CP violating phase ϕ_s and charge asymmetries in B_s decays

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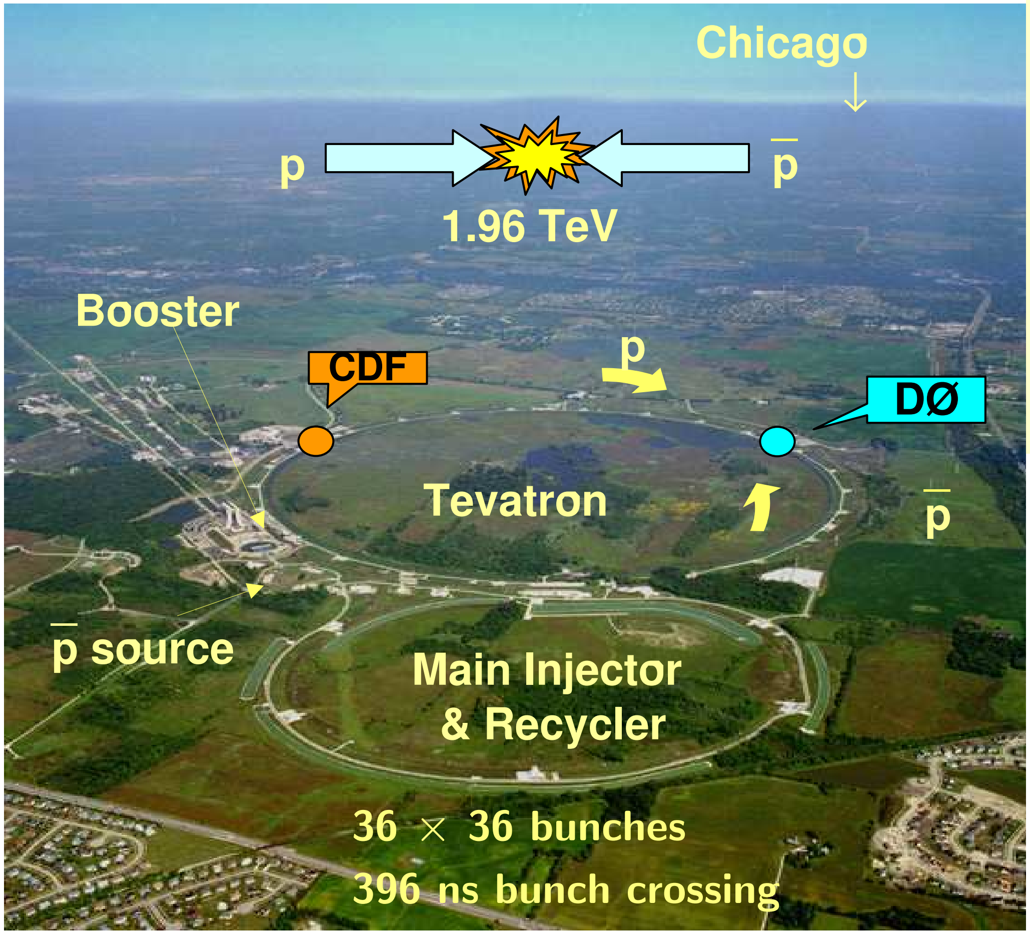
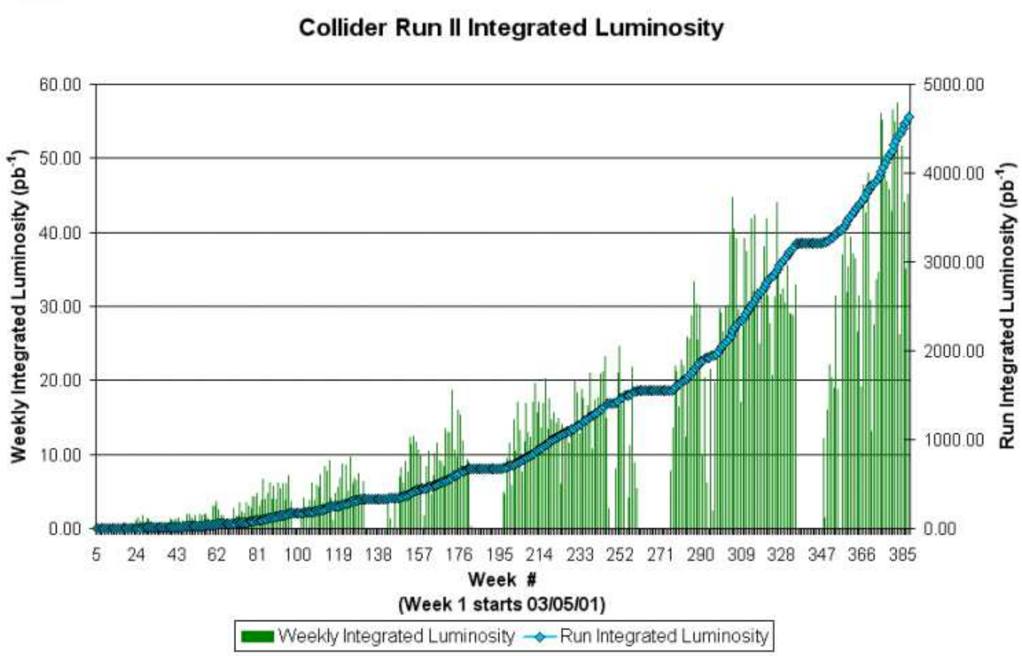
on behalf of the DØ collaboration

CKM 2008
5th Workshop on the Unitarity Triangle
Rome, Italy, 8-13 September, 2008

Fermilab Tevatron Run II

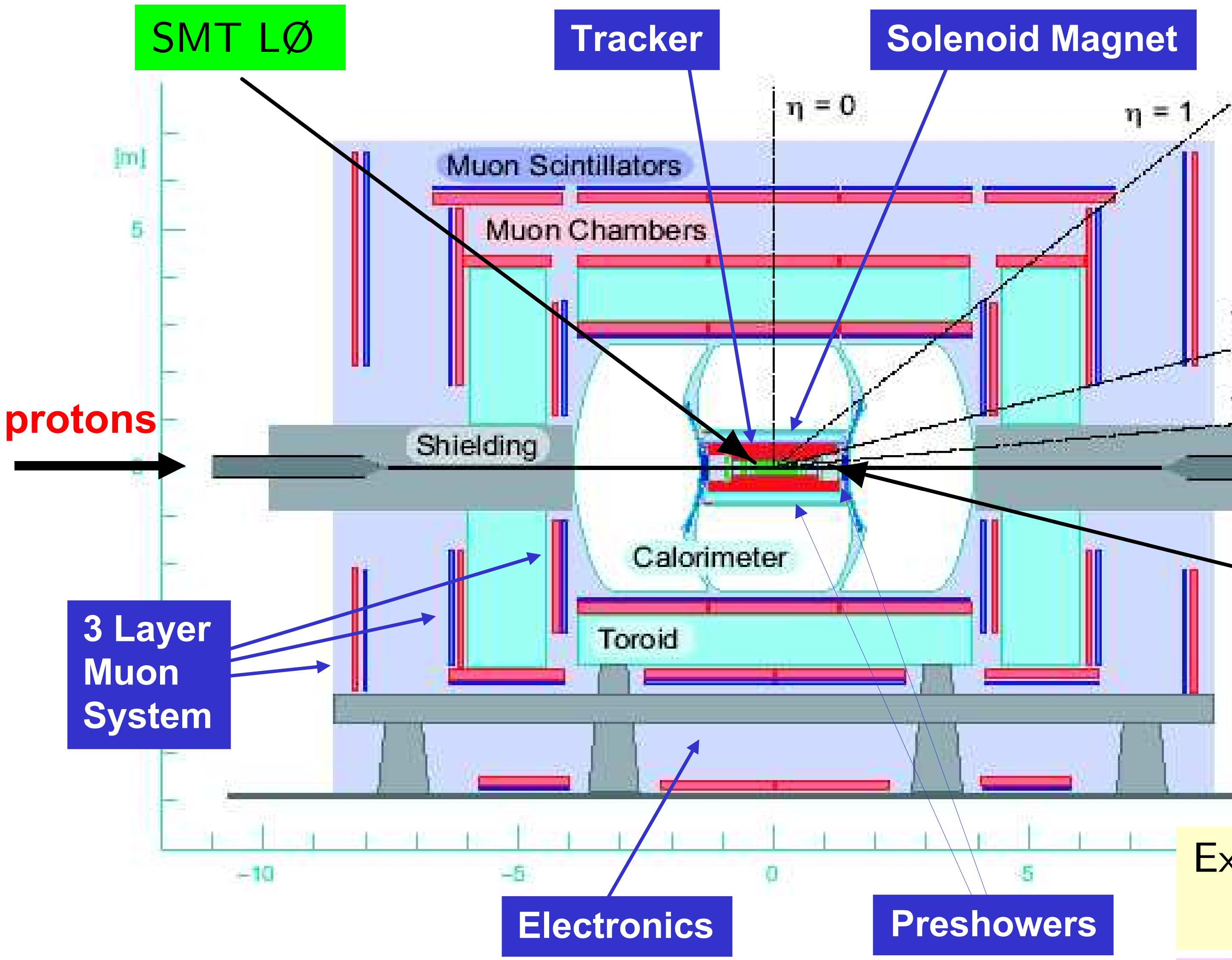


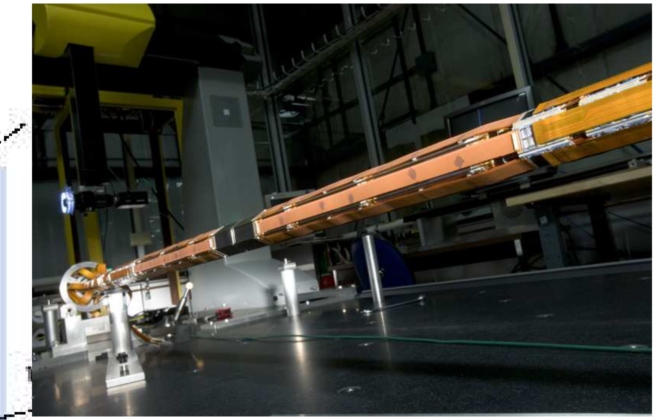
- Run II started in March 2001
- Peak Luminosity: $3.2 \cdot 10^{32}$ cm^{-2}s^{-1}
- Delivered: > 4.8 fb^{-1} (Run I: 0.16 fb^{-1})
- 6-8 fb^{-1} expected by end of 2009

