An Updated Measurement of the B_s Mixing Phase $\sin 2\beta_s$ at CDF

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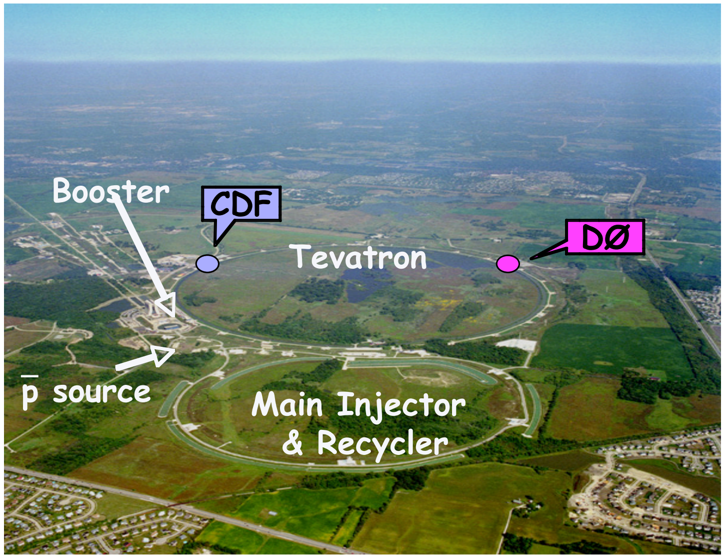
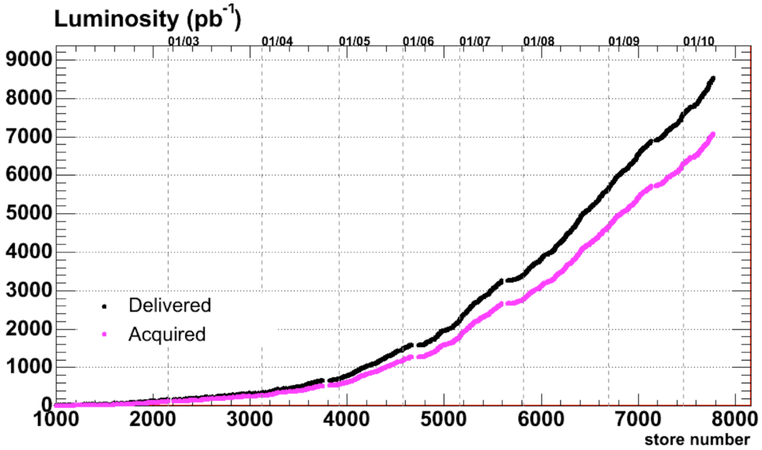
The Tevatron

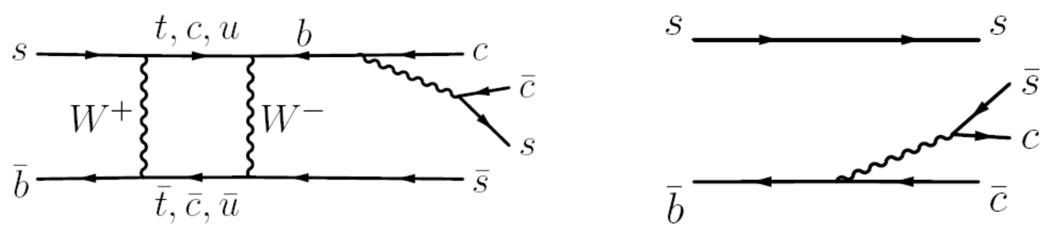
- p anti-p collisions at a center of mass energy of 1.96 TeV
- ~5 fb^{-1} data used for this analysis



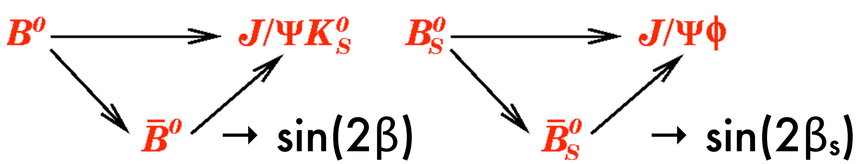


Possible New Physics in $B_s^0 \rightarrow J/\Psi\phi$

- $B_s^0 \rightarrow J/\Psi\phi$ decays can occur directly, or via mixing
- Mixing box diagram makes this system a prime place to seach for new physics



- CP violation can occur in interference between direct decays and decays via mixing

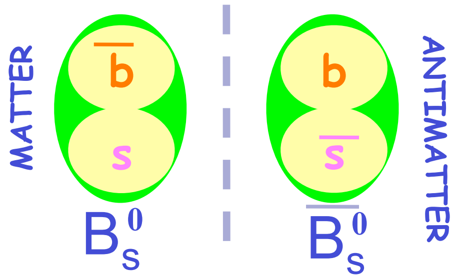


- New physics contributions could affect size of CP violation

CP Violation in B_s^0 Mixing

Time evolution of states is given by the time-dependent Schrodinger equation:

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



Diagonalizing M (mass matrix) and Γ (decay matrix) translates flavor eigenstates to heavy and light mass eigenstates

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

Observables are:

$$\boxed{\Delta m_s} = m_H - m_L \approx 2\,|\,M_{12}\,|$$ Mass difference/oscillation frequency

