B Hadron Spectroscopy and Lifetimes from Tevatron

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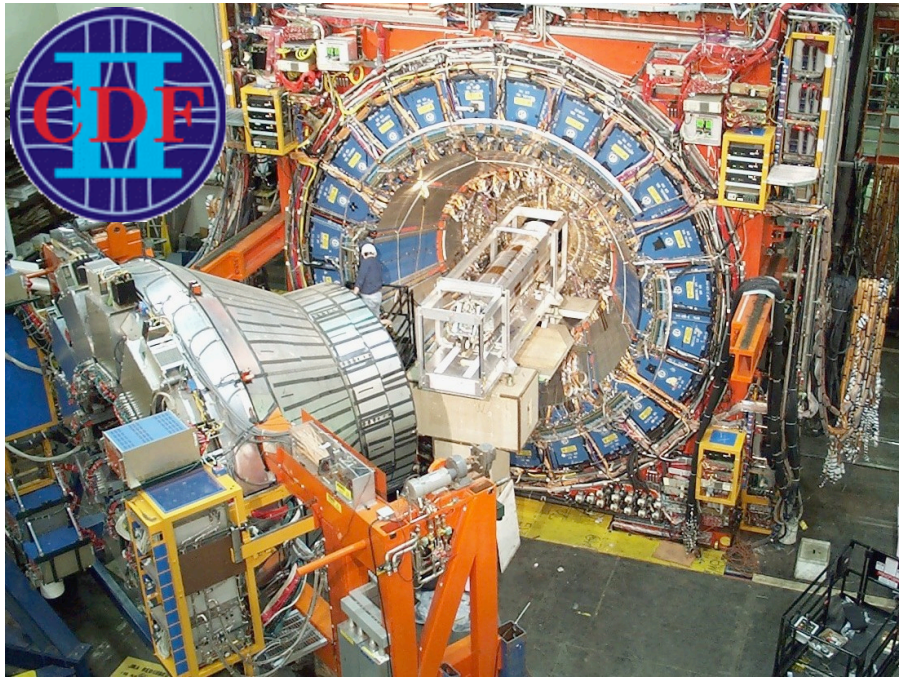
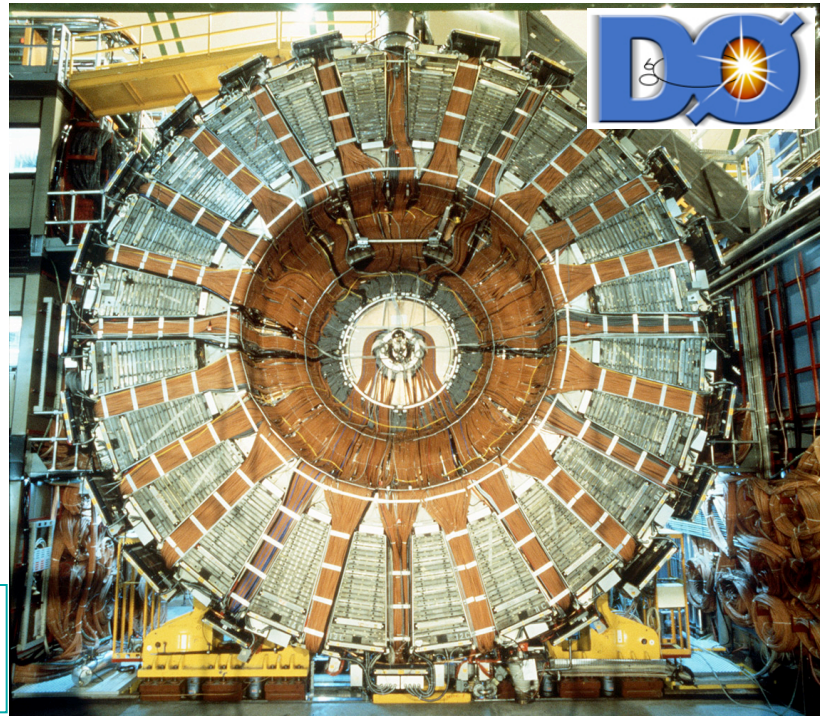
CDF and DØ Detectors in Run 2



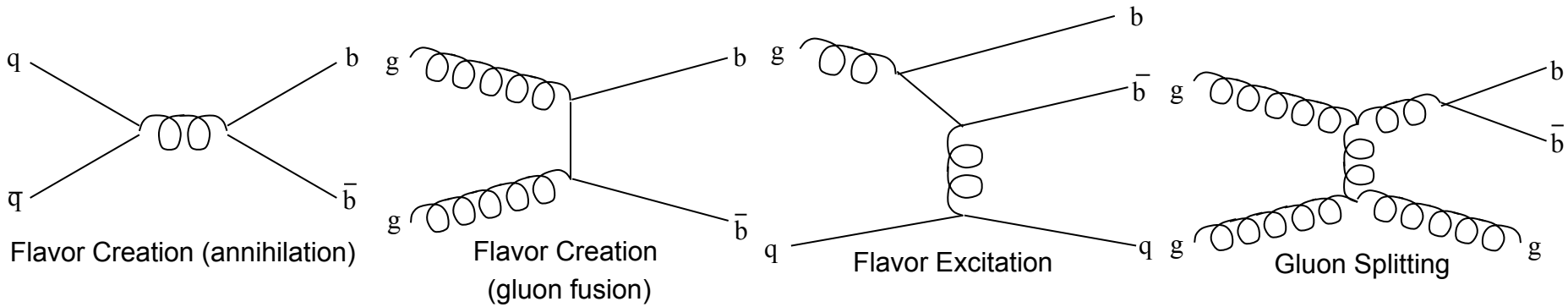
- L2 trigger on displaced vertices
- Excellent tracking resolution
- Good low momentum PID

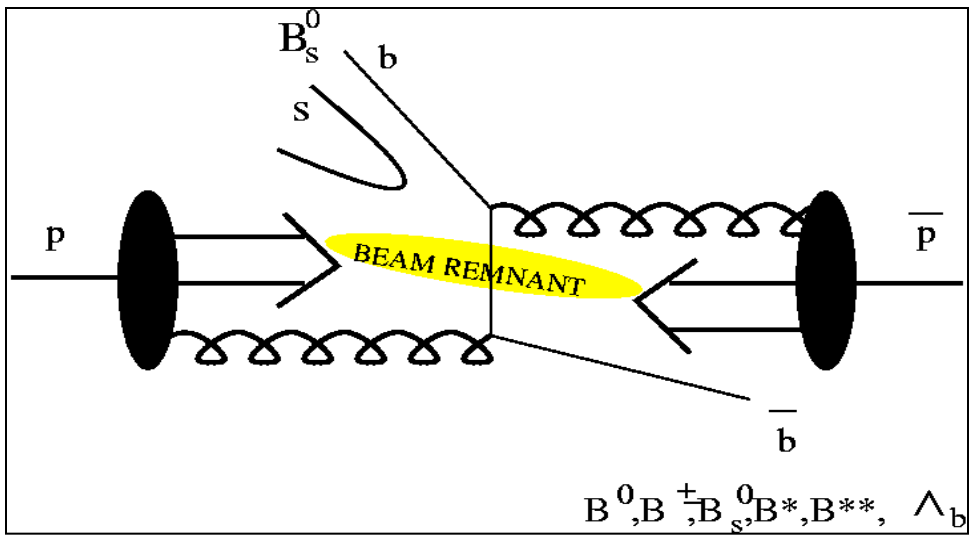
- Both detectors
  - Silicon microvertex tracker
  - Solenoid
  - High rate trigger/DAQ
  - Calorimeters and muons



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

B Production at Tevatron





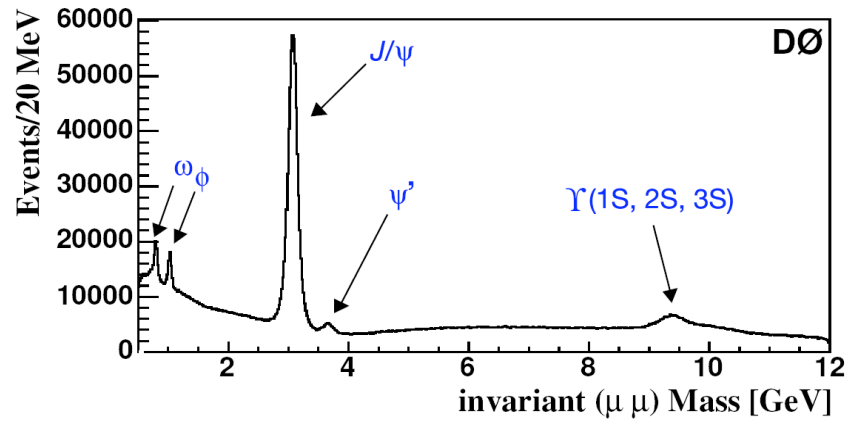
- Tevatron is a source of all B-hadron species, B_d, B_u, B_c, B_s and Λ_b
- $\sigma_b = 29.4 \pm 0.6 \pm 6.2\ \mu b$ ($|\eta| < 1$) (CDF)
- Huge cross-sections compared to the the B-factories but proportionally large backgrounds as well

