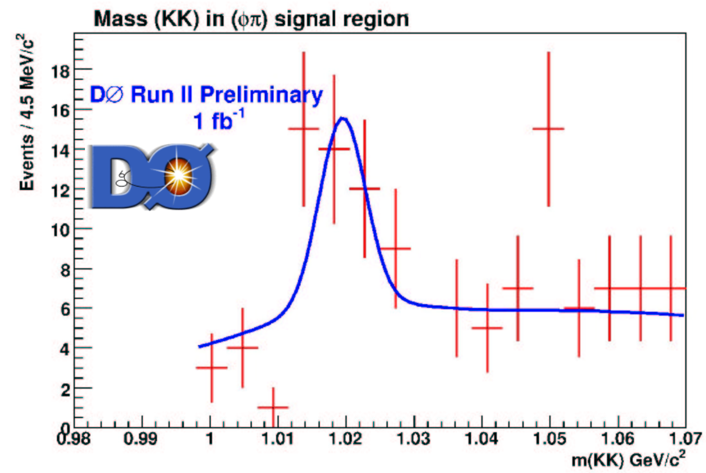
Start with μD_s sample ($D_s \to \phi\pi$), look for additional ϕ ($\mu D_s\phi$ sample)

Ratio of efficiencies estimated using simulated events.

Directly fit D_s mass distribution to extract N(μD_s). Unbinned likelihood fit to extract N($\mu\phi D_s$) (Lower stat.)

- **N(μD_S) = 15225 ± 310**
- **N($\mu\phi D_S$) = 19.3 ± 7.9**





BR(B_S -> $D_S^{(*)}$ $D_S^{(*)}$) =

<u>0.071±0.032±0.027</u>

$\Delta\Gamma/\Gamma$ = 2 x BR = 0.142±0.064±0.054

Dominant sources of systematics:

BR($B_s \to \mu\nu D_s^{(*)}$)
MC p_T reweighing

BR(B_s ->D_{s1}(2536)μνX)

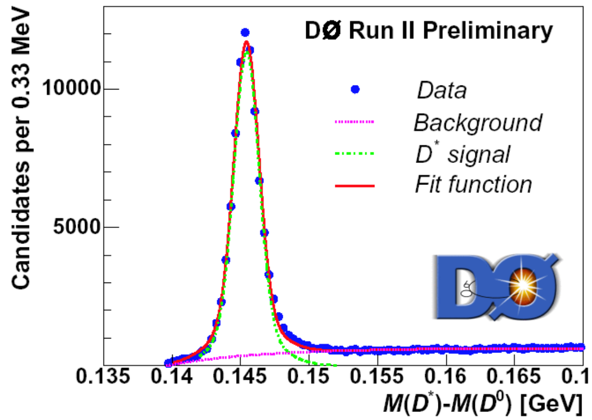
Reconstruct

$$B_s^0 \to D_{s1}^-(2536)\mu^+\nu, \quad D_{s1}^-(2536) \to D^{*-}K_S^0,$$
$$D^{*-} \to D^0\pi^-, \quad K_S^0 \to \pi^+\pi^-$$

Relative to semileptonic b -> D* μνX:

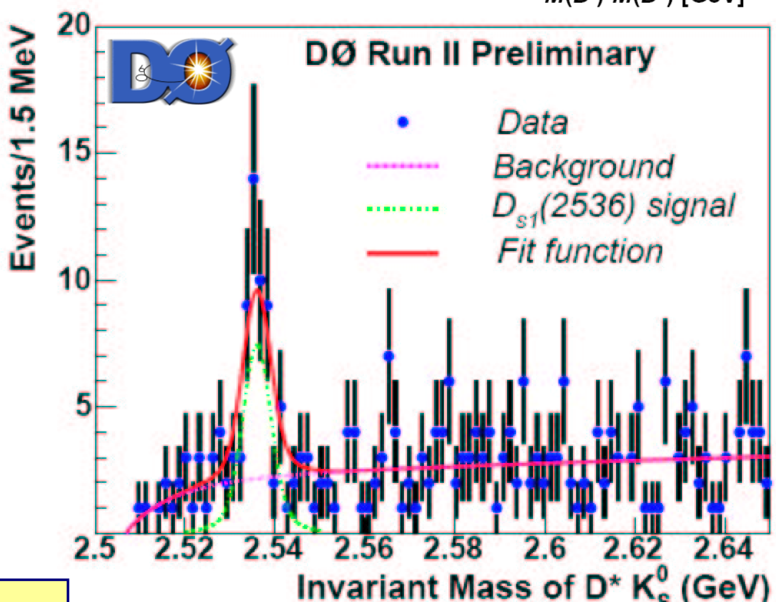
$$f(\bar b \to B_s^0) \cdot Br(B_s^0 \to D_{s1}(2536)\mu^+\nu X) \cdot Br(D_{s1}(2536) \to D^{*-}K_S^0) = Br(\bar b \to D^{*-}l^+\nu X) \cdot \frac{N_{D_{s1}(2536)}}{N_{D^*\mu}} \cdot \frac{1}{R_{D^*}^{gen}\varepsilon_{D_{s1}(2536)}}$$

$$R_{D^*}^{\rm gen} = \epsilon(B_s^0 \to D_{s1}\mu \to D^*\mu)/\epsilon(\bar b \to D^*\mu)$$



Result:

$$f(\bar b \to B_s^0) \cdot \mathcal{B}(B_s^0 \to D_{s1}^-(2536)\mu^+\nu X) \cdot \mathcal{B}(D_{s1}^- \to D^{*-}K_S^0) = (2.29 \pm 0.43 \pm 0.36) \times 10^{-4}$$



