Production, Lifetimes, and Masses of B and C Hadrons

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DØ and CDF Collaborations

Overview

What are we after here?

- b, c Quark Production
  - details of QCD, parton luminosities, fragmentation functions

- b, c Hadron Masses
- b, c Hadron Lifetimes
- b, c Hadron Decays

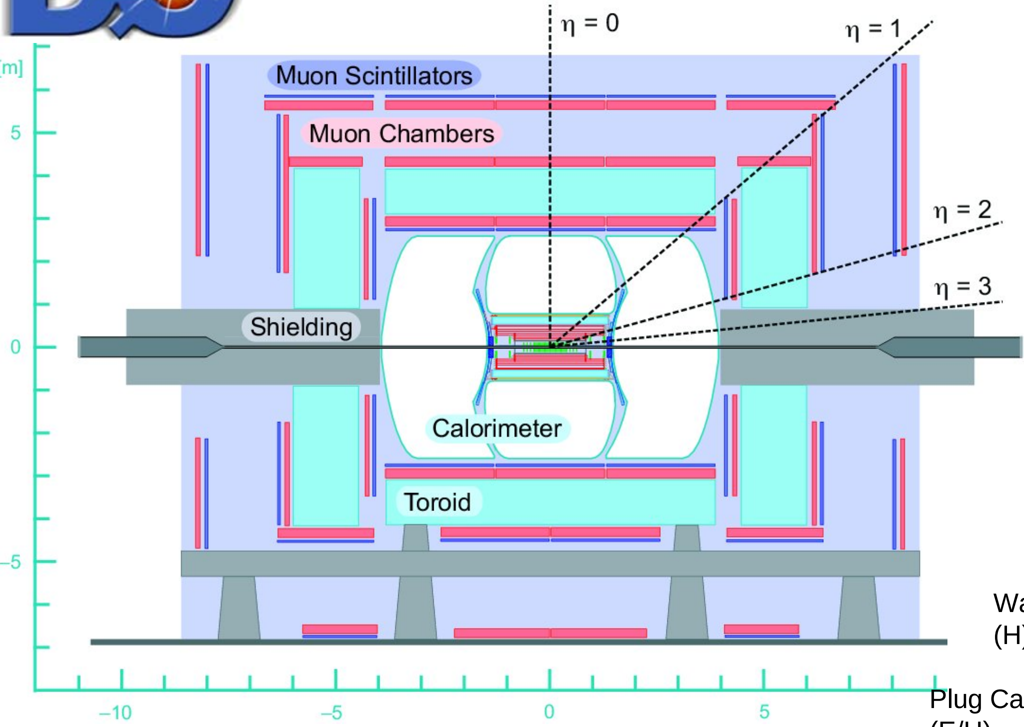
Tests of, inputs to HQE, CKM → **Extraction of CKM Parameters**

Heavy Quark Expansion

- Rare b, c Hadron Decays
  - New Physics?

Tevatron and B-Factories Largely Complementary

Tevatron Collider Detectors

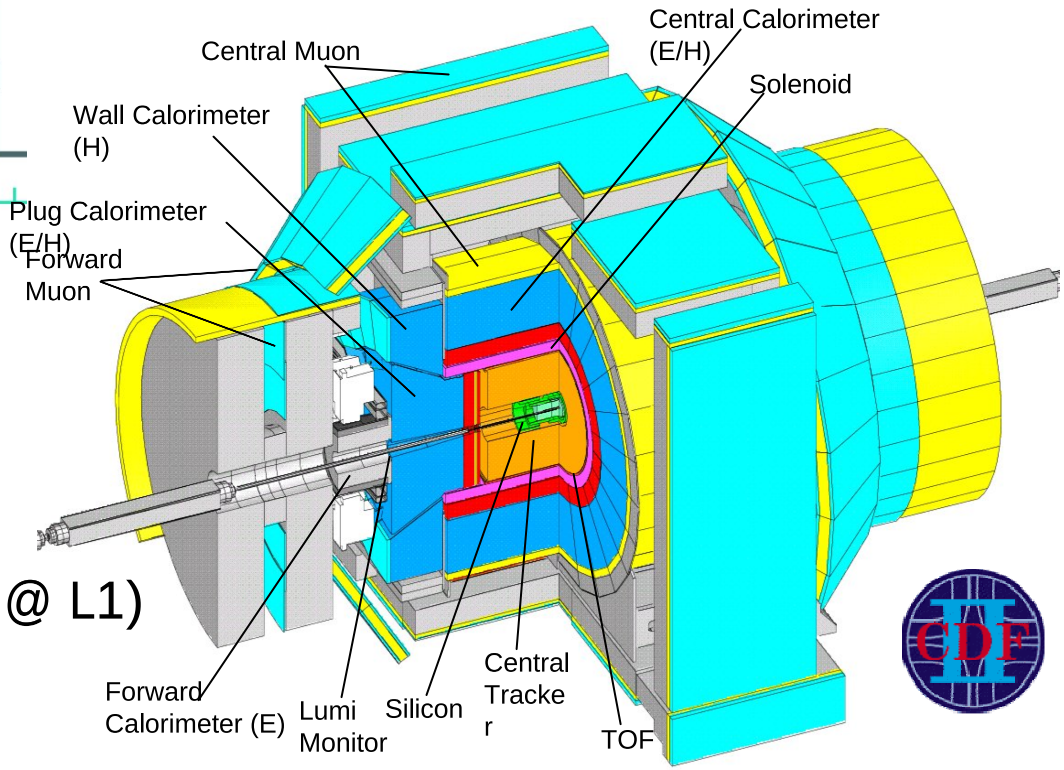


DØ:

- Excellent Muon Coverage |η|<2
- Excellent Tracking Coverage |η|<3
- (Impact Parameter Trigger @ L2)

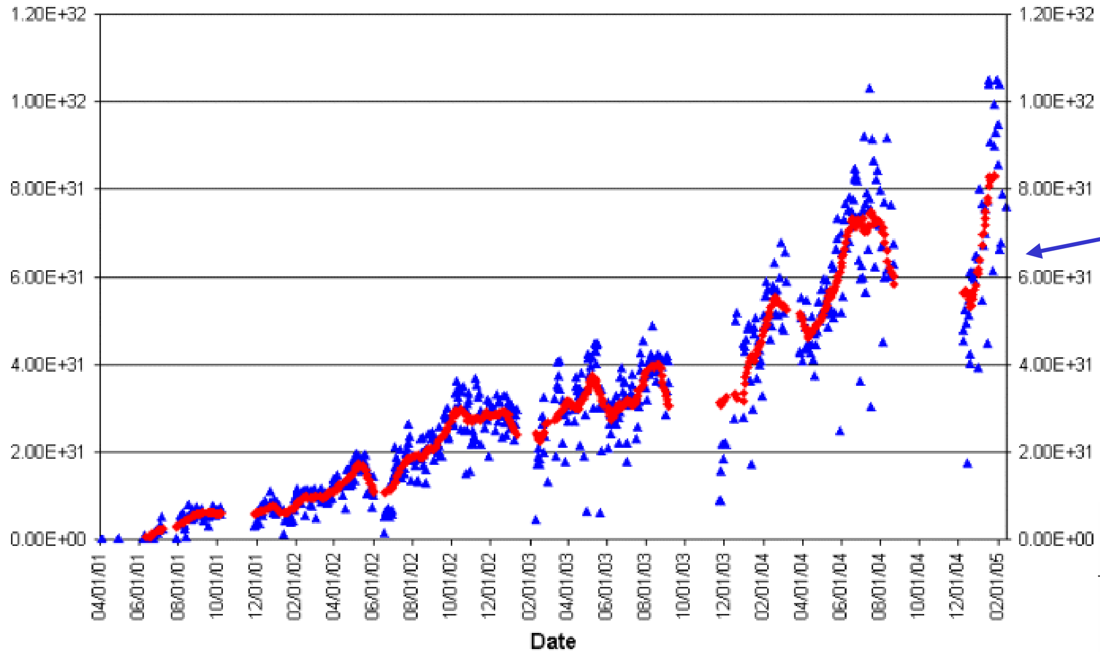
CDF:

- Excellent Mass Resolution
- Particle ID: TOF and dE/dx
- (Two-track invariant mass trigger @ L1)
- Impact Parameter Trigger @ L2