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

$$\boxed{\phi_s} = arg\left(\frac{-M_{12}}{\Gamma_{12}}\right)$$ CP Phase

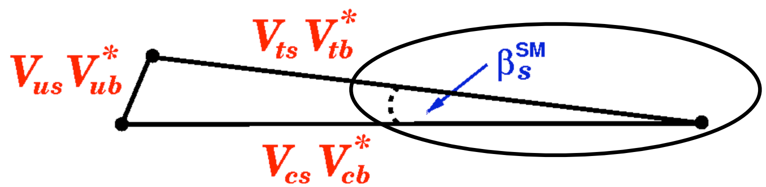
β_s in the Standard Model

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

Use unitary property of CKM matrix to derive unitary relations:

(2nd and 3rd columns)

$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$



Accessible through $B_s^0 \to J/\Psi\phi$ decays

$$\beta_s^{SM} = arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \sim \lambda^2 \approx 0.02$$

($\lambda = \sin(\theta_{Cabibbo})$)

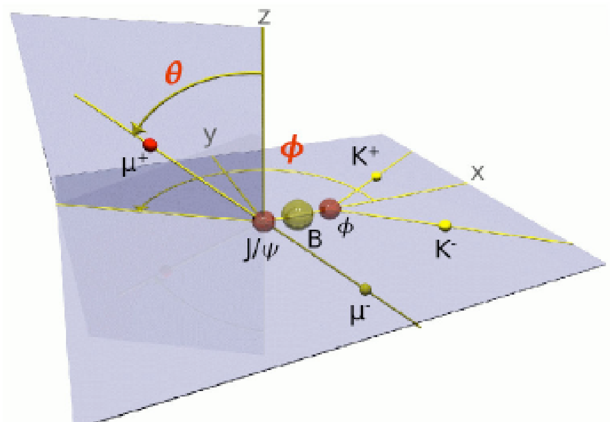
If a new phase, ϕ_s^{NP} exists,

$\phi_s = \phi_s^{SM} + \phi_s^{NP} \sim \phi_s^{NP}$, $2\beta_s = 2\beta_s^{SM} - \phi_s^{NP} \sim -\phi_s^{NP}$

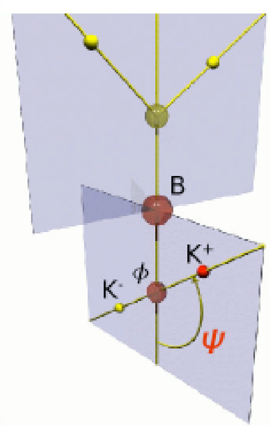
For large new physics phase, $2\beta_s = -\phi_s^{NP} = -\phi_s$

$B_s^0 \to J/\Psi\phi$ Phenomenology

- Final state includes L=0 (S-wave), L=1 (P-wave), L=2 (D-wave) contributions
- Spin states can be mapped to *CP* states
    - L=0 and L=2 → *CP* even, L=1 → *CP* odd



J/ψ rest frame



φ rest frame

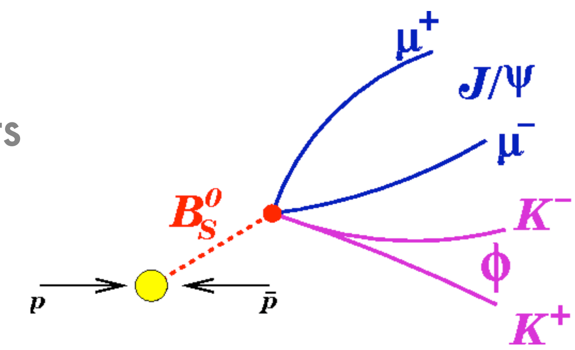
- Final state amplitudes identified by linear polarizations of J/Ψ and ϕ
    - $A_\perp(t)$ (transversely polarized, *CP* odd), $A_{||}(t)$ (transversely polarized, *CP* even), $A_0(t)$ (longitudinally polarized, *CP* even)
    - Define angles: $\vec{\rho} = (\theta, \varphi, \psi)$

Strong phases:

$$\delta_{||} = arg(A_{||}(0)A_0^*(0))$$
$$\delta_\perp = arg(A_\perp(0)A_0^*(0))$$

Analysis Strategy

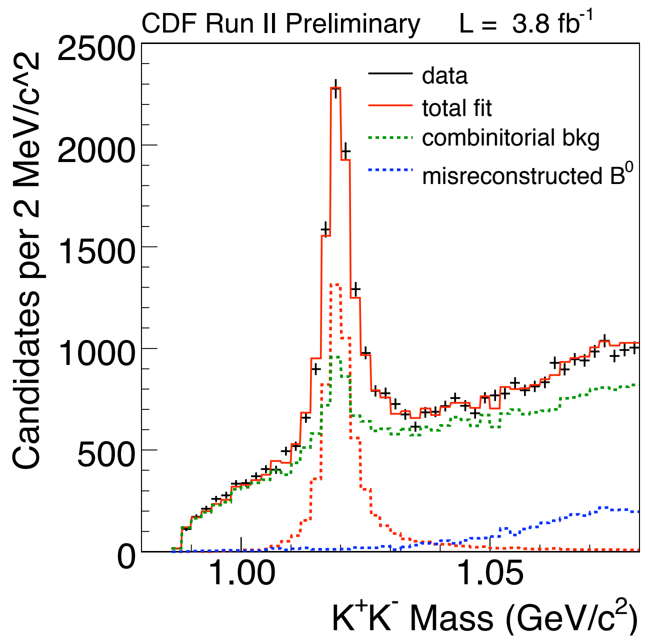
- Reconstruct $B_s^0 \rightarrow J/\Psi(\rightarrow \mu^+\mu^-)\phi(\rightarrow K^+K^-)$ events



