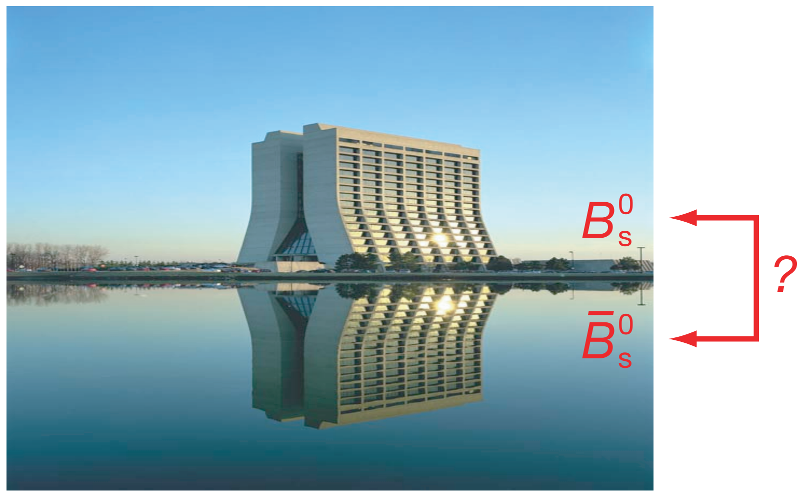
CP Violation Studies in the B_s^0 System at DØ



Rick Van Kooten

Indiana University

Representing the DØ Collaboration

35th International Conference on High Energy Physics

Paris, France

24 July 2010

CP Violation in B_s^0

Outline

Three kinds:

- In interference of decay and mixing amplitudes

$$\phi_s \neq 0 \text{ or } \pi$$

CP-violating phase

$B_s^0 \to J/\psi\phi$

DØ published in 2.8 fb^{-1}

PRL **102**, 241801 (2008)

↓

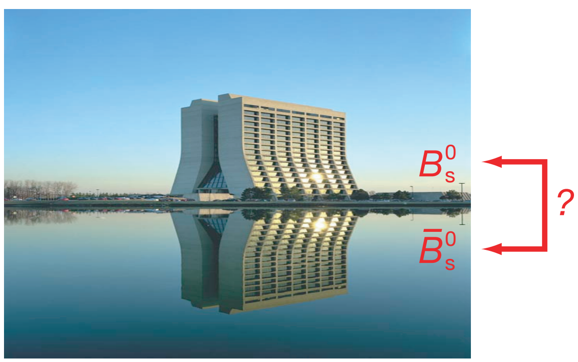
Prelim. update to 6.1 fb^{-1}

DØ Note 6098-CONF

- In mixing: $|q/p|^2 \neq 1$

- Dimuon Charge Asymmetry

(see B. Hoeneisen talk) arXiv:1005.2757 (acc. PRD)
arXiv:1007.0395 (acc. PRL)



- B_s^0 Semileptonic Asymmetry $B_s^0 \to D_s \mu\nu$

arXiv:0904.3907, accepted by PRD

→ Implications for B_s^0,
comparisons & combinations

DØ Note 6093-CONF

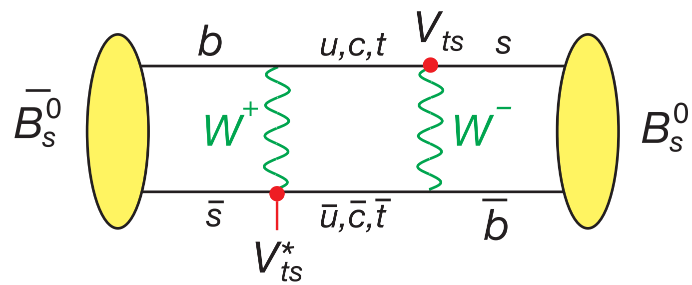
- In decay: $|\mathcal{A}_f|^2 \neq |\bar{\mathcal{A}}_{\bar{f}}|^2$ Assume no *CP* violation in decay

Neutral Meson Mixing

Particularly for B_s^0

Weak Eigenstates propagate according to Schrodinger:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$



Diagonalize

Mass Eigenstates: $|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$ *Heavy* $\quad |B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$ *Light*

If CP conserved in mixing, *p=q* $\quad |B_s^H\rangle = |B_s^{odd}\rangle \quad |B_s^L\rangle = |B_s^{even}\rangle$

$$\Delta m_s = M_H - M_L \sim 2|M_{12}|$$

$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$$

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \; ; \quad \tau = \frac{1}{\Gamma_s}$$

$$\phi_s^{SM} = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \sim 0.004 \text{ in SM}$$

CP-violating!

Neutral Meson Mixing

Particularly for B_s^0

Weak Eigenstates propagate according to Schrodinger:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

Diagonalize

Mass Eigenstates:

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

Heavy *Light*

If CP conserved in mixing, $p=q$

$$|B_s^H\rangle = |B_s^{odd}\rangle \qquad |B_s^L\rangle = |B_s^{even}\rangle$$

$$\Delta m_s = M_H - M_L \sim 2|M_{12}| = 17.77 \pm 0.12\ \mathrm{ps}^{-1}$$

← Precision! (better than theory)

$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$$

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$$

Tiny for B_d^0 meson, but not for B_s^0! eigenstates propagate with different lifetimes!

$$\phi_s^{SM} = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \sim 0.004 \text{ in SM}$$

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \quad ; \quad \tau = \frac{1}{\Gamma_s}$$

Neutral Meson Mixing

Particularly for B_s^0

Weak Eigenstates propagate according to Schrodinger:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M - \frac{i\Gamma}{2} & M_{12} - \frac{i\Gamma_{12}}{2} \\ M_{12}^* - \frac{i\Gamma_{12}^*}{2} & M - \frac{i\Gamma}{2} \end{pmatrix} \begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$

Diagonalize

Mass Eigenstates: $|B_s^H\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle$ (*Heavy*) $\quad |B_s^L\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle$ (*Light*)

If CP conserved in mixing, $p=q$: $\quad |B_s^H\rangle = |B_s^{odd}\rangle \quad |B_s^L\rangle = |B_s^{even}\rangle$

$$\Delta m_s = M_H - M_L \sim 2|M_{12}|$$

Sensitive to new physics

$$\Delta\Gamma_s^{CP} = \Gamma_{even} - \Gamma_{odd} \sim 2|\Gamma_{12}|$$

Not sensitive to new physics

$$\Delta\Gamma_s = \Gamma_L - \Gamma_H \sim 2|\Gamma_{12}|\cos\phi_s$$

Very sensitive to new physics

$$\phi_s^{SM} = \arg\left[-\frac{M_{12}}{\Gamma_{12}}\right] \sim 0.004 \text{ in SM}$$

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2} \quad ; \quad \tau = \frac{1}{\Gamma_s}$$

CP Violation in B_s^0 System

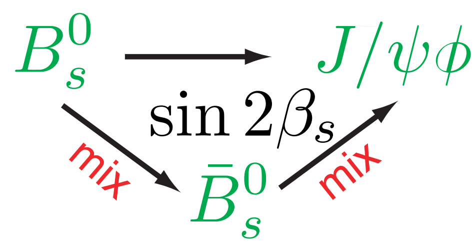
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- CP violation in SM occurs in complex phases in unitary CKM matrix; new physics: plenty of new phases!!

B_s unitarity condition

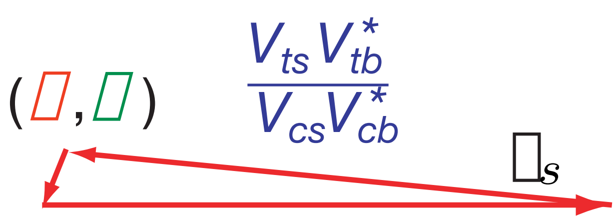
$$V_{us}V_{ub}^* + V_{cs}V_{cb}^* + V_{ts}V_{tb}^* = 0$$

Golden mode,
Tevatron



CP violation through interference of diagrams with and w/o mixing

"Squashed" Triangle



CP Violation in B_s^0 System

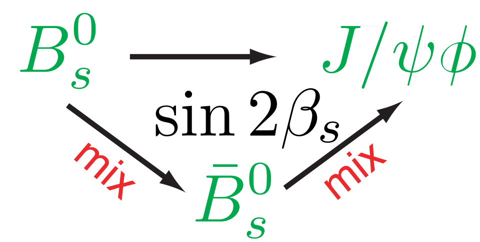
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

- CP violation in SM occurs in complex phases in unitary CKM matrix; new physics: plenty of new phases!!

B_s unitarity condition

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

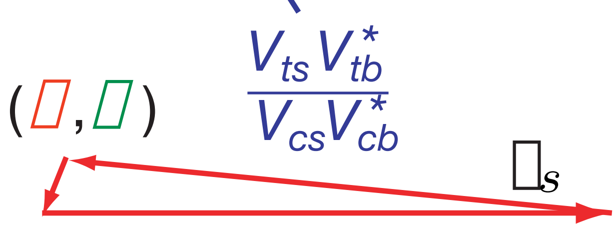
Golden mode, **Tevatron**



$$\phi_s^{J/\psi\phi} = -2\beta_s = -2\beta_s^{SM} + \phi_s^{NP}$$

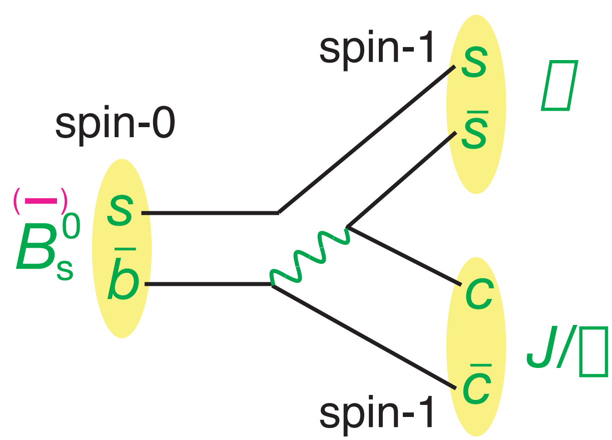
$-2\beta_s^{SM}$: −(0.038 ± 0.002)

