Rare Decays at the Tevatron

Sinéad M. Farrington

University of Liverpool

for the CDF and D0 Collaborations

Beauty 05

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Outline

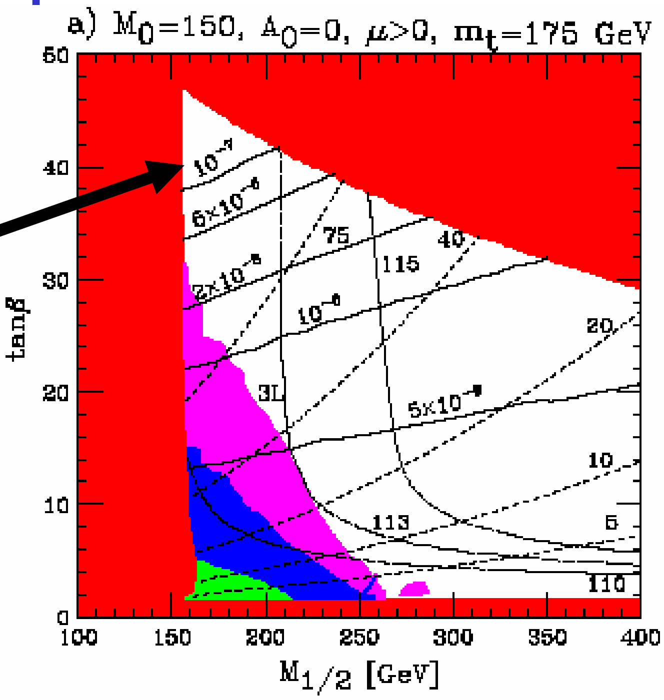
- **Overall motivations**
- $\mathbf{B^0_{d,s}} \rightarrow \mu^+\mu^-$
  - **Motivation**
  - **CDF and D0 methods**
  - **CDF and D0 results**
- $\mathbf{B^0_{d,s}} \rightarrow \mu^+\mu^-$ **$K^+/K^*/\phi$**
  - **Motivation**
  - **D0 sensitivity analysis**

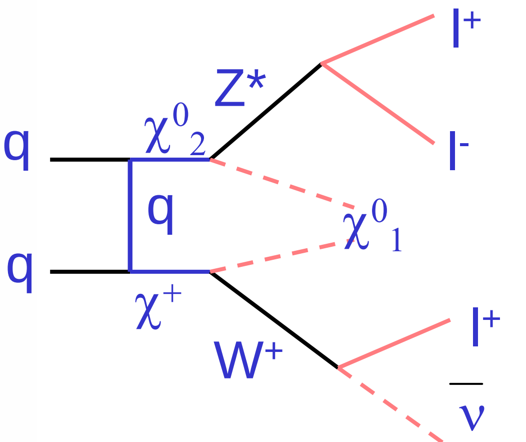
For discussion of Charmless B decays see following talk by Simone Donati

Searching for New Physics

- Two ways to search for new physics:
  - direct searches – seek e.g. Supersymmetric particles
  - indirect searches – test for deviations from Standard Model predictions e.g. branching ratios
- In the absence of evidence for new physics
  - set limits on model parameters

