B PHYSICS AT THE TEVATRON

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Split, Croatia

Physics @ the LHC October 3, 2008

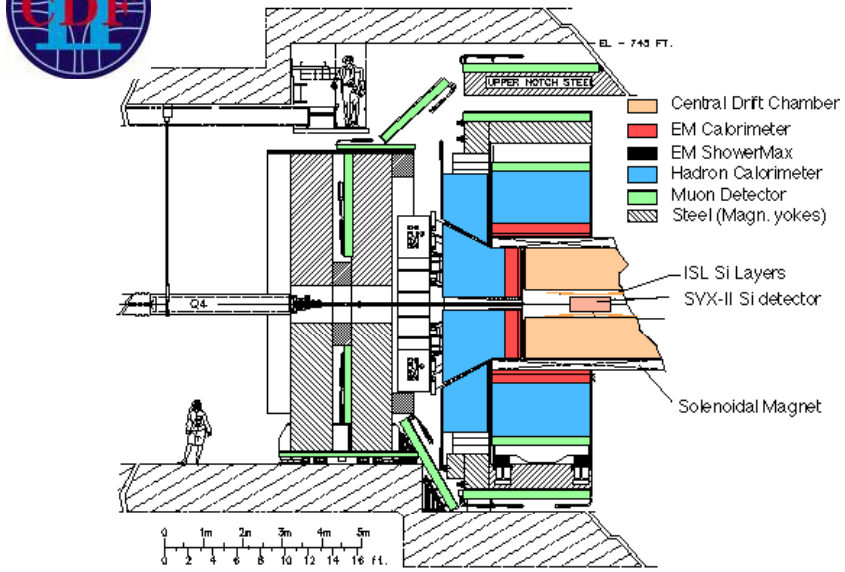
B Physics Program at Tevatron Has Been Tremendously Successful!

- Complements excellent programs at B-factories
- Many unique measurements made at Tevatron
  - Observation of B_s mixing, b-baryons
  - CPV in $B_s \rightarrow J/\psi\varphi$
- Several measurements (e.g. lifetimes, direct CPV) in B^0/B^+ systems are approaching sensitivity of BABAR/Belle

A Special Time for TeV(atron)

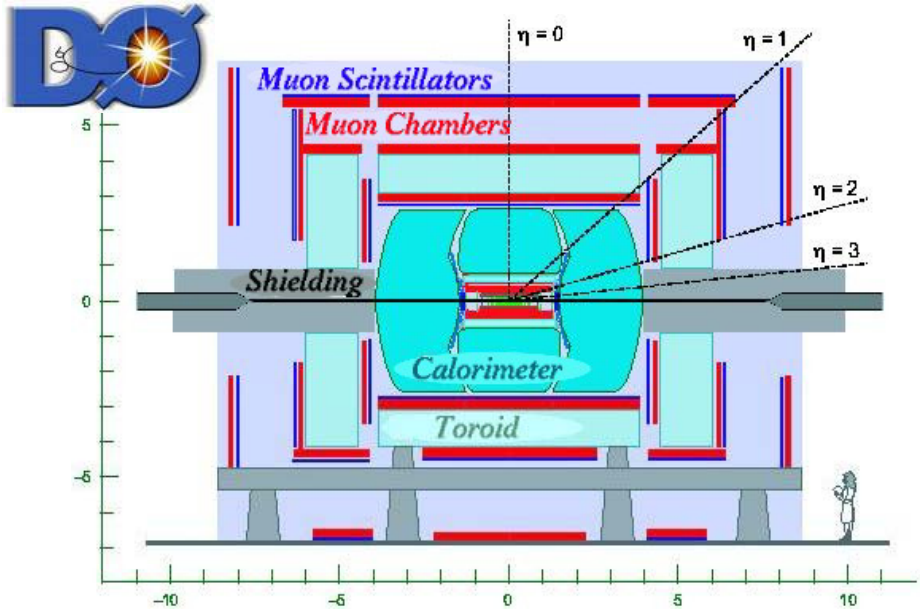
- Tevatron can contribute uniquely to B physics for the next few years
  - Transition between first run of B factories, LHC experiments
- At advent of LHC era, consider Tevatron B physics program present and future
  - Highlight recent results (from 2008)
  - Anticipate results to come
    - 2-4x the statistics can be added to many existing measurements before the end of Run II!

CDF and D0 Detectors Have Different Strengths in Detecting B Hadrons



Strong tracking system, ability to trigger on displaced tracks

$\Rightarrow$ Good mass resolution, high statistics in non-leptonic decays



Excellent calorimetry, muon id, can reverse direction of B field

$\Rightarrow$ Large sample of semi-leptonic decays, forward decays, good direct CPV meas.

Three Main Categories of B Physics Results Discussed Today

- Production
  - Birth of B hadrons
- Lifetimes
  - Death of B hadrons
- CP Violation
  - The curious things in between

$B_{(s)} \rightarrow \mu\mu$ will be discussed in context of SUSY, see Tuesday's talk by D. Toback for details

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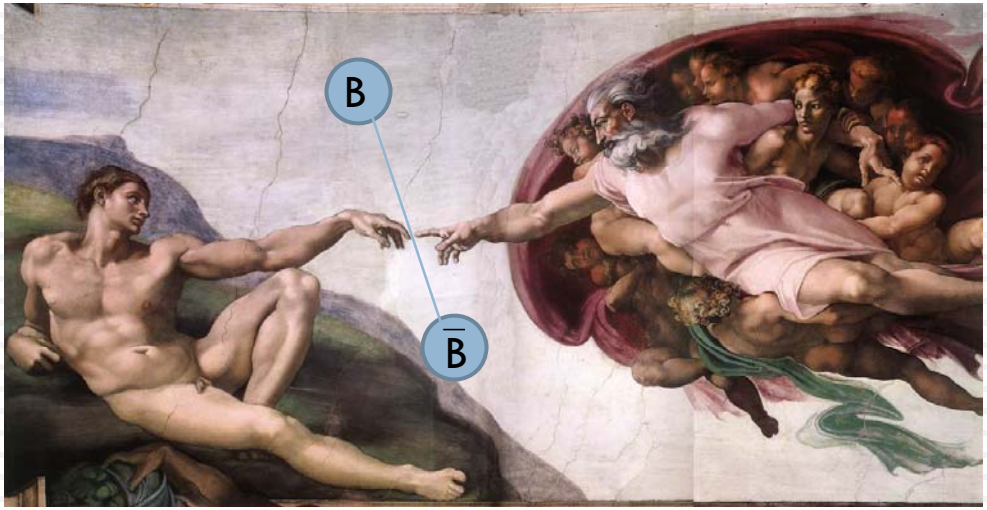
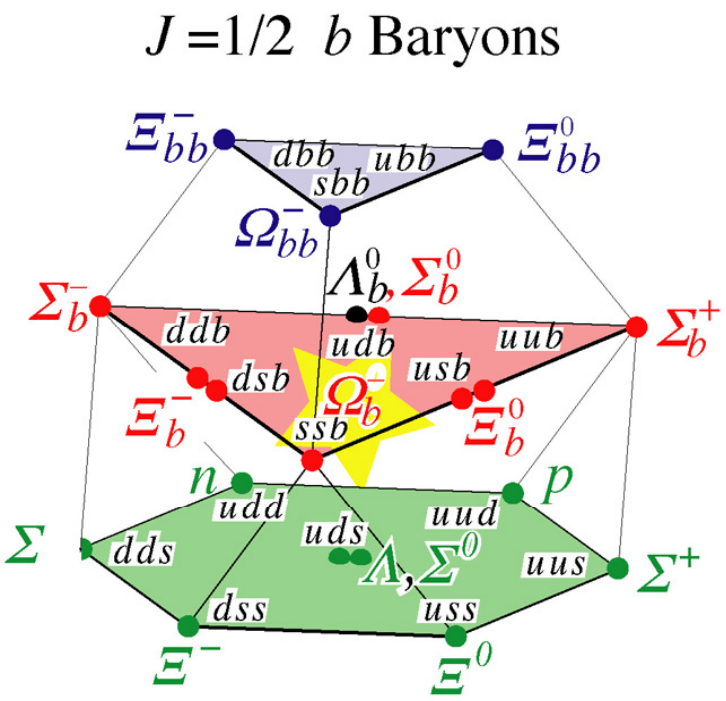
Production

MICHELANGELO Buonarroti
Creation of Adam
c. 1510



Searching for New Particles

- Look for things that we think should be there and also for things that shouldn't
  - Can find some surprises
    - e.g. X, Y, Z particles
  - Many b-baryons have not been observed until Run II!
    - Observed $\Sigma_b^{\pm}$ (2006), Ξ_b^- (2007) and recently Ω_b^- (2008)



Investigate Properties of X(3872)

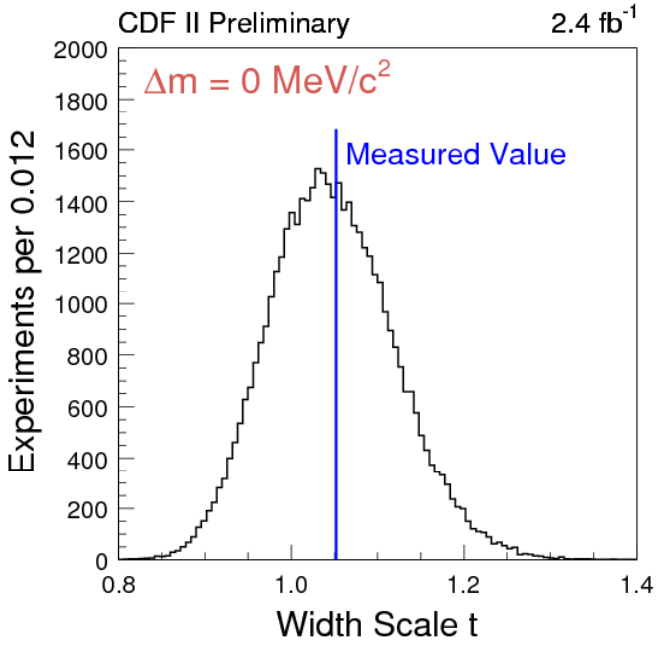
- First observed by Belle collaboration in 2003
- Observed in decay X(3872) $\rightarrow J/\psi\pi^+\pi^-$
  - Nature of particle is still unknown
    - D*D "molecule"? 4-quark state?
- Search for mass splitting, measure absolute mass
  - Observation of mass splitting offers evidence of tetra-quark
  - No mass splitting makes absolute mass interesting
    - Checks possibility of bound-state D*D

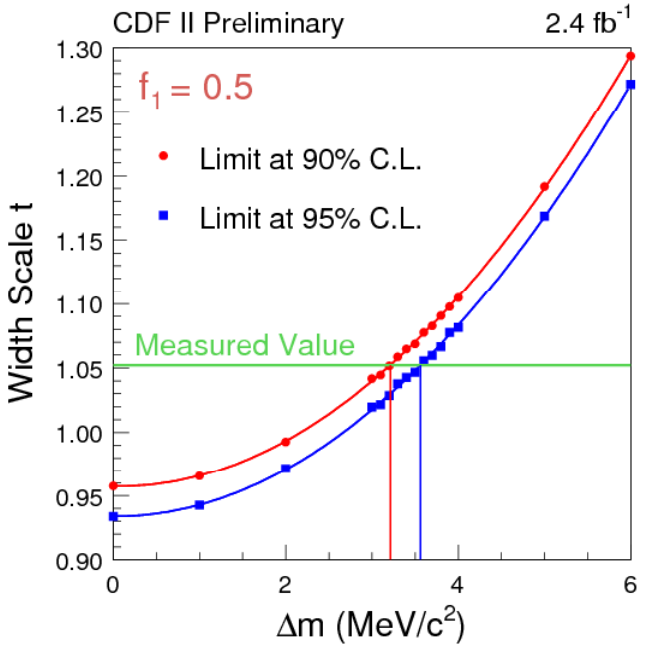
www-cdf.fnal.gov/physics/new/bottom/080724.blessed-X-Mass/

No Mass Splitting Observed in X(3872)

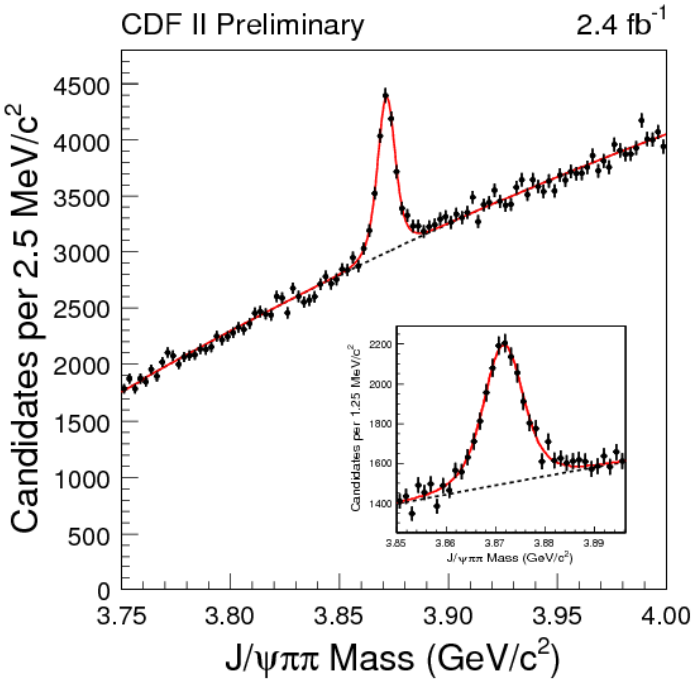
- Fit mass with Breit-Wigner convolved with resolution
  - Result consistent with no mass splitting
  - Assign upper limit CL