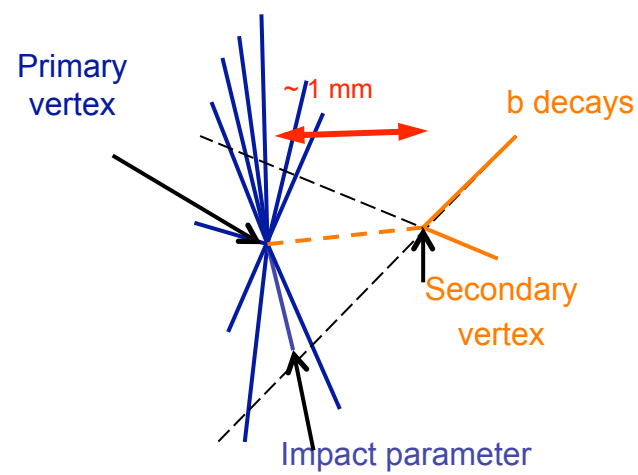
Since $\sigma(bb) << \sigma(pp)$ $\Rightarrow$ Events have to be selected with specific triggers

Trigger requirements: large bandwidth, background suppression, deadtimeless

Triggers for B Physics

- Single-/Di-lepton (CDF/DØ)
  A high p_T lepton or two leptons with lower p_T
  - J/Ψ modes, masses, lifetimes, x-section
  - Yields higher than Run I (low Pt threshold, increased acceptance)
- lepton + displaced track - semileptonic sample (CDF)
  - $p_T(e/\mu) > 4$ GeV/c, 120 μm < d0(Trk) < 1mm, $p_T(Trk) > 2$ GeV/c
  - Semileptonic decays, lifetimes, flavor tagging
  - B Yields 3x Run I
- Two displaced vertex tracks - hadronic sample (CDF)
  - $p_T(Trk) > 2$ GeV/c, 120 μm < d0(Trk) < 1mm, $\Sigma p_T > 5.5$ GeV/c
  - X-section, branching ratios, B_s mixing…



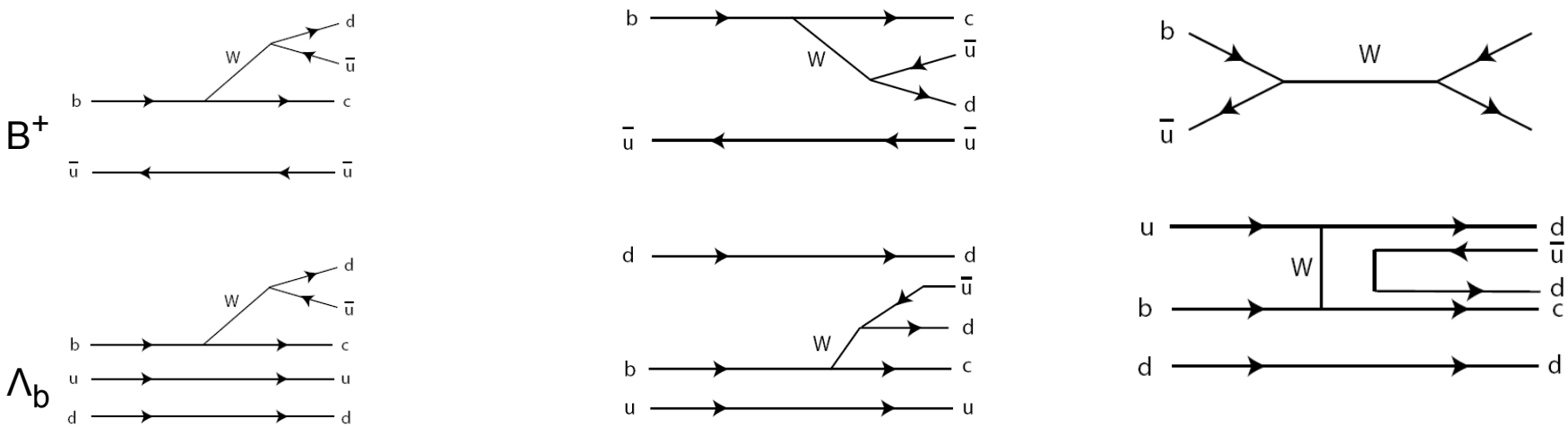


Interests in B Hadron Lifetimes

Heavy Quark Expansion

$$\Gamma = \frac{G_F^2 m_b^5}{192\pi^3}|V_{cb}|^2 \cdot \left[A_0 + A_2\left(\frac{\Lambda_{QCD}}{m_b}\right)^2 + A_3\left(\frac{\Lambda_{QCD}}{m_b}\right)^3\right]$$

I. Bigi et. al, Ann. Rev. Nucl. Part. Sci. 47 (1997) 591.



Spectator model: b hadron lifetimes are equal.

Pauli Interference: prolongs lifetimes, +5% for B^+, +3% for Λ_b

Weak Annihilation and Exchange: reduce lifetimes -7% Λ_b

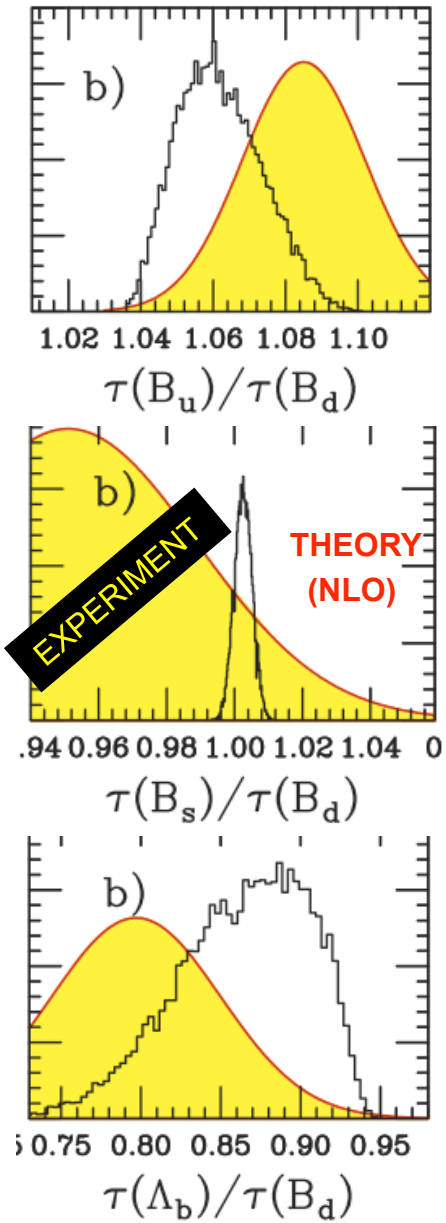
$$\tau(B^+) \gtrsim \tau(B^0) \approx \tau(B_s^0) > \tau(\Lambda_b) \gg \tau(B_c)$$

Interests in B Hadron Lifetimes *Continued…*

- The B^+,B^0 lifetimes are precisely measured at B-factories.
- Experimental error on $\tau(B_s^0)/\tau(B^0)$ far higher than theory error!
- World average of $\tau(\Lambda_b)/\tau(B^0)$ too low compared to $O(1/m_b^3)$ HQE prediction. CDF 2006 measurement was precise but too high!
- Lifetime ratio world averages:

	PDG 2008	Theory $O(1/m_b^4)$ [2004]
$\tau(B^+)/\tau(B^0)$ =	1.071 +- 0.009	1.06 ± 0.02
$\tau(B_s^0)/\tau(B^0)$ =	0.939 +- 0.021	1.00 ± 0.01
$\tau(\Lambda_b)/\tau(B^0)$ =	0.904 +- 0.032	0.86 ± 0.05