- Determine relative proportion of *CP*-odd to *CP*-even using angular analysis
- Increase sensitivity to β_s by separately tracking time evolution of B_s^0 and anti-B_s^0 with flavor tagging algorithms
- Combine angular analysis with time-dependent, flavor-tagged analysis in unbinned maximum likelihood fit
    - Extract parameters of interest: β_s, $\Delta\Gamma$ (decay width difference), $\tau(B_s^0)$ (B_s^0 average lifetime), transversity amplitudes, strong phases

Non-resonant KK/f_0 Contamination

- $B_s^0 \to J/\Psi K^+K^-$ and $B_s^0 \to J/\Psi f_0$ could contaminate $B_s^0 \to J/\Psi\phi$ signal and bias measurement of β_s
  - Include possibility of non-resonant KK/f_0 in likelihood
    - Model both states as flat in ϕ mass region
    - Perform mass integration over ϕ mass window



A fit to KK invariant mass does not show large S-wave contamination

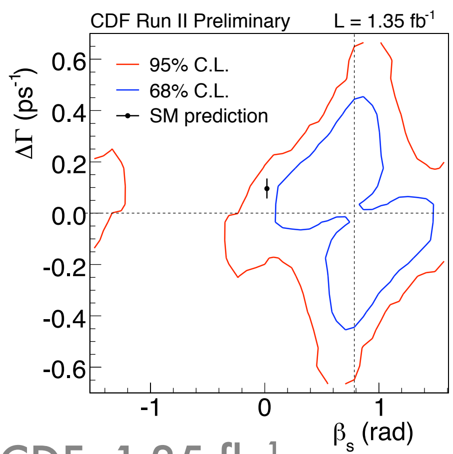
Symmetries of Likelihood

- The likelihood (before adding S-wave) reveals an exact symmetry

$$(\beta_s, \Delta\Gamma, \delta_\perp, \delta_{||}) \Leftrightarrow (\pi/2 - \beta_s, -\Delta\Gamma, \pi - \delta_\perp, 2\pi - \delta_{||})$$

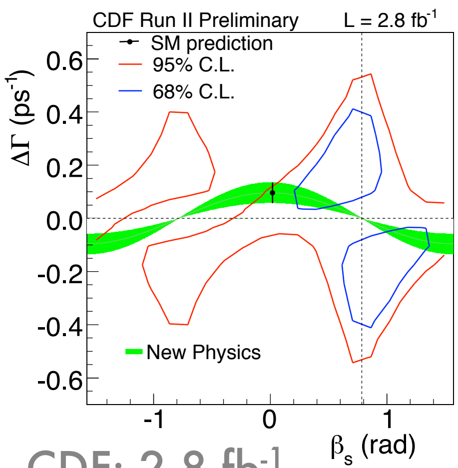
  - Creates an ambiguity in measurement of β_s
- Addition of (substantial) S-wave breaks the symmetry
  - S-P interference term is not invariant under the old transformation
  - Removes ambiguity, leaving one solution for β_s

