Properties of Heavy B Hadrons

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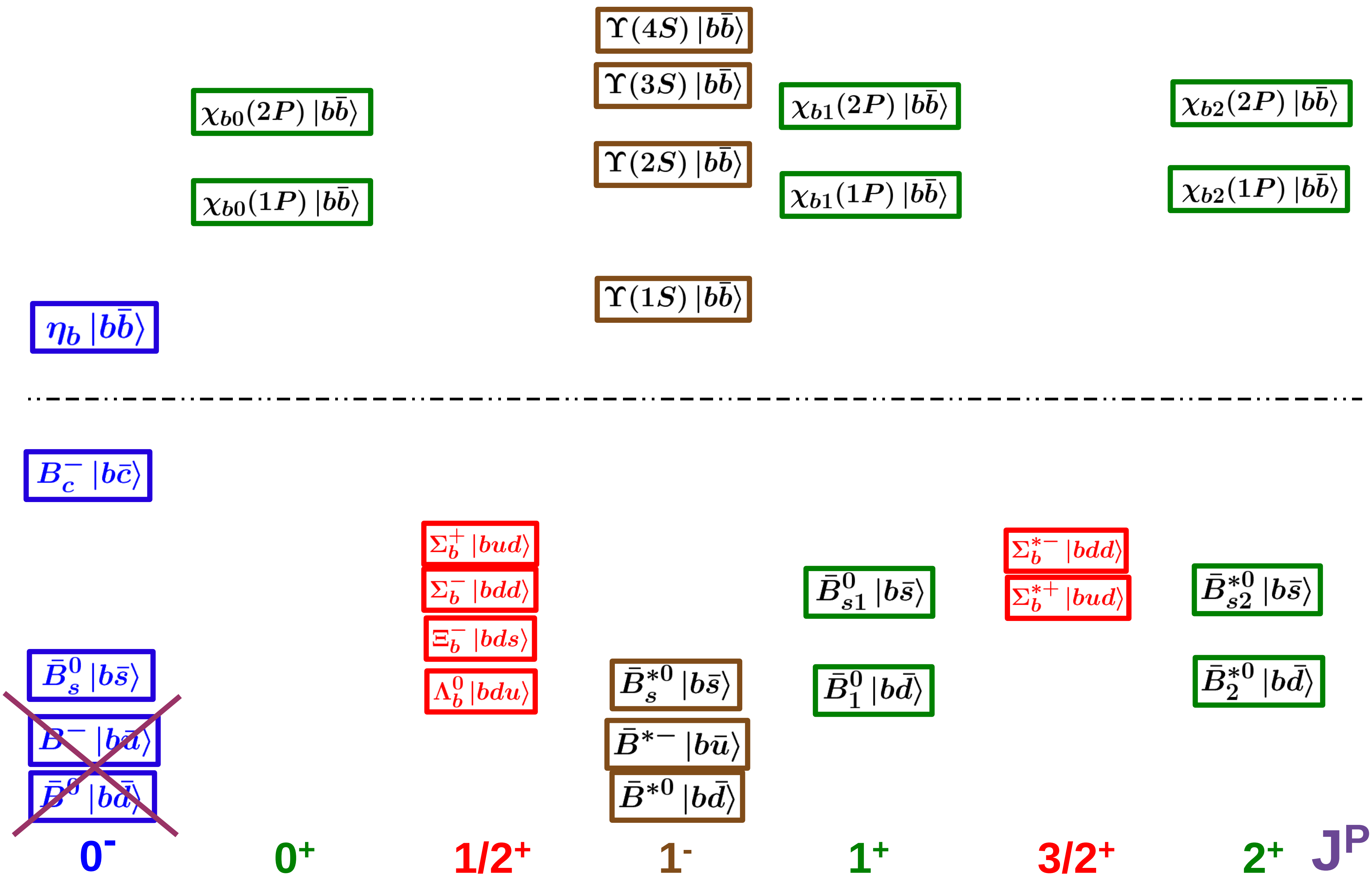
Heavy B Hadrons

- Mesons
- Baryons

Heavy = all but not B^0-B^+

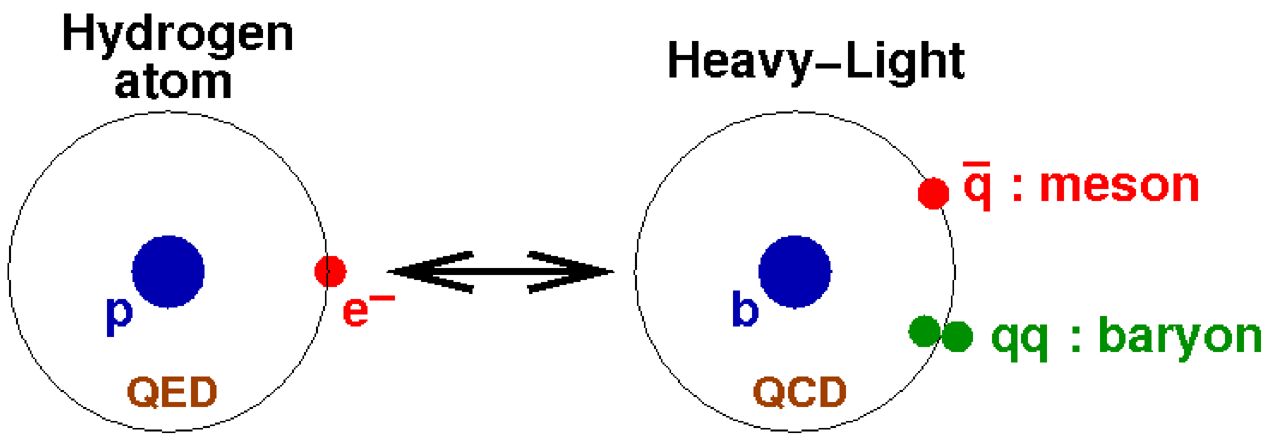


Properties

<u>Focus on:</u> **Masses, Lifetimes (Decays)**

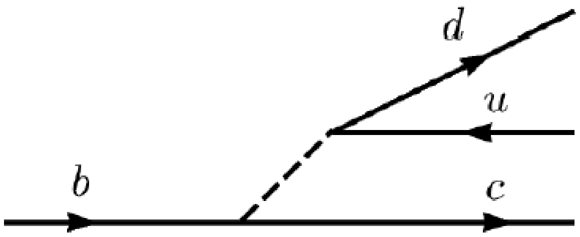
Why study B hadrons?

From hydrogen atom to B hadron spectroscopy



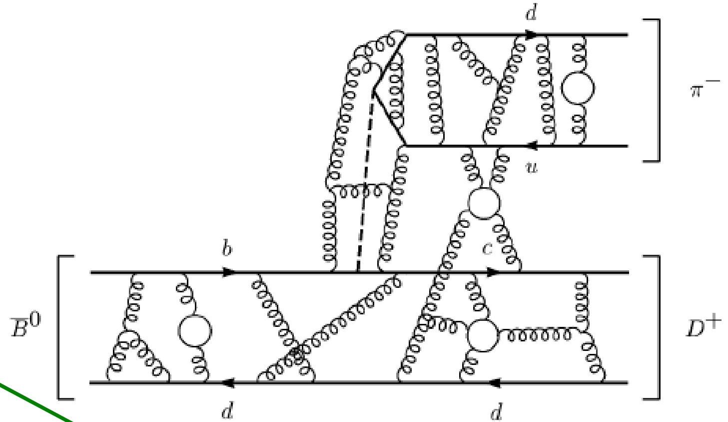
- **Heavy quark hadrons are the hydrogen atom of QCD**
  => study of B hadron states = study of (non-perturbative) QCD
- **Measurements of B hadron masses provide sensitive tests of potential models, HQET and all aspects of QCD including lattice gauge calculations**

B Hadron Lifetimes



- **Spectator model: *b* quark decays like free particle**
  => All *B* hadron lifetimes are equal !
- **In Reality: QCD => Lifetimes of *B* hadrons study interplay between strong and weak interaction**
- **Heavy quark expansion predicts *B* lifetimes:**

$$\Gamma_B = |V_{CKM}|^2 \sum_n c_n^{(f)} \left(\frac{\Lambda_{QCD}}{m_b}\right)^n \langle H_b|O_n|H_b\rangle$$



non-perturbative effects (sum rules, OPE, lattice)

$\mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)^2$ **meson vs baryon**

$\mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)^3$ **spectator effects (B^0 vs B^+ vs B^0_s)**

Allow for precise predictions:

(e.g. Bigi, Uraltsev; Tarantino; Gabbiani, Onishchenko, Petrov; Lenz, Nierste)

$$\frac{\tau(B^+)}{\tau(B^0)} = 1.06 \pm 0.02 \qquad \frac{\tau(B_s^0)}{\tau(B^0)} = 1.00 \pm 0.01 \qquad \frac{\tau(\Lambda_b^0)}{\tau(B^0)} = [\,(0.88 \pm 0.05), 0.94\,]$$

=> Test validity of HQE => Supply input for extraction of CKM matrix elements

A Brief History of (Life)Time(s)

VOLUME 51, NUMBER 15 PHYSICAL REVIEW LETTERS 10 OCTOBER 1983

Measurement of the Lifetime of Bottom Hadrons

N. S. Lockyer, J. A. Jaros, M. E. Nelson, G. S. Abrams, D. Amidei, A. R. Baden, C. A. Blocker, A. M. Boyarski, M. Breidenbach, P. Burchat, D. L. Burke, J. M. Dorfan, G. J. Feldman, G. Gidal, L. Gladney, M. S. Gold, G. Goldhaber, L. Golding, G. Hanson, D. Herrup, R. J. Hollebeek, W. R. Innes, M. Jonker, I. Juricic, J. A. Kadyk, A. J. Lankford, R. R. Larsen, B. LeClaire, M. Levi, V. Lüth, C. Matteuzzi, R. A. Ong, M. L. Perl, B. Richter, M. C. Ross, P. C. Rowson, T. Schaad, H. Schellman, D. Schlatter,[a] P. D. Sheldon, J. Strait,[b] G. H. Trilling, C. de la Vaissiere,[c] J. M. Yelton, and C. Zaiser

Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305, and Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720, and Department of Physics, Harvard University, Cambridge, Massachusetts 02138

(Received 2 August 1983)

The average lifetime of bottom hadrons was measured with the Mark II vertex detector at the storage ring PEP. The lifetime was determined by measuring the impact parameters of leptons produced in bottom decays. $\tau_b = (12.0^{+4.5}_{-3.6} \pm 3.0) \times 10^{-13}$ sec was found.

$$\tau_b = (1.20\ ^{+0.45}_{-0.36} \pm 0.30)\ \text{ps}$$

2006 APS Panofsky Prize

2006 W.K.H. Panofsky Prize in Experimental Particle Physics Recipient

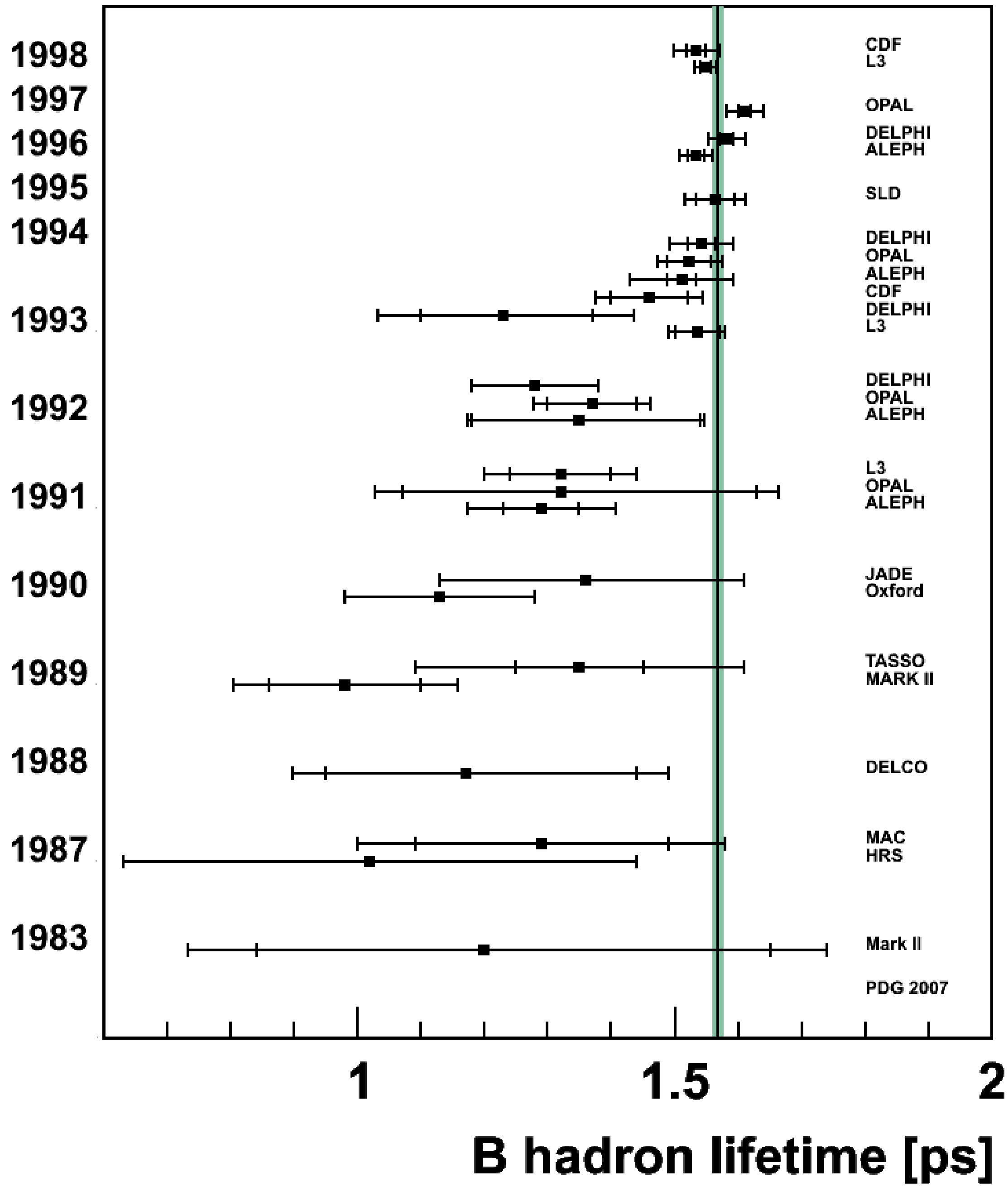
Email | Prir

Nigel Lockyer
University of Pennsylvania

Citation:

"For their leading contributions to the discovery of the long b-quark lifetime with the MAC and Mark II experiments at SLAC. The unexpectedly large value of the b-quark lifetime revealed the hierarchy of the Cabibbo-Kobayashi-Maskawa quark mixing matrix."