$BR(B \to \mu\mu) < 1 \times 10^{-7}$



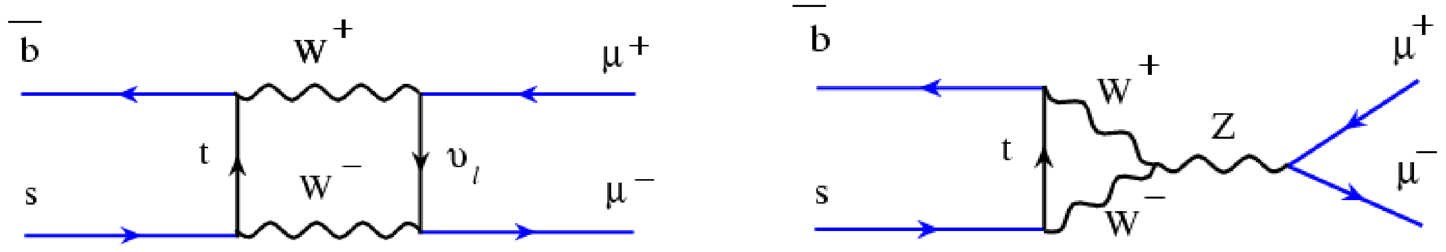


Trileptons: $2 fb^{-1}$

$$\mathbf{B^0_{d,s}} \to \mu^+\mu^-$$

$B \to \mu\mu$ in the Standard Model

- In Standard Model FCNC decay $B \to \mu\mu$ heavily suppressed



- Standard Model predicts $BR(B_s \to \mu^+\mu^-) = (3.4 \pm 0.5) \times 10^{-9}$

A. Buras Phys. Lett. B 566,115

- $B_d \to \mu\mu$ further suppressed by CKM coupling $(V_{td}/V_{ts})^2$

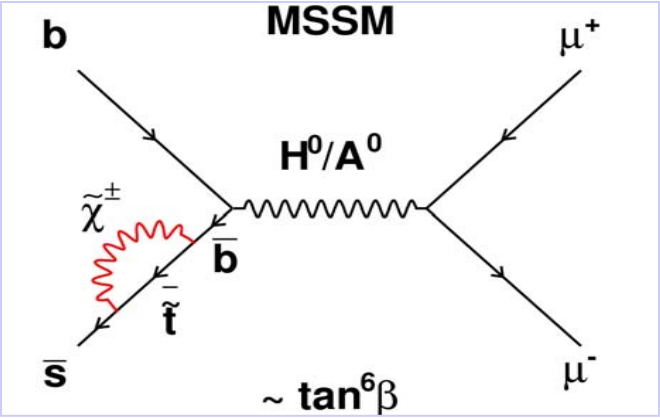
$$BR(B_d \to \mu^+\mu^-) = (1.00 \pm 0.14) \times 10^{-10}$$

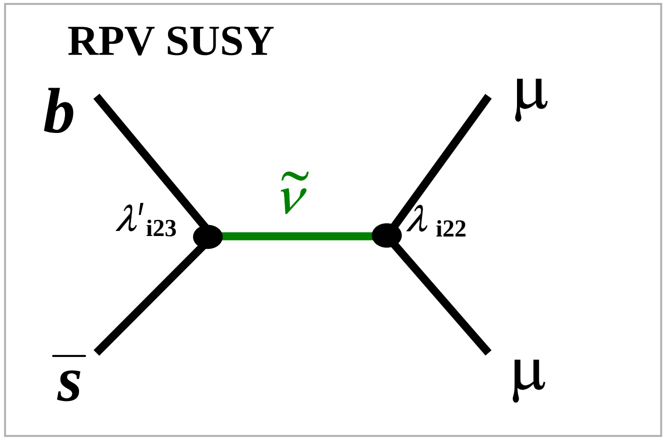
- Both below sensitivity of Tevatron experiments

Observe no events $\Rightarrow$ set limits on new physics
Observe events $\Rightarrow$ clear evidence for new physics

B → μμ in New Physics Models

- SUSY could enhance BR by orders of magnitude
  - MSSM: BR(B → μμ) ∝ $\tan^6\beta$
    - may be 100x Standard Model



