New Measurement of the B^0_s Mixing Phase at CDF

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Heavy Quarks and Leptons, INFN
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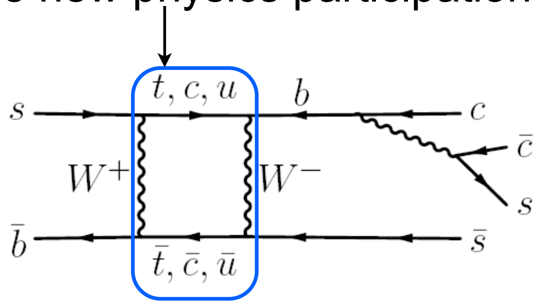
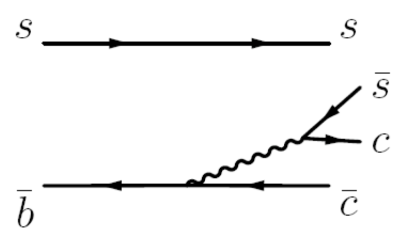
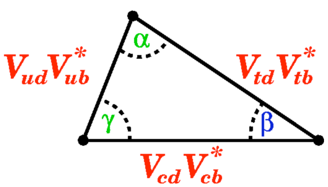
CP Violation in $B^0_s \to J/\psi\varphi$

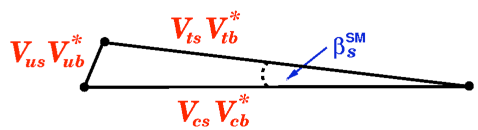
- Analogous to measurement of sin2β
- CPV in the interference between direct decays and decays via mixing

Could have new physics participation in loop process









- Use unitary property of CKM matrix to derive unitary triangles

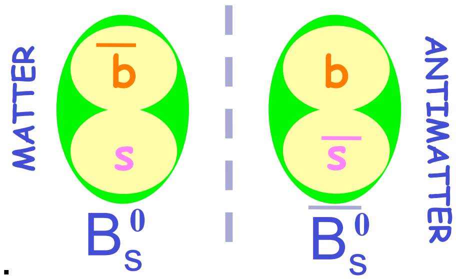
Large measured β_s must be due to new physics participation!

$$\beta_s = arg(-\frac{V_{tb}V^*_{ts}}{V_{cb}V^*_{cs}}) \approx 0.02$$

CP Violation in B^0_s Mixing

Time evolution of states is given by:

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



Flavor eigenstates → heavy and light mass eigenstates:

$$| B^H_s\rangle = p \mid B^0_s\rangle - q \mid \bar{B}^0_s\rangle \qquad | B^L_s\rangle = p \mid B^0_s\rangle + q \mid \bar{B}^0_s\rangle$$

Observables:

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

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

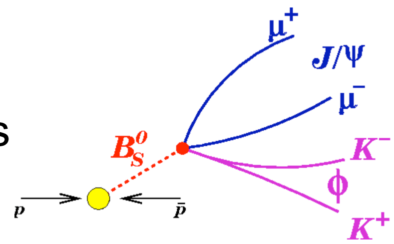
$$\phi_s = arg\left(\frac{-M_{12}}{\Gamma_{12}}\right)$$ CP Phase

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

Analysis Flow

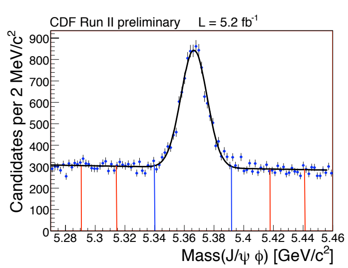
Reconstruct
signal events



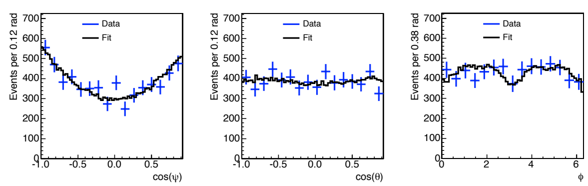
Use neural network
to suppress background

Simultaneously fit to:

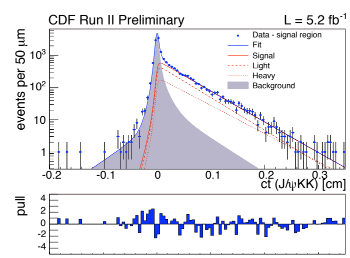
Mass:
Separate signal from
background



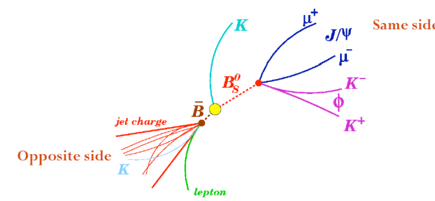
Angular Distributions:
Separate CP-odd from
CP-even contributions



Lifetime:
Determine time
dependence



Apply flavor tagging:
Distinguish B^0_s from
anti-B^0_s at production



Must handle: angular efficiencies, flavor tagging calibration

Likelihood Anatomy

- Probability density as a function of time and angles:

$$\left(\frac{d^4P(t,\vec{\rho})}{dtd\vec{\rho}}\right)_{(B_s^0,\bar{B}_s^0)} \propto |\ A_0\ |^2\ \mathcal{T}_{(+,+)}f_1(\vec{\rho}) + |\ A_{||}\ |^2\ \mathcal{T}_{(+,+)}f_2(\vec{\rho}) + |\ A_\perp\ |^2\ \mathcal{T}_{(-,-)}f_3(\vec{\rho})$$

$$+ |\ A_{||}\ ||\ A_\perp\ |\ \mathcal{U}_{(+,-)}f_4(\vec{\rho}) + |\ A_0\ ||\ A_{||}\ |\ cos(\delta_{||})\mathcal{T}_{(+,+)}f_5(\vec{\rho}) + |\ A_0\ ||\ A_\perp\ |\ \mathcal{V}_{(+,-)}f_6(\vec{\rho})$$