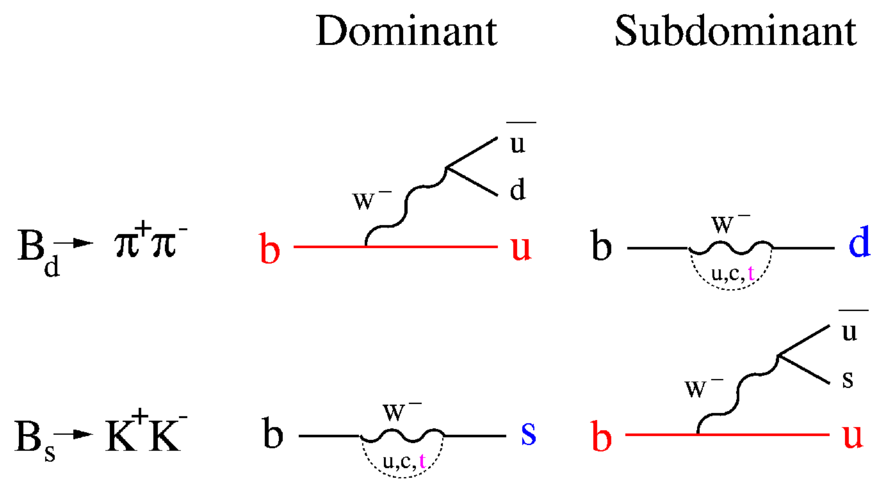
$N = 42.6 \pm 8.6 \quad \sim 5\,\sigma$

Comparison with theory

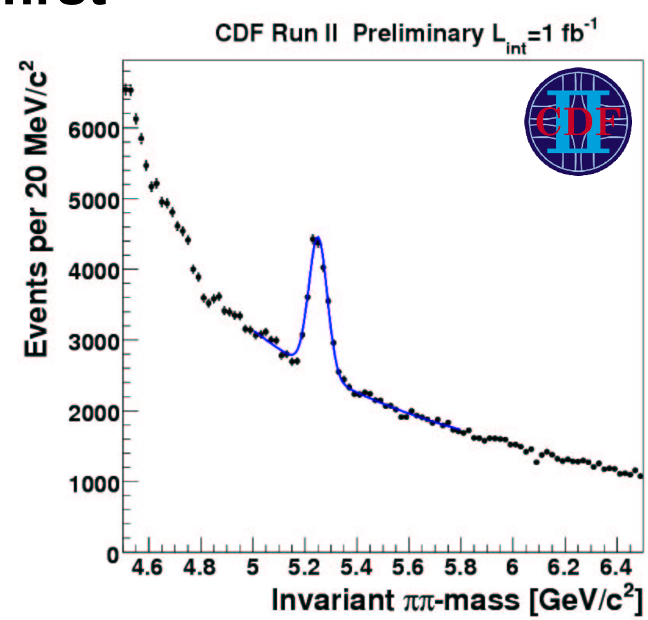
BR(B_s->D_{s1}μνX) = 0.86±0.16 ±0.13 ±0.09 %

ISGW2 0.53%, IQM 0.39%, HQET&QCD Sum rules 0.20%

Charmless *B -> hh*



- CDF performed comprehensive analysis of charmless 2-body decays *B -> hh*
- Joint study of B^0 and B_s decays into $\pi\pi$/Kπ/KK can shed light on SU(3) symmetry breaking
- Important to disentangle tree versus penguin contributions
- Remember: Direct CP violation in B decays first observed in B^0 -> K π
- CDF use 2-track hadronic trigger to collect large dataset of B -> hh
- Observe signal with offline confirmation of trigger cuts: ~8500 B -> hh events in 1 fb^{-1} of data



