Measurement of ϕ_s at DØ

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for the DØ collaboration

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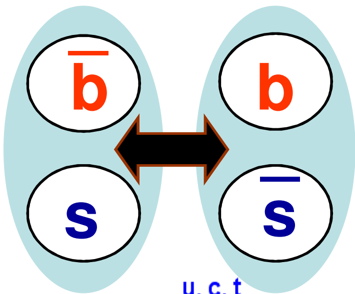
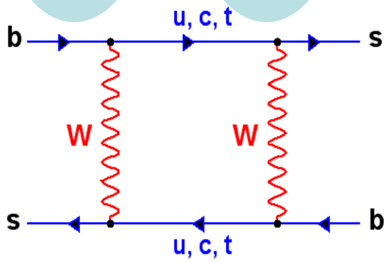
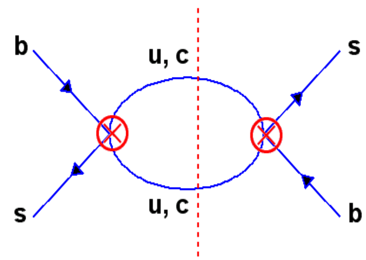
B_s Mixing



Schrödinger Equation: $$i\frac{\partial}{\partial t}\begin{pmatrix}|B_s^0(t)\rangle \\ |\overline{B_s^0}(t)\rangle\end{pmatrix} = \begin{pmatrix}M_{11}-\frac{i}{2}\Gamma_{11} & M_{12}-\frac{i}{2}\Gamma_{12} \\ M_{21}-\frac{i}{2}\Gamma_{21} & M_{22}-\frac{i}{2}\Gamma_{22}\end{pmatrix}\begin{pmatrix}|B_s^0(t)\rangle \\ |\overline{B_s^0}(t)\rangle\end{pmatrix}$$





- M_{12} stems from the real part of the box diagram, dominated by top
- Γ_{12} stems from the imaginary part, dominated by charm

Three physical quantities; M_{12} , $|\Gamma_{12}|$ and $arg(-M_{12}/\Gamma_{12})$

Diagonalization gives two physically observed "Light" and "Heavy" mass eigenstates

$$|B_s^H\rangle = N\,[\,p\,|B_s^0\rangle - q\,|\,\overline{B}_s^0\rangle\,]$$

$$|B_s^L\rangle = N\,[\,p\,|B_s^0\rangle + q\,|\,\overline{B}_s^0\rangle\,]$$

$$N = \frac{1}{\sqrt{p^2+q^2}}$$

$$\Gamma_s = \frac{\Gamma_L + \Gamma_H}{2}$$

$$\overline{\tau_s} = \frac{1}{\Gamma_s}$$

B_s Mixing

Observable		SM expectation (hep-ph/0612167)
CP violation weak phase	$\phi_s = arg(-M_{12}/\Gamma_{12})$	$(4.2 \pm 1.4)\ 10^{-3}$ rad
Decay width difference	$\Delta\Gamma_s = \Gamma_L - \Gamma_H = 2\lvert\Gamma_{12}\rvert\cos\phi_s$	$(0.096 \pm 0.039)\ ps^{-1}$
frequency of B_s- $\bar{B}_s$ oscillations	$\Delta M_s = M_H - M_L = 2\lvert M_{12}\rvert$	$(17.77 \pm 0.12)\ ps^{-1}$ (measured value)

$$|B_s^{Odd}\rangle = 1/\sqrt{2}\,(|B_s^0\rangle - |\bar{B}_s^0\rangle)$$

$$|B_s^{Even}\rangle = 1/\sqrt{2}(|B_s^0\rangle + |\bar{B}_s^0\rangle)$$

CP Eigenstates

$|B_s^H\rangle$ → CP odd

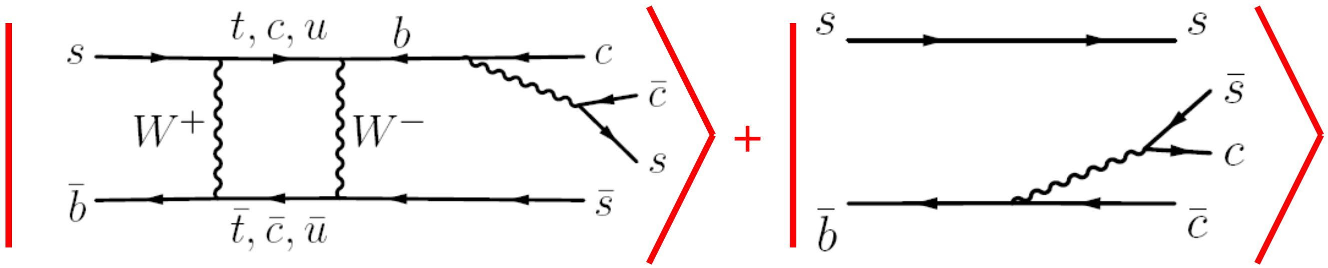
$|B_s^L\rangle$ → CP even

$for \quad \frac{q}{p} = 1$

i.e. no CP *violation*

'squashed' triangle → 'flat' triangle

CP-phase in $B_s \to J/\psi\phi$



✓ CP violating mixing phase in $B_s \to J/\psi\phi$ ($\phi_s^{J/\psi\phi}$ or $-2\beta_s$) is not equal to the CP violating mixing phase of B_s system i.e. $\phi_s^{J/\psi\phi} \neq \phi_s$

✓ Still small in SM ! $\phi_s^{J/\psi\phi} = -2\arg[-V_{ts}V_{tb}^{*}/V_{cs}V_{cb}^{*}] = (-0.04 \pm 0.01)$ rad

✓ New physics contributions alter $\phi_s^{J/\psi\phi}$ in the same way as for ϕ_s

$$\phi_s^{J/\psi\phi} \to \phi_s^{J/\psi\phi,SM} + \phi_s^{NP}$$

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

Large measured value of $\phi_s^{J/\psi\phi}$ is unambiguous sign of new physics!

