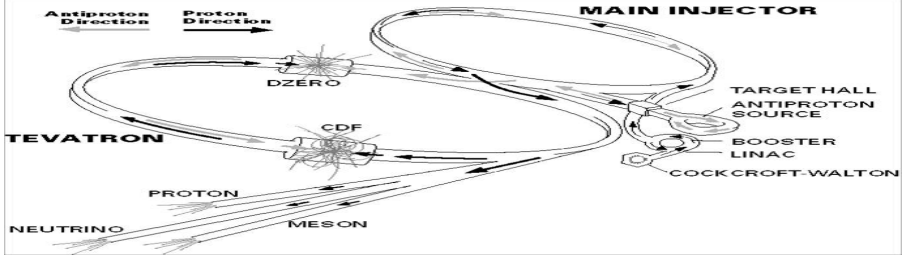

Rare B-decays at Tevatron

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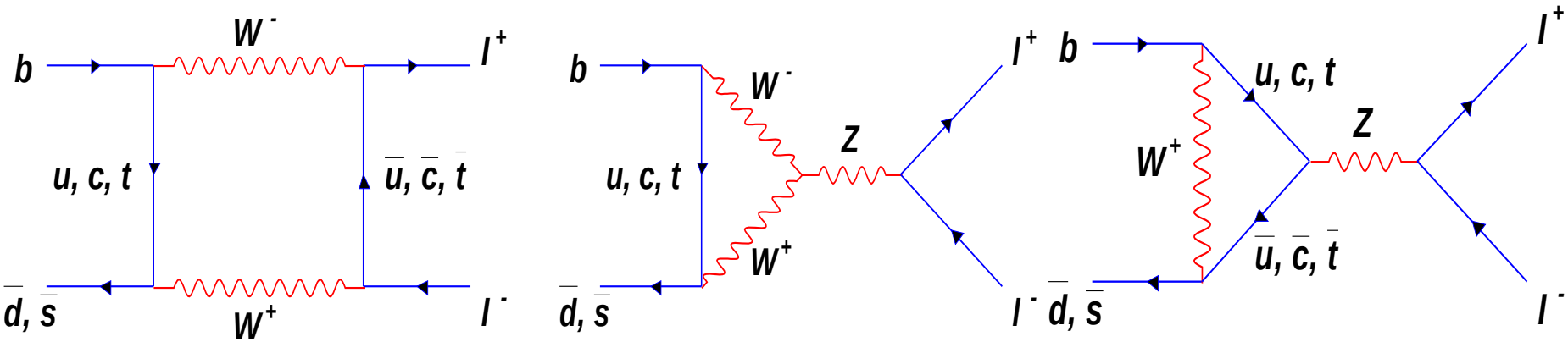
On behalf of D∅/CDF Collaboration

Plan of the Talk

- Motivation for rare B-decay Channels
- Searches at Tevatron
- DØ/CDF Detectors
- Analysis
- Results

Motivation

- di-leptonic decay modes of $B_{s,d}$ mesons are of type Flavor Changing Neutral Current
  - Forbidden in the Standard Model at tree level
  - Can proceed at higher order diagram

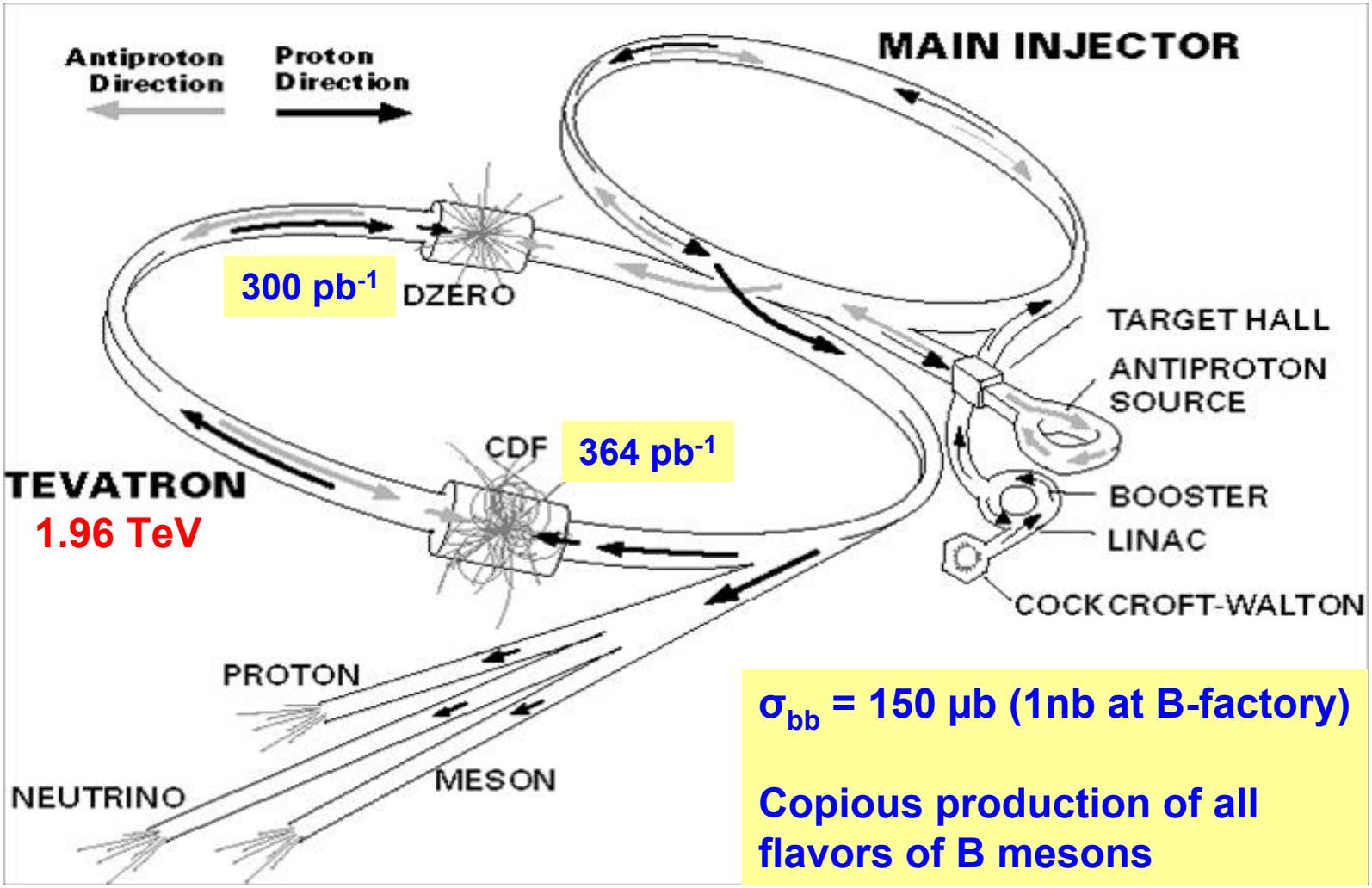


SM Branching Fractions

- *Estimated SM Branching fraction very small*
  - $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) = (3.4 \pm 0.4) \times 10^{-9}$
  - $\mathcal{B}(B_d \rightarrow \mu^+ \mu^-) = (1.5 \pm 0.9) \times 10^{-10}$
    - *Suppressed by* $|V_{td}/V_{ts}|^2 \sim 0.04$
  - $\mathcal{B}(B_s \rightarrow \mu^+ \mu^- \Phi) = (1.6 \pm 0.5) \times 10^{-6}$

