Study of CP Violation in $B_s \rightarrow J/\psi\phi$ Decays at CDF

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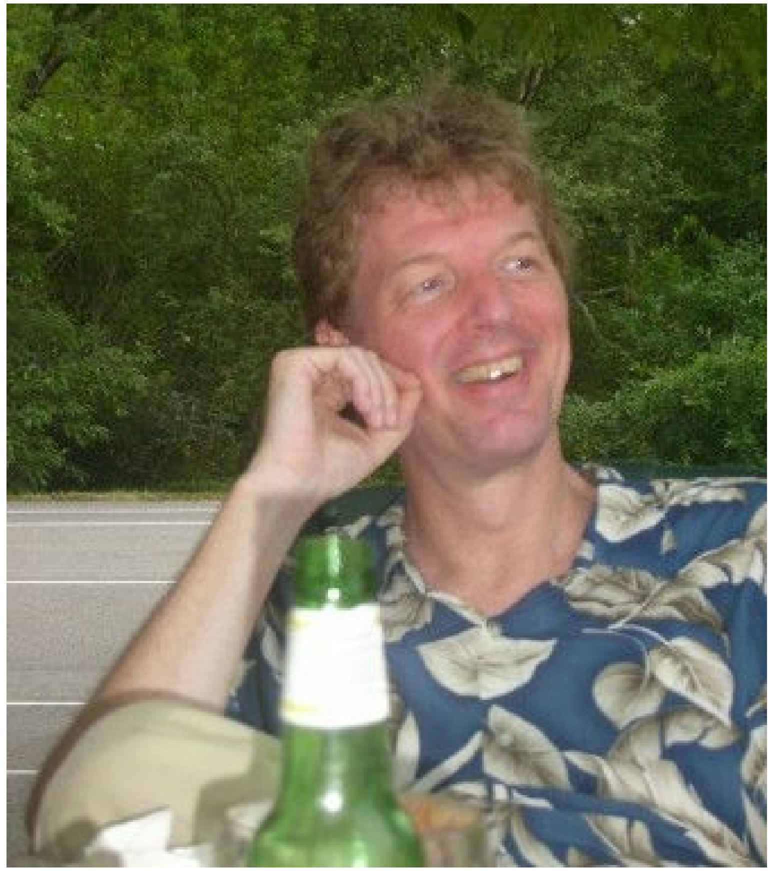


Dedication

To the memory of our dear friend and colleague,

Michael Perry Schmidt.

Introduction

A man said to the Universe:
“Sir, I exist!”
“However,” replied the Universe,
“The fact has not created in me
A sense of obligation.’”

- *Stephen Crane*

Beyond the Standard Model

- The search for physics beyond the standard model is pursued through a broad program of physics at the Tevatron
  - High p_T physics
    - Direct searches for evidence of new physics (SUSY, Technicolor, ???)
  - Flavor physics
    - New physics through participation in loop processes could contribute additional CP violating phases
- CP violation in B_s^0 meson system is an excellent way to search for new physics
  - Predicted to be extremely small in the SM, so any large CP phase is a clear sign of new physics!

What Is CP Violation?

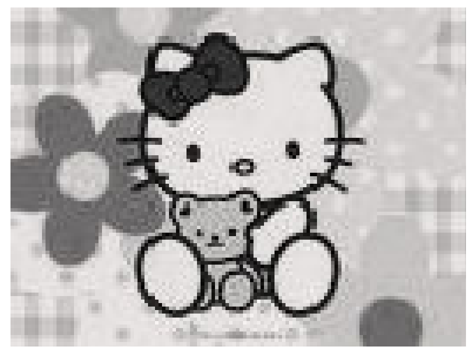
- CP violation is the non-conservation of charge and parity quantum numbers

Rate of

$$B_s^0$$

$\neq$

Rate of



$$\bar{B}_s^0$$

CP Violation in the Standard Model

- Described within framework of the CKM mechanism

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

Large CPV

Highly suppressed CPV

$$V_{\mathrm{CKM}} = \begin{pmatrix} 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda + \frac{1}{2}A^2\lambda^5[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}\lambda^2 - \frac{1}{8}\lambda^4(1 + 4A^2) & A\lambda^2 \\ A\lambda^3[1 - (1 - \frac{1}{2}\lambda^2)(\rho + i\eta)] & -A\lambda^2 + \frac{1}{2}A\lambda^4[1 - 2(\rho + i\eta)] & 1 - \frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

Large CPV

Suppressed CPV

where $\lambda \approx 0.23$

- Imaginary terms give rise to CP violation

Unitarity of CKM Matrix

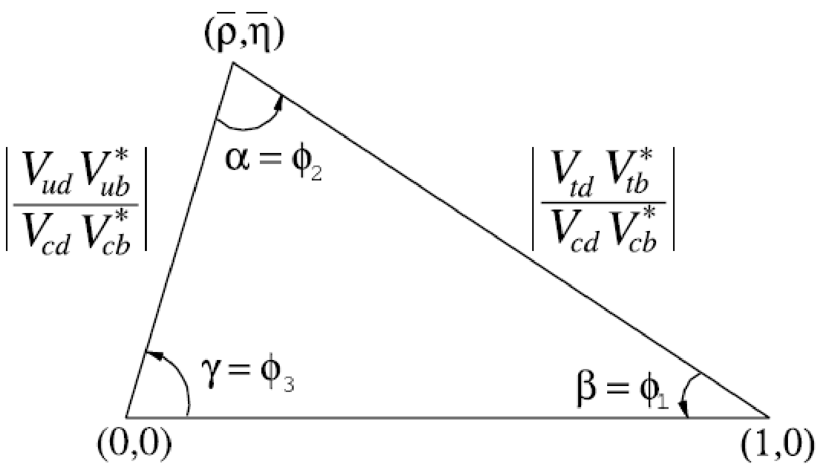
- By construction, CKM matrix must be unitary
  - $V^\dagger V = 1$
- Important to check this experimentally!
  - Evidence of non-unitarity would suggest presence of unknown physics contributions
- Can construct six unitarity relations between distinct columns or rows of CKM matrix

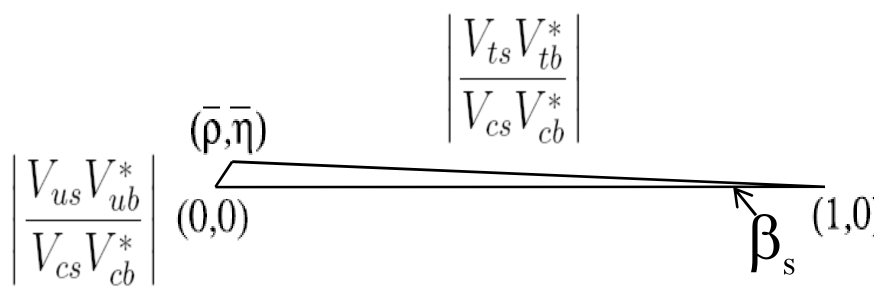
Unitarity Relations in $B^0/B_s{}^0$ Mesons

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

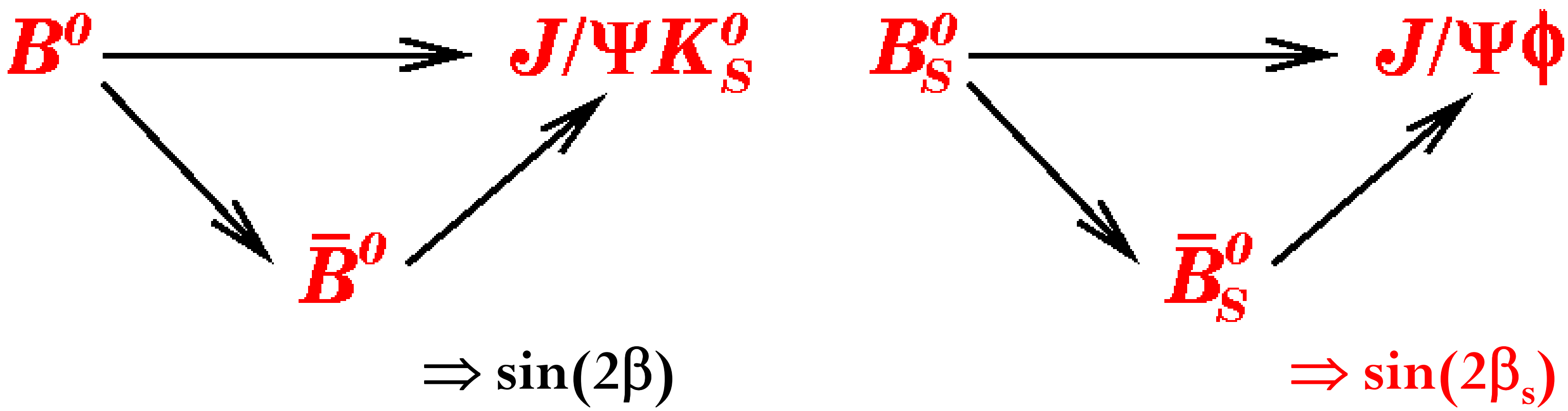
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

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





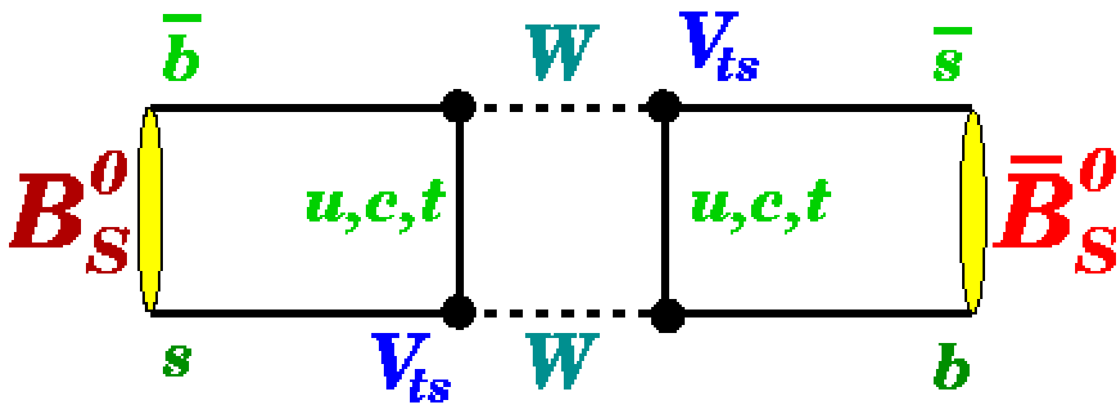
CP Violation in $B_s^0 \to J/\psi\varphi$



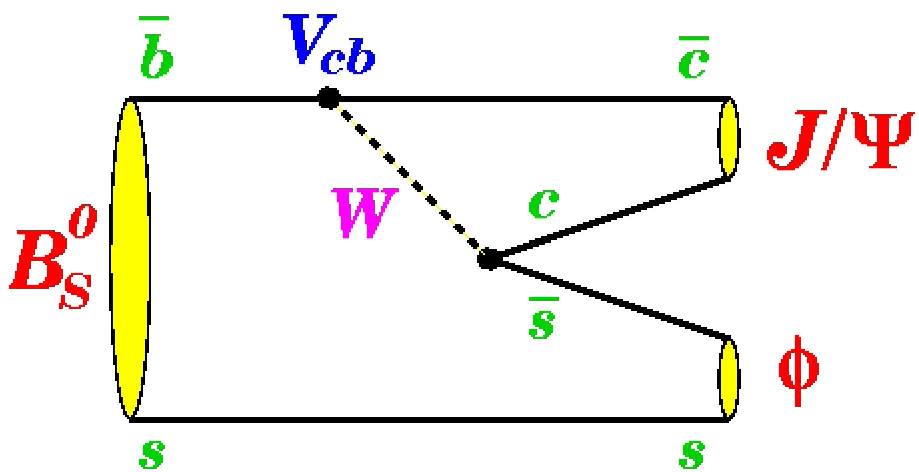
- CP violation arises from interference between mixing and decay amplitudes
  - $J/\psi\ K_s^0$ is CP even final state
  - $J/\psi\ \varphi$ final state is an admixture of CP even (~75%) and CP odd (25%)

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!



