Measurement of CP-violating phase ϕ_s at DØ

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http://www-d0.fnal.gov/~rakitin/DPF06.pdf

B_s Meson System

Schrödinger equation:

$$i\frac{d}{dt}\begin{pmatrix}|\overline{B_S}(t)\rangle \\ |B_S(t)\rangle\end{pmatrix} = (M - \frac{i}{2}\Gamma)\begin{pmatrix}|\overline{B_S}(t)\rangle \\ |B_S(t)\rangle\end{pmatrix}$$

$$\Longrightarrow \begin{matrix}|B_{S,H}\rangle = p|B_S(t)\rangle - q|\overline{B_S}(t)\rangle \\ |B_{S,L}\rangle = p|B_S(t)\rangle + q|\overline{B_S}(t)\rangle\end{matrix}$$

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

– $\Delta\Gamma_s = \Gamma_L - \Gamma_H \approx 2|\Gamma_{12}^s|\cos\phi_s$,

where $\phi_s = \arg\left(-\frac{M_{12}^s}{\Gamma_{12}^s}\right)$ – CP-violating phase

Semileptonic Asymmetry a_{SL}

- Assume flavor-specific decay $B_s \to f$ ($\overline{B_s} \to \bar{f}$), *e.g.* semileptonic $B_s \to \ell \overline{\nu_\ell} X$:
  $\Longrightarrow$ No "wrong-sign" decays $\langle \bar{f} | B_s \rangle = \langle f | \overline{B_s} \rangle = 0$
- Assume no direct CP-violation in $b \to c$, *i.e.* $\Gamma(B_s \to f) = \Gamma(\overline{B_s} \to \bar{f})$
- Then a good quantity to characterize CP-violation in B-mixing is the asymmetry:

$$a_{SL} = \frac{\Gamma(\overline{B_S}(t) \to f) - \Gamma(B_S(t) \to \bar{f})}{\Gamma(\overline{B_S}(t) \to f) + \Gamma(B_S(t) \to \bar{f})} = \mathrm{Im}\, \frac{\Gamma_{12}^S}{M_{12}^S} = \frac{\Delta\Gamma_S}{\Delta M_S} \tan\phi_s$$

- Within SM, non-zero a_{SL} corresponds to CP-violation in mixing - this mode not yet observed in B decays!

a_{SL} – Probe for New Physics

a_{SL} is small:

– Magnitude $|\Gamma^s_{12}/M^s_{12}| = O(m_b^2/m_t^2) << 1$ – model independent

– Phase $\arg(\Gamma^s_{12}/M^s_{12}) = O(|V_{us}|^2 m_c^2/m_b^2) << 1$ – in SM only

$\Longrightarrow |V_{us}| = \lambda = 0.22$ – Wolfenstein CKM parameter

- Γ^s_{12} governs decays (tree-level) – not sensitive to New Physics
- M^s_{12} governs oscillations (loop-level) – sensitive to New Physics (*e.g.* squark - gluino loops in SUSY)
- New Physics can change the phase of M^s_{12} thus increasing a_{SL}

a_{SL} is sensitive to New Physics

Integrated Asymmetry A_{SL}

- Measurement of a_{SL} does not demand initial state flavor tagging or resolution of fast B_s-$\overline{B_s}$ oscillations
- Can use untagged decay rate $\Gamma^{unt}(B_s \to f) = \Gamma(\overline{B_s} \to B_s \to f) + \Gamma(B_s \to f)$
- Time-integrated asymmetry:

$$A_{SL} = \frac{\int \Gamma^{unt}(\overline{B_S}(t) \to f)dt - \int \Gamma^{unt}(B_S(t) \to \bar{f})dt}{\int \Gamma^{unt}(\overline{B_S}(t) \to f)dt + \int \Gamma^{unt}(B_S(t) \to \bar{f})dt} = \frac{1}{2} a_{SL} \frac{x_S^2 + y_S^2}{1 + x_S^2} \approx \frac{1}{2} a_{SL},$$

where $x_s = \Delta M_S / \Gamma_S >> 1, y_S = \Delta\Gamma_S / (2\Gamma_S) < 1$ [Nierste,hep-ph/0406300]

Experimentally $A_{SL} = \frac{N(B_S \to \ell^+ X) - N(B_S \to \ell^- X)}{N(B_S \to \ell^+ X) + N(B_S \to \ell^- X)}$ – lepton charge asymmetry