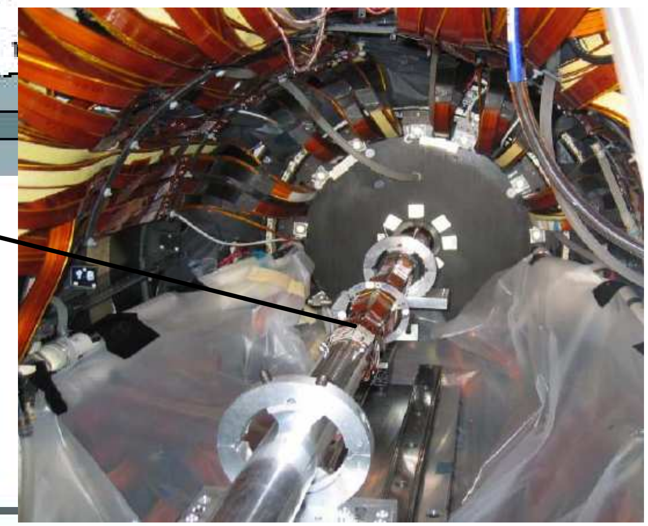


Thanks to all colleagues at DØ and Tevatron for their contributions to this talk

Run IIb, DØdetector and Layer Zero upgrade







Excellent noise performance:
$S/N = 18$

10% gain in IP resolution $[f(p_T)]$

25% gain in proper time resolution

Improved charged particle track reconstruction

Motivation

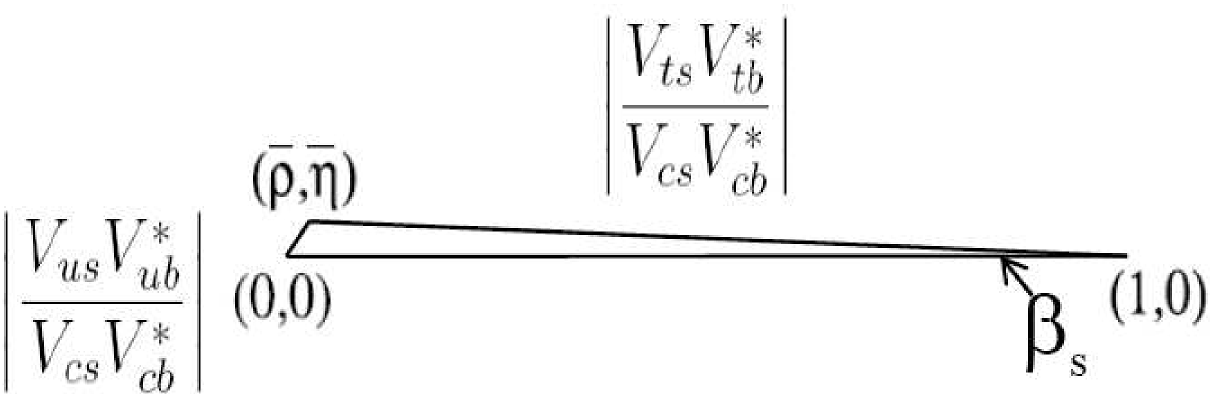
Why measuring B_s^0 mixing?

- B mesons live for a relatively long time ($c\tau_B \sim 0.5$ mm)
- $\frac{\Delta\Gamma_s}{\bar{\Gamma}_{B_s}} \simeq 1 \sim 10\%$
- Measuring CP asymmetries in B^0 decays will shed further light on $|V_{td}|$, $|V_{ts}|$
- Complementary to B factories (sensitive to A_{B^0})

- SM predicts relatively small CPV effects
- Measurement of large CPV contributions in $B_s^0 \to J/\psi\phi, D_s^- \mu^+ \nu X$ can provide indirect evidence for physics beyond the SM

B mixing

Unitarity triangle in B_S system



Area $\propto$ level of CP violation

- SM CP violation phase β_s^{SM} is predicted to be small[1]:

$$\phi_s^{\mathrm{SM}} = -2\beta_s^{\mathrm{SM}} = -2\mathrm{arg}\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \simeq 0.04 \pm 0.01 \text{ rad}$$

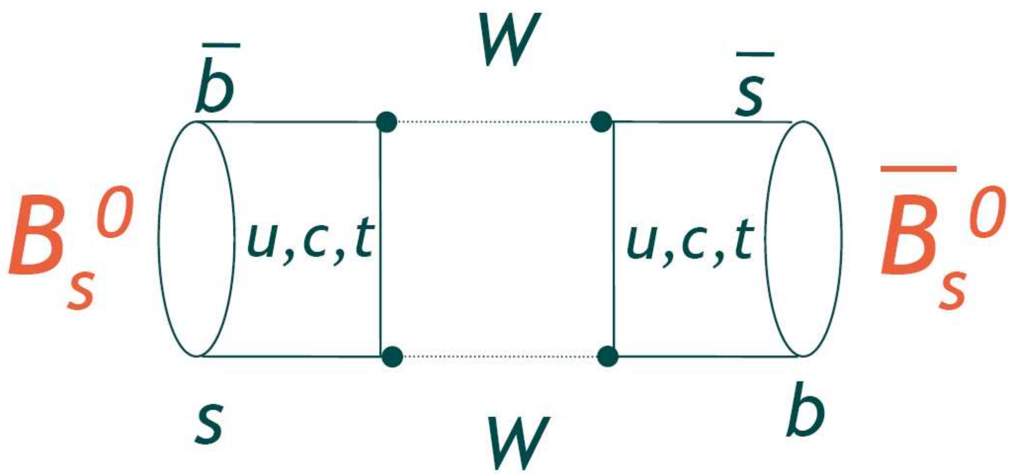
[1] A. Lenz and U. Nierste, JHEP **0706**, 072 (2007), arXiv:hep-ph/0612167

CP violation in $B_s^0 - \bar{B}_s^0$ mixing

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

In SM: Γ_{12} from long distance contributions; M_{12} dominated by top quark box diagram

Matter $\longleftrightarrow$ Antimatter



Mass eigenstates:

$|B_L>= p|B_s^0> +q|\bar{B}_s^0>$ $\approx$ CP even

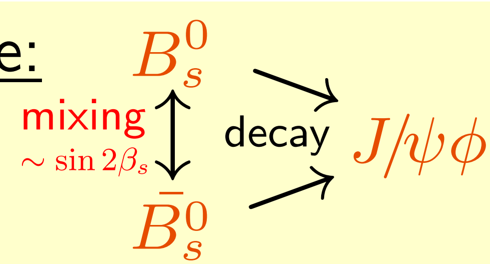
$|B_H>= p|B_s^0> -q|\bar{B}_s^0>$ $\approx$ CP odd

CPV: $|p/q| \neq 1$, or interference between direct/mixed decays

Charge asymmetry ($B \rightarrow \mu + X$):

$$A = \frac{N^{--} - N^{++}}{N^{--} + N^{++}} = \frac{1 - \left|\frac{p}{q}\right|^4}{1 + \left|\frac{p}{q}\right|^4}$$

Interference:



Asymmetry and ϕ_s measurements

- Dimuon charge asymmetry A_{B^0} in $p\bar{p} \to \mu\mu X$ decay

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- Charge asymmetry a_{sl}^s in $B_s^0 \to D_s \mu\nu X$ decay (time dependent & tagged)

- Charge asymmetry $A_{SL}^{s,\text{unt.}}$, $\frac{\Delta\Gamma_s}{\Delta m_s} \tan\phi_s$ in semileptonic $B_s^0 \to D_s \mu\nu X$ decays

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- CP violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decay (time dependent & tagged)

Dimuon charge asymmetry in $p\bar{p} \rightarrow \mu\mu X$

DØ Collab., Phys. Rev. **D 74**, 092001 (2006)

$\mathcal{L} = 1.0$ fb^{-1}

Measurement of dimuon charge asymmetry:

$A = \frac{N^{++} - N^{--}}{N^{++} + N^{--}}$ and $R = \frac{N^{++} + N^{--}}{N^{+-}}$

- $B^0_{(s)} \bar{B}^0_{(s)}$ direct-direct decays ($b \rightarrow \mu X$):

$$\frac{\mathcal{R}(\epsilon_{B^0})}{1+|\epsilon_{B^0}|^2} = \mathcal{I}\left\{\frac{\Gamma_{12}}{4M_{12}}\right\} = \frac{A_{B^0}}{4} = f \cdot A$$

- Corrected for asymmetric K decays
- f includes sequential decay $b \rightarrow c \rightarrow \mu X$

- General method
  used in many of our analyses

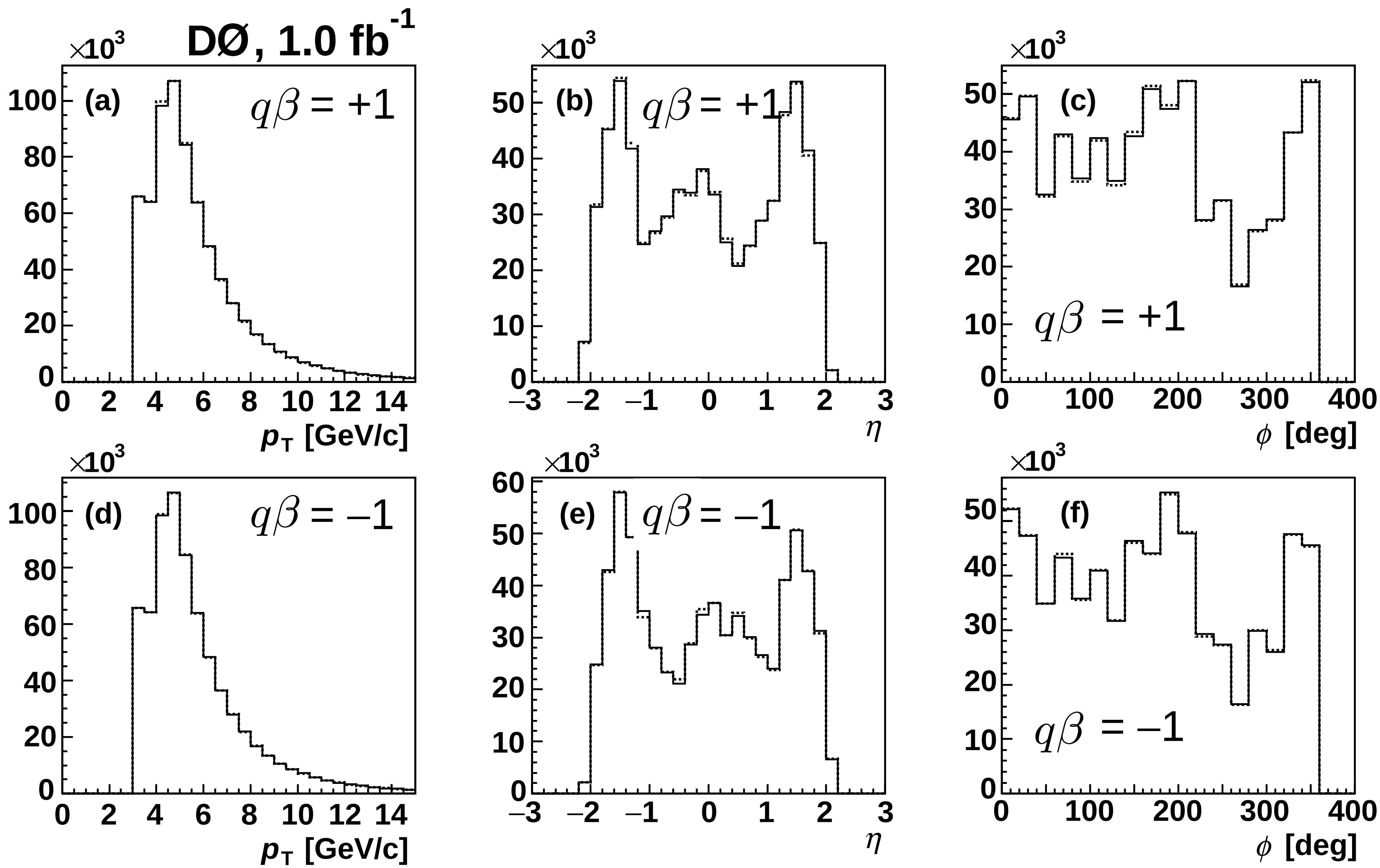
Event selection:

$B^0_{(s)} \rightarrow \mu^+ + X$ and $\bar{B}^0_{(s)} \rightarrow \mu^- + X$

- $p_T(\mu) > 4.2$ GeV $\vee$ $|p_z| > 6.4$ GeV
  ($\Rightarrow p_\mu \gtrsim 0.2$ GeV)
- $IP(\mu) < 0.3$ cm
- $p_T(\mu) < 15$ GeV
  (wrong sign μ's; W, Z background)
- good track fit χ^2
- $10^\circ < \theta(\mu,\mu) < 170^\circ$

Dimuon charge asymmetry in $p\bar{p} \rightarrow \mu\mu X$

Single muon p_T, η and ϕ distributions for opposite toroid and solenoid polarities:
Muon charge times toroid polarity: $q\beta$



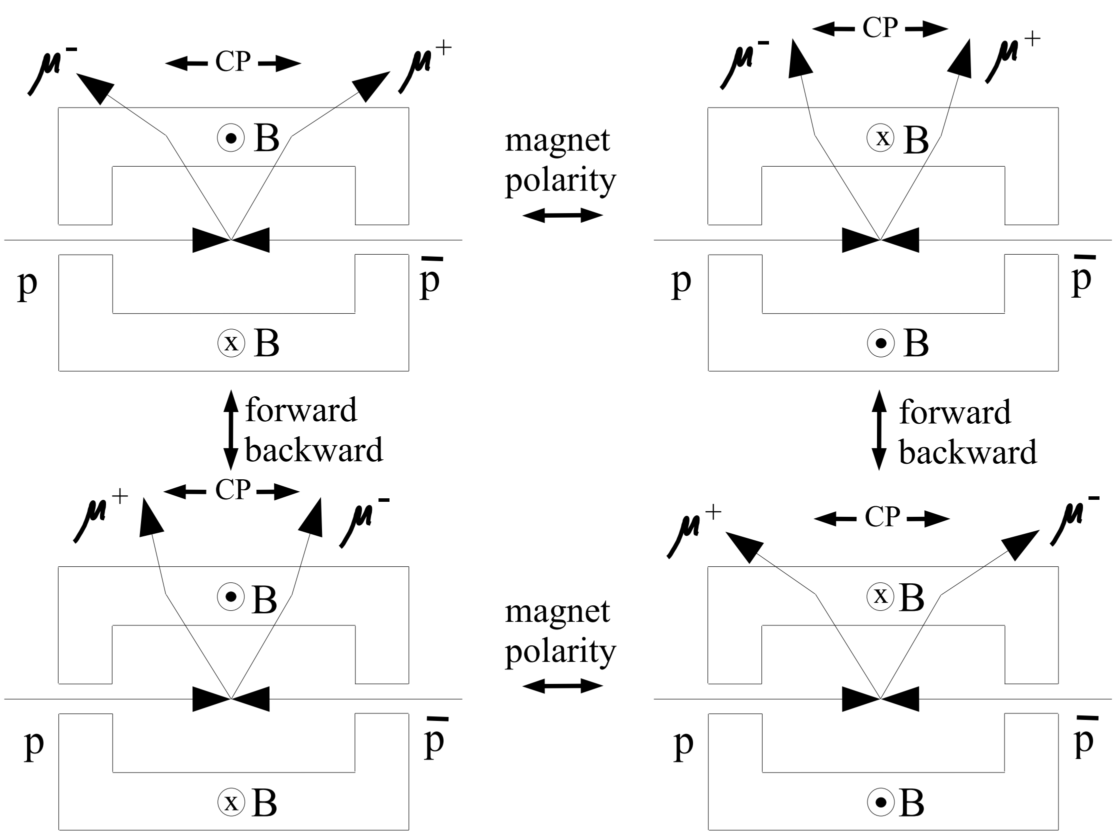
Dimuon charge asymmetry in $p\bar{p} \longrightarrow \mu\mu X$

- Magnet polarity flips every two weeks ⇒ Reduction of detector asymmetry effects

- Number of muons $n_q^{\beta\gamma}$ with charge $q = \pm 1$, toroid polarity $\beta = \pm 1$ and rapidity $\eta \gtrless 0$ $(\gamma = \pm 1)$, giving rise to eight equations, corresponding to eight subsamples

$$n_q^{\beta\gamma} = \frac{1}{4} N \epsilon^{\beta} (1 + qA)(1 + q\gamma A_{fb})(1 + \gamma A_{\text{det}})(1 + q\beta\gamma A_{\text{ro}})(1 + \beta\gamma A_{\beta\gamma})(1 + q\beta A_{q\beta})$$

