CP Violation in the B_s^0 System at the Tevatron

Derek Strom
Northwestern University
On Behalf of the CDF and DØ Collaborations

Flavor Physics & CP Violation Conference
National Taiwan University, Taipei, Taiwan
May 5, 2008

Introduction to CPV in B_s^0 Decays

CPV studies in B_s^0 decays aim to understand the source of CP Violation.

One of the last remaining places to search for New Physics!

The success of the *B*-factories has shown that large (>~10%) contributions of NP are excluded from tree-level B^+ and B^0 decays.

B_s^0 decays are much less constrained and even if the B_s^0 mixing measurement constrains the strength of NP, current experimental knowledge does not exclude large (up to π) phases from NP.

CP Violation in B_s^0 is an excellent place to search for NP since it is predicted to be small in the SM. A measurement of a large CP phase is a clear indication of NP.

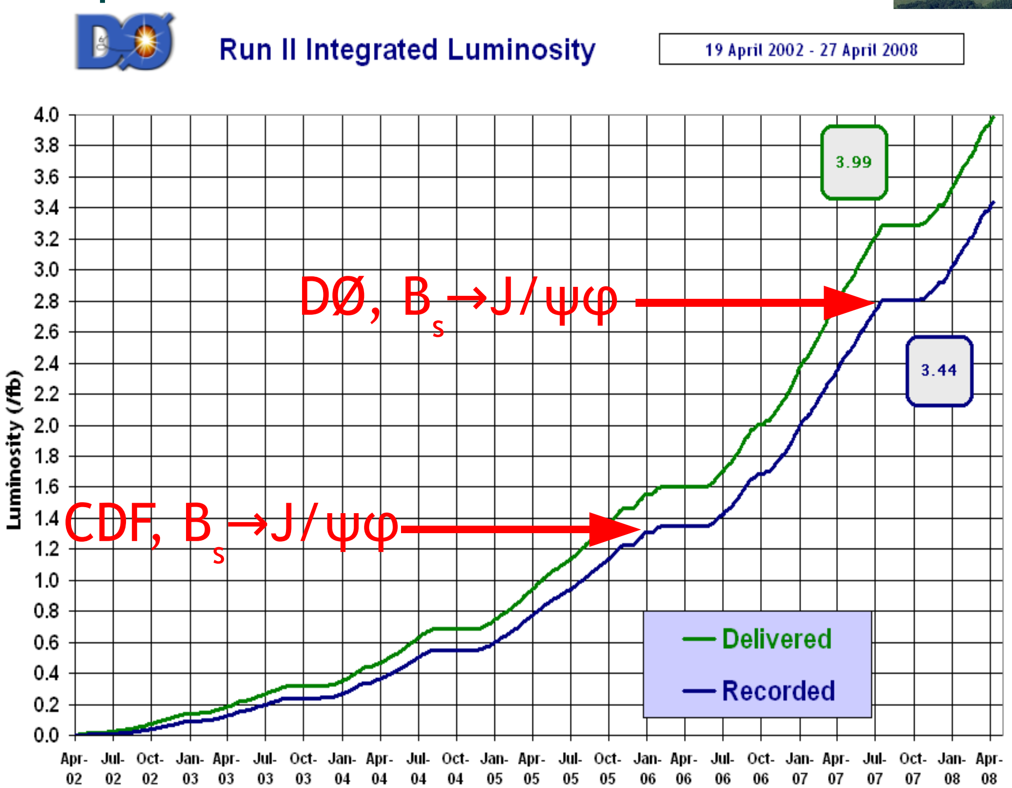
The Tevatron at Fermilab

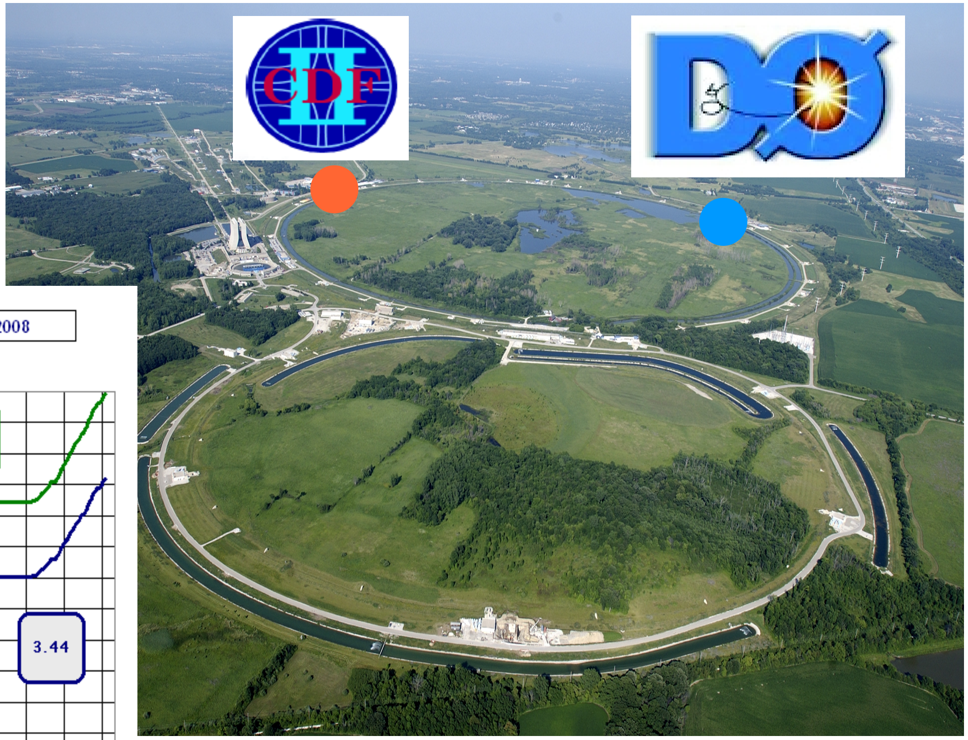
Proton on antiproton collisions at 1.96 TeV energy

Collider Experiments
CDF and DØ

Tevatron running with peak luminosity
~315 x 10^{30} cm^{-2} s^{-1}

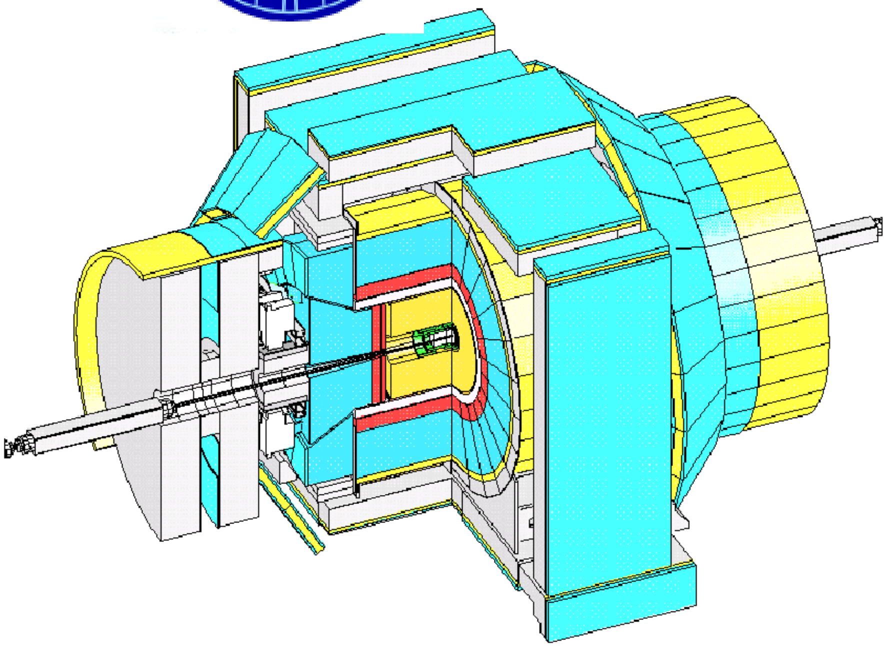
~3.9 fb^{-1} delivered, ~3.4 fb^{-1} recorded per experiment

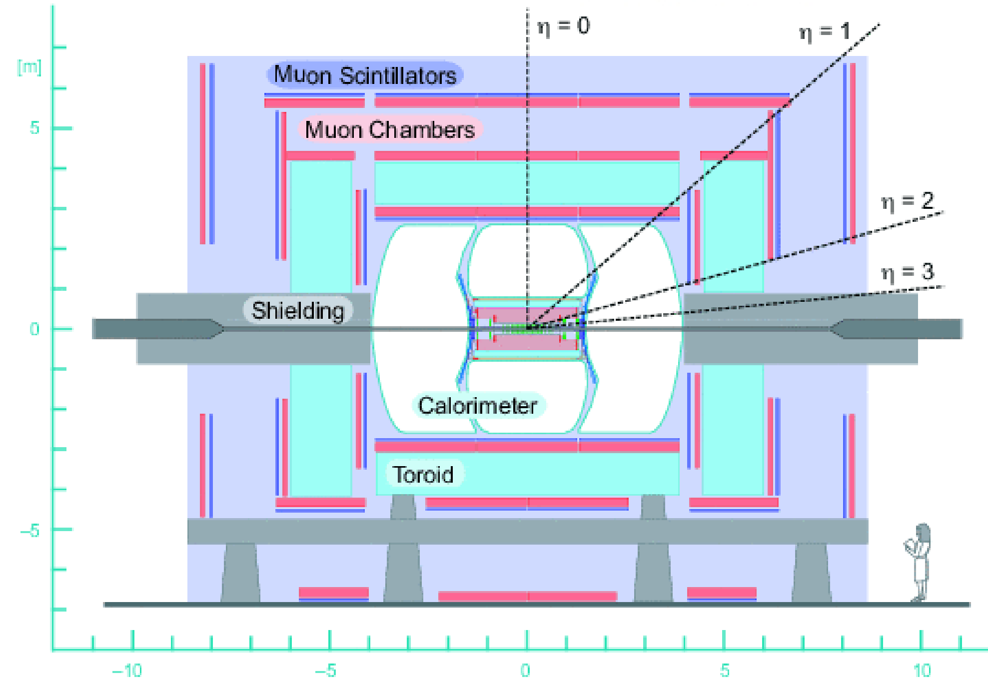




A lot of data already collected and waiting to be analyzed!