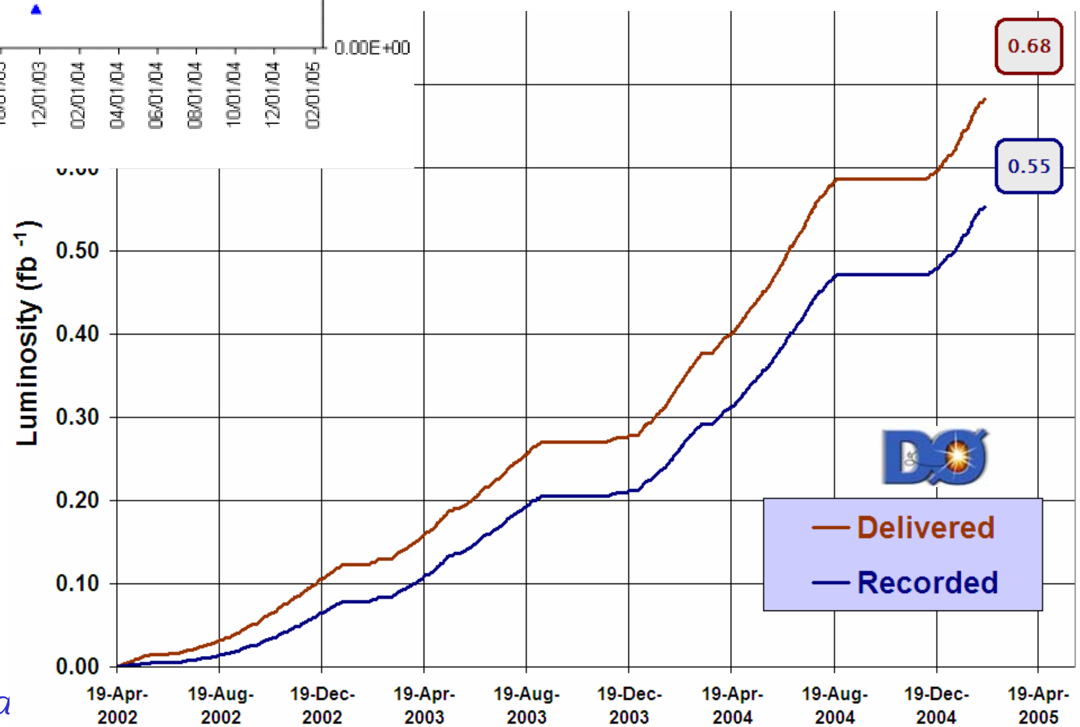
Tevatron Performance

- Instantaneous Luminosities above 1×10^{32} cm^{-2}s^{-1}



Excellent recovery after Fall shutdown

- Total Integrated Luminosities above 0.5 fb^{-1}
- Should reach ~1fb^{-1} by end of calendar 2005



Open Heavy Flavor Production

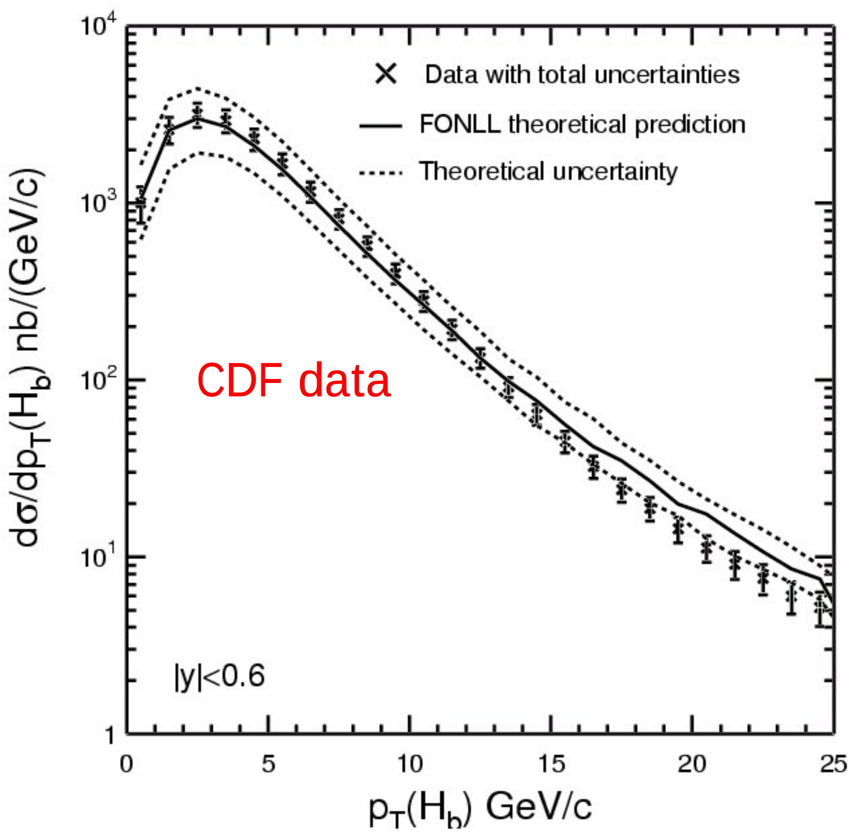
- Long-standing "discrepancies" between predicted and measured cross sections now resolved; combined effects of
  - better calculations (Fixed order (NLO)+ NLL= FONLL)
  - better understanding of fragmentation functions
    - relationship/difference between e^+e^- and hadron colliders
    - different moments of FF relevant
  - better estimate of theory errors
    - (upward!)
    - new appreciation of issues with "quark-level" measurements

e.g. Cacciari, Frixione, Mangano, Nason, Ridolfi, JHEP 0407 (2004) 033

- Total Cross sections (from CDF):
  - inclusive b cross section:
    - |y<1| 29.4±0.6±6.2 μb

      hep-ex/0412071 (submitted to PRD)
  - inclusive c cross section:
    - ~50x higher

      PRL **91**, 241804 (2003)

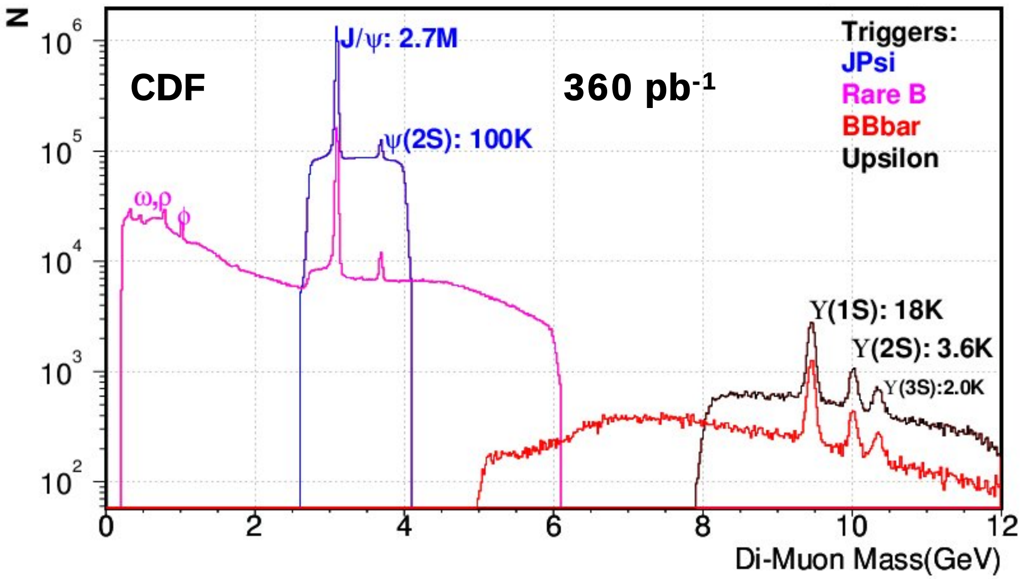


Comments: Tevatron as HF Factory

- The cross sections given on the previous slide imply
  - central (|y|<1) b's at 3kHz at current luminosities
    - ~2x this if you look out to |y|<2
  - central charm at 150kHz
  - ~2×10^{10} b's already seen by CDF and DØ in Run II
  - ~1×10^{12} charm hadrons already produced(!)

