$\phi_s^{J/\psi\phi}$ and Other CPV in B Decays

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(On behalf of the DØ Collaboration)

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Introduction

Overwhelming preponderance of matter over antimatter in the Universe implies CP violation beyond SM

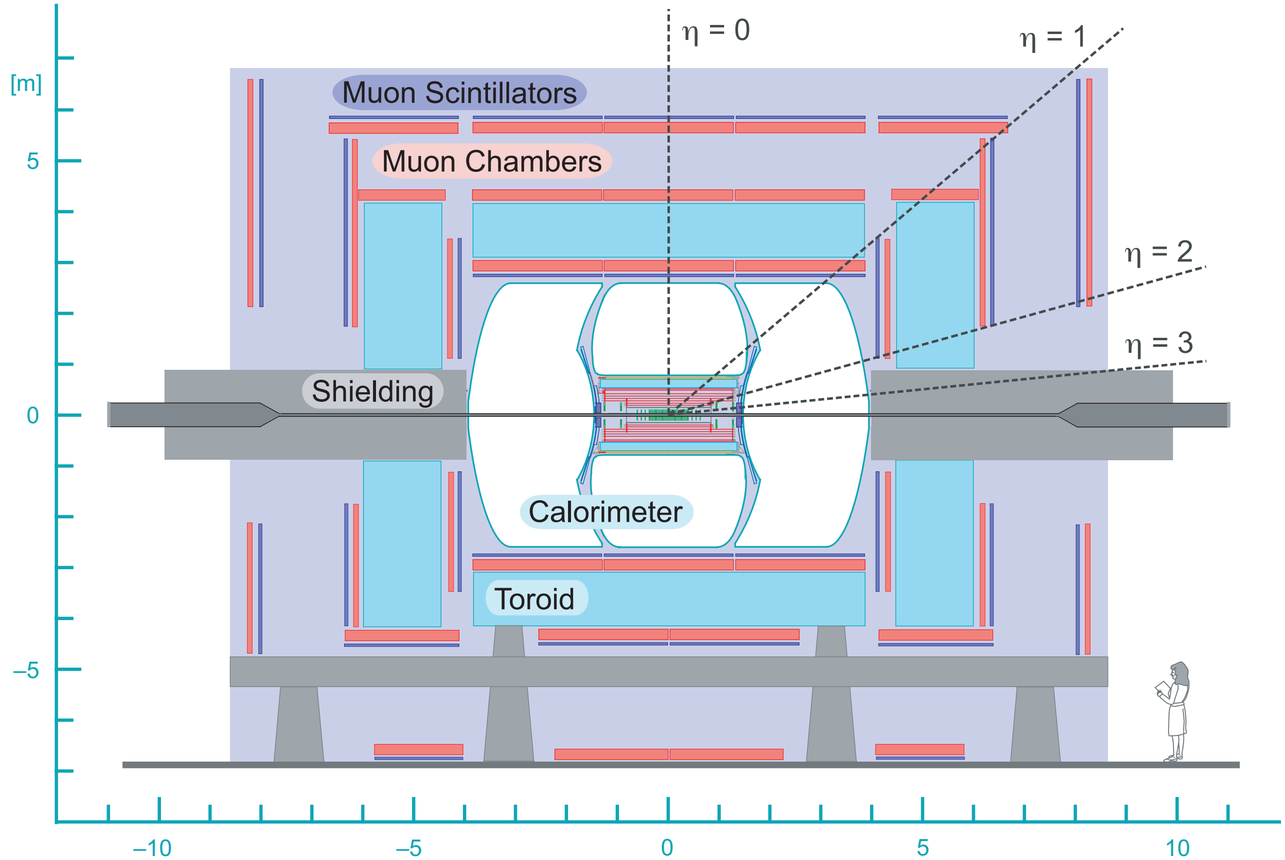
Study B-meson decays for which the Standard Model predicts small CP violation while model extensions allow for large CPV effects

- A_{CP} in $B^+ \to J/\psi K^+$
  (direct CPV)
- A^s_{SL} from $B^0_s \to D_s \mu\nu$
  (CPV in mixing)
- CPV in $B_s \to J/\psi\phi$
  (CPV in the mixing-decay interference)

DØ Detector

Multi-purpose detector at the FNAL Tevatron collider

- Excellent muon coverage and trigger
- Clean muon ID
- Solenoid and toroid
- Magnet polarity regularly reversed
- Vertex detector



A_{CP} in $B^+ \to J/\psi K^+$ (Direct CPV)

- $A_{CP} = \frac{N(B^- \to J/\psi K^-) \; - \; N(B^+ \to J/\psi K^+)}{(\qquad) + (\qquad)}$

- Predicted small ($\approx 3 \cdot 10^{-3}$) in the SM

- Some models predict a higher (10^{-2}) asymmetry

  W.S.Hou et al, arXiv:hep-ph/0605080

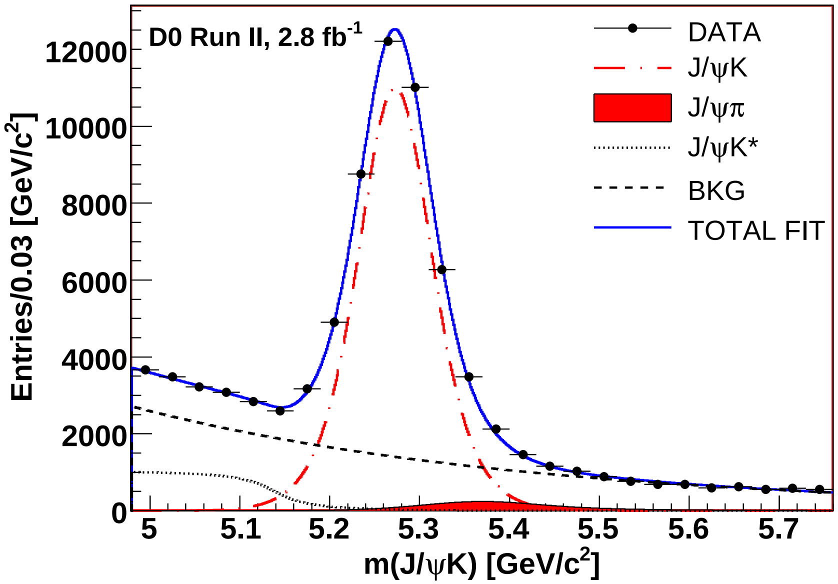
  – Flavor-violating Z'