Transversity Basis

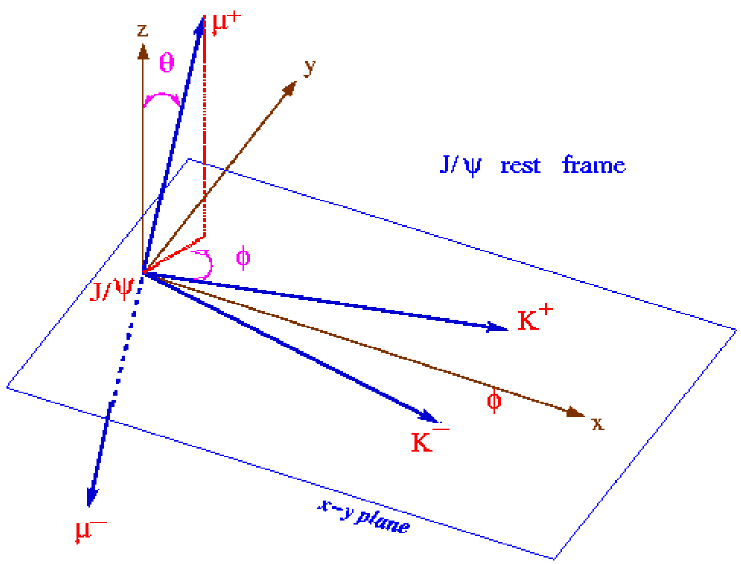
- $B_s \rightarrow V1 + V2$ ($J/\psi + \phi$) i.e. Spin $0 \rightarrow 1+1$ L= 0,1,2
- L = 0 and 2 corresponds to CP even; L=1 CP odd

➢ The Angular distribution is written in terms of three time-dependent linear polarization amplitudes

➢ With respect to decay axis: Parallel, perpendicular orientations of the transverse polarization ($A_\perp$ & $A_\parallel$) and longitudinal polarization (A_0)

➢ The Initial magnitude of polarization amplitudes satisfy the normalization condition
$|A_\perp(0)|^2 + |A_\parallel(0)|^2 + |A_0(0)|^2 = 1$ where
$|A_\perp(0)|^2$ is CP-odd content (~20%)

➢ Polarization amplitude phases relative to each other are known as "strong phases" which depend only on final state interactions
$\delta_\parallel = \arg(A_\parallel(0)\, A_0^*(0))$,
$\delta_\perp = \arg(A_\perp(0)\, A_0^*(0))$

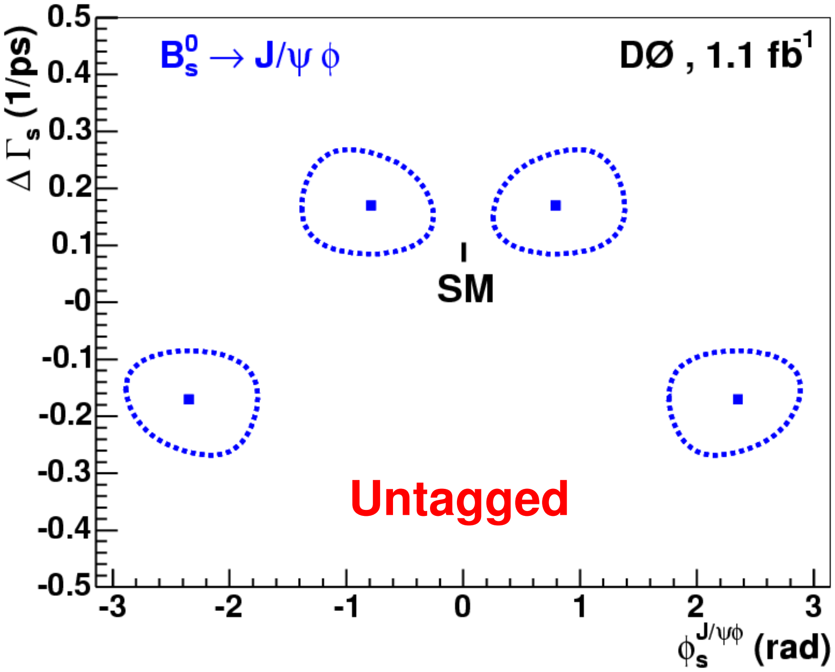


Fit Ambiguity

$$\delta_{1/2} = \delta_{\perp} - \delta_{\parallel/0}$$

$\Delta\Gamma_s \rightarrow -\Delta\Gamma_s$	$\cos\delta_1 > 0$
$\pm\phi_s \rightarrow \pi \pm \phi_s$	$\cos\delta_2 > 0$

4-fold ambiguity



Without initial b-flavor tag (B-tagging) and with the strong phases free, there is a 4-fold ambiguity of the solution in the ($\Delta\Gamma_s$, ϕ_s) plane