- *SUSY motivated models can enhance branching fraction significantly*

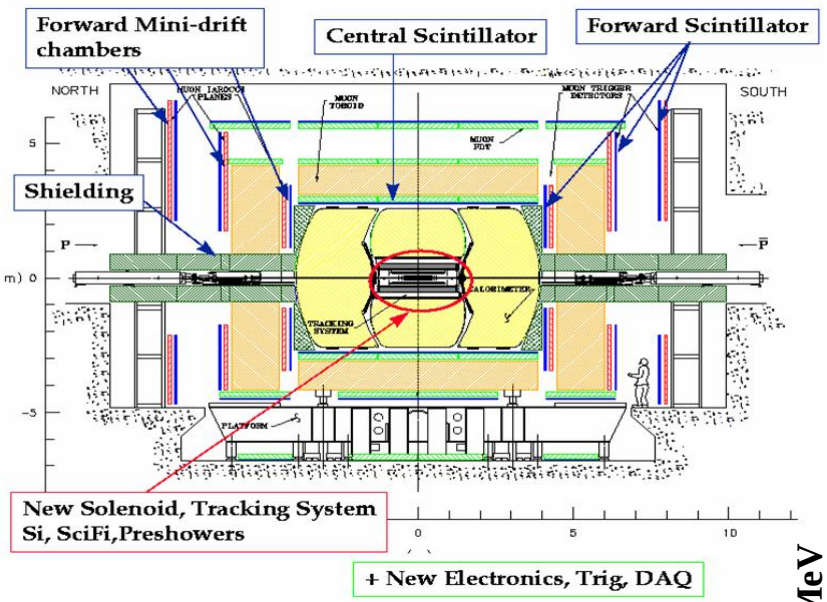
Searches at Tevatron

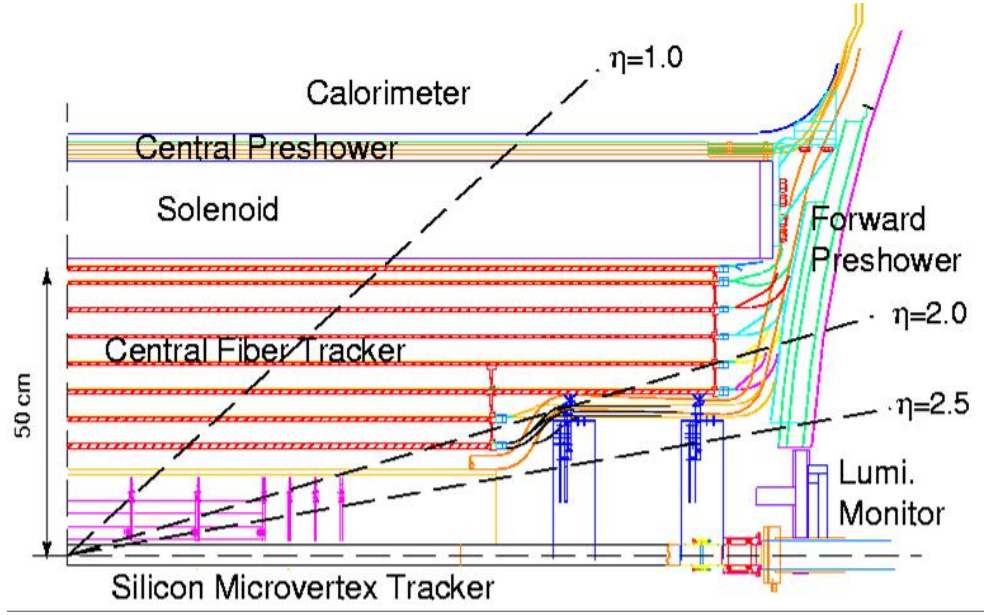


σ_{bb} = 150 μb (1nb at B-factory)

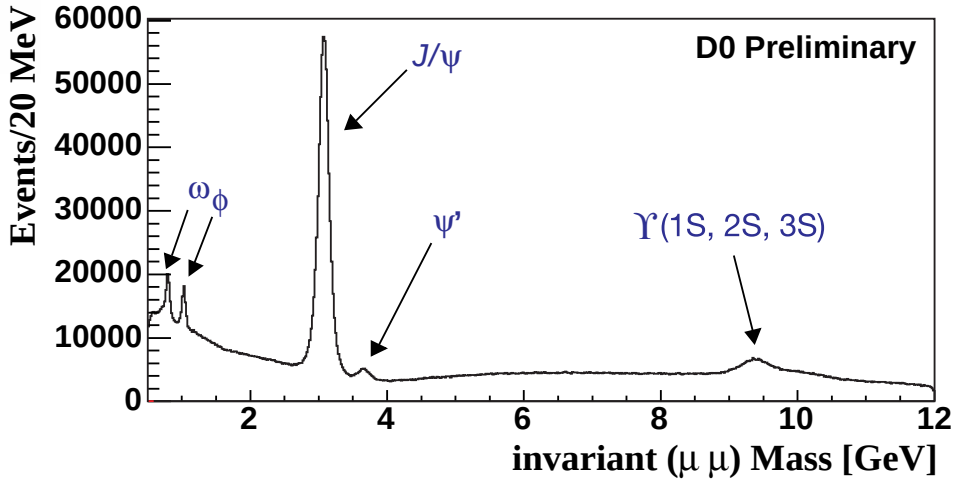
Copious production of all flavors of B mesons