of semileptonic B_s decays

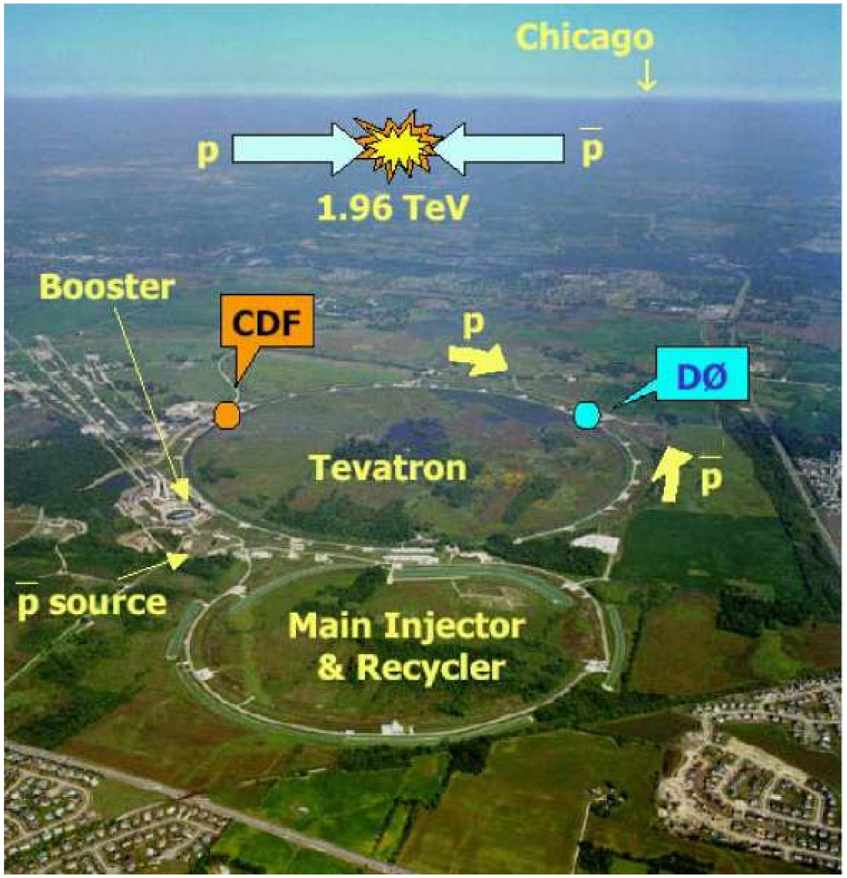
Measurement of ϕ_s

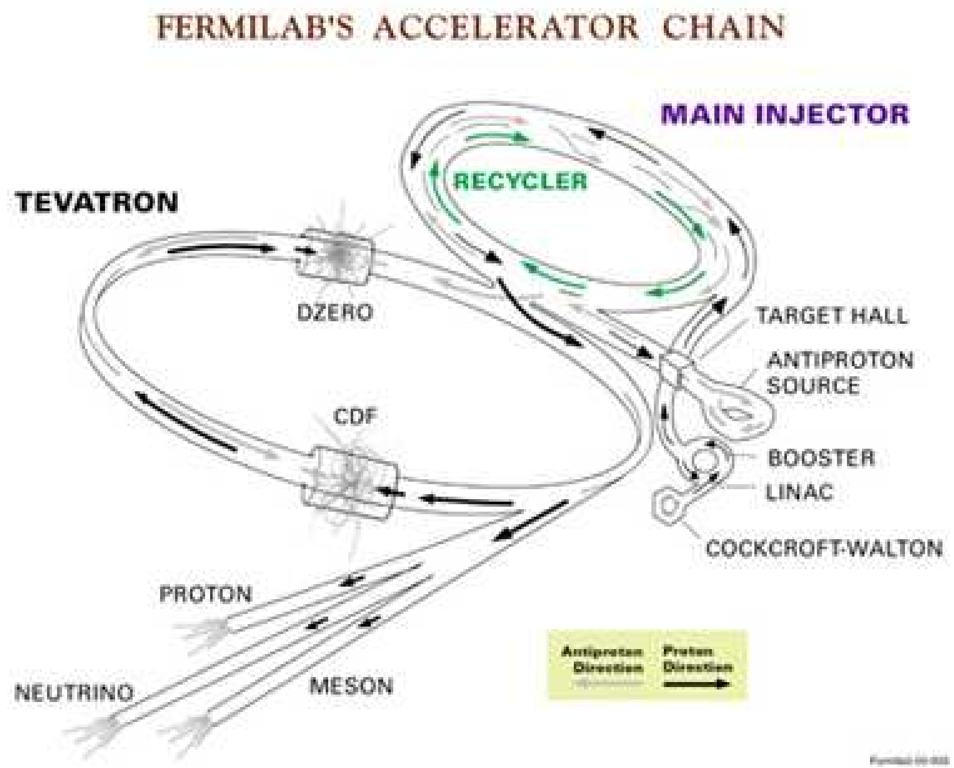
I am going to talk about three different constraints on ϕ_s:

- From dimuon asymmetry $A_{SL} = \dfrac{N(b\bar{b}\to\mu^+\mu^+X) - N(b\bar{b}\to\mu^-\mu^-X)}{N(b\bar{b}\to\mu^+\mu^+X) + N(b\bar{b}\to\mu^-\mu^-X)}$
- From B_s semileptonic asymmetry $A^s_{SL} = \dfrac{N(B_S\to\mu^+D_S^-X) - N(B_S\to\mu^-D_S^+X)}{N(B_S\to\mu^+D_S^-X) + N(B_S\to\mu^-D_S^+X)}$
- From time dependent polarization amplitudes in $B_s \to J/\psi\phi$ decay

