Results on A_{sl}^{b} and ϕ_s

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

Heavy Light

CP Violation

Three kinds:

- In decay: $|\mathcal{A}_f|^2 \neq |\bar{\mathcal{A}}_{\bar{f}}|^2$

$\overline{B}^0 \to K^-\pi^+$
$B^0 \to K^+\pi^-$
Different!

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

Dimuon Charge Asymmetry

Topic 2
- In interference of decay and mixing amplitudes e.g. $B_s^0 \to J/\psi\phi$

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

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

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

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

Dimuon Charge Asymmetry

Direct semileptonic decay

Neutral B meson oscillation and then semileptonic decay

- Measure CP violation *in mixing* via

$$A_{\rm sl}^b = \frac{N_b^{++} - N_b^{--}}{N_b^{++} + N_b^{--}}$$

Dimuon charge asymmetry of semileptonic *B* decays

- Measure ***raw*** asymmetries (regardless of muon source)

Semileptonic Charge Asymmetry

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

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

PRL **97**, 151801 (2006)

Semileptonic charge asymmetry

Dimuon charge asymmetry

Charge asymmetry of "wrong-sign" semileptonic *B* decays

- Define semileptonic charge asymmetry separately for B_d^0 and B_s^0

$$a_{\rm sl}^q = \frac{\Gamma(\overline{B}_q^0 \to \mu^+ X) - \Gamma(B_q^0 \to \mu^- X)}{\Gamma(\overline{B}_q^0 \to \mu^+ X) + \Gamma(B_q^0 \to \mu^- X)} \qquad q = d, s$$

$A^b_{\rm sl}$ at the Tevatron

- Both B^0_d and B^0_s produced at the Tevatron (unlike *B* factories at $\Upsilon(4S)$)

  with production fractions $f_d = 0.323 \pm 0.037$
  $f_s = 0.118 \pm 0.015$

- $A^b_{\rm sl}$ measured at the Tevatron: a linear combination of $a^d_{\rm sl}$ and $a^s_{\rm sl}$

$$A^b_{\rm sl} = (0.506 \pm 0.043)a^d_{\rm sl} + (0.494 \pm 0.043)a^s_{\rm sl}$$

Tevatron has access to ***both***

B Factories can provide independent measurement of $a^d_{\rm sl}$

Blinded Analysis

Central value of $A^b_{\rm sl}$ extracted from full data set only after the analysis method and all statistical and systematic uncertainties finalized

Raw Asymmetries

Count (billions!!)

$$a = \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)} = (0.955 \pm 0.003)\%$$

From 1.5×10^9 muons in inclusive sample

$$A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = (0.564 \pm 0.053)\%$$

From 3.7×10^6 events in like-sign dimuon sample

Both raw asymmetries have significant backgrounds, distinguish:

$A = K A_{sl}^b + A_{bkg}$ $\quad$ $a = k A_{sl}^b + a_{bkg}$ $\quad (a \simeq a_{bkg})$

- Asymmetries in detector backgrounds and reconstruction efficiencies
- "Dilution" due to other "prompt/physics" sources of muons

Detector-Related Backgrounds

Inclusive muon

Like-sign dimuon
(only linear terms kept)

$$a_{\rm bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + (1 - f_{\rm bkg})\delta$$

$$A_{\rm bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + (2 - F_{\rm bkg})\Delta$$

- f_K, f_π, f_p ; F_K, F_π, F_p fractions of each particle identified as muons
- a_K, a_π, a_p ; A_K, A_π, A_p charge asymmetry of each particle track identified as a muon
- δ ; Δ charge asymmetry of muon reconstruction
- $f_{\rm bkg} = f_K + f_\pi + f_p$; $F_{\rm bkg} = F_K + F_\pi + F_p$

The Big One: Kaons

Inclusive muon

$$a_{\rm bkg} = f_K a_K + f_\pi a_\pi + f_p a_p + (1 - f_{\rm bkg})\delta$$

Like-sign dimuon
(only linear terms kept)

$$A_{\rm bkg} = F_K A_K + F_\pi A_\pi + F_p A_p + (2 - F_{\rm bkg})\Delta$$

Dominant contribution (other asymmetries ~10 times smaller)

- Detector made of matter
- Different interaction cross-section for K^+ and K^-

...since $K^- N \to Y\pi$ has no $K^+ N$ equivalent

e.g., at $p_K = 1\,{\rm GeV}$

$\sigma(K^- d) \simeq 80\,{\rm mb}$ $\sigma(K^+ d) \simeq 33\,{\rm mb}$

a_K
$(+5.51 \pm 0.11)\%$
$a_K f_K$
$(+0.854 \pm 0.018)\%$
$A_K F_K$
$(+0.828 \pm 0.035)\%$

- K^+ travel further than K^- in material, more chance to decay to μ^+
- K^+ has more chance to punch-through/sail-through than K^-

Positive asymmetry in nature → Measure in data!