DØ Detector

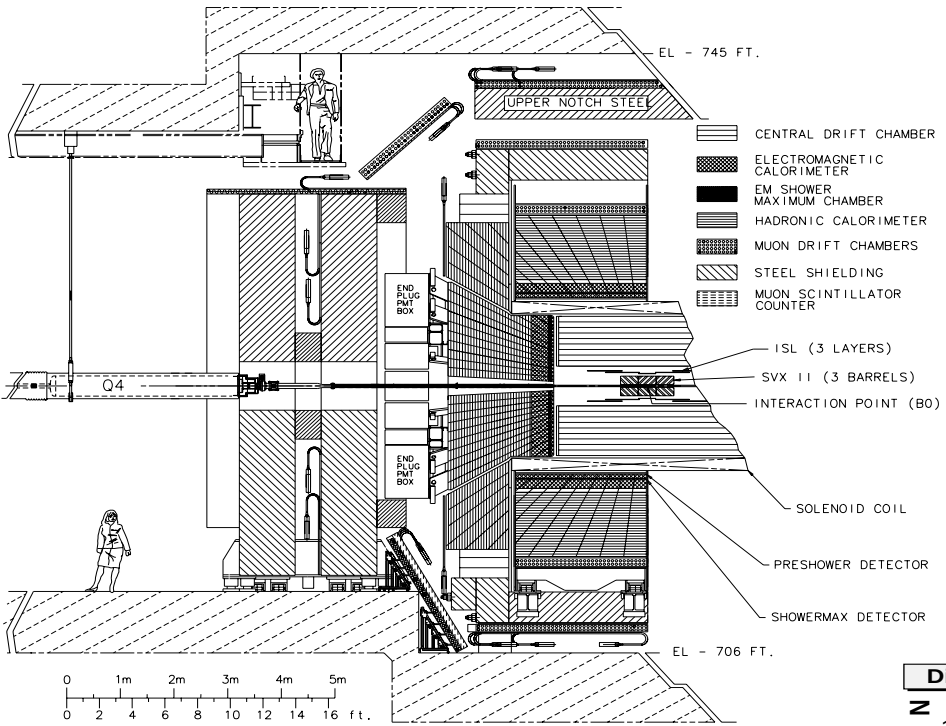


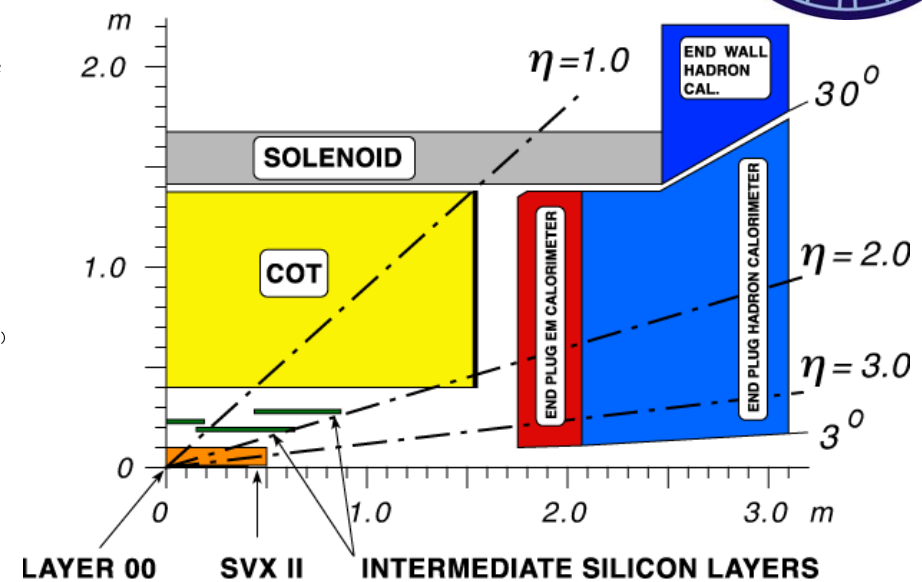


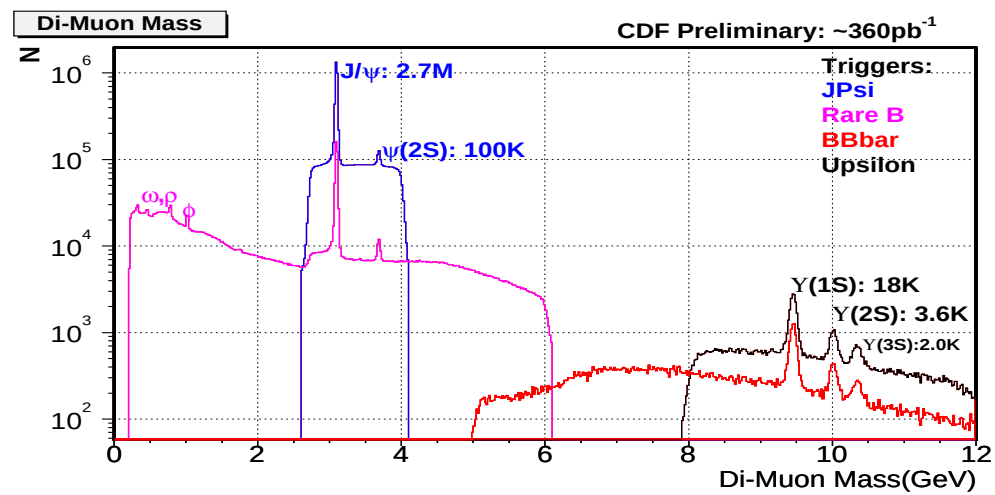
- ✓ **μ Coverage** $|\eta| < 2$
- ✓ $\sigma(P_T) \sim 0.2P_T\%$
- ✓ **PV:** $\sigma \sim 35\ \mu m$ (r-ϕ)
  $\sigma \sim 80\ \mu m$ (r-z)
- ✓ **SV:** $\sigma \sim 40\ \mu m$ (r-ϕ)



CDF Detector







- ✓ **μ Coverage:**
  - ✓ **CMU** $|\eta|<0.6$
  - ✓ **CMX** $0.6<|\eta|<1.0$
- ✓ $\sigma(p_T) \sim 0.1 p_T$ %
- ✓ **SV:** $\sigma \sim 40\mu m$

Methodology

- Identify di-muon candidates around signal mass region
  - Use displaced vertex, isolation etc. to eliminate background
  - Estimate no. of signal events and eff. in the signal mass region
- Use $B^{\pm} \rightarrow J/\psi\ K^{\pm}$ decay mode to get relative acceptance, trigger, reconstruction efficiency
  - Systematic effects cancels out
- Get Branching fraction using,

$$\mathcal{B}(B_s) \leq \frac{N_{ul}}{N_{B^{\pm}}} \frac{\varepsilon^{B^{\pm}}_{\mu\mu K}}{\varepsilon^{B_s}_{\mu\mu}} \frac{\mathcal{B}(B^{\pm} \rightarrow J/\psi K^{\pm})\, \mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{f_{b\rightarrow B_s} / f_{b\rightarrow B_{u,d}} + R\ \varepsilon^{B_d}_{\mu\mu} / \varepsilon^{B_s}_{\mu\mu}}$$

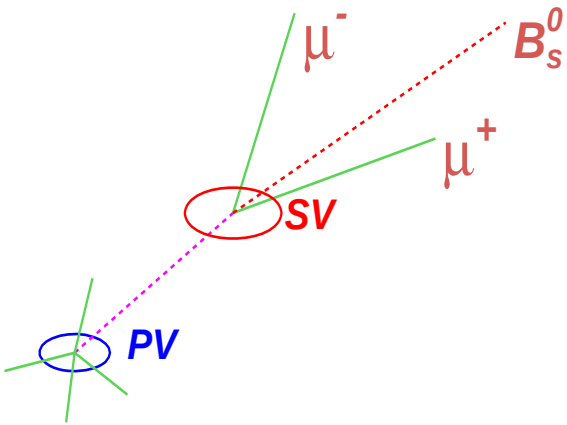
- $R = \mathcal{B}(B_d \rightarrow \mu^+\mu^-)/\mathcal{B}(B_s \rightarrow \mu^+\mu^-) \sim 1/25$

- Due to limited DØ Mass resolution B_s and B_d mass distribution cannot be completely separated

Event Selection

- Good Primary Vertex
- Good Muon tracks above certain p_t
- Good Secondary Vertex around Signal Mass

← Pre-selection



- **Pointing Angle:** Angle between B_s candidate's momentum vector and SV displacement vector

- **Decay Length Significance:** $L/\delta L$

- **Isolation**

$$I = \frac{p(B_s)}{p(B_s) + \text{Scalar Sum of non-muonic tracks momentum } (\Delta R<1)}$$

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\Phi^2}$$

Sideband and Signal Regions

	DØ	CDF
di-muon mass resolution (MeV/c^2)	σ=90	σ=25
Left Sideband region	$m_{Bs} - 9\sigma < M < m_{Bs} - 3\sigma$ (ΔM = 540 MeV)	$m_{Bs} - 28\sigma < M < m_{Bs} - 8\sigma$ (ΔM = 500 MeV)
Right Sideband region	$m_{Bs} + 3\sigma < M < m_{Bs} + 9\sigma$ (ΔM = 540 MeV)	$m_{Bs} + 4\sigma < M < m_{Bs} + 24\sigma$ (ΔM = 500 MeV)
Initial Signal region	$m_{Bs} - 3\sigma < M < m_{Bs} + 3\sigma$ (ΔM = 540 MeV)	$m_{Bs} - 8\sigma < M < m_{Bs} + 4\sigma$ (ΔM = 300 MeV)
Final Signal Region	$m_{Bs} - 2\sigma < M < m_{Bs} + 2\sigma$ (ΔM = 360 MeV)	$m_{Bs} - 2.5\sigma < M < m_{Bs} + 2.5\sigma$ (ΔM = 125 MeV)

DØ Event Selection ($B_s \rightarrow \mu^+ \mu^-$)

Definition	Value	# of Candidates
Good Vertex		5,826,444
Mass Window (GeV/c²)	$4.5 < m_{\mu\mu} < 7.0$	615,873
Muon Quality	Two medium	399,136
X^2/d.o.f. of SV	< 10	253,321
Muon p_t (GeV/c)	> 2.5	154,305
$\lvert\eta\rvert<2.0$	< 2.0	149,791
Tracking Hits	CFT>3, SMT>2	110,099
δL_{xy} (μm)	< 150	107,925
P_t of B_s (GeV/c)	> 5.0	45,696
Pointing Angle: α (rad)	< 0.2	3923
$L_{xy}/\delta L_{xy}$	> 18.5	36
Isolation	> 0.6	28
Normalization decay: $B^\pm \rightarrow J/\psi + K^\pm$		
X^2/d.o.f. of SV	< 20	
Kaon p_t (GeV/c)	> 0.9	
Cos(α) in Tr.plane	>0.9	

