ICHEP-2010 , 27 July 2010

Beyond the Standard Model searches through *B* physics at Tevatron

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on behalf of CDF and DØ collaborations

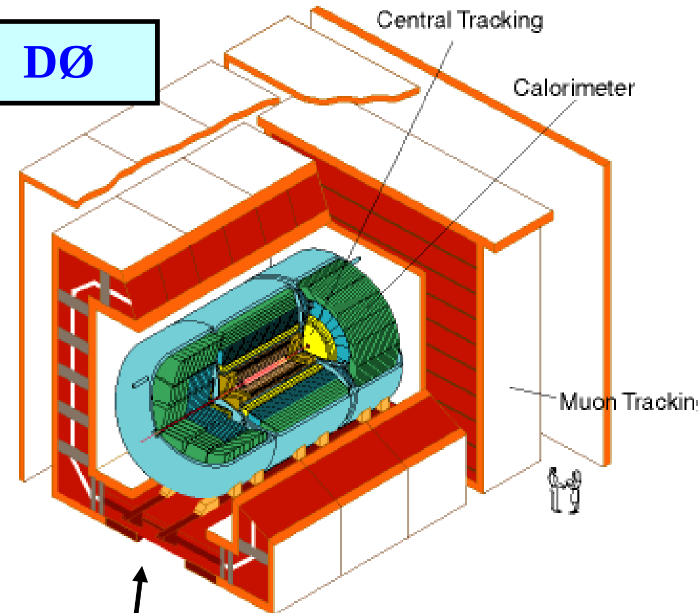
Flavour of New Physics

- The first flavour of new phenomena often comes from flavour physics
  - Weak decays of light hadrons – existence of charm quark
  - CP violation – third quark family
  - B^0 meson oscillation – heavy top quark
- *B* mesons are especially suitable for the beyond SM searches
  - Large mass of b quark – stronger coupling to new particles
  - Abundant production
  - Well developed technique of experimental selection
- B_s meson – "golden particle" for new physics searches
  - SM value of many B_s observables is suppressed
  - Many theories predict large NP contribution
  - Large CKM parameters amplify possible new effects

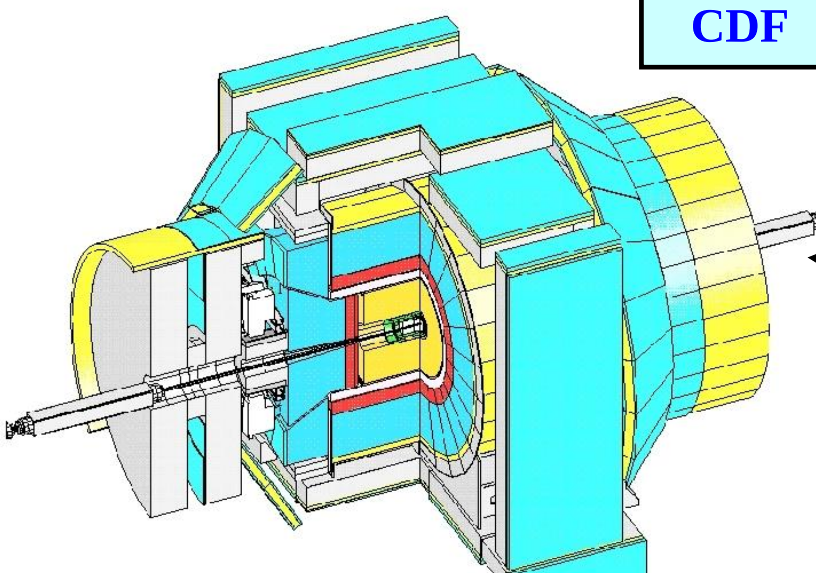
In this talk

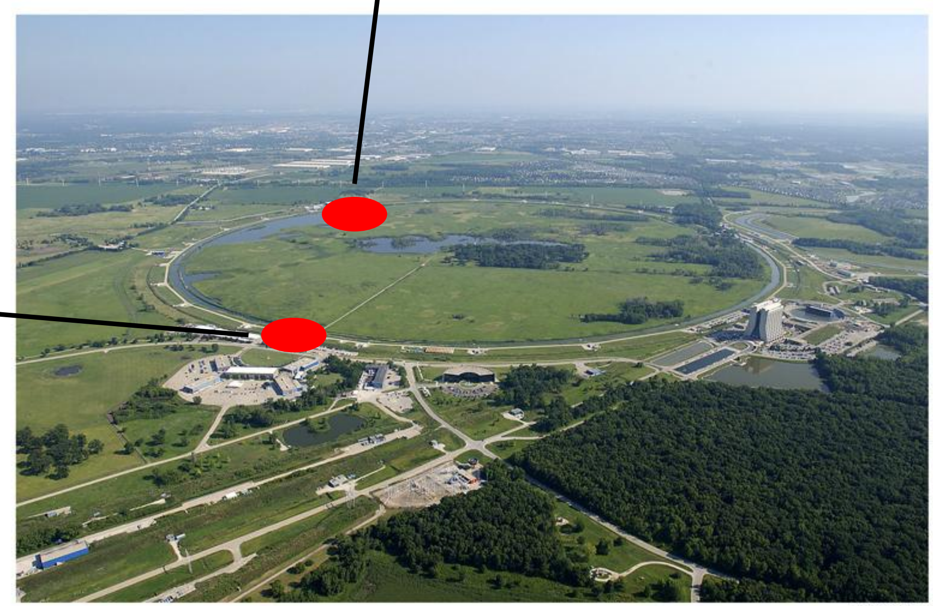
- New results from Tevatron are reviewed:
  - Rare decays
    - $B_{s,d} \rightarrow \mu^+ \mu^-$
    - $b \rightarrow s \mu^+ \mu^-$
  - CP Violation
    - Dimuon charge asymmetry A^b_{sl}
    - $B_s \rightarrow J/\psi\ \varphi$
    - $B_s \rightarrow \varphi\ \varphi$

DØ



CDF





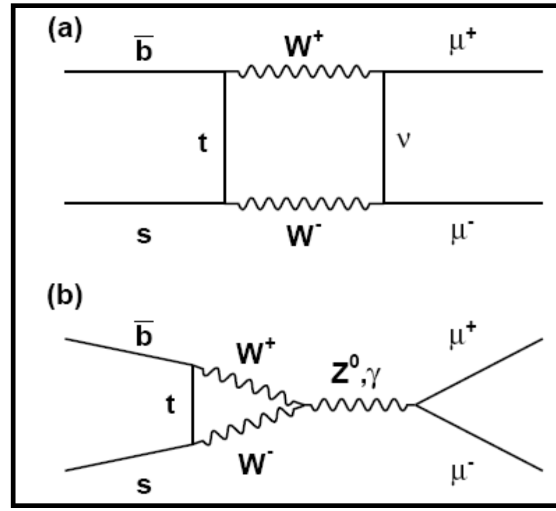
gh B]

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

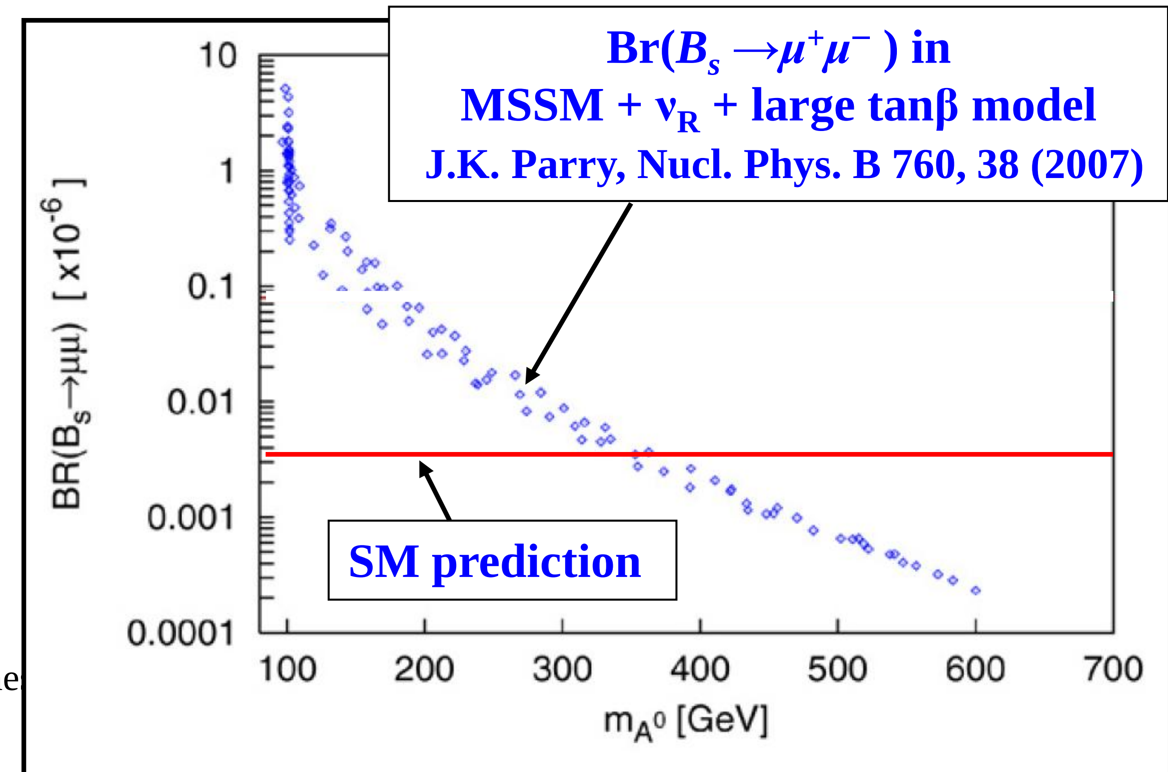
- Very small branching fraction in SM
  - Only loop diagrams contribute

$$\mathrm{Br}(B_s \to \mu^+\mu^-) = (3.6 \pm 0.3) \times 10^{-9}$$
$$\mathrm{Br}(B_d \to \mu^+\mu^-) = (1.1 \pm 0.1) \times 10^{-10}$$

  - A. Buras, Prog. Theor. Phys. 122, 145(2009)



- New physics can significantly modify this prediction
  - MSSM
  - SO(10)
  - SUSY R-parity violating models
  - ...