Mixing in B_s^0 Decays

Schrodinger equation governs $\bar{B}_s^0$- B_s^0 transitions

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

Mass eigenstates B_s^H and B_s^L are admixtures of flavor eigenstates

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

where

$$\Delta m_s = m_H - m_L \approx 2\,|M_{12}|$$

Frequency of oscillation between B_s^0 and $\bar{B}_s^0$

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

Width difference between heavy and light is related to the phase of the mixing

$$\boxed{q/p = \frac{V_{tb}V_{ts}^*}{V_{tb}^*V_{ts}}}$$

Standard Model CPV in B_s^0 Decays

- CP violation in $B_s^0 \to J/\psi\varphi$

CP observable: $\lambda_{J/\psi\varphi} = e^{i2\beta_s}$

Assume $|\lambda_{J/\psi\varphi}| = 1$
$\to$ no direct CPV

The CP phase in $B_s^0 \to J/\psi\varphi$ in the standard model is

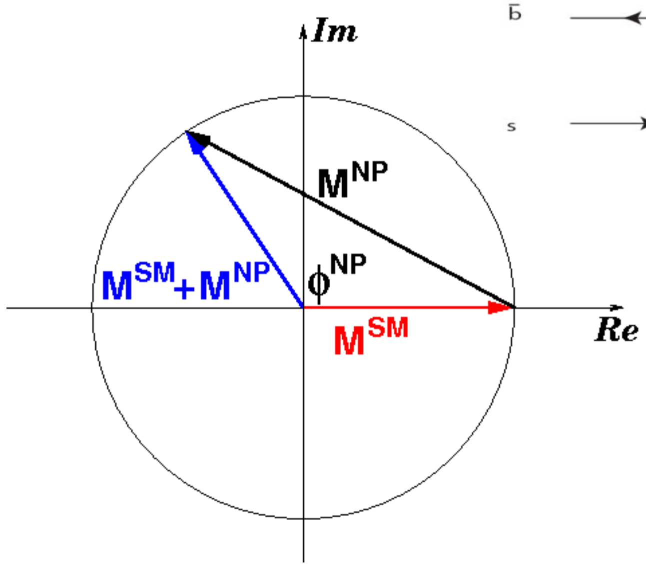
$$\beta_s = \arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \sim 0.02$$

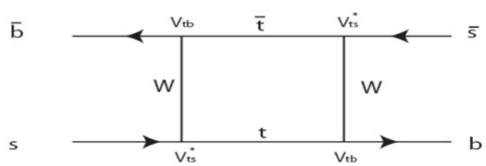
Very small CP phase!

Note: $Im(\lambda_{J/\psi\varphi}) = \sin(2\beta_s) \approx 0$,
Compared to $\sin(2\beta) \approx 0.70$ ($B^0 \to J/\psi K_s^0$)

New Physics in B_s^0 Decays

- $B_s^0 - \bar{B}_s^0$ oscillations recently 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!
- Both are needed to constrain new physics





$M_{12} = |M_{12}| e^{i\varphi_s}$,
where $\varphi_s^{SM} \sim 0.004$

New physics could
produce large CP phase!

New Physics CPV in B_s^0 Decays

- If large new physics phase present in mixing amplitude
  - $\varphi_s = \varphi_s^{SM} + \varphi_s^{NP} \sim \varphi_s^{NP}$
  - Can measure φ_s directly from asymmetry in B_s^0 semileptonic decays
- Same new physics phase φ_s^{NP} would add to β_s
  - In $B_s^0 \to J/\psi\varphi$, we would then measure $(2\beta_s - \varphi_s^{NP}) \sim -\varphi_s^{NP}$
  - Would also be sensitive to NP effects in $M_{12} = |M_{12}|e^{-i2\beta_s}$
- Observation of large CP phase in $B_s^0 \to J/\psi\varphi$

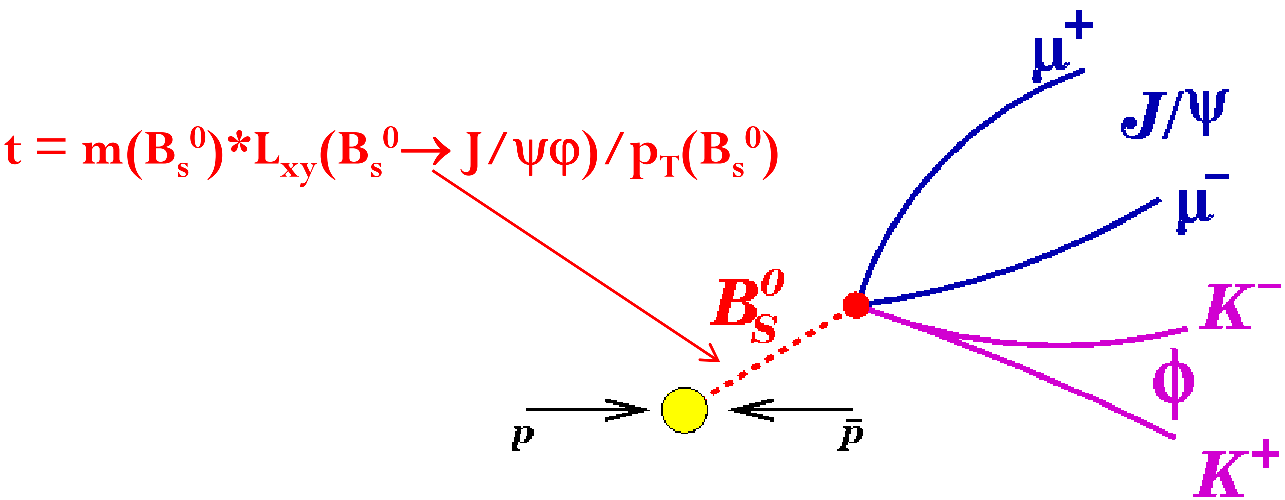
  $\Rightarrow$ unequivocal sign of new physics

Measurement Overview

"Men's activities are occupied in two ways -- in grappling with external circumstances and in striving to set things at one in their own topsy-turvy mind."

-William James

Properties of $B_s^0 \rightarrow J/\psi\varphi$ Decays



- Overview of decay
  - B_s^0 travels ~450 μm before decaying into J/ψ and φ
  - Spin-0 B_s^0 decays to spin-1 J/ψ and spin-1 φ
    $\Rightarrow$ final states with ℓ=0,1,2
- Properties of decay depend on decay time, CP at decay, and initial flavor of $\bar{B}_s^0/B_s^0$

Experimental Strategy

- Reconstruct $B_s^0 \to J/\psi(\to \mu^+\mu^-)\ \varphi(\to K^+K^-)$
- Use angular information from J/ψ and φ decays to separate angular momentum states which correspond to CP eigenstates
  - CP-even (ℓ=0,2) and CP-odd (ℓ=1) final states
- Identify initial state of B_s meson (flavor tagging)
  - Separate time evolution of B_s^0 and $\bar{B}_s^0$ to maximize sensitivity to CP asymmetry ($\sin 2\beta_s$)
- Perform un-binned maximum likelihood fit to extract signal parameters of interest (*e.g.* β_s, $\Delta\Gamma$)

Related Measurements

- $B_s^0 \to J/\psi\ \varphi$ decays without flavor tagging
  - B_s^0 mean lifetime ($\tau = 1/\Gamma$)
    - $\Gamma = (\Gamma_L + \Gamma_H)/2$
  - Width difference $\Delta\Gamma$
  - Angular properties of decay
- Decay of $B^0 \to J/\psi(\to \mu^+\mu^-)\ K^{*0}(\to K^-\pi^+)$
  - No width difference ($\Delta\Gamma \approx 0$)
  - Check measurement of angular properties of decay

Current Experimental Results

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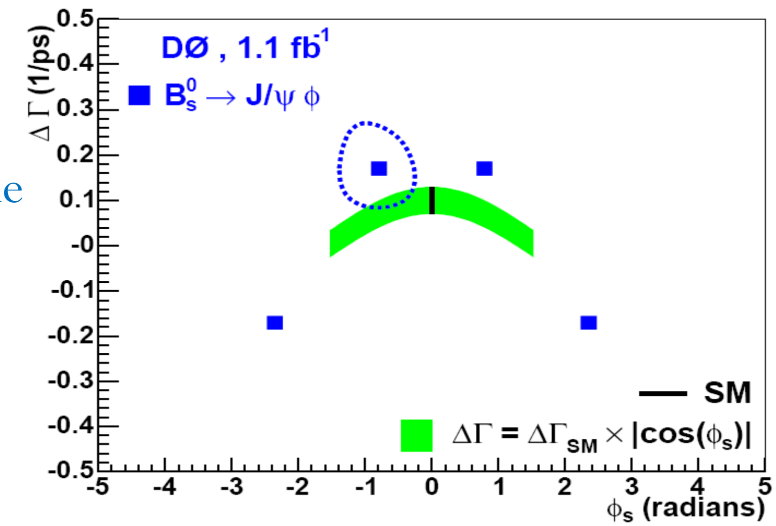
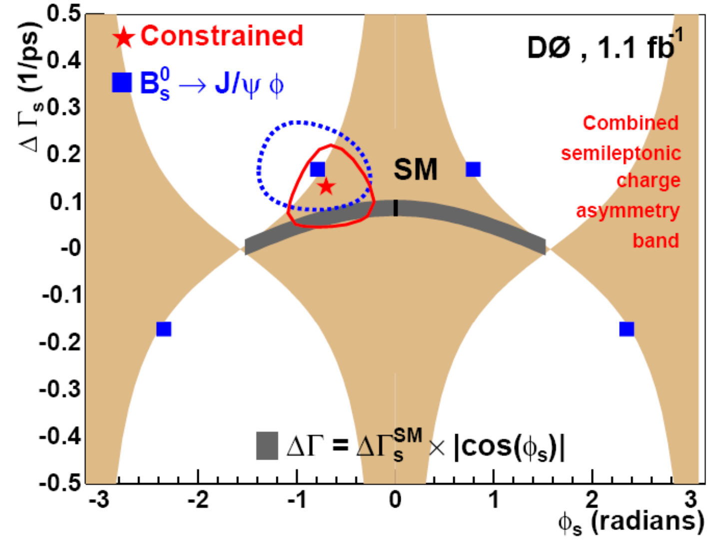
Phys. Rev. D 76, 057101 (2007)

Dotted line indicates 39% CL





- D0 measurement of CP phase made without flavor tagging
  - Four-fold ambiguity in determination of φ_s

$\tau(B_s^0) = 1.52 \pm 0.08$ (stat) $^{+0.01}_{-0.03}$ (syst) ps
$\Delta\Gamma = 0.17 \pm 0.09$ (stat) ± 0.02 (syst) ps^{-1}

Signal Reconstruction

"Begin at the beginning and go on till you come to the end: then stop."