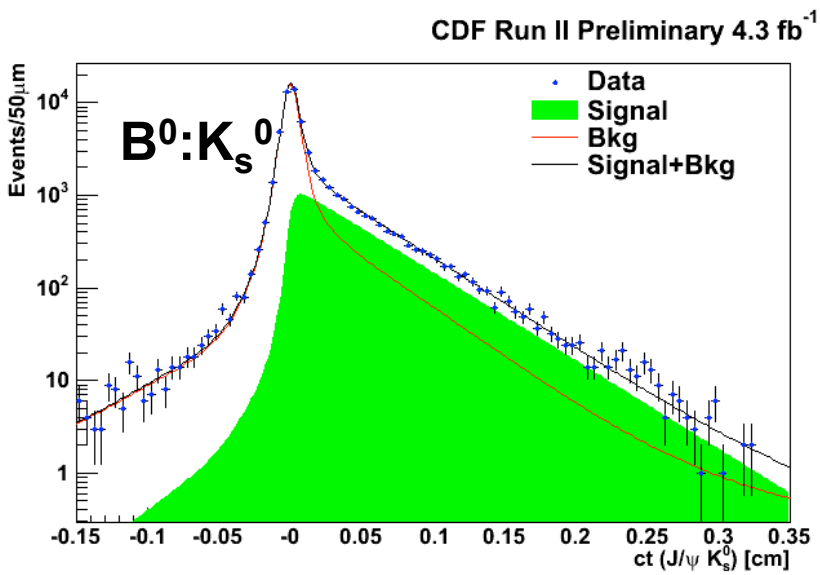
Gabbiani et al., PRD70 094031

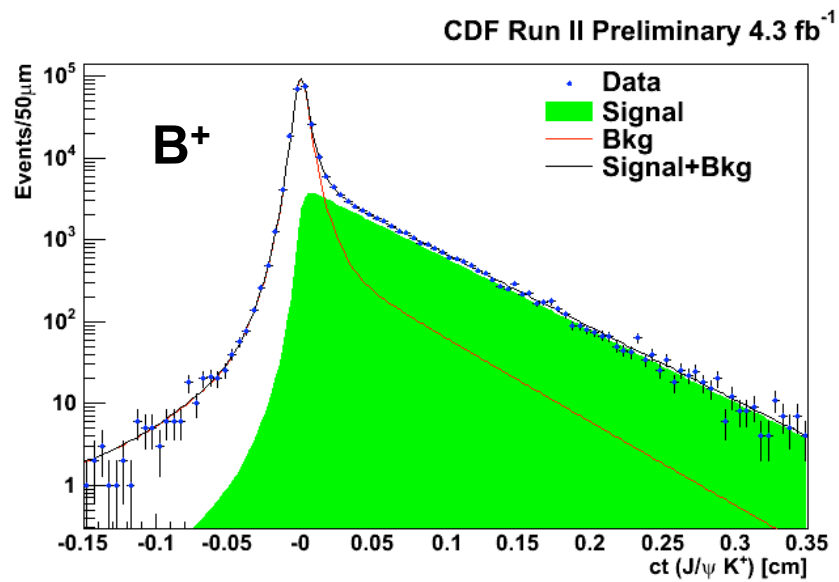


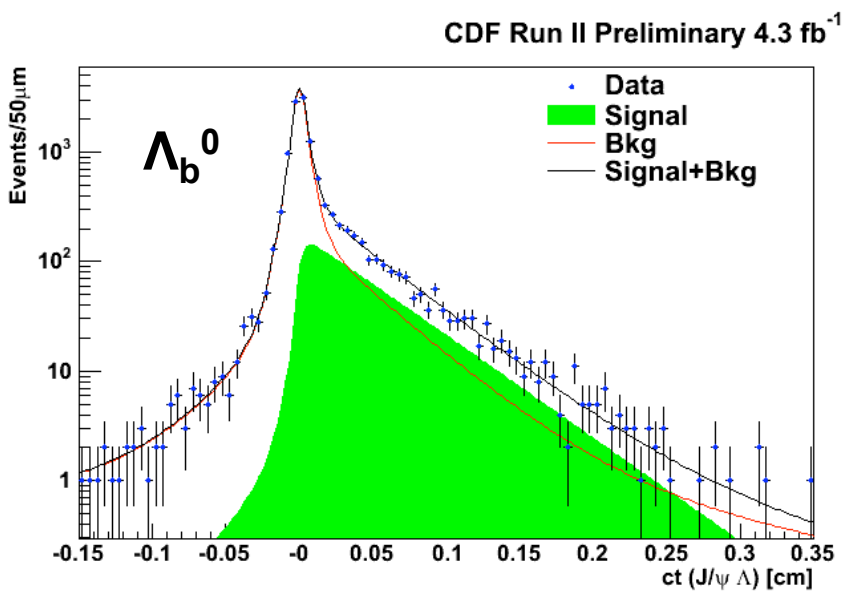
Lifetime Measurements at CDF

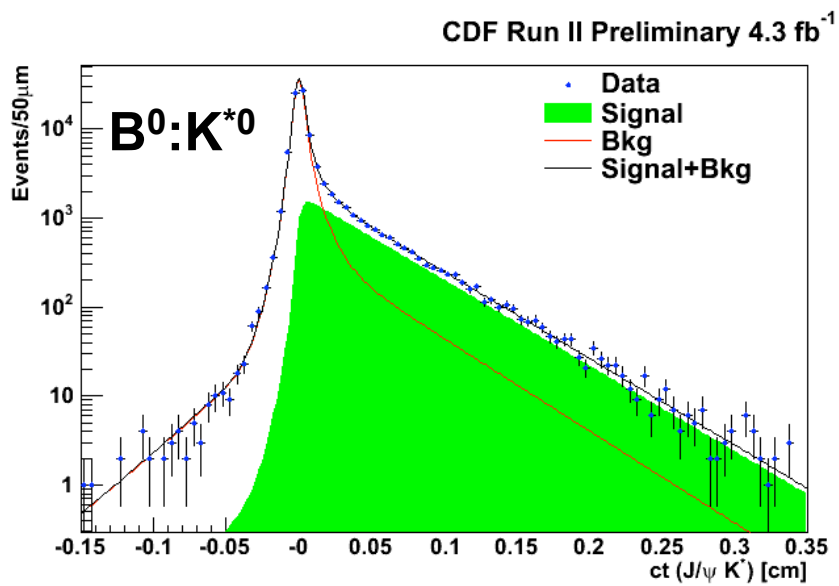
- Uses a **4.3 fb^{-1}** data sample obtained using CDF di-muon trigger.
- Signal modes: $B^+ \rightarrow J/\psi\ K^+$,
  $B^0 \rightarrow J/\psi\ K_s^0$, $B^0 \rightarrow J/\psi\ K^{*0}$,
  $\Lambda_b^0 \rightarrow J/\psi\ \Lambda$
- Yields: **B^+**: 45000 ± 230,
  B^0: 16860 ± 140 (K_s^0) , **B^0**: 12070 ± 120 (K^{*0})
  Λ_b^0: 1710 ± 50
- Lifetimes are extracted by simultaneous unbinned likelihood fit to B **mass**, proper decay time ***ct*** and its uncertainty **σ_{ct}**. Per candidate mass uncertainty, σ_m, is also used as an input to the fit.
- The proper decay time is modeled by an exponential convolved with a detector resolution functions comprised of 3 Gaussians.

Lifetime Projections from the Fits









Fit Results

$$\tau_{B^+} = 1.639 \pm 0.009(\text{stat.}) \pm 0.009(\text{syst.})\ \text{ps}$$

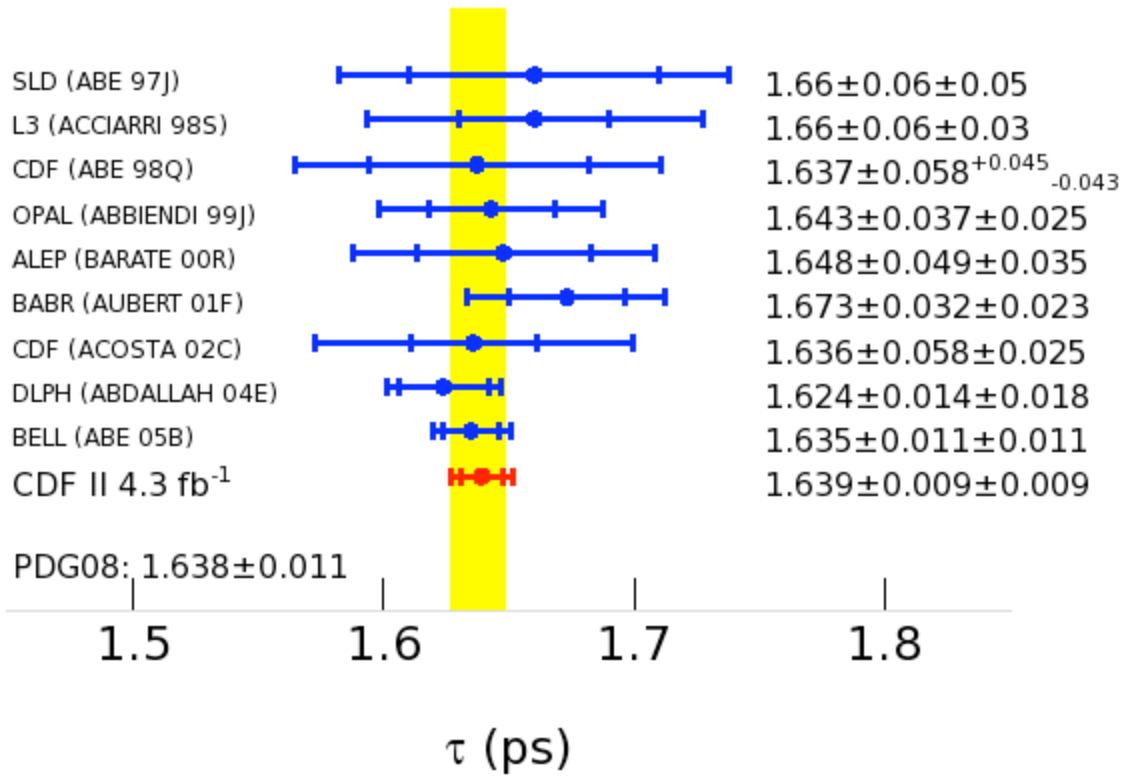
$$\tau_{B^0} = 1.507 \pm 0.010(\text{stat.}) \pm 0.008(\text{syst.})\ \text{ps}$$ (Weighted Avg)

$$\tau_{\Lambda_b^0} = 1.537 \pm 0.045(\text{stat.}) \pm 0.014(\text{syst.})\ \text{ps}$$

$$\frac{\tau_{B^+}}{\tau_{B^0}} = 1.088 \pm 0.009(\text{stat.}) \pm 0.004(\text{syst.})$$