Previous results



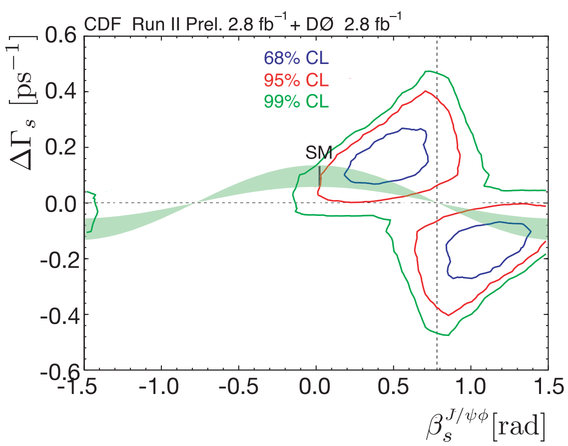
CDF: 1.35 fb^{-1}

P-value for SM point = 15%



CDF: 2.8 fb^{-1}

P-value for SM point = 7%

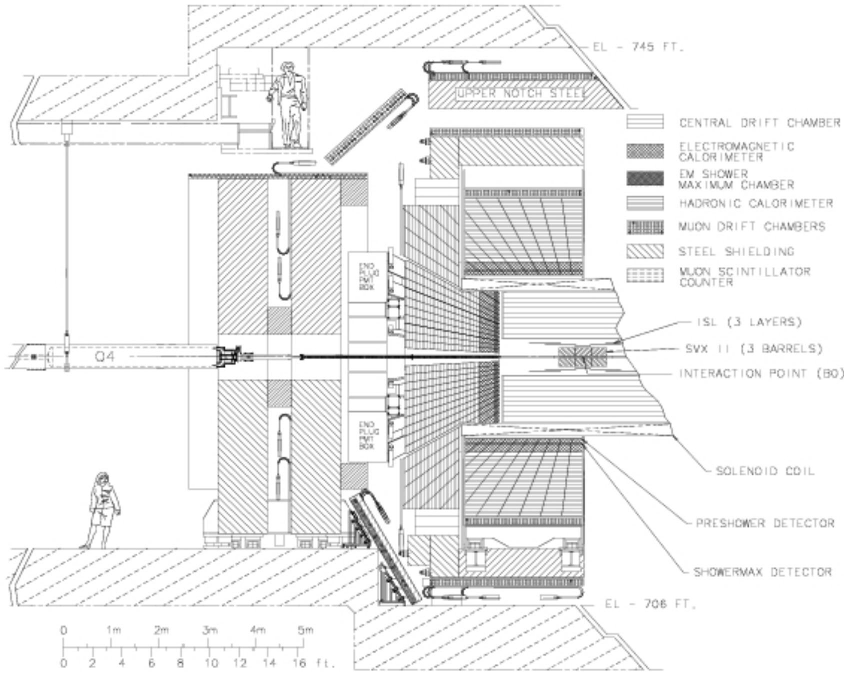


CDF: 2.8 fb^{-1} + DØ: 2.8 fb^{-1}

P-value for SM point = 3.4%

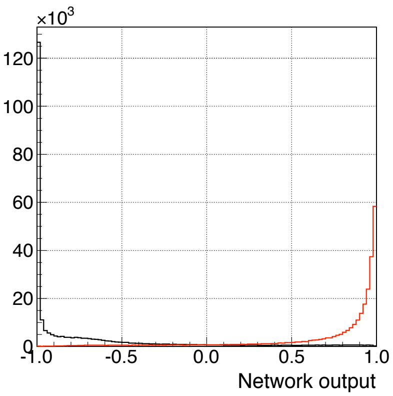
CDF

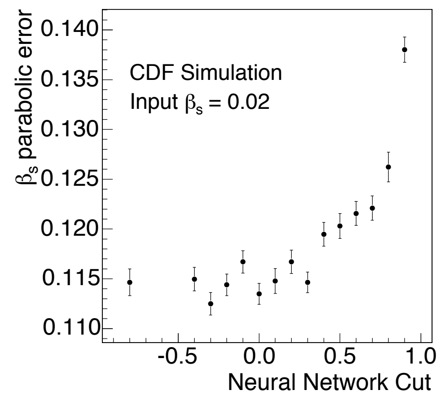
- Data collected at CDF using di-muon trigger
- This analysis relies on:
  - tracking subsystems for mass and spatial resolution
    - decay time resolution ~0.1ps (B lifetime is ~1.5ps)
  - particle identification (dE/dx and time of flight) for selection and tagging

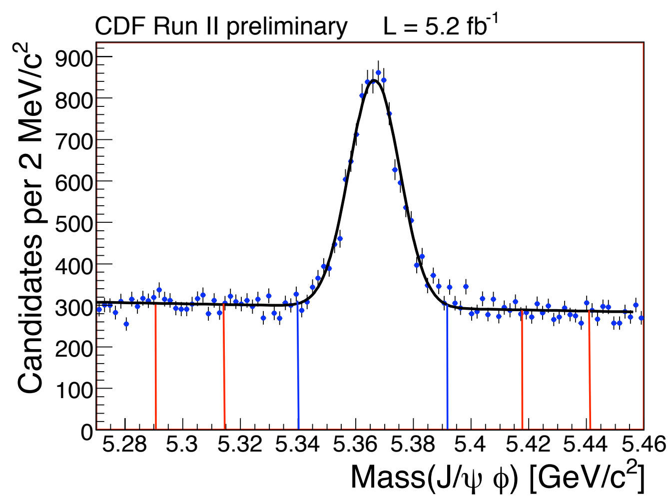


Signal Selection

- Suppress background using artificial neural network
  - Training variables include p_T of tracks and decay particles, vertex probability for decay particles
  - Cut on neural network output is chosen by minimizing β_s errors on pseudo-experiments