Time dependent terms:

$$\mathcal{T}_\pm = e^{-\Gamma t}[cosh\left(\frac{\Delta\Gamma t}{2}\right) \mp cos(2\beta_s)sinh\left(\frac{\Delta\Gamma t}{2}\right) \mp \boxed{\eta sin(2\beta_s)sin(\Delta m_s t)]}$$

$$\mathcal{U}_\pm = \pm e^{-\Gamma t}[sin(\delta_\perp - \delta_{||})cos(\Delta m_s t) - \boxed{cos(\delta_\perp - \delta_{||})cos(2\beta_s)sin(\Delta m_s t)} \pm cos(\delta_\perp - \delta_{||})sin(2\beta_s)sinh\left(\frac{\Delta\Gamma t}{2}\right)]$$

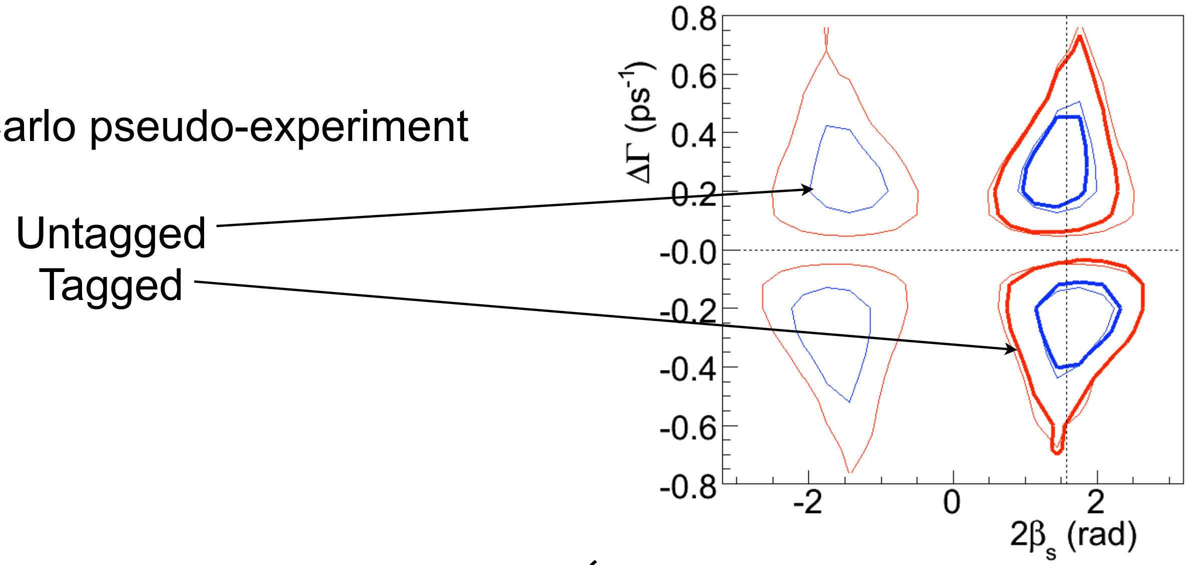
$$\mathcal{V}_\pm = \pm e^{-\Gamma t}[sin(\delta_\perp)cos(\Delta m_s t) - \boxed{cos(\delta_\perp)cos(2\beta_s)sin(\Delta m_s t)} \pm cos(\delta_\perp)sin(2\beta_s)sinh\left(\frac{\Delta\Gamma t}{2}\right)]$$

- Extract parameters of interest: β_s, $\Delta\Gamma$ (decay width difference), $\tau(B^0_s)$ (B^0_s average lifetime), A_0, $A_{||}$, $A_\perp$ (transversity amplitudes), $\varphi_{||}$, $\varphi_\perp$ (strong phases)

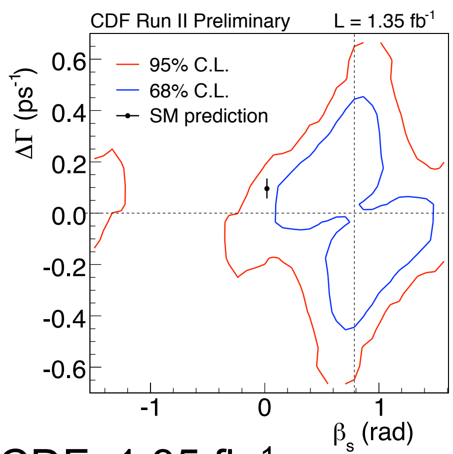
Flavor Tagging and Likelihood Symmetries

- Without flavor tagging, likelihood has two symmetries → four solutions
- $2\beta_s \to -2\beta_s$, $\delta_\perp \to \pi - \delta_\perp$
- $\Delta\Gamma \to -\Delta\Gamma$, $\delta_{||} \to 2\pi - \delta_{||}$,
- Flavor tagging removes $\beta_s \to -\beta_s$ symmetry → two solutions for β_s and $\Delta\Gamma$