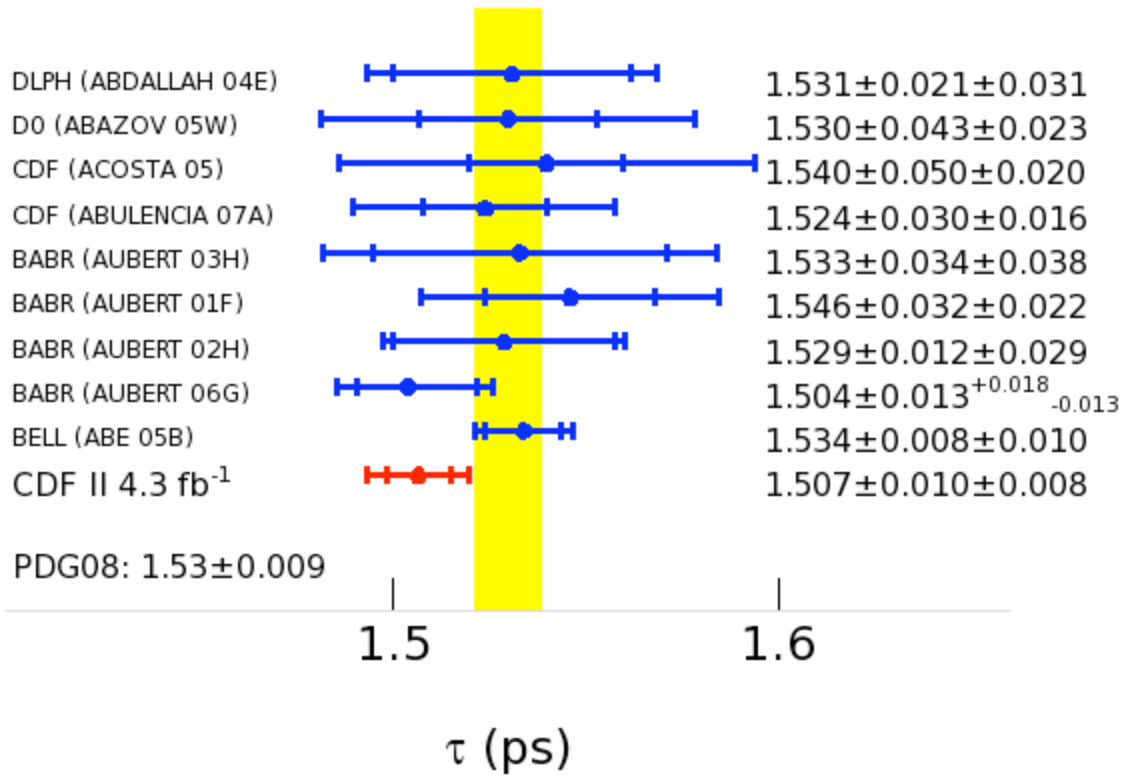
$$\frac{\tau_{\Lambda_b^0}}{\tau_{B^0}} = 1.020 \pm 0.030(\text{stat.}) \pm 0.008(\text{syst.})$$ (Theory: 0.86 ± 0.05)

$\tau(B^+)$ Comparison

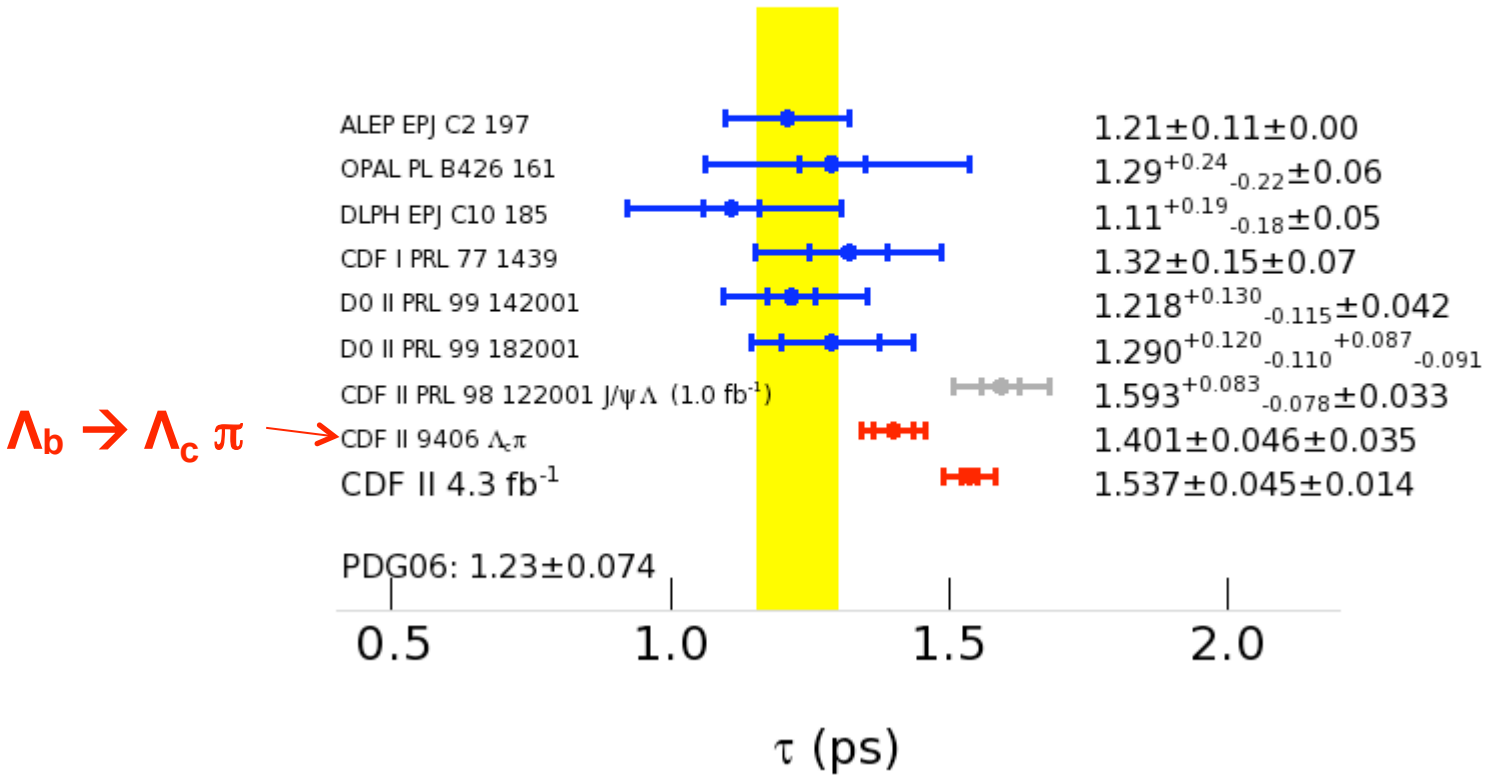


World best measurement!

$\tau(B^0)$ Comparison



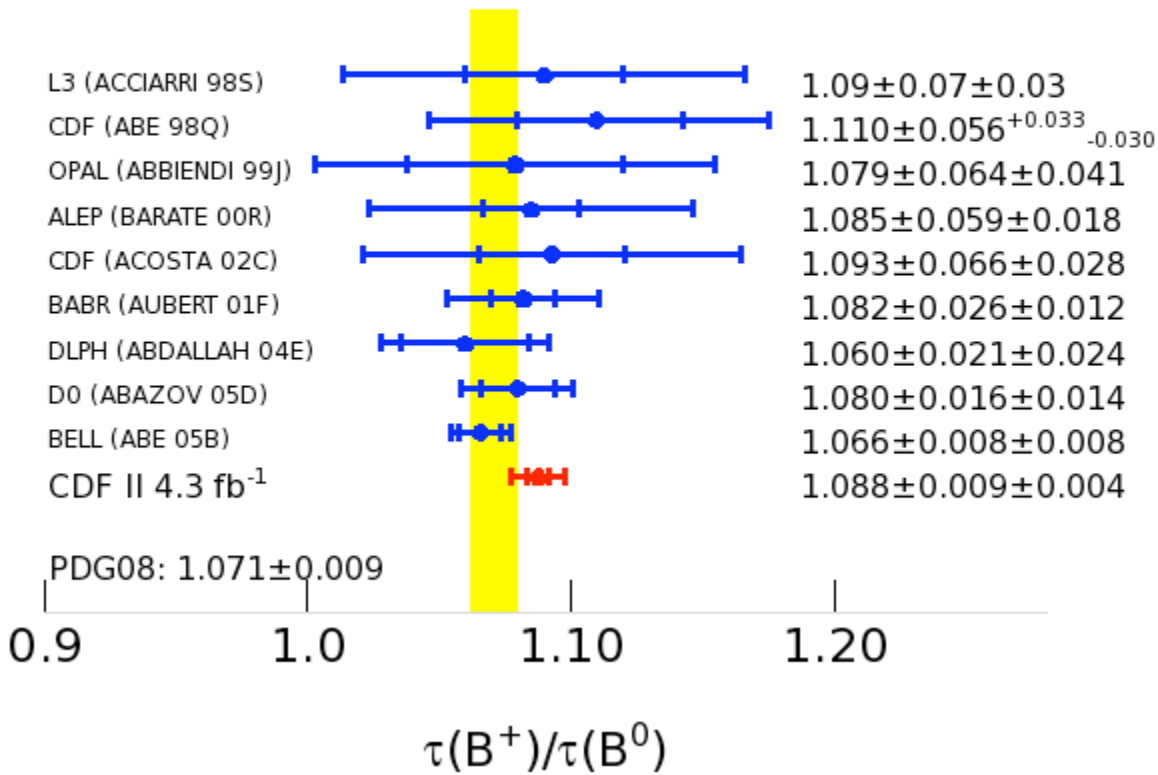
$\tau(\Lambda_b^0)$ Comparison



World best measurement!

Significantly above WA and in agreement with earlier measurement.