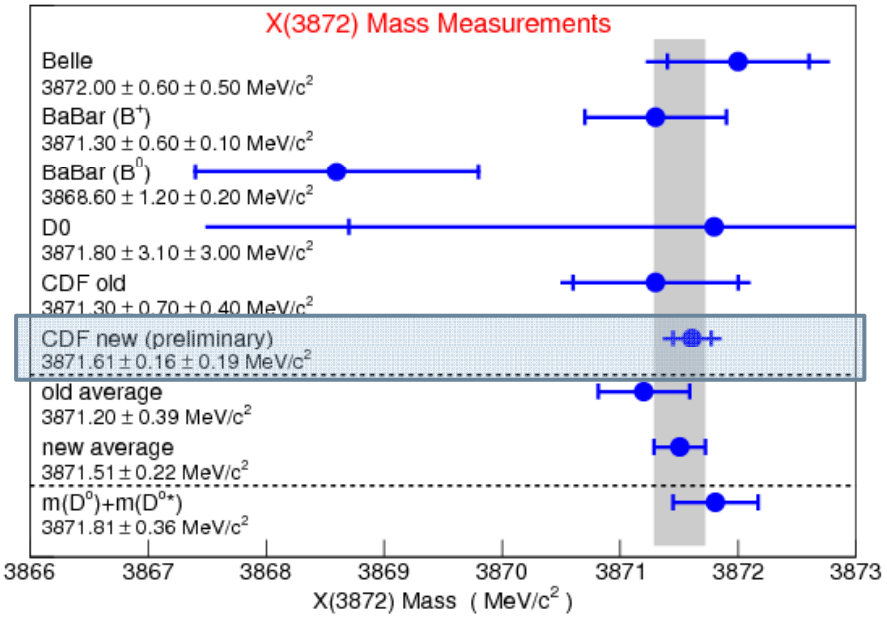
$\Delta m(X(3872)) < 3.2\ (3.6)\ \mathrm{MeV}/c^2$ at 90% (95%) C.L.





Most Precise Measurement of X(3872) Mass





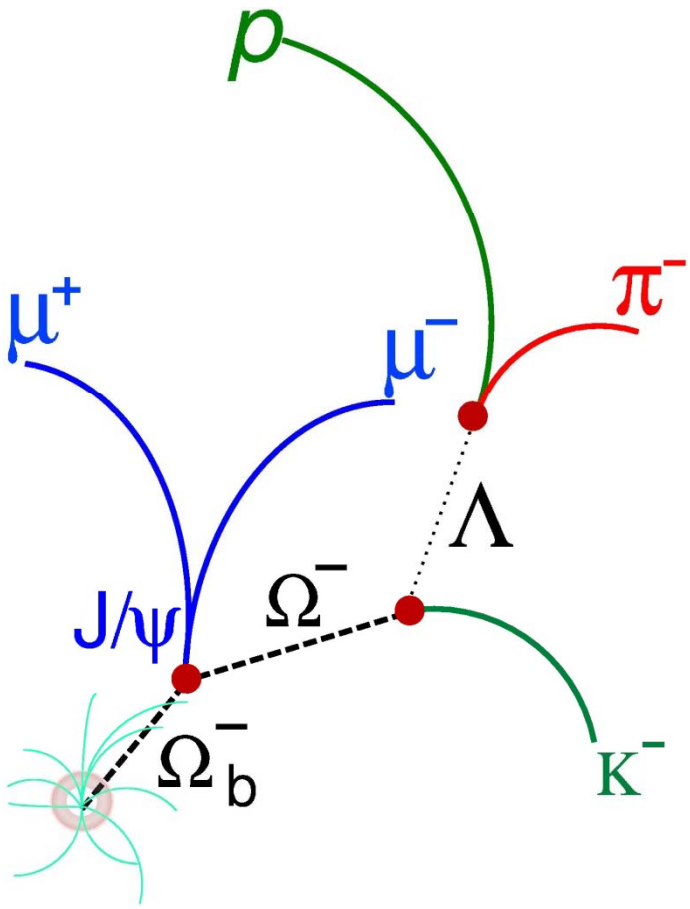
$m(X(3872)) = 3871.61 \pm 0.16\ (stat) \pm 0.19\ (syst)\ MeV/c^2$

Measured mass is below D*D threshold, although uncertainties are within threshold

$\Rightarrow$ D*D bound state is still a possibility

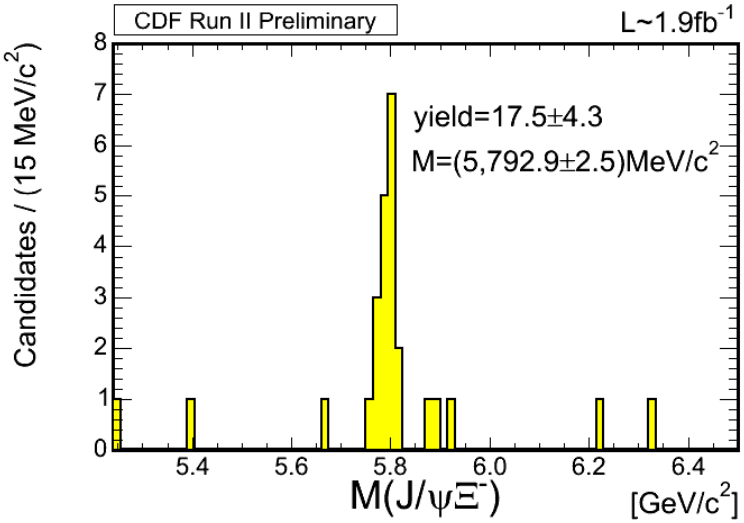
First Observation of Ω_b^- Baryon

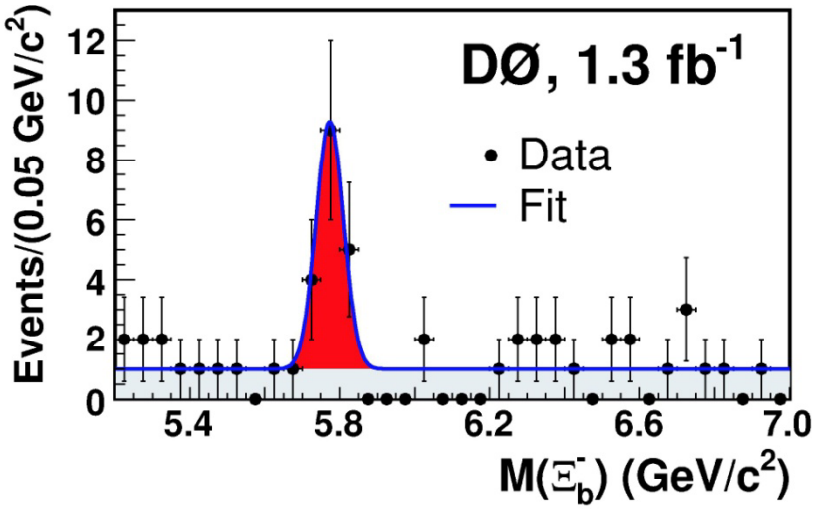
- Announced by D0 on Aug. 29, 2008
- Observation made with 1.3 fb^{-1} of data
  - Builds on previous observation of Ξ_b^-



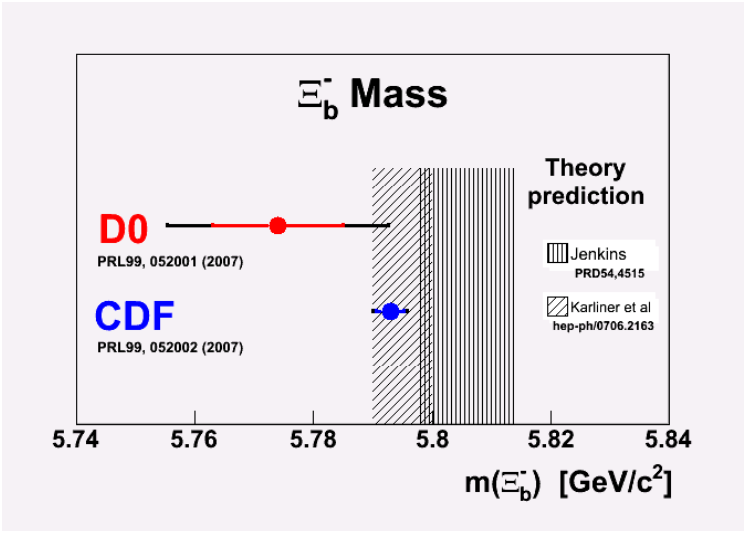
arXiv:0808.4142, submitted to PRL

Previous Observation of Ξ_b^-



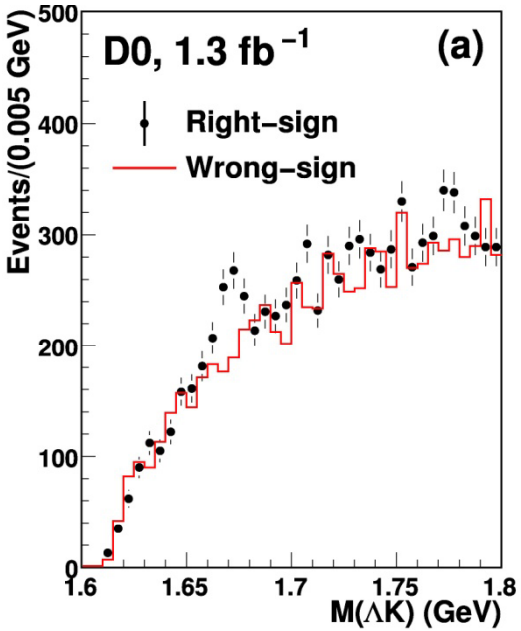


- In 2007, both CDF and D0 observed the Ξ_b^- and made a precise determination of its mass
  - $\Xi_b^- \to J/\psi \Xi^- \to [\mu^+\mu^-][\Lambda^0\pi^-]$, $\Lambda^0 \to p\pi^-$

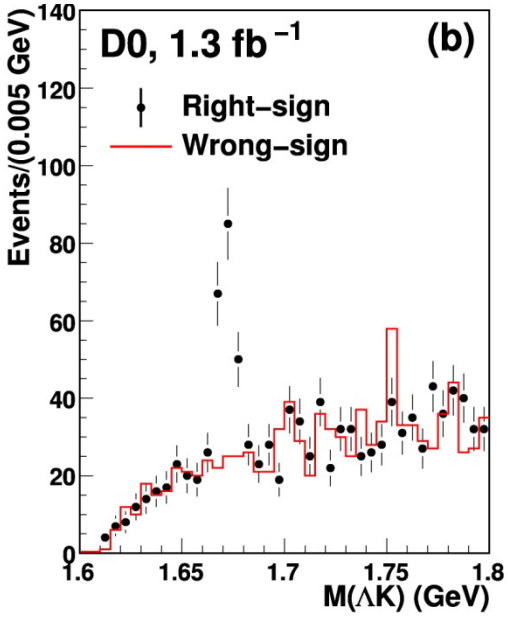


Ω^- Reconstruction Improved with Special Selection Techniques

- Use boosted decision tree (BDT) to improve identification of Ω^- signal



Before BDT



After BDT

Veto
$\Xi^- \to \Lambda^0 \pi^-$

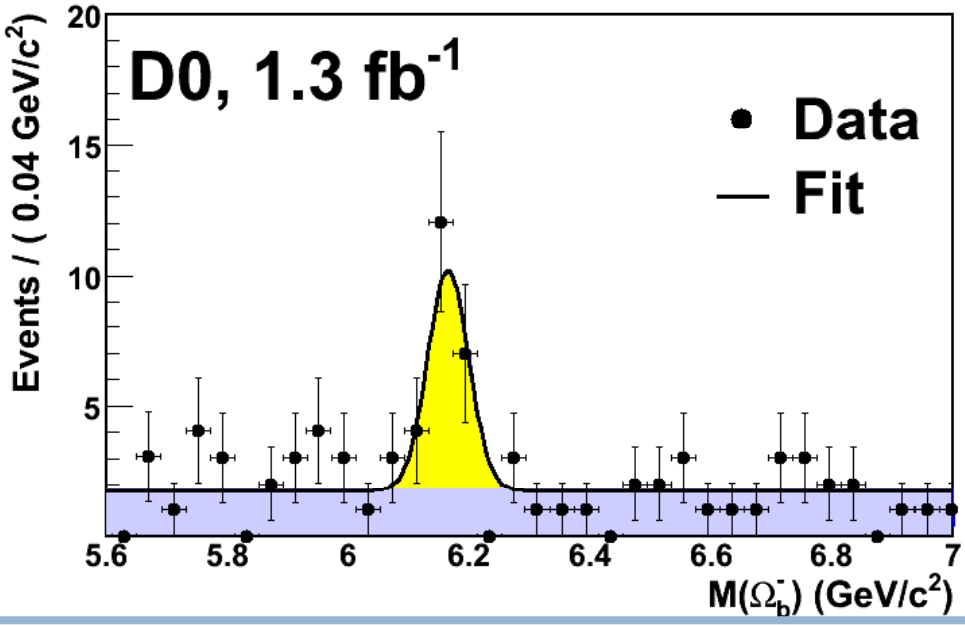
Re-process data with higher IP req. to increase Ξ^-/Ω^- acceptance!