All three measurements have been performed at DØ experiment at Tevatron

Tevatron Collider at Fermilab

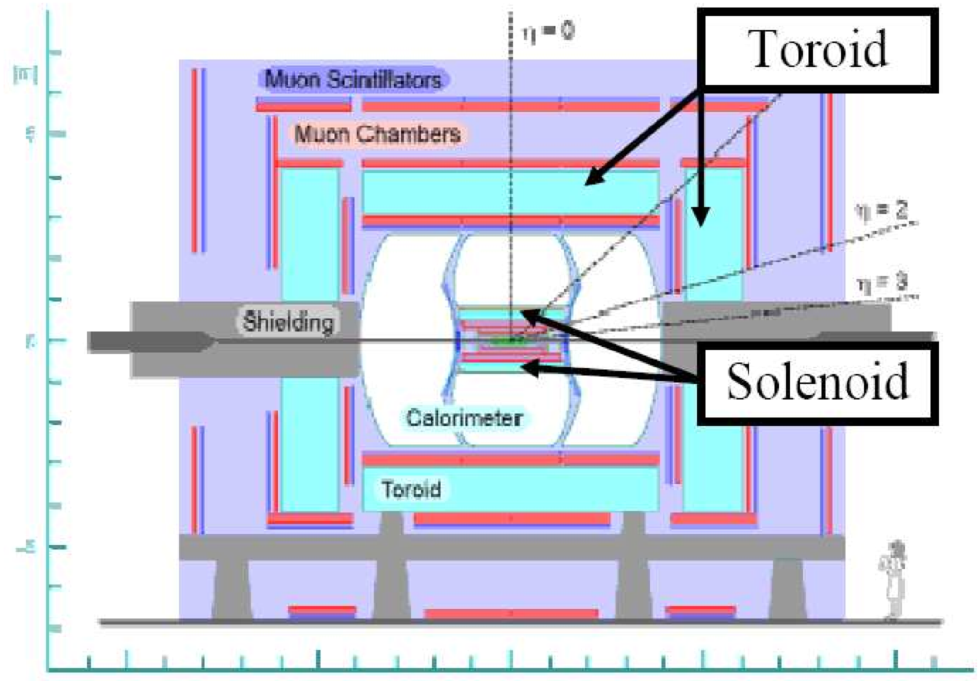




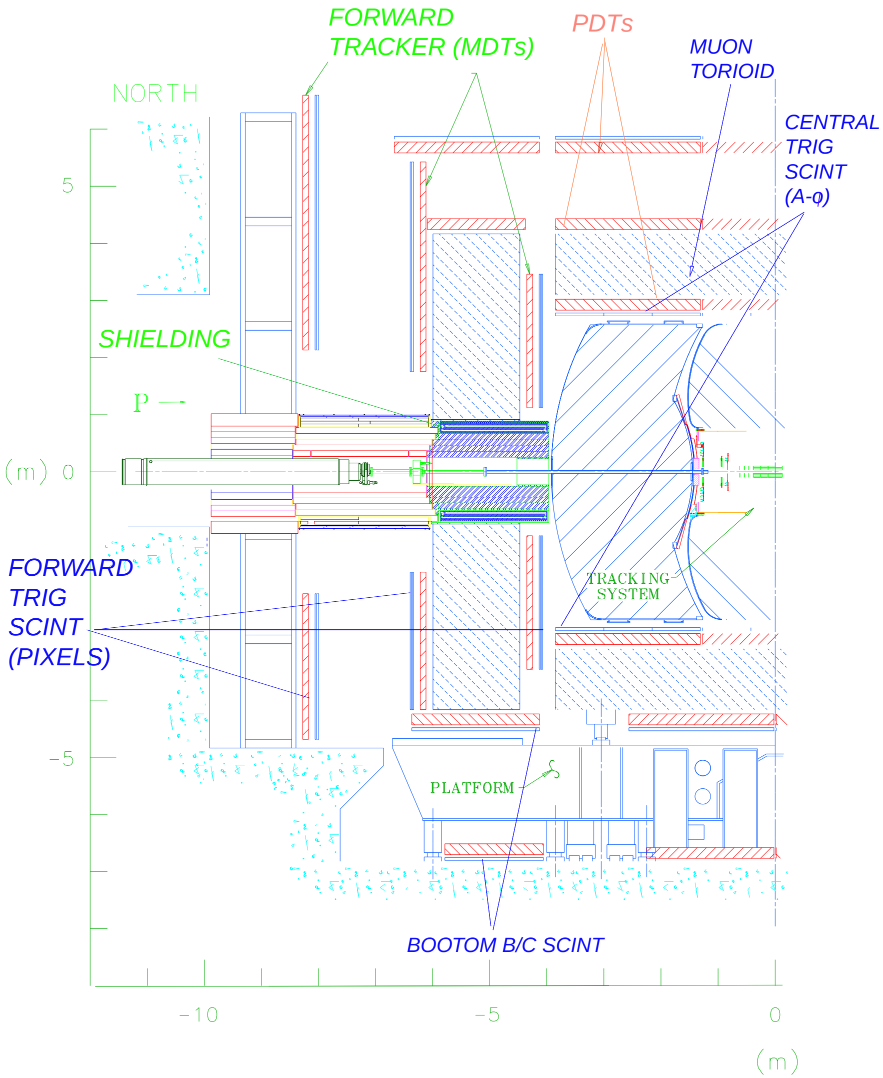
- 36×36 $p\bar{p}$ bunches, 10^{12} (10^{10}) p ($\bar{p}$) per bunch
- Bunches collide every 396 ns at CM energy 1.96 TeV
- Record $\mathcal{L}_{inst} = 1.72 \times 10^{32}$ cm^{-2} sec^{-1}
- $\int \mathcal{L} dt = 27$pb^{-1}/week
- Total integrated $\mathcal{L} > 1.4$ fb^{-1} ($\sim$1.3 fb^{-1} on tape, $\sim$330-1300 pb^{-1} used)
- High Energy Physics Frontier until LHC turn-on

DØ Detector

- Multi-purpose detector
- Silicon and fiber tracker in 2 T solenoid, coverage $|\eta| < 3$
  - Huge tracking density capability
  - Precise vertexing and tracking
- Calorimeter (EM + hadronic), coverage $|\eta| < 4.2$
- Muon system (central + forward), coverage $|\eta| < 2$
  - Very low punch-through
  - Strong suppression of cosmic background
- Two magnets – solenoid and toroid