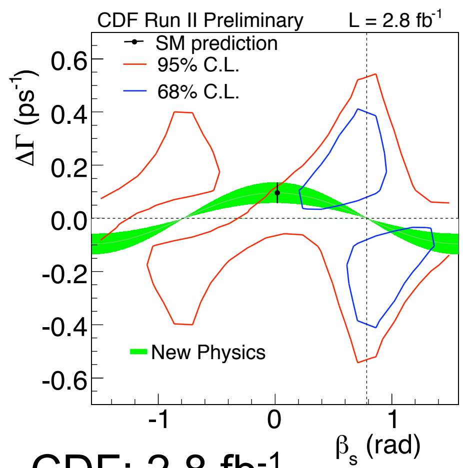
Toy Monte Carlo pseudo-experiment



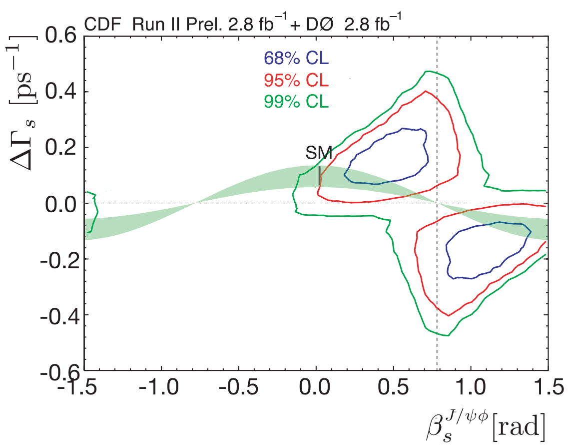
Previous results



CDF: 1.35 fb^{-1}
1.5σ consistency with SM



CDF: 2.8 fb^{-1}
1.8σ consistency with SM

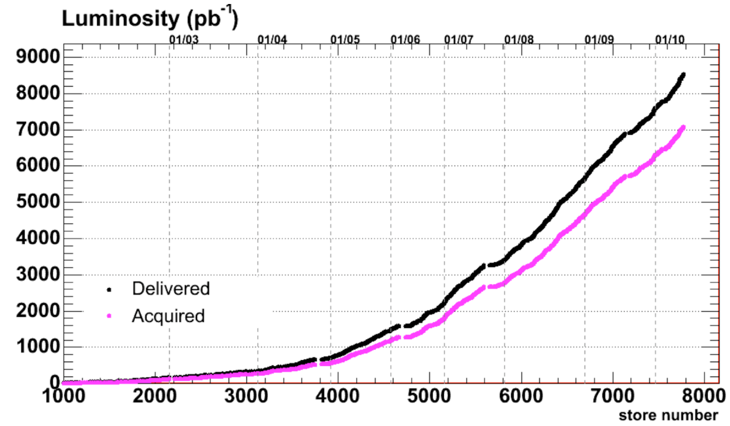


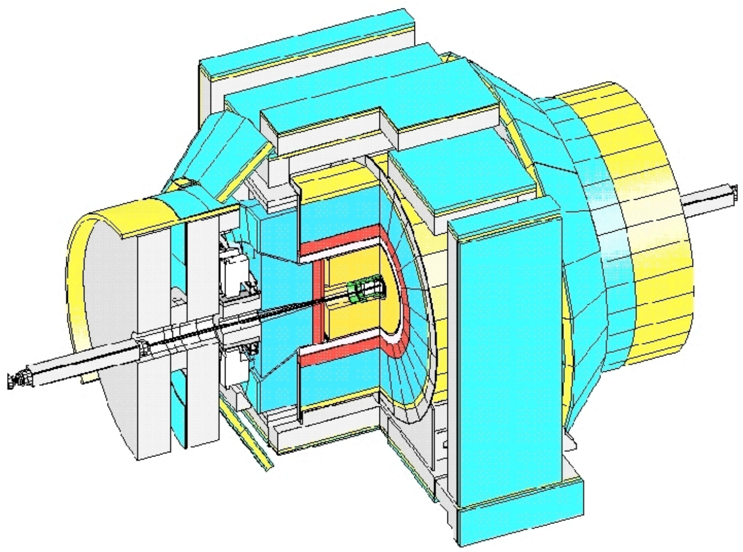
CDF: 2.8 fb^{-1} + D∅: 2.8 fb^{-1}

2.3σ consistency with SM

The Tevatron and CDF

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

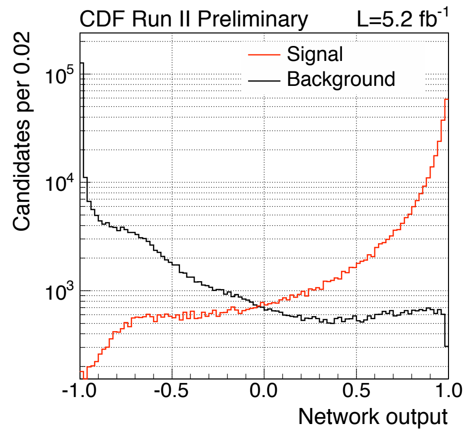


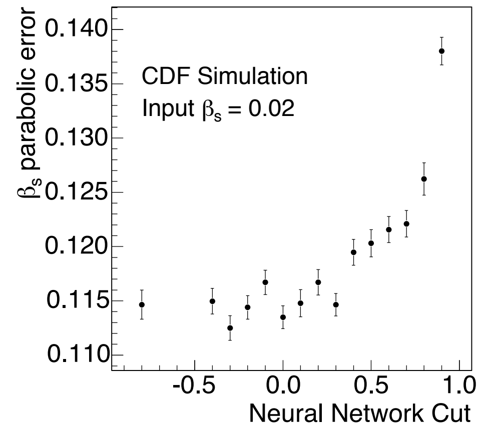


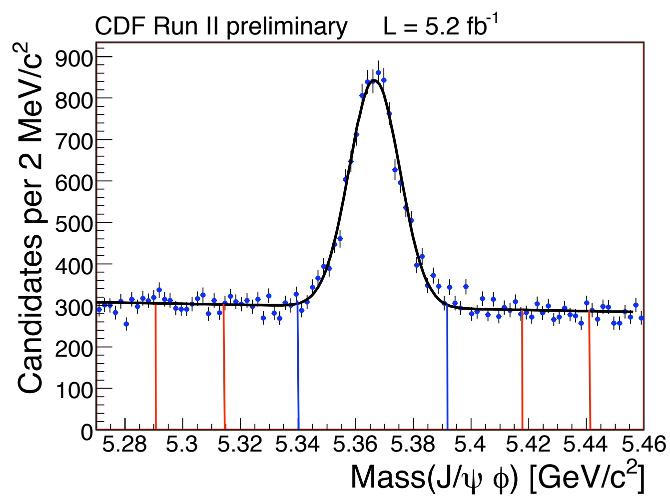
- Analysis relies on
