B-Physics at the Tevatron

John Ellison
University of California, Riverside
for the CDF and DØ Collaborations

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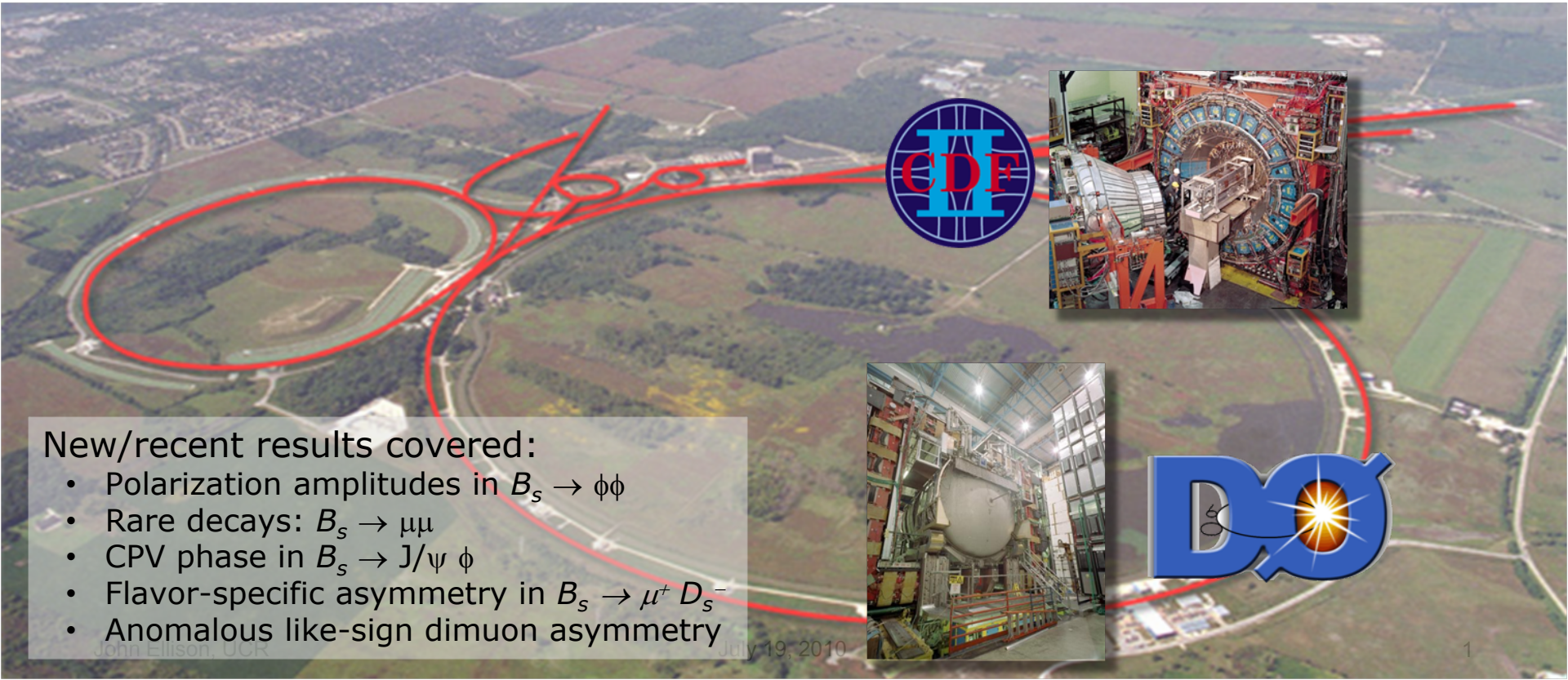


New/recent results covered:

- Polarization amplitudes in $B_s \to \phi\phi$
- Rare decays: $B_s \to \mu\mu$
- CPV phase in $B_s \to J/\psi\ \phi$
- Flavor-specific asymmetry in $B_s \to \mu^+ D_s^-$
- Anomalous like-sign dimuon asymmetry

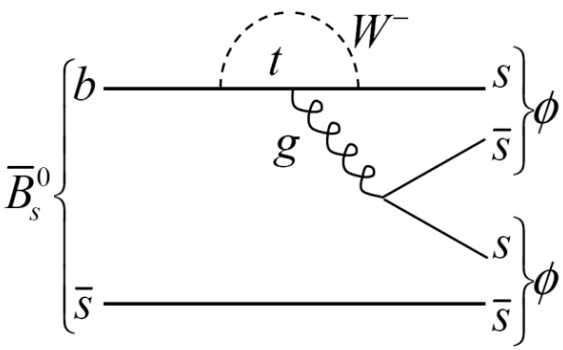
$B_s \to \phi\phi$

- Penguin $b \to s$ transition

  $P \to VV$: three polarization amplitudes

  A_0 $A_\parallel$ $A_\perp$

  Longitudinal Transverse



- "Polarization puzzle"
  - SM expectation: $|A_0|^2 \gg |A_\parallel|^2 \approx |A_\perp|^2$
    - confirmed in $b \to u$ tree-level decays
    - evidence in $b \to d$ penguin decays

  while for $b \to s$ find $|A_0|^2 \approx |A_\parallel|^2 \approx |A_\perp|^2$

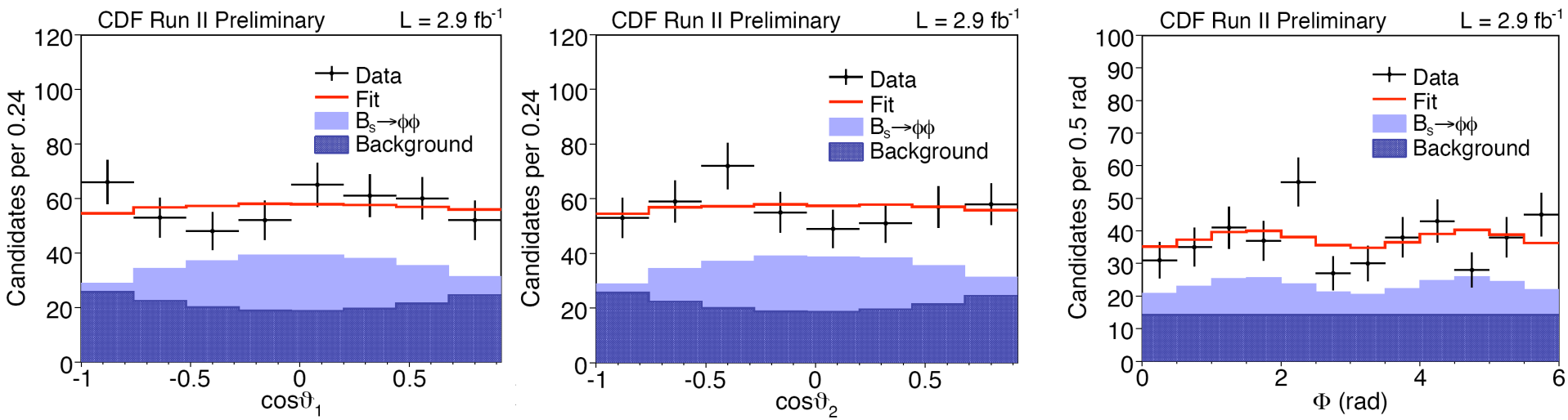
- Use $B_s \to \phi\phi$ decays to check