Result

- Like-sign dimuons and single muons have common sources of backgrounds. Partially cancel in the combination:

$$A' = (A - \alpha a) = (K - \alpha k)A^b_{sl} + (A_{\rm bkg} - \alpha a_{\rm bkg})$$

- α technique, to constrain background (reduced systematic)

$\alpha = 0.959$ minimizes $\delta A^b_{\rm sl}$

$$A^b_{\rm sl} = (-0.957 \pm 0.251\,({\rm stat}) \pm 0.146\,({\rm syst}))\%$$

3.2σ deviation from

$$A^b_{\rm sl}(SM) = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$$

- Consistent with prior DØ dimuon result with 1.0 fb^{-1} (Phys. Rev. **D** 74, 092001 (2006))

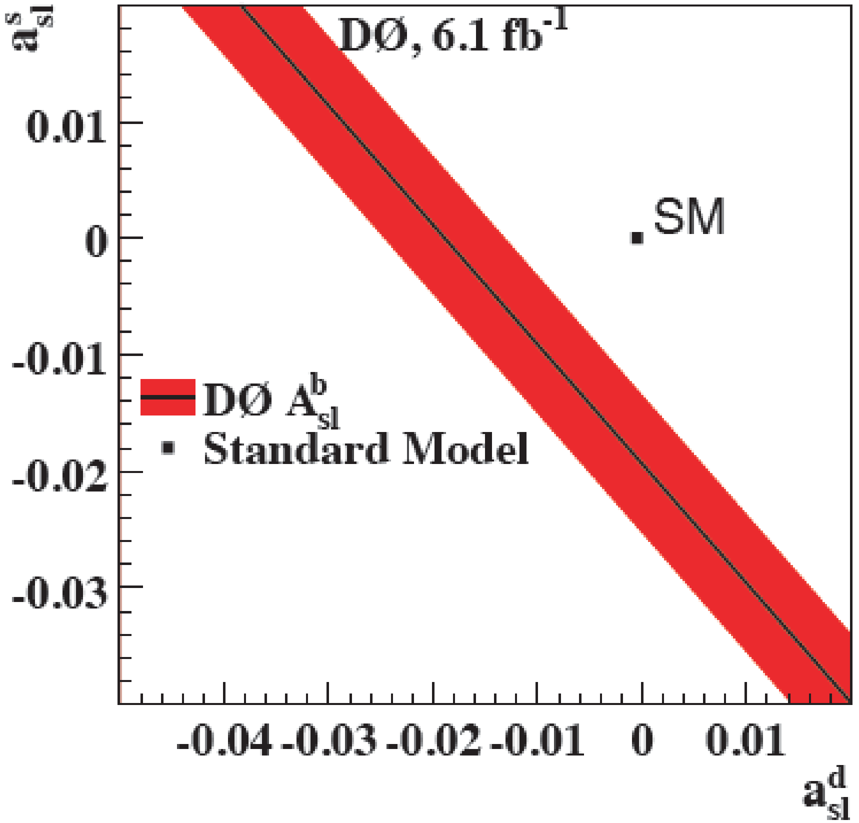
$$A^b_{\rm sl} = (-0.53 \pm 0.31)\%$$

1.7σ deviation from SM

Consistency with Other Results

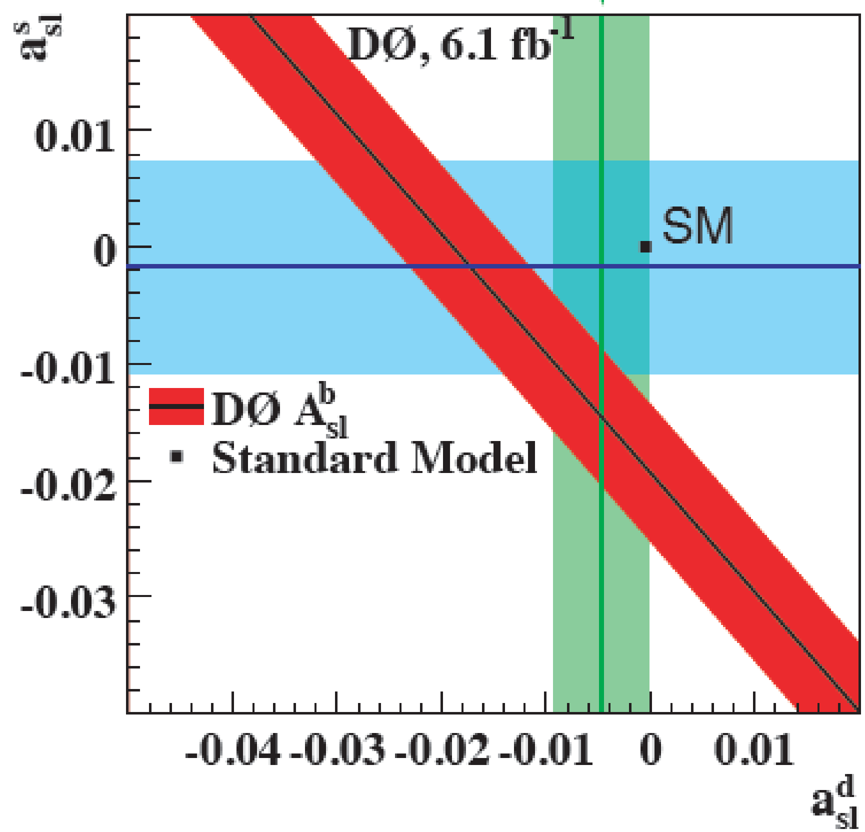
- Recall that measured asymmetry is a linear combination:

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



Consistency with Other Results

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



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

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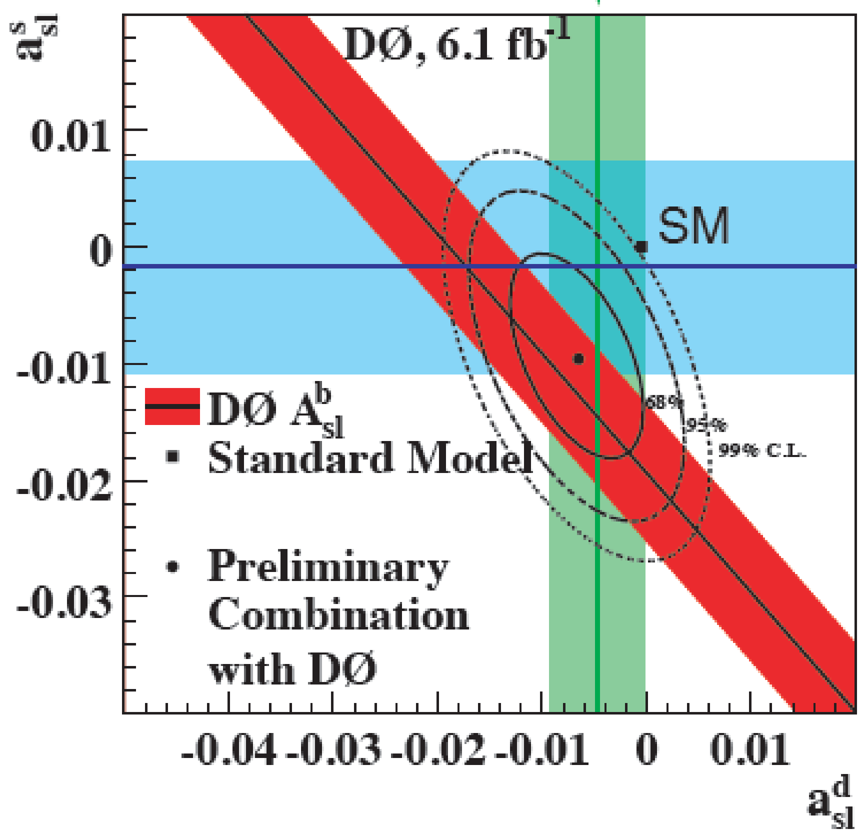

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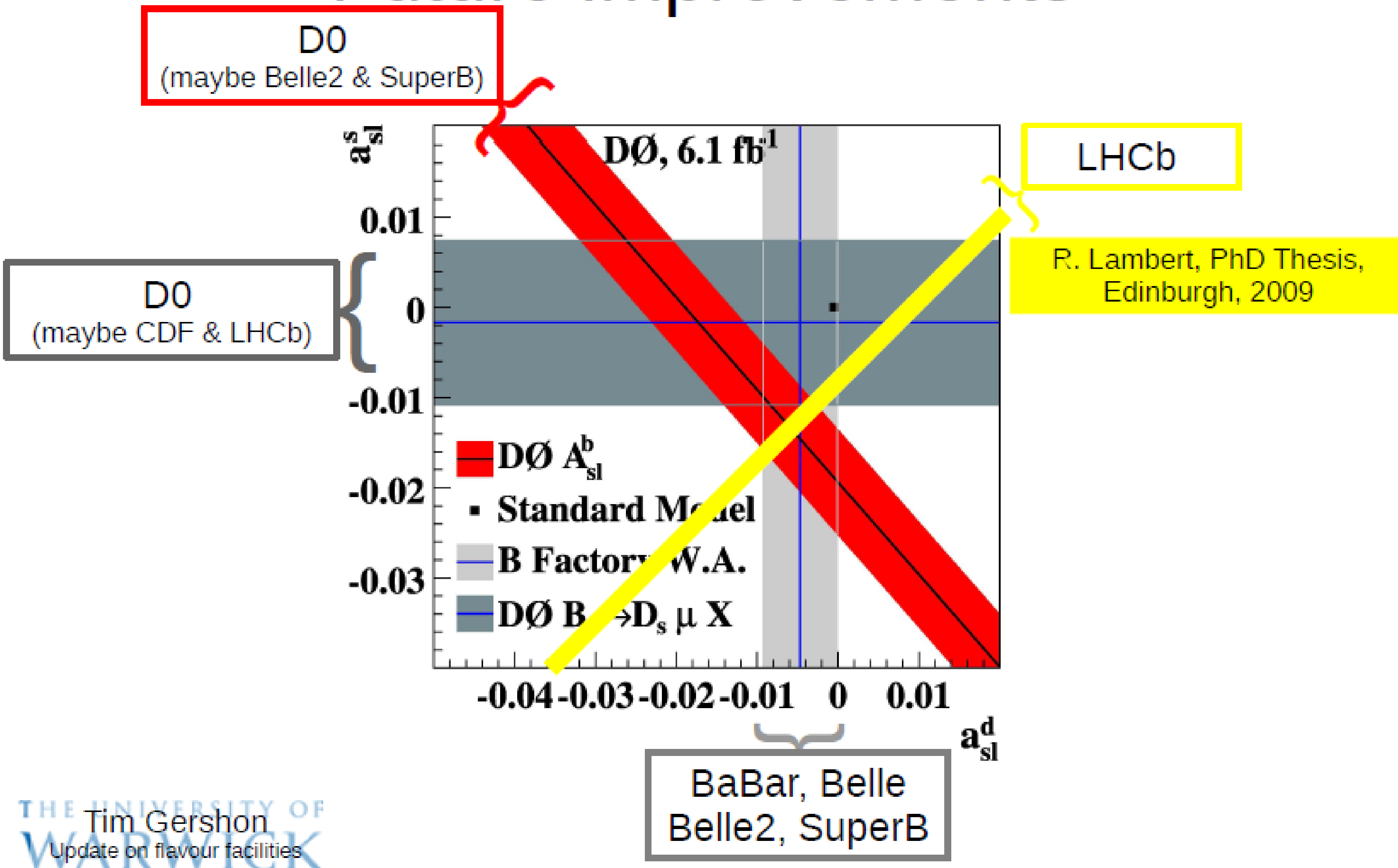
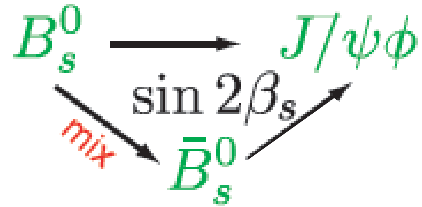
Future improvements