⇒ Near infinite statistics for some measurements

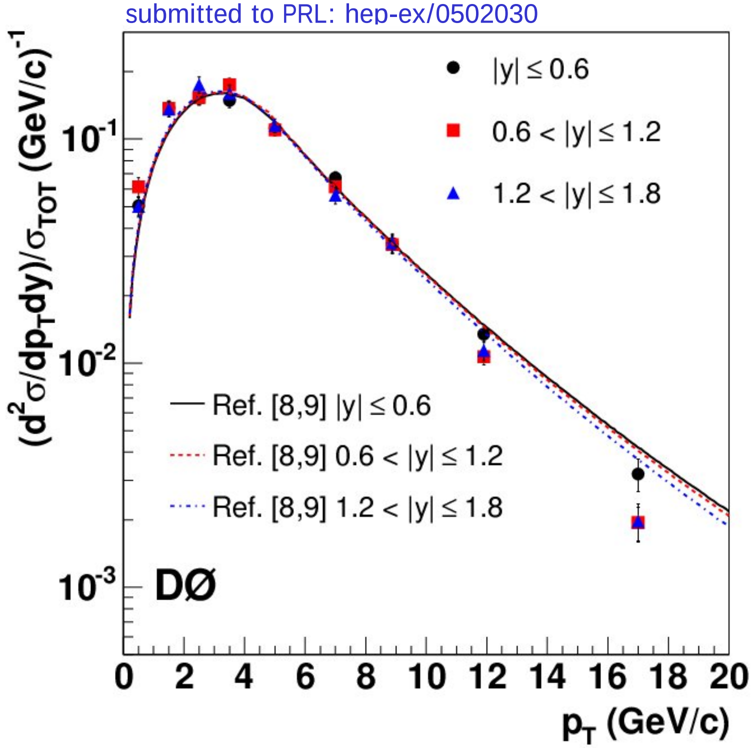
⇒ If you can trigger…

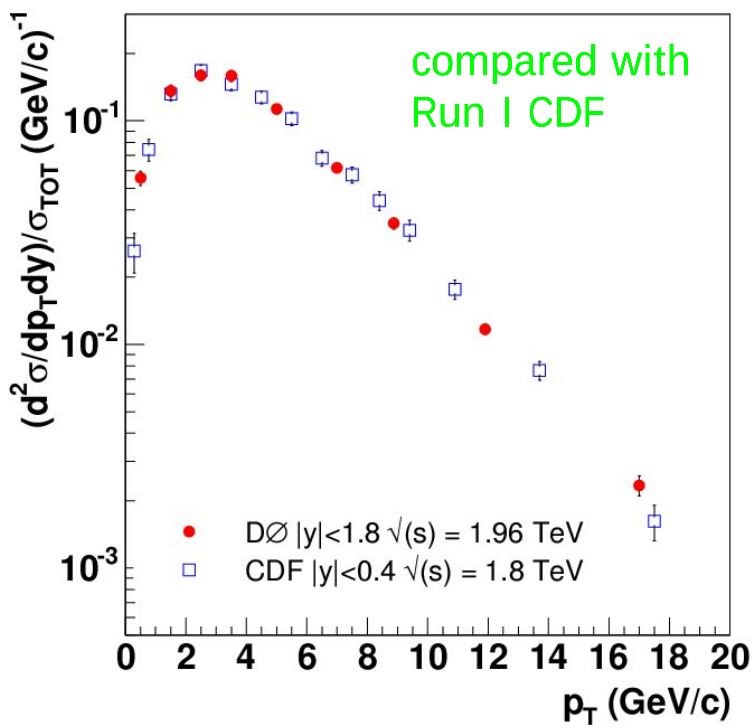


- Rely heavily on muon triggers
  - J/ψ decays are golden
  - semi-leptonic decays
  - rare decays with leptons
- Tracks with significant b/σ_b
- Missing neutrals troublesome
  - forget π^0 identification
  - all-charged decay modes

Quarkonia Production

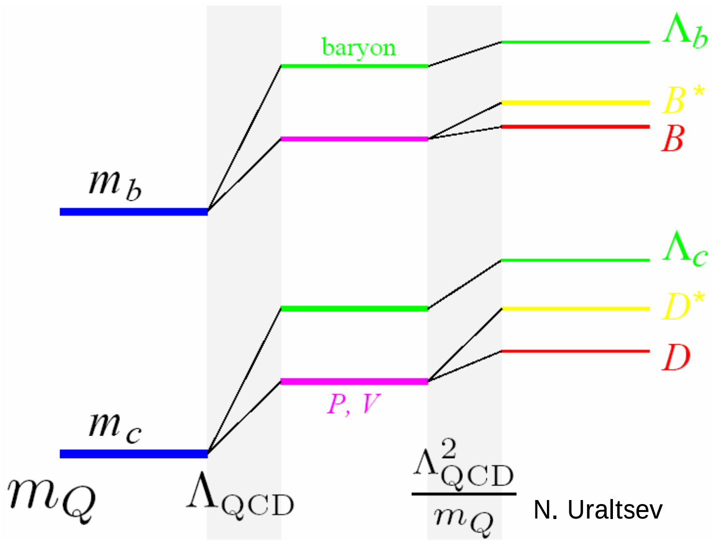
- Slightly different theoretical context
  - Non-relativistic QCD (NRQCD) Lepage et al., PRD **46** 4052 (1992)
  - Production described by short distance cross sections ⊕ non-perturbative matrix elements for evolution to quarkonium state.
  - color octet modes required on top of color singlet to describe production (demonstrated by CDF in Run I)
- New results from DØ: Υ(1s) production, Υ→μμ final state





B Hadron Masses

- In HQE, mass splittings are calculable corrections



evaluation of Λ^2_{QCD}/m_Q terms requires knowledge of light quark dynamics in the presence of the heavy quark field

Bigi, Shifman, Uraltsev, Vainshtein

not "calculable"

$$M_B = m_b + \overline{\Lambda} + \frac{\mu_\pi^2 - \mu_G^2}{2m_b} + \frac{\mu_3^2}{m_b^2} + \ldots$$

hadronization and bound state effects given in terms of local HQ operators

⇒ Same operators used for CKM analyses!

CDF Results: (preliminary)

m_{B^+} = 5279.10 ± 0.41 ± 0.36 MeV

m_{B^0} = 5279.63 ± 0.53 ± 0.33 MeV

m_{B_s} = 5366.01 ± 0.73 ± 0.33 MeV

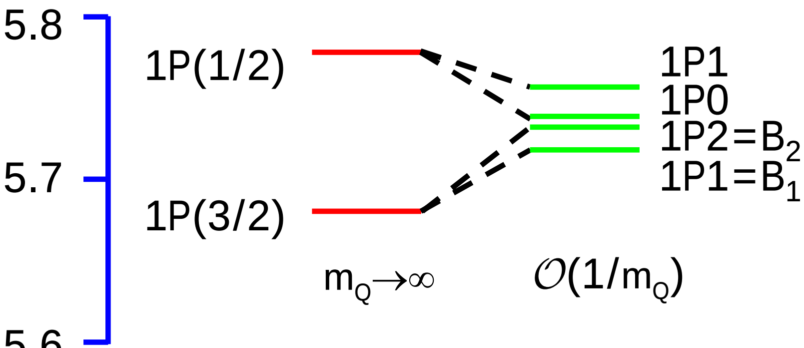
m_{Λ_b} = 5619.7 ± 1.2 ± 1.2 MeV

Using exclusive all-charged (J/ψ) decay modes.

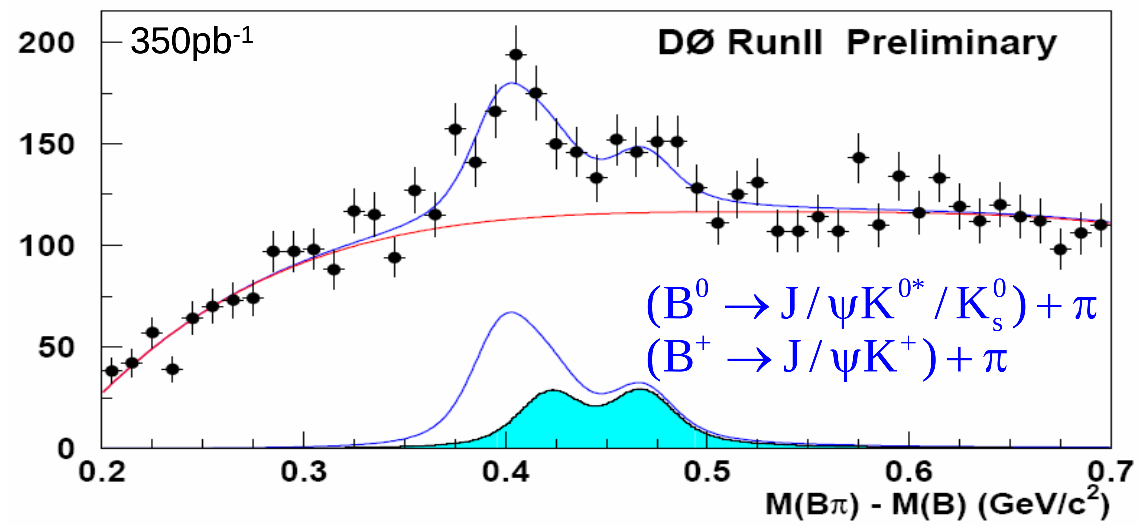
All world-best or very competitive measurements

Excited B states

- Splittings predicted by HQE with relativistic light quarks:



Ebert, Faustov, Galkin



DØ:

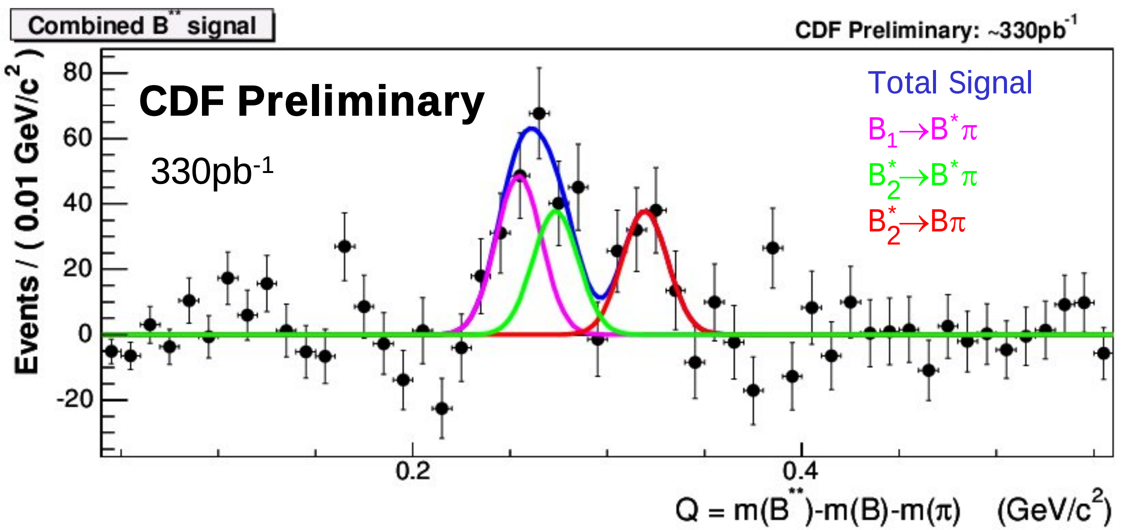
$M(B_1) = 5724 \pm 4 \pm 7$ MeV/c^2

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

Theory prediction (EFG):

$M(B_1) = 5719$ MeV/c^2

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



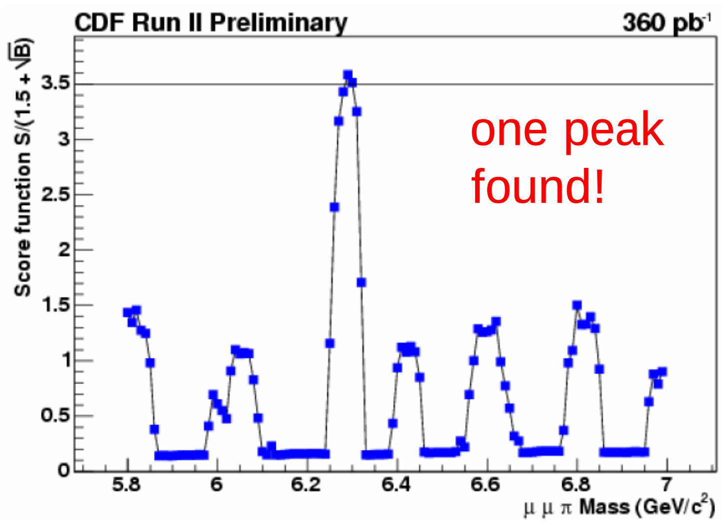
B_c Mass Measurement

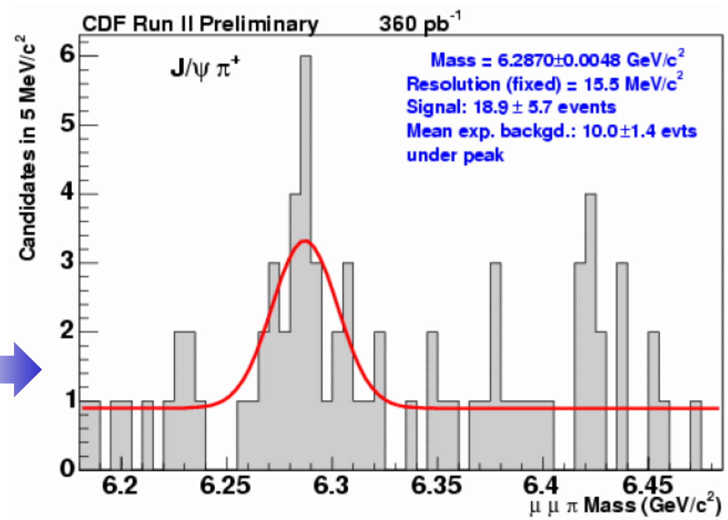
b,c both decay weakly

- CDF: Novel technique using exclusive final state
  - $B_c \to J/\psi\pi^\pm$ (BR = 13%, BR($B_c \to J/\psi\pi^\pm \to \mu\mu\pi^\pm$) = 7.8×10^{-5})
  - Power of di-muon trigger, all-charged final state
  - First "physics use" of L00

    ⇒ Optimal lifetime resolution needed for background rejection
  - Analysis technique: "Blind" search for final state using MC, $B^+ \to J/\psi K^\pm$ decays to optimize selection criteria
    - search for significant peak of width ~detector resolution above background; criteria set by ToyMC studies
      - chance of false positive <0.1%

$m(B_c) = 6.2870 \pm 0.0048 \pm 0.0011$ GeV/c^2





100x more precise than previous DØ, CDF results from semi-leptonic decays

B Hadron Lifetimes

- HQE: no leading order corrections $\propto 1/m_Q$
  - General feature of QCD gauge structure

$$\delta\tau_{H_b} \sim \mathcal{O}\left(\frac{\Lambda^2_{\rm QCD}}{m_b^2}\right) + \mathcal{O}\left(\frac{\Lambda^3_{\rm QCD}}{m_b^3}\right) + \ldots$$

$$-\frac{1}{2}\frac{\mu_\pi^2}{m_b^2} - c_G\frac{\mu_G^2}{2m_b^2}$$

mesons vs. baryons, $\mathcal{O}$(1%)

$$\langle B|\bar{b}\Gamma q \cdot \bar{q}\Gamma' b|B\rangle$$

B^0 vs. B^+ vs. B_s, $\mathcal{O}$(3-20%)

- Precise predictions possible:

$$\tau(B^+)/\tau(B^0) = 1.06 \pm 0.02$$

e.g. Tarantino; Gabbiani, Onishchenko, Petrov

$$\left|1 - \frac{\tau(B_s)}{\tau(B^0)}\right| \leq 0.02$$

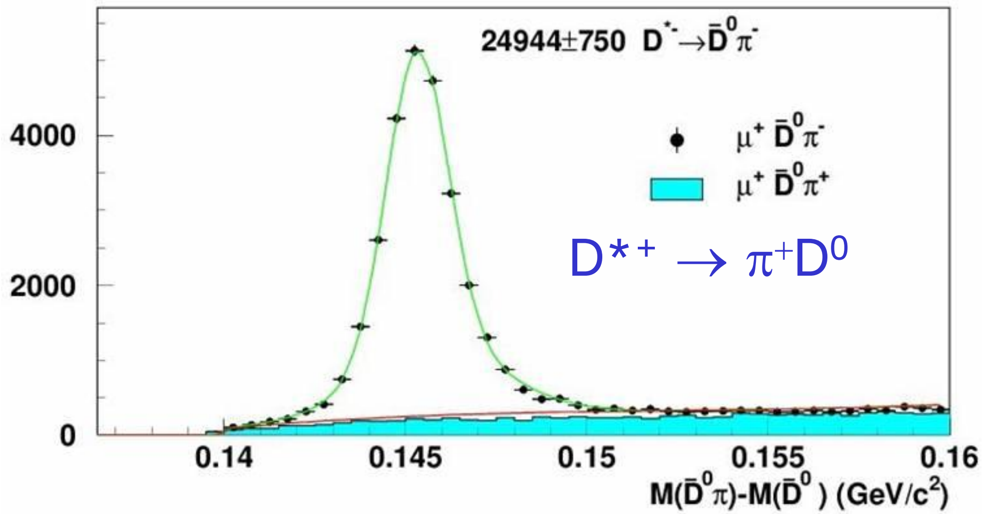
$$\tau(\Lambda_b)/\tau(B^0) = 0.86 \pm 0.05$$