- χ^2 fit to number of events in each subsample yields asymmetries



- N = number of selected events
- ϵ^{β} = fraction of luminosity with toroid polarity β $(\epsilon^+ + \epsilon^- = 1)$
- A = raw charge asymmetry to be measured
- A_{fb} = forward backward asymmetry (more muons go into proton direction)
- A_{det} = North south asymmetry of detector
- A_{ro} = Range out asymmetry (charged track magnet polarity acceptance)
- $A_{\beta\gamma}$ = After magnet polarity flip remaining detector forward backward asymmetry
- $A_{q\beta}$ = Detector asymmetry between north and south bending tracks

Dimuon charge asymmetry in $p\bar{p} \to \mu\mu X$

Toroid $\times$ solenoid polarity	-1	1
A_{fb}	0.0006 ± 0.0006	0.0001 ± 0.0007
A_{det}	-0.0187 ± 0.0006	-0.0165 ± 0.0007
A_{ro}	-0.0268 ± 0.0006	-0.0283 ± 0.0007
$A_{q\beta}$	-0.0059 ± 0.0006	-0.0069 ± 0.0007
$A_{\beta\gamma}$	-0.0002 ± 0.0006	-0.0015 ± 0.0007
R	0.4603 ± 0.0013	0.4610 ± 0.0013
A	0.0005 ± 0.0018	-0.0016 ± 0.0019

- Combining same and opposite magnet polarities yields:

  $A = -0.0005 \pm 0.0013$ (stat)

- Reaction $K^- + N \to$ hyperon $+\pi$ has no $K^+ + N$ analog $(N(K^+) > N(K^-)) \Rightarrow$ correction $\Rightarrow$

  $A = -0.0028 \pm 0.0013$ (stat) ± 0.0009 (syst)

$\frac{\mathcal{R}(\epsilon_{B^0})}{1+|\epsilon_{B^0}|^2} = \frac{A_{B^0}}{4} \equiv f \cdot A = -0.0023 \pm 0.0011$ (stat) ± 0.0008 (syst)
where $f = 0.814 \pm 0.105$ (syst)

$A_{B^0} + 0.72 A_{B^0_s} = -0.0092 \pm 0.0044$ (stat) ± 0.0032 (syst)

- A_{B_0}(PDG) $= -0.0004 \pm 0.0056$
- Measurement complementary to B factories (sensitive to A_{B^0}, not $A_{B^0_s}$)

CP violation in $B_s^0 \to D_s^- \mu^+ \nu X, D_s^- \to \phi\pi^-$

DØ Collab., Run II Preliminary (2008), DØ note 5730-CONF

$\mathcal{L} = 2.8\ \text{fb}^{-1}$

New search for CP violation in $B_s^0 \to \mu D_s \nu X$ with $D_s \to \phi\pi, \quad \phi \to K^+K^-$ by charge asymmetry measurement using time dependent analysis with flavour tagging

Proper decay length:

$c\tau_{B_s^0} = x^M \cdot K$

with Visible proper decay length (VPDL):

$$x^M = \left(\frac{\overrightarrow{d_T^{B_s^0}} \cdot \overrightarrow{p_T^{\mu D_s^-}}}{|p_T^{\mu D_s^-}|^2} \right) \cdot c M_{B_s^0}$$

$\overrightarrow{d_T^{B_s^0}}$ = transverse decay length

and K-factor: $K = \frac{p_T^{\mu D_s^-}}{p_T^{B_s^0}}$ determined from MC

Selection of final state:

$B_s^0 \to \mu D_s \nu X$ with $D_s \to \phi\pi, \quad \phi \to K^+K^-$

- $p_T(\mu) > 2$ GeV
- $p(\mu) > 3$ GeV

($\Rightarrow$ hits in CFT and SMT)

- $p_T(K$ candidate track$) > 0.7$ GeV
- $p_T(\pi$ candidate track$) > 0.5$ GeV, $Q_\pi = -Q_\mu$

Reconstruction of ϕ and D_s

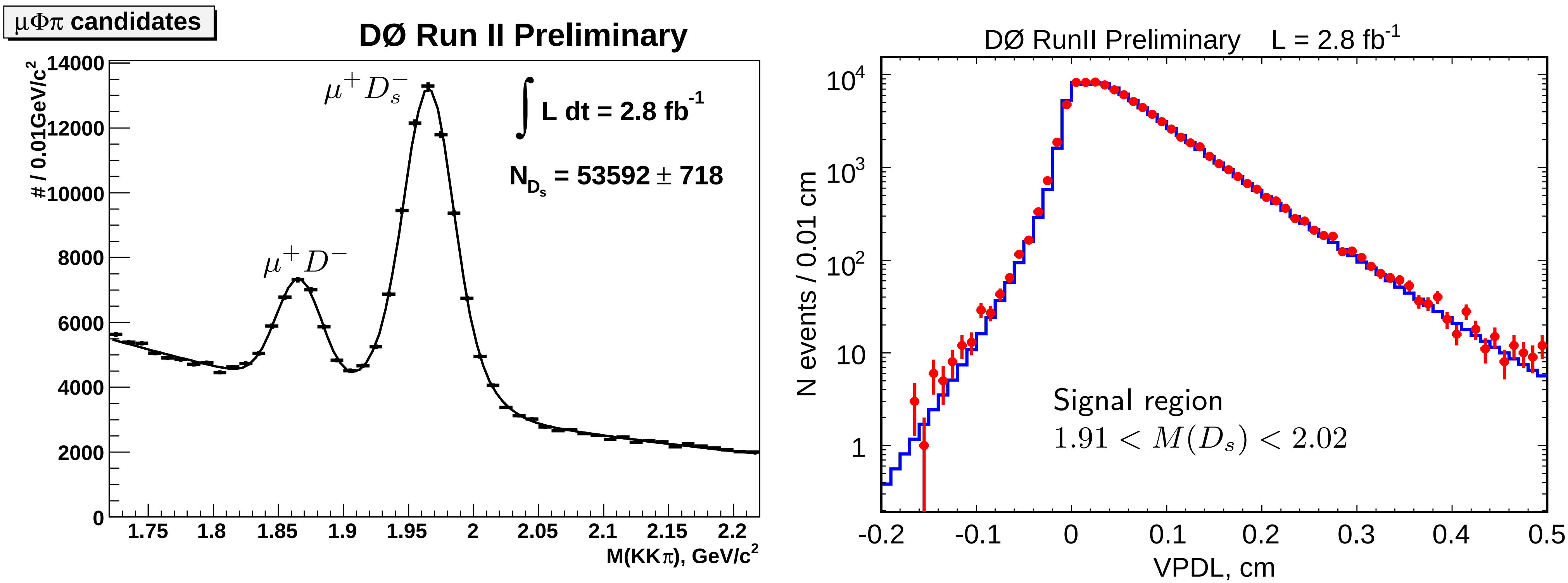
Sideband subtraction + likelihood ratio
to maximise significance of B_s^0 signal

OS + SS flavour at production tagging

Flavour at decay from muon charge

CP violation in $B_s^0 \to D_s^- \mu^+ \nu X, D_s^- \to \phi\pi^-$

Data sample, mass and decay length fits



- Muons with charge $q = \pm 1$, pseudorapidity of $D_s\mu$ system $\eta \gtrless 0$ $(\gamma = \pm 1)$ and toroid polarity $\beta = \pm 1$, give rise to eight equations, corresponding to eight subsamples:

$$p^{q\beta\gamma}(x, K, d_{pr}; a_{sl}) = p_{VPDL}(x, K, d_{pr}; a_{sl}) \cdot \epsilon^{\beta}(1+q\gamma A_{fb})(1+\gamma A_{\text{det}})(1+q\beta\gamma A_{\text{ro}})(1+\beta\gamma A_{\beta\gamma})(1+q\beta A_{q\beta})$$

- Unbinned likelihood fit yields asymmetries (for each $a_{sl} \in \{a_{sl}^s, a_{sl}^d, a_{sl}^{\text{bkg.}}\}$ respectively)

CP violation in $B_s^0 \to D_s^- \mu^+ \nu X, D_s^- \to \phi\pi^-$

Asymmetry results

- B_s oscillation frequency fixed at $\Delta m_s = 17.77$ ps^{-1}
- Fit results from Run IIa and Run IIb combined

Parameter	Run II, $\int \mathcal{L}dt = 2.8$ fb^{-1}
a_{sl}^s	-0.0024 ± 0.0117
a_{sl}^d	-0.0787 ± 0.0371
a_{bkg}	-0.0182 ± 0.0271
A_{fb}	0.0000 ± 0.0021
A_{det}	0.0001 ± 0.0021
A_{ro}	-0.0323 ± 0.0021
$A_{\beta\gamma}$	-0.0005 ± 0.0021
$A_{q\beta}$	0.0029 ± 0.0021

Systematic errors:

- $c\bar{c}$ contribution
- efficiency vs. VPDL
- $B_s \to D^{(*)}\mu\nu$ branching fractions

Final result: (DØ Run II Preliminary)

- $a_{sl}^s = -0.0024 \pm 0.0117$ (stat) $^{+0.0015}_{-0.0024}$ (syst)

Former DØ result $A_{SL}^{s,\text{unt.}}$:

- time integrated
- untagged

DØ Collab., Phys. Rev. Lett. **98**, 151801 (2007)

$\mathcal{L} = 1.3$ fb^{-1}

- A is related to $A_{SL}^{s,\text{unt.}}$ via $A = f_s \cdot A_{SL}^{s,\text{unt.}} + f_d \cdot A_{SL}^{d,\text{unt.}}$ where $f_{s(d)}$ is fraction of $B_s^0(B_d^0) \to \mu D_s \nu X$ decays in μD_s sample.