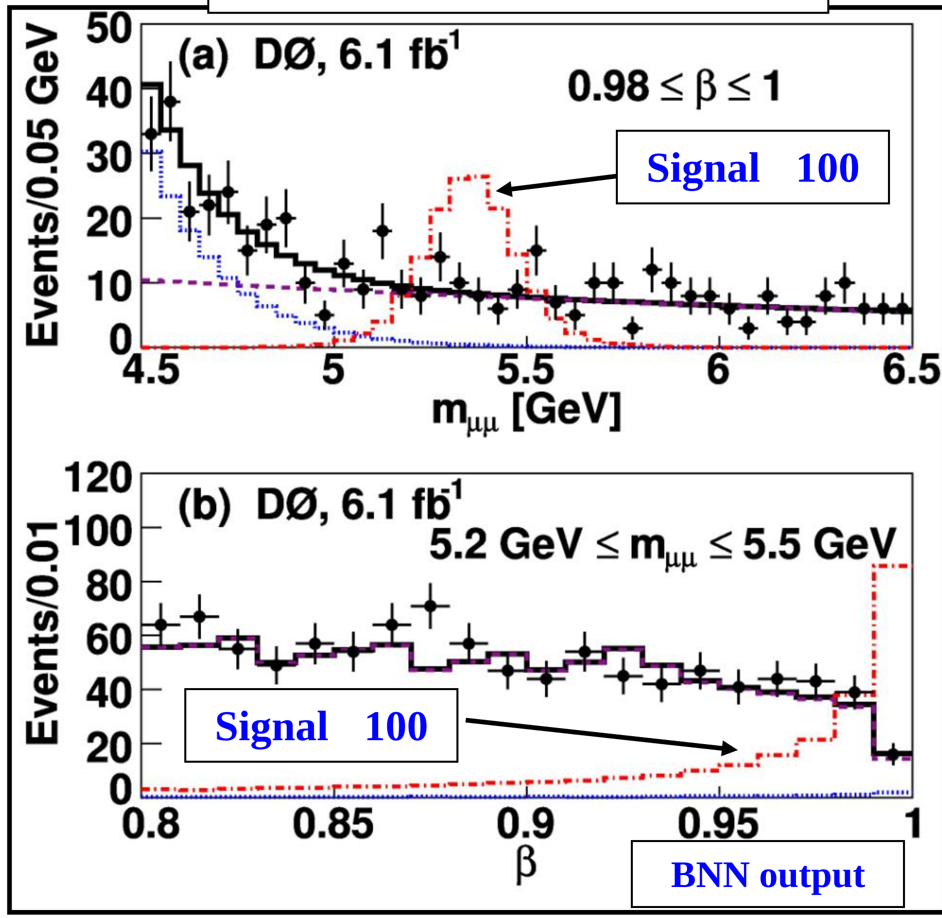


$B_s \to \mu^+\mu^-$ (DØ)

B. Casey, ICHEP-2010,
DØ Collab., arXiv:1006.3469

- 6.1 fb^{-1} of data analyzed
- Many improvements of analysis compared to previous published result
  - Improved muon identification and trigger selection
  - Bayesian NN is used instead of Likelihood ratio method
  - Limits are calculated in several bins of BNN variable and M(μμ)

$$\text{Br}(B_s \to \mu^+\mu^-) < 5.1\times10^{-8}\,(95\%\ C.L.)$$
$$\text{Expected}\ :\ 4.2\times10^{-8}\,(95\%\ C.L.)$$



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

- 3.7 fb^{-1} of data analyzed
- Several discriminating variables are combined in NN
  - ~ 25% better background rejection than in likelihood ratio method
- Limits are calculated in several bins of NN variable and M(μμ)
  - ~15% improvement in sensitivity

$$Br(B_s \to \mu^+\mu^-) < 4.3 \times 10^{-8} (95\%\ C.L.)$$

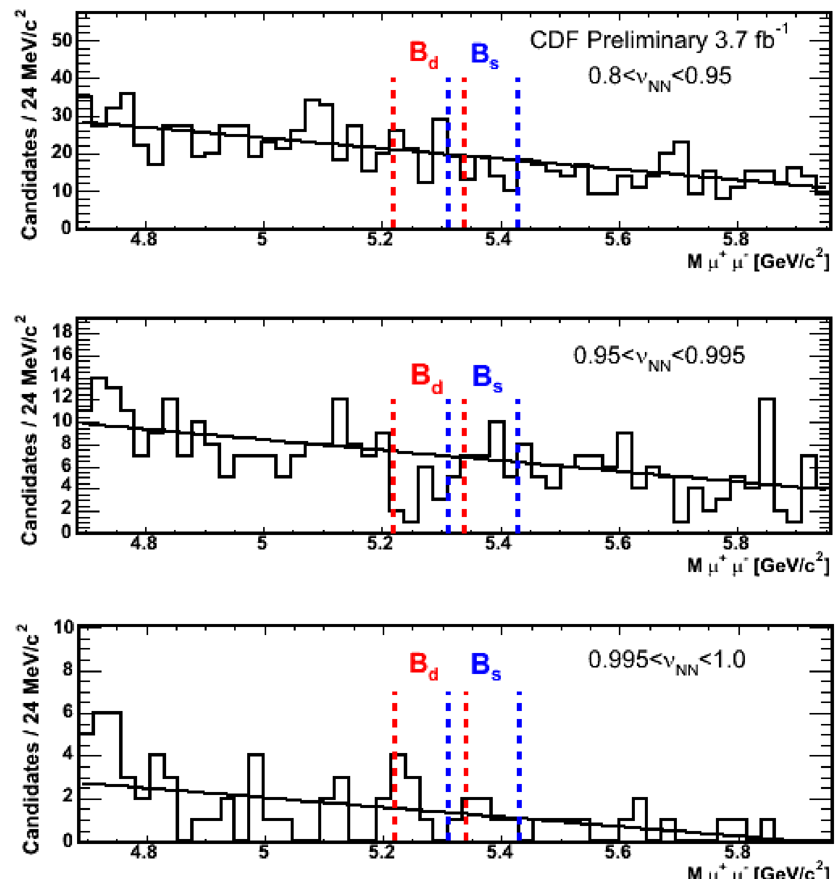
$$\text{Expected} : 3.3 \times 10^{-8} (95\%\ C.L.)$$

$$Br(B_d \to \mu^+\mu^-) < 7.6 \times 10^{-9} (95\%\ C.L.)$$

$$\text{Expected} : 9.1 \times 10^{-9} (95\%\ C.L.)$$

World's best upper limit on $Br(B_s \to \mu^+\mu^-)$ and $Br(B_d \to \mu^+\mu^-)$

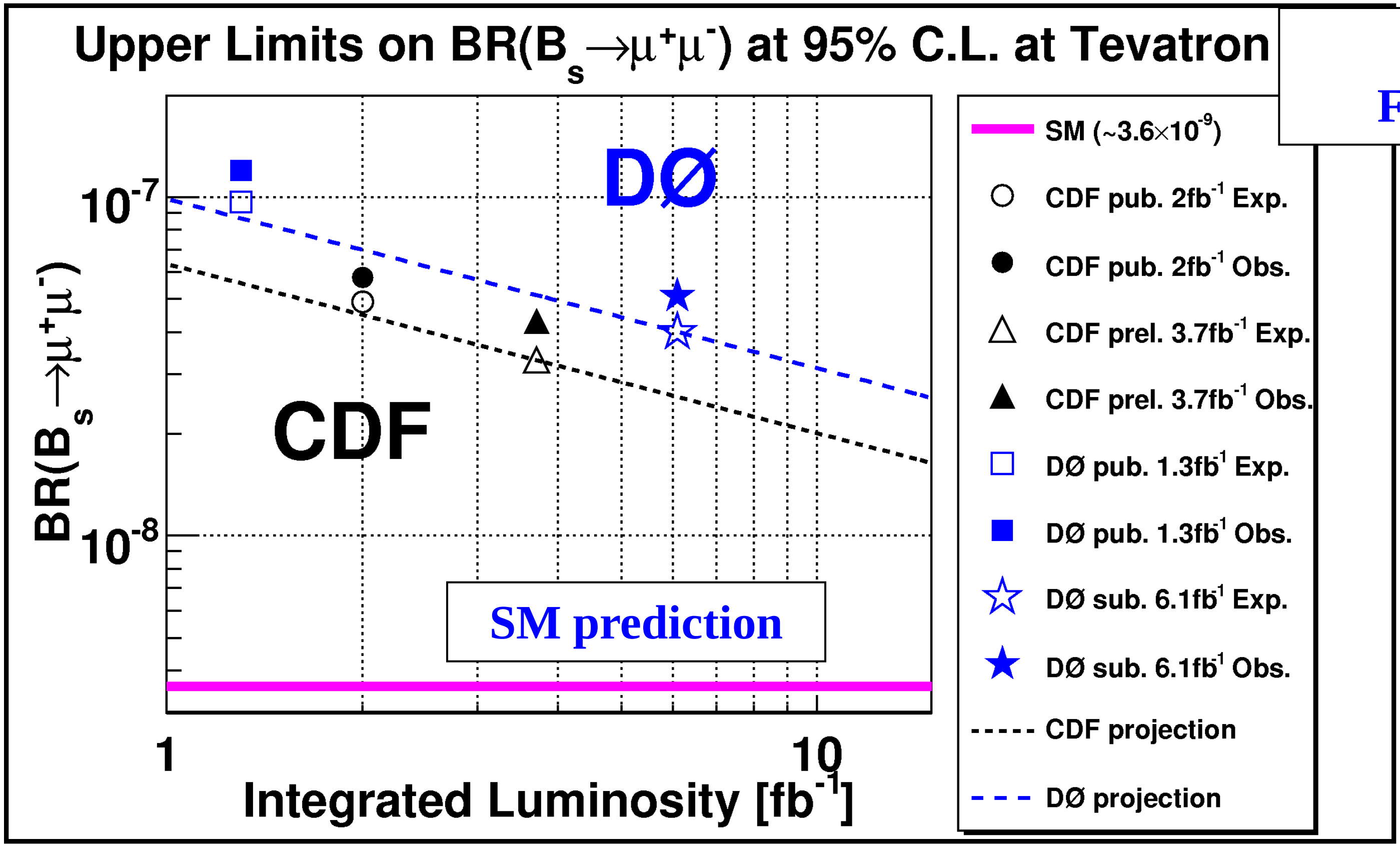
M. Rescigno, ICHEP-2010, CDF Public note 9892