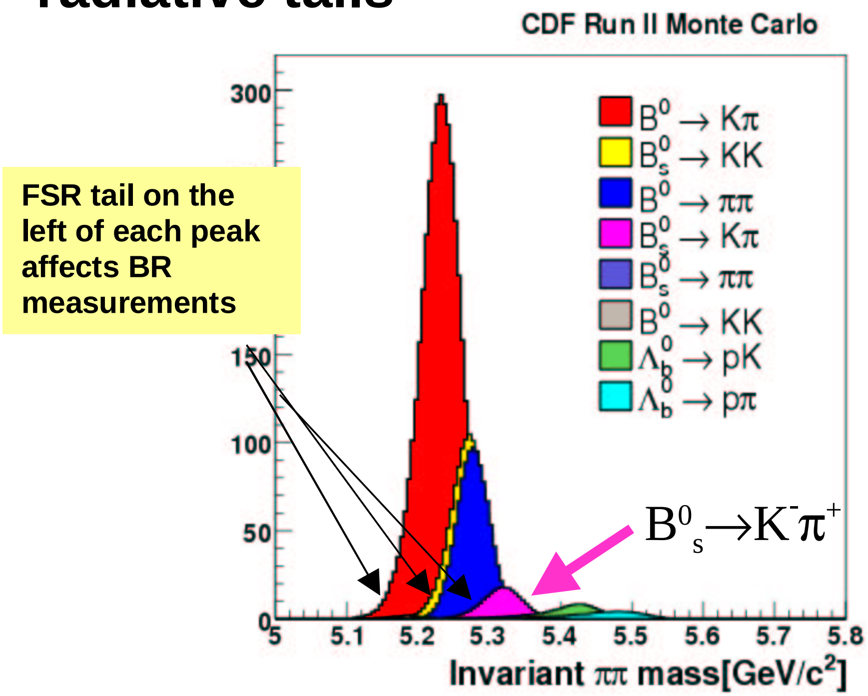
Charmless *B -> hh*

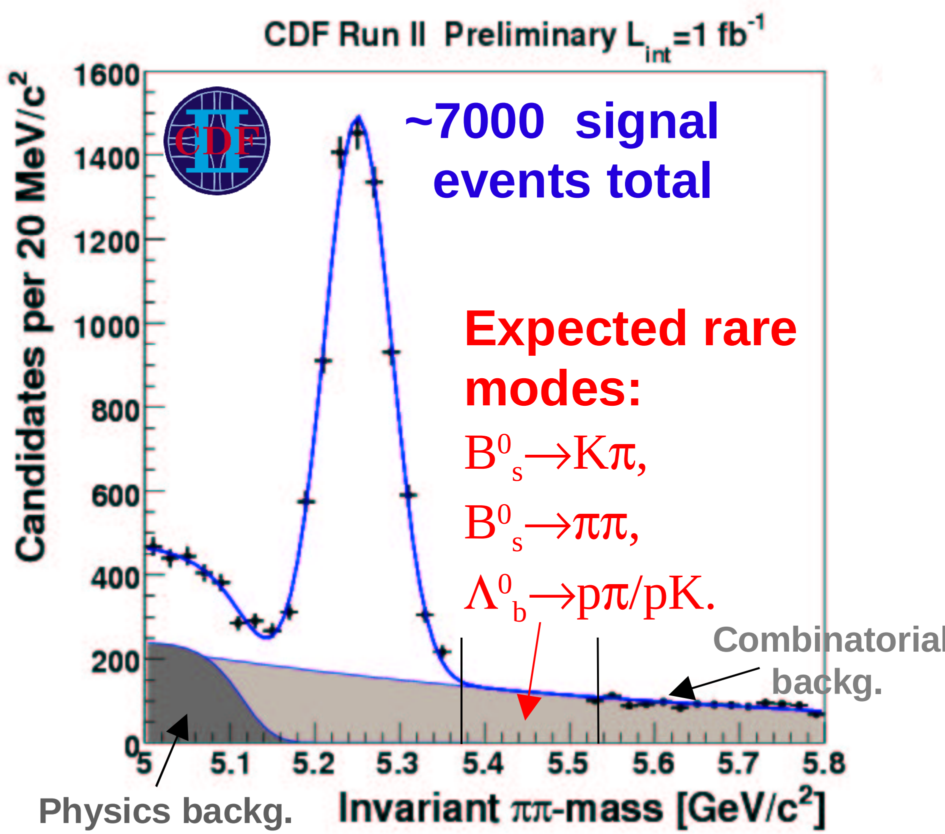
- **Optimize cuts using signal MC and sideband backgrounds:**

2 sets: - Measure CP asymmetry in B -> K π (talk by Ay Cano)

- Search for rare decays such as B_s -> Kπ & measure BR <---

- **Despite excellent mass resolution (~20 MeV) modes overlap**
- **BR measurements sensitive to shape of mass resolution: radiative tails**

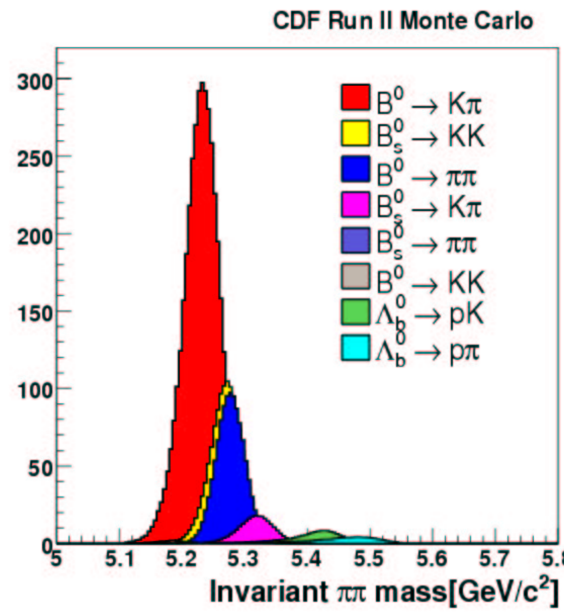


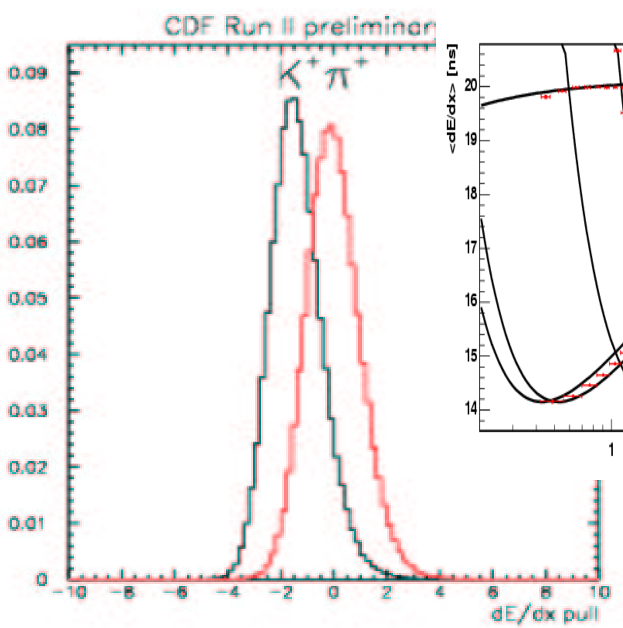


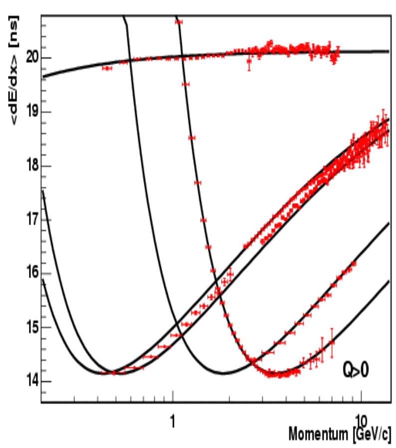
Charmless *B -> hh*

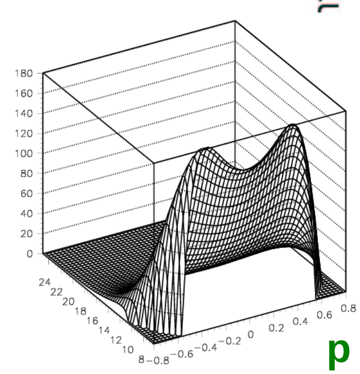
- Disentangle overlapping modes by
  - Invariant mass information: m(ππ)
  - Kinematic discriminates