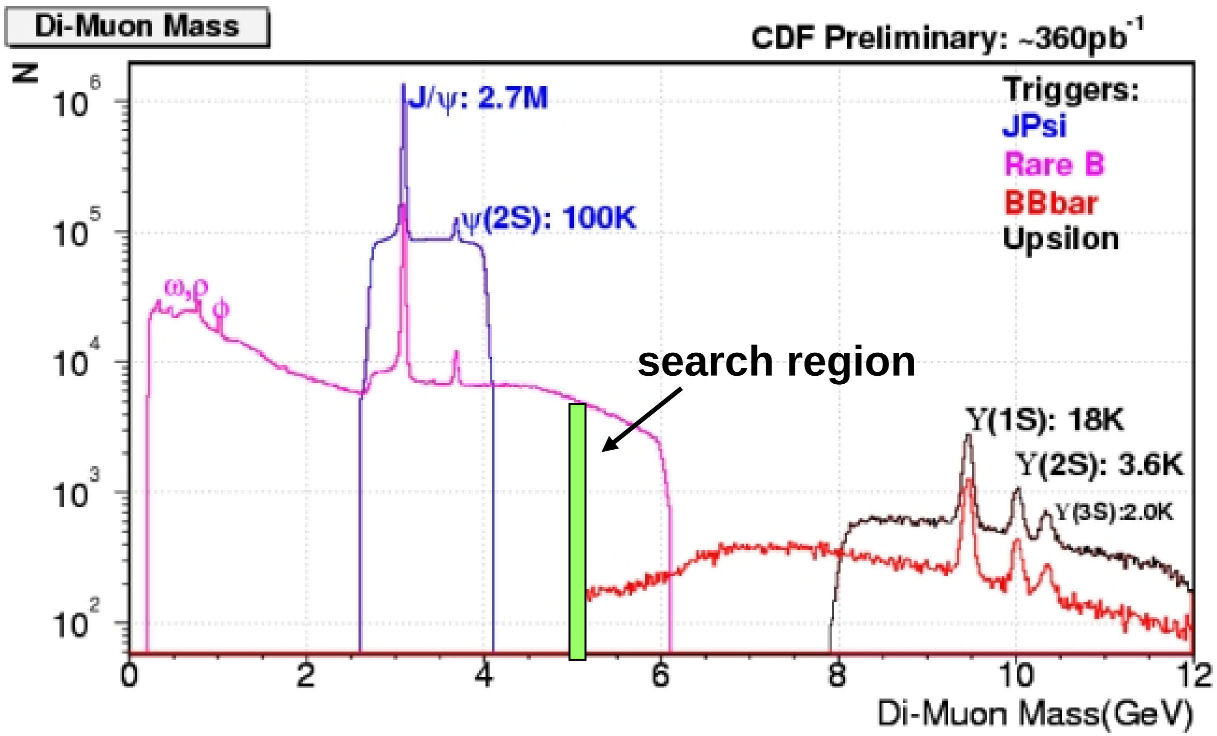


- R-parity violating SUSY: tree level diagram via sneutrino
  - observe decay for low tan β
- mSUGRA: B → μμ search complements direct SUSY searches
  - Low tan β ⇒ observation of trilepton events
  - High tan β ⇒ observation of B → μμ

A. Dedes et al, hep-ph/0207026

- Or something else!

The Challenge



- Large combinatorial background
- Key elements are
  - determine efficiencies
  - select discriminating variables
  - estimate background

Methodology

- Search for muon pairs in B_d/B_s mass windows
- D0 search for only B_s and correct for B_d decays
- Approximately 360pb^{-1}(CDF) /300pb^{-1}(D0) integrated luminosity
- Unbiased optimisation, signal region blind
- Aim to measure BR or set limit

$$BR(B_s \to \mu^+\mu^-) = \frac{N_{Bs}}{N_{B+}} \frac{\alpha_{B+} \cdot \varepsilon_{B+}^{total}}{\alpha_{Bs} \cdot \varepsilon_{Bs}^{total}} \frac{f_u}{f_s} BR(B^+ \to J/\psi K^+) BR(J/\psi \to \mu^+\mu^-)$$

- Reconstruct normalisation mode ($B^+ \to J/\psi\ K^+$)
- Construct discriminant to select B signal and suppress dimuon background (CDF)
- Use cuts analysis to suppress dimuon background (D0)
- Measure background
- Measure the acceptance and efficiency ratios