  – 4th generation

- Precision of $\mathcal{O}(10^{-3})$ required

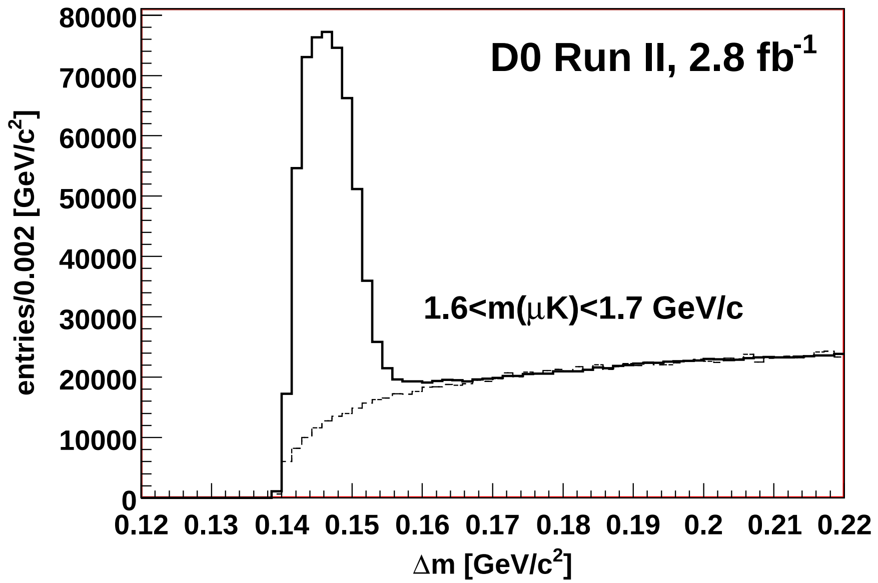
A_{CP} in $B^+ \to J/\psi K^+$ (Direct CPV)

- 40,000 signal events in 2.8 fb^{-1}
- Magnet polarity reversals to measure effects of detector asymmetries
  found to be consistent with zero
  but they are *measured*
  - no relying on assumptions
- A thorough study of the difference between K^+ and K^- interactions with detector material



- DØ: $+0.0075 \pm 0.0061(stat) \pm 0.0027(syst)$ PRL 100, 211802 (2008)
  WA: $+0.017 \pm 0.016$ (B factories+LEP)

$B^+ \to J/\psi K^+$: Kaon Detection Asymmetry



- $\sigma(K^- N) > \sigma(K^+ N)$
  (no $K^+ N$ analog to $K^- N \to Y\pi$)
  Reconstruction efficiency of K^- is lower
  Requires a correction to A_{CP}

- Hard to model, use data
  Select $D^* \to D^0\pi$; $D^0 \to \mu^+\nu K^-$
  $\approx 10^7$ events
  D^* detected as a peak in $\Delta M = m(\mu K\pi) - m(\mu K)$
  width dependent on $m(\mu K)$

- Measure the K^- - K^+ asymmetry vs $p_T(K)$
  Use a weighted average $A_K = -0.0145 \pm 0.0010$ to correct A_{CP}

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

2×2 Schrödinger equation, complex 2×2 matrices M_s and Γ_s

3 physics quantities:

$$|M_{12}|, \quad |\Gamma_{12}|, \quad \phi_s = \arg(-\frac{M_{12}}{\Gamma_{12}})$$

2 mass eigenstates, with masses $M_{L,H}$ and widths $\Gamma_{L,H}$

Measured quantities:

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

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

$$A_{\rm SL}^s = Im\frac{\Gamma_{12}}{M_{12}} = |\frac{\Gamma_{12}}{M_{12}}| \sin\phi_s$$

CPV in B_s Decays

Standard Model predicts very small CP violation in B_s mixing (A. Lenz and U. Nierste, arXiv:hep-ph/0612167)

i.e. mass eigenstates are nearly orthogonal and pure CP states.

$$|\Gamma_{12}| = 0.096 \pm 0.039 ps^{-1}$$

$$A^s_{\mathrm{SL}}(SM) = |\frac{\Gamma_{12}}{M_{12}}| \sin\phi_s(SM) \approx 2 \cdot 10^{-5}$$

$$\phi_s(SM) = \mathcal{O}(|V_{us}|^2 \frac{m_c^2}{m_b^2}) \approx 4 \cdot 10^{-3}$$

Sensitivity to New Physics!