Pre-selection Cuts

Final Cuts

Data Sample $\mathcal{L}$ = 300 pb^{-1}

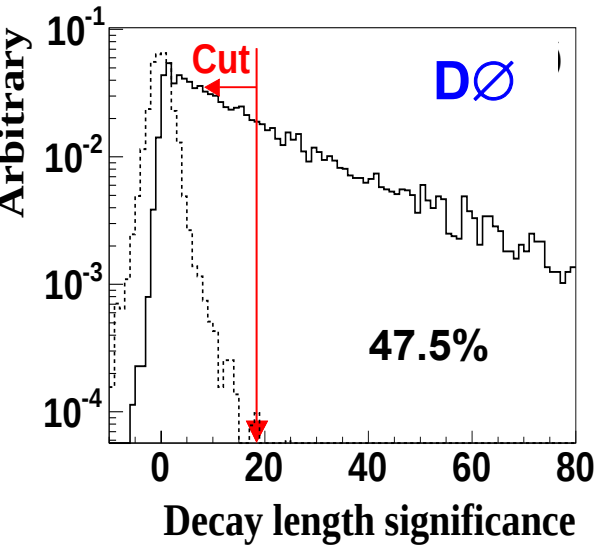
$$N_{B^\pm} = 906 \pm 35 \pm 22$$

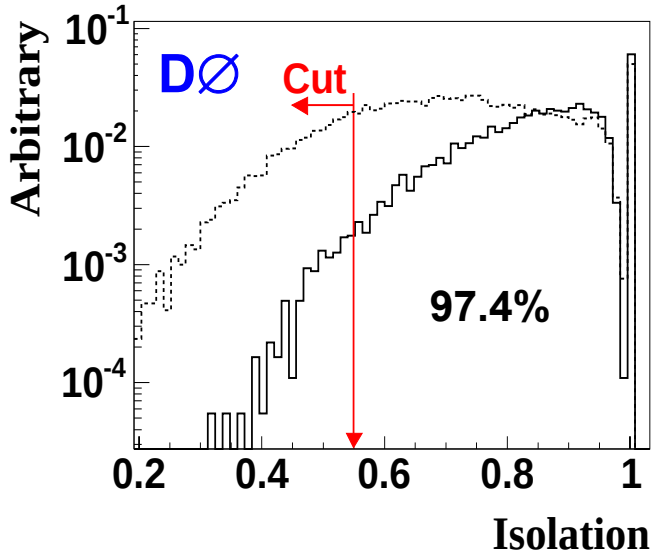
Optimization

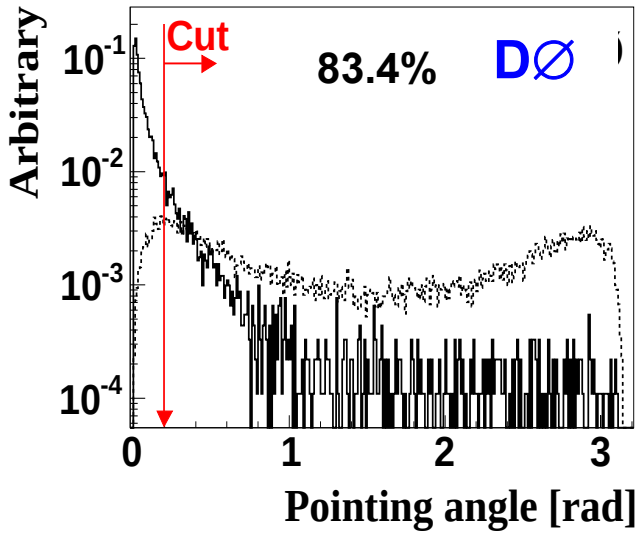
Cuts obtained using random grid search and Punzi's optimization procedure

$$P = \frac{\varepsilon_{\mu\mu}^{B_s}}{a/2 + \sqrt{N_{back}}}$$

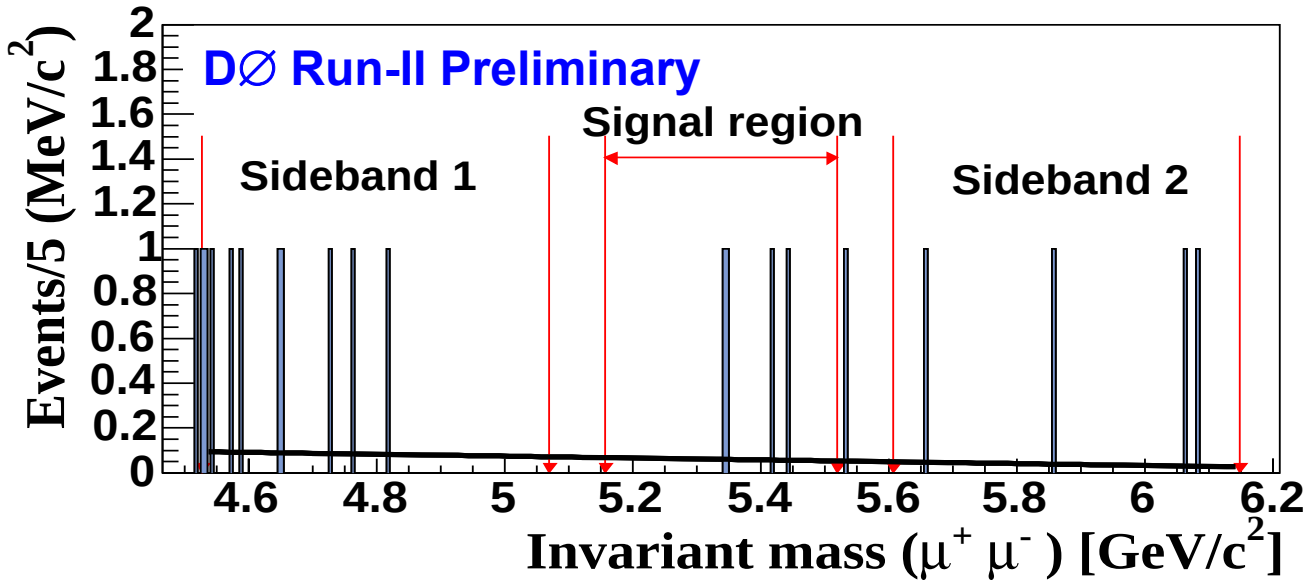
- $\varepsilon_{\mu\mu}(B_s)$ is reconstruction eff. at pre-selection level
- a=2 for 95%C.L.
- Overall Signal Eff. (38.6 ± 0.7)%

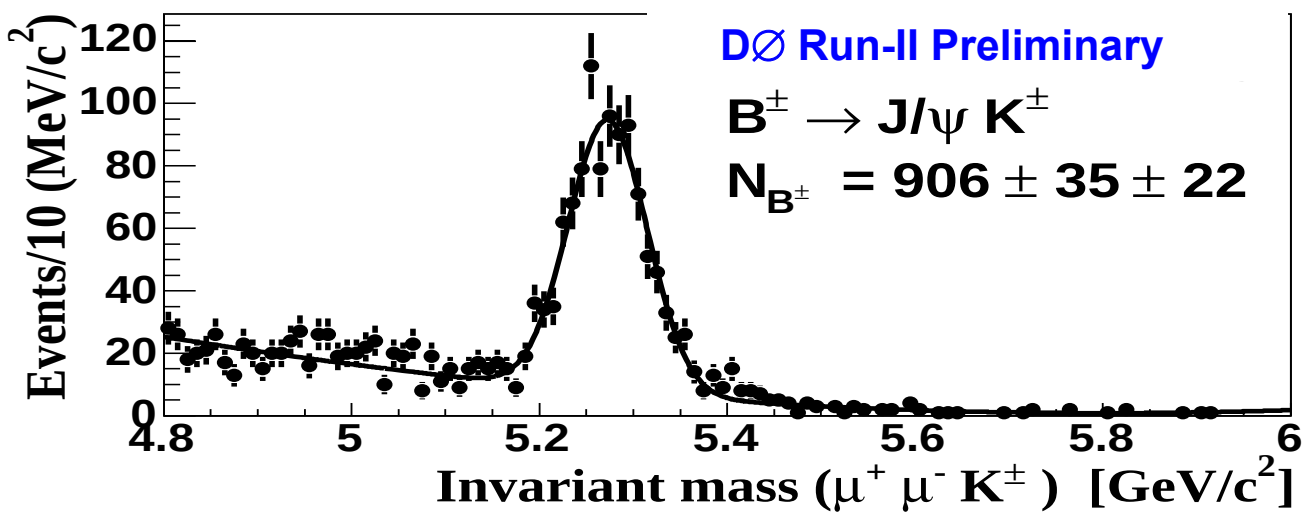






Mass Distributions





CDF Event Selection ($\mathcal{L}$ = 364/336 pb^{-1})