- Also, comparisons of CPV phase in $B_s \to \phi\phi$ and $B_s \to J/\psi\,\phi$ possible in future

$B_s \to \phi\phi$

- CDF new result: select $B_s \to \phi\phi \to [K^+ K^-]\,[K^+ K^-]$ from hadronic two-track trigger, 2.9 fb^{-1}

- Measure polarization amplitudes from fit to mass and 3 decay angles ($\vartheta_1, \vartheta_2, \Phi$) of reconstructed B_s decay products



$B_s \to \phi\phi$ Results

- Fit results:

$$
\begin{aligned}
|A_0|^2 &= 0.348 \pm 0.041(\text{stat}) \pm 0.021(\text{syst}) \\
|A_{\parallel}|^2 &= 0.287 \pm 0.043(\text{stat}) \pm 0.011(\text{syst}) \\
|A_{\perp}|^2 &= 0.365 \pm 0.044(\text{stat}) \pm 0.027(\text{syst}) \\
\cos\delta_{\parallel} &= -0.91^{+0.15}_{-0.13}(\text{stat}) \pm 0.09(\text{syst})
\end{aligned}
$$

CDF Run II Preliminary
CDF Note 9892

- Expected SM prediction disfavored:

$$|A_0|^2 \approx |A_{\parallel}|^2 \approx |A_{\perp}|^2 \quad \text{instead of} \quad |A_0|^2 \gg |A_{\parallel}|^2 \approx |A_{\perp}|^2$$

$$1 - |A_0|^2 \propto |A_{\parallel}|^2 + |A_{\perp}|^2$$

- Comparison with various models

	$\lvert A_0\rvert^2$ [%]	$1 - \lvert A_0\rvert^2$ [%]
CDF Run II	$34.8 \pm 4.1(\text{stat}) \pm 2.1(\text{syst})$	$65.2 \pm 4.1(\text{stat}) \pm 2.1(\text{syst})$
QCD factorization (2007) [a]	48^{+0+26}_{-0-27}	52^{+0+26}_{-0-27}
QCD factorization (2008) [b]	34 ± 28	66 ± 28
Naive factorization [c]	88.3	11.7
NLO EWP [d]	86.3	13.7
perturbative QCD [e]	$61.9^{+3.6+2.5+0.0}_{-3.2-3.3-0.0}$	$38.1^{+3.6+2.5+0.0}_{-3.2-3.3-0.0}$

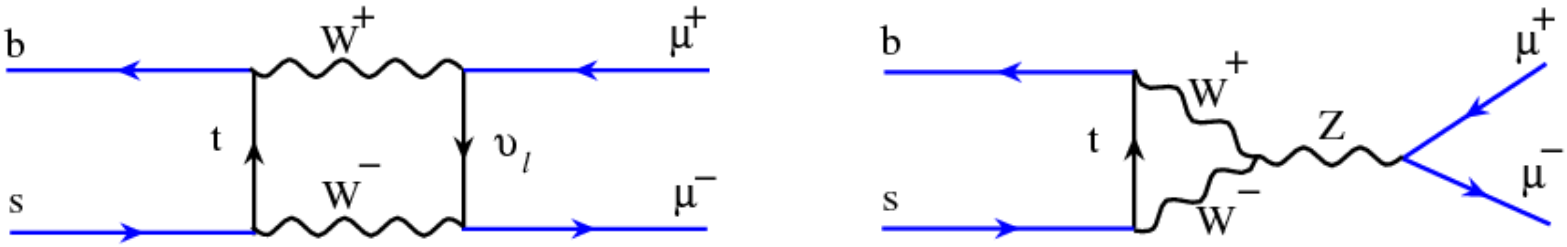
a M. Beneke et al., *Nucl. Phys. B* **774** 64 (2007)
b A. Datta et al., *Eur. Phys. J. C* **60** 279 (2009)
c X. Li et al., *Phys. Rev. D* **71** 019902(E) (2005)
d D. Du and L. Guo, *J. Phys. G* **23** 525 (1997)
e Ali et al., *Phys. Rev. D* **6** 074018 (2007)

Naïve QCD calculation does not agree with data

QCD factorization seems to give better description

$B_{s,d} \to \mu^+\mu^-$

- FCNC processes, via GIM-suppressed box and penguin diagrams:



suppressed by $|V_{td} / V_{ts}|^2$

- Rare decays with very small branching fractions

- SM predictions: [A.J. Buras, *Prog. Theor. Phys.* **122**, 145 (2009)]

$$Br[B_s^0 \to \mu^+\mu^-] = (3.6 \pm 0.3) \times 10^{-9}$$

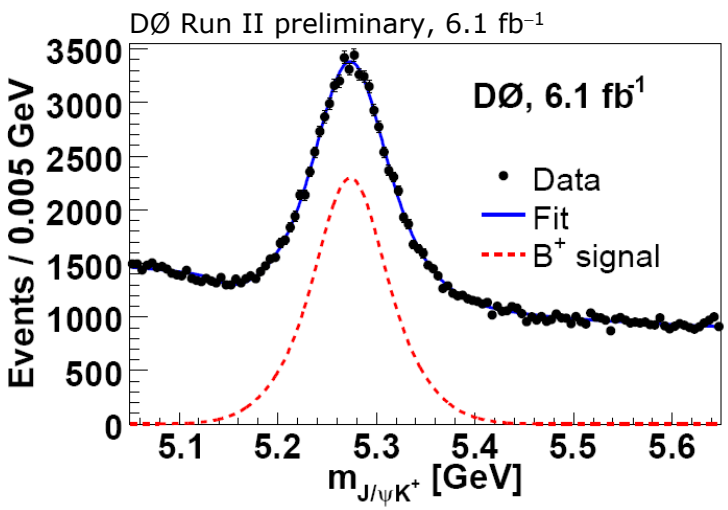
$$Br[B^0 \to \mu^+\mu^-] = (1.1 \pm 0.1) \times 10^{-10}$$

