Rare B_s Decays at DØ

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B physics at Tevatron

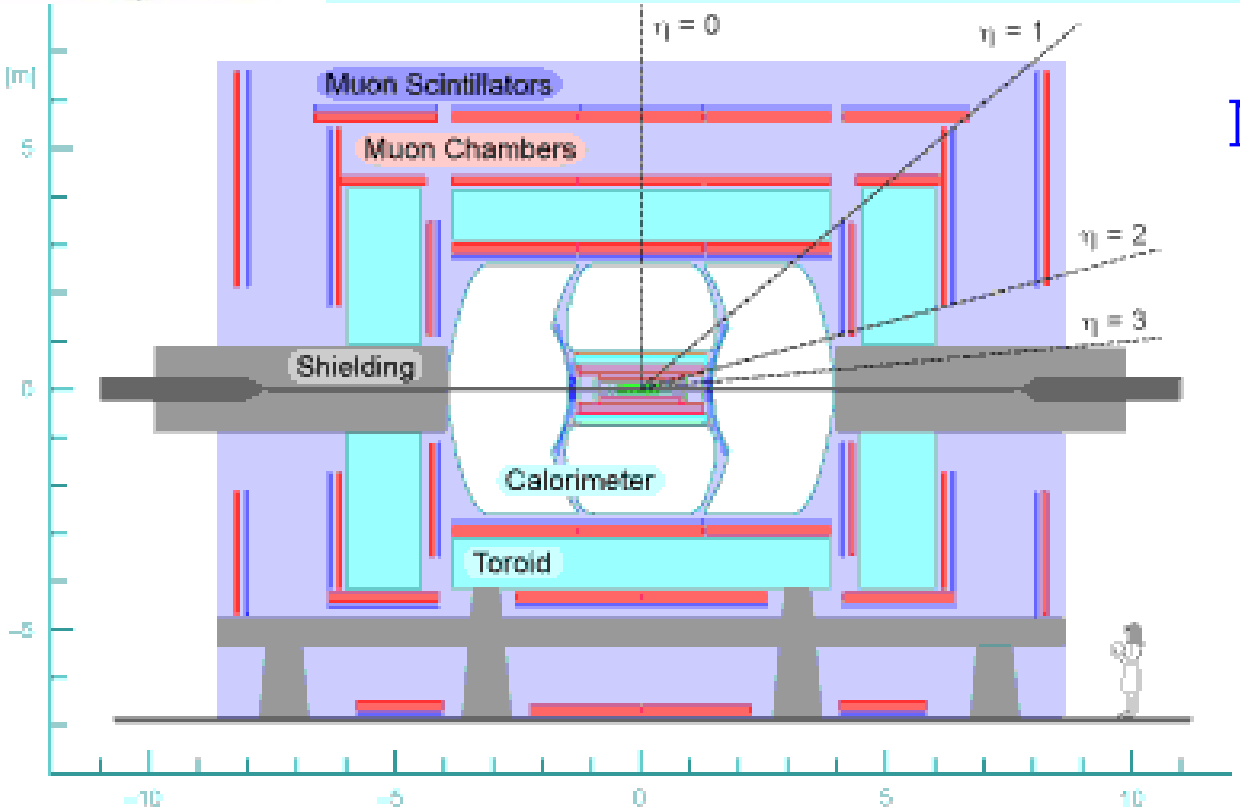
Tevatron has a complementary program to B factories

- expect about 10^{10} bbar pairs/year at $4*10^{31}cm^{-2}s^{-1}$
- DØ is competitive in di-muon modes !
- can study B_s, as well as other heavier b hadrons (B_c, B^{**}, Λ_b)

Tevatron is effectively a B_s factory, with wide program:

- B_s lifetime
- B_s lifetime difference between different mass / CP states
- B_s oscillations
- CP violation
- search for rare decays (sensitive to physics beyond SM)

The DØ Detector

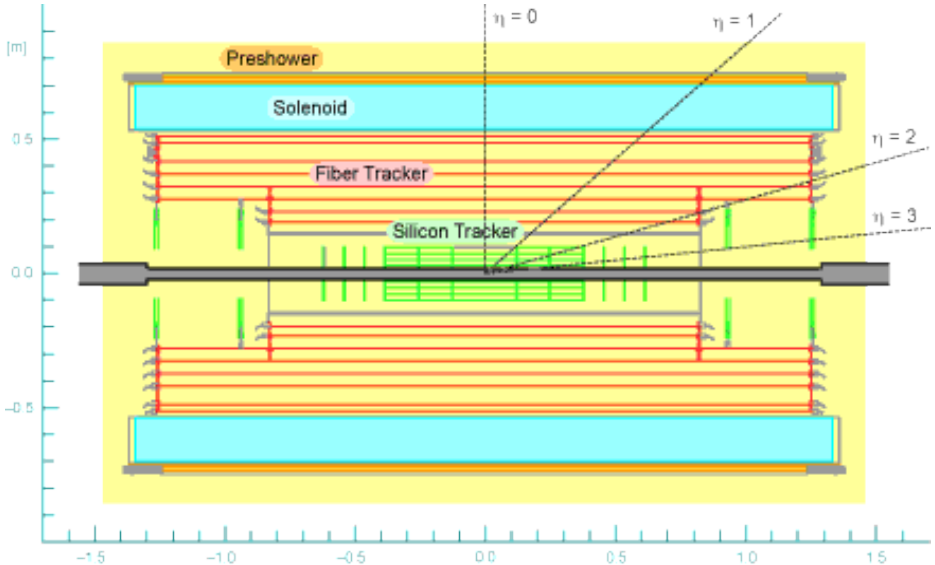


Muon system:

