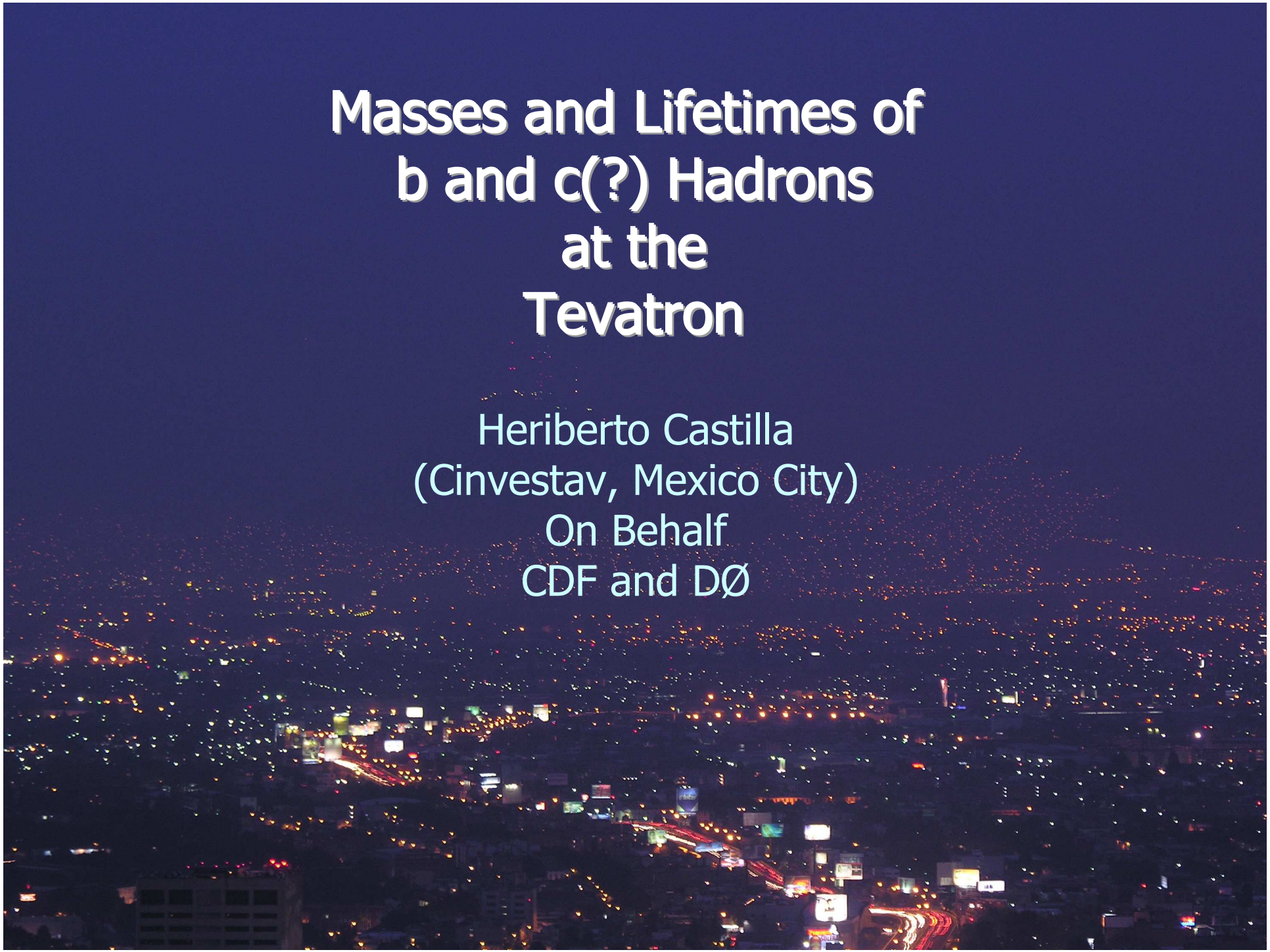
Masses and Lifetimes of b and c(?) Hadrons at the Tevatron

Heriberto Castilla
(Cinvestav, Mexico City)
On Behalf
CDF and DØ

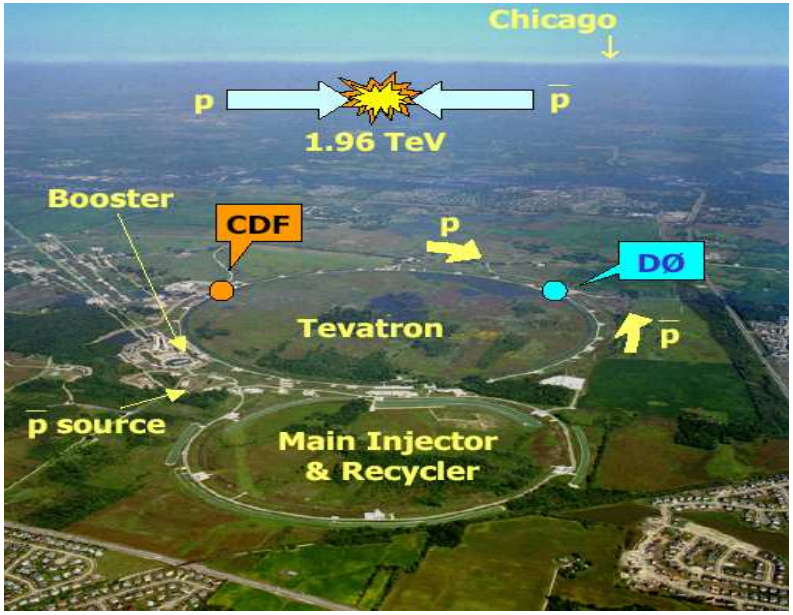


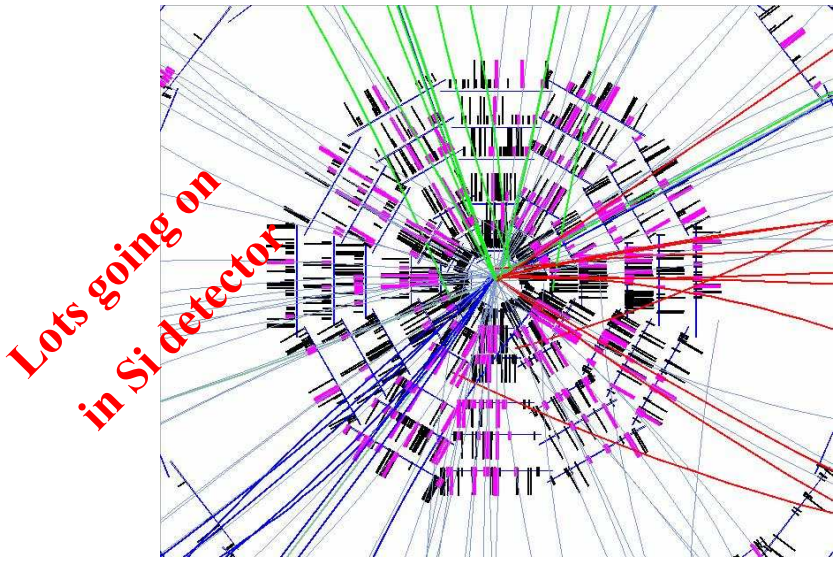
The Tevatron is a B factory

- Variety of B Physics
  - $\sigma(p\bar{p} \to bX) \approx 100\,\mu b$
  - $\mathcal{L}_{inst} \sim 100\,\mu b^{-1}s^{-1} \to 10$ kHz (Bs)
    - Only ~5% reconstructable
  - All species of b hadrons:

    B^0, B^+, B_s, B_c, Λ_b, Ξ_b, B^{**}
- But
  - $\sigma(p\bar{p} \to X)$ O(10^3) higher
  - Hard to find "other b"
    - ~ 30% acceptance
  - Boost larger B factories

    smaller LEP





Introduction: CDF and D0 detectors

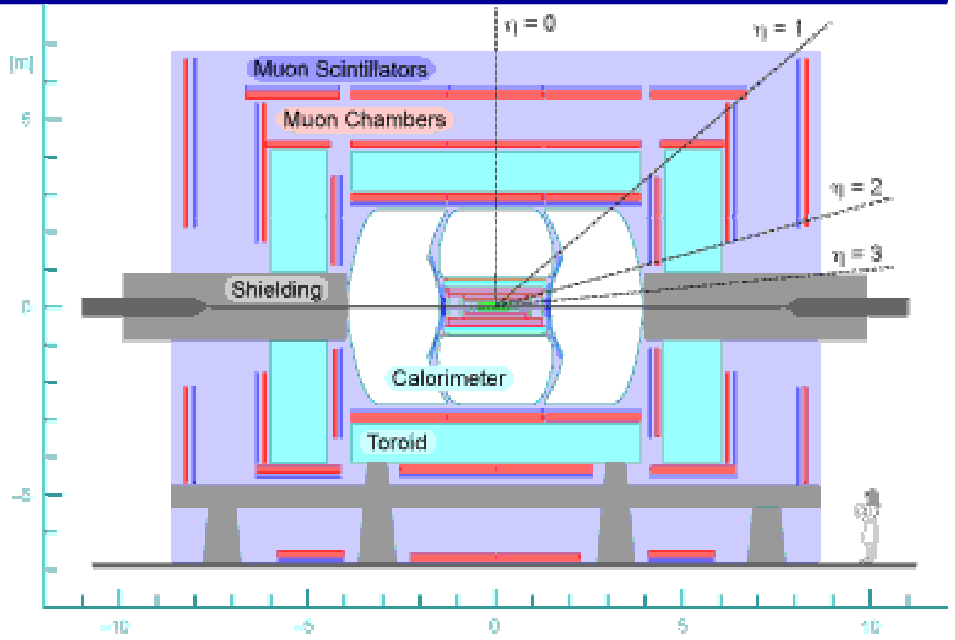
Great *b*-physics capabilities

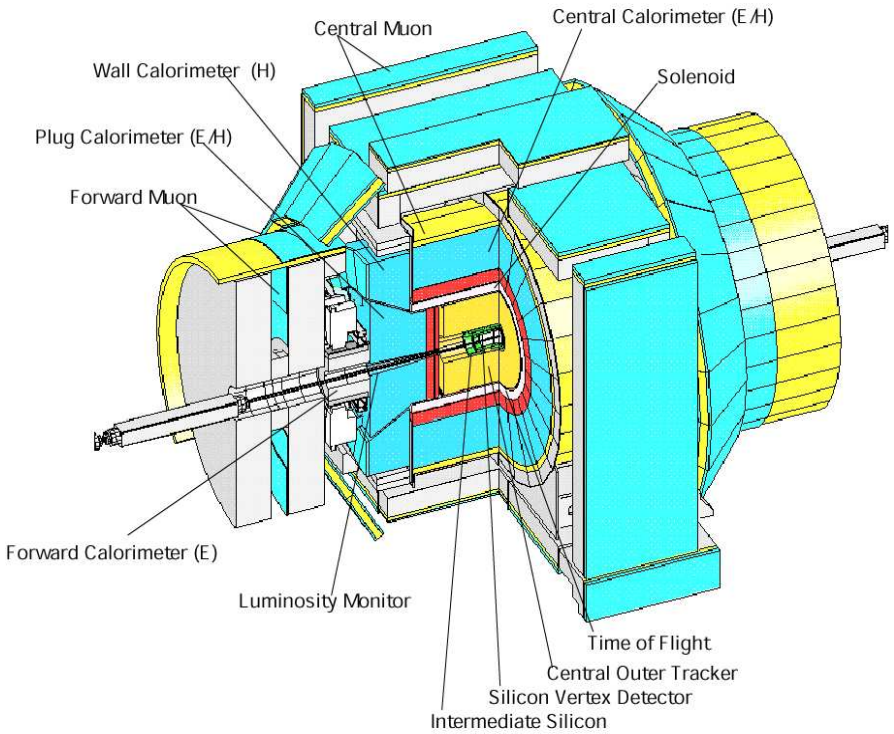
D0:

Excellent muon trigger and coverage

Tracking coverage $|\eta| < 2$

Tracking: Silicon + SciFib,





CDF:

Excellent p_T resolution,

displaced track trigger

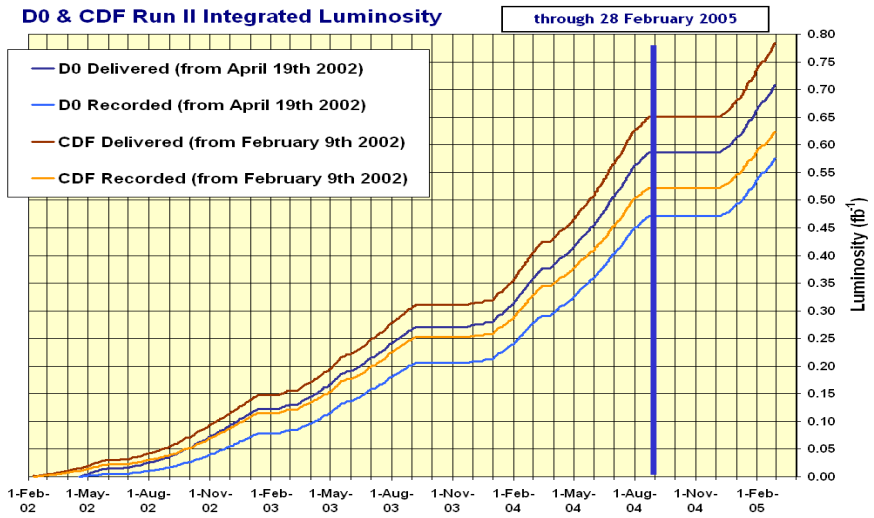
→ fully hadronic decay modes

Tracking: Silicon + Drift Chamber

dE/dx, ToF particle ID

Data sets (CDF and D0)

- Data collected in the period 2002-2004
  - ~ 500 pb^{-1} recorded
  - D0: ~ 220-450 pb^{-1} used for B physics
  - CDF:
    - ~ 240-360 pb^{-1} used for B physics
    - Lost ~ 100 pb^{-1} due to Central Tracking Chamber ageing problem
      - Now completely resolved



Trigger issues

CDF, D0: $p\bar{p}\,@\sqrt{s} = 1.96\,TeV$

b Production cross section: $\sigma\left(p\bar{p} \to \bar{b}X\right) = \left(29.4 \pm 0.6_{(stat)} \pm 6.2_{(sys)}\right)\mu b$

$|y| < 1$ CDF submitted to PRD hep-ex/0412071

Inelastic cross section: ≈ 60 mb→ factor 1/1000 trigger.

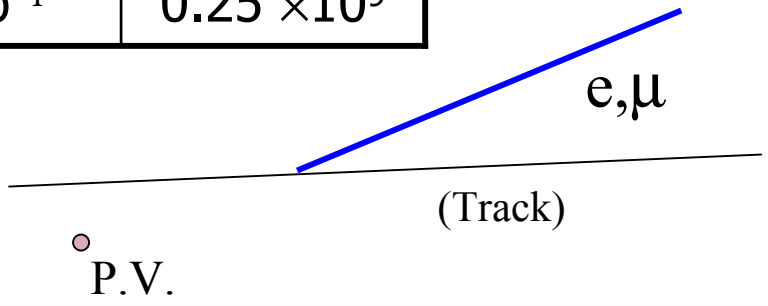
Compare with *b*-factories: σ is 10^3 higher,

L is pb^{-1} (TeVatron) vs. fb^{-1} ($\Upsilon(4S)$)

	σ (μb)	L $cm^{-2}\ s^{-1}$	Integrated L	*b*-events
Tevatron	29	1.2×10^{32}	600 $pb^{-1} \times 2$	13.8×10^9
KEK	0.001	1.52×10^{34}	371 fb^{-1}	0.37×10^9
BaBar	0.001	0.95×10^{34}	256 fb^{-1}	0.25×10^9

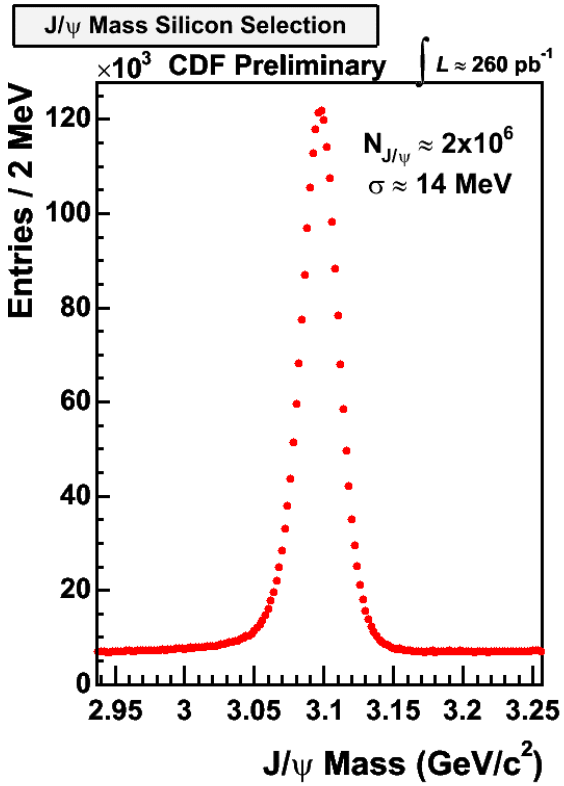
Trigger crucial point:

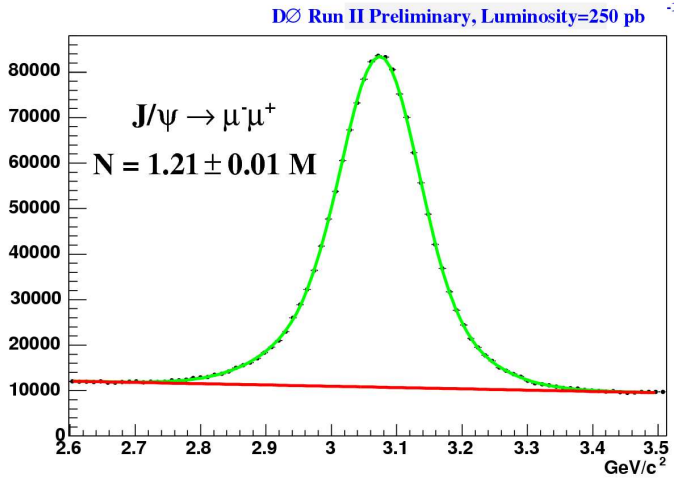
- 2 μ from J/ψ,
- soft lepton, (soft lepton+non prompt track)
- 2 non-prompt tracks (CDF)



Data samples

- J/ψ samples:
  - Millions! ~ 20% are from B's
  - Reconstruct exclusive $B/\Lambda_B \rightarrow J/\psi\ K/\Lambda^0$ modes
- Semi-leptonic B → D lν X samples:
  - ~ 100K events with fully reconstructed D
    - D0 has larger muon acceptance
    - CDF lowers lepton trigger pt by requiring additional displaced track
- Fully hadronic decays
  - ~ 10K (CDF) events fully reconstructed B's
  - Requires trigger on secondary vertex (SVT)





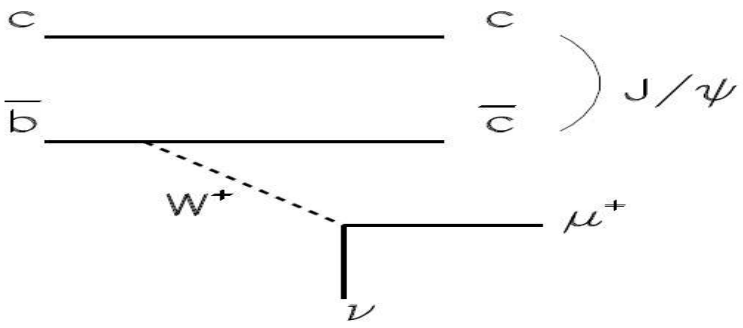
Mass measurements (Why?)

- Spectroscopy of heavy-light quark system, to complement quarkonia
- Verify detailed calculation and hypothesis (potential, NRQCD ….)
- Validation of Lattice QCD
- Spectroscopy of heavy-heavy mesons: quarkonia vs. B_c.