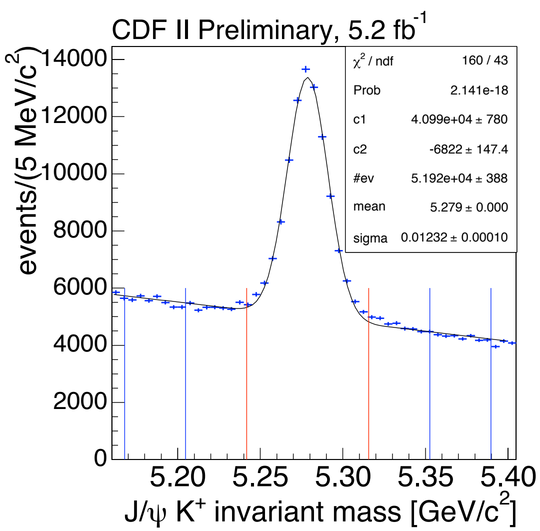


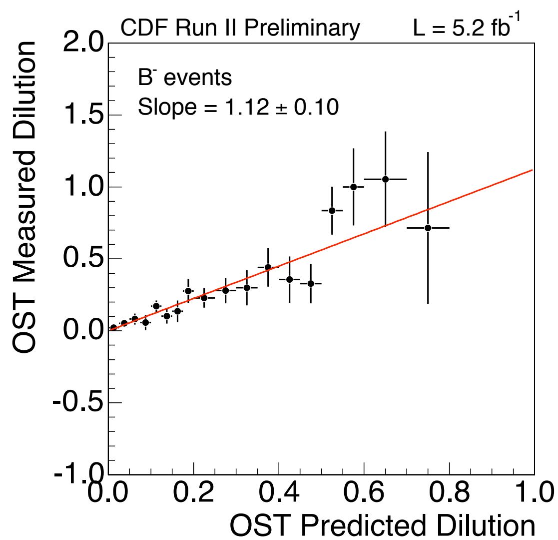


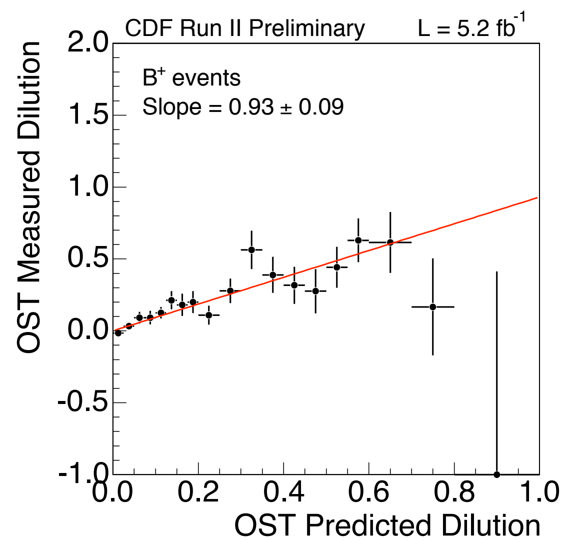


OST Calibration

- Calibrate opposite side tagger using $B^+ \rightarrow J/\Psi\ K^+$ events, which have same opposite side fragmentation behavior as B_s^0
- $B^+ \rightarrow J/\Psi\ K^+$ decays are self-tagging
  - Compare measured to predicted dilution

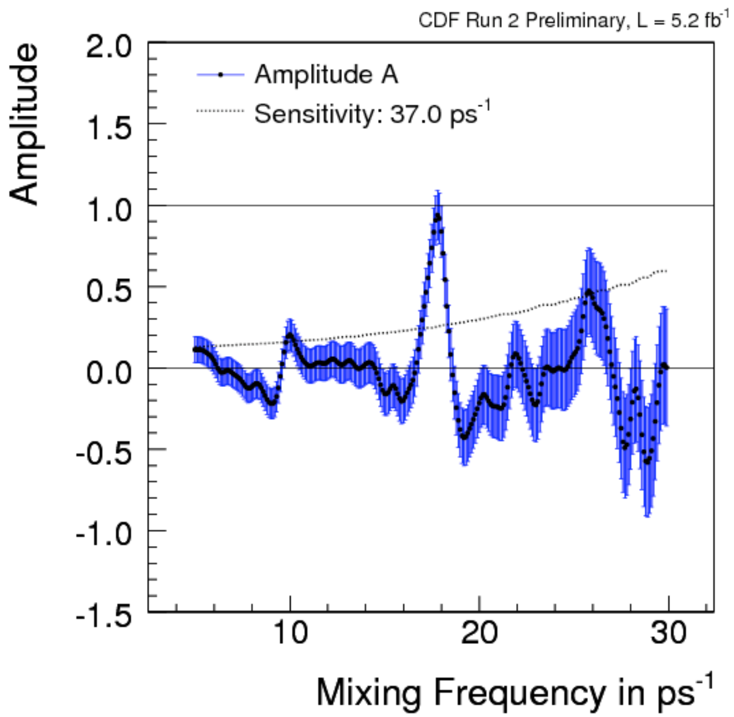






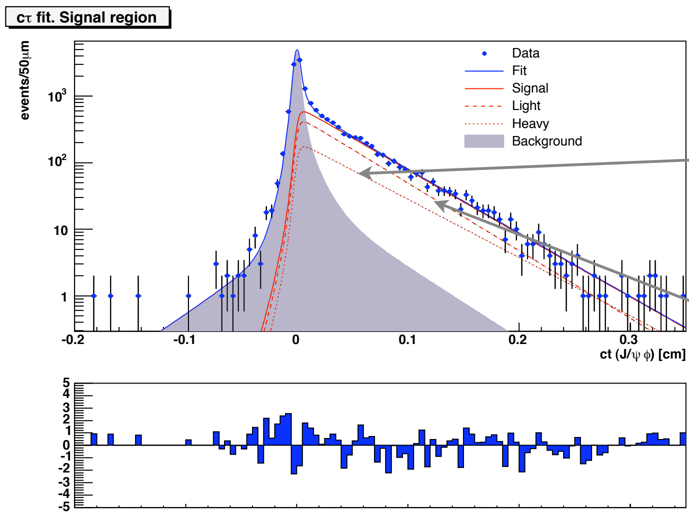
SSKT Calibration

- Remeasured B_s^0 mixing on 5.2 fb^{-1} of data
  - $B_s^0 \to D_s^- \pi^+$ and $B_s^0 \to D_s^- (3\pi)^+$ channels
- For amplitude scan of Δm_s, probability normalized such that A=1 at true value of Δm_s
  - Measured amplitude relates measured to predicted dilution
  - A = 0.94 ± 0.15 (stat) ± 0.13 (syst)
  - Δm_s = 17.79 ± 0.07 ps^{-1}



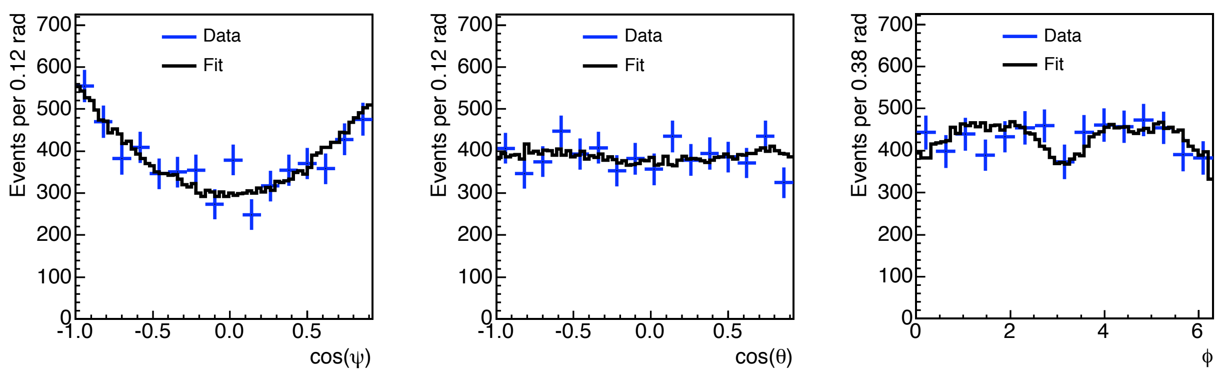
Fit Projections

Check performance of fit with fit projections of proper time and transversity angles