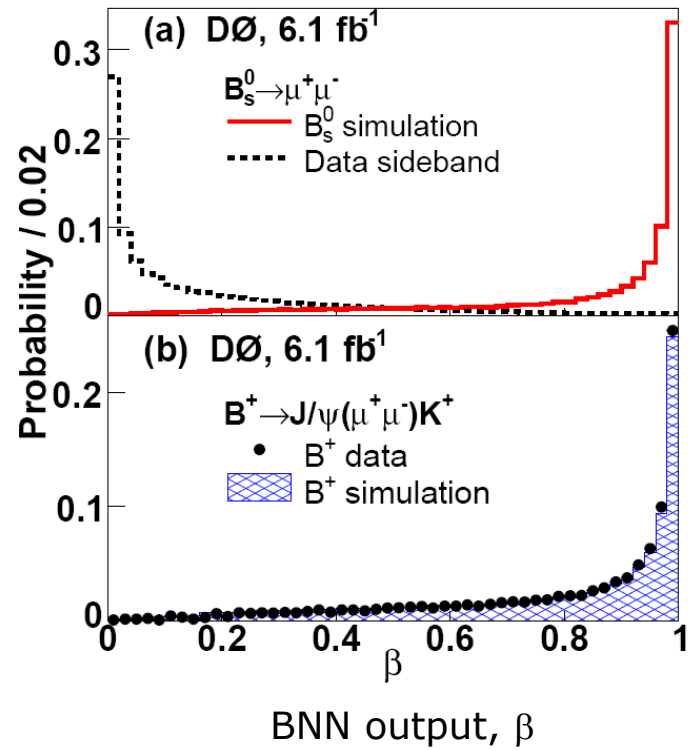
  - SM signal is beyond the current sensitivity of DØ/CDF at the Tevatron
  - But new physics can significantly enhance Br, e.g. MSSM (~$\tan^6\beta$), SUSY R-parity violating models, GUTs, …

- Current observation of $B \to \mu^+\mu^-$ would imply new physics

$B_s \to \mu^+\mu^-$ Analysis

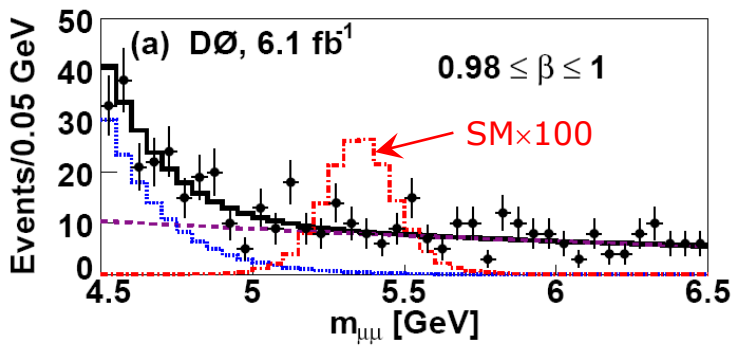
- New DØ result based on 6.1 fb^{-1}
- Use Bayesian neural network with 5 variables:
  - B_s transverse momentum and pointing angle; vertex χ^2 and transverse decay length significance; smallest i.p significance of the two muons
- Control sample of $B^+ \to J/\psi[\to \mu^+\mu^-]K^+$ events used for normalization





$B_{s,d} \to \mu^+\mu^-$ Results

- DØ Result from new analysis
  Blinded analysis



$$Br[B_s^0 \to \mu^+\mu^-] < 5.1\times10^{-8} \text{ at 95\% C.L.}$$
$$(3.8\times10^{-8} \text{ expected})$$

New result, arXiv:1006.3469, submitted to PLB

- CDF preliminary results from 3.7 fb^{-1} analysis

$$Br[B_s^0 \to \mu^+\mu^-] < 4.3\times10^{-8} \text{ at 95\% C.L.}$$
$$(3.3\times10^{-8} \text{ expected})$$
$$Br[B^0 \to \mu^+\mu^-] < 7.6\times10^{-9} \text{ at 95\% C.L.}$$
$$(9.1\times10^{-9} \text{ expected})$$

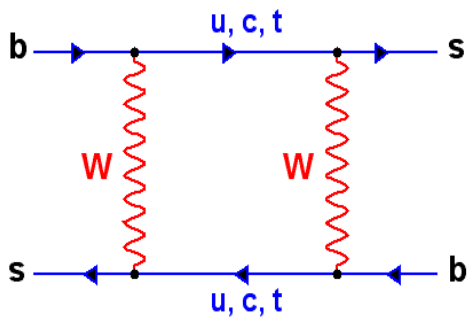
CDF Run II Preliminary
CDF Note 9892

CP Violation via B_s Mixing

$$B_s^0 \Leftrightarrow \bar{B}_s^0$$

Schrödinger Equation:

$$i\frac{d}{dt}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix} = \begin{pmatrix} M_{11}^s - \frac{i}{2}\Gamma_{11}^s & M_{12}^s - \frac{i}{2}\Gamma_{12}^s \\ M_{12}^{s*} - \frac{i}{2}\Gamma_{12}^{s*} & M_{11}^s - \frac{i}{2}\Gamma_{11}^s \end{pmatrix}\begin{pmatrix} B_s^0 \\ \bar{B}_s^0 \end{pmatrix}$$



- Mass eigenstates:

$$|B_{sL}\rangle = p|B_s^0\rangle + q|\bar{B}_s^0\rangle \quad \approx CP \text{ even}$$

$$|B_{sH}\rangle = p|B_s^0\rangle - q|\bar{B}_s^0\rangle \quad \approx CP \text{ odd}$$

- Observables:

$$\Delta M_s = 2|M_{12}^s|$$

$$\Delta\Gamma_s = 2|\Gamma_{12}^s|\cos\phi_s$$

$$\phi_s = \arg(-M_{12}^s/\Gamma_{12}^s)$$

$$\phi_s^{J/\psi\phi} = \arg(-M_{12}^s)$$

- CPV in mixing: |q/p| ≠ 1 $\quad \phi_s \simeq 0.0042$ (in SM)[1]

- CPV via interference between mixing and decay:

$$\begin{tikzcd} |B_s^0\rangle \arrow[rr, "\sin 2\beta_s"] \arrow[dr, "\text{mix}"'] & & J/\psi\,\phi \\ & |\bar{B}_s^0\rangle \arrow[ur] & \end{tikzcd}$$

$$\phi_s^{J/\psi\phi} = -2\beta_s = -2\arg\left(-\frac{V_{ts}V_{tb}^*}{V_{cs}V_{cb}^*}\right) \approx -0.04 \text{ (in SM)}^1$$