CP Violation: Another way to test

Golden mode,
Tevatron

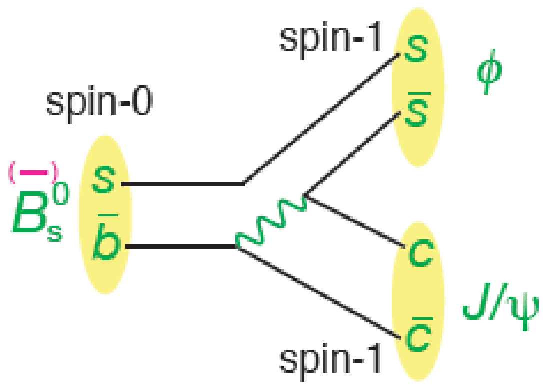


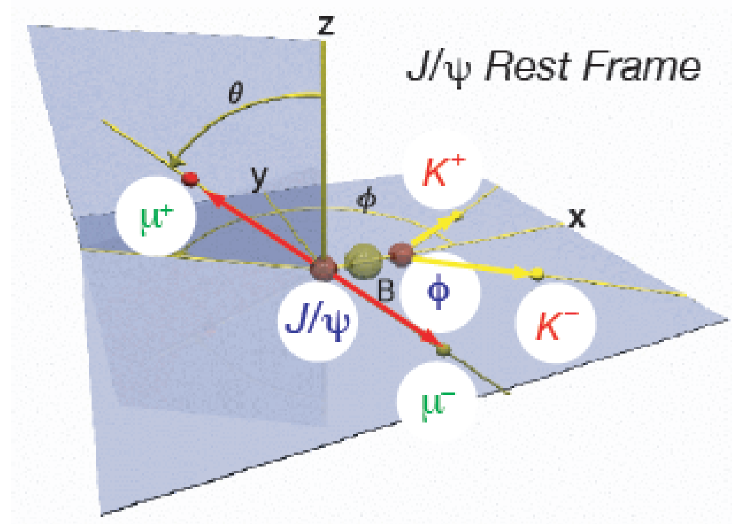
CP violation through
interference of diagrams
with and w/o mixing

$$\phi_s^{J/\psi\phi} = -2\beta_s = \underbrace{-2\beta_s^{SM}}_{-(0.038 \pm 0.002)} + \phi_s^{NP}$$

If new physics in mixing, same new phase angle in $B_s^0 \to J/\psi\phi$!

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

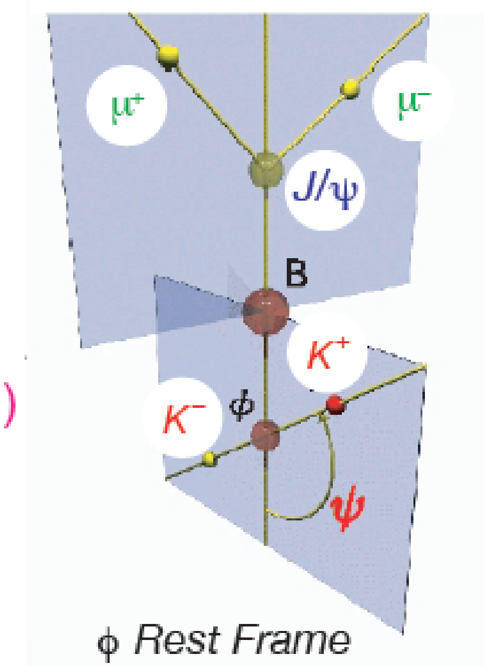




- Decays into two vector mesons that are either *CP*-odd (*L*=1) or *CP*-even (*L*=0,2)
- Time-dependent angular distributions allow separation of components
- Simultaneous fit to two lifetimes $(1/\Gamma_H, 1/\Gamma_L)$ and three angles "transversity basis"

$A_\perp$ transverse perp. → *CP*-odd

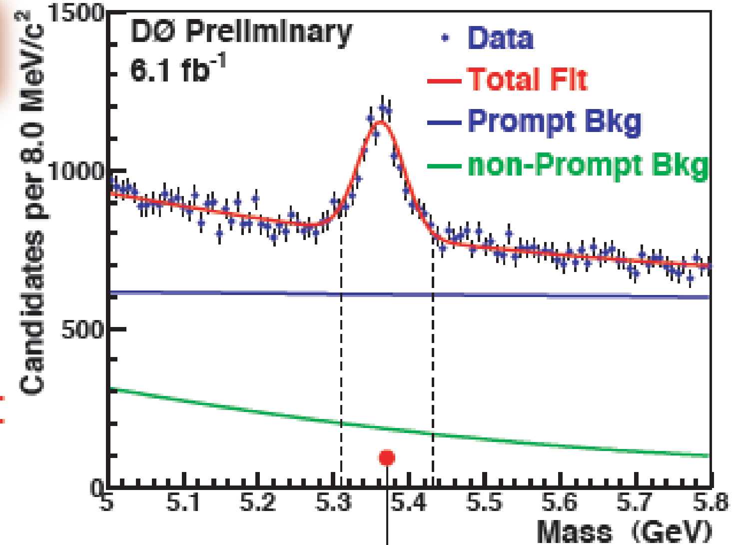
$A_\parallel$ transverse para.
A_0 longitudinal → *CP*-even



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:

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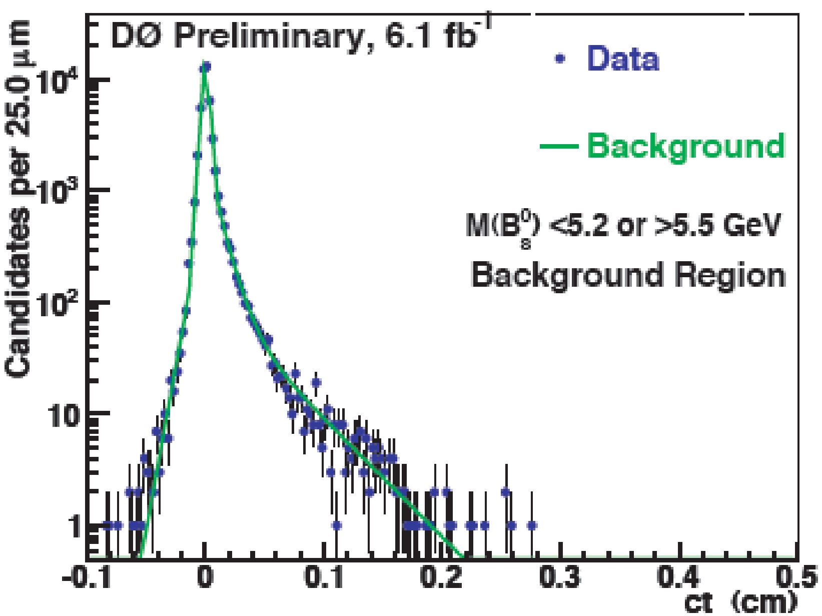
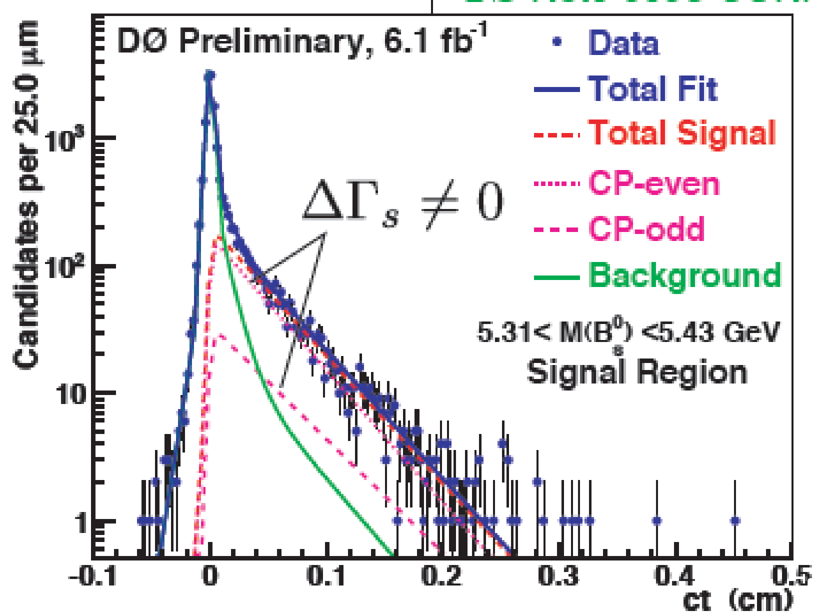


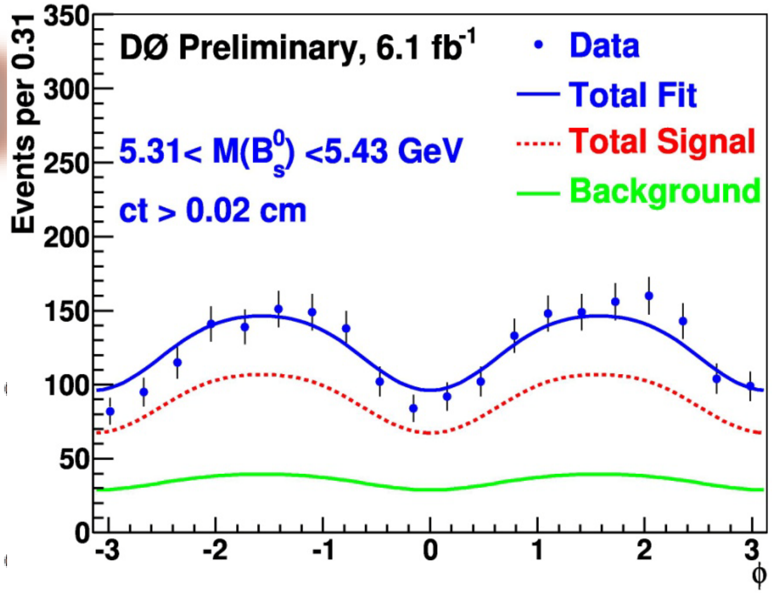


CP Violation in $B_s^0 \to J/\psi\phi$

3. Decay product angles

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)