$\tau(B^+)/\tau(B^0)$ Comparison



Good agreement with WA

Spectroscopy Results

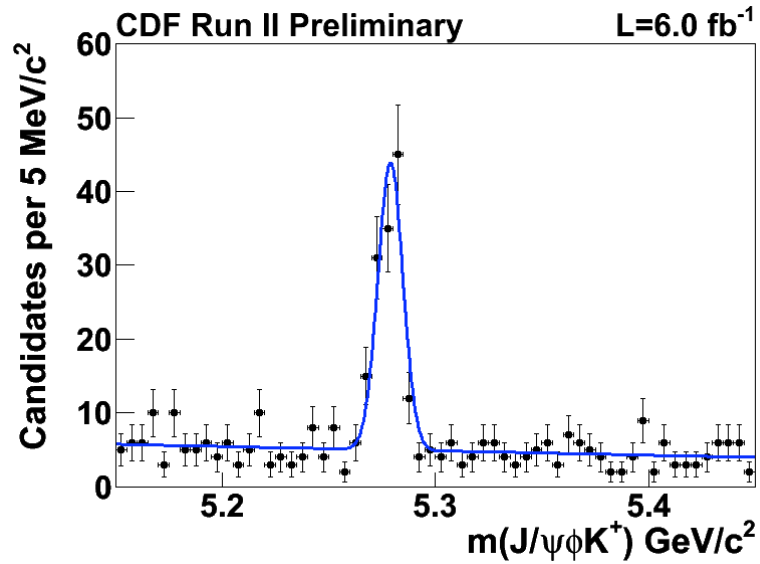
Observation of New Y(4140) State

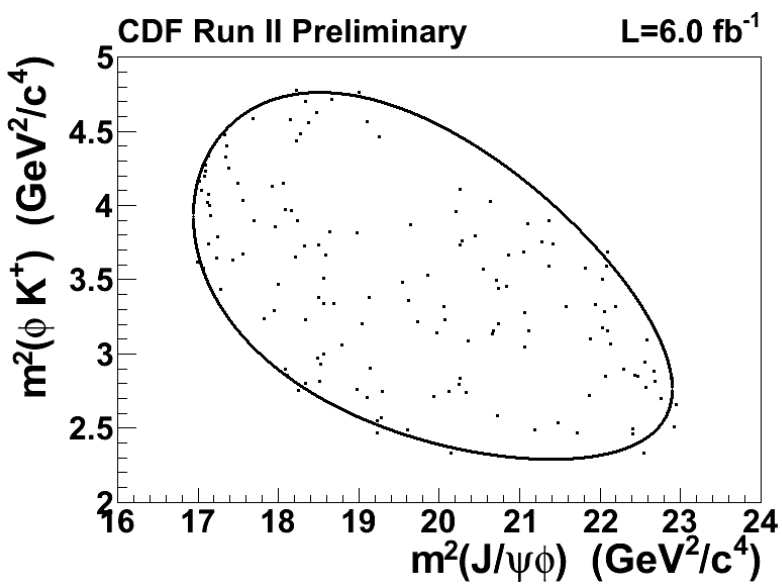
- Observed in the J/ψ φ Mass Spectrum of $B^+ \rightarrow J/\psi\ \varphi\ K^+$ decays from a **6 fb^{-1}** CDF di-muon sample.
- Comes from the update of an earlier analysis comprising of 2.7 fb^{-1} data, 14 ± 5 signal events. Reported significance 3.8σ. Published in **Phys.Rev.Lett.102:242002,2009.**
- Decay mode: $B^+ \rightarrow$ **Y(4140)** K^+, **Y(4140) →J/ψ φ**;

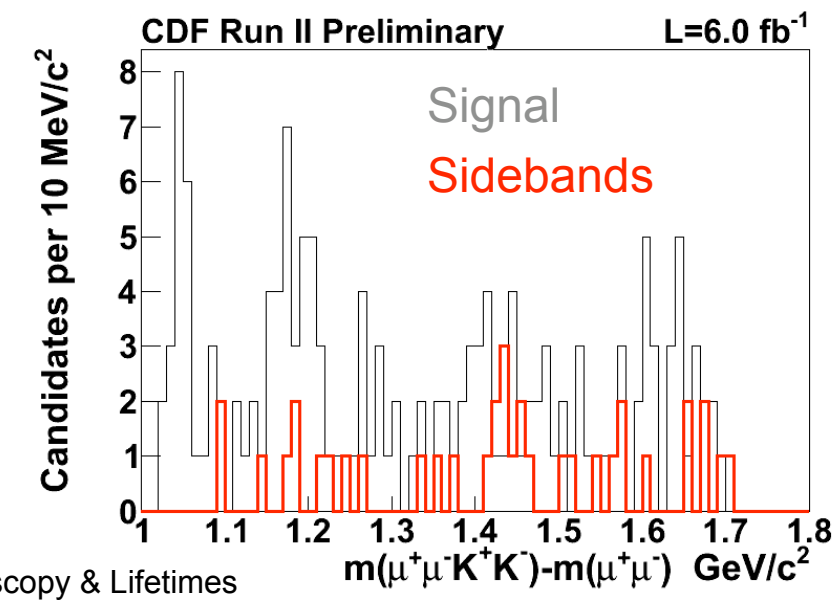
  $J/\Psi \rightarrow \mu^+\mu^-$, $\varphi \rightarrow K^+ K^-$
- Joins the fleet of exotic charmonium-like states, X(3872), Y(3930) etc., beyond open-charm pair production threshold.
- Analysis highlights:
  - Optimize signal: $L_{xy}(B^+)$ > 500 μm cut requires displaced secondary vertex, Kaon PID likelihood ratio > 0.2 reduces combinatorics.
  - The signal is observed as an excess in the $\Delta M = M(\mu^+\mu^-K^+K^-) - M(\mu^+\mu^-)$ distribution, **modeled by a S-wave relativistic BW** function.

Observation of Y(4140)

- B+ yield: 115 ± 12 events
- Signal region: ± 3σ, Sidebands [-9,-6]σ or [6,9]σ
- Dalitz distribution shows events uniformly distributed in the expected phase space.





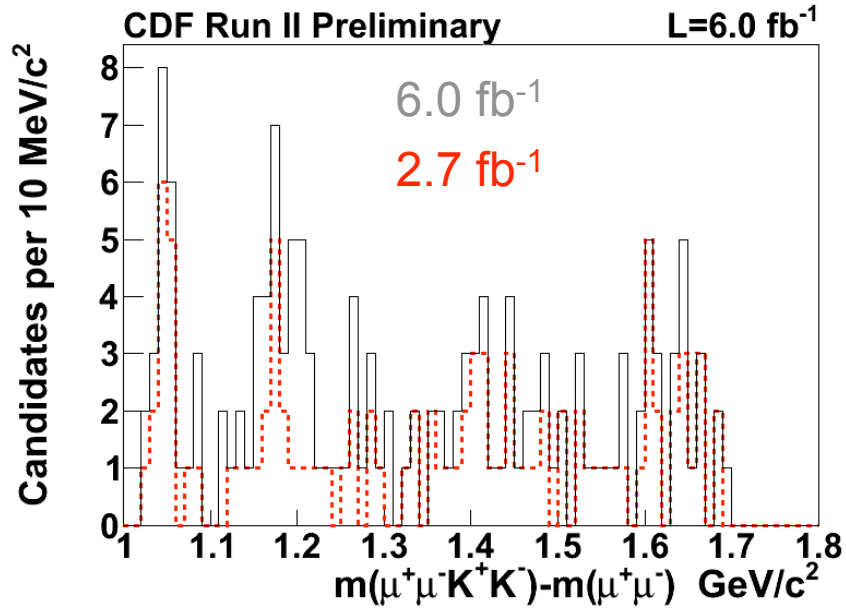


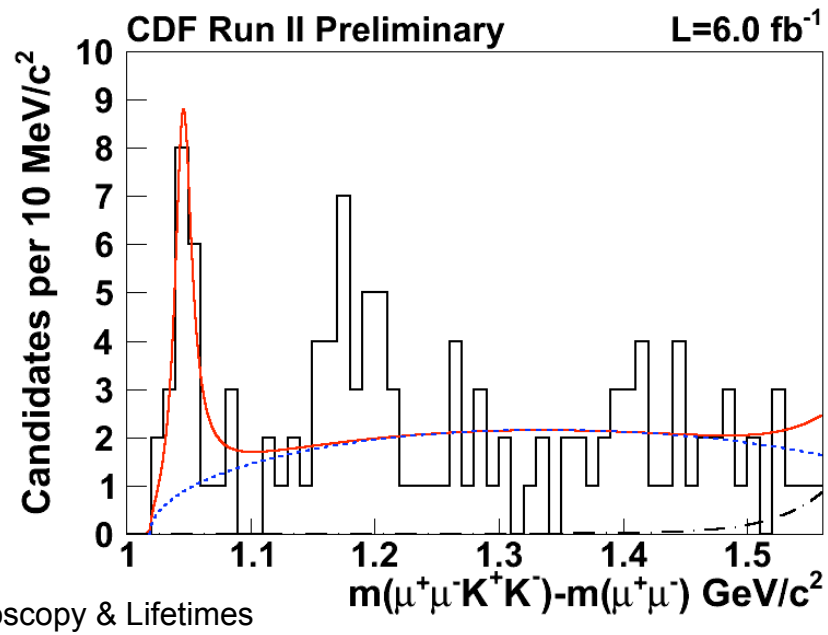
Observation of Y(4140)

- Comparison of old and updated samples show clear enhancement in the signal region.
- ΔM unbinned likelihood fit:
  - Signal: Rel. S-wave BW convoluted with a Gaus resolution function.
  - Background: 3-body phase space
  - $B^0_s \rightarrow \psi' \varphi$ contamination in high ΔM region modeled from MC.
- Yield: 19 ± 6 events,

  ΔM: $1046.7\ ^{+2.9}_{-3.0}$ MeV/c^2

  Width: $15.3\ ^{+10.4}_{-6.1}$ MeV/c^2





Observation of Y(4140)

- Significant excess above background at ΔM=1.18 GeV/c^2.
- Fitting it along with Y(4140) doesn't change the results compared to Y(4140)-only fit.
- Final results:
  - Y(4140):

$$m = 4143.4^{+2.9}_{-3.0}\ (\text{stat.}) \pm 0.6\ (\text{syst.})\ \text{MeV/c}^2$$
$$\Gamma = 15.3^{+10.4}_{-6.1}\ (\text{stat.})\ \pm\ 2.5\ (\text{syst.})\ \text{MeV/c}^2$$