-Alice in Wonderland

$B_s^0 \to J/\psi\varphi$ Signal Selection

- Use an artificial neural network (ANN) to efficiently separate signal from background
- ANN training
  - Signal from Monte Carlo reconstructed as it is in data
  - Background from $J/\psi\varphi$ sidebands
    - $m(J/\psi\varphi) \in [5.1820, 5.2142]\ \mathrm{GeV}/c^2$
      $\cup\ [5.3430, 5.3752]\ \mathrm{GeV}/c^2$

$B_s^0 \to J/\psi\varphi$ Neural Network

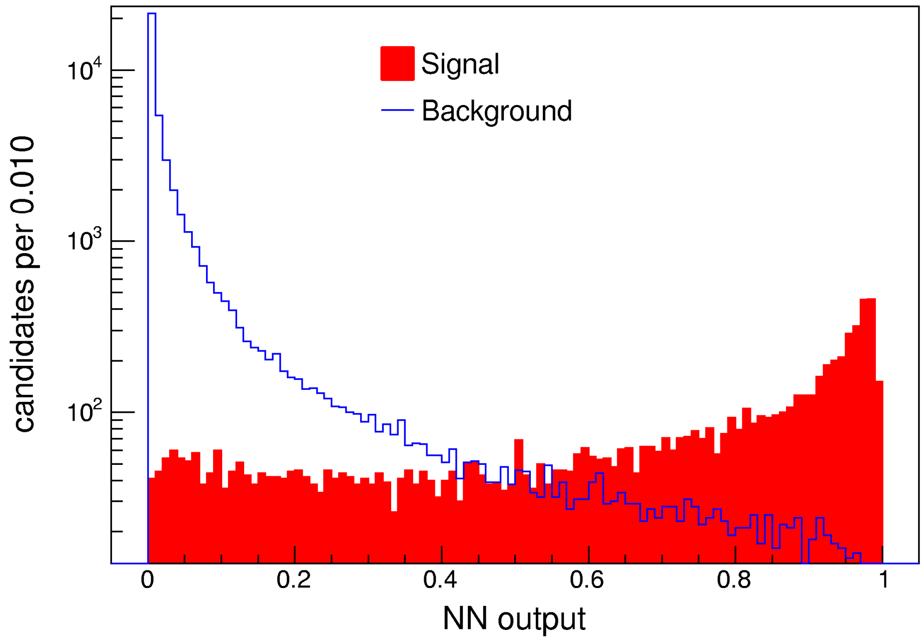
Variables used in network

B_s^0: p_T and vertex probability

J/ψ: p_T and vertex probability

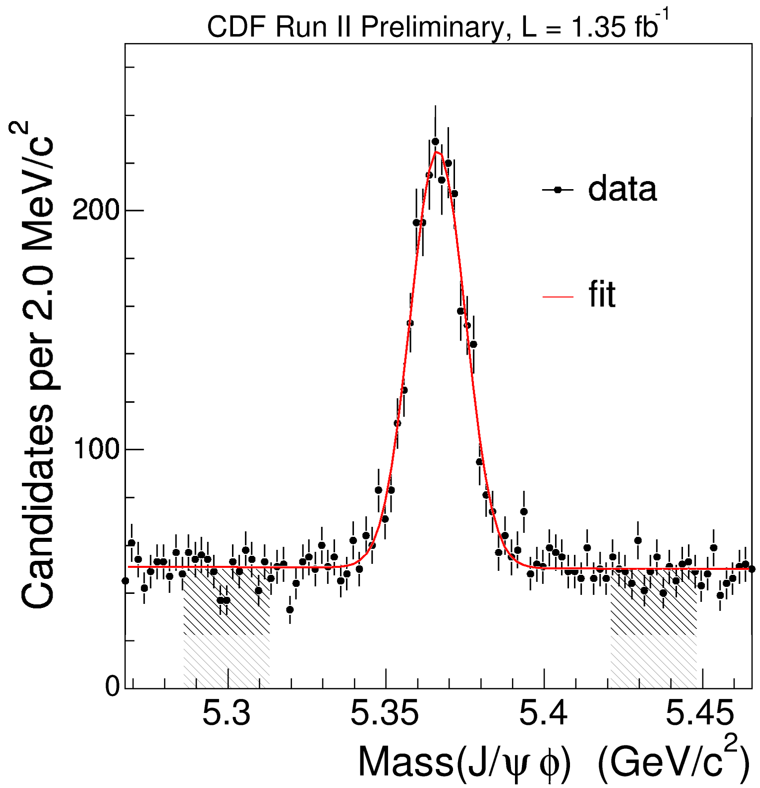
φ: mass and vertex probability

K^+, K^-: p_T and PID (TOF, dE/dx)



Optimization of ANN selection: $\frac{S}{\sqrt{S+B}}$

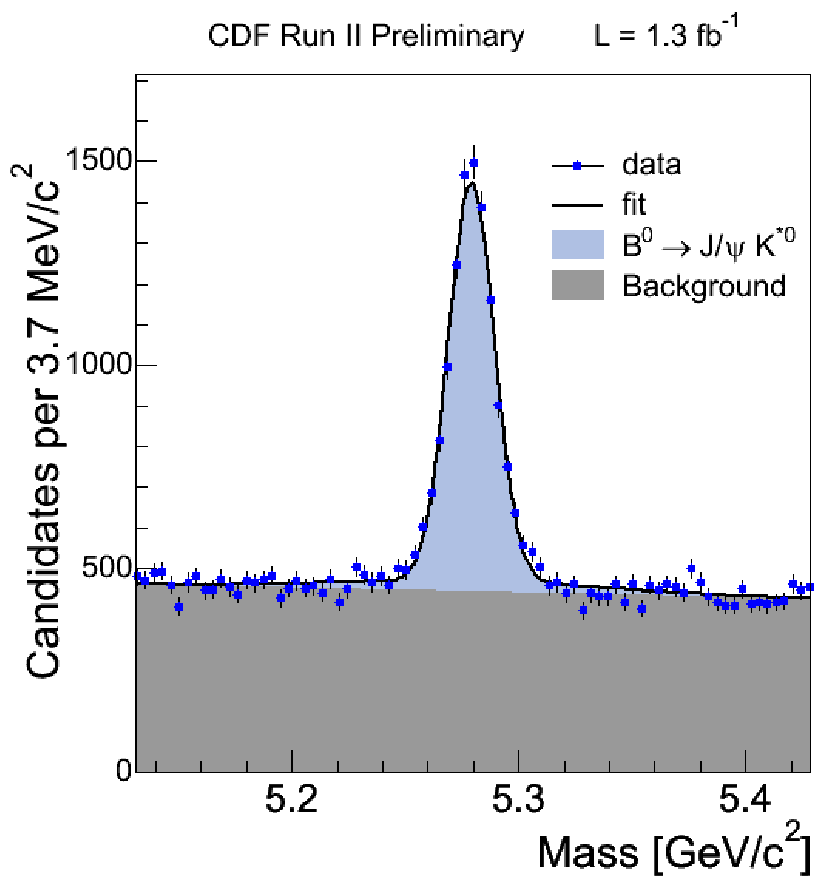
$B_s^0 \rightarrow J/\psi\varphi$ Signal



N(B_s^0) ~ 2000 in 1.35fb^{-1} (with flavor tagging)

2500 in 1.7 fb^{-1} (without flavor tagging)

$B^0 \to J/\psi K^{*0}$ Signal



$N(B^0) \sim 7800$ in $1.35\ fb^{-1}$

Angular Analysis of Final States

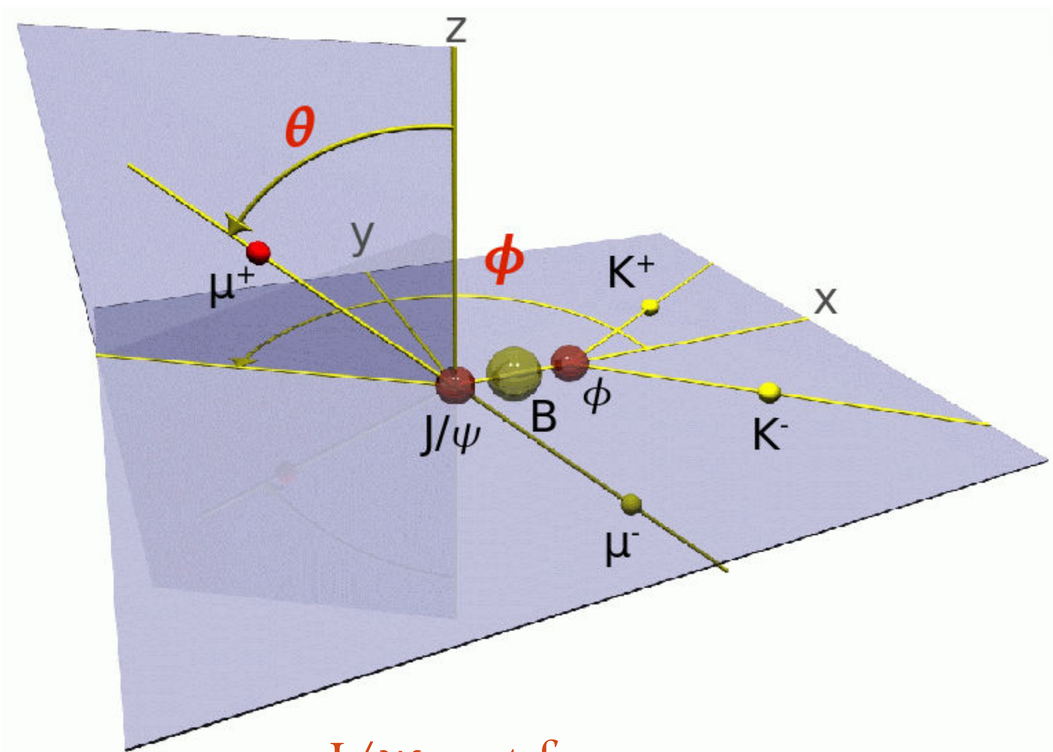
"[In this business] everybody's got an angle."