$$\phi_s = \phi_s(SM) + \phi_s^{\Delta}$$

Semileptonic Charge Asymmetry A_{SL}^{s}

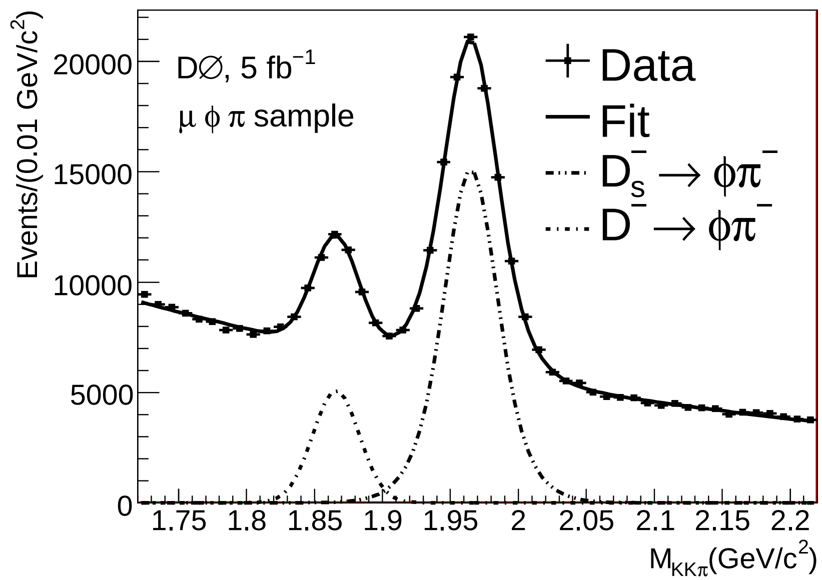
- Measure difference in mixing rate for B_s and $\overline{B}_s$ (asymmetry in the "wrong-sign" semileptonic decays induced by oscillations)

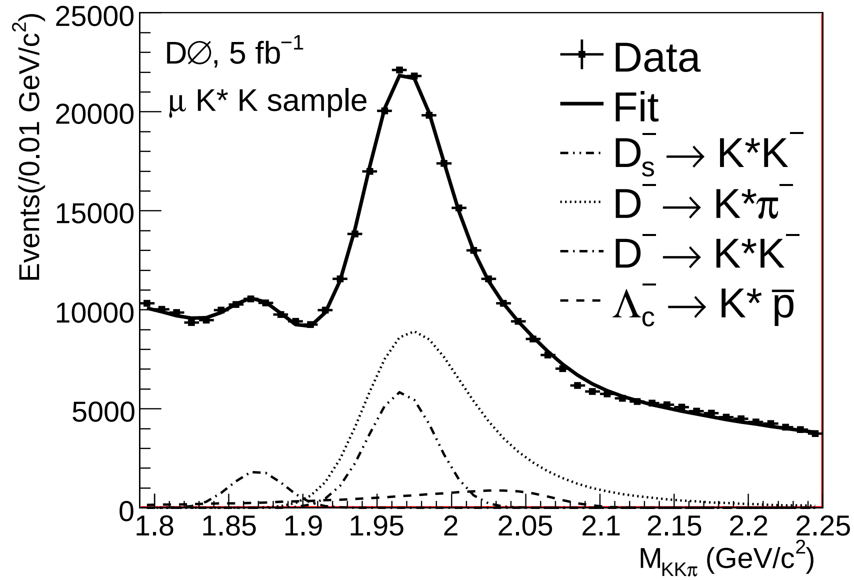
- Use $B_s \to D_s \mu X$ with $D_s \to \phi\pi$ ≈ 81000 events and $D_s \to K^* K$ ≈ 33000 events

- Use flavor tag when available

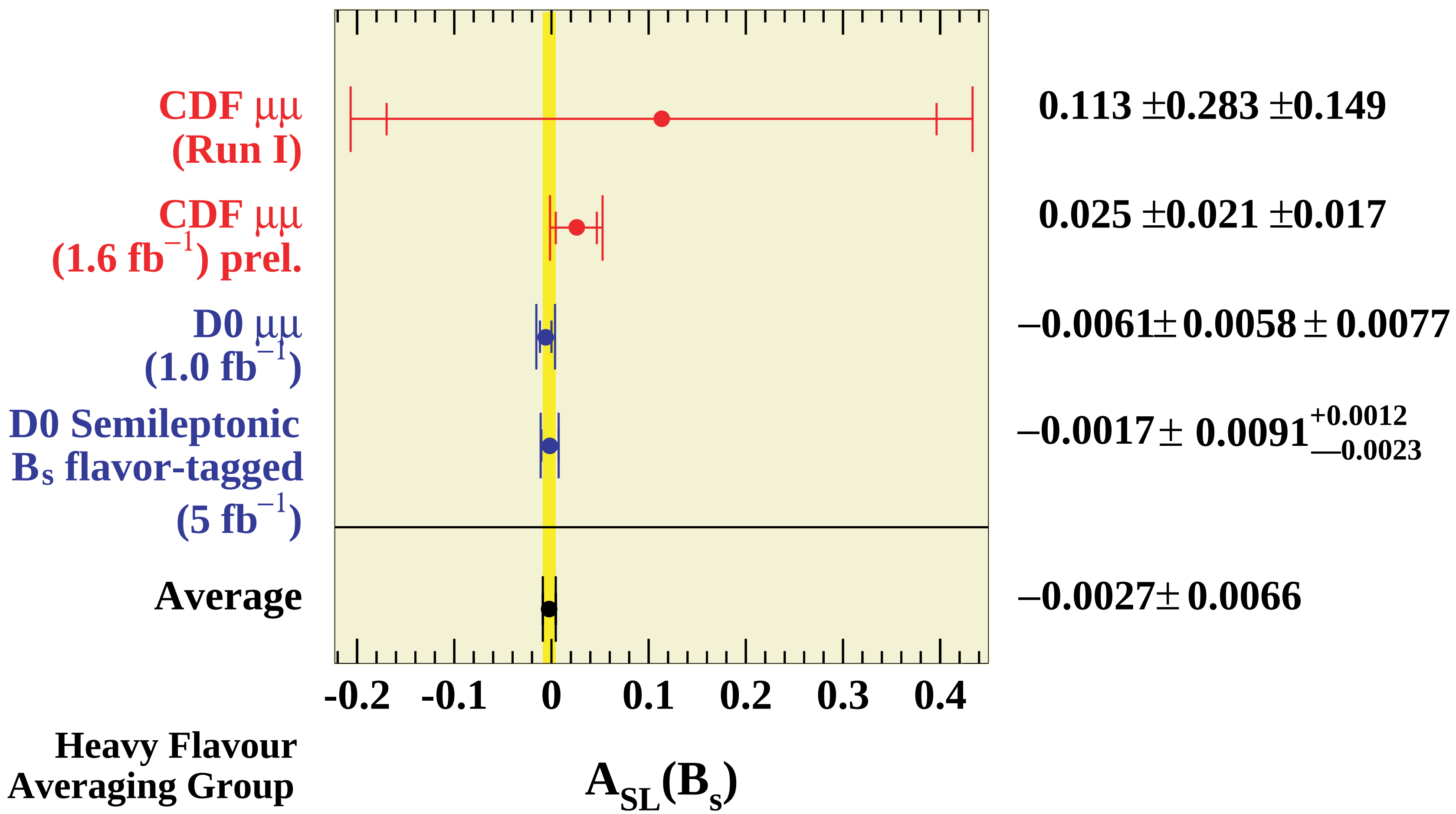
- Result: $A_{SL}^{s} = -0.0017 \pm 0.0091^{+0.012}_{-0.023}$