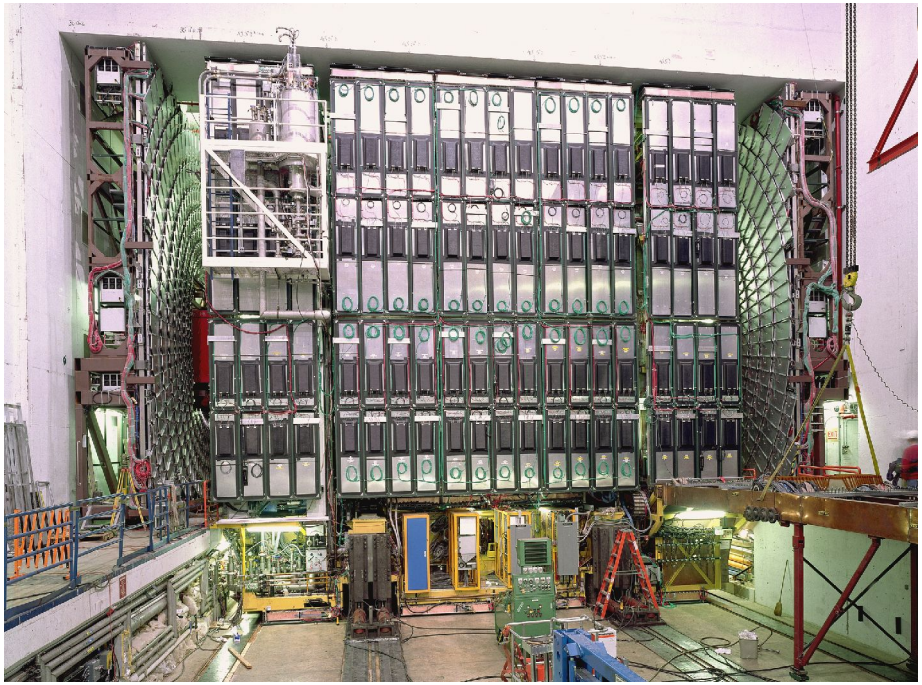
- 3 layers of drift tubes
- scintillating counters between layers
- 1.8 T toroidal magnet
- covers up to |η|<2
- beamline shielding to reduce background

Central tracking system:

- silicon microstrip detector(SMT)
- central fiber tracker(CFT)
- 2 T solenoidal magnet
- tracking/vertexing up to |η|<2



Muon Reconstruction



Muon Trigger:

- trigger over full coverage ($|\eta|<2$)
- based on scintillator hits
- high efficiency
- low background
- write out almost all di-muons!

Muon Reconstruction:

- require hits in at least 2 out of 3 muon layers
- momentum measured in toroid
- require central track match to improve momentum resolution
- require hits in SMT to improve vertex resolution

Rare B_s^0 Decays

$B_s^0 \to \mu\mu\,\phi$ Search

$B_s^0 \to \mu\mu$ Search

$B_s^0 \to \psi(2S)\,\phi$ Observation

General Considerations:

- all analyses use di-muons(high eff. & low backg.)
- all use vertexing capability of D∅ silicon detector

Analysis procedure:

- perform some pre-selection cuts
- apply further cuts, optimised for the signal in question
- normalize result to a similar, but higher statistics channel to cancel some systematics

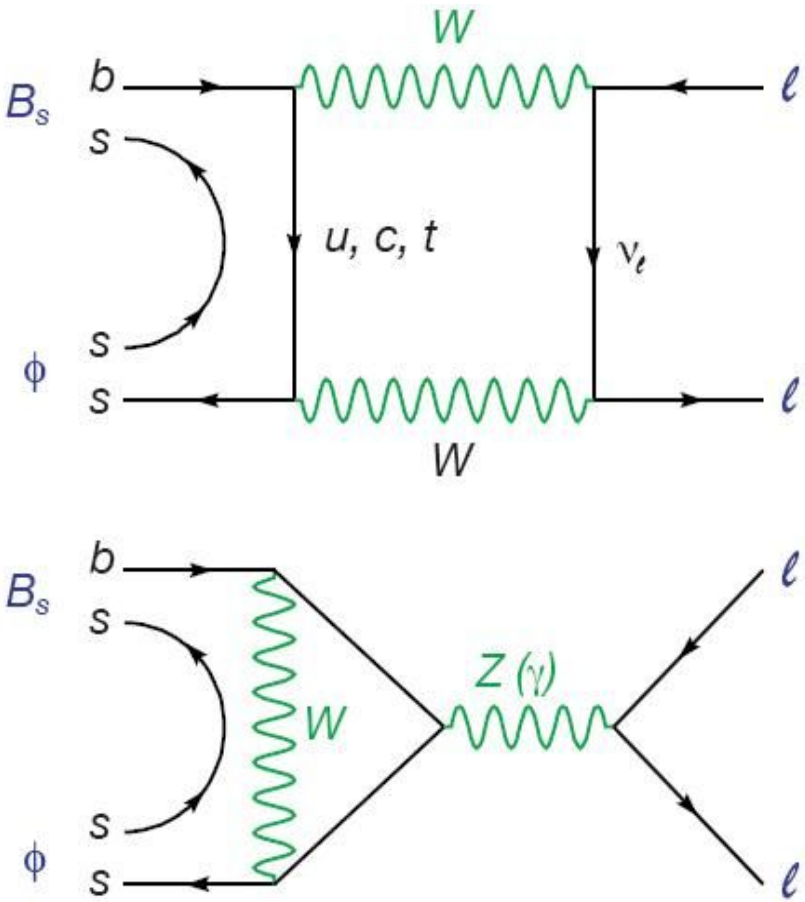
$B_s^0 \to \mu\mu\,\phi$ Search

SM forbids FCNC at tree level:

- SM prediction for $B(B_s^0 \to \mu\mu\phi)$
  $\sim 1.6 \times 10^{-6}$ (C.Q.Geng, C.C.Liu)

- enhanced in various SUSY models
  e.g. 2 higgs doublet model
  (G. Erkol & G. Turan)

- Observation of excess would
  indicate new physics !



Only current limit:

CDF, Run I: $B(B_s^0 \to \mu\mu\,\phi) < 6.7 \times 10^{-5}$ (95% CL) (PRD 65, 1111101)

$B_s^0 \to \mu\mu\,\phi$ Search

Pre-selection of B_s candidates:

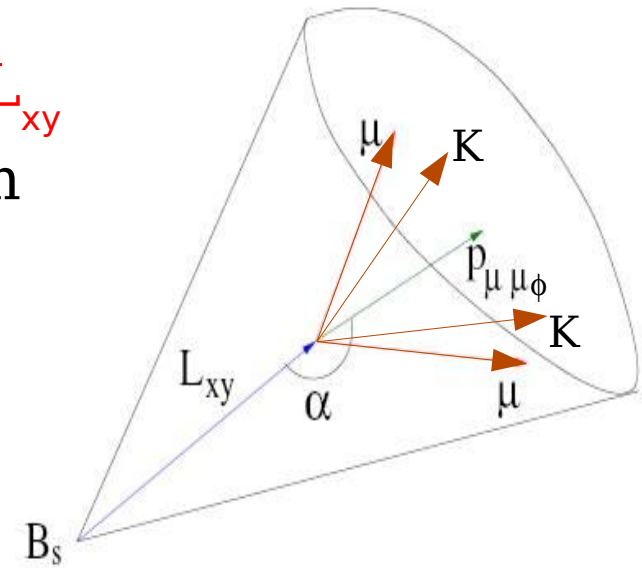
- select 2 good muons: $p_T > 2.5$ GeV , $|\eta| < 2.0$
- di-muon vertex, with resolution: $\delta L_{xy} < 0.15$ mm
- di-muon mass window: 0.5 – 4.4 GeV
- exclude J/ψ and $\psi(2S)$ mass regions
- require 2 additional tracks (K candidates): $p_T > 0.7$ GeV
- good match of K candidates to the di-muon vertex
- require K pair to match ϕ mass: 1.008 – 1.032 GeV
- B_s candidate: $p_T > 5.0$ GeV
- B_s candidate mass: 4.4 – 6.2 GeV

$B_s^0 \to \mu\mu\,\phi$ Search

Final selection based on following discriminating variables:

- transverse decay length significance $L_{xy}/\delta L_{xy}$
- collinearity angle α between B_s momentum and a vector pointing from PV to SV
- isolation I of $\mu\mu\phi$ system:

$$I = \frac{|\vec{p}(\mu\mu\phi)|}{|\vec{p}(\mu\mu\phi)| + \sum_{track\, i \neq B} p_i(\Delta R < 1)}$$



To optimize the cuts and keep signal region as a blind box perform a random grid search:

Maximize the variable:

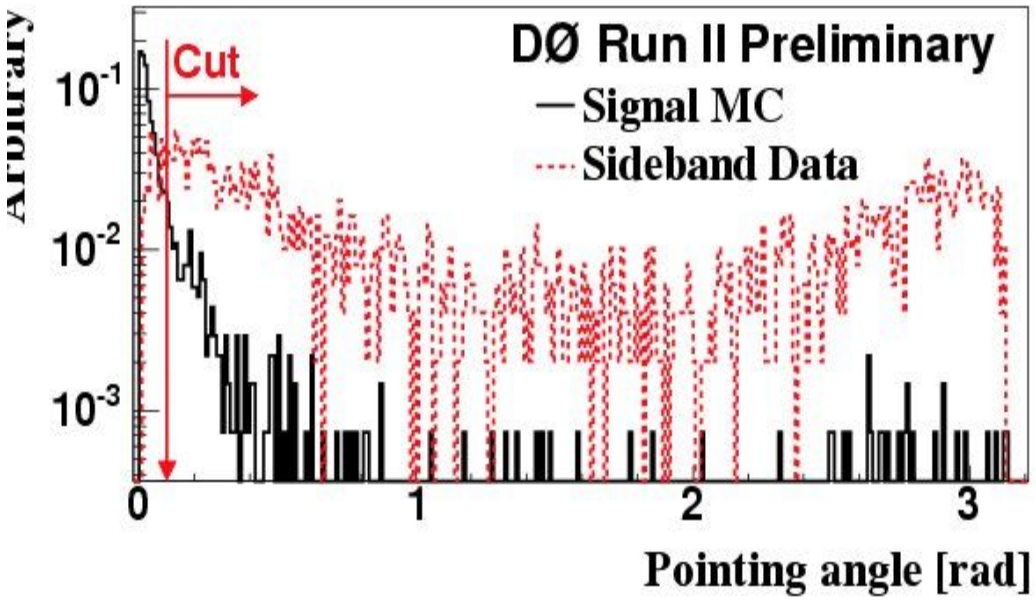
$$P = \frac{\epsilon_{\mu\mu\phi}}{\frac{a}{2} + \sqrt{N_{Back}}}$$

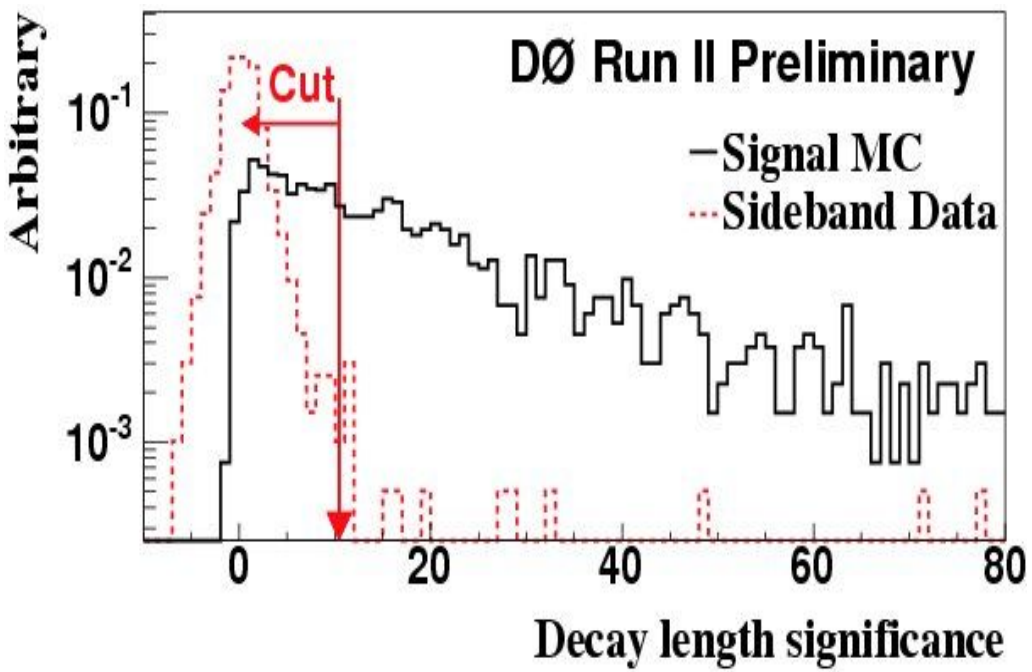
ε = efficiency (from MC)
N = expected background
a = #σ (2=95% CL)