-Bing Crosby in "White Christmas"

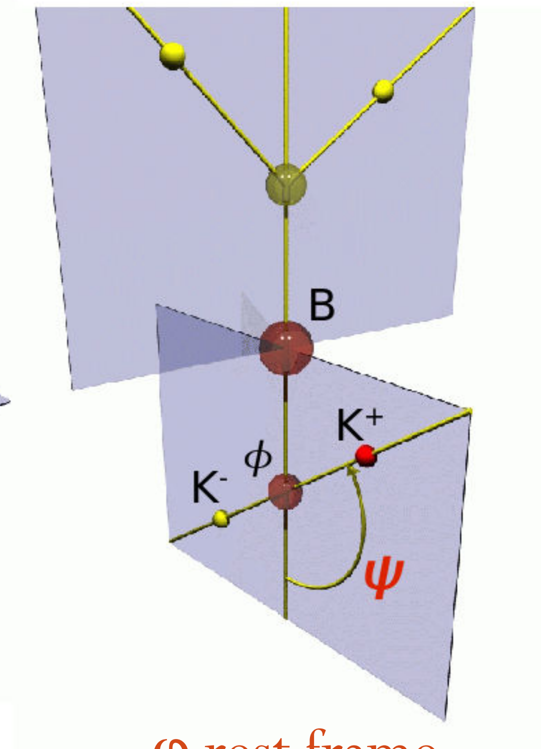
Identifying CP of Final States

- J/ψ, φ vector mesons
  $\rightarrow$ definite angular distributions for CP-even (S- or D-wave) and CP-odd (P-wave) final states
- Use transversity basis to describe angular decay
  - Express angular dependence in terms of linear polarization
  - Transversely polarized: $A_\perp(t)$ and $A_\parallel(t)$
  - Longitudinally polarized: $A_0(t)$
  - Can determine initial magnitude of polarizations and their phases relative to each other
    - $|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2 = 1$
    - $\delta_\parallel = \arg(A_\parallel(0)\, A_0^*(0))$, $\delta_\perp = \arg(A_\perp(0)\, A_0^*(0))$

Definition of Transversity Angles



J/ψ rest frame



φ rest frame

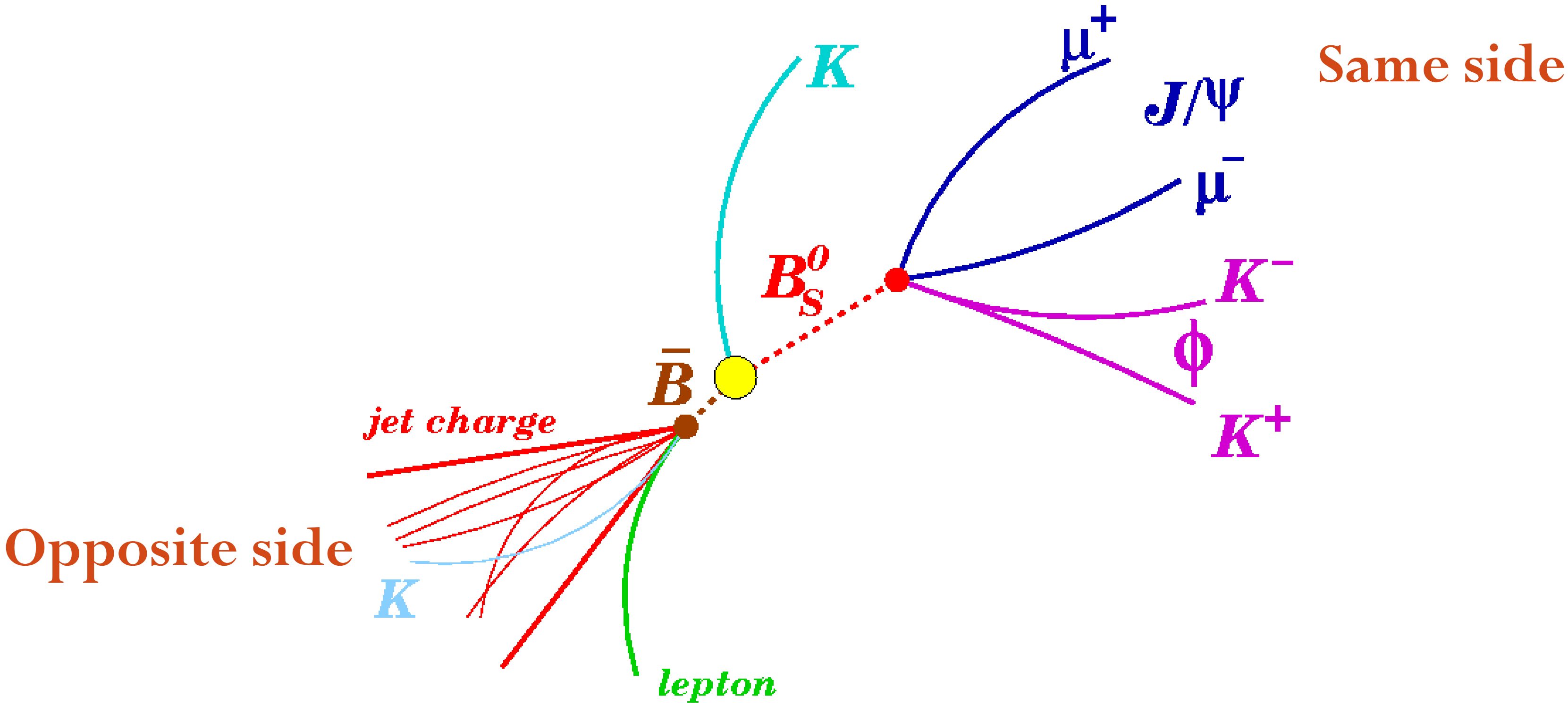
VV final state defines 3D coordinate system

Flavor Tagging

"Time is a sort of river of passing events, and strong is its current; no sooner is a thing brought to sight than it is swept by and another takes its place, and this too will be swept away. "

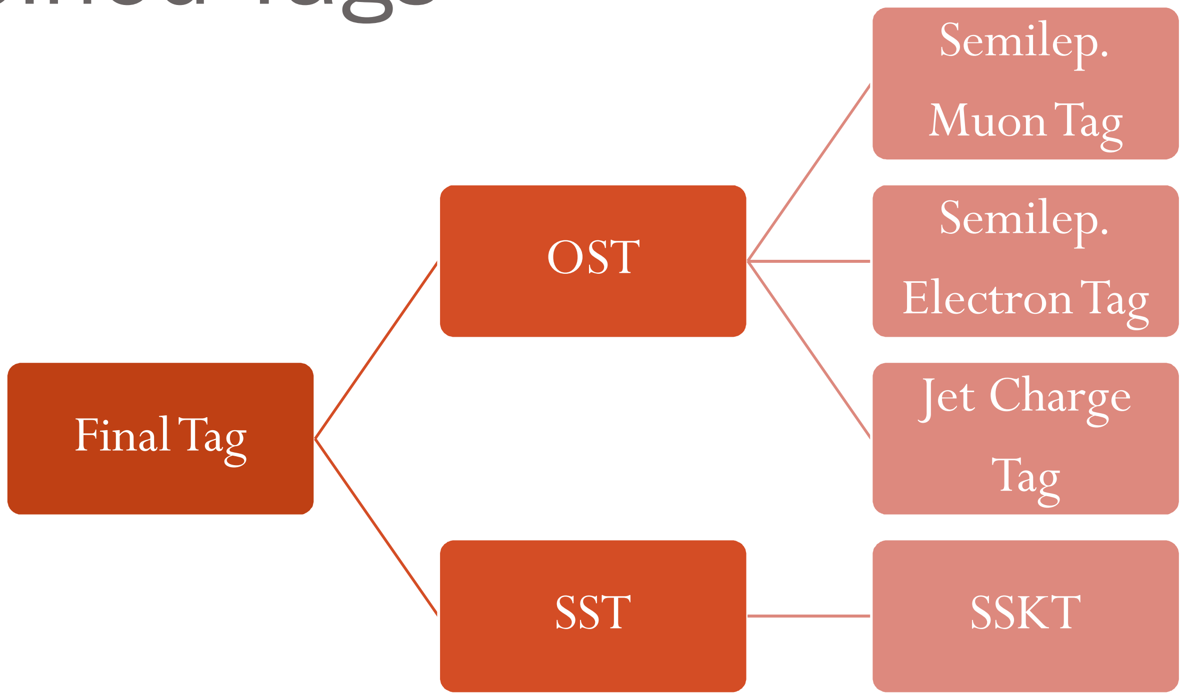
- *Marcus Aurelius Antonius*

Basics of Flavor Tagging



- b quarks generally produced in pairs at Tevatron
  - Tag either b quark which produces J/ψφ, or other b quark

Combined Tags



- OST
  - $\varepsilon = (96 \pm 1)\%$, average $\mathcal{D} = (11 \pm 2)\%$
- SSKT
  - $\varepsilon = (50 \pm 1)\%$, average $\mathcal{D} = (27 \pm 4)\%$
  - Calibrated only for first 1.35 fb^{-1} of data

Un-binned Likelihood Fit

"Like stones, ~~words~~ PDFs are laborious and unforgiving, and the fitting of them together, like the fitting of stones, demands great patience and strength of purpose and particular skill."

- Edmund Morrison (paraphrased)

Observables and Parameters in Fit

- Measured quantities that enter fit function
  - B_s^0 decay time and its error, transversity angles, reconstructed mass of B_s^0 and its error, flavor tag decision, dilution D
- Fit for parameters of interest (β_s, $\Delta\Gamma$) plus many nuisance parameters (e.g. mean width $\Gamma = (\Gamma_L+\Gamma_H)/2$, $|A_\perp(0)|^2, |A_\parallel(0)|^2, |A_0(0)|^2, \delta_\parallel, \delta_\perp \ \ldots$)
  - Simultaneous fit to mass (separate signal from background) and lifetime distributions (separate CP even and odd terms with angular dependence and time evolution with flavor tagging)

Signal Probability Distribution

- Signal PDF for a single tag

$$P_s(t,\vec{\rho},\xi|\mathcal{D},\sigma_t) = \frac{1+\xi\mathcal{D}}{2}P(t,\vec{\rho}|\sigma_t)\epsilon(\vec{\rho}) + \frac{1-\xi\mathcal{D}}{2}\bar{P}(t,\vec{\rho}|\sigma_t)\epsilon(\vec{\rho})$$

B_s^0

$\bar{B}_s^0$

- Signal probability depends on
  - Tag decision $\xi = \{-1, 0, +1\}$
  - Event-per-event dilution $\mathcal{D}$
  - Sculpting of transversity angles due to detector acceptance, $\varepsilon(\rho)$
    - $\rho = \{\cos\theta_T, \varphi_T, \cos\psi_T\}$
- Convolve time dependence with Gaussian proper time resolution function with mean of 0.1 ps and RMS of 0.04 ps