Observe Significant Ω_b^- Signal

- Observe 17.8 ± 4.9 (stat) ± 0.8 (syst) events
  - m = 6.165 ± 0.010(stat) ± 0.013 (syst) GeV/c^2

Expect 5.94–6.12 GeV/c^2 from theory

Calculate signal significance to be 5.4σ



$$\frac{f(b\to\Omega_b^-)Br(\Omega_b^-\to J/\psi\,\Omega^-)}{f(b\to\Xi_b^-)Br(\Xi_b^-\to J/\psi\,\Xi^-)}=0.80\pm0.32(stat)^{+0.14}_{-0.22}(syst)$$

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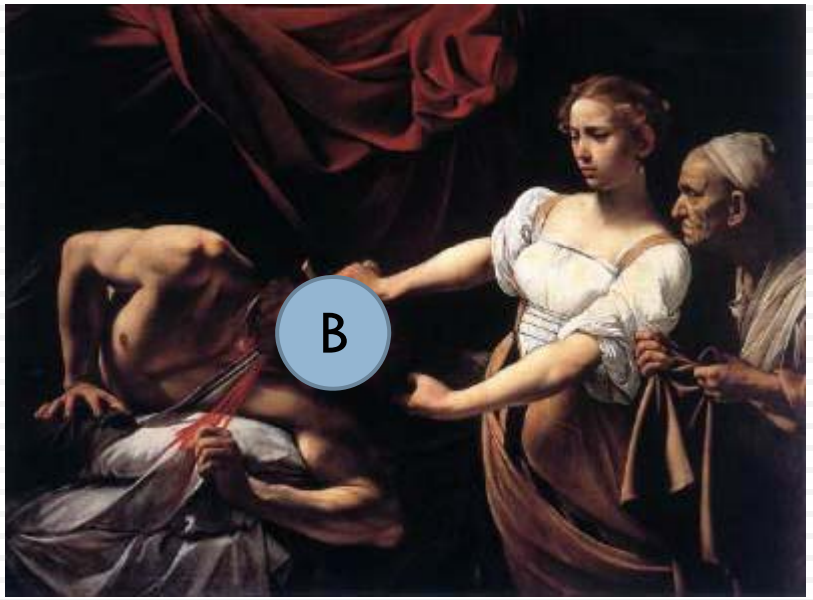
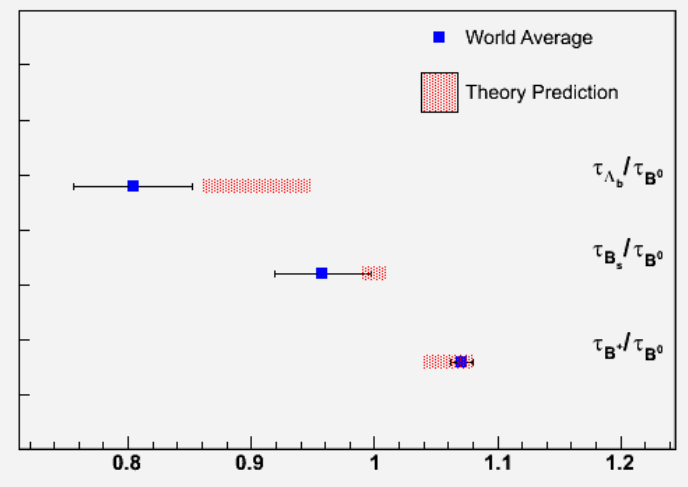
Lifetimes



CARAVAGGIO
Judith Beheading Holofernes
c. 1598

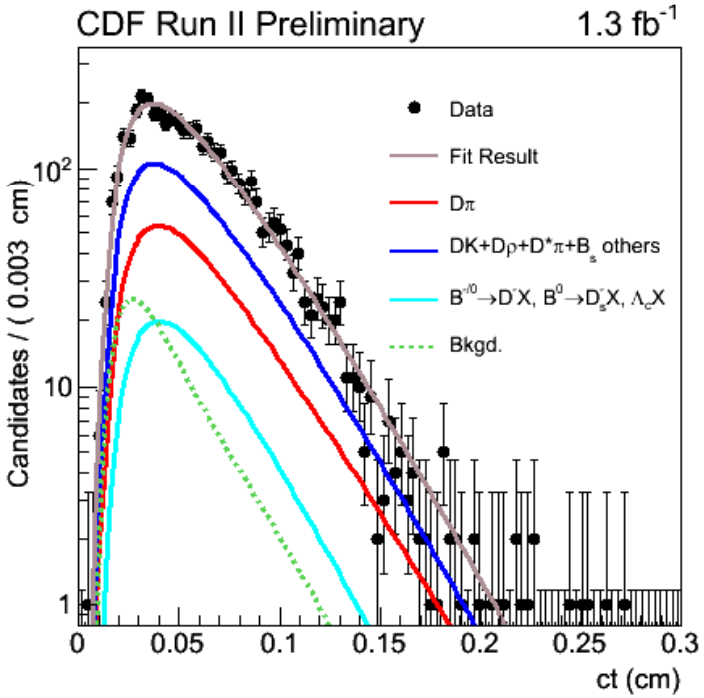
Why Measure Lifetimes?

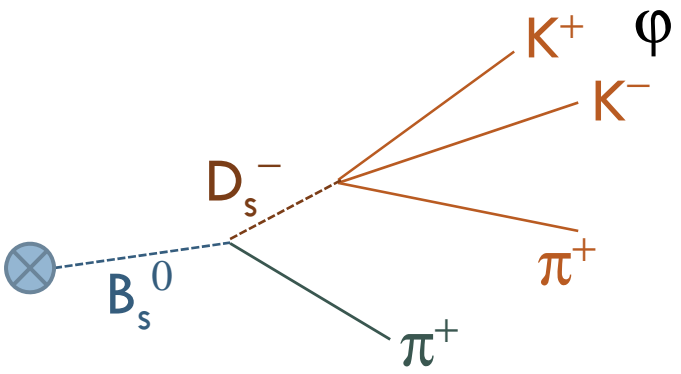


HFAG 2006

- Test HQET predictions
  - Have previously seen1-2σ discrepancies between lifetime predictions and measurements in B_s^0, Λ_b^0
    - Expect $\tau(B^+) > \tau(B^0) \approx \tau(B_s^0) > \tau(\Lambda_b^0) \gg \tau(B_c^+)$
- Because they're there?
  - Fundamental quantity, give complete picture of B's
  - Useful for other measurements (e.g. b-tagging)

B_s^0 Lifetime Now Agrees with HQET





Partially reco. decays double statistics!

$c\tau(B_s^0) = 455 \pm 12$ (stat.) $\pm$ 7 (syst.) μm

Very compatible with HQET predictions that $c\tau(B^0) \approx c\tau(B_s^0)$

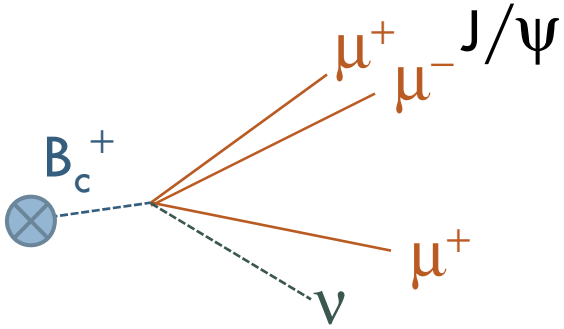
($c\tau(B^0) = 458.7 \pm 2.7$, PDG 2008)

- Blinded measurement of lifetime in 1.3 fb^{-1} of data
  - Data collected with displaced track trigger

    $\Rightarrow$ must correct for trigger bias (use Monte Carlo)

www-cdf.fnal.gov/physics/new/bottom/080207.blessed-bs-lifetime/

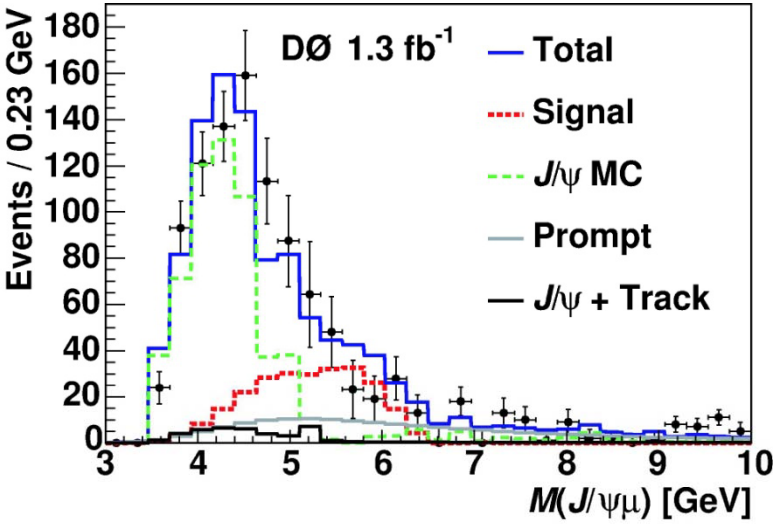
B_c^+ Lifetime Agrees with Theoretical Predictions

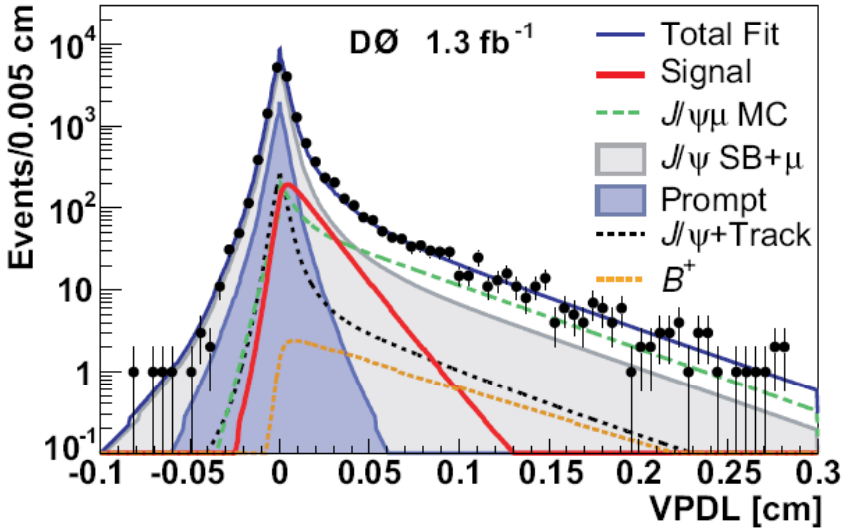


arXiv:0805.2614,
submitted to PRL

- Simultaneously fit mass and lifetime

$c\tau(B_c^+) = 134.3 \pm 11\ (stat) \pm 10\ (syst)\ \mu m$

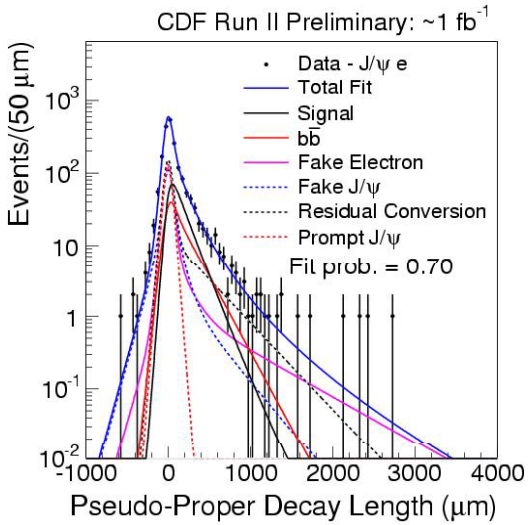


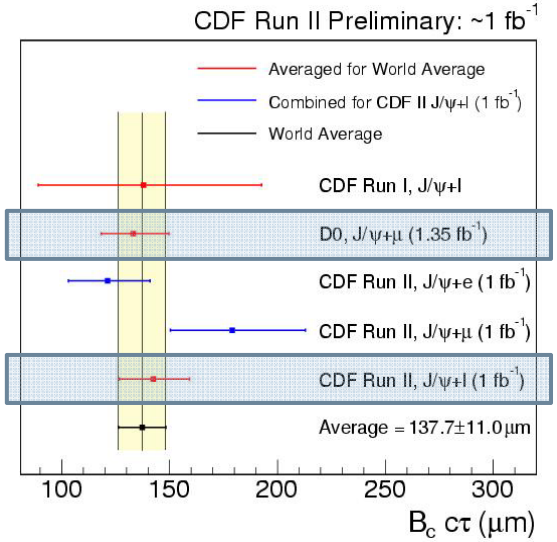


B_c^+ Lifetime Agrees with Theoretical Predictions and D0

- Fit e, μ channels separately, combine $\mathcal{L}$ afterwards

$$c\tau(B_c^+) = 142 \pm 15\ (\text{stat}) \pm 6\ (\text{syst})\ \mu\text{m}$$





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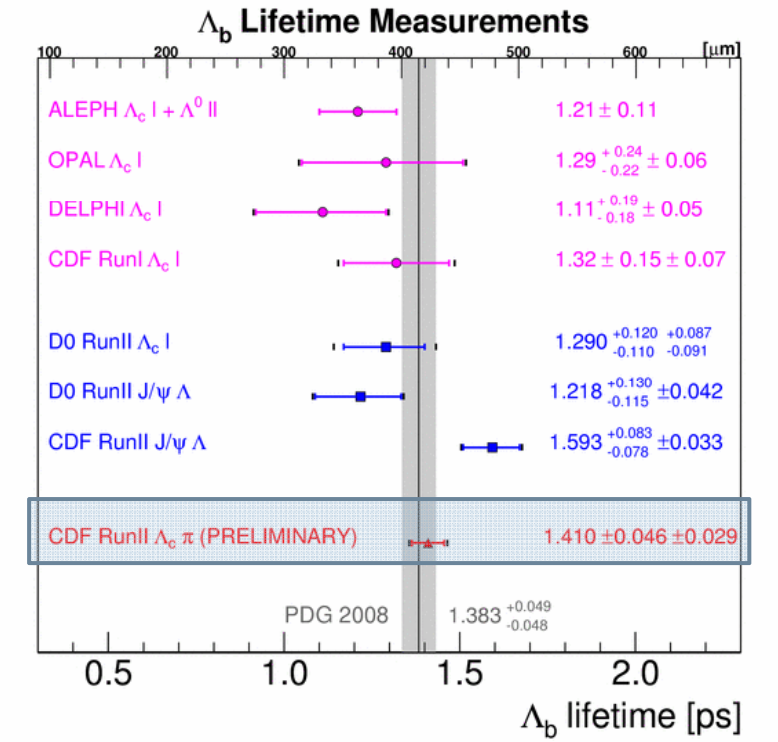
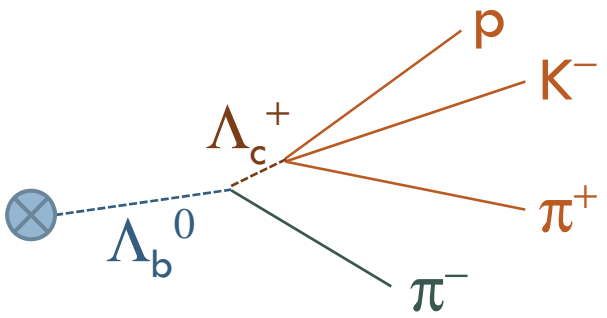
Λ_b^0 Lifetime Question Closer to Resolution