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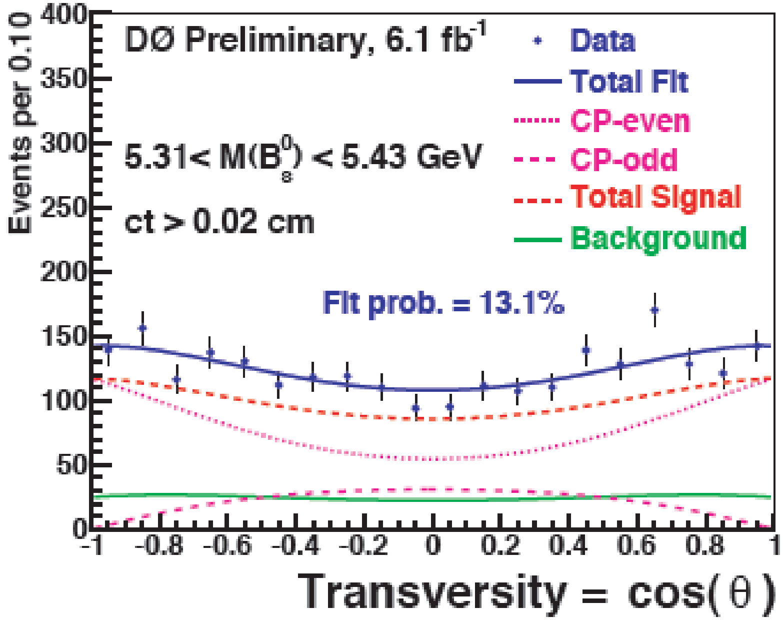
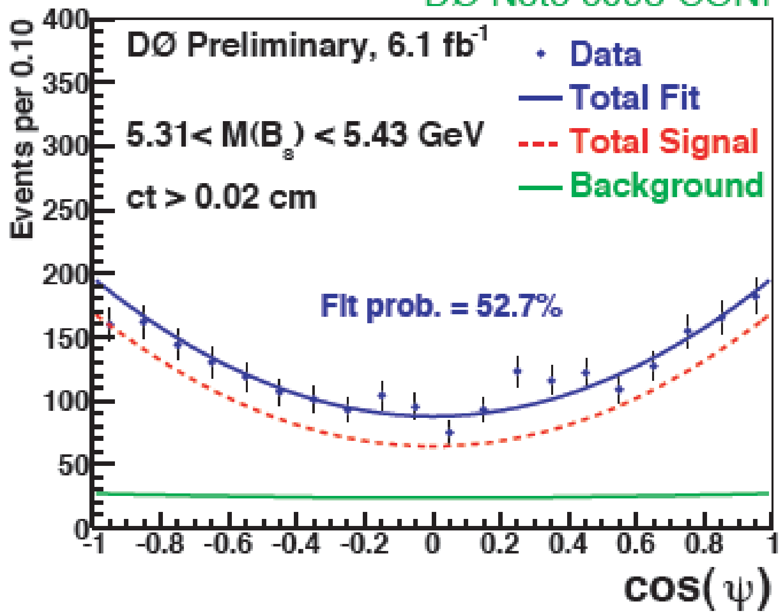
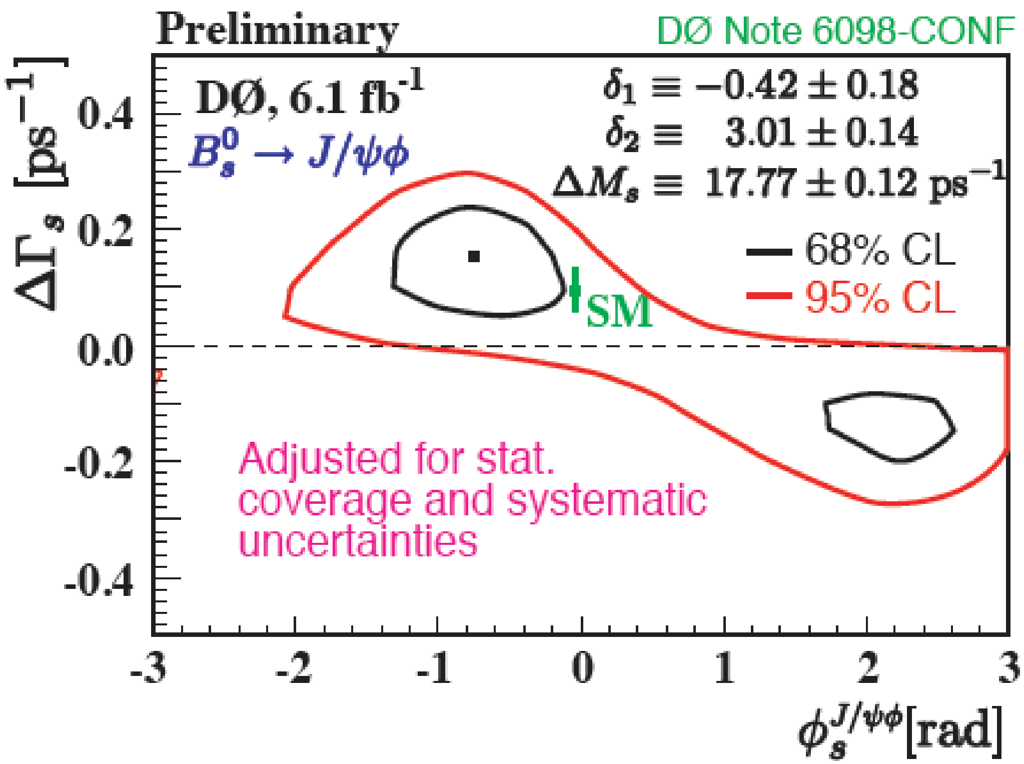