arXiv:hep-ex/0904.3907





All A^s_{SL} Results



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

$B_s^0 \to J/\psi\phi$
$P \to VV$ (reminiscent of $\pi^0 \to \gamma\gamma$ but massive particles)

Decompose decay amplitude into 3 components corresponding to 3 polarization states: longitudinal, transverse and mutually parallel, and transverse and mutually perpendicular:
A_0, $A_\parallel$ (CP-even), and $A_\perp$ (CP-odd)

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2 amplitudes: $B_s^0 \to J/\psi\phi$ and $B_s^0 \to \overline{B}_s^0 \to J/\psi\phi$

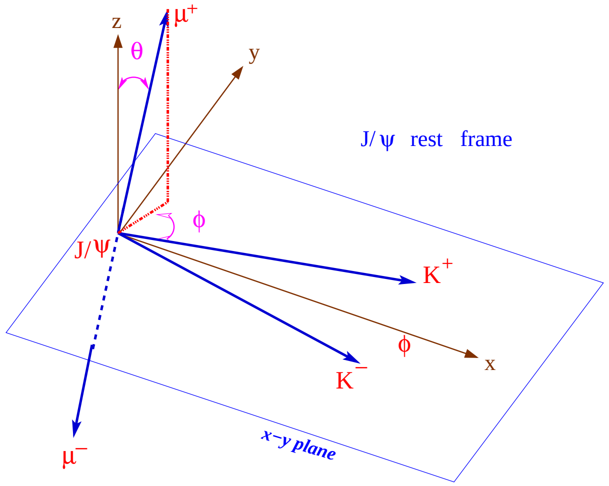
Time-dependent CP violation if the relative phase of the decay and mixing amplitudes $\phi_s^{J/\psi\phi}$ is nonzero

L and H mass eigenstates have both CP components
$< CP >$ from an initial pure B_s^0 or pure $\overline{B}_s^0$ state oscillates with a mixing frequency ΔM_s

Time-dependent Angular Distribution

$\frac{d^4\Gamma}{dt\,d\cos\theta\,d\varphi\,d\cos\psi} \propto$ I. Dunietz, R. Fleischer, and U. Nierste, Phys. Rev. D **63**, 114015 (2001)

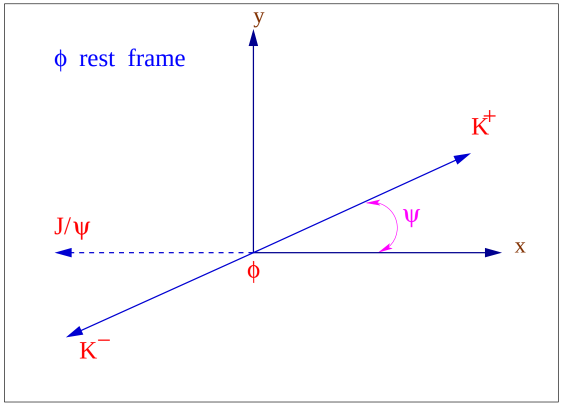
$$2\cos^2\psi(1-\sin^2\theta\cos^2\varphi)|A_0(t)|^2$$
$$+\sin^2\psi(1-\sin^2\theta\sin^2\varphi)|A_\parallel(t)|^2$$
$$+\sin^2\psi\sin^2\theta|A_\perp(t)|^2$$
$$+(1/\sqrt{2})\sin 2\psi\sin^2\theta\sin 2\varphi\mathrm{Re}(A_0^*(t)A_\parallel(t))$$
$$+\ (1/\sqrt{2})\sin 2\psi\sin 2\theta\cos\varphi\mathrm{Im}(A_0^*(t)A_\perp(t))$$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



$$|A_{0,\parallel}(t)|^2 = |A_{0,\parallel}(0)|^2[\mathcal{T}_+ \pm e^{-\overline{\Gamma}t}S\ \sin(\Delta M_s t)]$$
$$|A_\perp(t)|^2 = |A_\perp(0)|^2[\mathcal{T}_- \mp e^{-\overline{\Gamma}t}S\ \sin(\Delta M_s t)]$$
$$\mathcal{T}_\pm = (1/2)[(1\pm C)e^{-\Gamma_L t} + (1\mp C)e^{-\Gamma_H t}]$$
$$S = \sin(\phi_s^{J/\psi}),\ \text{and}\ C = \cos(\phi_s^{J/\psi})$$

(upper/lower sign for the initial $B/\overline{B}$)

$$\phi_s^{J/\psi\phi} = 2\arg[-V_{tb}V_{ts}^*/V_{cb}V_{cs}^*] + \phi_s^\Delta$$
$$= -0.04 + \phi_s^\Delta$$