CDF

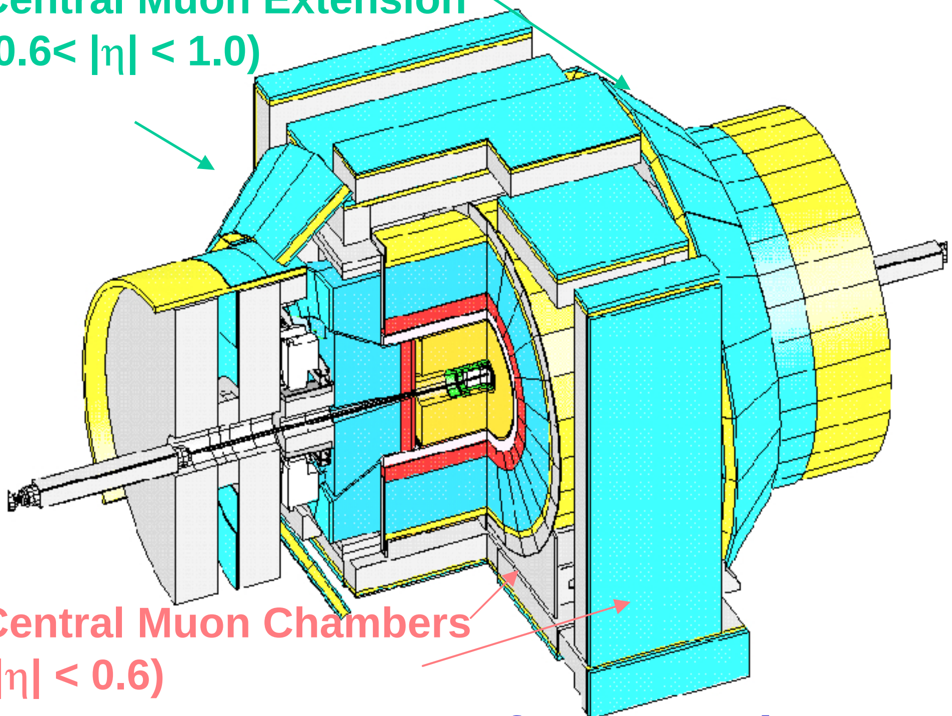
D0

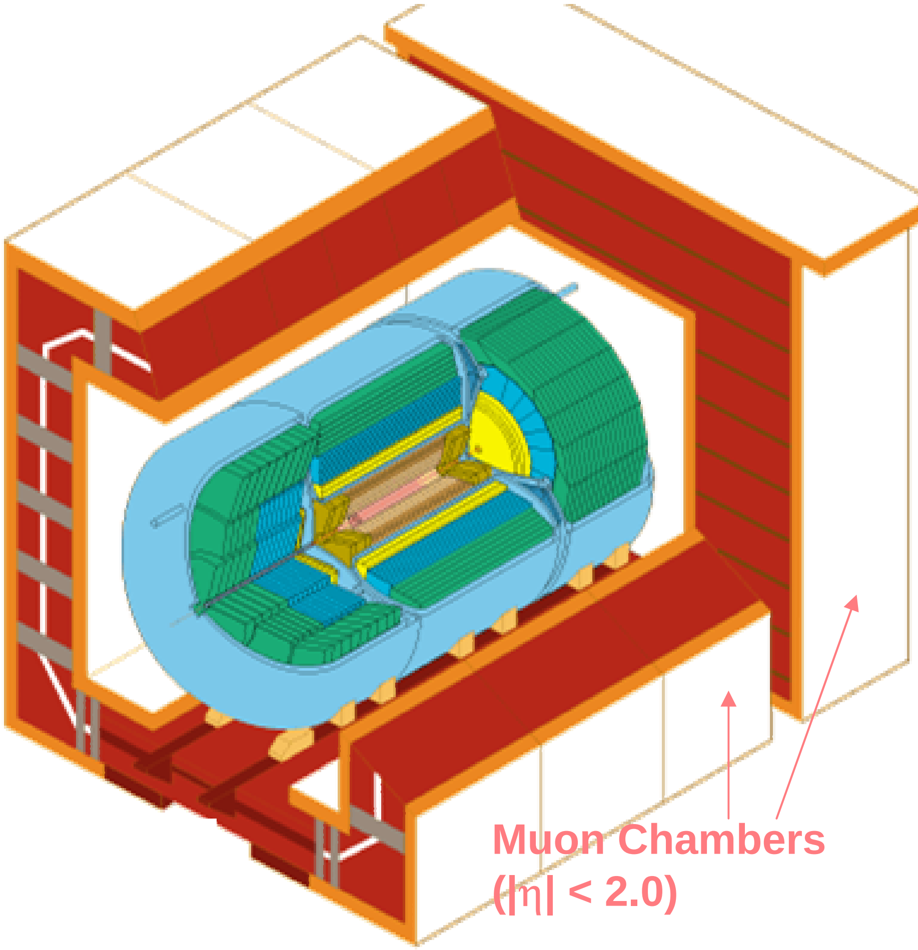
CDF

- six dedicated rare B triggers
- using all chambers to |η|≤1.1
- excellent tracking

D0

- four dedicated rare B triggers