CP Violation in $B_s^0 \to J/\psi\phi$ — Results

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

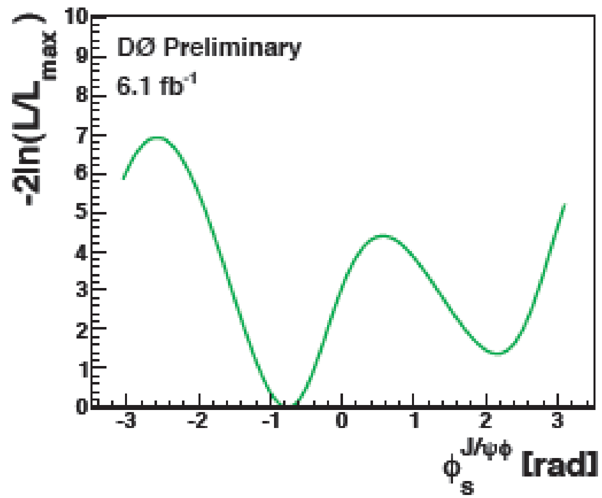


$A_\perp(t=0)\,, |A_0(0)|^2 - |A_\parallel(0)|^2$

consistent with $B_d^0 \to J/\psi K^*$

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

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



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 $B_s^0 \to D_s \mu \nu$

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

DØ Note 6093-CONF

- Allows for interesting comparison/combination:

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

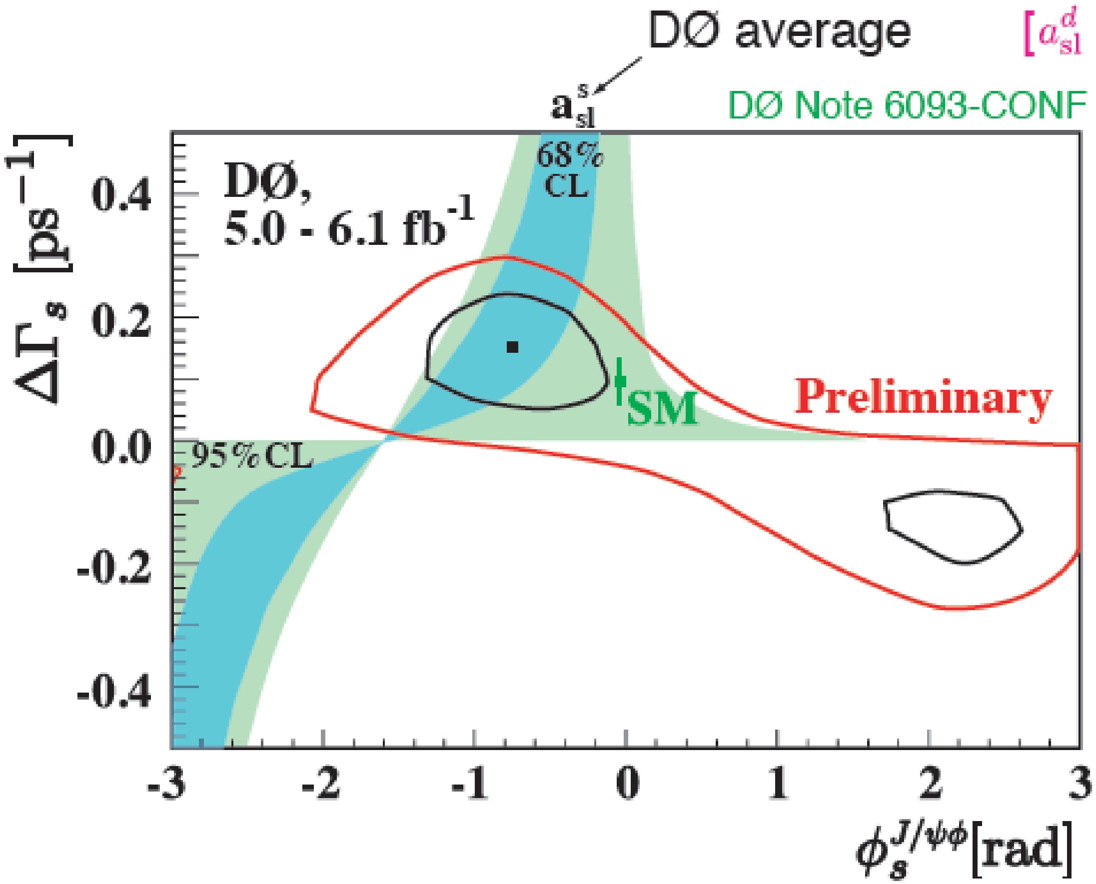
$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