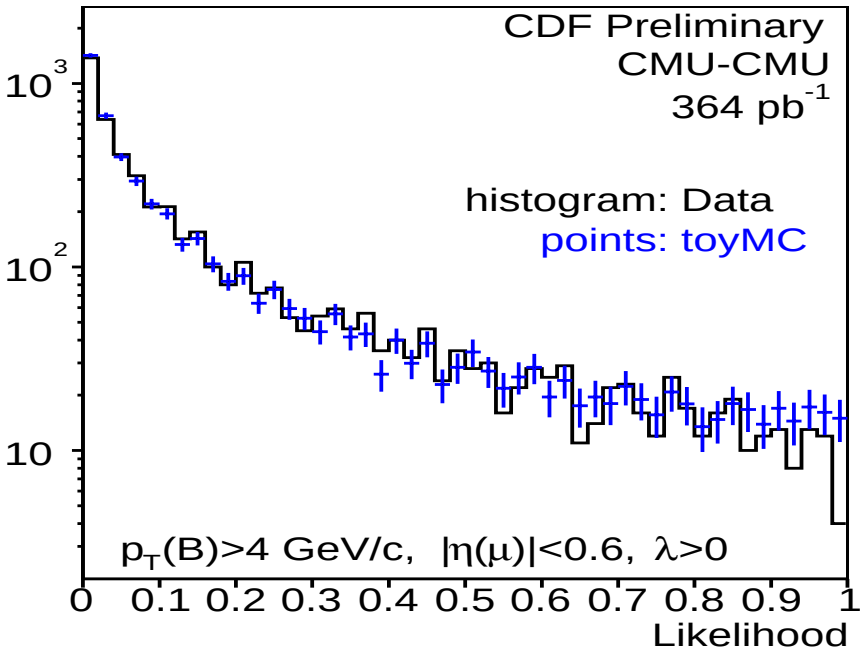
Definition	Value
Baseline requirement:	
Trigger Match, Good Run,	at least one of the dimuon trigger,
Track Quality	track satisfying COT/Silicon requirements
Muon Quality	p_t>2.0 (2.2) GeV in CMU (CMX)
B-hadron	p_t(B)>4 GeV and |y(B)|<1
Vertex requirement:	
$\mu^+\mu^-$ Vertex	$X^2 < 15$, $L_{3D} < 1.0$ cm, $\sigma_{3D}<0.0150$ cm $4.669 < M_{vtx} < 5.969$ GeV
Proper Decay Length (λ)	$0 < \lambda < 0.3$ cm and $\lambda/\sigma(\lambda) > 2$
Surviving Events:	22459 (14305) in CMU-CMU (CMU-CMX)
Additional Cuts:	Iso > 0.50 and $\Delta\alpha$<0.7 rad
Surviving Events:	6242 (4908) in CMU-CMU (CMU-CMX)

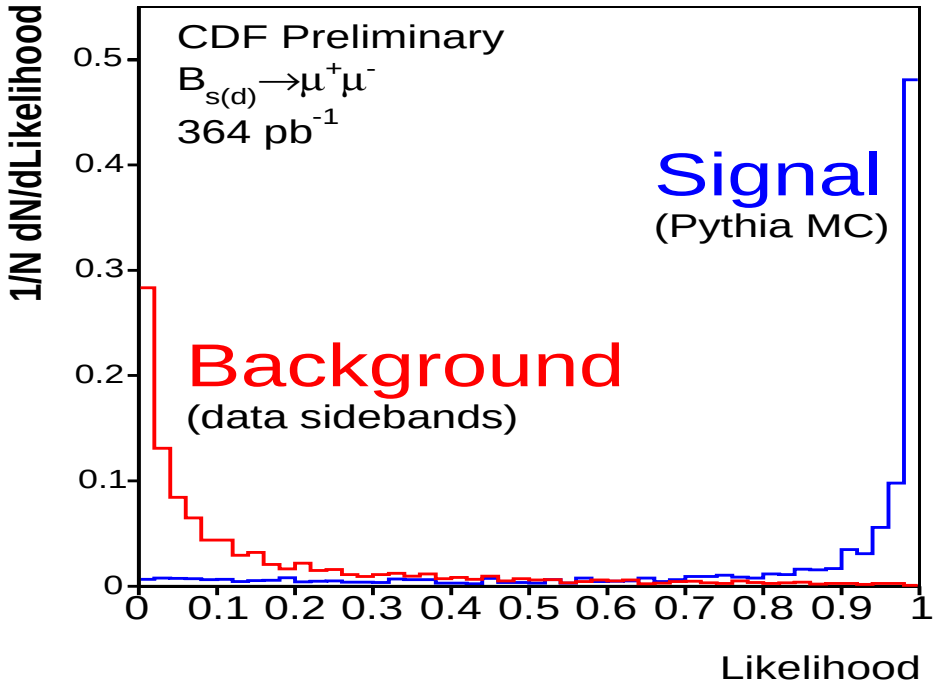
CDF: Relative likelihood Parameter

$$LH = \frac{\prod_i P_s(x_i)}{\prod_i P_s(x_i) + \prod_i P_b(x_i)}$$

x_j ➔ Isolation, Pointing Angle, Proper decay length

These variables are un-correlated



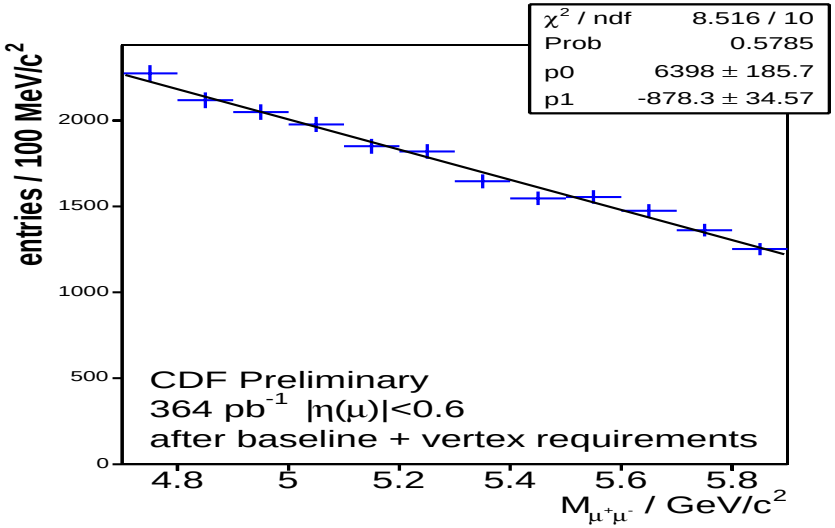


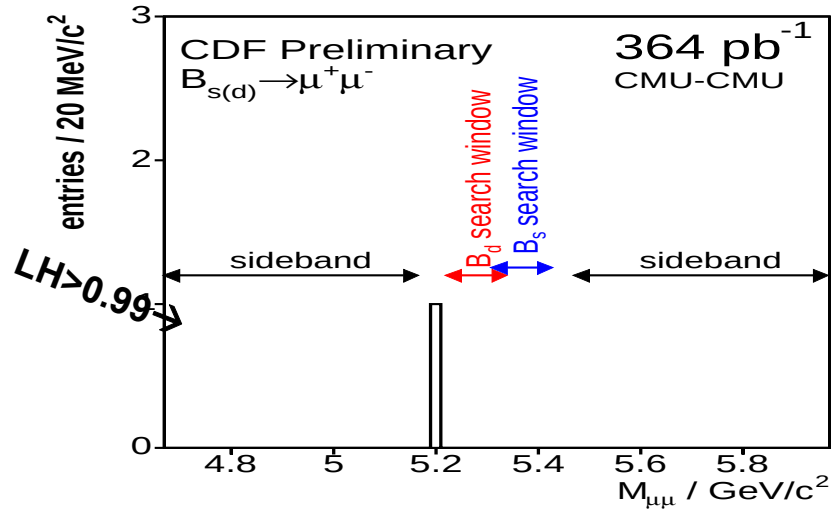
LH Cut optimized for the sensitivity:

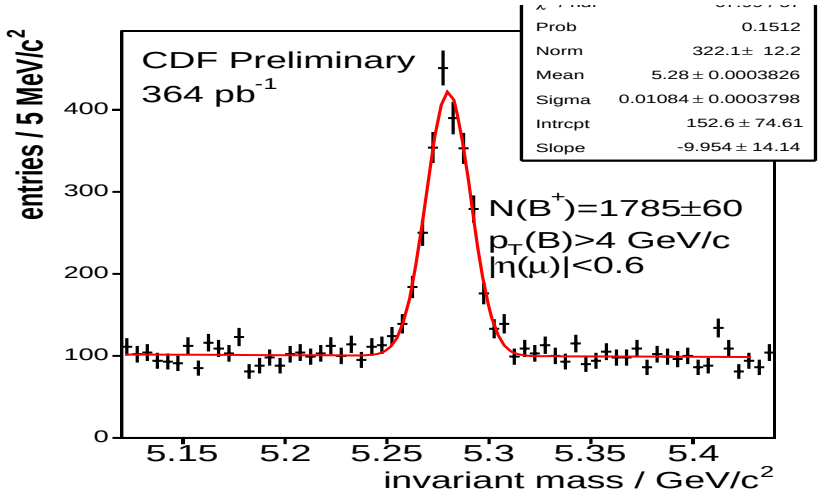
LH>0.99 ➔ Signal Efficiency ~ 38%

background rejection of 99.9% (NOT applied on $B^{\pm}$ data events)