Collider Detectors





Relevant for B physics

CDF Tracker: mass resolution, vertexing

Silicon & L00
Large radii drift chamber
excellent momentum resolution
dE/dx and particle id

Triggered Muon Coverage: |η| < 1

Time of flight, particle ID

DØ Tracker: coverage, vertexing

Silicon & scintillating fiber
Small radii, |η| < 2
New layer 0 silicon on beam pipe
Improves impact parameter res.

Triggered Muon Coverage: |η| < 2

Single muon
Di-muon

B_s^0-$\overline{B}_s^0$ Mixing

Flavor eigenstates propagate according to the Schrodinger Eq.

$$i\frac{d}{dt}\begin{pmatrix} B_s(t) \\ \bar{B}_s(t) \end{pmatrix} = \left(\begin{bmatrix} m & M_{12}^s \\ M_{12}^{s*} & m \end{bmatrix} - \frac{i}{2}\begin{bmatrix} \Gamma & \Gamma_{12}^s \\ \Gamma_{12}^{s*} & \Gamma \end{bmatrix} \right) \begin{pmatrix} B_s(t) \\ \bar{B}_s(t) \end{pmatrix}$$

Diagonalizing gives two physically observed
"Heavy" and *"Light"* mass eigenstates

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

Observables

$$\Delta M_s = M_H - M_L \approx 2|M_{12}|$$

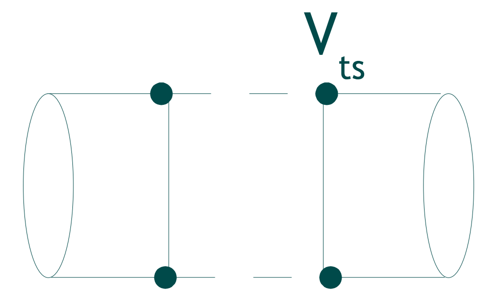
$$\Delta\Gamma^{CP} = \Gamma_{even} - \Gamma_{odd} \approx 2|\Gamma_{12}|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}|\cos(\varphi_s) \qquad \varphi_s = \arg(-M_{12}/\Gamma_{12})$$

CP Violation in the B_s^0 System

CKM Matrix

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

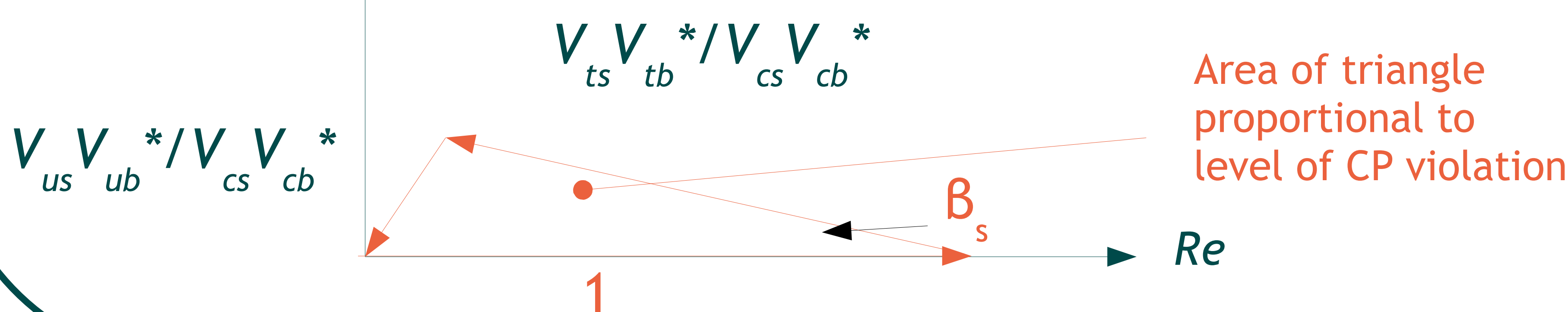


SM accommodates CPV by introducing a single complex phase in the CKM matrix

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

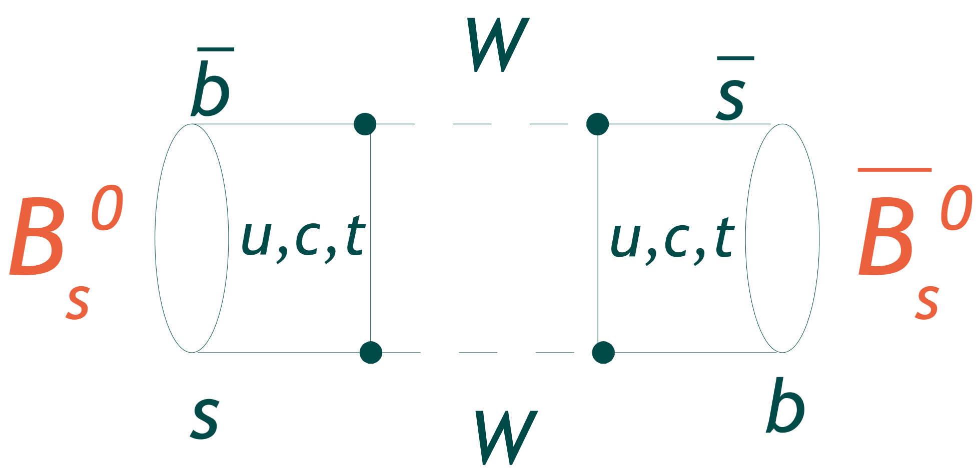
$V_{ts} >> V_{ub}$

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



CP Violation in B_s^0- $\bar{B}_s^0$ Mixing

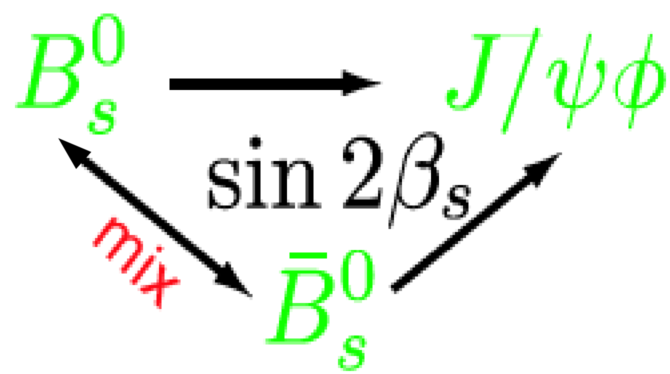
Matter ⟷ Antimatter



Semileptonic asymmetry

$N(B_s^0 \rightarrow D^{--})$ vs $N(\bar{B}_s^0 \rightarrow B_s^0 \rightarrow D^{--})$

Interference



CP Violation in the B_s^0 System

How could new physics affect these phases?

$$2\beta_s^{SM} \rightarrow \overset{\sim 0.04}{2\beta_s^{SM}} - \phi_s^{NP}$$

$$\phi_s^{SM} = \arg[-M_{12}/\Gamma_{12}] \rightarrow \underset{\sim 0.004}{\phi_s^{SM}} + \phi_s^{NP}$$

Both CDF and DØ measure the phase responsible for CP violation in $B_s^0 \rightarrow J/\psi\varphi$ decays

$$\underset{\text{DØ}}{\phi_s^{J/\psi\phi}} = \underset{\text{CDF}}{-2\beta_s^{J/\psi\phi}} \approx \underset{\text{If large}}{\phi_s^{NP}}$$

Topics Covered in this Talk

Semileptonic Asymmetry	Mixing and Decay $B_s^0 \rightarrow J/\psi\varphi$
DØ, 1.3 fb^{-1} PRL 98, 151801 (2007)	DØ, 1.1 fb^{-1} PRL 98, 121801 (2007)
DØ, 1.0 fb^{-1} PRD 74, 092001 (2006)	DØ, 2.8 fb^{-1} submitted to PRL
Combined: PRD 76, 057101 (2007)	CDF, 1.35 fb^{-1} PRL 100, 161802 (2008)
CDF, 1.6 fb^{-1} CDF note 9015	

CP Violation: Semileptonic Asymmetry

Measured semileptonic asymmetries

$$a_{sl}^{s} \equiv \frac{N(\bar{B}_s \to f) - N(B_s \to \bar{f})}{N(\bar{B}_s \to f) + N(B_s \to \bar{f})} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$$

DØ, 1.3 fb^{-1}, PRL 98, 151801 (2007)

$$N(B_s^0 \to D_s^- \mu^+ \nu)$$

vs.

$$N(\bar{B}_s^0 \to D_s^+ \mu^- \bar{\nu})$$

+

DØ, 1 fb^{-1}, PRD 74, 092001 (2006)

$$N(b\bar{b} \to \mu^+ \mu^+ X)$$

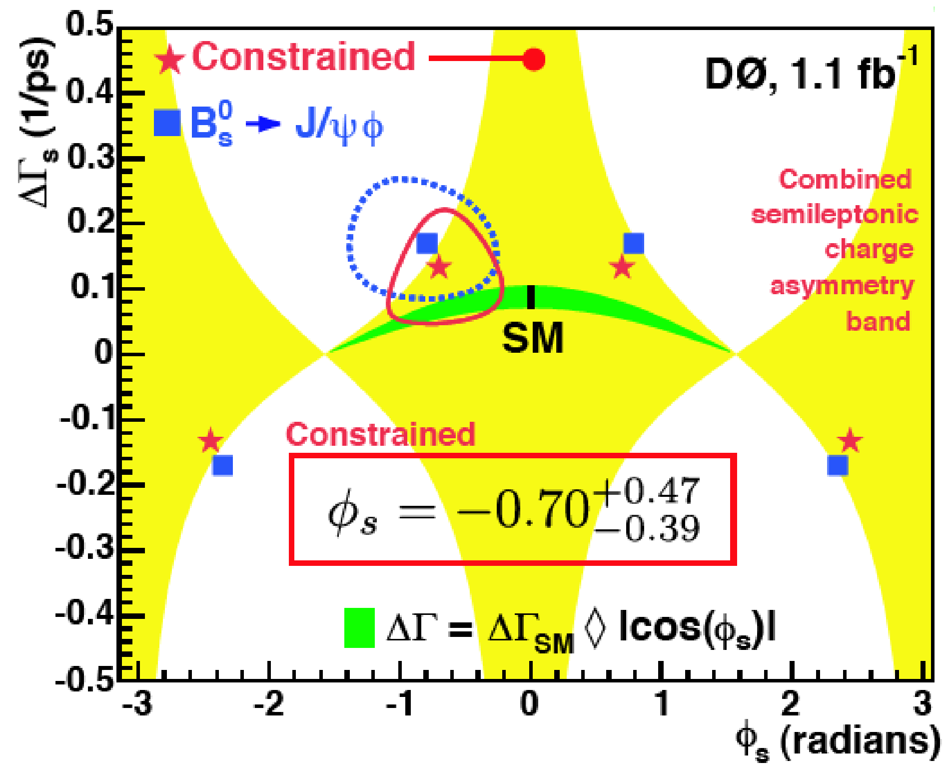
vs.

$$N(b\bar{b} \to \mu^- \mu^- X)$$

=

$$a_{SL}^{s} = 0.0001 \pm 0.0090$$

PRD 76, 057101 (2007)



Regular flipping of polarity of solenoid (tracking) and toroid (muons) helps control systematic uncertainties.