M(μμ) for three ranges of NN variable

$B_{s,d} \to \mu^+\mu^-$: past and future

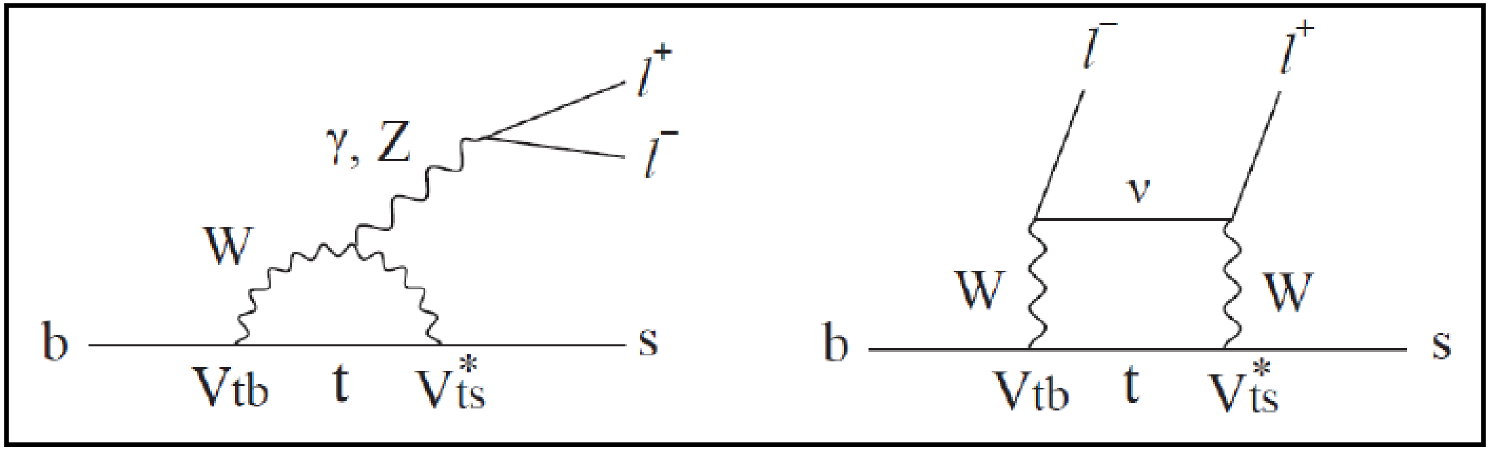
M. Aoki,
FPCP-2010



- The expected limit scales better than $1/\sqrt{N}$
- Combination of CDF and DØ results to follow

$b \to s \mu^+ \mu^-$

- Suppressed in SM – can proceed only through loop diagrams
- Sensitive to new physics
- Experimental observables:
  - Branching fractions
  - K^* longitudinal polarization (F_L)
  - Muon forward-backward asymmetry (A_{FB})
- All quantities are measured w.r.t. $q^2 = M(\mu\mu)^2$

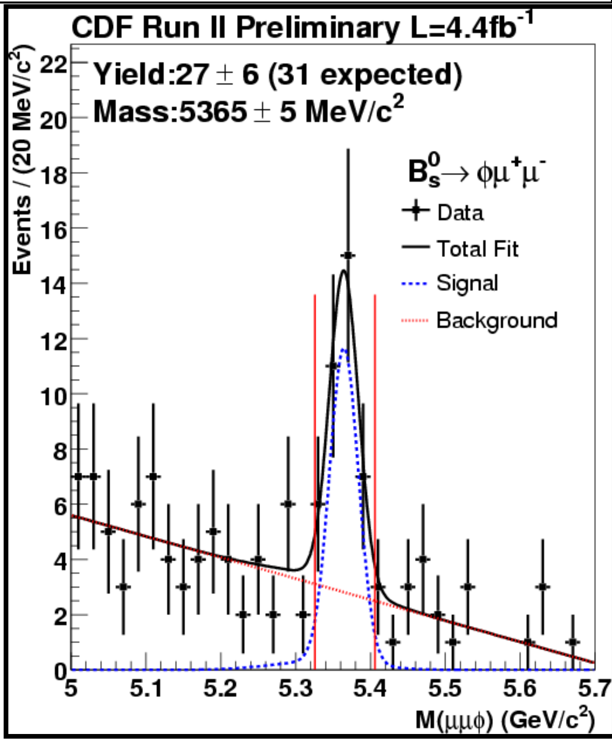


$b \to s\,\mu^+\mu^-$

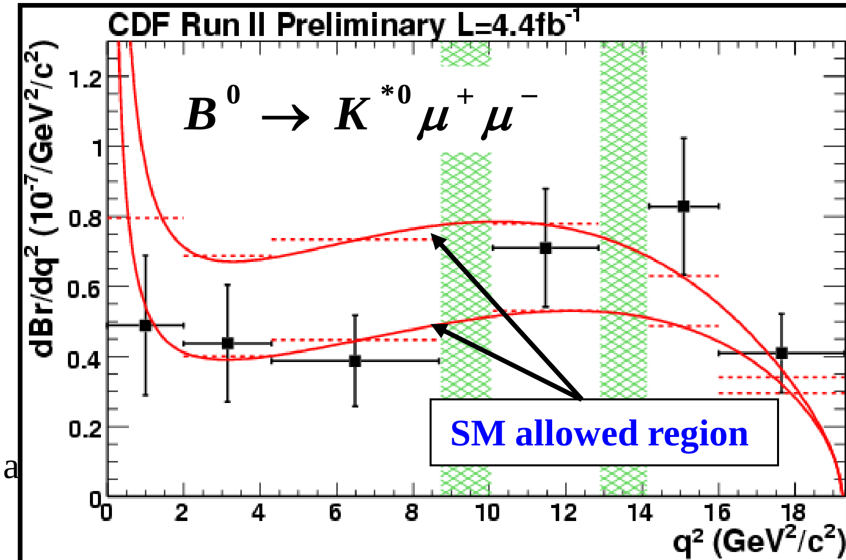
M. Rescigno, ICHEP-2010,
CDF Public note 10047

$$\mathrm{Br}(B^+ \to K^+\mu^+\mu^-) = (0.38 \pm 0.05 \pm 0.03)\times 10^{-6}$$
$$\mathrm{Br}(B^0 \to K^{*0}\mu^+\mu^-) = (1.06 \pm 0.14 \pm 0.09)\times 10^{-6}$$
$$\mathrm{Br}(B_s^0 \to \varphi\mu^+\mu^-) = (1.44 \pm 0.33 \pm 0.46)\times 10^{-6}$$

- 4.4 fb^{-1} of data analyzed
- Consistent with SM expectation
- Competitive and consistent with B factories



First observation (6.3 σ)
of $B_s \to \varphi\mu^+\mu^-$



$b \to s\,\mu^+\mu^-$: A_{FB}

M. Rescigno, ICHEP-2010, CDF Public note 10047

- A_{FB} is sensitive to the NP contribution
- In the theoretically cleanest range:

$$A_{FB} = 0.43^{+0.36}_{-0.37} \pm 0.06 \quad (\text{CDF}, \quad 1 < q^2 < 6\ \text{GeV}^2)$$

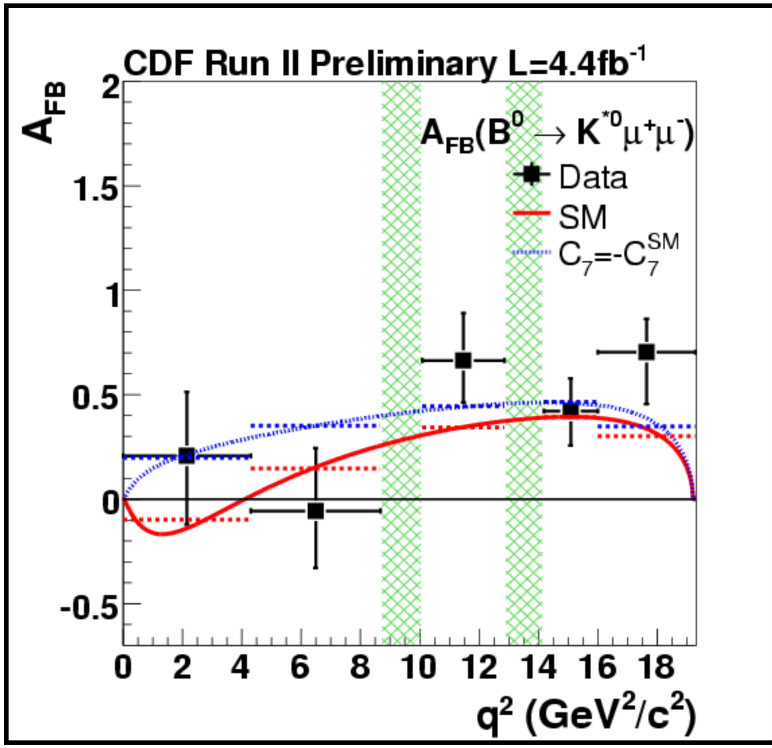
- Consistent and competitive with B factories:

$$A_{FB} = 0.26^{+0.27}_{-0.30} \pm 0.07 \quad (\text{Belle}, \quad 1 < q^2 < 6\ \text{GeV}^2)$$
$$A_{FB} = 0.24^{+0.18}_{-0.23} \pm 0.05 \quad (\text{BaBar}, \quad 0.1 < q^2 < 6.25\ \text{GeV}^2)$$