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

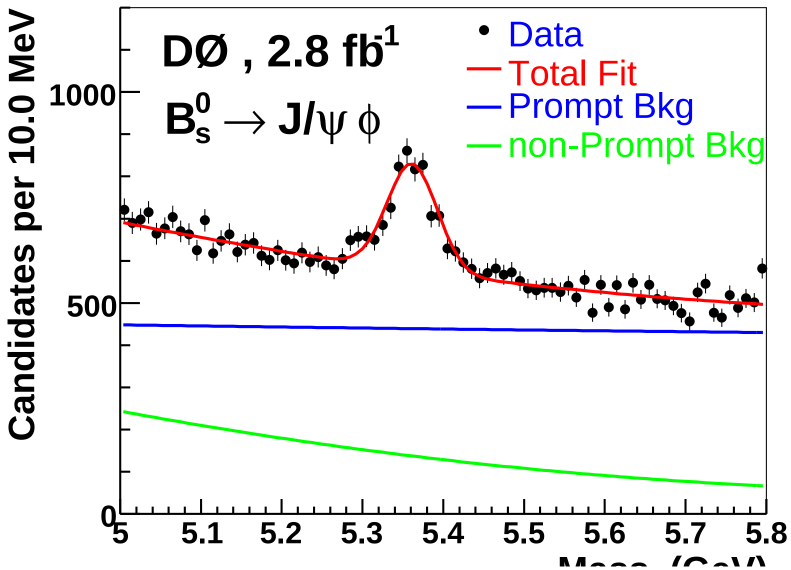
- Reconstruct $B_s^0 \to J/\psi\phi$, $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- Tag the initial flavor
- Perform maximum likelihood fitting to extract physics parameters: $\phi_s^{J/\psi\phi}$, $\Delta\Gamma_s$, $\overline{\tau}_s$, and the complex polarization amplitudes A_0, $A_\parallel$, and $A_\perp$ at $t = 0$
  using $\Delta M_s = 17.77 \pm 0.12\ \text{ps}^{-1}$ as measured by CDF
- Signal: $\frac{d^4\Gamma}{dt d\cos\theta d\varphi d\cos\psi}$ (sculpted by detector acceptance)
- Background: polynomials/exponentials/Gaussians describing distributions in mass, angles, proper decay time, for the "prompt" and "non-prompt" bkg separately
- A total of 33 free parameters
- Correct for non-Gaussian uncertainties, systematic effects

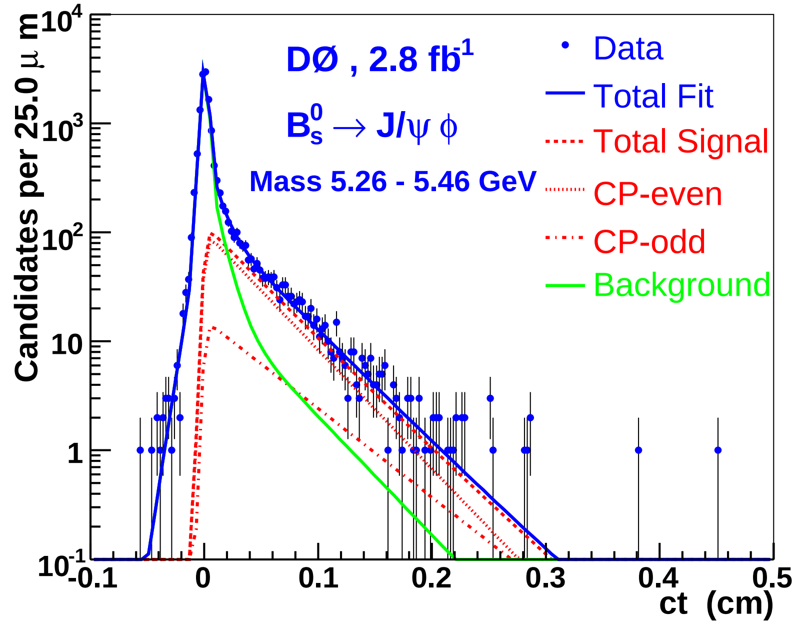
$B_s^0 \to J/\psi\phi$ Data

- Select candidates
  $B_s^0 \to J/\psi\phi$
  $J/\psi \to \mu^+\mu^-$, $\phi \to K^+K^-$
- apply kinematic
  and vertex quality cuts

  $\approx$ 48,000 events
  $\approx$ 2,000 signal events

Large bkg but mostly "prompt"
The prompt peak provides
in situ calibration of $\sigma(t)$
High signal purity at $ct > 100\ \mu$m





Flavor Tagging

- The flavor of the B_s meson at production is determined by combining information from several algorithms
  - Opposite-side tag
    calibrated with $B_s \to \mu\nu D_s$, verified with $B \to J/\psi K$ and with MC
    - muon or electron
    - Charge of the opposite-side vertex
    - Total charge of the opposite-side jet
  - Same-side tag: Charge of a track closest to B_s
    Calibrated with MC
- Effective tagging power

$$P = \epsilon \cdot \mathcal{D}^2 = (4.68 \pm 0.54)\% \qquad \mathcal{D} = \frac{N_{\mathrm{correct}} - N_{\mathrm{wrong}}}{N_{\mathrm{correct}} + N_{\mathrm{wrong}}}$$