CP Violation: Semileptonic Asymmetry

Measured semileptonic asymmetries

DØ, 1.3 fb^{-1}, PRL 98, 151801 (2007)

$$N(B_s^0 \to D_s^- \mu^+ \nu)$$
vs.
$$N(\bar{B}_s^0 \to D_s^+ \mu^- \bar{\nu})$$

+

DØ, 1 fb^{-1}, PRD 74, 092001 (2006)

$$N(b\bar{b} \to \mu^+ \mu^+ X)$$
vs.
$$N(b\bar{b} \to \mu^- \mu^- X)$$

=

$$a_{SL}^s = 0.0001 \pm 0.0090$$

PRD 76, 057101 (2007)

$$a_{sl}^s \equiv \frac{N(\bar{B}_s \to f) - N(B_s \to \bar{f})}{N(\bar{B}_s \to f) + N(B_s \to \bar{f})} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$$

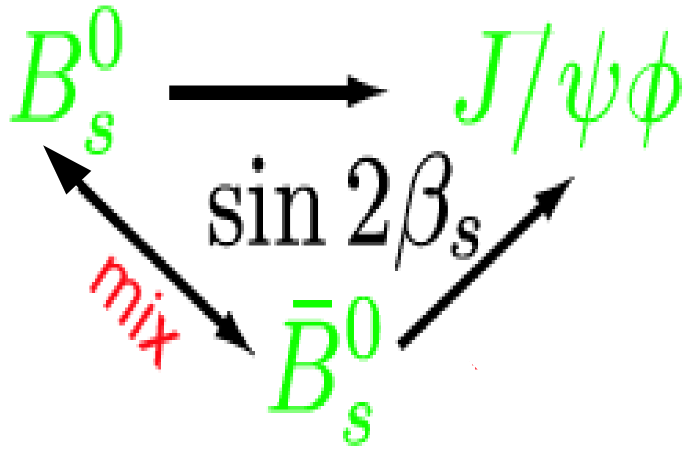
CDF, 1.6 fb^{-1}, CDF Note 9015

$$N(b\bar{b} \to \mu^+ \mu^+ X)$$
vs.
$$N(b\bar{b} \to \mu^- \mu^- X)$$

$$a_{SL}^s = 0.020 \pm 0.021 \pm 0.018$$

Regular flipping of polarity of solenoid (tracking) and toroid (muons) helps control systematic uncertainties.

CP Violation in $B_s^0 \rightarrow J/\psi\Phi$ decays



CP violation becomes observable in these decays due to the interference between the mixing and decay amplitudes.

$J/\psi + \Phi$ is an admixture of states that are both CP(even) and CP(odd)

Angular analysis is used to separate the CP components and measure the lifetimes of each component

Flavor Tagging gives us useful information on the flavor of the produced B_s^0 meson

$B_s^0 \rightarrow J/\psi\Phi$

J/ψ and φ are vector particles and have definite angular distributions for CP-even and CP-odd final states.

$B_s \rightarrow V1 + V2\ (J/\psi + \varphi)$ Spin $0 \rightarrow 1 + 1$ $\ell = 0,1,2$

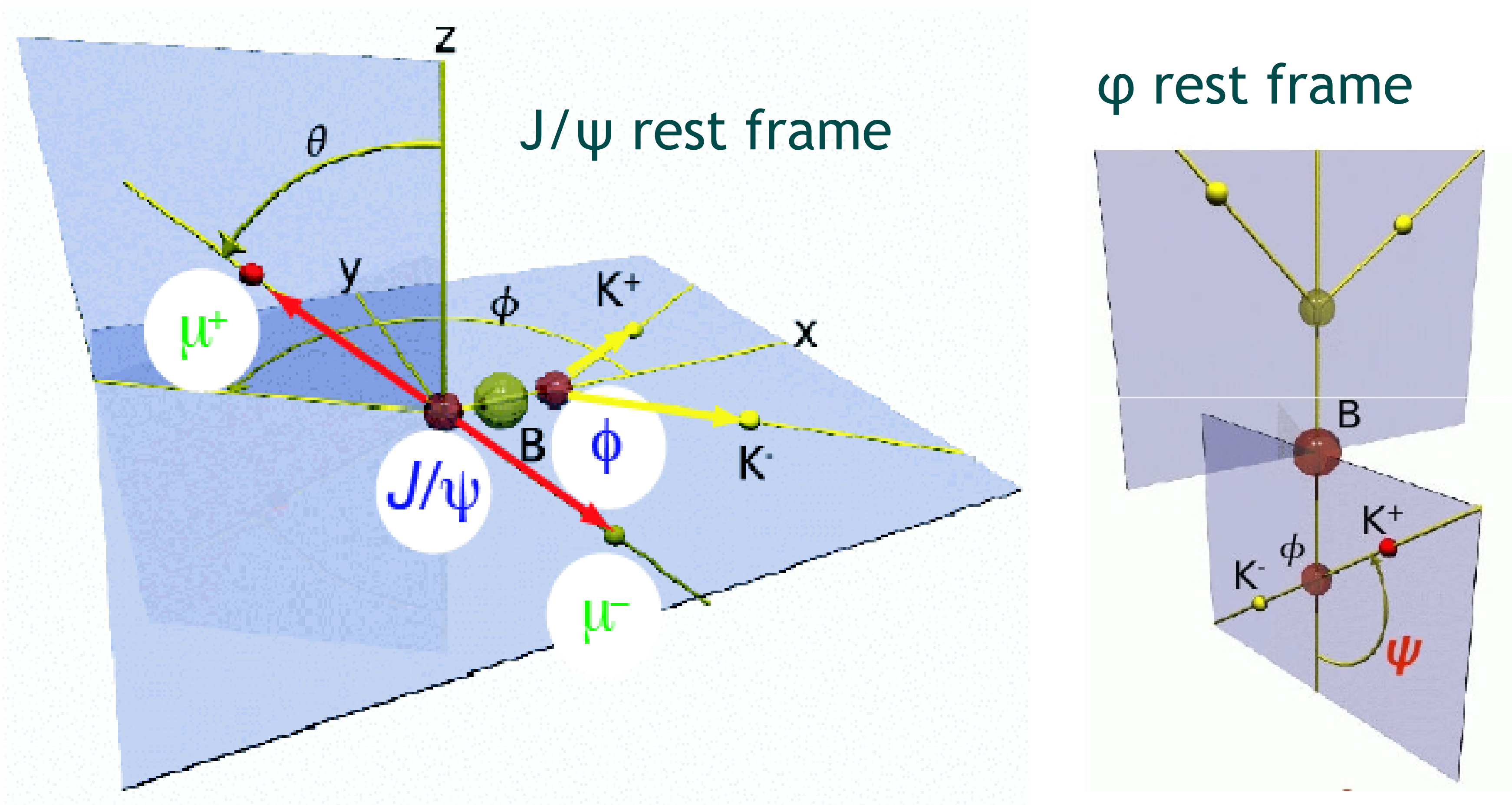
Parameterized angular decay in the Transversity basis.

Angular dependencies are described in terms of polarization amplitudes:

- A_0: Both vectors longitudinally polarized ($\ell = 0,2$) CP even
- $A_\parallel$: Transversely polarized and vectors parallel ($\ell = 0,2$) CP even
- $A_\perp$: Transversely polarized and vectors perpendicular ($\ell = 1$) CP odd

$$|A_\parallel(0)|^2 + |A_\perp(0)|^2 + |A_0(0)|^2 = 1$$

Angular Analysis



Angles θ (transversity), φ and ψ. ψ is the angle between $\vec{p'}_{K+}$ and the x-axis in the rest frame of ϕ.