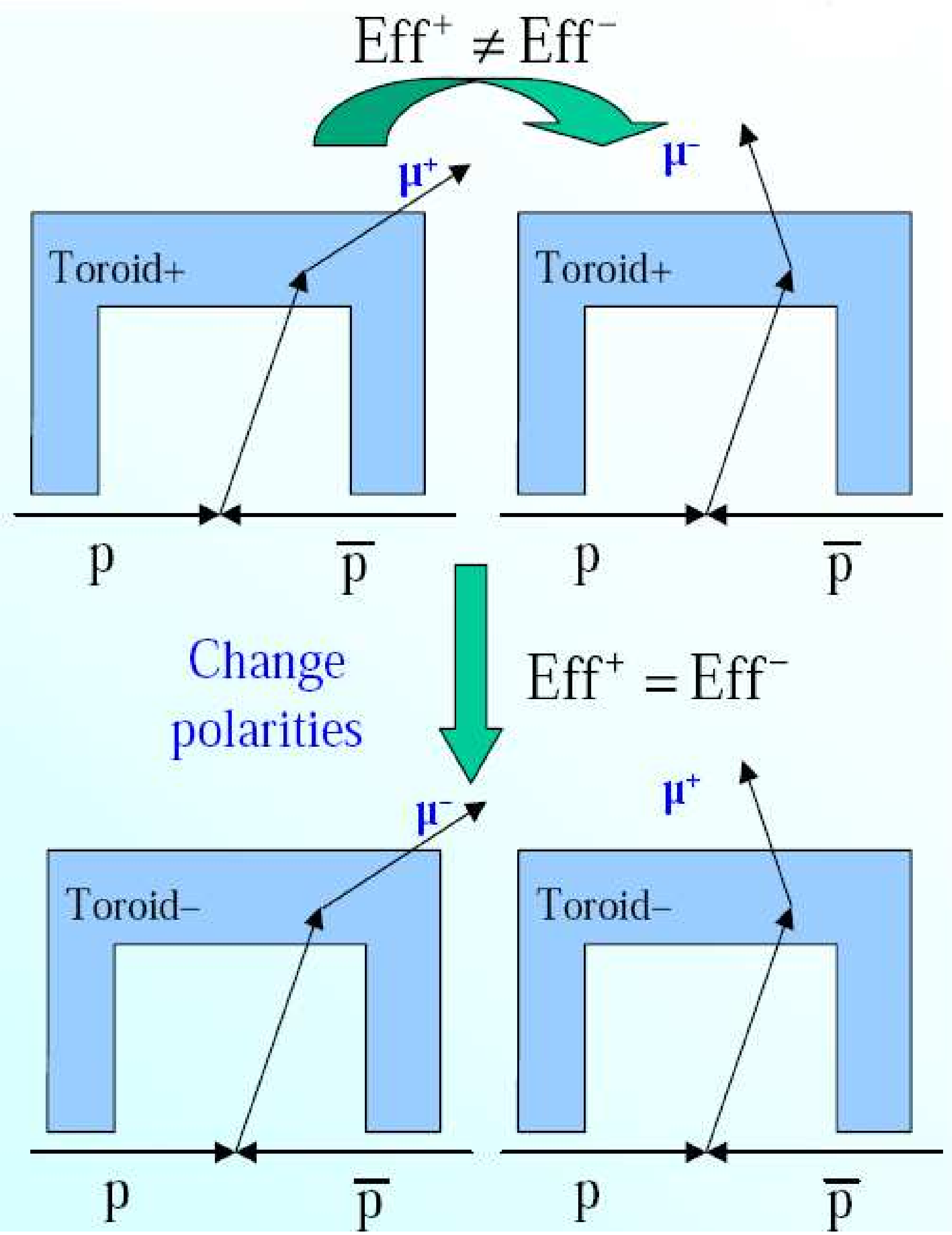


DØ Muon System



- ~ 5*M* dimuon events collected (1 fb^{-1})
- Detector asymmetries diminished by reversing solenoid and toroid polarities approximately once a week.

Magnet polarity



- Reversing magnet polarity helps reduce detector asymmetries in muon reconstruction
- Systematics is also diminished

Dimuon A_{SL} Measurement

(1st constraint on ϕ_s)

- Collect sample of N events with two muons of the same charge
- Divide it into 8 categories according to:
  - ☞ Toroid polarity, β
  - ☞ Sign of muon pseudorapidity, γ
  - ☞ Muon charge, q
- Number of events in each category:

$$n_q^{\beta\gamma} = \frac{1}{4} N \varepsilon^\beta (1 + qA_{SL}^{raw})(1 + \gamma A_{det})(1 + q\gamma A_{fb})(1 + q\beta A_{q\beta})(1 + \beta\gamma A_{\beta\gamma})(1 + q\beta\gamma A_{ro})$$

where

  - N - number of signal events in the sample
  - ε^β - fraction of integrated luminosity with toroid polarity β ($\varepsilon^+ + \varepsilon^- = 1$)
  - A_{SL}^{raw} - integrated raw charge asymmetry we want to measure
  - A_{fb} - detector forward-backward asymmetry (more μ go in proton direction)
  - A_{det} - north-south asymmetry of the detector
  - A_{ro} - range-out asymmetry (decrease of acceptance of μ bent towards toroid)
  - $A_{\beta\gamma}$ - detector forward-backward asymmetry remaining after toroid polarity flip
  - $A_{q\beta}$ - change in muon reconstruction effi ciency after toroid polarity flip

- Fit for 8 $n_q^{\beta\gamma} \Longrightarrow$ obtain 8 linear equations with 8 unknowns

Dimuon A_{SL} Results

Numbers of events:

Tor*Sol polarity	-1	+1
N^{++}	177,950	156,183
N^{--}	176,939	156,148
N^{+-}	1,175,547	1,029,604

Raw asymmetry:

$$A_{SL}^{raw} = -0.013 \pm 0.012(stat) \pm 0.008(syst)$$

Must be corrected for fraction of flavor-specific B decays: $A_{SL} = f \times A_{SL}^{raw}$

Using Monte Carlo:

- Signal: $\overline{b} \to \mu^+; b \to \overline{b} \to \mu^+$
- Background that dilutes asymmetry: $\overline{b} \to \mu^+; b \to c \to \mu^+$
- Background with false asymmetries: $b \to c \to K^+ \to \mu^+$
  - Reaction $K^- + N \to \text{hyperon} + \pi$ has no analog $K^+ + N$ therefore $K^+ \to \mu^+$ more often

Dimuon A_{SL} Results

Check: Measured ratio of number of same-sign B pairs to number of opposite-sign B pairs: $\chi(\text{meas. } D\text{Ø}) = 0.136 \pm 0.001 \pm 0.024$ is comparable to $\chi(PDG) = 0.1281 \pm 0.0076$

$\Longrightarrow$ So that we know that sample composition is correct

Corrected asymmetry:

$$A_{SL} = -0.0044 \pm 0.0040(stat.) \pm 0.0028(syst.)$$

(DØ Conference Note 5042)

SM loop prediction: $A_{SL} = -0.00050 \pm 0.00011$ [hep-ph/0406300]

Current precision is an order of magnitude away from SM precision.