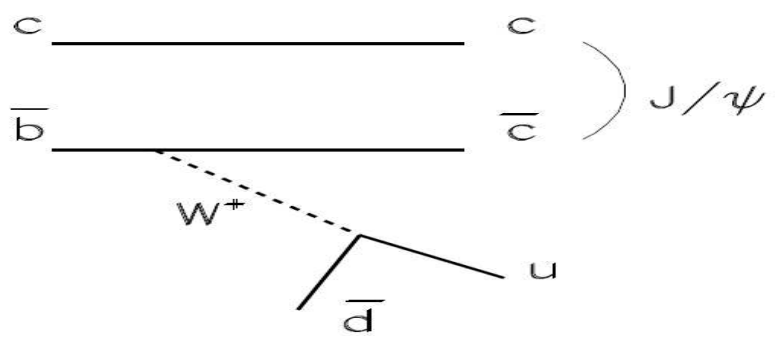
The B_c: a unique system

- Only meson to have 2 spectator-model weak decays with comparable amplitudes (*b* and *c* decays).
- Possible contamination for B_s decays

$B_c^+ \to J/\psi \mu^+ \nu$

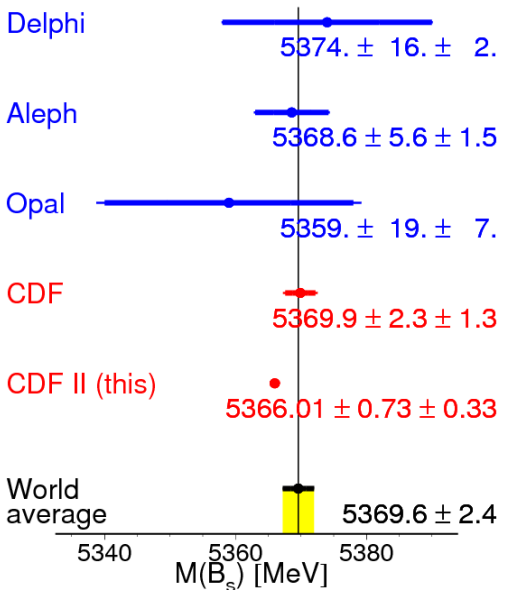


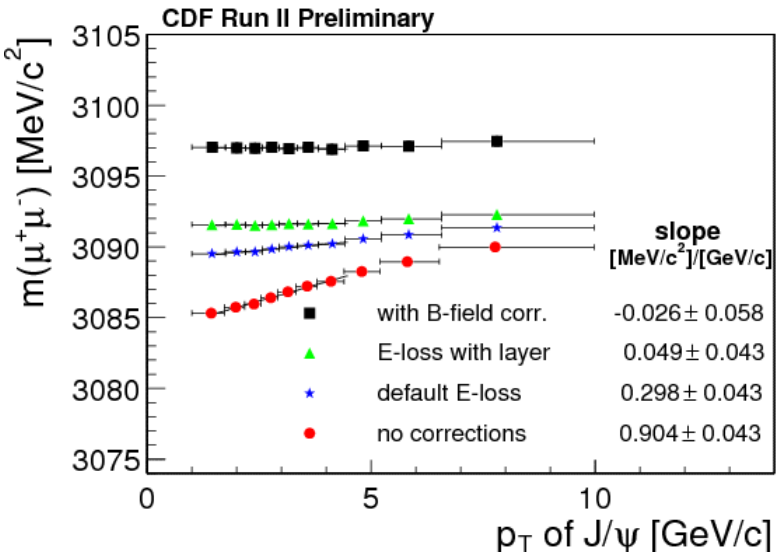
$B_c^+ \to J/\psi \pi^+$

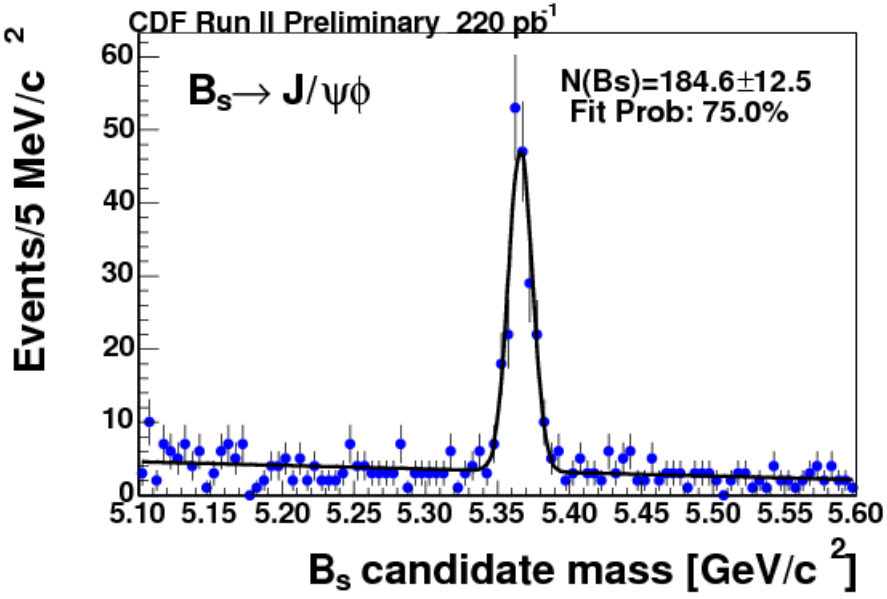


CDF B Mass Measurements

- Exclusive decays: $B \rightarrow J/\psi X$
- Momentum Scale
  - Alignment
  - Energy Loss per Track
  - Magnetic Field Scale
- J/ψ Trigger

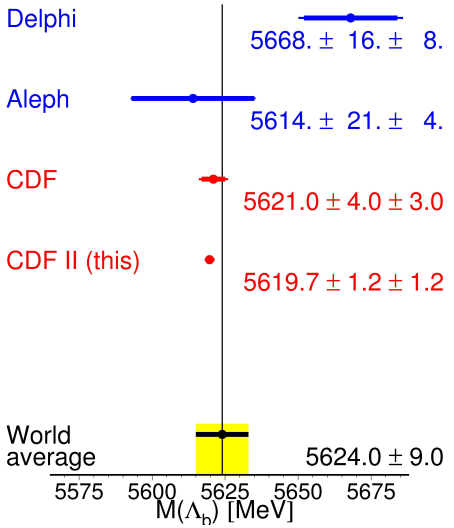


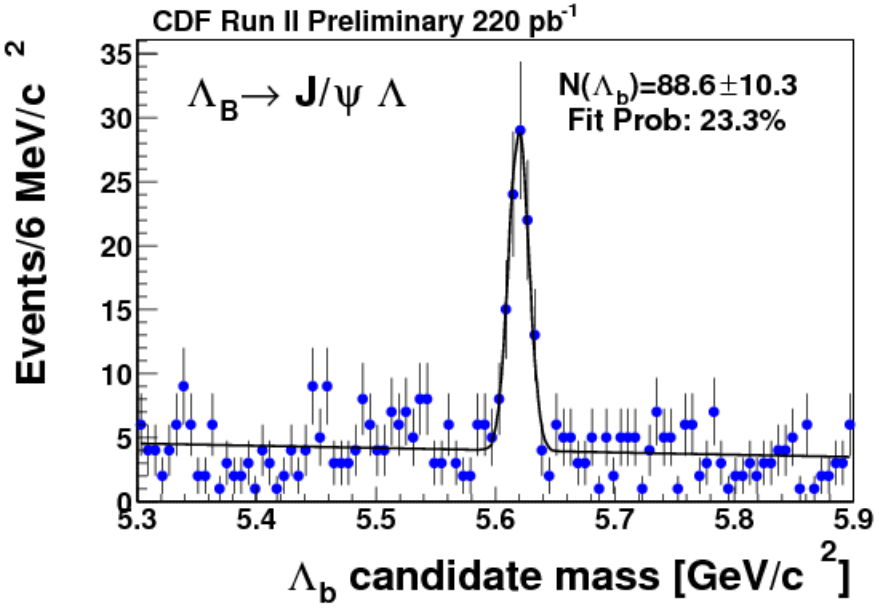




CDF B ...

- B decays
  - $B^+ \to J/\psi K^+$
  - $B^0 \to J/\psi K^{0*}$
  - $B_s^0 \to J/\psi \phi$
  - $\Lambda_b \to J/\psi \Lambda^0$
- Unbinned likelihood fit
- Results
  - $m(B^+) = 5279.10 \pm 0.41 \pm 0.36 MeV/c^2$
  - $m(B^0) = 5279.63 \pm 0.53 \pm 0.33 MeV/c^2$
  - $m(B_s^0) = 5366.01 \pm 0.73 \pm 0.33 MeV/c^2$
  - $m(\Lambda_b) = 5619.7 \pm 1.2 \pm 1.2 MeV/c^2$





CDF B_c Mass $B_c^+ \to J/\psi\pi^+$

- $\int \mathcal{L}dt = 360\, pb^{-1}$ J/ψ trigger
- Potential Models, Lattice QCD } Prediction ~ 6.3 GeV/c²
- Cuts Optimization
  - Signal (MC)
  - Background (Data)
- Control Sample: $B^+ \to J/\psi K^+$
- Significance Function:

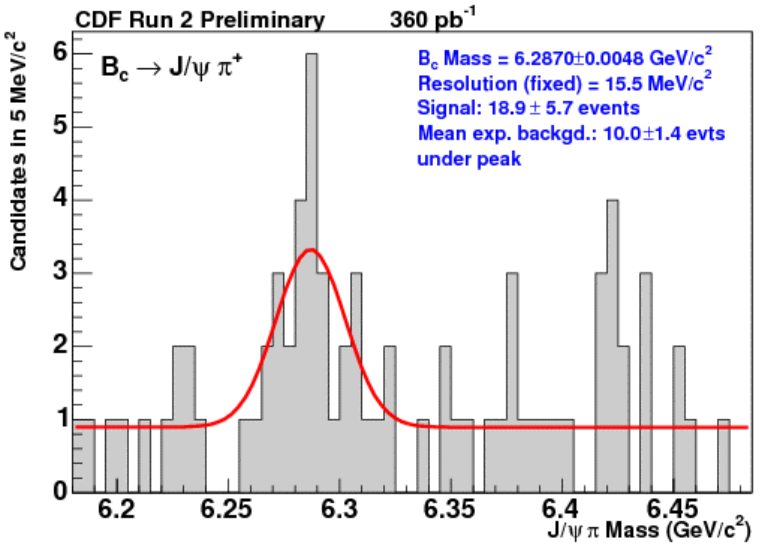
$$\Sigma = \frac{S}{1.5 + \sqrt{B}}$$

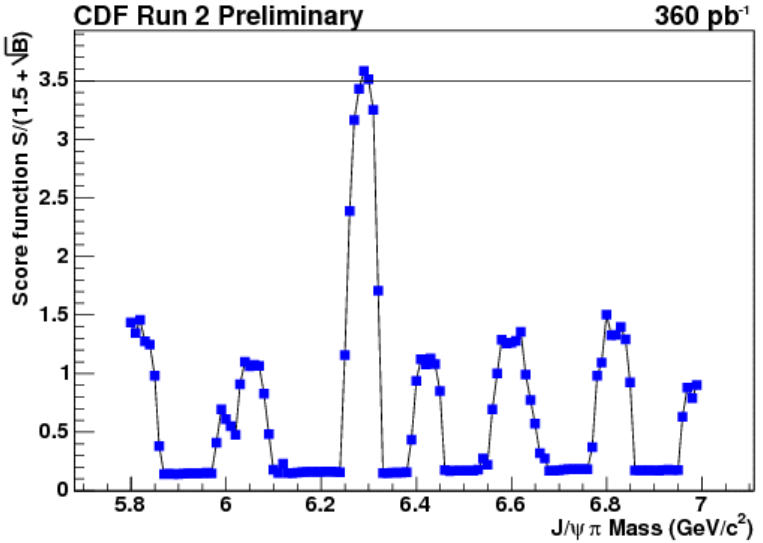
- Search Window: 5.6 – 7.2 GeV/c²
- Result:

$$m(B_c^+) = 6287.0 \pm 4.8 \pm 1.1 MeV/c^2$$

N(Bc) : 18.9 ± 5.7 events

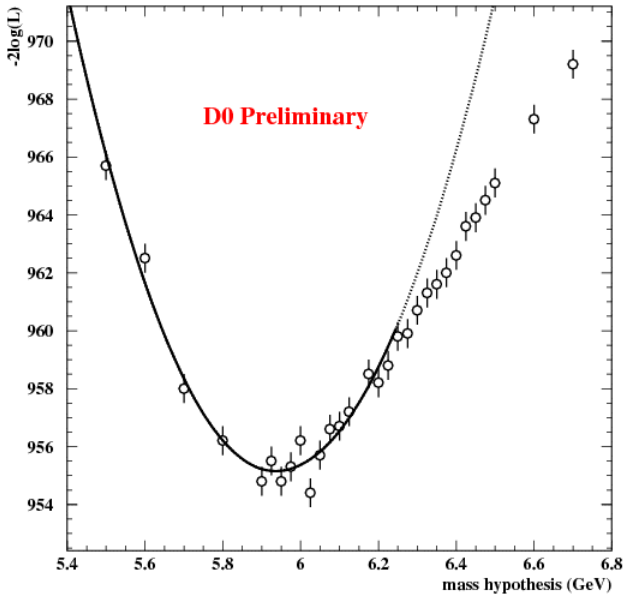
- Evidence in fully reconstructed decay

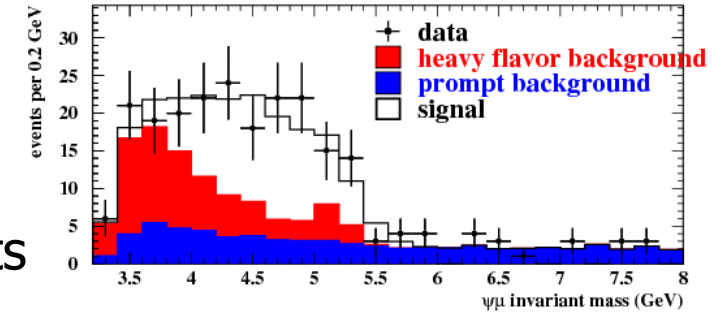


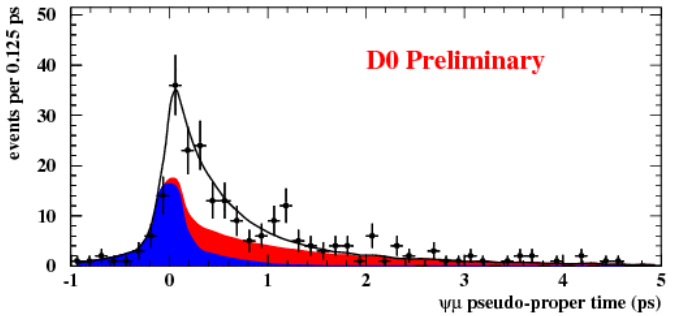


D0 Bc Mass and lifetime

- $B_c^+ \rightarrow J/\psi \mu^+ \nu$
- Last Ground State of B mesons to be observed
- Predictions: 6.3 GeV/c^2 & 0.3-0.5 ps
- $\int \mathcal{L} dt = 210\, pb^{-1}$
- $J/\psi + 1$ track (not muon)
- Test on $B_c^+ \rightarrow \psi(2S)\mu^+ X$
- Unbinned likelihood Fit (Mass and lifetime)
-
  - J/ψ "handle"
  - $J/\psi + 1$ track sample (vertex fit)
  - Tested in MC signal events
  - Backgrounds: Prompt, B mesons, true J/ψ + muon events
- Mass Hypothesis: 5.5 – 6.7 GeV/c^2 (0.10)
- Pseudo-proper time (corrected with MC)
- Results:
  - $m(B_c^+) = 5.95^{+0.14}_{-0.13} \pm .34 GeV/c^2$
  - $\tau(B_c^+) = 0.448^{+0.123}_{-0.096} \pm .121 ps$

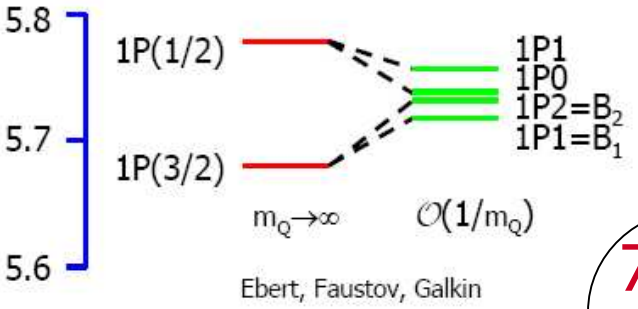




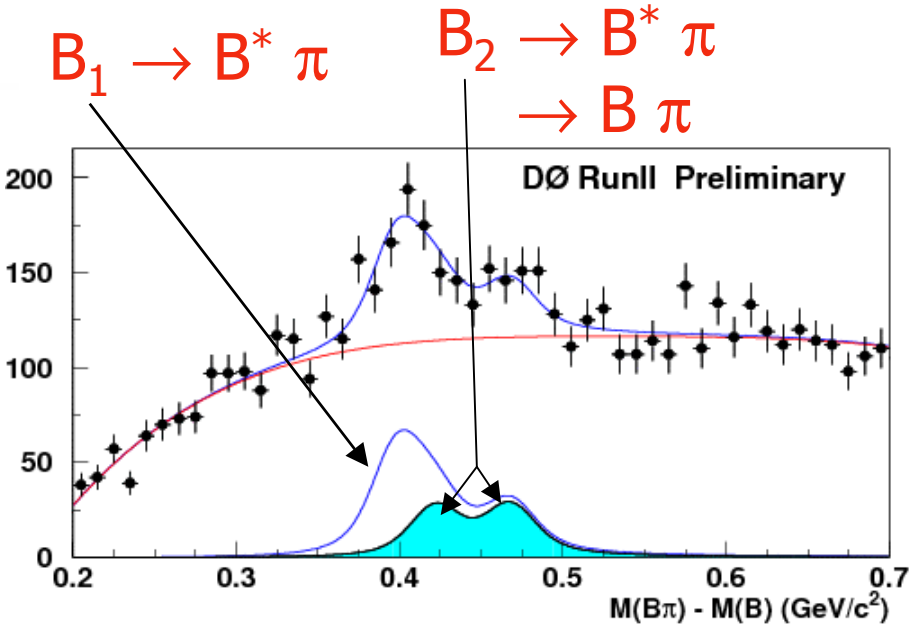


Excited B states

Splittings predicted by HQE



7K B^+
3K B^0



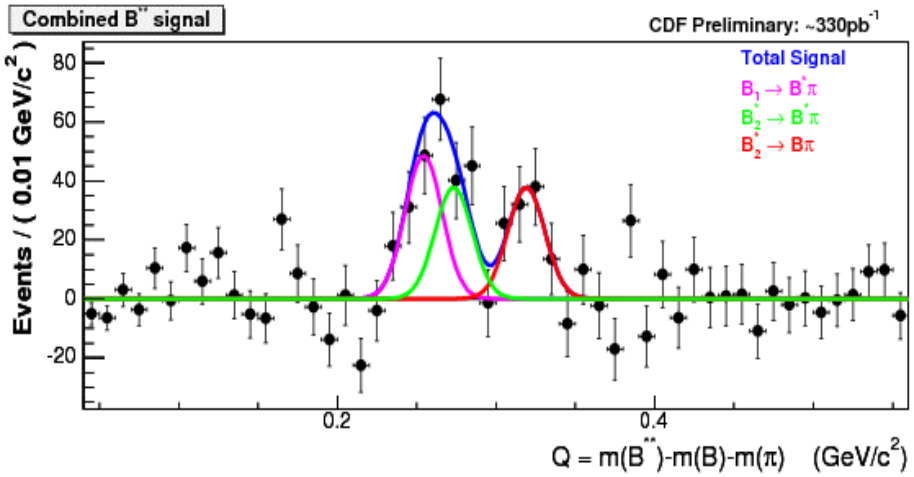
$(B^0 \to J/\psi K^{0*}/K_s^0) + \pi$
$(B^+ \to J/\psi K^+) + \pi$

D0:

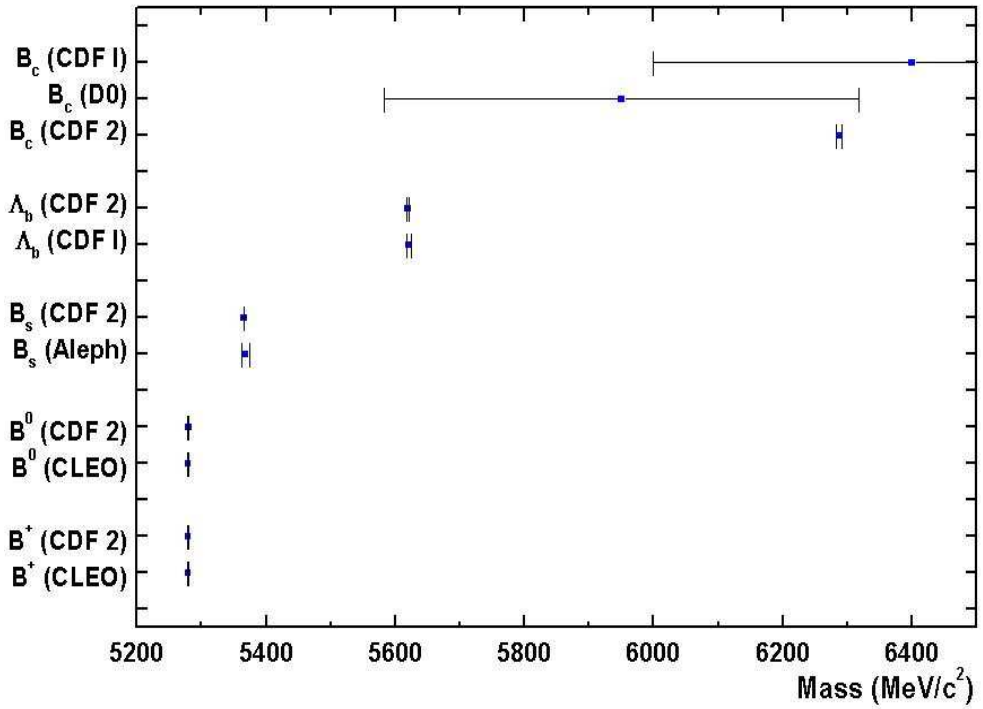
$M(B_1) = 5724 \pm 4 \pm 7$ MeV/c^2
$\Delta M(B_2 - B_1) = 23.6 \pm 7.7 \pm 3.9$ MeV/c^2

Theoretical Prediction:

$M(B_1) = 5719$ MeV/c^2
$\Delta M(B_2 - B_1) = 14$ MeV/c^2



Summary of mass measurements

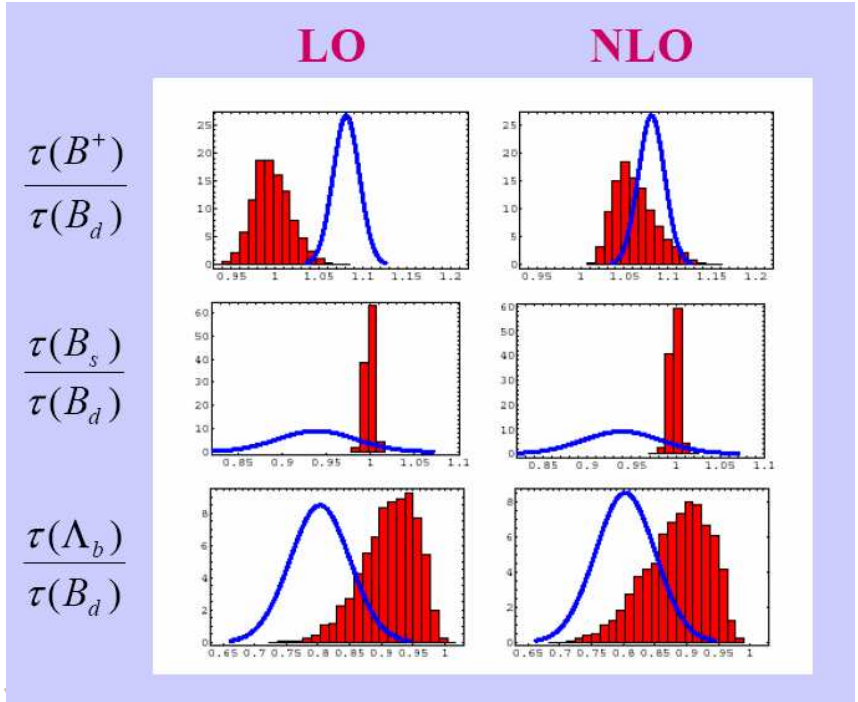


B hadron lifetimes

- B hadron decays dominated by b-quark decay
  - Effect of spectator quarks can be included with perturbative expansions in terms of $1/m_b$ (HQE)
    - Expect small differences between lifetimes of different species
    - Non-perturbative ME from lattice, Wilson coeff. from perturbative QCD
      - NLO improves agreement
    - Ratios reduce theory uncertainties

October 2003

Experiment



Theory

Exclusive B Decays (J/ψ)

No neutrinos involved
Limited Statistics
B^+, B^0 benchmarks
B_s^0 (~87% CP even)

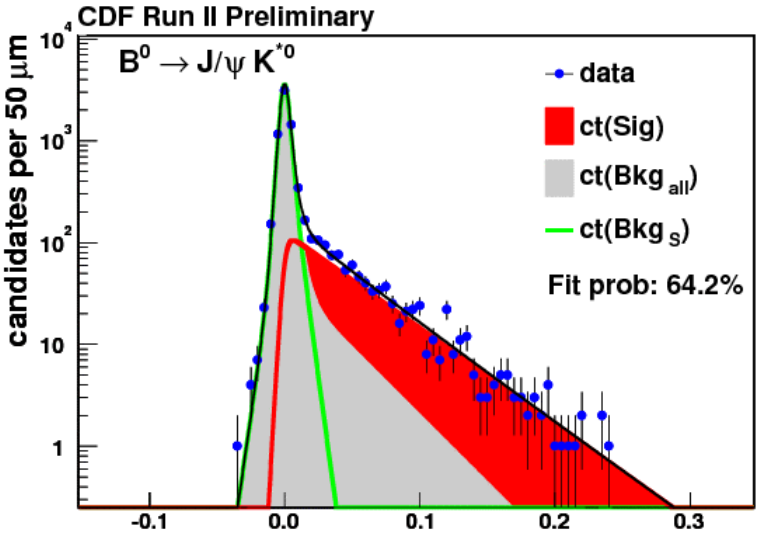
DØ

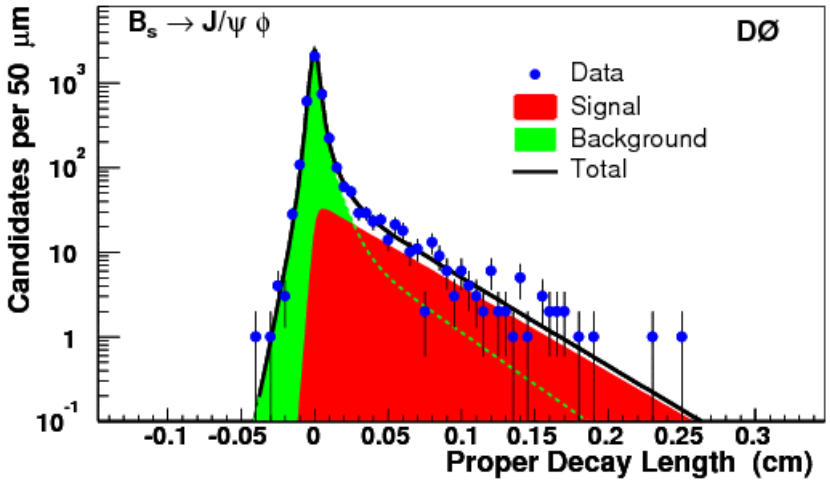
PRL 94, 071802 (2005)

$$B_s \to J/\psi\phi \qquad \tau_{B_s} = 1.444\ ^{+0.098}_{-0.090} \pm 0.023\ ps$$
$$\tau_{B_s}/\tau_{B^0} = 0.980\ ^{+0.076}_{-0.071} \pm 0.003$$
$$\Lambda_B \to J/\psi\Lambda \qquad \tau_{\Lambda_B} = 1.22\ ^{+0.22}_{-0.18} \pm 0.04\ ps$$
$$\tau_{\Lambda_B}/\tau_{B^0} = 0.87\ ^{+0.17}_{-0.14} \pm 0.03$$
$$B_c \to J/\psi\mu \qquad \tau_{B_c} = 0.448\ ^{0.123}_{-0.06} \pm 0.121$$
$$\tau(B^+/B^0) = 1.080 \pm 0.016 \pm 0.014$$

CDF

$$B_s \to J/\psi\phi \qquad \tau_{B_s} = 1.369 \pm 0.100^{+0.008}_{-0.010}\ ps$$
$$B^0 \to J/\psi K^{*0} \qquad \tau_{B^0} = 1.539 \pm 0.051 \pm 0.008\ ps$$
$$B^+ \to J/\psi K^+ \qquad \tau_{B^+} = 1.662 \pm 0.033 \pm 0.008\ ps$$
$$\tau(B^+/B^0) = 1.119 \pm 0.046 \pm 0.014$$

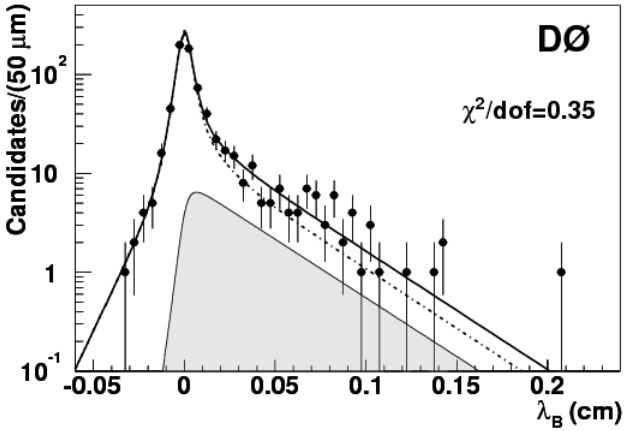


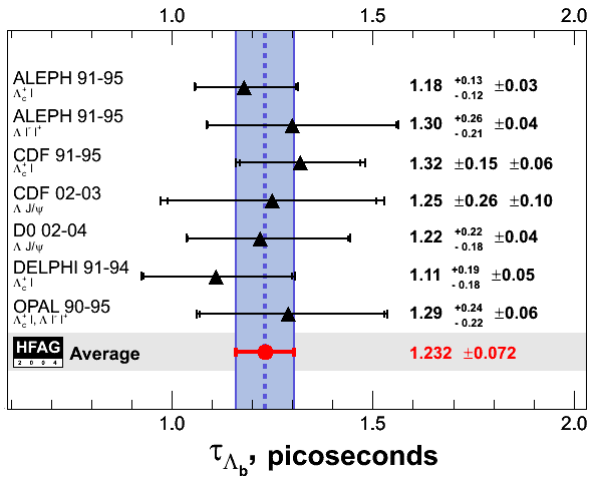


B vertex (DØ), J/ψ vertex CDF
Background modeling (understood)

Λ_b lifetime

- Discrepancy between theory (HQE) and Experiment (Ratio)
- Previously Semileptonic Λ_b Decays (ν feature)
- First time in an exclusive decay $\Lambda_b \to J/\psi \Lambda^0$ Signal (No $c\tau$ cuts)
- Background Modeling
  - Prompt
  - Exponentials
- Λ_b vertex used (D0) J/ψ vertex for CDF
- $$c\tau = L_{xy} \frac{cM_B}{p_T^B}$$
- Simultaneous fit to Mass and LFT
- Sources of Systematic errors
  - Contamination
  - Lifetime resolution
  - Alignment
- Error dominated by statistics