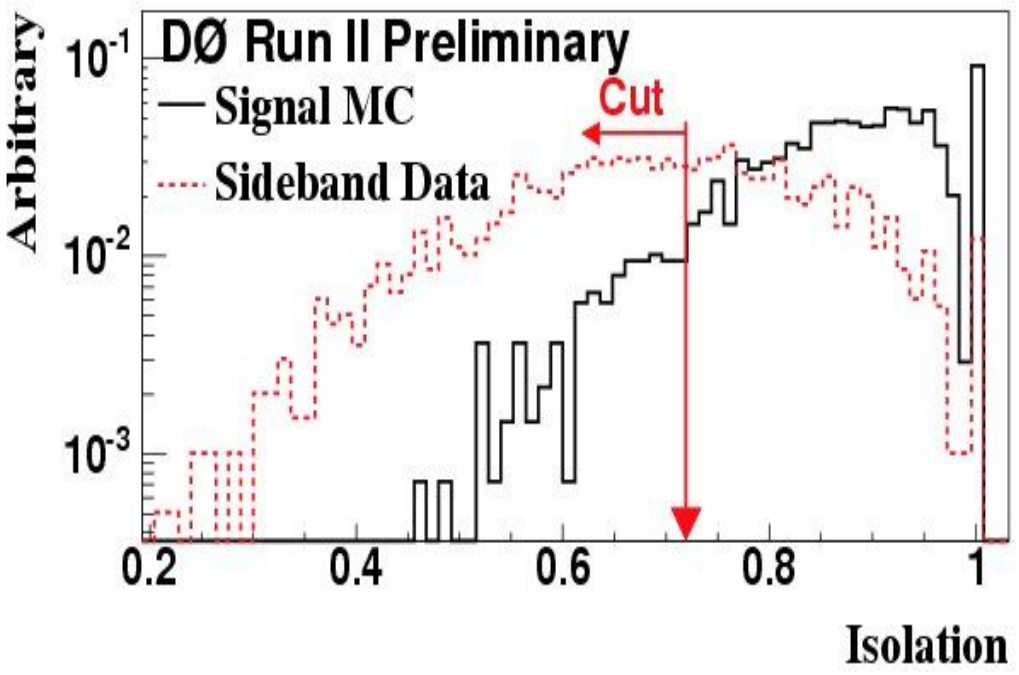
$B_s^0 \to \mu\mu\,\phi$ Search

Optimized discriminating cuts:

- pointing angle < 0.1
- decay length significance > 10.3
- isolation > 0.72

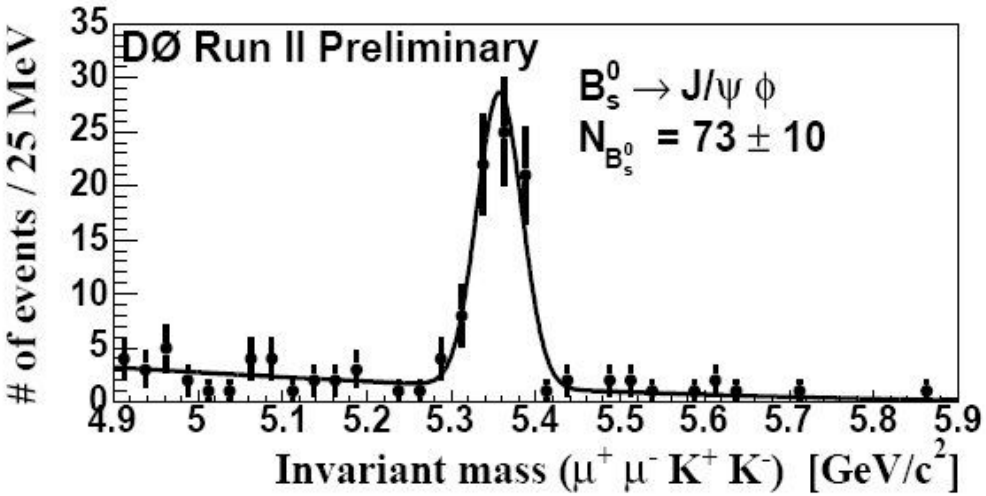






$B_s^0 \to \mu\mu\,\phi$ Search

Normalisation channel: $B_s^0 \to J/\psi\,\phi \to \mu\mu KK$



Uncertainties:

- background extrapolation from sidebands: 25%
- number of $J/\psi\,\phi$:14%
- CP state in MC: 8%
- relative efficiencies: 7.5%

Feldman -Cousins limit

$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-\phi)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = \frac{\mu(n_{obs}, n_{back})}{N_{B_s^0}} \cdot \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\mu\mu\phi}} \cdot \mathcal{B}(J/\psi \to \mu\mu)$$