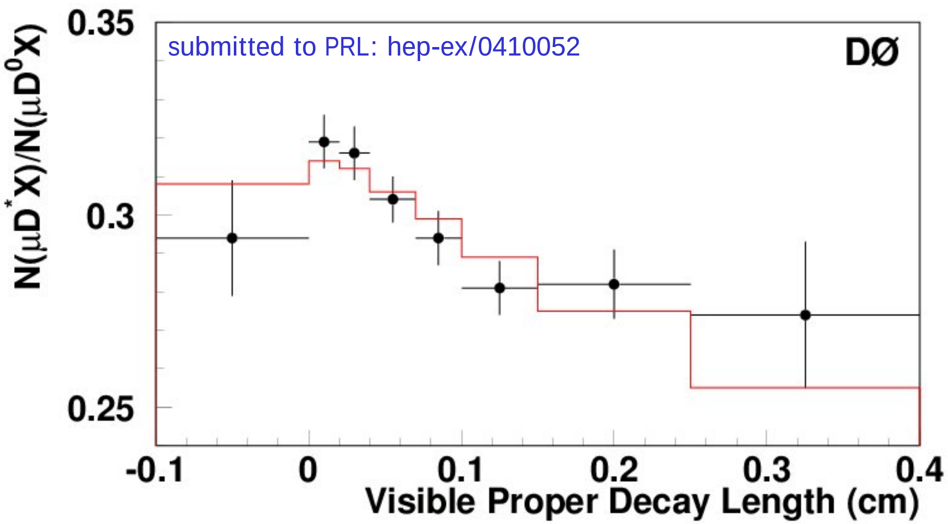
e.g. Gabbiani, Onishchenko, Petrov

  - verification tests calculational validity of HQE, supplies needed input for extraction of CKM parameters

B^0, B^+ Lifetimes

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

c.f. new Belle result

B_s Lifetime

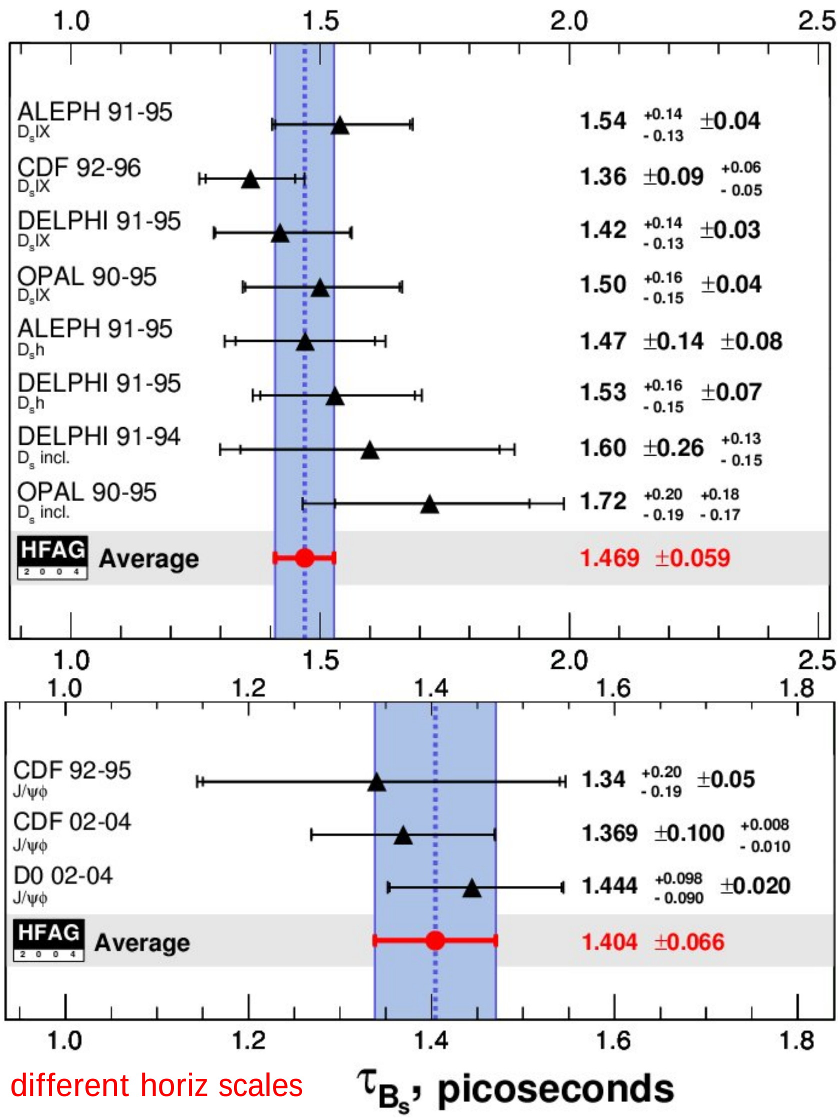
- Only (really) available at the Tevatron