Signal Probability Distribution

- General relation for B-> VV

B_s^0:
$$\frac{d^4P(t,\vec{\rho})}{dtd\vec{\rho}} \propto |A_0(0)|^2\mathcal{T}_+f_1(\vec{\rho}) + |A_\parallel(0)|^2\mathcal{T}_+f_2(\vec{\rho}) + |A_\perp(0)|^2\mathcal{T}_-f_3(\vec{\rho}) + |A_\parallel(0)||A_\perp(0)|\mathcal{U}_+f_4(\vec{\rho}) + |A_0(0)||A_\parallel(0)|\cos(\delta_\parallel)\mathcal{T}_+f_5(\vec{\rho}) + |A_0(0)||A_\perp(0)|\mathcal{V}_+f_6(\vec{\rho})$$

$\bar{B}_s^0$:
$$\frac{d^4\bar{P}(t,\vec{\rho})}{dtd\vec{\rho}} \propto |A_0(0)|^2\mathcal{T}_+f_1(\vec{\rho}) + |A_\parallel(0)|^2\mathcal{T}_+f_2(\vec{\rho}) + |A_\perp(0)|^2\mathcal{T}_-f_3(\vec{\rho}) + |A_\parallel(0)||A_\perp(0)|\mathcal{U}_-f_4(\vec{\rho}) + |A_0(0)||A_\parallel(0)|\cos(\delta_\parallel)\mathcal{T}_+f_5(\vec{\rho}) + |A_0(0)||A_\perp(0)|\mathcal{V}_-f_6(\vec{\rho}),$$

Time dependence appears in $T_\pm$, $U_\pm$, $V_\pm$. Different for B_s^0 and $\bar{B}_s^0$!

Time-evolution with Flavor Tagging

- Separate terms for Bs, Bs-bar

CP asymmetry

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

where $\eta = +1$ for P and -1 for $\bar{P}$

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

Dependence on $\cos(\Delta m_s t)$

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

Time-evolution without Flavor Tagging

- Separate terms for Bs, Bs-bar

CP asymmetry

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

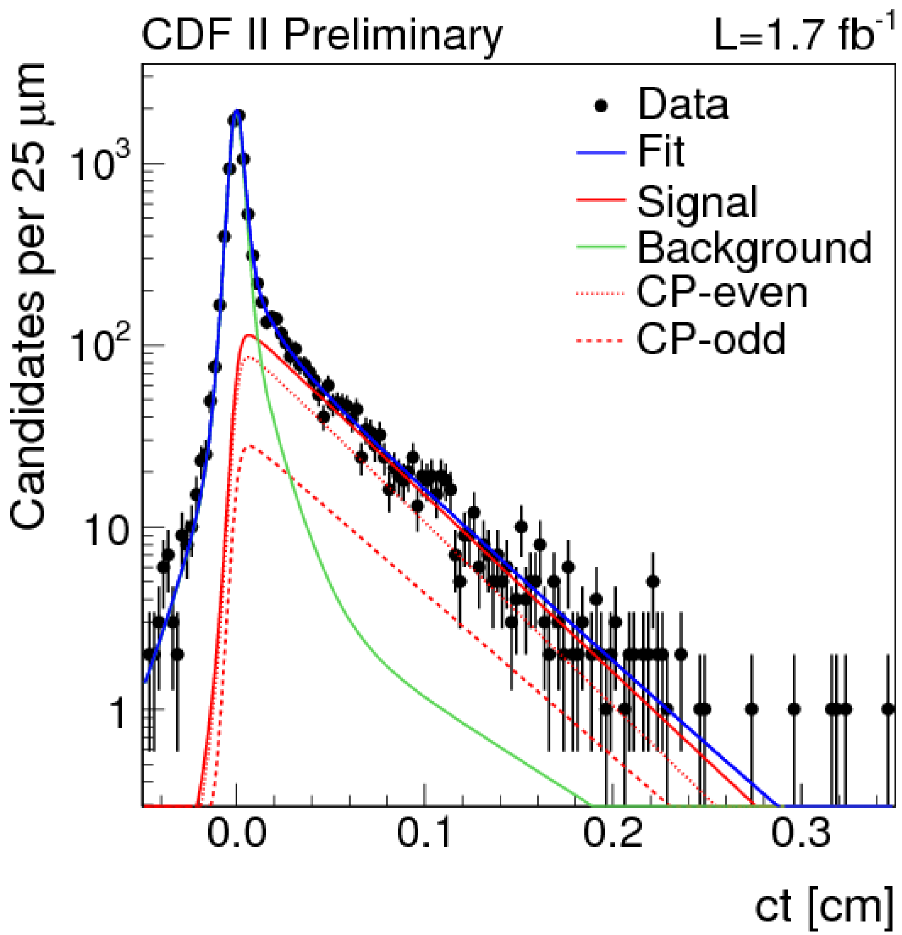
where $\eta = +1$ for P and -1 for $\bar{P}$

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

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

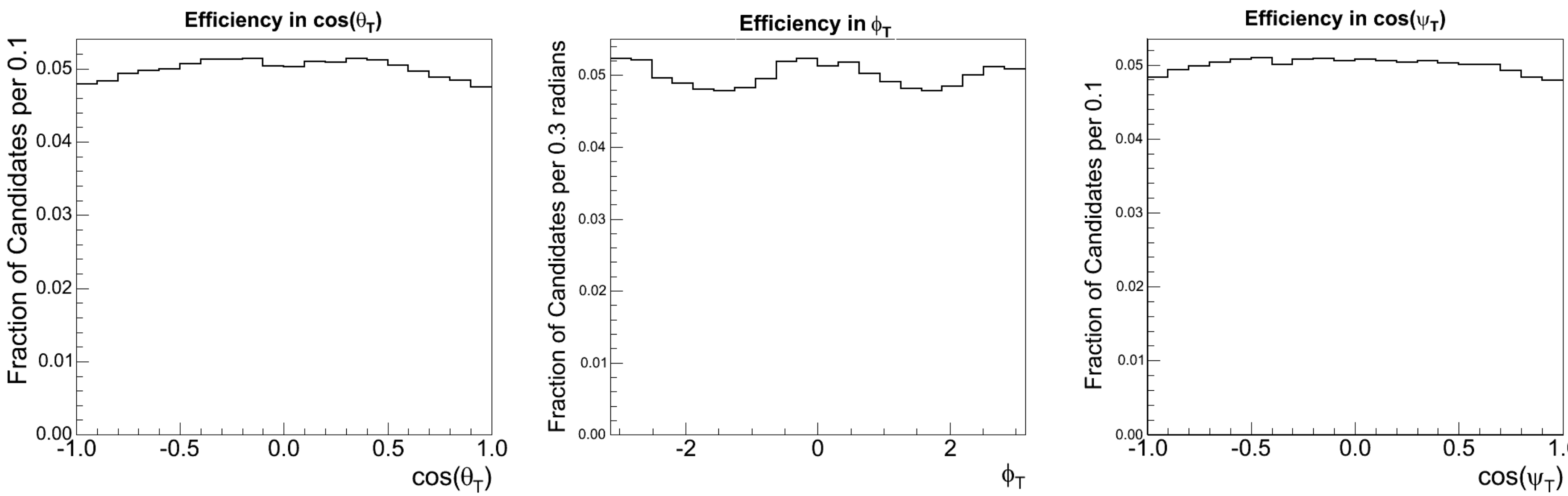
B_s^0 Lifetime Projection

No flavor tagging, $2\beta_s$ fixed to SM value



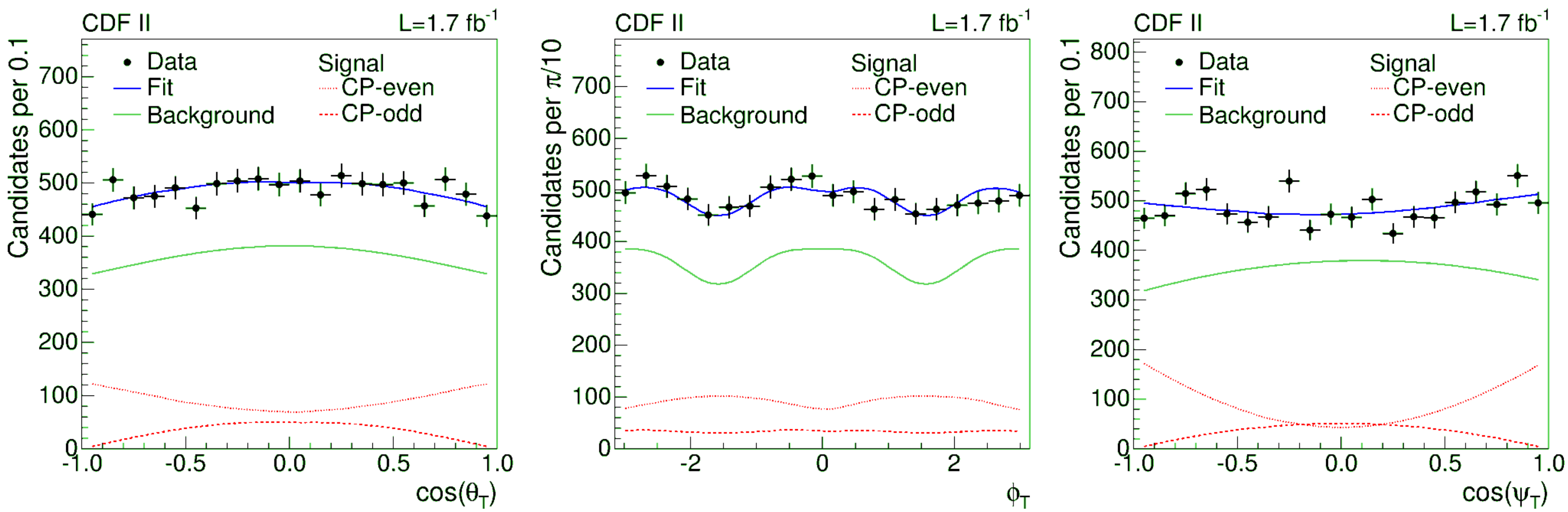
Detector Sculpting of Angles

- Use Monte Carlo passed through detector simulation and reconstruction as in data to determine angular sculpting