$A(\mu D_s) = 0.0102 \pm 0.0081$ (stat)

$A_{SL}^{s,\text{unt.}} = [1.23 \pm 0.97$ (stat) ± 0.17 (syst)$] \times 10^{-2}$

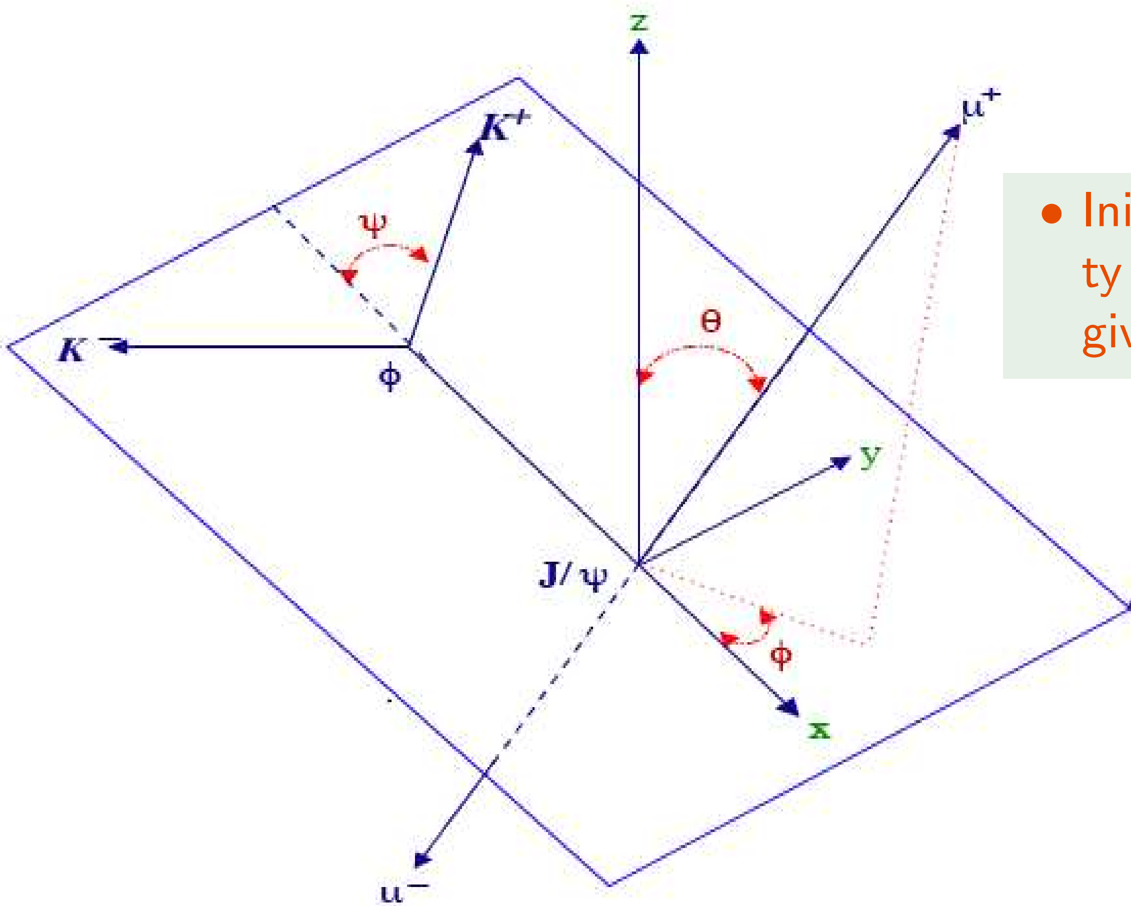
$\frac{\Delta\Gamma_s}{\Delta m_s} \tan\phi_s = [2.45 \pm 1.93$ (stat) ± 0.35 (syst)$] \times 10^{-2}$ $\quad (\Delta m_s/\overline{\Gamma_s} \gg 1)$

- Together with $\Delta\Gamma_s$ and Δm_s measurements $\Rightarrow$ Constraints on CP-violating phase ϕ_s

$B_s^0 \to J/\psi(\to \mu^+\mu^-)\phi(\to K^+K^-)$

- Pseudoscalar $\to$ Vector + Vector, i.e. spin 0 $\to$ 1 + 1
  - $L = 0, 2$ (Amplitudes $A_0, A_{||}$): CP even, $L = 1$ (Amplitude $A_\perp$): CP odd
  - CP even and CP odd components have different angular distributions

- Fit to time dependend angular distributions of $B_s^0 \to J/\psi\phi$ allows separation between CP even and CP odd components



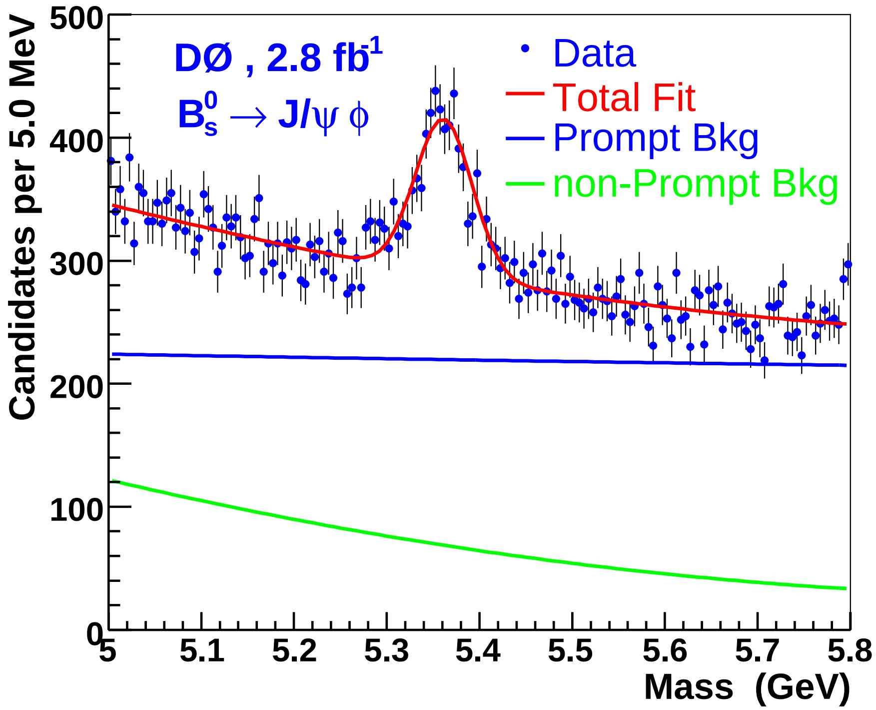
- Initial state flavour tag improves sensitivity and removes sign ambiguity on ϕ_s for a given $\Delta\Gamma_s$ (obtained in a previous analysis)

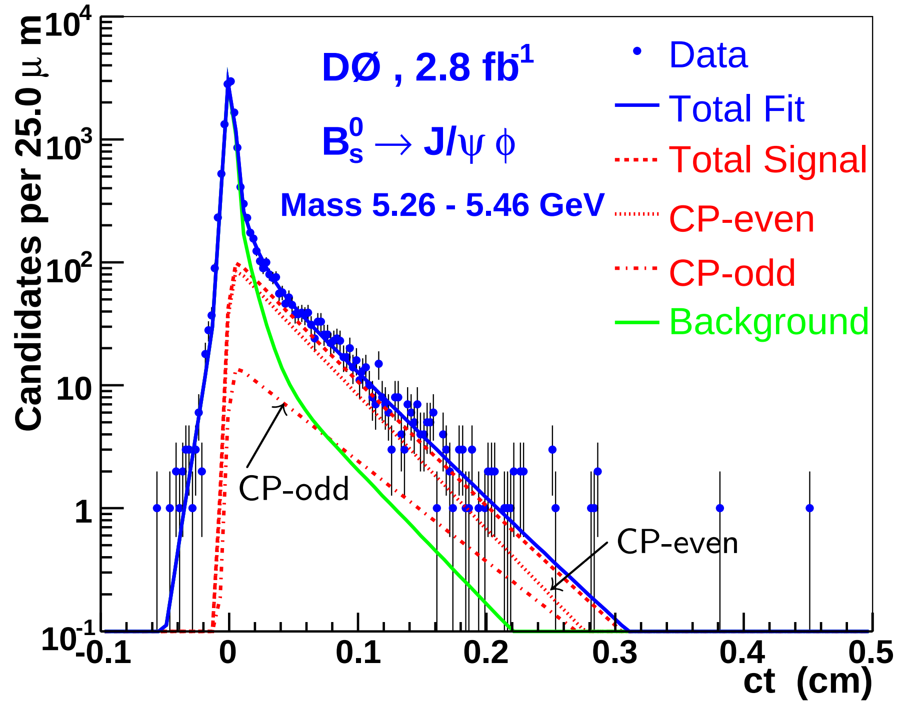
Decay angles θ, ϕ, ψ

Mixing parameters in $B_s^0 \to J/\psi\phi$

DØ Collab., FERMIILAB-PUB-08/033-E, arXiv:0802.2255, (submitted to PRL)