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

Loose δ_i constraints to $B_d \to J/\psi K^*$ values

$$\overline{\tau}(B_s^0) = 1.52 \pm 0.06(stat)\ \text{ps}$$

$$\Delta\Gamma_s = 0.19 \pm 0.07(stat)\ \text{ps}^{-1}$$

$$\phi_s^{J/\psi\phi} = -0.57^{+0.24}_{-0.30}(stat)$$

Free δ_i

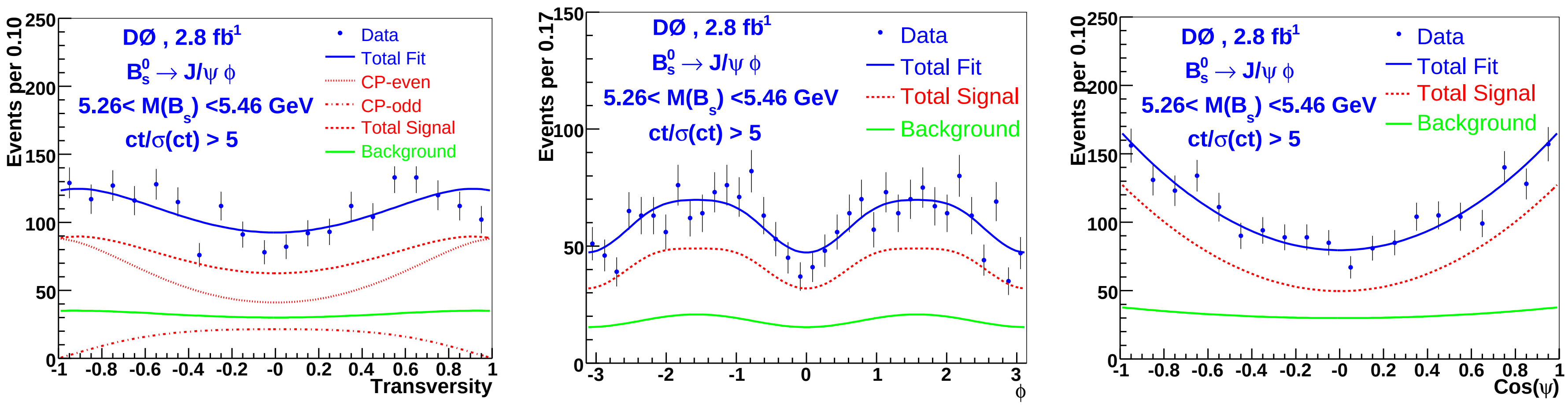
$$\overline{\tau}(B_s^0) = 1.52 \pm 0.06(stat)\ \text{ps}$$

$$\Delta\Gamma_s = 0.20^{+0.06}_{-0.08}(stat)\ \text{ps}^{-1}$$

$$\phi_s^{J/\psi\phi} = -0.59^{+0.31}_{-0.28}(stat)$$

(and $\Delta\Gamma_s \to -\Delta\Gamma_s$, $\phi_s^{J/\psi\phi} \to \pi - \phi_s^{J/\psi\phi}$)

PRL. 101, 241801 (2008)



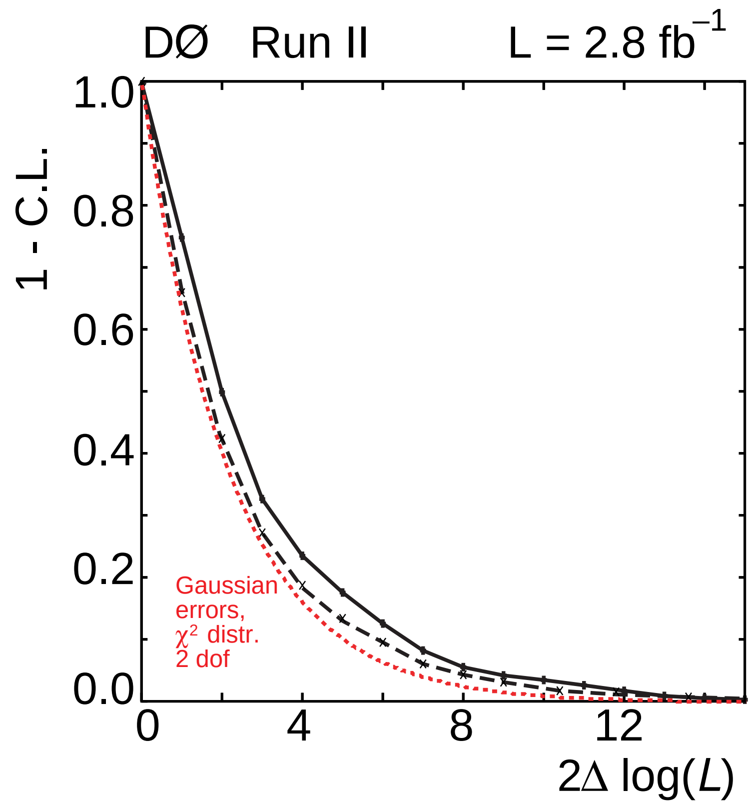
Non-Gaussian Uncertainties

The likelihood value at each point in the $\Delta\Gamma_s$ vs $\phi_s^{J/\psi\phi}$ plane must be adjusted for non-Gaussian behavior

To determine the correspondence between (1 - CL) and $2\Delta log(L)$, 2,000 pseudo-experiments with DØ statistics are generated

To account for systematic effects, alternative (1 - CL) vs $2\Delta log(L)$ curves are obtained for a number of "alternative universes", generated with a variation of flavor tagging dilution and detector acceptance parameters.