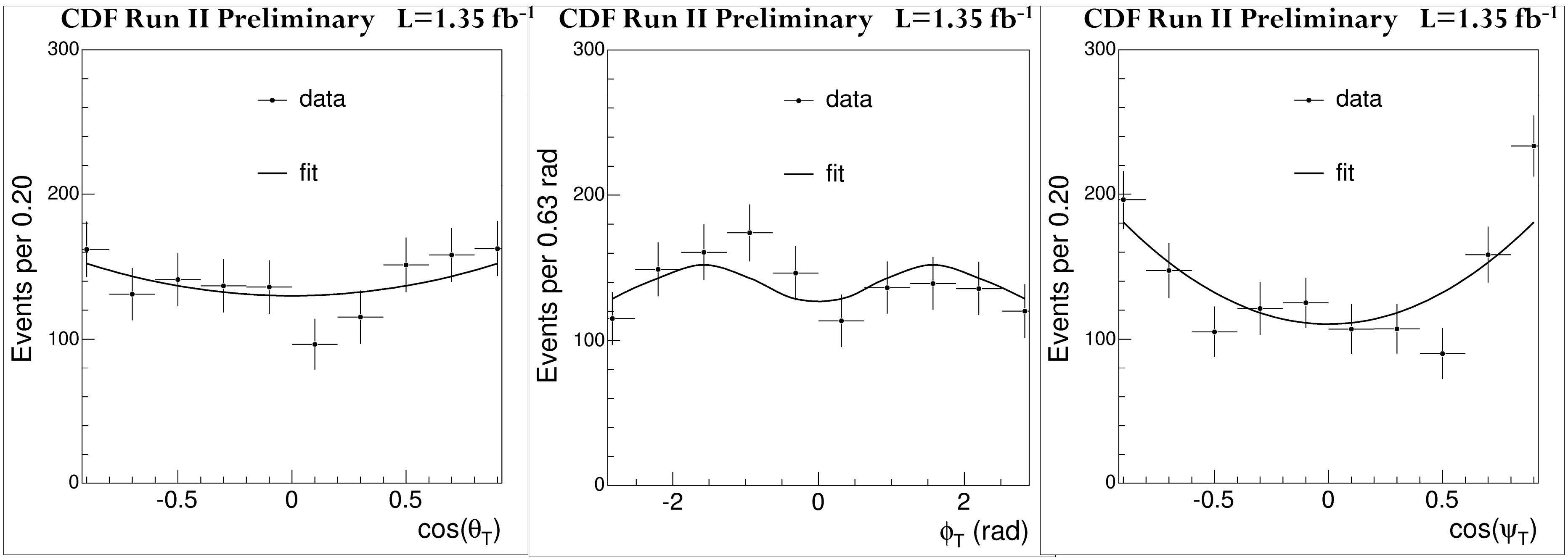
Deviation from flat distribution indicates detector effects!

B_s^0 Angular Fit Projections



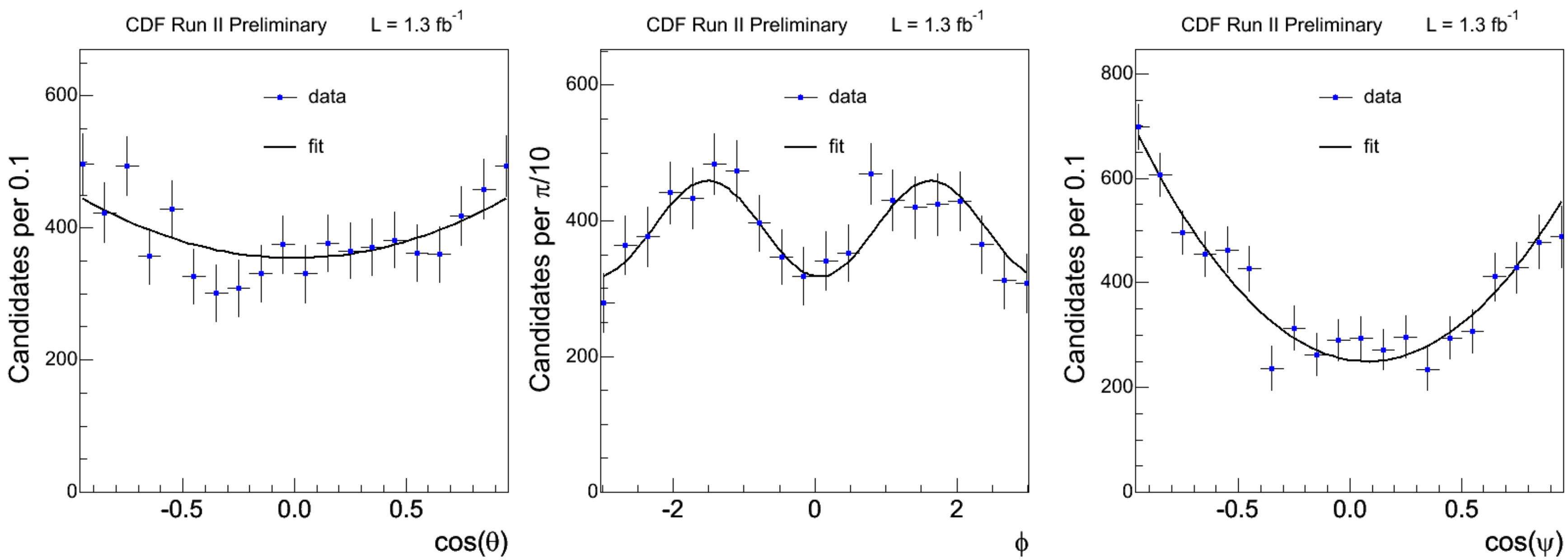
Uncorrected for detector sculpting effects.

Corrected B_s^0 Angular Fit Projections



Corrected for detector sculpting.

Compare B^0 Angular Fit Projections



Acceptance corrected distributions- fit agrees well!

Validates treatment of detector acceptance!

Cross-check with B^0 Decays

- Fit results for $B^0 \rightarrow J/\psi\, K^{*0}$

$$c\tau = 456 \pm 6\ (\mathrm{stat}) \pm 6\ (\mathrm{syst})\ \mu\mathrm{m}$$
$$|A_0(0)|^2 = 0.569 \pm 0.009\ (\mathrm{stat}) \pm 0.009\ (\mathrm{syst})$$
$$|A_\parallel(0)|^2 = 0.211 \pm 0.012\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})$$
$$\delta_\parallel = -2.96 \pm 0.08\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})$$
$$\delta_\perp = 2.97 \pm 0.06\ (\mathrm{stat}) \pm 0.01\ (\mathrm{syst})$$

- Results are in good agreement with BABAR and errors are competitive!

$$|A_0(0)|^2 = 0.556 \pm 0.009\ (\mathrm{stat}) \pm 0.010\ (\mathrm{syst})$$
$$|A_\parallel(0)|^2 = 0.211 \pm 0.010\ (\mathrm{stat}) \pm 0.006\ (\mathrm{syst})$$
$$\delta_\parallel = -2.93 \pm 0.08\ (\mathrm{stat}) \pm 0.04\ (\mathrm{syst})$$
$$\delta_\perp = 2.91 \pm 0.05\ (\mathrm{stat}) \pm 0.03\ (\mathrm{syst})$$

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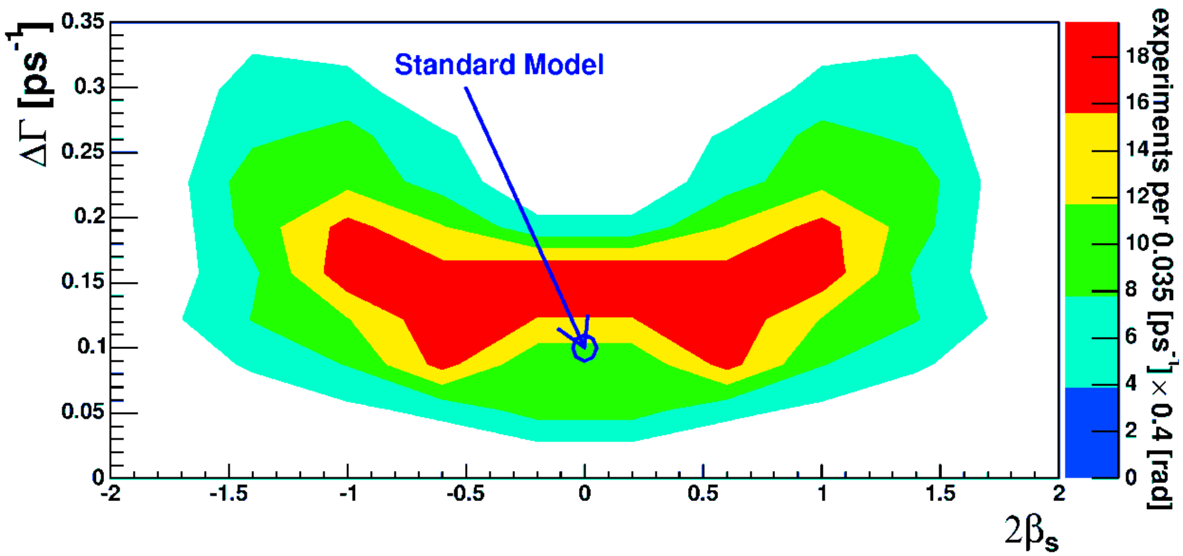
Additional Complications

- Two exact symmetries are present in $B_s^0 \to J/\psi\varphi$ untagged analysis
  - $2\beta_s \to -2\beta_s,\ \delta_\perp \to \delta_\perp + \pi$
  - $\Delta\Gamma \to -\Delta\Gamma,\ 2\beta_s \to 2\beta_s + \pi$
  - Gives four equivalent solutions in β_s and $\Delta\Gamma$!
- Also observe biases in pseudo-experiments for fit parameters under certain circumstances

Biases in Untagged Fits

- Can still reliably quote some point estimates with $2\beta_s$ fixed to standard model prediction
  - Mean lifetime, $\Delta\Gamma$, $|A_0(0)|^2$, $|A_\parallel(0)|^2$, $|A_\perp(0)|^2$
- When $2\beta_s$ floats freely in fit, see significant biases in pseudo-experiments



Untagged B_s^0 Decays

- Fit results with $2\beta_s$ fixed to SM value (w/ 1.7 fb^{-1} of data)

  $\tau(B_s^0) = 1.52 \pm 0.04 \pm 0.02$ ps

  $\Delta\Gamma = 0.076 + 0.059 - 0.063 \pm 0.006\ ps^{-1}$

- Best measurement of width difference, mean B_s^0 lifetime
  - 30-50% improvement on previous best measurements
  - Good agreement with D0 results (Phys. Rev. D 76, 031102, (2007))

  $\tau(B_s^0) = 1.52 \pm 0.08\ (stat)\ ^{+0.01}_{-0.03}\ (syst)$ ps

  $\Delta\Gamma = 0.17 \pm 0.09\ (stat) \pm 0.02\ (syst)\ ps^{-1}$

- Also measure angular amplitudes

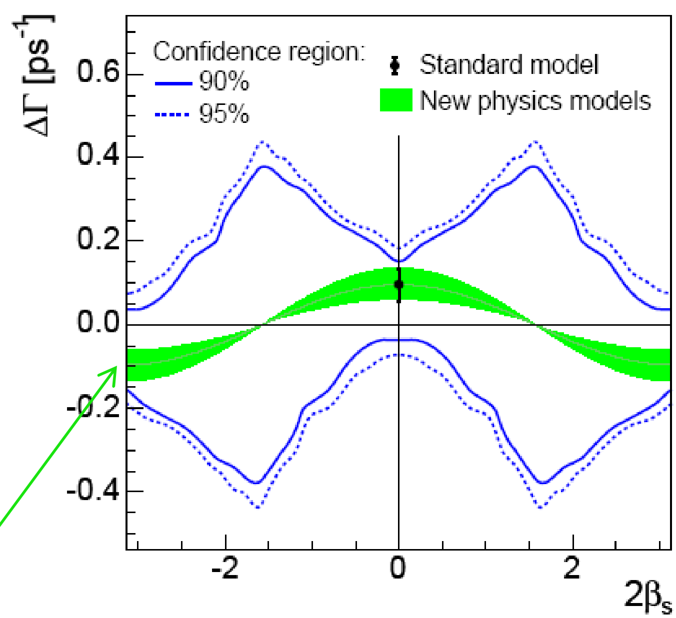
  $|A_0(0)|^2 = 0.531 \pm 0.020\ (stat) \pm 0.007\ (syst)$