Sample Composition

- Two different integrated asymmetries for B_d and B_s mesons – A_{SL}^d and A_{SL}^s

- In hadronic environment the measured dimuon asymmetry is some

  combination of both: $A_{SL} = \frac{f_d Z_d A_{SL}^d + f_s Z_s A_{SL}^s}{f_d Z_d + f_s Z_s} \approx 0.6 A_{SL}^d + 0.4 A_{SL}^s$,

  where $Z_q = \frac{1}{1-(\Delta\Gamma_q/2\Gamma_q)^2} - \frac{1}{1+(\Delta M_q/\Gamma_q)^2}$ [Grossman *et al.*, hep-ph/0605028]

- In $\Upsilon(4S)$ resonance $A_{SL} = A_{SL}^d$

ε_B

Observable quantities in B_s system depend on $\frac{\text{Re } \varepsilon_B}{1+|\varepsilon_B|^2}$, where $\varepsilon_B = \frac{1+q/p}{1-q/p}$

$$\frac{Re\ \varepsilon_B}{1+|\varepsilon_B|^2} = \frac{1}{4}A_{SL} = -0.0011 \pm 0.0010(stat.) \pm 0.0007(syst.)$$

OPAL 1± 14 ± 3 (2000)

ALEPH -3.2 ± 6.5 (2001)

CLEO 3.5 ± 10.3 ± 1.5 (2001)

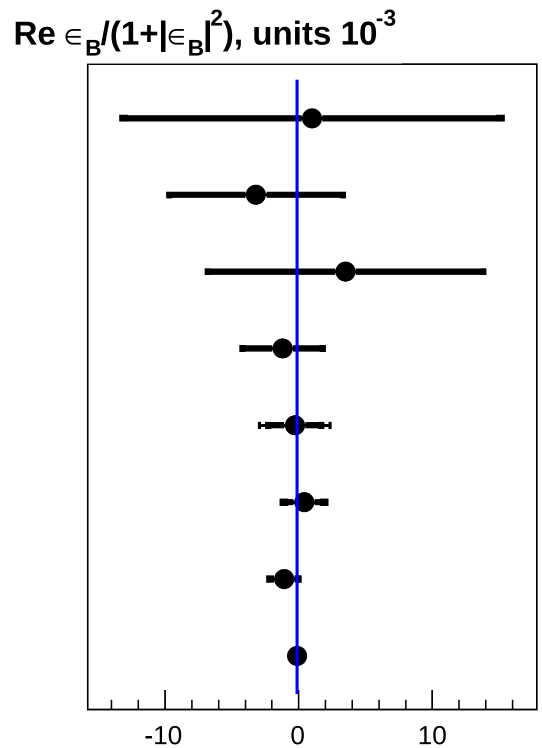
PDG -1.2 ± 3.0 (2005)

Belle -0.3 ± 2.0 ± 1.7 (2005)

BaBar 0.4 ± 1.4 ± 1.0 (2006)

D0 -1.1± 1.0 ± 0.7 (2006)

SM -0.125 ± 0.028



This plot is for illustrational purposes only, because some measurements include A_{SL}^{s} and some - do not

A_{SL}^{s} Extraction:

Knowing A_{SL} and A_{SL}^{d} one can extract A_{SL}^{s}:

- Previous measurements of A_{SL}^{d}:
  - BABAR: 0.0016 ± 0.0066 [Phys.Rev.Lett.**96**, 251802 (2006)]
  - BELLE: -0.0011 ± 0.0106 [Phys.Rev.D**73**,112002 (2006)]
  - CLEO: 0.014 ± 0.042 [Phys.Rev.Lett.**86**, 5000 (2001)]

  Average: $A_{SL}^{d} = +0.0011 \pm 0.0055$ [hep-ph/0605028]

- Hence $A_{SL}^{s} = -0.008 \pm 0.011$ [hep-ph/0605028]

- Also, $A_{SL}^{s} = \dfrac{N(B_S \to \mu^+ D_S^- X) - N(B_S \to \mu^- D_S^+ X)}{N(B_S \to \mu^+ D_S^- X) + N(B_S \to \mu^- D_S^+ X)}$ was **directly** measured at DØ (2nd measurement constraining ϕ_s)

A_{SL}^{s} Measurement

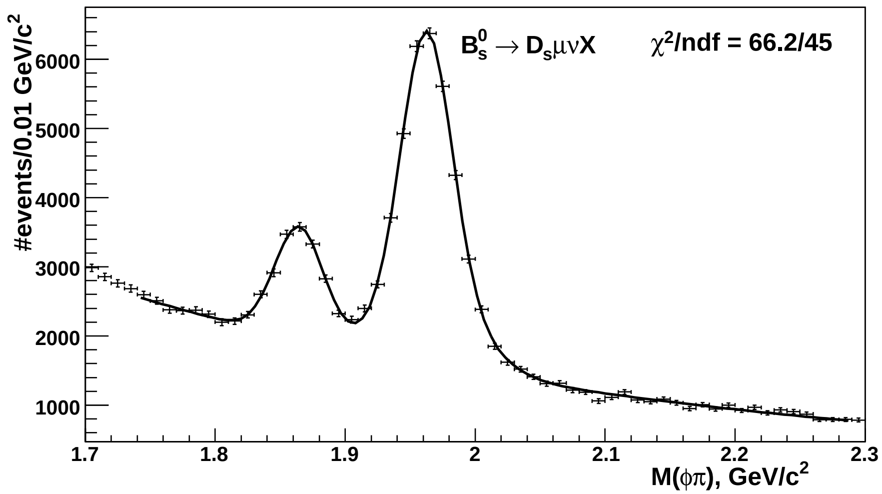
(2nd constraint on ϕ_s)

Signature: $B_s \to \mu\nu_\mu D_s, D_s \to \phi\pi, \phi \to K^+K^-$

Main cuts:

- Proper lifetime of $B_s > 0$ to reject c-$\bar{c}$ background
- Charge correlation $q_\mu \cdot q_\pi < 0$ to reject combinatorial background
- Inv. mass window $1.004\ \mathrm{GeV}/c^2 < m(K^+K^-) < 1.034\ \mathrm{GeV}/c^2$ to select ϕ events