The most conservative value (the largest (1 - CL)) is taken at a given $2\Delta log(L)$



solid line: 1-CL with systematics

Results: CL at a grid of points $(\phi_s^{J/\psi\phi}, \Delta\Gamma_s)$ with info on $\overline{\tau}_s$, $A_\perp$, δ_i

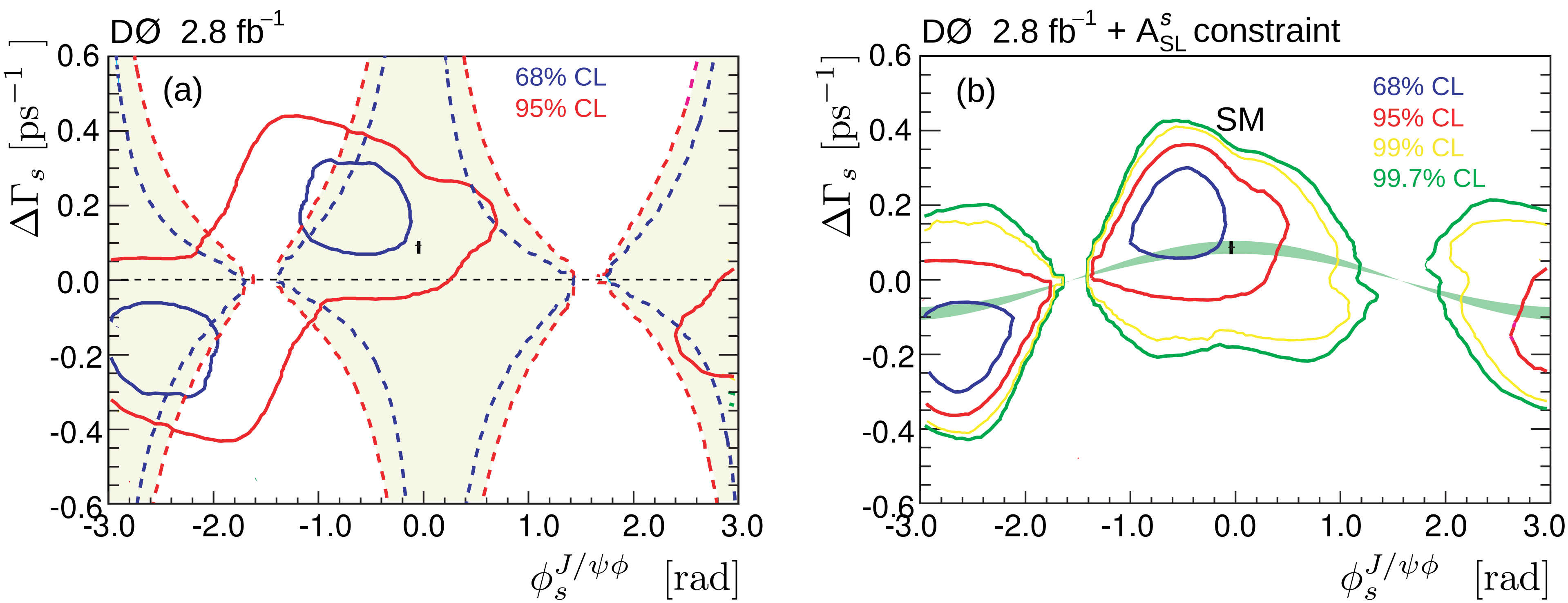
$\Delta\Gamma_s$ vs $\phi_s^{J/\psi\phi}$

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

With $A_{SL}^s = -0.0027 \pm 0.0066$

SM p-value = 24%

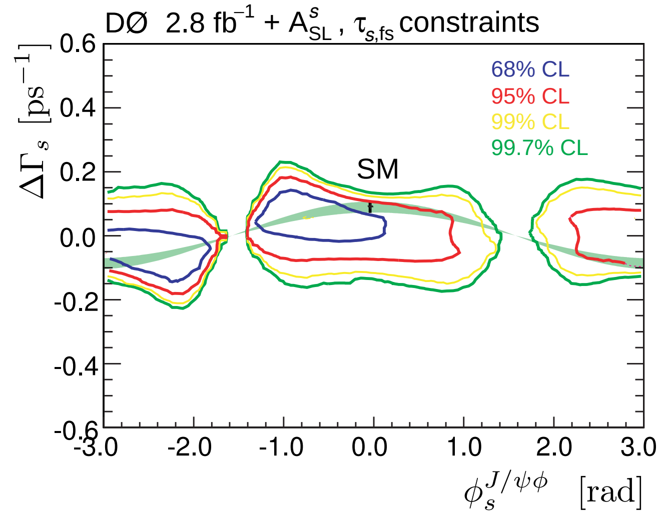
Conference Note 5933-CONF



$\Delta\Gamma_s$ vs $\phi_s^{J/\psi\phi}$ with Additional Constraints

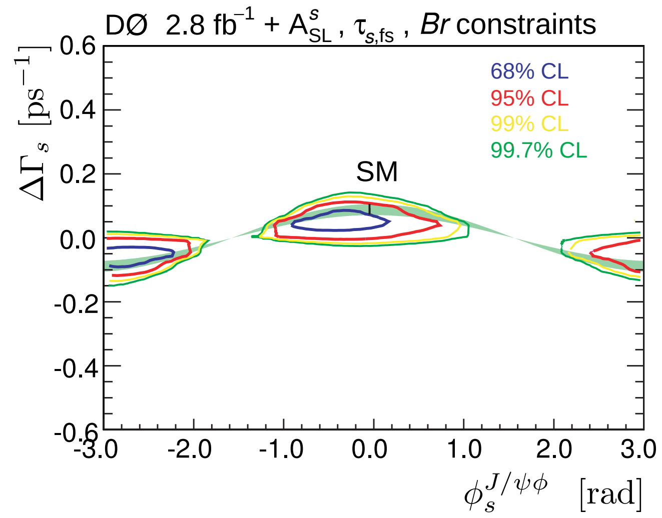
$B_s^0 \to J/\psi\phi$ (DØ)
$+A_{SL}^s + \tau_s(SL)$ (World Average)

SM p-value = 12%



$B_s^0 \to J/\psi\phi$
$+A_{SL}^s + \tau_s(SL) +$
$\mathcal{B}(B_s \to D_s^{(*)+} D_s^{(*)-})$ (DØ)