- If new CPV phase from physics:

$$\phi_s \to \phi_s - \phi_s^{NP}$$

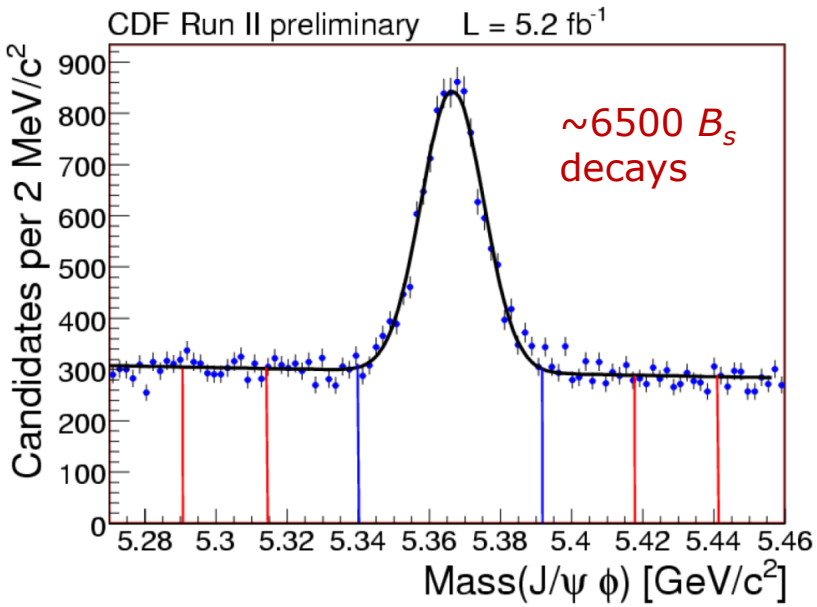
$$2\beta_s \to 2\beta_s^{SM} - \phi_s^{NP}$$

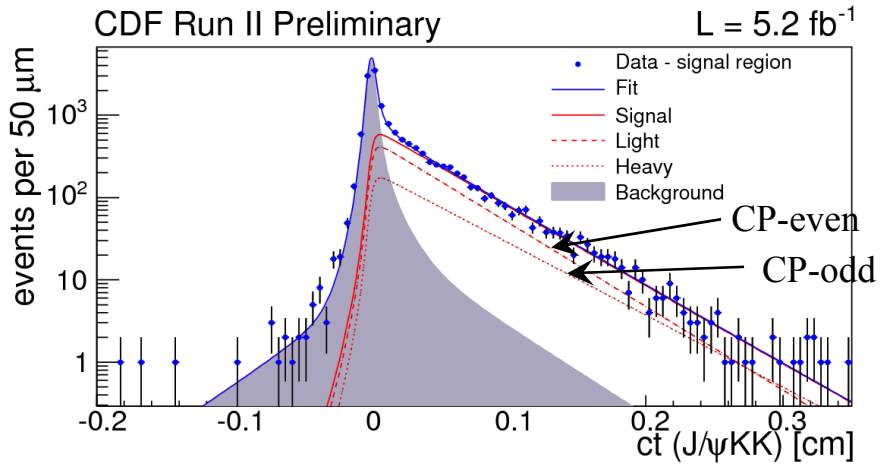
[1] A. Lenz and U. Nierste, JHEP **06**, 072, (2007), arXiv:0612167

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

- New CDF analysis, 5.2 fb^{-1}

$$J/\psi \to \mu^+\mu^- \quad \phi \to K^+K^-$$





- Use a maximum likelihood fit to mass, lifetime, and 3 decay angles
  - Allows separation of CP-even and CP-odd components
  - ΔM_s constrained to measured value
- B_s flavor at production determined using opposite-side + same-side tagging

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

- Improvements over previous (2.8 fb^{-1}) analysis:
  - Include potential contamination of signal by $B_s \to J/\psi\, KK$ (KK non-resonant) and $B_s \to J/\psi\, f_0$, where KK and f_0 are S-wave states
  - Improvements in NN selection
  - Optimization and full calibration of particle ID and flavor tagging

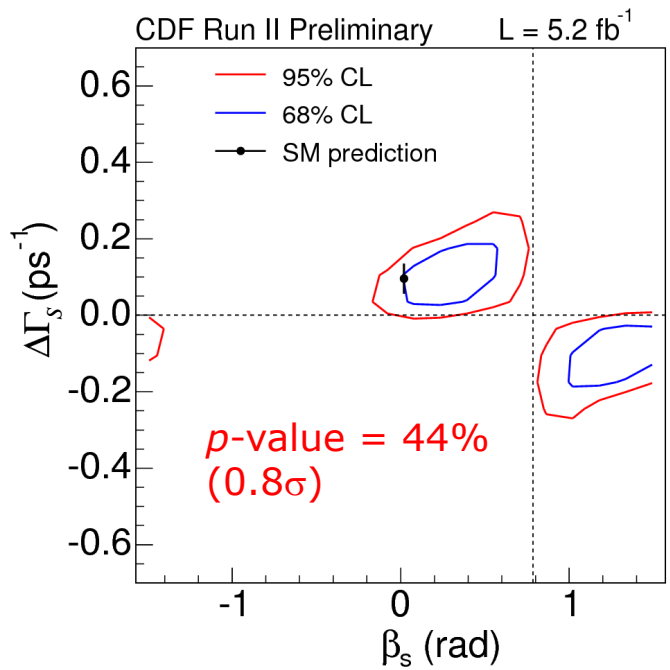
- Results of fit

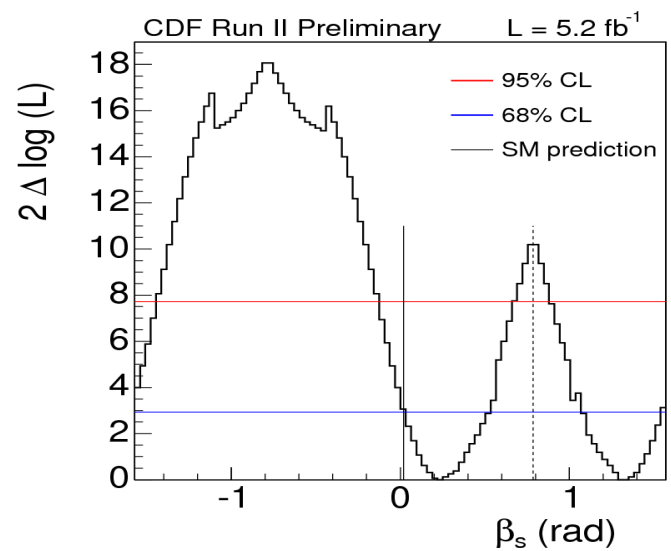
$$\bar{\tau}(B_s^0) = 1.53 \pm 0.025\ (\text{stat.}) \pm 0.012\ (\text{syst.})\ \text{ps}$$
$$\Delta\Gamma_s = 0.075 \pm 0.035\ (\text{stat.}) \pm 0.01\ (\text{syst.})\ \text{ps}^{-1}$$