$D_s \ell \nu$ + $D_s X$

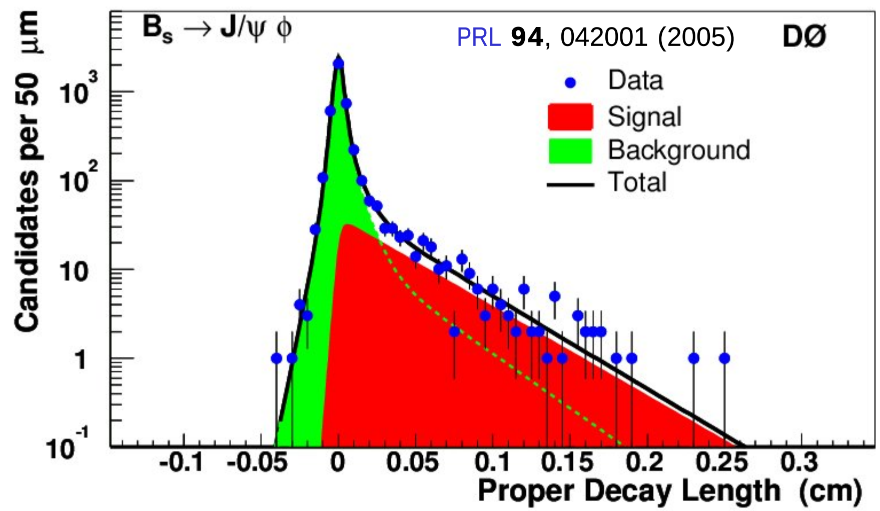
CP mix

$J/\psi\phi$

~CP even



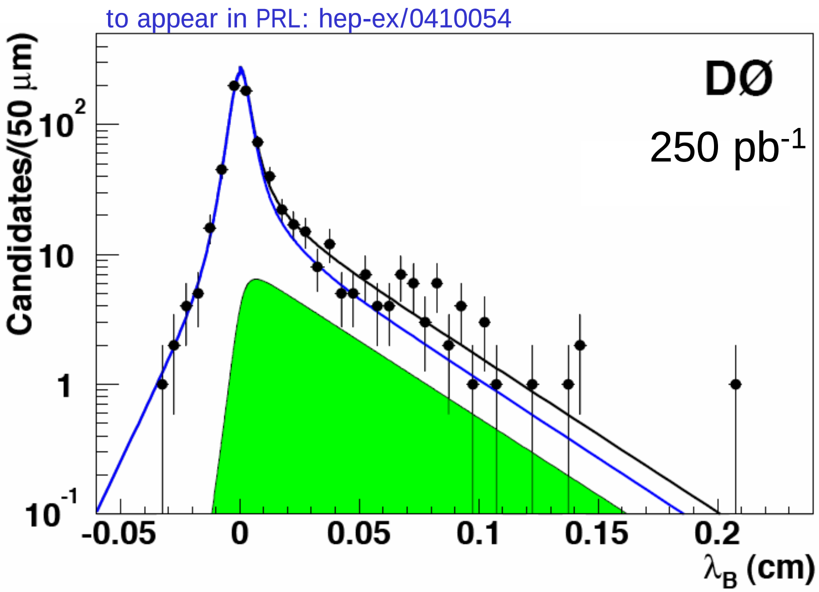
note different horiz scales

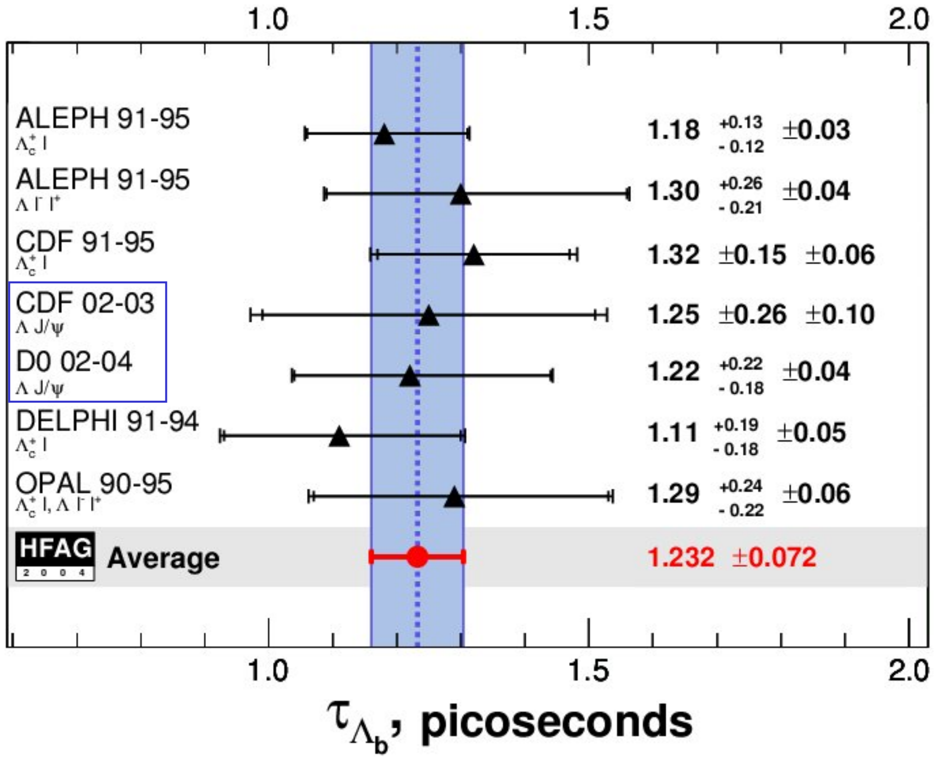


- $1-\tau(B_s)/\tau(B^0) = 0.061 \pm 0.044$
- HQE: $\lesssim 0.02$
- DØ preparing updates with much higher statistics
  - huge jump in precision forthcoming (Moriond)

Λ_b Lifetime

- Another "Tevatron-only" state:





- Exclusive $J/\psi\Lambda$ final state
  - all charged particles
  - very clean
  - will dominate with higher luminosity

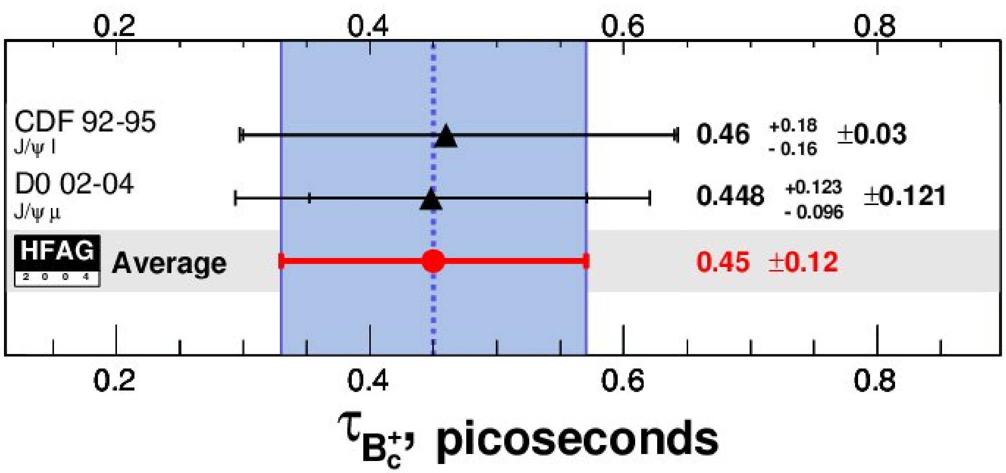
HQE:

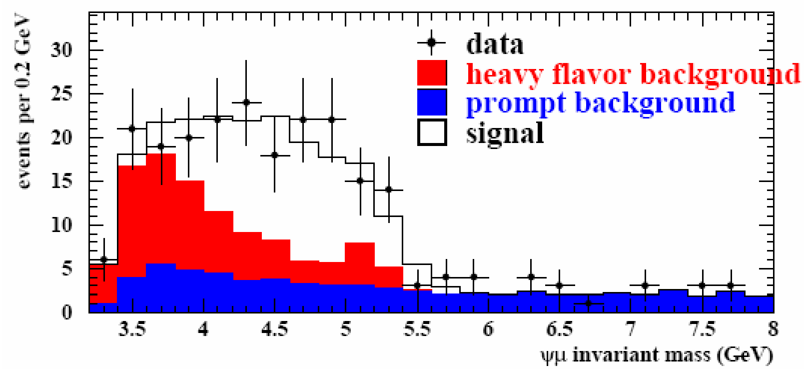
$\tau(\Lambda_b)/\tau(B^0) \approx 0.86$

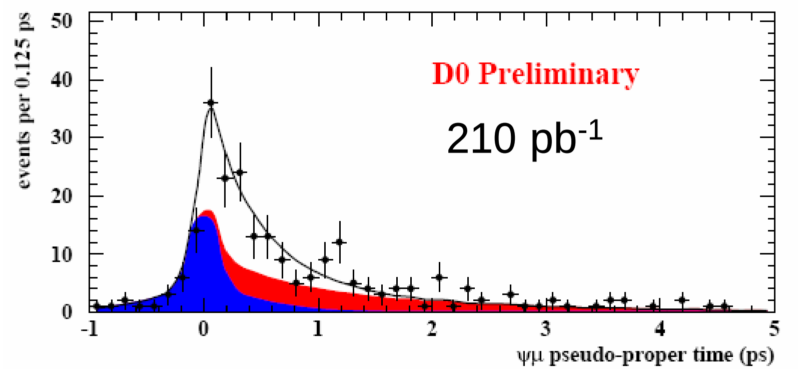
- World Average: $\tau(\Lambda_b)/\tau(B^0) = 0.803 \pm 0.047$

B_c Lifetime

- Only observed at the Tevatron







- Recent DØ results use J/ψμ final state
  - ψμ invariant mass as discriminant
  - systematic errors very preliminary
    - will come down substantially
    - update coming with much larger luminosity
- World Average: $\tau(B_c) = 0.45 \pm 0.12$ ps

HQE:

$\tau(B_c) \ll \tau(B^0)$ ✓

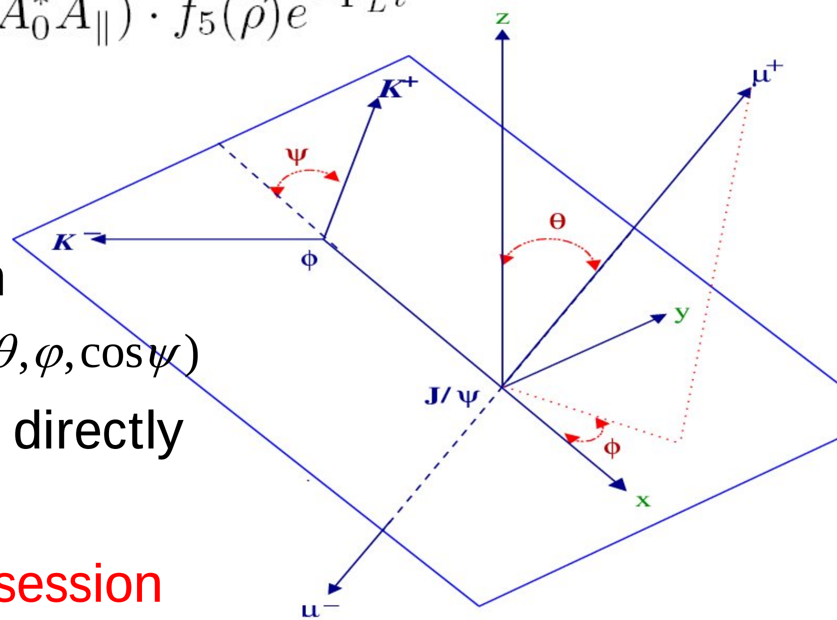
$\Delta\Gamma_s/\Gamma_s$

- First Tevatron measurement with direct bearing on *CP* violation and mixing in the B_s system (New Physics!)
  - define Heavy (H) and Light (L) B_s states:
  - Γ_H and Γ_L are partial widths, $\Delta\Gamma_s = \Gamma_L - \Gamma_H$, $\Gamma_s = 1/2(\Gamma_H + \Gamma_L)$
  - Differential decay rate (Lifetime difference!):

$$\frac{d^4\mathcal{P}(\vec{\rho},t)}{d\vec{\rho}\,dt} \propto |A_0|^2 e^{-\Gamma_L t}\cdot f_1(\vec{\rho}) + |A_{\|}|^2 e^{-\Gamma_L t}\cdot f_2(\vec{\rho})$$
$$+ |A_\perp|^2 e^{-\Gamma_H t}\cdot f_3(\vec{\rho}) + \mathrm{Re}(A_0^* A_{\|})\cdot f_5(\vec{\rho}) e^{-\Gamma_L t}$$