  - Mass and decay time resolution (~0.1 ps compared to B lifetime ~1.5 ps)
  - Particle Identification

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
  - Reconstruct ~6500 signal events

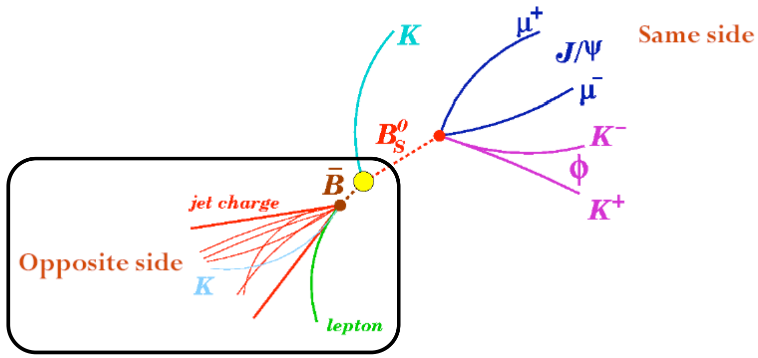


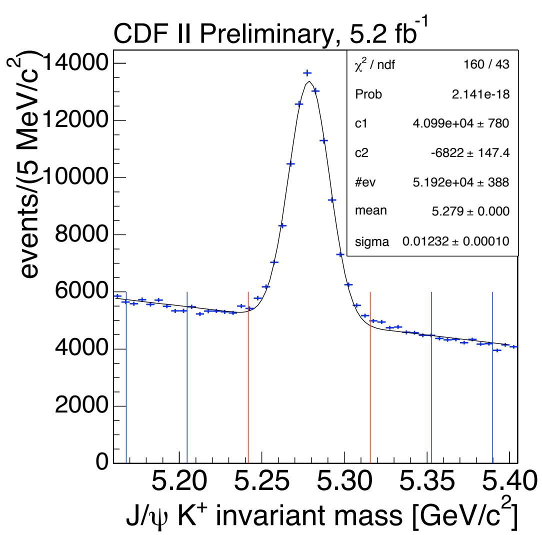


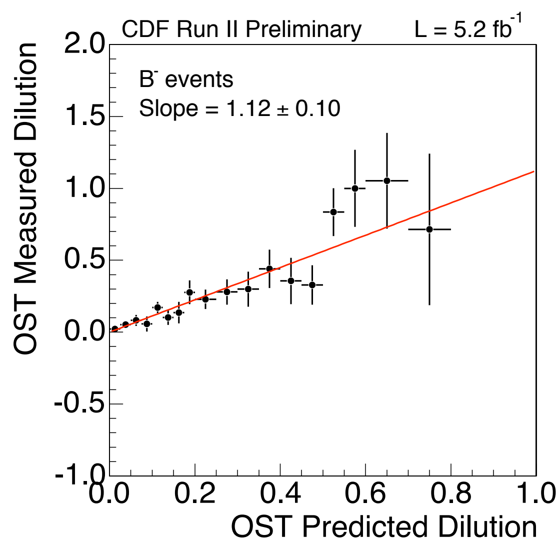


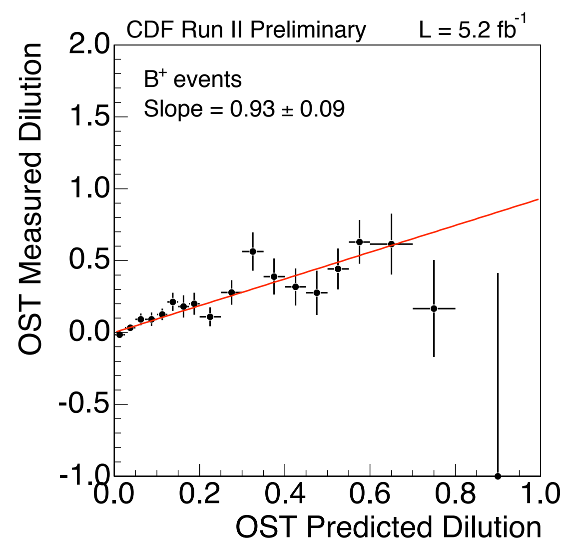
OST Calibration

- Calibrate opposite side tagger on $B^+ \to J/\Psi\, K^+$ events, which have same opposite side fragmentation behavior as B_s^0
- $B^+ \to J/\Psi\, K^+$ decays are self-tagging
  - Compare measured to predicted dilution
  - Tagging power εD^2 = 1.2±0.2%