B Hadron Lifetime History

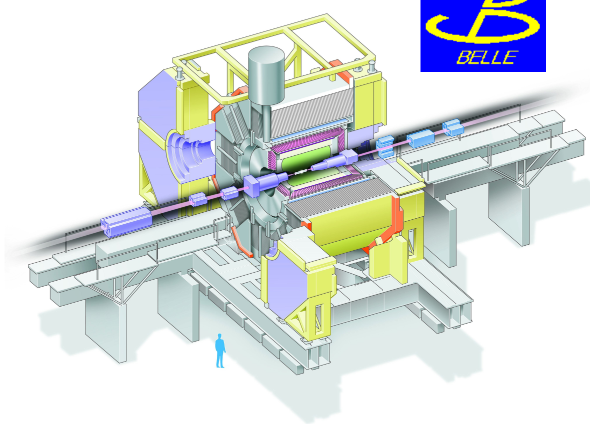


Production of Heavy B Hadrons

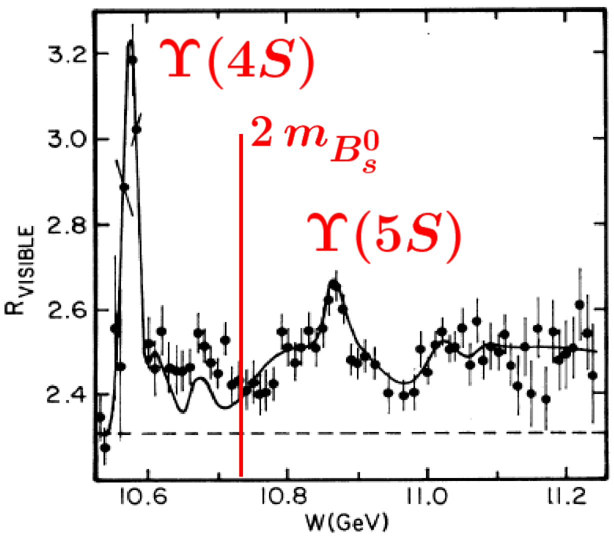
Tevatron: $p\,\bar{p} \longrightarrow b\bar{b}X$ **(all heavy B hadrons produced)**

$\bar{B}^0 = |b\,\bar{d}\rangle,\;\; B^- = |b\,\bar{u}\rangle \quad \Lambda_b^0 = |b\,d\,u\rangle,\;\; \Sigma_b^- = |b\,d\,d\rangle$

$\bar{B}_S^0 = |b\,\bar{s}\rangle,\;\; B_c^- = |b\,\bar{c}\rangle \quad \Xi_b^- = |b\,d\,s\rangle$



$\Upsilon(5S)$**:** $e^+e^- \longrightarrow \Upsilon(5S) \longrightarrow B_s\bar{B}_s / B_s^*\bar{B}_s / B_s^*\bar{B}_s^*$



Measurement of branching fractions:

$\mathcal{B}(B_s^0 \to D_s^-\pi^+) = (3.33^{+0.32}_{-0.30}{}^{+0.69}_{-0.65}) \times 10^{-3}$

$\mathcal{B}(B_s^0 \to D_s^\mp K^\pm) = (2.2\,^{+1.1}_{-0.9} \pm 0.5) \times 10^{-4}$

compatible with CDF

Belle at KEKB:

Datasets on $\Upsilon(5S)$:

2005: 1.86 fb^{-1}

2006: 21.7 fb^{-1}

$\mathcal{B}(B_s^0 \to J/\psi\phi) = (1.15\;^{+0.28}_{-0.30}) \times 10^{-3}$

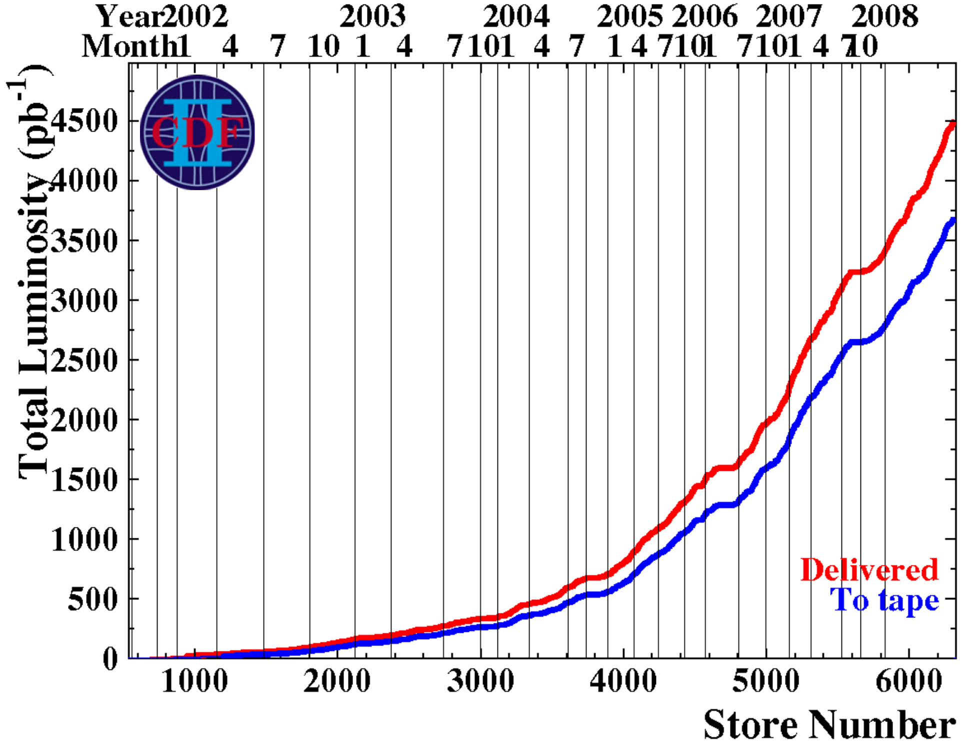
stat. + syst.

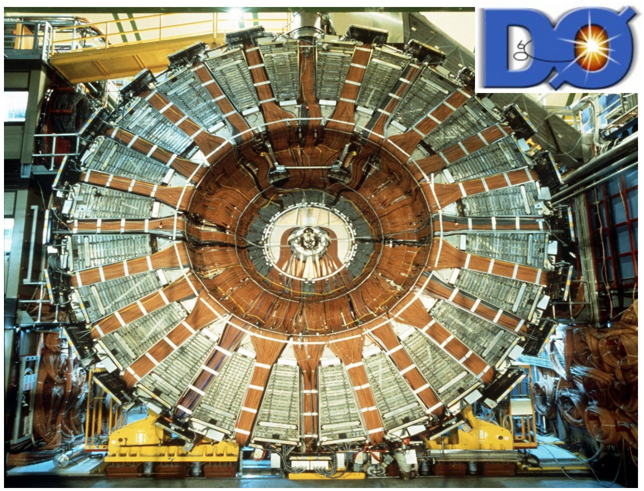
compatible with PDG

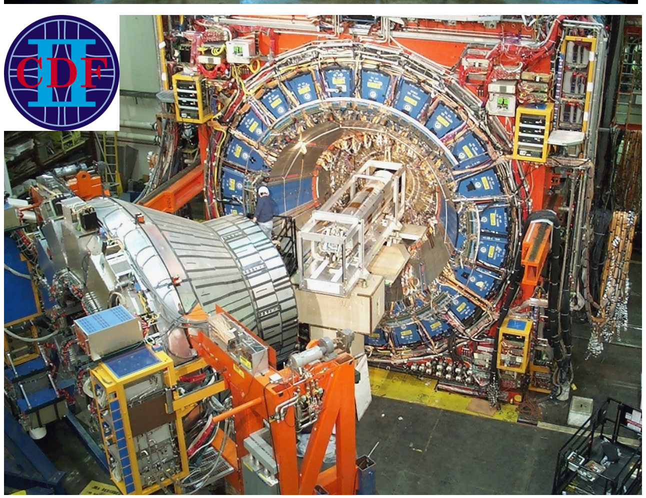
Exp. Equipment

Tevatron is running well:

- ~4.5 fb^{-1} deliv., ~3.7 fb^{-1} on tape
- ~1-3 fb^{-1} used for analysis







CDF and D0 detectors:

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

B Meson States

B_s^0

Neutral B_s^0 System

B_s^0 System: 2 flavour eigenstates: $B_s^0 = |\bar{b}s\rangle$ & $\bar{B}_s^0 = |b\bar{s}\rangle$

Time evolution of states governed by Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix} = \Bigg[\underbrace{\begin{pmatrix} M_0 & M_{12} \\ M_{12}^* & M_0 \end{pmatrix}}_{\text{mass matrix}} - \frac{i}{2}\underbrace{\begin{pmatrix} \Gamma_0 & \Gamma_{12} \\ \Gamma_{12}^* & \Gamma_0 \end{pmatrix}}_{\text{decay matrix}}\Bigg] \begin{pmatrix} B_s^0(t) \\ \bar{B}_s^0(t) \end{pmatrix}$$

Mass eigenstates are admixture of B_s^0 flavour eigenstates:

$$|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle \qquad |B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle \qquad \frac{q}{p} = \frac{V_{tb}^* V_{ts}}{V_{tb} V_{ts}^*}$$

where $\Delta m_s = m_H - m_L \sim 2|M_{12}|$ Oscillations between B_s^0 & $\bar{B}_s^0$

$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2\,|\Gamma_{12}|\cos(\phi_s)$ Lifetime / width difference

$\phi_s = \arg(-M_{12}/\Gamma_{12})$ CP phase

Assume no CP violation ($\phi_s^{SM} \sim 0.004$) => mass eigenstate = CP eigenstate

=> $\Gamma_L \sim$ CP even (short lived) & $\Gamma_H \sim$ CP odd (long lived)

Experimental observables describing system:

m_H, m_L => Δm_s, $\Gamma_s = (\Gamma_H + \Gamma_L)/2 = 1/\tau_s$, $\Delta\Gamma_s$, ϕ_s

B_s^0 Lifetimes

Since $\Delta\Gamma \neq 0$: Different measurements have different meanings

1) Flavour specific lifetime:

- Equal mix of B_s^H & B_s^L at t=0

  e.g. semileptonic decays $B_s^0 \rightarrow D_s l \nu X$

- Fit of single exponential measures $\tau(B_s^0)_{\text{fl.spec.}} = \frac{1}{\Gamma_s} \frac{1 + \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}{1 - \left(\frac{\Delta\Gamma_s}{2\Gamma_s}\right)^2}$

2) *CP* specific lifetime:

- Assumed to be either *CP* even or odd

  e.g. $B_s^0 \rightarrow K^+K^-$ or $B_s^0 \rightarrow D_s^+D_s^-$ assumed *CP* even:

  => lifetime measures Γ_L

3) Disentangle mixed *CP* state

- e.g. $B_s^0 \rightarrow J/\psi\ \phi$: Fit for *CP* components

B_s^0 Flavour Specific Lifetime

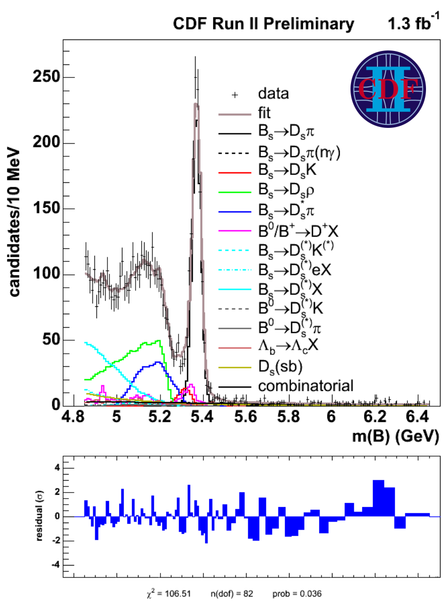
CDF: New precise result using partially & fully rec. $B_s^0 \rightarrow D_s\pi X$