Fit Ambiguity

$$\delta_{1/2} = \delta_{\perp} - \delta_{\parallel/0}$$

$\Delta\Gamma_s \rightarrow -\Delta\Gamma_s$ $\cos\delta_1 > 0$

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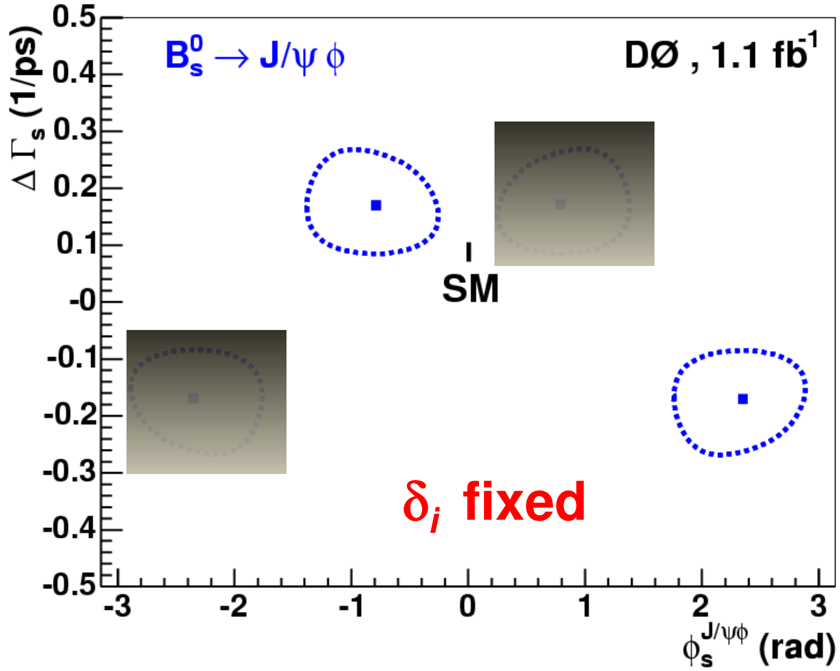
4-fold ambiguity

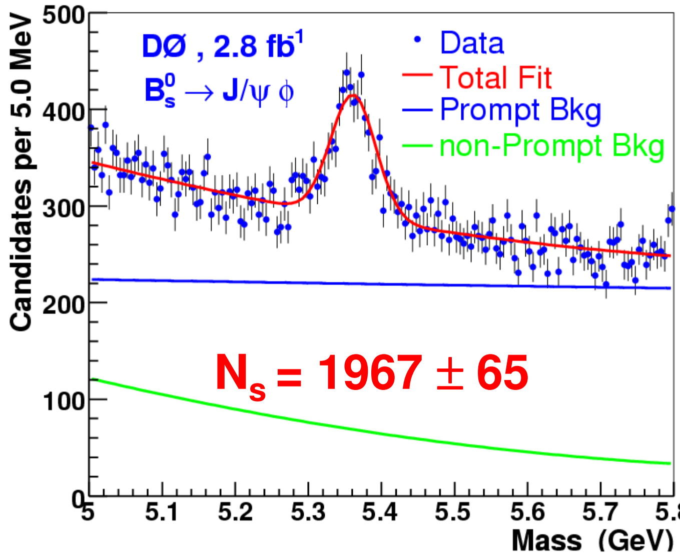


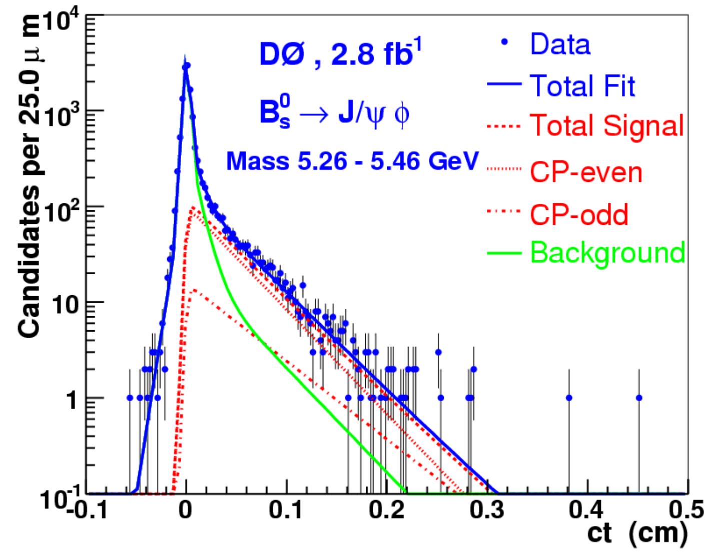
Under flavor U(3) symmetry , strong phases and amplitudes are expected to be similar for $B_s \rightarrow J/\psi\phi$ & $B_d \rightarrow J/\psi K^*$

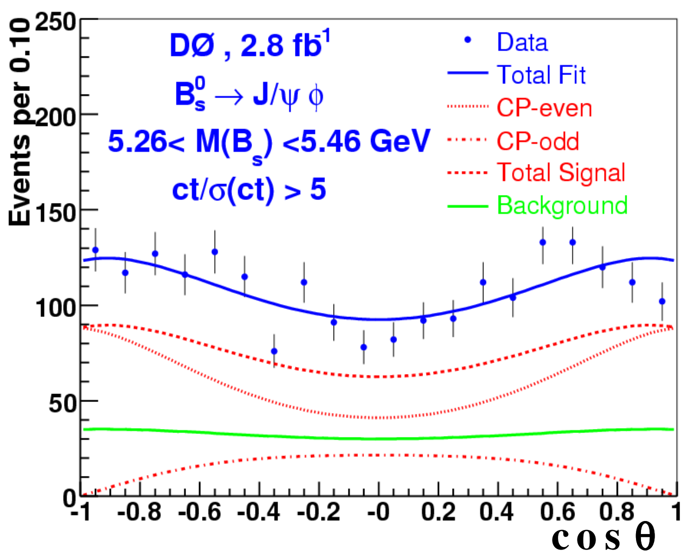
arXiv:0808.3761v5 [hep-ph] , Michael Gronau, Jonathan L. Rosner