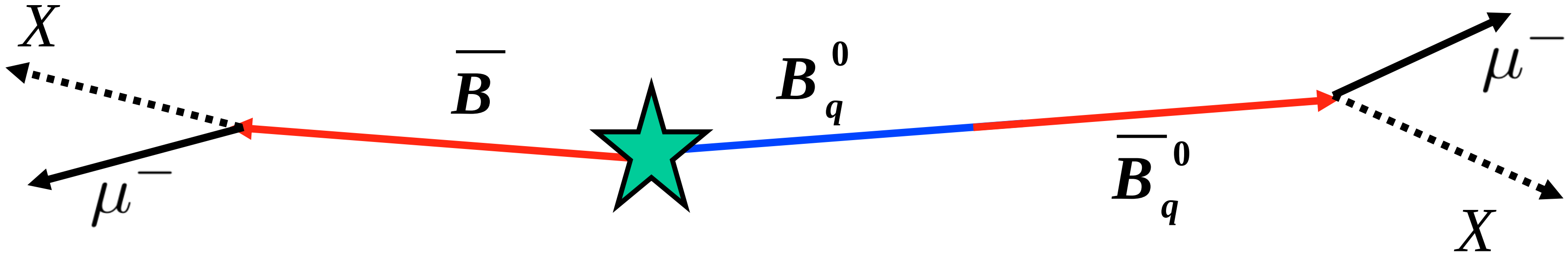
- Consistent with SM expectation

$$A_{FB} = -0.05^{+0.03}_{-0.04} \quad (\text{SM}, \quad 1 < q^2 < 6\ \text{GeV}^2)$$

  - C. Bobeth *et al.* arXiv:1006.5013
- Precision will be improved



Dimuon charge asymmetry



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

N_b^{++} (N_b^{--}) – number of same-sign $\mu^+\mu^+$ ($\mu^-\mu^-$) events from $B \to \mu X$ decay

- Both B_d and B_s contribute in A^b_{sl} at Tevatron :

$$A_{sl}^b = (0.506 \pm 0.043)a_{sl}^d + (0.494 \pm 0.043)a_{sl}^s$$

B_d contribution

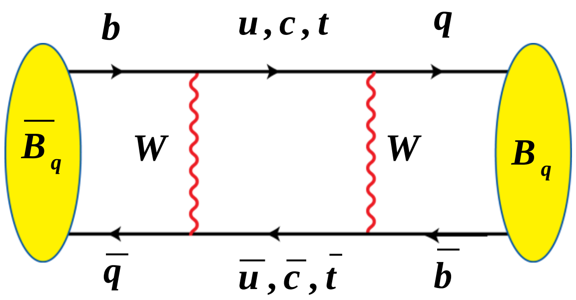
B_s contribution

– a^q_{sl} is the charge asymmetry of "wrong sign" semileptonic B^0_q ($q = d,s$) decays:

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

CP violation in mixing

- Non-zero A^b_{sl} means CP violation in mixing
- Source of this type of CP violation – complex phase ϕ_q of B_q ($q=d,s$) mass matrix



$$\Delta M_q = M_H - M_L \approx 2\left|M_q^{12}\right|$$

$$\Delta\Gamma_q = \Gamma_L - \Gamma_H \approx 2\left|\Gamma_q^{12}\right| \cos \phi_q$$

$$\phi_q = \arg\left(-\frac{M_q^{12}}{\Gamma_q^{12}}\right)$$

$$\left\|\mathbf{M}_q\right\| = \begin{bmatrix} M_q & M_q^{12} \\ (M_q^{12})^* & M_q \end{bmatrix} - \frac{i}{2}\begin{bmatrix} \Gamma_q & \Gamma_q^{12} \\ (\Gamma_q^{12})^* & \Gamma_q \end{bmatrix}$$

- For B_q meson, a^q_{sl} is related to the CP-violating phase ϕ_q :

$$a^q_{sl} = \frac{\Delta\Gamma_q}{\Delta M_q}\tan(\phi_q)$$

SM prediction

- SM predicts very small values of ϕ_q and $A^b{}_{\text{sl}}$:

$$\phi_d^{SM} = -0.091\,^{+0.026}_{-0.038}$$
$$\phi_s^{SM} = 0.0042 \pm 0.0014$$
$$A_{sl}^{b,SM} = (-2.3\,^{+0.5}_{-0.6}) \times 10^{-4}$$

  - A. Lenz, U. Nierste, J. High Energy Phys. 0706, 072 (2007)
  - These values are below current experimental sensitivity
- New physics contribution can significantly change these values

$$\phi_d = \phi_d^{SM} + \phi_d^{NP}$$
$$\phi_s = \phi_s^{SM} + \phi_s^{NP}$$

Non-zero $A^b{}_{\text{sl}}$ would indicate the presence of new physics

Measurement strategy

- Measure two raw asymmetries (include muons from all sources):

raw dimuon charge asymmetry

$$A \equiv \frac{N(\mu^+\mu^+) - N(\mu^-\mu^-)}{N(\mu^+\mu^+) + N(\mu^-\mu^-)} = (0.564 \pm 0.053)\%$$

raw inclusive muon charge asymmetry

$$a \equiv \frac{n(\mu^+) - n(\mu^-)}{n(\mu^+) + n(\mu^-)} = (0.955 \pm 0.003)\%$$

- Both asymmetries contain contributions from A^b_{sl} and detector-related background asymmetries

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

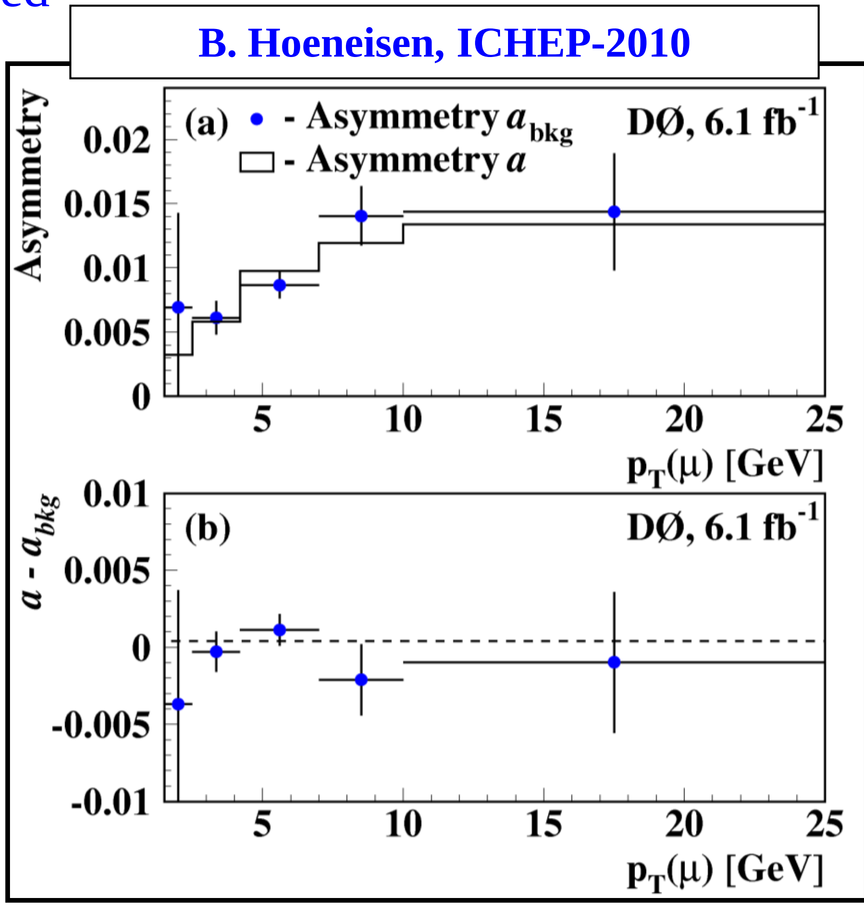
$$a = k\, A^b_{sl} + a_{bkg}$$

  - contribution from A^b_{sl} to a is strongly suppressed by k=0.041 0.003

- Determine background contributions A_{bkg} and a_{bkg} using data with minimal input from simulation
- Exploit the correlation of background content in raw asymmetries to reduce the uncertainty on A^b_{sl}