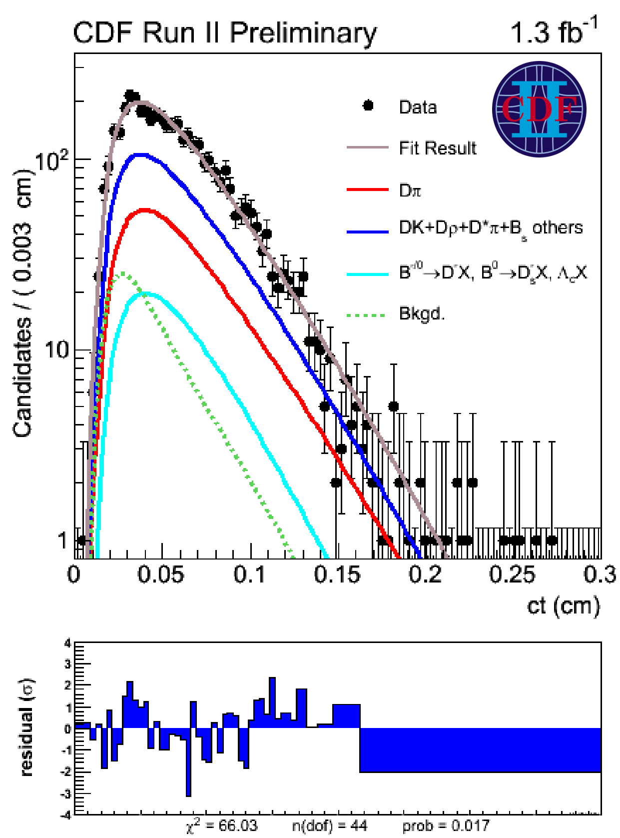
~1100 fully & ~2000 partially rec. events

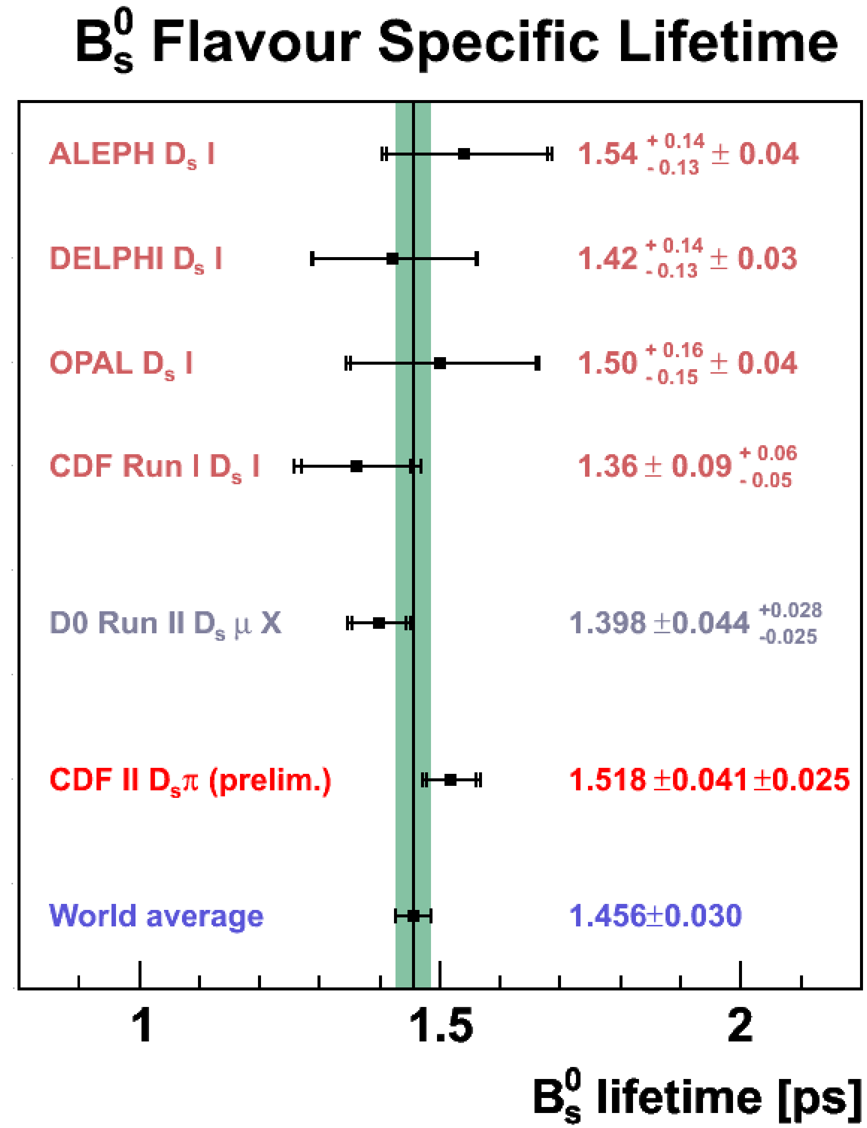
$\tau(B_s^0) = (1.518 \pm 0.041 \pm 0.025)$ ps

=> $\tau(B_s^0) / \tau(B^0) = 0.99 \pm 0.03$

world avg. $\tau(B_s^0) / \tau(B^0) = 0.95 \pm 0.02$

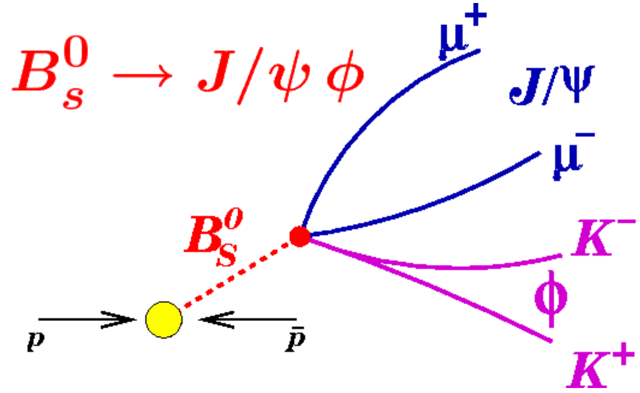




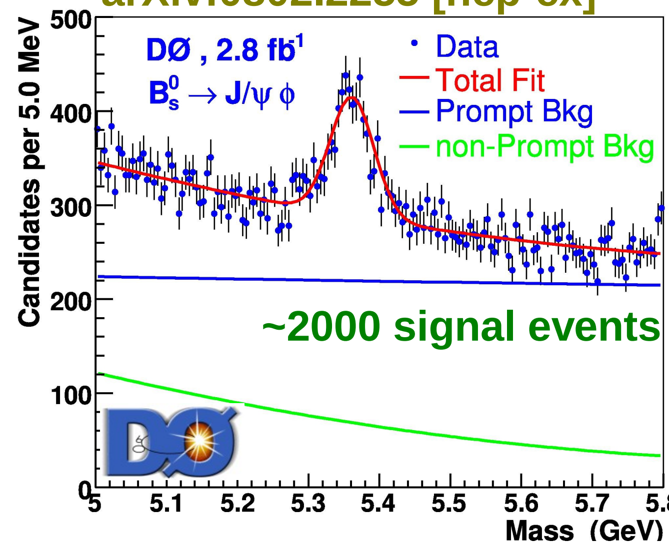


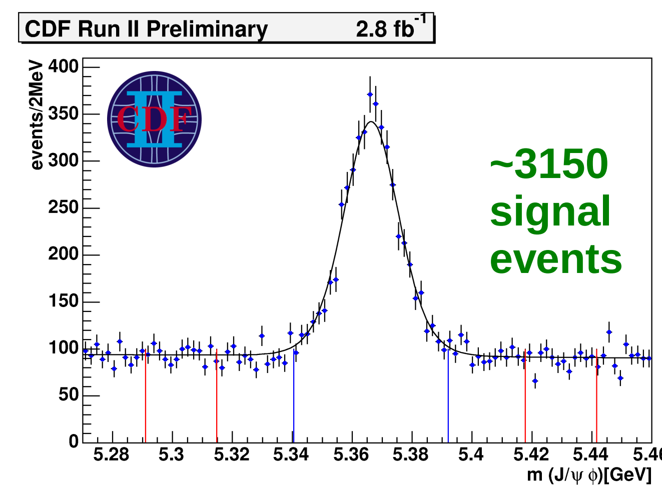
B_s^0 -> J/ψ φ Lifetime

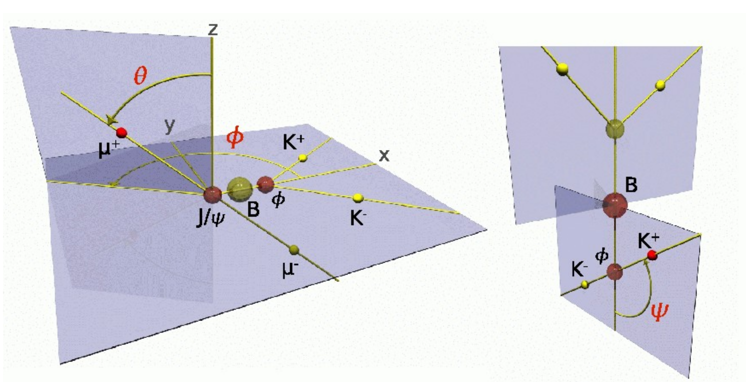
- <u>Status of analyses:</u>
  - D0: Result with 2.8 fb^{-1} subm. to PRL
  - CDF: Update to published result with more data (2.8 fb^{-1}) (NEW)
- Decay $B_s^0 \to J/\psi\,\phi$ (spin-0 -> spin-1 + spin-1) leads to 3 different angular momentum final states:
  - L=0 (s-wave), L=2 (d-wave) -> CP even
  - L=1 (p-wave) -> CP odd
- Use decay angular distribution in transversity basis $\vec{\rho} = (\cos\theta,\ \phi,\ \cos\psi)$ to disentangle CP states => mainly CP even



arXiv:0802.2255 [hep-ex]







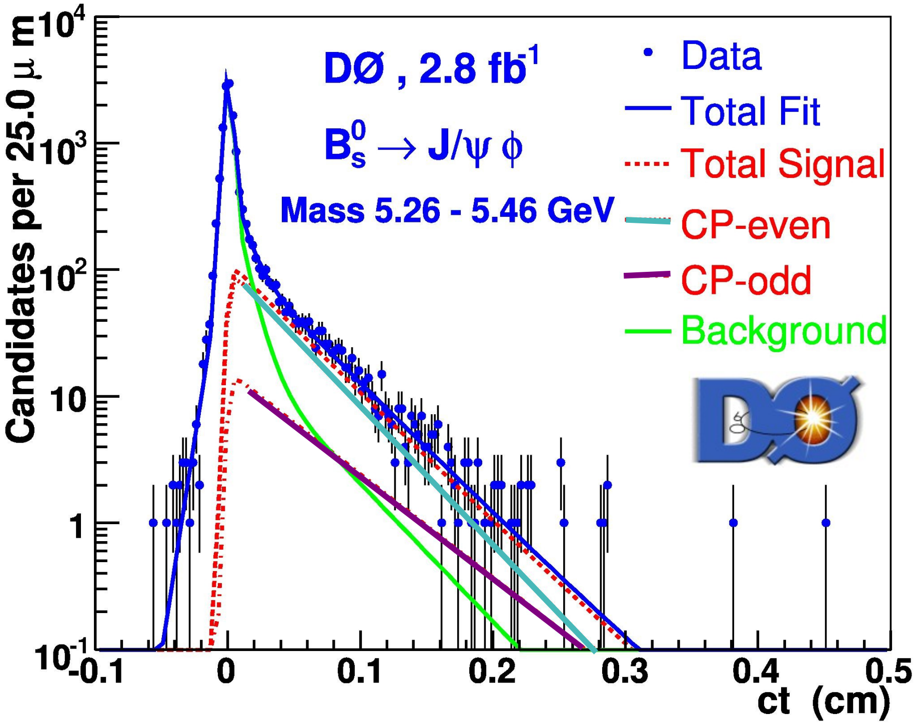
$B_s^0 \to J/\psi\ \phi$ Analysis

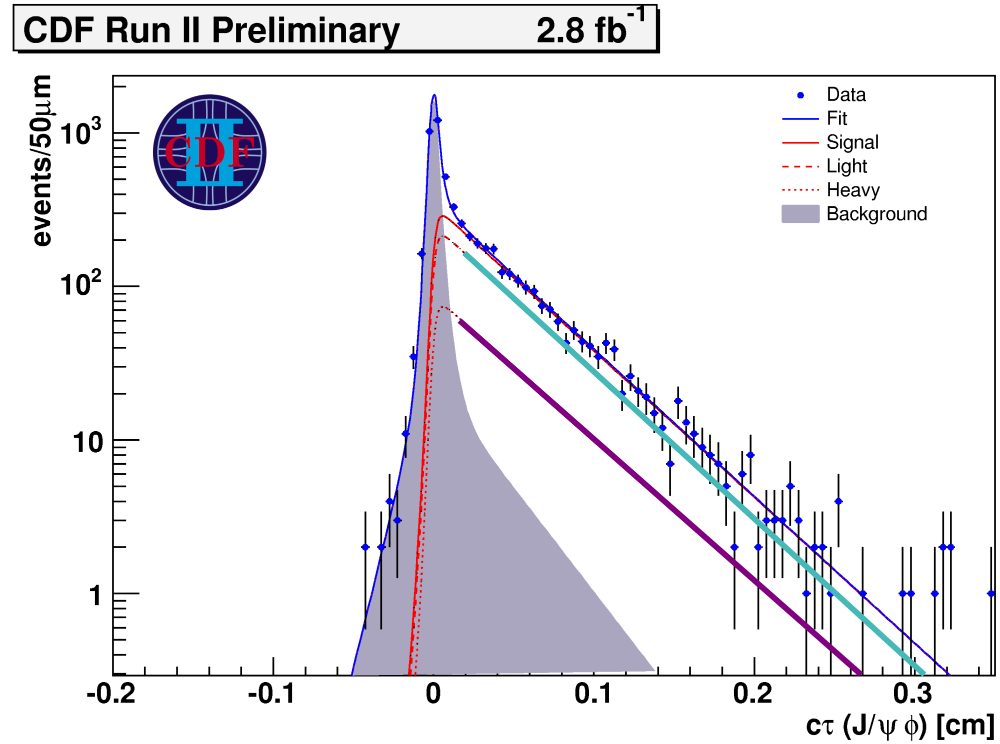
Results:

- **Measurement of lifetime and $\Delta\Gamma$**

CP even
CP odd

arXiv:0802.2255 [hep-ex]

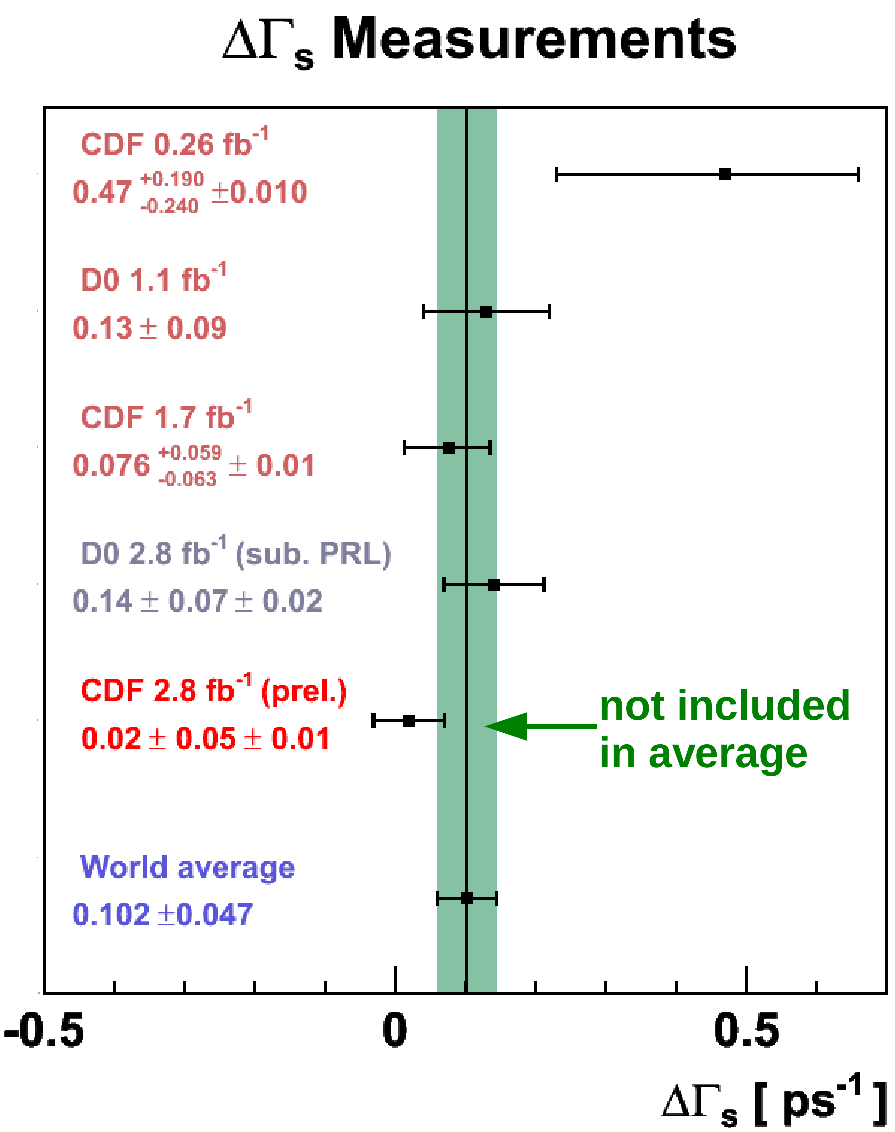


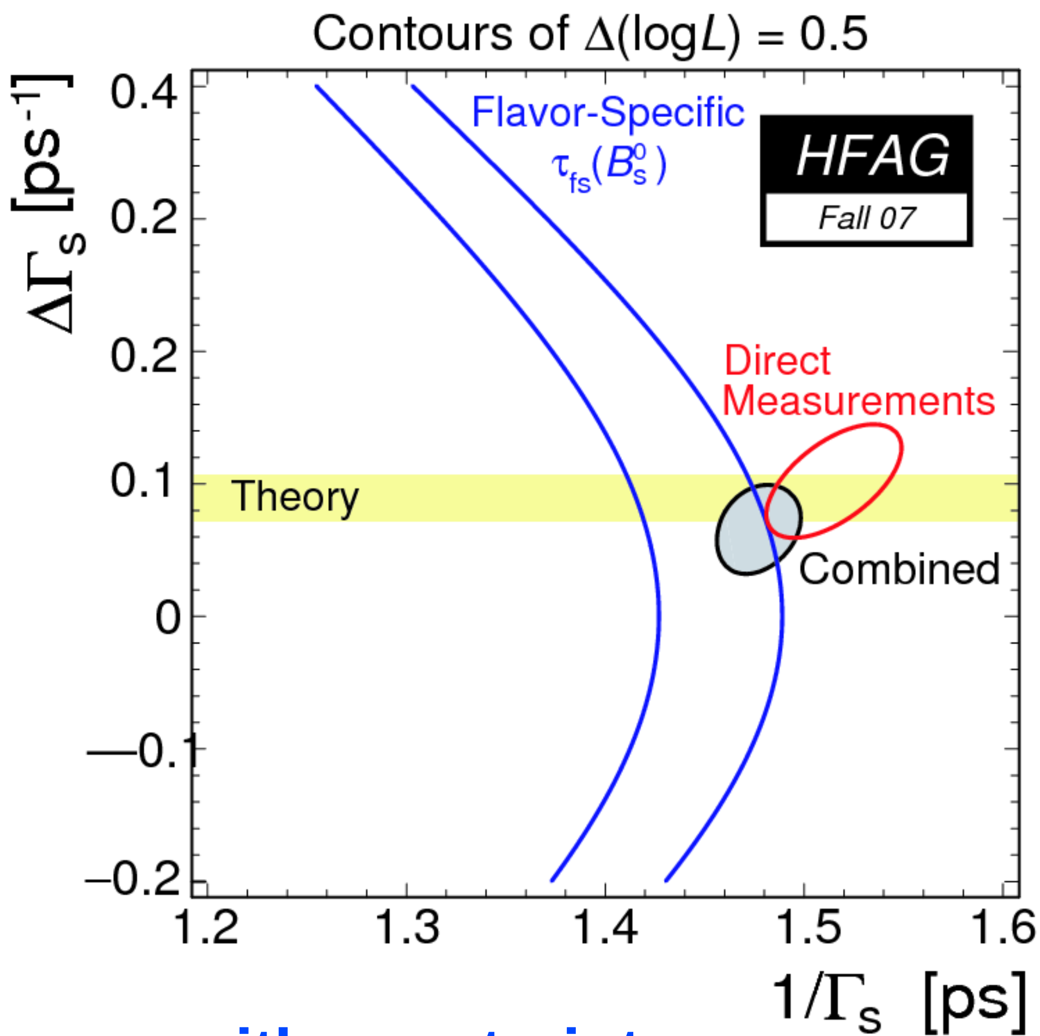


$\tau_s = 1/\Gamma_s = (1.53 \pm 0.06 \pm 0.01)$ ps
$\Delta\Gamma_s = (0.14 \pm 0.07 \pm 0.02)$ ps^{-1}

$\tau_s = 1/\Gamma_s = (1.53 \pm 0.04 \pm 0.01)$ ps
$\Delta\Gamma_s = (0.02 \pm 0.05 \pm 0.01)$ ps^{-1}

$\Delta\Gamma_s$ Summary





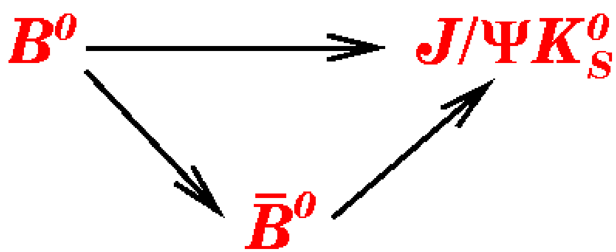
with constraints:

$$\Delta\Gamma_s = (0.067\ ^{+0.031}_{-0.036})\ \text{ps}^{-1}$$

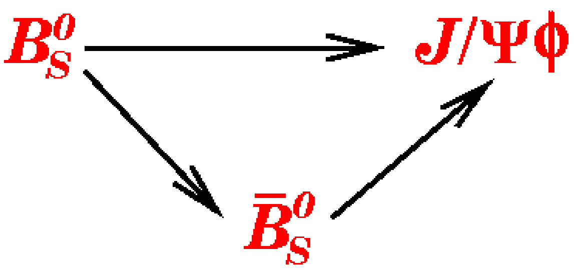
$B_s^0 \to J/\psi\ \phi$ Analysis

- With flavor tagging measure time dep. *CP* asym. => determ. β_s

  Analogy to measurement of CKM angle β in $B^0 \to J/\psi K_S^0$

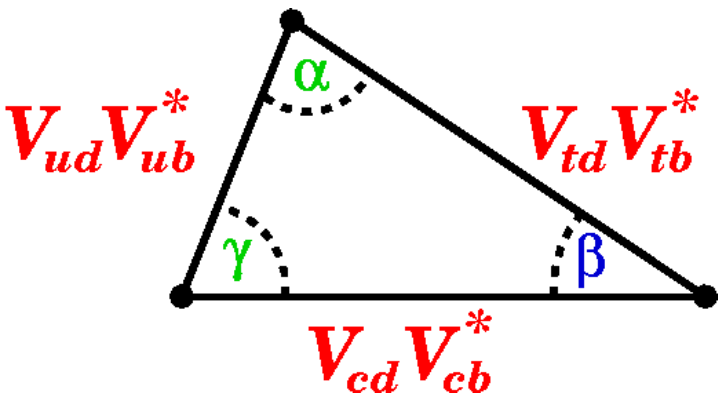


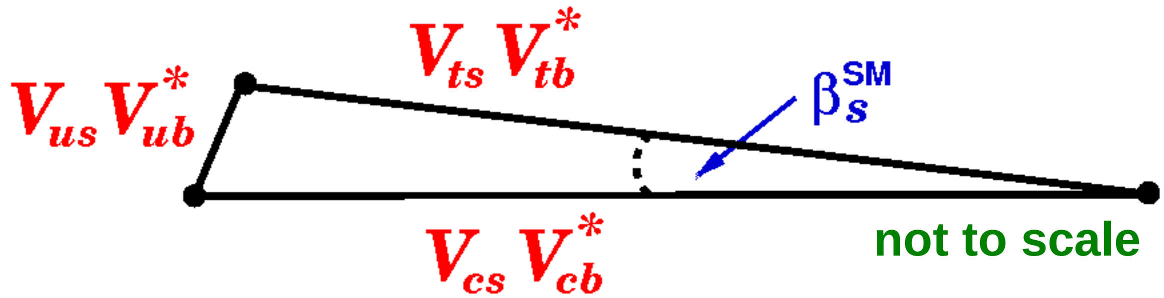
=> sin 2β



=> sin $2\beta_s^{SM}$

$$\beta_s^{\rm SM} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right)$$





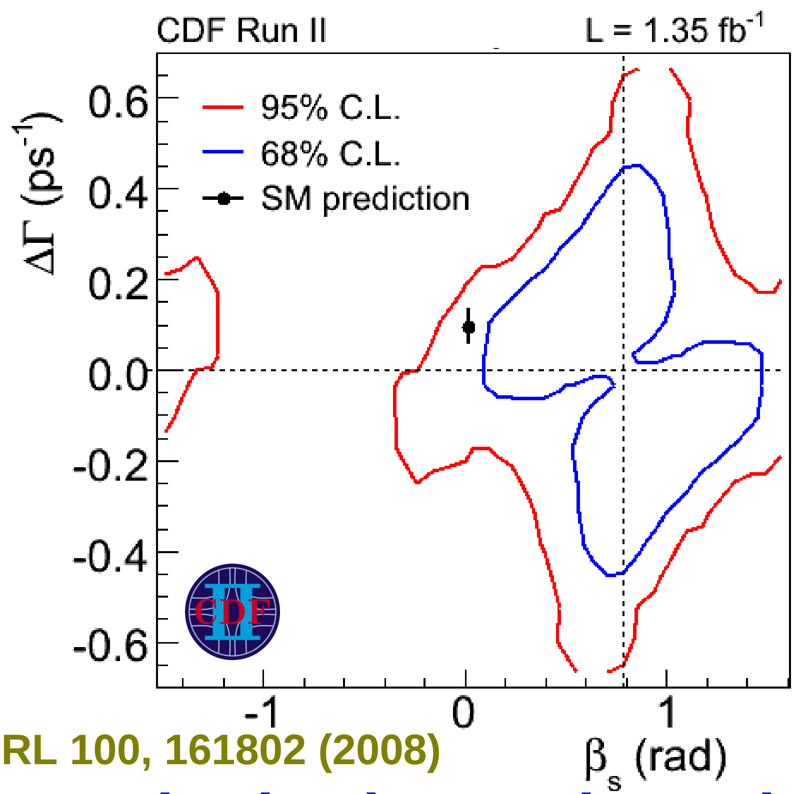
Expect β_s to be small in SM ($|\beta_s^{SM}| \approx 0.02$) - beyond current reach

=> Current interest: Search for enhanced CP violation through new physics: $2\beta_s^{J/\psi\phi} = 2\beta_s^{\rm SM} - \phi_s^{\rm NP}$