  $|A_\parallel(0)|^2 = 0.230 \pm 0.026\ (stat) \pm 0.009\ (syst)$

  $|A_\perp(0)|^2 = 0.239 \pm 0.029\ (stat) \pm 0.011\ (syst)$

Untagged $2\beta_s$-$\Delta\Gamma$ Confidence Region

- Quote instead Feldman-Cousins confidence region
  - Use likelihood ratio to determine probability of result to fluctuate above a given value of input parameters (p-value)



p-value at standard model point is 22%

$\Delta\Gamma = 2|\Gamma_{12}|\cos(2\beta_s)$

Exact Symmetries in Tagged Decays

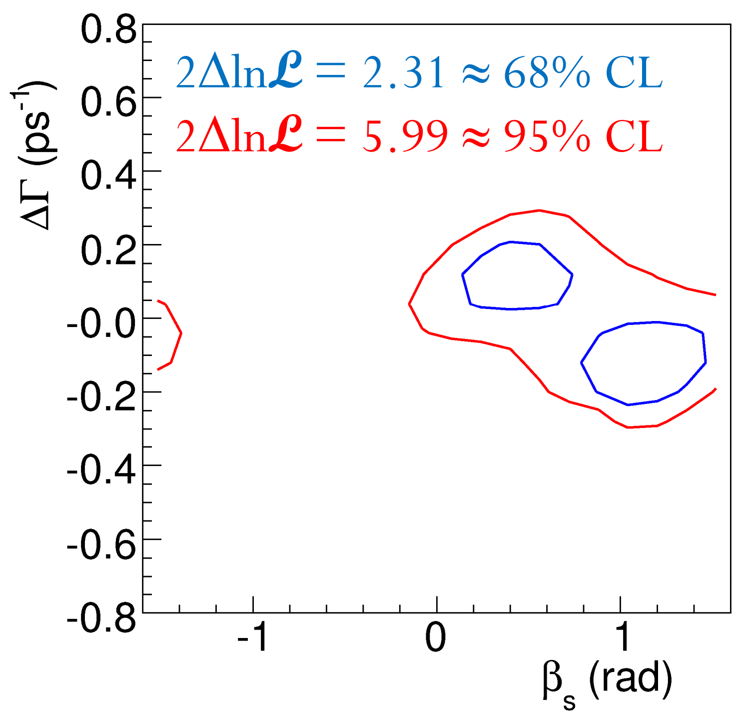
- With flavor tagging, exact symmetry is present in signal probability distribution

$$2\beta_s \to \pi - 2\beta_s$$
$$\Delta\Gamma \to -\Delta\Gamma$$
$$\delta_\parallel \to 2\pi - \delta_\parallel$$
$$\delta_\perp \to \pi - \delta_\perp$$

  - Leads to two equivalent solutions in β_s and $\Delta\Gamma$!
  - Can remove exact symmetry by boxing one of the parameters

Check Fit with Pseudo-Experiments

- Check β_s–$\Delta\Gamma$ likelihood profile on Toy MC with exact symmetry removed
  - Approximate symmetry is still significant with current level of signal statistics!

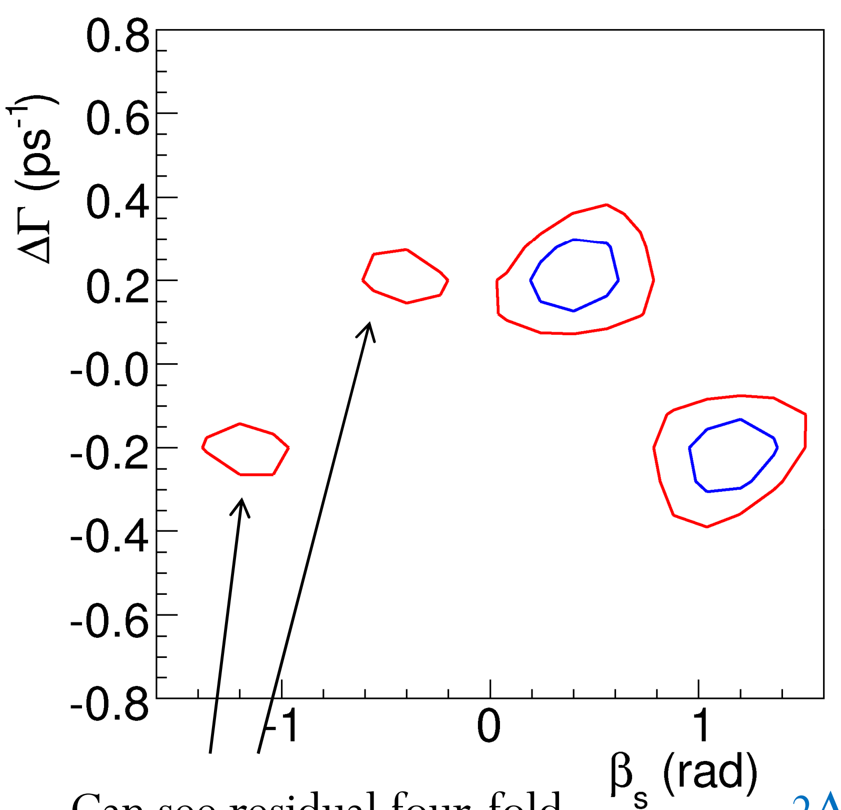


Likelihood profile is not parabolic; cannot reliably separate the two minima!

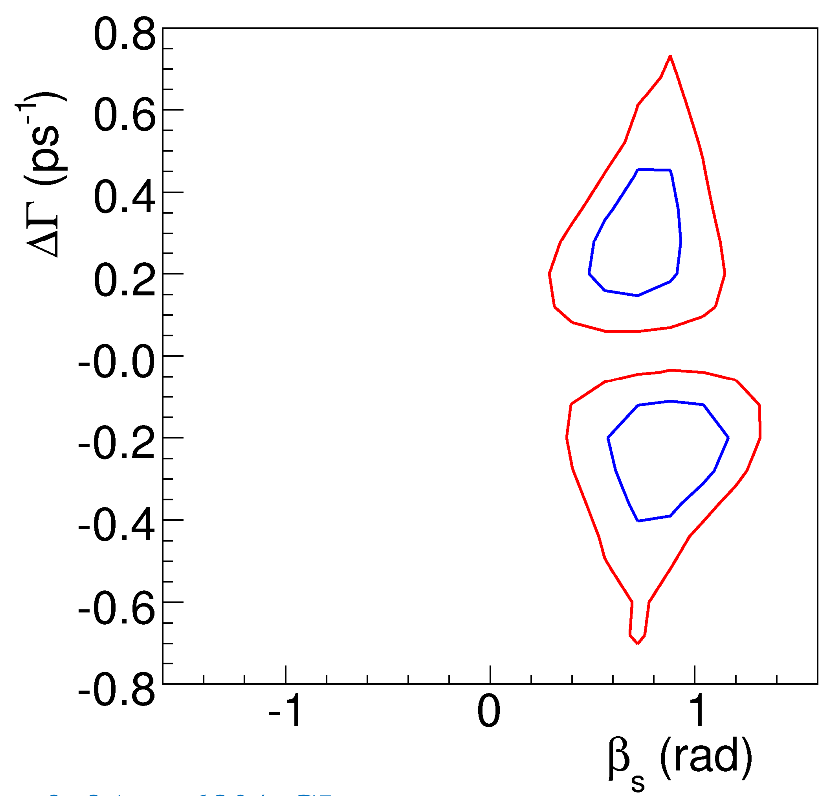
Generated with $\beta_s = 0.40$

More Pseudo-Experiments

Generated with $\beta_s = 0.40$



Generated with $\beta_s = 0.80$



Can see residual four-fold symmetry in some cases!

$2\Delta\ln\mathcal{L} = 2.31 \approx 68\%$ CL

$2\Delta\ln\mathcal{L} = 5.99 \approx 95\%$ CL

Fits with Flavor Tagging

- Don't have parabolic minima → can't quote point estimate!
- Again quote confidence regions using Feldman-Cousins likelihood ratio ordering method
- 2D profile of $2\beta_s$ vs $\Delta\Gamma$
- 1D intervals in $2\beta_s$
  - Quote results with and without external theory constraints