Lifetime distribution for B_s^H

Lifetime distribution for B_s^L



Results: Lifetime and Width Difference

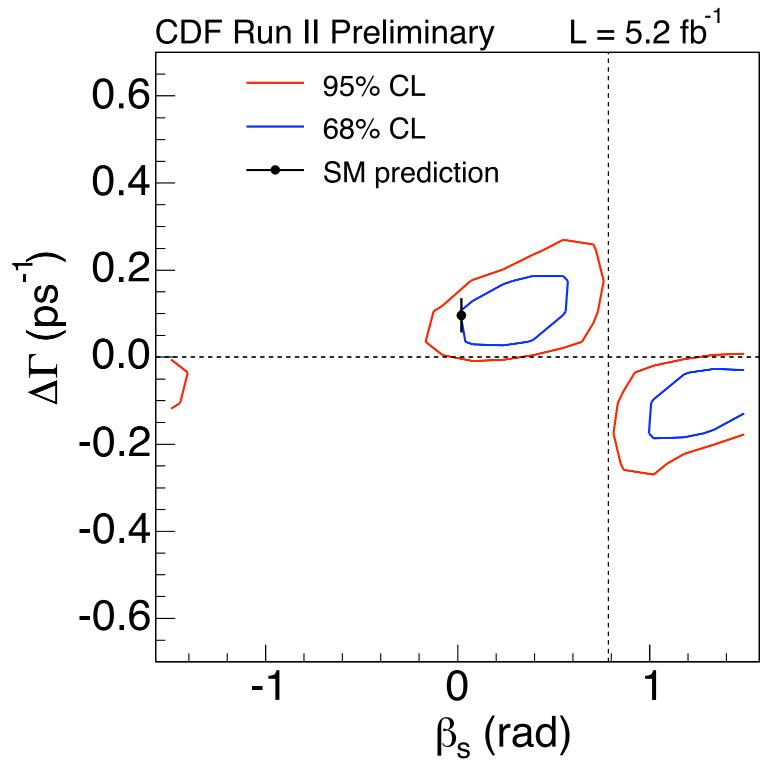
- Likelihood shows biases (particularly for β_s) and non-Gaussian behaviors
  - Likelihood with *CP* violation fixed to zero is well-behaved, use to make point estimates

$$
\begin{aligned}
c\tau_s &= 458.7 \pm 7.5(stat) \pm 3.6(syst)\mu m \\
\Delta\Gamma_s &= 0.075 \pm 0.035(stat) \pm 0.01(syst)ps^{-1} \\
|A_{||}(0)|^2 &= 0.231 \pm 0.014(stat) \pm 0.015(syst) \\
|A_0(0)|^2 &= 0.524 \pm 0.013(stat) \pm 0.015(syst) \\
\phi_\perp &= 2.95 \pm 0.64(stat) \pm 0.07(syst)
\end{aligned}
$$

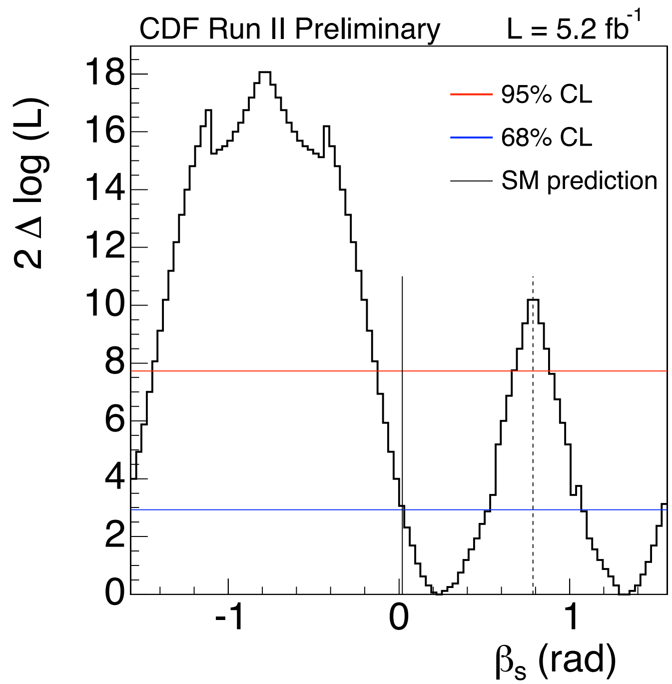
Systematics include modeling of angular efficiency, mass distributions, resolution function, background lifetime, background angular distributions, tracking alignment

Results: Final contour

- Profile likelihood ordering technique used to guarantee coverage at 68% and 95% confidence levels
- P-value at SM point is 44%
- Two solutions are still of nearly identical depth, cannot choose one solution over the other