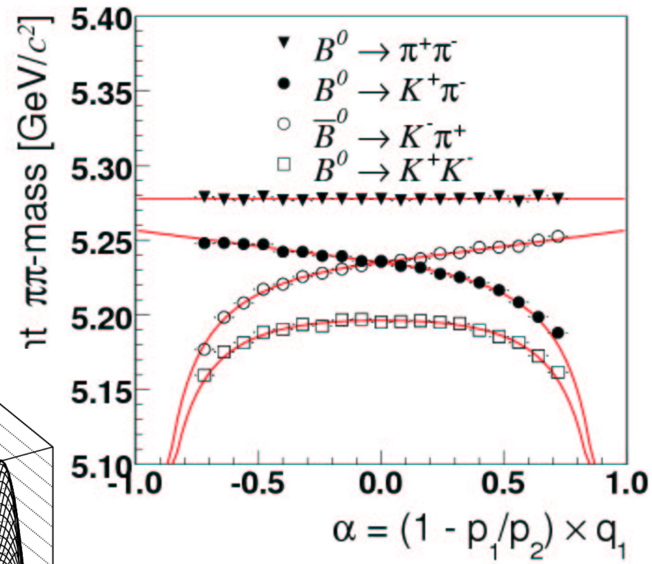
    $\alpha = (1-p_{min}/p_{max})q_{min}$ signed momentum imbalance
  - PID through dE/dx
- Use 1.5 mio D* -> $D^0\pi$, D^0 -> Kπ to accurately calibrate dE/dx over tracking volume & time





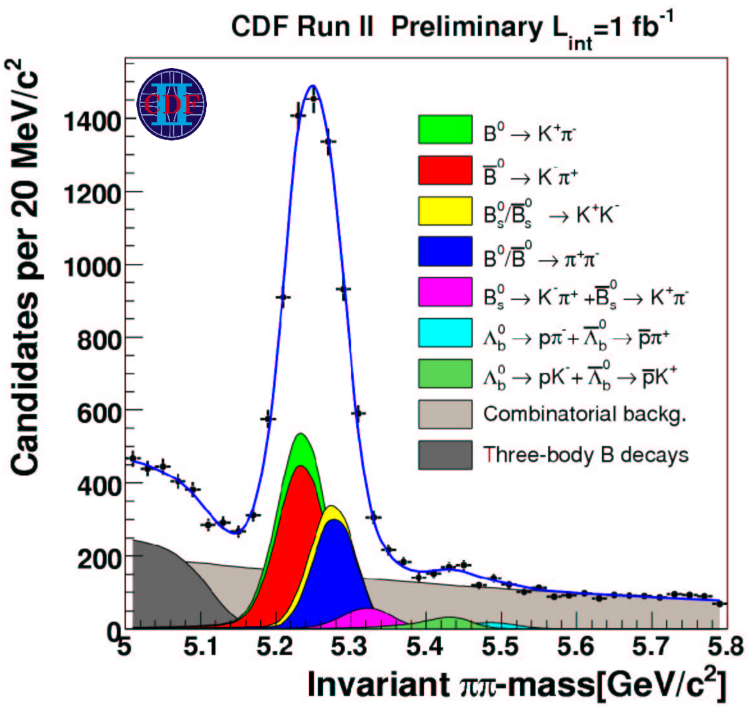




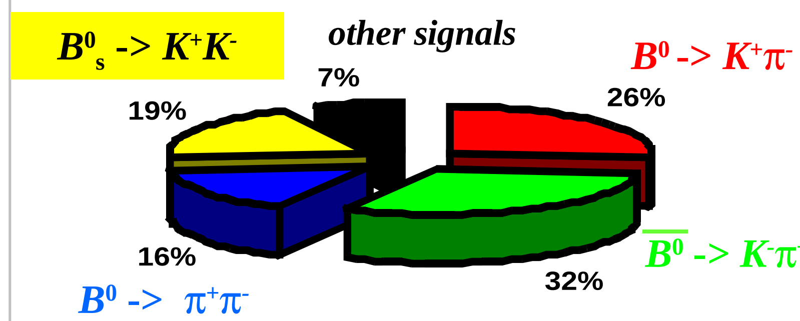


p imbalance

$B^0 \to \pi^+\pi^-$ & $B_s^0 \to K^+K^-$



Uncorrected fractions



parameter	fraction	yield
$B^0 \to \pi^+\pi^-$ + c.c.	(0.160 ± 0.009)	1121 ± 63
$B^0 \to K^+\pi^-$ + c.c.	(0.577 ± 0.010)	4045 ± 84
$B_s^0 \to K^+K^-$ + c.c.	(0.186 ± 0.009)	1307 ± 64

$$\frac{BR(B^0 \to \pi^+\pi^-)}{BR(B^0 \to K^+\pi^-)} = 0.259 \pm 0.017\ (stat.) \pm 0.016\ (syst.)$$

$$\frac{f_s \cdot BR(B_s^0 \to K^+K^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.324 \pm 0.019\ (stat.) \pm 0.041\ (syst.)$$

Using HFAG (Aug'06):

[redacted] (good agreement with B factories)

$BR(B^0_s \to K^+K^-)$ and $BR(B^0 \to \pi^+\pi^-)$ are becoming high precision measurement.