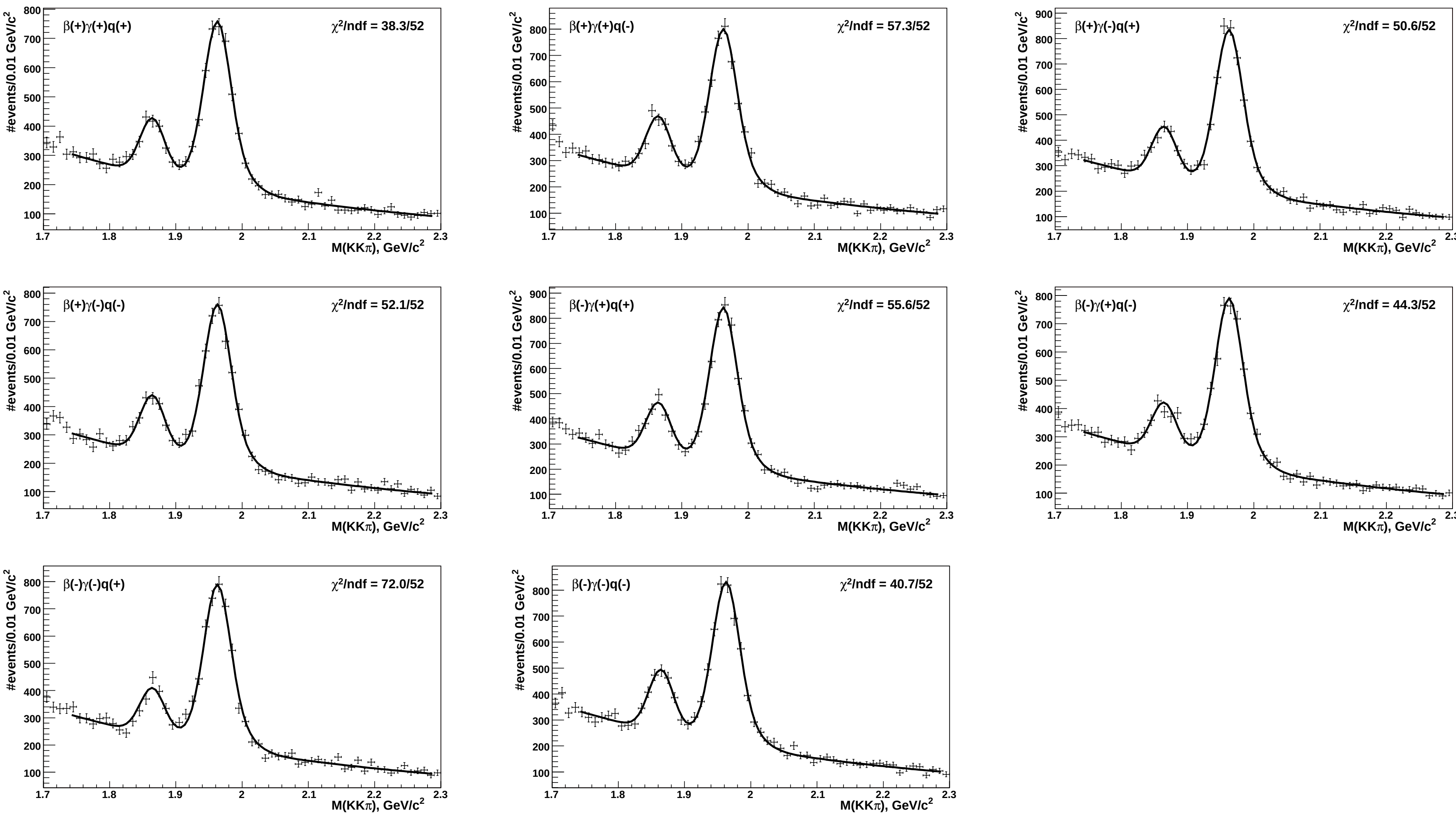
$\Longrightarrow$ 27K D_s's



Similar procedure for extracting A_{SL}^{s} with 8 linear equations and 8 unknowns

A^s_{SL} Measurement

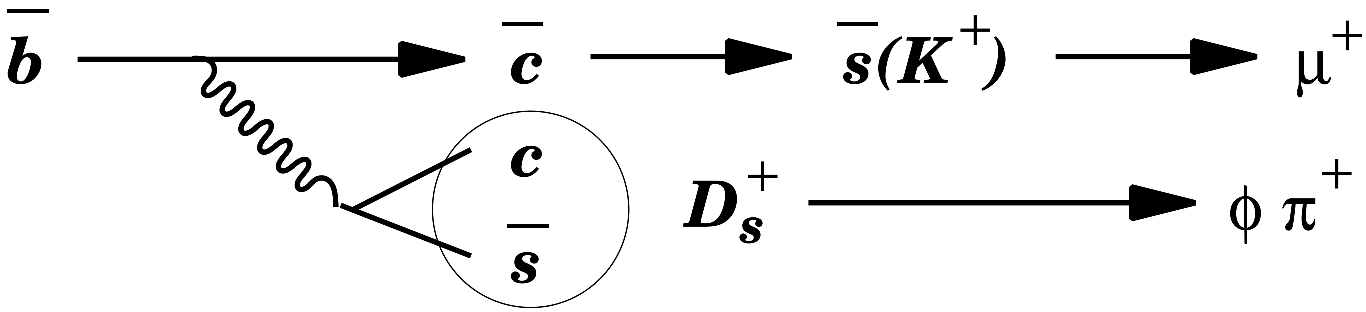
Eight sub-samples:



Fitted with fixed means and widthes of the peaks, fixed background slopes

Contributing physics asymmetries:

- Muons from charge asymmetric K decay:
  - Inelastic cross-section $\sigma(K^{-}N) > \sigma(K^{+}N)$
  - K^{+} last longer, $K^{+} \rightarrow \mu^{+}\nu$ more often