Results: β_s Scan



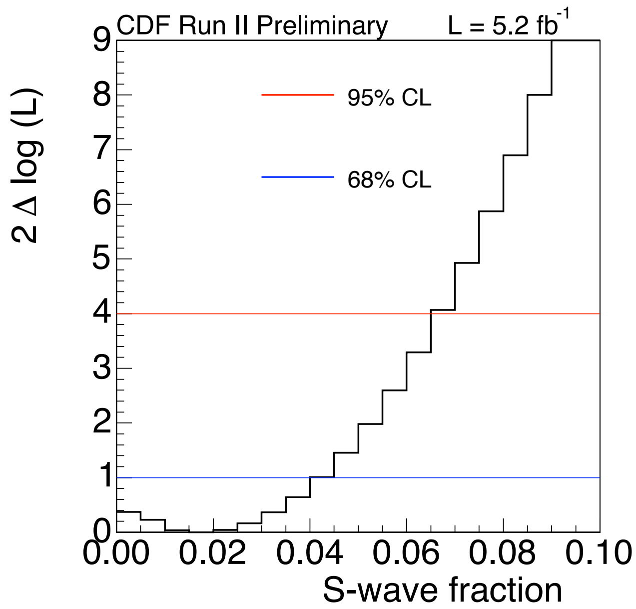
P-value at SM point is 31%

$\beta_s \in$ [0.02, 0.52] U [1.08, 1.55] at 68% CL

$\beta_s \in$ [-0.13, 0.68] U [0.89, π/2] U [-π/2, -1.44] at 95% CL

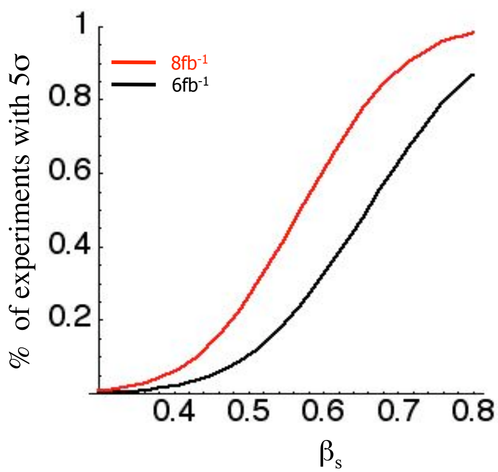
Results: S-wave Fraction

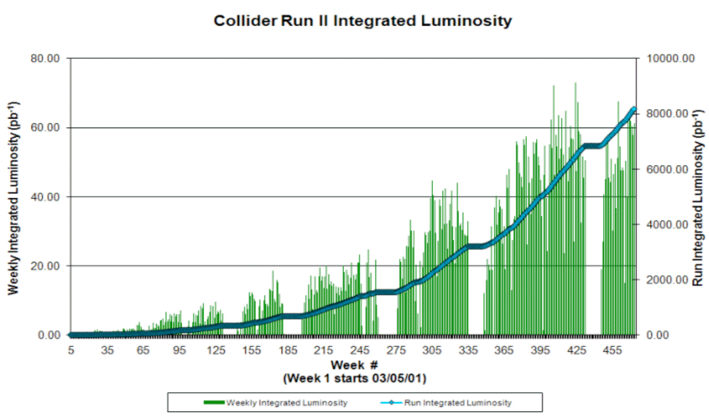
- Likelihood scan of S-wave fraction finds non-resonant KK/f_0 fraction <6.7 at 95% CL



Conclusions

- Latest measurement of β_s using $B_s^0 \rightarrow J/\Psi\phi$ decays
- Errors on β_s have decreased significantly from previous measurements
- Consistency with Standard Model expection has improved from previous measurements
- CDF will double data sample by end of Run II, allowing even more precise measurement





Backup

Some Equations

Time dependence of transversity amplitudes is given by

$$A_i = \frac{e^{-imt}e^{-\Gamma t/2}}{\sqrt{\tau_H + \tau_L \pm \cos 2\beta_s\,(\tau_L - \tau_H)}}\left[E_+(t) \pm e^{2i\beta_s}E_-(t)\right]A_i(0)$$

$$\bar{A}_i = \frac{e^{-imt}e^{-\Gamma t/2}}{\sqrt{\tau_H + \tau_L \pm \cos 2\beta_s\,(\tau_L - \tau_H)}}\left[\pm E_+(t) + e^{-2i\beta_s}E_-(t)\right]A_i(0)$$

where $E_\pm(t) \equiv \frac{1}{2}\left[e^{+\left(\frac{-\Delta\Gamma}{4}+i\frac{\Delta m_s}{2}\right)t} \pm e^{-\left(\frac{-\Delta\Gamma}{4}+i\frac{\Delta m_s}{2}\right)t}\right]$

If we form the vectors A and $\bar{\text{A}}$ we can express the B or anti-B probability as a function of time and angle

$$\mathbf{A}(t) = (A_0(t)\cos\psi, -\frac{A_\parallel(t)\sin\psi}{\sqrt{2}}, i\frac{A_\perp(t)\sin\psi}{\sqrt{2}})$$

$$\bar{\mathbf{A}}(t) = (\bar{A}_0(t)\cos\psi, -\frac{\bar{A}_\parallel(t)\sin\psi}{\sqrt{2}}, i\frac{\bar{A}_\perp(t)\sin\psi}{\sqrt{2}})$$

$$P_B(\theta,\phi,\psi,t) = \frac{9}{16\pi}|\mathbf{A}(t)\times\hat{n}|^2$$

$$P_{\bar{B}}(\theta,\phi,\psi,t) = \frac{9}{16\pi}|\bar{\mathbf{A}}(\mathbf{t})\times\hat{n}|^2$$

where $\hat{n} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$

Likelihood

Likelihood is given by:

$$\begin{aligned}\mathcal{L} &= f_s \cdot P_s(m) \cdot P_s(\xi) \cdot T(t,\psi,\theta,\phi,\mathcal{D},\xi) \cdot P_s(\sigma_t) \cdot P_s(\mathcal{D}) \\ &+ (1-f_s) \cdot P_b(m) \cdot P_b(\xi) \cdot P_b(t,\sigma_t) \cdot P_b(\psi) \cdot P_b(\theta) \cdot P_b(\phi) \cdot P_b(\sigma_t) \cdot P_b(\mathcal{D})\end{aligned}$$