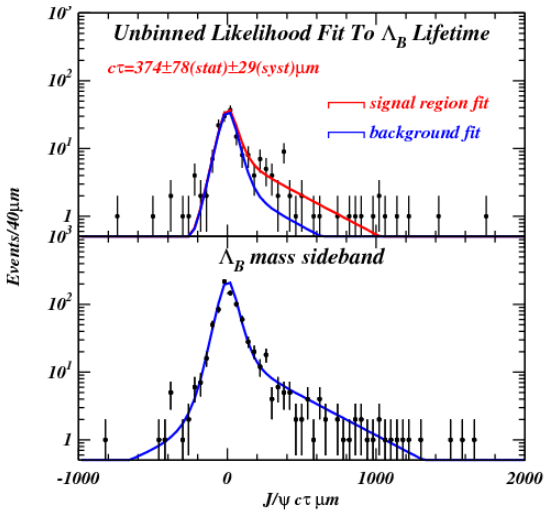


DØ PRL 94,102001 (2005)

$$\tau(\Lambda_b) = 1.22^{+0.22}_{-0.18} \pm 0.14\ ps$$

CDF Preliminary

$$\tau(\Lambda_b) = 1.22 \pm 0.26 \pm 0.10\ ps$$

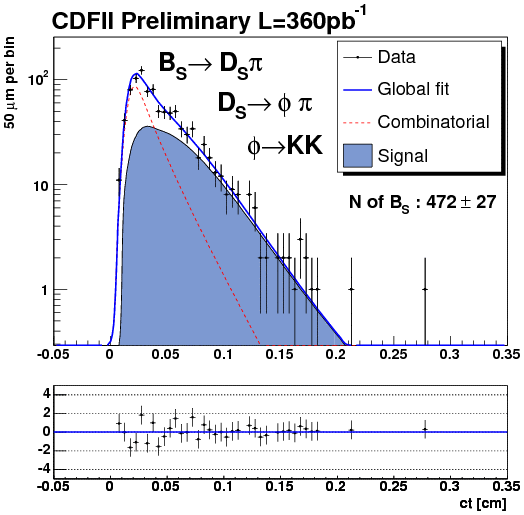


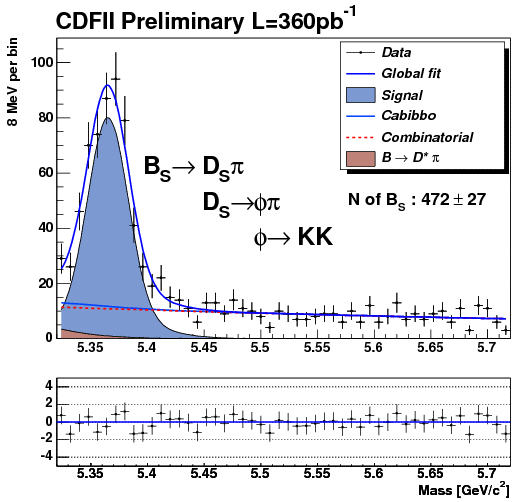
Fully Hadronic Decays

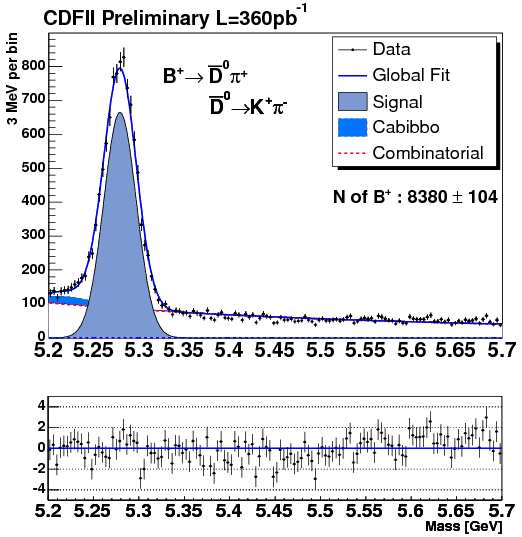
- SVT Trigger ⇔ enriched B samples
- Bias the Lifetime Distributions
- Mixing samples, same trigger Measurement important
- Decay modes

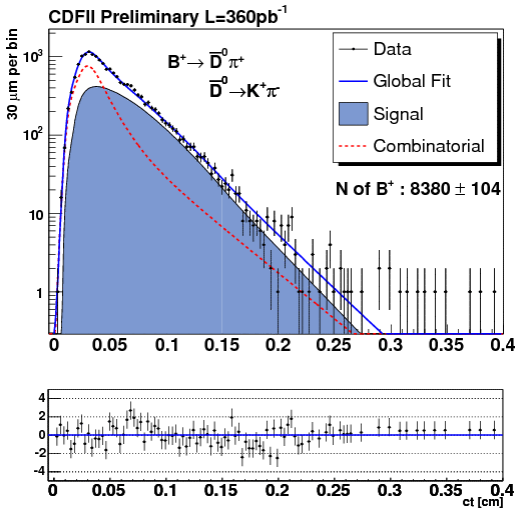
$$B^+ \to \bar{D}^0\pi^+$$
$$B^0 \to \bar{D}^-\pi^+(3\pi)$$
$$B_s^0 \to \bar{D}_s^-\pi^+(3\pi)$$

- MC solution (Eff. vs Proper time)
- Tested in $B^+ \to J/\psi K^+$









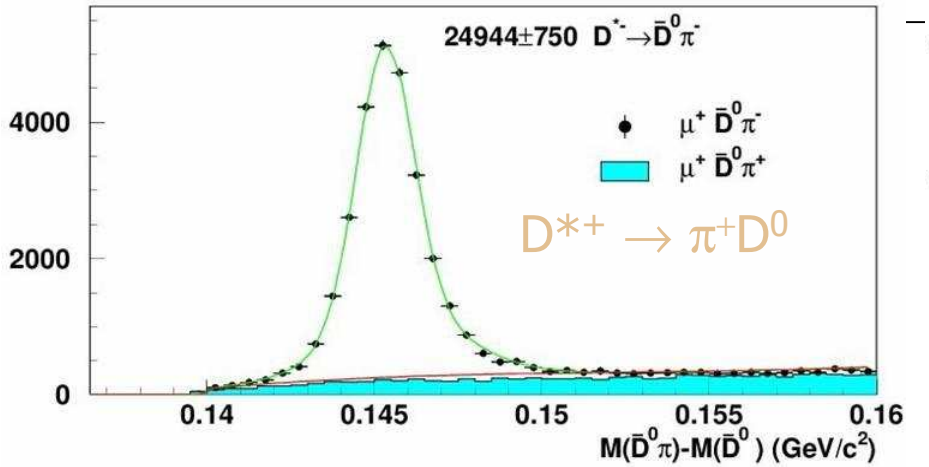
- Benchmarks
- Mass and Lifetime simultaneous fits
- Wide mass windows
  Fix contributions
- Narrow Window: fit
- $\tau(B^+) = 1.66 \pm 0.03 \pm 0.01\ ps$
  $\tau(B^0) = 1.51 \pm 0.02 \pm 0.01\ ps$
  $\tau(B_s^0) = 1.60 \pm 0.10 \pm 0.02\ ps$

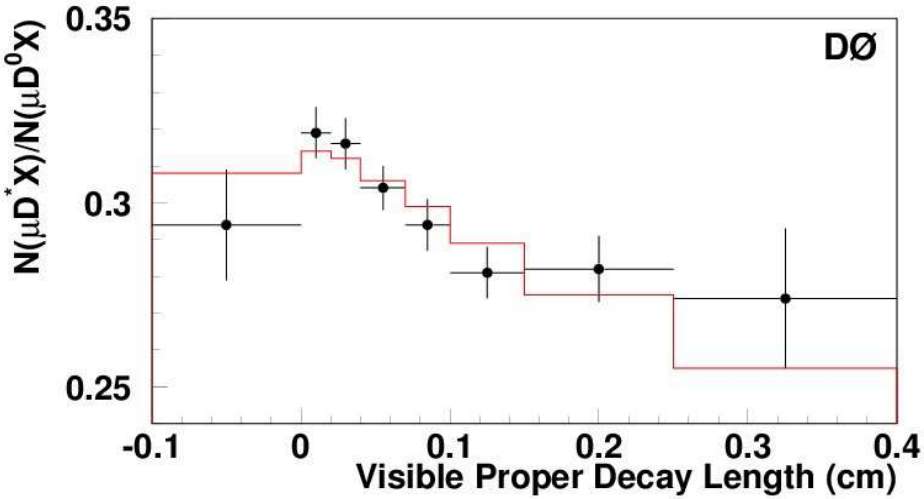
B^0, B^+ Lifetimes

- Dominated by B-Factory results
- But: innovative technique from DØ

$$\chi^2(\varepsilon_\pi, k) = \sum_i \frac{(r_i - r_i^e(\varepsilon_\pi, k))^2}{\sigma^2(r_i)}$$

  - ratio of $n(B^+)/n(B^0)$ vs. proper time gives $\tau(B^+)/\tau(B^0)$
  - many systematic errors cancel
  - $B \to \mu D^* X \approx B^0$, $B \to \mu D^0 X \approx B^+$, measured BRs used for populations





HQE:

$\tau(B^+)/\tau(B^0) \approx 1.06$

$\tau(B^\pm)/\tau(B^0) = 1.080 \pm 0.016 \pm 0.014$

(was) World's Best Measurement

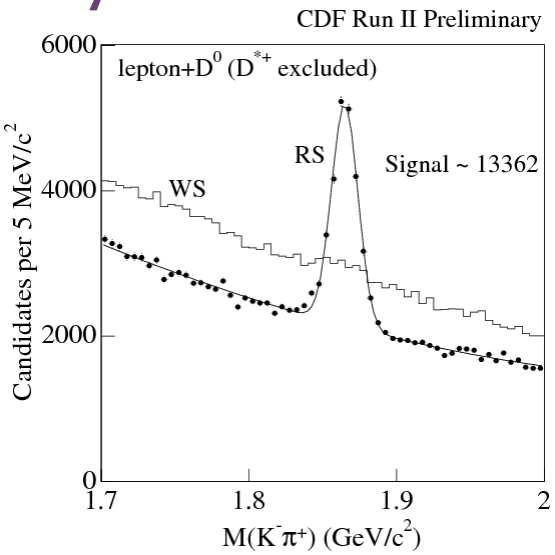
PRL 94, 182001 (2005)