- using all chambers to |η|≤2.0
- excellent muon coverage

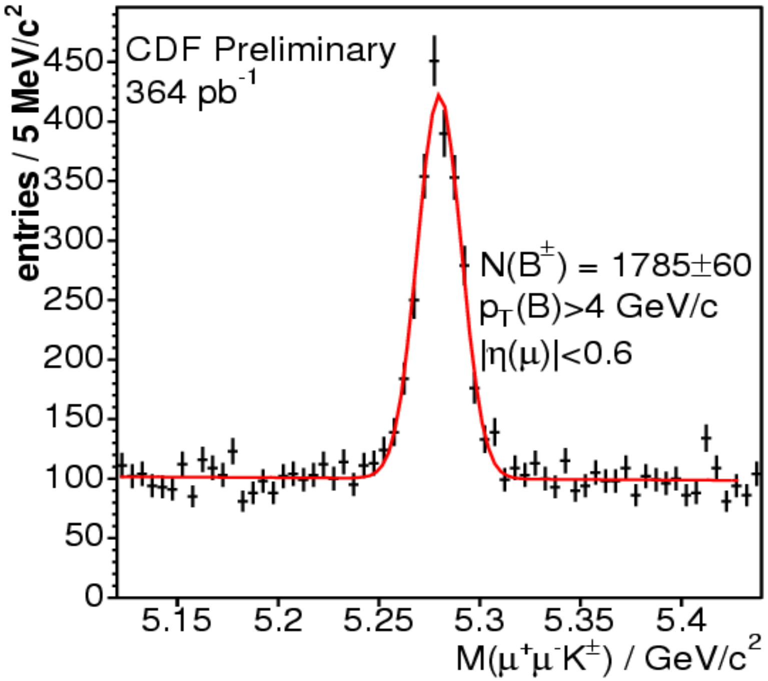




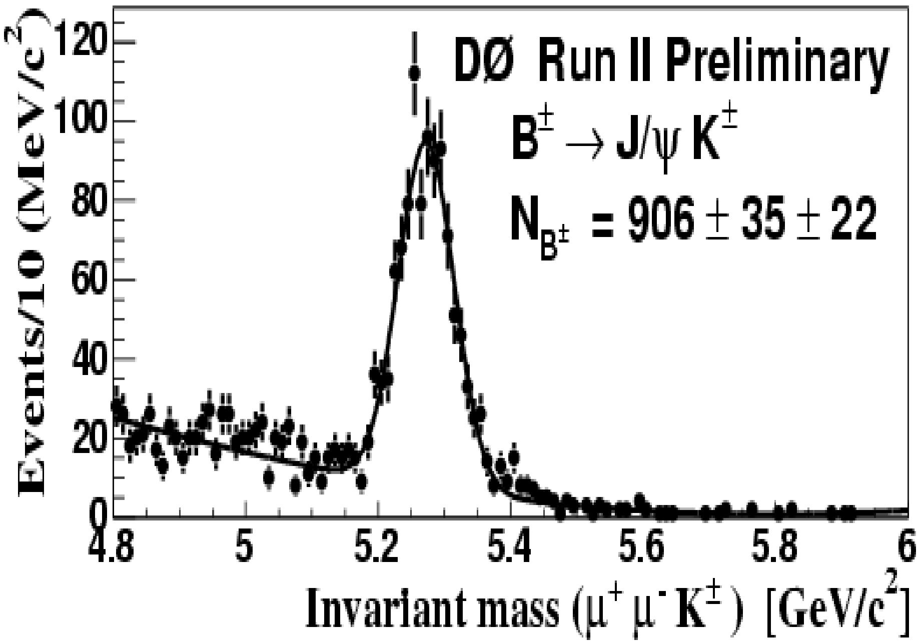
- Use two types of muon pairs:
  - central-central
  - central-extension