Differential Decay Rate and Amplitudes

$$\frac{d^4\Gamma\left[B_s^0(t) \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)\right]}{d\cos\theta \quad d\varphi \quad d\cos\psi \quad dt} \propto$$

$$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)\cdot|A_0(t)|^2$$
$$+\sin^2\psi(1-\sin^2\theta\sin^2\varphi)\cdot|A_{\parallel}(t)|^2$$
$$+\sin^2\psi\sin^2\theta\cdot|A_{\perp}(t)|^2$$
$$+(1/\sqrt{2})\sin 2\psi\sin^2\theta\sin 2\varphi\cdot\Re(A_0^*(t)A_{\parallel}(t))$$
$$+(1/\sqrt{2})\sin 2\psi\sin 2\theta\cos\varphi\cdot\Im(A_0^*(t)A_{\perp}(t))$$
$$-\sin^2\psi\sin 2\theta\sin\varphi\cdot\Im(A_{\parallel}^*(t)A_{\perp}(t)).$$

Polarization Amplitudes

Upper sign: Time evolution of pure $B_s^0 \rightarrow J/\psi\Phi$ at t=0

Lower sign: Time evolution of pure $\overline{B}_s^0 \rightarrow J/\psi\Phi$ at t=0

$$
\begin{aligned}
|A_0(t)|^2 &= |A_0(0)|^2 \left[\mathcal{T}_+ \pm e^{-\overline{\Gamma} t} \sin\phi_s \sin(\Delta M_s t)\right], \\
|A_\parallel(t)|^2 &= |A_\parallel(0)|^2 \left[\mathcal{T}_+ \pm e^{-\overline{\Gamma} t} \sin\phi_s \sin(\Delta M_s t)\right], \\
|A_\perp(t)|^2 &= |A_\perp(0)|^2 \left[\mathcal{T}_- \mp e^{-\overline{\Gamma} t} \sin\phi_s \sin(\Delta M_s t)\right],
\end{aligned}
$$

where

$$
\mathcal{T}_\pm = (1/2)\left[(1 \pm \cos\phi_s) e^{-\Gamma_L t} + (1 \mp \cos\phi_s) e^{-\Gamma_H t}\right].
$$

$$
\begin{aligned}
\Re(A_0^*(t) A_\parallel(t)) = {} & |A_0(0)||A_\parallel(0)| \cos(\delta_2 - \delta_1)[\mathcal{T}_+ \\
& \pm e^{-\overline{\Gamma} t} \sin\phi_s \sin(\Delta M_s t)],
\end{aligned}
$$

$$
\begin{aligned}
\Im(A_0^*(t) A_\perp(t)) = {} & |A_0(0)||A_\perp(0)|[e^{-\overline{\Gamma} t}(\pm \sin\delta_2 \cos(\Delta M_s t) \mp \\
& \cos\delta_2 \sin(\Delta M_s t) \cos\phi_s) - (1/2)\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right) \sin\phi_s \cos\delta_2],
\end{aligned}
$$

$$
\begin{aligned}
\Im(A_\parallel^*(t) A_\perp(t)) = {} & |A_\parallel(0)||A_\perp(0)|[e^{-\overline{\Gamma} t}(\pm \sin\delta_1 \cos(\Delta M_s t) \mp \\
& \cos\delta_1 \sin(\Delta M_s t) \cos\phi_s) - (1/2)\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right) \sin\phi_s \cos\delta_1],
\end{aligned}
$$

Polarization Amplitudes (no Flavor Tagging)

Assuming equal production rate of B_s^0 and $\overline{B}_s^0$

Opposite terms vanish, but still sensitive to φ_s

$$|A_0(t)|^2 = |A_0(0)|^2 \left[\mathcal{T}_+ \quad\quad \right],$$

$$|A_{\parallel}(t)|^2 = |A_{\parallel}(0)|^2 \left[\mathcal{T}_+ \quad\quad \right],$$

$$|A_{\perp}(t)|^2 = |A_{\perp}(0)|^2 \left[\mathcal{T}_- \quad\quad \right],$$

where

$$\mathcal{T}_\pm = (1/2)\left[(1 \pm \cos\phi_s)e^{-\Gamma_L t} + (1 \mp \cos\phi_s)e^{-\Gamma_H t}\right].$$

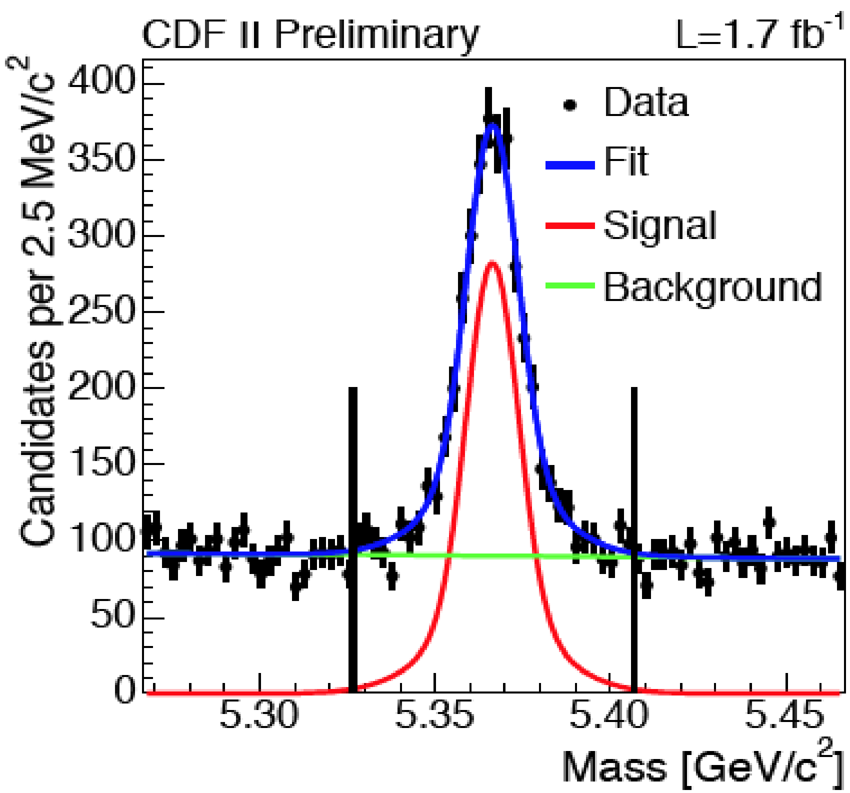
$$\Re(A_0^*(t)A_{\parallel}(t)) = |A_0(0)||A_{\parallel}(0)|\cos(\delta_2 - \delta_1)[\mathcal{T}_+ \quad\quad],$$

$$\Im(A_0^*(t)A_{\perp}(t)) = |A_0(0)||A_{\perp}(0)|[\ e^{-\overline{\Gamma}t} \quad\quad - (1/2)\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\sin\phi_s\ \cos\delta_2],$$

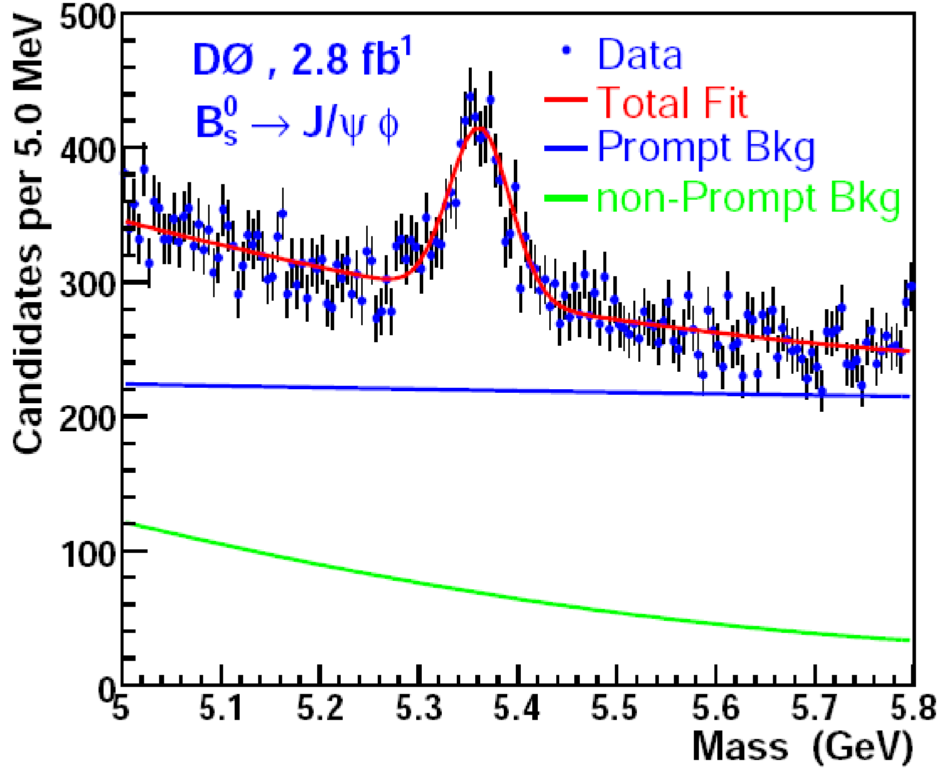
$$\Im(A_{\parallel}^*(t)A_{\perp}(t)) = |A_{\parallel}(0)||A_{\perp}(0)|[\ e^{-\overline{\Gamma}t} \quad\quad - (1/2)\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\sin\phi_s\ \cos\delta_1],$$