$c\tau(\Lambda_b^0) = 423 \pm 14\ (stat) \pm 9\ (syst)\ \mu m,$

$c\tau(\Lambda_b^0)\ /c\ \tau(B^0) = 0.92 \pm 0.04$

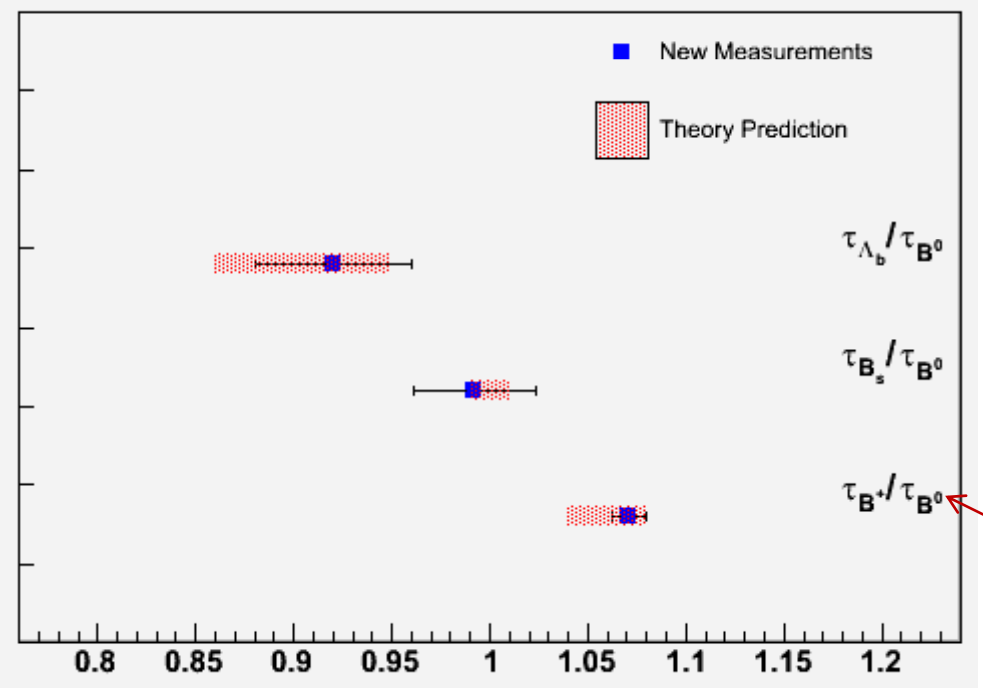
PDG 2007

- Measure lifetime in displaced track sample
  - First fit mass, then lifetime

www-cdf.fnal.gov/physics/new/bottom/080703.blessed-lblcpi-ct/

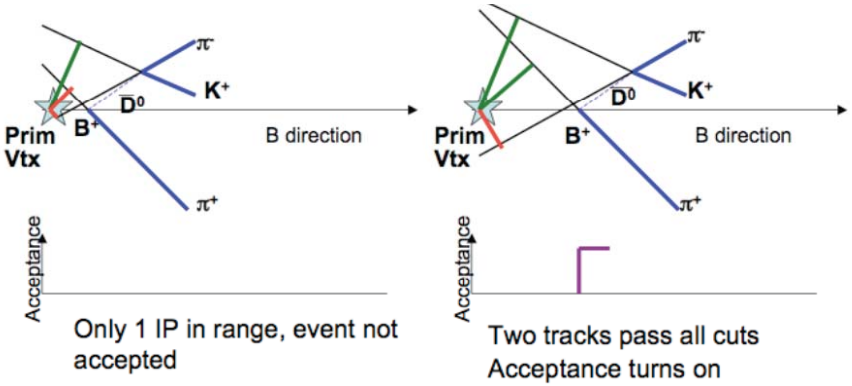
New Measurements Are in Good Agreement with Predicted Lifetimes

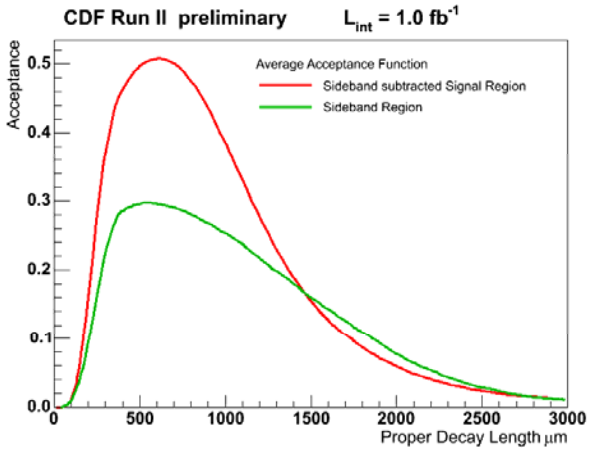
New measurements of lifetime are in good agreement with theoretical predictions!



New Technique Used to Measure B^+ Lifetime

- Measured in displaced track sample
  - Novel method for correcting for trigger bias without using Monte Carlo





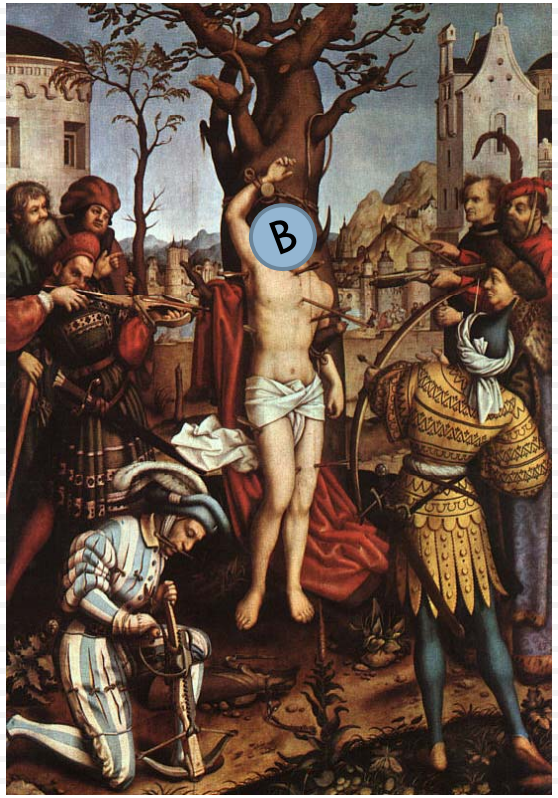
Use acceptance function to correct for trigger bias on event-by-event basis

$c\tau(B^+) = 498.2 \pm 6.8$ (stat.) $\pm$ 4.5 (syst.) μm,

($c\tau(B^+) = 491.1 \pm 3.3$ μm, PDG 2008)

www-cdf.fnal.gov/physics/new/bottom/080612.blessed-MCfree_Blifetime/

CP Violation

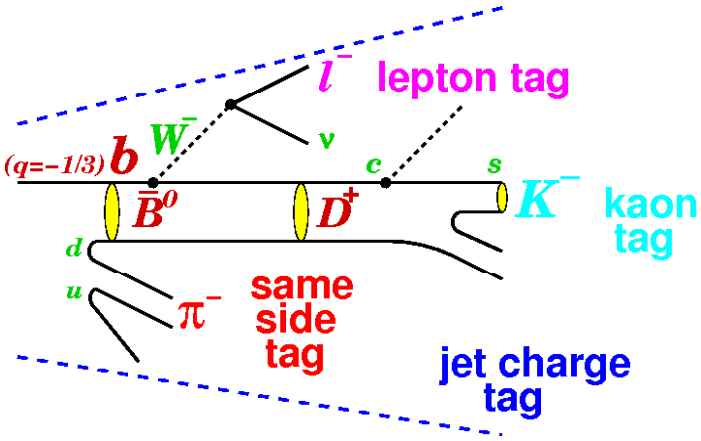


HOLBEIN, Hans the Elder
The Martyrdom of Saint Sebastian
c. 1516

Three Types of CP Violation

- Decay of hadrons (direct CPV)
  - Only type of CPV for charged mesons
- Mixing of neutral mesons (indirect CPV)
  - Semi-leptonic decays of neutral meson
- Interference between mixing and decay
  - $B^0 \to J/\psi\, K_s^0 \Rightarrow \sin 2\beta$
  - $B_s^0 \to J/\psi\varphi \Rightarrow \sin 2\beta_s$

Use flavor tagging for more powerful measurement of CP phases!



CPV Phases in B_s^0 Sensitive to New Physics

Mixing governed by Schrodinger eqn.

$$i\frac{d}{dt}\begin{pmatrix}|B_s^0(t)\rangle\\ |\bar{B}_s^0(t)\rangle\end{pmatrix} = \left(\mathbf{M}-\frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix}|B_s^0(t)\rangle\\ |\bar{B}_s^0(t)\rangle\end{pmatrix}$$

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

$\Delta m_s = m_H - m_L \approx 2|M_{12}|$ ← Measured at Tevatron in 2006!

$\Delta\Gamma = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\varphi_s)$,

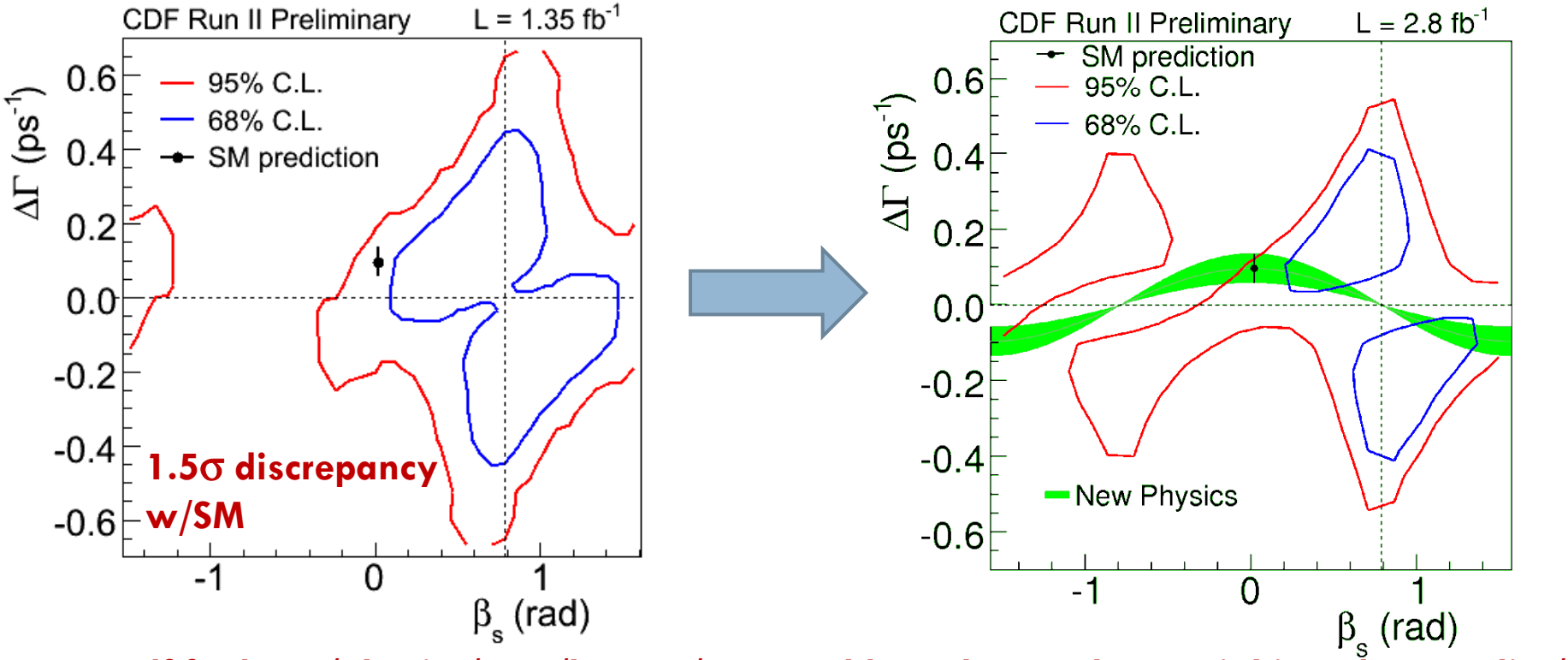
where $\varphi_s = \arg(-M_{12}/\Gamma_{12}) \sim 0.004$ in SM