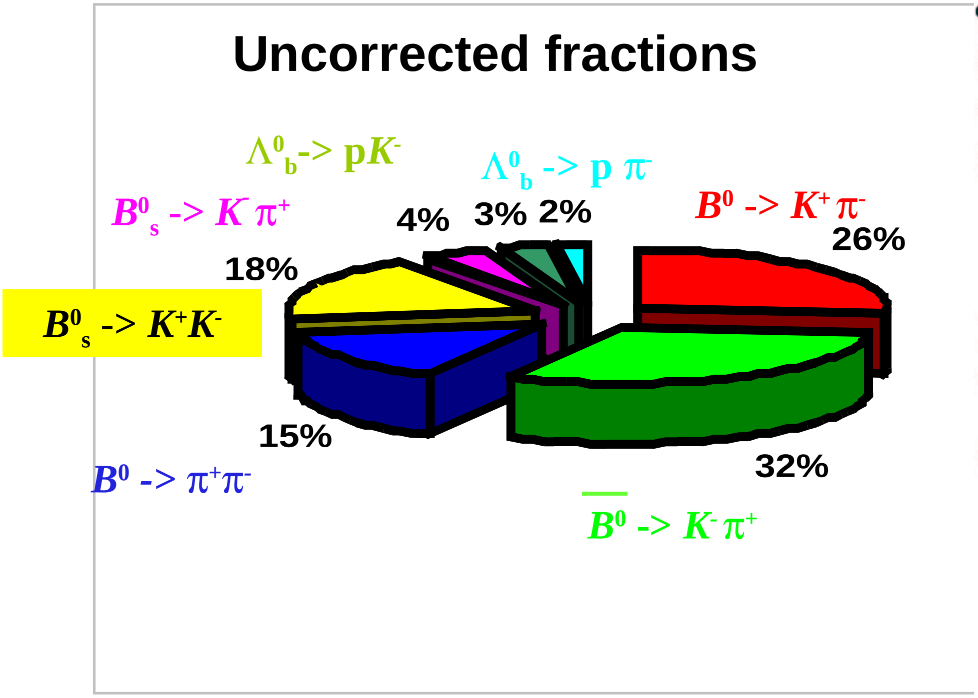
Theoretical expectations are not completely in agreement.

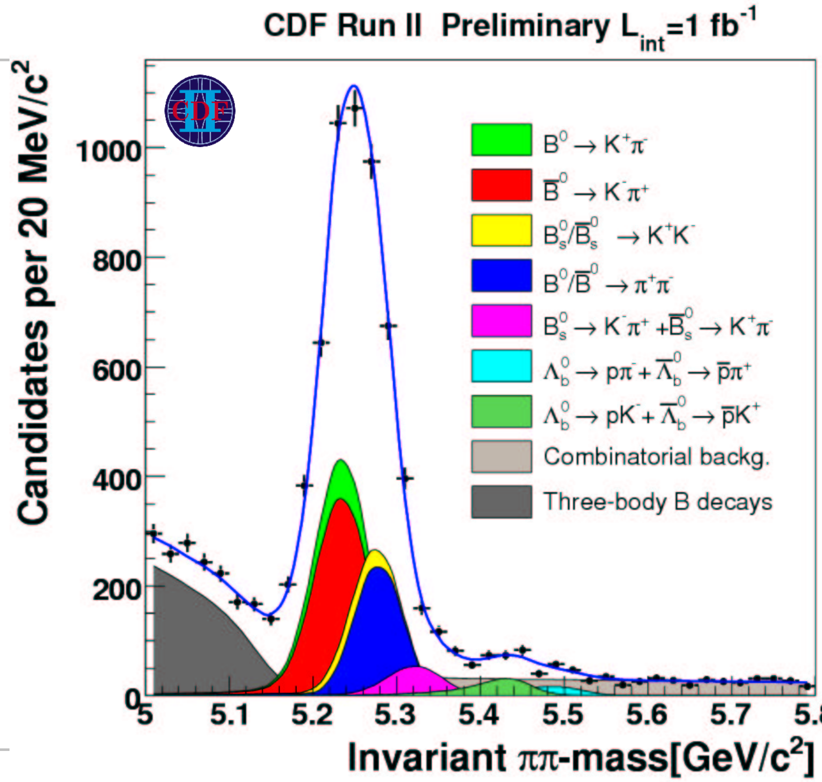
[Matias et al. PRL97, 061801, 2006] $BR(B^0_s \to K^+K^-)/BR(B^0 \to K^+\pi^-) \sim 1$

[Khodjamirian et al. PRD68:114007, 2003] predict large SU(3) breaking ~2 <--- Disfavored by CDF.

Charmless $B \to hh$

Search for rare modes:





New rare modes observed

$$N_{\rm raw}(B^0_s \to K^-\pi^+) = 230 \pm 34\ (stat.) \pm 16\ (syst.) \quad (8\sigma)$$

$$N_{\rm raw}(\Lambda^0_b \to p\pi^-) = 110 \pm 18\ (stat.) \pm 16\ (syst.) \quad (6\sigma)$$

$$N_{\rm raw}(\Lambda^0_b \to pK^-) = 156 \pm 20\ (stat.) \pm 11\ (syst.) \quad (11\sigma)$$

Charmless *B -> hh*

First observation: $B_s^0 \to K^- \pi^+$

$$N_{\rm raw}(B_s^0 \to K^-\pi^+) = 230 \pm 34\ (stat.) \pm 16\ (syst.)$$

$$\frac{f_s \cdot BR(B_s^0 \to K^-\pi^+)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.066 \pm 0.010\ (stat.) \pm 0.010\ (syst.)$$

Using HFAG: [redacted]

[Beneke&Neubert NP B675, 333(2003)]: ~[7-10] $\cdot 10^{-6}$
[Yu, Li, Yu, PRD71: 074026 (2005)]: ~[6-10]$\cdot 10^{-6}$
[Williamson, Zupan. PRD74 (2006) 014003]: ~4.9 $\cdot 10^{-6}$

Upper limits: $B_s^0 \to \pi^+\pi^-$ & $B^0 \to K^+K^-$

$$\frac{f_s \cdot BR(B_s^0 \to \pi^+\pi^-)}{f_d \cdot BR(B^0 \to K^+\pi^-)} = 0.007 \pm 0.004\ (stat.) \pm 0.005\ (syst.)$$ 1.5 σ

$$\frac{BR(B^0 \to K^+K^-)}{BR(B^0 \to K^+\pi^-)} = 0.020 \pm 0.008\ (stat.) \pm 0.006\ (syst.)$$ 1.5 σ

Both modes are annihilation-dominated decays. B^0 same resolution as B factories.