CP Violation in $B_s^0 \rightarrow J/\psi\ \phi$

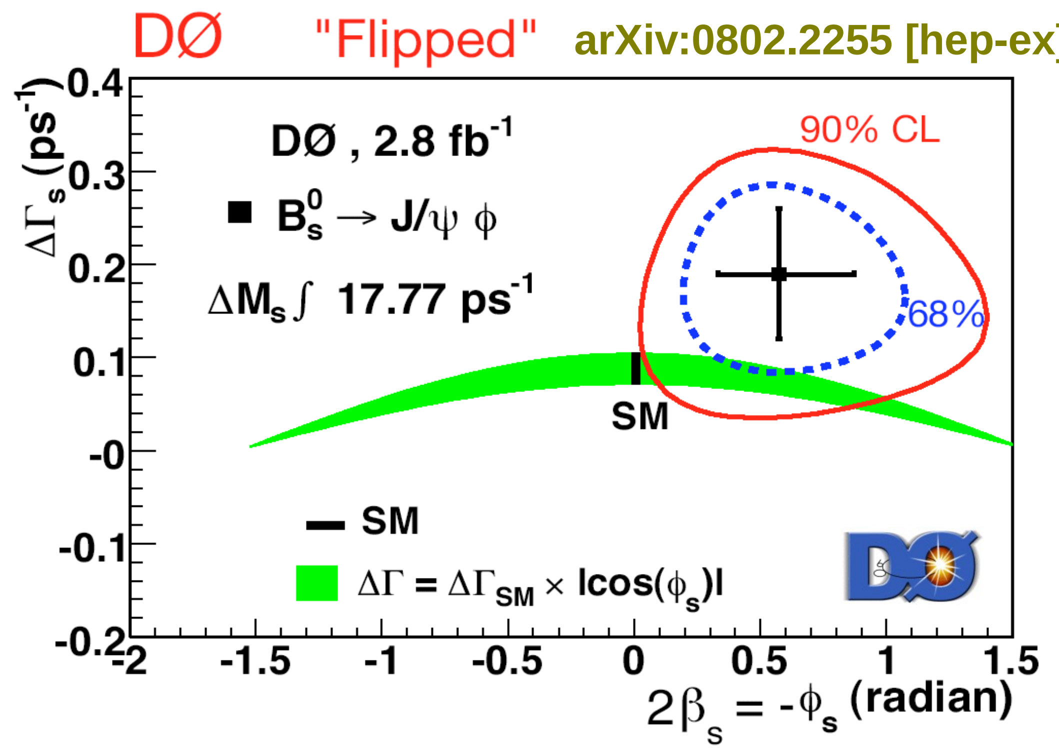
Winter Conferences 2008:

- **First results from CDF (1.35 fb^{-1}) & D0 (2.8 fb^{-1}) presented**
- **Expressed as confidence regions in β_s-$\Delta\Gamma_s$ plane**



PRL 100, 161802 (2008)

p-value(SM): <u>0.15 (~1.5σ)</u>



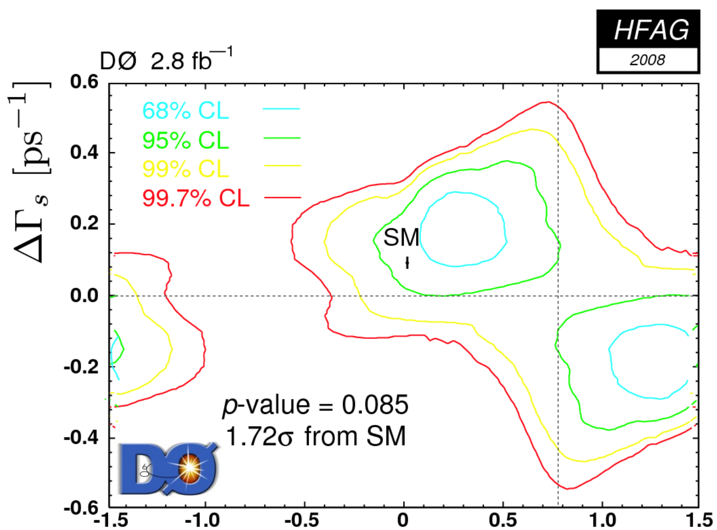
Use external constraints on strong phases

p-value(SM): <u>0.066 (~1.8σ)</u>

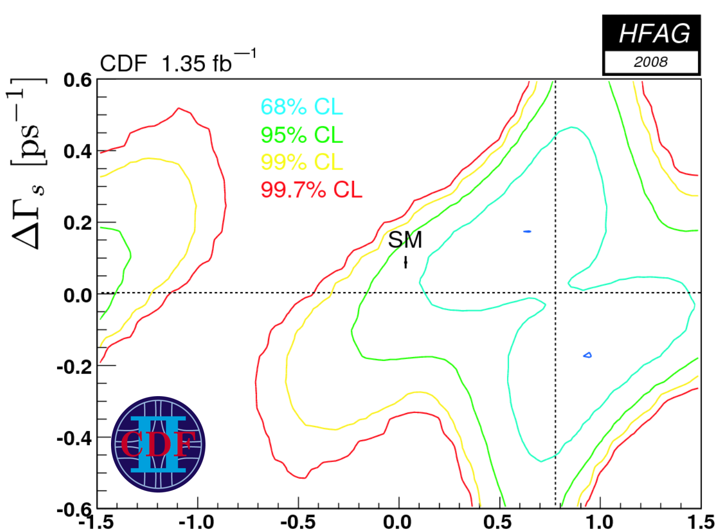
Mild inconsistency with SM (but in same direction)

CP Violation in $B_s^0 \to J/\psi\ \phi$

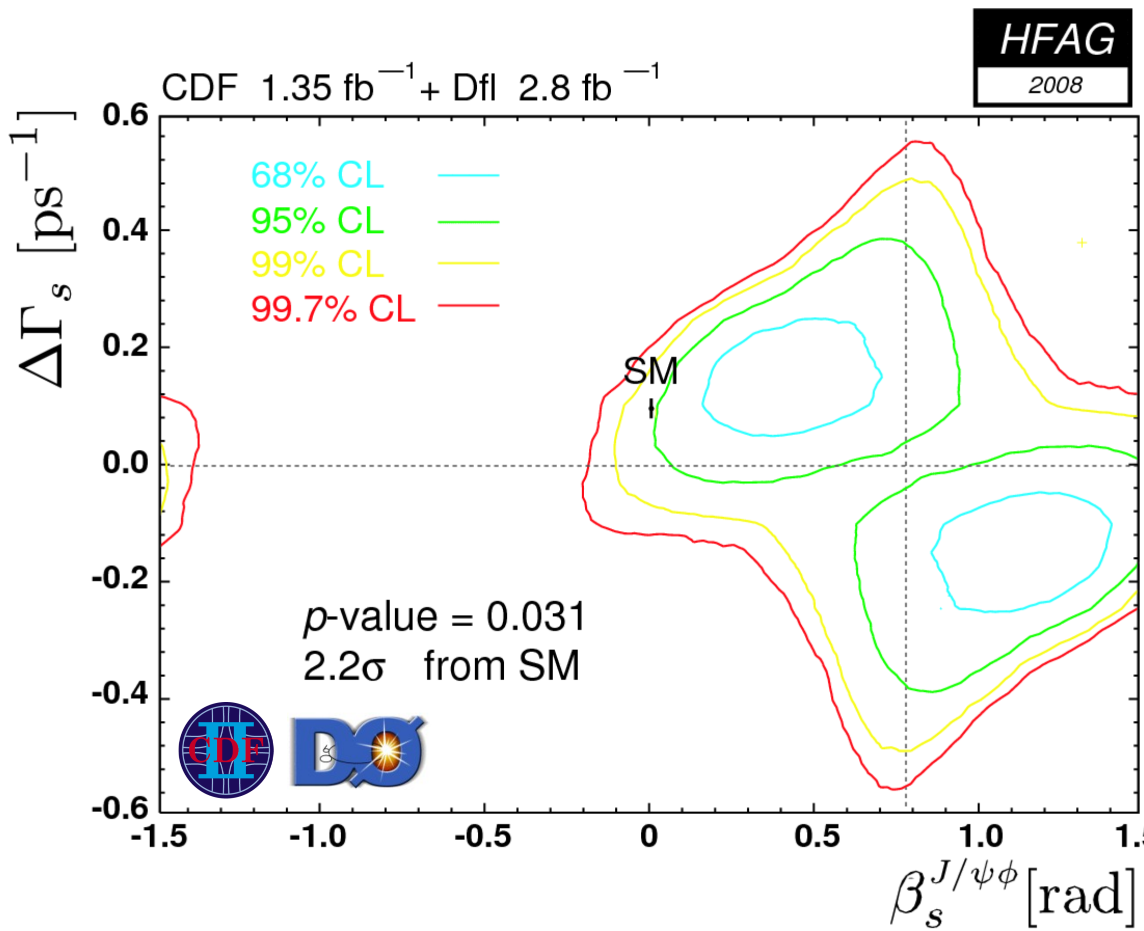
New: D0 released data with no constraint for average with CDF



arXiv:0802.2255 [hep-ex]



PRL 100, 161802 (2008)



β_s in [0.14,0.73] or [0.83,1.42] at 90% CL

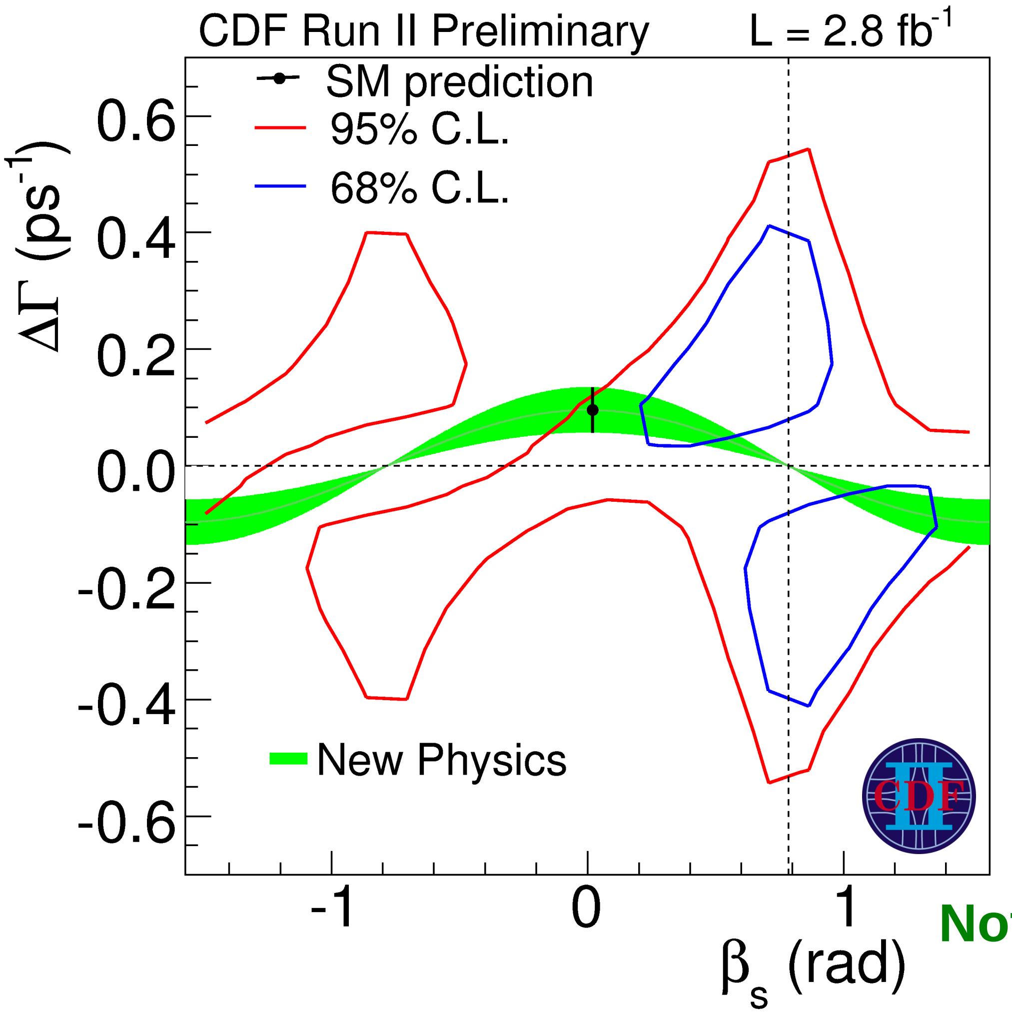
Combined p-value(SM): 0.031 (~2.2σ)

CP Violation in B_s^0 -> $J/\psi\ \phi$

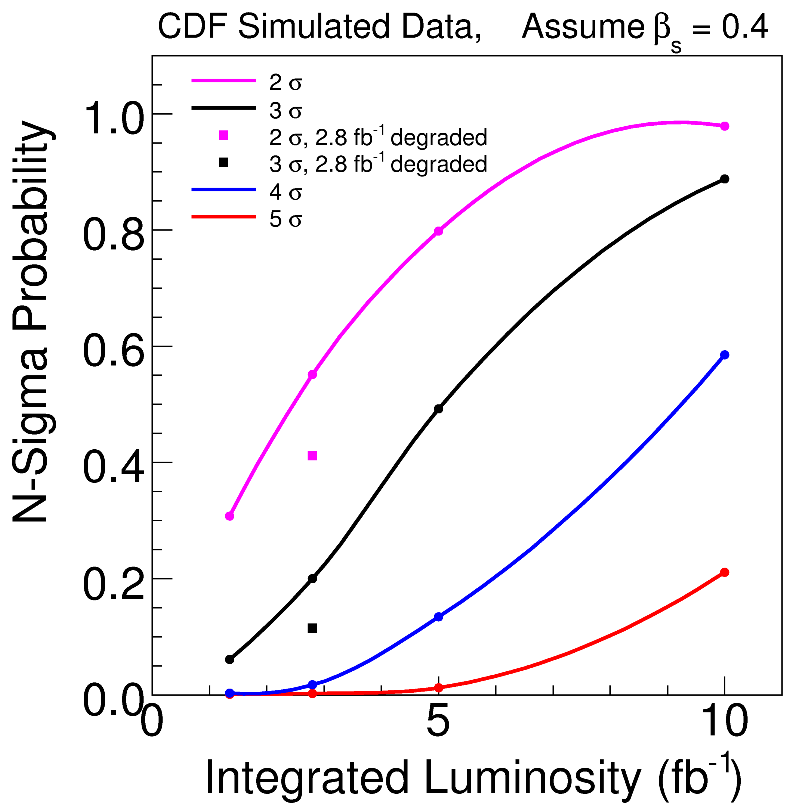
New: **CDF released update with 2.8 fb^{-1}**

New data confirm trend of published result

- β_s in [0.28, 1.29] at 68% CL
- p-value(SM): 0.07 (~1.8σ)



Expect more to come !