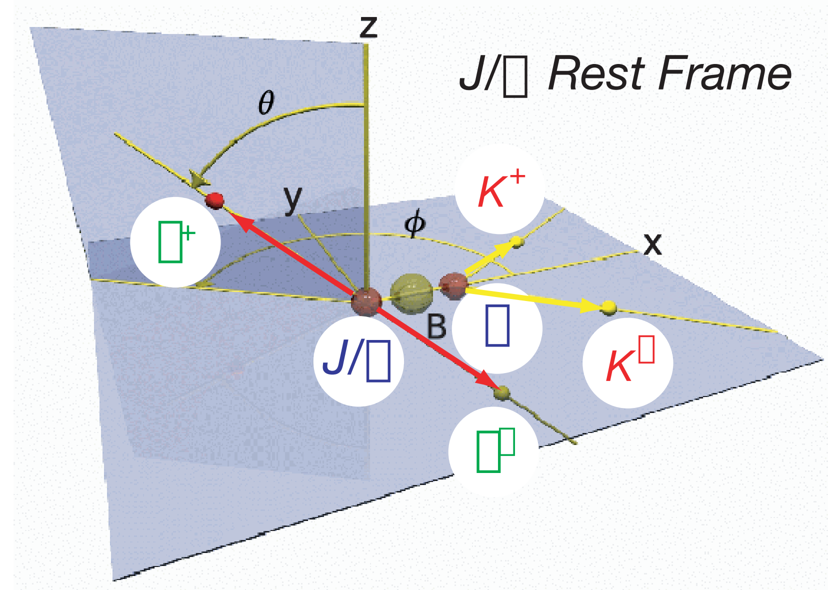
"Squashed" Triangle

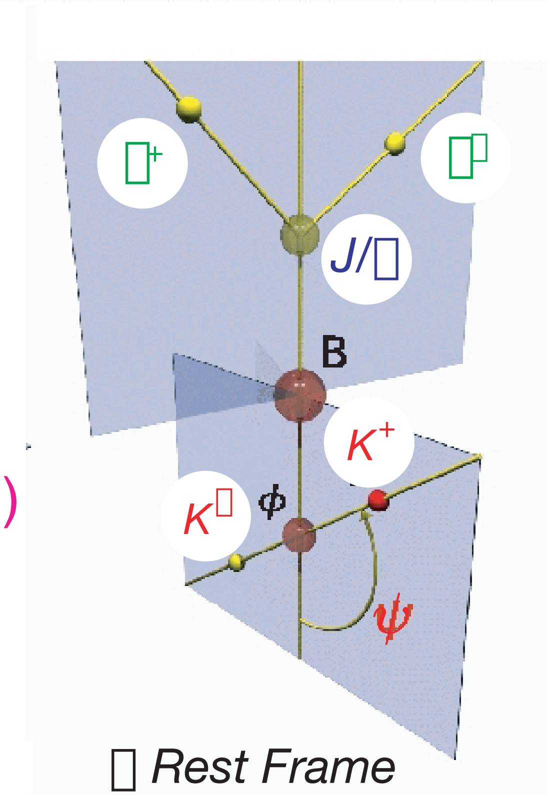


CP violation through interference of diagrams with and w/o mixing

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







- Decays into two vector mesons that are either *CP*-odd (*L*=1) or *CP*-even (*L*=0,2)
- Time-dependent angular distributions allow separation of components
- Simultaneous fit to two lifetimes $(1/\Gamma_H, 1/\Gamma_L)$ and three angles "transversity basis"

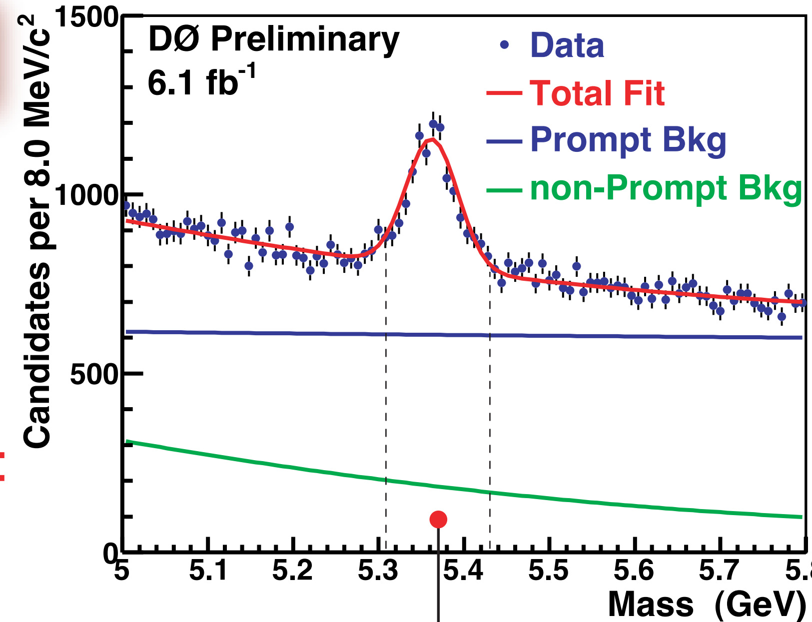
$A_\perp$ transverse perp. → *CP*-odd

$A_\parallel$ transverse para. → *CP*-even
A_0 longitudinal

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

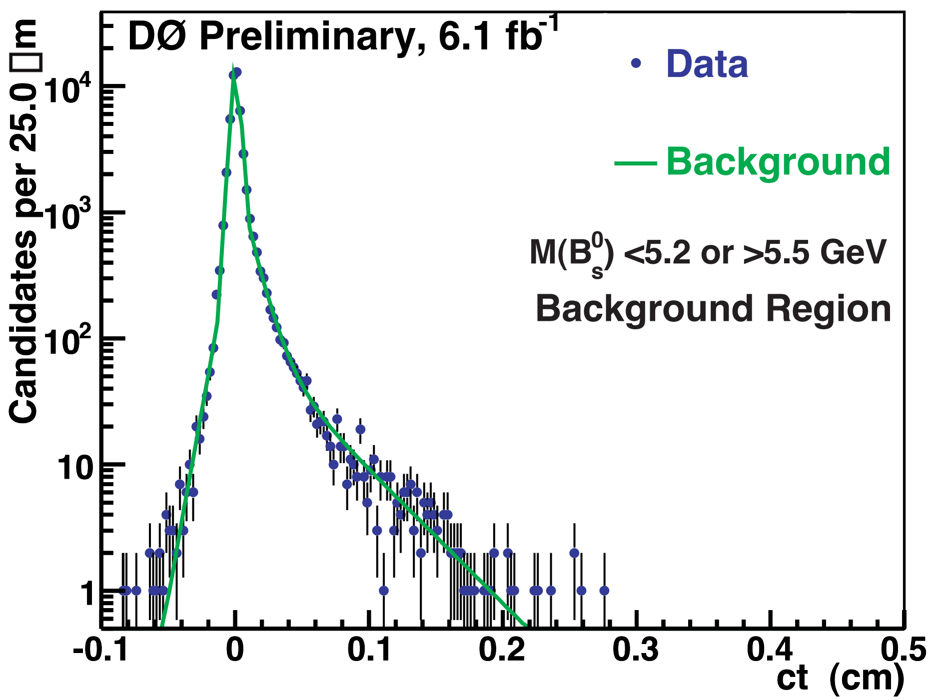
Select events in 6.1 fb^{-1} of data

- Vertex constraint
- Kinematic constraint to *J/*ψ mass

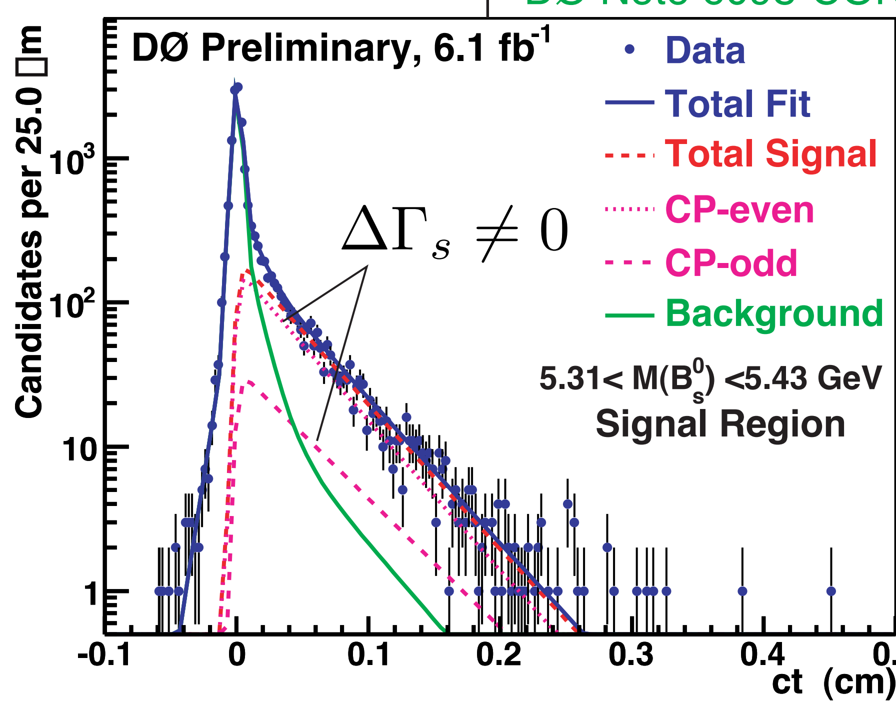


Multidimensional unbinned likelihood fit to:

1. B_s^0 mass, 3435 ± 84 signal events
2. Lifetime:



DØ Note 6098-CONF



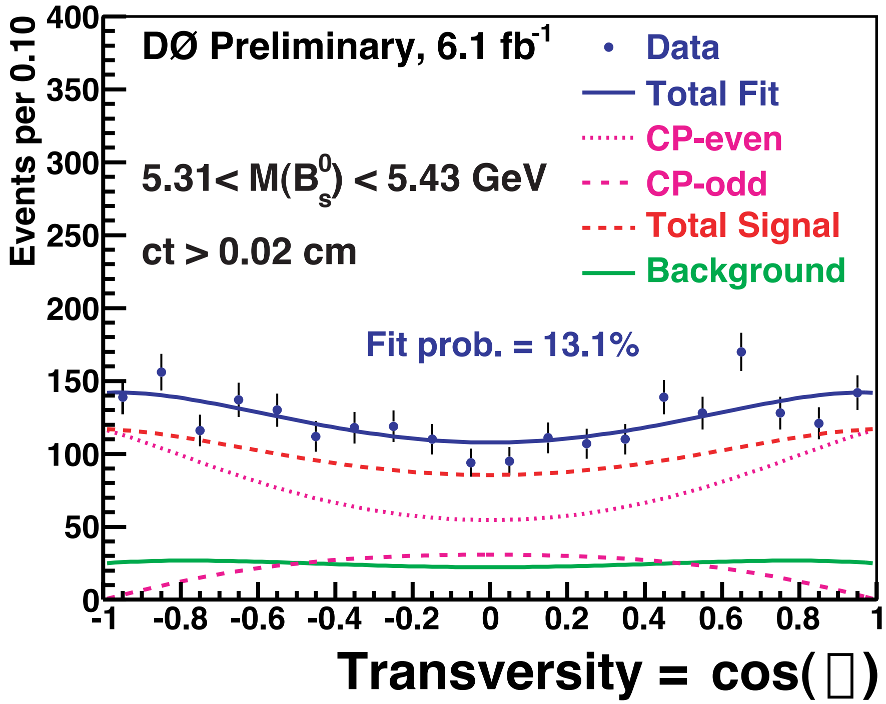
CP Violation in $B_s^0 \to J/\psi\phi$

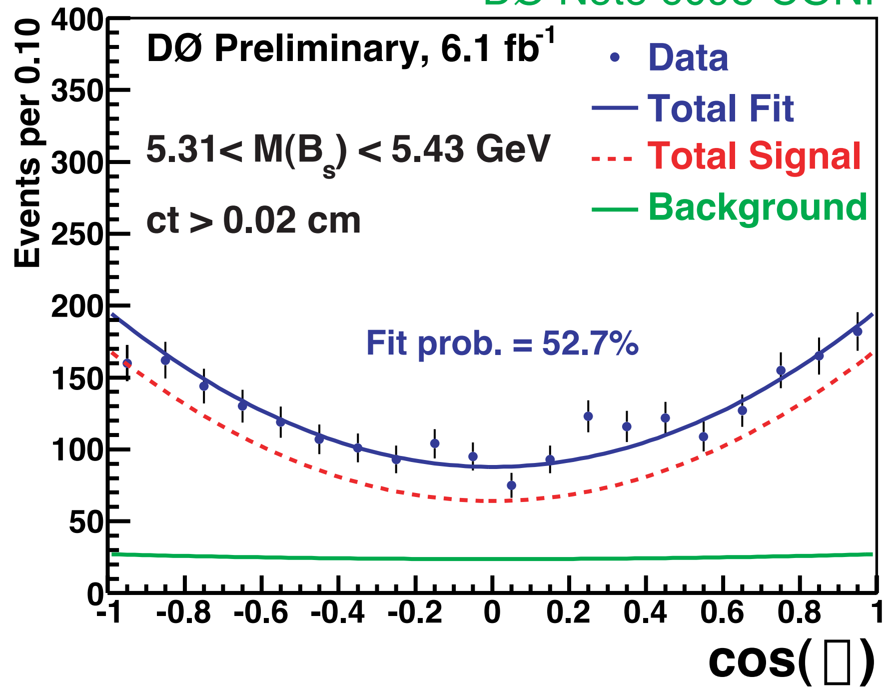
3. Decay product angles

- Detector acceptance distorts the angular distributions
- Use MC simulation to determine efficiency and include in fit
- Reweight MC to match data kinematics

- Assume that (K^+K^-) system in the decay $B_s^0 \to J/\psi K^+K$ is in a *P*-wave
- Any *S*-wave?

DØ Note 6098-CONF

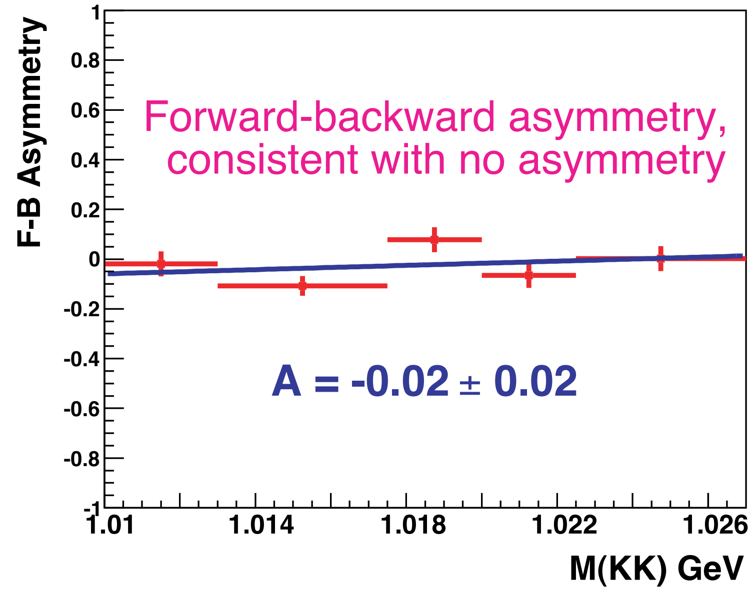




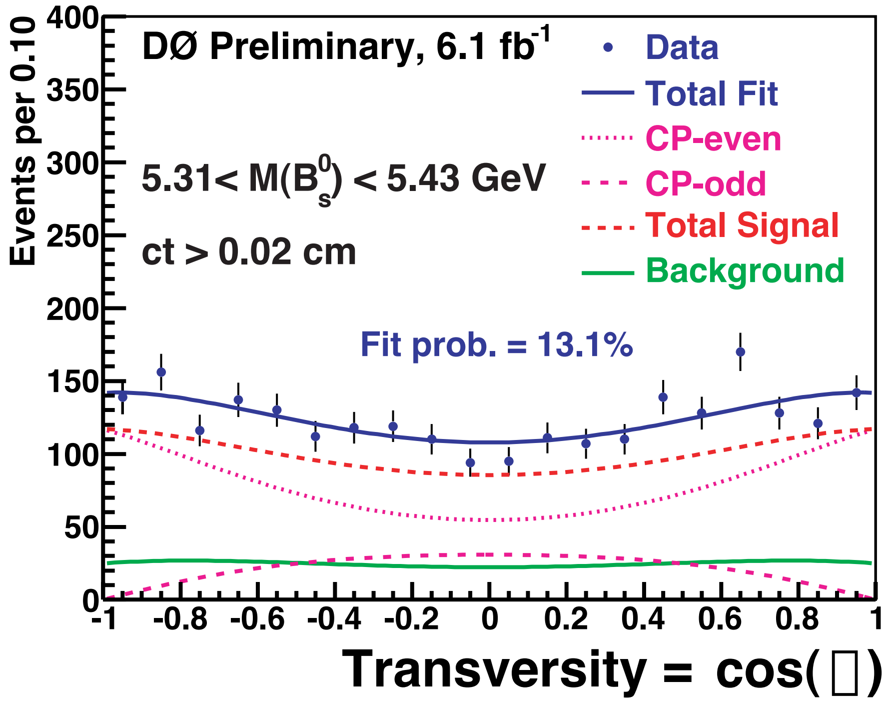
CP Violation in $B_s^0 \to J/\psi\phi$

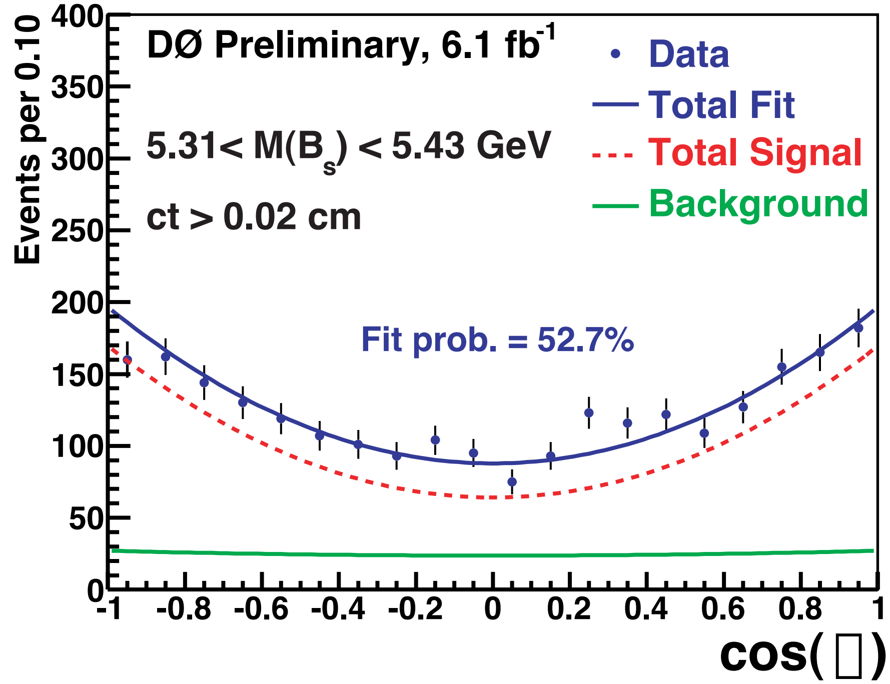
3. Decay product angles

- Detector acceptance distorts the angular distributions
- Use MC simulation to determine efficiency and include in fit
- Reweight MC to match data kinematics



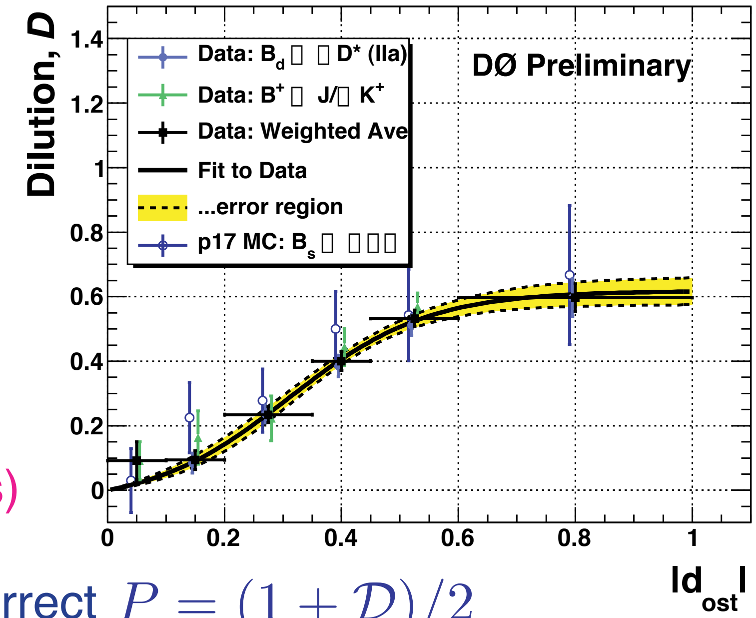
- Any *S*-wave? small, not included (yet)





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

4. Tag the flavor: B_s^0 or $\bar{B}_s^0$ at time of production



- Opposite-side tagging: electron, muon charge; sec. vertex charge (plus including lepton), event charge (opp. tracks)
- Calibrated using B_d^0 and $B^{\pm}$, probability correct $P = (1 + \mathcal{D})/2$

5. Constraints

- Gaussian constraint for oscillation frequency: $\Delta M_s = 17.77 \pm 0.12\,\mathrm{ps}^{-1}$
- Strong phases between polarization amplitudes $\delta_1 = -\delta_{\parallel} + \delta_{\perp}$
  $\delta_2 = -\delta_0 + \delta_{\perp}$

Gronau & Rosner: $B_d^0 \to J/\psi K^*$: magnitudes of polarization amplitudes
(PL B**336**, 321 (2008)) $B_s^0 \to J/\psi\phi$ should be similar, strong phases equal to within10 deg.