assumimg $\beta_s = 0$

- Bounds on CP violating phase:

$$\beta_s = [0.02,\ 0.52] \cup [1.08,\ 1.55] \quad \text{at 68\% C.L.}$$
$$\beta_s = [-\pi/2,\ -1.44] \cup [-0.13,\ 0.68] \cup [0.89,\ \pi/2] \quad \text{at 95\% C.L.}$$





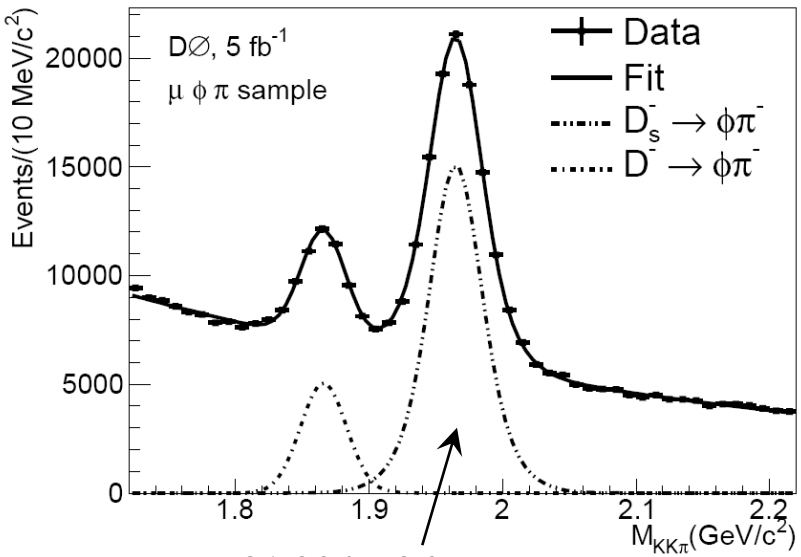
CPV in Semileptonic B_s Decays

- Search for CP Violation in $B_s^0 \to D_s^- \mu^+ \nu X$, $(D_s^- \to \phi\pi^-$ or $K^* K^-)$ from measurement of the flavor-specific asymmetry using a time-dependent analysis with flavor tagging

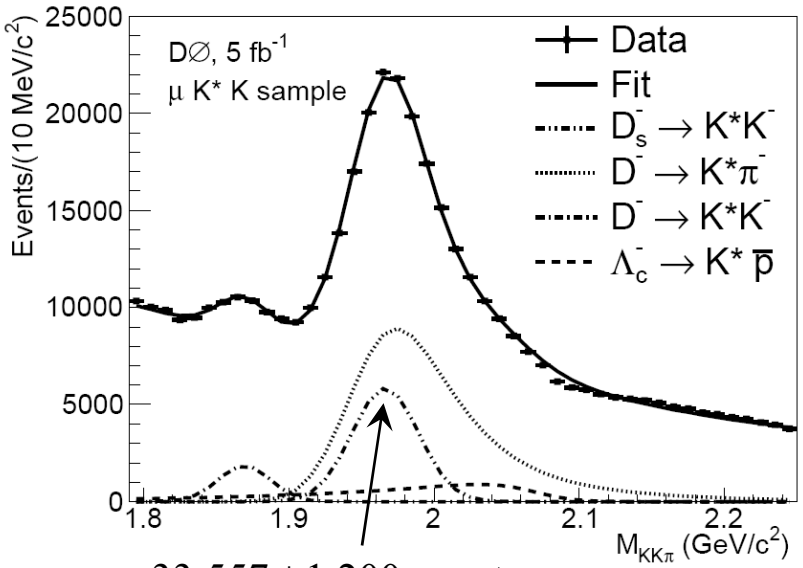
$$a_{fs}^s = \frac{\Gamma(\bar{B}_s^0(t) \to f) - \Gamma(B_s^0(t) \to \bar{f})}{\Gamma(\bar{B}_s^0(t) \to f) + \Gamma(B_s^0(t) \to \bar{f})}$$

Related to CPV phase: $a_{fs}^s = \frac{\Delta\Gamma_s}{\Delta m_s} \tan\phi_s$

- DØ search (5 fb^{-1}): technique similar to B_s oscillation analysis, modified to include CPV and study of detector asymmetries

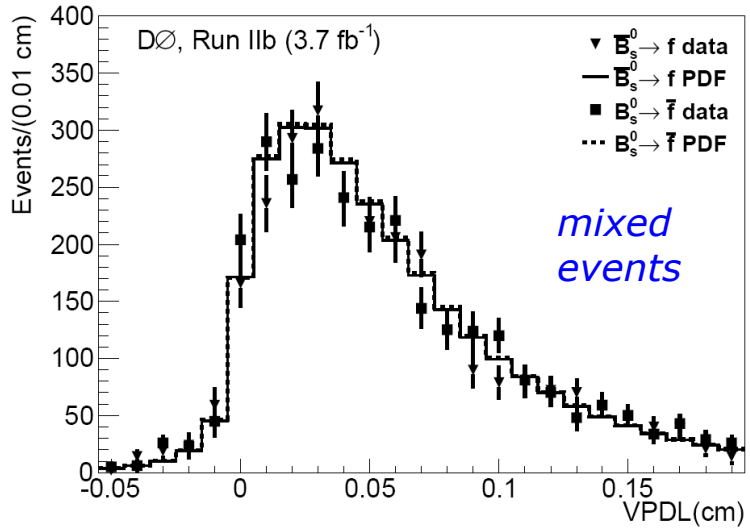


$81{,}394 \pm 865$ events



$33{,}557 \pm 1{,}200$ events

Flavor-Specific Asymmetry



$f = \mu^- X$

$\bar{f} = \mu^+ X$

Visible Proper Decay Length (cm)

- Result of time-dependent fit:

$$a_{fs}^s = -0.0017 \pm 0.0091\ (\text{stat.})\ ^{+0.0014}_{-0.0015}\ (\text{syst.})$$