- CPV in $B_s^0 \to J/\psi\varphi$ gives access to phase, sensitive to NP

$$\beta_s^{J/\psi\varphi} = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \sim 0.02$$ ← SM prediction

Discrepancy with SM Remains in CDF's Flavor-Tagged $B_s^0 \to J/\psi\phi$

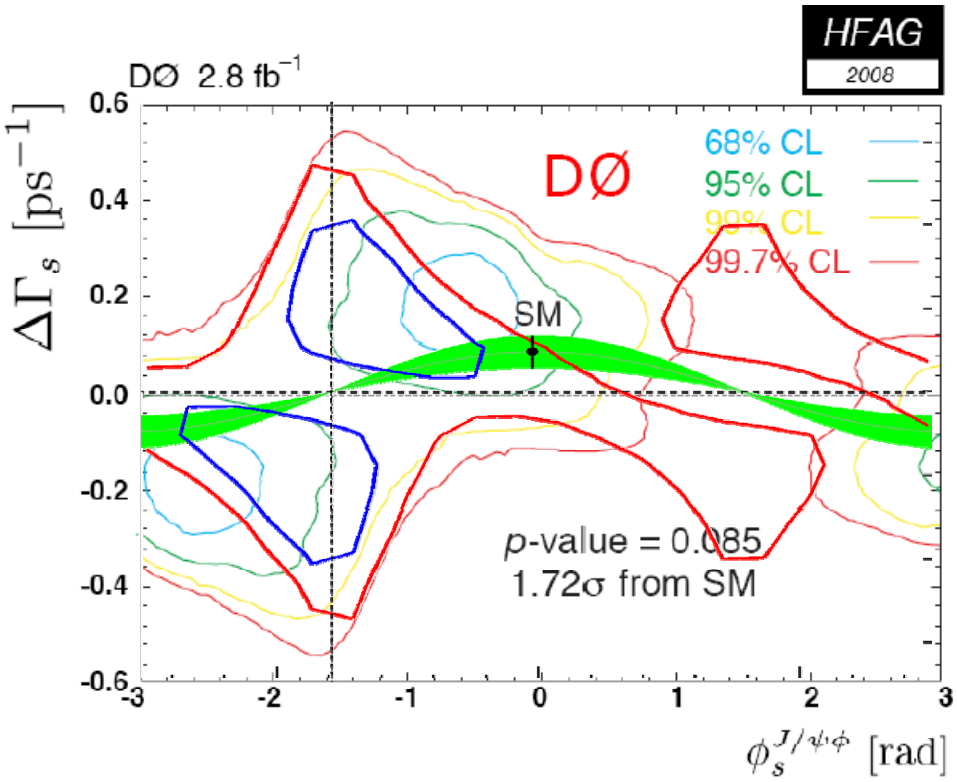
- Recent update finds 1.8σ (p-value = 7%) discrepancy with SM prediction for $\beta_s^{J/\psi\phi}$
  - Expect further improvement in statistical precision shortly!



www-cdf.fnal.gov/physics/new/bottom/080724.blessed-tagged_BsJPsiPhi_update_prelim/

Similar Discrepancy Observed by D0 in Flavor-Tagged $B_s^0 \to J/\psi\varphi$

- D0 result very similar to CDF's!
  - Discrepancy w/SM is 1.7σ, p-value = 0.085



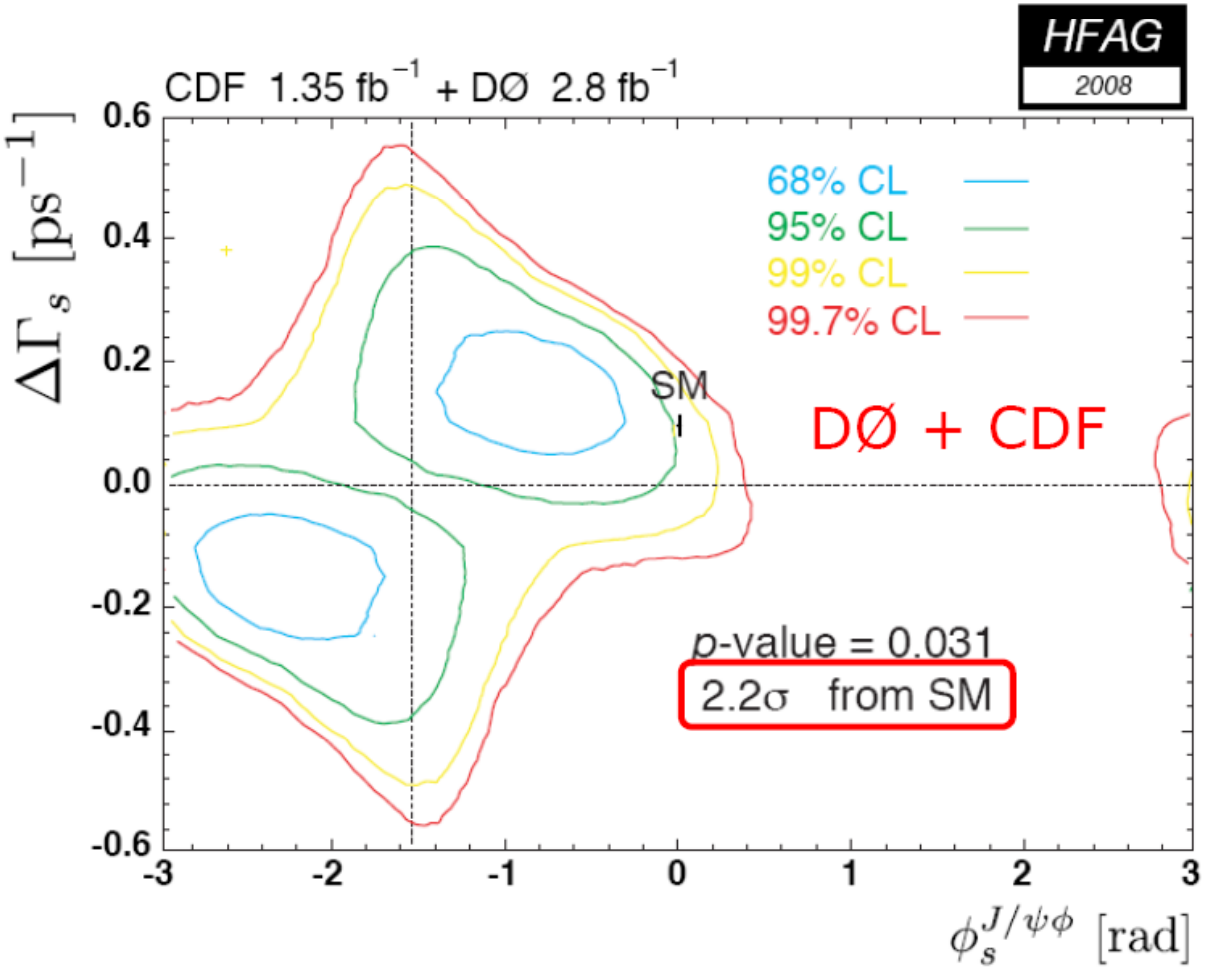
arXiv:0808.1297v1

Trend is identical,
$\varphi_s^{J/\psi\varphi} \equiv -2\beta_s$

D0 finds agreement in strong phase $\delta_{||}$ between $B_s^0 \to J/\psi\varphi$ (assuming $\varphi_s^{J/\psi\varphi} = 0$) and $B^0 \to J/\psi\, K^{*0}$

⇒ Use phases in $B^0 \to J/\psi\, K^{*0}$ to choose one of two solutions?

More Significant Discrepancy in Combined $B_s^0 \to J/\psi\phi$ Result



arXiv:0808.1297v1

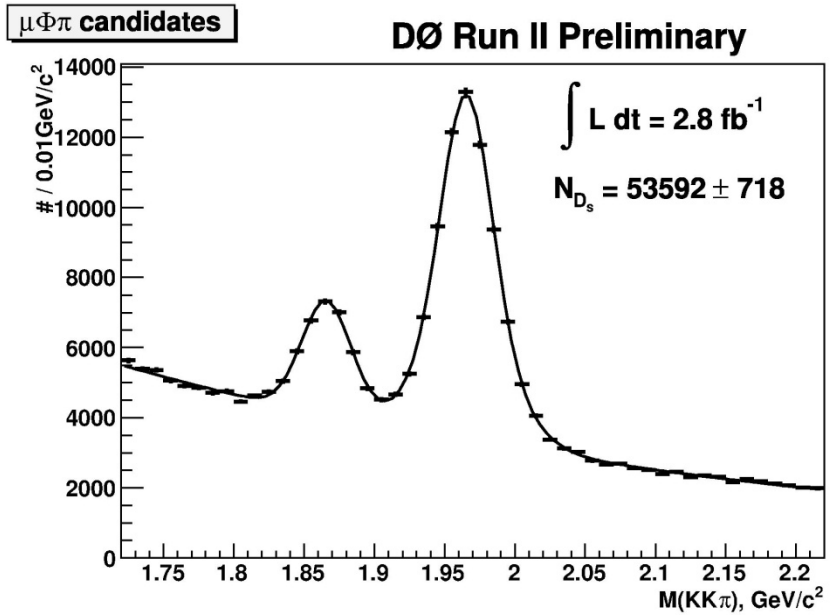
New CDF result not included in combination!

G. Hou et al suggest that discrepancy might be due to t' quark w/mass ~300 GeV/c^2 – 1 TeV/c^2

See G. Giurgiu's talk in Friday parallel session for details!

Most Precise Measurement of B_s^0 Semileptonic Asymmetry

- New flavor-tagged measurement of B_s^0 semileptonic asymmetry, a^s_{sl}
  - $B_s^0 \rightarrow D_s^- \mu^+ \nu X \rightarrow [\phi\pi^-]\, \mu^+ \nu X$
  - Depends on lifetime, $\Delta\Gamma$, Δm_s, and a^s_{sl}



Most precise measurement to date!

$$a^s_{sl} = -0.0024 \pm 0.0117(stat)^{+0.0015}_{-0.0024}(syst)$$

Previous, untagged measurement
$a^s_{sl} = 0.0245 \pm 0.0193$ (stat) ± 0.0035 (syst)

www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B55/

$\Delta\Gamma/\Gamma$ Measured in $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ Consistent with World Average

- Measure branching ratio to determine $\Delta\Gamma$ (2.8 fb^{-1})
  - Search for one $D_s \to \varphi\pi$, other to $D_s \to \varphi\mu\nu$

Under certain theoretical assumptions, $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ is nearly CP even

$$2Br(B_s \to D_s^{(*)} D_s^{(*)}) \simeq \Delta\Gamma_s^{CP} \left[\frac{1+\cos\phi_s}{2\Gamma_L} + \frac{1-\cos\phi_s}{2\Gamma_H} \right]$$

Find

$$Br(B_s^0 \to D_s^{(*)} D_s^{(*)}) = 0.042 \pm 0.015(\text{stat}) \pm 0.017(\text{syst})$$

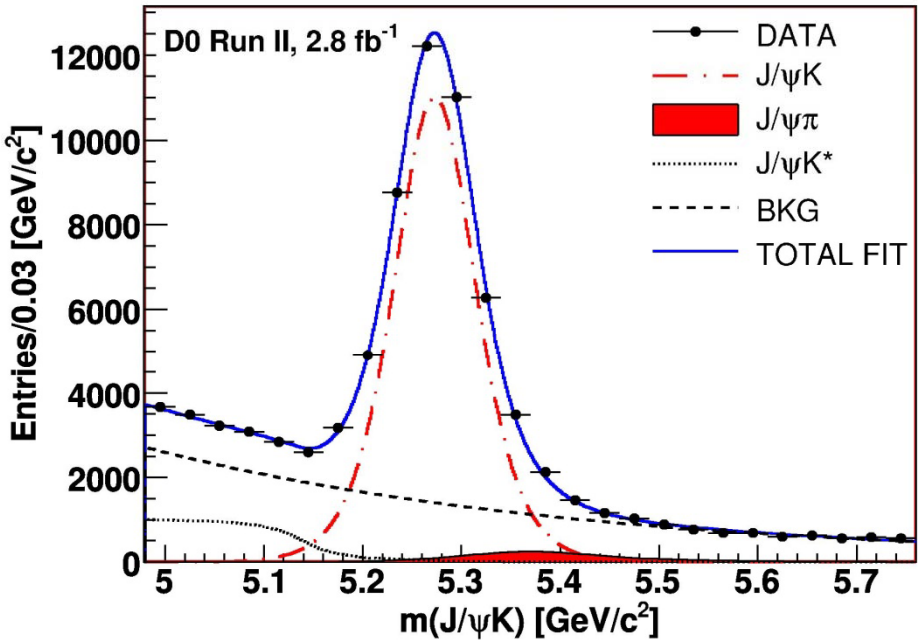
Assuming SM, $\varphi_s = 0$, $\Delta\Gamma^{CP} = \Delta\Gamma$

$$\frac{\Delta\Gamma_s}{\Gamma_s} = 0.088 \pm 0.030(\text{stat}) \pm 0.036(\text{syst})$$

Consistent with WA (2007) $\Delta\Gamma/\Gamma = 0.096^{+0.048}_{-0.053}$

www-d0.fnal.gov/Run2Physics/WWW/results/prelim/B/B53/

New Measurement of Direct CPV in $B^+ \to J/\psi K^+(\pi^+)$



PRL **100,** 211802 (2008)

- SM predicts $A_{CP}(B^+ \to J/\psi K^+) \sim 0.003$
  - NP might produce asymmetries up to ~0.01

$$A_{CP}(B^+ \to J/\psi K^+(\pi^+)) = \frac{N(B^- \to J/\psi K^-(\pi^-)) - N(B^+ \to J/\psi K^+(\pi^+))}{N(B^- \to J/\psi K^-(\pi^-)) + N(B^+ \to J/\psi K^+(\pi^+))}$$

$A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061\ (\text{stat}) \pm 0.0027\ (\text{syst})$

$A_{CP}(B^+ \to J/\psi \pi^+) = -0.09 \pm 0.08\ (\text{stat}) \pm 0.03\ (\text{syst})$

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Looking to the Future

MCGUINNESS, Ryan
The Need to Know
2008

Many Interesting New and Updated Measurements to Come!