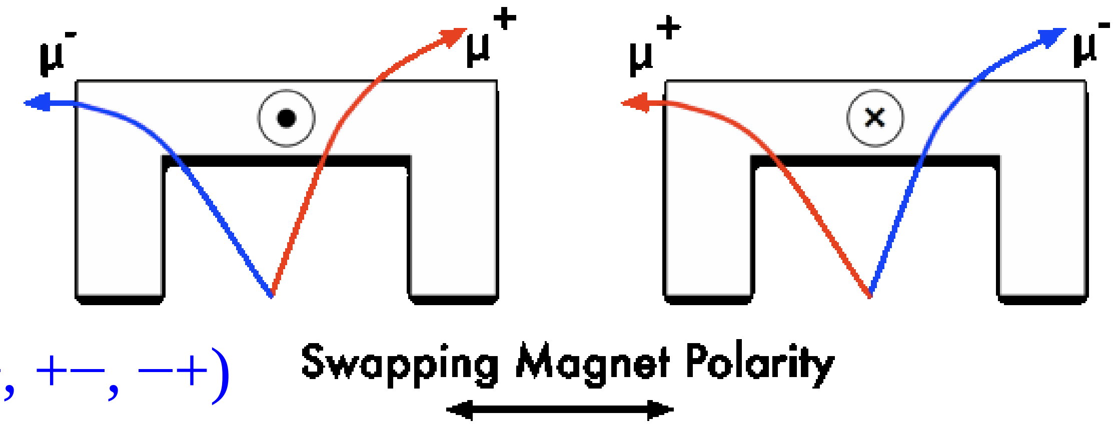
Test of background description

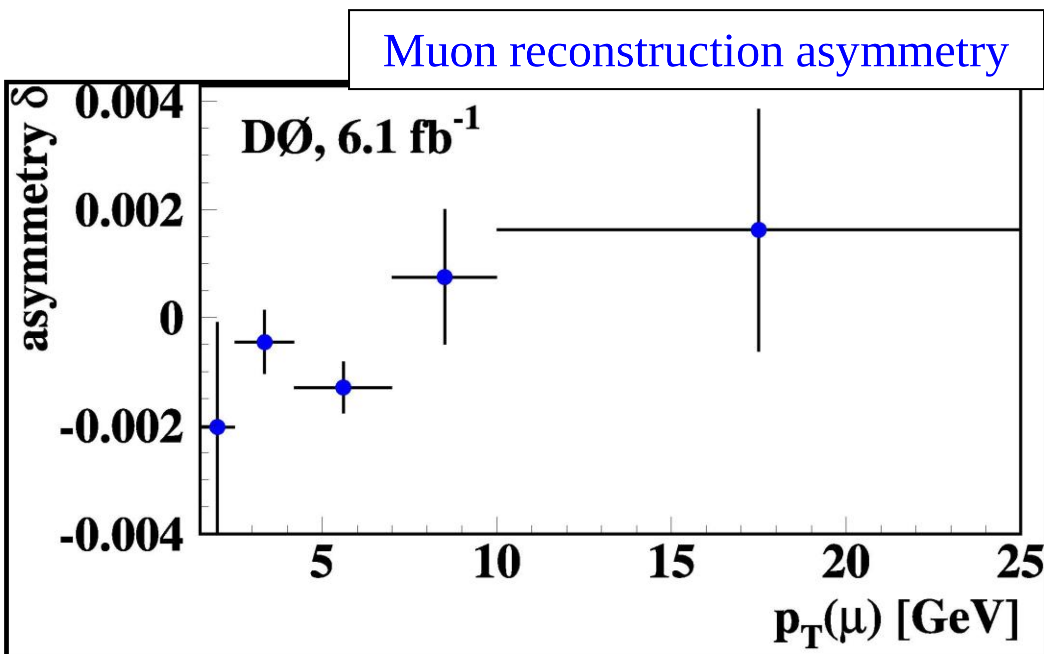
- Raw inclusive muon asymmetry a is dominated by the background asymmetry a_{bkg}
- a_{bkg} is measured in data
- Compare a and a_{bkg} to verify the background description
- This comparison is done as a function of muon p_T
- Good consistency between observed and expected asymmetries
  - χ^2/dof = 2.4/5 for the difference between these two distributions



Original experimental technique

- Polarities of DØ solenoid and toroid are reversed every ~2 weeks
- 4 equal sized samples with different polarities (++, ––, +–, –+)
- difference in reconstruction efficiency between positive and negative particles minimized
- Reconstruction asymmetries reduced from ~1% to <0.1%
  - To be compared with raw dimuon asymmetry A= (0.564 0.053)%





Evidence for an anomalous like-sign charge asymmetry

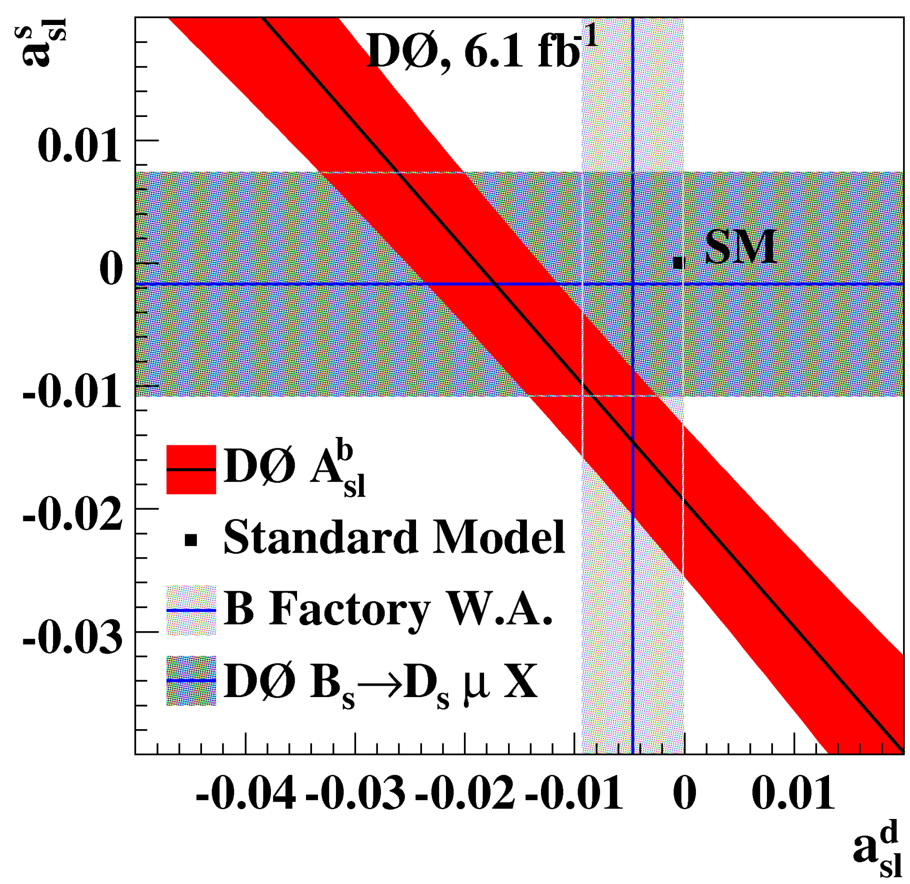
$$A^b_{sl} = (-0.957 \pm 0.251\ (\text{stat}) \pm 0.146\ (\text{syst}))\%$$

- This result differs from the SM prediction by ~3.2 σ
- A^b_{sl} produces a band in a^d_{sl} v.s. a^s_{sl} plane:

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

- Obtained result agrees well with other measurements of a^d_{sl} and a^s_{sl}

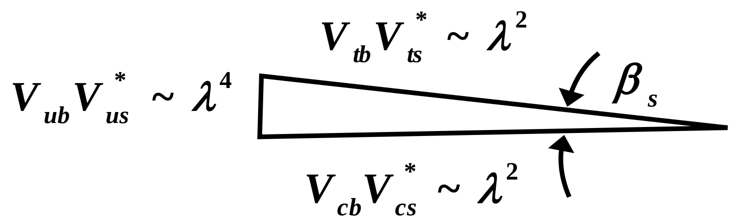
B. Hoeneisen, ICHEP-2010,
DØ Collab., arXiv:1005.2757 accepted by PRD
DØ Collab., arXiv:1007.0395 accepted by PRL



Decay $B_s \to J/\psi\ \varphi$

- Another way to probe CP violation in B_s mixing
- CP violation in $B_s \to J/\psi\varphi$ decay is described by the phase $\phi^{J/\psi\varphi}$
- Within the SM $\phi^{J/\psi\varphi}$ is related to the angle β_s of the (bs) unitarity triangle:

$$\phi^{J/\psi\varphi,SM} = -2\beta_s = 2\arg\left(-\frac{V_{tb}V_{ts}^*}{V_{cb}V_{cs}^*}\right) = -0.038 \pm 0.002$$



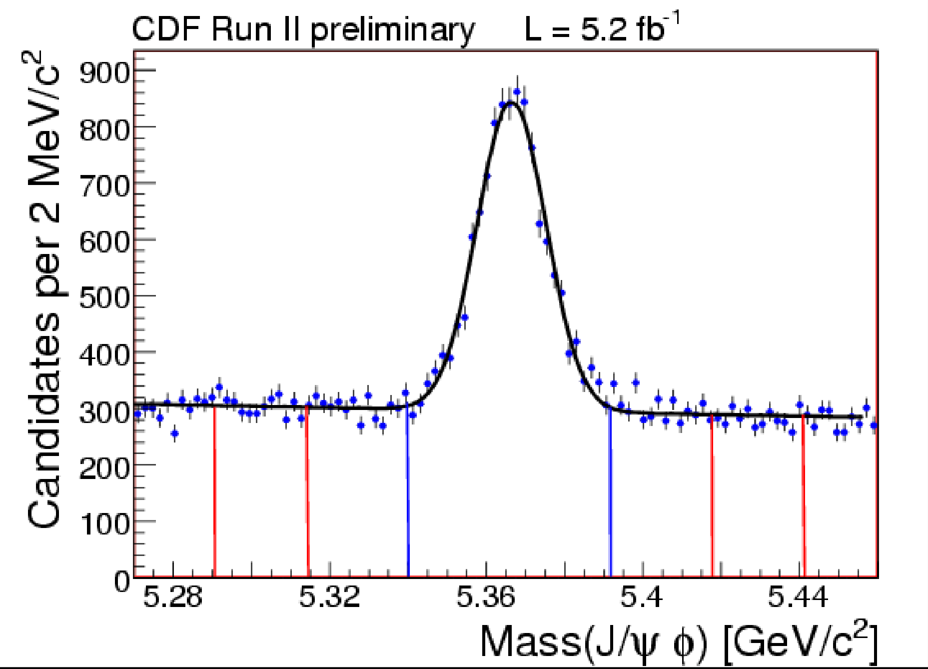
- It can be significantly modified by the new physics contribution:

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

ϕ_s^{NP} is the same for $\phi^{J/\psi\varphi}$ and ϕ_s

$B_s \to J/\psi\ \varphi$ (CDF)