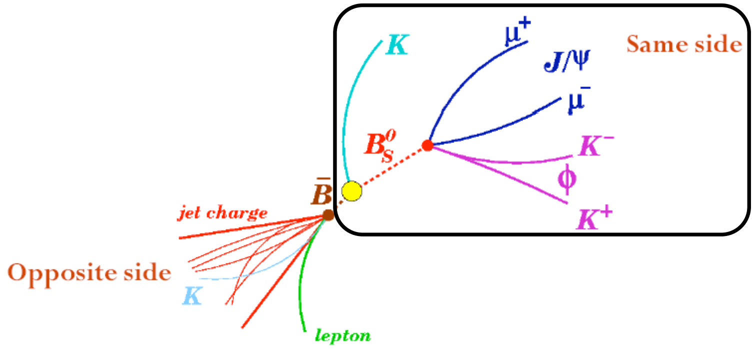


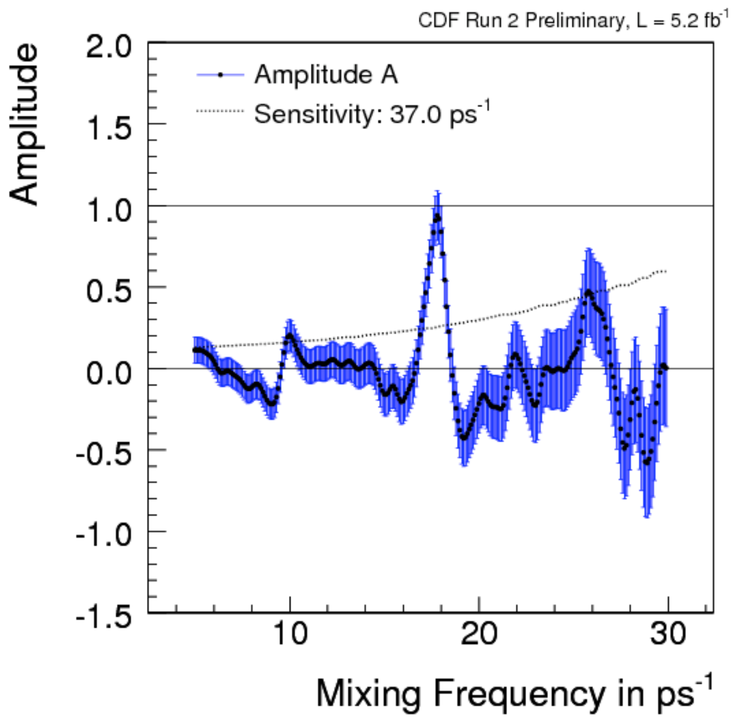




SSKT Calibration

- Remeasured B_s^0 mixing on 5.2 fb^{-1} of data
  - $B_s^0 \rightarrow D_s^- \pi^+$ and $B_s^0 \rightarrow D_s^- (3\pi)^+$ 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
  - $A = 0.94 \pm 0.15$ (stat) ± 0.13 (syst)
  - $\Delta m_s = 17.79 \pm 0.07$ ps^{-1} (stat) (Consistent with world average)
  - Tagging power $\varepsilon D^2 = 3.1 \pm 1.4\%$

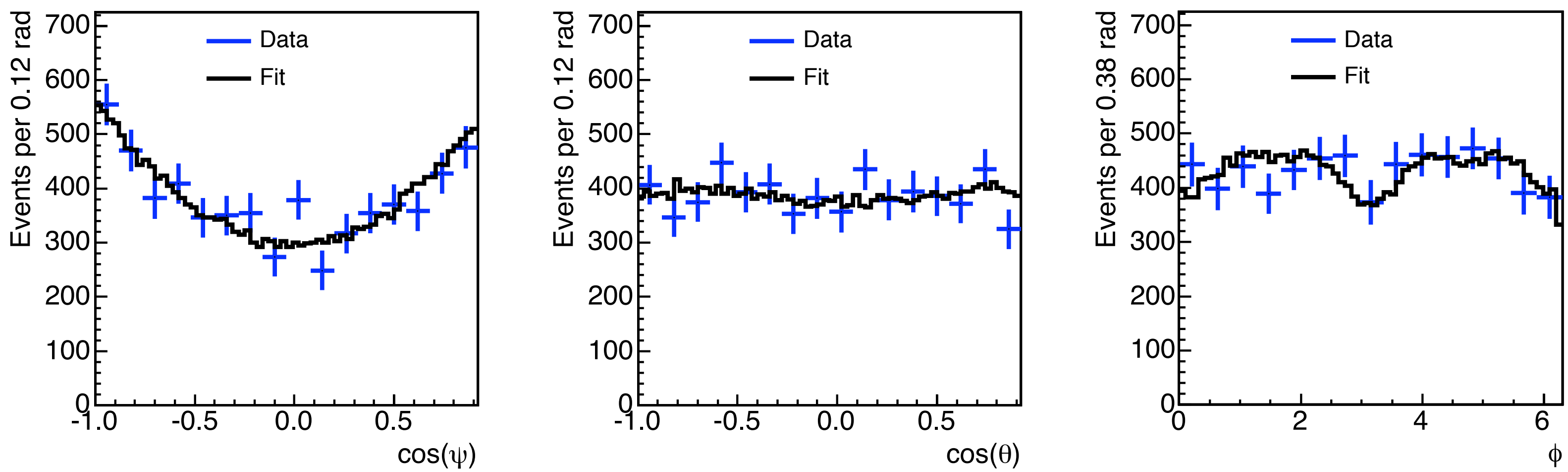




S-wave Contamination

- $B_s^0 \rightarrow J/\Psi K^+K^-$ and $B_s^0 \rightarrow J/\Psi f_0$ could contaminate $B_s^0 \rightarrow J/\Psi\phi$ signal and bias measurement of β_s
  - Include possibility of non-resonant KK/f_0 in likelihood
    - Model KK and f_0 as flat in (narrow) ϕ mass region
    - Model ϕ as relativistic Breit-Wigner
    - Perform mass integration over ϕ mass window
    - S-wave terms enter in angular part of likelihood