Mass Distributions







Branching Fraction

	DØ		CDF	
	Value	Error	Value	Error
$\varepsilon^{B^\pm}_{\mu\mu K} / \varepsilon^{B_s}_{\mu\mu}$	0.229	6.9%	0.274 0.174	7.7% (CMU) 7.8% (CMX)
$N_{B^\pm}$	906	4.6%	1785 696	3.4% 5.6%
$f_{b\to B_s} / f_{b\to B_{u,d}}$	0.270	12.7%	0.270	12.7%
$10^5 \times \mathcal{B}(B^+ \to J/\psi(\to \mu\,\mu)\, K^+)$	5.880	4.4%	5.880	4.4%
$\varepsilon^{LH}_{B_s}$			0.378 0.391	10% 6%
Cum. Error		15.8%		~18%
Exp. N_{bkg}	4.3	28%	0.81 0.66	15% 20%
Obs. Events	4		0	

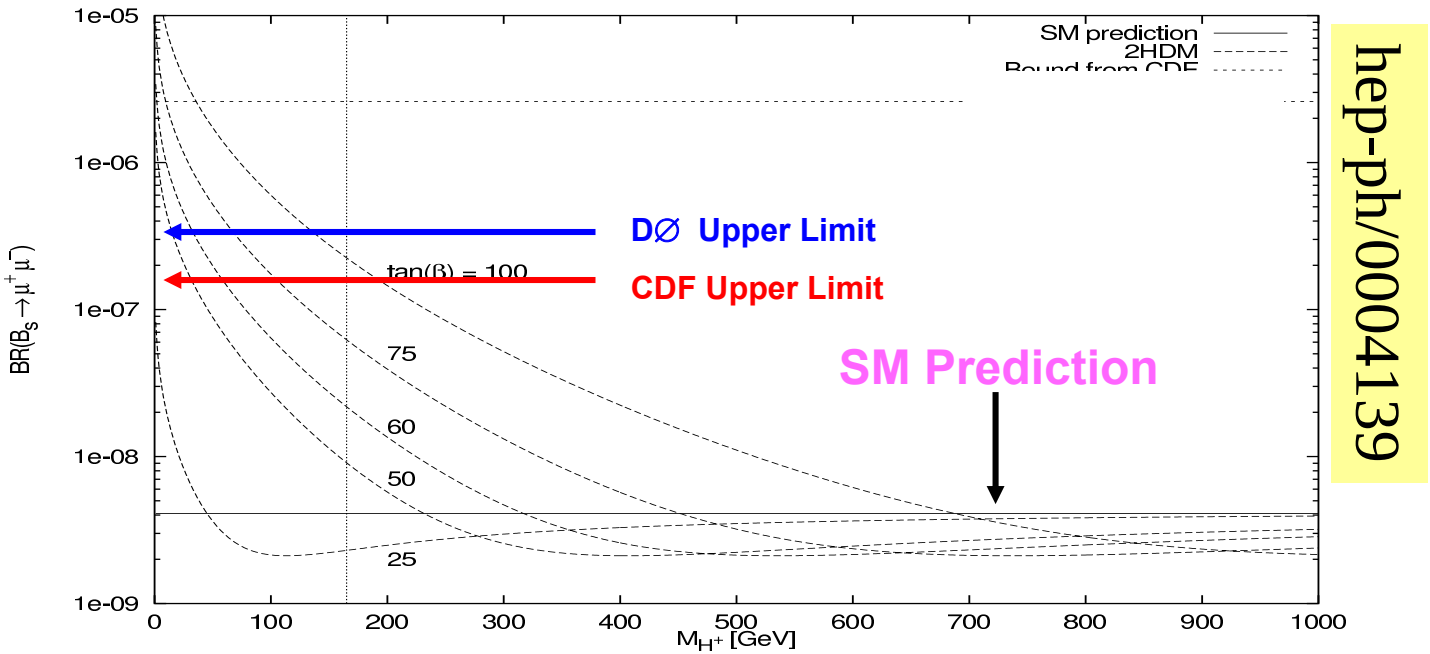
Branching Fractions contd.

- **CDF Results**
  - $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$
    - ✓ $< 1.5\ (2.0) \times 10^{-7}$ at 90% (95%) CL ($\mathcal{L}$ = 364/336 pb^{-1})
  - $\mathcal{B}(B_d \rightarrow \mu^+\mu^-)$
    - ✓ $< 3.8\ (4.9) \times 10^{-8}$ at 90% (95%) CL ($\mathcal{L}$ = 364/336 pb^{-1})
    - ✓ $< 8.3 \times 10^{-8}$ at 90% CL by BaBar ($\mathcal{L}$ = 111 fb^{-1})
- **DØ Results ($\mathcal{L}$=300pb^{-1})**
  - $\mathcal{B}(B_s \rightarrow \mu^+\mu^-)$
    - ✓ $< 3.0\ (3.7) \times 10^{-7}$ at 90% (95%) CL using F.C. procedure
    - ✓ $< 3.2\ (4.0) \times 10^{-7}$ at 90% (95%) CL using Bayesian method

SUSY Sensitivity

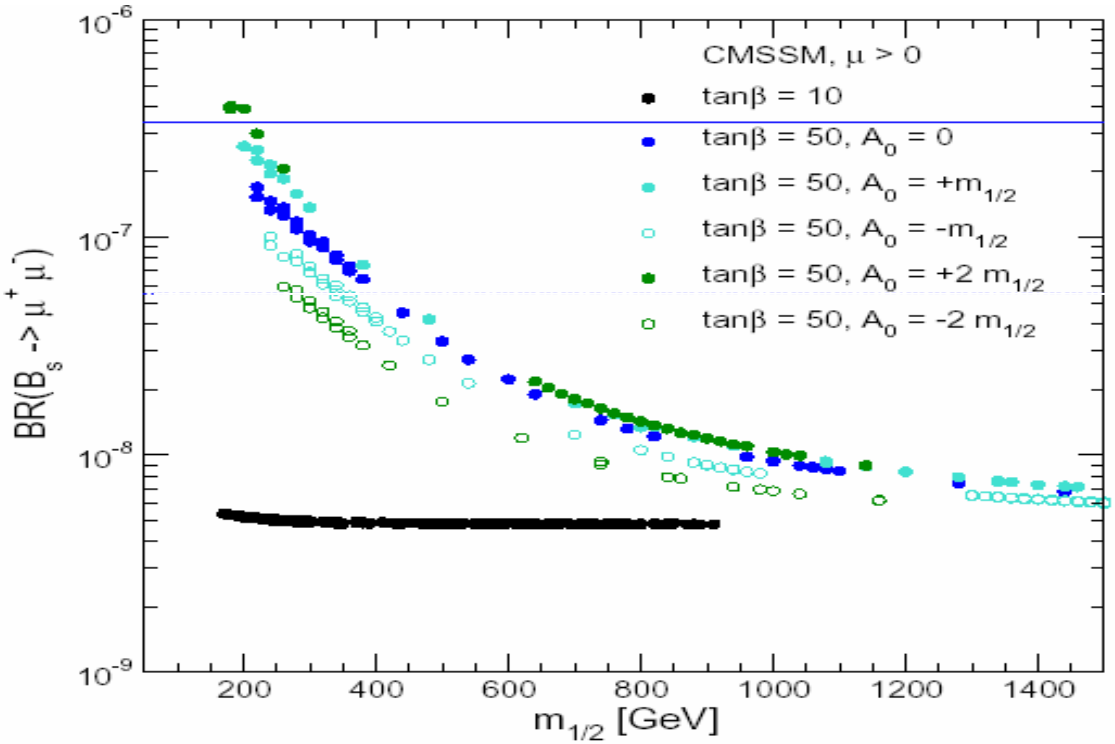
In 2 Higgs Doublet Model (2HDM), BF primarily depends tanβ and Mass of H