Using HFAG:

[redacted] ($< 0.7 \cdot 10^{-6}$ @ 90% C.L.)

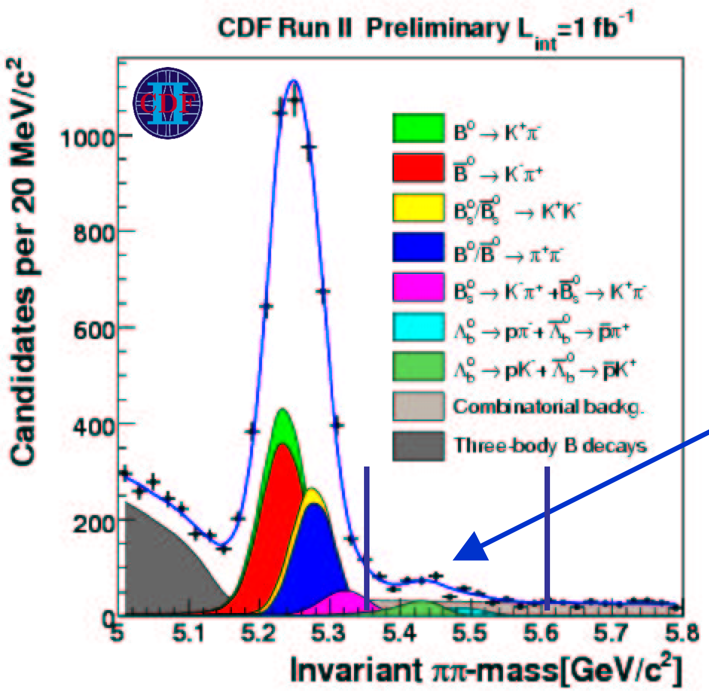
Expected [0.01 - 0.2] $\cdot 10^{-6}$ [Beneke&Neubert NP B675, 333(2003)]

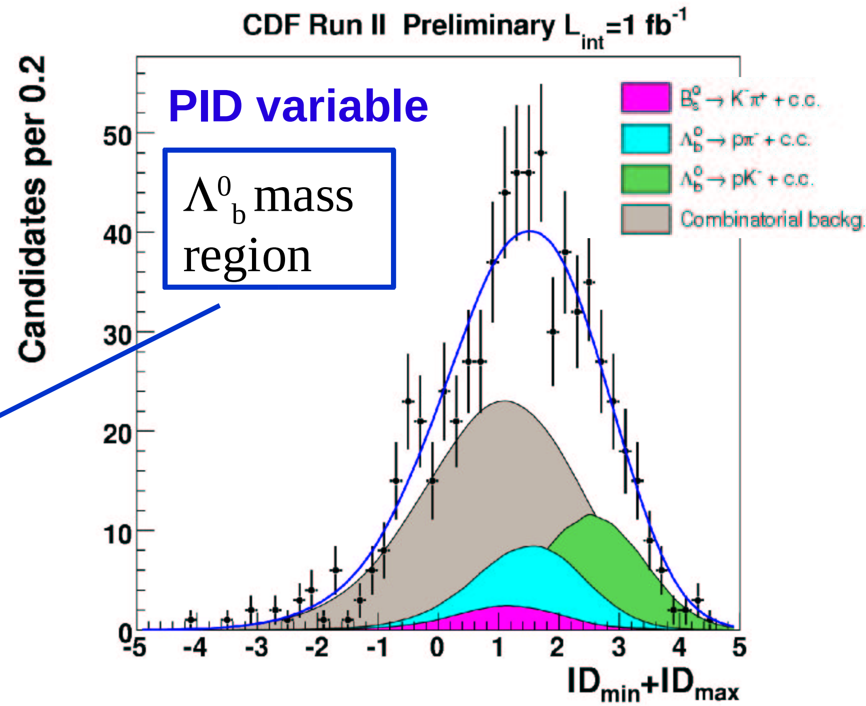
[redacted] ($<1.36 \cdot 10^{-6}$ @ 90% C.L.)

Expected: [0.007 - 0.08] $\cdot 10^{-6}$ [Beneke&Neubert NP B675, 333(2003)]
Expected: 0.42 ± 0.06 [Ying Li et al. hep-ph/0404028]

Charmless *B -> hh*

First observations: $\Lambda_b^0 \to p\,\pi^-$ & $\Lambda_b^0 \to p\,K^-$





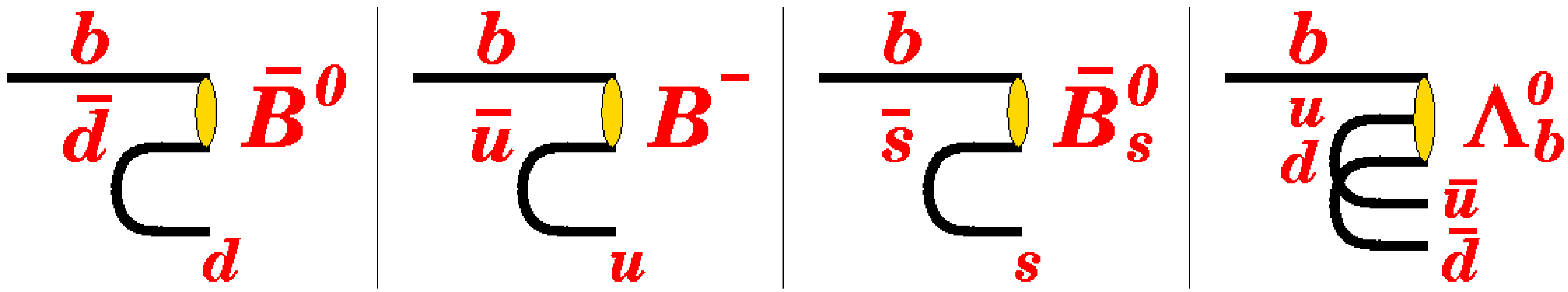
$$N_{\rm raw}(\Lambda_b^0 \to pK^-) = 156 \pm 20\ (stat.) \pm 11\ (syst.)$$ **11 σ**