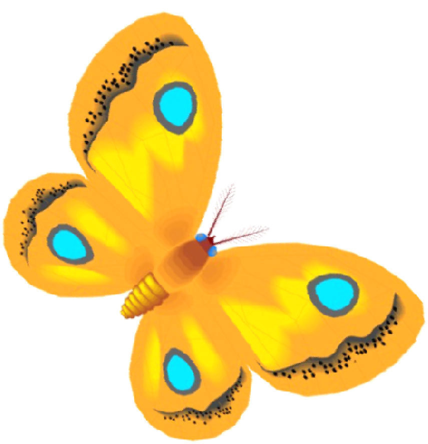
Flavor Tagged Results

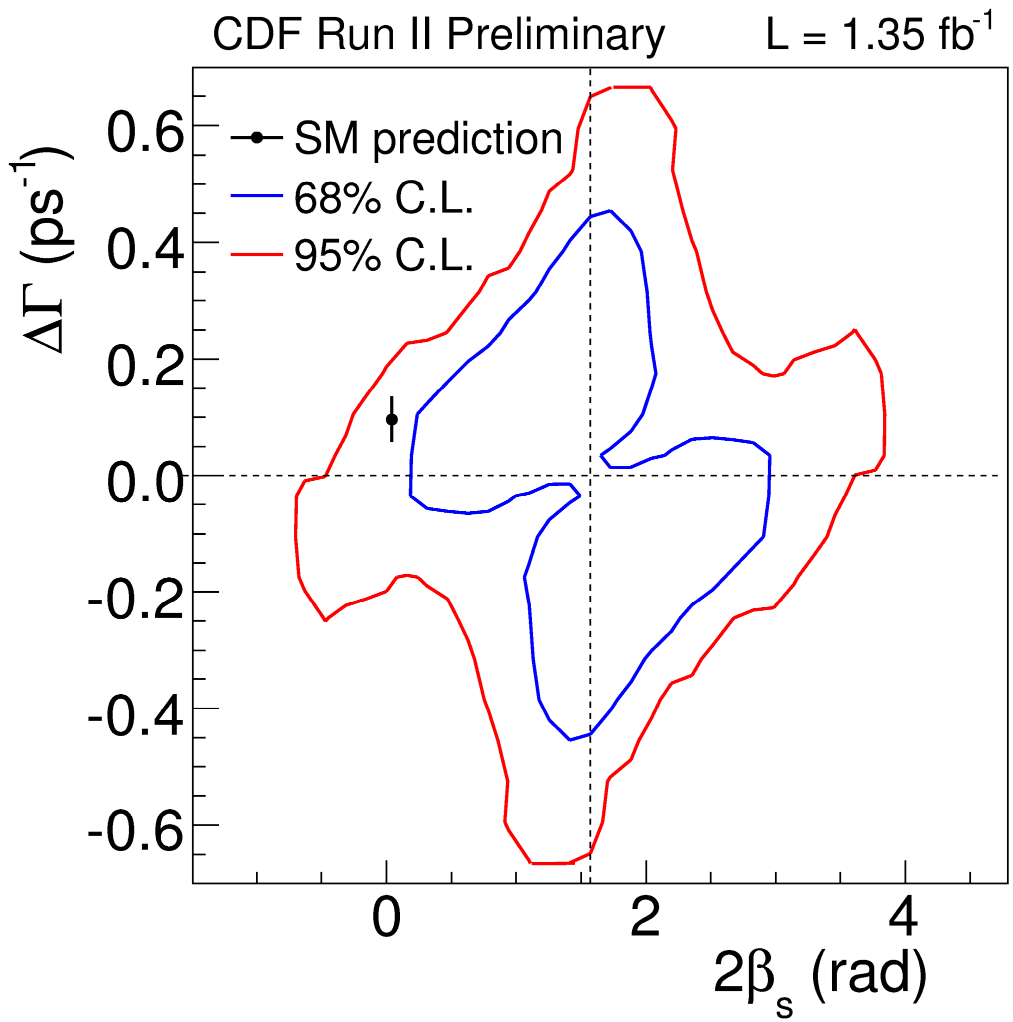
"Happiness is a butterfly, which, when pursued, is always just beyond your grasp, but which, if you will sit down quietly, may alight upon you."

- *Nathaniel Hawthorne*

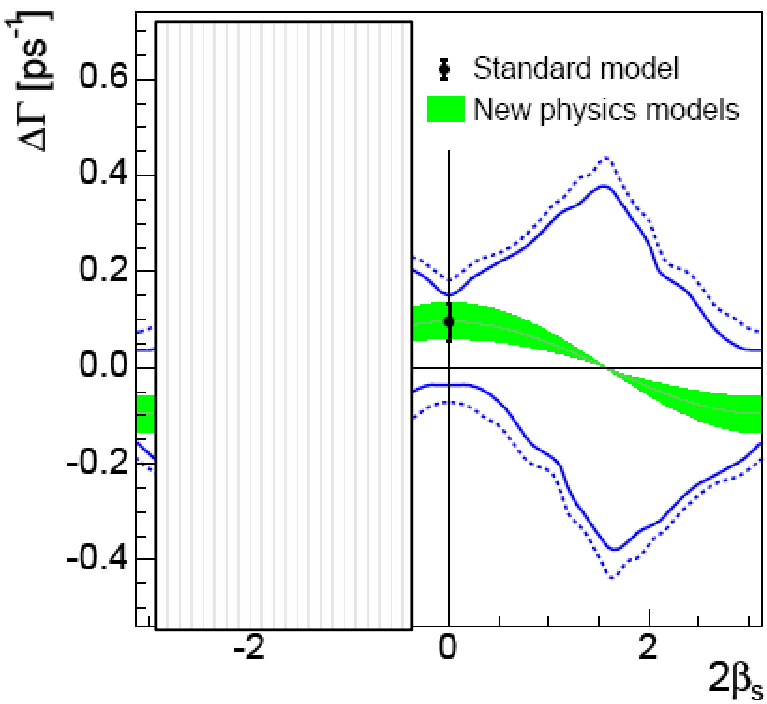
Flavor Tagged $2\beta_s$-$\Delta\Gamma$ Confidence Region

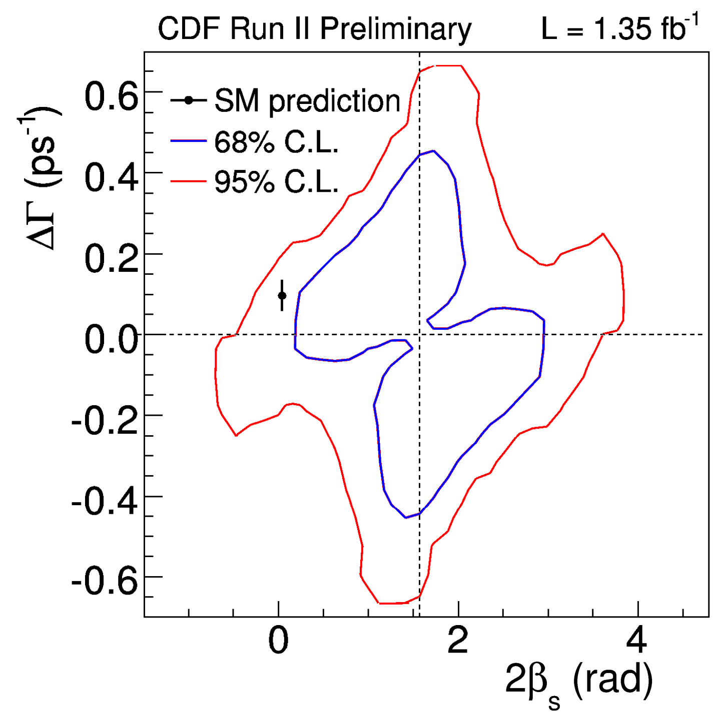
Probability of fluctuation from SM to observation is 15% (1.5σ)





Improvement from Flavor Tagging



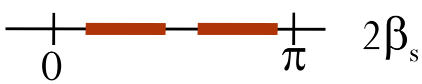


With flavor tagging, phase space for $2\beta_s$ is half that without flavor tagging!

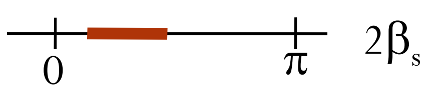
β_s 1D Intervals

- One-dimensional Feldman-Cousins confidence interval

  - $2\beta_s \in [0.32, 2.82]$ at 68% CL
- Constraining $\Delta\Gamma = 2|\Gamma_{12}|\cos(2\beta_s)$, where $|\Gamma_{12}| = 0.048 \pm 0.018$

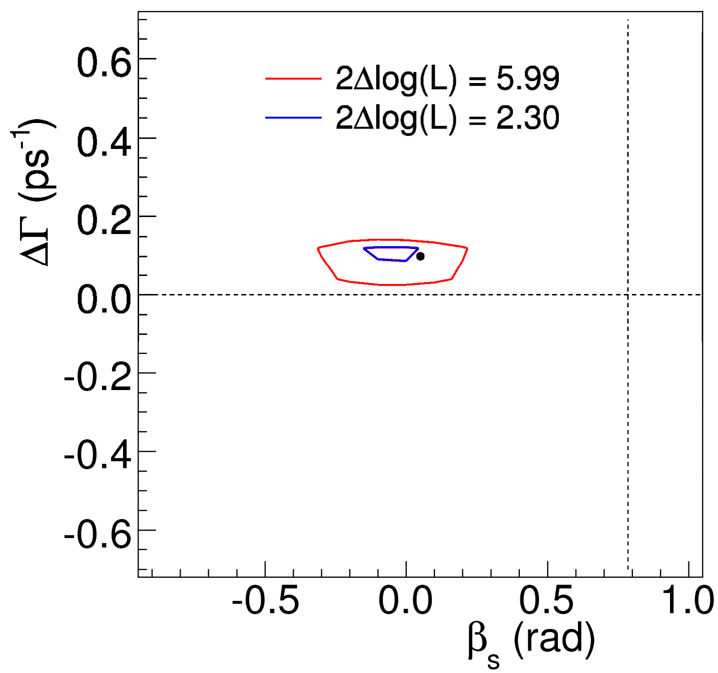


  - $2\beta_s \in [0.24, 1.36] \cup [1.78, 2.90]$ at 68% CL
- Constraining $\Delta\Gamma = 2|\Gamma_{12}|\cos(2\beta_s)$, Γ to PDG B^0 lifetime, and $\delta_{\parallel} = -2.92 \pm 0.11$ and $\delta_{\perp} = 2.72 \pm 0.09$ (BABAR results, hep-ex/0411016)

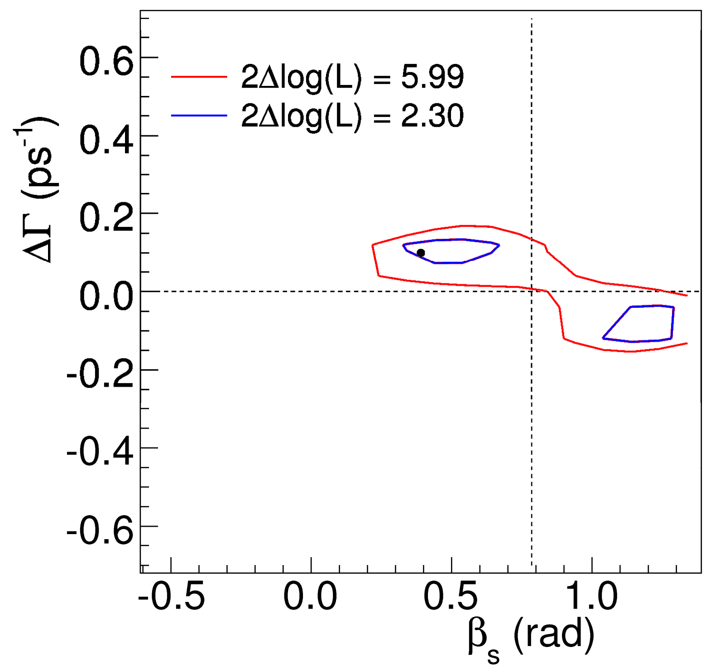


  - $2\beta_s \in [0.40, 1.20]$ at 68% CL

Future Sensitivity



Pseudo-experiments generated with β_s=0.02



Pseudo-experiments generated with $\beta_s=\pi/8$

Projected Confidence Regions in 6 fb^{-1} assuming same yield per fb^{-1} in future and same tagging efficiency and dilution

Conclusions

"Congratulations, you are one step closer to hitting bottom."

-Brad Pitt in "Fight Club"

Significant Improvement in CP Phase

- CDF significantly improves knowledge of β_s / φ_s^{NP}
  - 1.5σ consistency with SM predicted phase
  - Have reduced space available for new physics by factor of two!
    - Provide significantly tighter constraints on NP
- CDF also provides best measurement of mean B_s^0 lifetime, width difference in context of standard model
- Two exciting new results submitted to PRL today!
  - arXiv:0712.2348 (untagged measurement)
  - arXiv:0712.2397 (tagged measurement)