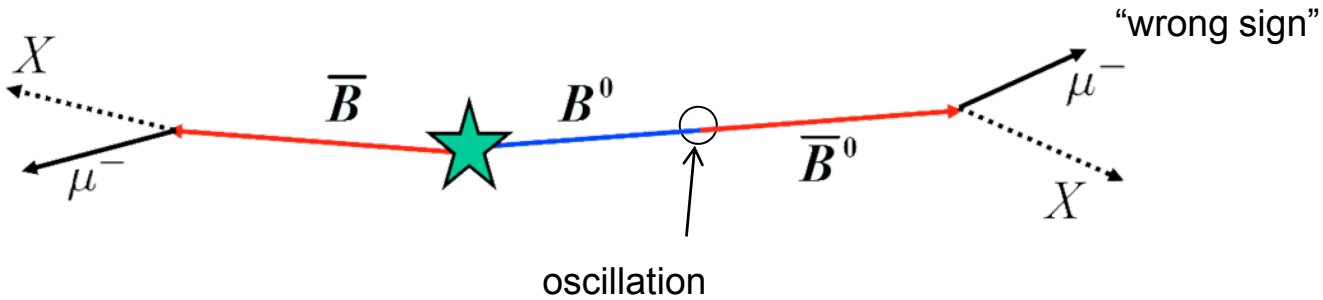
  - Most precise measurement to date

    arXiv:0904.3907, accepted by PRD

- cf. SM prediction: $a_{fs}^s = (-2.06 \pm 0.57) \times 10^{-5}$

  A. Lenz and U. Nierste, JHEP **06**, 072, (2007)

Like-Sign Dimuon Asymmetry



- Measure CPV in mixing using the dimuon charge asymmetry of semileptonic B decays:

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

- Contributions from B_d and B_s: $A_{sl}^b = (0.506 \pm 0.043) a_{sl}^d + (0.494 \pm 0.043) a_{sl}^s$

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

"wrong-sign" semileptonic charge asymmetries

- SM prediction is very small $A_{sl}^b = (-2.3^{+0.5}_{-0.6}) \times 10^{-4}$
  - New physics can change this value by changing the CPV phases

$$a_{sl}^q = \frac{\Delta\Gamma_q}{\Delta M_q} \tan\phi_q$$

Measurement Strategy

- Measure two raw asymmetries:
  - Like-sign dimuon asymmetry $A = \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = (0.564 \pm 0.053)\%$

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

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

    (From 1.5×10^9 muons in inclusive sample)

- Relation to A_{sl}^b:

$$A = K\, A_{sl}^b + A_{\text{bkg}}$$

$$a = k\, A_{sl}^b + a_{\text{bkg}}$$

Non-symmetric background processes from "prompt/physics" sources – measured from data

Dilution due to other processes that do not contribute to asymmetry – measured from simulation of b- and c-quark decays (K >> k)

- Backgrounds

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

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

Background from kaons is dominant (others ~10 times smaller) – measured from data with minimal input from MC

- Blinded analysis
  - Central value of A_{sl}^b extracted from full dataset only after analysis method and uncertainties finalized

Result

$$A_{sl}^{b} = (-0.957 \pm 0.251\ (\text{stat.}) \pm 0.146\ (\text{syst.}))\%$$

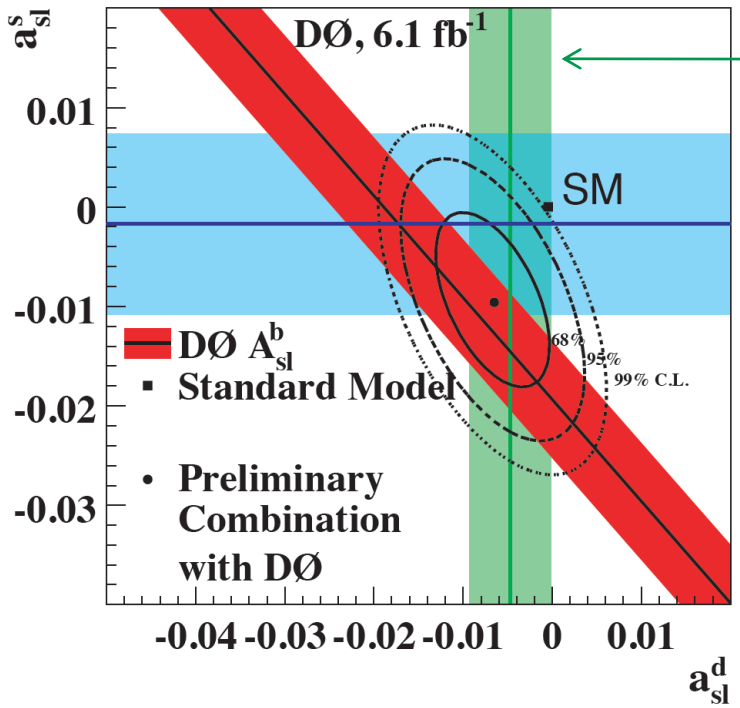
3.2σ deviation from SM

DØ Run II
arXiv:1007.0395, submitted to PRL
arXiv:1005.2757, accepted by PRD

compared with SM prediction: $A_{sl}^{b} = -0.023^{+0.005}_{-0.006}\ \%$

A. Lenz and U. Nierste, JHEP **06**, 072, (2007)

- Comparison with other measurements:



World average a_{sl}^{d} from Babar and Belle

DØ direct measurement of a_{sl}^{s} (p.12)

Summary and Outlook

Significant advances in B-physics at the Tevatron, complementary to B-factories

e.g. new/recent measurements reported here:

- First measurements of $B_s \to \phi\phi$
- Search for FCNC in $B_s \to \mu^+\mu^-$ $\quad Br[B_s^0 \to \mu^+\mu^-] < 5.1\times10^{-8}$ at 95% C.L.
- Search for CP violation:

$$B_s^0 \to D_s^- \mu^+ \nu X \qquad a_{fs}^s = -0.0017 \pm 0.0091\ (\text{stat.})\ ^{+0.0014}_{-0.0015}\ (\text{syst.})$$

$$B_s^0 \to J/\psi\,\phi \qquad \beta_s = [0.02,\ 0.52] \cup [1.08,\ 1.55] \quad \text{at 68\% C.L.}$$

- Anomalous like-sign dimuon asymmetry:

$$A_{sl}^b = (-0.957 \pm 0.251\ (\text{stat.}) \pm 0.146\ (\text{syst.}))\%$$

3.2σ deviation from SM !