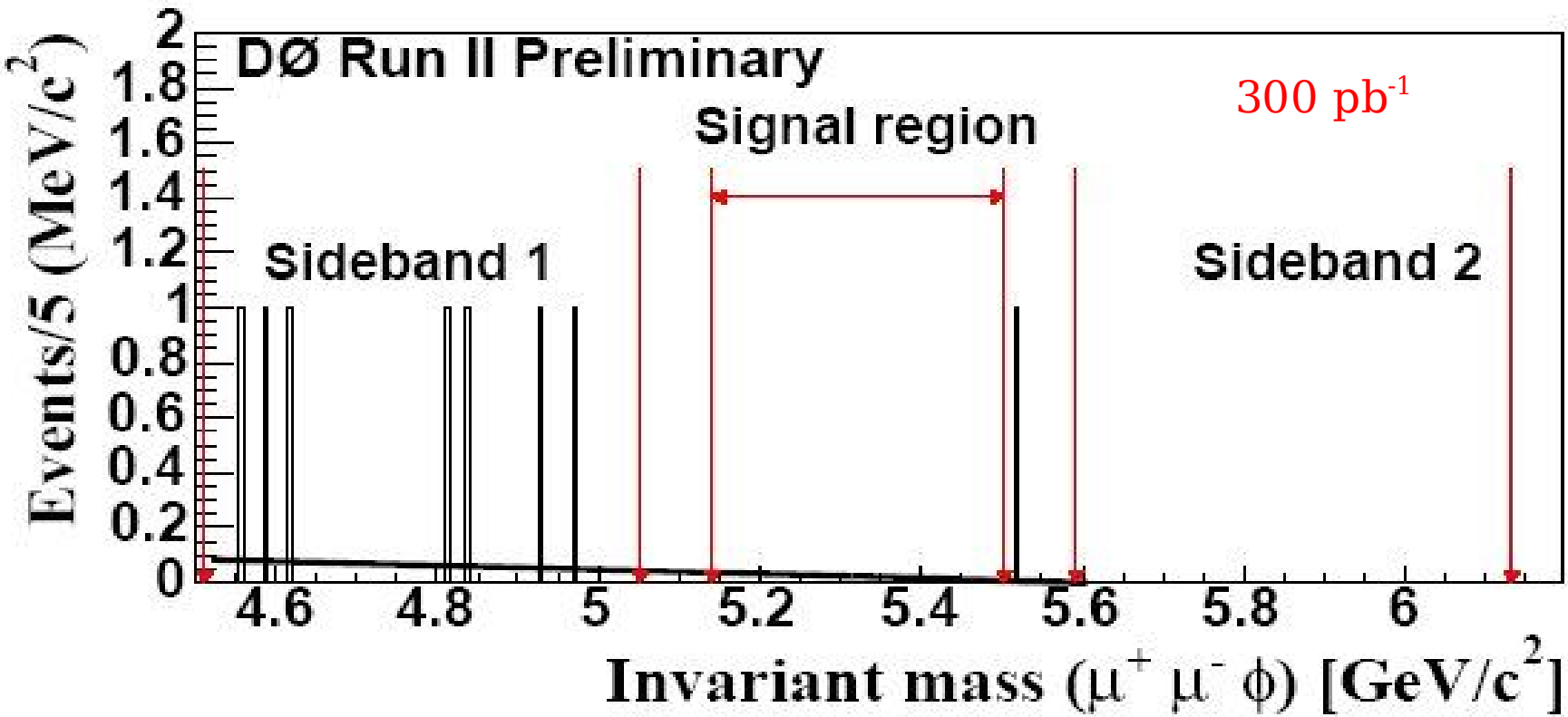
From MC

From PDG

$B_s^0 \to \mu\mu\,\phi$ Search

Opening the box:

After analysing 300 pb^{-1}, we find 0 events in signal region while the expected background is 1.6 ± 0.4



$B_s^0 \to \mu\mu\,\phi$ Search

Results interpreted with frequentist confidence interval

- parameterise uncertainties by probability functions
- integrate using Feldman-Cousins scheme

Expected sensitivity: $\mathcal{B}(B_s^0 \to \mu^+\mu^-\phi)$ < 1.0 x 10^{-5} (95%C.L.)

Limit (based on 300 pb^{-1}, observing no events):

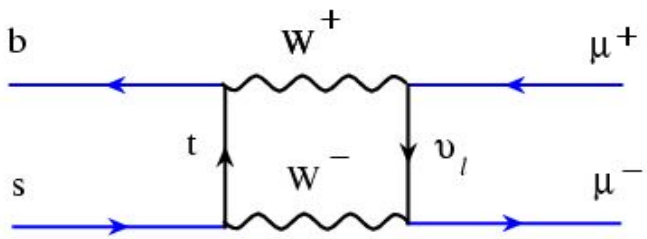
$$\frac{\mathcal{B}(B_s^0 \to \mu^+\mu^-\phi)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} < 4.4\ (3.5) \times 10^{-3} \text{ at } 95\ (90)\ \%\ \text{C.L.}$$

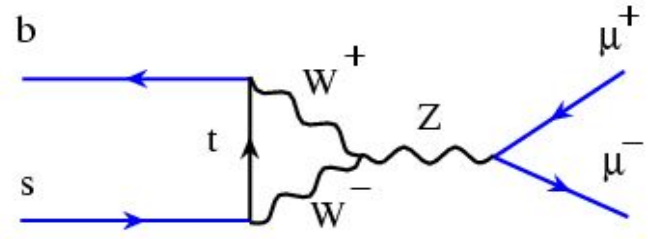
Using world average for $B(B_s^0 \to J/\psi\,\phi) = (9.3 \pm 3.3) \times 10^{-4}$

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) < 4.1\ (3.2) \times 10^{-6} \text{ at } 95\ (90)\ \%\ \text{C.L.}$$

$B_s^0 \to \mu\mu$ Search

Same motivation as $B(B_s^0 \to \mu\mu\phi)$: search for FCNC





- SM prediction for $B(B_s^0 \to \mu\mu) = (3.42 \pm 0.54) \times 10^{-9}$
  Buchalla & Buras, Misiak & Urban
- significantly smaller than $B(B_s^0 \to \mu\mu\phi)$
- expect no events in Run II (DØ + CDF)

Observation would indicate new physics:

- SUSY $B(B_s^0 \to \mu\mu)$ rises with $\tan\beta$, (e.g. $\tan^6\beta$ in MSSM)
- R-parity violating SUSY allows a tree level diagram
- complementary to $b \to s\gamma$

This is an update, using $300 pb^{-1}$ (previously $240 pb^{-1}$)

$B_s^0 \to \mu\mu$ Search

Apply same basic di-muon pre-selection:

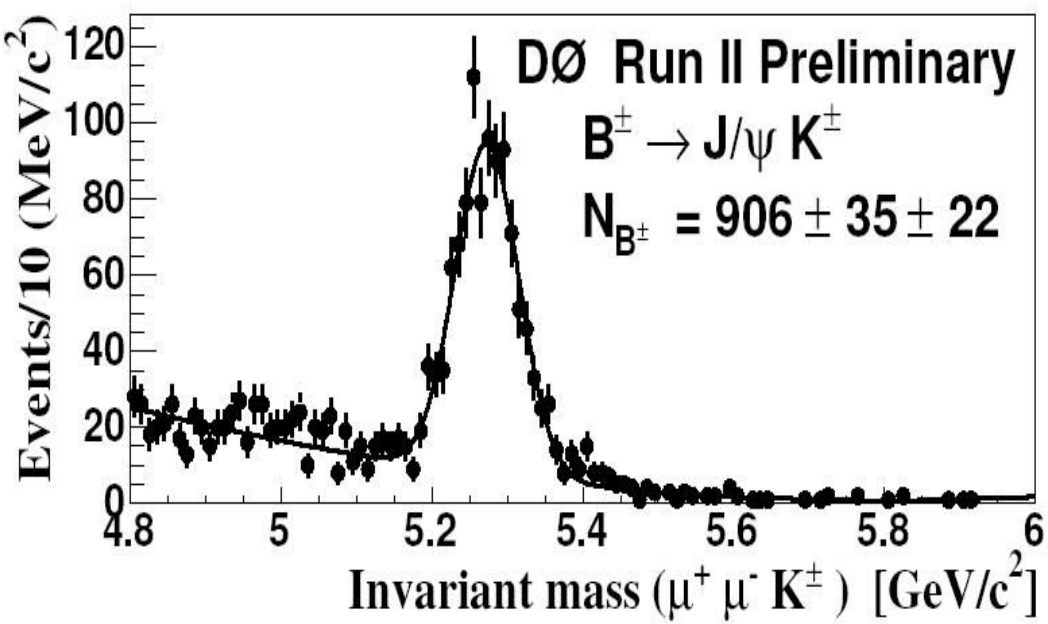
- di-muon mass window 4.5 – 6.2 GeV

Use same discriminating variables and procedure as $B_s^0 \to \mu\mu\phi$:

- opening angle < 0.11
- decay length significance > 11.1
- isolation >0.74

Normalization channel $B^\pm \to J/\psi\, K^\pm \to \mu\mu K^\pm$:

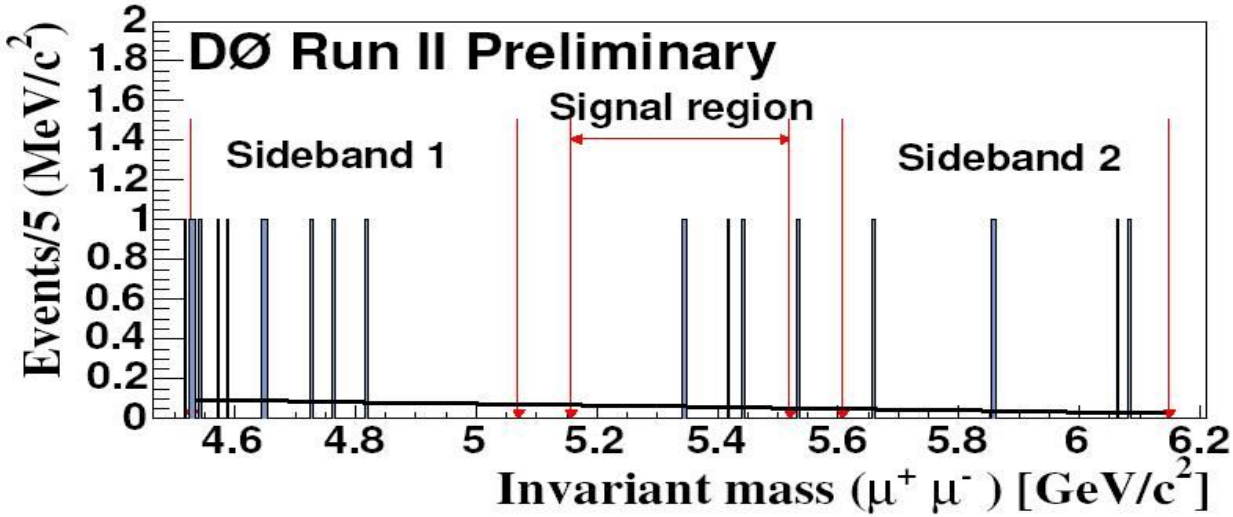
- di-muon compatible with J/ψ
- additional track ($K^\pm$), p_T >0.9GeV and originate from same vertex
- apply discriminating cuts



$B_s^0 \to \mu\mu$ Search

Opening the box:

After analysing 300 pb^{-1}, we get 4 events in signal region, while the expected background is 4.1 ± 1.2



Uncertainties:

- signal / normalization eff.
- MC statistics
- branching fractions (PDG)

$$\mathcal{B}(B_s) \leq \frac{N_{\rm ul}}{N_{B^\pm}} \cdot \frac{\epsilon^{B^\pm}_{\mu\mu K}}{\epsilon^{B_s}_{\mu\mu}} \cdot \frac{\mathcal{B}_1(B^\pm)\cdot\mathcal{B}_2(J/\psi)}{\frac{f_{b\to B_s}}{f_{b\to B_{u,d}}} + R\cdot\frac{\epsilon^{B_d}_{\mu\mu}}{\epsilon^{B_s}_{\mu\mu}}}$$

PDG

MC

PDG

MC

$B_s^0 \to \mu\mu$ Search

Interpret results with frequentist confidence interval

- uncertainties parameterised by probability functions
- integrate using Feldman-Cousins scheme

Published DØ limit (240 pb^{-1}):

Expected sensitivity: $B(B_s^0 \to \mu\mu) <$ 4.2×10^{-7} at 95 % CL

$B(B_s^0 \to \mu\mu) <$ $5.0\ (4.1) \times 10^{-7}$ at 95 (90) % CL (PRL 94, 071802)

Updated DØ result (300 pb^{-1}):

Expected sensitivity: $B(B_s^0 \to \mu\mu) <$ 3.6×10^{-7} at 95 % CL

$B(B_s^0 \to \mu\mu) <$ $3.7\ (3.0) \times 10^{-7}$ at 95 (90) % CL (preliminary)

Latest preliminary CDF result (364pb^{-1}):

- Expected sensitivity: $B(B_s^0 \to \mu\mu) < 2 \times 10^{-7}$ at 90% CL
- $B(B_s^0 \to \mu\mu) < 2.1\ (1.6) \times 10^{-7}$ at 95 (90) % CL