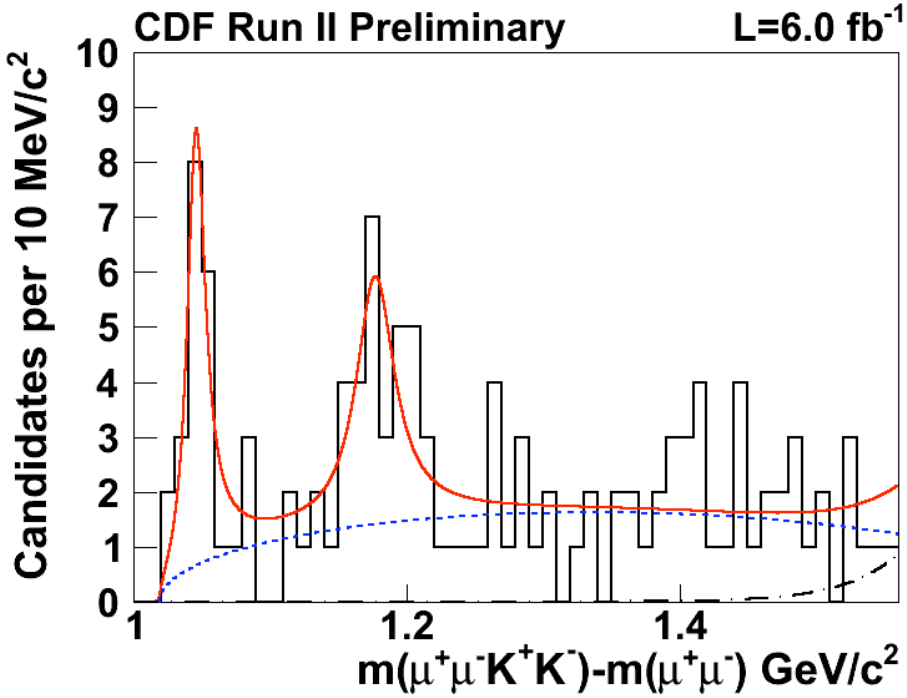
> 5.0σ significance

(Based on p-values from Toy MC tests)

  - Second peak:

$$m = 4274.4^{+8.4}_{-6.7}\ (\text{stat.})\ \text{MeV/c}^2$$
$$\Gamma = 32.3^{+21.9}_{-15.3}\ (\text{stat.})\ \text{MeV/c}^2$$

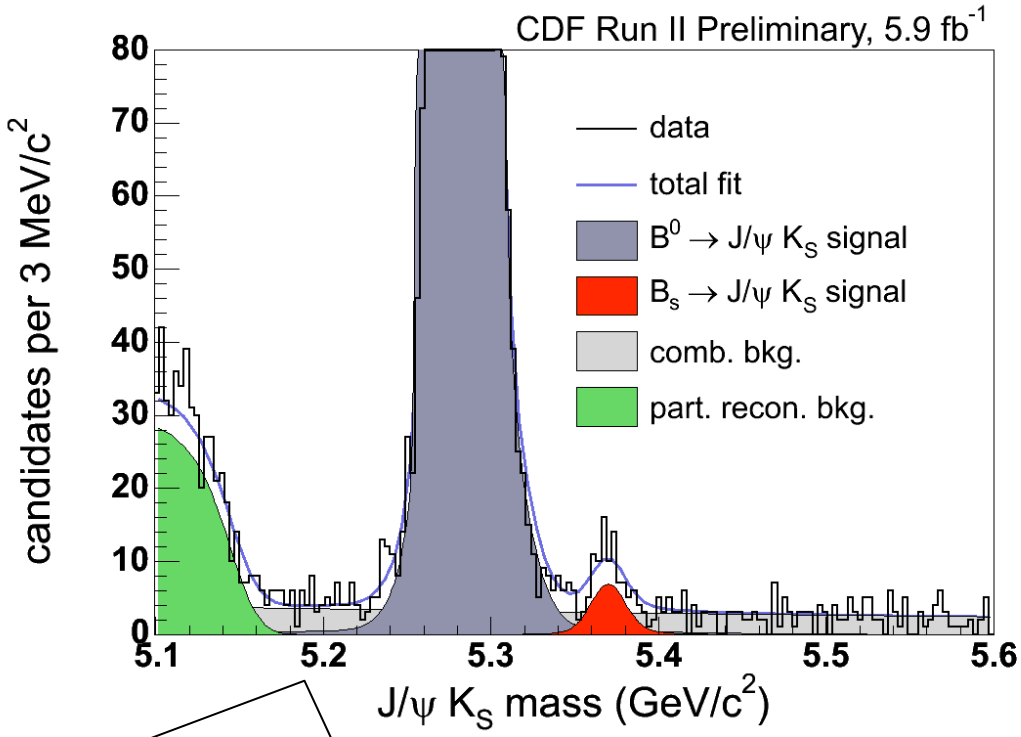
3.1σ significance

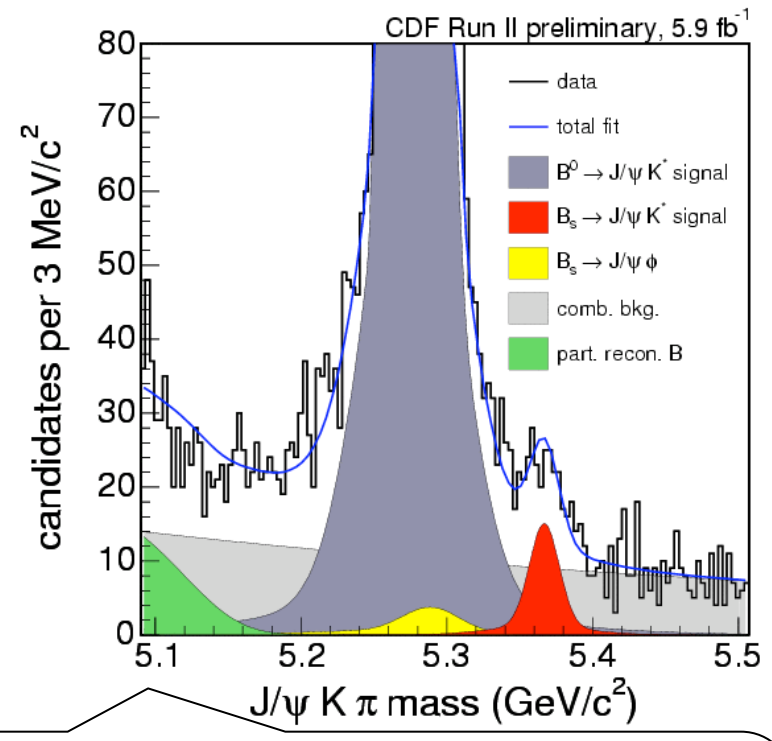


First Observation of $B_s^0 \rightarrow J/\psi K^{*0}$ and $B_s^0 \rightarrow J/\psi\ K_s^0$

- $B_s^0 \rightarrow J/\psi\ K_s^0$:
  - CP eigenstate, lifetime measures $\tau(B_s^0)_{heavy}$
  - Can be used to extract the CKM angle γ (R. Fleischer, Eur. Phys. J. C10:299-306,1999).
- $B_s^0 \rightarrow J/\psi K^{*0}$:
  - Admixture of CP final states. Estimate penguin contribution to $J/\psi\ \varphi$.
  - A large sample can be used to measure $\sin(2\beta_s)$ as a complementary mode to $B_s^0 \rightarrow J/\psi\ \varphi$.
- Procedure:
  - Reconstruct the signal modes in B_s^0 and B^0 samples from **6 fb^{-1}** of CDF di-muon triggered data.
  - After signal optimization apply binned likelihood fits to mass distributions to extract signal yield fractions between B_s^0 and B^0 modes.
  - Finally measure: $f_s\, BR(B_s \rightarrow J/\psi\ K^{(*)0}_{(S)}) \,/\, f_d\, BR(B^0 \rightarrow J/\psi\ K^{(*)0}_{(S)})$

First Observation of $B_s^0 \rightarrow J/\psi K^{*0}$ and $B_s^0 \rightarrow J/\psi\ K_s^0$





Yields: B_s^0: **64 ± 14**, B^0: **5954 ± 79**

BR($B_s \rightarrow J/\psi\ K^*$) = (3.5 ± 0.6 (stat.) ± 0.4 (syst.) ± 0.4 (frag.) ± 0.4 (PDG)) . 10^{-5}

7.2σ significance w.r.t. null hypothesis

Yields: B_s^0: **151 ± 25**, B^0: **9530 ± 110**

BR($B_s \rightarrow J/\psi\ K^*$) = (8.3 ± 1.2 (stat.) ± 3.3 (syst.) ± 1.0 (frag.) ± 0.4 (PDG)) . 10^{-5}