Note: Suboptimal analysis without use of PID (reduce data sample)

B_c^+

B_c Meson

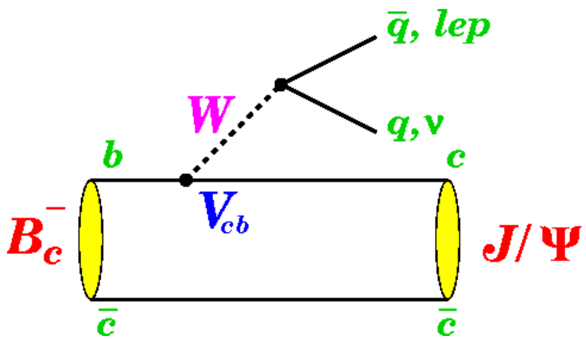
$$B_c^- = |b\,\bar{c}\rangle$$

- Weakly decaying particle which contains 2 heavy quarks
- Both quarks contribute to decay width

- via b quark:

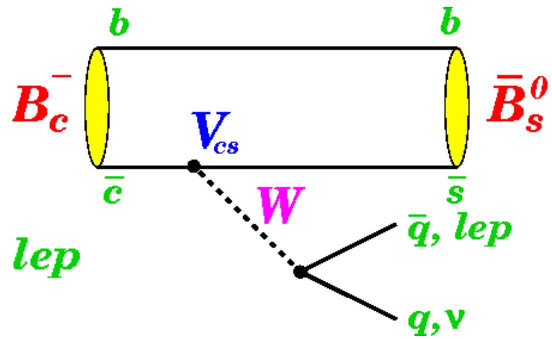
discovery mode

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



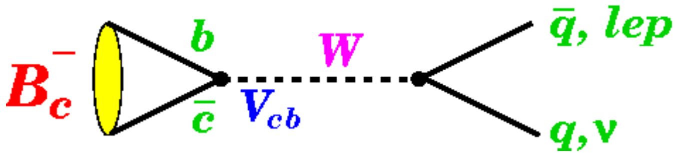
- via c quark:

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



- via annihilation:

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



- Theory predicts lifetime of ~0.5 ps

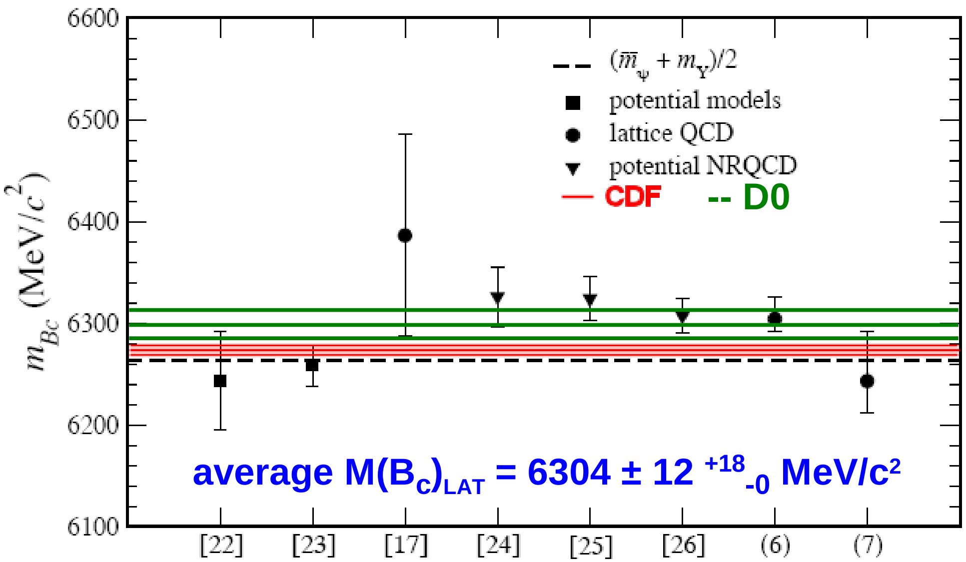
B_c Mass

- **Use fully reconstructed**
  $B_c^- \rightarrow J/\psi(\rightarrow \mu^+\mu^-)\ \pi^-$
  for precise mass measurement
- **2008 world average B_c mass:**

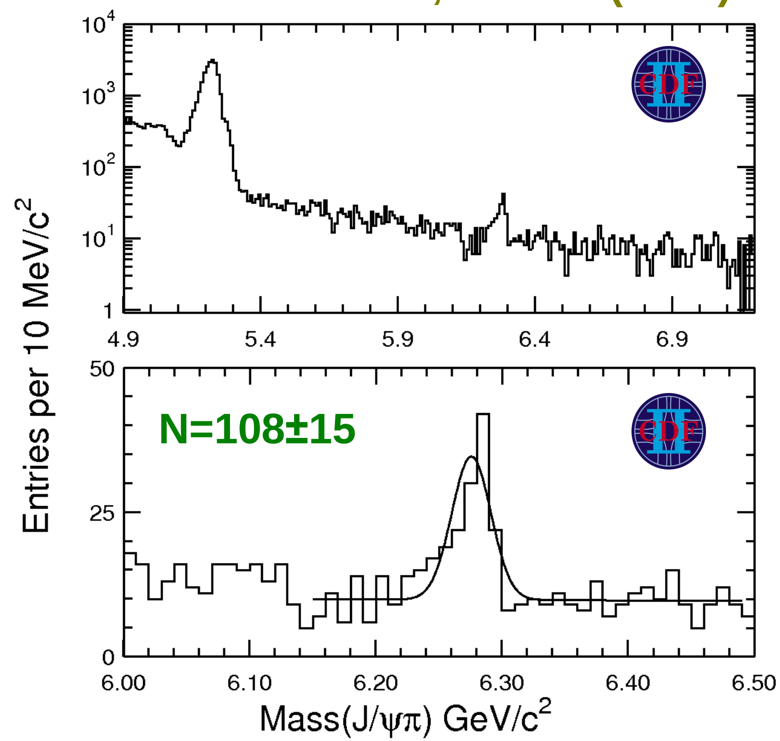
  $m(B_c) = (6276 \pm 4)\ \text{MeV}/c^2$

- **Comparison to predictions:**

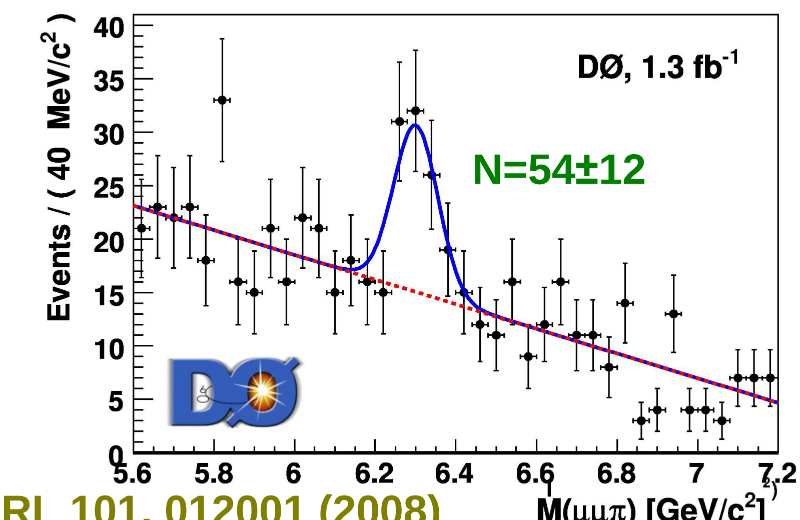
Experimental measurements with small uncertainties start to challenge theoretical models and lattice techniques



PRL 100, 182002 (2008)



$m(B_c) = (6275.6 \pm 2.9 \pm 2.5)\ \text{MeV}/c^2$



PRL 101, 012001 (2008)

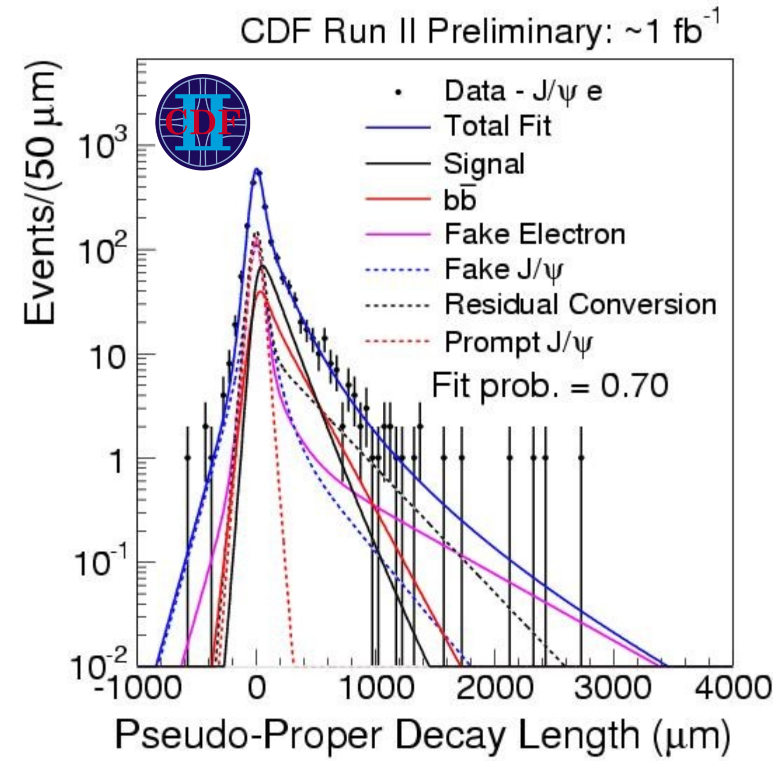
$m(B_c) = (6300 \pm 14 \pm 5)\ \text{MeV}/c^2$

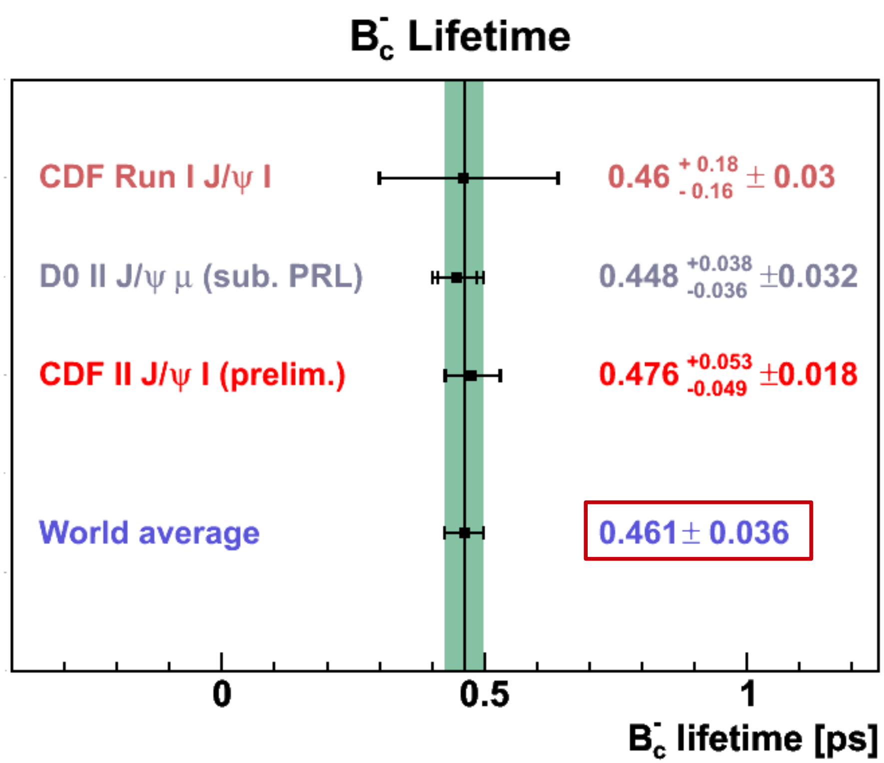
B_c Lifetime

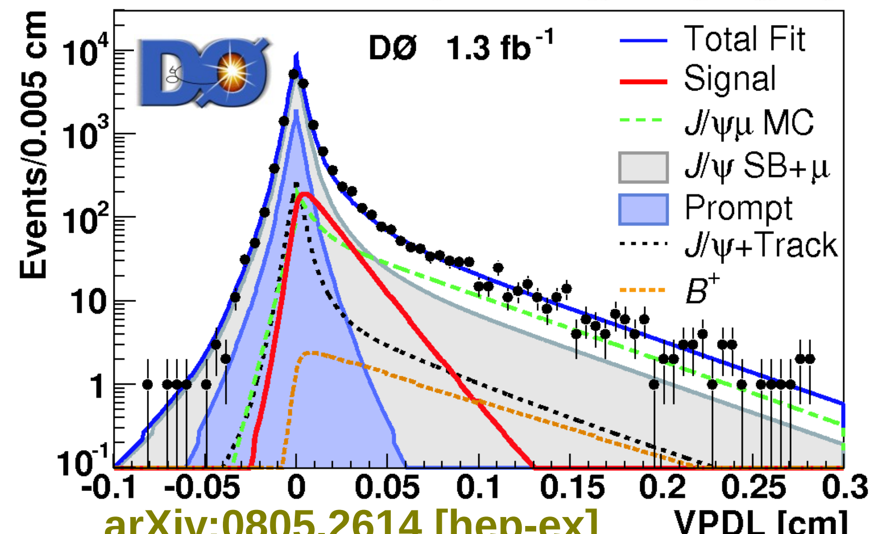
- **CDF/D0 use semilept. $B_c^{\pm} \to J/\psi \ell^{\pm} \nu X$**
- **Main issue: control backgrounds**
- **CDF: e + mu combined:**