$B_s^0 \to \mu\mu$ Search

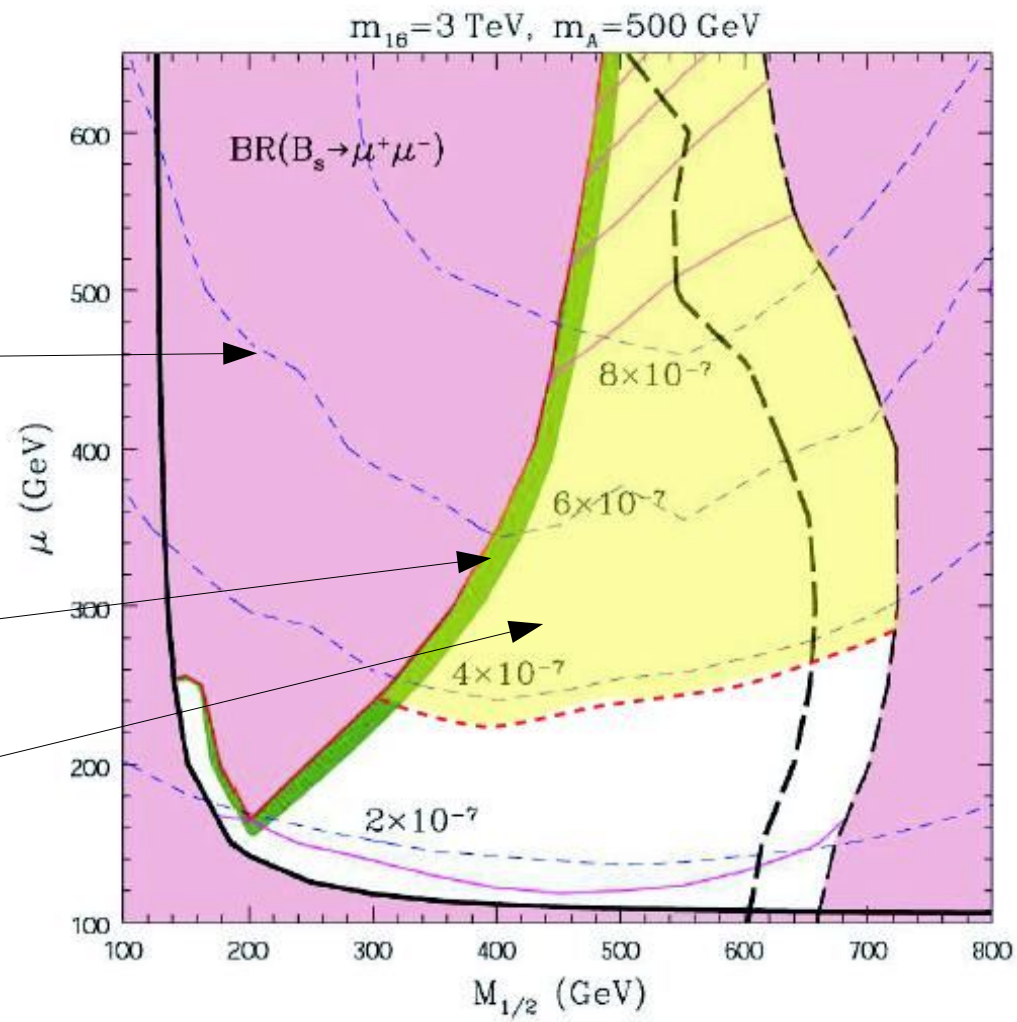
An example of the impact of new limit:

e.g. Dermisek et al, hep-ph/0304101
dark matter and SO(10)
with soft SUSY breaking

Contours of $B(B_s^0 \to \mu\mu)$

Allowed by
dark matter constraints

Excluded by DØ Run II



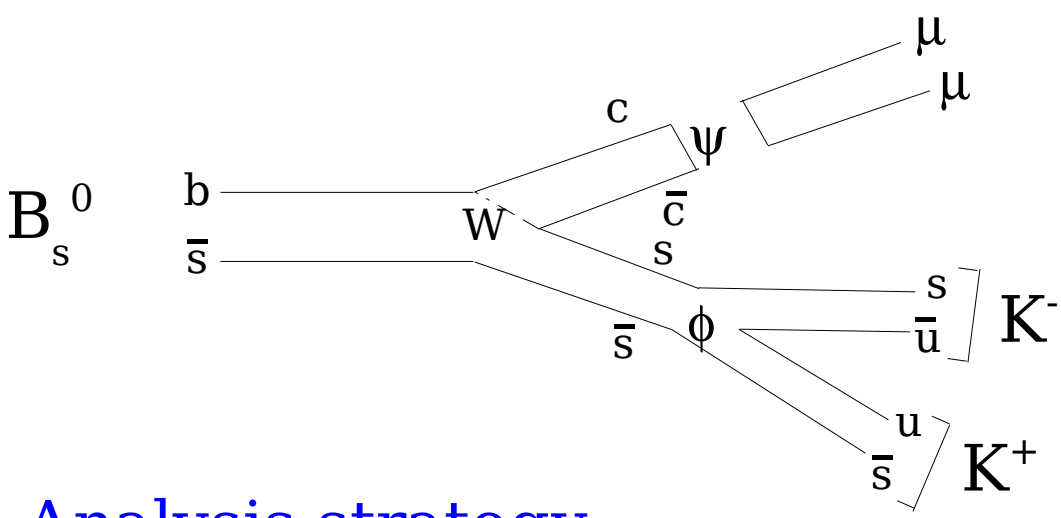
$B_s^0 \to \psi(2S)\,\phi$ Observation

In B system, decays to $J/\psi\,\phi$ and $\psi(2s)\phi$ observed

- rate for $\psi(2S)$ expected to be ~60 % that of J/ψ.

For B_s system, DØ has many decays to $J/\psi\,\phi$

- only previous observation of $\psi(2S)\phi$ - ALEPH (1 candidate)



Analysis is similar $B_s^0 \to \mu\mu\phi$, but now look on ressonant decay

Analysis strategy:

Look for both $B_s^0 \to \psi(2S)\,\phi$ and $B_s^0 \to J/\psi\,\phi$ to extract ratio

As a cross check:

- measure ratio of $B^\pm \to \psi\,(2S)K^\pm$ to $B^\pm \to J/\psi\,K^\pm$
- has been measured (PDG)

$B_s^0 \to \psi(2S)\,\phi$ Observation

Same basic di-muon pre-selection as $B_s^0 \to \mu\mu\phi$ analysis:

- di-muons invariant mass compatible with J/ψ or $\psi(2S)$
- add additional tracks (K candidates) p_T >0.9 GeV
- require good match to the di-muon vertex
- require K pair to match ϕ mass: 1.008-1.032 GeV
- B decay length significance >4.0 to remove prompt background
- collinearity angle between $B^{\pm}$ and decay products >0.9

For $B_s^0 \to \psi(2s)\phi$ and $B_s^0 \to J/\psi\,\phi$ use same discriminating variables and optimization procedure as in $B_s^0 \to \mu\mu\phi$

$B_s^0 \to \psi(2S)\,\phi$ Observation

$B_s^0 \to \psi(2s)\phi$:

Gaussian + linear background:

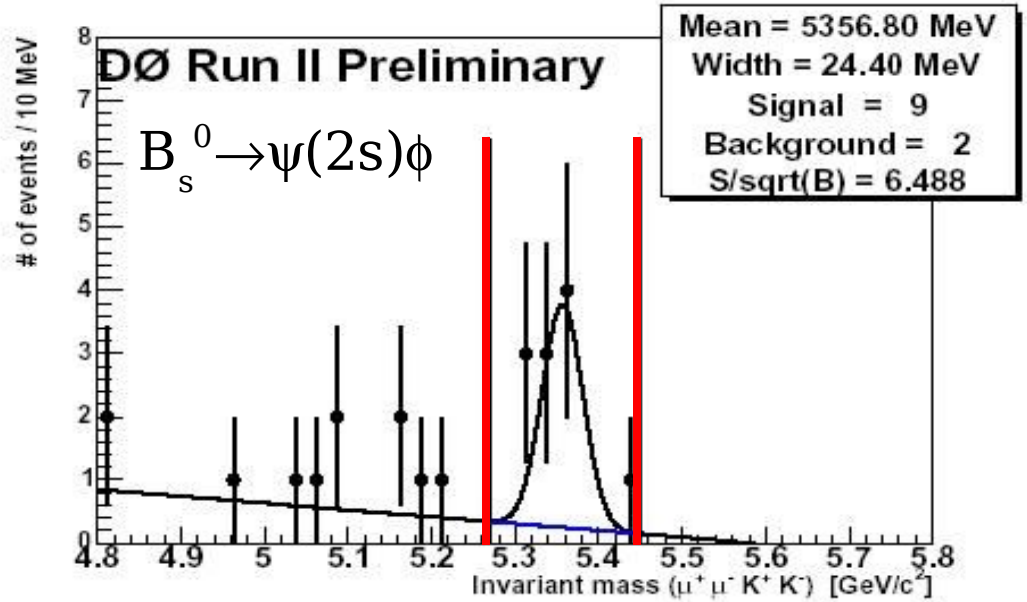
8.6 ± 3.3 signal events

1.8 ± 1.3 background events

$S/\sqrt{B} = 6.5$

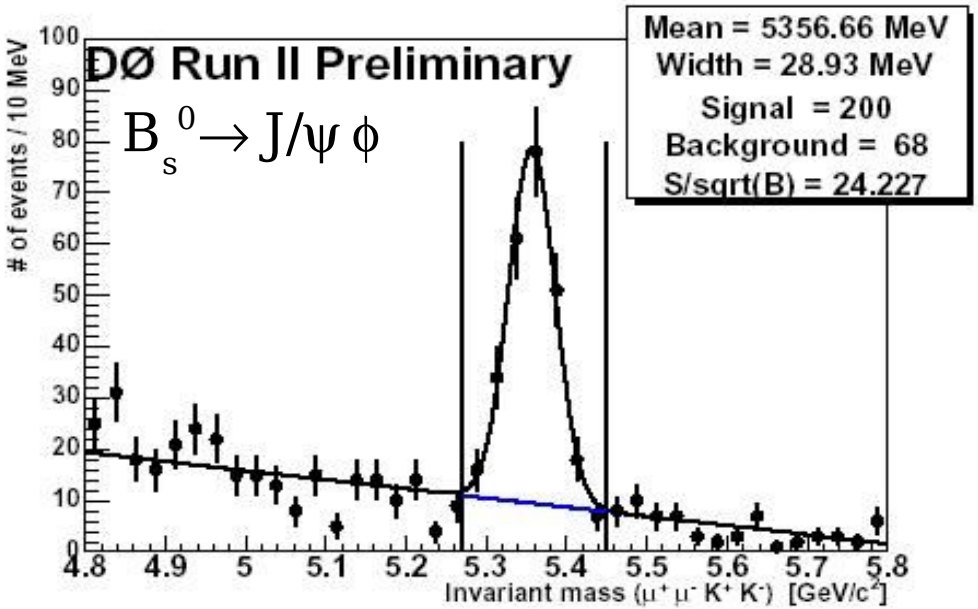
Probability of b.g. fluctuation:

1.1×10^{-4}



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

110 ± 11 signal events over background after discriminating cuts



$B_s^0 \to \psi(2S)\,\phi$ Observation

$$\frac{\mathcal{B}(B_s^0 \to \psi(2S)\,\phi)}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)} = \frac{N_{B_s^0 \to \psi(2s)\,\phi}}{N_{B_s^0 \to J/\psi\,\phi}} \cdot \frac{\epsilon_{J/\psi\,\phi}}{\epsilon_{\psi(2S)\,\phi}} \cdot \frac{\mathcal{B}(J/\psi \to \mu^+\mu^-)}{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}$$

MC

Take measured values:
$B(J/\psi \to \mu\mu) = (5.88 \pm 0.1)\ \%$
$B(\psi(2S) \to \mu\mu) = (0.73 \pm 0.08)\ \%$

DØ result, based on 300 pb^{-1}:

$$\frac{\mathcal{B}(B_s^0 \to \psi(2S)\,\phi)}{\mathcal{B}(B_s^0 \to J/\psi\,\phi)} = 0.58 \pm 0.24\ (\text{stat}) \pm 0.06\ (\text{syst}) \pm 0.07\ (\text{B})$$

CDF result (370pb^{-1}): $0.52 \pm 0.13(\text{stat}) \pm 0.04(\text{syst}) \pm 0.06$ (B)

Cross check channel: $B(B^\pm \to \psi\,(2S)K^\pm)\ /\ B(B^\pm \to J/\psi\,K^\pm)$

DØ ratio $= 0.60 \pm 0.07\ (\text{stat}) \pm 0.04\ (\text{syst}) \pm 0.06$ (B)

BaBar ratio $= 0.64 \pm 0.06\ (\text{stat}) \pm 0.06\ (\text{syst})$ PRD 65, 032001 (2002)

Conclusions

$B_s^0 \to \mu\mu\,\phi$ Search:

- limit based using 300 pb^{-1}:

  $B(B_s^0 \to \mu\mu\phi) < 4.1\ (3.2) \times 10^{-6}$ at 95 (90) % C.L.

- new limit, x16 better than best published result (CDF Run I) !
- publish soon.

$B_s^0 \to \mu\mu$ Search:

- updated limit using 300 pb^{-1}

  $B(B_s^0 \to \mu\mu) < 3.7(3.0) \times 10^{-7}$ at 95(90) % CL (preliminary)

- official combination with CDF well underway.

$B_s^0 \to \psi(2s)\,\phi$ Observation:

- new observation result using 300 pb^{-1}

  $B(B_s^0 \to \psi(2s)\,\phi) / B(B_s^0 \to J/\psi\,\phi) = 0.58 \pm 0.24\ (\text{stat}) \pm 0.06\ (\text{syst}) \pm 0.07(\text{B})$

- publish soon.