Constrain strong phases to world average values for $B_d^0 \to J/\psi K^*$:

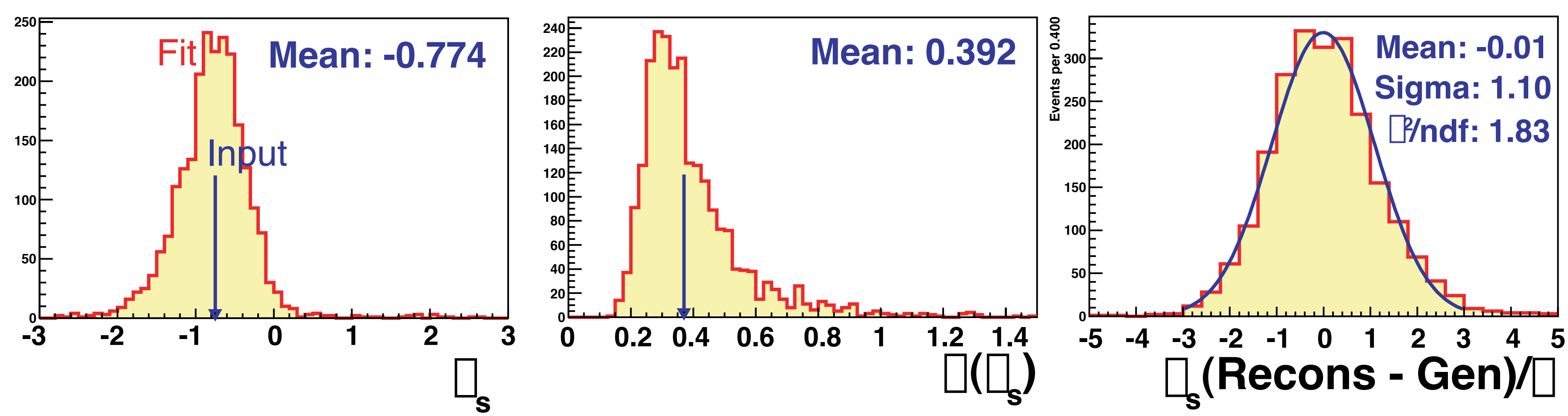
$$\delta_1 = -0.42 \pm 0.18$$
$$\delta_2 = 3.01 \pm 0.14$$

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

6. Checks:

- Full MC simulations with $\phi_s^{J/\psi\phi} \neq 0, \Delta\Gamma_s \neq 0$
  - → no significant biases observed
- Ensemble of toy MC samples, each experiment, same statistics as data
  - → no significant biases, check uncertainties
    (although sig. biases if δ_i allowed to float)
  - → determine adjustment for correct statistical coverage of CL regions
  - → effects of external systematic uncertainties

e.g.,

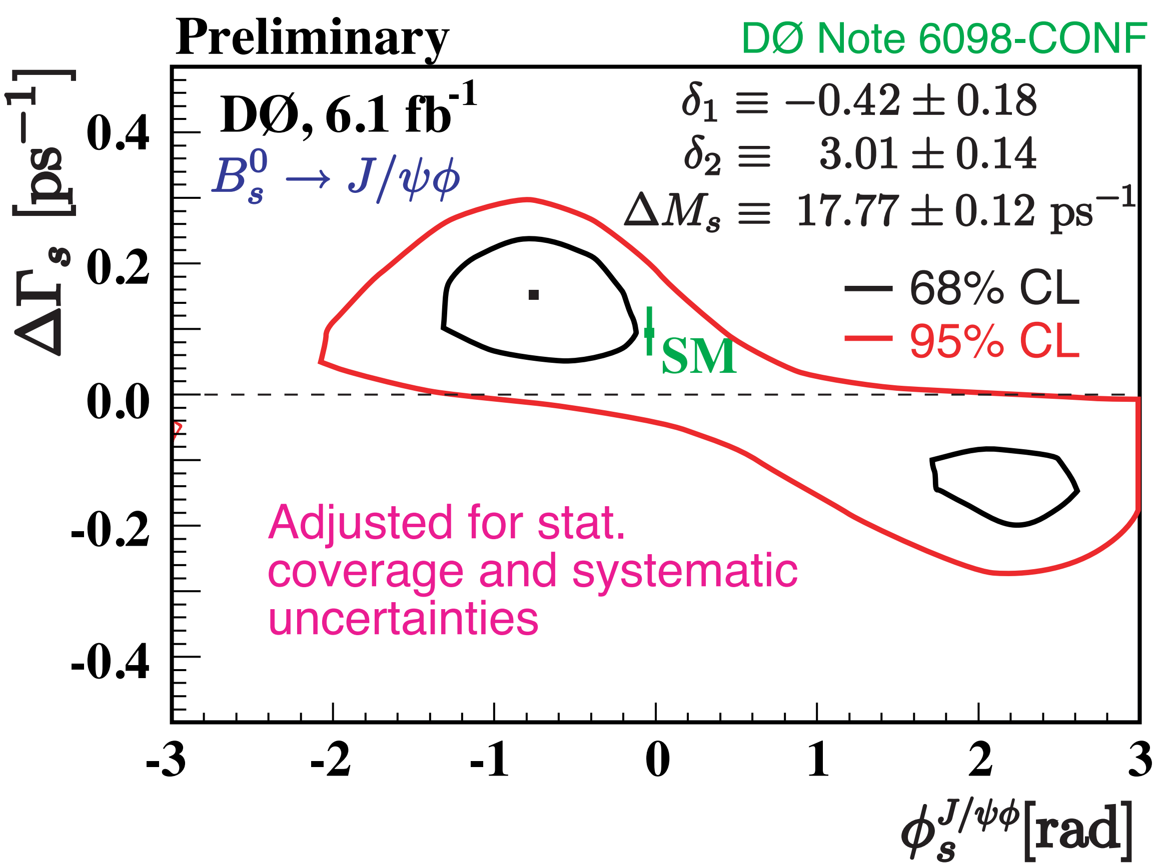


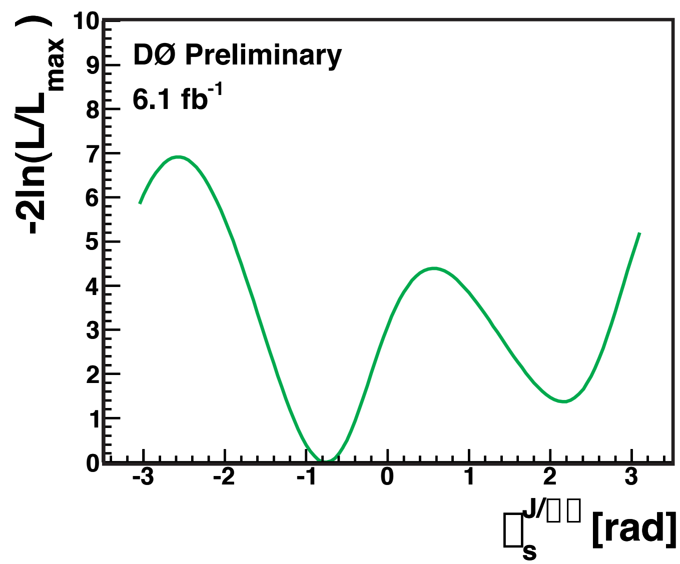
CP Violation in $B_s^0 \to J/\psi\phi$

Results

$$\bar{\tau}_s = 1.45 \pm 0.04 \pm 0.01\,\text{ps}$$
$$\Delta\Gamma_s = 0.15 \pm 0.06 \pm 0.01\,\text{ps}^{-1}$$
$$\phi_s^{J/\psi\phi} = -0.76^{+0.38}_{-0.36} \pm 0.02$$

$A_\perp(t=0)\,, |A_0(0)|^2 - |A_\parallel(0)|^2$
consistent with $B_d^0 \to J/\psi K^*$





Semileptonic Charge Asymmetry

- "Right-sign" decay: $B \rightarrow \mu^+ X$
- "Wrong-sign" decay: $\overline{B} \rightarrow \mu^+ X$ *only* possible via flavor oscillation of B_d^0 and B_s^0

$$a_{\rm sl}^b = \frac{\Gamma(\overline{B} \rightarrow \mu^+ X) - \Gamma(B \rightarrow \mu^- X)}{\Gamma(\overline{B} \rightarrow \mu^+ X) + \Gamma(B \rightarrow \mu^- X)} = A_{\rm sl}^b = \frac{1 - |q/p|^4}{1 + |q/p|^4}$$

PRL **97**, 151801 (2006)

Semileptonic charge asymmetry ($a_{\rm sl}^b$)

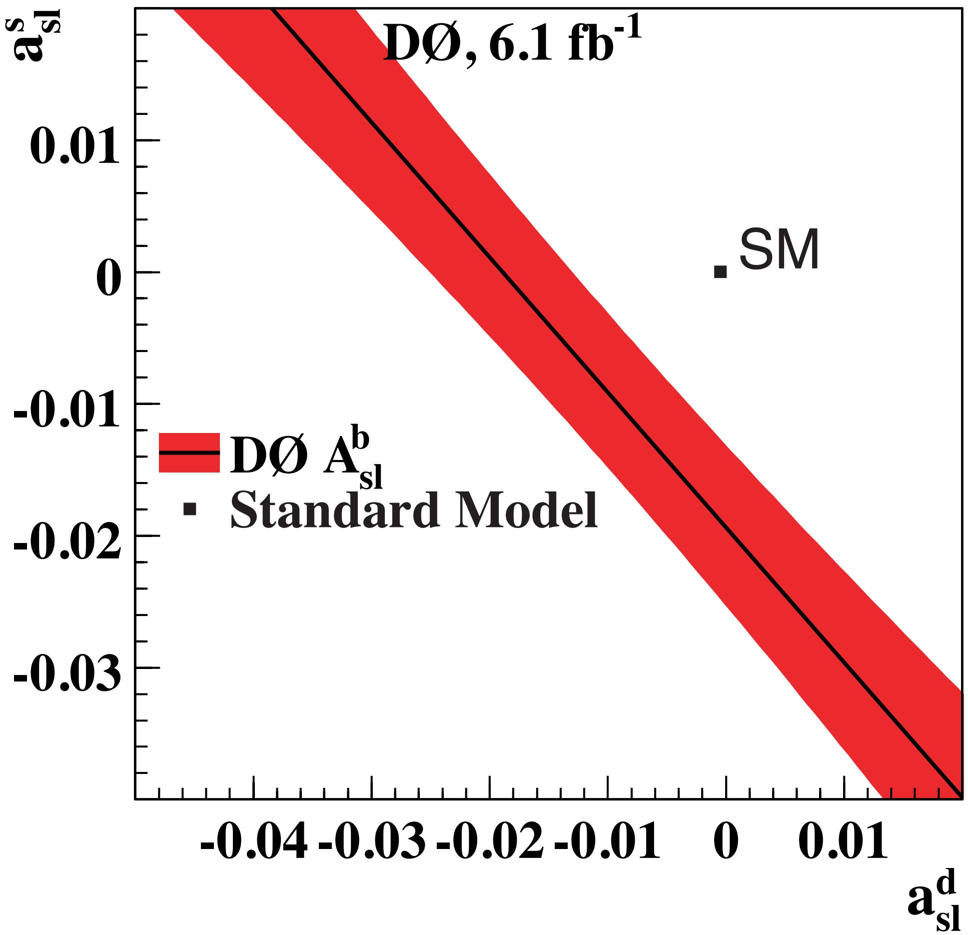
Dimuon charge asymmetry ($A_{\rm sl}^b$)

Another way to test measure CP violation!