B_s^0 Invariant Mass

CDF



DØ

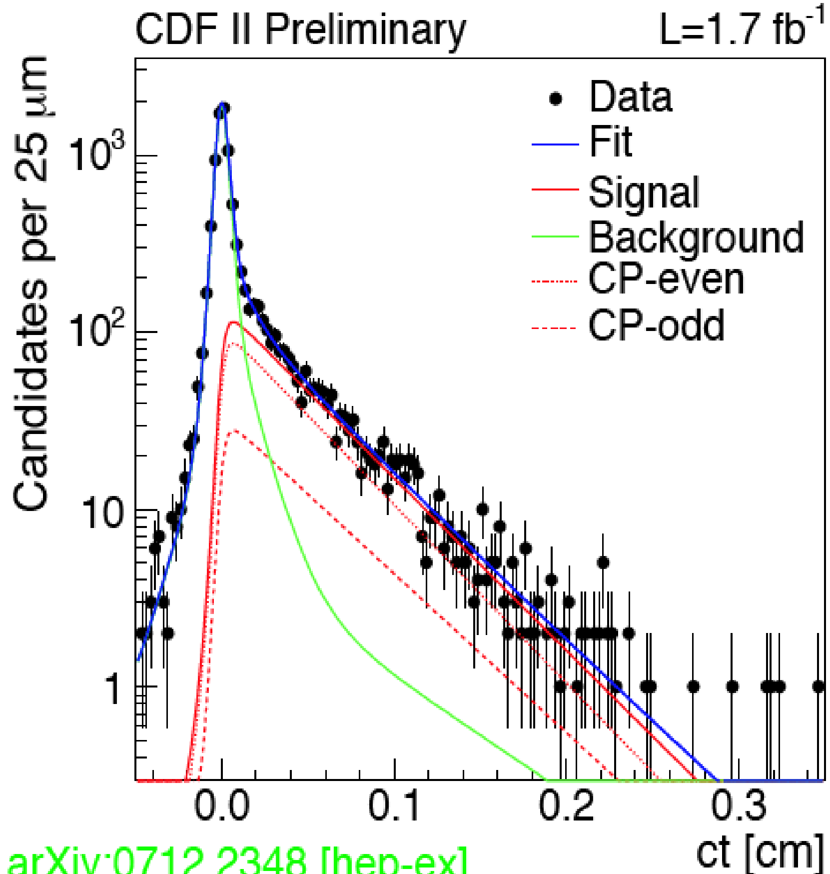


~ 2500 B_s^0 candidates

~ 2000 B_s^0 candidates

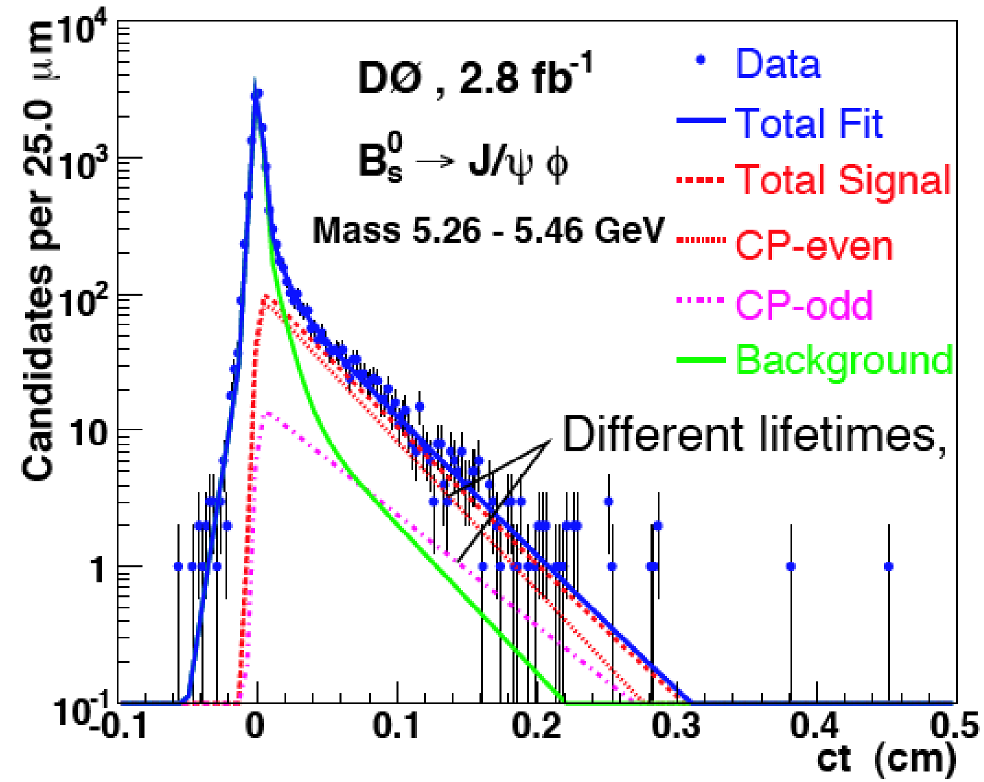
$\Delta\Gamma_s$ CP Conservation, $\varphi_s = 0$

CDF



arXiv:0712.2348 [hep-ex]

DØ



arXiv:0802.2255 [hep-ex]

$$\Delta\Gamma_s = 0.076^{+0.059}_{-0.063} \pm 0.006\,\text{ps}^{-1}$$

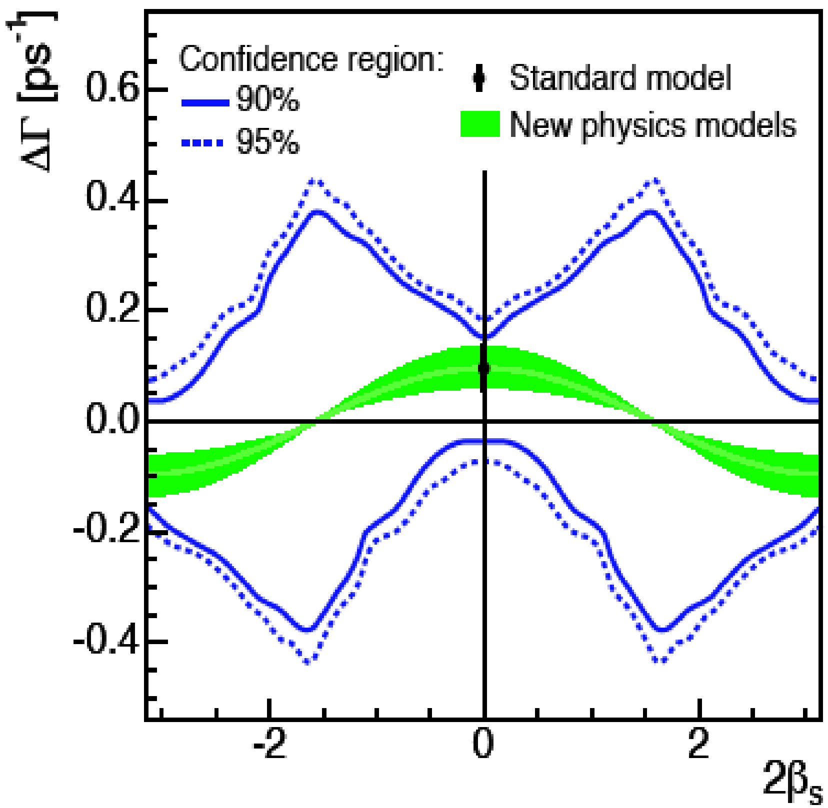
$$\bar{\tau}_s = 1.52 \pm 0.04 \pm 0.02\,\text{ps}$$

$$\Delta\Gamma_s = 0.14 \pm 0.07\,\text{ps}^{-1}$$ (Stat + syst)

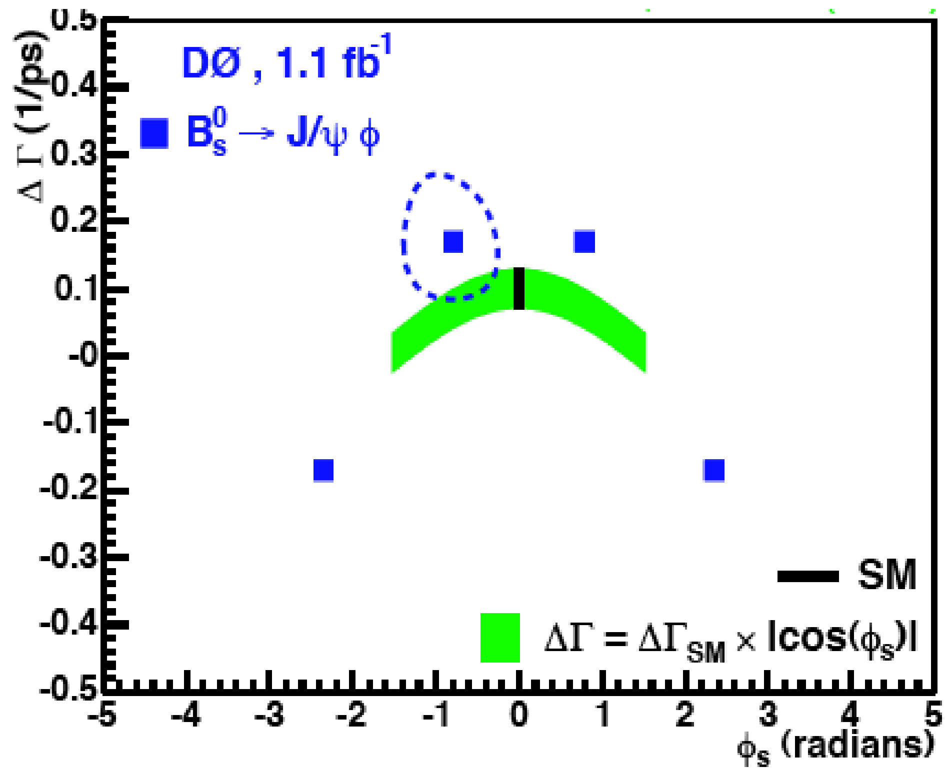
$$\bar{\tau}_s = 1.53 \pm 0.05 \pm 0.01\,\text{ps}$$

Sensitivity to φ_s (no Flavor Tagging)