- Updates to CPV measurements
  - Expect 2-4x higher yield depending on measurement
  - More flavor-tagged CPV results
- Updated lifetimes with higher statistics
  - Updated $B \to J/\psi X$ lifetimes with 2x more data
    - Will give most precise B^+, Λ_b^0 lifetimes to date
  - New lifetime measurements with novel techniques
    - $B_s^0 \to D_s^- \pi^+$ lifetime measured with MC-free method
- Observation of new states?

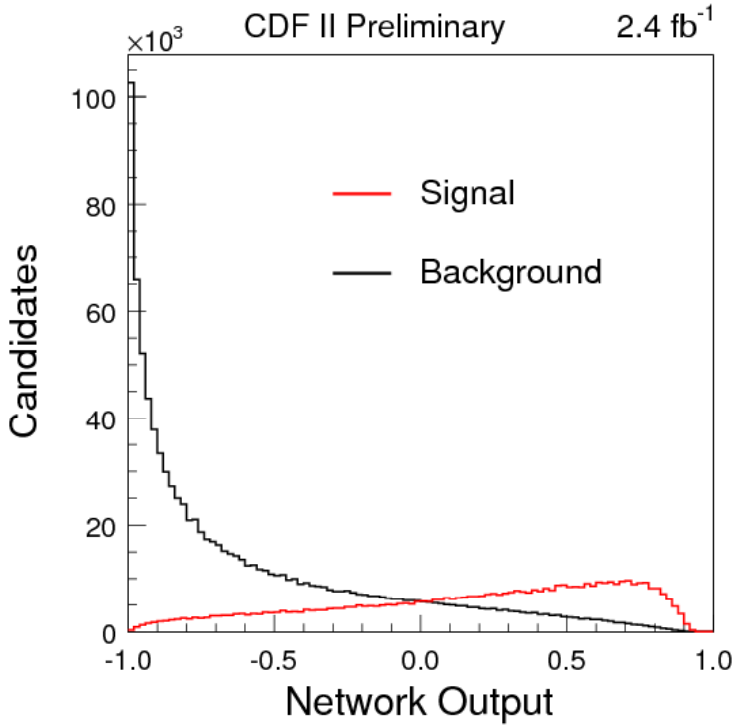
Valuable Contributions to Study of B Hadrons Made at Tevatron

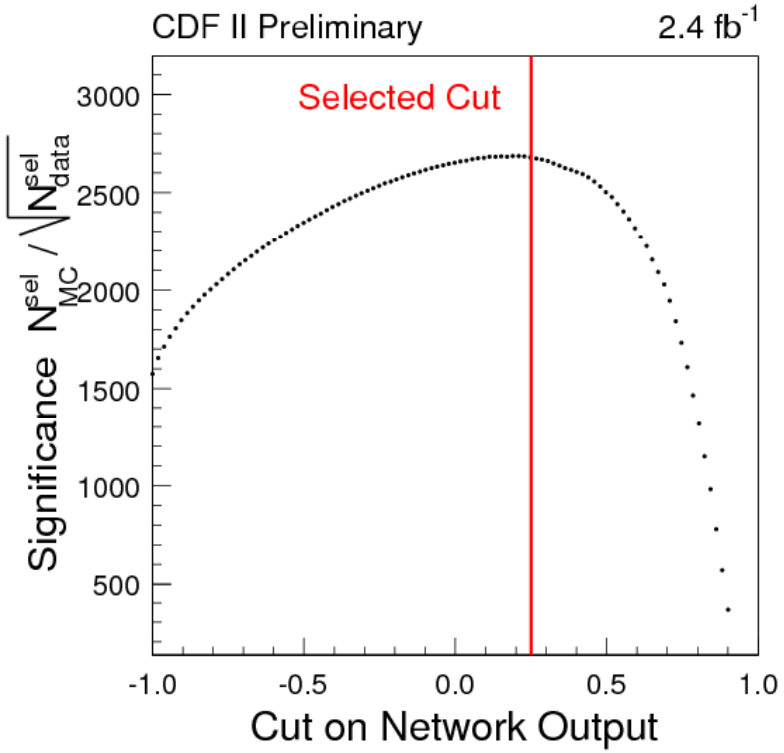
- Exciting time for B physics at the Tevatron!
  - Many significant contributions to knowledge of B hadrons has been made
  - Expect many interesting, important updates in the next couple of years!
- Look forward to contributions to field from LHC experiments!

Back-up

Selection of X(3872)

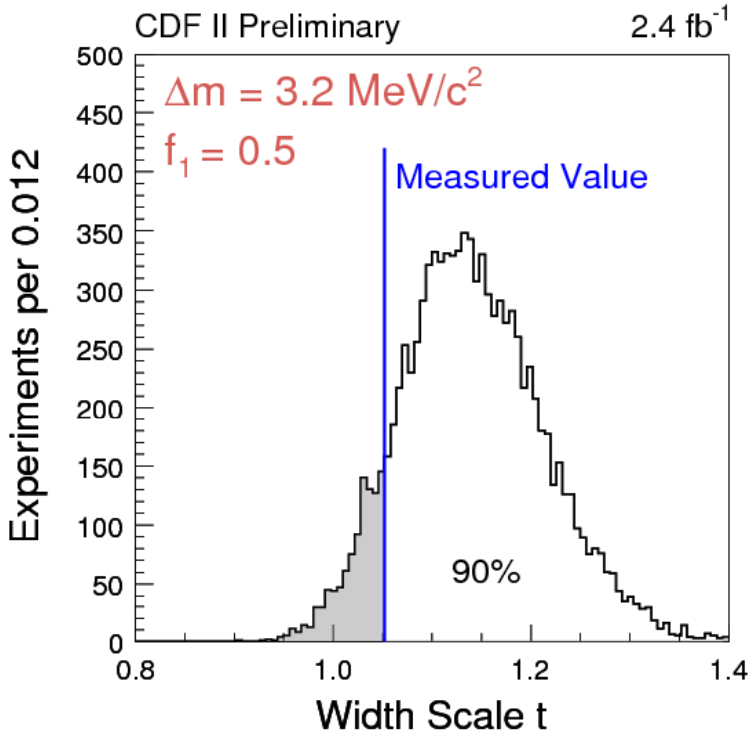
- Use ANN to select events
  - Optimize selection on Monte Carlo (signal) and mass sidebands (background)

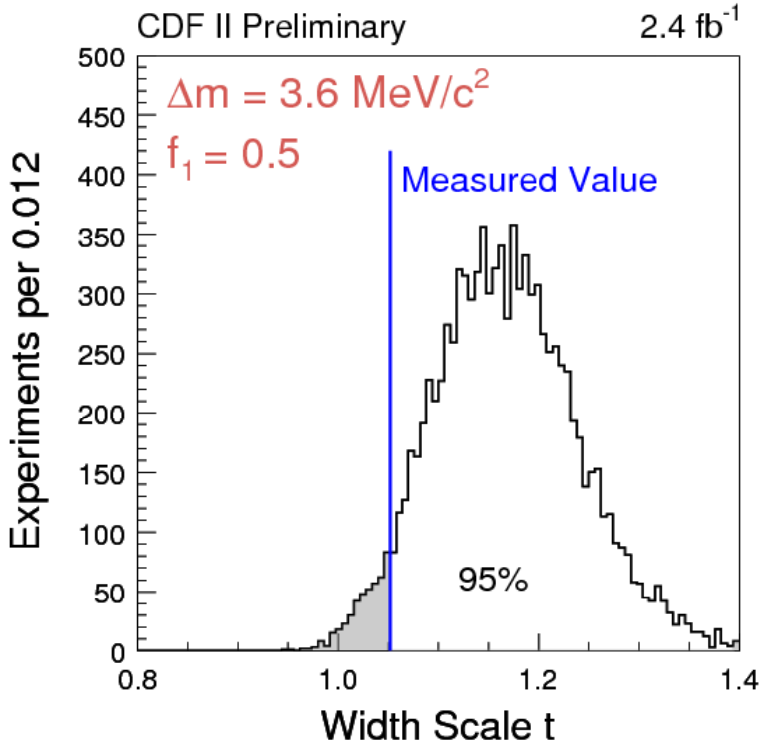




Mass Splitting of X(3872)

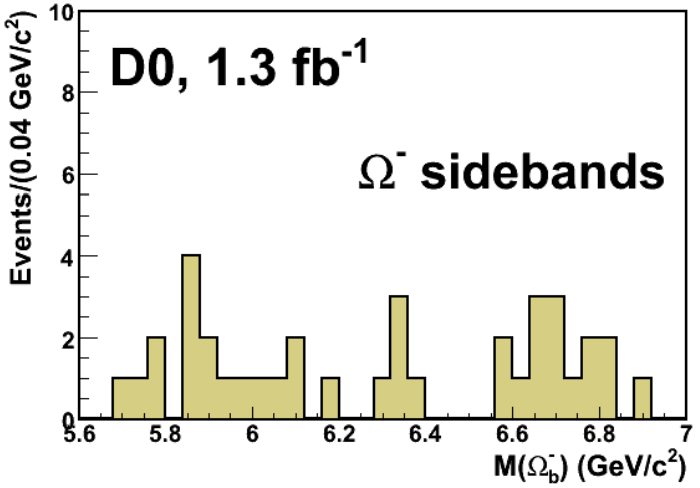
- Model resolution with Monte Carlo simulation
  - Width scale floats freely in fit

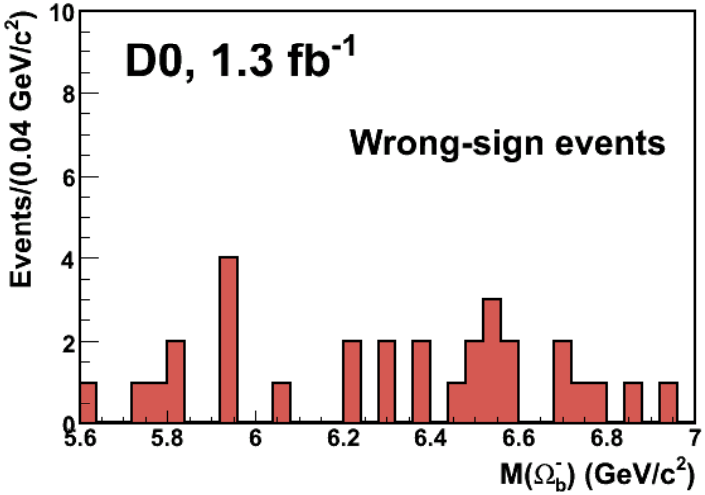


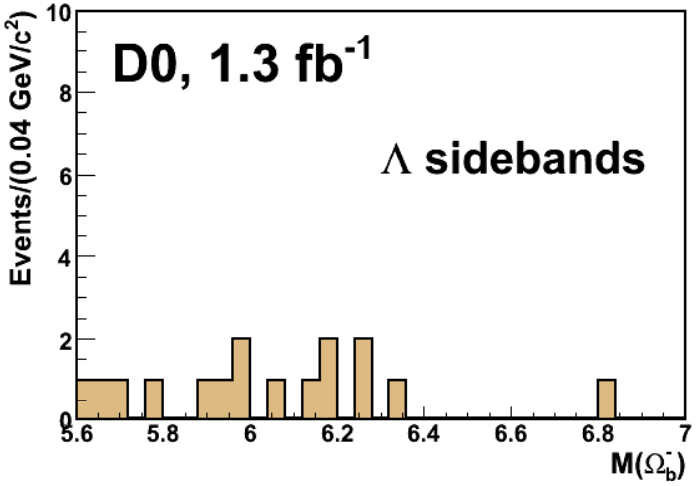


Cross-Checks of Ω_b^- Signal (1)

- Check WS events and mass sidebands for spurious excesses
  - None observed!