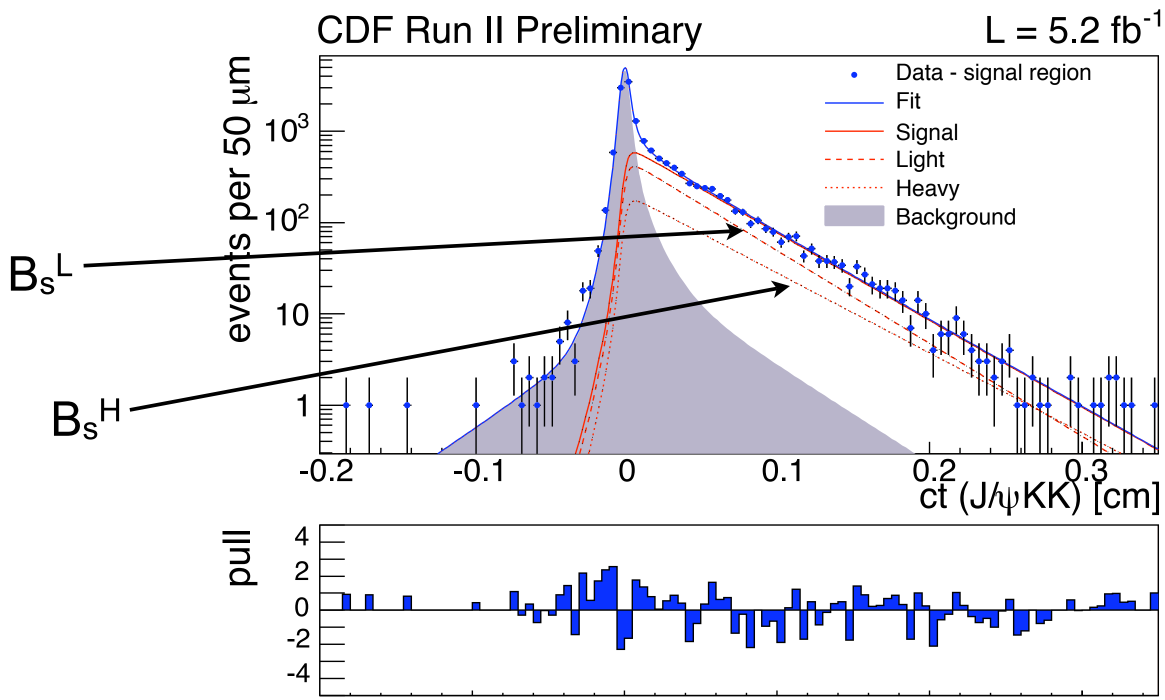
Angular Analysis



For Standard Model β_s:

$$|A_{||}(0)|^2 = 0.231 \pm 0.014(stat) \pm 0.015(syst)$$
$$|A_0(0)|^2 = 0.524 \pm 0.013(stat) \pm 0.015(syst)$$
$$\phi_\perp = 2.95 \pm 0.64(stat) \pm 0.07(syst)$$

Lifetime Measurement



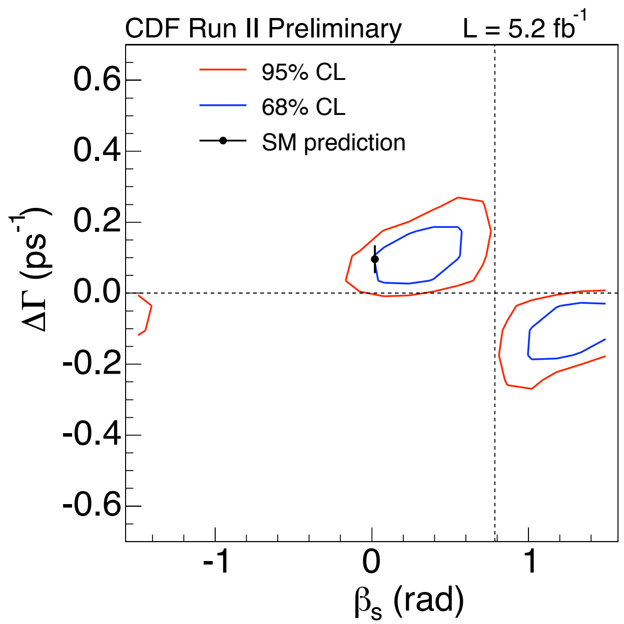
For Standard Model β_s:
(World's best measurements)