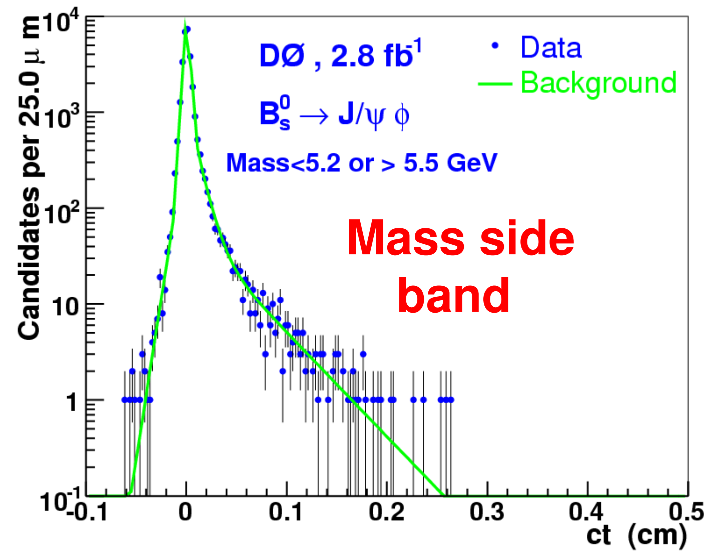
Constraining strong phases will result in 2-fold ambiguity

Input Variables





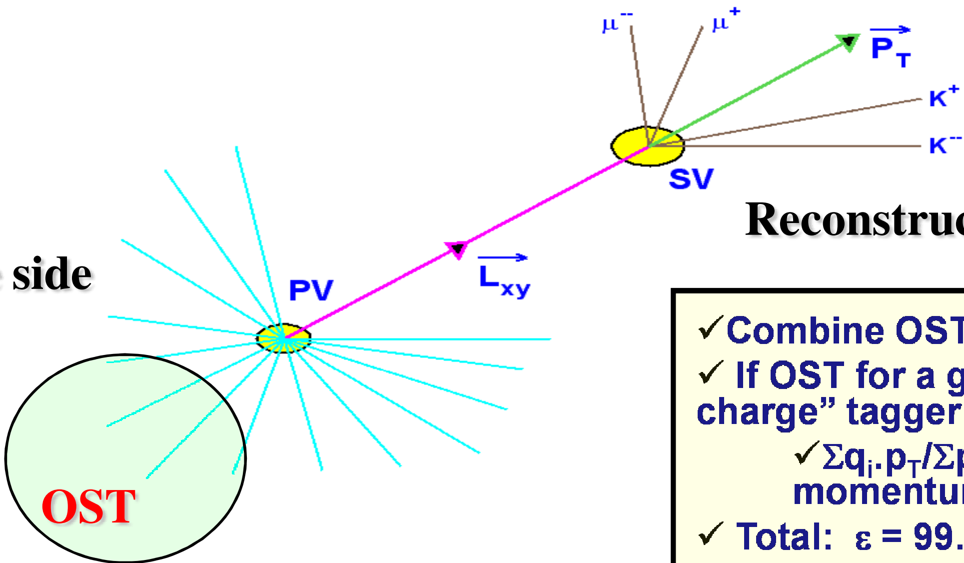




Flavor Tagging

Opposite to reconstructed B_s side (due to b , $\bar{b}$ production)

On reconstructed B_s side (due to correlation between B_s flavor and the charge of fragmentation K)