Normalisation Mode (CDF)

- **Reconstruct normalisation mode ($B^+ \rightarrow J/\psi\ K^+$)**

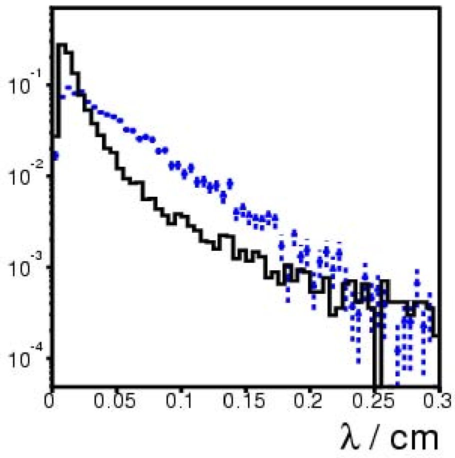


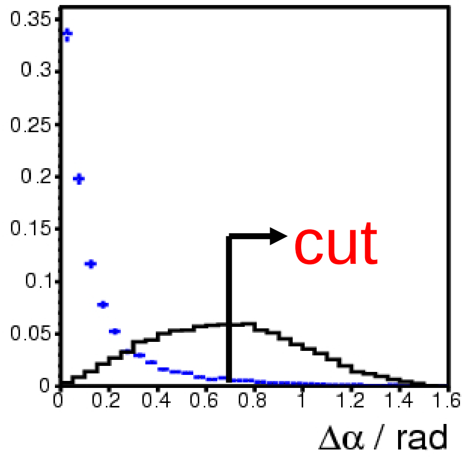
central-central muons

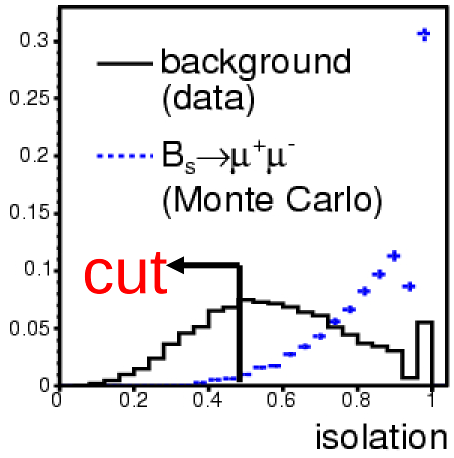


B → μμ Optimisation (CDF)