G. Giurgiu, ICHEP-2010, CDF Public note 10206



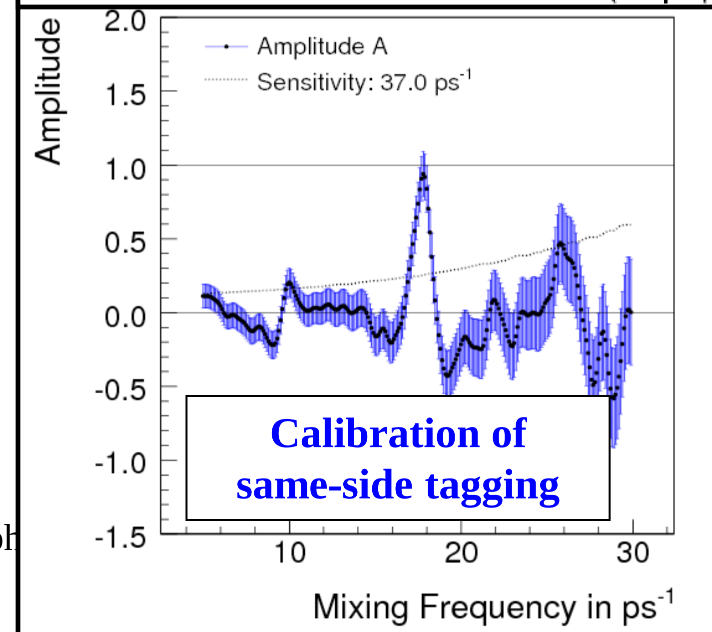
- 5.2 fb^{-1} of data analyzed
- ~6500 signal events
- Same side flavour tagging calibrated in data
- Strong phases are free
- S wave included in the fit

  < 6.5% at 95% CL

$$\tau_s = \mathbf{1.529 \pm 0.025\ (stat)\ \pm 0.012\ (syst)\ \ ps}$$

$$\Delta\Gamma_s = \mathbf{0.075 \pm 0.035\ (stat)\ \pm 0.01\ (syst)\ \ ps^{-1}}$$

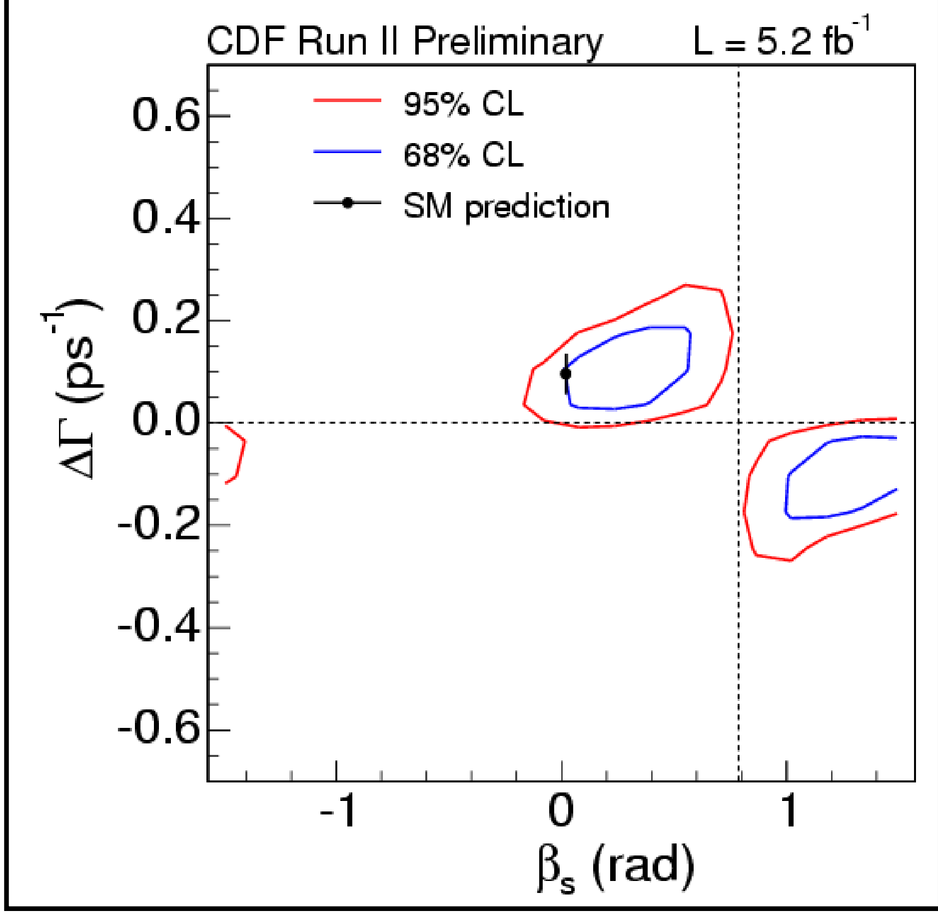
Most precise measurements of $\tau(B_s)$ and $\Delta\Gamma_s$



$B_s \rightarrow J/\psi\ \varphi$ (CDF)

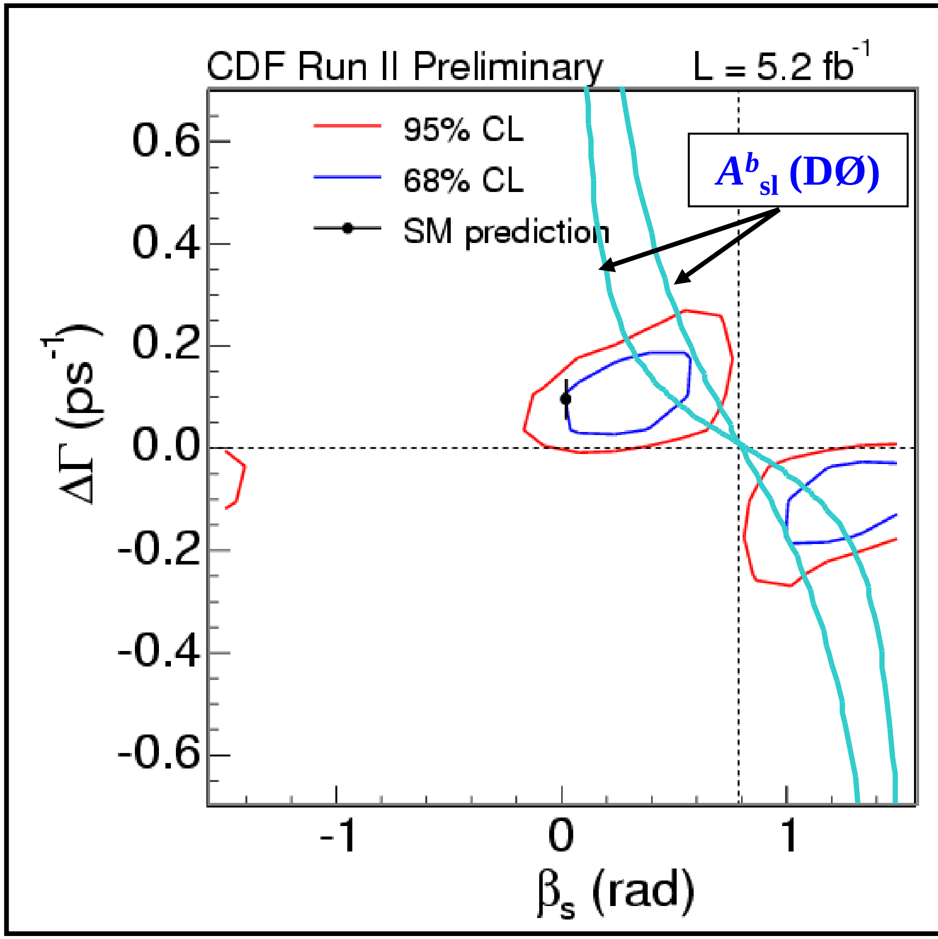
G. Giurgiu, ICHEP-2010, CDF Public note 10206

- Result of angular analysis consistent with SM prediction
  - p-value is 44% (0.8 σ)



$B_s \rightarrow J/\psi\ \varphi$ (CDF)

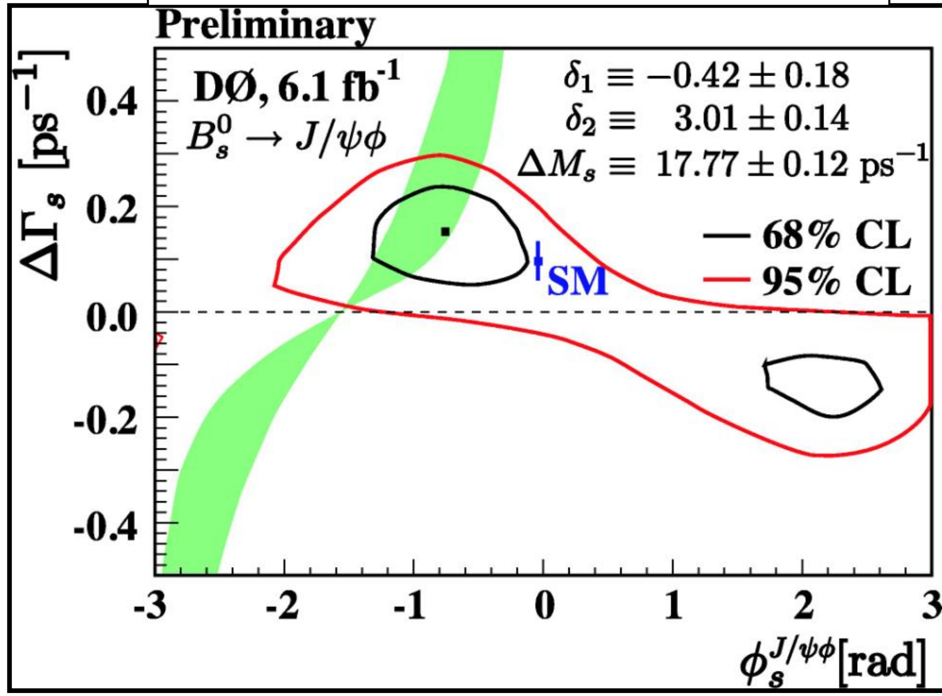
- Result of angular analysis consistent with SM prediction
  - p-value is 44% (0.8 σ)
- Results of CDF and DØ are consistent within ~1σ



$B_s \to J/\psi\ \varphi$ (DØ)