Dimuon Charge Asymmetry

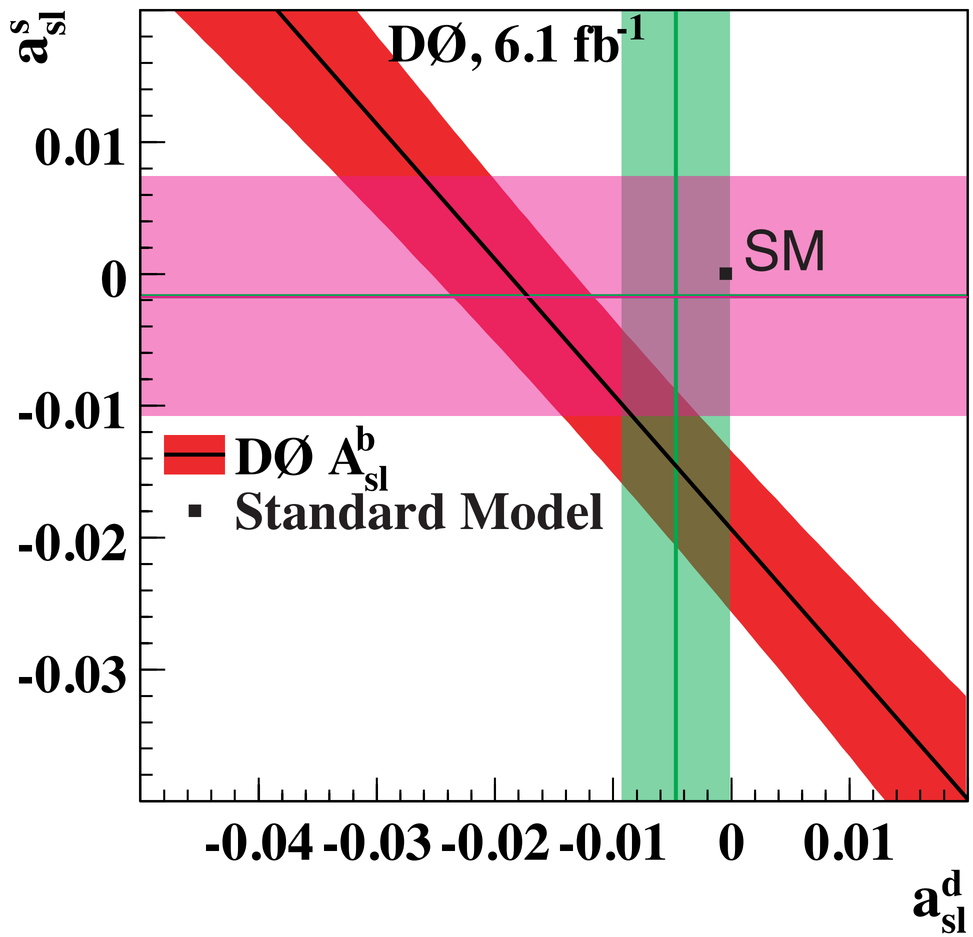
- Recall that measured dimuon asymmetry is a linear combination:

$$A^b_{\rm sl} = 0.506\, a^d_{\rm sl} + 0.494\, a^s_{\rm sl}$$



Consistency with Other Results

- Consistent with world average of $a_{\rm sl}^{d} = (-0.47 \pm 0.46)\%$ from B factories
  (BaBar, Belle, CLEO; HFAG)



- Consistent with DØ direct measurement of $a_{\rm sl}^{s} = (-0.17 \pm 0.91)\%$ using DØ $B_s^0 \to D_s \mu\nu$
  (arXiv:0904.3907, accepted by PRD)

Extracting $a_{\rm sl}^s$

N.B.: allows some level of CP violation in B_d^0 as well in rest of what follows

- Input world average of $a_{\rm sl}^d = (-0.47 \pm 0.46)\%$ from *B* factories into:

$$A_{\rm sl}^b = (0.506 \pm 0.043) a_{\rm sl}^d + (0.494 \pm 0.043) a_{\rm sl}^s$$

From dimuon asymmetry:

$$a_{\rm sl}^s = (-1.46 \pm 0.75)\%$$

c.f. $a_{\rm sl}^s(SM) = (-0.0021 \pm 0.0006)\%$

Combine with DØ independent measurement of $a_{\rm sl}^s$ from $B_s^0 \rightarrow D_s \mu\nu$

Combined:

$$a_{\rm sl}^s(\text{DØ}) = (-1.00 \pm 0.59)\%$$

DØ Note 6093-CONF

- Allows for interesting comparison/combination:

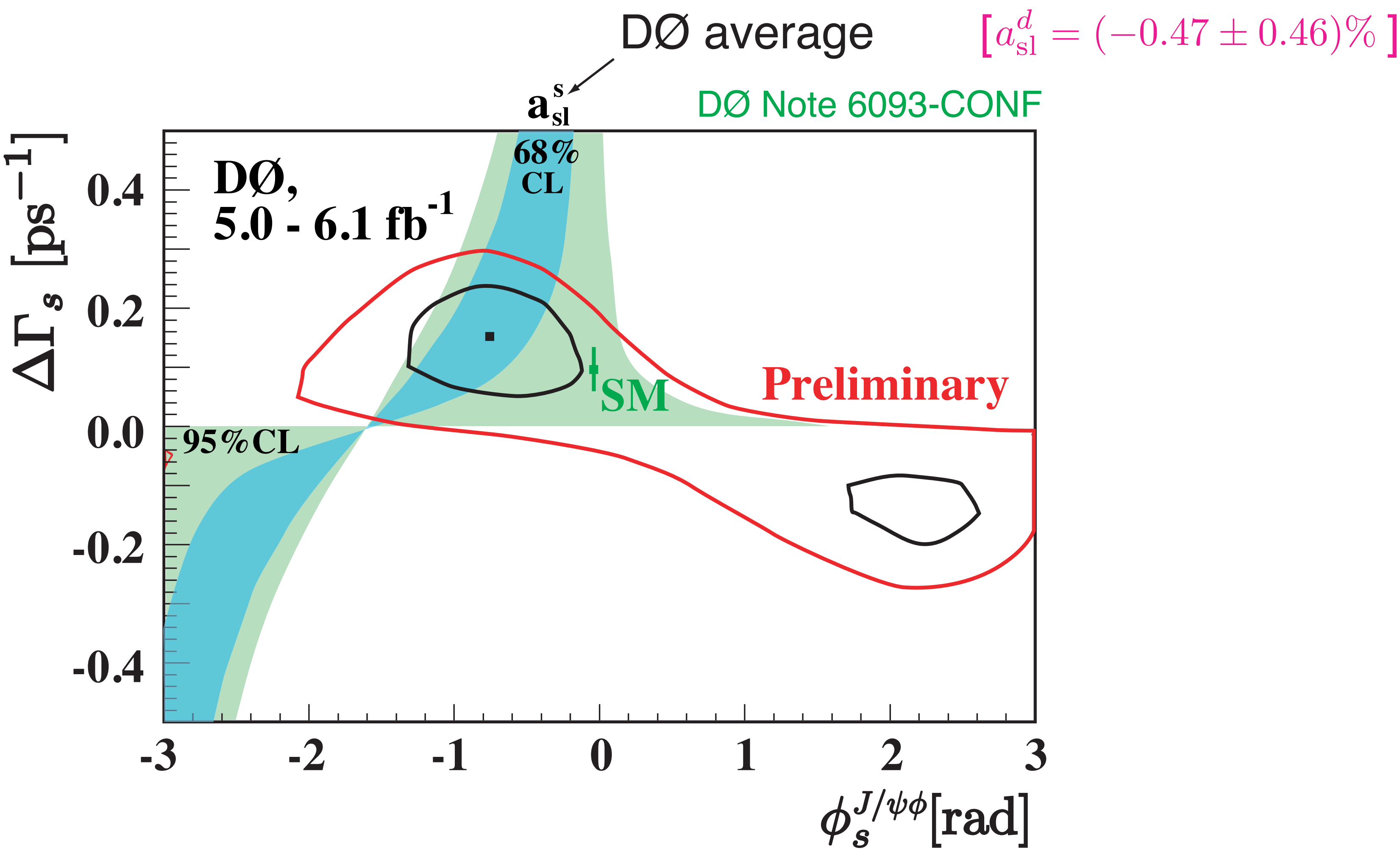
$$a_{\rm sl}^s = \frac{\Delta\Gamma_s}{\Delta M_s} \tan \phi_s$$

$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

(0.0042 ± 0.0014)