Signal fraction   Mass   Tag Decision   Proper time error   Dilution

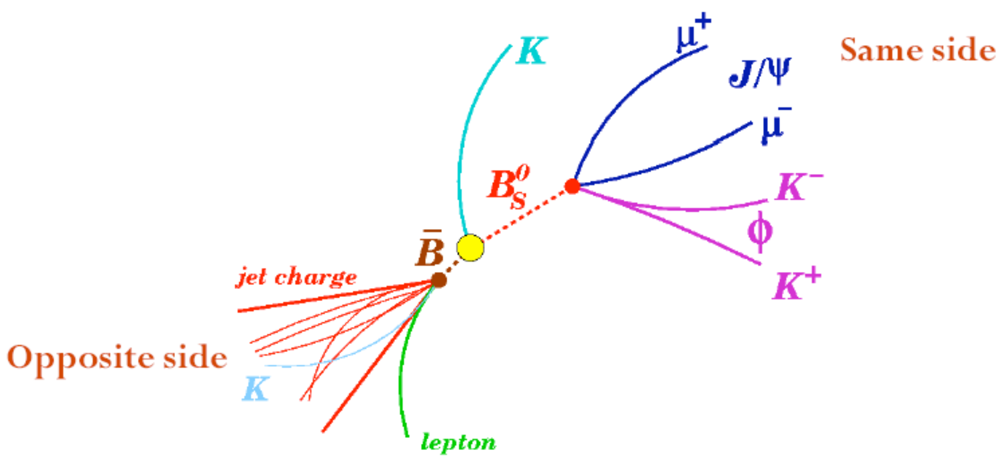
Dilution scale factor   Proper time   Angles   Angular Efficiency

$$T(t,\psi,\theta,\phi,\mathcal{D}_1,\mathcal{D}_2,\xi_1,\xi_2) = \frac{1+\xi_1 s_1 \mathcal{D}_1}{1+|\xi_1|}\frac{1+\xi_2 s_2 \mathcal{D}_2}{1+|\xi_2|} P(t,\psi,\theta,\phi)\frac{\epsilon(\psi,\theta,\phi)}{N} \otimes G_1(\sigma_t)G_2(\sigma_t)$$
$$+\frac{1-\xi_1 s_1 \mathcal{D}_1}{1+|\xi_1|}\frac{1-\xi_2 s_2 \mathcal{D}_2}{1+|\xi_2|} \bar{P}(t,\psi,\theta,\phi)\frac{\epsilon(\psi,\theta,\phi)}{N} \otimes G_1(\sigma_t)G_2(\sigma_t)$$

Normalization   Detector resolution

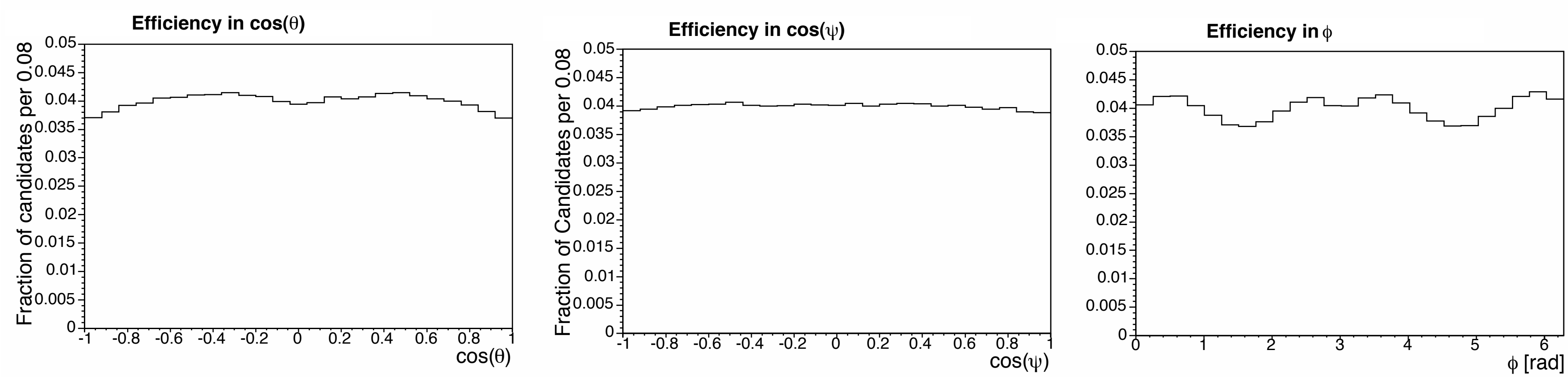
Flavor Tagging

- Most *b* quarks at Tevatron produced in *b* anti-*b* pairs
- Same side tagger uses charge of kaon produced in association with B_s^0 meson
- Opposite side tagger uses charge of decay products from event's other B hadron
- Tagging algorithms return a tag decision and a predicted dilution (related to probability of correct tag: $P_{Correct} = (1+D)/2$)



Detector Sculpting

- Account for detector sculpting of transversity angles
  - Calculate angular efficiencies on realistic $B_s^0 \to J/\Psi\phi$ Monte Carlo



Modeling Background Angles

- Background angles are described empirically using B_s^0 mass sidebands