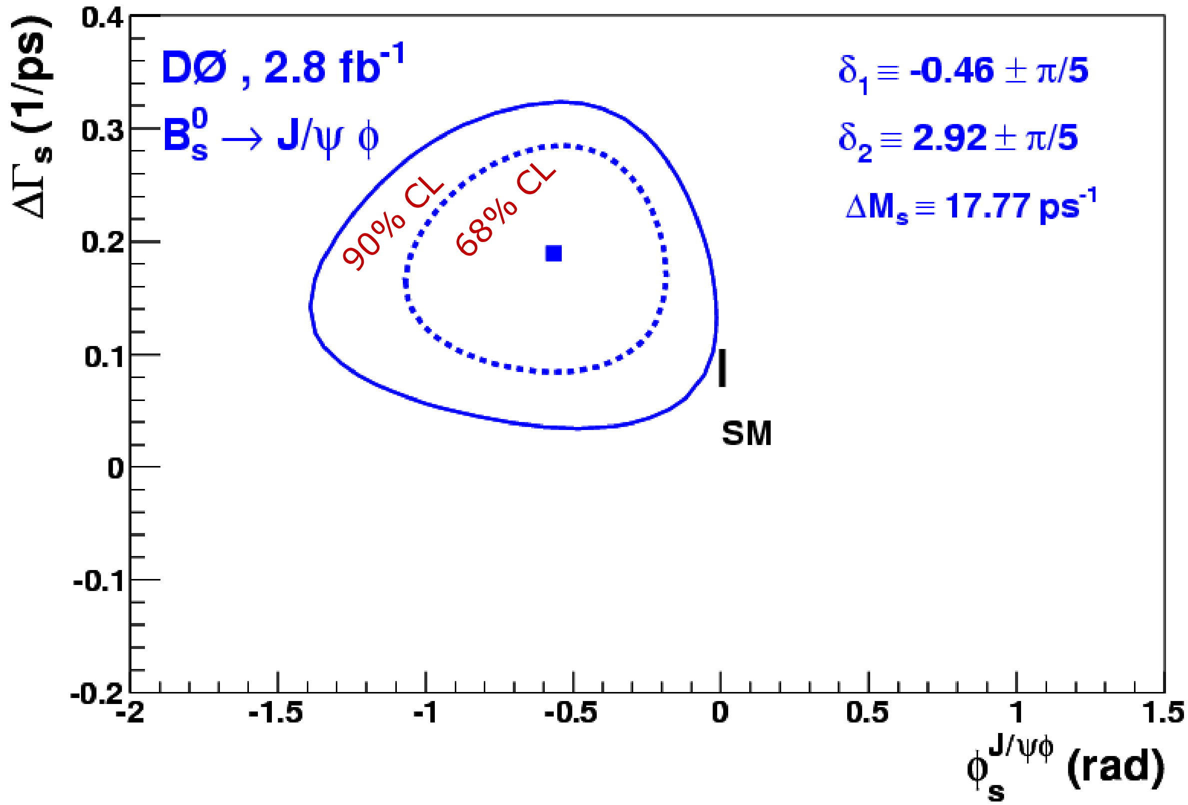


- ✓Combine OST and SST using likelihood ratio method
- ✓ If OST for a given event is not available use "Event charge" tagger
  - ✓$\Sigma q_i.p_T/\Sigma p_T$: sum of charges weighted with momentum in 0.6 cone on opposite side
- ✓ Total: ε = 99.7% & εD^2 = 4.68%

- ✓ Unbinned maximum likelihood fit to mass, lifetime and decay angles
- ✓ Weight applied to the angular distribution of B_s and $\bar{B}_s$ according to tagging probability (p), whenever available, otherwise p = 0.5

Only Tagged Results are shown in rest slides

Result, $\Delta\Gamma_s$ vs ϕ_s



PRL 101, 241801 (2008)

strong phases constrained

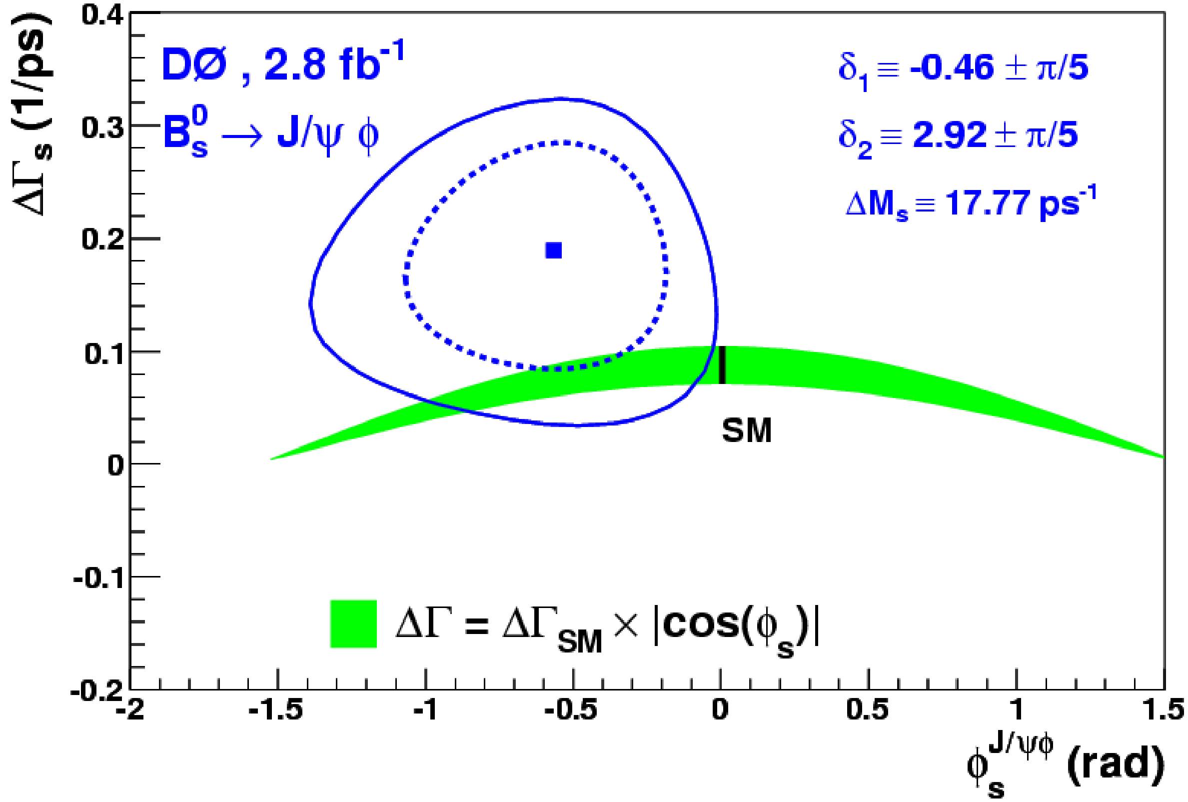
Probability of SM
6.6% ~1.8σ

$$\phi_s = -0.57^{+0.24}_{-0.30}(\text{stat})^{+0.07}_{-0.02}(\text{syst})\ \text{rad}$$

$$\Delta\Gamma_s = 0.19 \pm 0.07(\text{stat})^{+0.02}_{-0.01}(\text{syst})\ \text{ps}^{-1}$$