$\mathcal{L} = 2.8$ fb^{-1}





Selection of final state:

$B_s^0 \to J/\psi\phi$ with $J/\psi \to \mu^+\mu^-$ $\phi \to K^+K^-$

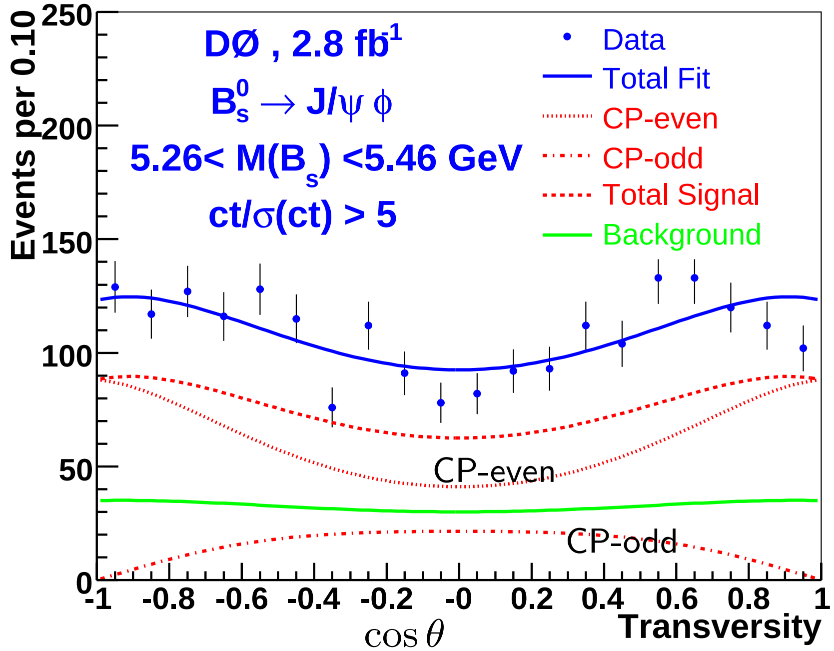
- $p_T(\mu) > 1.5$ GeV (central track match)
- $p_T(B_s^0) > 6$ GeV
- $p_T(\phi) > 1.5$ GeV (highest p_T)
- $p_T(K) > 0.7$ GeV
- Flavour tagging by likelihood ratio method

SS + OS tagging

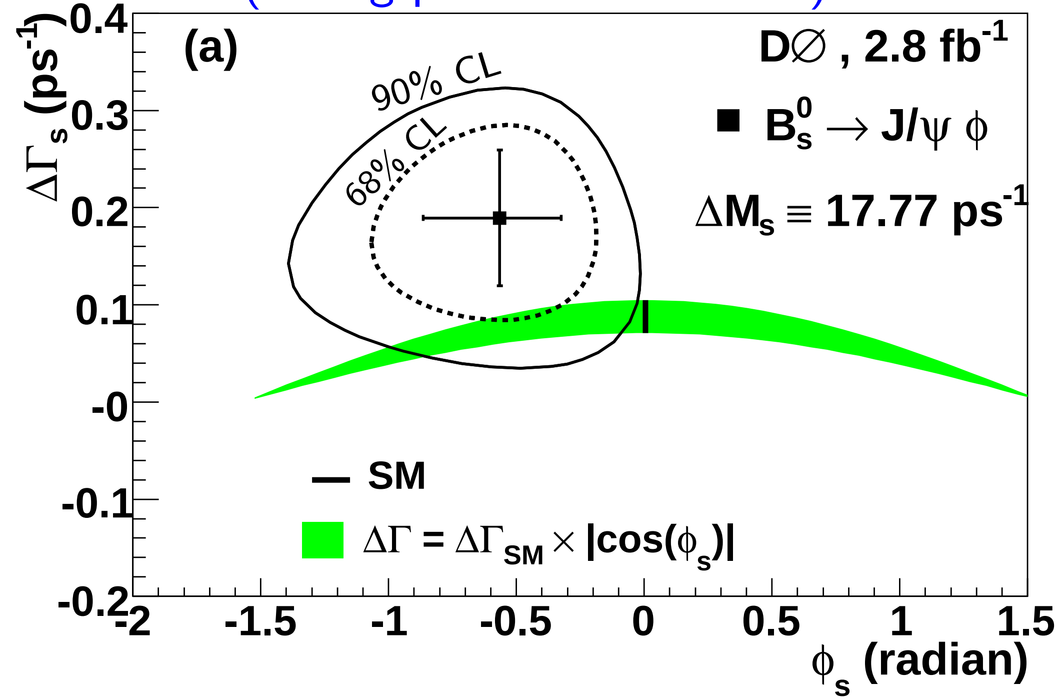
- Maximum likelihood fit to mass, lifetime, 3 decay angles
  - ΔM_s constrained to measured value (CDF)
  - Strong phases constrained to values measured for B_d (B-factories) allowing some degree of violation of $SU(3)$ symmetry

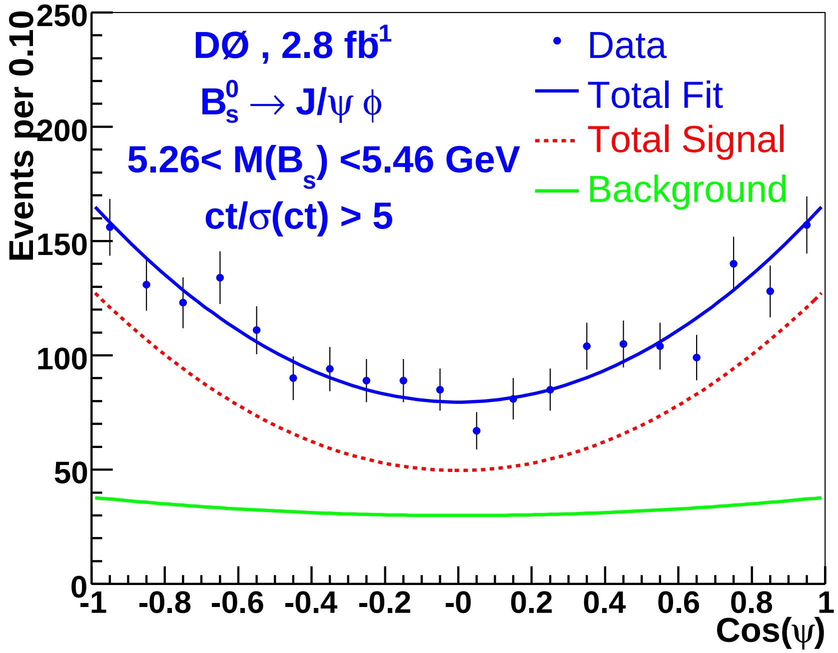
- A. S. Dighe, I. Dunietz, R. Fleischer, Eur. Phys. J. **C6**, 647-662 (1999), CERN-TH-98-85, FERMILAB-PUB-98-093-T, IC-98-25, hep-ph/9804253
- I. Dunietz, R. Fleischer, U. Nierste, Phys. Rev. **D63**, 114015 (2001), FERMILAB-PUB-00-245-T, DESY-00-171, CERN-TH-2000-333, hep-ph/0012219

Mixing parameters in $B_s^0 \to J/\psi\phi$



(strong phases constrained)





$\overline{\tau}(B_s^0) = 1.52 \pm 0.05$ (stat) ± 0.01 (syst) ps

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

CP violating phase:

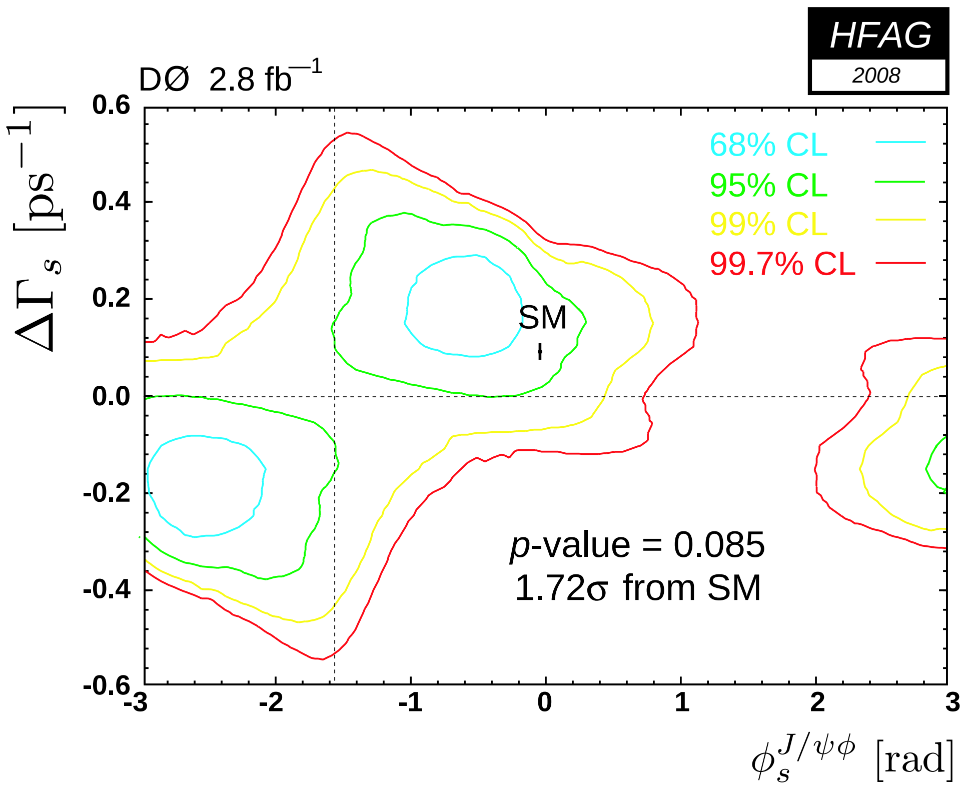
$\phi_s = -0.57^{+0.24}_{-0.30}$ (stat) $^{+0.07}_{-0.02}$ (syst) rad