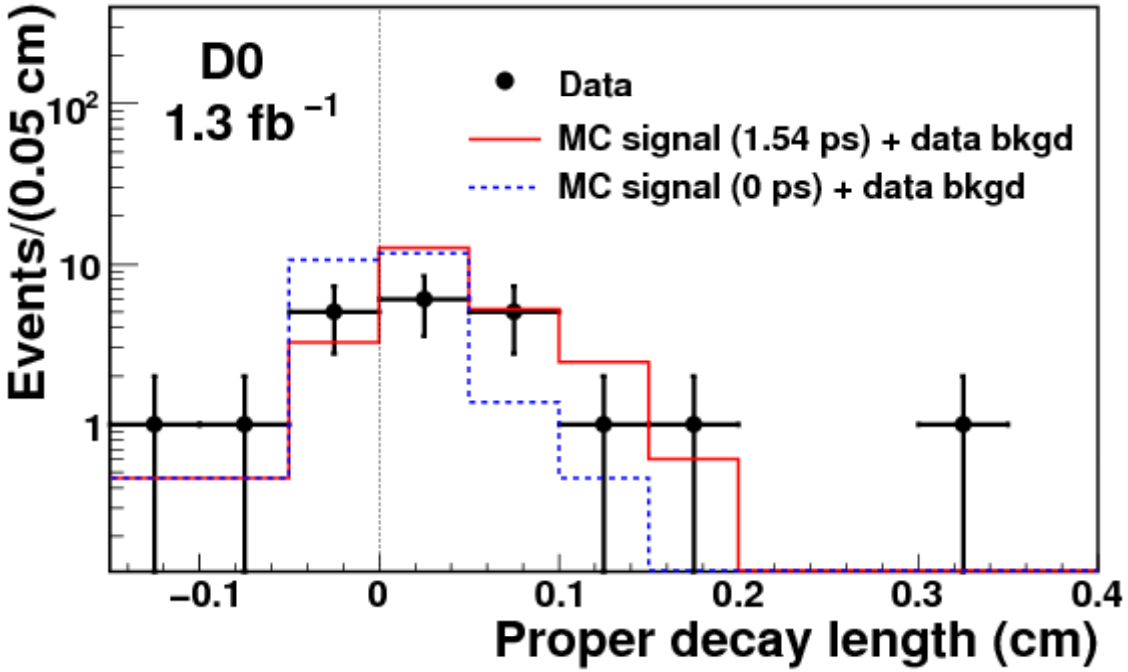




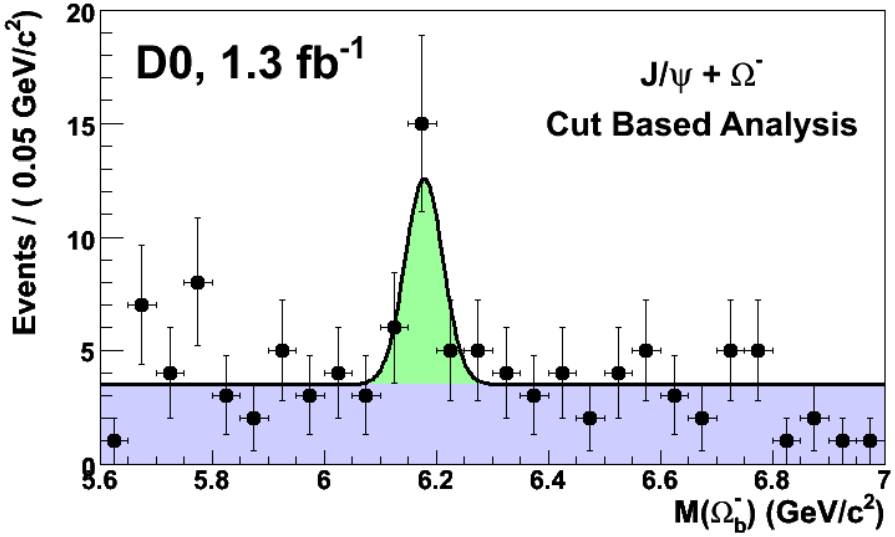


Cross-Checks of Ω_b^- Signal (2)

- Check lifetime distribution of Ω_b^- candidate events
  - Consistent with B hadron lifetime



Cut-based Analysis of Ω_b^-



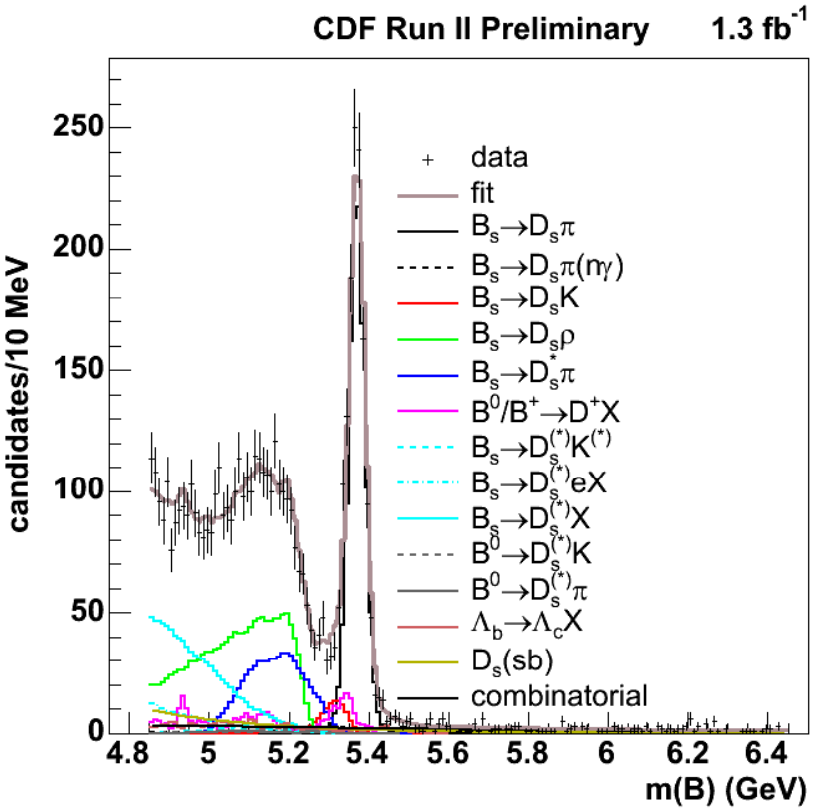
- Alternatively, try using simpler cut-based analysis
  - Find 15.7 ± 5.3 (stat) events
  - m = 6.177 ± 0.015 GeV/c^2
  - Signal significance is 3.9σ

Ω_b^- Significance Calculation

- Evaluate significance from likelihood ratio of background only hypothesis (L_B) to signal + background hypothesis (L_{S+B})

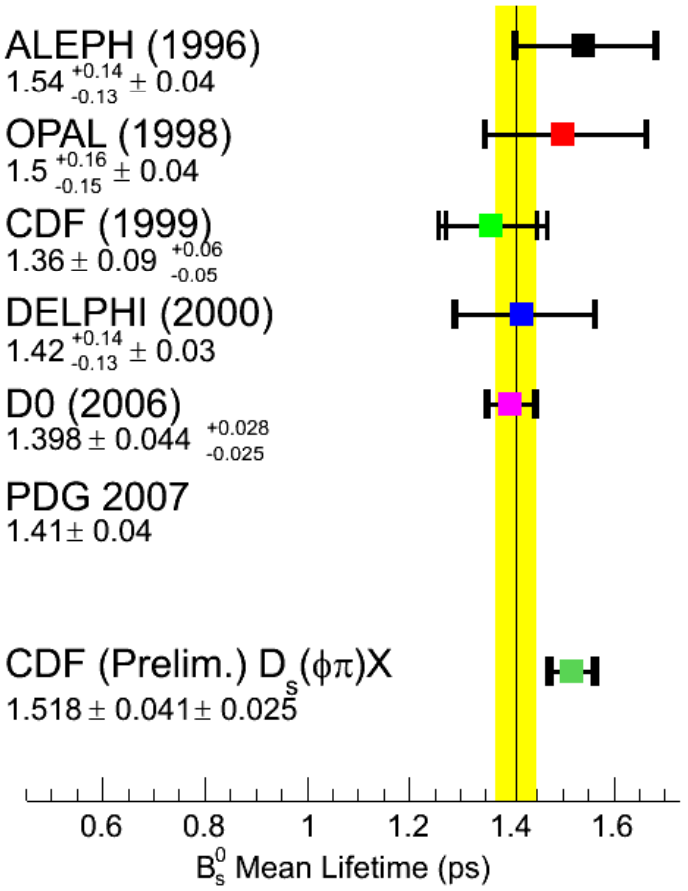
$$\sqrt{-2\Delta \ln L} = \sqrt{-2\ln\left(\frac{L_B}{L_{S+B}}\right)}$$

B_s^0 Mass Fit in Lifetime Measurement



- Perform simultaneous unbinned maximum likelihood fit to mass and lifetime
  - Use partially reconstucted decays to double statistics
    - e.g. $B_s^0 \to D_s^- \rho^+ (\to \pi^0 \pi^+)$
  - ~2200 B_s^0 candidates

Comparison of B_s^0 Lifetime with Prev. Results

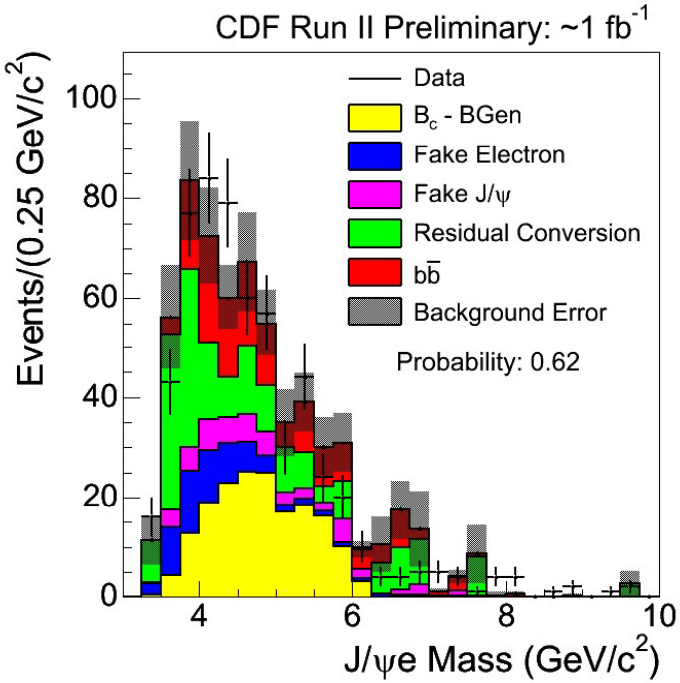


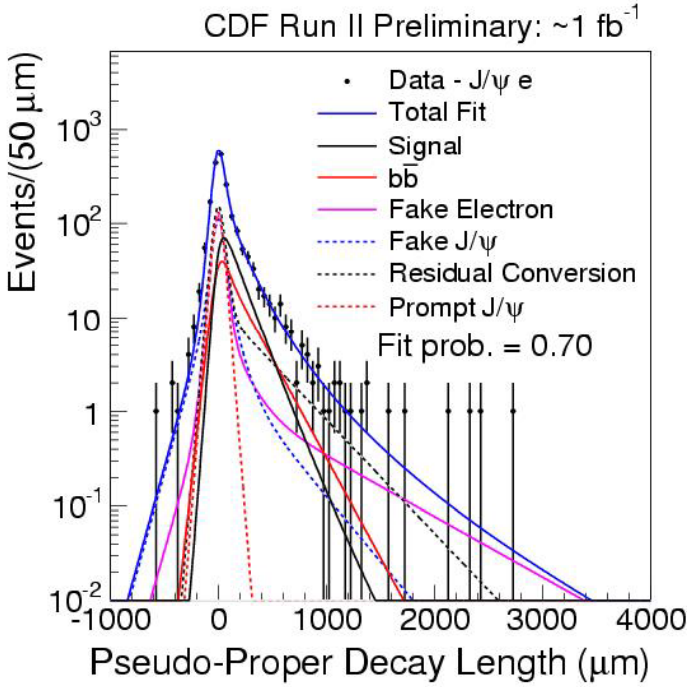
- B_s^0 lifetime is higher than recently measured B_s^0 lifetimes in flavor-specific decay modes
  - Expect 50% of Γ_L, Γ_H in flavor-specific modes

Measurement of $B_c^+ \to J/\psi e^+ X$ Lifetime

- Fit lifetime only, use mass as cross-check
  - Determine all background shapes and normalizations from data if possible, MC otherwise ⇒ constrain in fit

$$c\tau(B_c^+ \to J/\psi e^+ X) = 122\ ^{+18}_{-16}\ (\text{stat})\ \mu\text{m}$$