The Tevatron is running very well and prospects look good

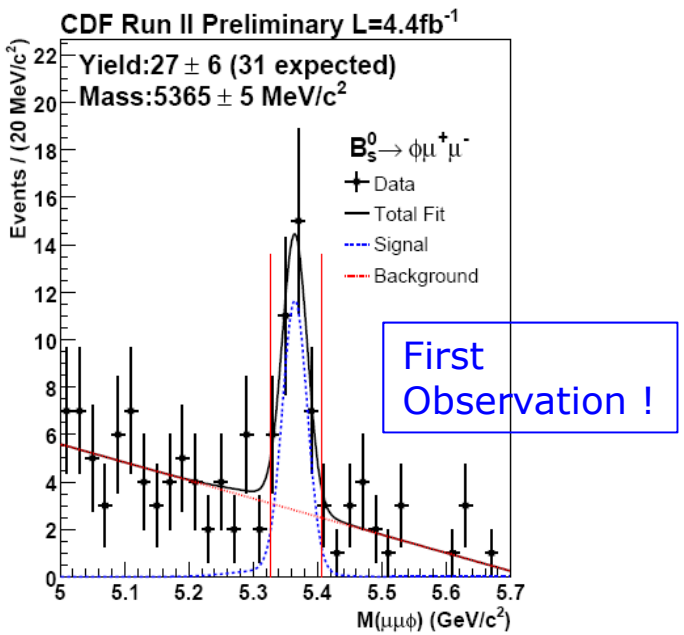
- Planning to run through 2011 – up to ~10 fb^{-1}
- Extended running to 2014 under consideration

Extra Slides

$B_s \to \phi\mu^+\mu^-$ and $B \to K^{(*)}\mu^+\mu^-$

- Recent preliminary measurements by CDF

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

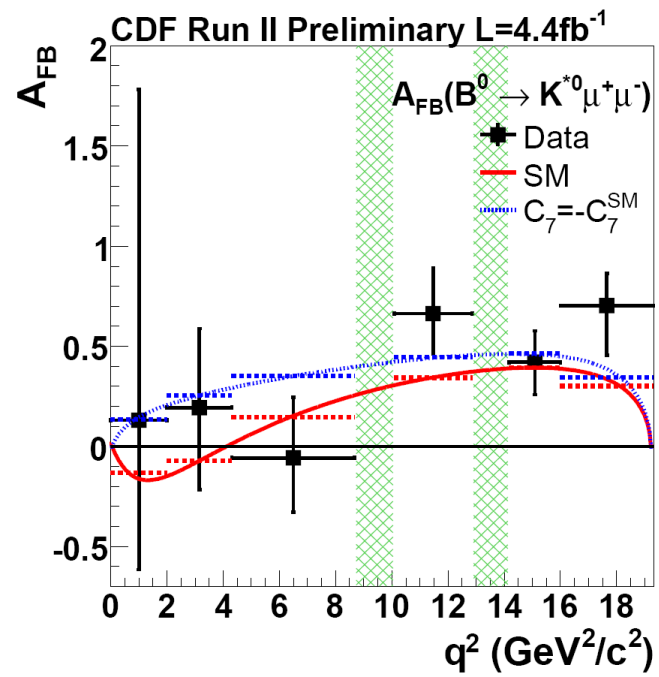


Forward-backward asymmetry in $B^0 \to K^{*0}\mu^+\mu^-$

Sensitive to NP contributions

Competitive with B-factories

$$B^0 \to K^{*0}(K^+\pi^-)\mu^+\mu^-$$



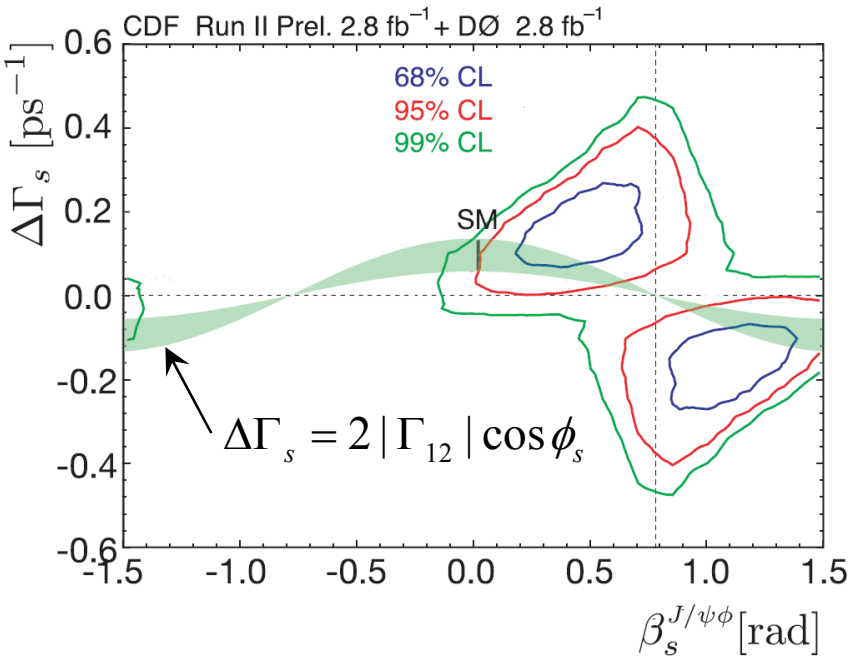
$$Br[B_s^0 \to \phi\mu^+\mu^-] = (1.44 \pm 0.33^{\text{stat}} \pm 0.46^{\text{syst}}) \times 10^{-6}$$
$$Br[B^0 \to K^{*0}\mu^+\mu^-] = (1.06 \pm 0.14^{\text{stat}} \pm 0.09^{\text{syst}}) \times 10^{-6}$$
$$Br[B^+ \to K^+\mu^+\mu^-] = (0.38 \pm 0.05^{\text{stat}} \pm 0.03^{\text{syst}}) \times 10^{-6}$$