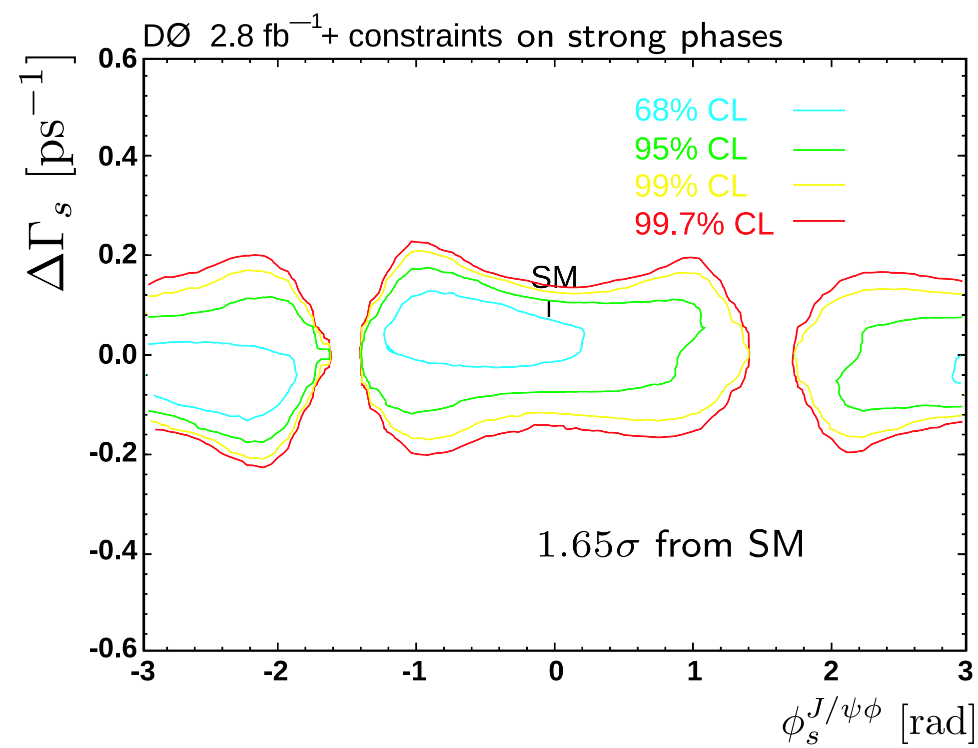
- Probability of SM 6.6% $\Rightarrow\ \sim 1.8\sigma$

Constraint from charge asymmetry A^s_{SL}

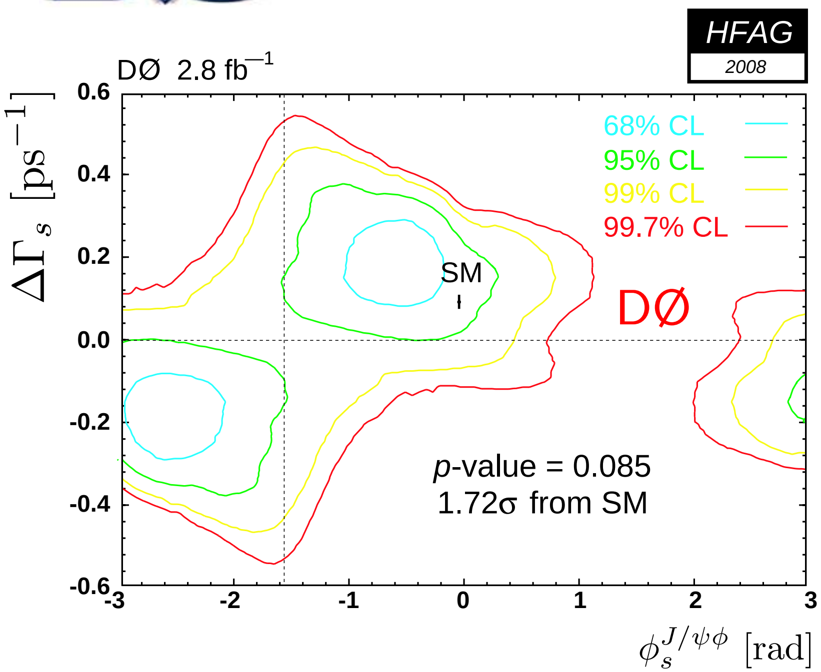
From measurements of $A^s_{SL} = \frac{N(\bar{B}_s \to \ell^+ X) - N(B_s \to \ell^- X)}{N(\bar{B}_s \to \ell^+ X) + N(B_s \to \ell^- X)} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$

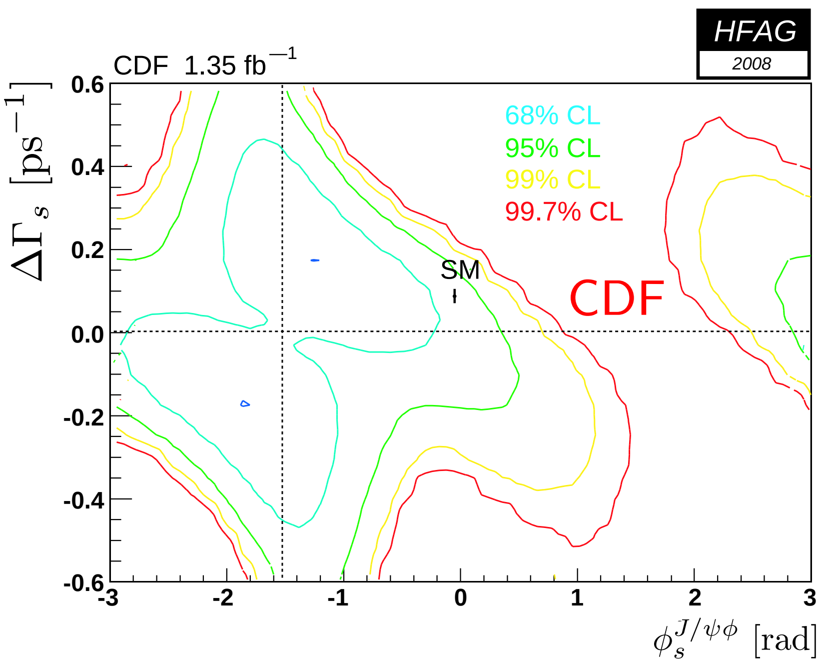
- Fix ΔM_s to measured value and constrain $\Delta\Gamma_s \tan\phi_s$
- World average $A_{SL} = 0.0016 \pm 0.0085$
  - Does not contain new DØ measurement (DØ note 5730-CONF)