$$N_{\rm raw}(\Lambda_b^0 \to p\pi^-) = 110 \pm 18\ (stat.) \pm 16\ (syst.)$$ **6 σ**

$$\frac{BR(\Lambda_b^0 \to p\pi^-)}{BR(\Lambda_b^0 \to pK^-)} = 0.66 \pm 0.14\ (stat.) \pm 0.08\ (syst.)$$

B Fragmentation Fractions

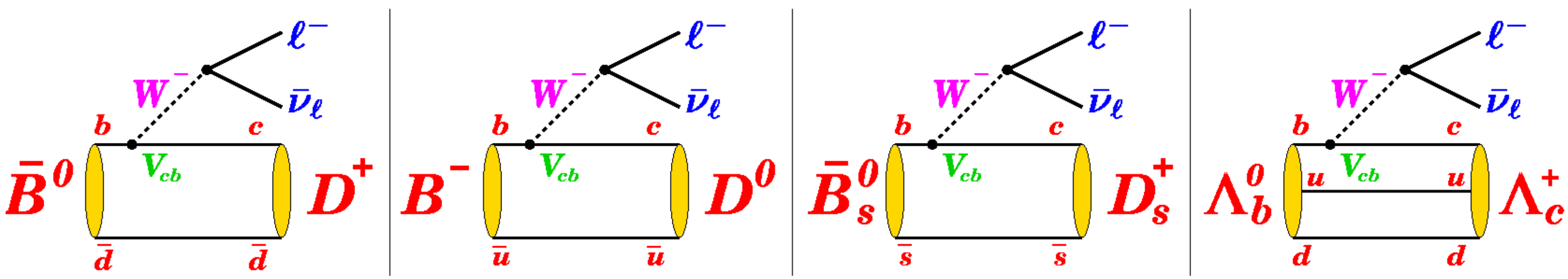
- Fragmentation fractions needed for ratio of BR measurements
- Measurement of b-quark fragmentation into $B^0,\ B^+,\ B^0_S,\ \Lambda^0_b$



- CDF in Run I: $f_S = (16.0 \pm 2.5)\%$
- PDG 2004 (LEP: Z->bb=): $f_S = (10.7 \pm 1.1)\%$

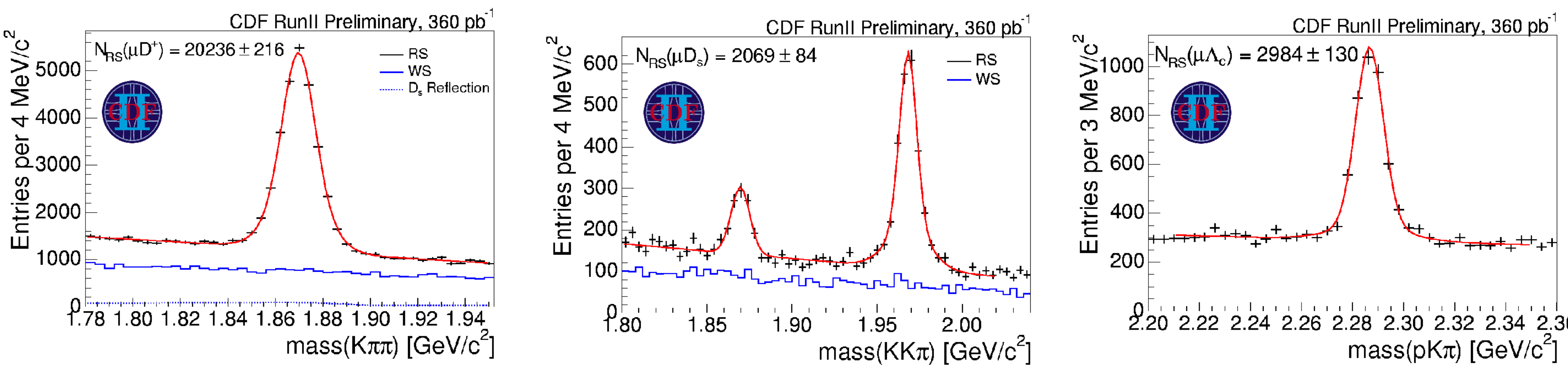
=> Does hadronic environment influence fragmentation?