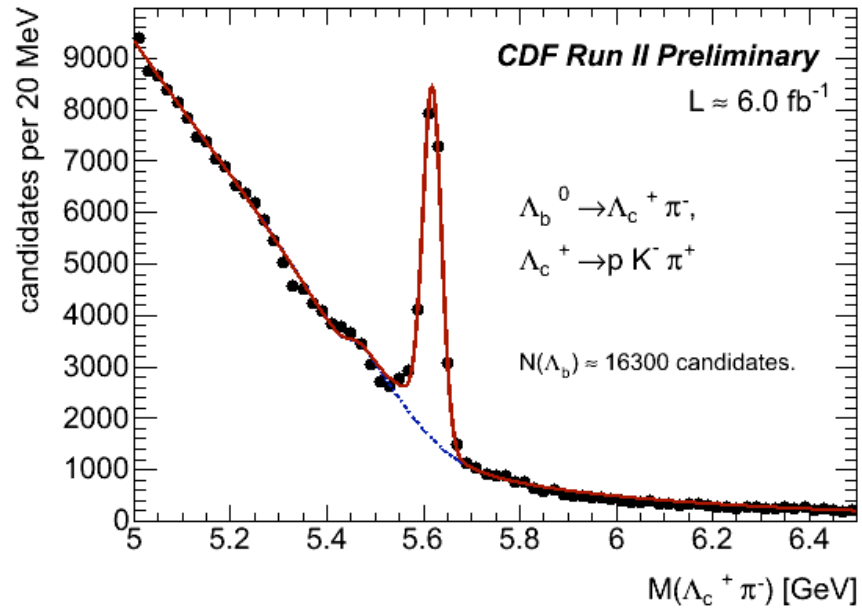
8σ significance w.r.t. null hypothesis

Bottom Baryon Resonances Σ_b and Σ_b^*

- Discovered in 2006 by CDF.
- Uses **6 fb^{-1}** data from CDF Two Track Trigger (TTT).
- Reconstruction mode:

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

- Analysis is performed on the Q-value, **$Q = m(\Lambda_b^0 \pi^\pm) - m(\Lambda_b^0) - m(\pi^\pm)$**, where the Λ_b^0 resolution is canceled out by taking the difference.
- **Main background:** random tracks from hadronization and underlaying events combining with real Λ_b^0

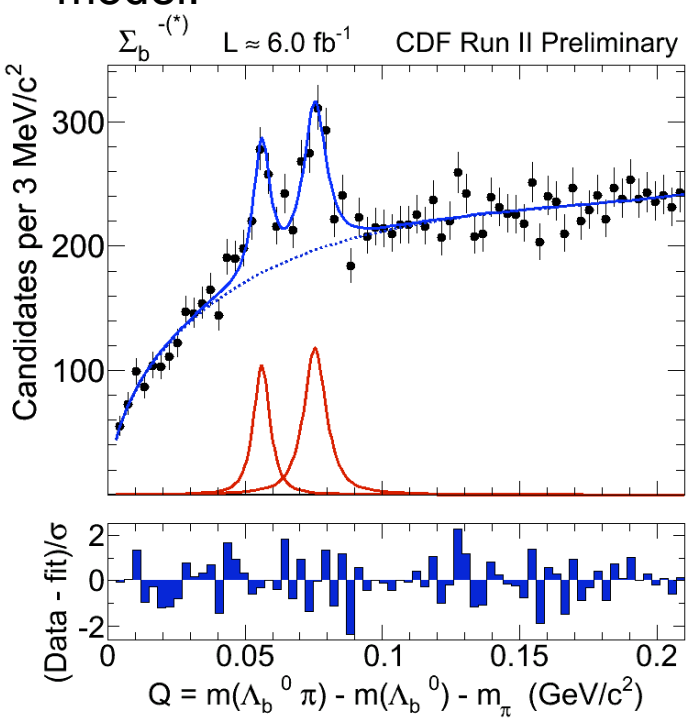


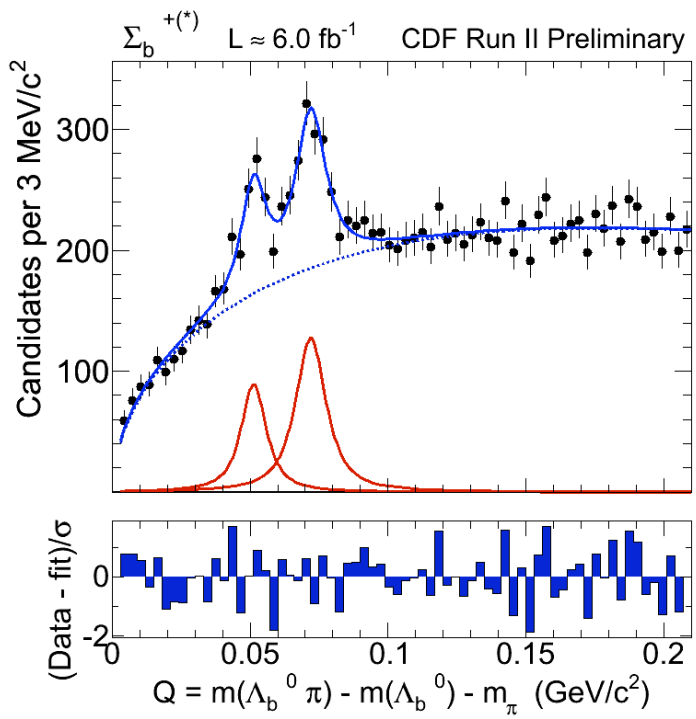
World's largest Λ_b sample!

- Binned mass fit components
  - the $\Lambda_b \rightarrow \Lambda_c^+ \pi^-$ signal
  - a combinatorial background
  - partially and fully reconstructed B mesons and Λ_b^0 baryons.

Σ_b and Σ_b^* Mass Fit

- The signal peaks are described by modified Breit-Wigner distributions convoluted with two gaussians to account for the detector resolution
- Sources of systematics are:
  - Fit procedure.
  - Uncertainties on the momentum scale.
  - Assumptions made in the fitter for detector resolution and the background model.





Σ_b and Σ_b^* Mass and Width Results

- From the Q-values obtain isospin mass splittings:

$$m(\Sigma_b^+) - m(\Sigma_b^-) = -4.2^{+1.1}_{-0.9}(\text{stat.})^{+0.07}_{-0.09}\ (\text{syst.})\ \text{MeV/c}^2$$

$$m(\Sigma_b^{*+}) - m(\Sigma_b^{*-}) = -3.0 \pm 0.9(\text{stat.})^{+0.12}_{-0.13}\ (\text{syst.})\ \text{MeV/c}^2$$

- The widths:

$$\Gamma(\Sigma_b^+) = 9.2^{+3.8}_{-2.9}(\text{stat.})^{+1.0}_{-1.1}\ (\text{syst.})\ \text{MeV/c}^2$$

$$\Gamma(\Sigma_b^-) = 4.3^{+3.1}_{-2.1}(\text{stat.})^{+1.0}_{-1.1}\ (\text{syst.})\ \text{MeV/c}^2$$

$$\Gamma(\Sigma_b^{*+}) = 10.4^{+2.7}_{-2.2}(\text{stat.})^{+0.8}_{-1.2}\ (\text{syst.})\ \text{MeV/c}^2$$

$$\Gamma(\Sigma_b^{*-}) = 6.4^{+2.2}_{-1.8}(\text{stat.})^{+0.7}_{-1.1}\ (\text{syst.})\ \text{MeV/c}^2$$

- Using the CDF Run2 Λ_b mass obtain the absolute masses:

$$m(\Sigma_b^+) = 5811.2^{+0.9}_{-0.8}(\text{stat.}) \pm 1.7\ (\text{syst.})\ \text{MeV/c}^2$$

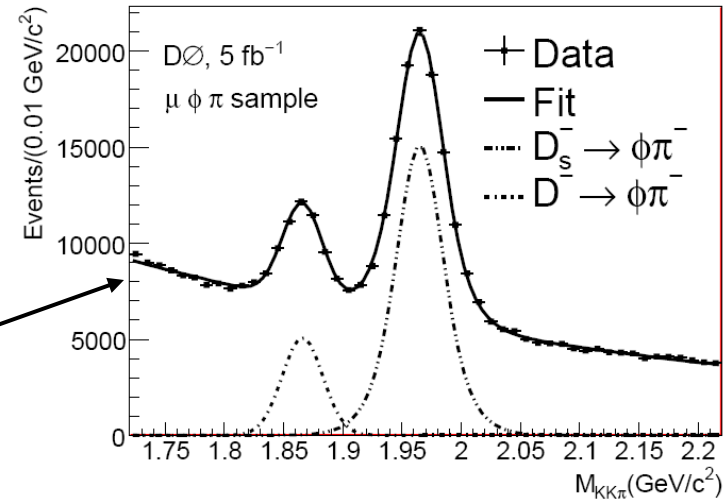
$$m(\Sigma_b^-) = 5815.5^{+0.6}_{-0.5}(\text{stat.}) \pm 1.7\ (\text{syst.})\ \text{MeV/c}^2$$

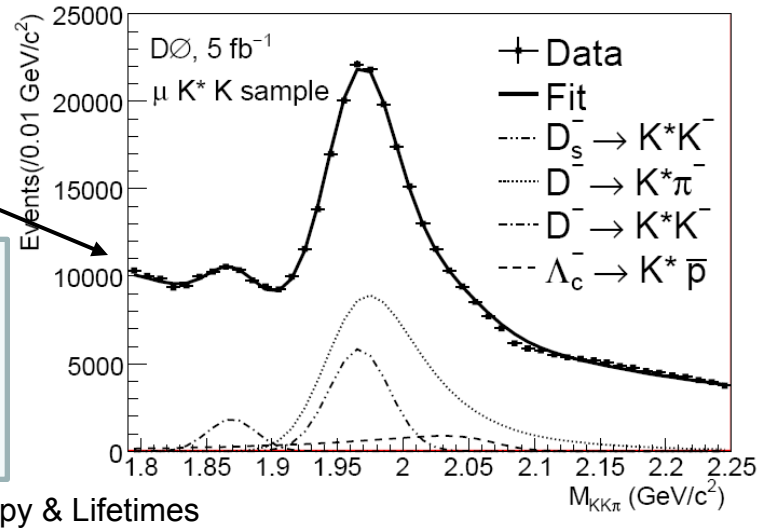
$$m(\Sigma_b^{*+}) = 5832.0 \pm 0.7(\text{stat.}) \pm 1.8\ (\text{syst.})\ \text{MeV/c}^2$$

$$m(\Sigma_b^{*-}) = 5835.0 \pm 0.6(\text{stat.}) \pm 1.8\ (\text{syst.})\ \text{MeV/c}^2$$