Measurements consistent with SM and B-factories

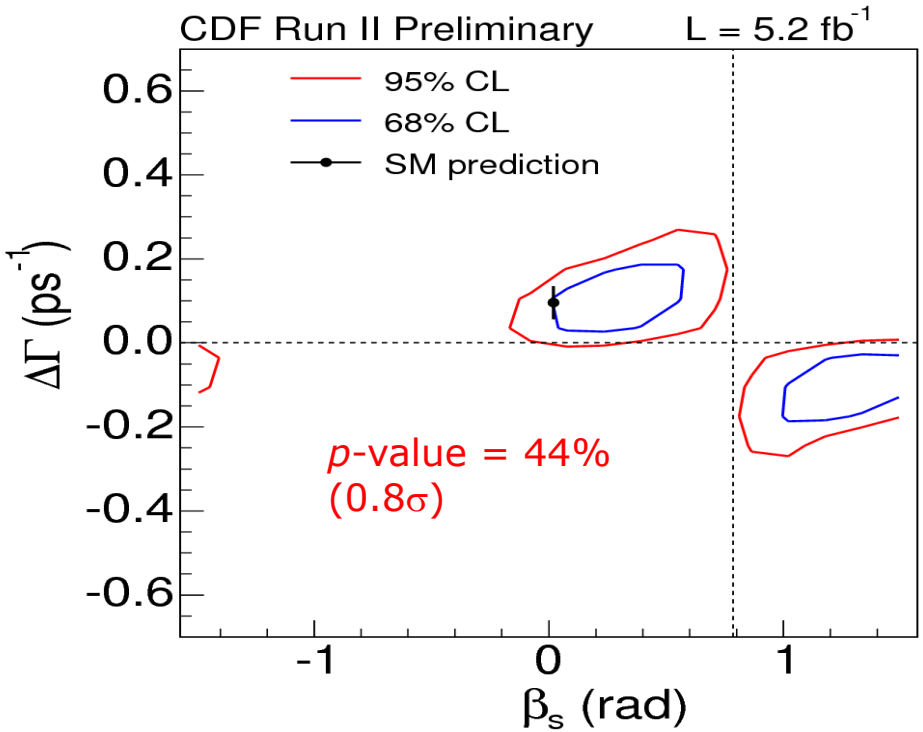
CDF Note 10047

$$q^2 = m_{\mu\mu}^2$$

Comparison with Previous Results



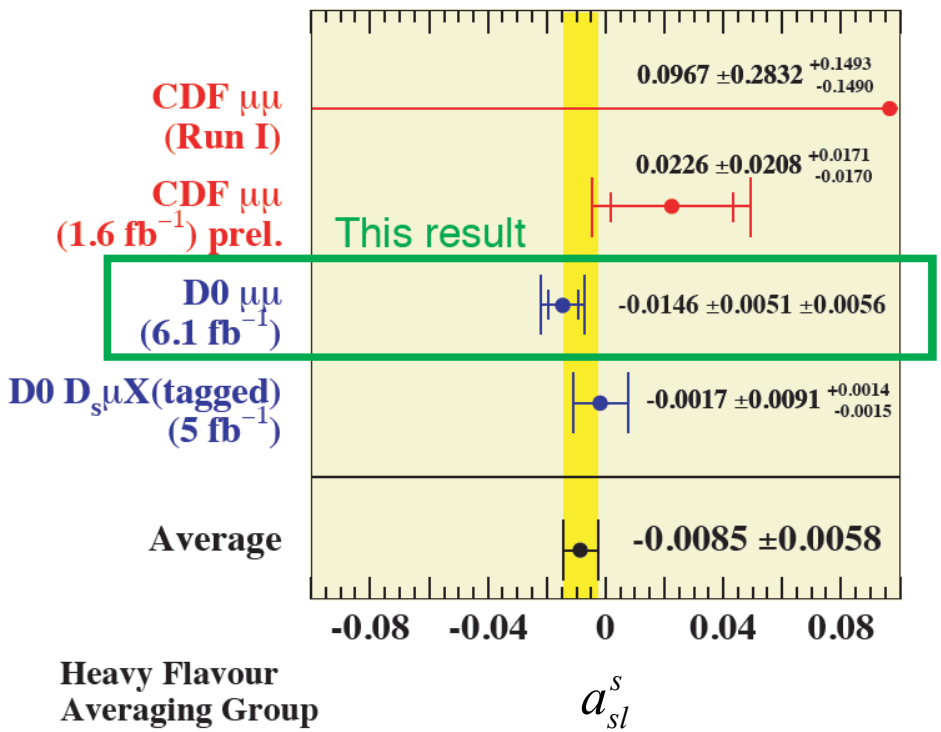
p-value = 3.4% (2.12σ from SM)



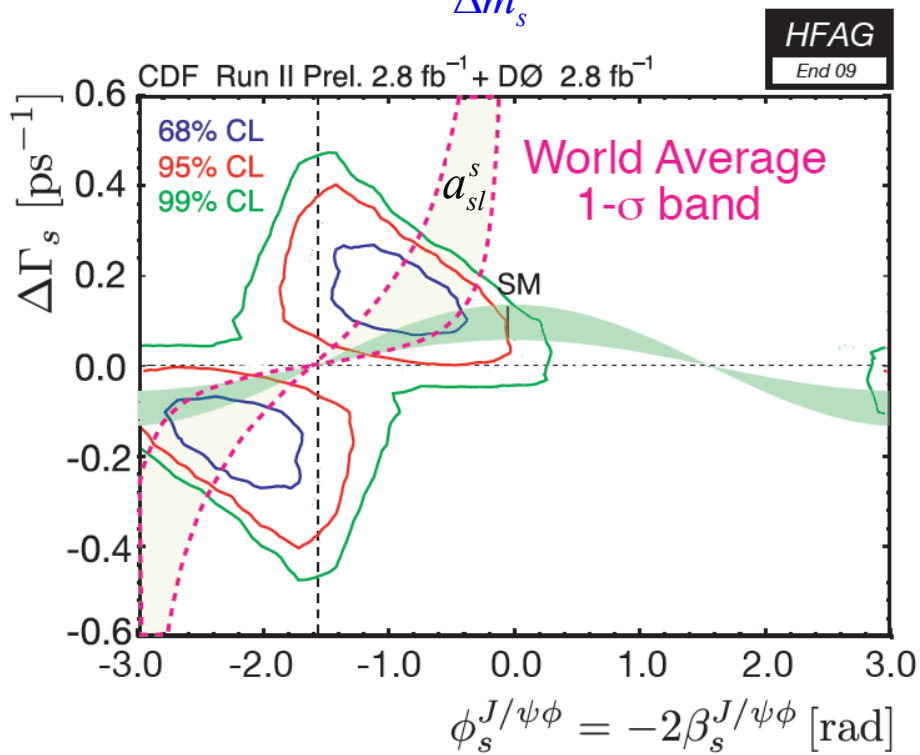
Comparison with a^s_{sl} and $B_s \to J/\psi\ \phi$

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

Extract a^s_{sl} from A^b_{sl} using WA a^d_{sl} :



$$a^s_{sl} = \frac{\Delta\Gamma_s}{\Delta m_s}\tan\phi_s$$



(Does not include CDF 5.2 fb^{-1} update)