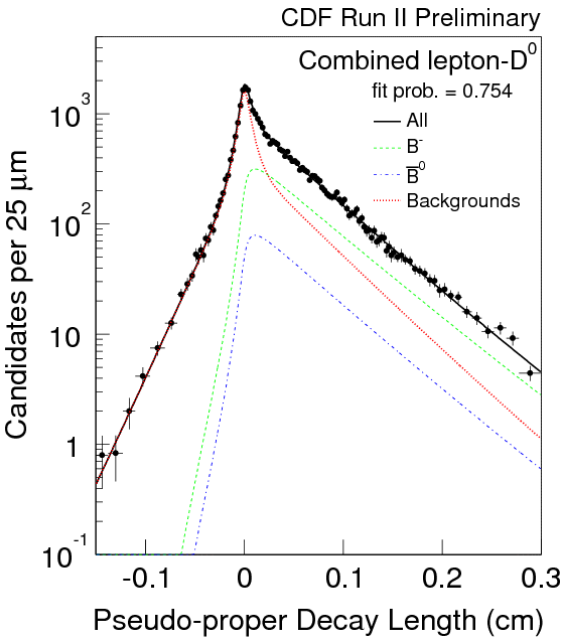
c.f. new Belle result

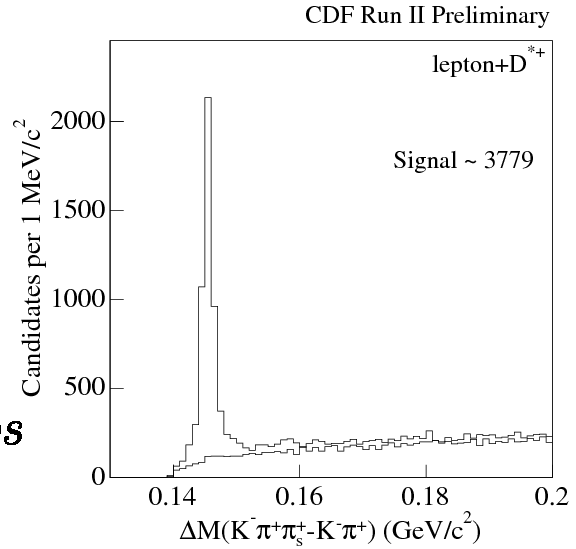
CDF Semileptonic B Decays

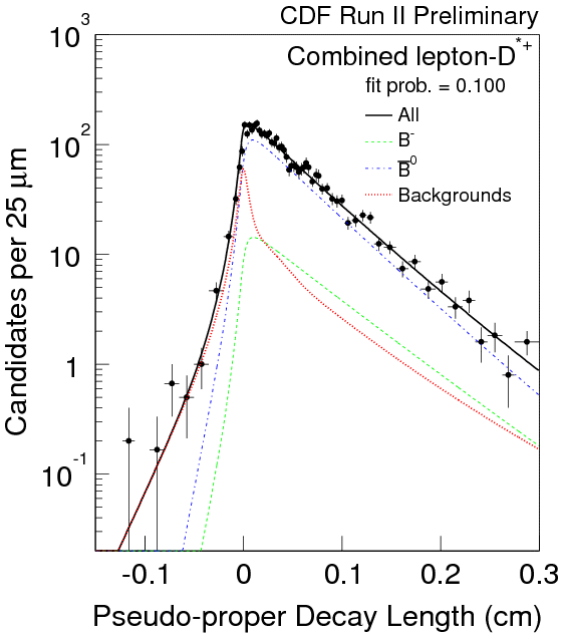
- Single lepton triggers
- $\int \mathcal{L}dt \sim$ 260 pb-1
- Decay channels
  - $B^- \to l^- \nu D^0 X$
  - $B^0 \to l^- \nu D^{*+} X$
- Simultaneous fits to D^0 and D^{+*} samples
- B vertex (l +D^0)
- Not seen ν (MC)
- Systematic Sources
  - Sample Composition
  - Charm Back component
  - ν correction
- $\tau(B^-) = 1.653 \pm 0.029^{+0.033}_{-0.031}\ ps$

$\tau(B^0) = 1.473 \pm 0.036 \pm 0.054\ ps$









DØ B_s^0 Semileptonic Decay

- B_s^0 lifetime $\Rightarrow$ Mixing, CPV & New Physics
  Flavor Specific (50% CP even at t=0)

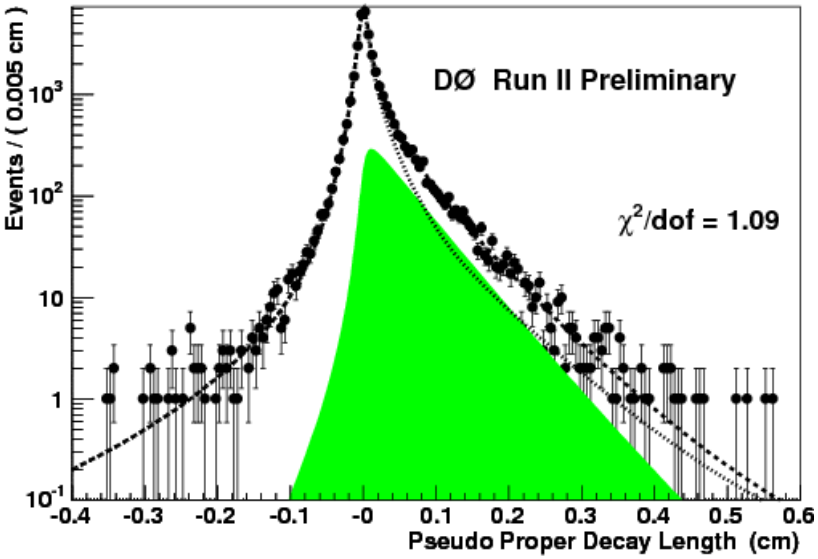
- $\mathcal{L} \sim$ 1.17x10^{32} cm^2/s
  $\int \mathcal{L}dt \sim$ 400 pb^{-1}

- $\sqrt{s} = 1.96TeV + \int \mathcal{L}dt$ + good μ-trigger/Id + good tracking
  $B_s^0 \longrightarrow D_s \mu\nu$
  No cτ cuts

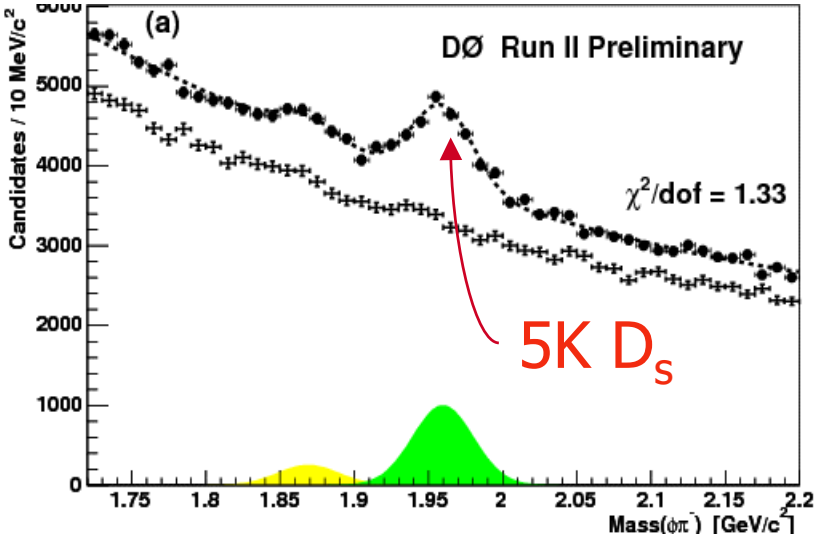
- Simultaneous fit to Mass(Ds) and Lifetime(B_s^0)

- $c\tau_{vis} = L_{xy} \frac{m(B_s^0)}{p_T(D_s\mu)}$
  Correction for the neutrino (MC)

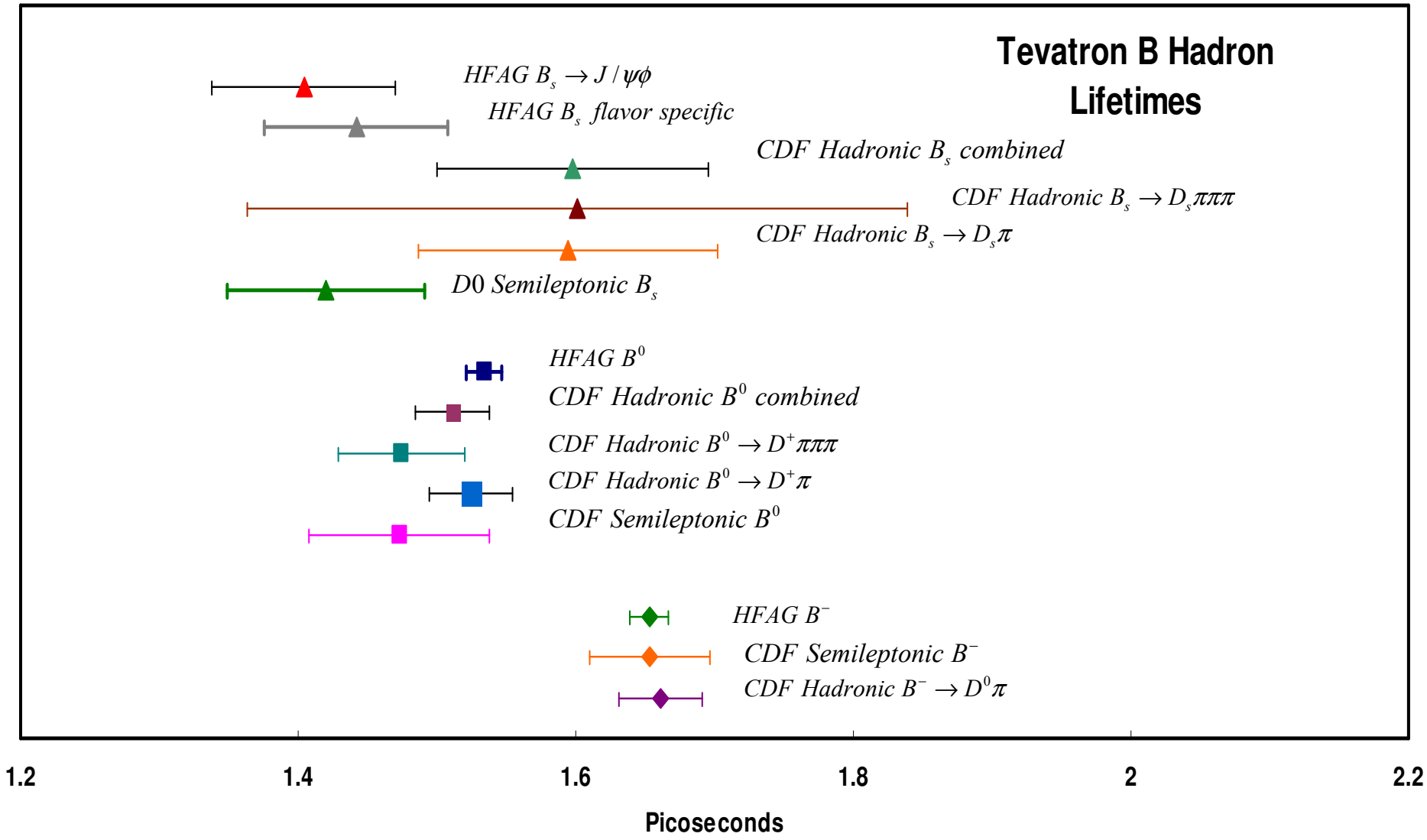
- Systematics dominated by background modeling



$\tau(B_s^0)$ = 1.420±0.043±0.057 ps



Summary of new lifetime results



Conclusion and Perspectives

- CDF and DØ strong contenders
  Masses and lifetimes
- Masses: errors competitives or world´s best
- Lifetimes: B^+, B^0 used as benchmarks for measurement techniques
- B^0_s, B_c & Λ_b : monopoly for some time

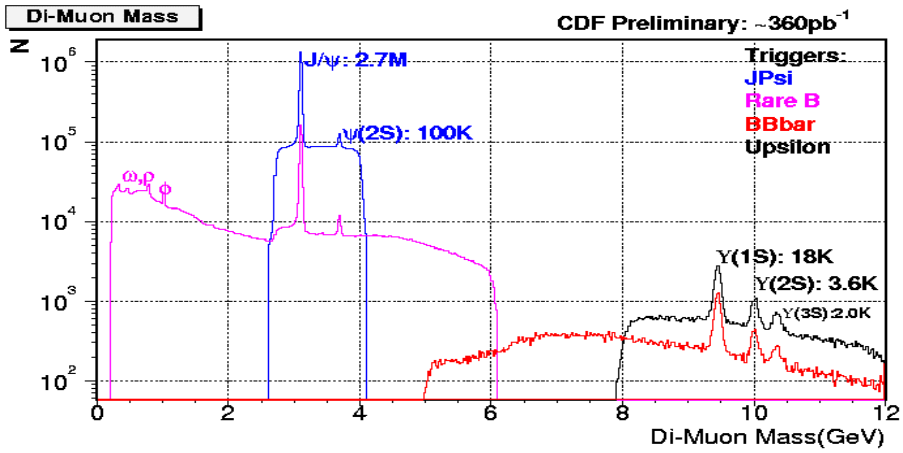
- We have explored:
  - Exclusive decays (J/ψ) Low statistics
  - Semileptonic decays (Background understanding)
  - Fully hadronic decays (Biases)