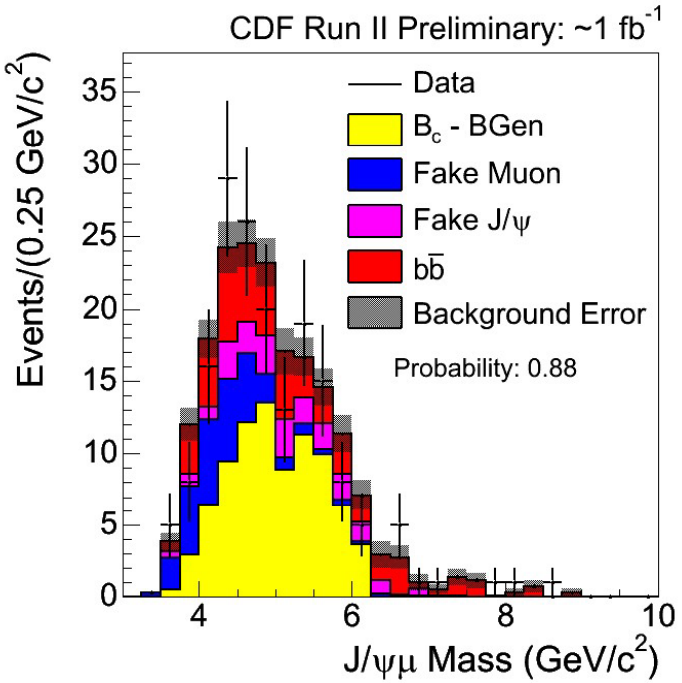


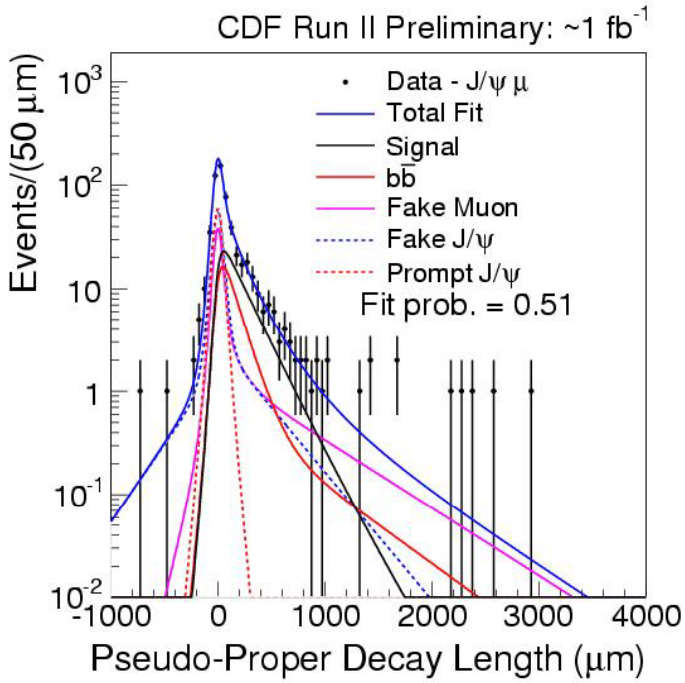


Measurement of $B_c^+ \to J/\psi\mu^+X$ Lifetime

- Fit lifetime only, use mass as cross-check
  - Determine all background shapes and normalizations from data if possible, MC otherwise ⇒ constrain in fit

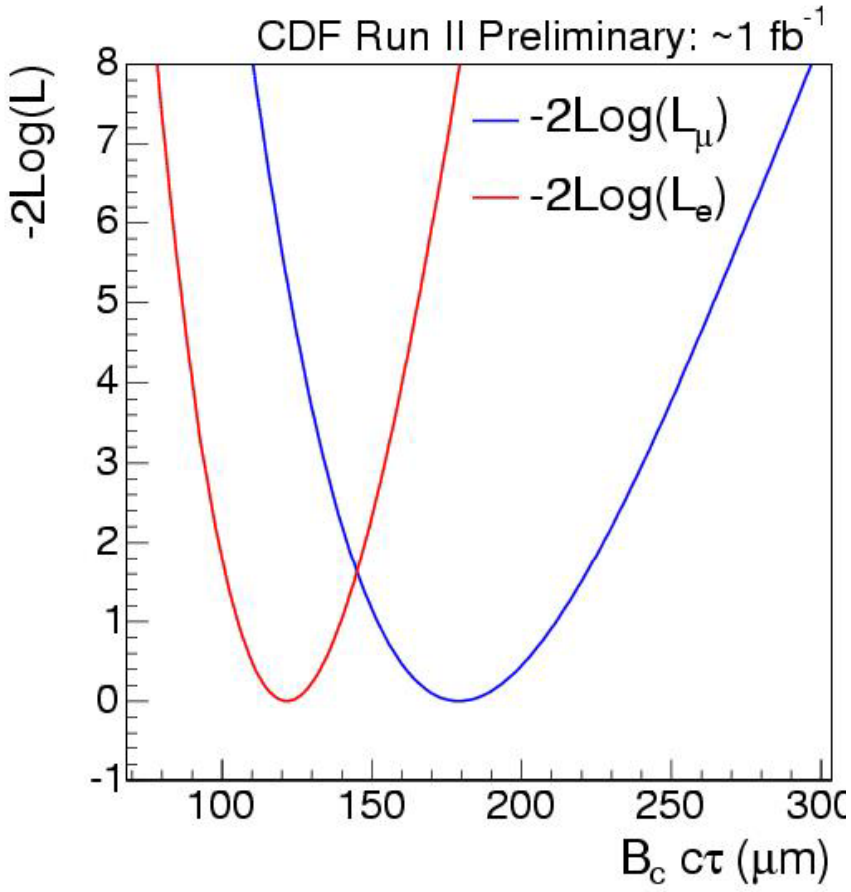
$$c\tau(B_c^+ \to J/\psi\mu^+X) = 179\ ^{+33}_{-27}\ (\text{stat})\ \mu\text{m}$$

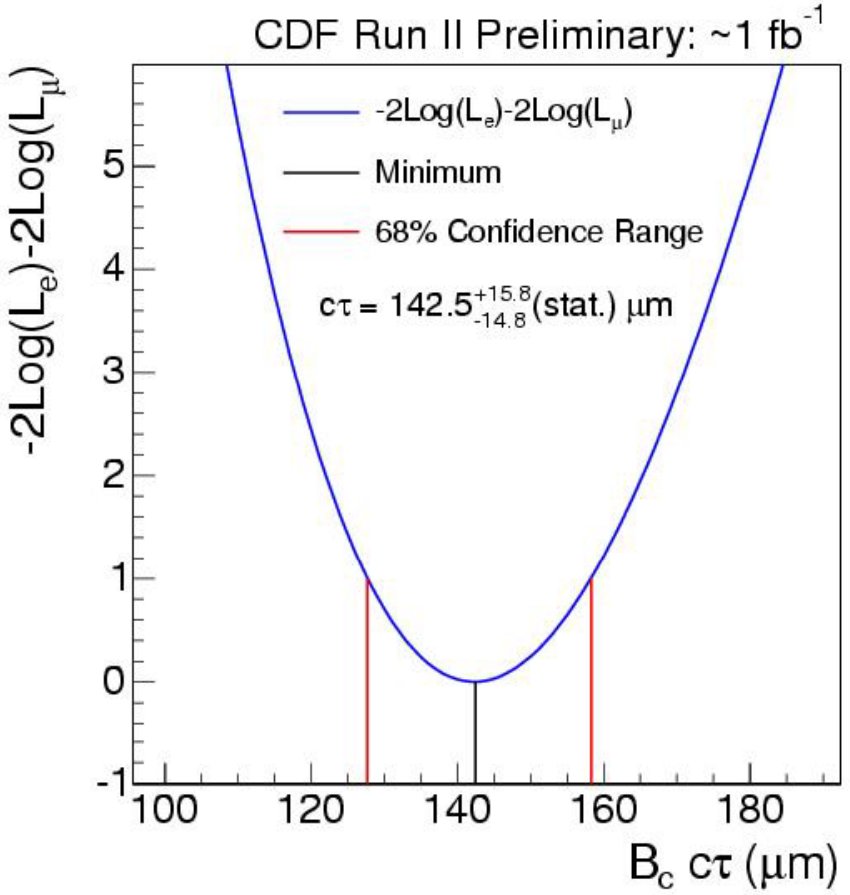




Combination of Semilep. B_c^+ Lifetimes

- Combine $-2\ln L_e$, $-2\ln L_\mu$

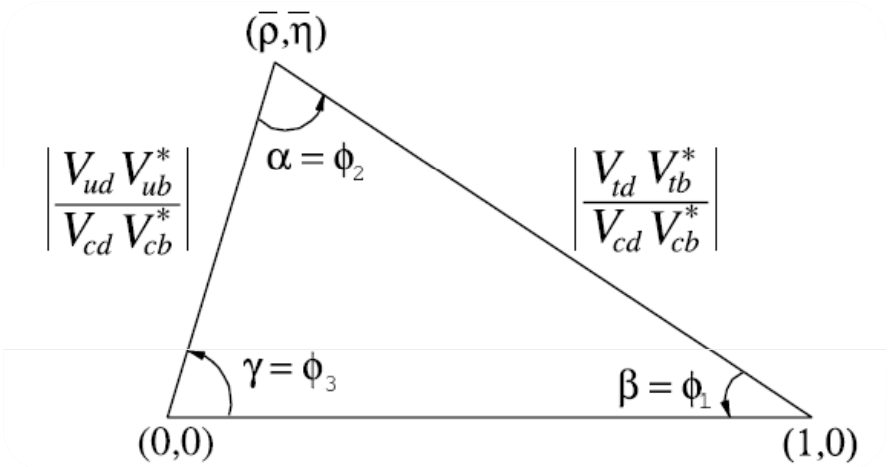


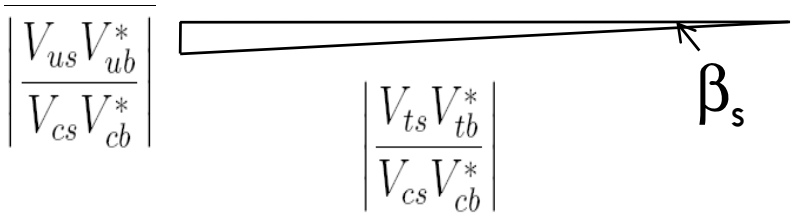


Unitarity Relations in B^0/B_s^0

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0 \qquad V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

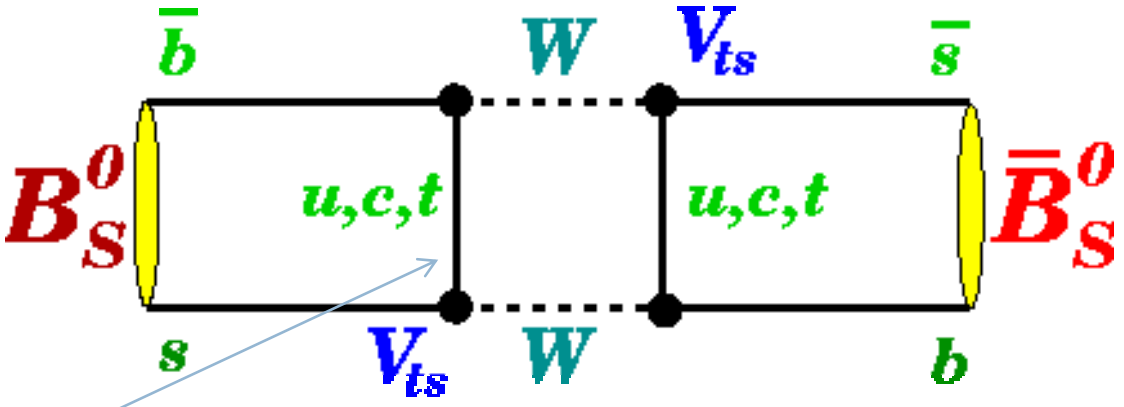




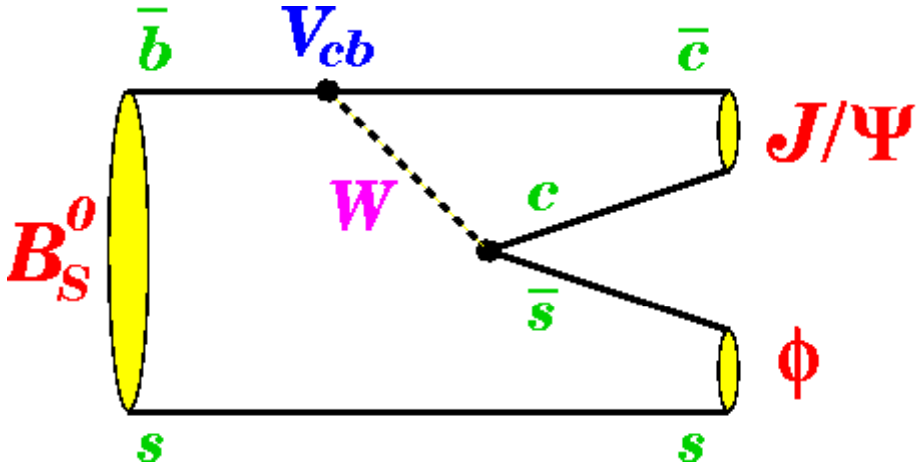
Mixing and Decay in B_s^0

Mixing between particle and anti-particle occurs through the loop processes

Oscillations are very fast- ~3 trillion times per second!

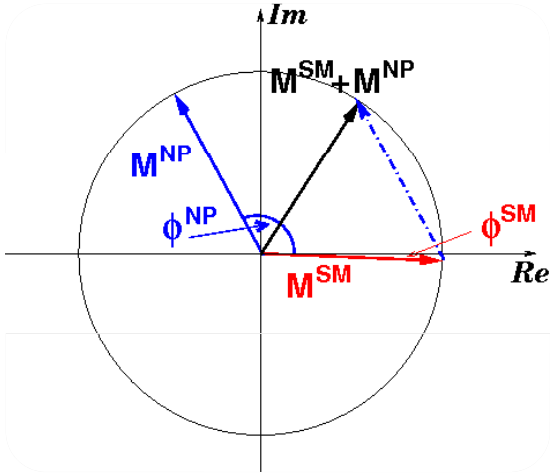


New particles can contribute to box diagram!



New Physics in B_s^0 Decays

- $B_s^0 - \overline{B}_s^0$ oscillations observed by CDF
  - Mixing frequency Δm_s now very well-measured
  - Precisely determines $|M_{12}|$ - in good agreement w/SM pred.
- Phase of mixing amplitude is still very poorly determined!



$M_{12} = |M_{12}|e^{i\varphi_m}$,
where $\varphi_m = \arg(V_{tb}V_{ts}^*)^2$

New physics could produce large CP phase!