CDF



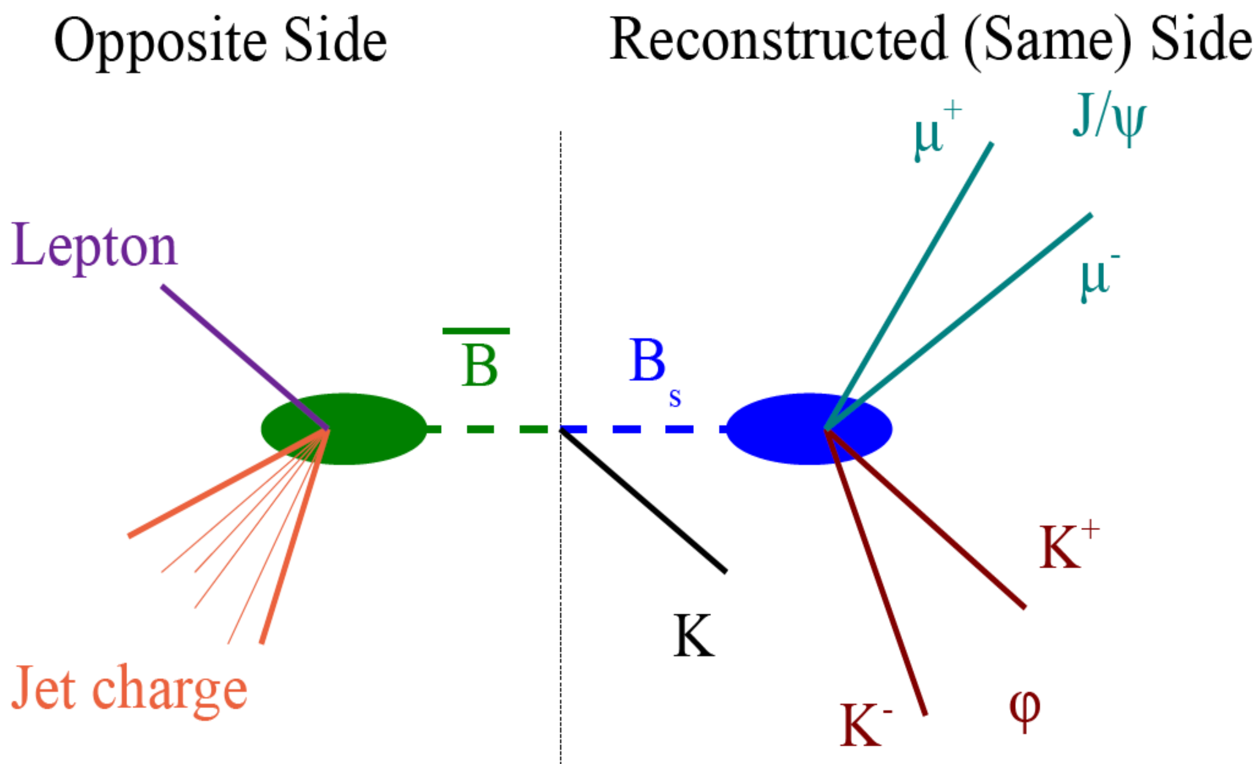
DØ



However, four-fold ambiguity reduces to two-fold after applying flavor tagging.

Flavor Tagging

Measurement of B_s^0 or $\overline{B}_s^0$ flavor at production

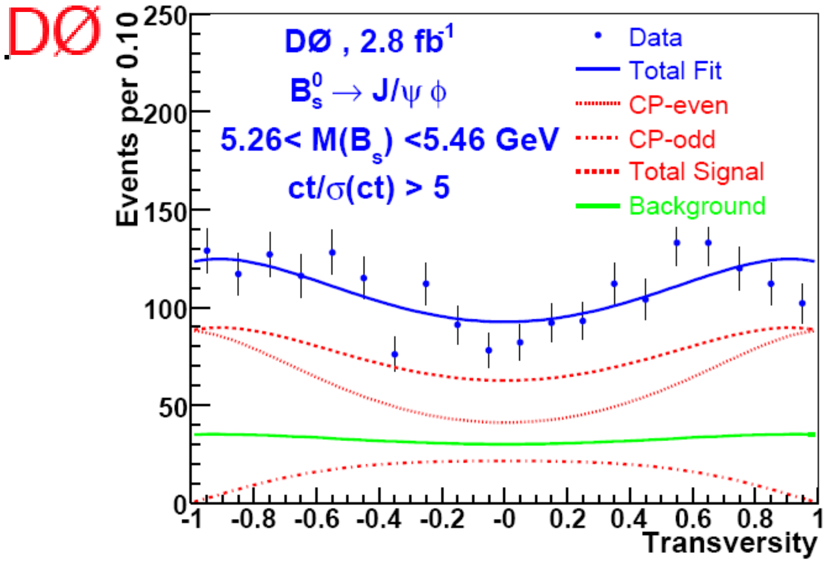


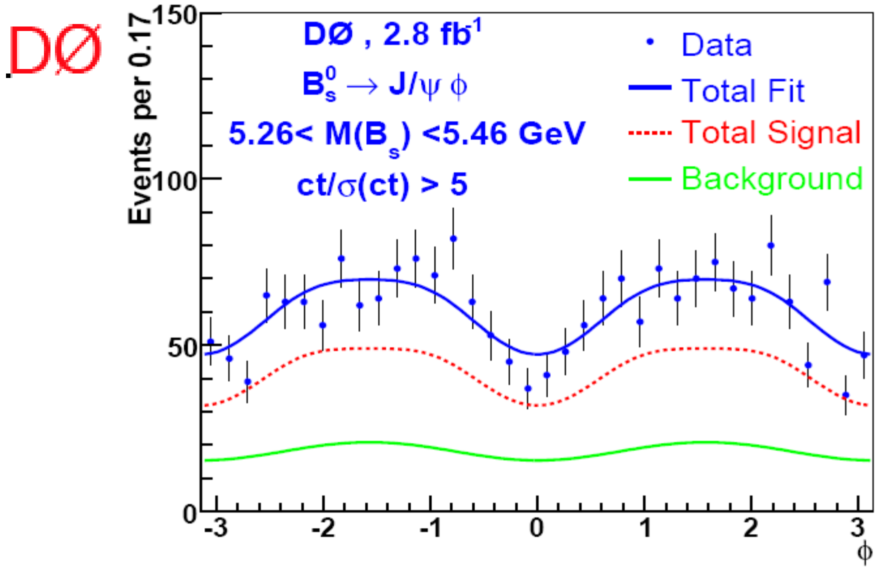
$$\mathcal{D} \equiv \frac{N_{\rm cor} - N_{\rm wr}}{N_{\rm cor} + N_{\rm wr}},$$
$$\varepsilon \equiv \frac{N_{\rm cor} + N_{\rm wr}}{N_{\rm tot}},$$
$$\mathcal{P} \equiv \varepsilon \mathcal{D}^2.$$

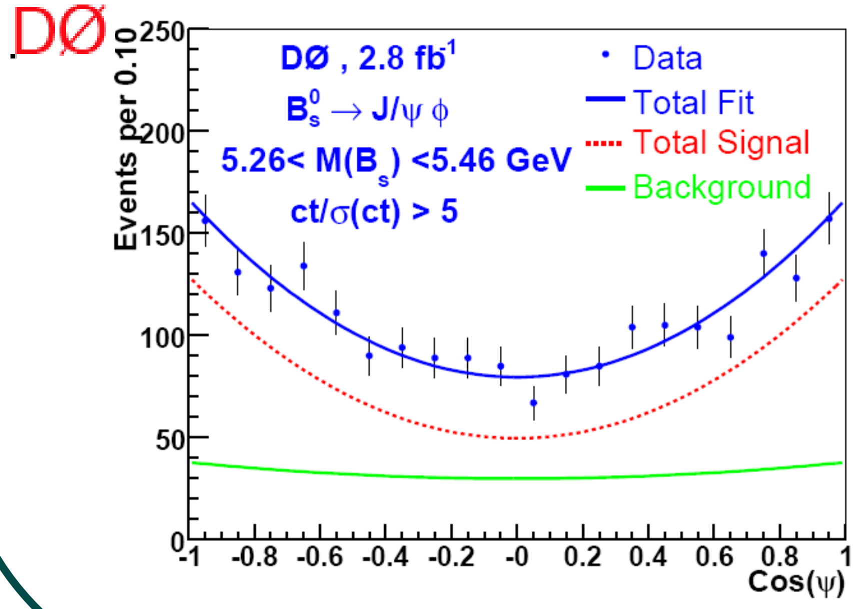
b quarks produced in pairs

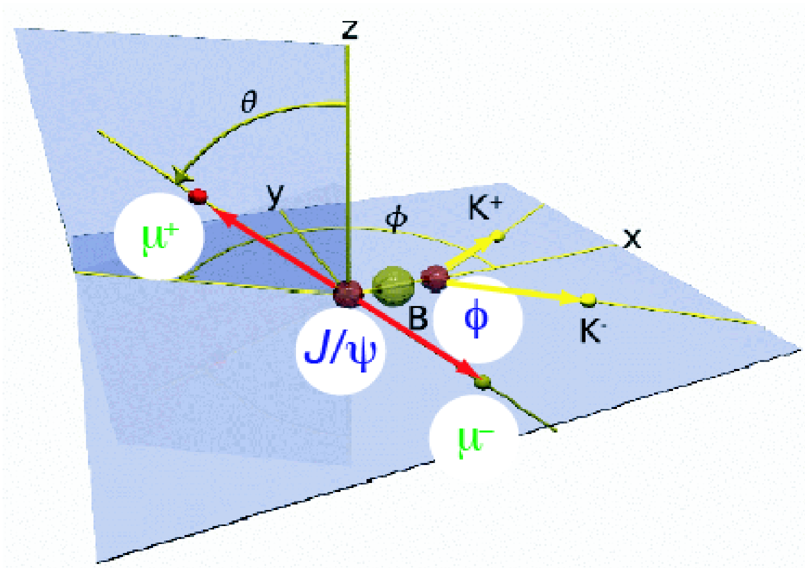
εD^2 for $B_s^0 \rightarrow J/\psi\varphi$ is 4 – 5 %