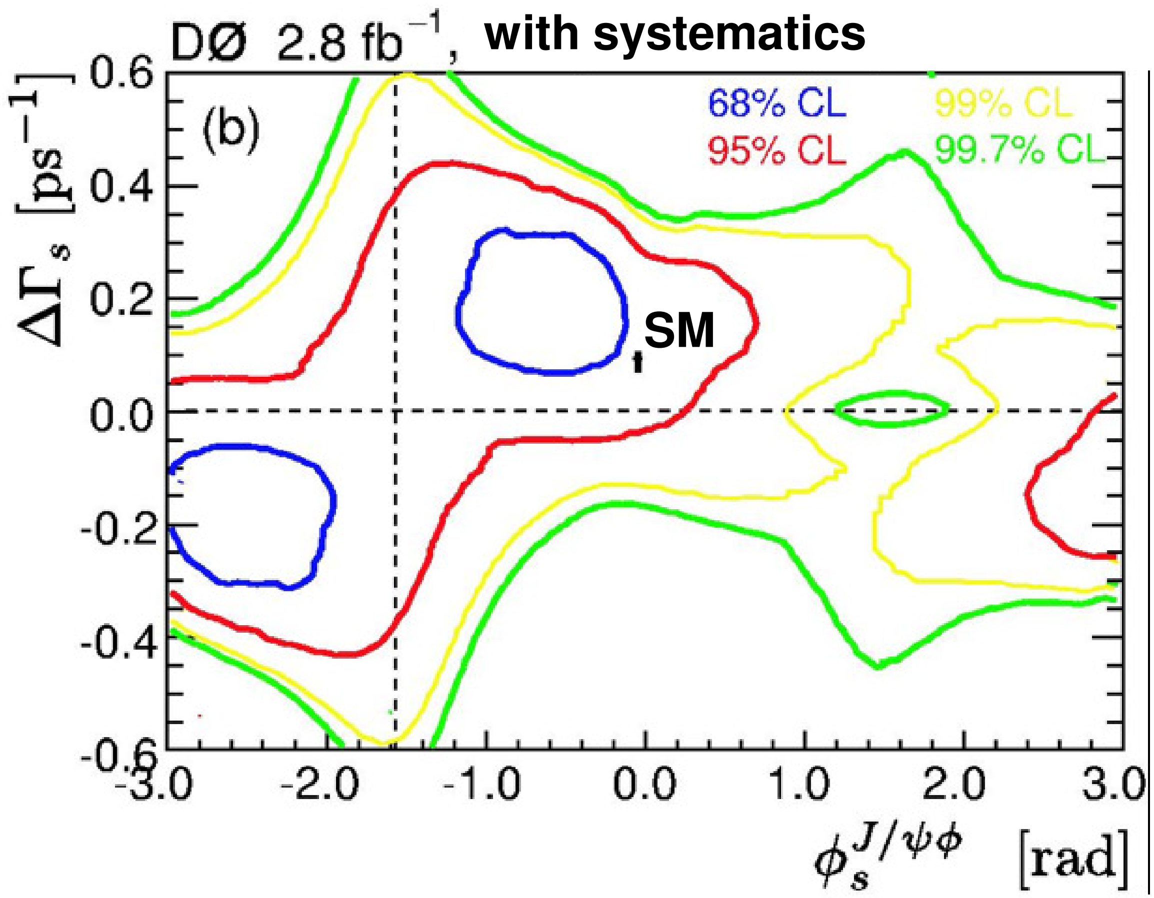
$$\overline{\tau_s} = 1.52 \pm 0.05(\text{stat}) \pm 0.01(\text{syst})\ \text{ps}$$

Result, $\Delta\Gamma_s$ vs ϕ_s



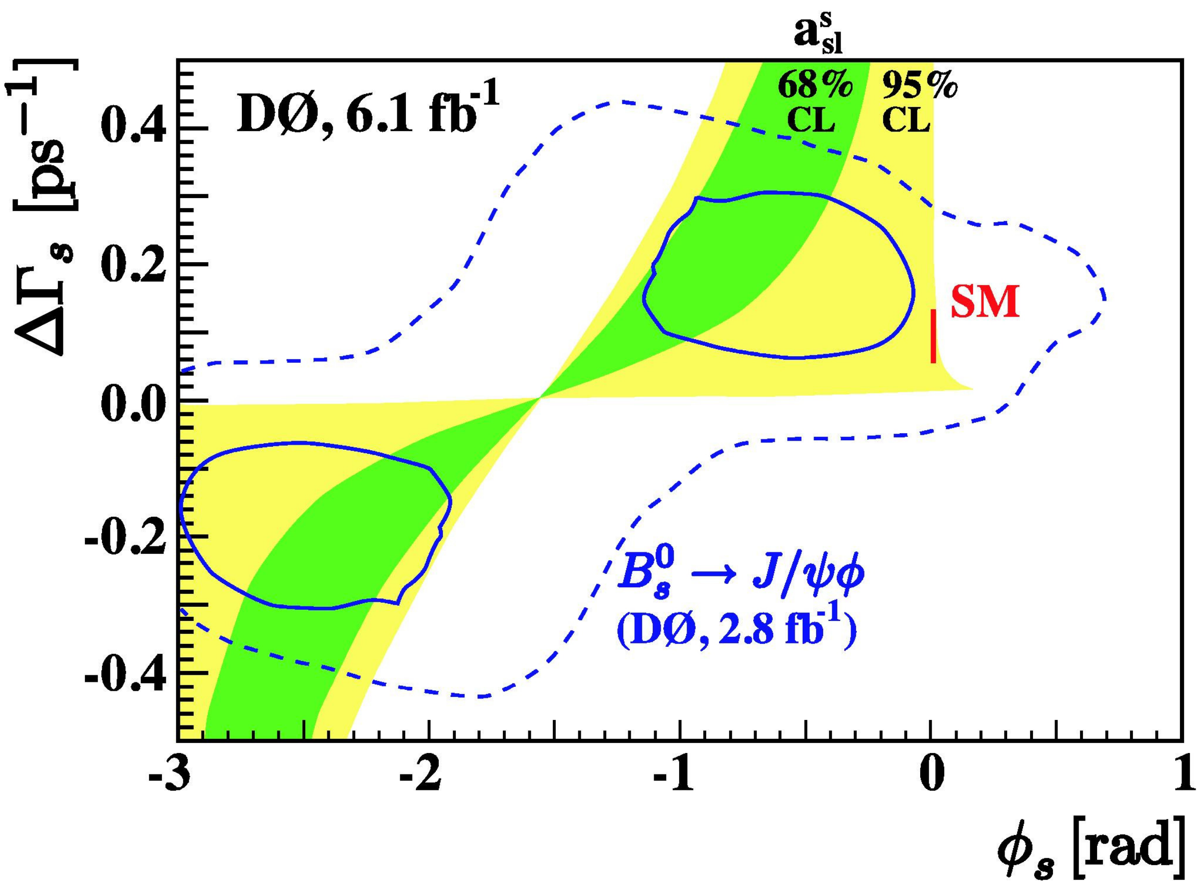
Green band: Region allowed in some new physics models