CDF: Measurement of b-quark fragmentation fractions with high statistics semileptonic b -> clν samples using lepton-SVT data

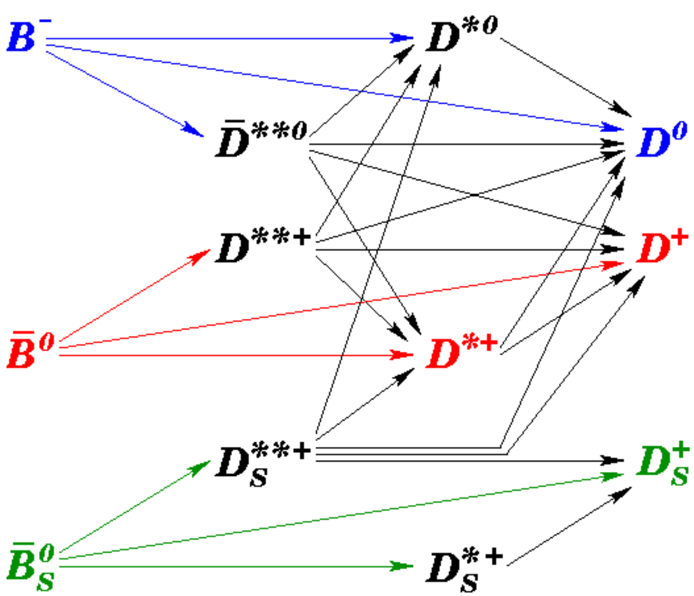


B Fragmentation Fractions

Data: Large lepton-charm yields



- Sample Composition: Disentangle feed down from D^{**} using MC
- Need good understanding of reconstruction efficiencies (data/MC agreement)
- Also measure f_{baryon}



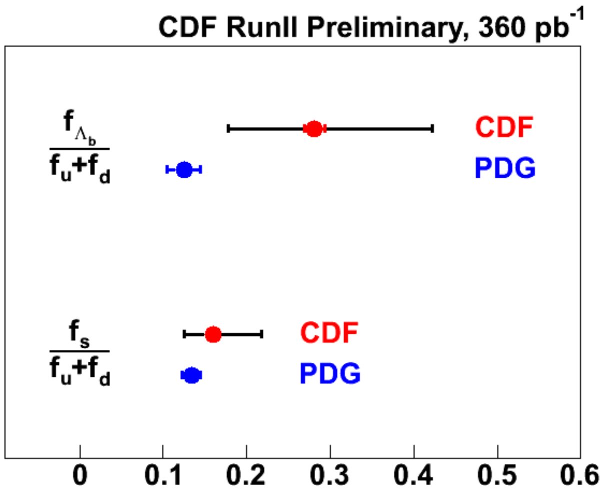
B Fragmentation Fractions

Results:

$$\frac{f_u}{f_d} = 1.054 \pm 0.018(\text{stat})^{+0.025}_{-0.045}(\text{syst}) \pm 0.082(BR)$$

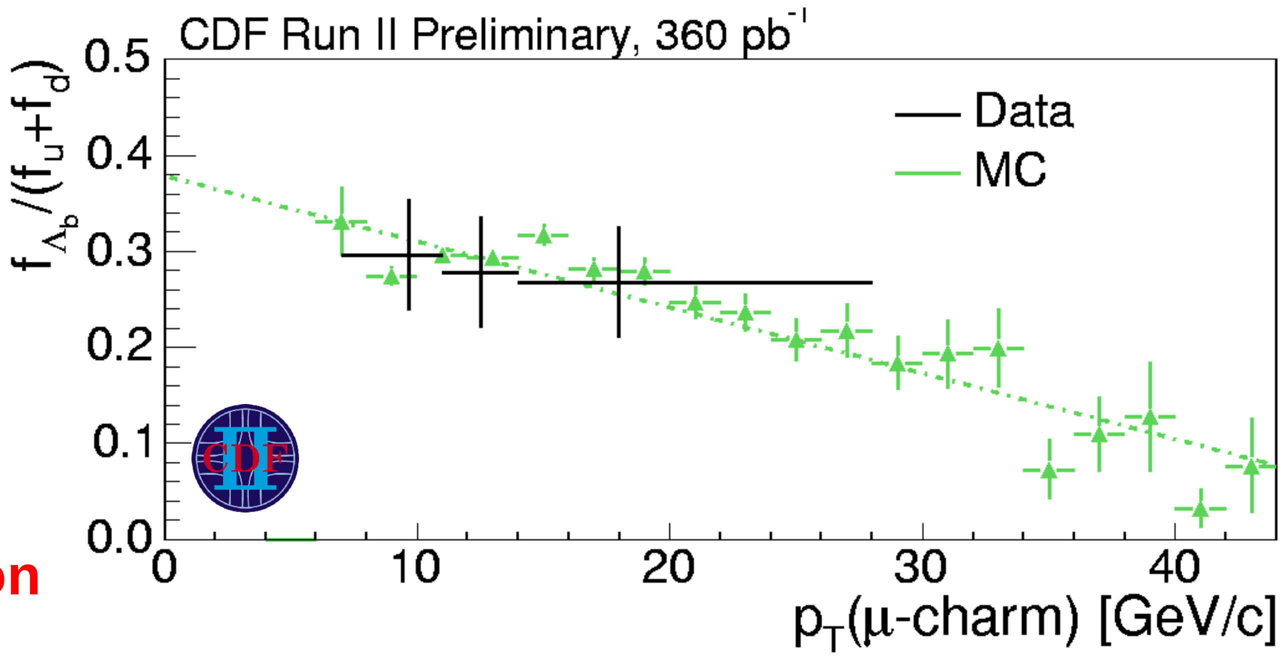
$$\frac{f_s}{f_u+f_d} = 0.160 \pm 0.005(\text{stat})^{+0.011}_{-0.010}(\text{syst})^{+0.057}_{-0.034}(BR)$$

$$\frac{f_{\Lambda_b^0}}{f_u+f_d} = 0.281 \pm 0.012(\text{stat})^{+0.058}_{-0.056}(\text{syst})^{+0.128}_{-0.086}(BR)$$



Surprising result:

- Large baryon fragmentation fraction
- Indication of momentum dependence of baryon fragmentation



Conclusions

- Tevatron offers rich heavy flavour program
- Many new result in spectroscopy and decay
  - Observation of excited B_S** states
  - Observation of Σ_b baryon states
- New and competitive branching fractions results
  - New B_S Decays modes observed
  - New results on charmless B -> hh decays
  - Observation of rare charmless Λ_b^0 decay modes
- Result on Fragmentation Fractions

Conclusions

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