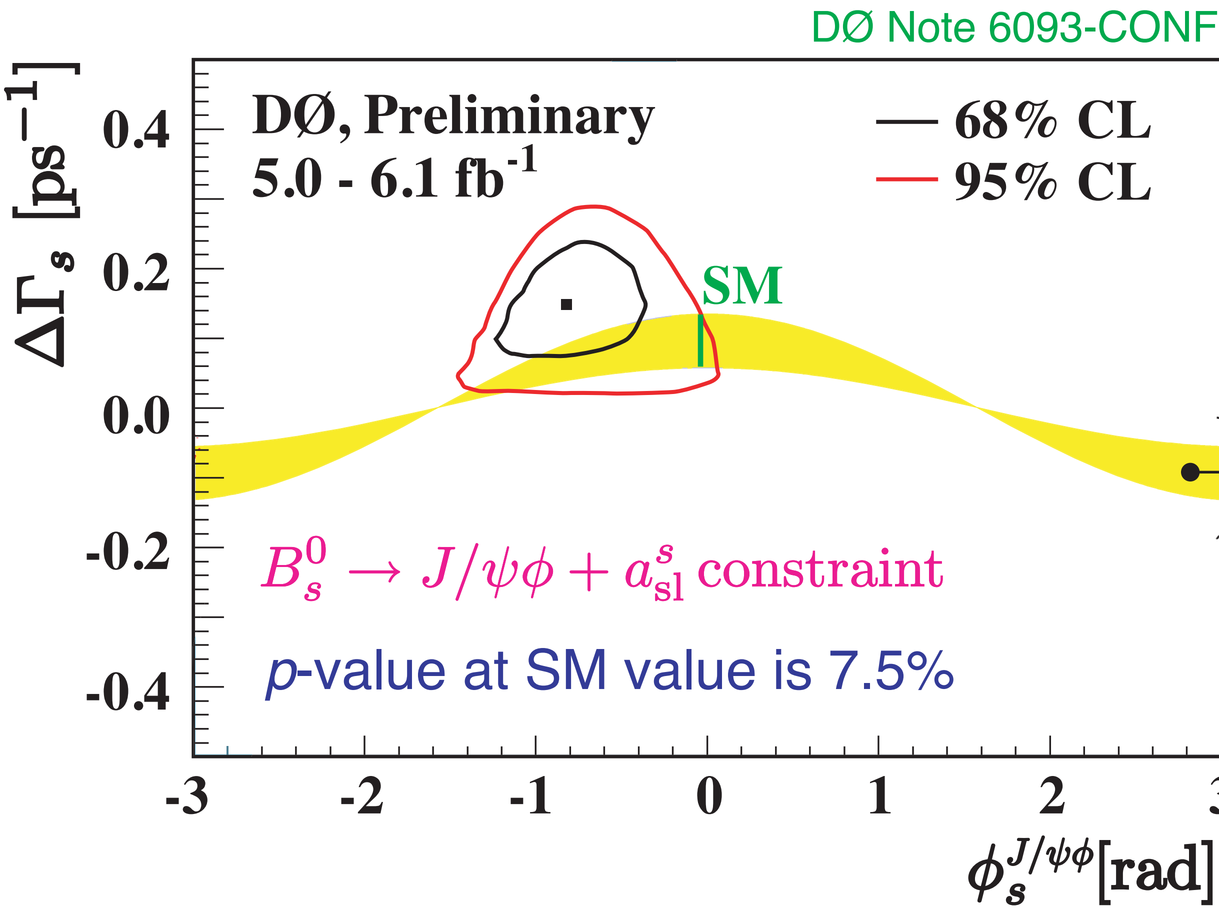
Same new physics phase as in $\phi_s^{J/\psi\phi}$ if new physics only in M_{12} of B_s^0 system

Comparison



- Assuming one new physics phase affecting M_{12} in the B_s^0 system

Combination



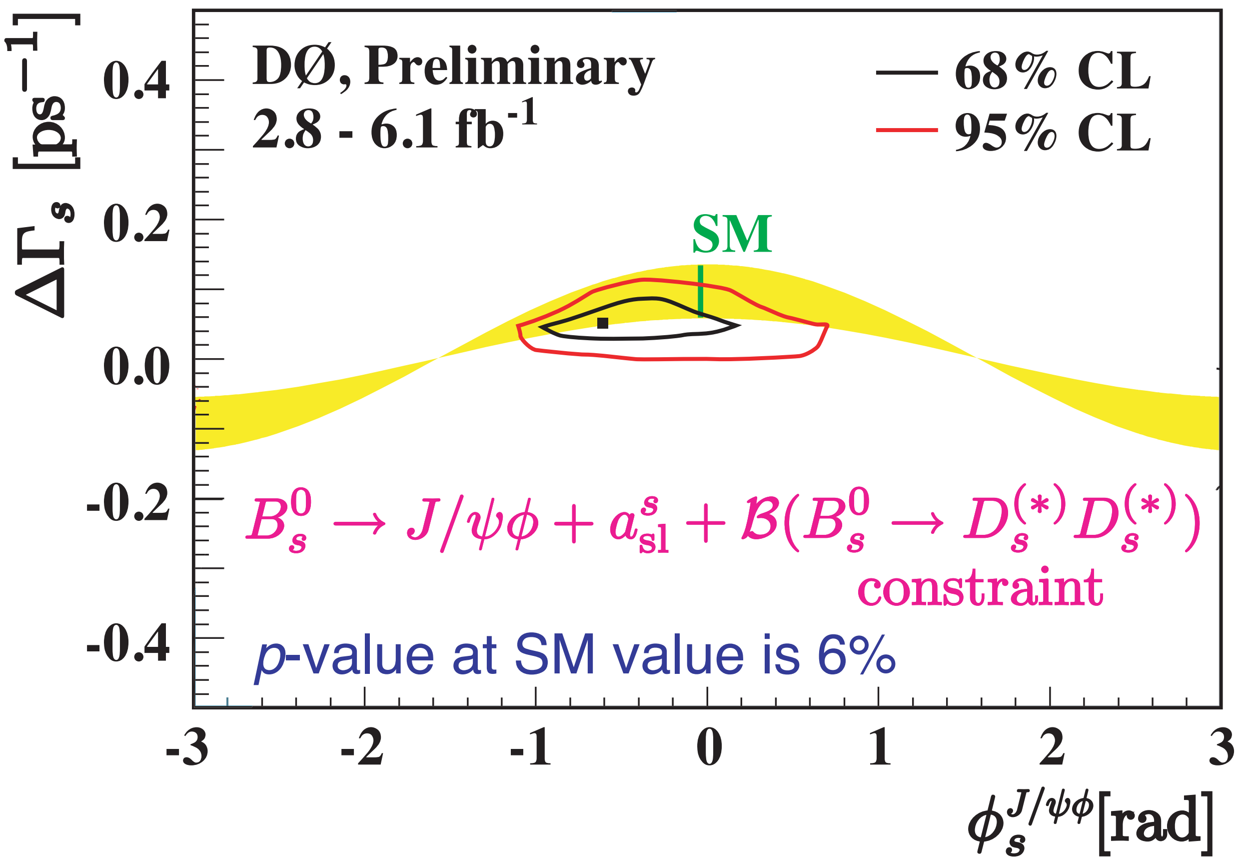
$\Delta\Gamma_s = 2|\Gamma_{12}|\cos\phi_s$

region of new physics models where M_{12} affected

Combination, *Br*

- $B_s^0 \to D_s^{(*)+} D_s^{(*)-}$ is *CP*-even to ~5%, ~saturates $\Gamma_s^{CP\,\mathrm{even}}$

DØ Note 6093-CONF



DØ, 2.8 fb^{-1}
PRL 102, 091801 (2009)

$$\mathcal{B}(B_s^0 \to D_s^{(*)+} D_s^{(*)-}) \simeq \frac{\Delta\Gamma_s}{2\Gamma_s \cos\phi_s}\left[\frac{1}{1-2x_f} - \frac{\Delta\Gamma_s \cos\phi_s}{2\Gamma_s}\right] = 0.035 \pm 0.015$$

$\oplus$ 30% theory unc.

Summary

- Using 6.1 fb^{-1} of data, DØ has made a preliminary update of their previously published (with 2.8 fb^{-1}) $B_s^0 \to J/\psi\phi$ analysis to find:

$$\Delta\Gamma_s = 0.15 \pm 0.06 \pm 0.01\,\mathrm{ps}^{-1}$$
$$\phi_s^{J/\psi\phi} = -0.76^{+0.38}_{-0.36} \pm 0.02$$

CP-violating phase

$$0.014 < \Delta\Gamma_s < 0.263\,\mathrm{ps}^{-1} \qquad -0.235 < \Delta\Gamma_s < -0.040\,\mathrm{ps}^{-1}$$
$$-1.65 < \phi_s^{J/\psi\phi} < 0.24 \qquad 1.14 < \phi_s^{J/\psi\phi} < 2.93$$

at 95% CL

- Consistent with the *CP*-violating a_{sl}^s semileptonic charge asymmetry for B_s^0 extracted from the DØ dimuon semileptonic charge asymmetry (A_{sl}^b > 3σ from SM) and from DØ $B_s^0 \to D_s\mu\nu$ asymmetry analysis

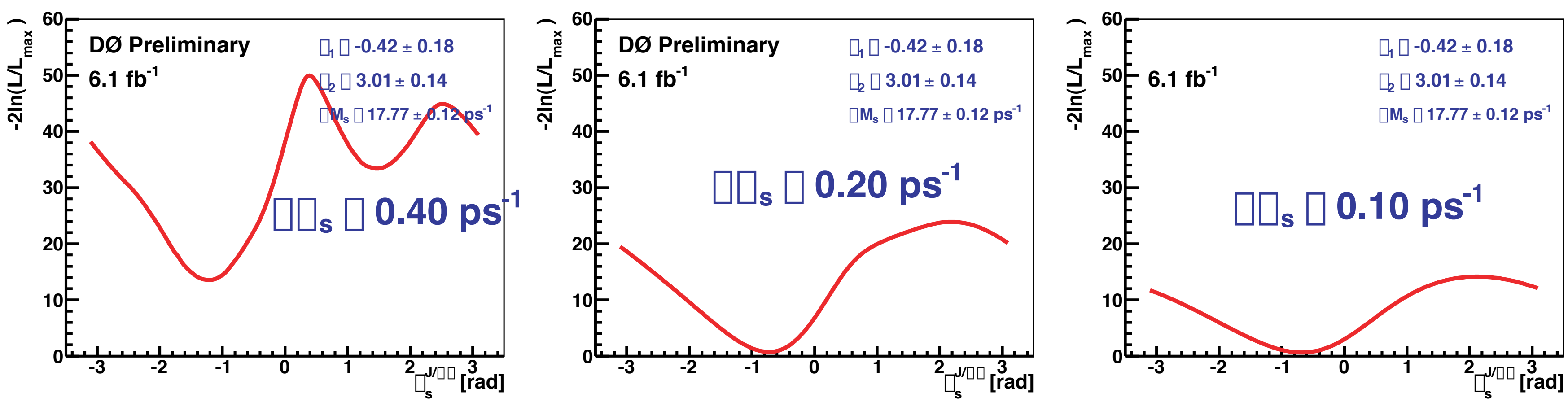
- Combinations of DØ results indicate consistency with SM in the B_s^0 system at the level of 6 – 7.5%