Result, $\Delta\Gamma_s$ vs ϕ_s



- ✓ **strong phases free**
- ✓ **Including all syst. effects**
- ✓ **Including $\Delta M_S = 17.77 \pm 0.12\ ps^{-1}$**

a_{SL}^{s} result overlay

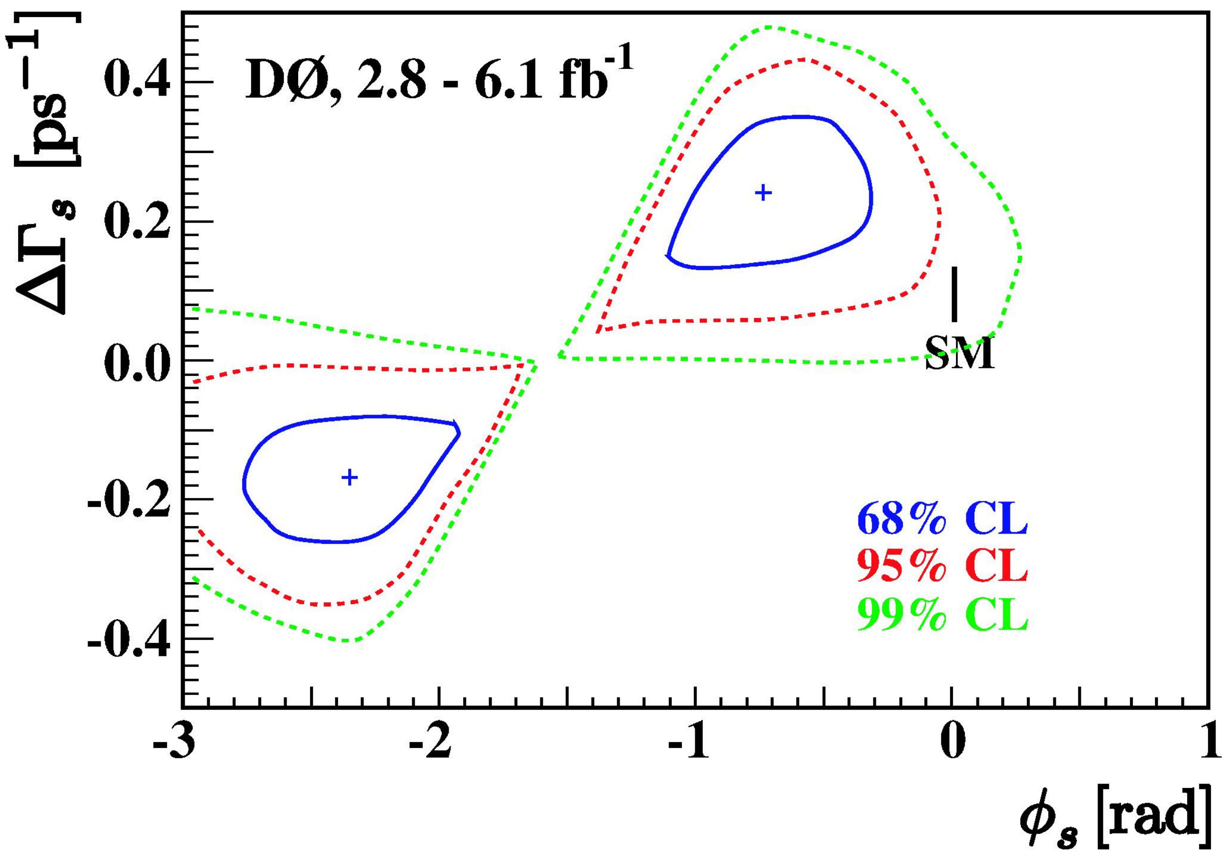


- ✓ new a_{SL}^{s} measurement at DØ with 6.1 fb^{-1} data
- ✓ a_{SL}^{s} can be translated to a band in ($\Delta\Gamma_s$, ϕ_s) plane
- ✓ a_{SL}^{s} result is consistent with DØ ϕ_s measurement from $B_s^0 \to J/\psi\phi$ (2.8 fb^{-1} data)

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

$$a_{SL}^{s} = -0.0146 \pm 0.0075$$

Combination



✓ New a_{SL}^{s} result (6.1 fb^{-1} data) is combined with DØ measurement of ϕ_s from $B_s^0 \rightarrow J/\psi\phi$ (2.8 fb^{-1} data)