Angular Fit Projections







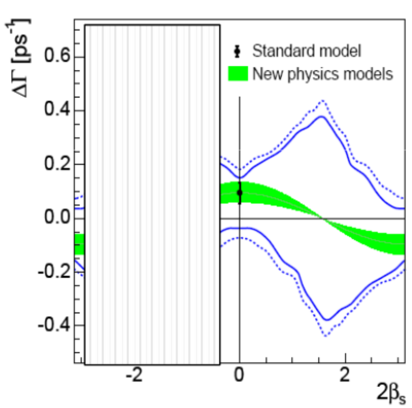


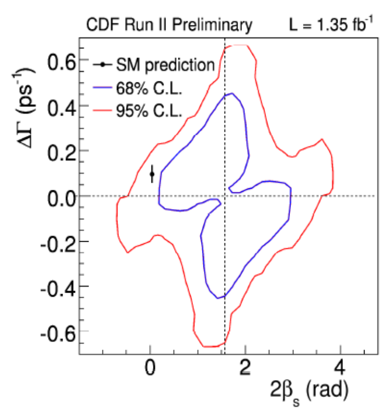
Results with Flavor Tagging

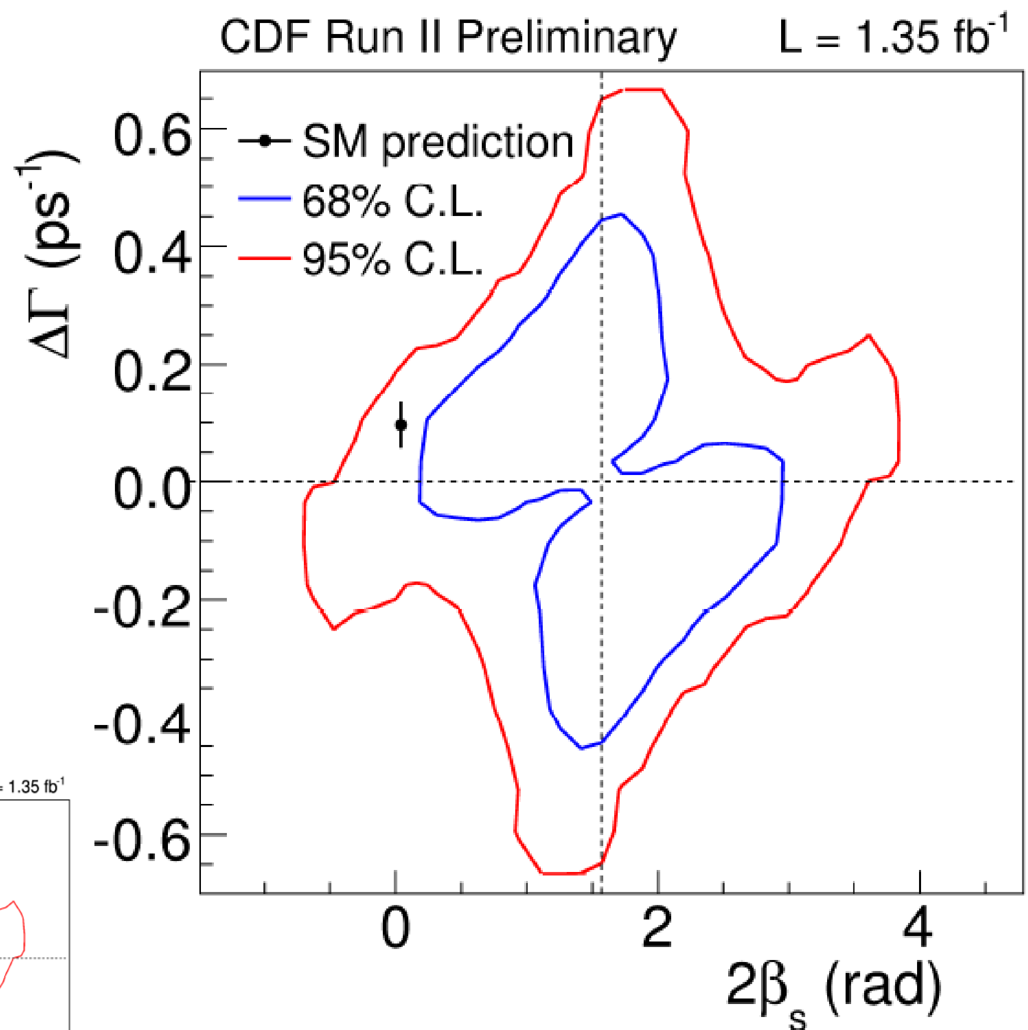
$2\beta_s$ – $\Delta\Gamma$ Confidence Region

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

$2\beta_s$ phase space is halved.



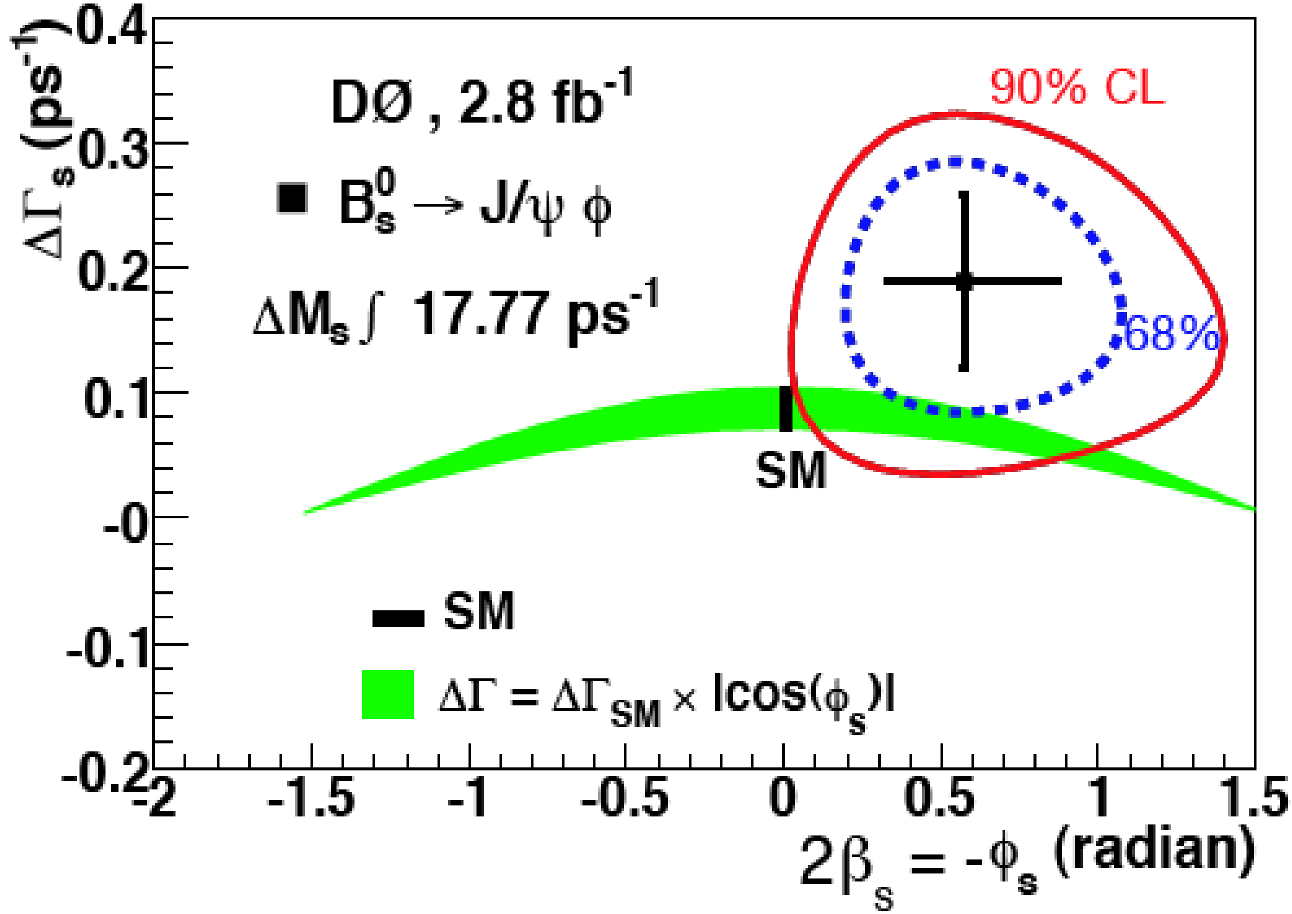




Results with Flavor Tagging

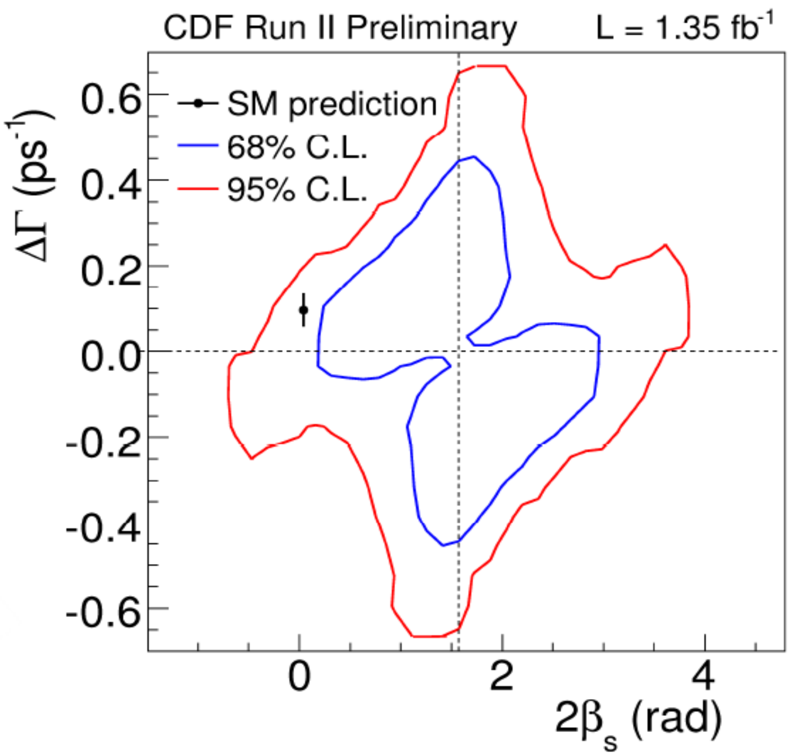
$2\beta_s$ – $\Delta\Gamma$
Confidence Region

Probability of fluctuatio
from SM to observation
6.6% (1.8σ)