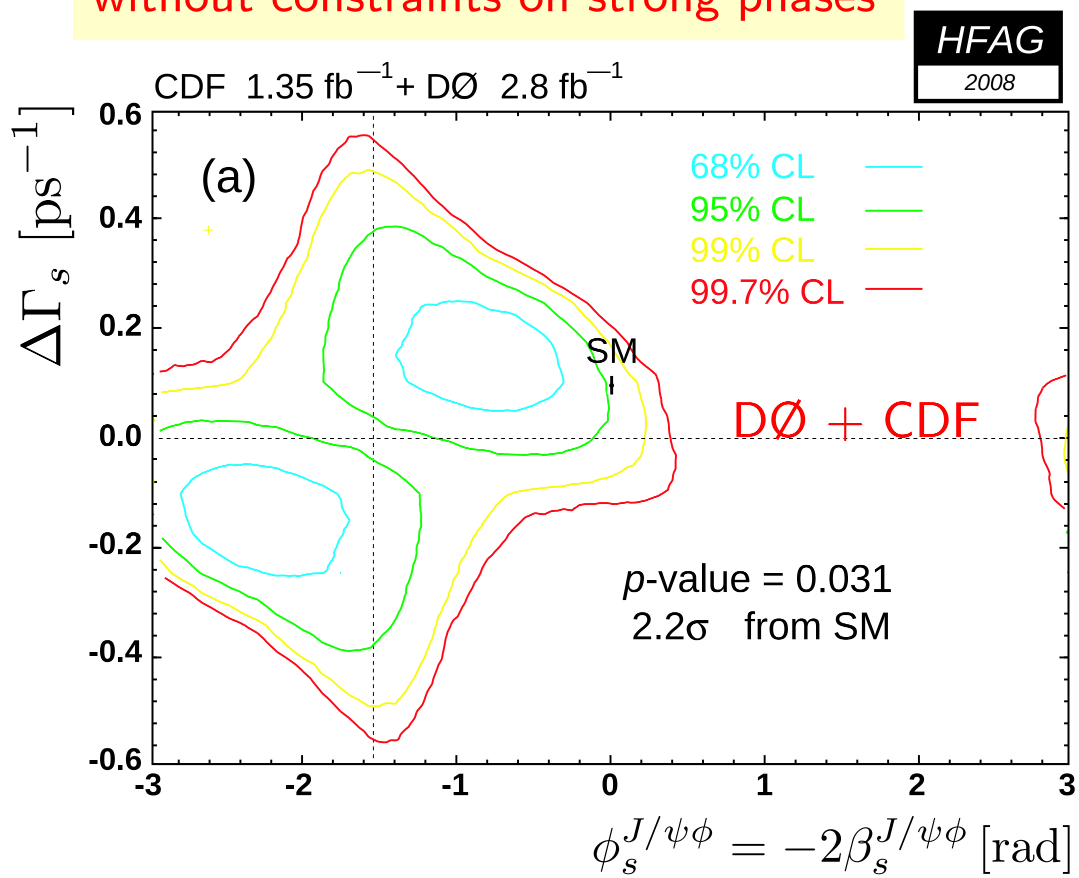


DØ + CDF combined $\Delta\Gamma_s$ vs. ϕ_s results





Combination of results
without constraints on strong phases



$\phi_s = -2.37^{+0.38}_{-0.27}$ rad, $-0.75^{+0.27}_{-0.38}$ rad

$\Delta\Gamma_s = -0.150^{+0.66}_{-0.59}$ ps^{-1}, $0.150^{+0.59}_{-0.66}$ ps^{-1}

90% C.L. intervals (1-d regions):

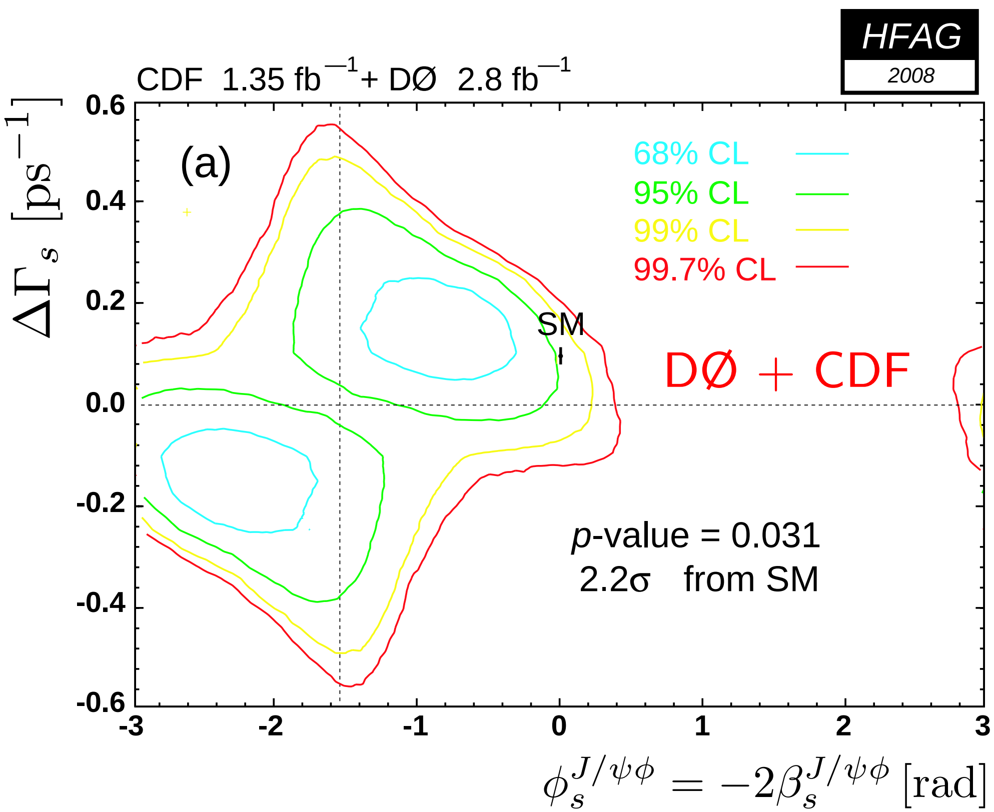
$\phi_s \in [-2.85, -1.65], [-1.47, -0.29]$

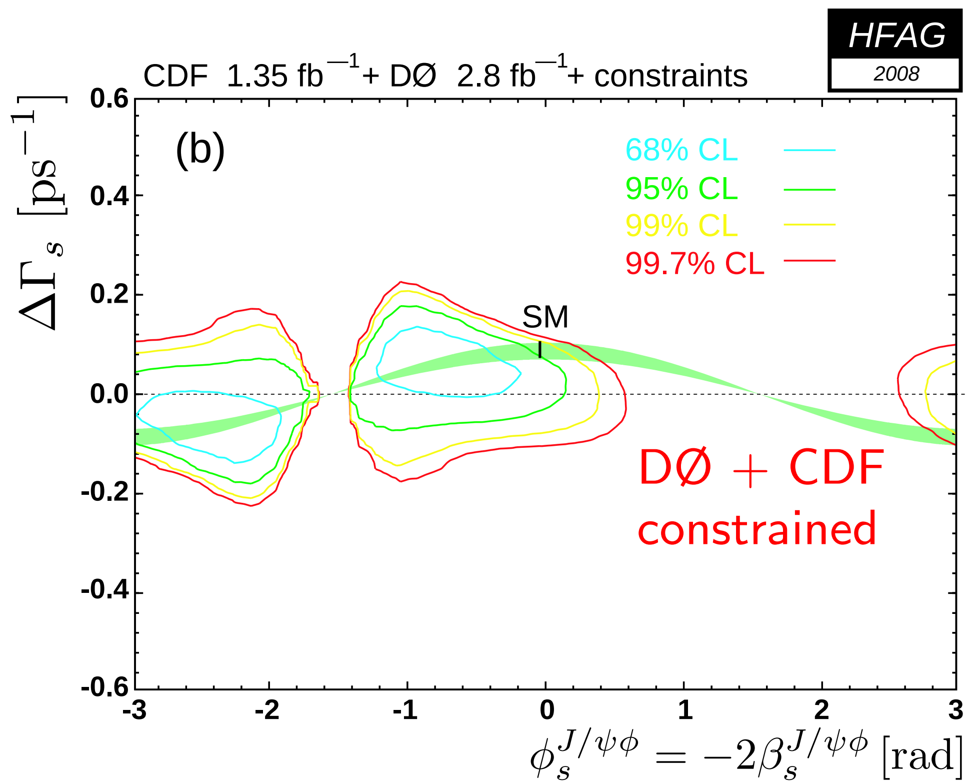
$\Delta\Gamma_s \in [-0.265, -0.036], [0.036, 0.265]$

$\Delta\Gamma_s$ vs. ϕ_s result with constraints from A_{SL}

From measurements of $A^s_{SL} = \frac{N(\bar{B}_s \to \ell^+ X) - N(B_s \to \ell^- X)}{N(\bar{B}_s \to \ell^+ X) + N(B_s \to \ell^- X)} = \frac{\Delta\Gamma_s}{\Delta M_s} \tan\phi_s$

- Fix ΔM_s to measured value and constrain $\Delta\Gamma_s \tan\phi_s$
- World average $A_{SL} = 0.0016 \pm 0.0085$
  - Does not contain new DØ measurement (DØ note 5730-CONF)





Summary

- Tevatron and DØ are performing well (CDF too)

- Dimuon charge asymmetry $A_{B^0} = -0.0092 \pm (0.0044)$ (stat) ± 0.0032 (syst)

- Charge asymmetry in $B_s^0 \to D_s \mu \nu X$ decay: $a_{sl}^s = -0.0024 \pm 0.0117$ (stat) $^{+0.0015}_{-0.0024}$ (syst)

- Charge asymmetry in semileptonic B_s^0 decays
  - $A_{SL}^{s,\text{unt.}} = [1.23 \pm 0.97$ (stat) ± 0.17 (syst)$] \times 10^{-2}$
  - $\frac{\Delta\Gamma_s}{\Delta m_s} \tan \phi_s = [2.45 \pm 1.93$ (stat) ± 0.35 (syst)$] \times 10^{-2}$ (assuming $\Delta m_s / \overline{\Gamma}_s \gg 1$)

- CP violating phase in $B_s^0 \to J/\psi \phi$: $\phi_s = -0.57^{+0.24}_{-0.30}$ (stat) $^{+0.07}_{-0.02}$ (syst) rad
  - New DØ + CDF combined results without strong phase constraints:

  $\sim 2.2\sigma$ deviation from SM: $\phi_s = -2.37^{+0.38}_{-0.27}$ rad, or $\phi_s = -0.75^{+0.27}_{-0.38}$ rad

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