  $\tau(B_c) = (0.476\ ^{+0.053}_{-0.049} \pm 0.018)$ ps
- **D0: mu only:**

  $\tau(B_c) = (0.448\ ^{+0.038}_{-0.036} \pm 0.032)$ ps







arXiv:0805.2614 [hep-ex]

Theory predictions: 0.47 - 0.59 ps
(waiting for lifetime from fully rec. B_c)

B Baryons

- Λ_b
- Σ_b
- Ξ_b

Λ_b Lifetime

Λ_b Lifetime in 2006:

- **World average:**

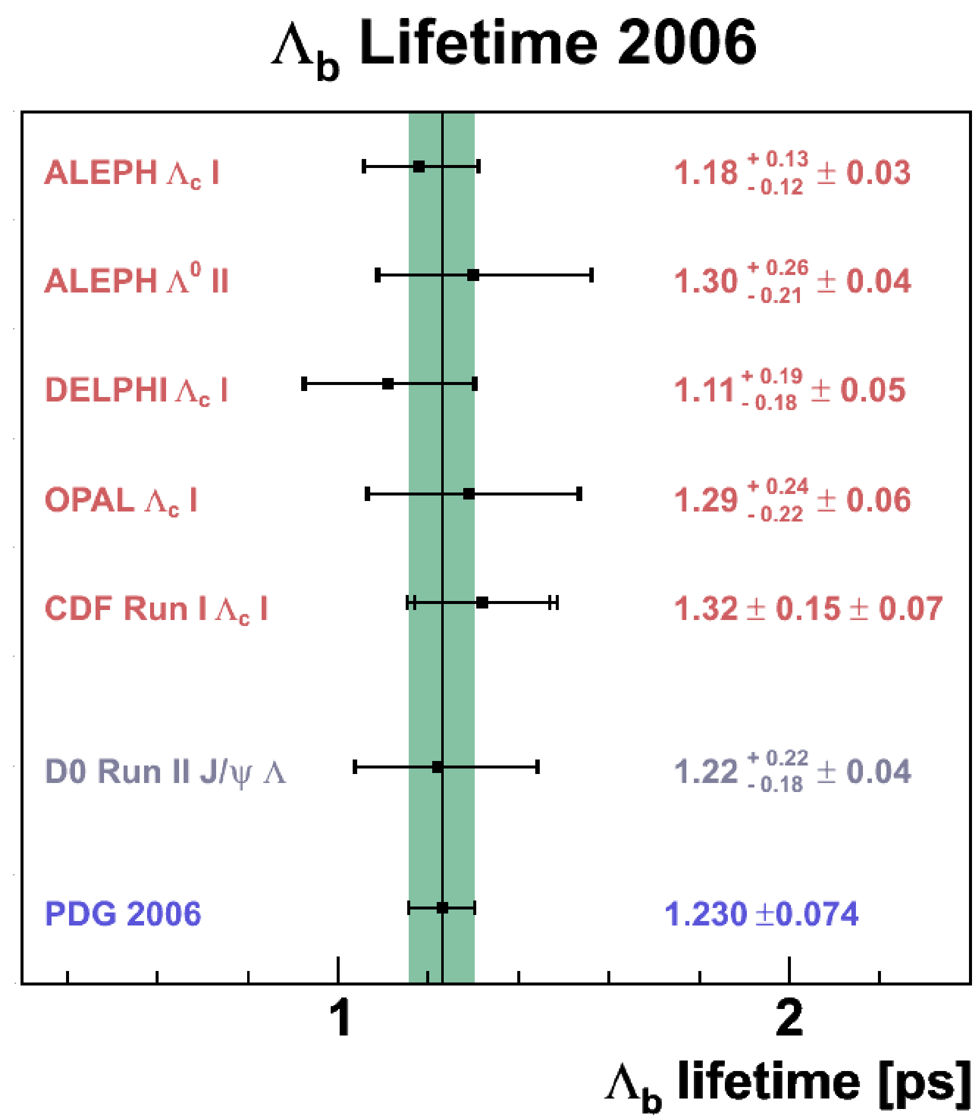
  $\tau(\Lambda_b)$ = (1.230 ± 0.074) ps

  $\tau(\Lambda_b)$ / $\tau(B^0)$ = (0.804 ± 0.049)

- **Theory prediction:**

  $\tau(\Lambda_b)$ / $\tau(B^0)$ = [(0.88± 0.05) , 0.94]

- Long-standing puzzle of Λ_b lifetime being smaller than prediction



Λ_b Lifetime in 2007

Fully reconst. $\Lambda_b \to J/\psi\ \Lambda$

$\tau(\Lambda_b) = (1.218\ ^{+0.130}_{-0.115} \pm 0.042)$ ps

$\tau(\Lambda_b) / \tau(B^0) = (0.811\ ^{+0.096}_{-0.087} \pm 0.034)$

Semileptonic mode $\Lambda_b \to \Lambda_c \mu\nu X$

$\tau(\Lambda_b) = (1.290^{+0.119}_{-0.111}\ ^{+0.087}_{-0.091})$ ps

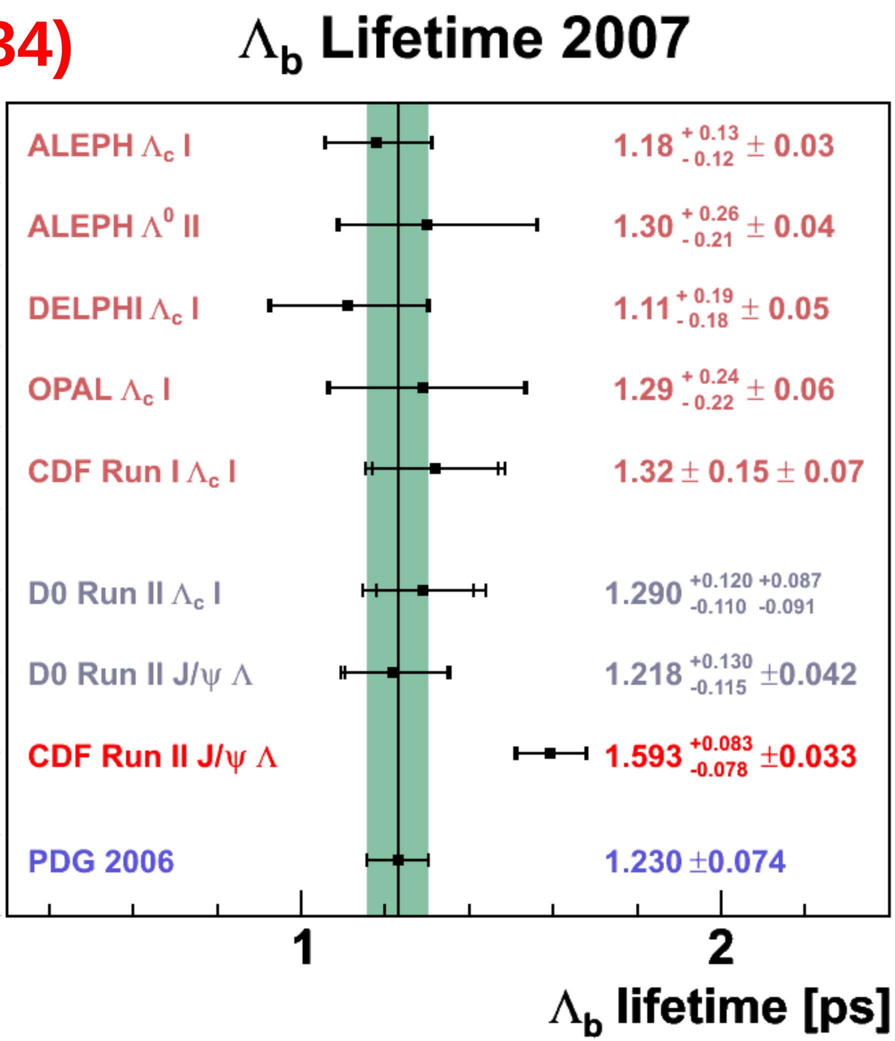
Results in agreement with PDG'06

Also fully rec. $\Lambda_b \to J/\psi\ \Lambda$

$\tau(\Lambda_b) = (1.580 \pm 0.077 \pm 0.012)$ ps

$\tau(\Lambda_b) / \tau(B^0) = (1.018 \pm 0.062 \pm 0.007)$

$\tau(B^0) = (1.551 \pm 0.019 \pm 0.011)$ ps



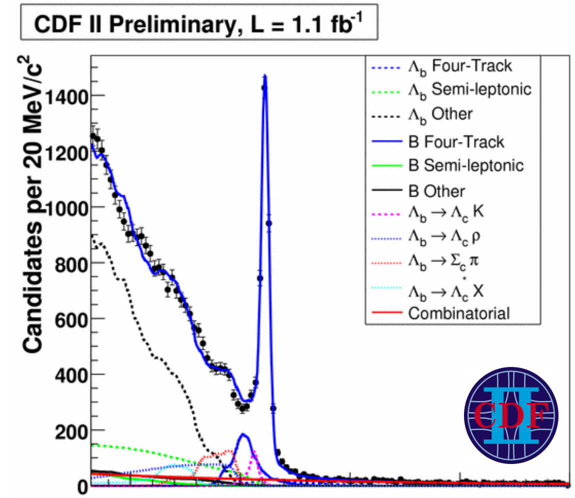
BIG Surprise: ~3σ above PDG'06

But: $\tau(B^0)$ comes out ok

Λ_b Lifetime in 2008

<u>CDF:</u> New precision measurement of Λ_b lifetime in hadronic mode $\Lambda_b \to \Lambda_c \pi$

~2900 fully rec. $\Lambda_b \to \Lambda_c \pi$ signal events

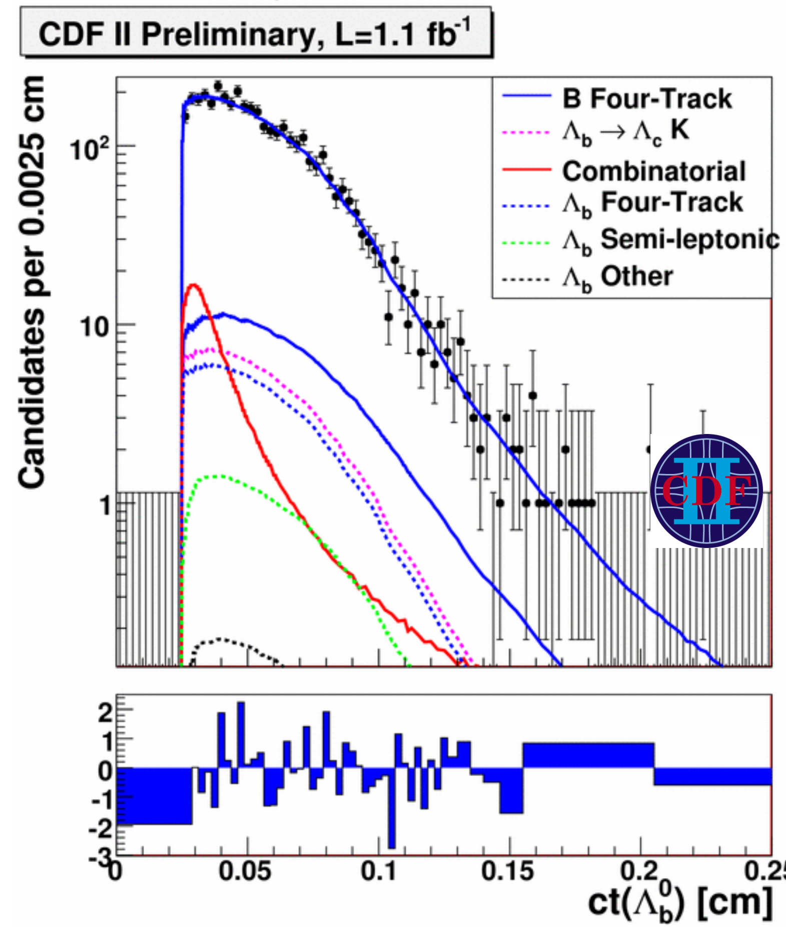


$\tau(\Lambda_b) = (1.410 \pm 0.046 \pm 0.029)$ ps

$\tau(\Lambda_b) / \tau(B^0) = (0.922 \pm 0.039)$

($\tau(B^0)$ from PDG'07)