- **Chosen three primary discriminating variables:**







- **proper decay length (λ)**

$$\lambda = \frac{cL_{3D}M_{vtx}}{|\vec{p}(B)|}$$

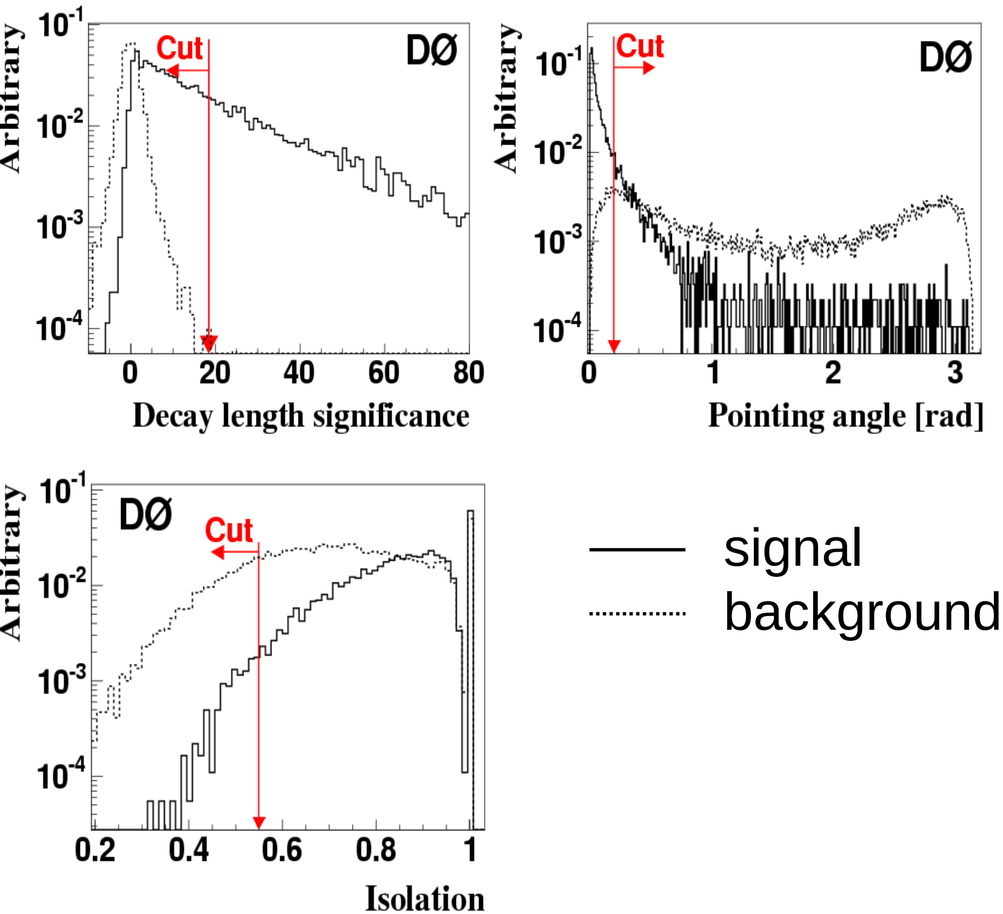
- **Pointing (Δα) |ϕ $_B$ − ϕ $_{vtx}$|**

- **Isolation (Iso)**

$$Iso = \frac{p_T(B)}{p_T(B) + \sum_i p_T^i(\Delta R_i < 1.0)}$$

B → μμ Optimisation (D0)

- Similar three primary discriminating variables



- D0 use 2d lifetime variables instead of 3d
- Optimise using MC for signal, data sidebands for background
- Random grid search, optimising for 95% C.L.

Likelihood Ratio Discriminant (CDF)

- First iteration of analysis used standard cuts optimisation
- Second iteration uses the more powerful likelihood discriminant