CP-even angular configurations (L=0, 2)

CP-odd angular configuration (L=1)



  - rate depends on relative orientation of meson polarization $\vec{\rho} = (\cos\theta, \varphi, \cos\psi)$
  - Constraints/measurement of $\Delta\Gamma_s/\Gamma_s$ directly relevant to observing B_s mixing
    ⇒See Stephie's talk in CP-Mixing session

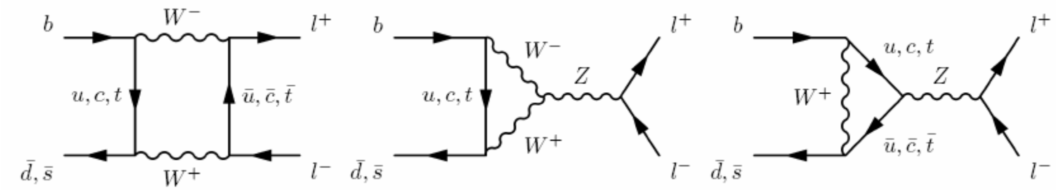
Rare B Decays (I)

- Probe high-mass corrections to decay amplitudes
- New Physics!
- Classic Tevatron mode:

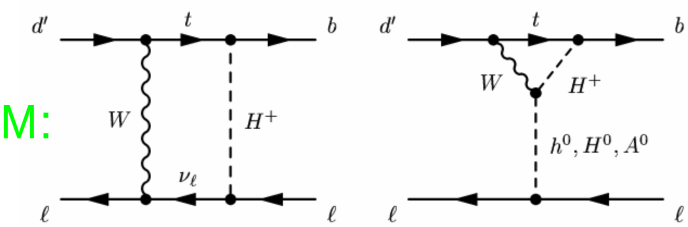
  $B_s \to \mu\mu$

  - SM BR ~ 4×10^{-9}
  - BR could be 100x larger in some SUSY models
    - depends on H^+ mass and $\tan^N\beta$, N>6

SM:



MSSM:



CDF: BR($B_s \to \mu\mu$)< 7.5×10^{-7} (95% CL)*

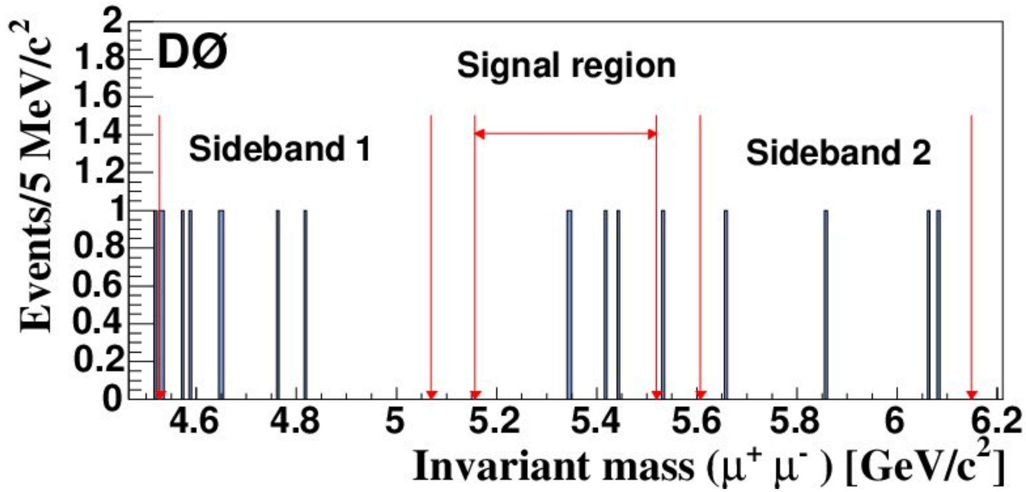
PRL 93 032001 (2004)

*Working on multivariate technique

DØ: BR($B_s \to \mu\mu$)< 5.0×10^{-7} (95% CL)*

to appear in PRL: hep-ex/0410039

*Will update for Moriond

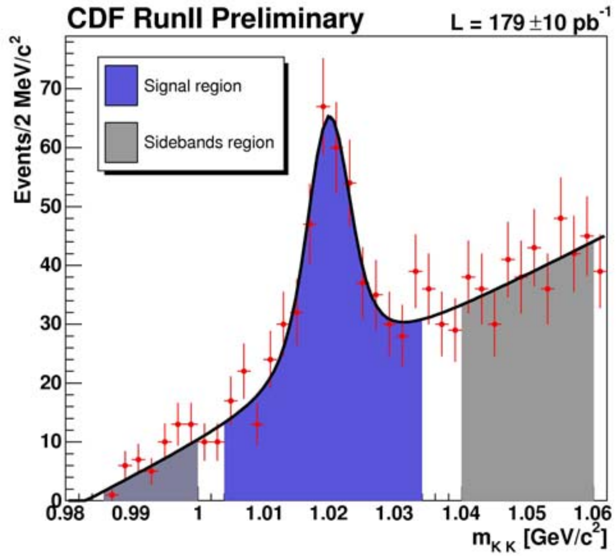


Rare B Decays (II)

- Charmless B_s Decays

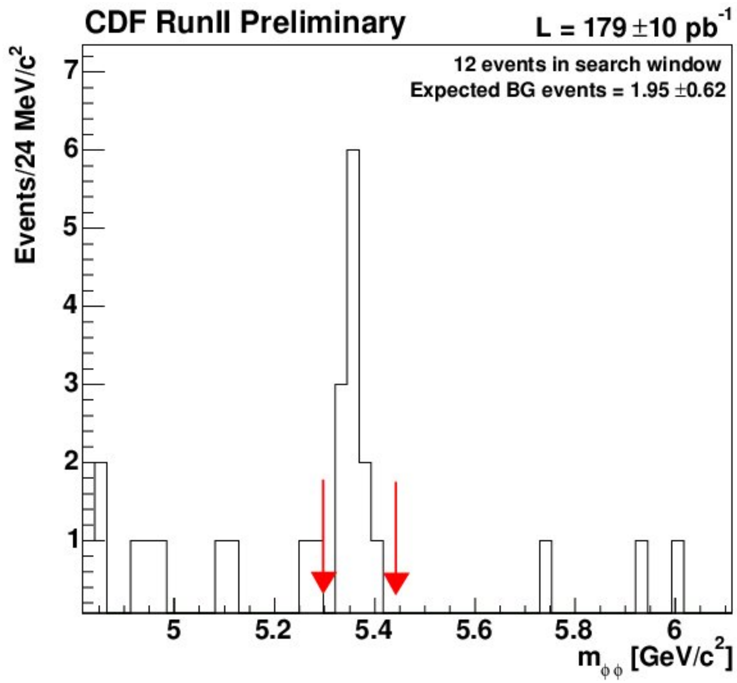
  $B_s \to \phi\phi$

  – Decay amplitude comprises QCD and electroweak penguin contributions
    - may be dominated by EW penguin
    - $\phi\phi$ decay normalized to $B_d \to J/\psi K^{0*}$



$BR(B_s \to \phi\phi) = (1.4 \pm 0.6 \pm 0.2 \pm 0.5(BR's)) \times 10^{-5}$

- First step in program to explore other charmless B_s decays
- e.g. $B_s \to \phi\pi$ dominated purely by EW penguin contributions
- search for anomalies, constrain penguin contributions to other final states

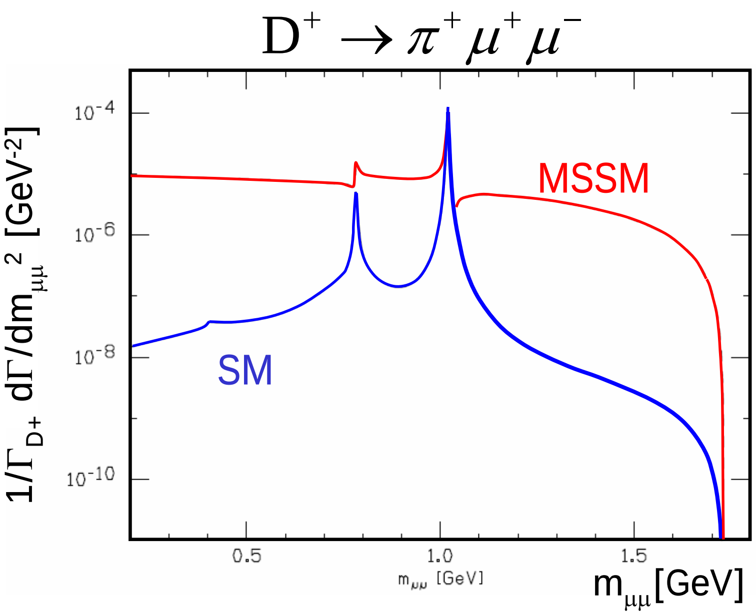


Rare C Decays

- Some models allow FCNC in the up-quark sector
  - e.g. RPV SUSY: FCNC allowed at tree level in some cases
  - CDF: Br($D^0 \to \mu\mu$) < 3.1×10^{-6} @ 95% CL PRD 68 091101 (2003)
  - Just scratching the surface, really
    - CDF has two-track "charm" trigger
    - DØ can use excellent muon coverage