SM p-value = 10%

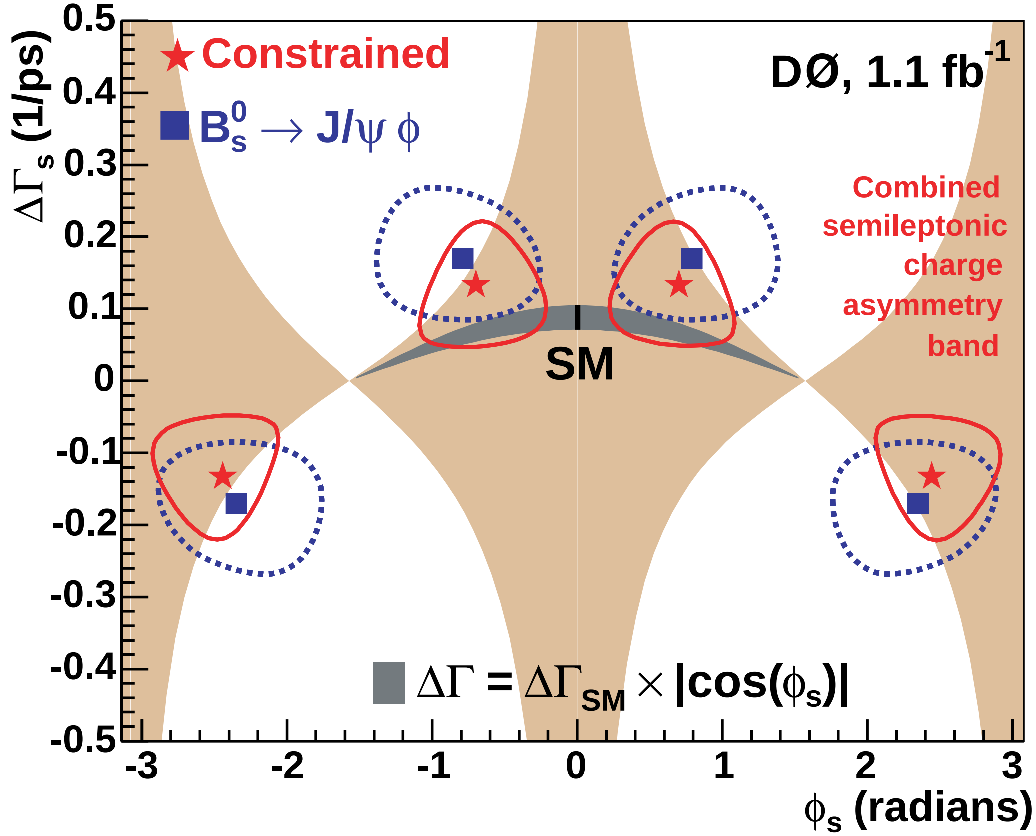


Summary

- Significant results on CP symmetry in B decays
- $A_{CP}(B^+ \to J/\psi K^+) = +0.0075 \pm 0.0061(stat) \pm 0.0027(syst)$
  uncertainty half that of the previous world average
- $A^s_{SL} = -0.0017 \pm 0.0091^{+0.012}_{-0.023}$
  best measurement
- Constraining $\Delta\Gamma_s$ vs $\phi_s^{J/\psi\phi}$; SM p-value = 10% (stat. limited)
- Combine with CDF results for Tevatron average (see G. Punzi talk)
- Good prospects; $\times(3-4)$ more data by the end of the run
  expected to run through 2011

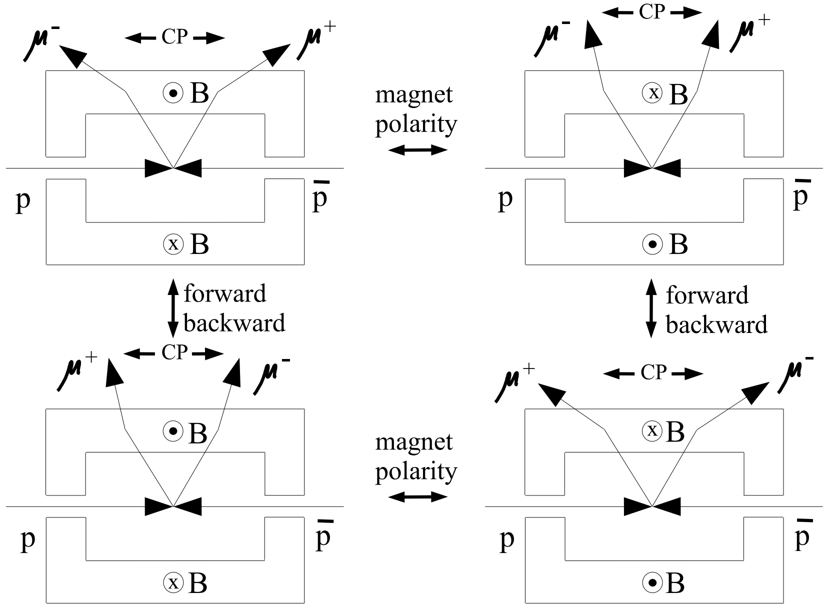
History of $\Delta\Gamma_s$ vs $\phi_s^{J/\psi\phi}$ Measurements at DØ

- *Untagged* $B_s^0 \to J/\psi\phi$ events
  4-fold ambiguity
  1.1 fb^{-1}
  PRL 98, 121801 (2007)
- Combination with A_{SL}^s
  Phys. Rev. D 76, 057101 (2007)



Backup

Reversing Toroid Polarity



- Different detector geometry/total material along the trajectory of a +ve and -ve muon
- Trajectory of μ^+ = trajectory of μ^- with a reversed toroid polarity