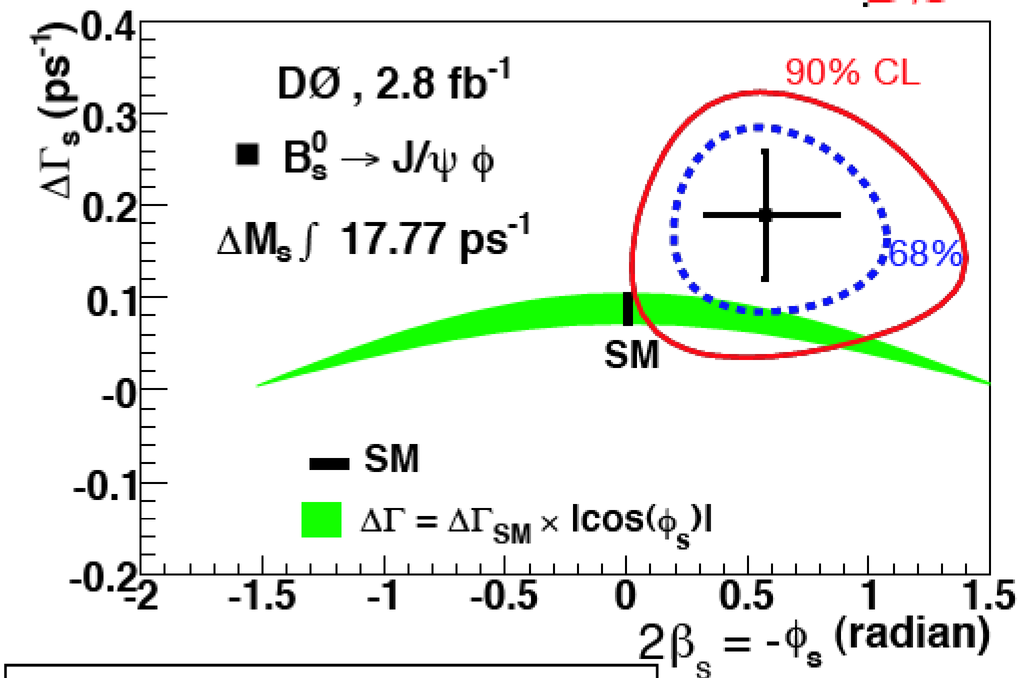


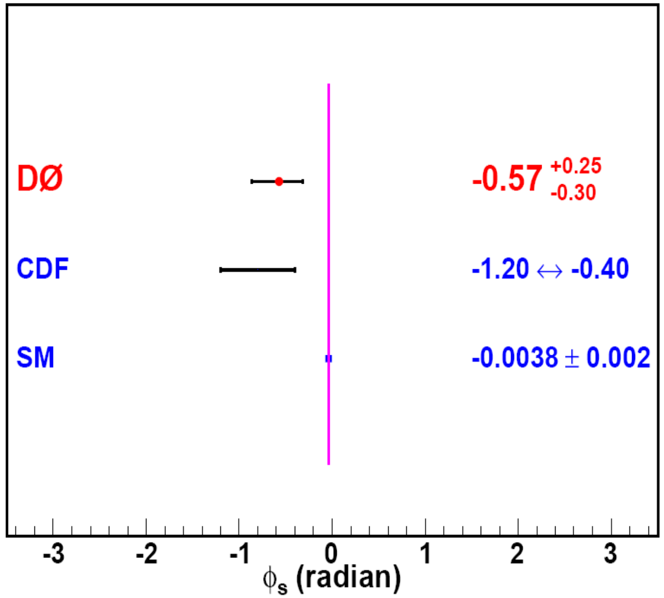
Results with Flavor Tagging

CDF



DØ





Summary

CP Violation is an excellent place to search for new physics beyond the Standard Model.

A large φ_s would be a clear indicator of new physics.

CP studies in the B_s^0 system at CDF and DØ possibly already providing hints of new physics.

A lot of data has been collected and waiting to be analyzed.

Increased datasets will shed more light on the status of CP Violation in the B_s^0 system in the near future.

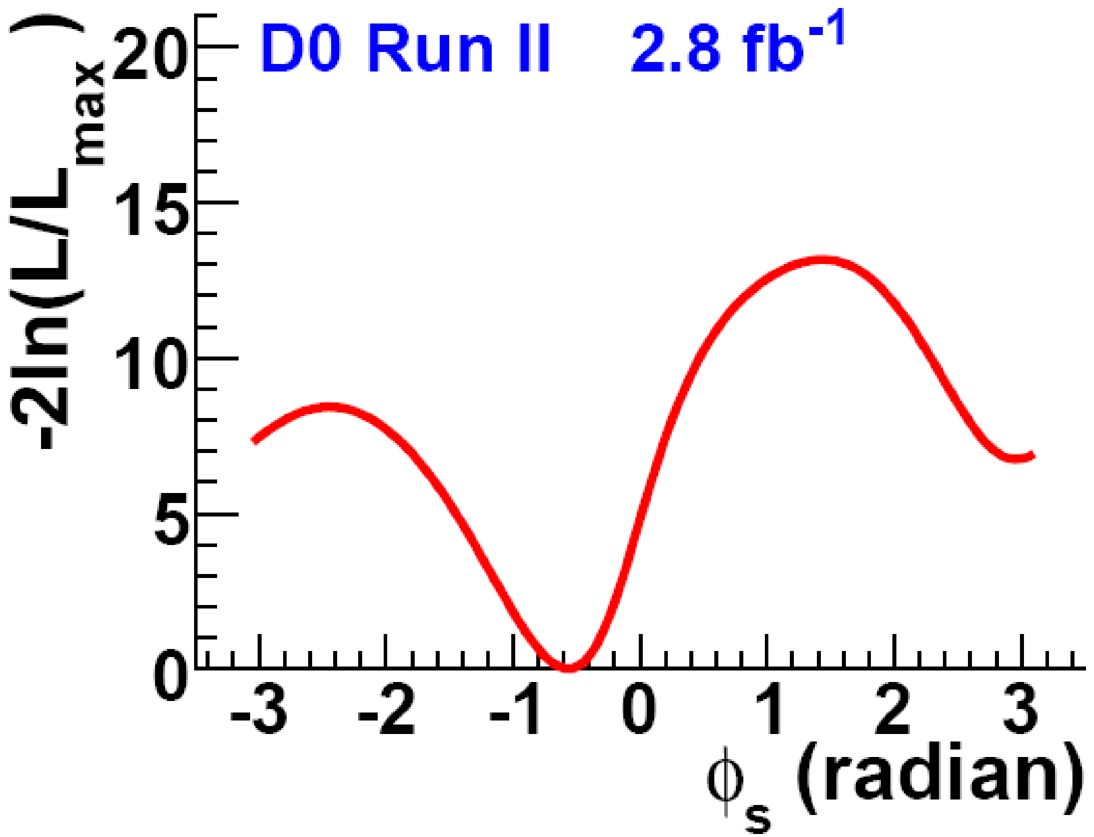
Backup Slides

Systematic Uncertainties

Source	$\bar{\tau}_s$ (ps)	$\Delta\Gamma_s$ (ps^{-1})
Acceptance	± 0.003	± 0.003
Signal mass model	-0.01	$+0.006$
Flavor purity estimate	± 0.001	± 0.001
Background model	$+0.003$	$+0.02$
ΔM_s input	± 0.01	± 0.001
Total	± 0.01	$+0.02, -0.01$

Source	$\|A_\perp(0)\|$	$\|A_0(0)\|^2 - \|A_\parallel(0)\|^2$	ϕ_s
Acceptance	± 0.005	± 0.03	± 0.005
Signal mass model	-0.003	-0.001	-0.006
Flavor purity estimate	± 0.001	± 0.001	± 0.01
Background model	-0.02	-0.01	$+0.02$
ΔM_s input	± 0.001	± 0.001	$+0.06, -0.01$
Total	$+0.01, -0.02$	± 0.03	$+0.07, -0.02$

Likelihood Profile

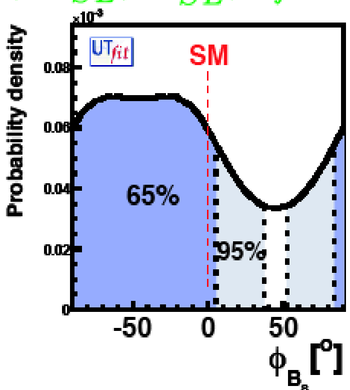


Likelihood profile of ϕ_s.

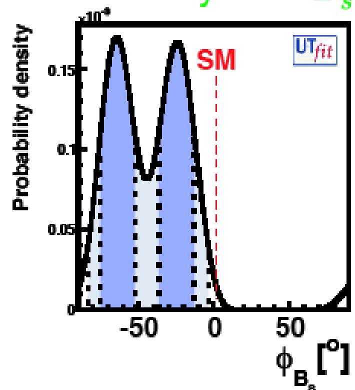
Combination

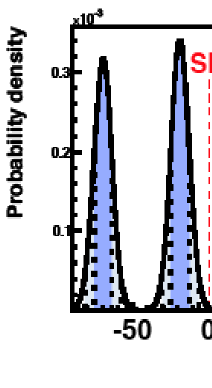
UTfit group, arXiv:0803.0659:

Δm_s, A^s_{SL}, $A^{\mu\mu}_{SL}$, τ_{fs}

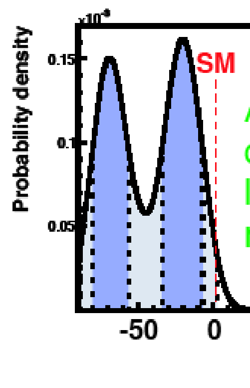


Add only CDF $B^0_s \to J/\psi\phi$



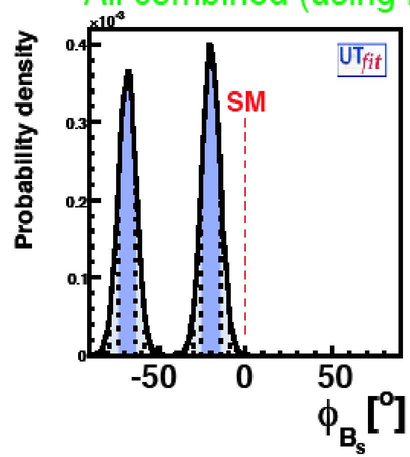


Add only DØ, assumed Gaussian errors



Add only DØ, likelihood, no correlations

All combined (using DØ Gauss. assumption)



> 3σ deviation from SM

- Intriguing, results from DØ, CDF with more data needed

New HFAG Result