- 6.1 fb^{-1} of data analyzed
- Only the opposite flavour tagging is used
- Strong phases are constrained to the values from $B^0 \to J/\psi K^{*0}$
- $\tau(B_s)$ and $\Delta\Gamma_s$ are consistent with other measurements

R. Van Kooten, ICHEP-2010, DØnote 6098-CONF



$$\tau_s = 1.47 \pm 0.04 \pm 0.01\ \text{ps}$$
$$\Delta\Gamma_s = 0.15 \pm 0.06 \pm 0.01\ \text{ps}^{-1}$$
$$\phi_s = -0.76^{+0.38}_{-0.36} \pm 0.02$$

$0.014 < \Delta\Gamma_s < 0.263\ \text{ps}^{-1}$ (95% C.L.)
$-1.65 < \phi^{J/\psi\varphi} < 0.24$ (95% C.L.)

and

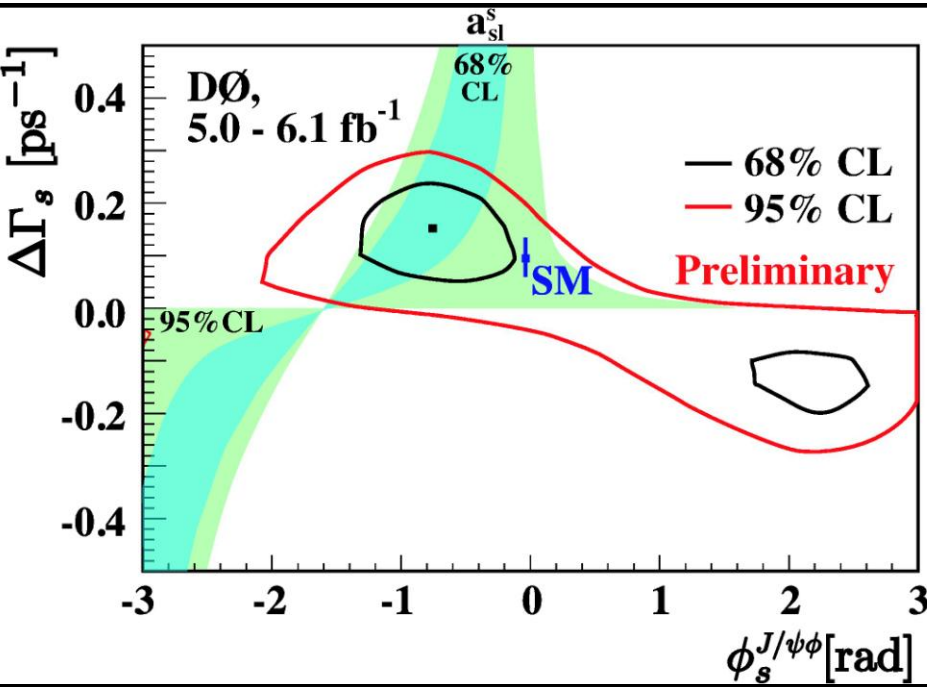
$-0.235 < \Delta\Gamma_s < -0.040\ \text{ps}^{-1}$ (95% C.L.)
$1.14 < \phi^{J/\psi\varphi} < 2.93$ (95% C.L.)

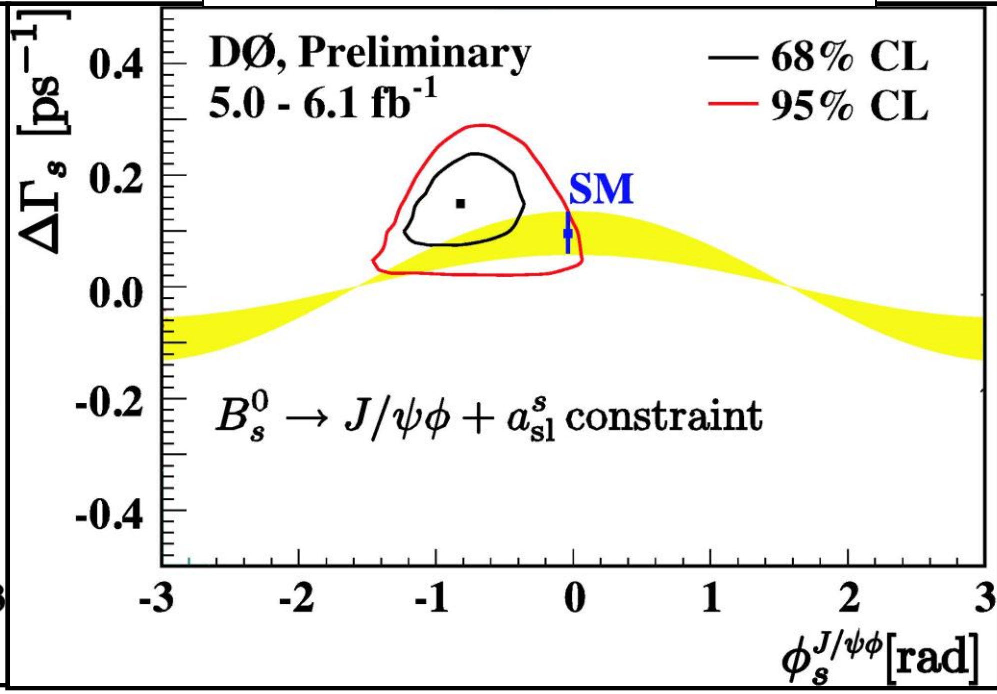
Combination of DØ results

- $B_s \rightarrow J/\psi\ \varphi$
- A^b_{sl}
- a^s_{sl} from $B_s \rightarrow D_s \mu \nu$
- p-value at SM point is 7.5%

$$a^s_{sl} = (-1.00 \pm 0.59)\% \quad \text{(D0)}$$

R. Van Kooten, ICHEP-2010
DØ Note 6093-CONF

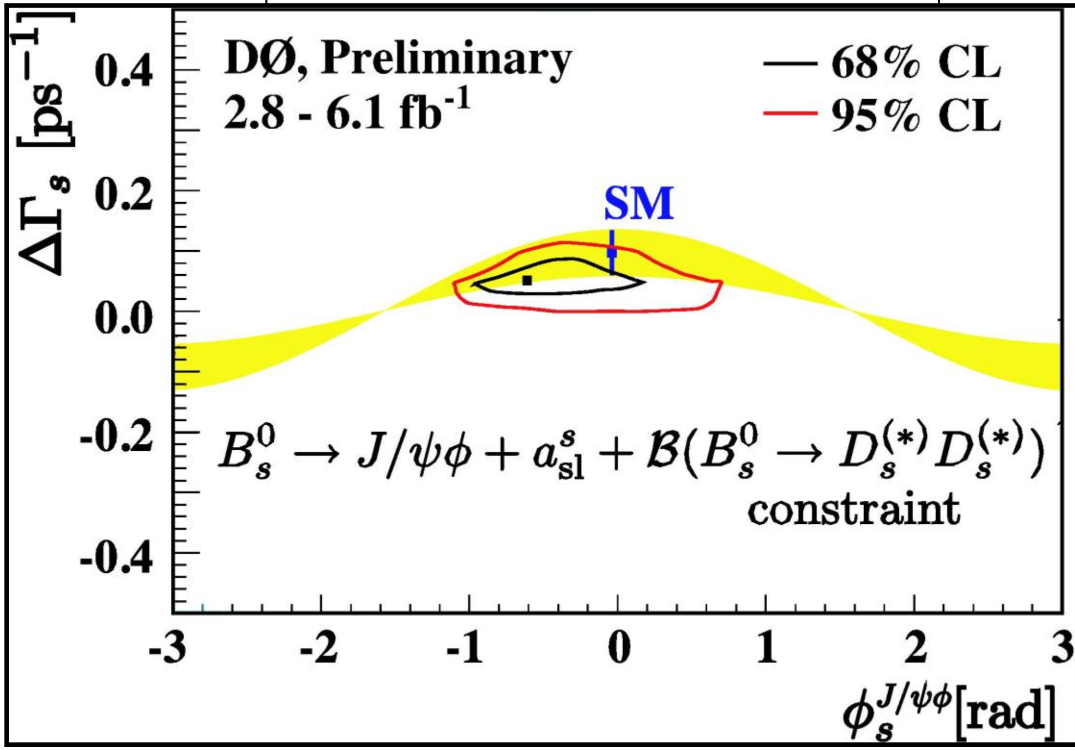




Combination of DØ results

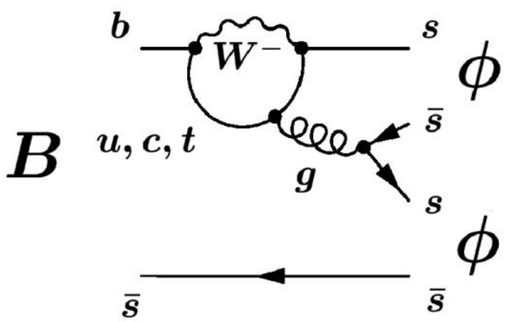
- $B_s \rightarrow J/\psi\ \varphi$
- A^b_{sl}
- a^s_{sl} from $B_s \rightarrow D_s \mu \nu$
- $\Delta\Gamma_s^{CP}$ from $B_s \rightarrow D_s^{(*)+} D_s^{(*)-}$
  - $D_s^{(*)+} D_s^{(*)-}$ is mainly CP-even and Br($B_s \rightarrow D_s^{(*)+} D_s^{(*)-}$) is proportional to $\Delta\Gamma_s^{CP}$
- p-value of SM point is 6%

R. Van Kooten, ICHEP-2010
DØ Note 6093-CONF



$B_s \rightarrow \varphi\varphi$

- Complementary channel to study the CP violation in B_s decays
- Decay through $b \rightarrow s$ penguin diagram
- CDF collected enough statistics to measure $Br(B_s \rightarrow \varphi\varphi)$ and perform an angular analysis
- 2.9 fb^{-1} of data analyzed