Example:

- $c \to u\ell^+\ell^-$ particularly sensitive (Burdman, Golowich, Hewett, Pakvasa)



DØ: First evidence for $D_s^+ \to \pi\mu^+\mu^-$. Analysis will be shown at Moriond

Conclusions

- LOTS of B, C hadrons to play with!
  - $2x10^{10}$ b's, $1x10^{12}$ c's produced so far in Run II
- Tevatron poised to dominate in
  - (some) lifetime measurements
  - rare decays, especially those with leptonic modes
  - B_s mixing
- Many possible contributions to bolstering HQE knowlege:
  - precise lifetime measurements
  - precise mass measurements
  - excited B, C states

  $\Rightarrow$ clarify extraction of CKM parameters with better understanding of underlying theory
- We can always hope for surprises!

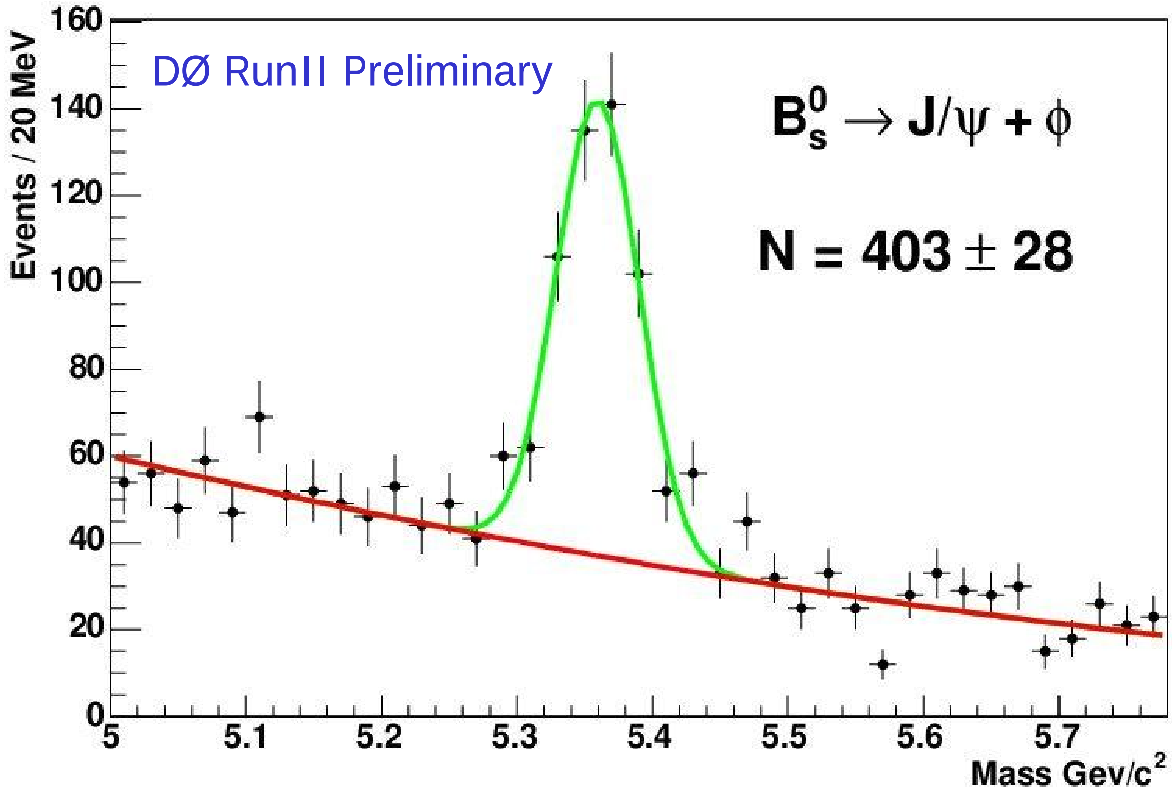
Thanks to CDF, DØ B-physics conveners and analyzers

Backup Slides

Typical B Selections

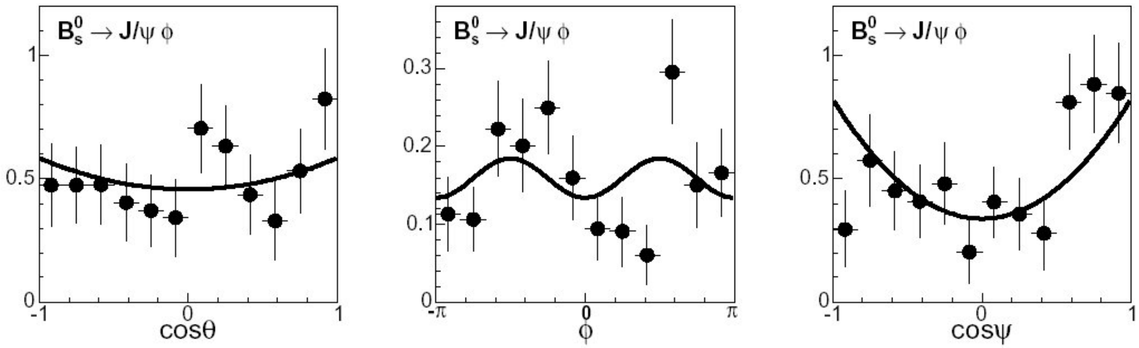
$B_s \rightarrow J/\psi\phi$

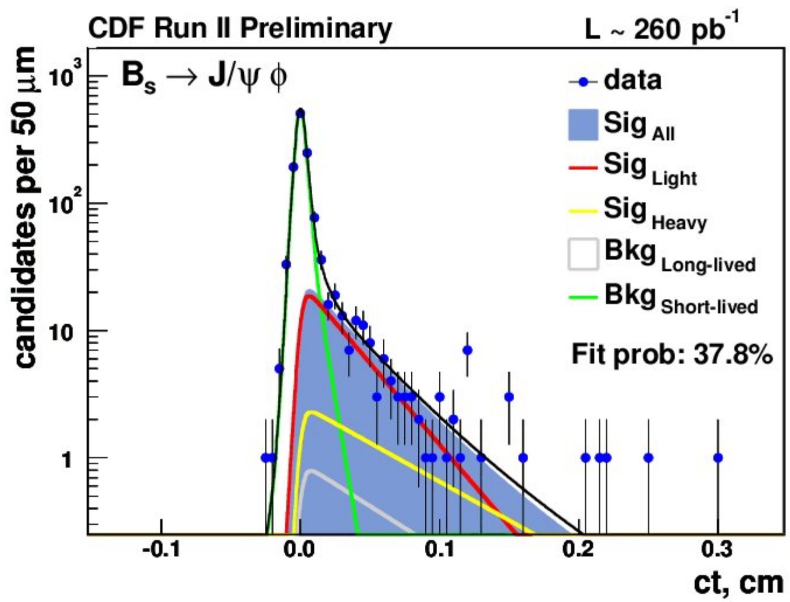
- $p_T(J/\psi) > 3$ GeV
- $p_T(K) > 0.4$ GeV
- $L(B_s)/\sigma_L > 3.0$
- $\cos(\theta(L, p_B)) > 0.95$
- $b(B_s)/\sigma_b < 6$



$\Delta\Gamma_s/\Gamma_s$

- CDF: Measurement Strategy
  - Choose definite CP state: $B_s \to J/\psi\phi$
  - time-dependent angular distributions select Γ_H, Γ_L components





- CDF Results: $\Delta\Gamma_s/\Gamma_s = 0.65^{+0.25}_{-0.33} \pm 0.01$
  $\Delta\Gamma_s = 0.47^{+0.19}_{-0.24} \pm 0.01\ \text{ps}^{-1}$
- c.f. Theory: $|\Delta\Gamma_s|/\Gamma_s < 0.29$ at 95% CL
- constraint on Δm_s: $\Delta m_s = 125^{+69}_{-55}$
- current limit: $\Delta m_s > 14.5\ \text{ps}^{-1}$ at 95% CL
- Very interesting result

forthcoming DØ result for Moriond