(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

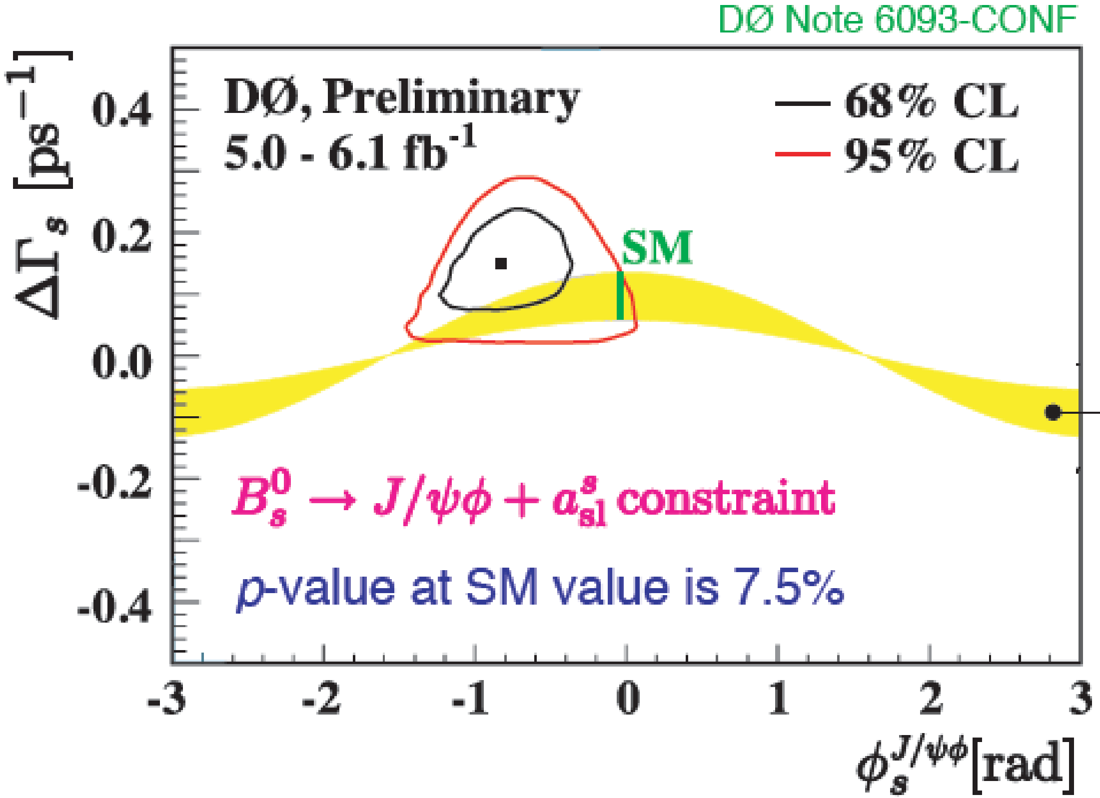
Comparison

$[a_{sl}^d = (-0.47 \pm 0.46)\%]$



- 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 $\Gamma_s^{CP\,\mathrm{even}}$

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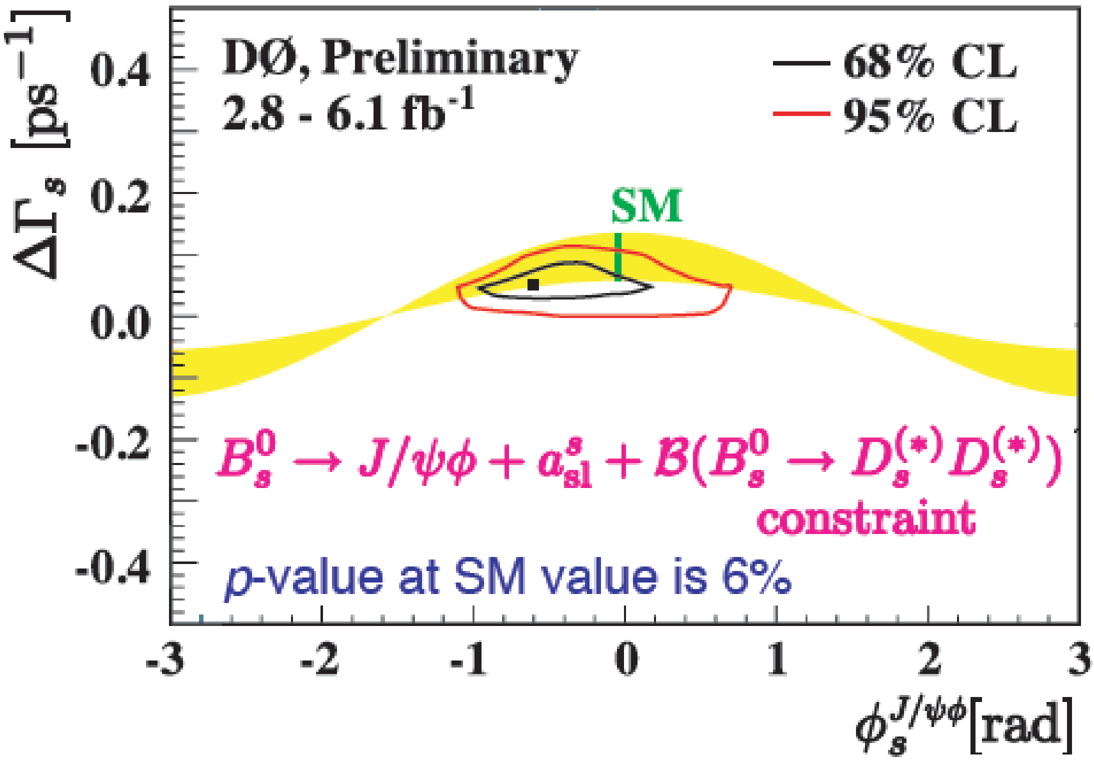

DØ, 2.8 fb^{-1}
PRL 102, 091801 (2009)

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

$\oplus$ 30% theory unc.

x_f is the fraction of the CP-odd component of the decay

Summary $A^b_{\rm sl}$

- We have made a new measurement of the like-sign dimuon asymmetry which is significantly different from zero
- Under the assumption it is due to *B*-physics, we extract:

$$A^b_{\rm sl} = (-0.957 \pm 0.251\,({\rm stat}) \pm 0.146\,({\rm syst}))\%$$

- Result is consistent with all other measurements of CP violation in *B* mixing, but inconsistent with the SM at 99.8% CL (3.2σ)
- Obtained using very little input from simulation, and all tests show excellent consistency
- Dominant uncertainty is statistical – precision can be improved with more events (luminosity, triggers, efficiency)
- Both DØ and CDF seeing trends (~95% CL, ~2σ) in independent different analyses sensitive to a similar effect

Summary

ϕ_s & combination with a^b_{sl}

- Using 6.1 fb^{-1} of data, DØ has made a preliminary update of their previously published (with 2.8 fb^{-1}) $B^0_s \to J/\psi\phi$ 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^s_{sl} semileptonic charge asymmetry for B^0_s extracted from the DØ dimuon semileptonic charge asymmetry

  ($A^b_{sl} > 3\sigma$ from SM)

  and from DØ $B^0_s \to D_s\mu\nu$ asymmetry analysis

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

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