✓ Combined result excludes the SM expectation by more than 95%CL

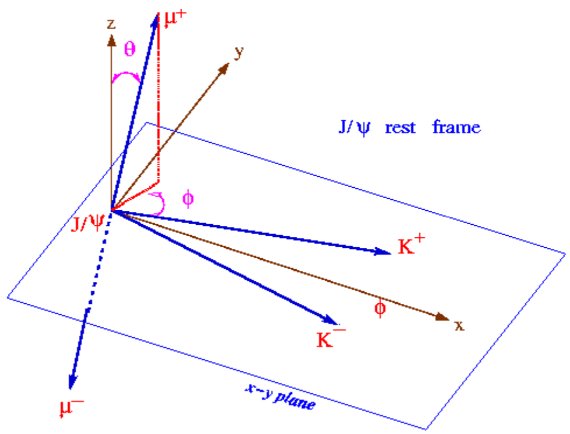
Summary & Outlook

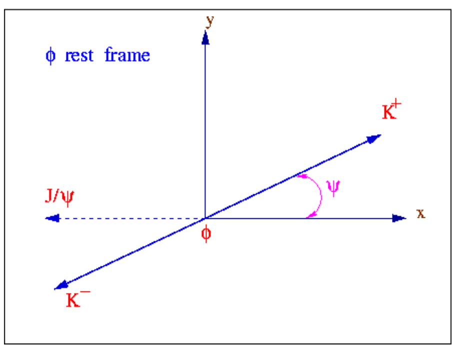
- Measurement of CP violation weak phase, ϕ_s provides direct window for New Physics search
- Results from a_{SL}^{s} measurement at DØ with 6.1 fb^{-1} data are in agreement with ϕ_s measurement at DØ with 2.8 fb^{-1} data
- The new a_{SL}^{s} measurement added more excitement to look for an updated ϕ_s measurement
- Updated measurement is expected soon with more than twice the data and several improvements
  - Boosted decision tree (BDT) selection of candidates
  - Improved tagging methods
- We will do combination of all DØ results, possibly also a combination with CDF

Additional Slides

Angular Distribution

- $B_s \rightarrow V1 + V2\ (J/\psi + \phi)$ i.e. Spin $0 \rightarrow 1+1$ L= 0,1,2
- L = 0 and 2 corresponds to CP even; L=1 CP odd
- Angular distribution can be written in helicity basis , **BUT** generally Transversity basis is used to write angular distribution , where polar coordinates are defined in "J/ψ rest frame" and "φ rest frame"





$$\frac{d^3\Gamma\left[B_s^0(t)\rightarrow J/\psi(\rightarrow\mu^+\mu^-)\phi(\rightarrow K^+K^-)\right]}{d\cos\theta\ \ d\varphi\ \ d\cos\psi}\propto$$

$$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi) \qquad |A_0(t)|^2$$

$$+\ \sin^2\psi(1-\sin^2\theta\sin^2\varphi) \qquad |A_\parallel(t)|^2$$

$$+\ \sin^2\psi\sin^2\theta \qquad |A_\perp(t)|^2$$

$$+\ \frac{1}{\sqrt{2}}\sin 2\psi\sin^2\theta\sin 2\varphi \qquad Re(|A_0^*(t)||A_\parallel(t)|)$$

$$+\ \frac{1}{\sqrt{2}}\sin 2\psi\sin 2\theta\cos\varphi \qquad Im(|A_0^*(t)||A_\perp(t)|)$$

$$-\ \sin^2\psi\sin 2\theta\sin\varphi \qquad Im(|A_\parallel(t)||A_\perp(t)|)$$

Polarization Amplitudes

Polarization Amplitudes

hep-ph/9804253 & hep-ph/0012219

$$|A_0(t)|^2 = |A_0(0)|^2 \left[\mathcal{T}_+ \pm e^{-\bar{\Gamma}t}\sin\phi_s \sin(\Delta M_s t)\right]$$

$$|A_{||}(t)|^2 = |A_{||}(0)|^2 \left[\mathcal{T}_+ \pm e^{-\bar{\Gamma}t}\sin\phi_s \sin(\Delta M_s t)\right]$$

$$|A_\perp(0)|^2 = |A_\perp(0)|^2 \left[\mathcal{T}_- \mp e^{-\bar{\Gamma}t}\sin\phi_s \sin(\Delta M_s t)\right]$$

$$\mathcal{T}_+ = \frac{1}{2}\left\{(1+cos\phi_s)e^{-\Gamma_L t} + (1-cos\phi_s)e^{-\Gamma_H t}\right\}$$

$$\mathcal{T}_- = \frac{1}{2}\left\{(1-cos\phi_s)e^{-\Gamma_L t} + (1+cos\phi_s)e^{-\Gamma_H t}\right\}$$

$$Re(A_0^*(t)A_{||}(t)) = |A_0(0)||A_{||}(0)|\cos(\delta_2-\delta_1)\left[\mathcal{T}_+ \pm e^{-\bar{\Gamma}t}\sin\phi_s \sin(\Delta M_s t)\right]$$

$$Im(A_0^*(t)A_\perp(t)) = |A_0(0)||A_\perp(0)|\left[e^{-\bar{\Gamma}t}(\pm\sin\delta_2\cos(\Delta M_s t) \mp \cos\delta_2 \sin(\Delta M_s t)\cos\phi_s) - \frac{1}{2}\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\sin\phi_s \cos\delta_2\right]$$

$$Im(A_{||}^*(t)A_\perp(t)) = |A_{||}(0)||A_\perp(0)|\left[e^{-\bar{\Gamma}t}(\pm\sin\delta_1\cos(\Delta M_s t) \mp \cos\delta_1 \sin(\Delta M_s t)\cos\phi_s) - \frac{1}{2}\left(e^{-\Gamma_H t} - e^{-\Gamma_L t}\right)\sin\phi_s \cos\delta_1\right]$$

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

Lower sign corresponds to: Time evolution of pure $\bar{B}_s^0 \rightarrow J/\psi\ \phi$ at t=0

- ✓ $\bar{\Gamma}$ → average decay width of two physical eigenstates
- ✓ δ_1 δ_2 → CP-conserving strong phase ; ~ |π| and 0
- ✓ $A_0(0)$, $A_{||}(0)$ → CP-even linear polarization amplitude at t=0
- ✓ $A_\perp(0)$ → CP-odd linear polarization amplitude at t=0

Transversity Angles