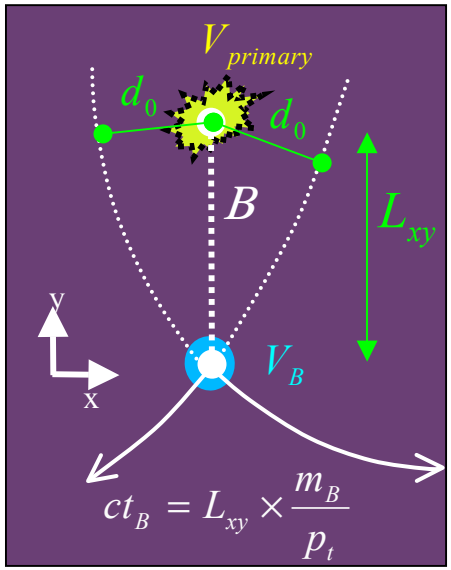
  … And succeeded.

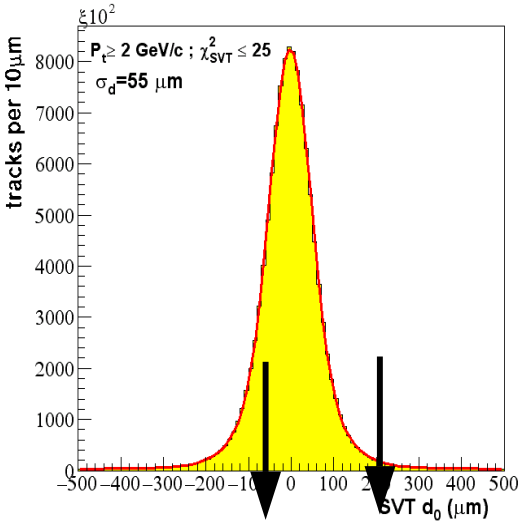
Backup Slides

Triggering: Heavy Flavor → Tape

- $H_b \rightarrow X(J/\psi \rightarrow \mu\mu)$
  - 2 track ↔ μ matches within $m_{\mu\mu}$ window
- $H_b \rightarrow \not{E}\nu X$
  - Lepton signature in p_T range
- $H_b \rightarrow$ *hadrons*
  - Displaced tracks and vertex







Triggers and data samples

Canonical

Di-Muon (J/ψ)

Pt(μ) > 1.5 GeV/c

J/ψ modes down to low Pt(J/ψ) (~ 0 GeV)

- $\Delta\Gamma_s$ in fully rec. decays
- $B_c \rightarrow J/\psi\pi$
- Masses, lifetimes of B_d, B_s, Λ_b
- Quarkonia
- X(3872)
- Rare decays ($B_{S(d)} \rightarrow \mu\mu$ & $D^0 \rightarrow \mu\mu$)

New for run II

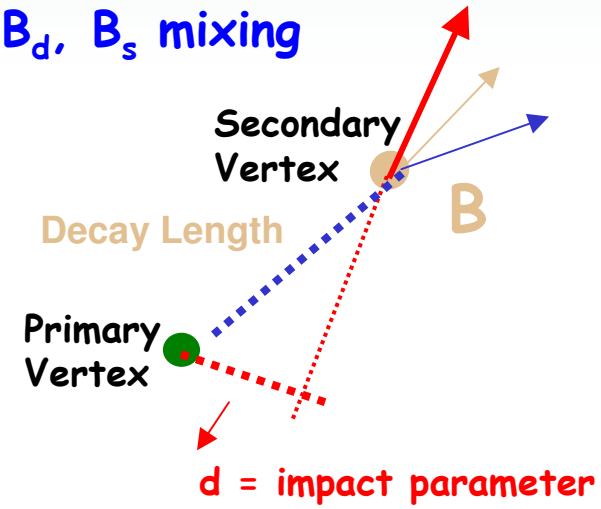
Displaced trk + lepton (e, μ)

IP(trk) > 120μm

Pt(lepton) > 4 GeV/c

Semileptonic modes

- Hadronic Moments
- High statistics lifetimes
- B_d, B_s mixing



2-Track Trig.

Pt(trk) > 2 GeV/c

IP(trk) > 100 μm

Fully reconstructed hadronic modes

- $B_{d,s}$ 2-body charmless decays
- $B_s \rightarrow \phi\phi$ & $B^{\pm} \rightarrow \phi K^{\pm}$
- $\Lambda_b \rightarrow \Lambda_c\pi$, $\Lambda_b \rightarrow ph$
- A_{CP} in 2-body D decays
- B_d, B_s mixing & lifetimes

B Hadron Masses

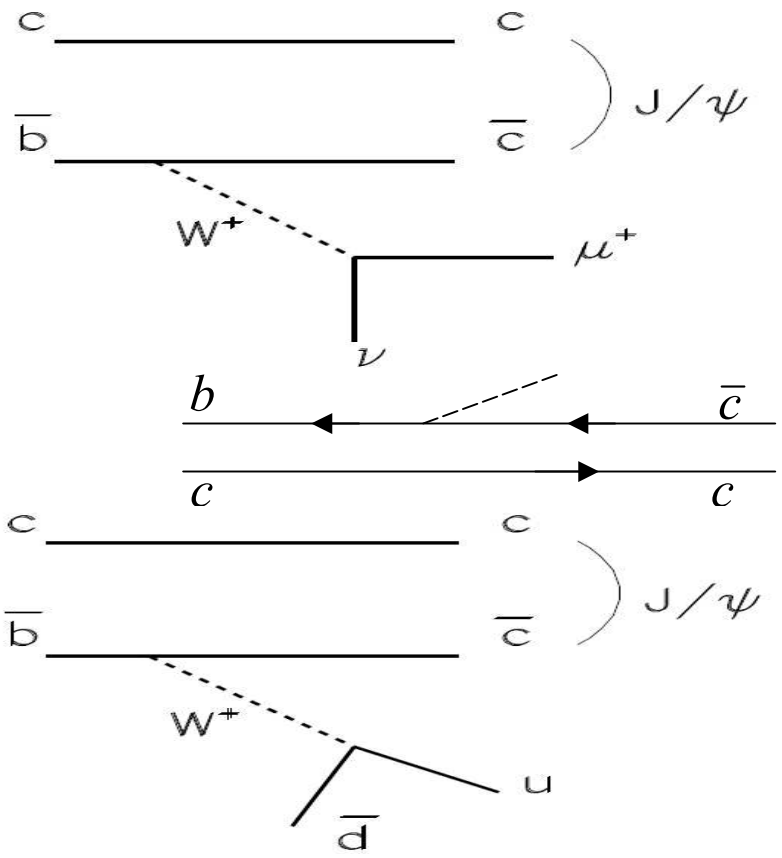
Why we want to measure the masses.
What has been measured before and with
What precision

Mass measurements (Why?)

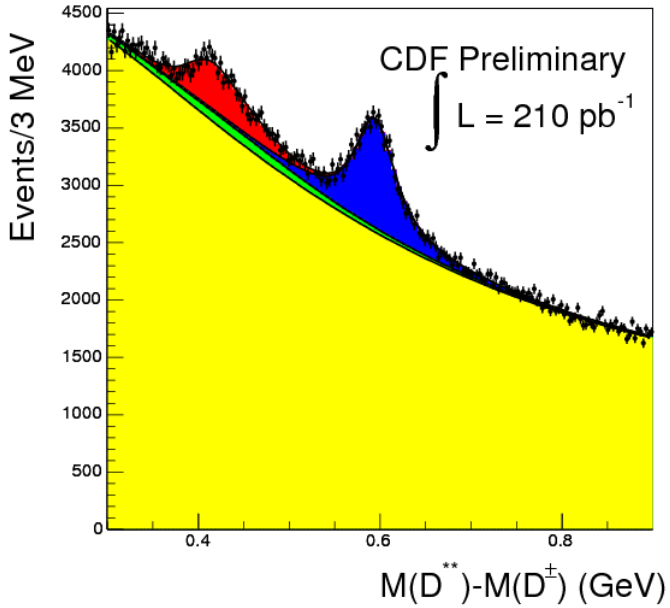
- Spectroscopy of heavy-light quark system, to complement quarkonia
- Verify detailed calculation and hypothesis (potential, NRQCD ….)
- Validation of Lattice QCD
- Spectroscopy of heavy-heavy mesons: quarkonia vs. B_c.

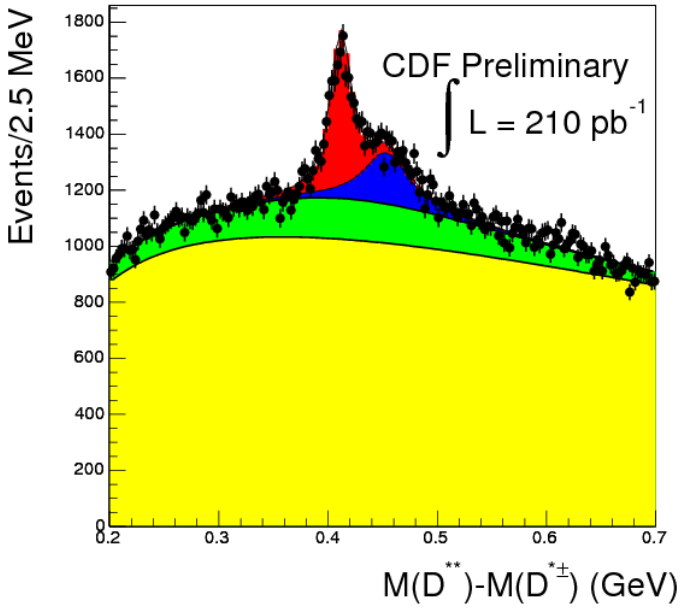
The B_c: a unique system

- Only meson to have 2 spectator-model weak decays with comparable amplitudes (*b* and *c* decays).
- Possible contamination for B_s decays



Excited Charm mesons





Lifetimes

Theoretical interests for the lifetimes, HQE, new predictions, etc.

Exclusive Decays

Fully Hadronic Decays

Direct Measurement of ratio

Bc lifetime

Semileptonic Decays

Advantages, characteristics,
Integrated luminosity, etc.