- BF α $(\tan\beta)^4$



SUSY Sensitivity

In MSSM Model BF α $(\tan\beta)^6$



hep-ph/0411216

Search for $B_s \rightarrow \mu^+ \mu^- \Phi$

- Similar methodology
- Normalization using $B_s \rightarrow J/\psi\ \Phi$
- Similar Pre-selection criteria similar
  - Additional criteria on Kaon p_t (>0.7 GeV) and Φ mass range ($1.008 < m_\Phi < 1.032$)
    - # of candidates 2602
- Final Cuts
  - Pointing Angle < 0.1 rad, $L/\delta L > 10.3$, Iso > 0.72
  - Overall Efficiency 54 ± 3%
  - Observed Events 0
  - Expected background 1.6 ± 0.4

DØ Event Selection ($B_s \rightarrow \mu^+ \mu^- \Phi$)

Definition	Value	# of Events
Good Vertex		1,555,320
Mass Window (GeV/c^2)	$0.5 < m_{\mu\mu} < 4.4$ Excl. J/ψ,Ψ(2S)	530,892
Muon Quality	Two medium	276,875
X^2/d.o.f. of vertex	< 10	127,509
Muon p_t (GeV/c)	> 2.5	73,555
$\|\eta\|<2.0$	< 2.0	72,350
Tracking Hits	CFT>3, SMT>2	58,012
δL_{xy} (μm)	< 150	54,752
P_t of B_s (GeV/c)	> 5.0	54,399
B_s X^2/d.o.f	< 36	53195
Kaon p_t	>0.7	9639
Φ Mass	$1.008 < m_\Phi < 1.032$	2602
Pointing Angle: α (rad)	< 0.1	
$L_{xy}/\delta L_{xy}$	> 10.3	
Isolation	> 0.72	8

Mass region definitions

- *Total region of interest*
  - ✓ ***4.516 - 6.136 GeV***
    ΔM = 1620 MeV
- *Signal Region*
  - ✓***Optimization: 5.056-5.596***
    ΔM = 540 MeV
  - ✓***Final: 5.138 - 5.513***
    ΔM = 375 MeV
- *Background*
  - ✓***Sideband-I 4.516-5.056***
  - ✓***Sideband-II 5.596-6.136***
    ΔM = 540 MeV

Normalization Channel

- $B_s \rightarrow J/\psi\ \Phi$
  - ✓Same Cuts
  - ✓$N_{Bs} = 73 \pm 10$

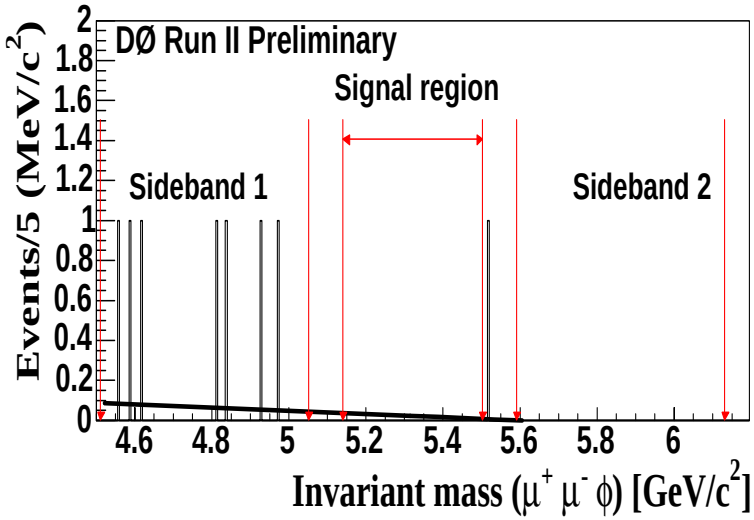
Uncertainties ($B_s \rightarrow \mu^+ \mu^- \Phi$)

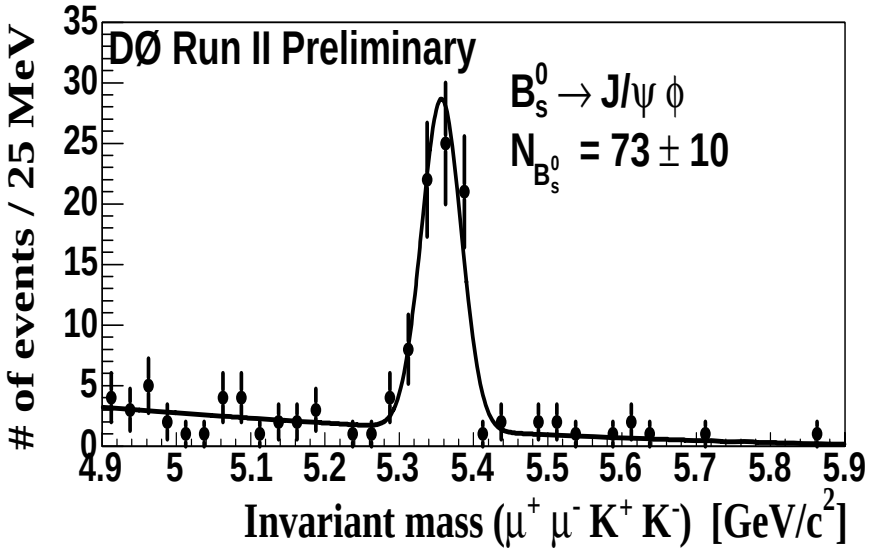
Source	Relative Uncertainty (%)
$\mathcal{B}(B_s \rightarrow J/\psi\, \Phi)$	36
$\mathcal{B}(J/\psi \rightarrow \mu\mu)$	1.7
$\varepsilon_{J/\psi}/\varepsilon_{\mu\mu\Phi}$	7.5
# of $B_s \rightarrow \mu^+ \mu^- \Phi$	13.7
MC Weighting	3.5
CP Odd/Even lifetime difference	8.0
Total	18
Background Uncertainty	25

Sensitivity to $B_s \rightarrow \mu^+ \mu^- \Phi$

$$\frac{\mathcal{B}(B_s \rightarrow \mu\mu\phi)}{\mathcal{B}(B_s \rightarrow J/\psi\phi)} = \frac{N_{ul}}{N_{B_s \rightarrow J/\psi\phi}} \frac{\varepsilon_{J/\psi\phi}}{\varepsilon_{\mu\mu\phi}} \mathcal{B}(J/\psi \rightarrow \mu\mu)$$

< 4.4 x 10^{-3}





$$N_{B_s \rightarrow J/\psi\varphi} = 73 \pm 10, \quad \frac{\varepsilon_{J/\psi\phi}}{\varepsilon_{\mu\mu\varphi}} = 2.80 \pm 0.21, \quad \mathcal{B}(B_s^0 \rightarrow J/\psi\varphi) = (9.3 \pm 3.3)10^{-4}$$

Results

Decay Mode	CDF ($\mathcal{L}$ 364/336 pb^{-1}) 95% CL Limit	DØ ($\mathcal{L}$ 300 pb^{-1}) 95% CL Limit	Standard Model Bran. Fraction Prediction
$B_s \rightarrow \mu^+\mu^-$	$\mathcal{B} < 2.0 \times 10^{-7}$	$\mathcal{B} < 3.7 \times 10^{-7}$	$3.4 \pm 0.4 \times 10^{-9}$
$B_d \rightarrow \mu^+\mu^-$	$\mathcal{B} < 4.9 \times 10^{-8}$	———	$1.5 \pm 0.9 \times 10^{-10}$
$B_s \rightarrow \mu^+\mu^- \Phi$	———	$\mathcal{B} < 4.1 \times 10^{-6}$	$1.6 \pm 0.5 \times 10^{-6}$