- <u>World best measurement</u>
  => as precise as current world average

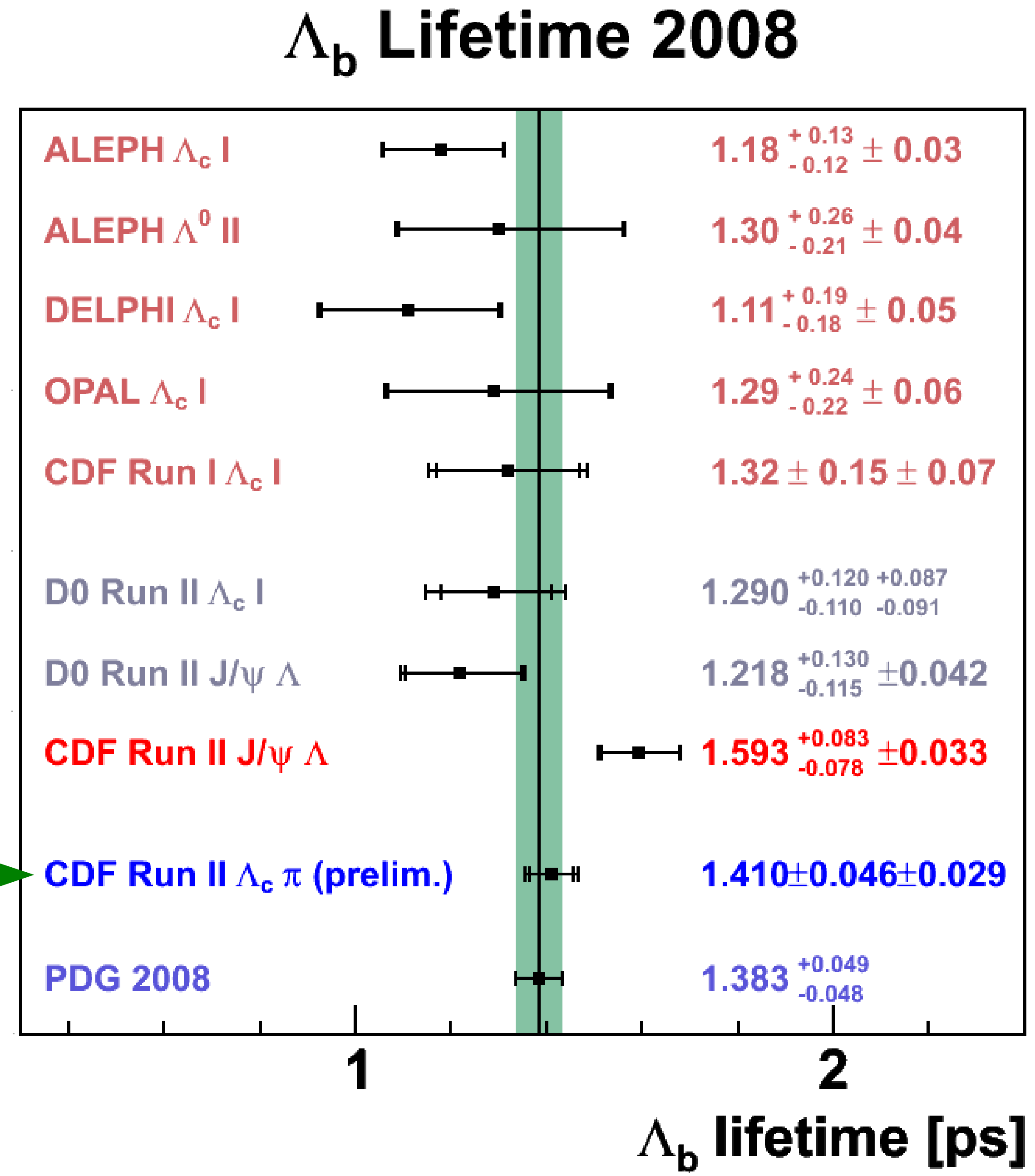


Λ_b Lifetime in 2008

- New CDF result in good agreement with world average and theory prediction

- Longstanding puzzle resolved ?

not included in average



Σ_b Baryon

Motivation:

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

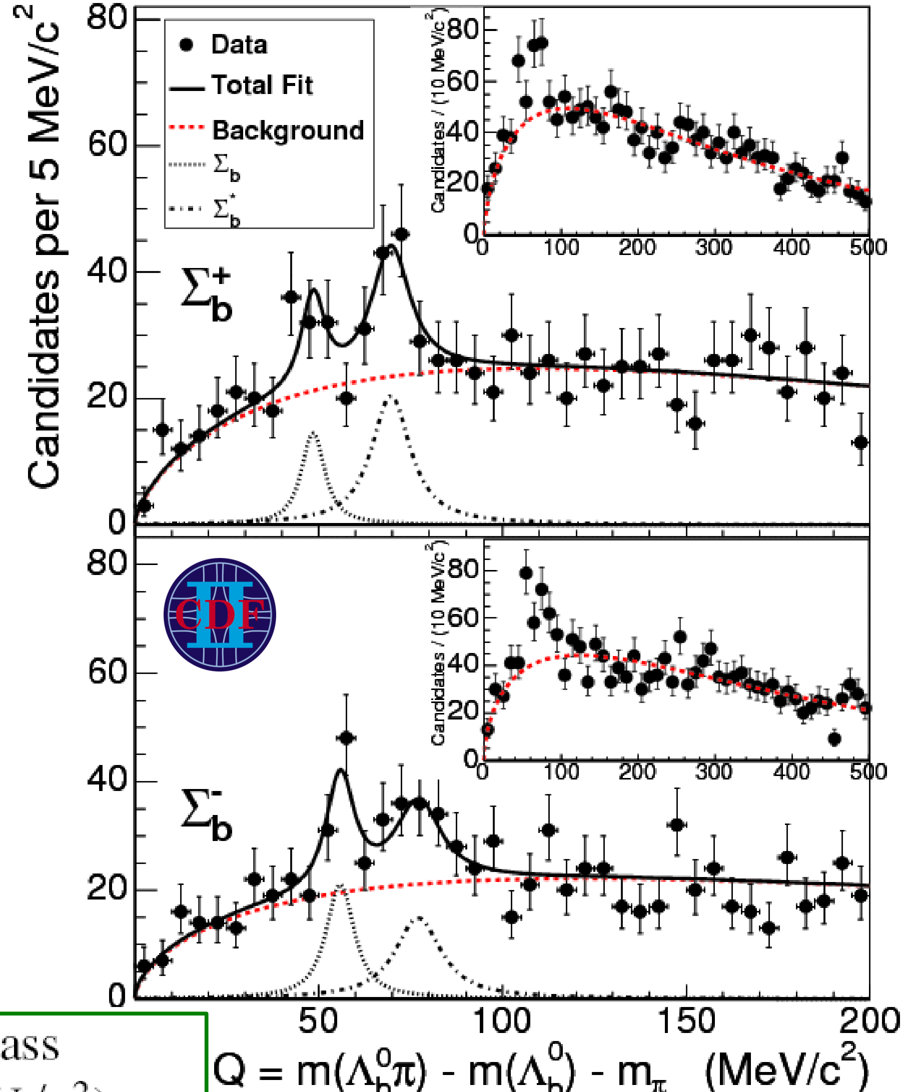
=> Search for

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

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

Use large sample of Λ_b: ~3000

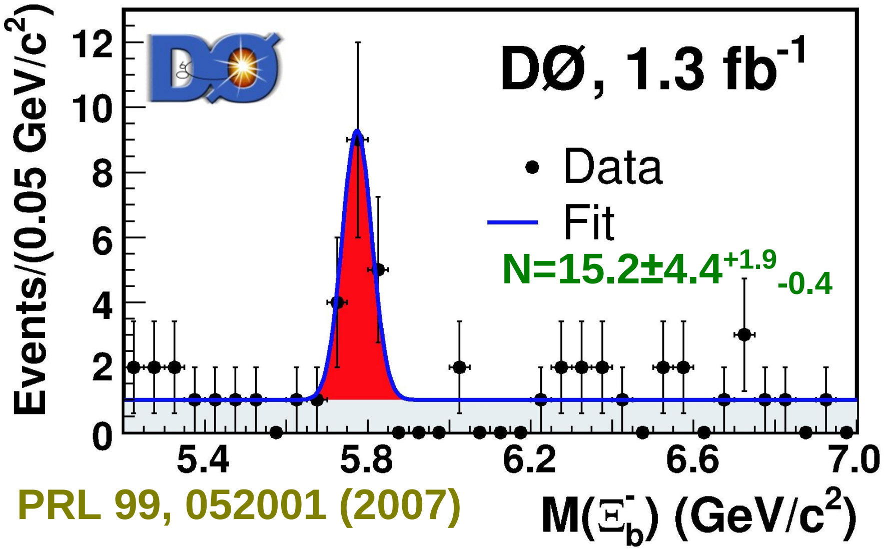
Observe peaks with >5σ w.r.t. no signal



PRL 99, 202001 (2007)

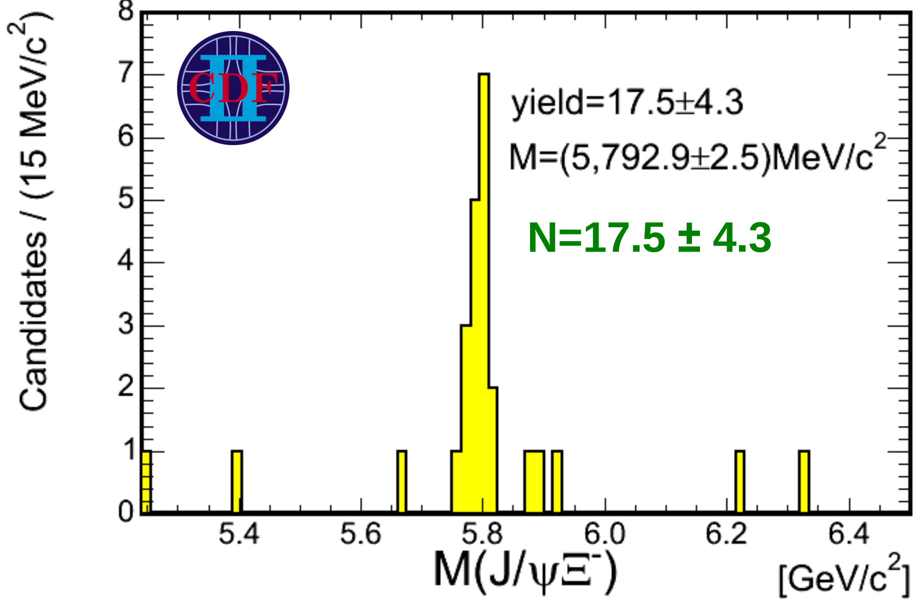
State	Yield	Q or $\Delta_{\Sigma_b^*}$ (MeV/c^2)	Mass (MeV/c^2)
Σ_b^+	32^{+13+5}_{-12-3}	$Q_{\Sigma_b^+} = 48.5^{+2.0+0.2}_{-2.2-0.3}$	$5807.8^{+2.0}_{-2.2} \pm 1.7$
Σ_b^-	59^{+15+9}_{-14-4}	$Q_{\Sigma_b^-} = 55.9 \pm 1.0 \pm 0.2$	$5815.2 \pm 1.0 \pm 1.7$
Σ_b^{*+}	77^{+17+10}_{-16-6}	$\Delta_{\Sigma_b^*} = 21.2^{+2.0+0.4}_{-1.9-0.3}$	$5829.0^{+1.6+1.7}_{-1.8-1.8}$
Σ_b^{*-}	69^{+18+16}_{-17-5}		$5836.4 \pm 2.0^{+1.8}_{-1.7}$

Ξ_b Baryon



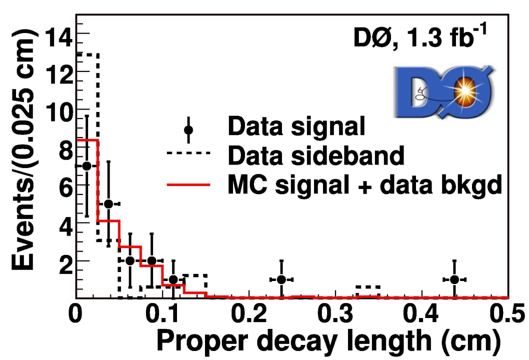
PRL 99, 052001 (2007)

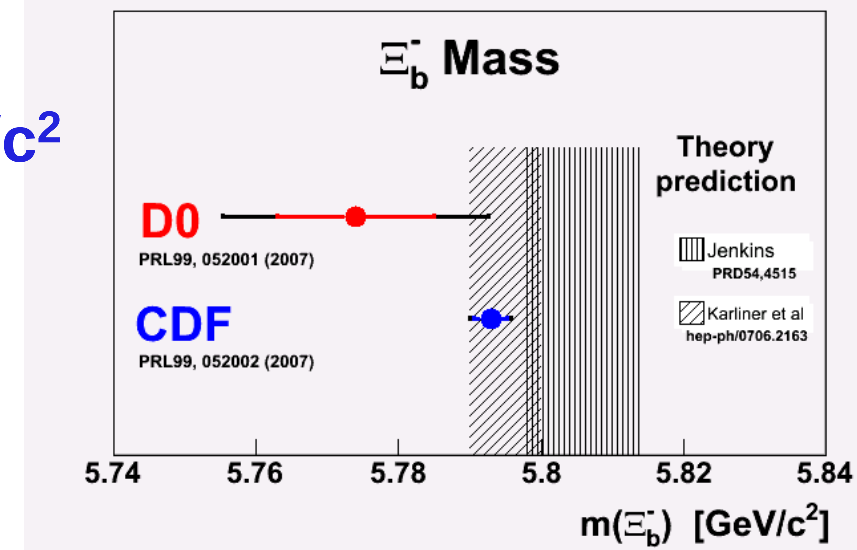
PRL 99, 052002 (2007)



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**
- **World avg: M(Ξ_b) = 5792.4 ± 3.0 MeV/c^2**
- **D0: Lifetime consistent with expectations**





Conclusions

- Tevatron offers rich heavy flavour program
- Many new result on properties of heavy B hadrons:
  - Lifetimes and $\Delta\Gamma$ in B_s^0 decays
  - CP violation in $B_s^0 \to J/\psi\ \phi$ remains interesting
  - Puzzle with Λ_b lifetime resolved?
  - Heavy baryons Σ_b, Ξ_b established
  - Next discoveries: Ω_b, Ξ_{bc}, β_s large, ... ???
- Tevatron will accumulate more data until the end of Run II
- Expect many more results from LHC