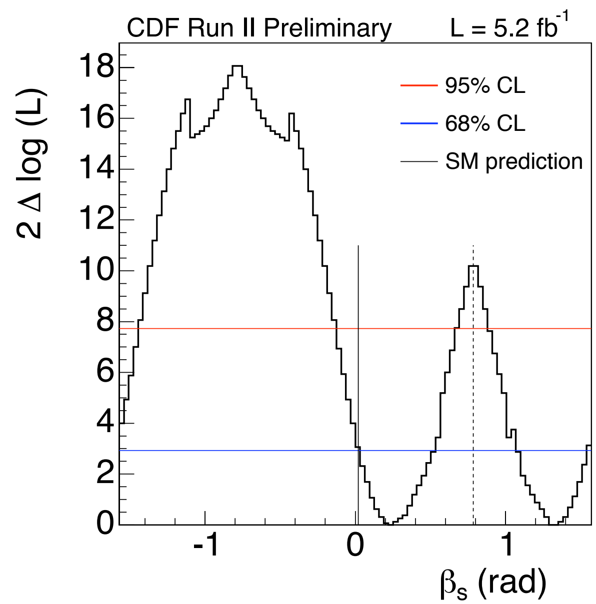
$$c\tau_s = 458.7 \pm 7.5(stat) \pm 3.6(syst)\mu m$$

$$\Delta\Gamma_s = 0.075 \pm 0.035(stat) \pm 0.01(syst)ps^{-1}$$

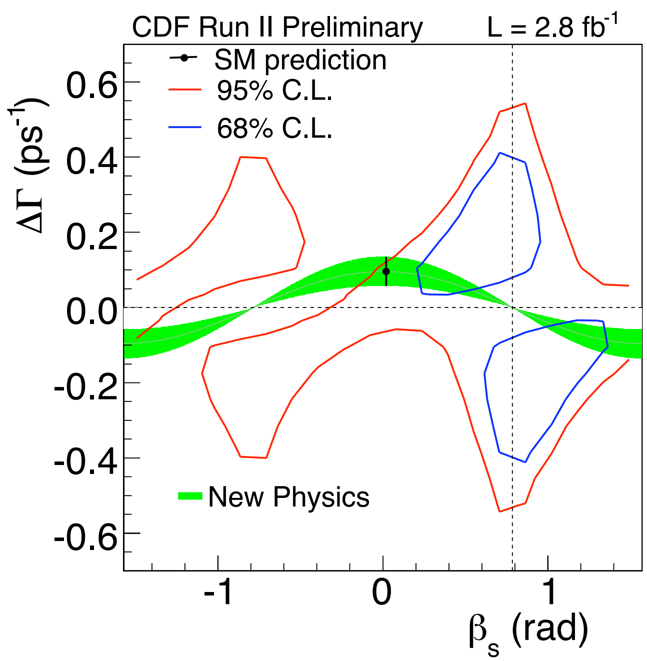
β_s-ΔΓ Contours

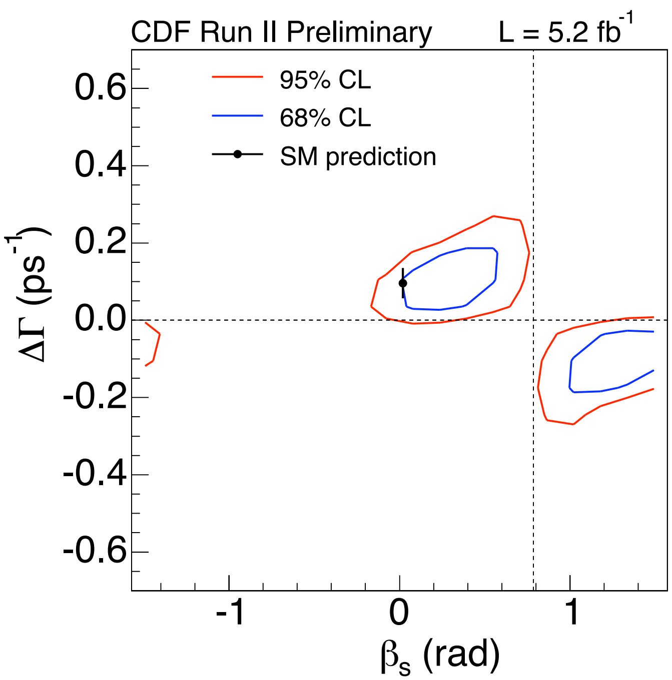
- Profile likelihood ordering technique used to guarantee coverage at 68% and 95% confidence levels
- 0.8σ consistency with SM
- $\beta_s \in [0.28, 0.52] \cup [1.08, 1.55]$ at 68% CL
- Similar consistency with SM to 2D case





Comparison to Previous Measurement

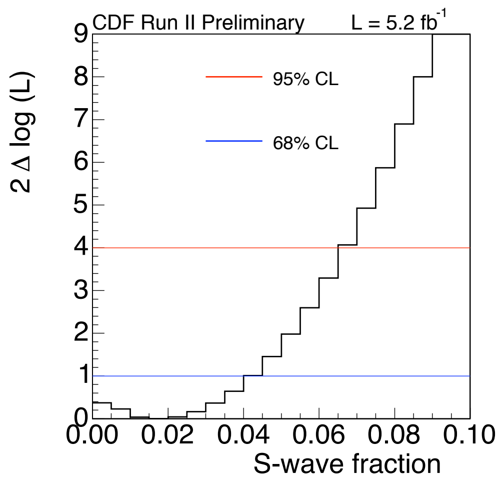




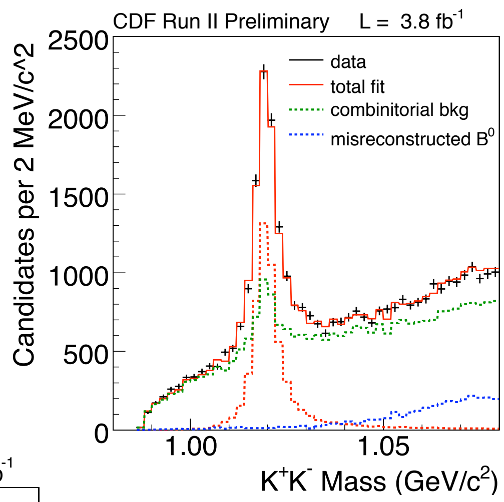
Size of contour has decreased significantly with increased statistics and analysis improvements