Lot of new data to be included

Integrated Luminosity inching toward fb^{-1}

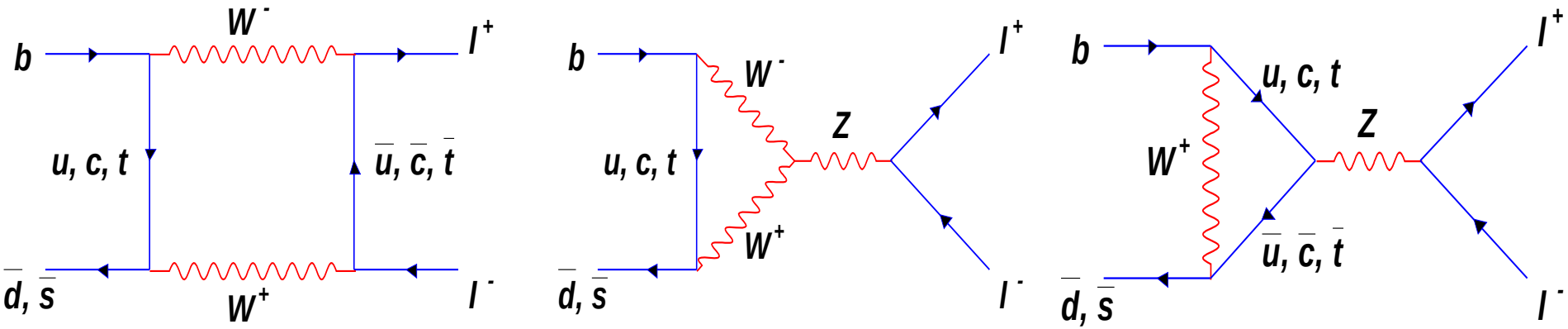
Above limits to be improved further, Combined analysis to be carried out

Backup Slides

Decay Channels

$B_{s/d} \rightarrow \mu^+ \mu^-$

SM Main Contributing Diagrams



Estimated SM Branching Fractions

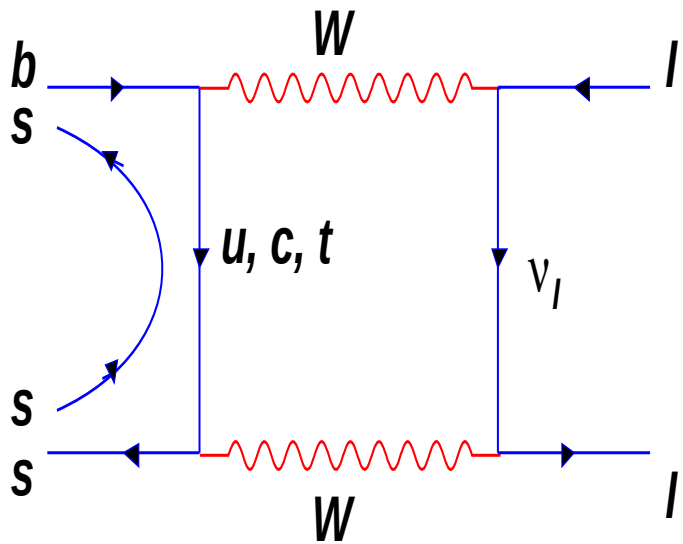
$B(B_s \rightarrow \mu^+ \mu^-) = (3.4 \pm 0.4) \times 10^{-9}$!

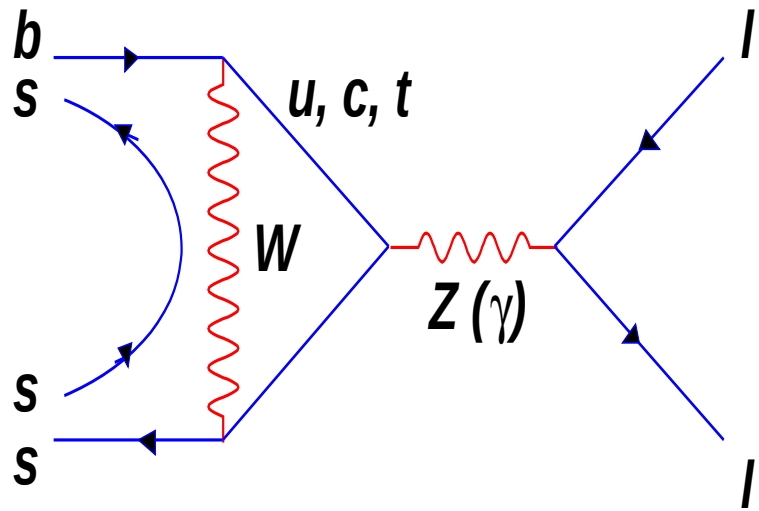
$B(B_d \rightarrow \mu^+ \mu^-) = (1.5 \pm 0.9) \times 10^{-10}$!

Supressed by $|V_{td}/V_{ts}|^2 \sim 0.04$

Decay Channels

$B_s \rightarrow \mu^+ \mu^- \varphi$





SM Branching Fraction

$(1.6 \pm 0.5) \times 10^{-6}$

Feldman Cousins Method

- Assume that there is only background, n_{back}
- For each value of n_{obs}, find a 95% CL upper limit $\mu(n_{obs}, n_{back})$

$$< \mu(n_{back}) > \; = \sum_{n_{obs}=0}^{\infty} \mu(n_{obs}, n_{back}) \; \frac{(n_{back})^{n_{obs}}}{(n_{obs})!} \; \exp(-n_{back})$$

PDG/DØ Values

	PDG	DØ
J/ψ Mass	3.097 GeV	3.072 GeV
B_d Mass	5.279 GeV	5.242 GeV
B_s Mass	5.369 GeV	5.331 GeV
$\mathcal{B}(J/\psi \rightarrow \mu\,\mu)$	$(5.88 \pm 0.10) * 10^{-2}$	
$\mathcal{B}(B^+ \rightarrow J/\psi\, K^+)$ with $J/\psi \rightarrow \mu\,\mu$	$(5.88 \pm 0.26) * 10^{-5}$	
$\mathcal{B}(B_s \rightarrow J/\psi\, \varphi)$	$(9.3 \pm 3.3) \times 10^{-4}$	
$\mathcal{B}(B_s \rightarrow \mu\,\mu)$	$(3.4 \pm 0.4) \times 10^{-9}$	
$\mathcal{B}(B_d \rightarrow \mu\,\mu)$	$(1.5 \pm 0.9) \times 10^{-10}$	

DØ Branching Fraction

- Trigger Efficiency
  - Simulate $B^{\pm} \rightarrow J/\psi\ K^{\pm}$ and $B_s \rightarrow \mu^+ \mu^-$
  - Re-weight MC sample w.r.t. p_t of observed p_t distribution $B^{\pm}$ candidates
  - $\varepsilon_{\mu\mu}(B_d)/\varepsilon_{\mu\mu}(B_s) = 0.229 \pm 0.008 \pm 0.014$ (6.9%)

- $N_{B\pm} = 906 \pm 35 \pm 22$ (4.6%)
- $f_s/f_{u,d} = 0.270 \pm 0.034$ (12.7%)
- $\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow \mu\ \mu)\ K^+) = (5.880 \pm 0.235) \times 10^{-5}$ (4.4%)
- Expected Background: 4.3 ± 1.2 (28%)
- Observed Events: 4
- $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 3.7\ (3.0)\ 10^{-7}$ at 95%(90%) C.L. using F.C. scheme
- $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 4.0\ (3.2)\ 10^{-7}$ at 95%(90%) C.L. using Bayesian scheme

CDF Branching Fraction

- Relative Acceptance/Trigger/Reco. Efficiency
  - Simulate $B^{\pm} \rightarrow J/\psi\ K^{\pm}$ and $B_s \rightarrow \mu^+ \mu^-$
  - Re-weight MC sample w.r.t. pt of observed p_t distribution $B^{\pm}$ candidates
  - $\varepsilon_{\mu\mu}(B_d)/\varepsilon_{\mu\mu}(B_s) = 0.229 \pm 0.008 \pm 0.014$ (6.9%)xxx
- $N(B^{\pm}) = 1785 \pm 60$ (3.4%) 696 ± 39 (5.6%)
- $f_s/f_{u,d} = 0.270 \pm 0.034$ (12.7%)
- $\mathcal{B}(B^+ \rightarrow J/\psi(\rightarrow \mu\ \mu)\ K^+) = (5.880 \pm 0.235) \times 10^{-5}$ (4.4%)
- Exp. Background: 0.81 ± 0.12 (14.8%) 0.66 ± 0.13 (19.7%)
- Observed Events: 0
- $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 3.7\ (3.0)\ 10^{-7}$ at 95%(90%) CL using F.C. scheme
- $\mathcal{B}(B_s \rightarrow \mu^+ \mu^-) < 4.0\ (3.2)\ 10^{-7}$ at 95%(90%) CL using Baysian scheme