- *Future*: add data, add modes (e.g., $B_s^0 \to J/\psi f_0$), same-side tagging, combine with CDF

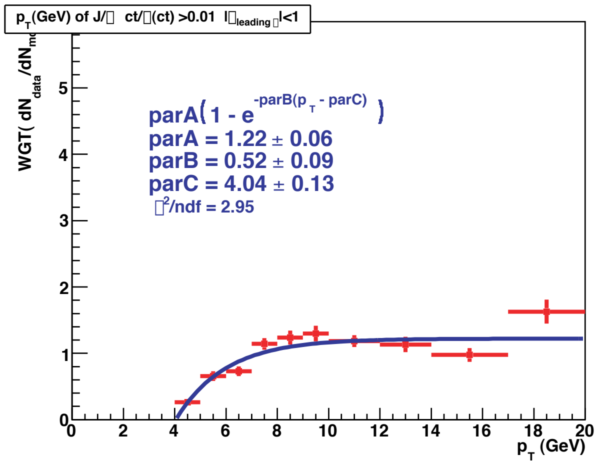
Backups

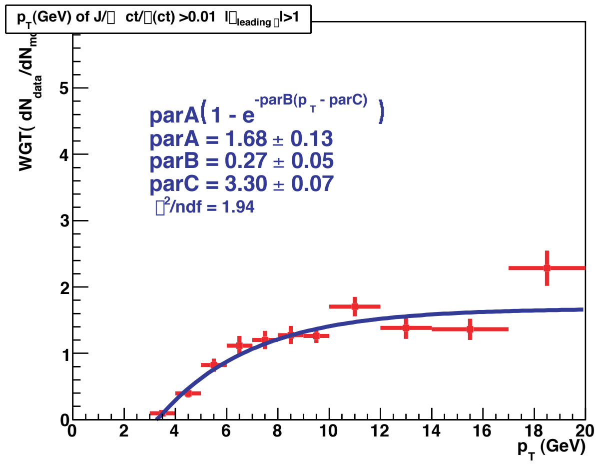
	Full Sample	First 2.8 fb^{1}	Last 3.3 fb^{1}
All Candidates	82808	47442	35366
Signal	3435 ± 84	1999 ± 66	1449 ± 50
B_s^0 Mass (MeV)	5362.4 ± 0.8	5362.2 ± 1.0	5362.7 ± 1.2
B_s^0 Mass Width (MeV)	30.4 ± 0.7	29.5 ± 0.9	31.7 ± 1.1
Proper length error scale	1.268 ± 0.006	1.261 ± 0.007	1.271 ± 0.008
$\bar{\tau}_s$ (ps)	1.47 ± 0.04	1.45 ± 0.07	1.46 ± 0.06
$\Delta\Gamma_s$ (ps^{1})	0.15 ± 0.06	0.23 ± 0.08	0.07 ± 0.07
$A_\perp(0)$	0.44 ± 0.03	0.42 ± 0.04	0.47 ± 0.04
$\lvert A_0(0)\rvert^2 - \lvert A_{\lvert\lvert}(0)\rvert^2$	0.35 ± 0.03	0.32 ± 0.04	0.40 ± 0.04
$\phi_s^{J/\psi\phi}$	0.76 ± 0.37	0.86 ± 0.33	0.37 ± 0.81

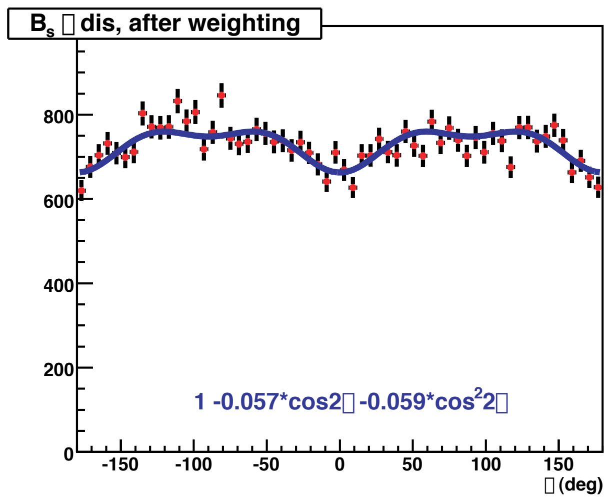
	$A_\perp(0)$	$\Delta\Gamma_s$	$\phi_s^{J/\psi\phi}$
$\bar{\tau}_s$	-0.40	-0.03	0.71
$A_\perp(0)$		-0.54	-0.36
$\Delta\Gamma_s$			-0.18

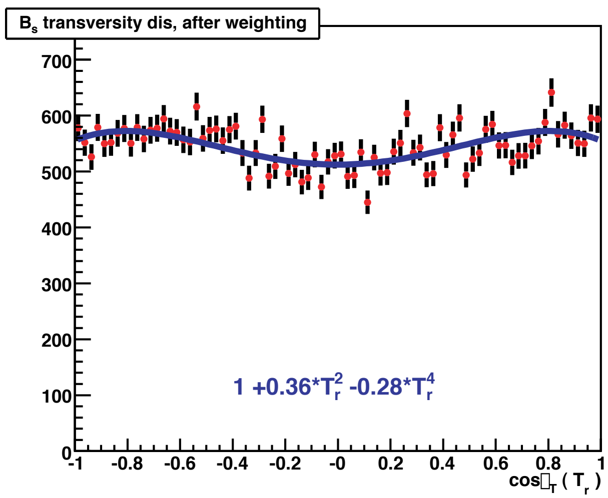


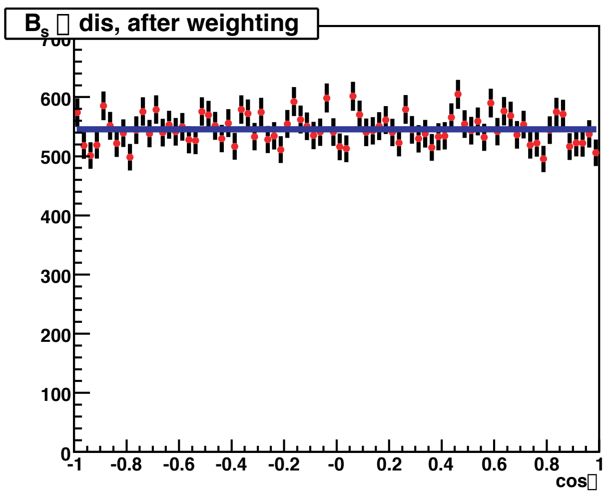
Weighting & Acceptance Corrections





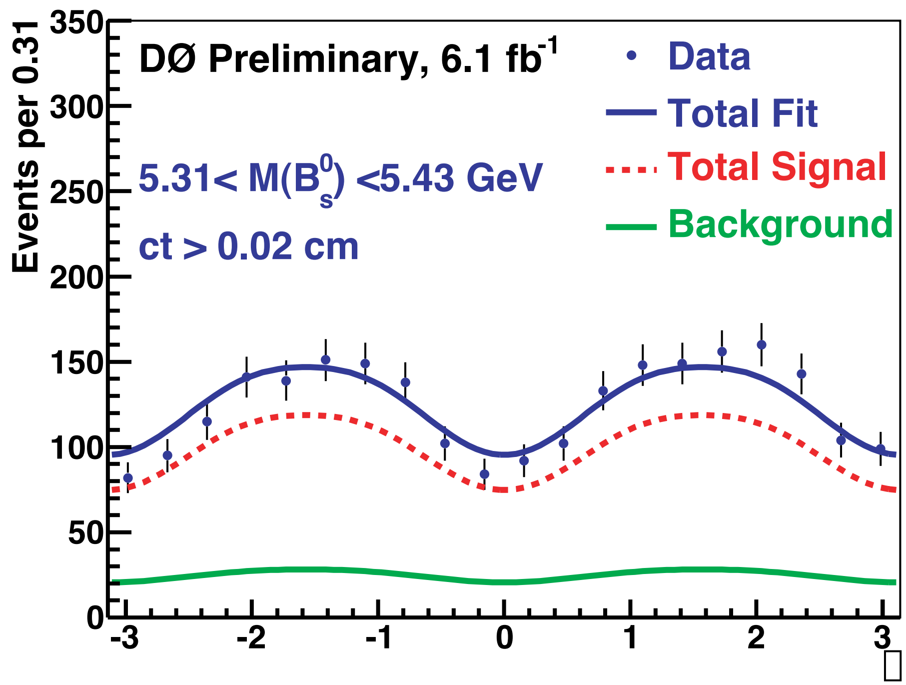






Systematics

Source	$\bar{\tau}_s$ ps	$\Delta\Gamma_s$ ps ^{1}	$A_\perp(0)$	$\phi_s^{J/\psi\phi}$
Matching the MC kinematics to data	±0.001	±0.001	±0.001	±0.01
Acceptance function	±0.01	±0.01	±0.01	±0.01
Flavor tagging parameters	±0.001	±0.001	±0.001	±0.01
Total	±0.01	±0.01	±0.01	±0.02

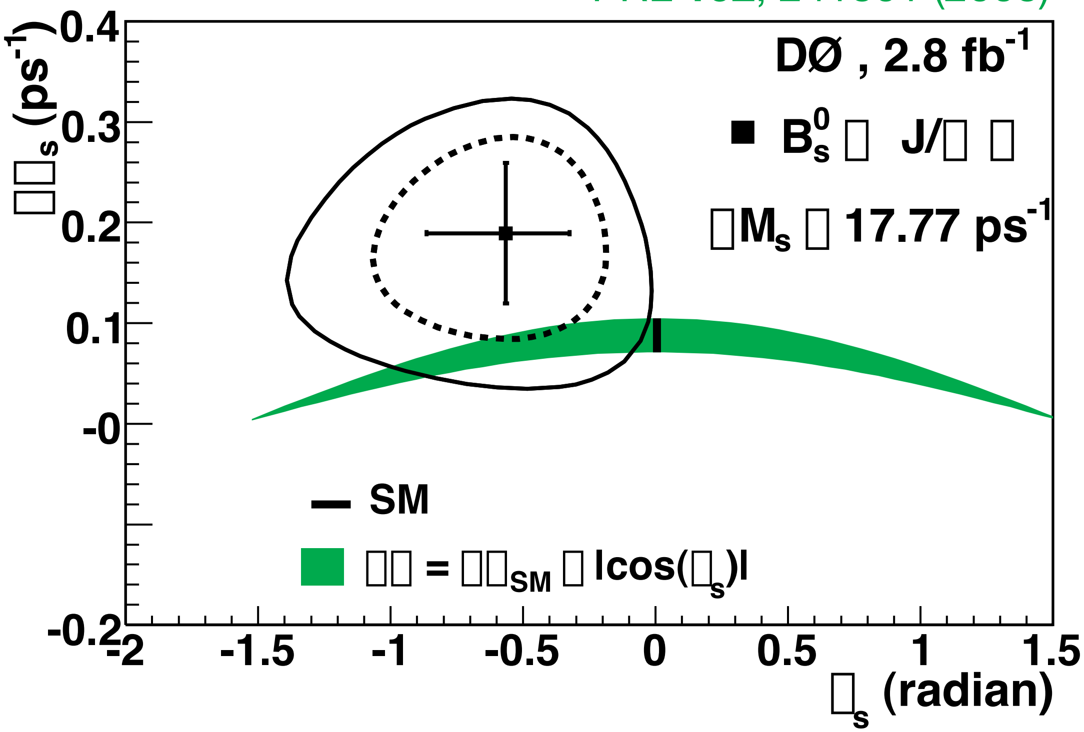


No Flavor Tag

$$\Delta\Gamma_s = 0.15 \pm 0.06\,\mathrm{ps}^{-1} \qquad \Delta\Gamma_s = -0.15 \pm 0.06\,\mathrm{ps}^{-1}$$
$$\phi_s^{J/\psi\phi} = \pm(0.90 \pm 0.42) \qquad \phi_s^{J/\psi\phi} = \pm(2.24 \pm 0.42)$$