Measurement of B_s^0 Semileptonic Asymmetry

- Measure flavor-specific asymmetry, a^s_{fs}, in **5 fb^{-1}**
  - Time-dependent
  - Flavor-tagged
- Reconstruct **$B_s^0 \to \mu^+ D_s^- X$**
  - $D_s^- \to \varphi\pi^- \to (K^-K^+)\pi^-$
  - $D_s^- \to K^{*0}K^-$
- Provides complementary way of measuring CP violating phase φ_s





arXiv:0904.3907

$$a^s_{fs} = \frac{\Gamma_{\overline{B}^0_s(t)\to f} - \Gamma_{B^0_s(t)\to \bar{f}}}{\Gamma_{\overline{B}^0_s(t)\to f} + \Gamma_{B^0_s(t)\to \bar{f}}}$$

Flavor-Specific Asymmetry

Extract asymmetry with un-binned maximum likelihood fit

$$\Gamma_{B_s^0 \to \bar{f}} = N_f \left|\overline{A}_{\bar{f}}\right|^2 \frac{1}{2}\left(1 - a_{fs}^s\right) e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\left(\Delta m_s t\right)\right]$$

$$\Gamma_{\overline{B}_s^0 \to f} = N_f \left|\overline{A}_{\bar{f}}\right|^2 \frac{1}{2}\left(1 + a_{fs}^s\right) e^{-\Gamma_s t}\left[\cosh\left(\frac{\Delta\Gamma_s t}{2}\right) - \cos\left(\Delta m_s t\right)\right]$$

Find

$$a_{fs}^s = \left[-1.7 \pm 9.1(stat)^{+1.2}_{-2.3}(syst)\right] \times 10^{-3}$$

Uncertainties improved by factor of 2 over previous direct measurement!

Standard model prediction: $a^s_{fs} = (0.021 \pm 0.006) \times 10^{-3}$

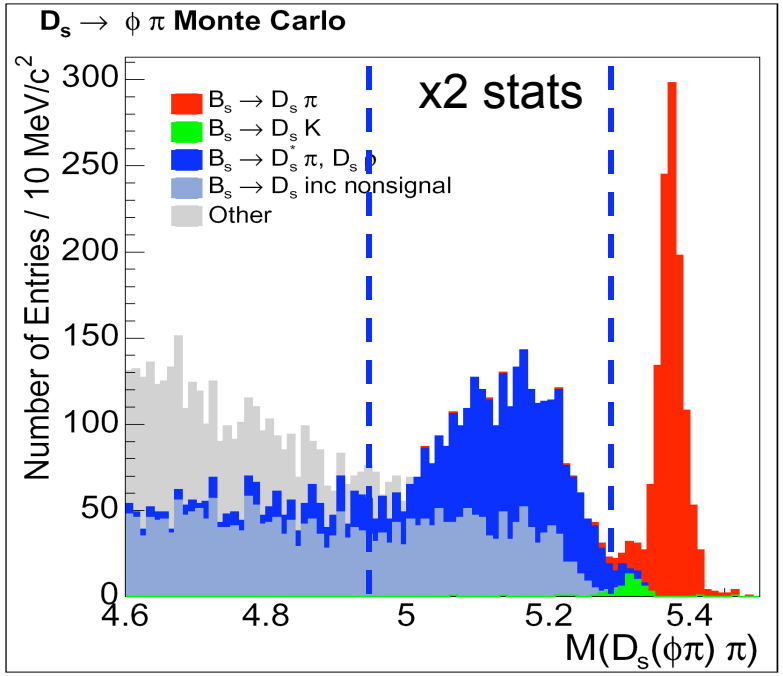
Conclusions

- Very rich heavy flavor program at the Tevatron. With over 8 fb^{-1} accumulated data per experiment and more to come, heavy flavor physics at Tevatron is in a high precision era.
- World's best B_s and Λ_b lifetime measurements from CDF are in agreement with the world average and HQE predictions. The B^+ and B^0 lifetimes are competitive with B-factories.
- Observation of new hadrons and precision measurements of the properties of the established ones put the theoretical models to stringent tests.
- Stay tuned for more!!
  - CDF: http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
  - DØ: http://www-d0.fnal.gov/Run2Physics/WWW/results/b.htm

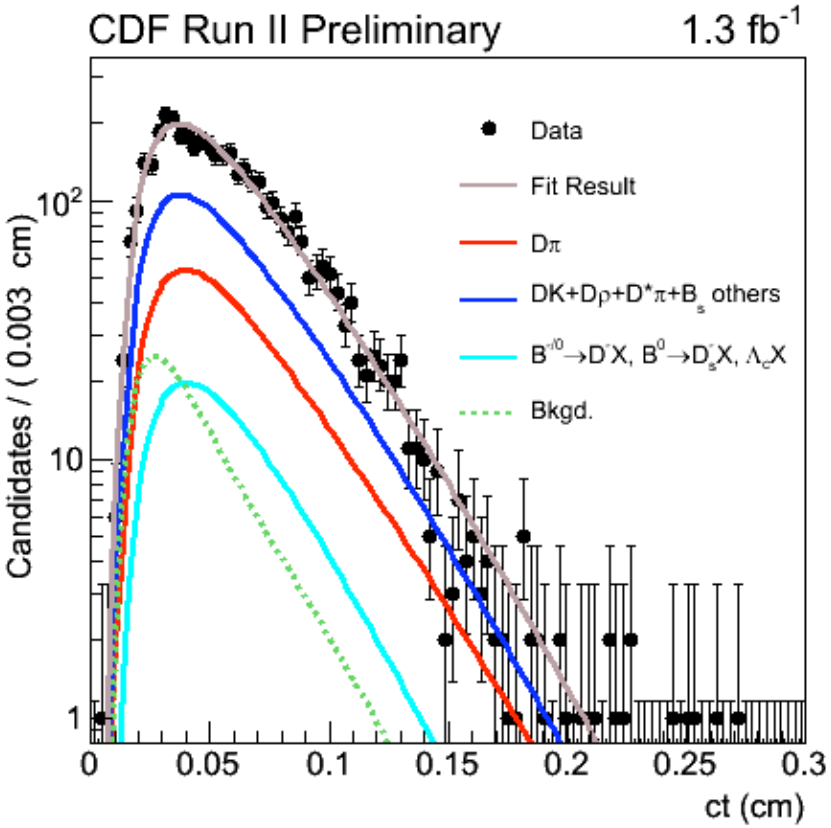
BACKUP SLIDES

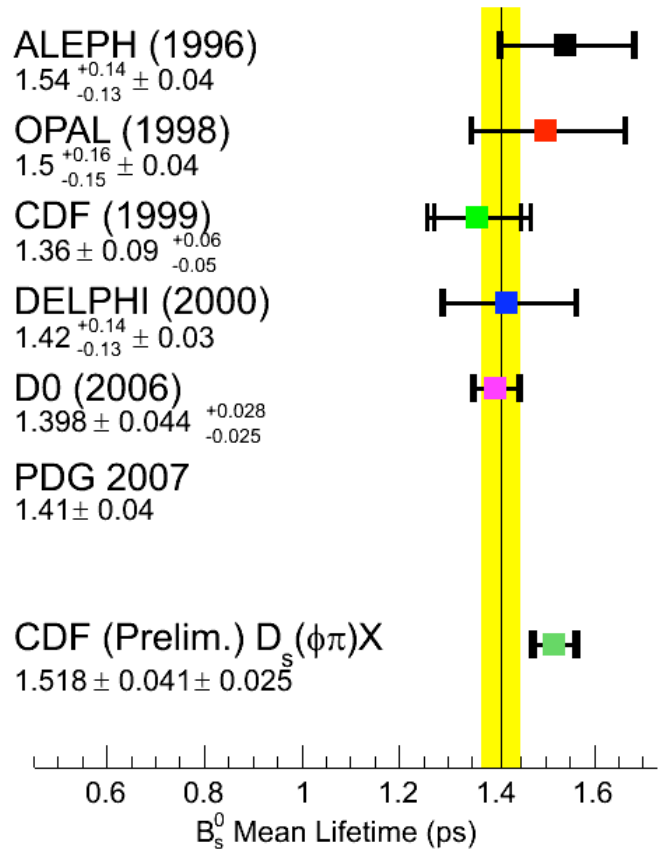
B_s Lifetime in $B_s \rightarrow D_s^+(\phi\pi)\,\pi^-\,X$

- Data sample:
  - **1.3 fb-1**, collected with displaced vertex trigger
  - ~ 1100 fully reconstructed events
  - ~ 2000 partially reconstructed events
- Lifetime bias is modeled with a trigger efficiency curve from MC
- Partially reconstructed channels:
  $B_s \rightarrow D_s^* \pi$, $D_s \rho^-(\pi^0 \pi^-)$
  triple the statistics!



B_s Lifetime in $B_s \rightarrow D_s^+(\phi\pi)\,\pi^-\,X$





Flavor-specific $\tau(B_s) = 1.518 \pm 0.041\,(\text{stat}) \pm 0.025\,(\text{syst})\,\text{ps}$

World best measurement!