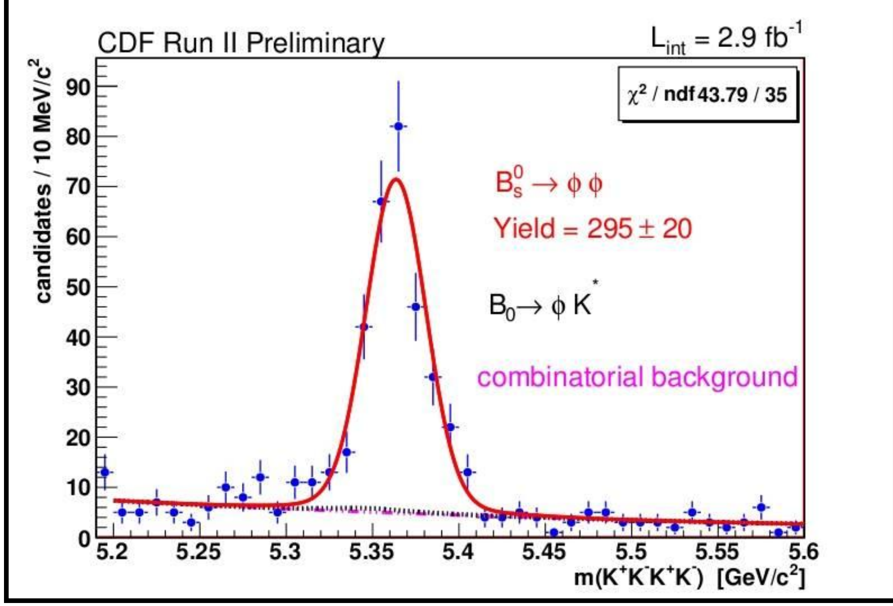
- First measurement of polarization amplitudes

M. Rescigno, ICHEP-2010
CDF Public notes 10064 and 10120

$$|A_0|^2 = 0.348 \pm 0.041 \text{ (stat)} \pm 0.021 \text{ (syst)}$$

$$|A_{\parallel}|^2 = 0.287 \pm 0.043 \text{ (stat)} \pm 0.011 \text{ (syst)}$$

$$|A_{\perp}|^2 = 0.365 \pm 0.044 \text{ (stat)} \pm 0.027 \text{ (syst)}$$



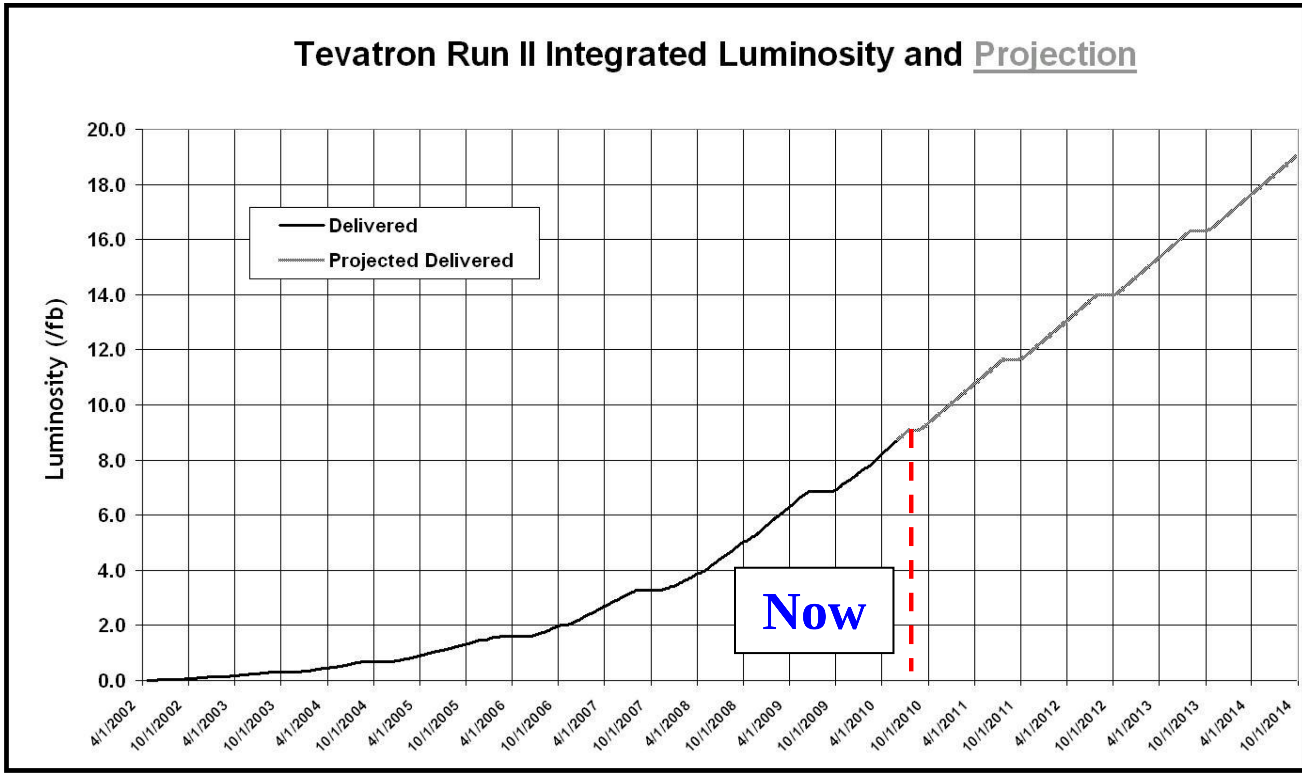
- Large transverse polarization fraction observed

$$f_L = 0.348 \pm 0.041 \text{ (stat)} \pm 0.021 \text{ (syst)}$$

$$f_T = 0.652 \pm 0.041 \text{ (stat)} \pm 0.021 \text{ (syst)}$$

Not the final word yet

- Tevatron experiments now collect >2 fb^{-1} / year
- By the end of 2011 run, the statistics of all measurements will be at least doubled
- Uncertainties of almost all measurements are statistically dominated



Tevatron experiments have excellent prospects to make a strong statement on the contribution of new physics in *B* decays

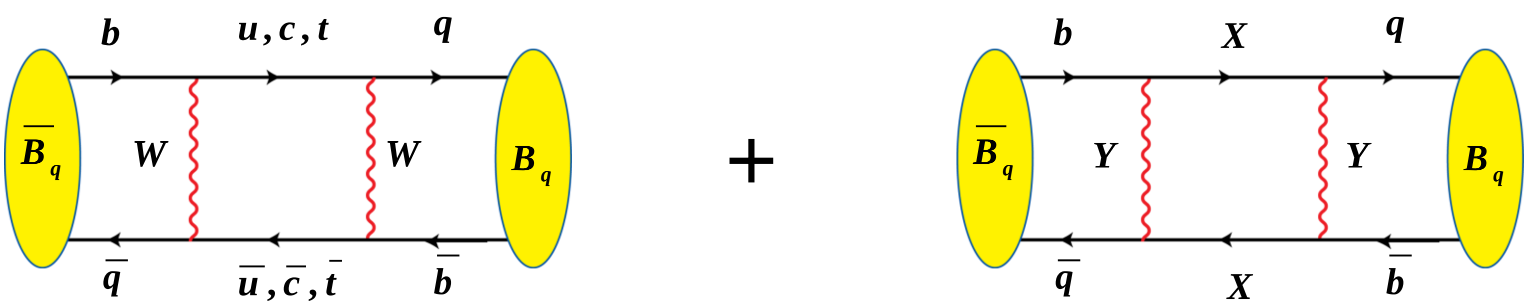
Conclusions

- B physics can provide the first indication of new phenomena beyond the SM
- Extensive study at Tevatron are performed
- New results in $B_s \to \mu^+\mu^-$, $b \to s\,\mu^+\,\mu^-$ and $B_s \to \varphi\varphi$ have been shown
- Evidence for an anomalous asymmetry A^b_{sl} at 3.2σ by DØ
- New results in $B_s \to J/\psi\,\varphi$ by CDF and DØ demonstrate a better consistency with the SM
- All new results are consistent with A^b_{sl} measurement
- Combination of all DØ results for B_s system gives p-value = 6.0% of the SM
- Excellent prospects for the future improvement of precision

Backup slides

Search Strategy

- Study the processes where the Standard Model predicts a small or zero signal, and where the contribution of new physics (NP) can be significant
  - Small theoretical uncertainties
  - Deviation from the zero level is much easier to observe experimentally
- Processes involving loop diagrams are especially promising
  - Allow contribution of new particles and interactions
  - Act like a virtual accelerator
    - No upper limit on the mass of intermediate particles
    - No breakdowns, stops, power consumption etc.



...it happens

- Latest part of statistics is better consistent with the SM both in CDF and DØ

$B_s \to J/\psi\varphi$ (DØ)

	Full Sample	First 2.8 fb^{-1}	Last 3.3 fb^{-1}
All Candidates	82808	47442	35366
Signal	3435 ± 84	1999 ± 66	1449 ± 50
B_s^0 Mass (MeV)	5362.4 ± 0.8	5362.2 ± 1.0	5362.7 ± 1.2
B_s^0 Mass Width (MeV)	30.4 ± 0.7	29.5 ± 0.9	31.7 ± 1.1
Proper length error scale	1.268 ± 0.006	1.261 ± 0.007	1.271 ± 0.008
$\overline{\tau}_s$ (ps)	1.47 ± 0.04	1.45 ± 0.07	1.46 ± 0.06
$\Delta\Gamma_s$ (ps^{-1})	0.15 ± 0.06	0.23 ± 0.08	0.07 ± 0.07
$A_\perp(0)$	0.44 ± 0.03	0.42 ± 0.04	0.47 ± 0.04
$\lvert A_0(0)\rvert^2 - \lvert A_{\parallel}(0)\rvert^2$	0.35 ± 0.03	0.32 ± 0.04	0.40 ± 0.04
$\phi_s^{J/\psi\phi}$	-0.76 ± 0.37	-0.86 ± 0.33	-0.37 ± 0.81