☞ Suppressed by requirement $q_{\pi} \cdot q_{\mu} < 0$

- Different inelastic interaction of π^{+} and π^{-} with detector material
  - Inelastic $\sigma(\pi^{-}N) > \sigma(\pi^{+}N)$ by $1.3 \pm 0.3\%$ in $1 - 2$ GeV/c [PDG 2006]
  - More π^{-} may get lost, hence the whole events

☞ Induced asymmetry less than 2×10^{-4}

☞ Has no effect at present accuracy level

A_{SL}^{s} Results

Raw asymmetry:

$$A^{raw} = 0.0102 \pm 0.0081(stat.)$$

Similarly to dimuon asymmetry must be corrected

for fraction of flavor-specific B_s decays: $A_{SL}^{s} = f^{s} \times A^{raw}$

- Signal: $B_s \to \mu D_s X$ and $B_s \to \tau D_s X \to \mu D_s X$
- Background: $B_s \to D_s D_s X, D_s \to \mu \nu X$
- Background: b or $c \to D_s$, another b or $c \to \mu$

Corrected asymmetry:

$$A_{SL}^{s} = 0.0123 \pm 0.0097(stat.) \pm 0.0017(syst.)$$

(DØ Conference Note 5143, to be submitted to PRL)

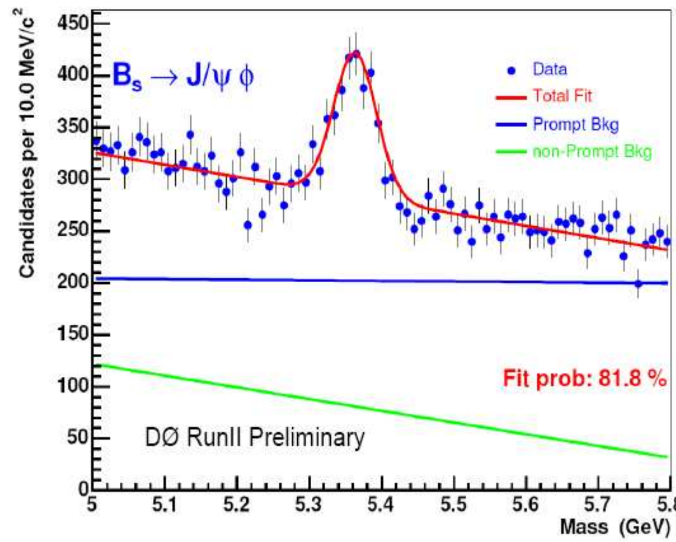
- World first direct measurement of A_{SL}^{s}
- Constrains $\frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s = 0.0245 \pm 0.0193(stat.) \pm 0.0035(syst.)$

☞ SM prediction for $2 \cdot A_{SL}^{s} = (0.000021 \pm 0.000004)$ [hep-ph/0406300]

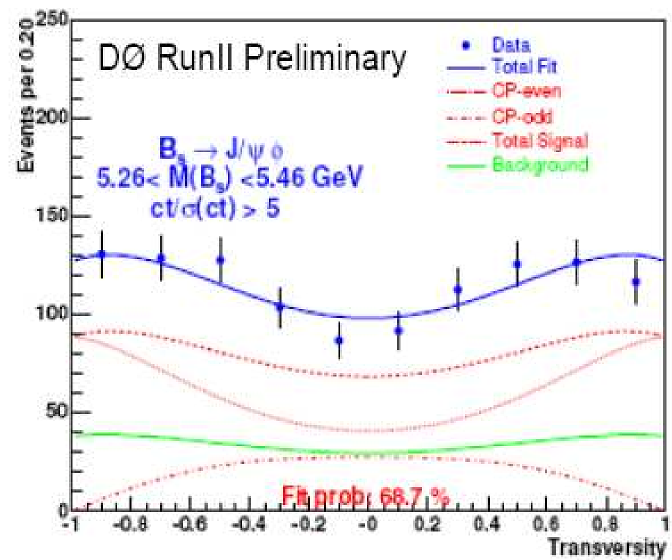
☞ New Physics may significantly increase this value, up to 0.005

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

(3rd measurement of ϕ_s)



- Clean signal selection
- Predominantly CP-even final state
- Angular analysis is needed to disentangle small CP-odd component
- Time-evolution of polarization amplitudes A_0, $A_\parallel$ (CP-even) and $A_\perp$ (CP-odd) depends on width difference $\Delta\Gamma_s$ and CP-violating phase ϕ_s



$B_s \to J/\psi\phi$ Results

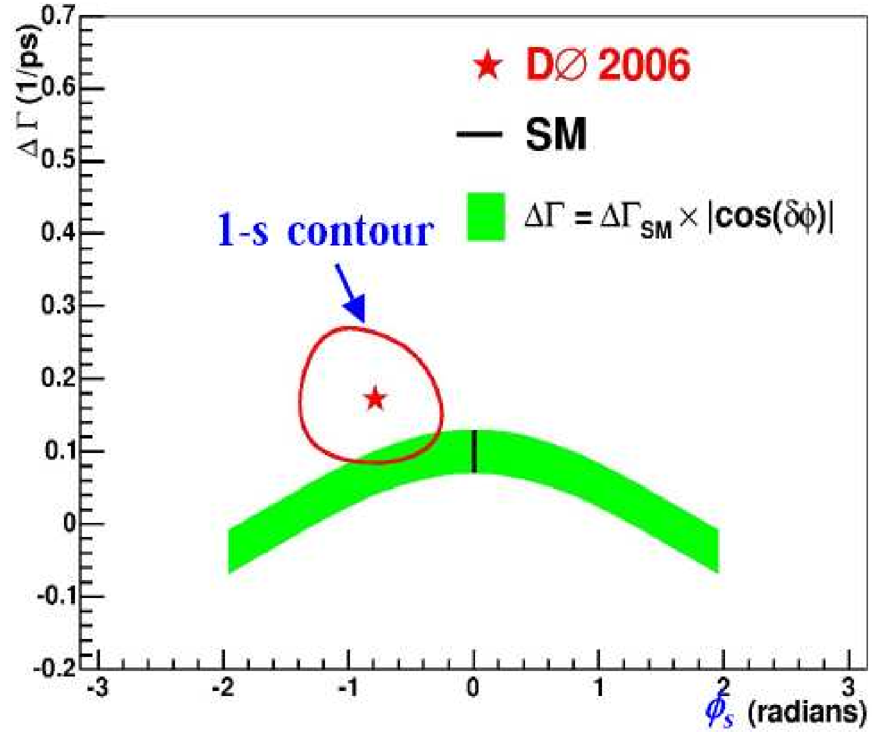
$$\Delta\Gamma_s = 0.17 \pm 0.09 \pm 0.03 \text{ ps}^{-1}$$

$$\phi_s = -0.79 \pm 0.56 \pm 0.01$$

[DØ Conference Note 5144]