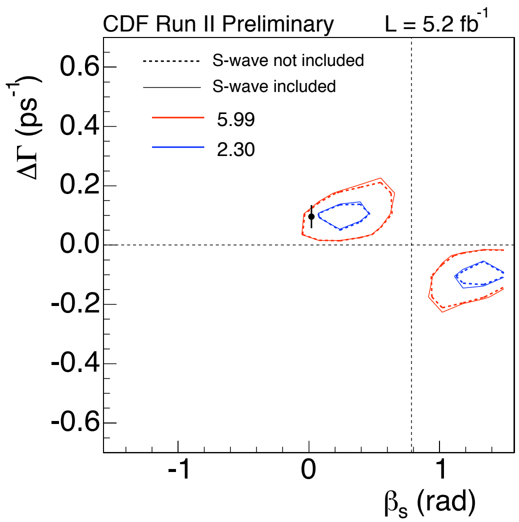
Effect of S-wave

Likelihood scan of S-wave fraction finds S-wave contamination <7% at 95% CL



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

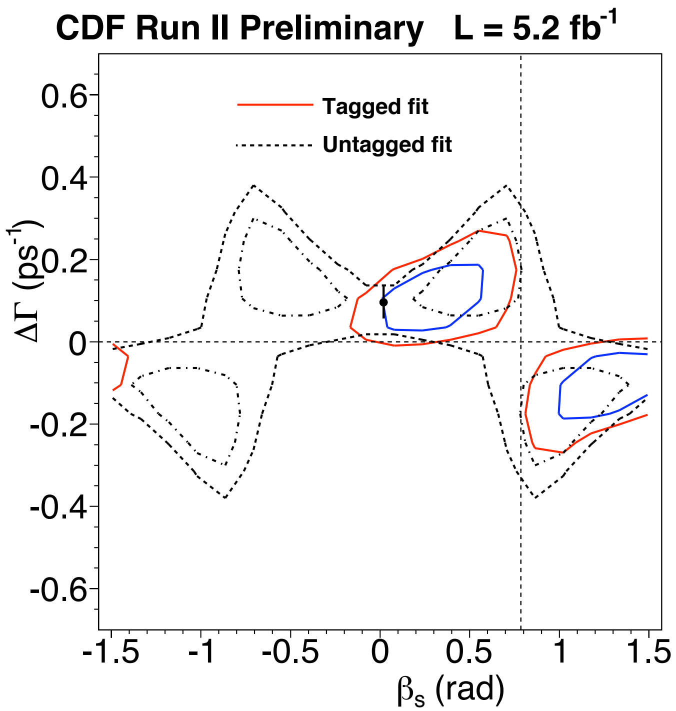




β_s-$\Delta\Gamma$ contour with S-wave included in fit is not significantly different than fit without S-wave

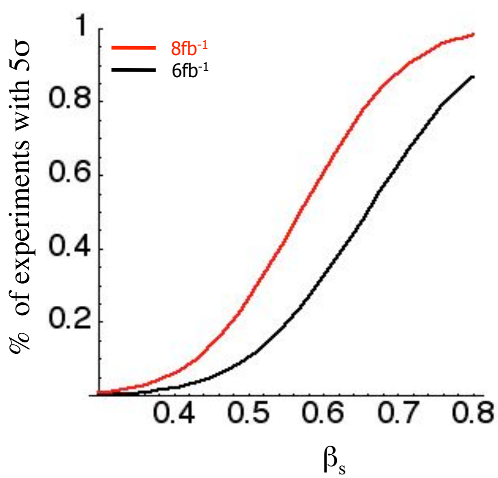
Tagged versus Untagged Contours

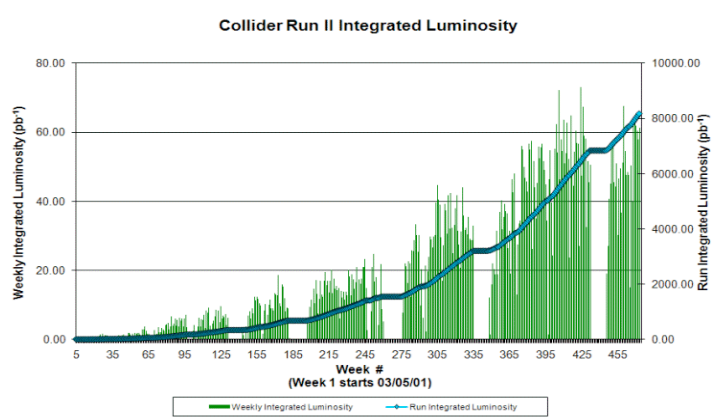
Good agreement between contours with and without flavor tagging included in fit



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
- More details: CDF public note 10206, PRL 100, 161802 (2008)





Backup

Detector Sculpting

- Account for detector sculpting of transversity angles
  - Calculate angular efficiencies on realistic $B_s^0 \to J/\Psi\phi$ Monte Carlo
    - Generate angles flat
    - Parameterize after going through full CDF reconstruction