Comparison to Previous Results

PRL **102**, 241801 (2008)



Not adjusted for coverage or systematics

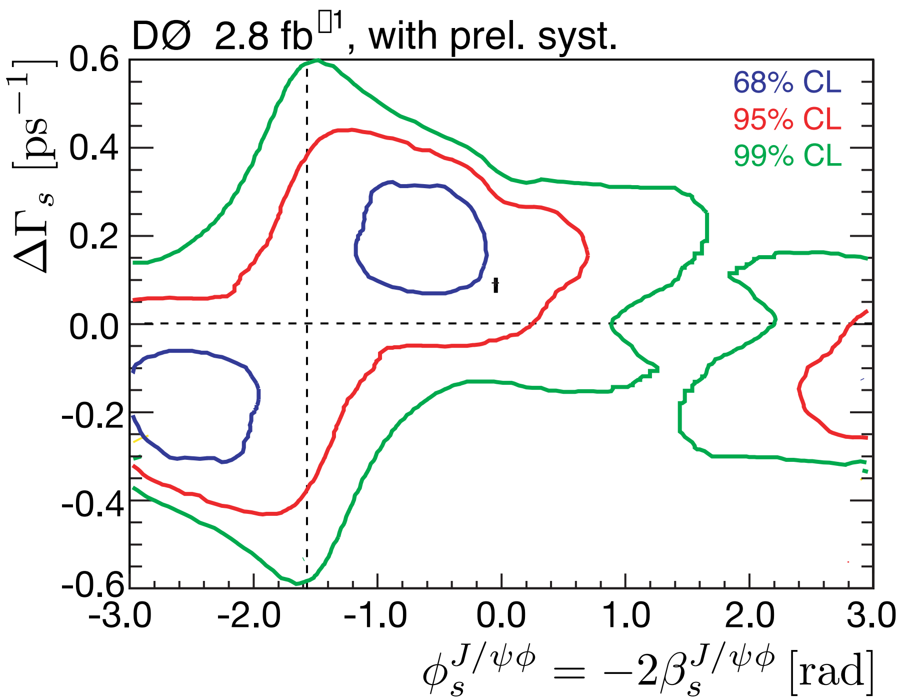
Constrain strong phases to values of $B_d^0 \to J/\psi K^*$ but more weakly, Gaussian constraint of $\pm\pi/5$

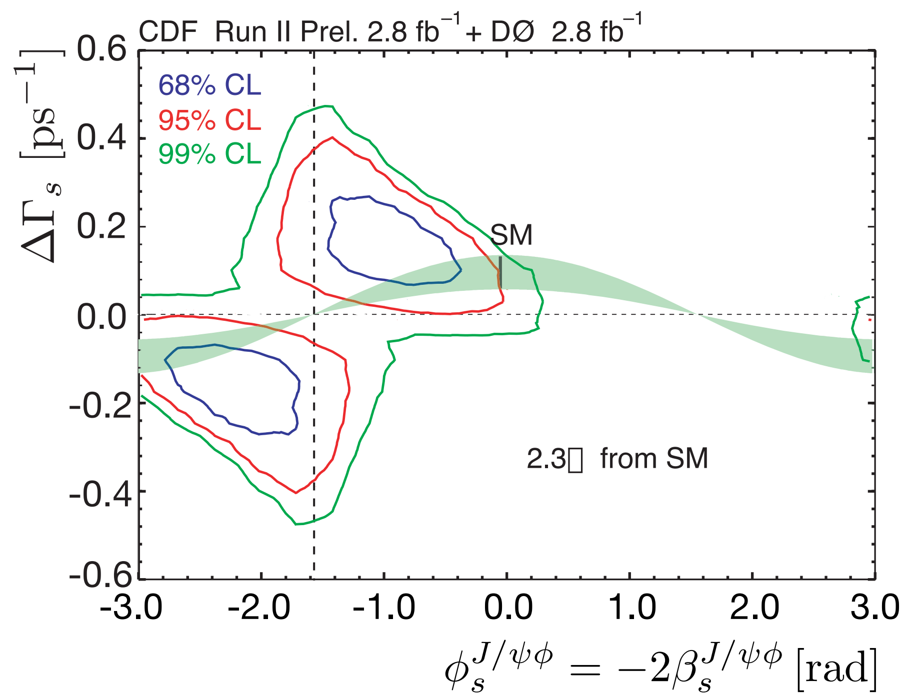
$$\Delta\Gamma_s = 0.19 \pm 0.07^{+0.02}_{-0.01}$$
$$\phi_s^{J/\psi\phi} = -0.57^{+0.24+0.07}_{-0.30-0.02}$$

Comparison to Previous Results

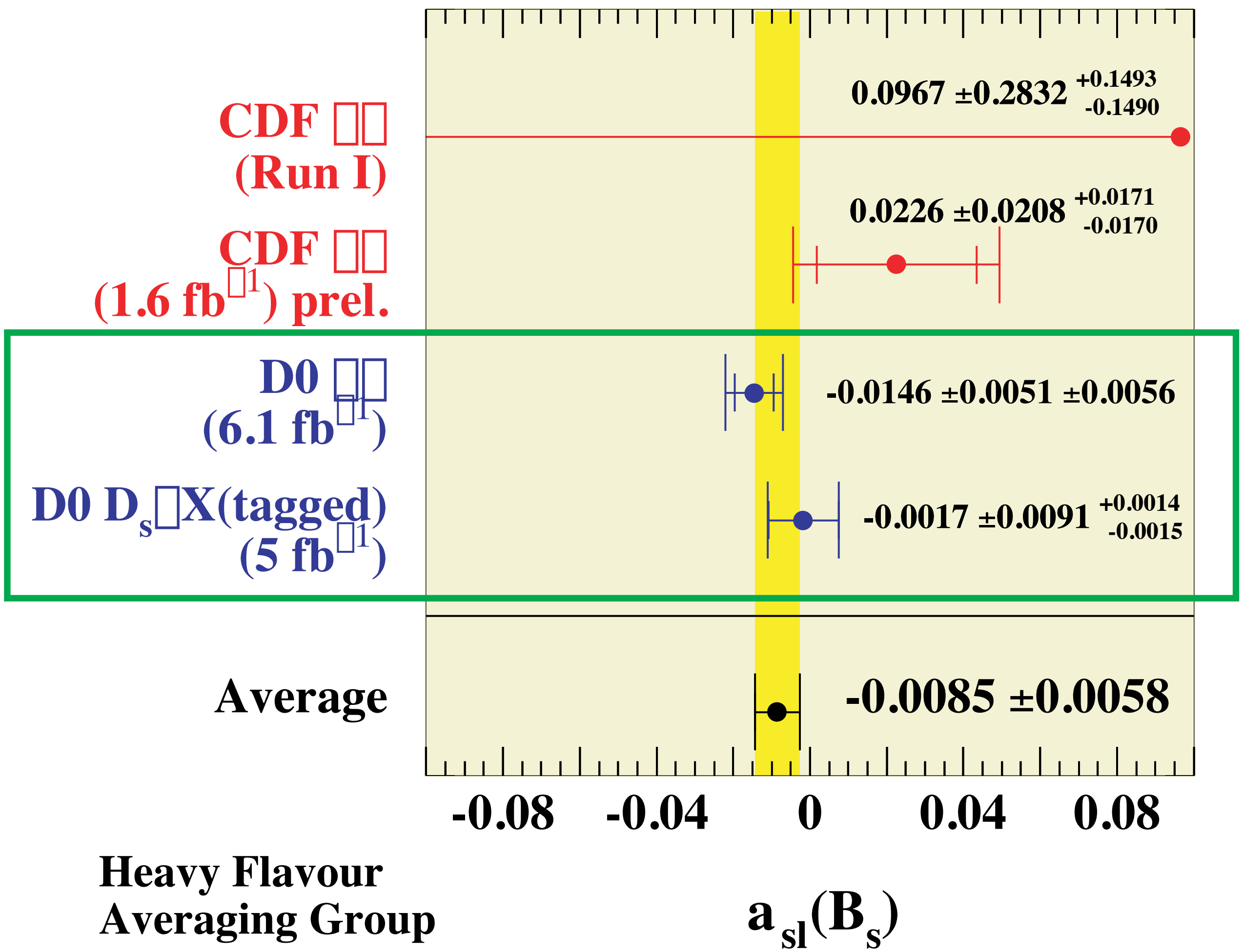
- Improvements in the track reconstruction efficiency
- Refinement in the vertex fitting and in the proper time uncertainty calculation
- Detector acceptance corrections derived for the present data set
- Gaussian constraint for oscillation frequency (instead of fixed)
- Constrain strong phases to world average values for $B_d^0 \to J/\psi K^*$

DØ Note 5928-CONF:





Published result, no strong phase δ$_i$ constraint



CDF
(Run I)
0.0967 ±0.2832 +0.1493 -0.1490
CDF
(1.6 fb-1) prel.
0.0226 ±0.0208 +0.0171 -0.0170
D0
(6.1 fb-1)
-0.0146 ±0.0051 ±0.0056
D0 Ds X(tagged)
(5 fb-1)
-0.0017 ±0.0091 +0.0014 -0.0015
Average
-0.0085 ±0.0058
-0.08
-0.04
0
0.04
0.08
Heavy Flavour
Averaging Group
a sl(Bs)