- Most precise direct measurement of $\Delta\Gamma_s$
- First measurement of ϕ_s
- Consistent with SM prediction:

  $\Delta\Gamma_s = 0.10 \pm 0.03 \text{ ps}^{-1}$, $\phi_s \approx 0.005$



Combined constraints on $\Delta\Gamma_s$ and ϕ_s

Adding constraint from charge asymmetry measurement

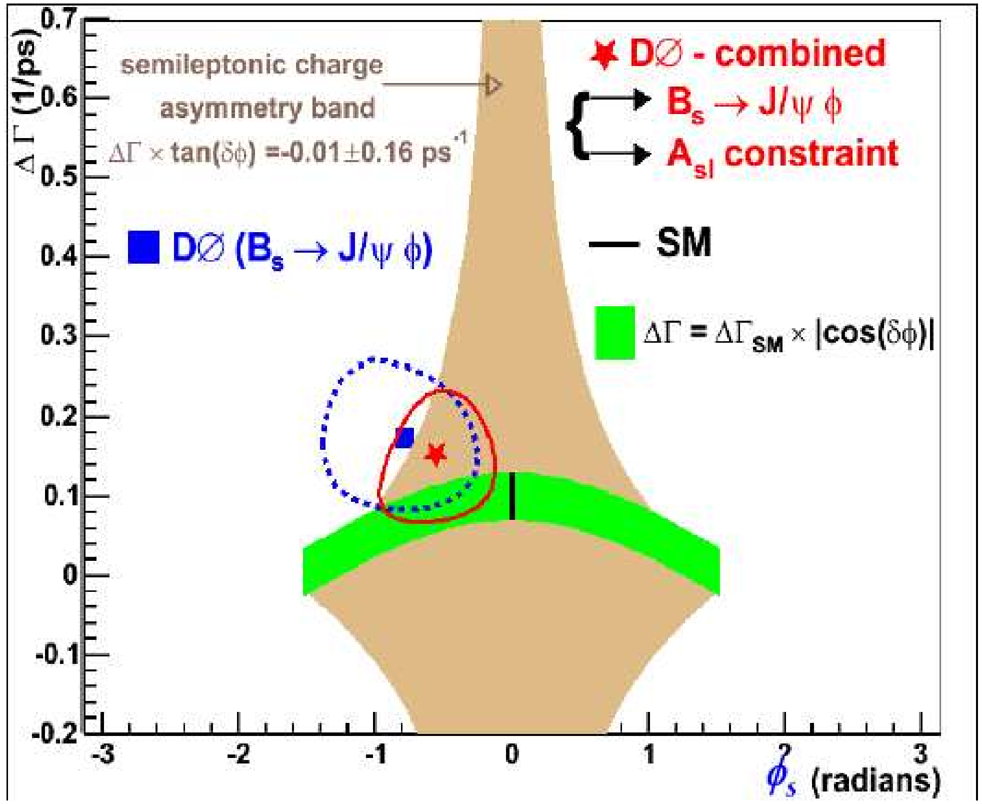
$$\Delta\Gamma_s \tan\phi_s = A_{SL}^s \cdot \Delta M_s = -0.01 \pm 0.16\ \text{ps}^{-1}$$

(assuming $\Delta M_s = 17.3 \pm 0.3\ \text{ps}^{-1}$, CDF)

we obtain

$$\Delta\Gamma_s = 0.15^{+0.09}_{-0.08}\ \text{ps}^{-1}$$
$$\phi_s = -0.56^{+0.44}_{-0.41}$$

[DØ Conference Note 5189]



Summary

- DØ constrained CP-violating phase ϕ_s in three analyses
- 1st: Dimuon asymmetry measured at DØ to be

$$A_{SL} = -0.0044 \pm 0.0040(stat.) \pm 0.0028(syst.)$$

  - Express measured dimuon $A_{SL} = \frac{f_d Z_d A_{SL}^d + f_s Z_s A_{SL}^s}{f_d Z_d + f_s Z_s} \approx 0.6 A_{SL}^d + 0.4 A_{SL}^s$, where Z_q were given earlier
  - By using A_{SL}^d measured at BaBar,Belle,CLEO we can extract $A_{SL}^s = -0.008 \pm 0.011$

- 2nd: A_{SL}^s directly measured at DØ in semileptonic B_s decays

$$A_{SL}^s = 0.0123 \pm 0.0097(stat.) \pm 0.0017(syst.)$$

- 3rd: $B_s \rightarrow J/\psi\phi$ analysis (measurement rather than constraint):

$$\Delta\Gamma_s = 0.17 \pm 0.09 \pm 0.03 \text{ ps}^{-1}$$

$$\phi_s = -0.79 \pm 0.56 \pm 0.01$$

Summary

- Combining first two results we obtain constraint on CP-violating parameter:

$$\frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s = -0.0006 \pm 0.0091$$

[DØ Conference Note 5189]

- Consistent with zero $\Longrightarrow$ too early to report evidence of CP-violation in mixing in B decays
- Adding to the results from $B_s \to J/\psi\phi$ analysis we get

$$\Delta\Gamma_s = 0.15^{+0.09}_{-0.08}\ \text{ps}^{-1} \qquad \phi_s = -0.56^{+0.44}_{-0.41}$$

[DØ Conference Note 5189]

- This is consistent with SM prediction