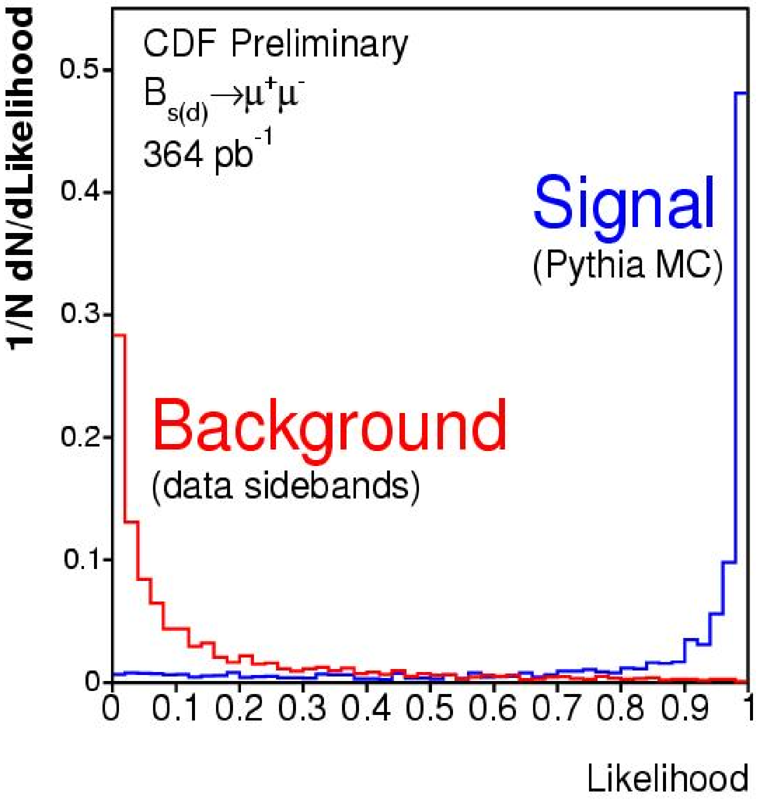
$$L = \frac{\prod_i P_{sig}(x_i)}{\prod_i P_{sig}(x_i) + \prod_i P_{bkg}(x_i)}$$

- i: index over all discriminating variables
- $P_{sig/bkg}(x_i)$: probability for event to be signal / background for a given measured x_i

- Obtain probably density functions of variables using
  - background: Data sidebands
  - signal: Pythia Monte Carlo sample

Optimisation (CDF)

Likelihood ratio discriminant:



Optimise likelihood and $p_t(B)$ for best 90% C.L. limit

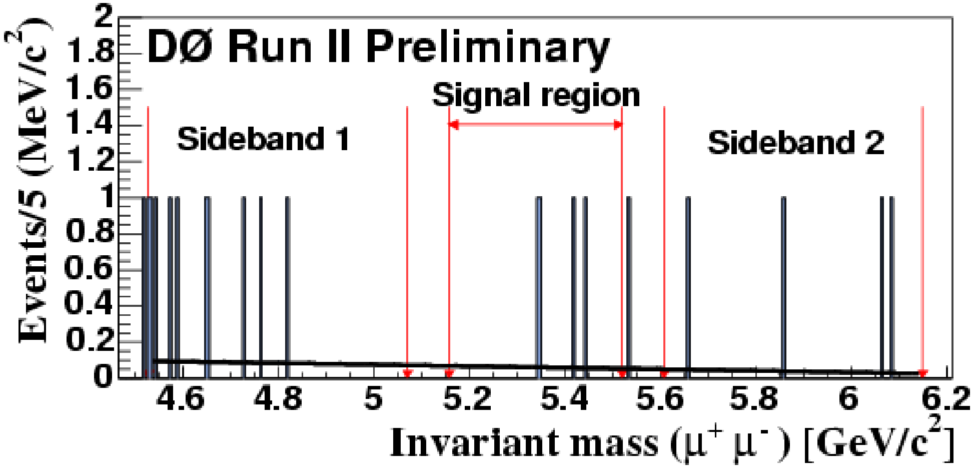
- **Bayesian approach**
- **consider statistical and systematic errors**
- **Assume 1fb^{-1} integrated luminosity**

Expected Background (CDF/D0)

- Extrapolate from data sidebands to obtain expected events
- CDF:
  - Scale by the expected rejection from the likelihood ratio cut
  - Expected background: 0.81 ± 0.12 (central-central dimuon)
    0.66 ± 0.13 (central-extended dimuon)
  - Tested background prediction in several control regions and find good agreement
- D0:
  - Expected background: 4.3 ± 1.2

Unblinded Results (D0)

- Apply optimised cuts
- Unblinded results for $B_s \rightarrow \mu\mu$:



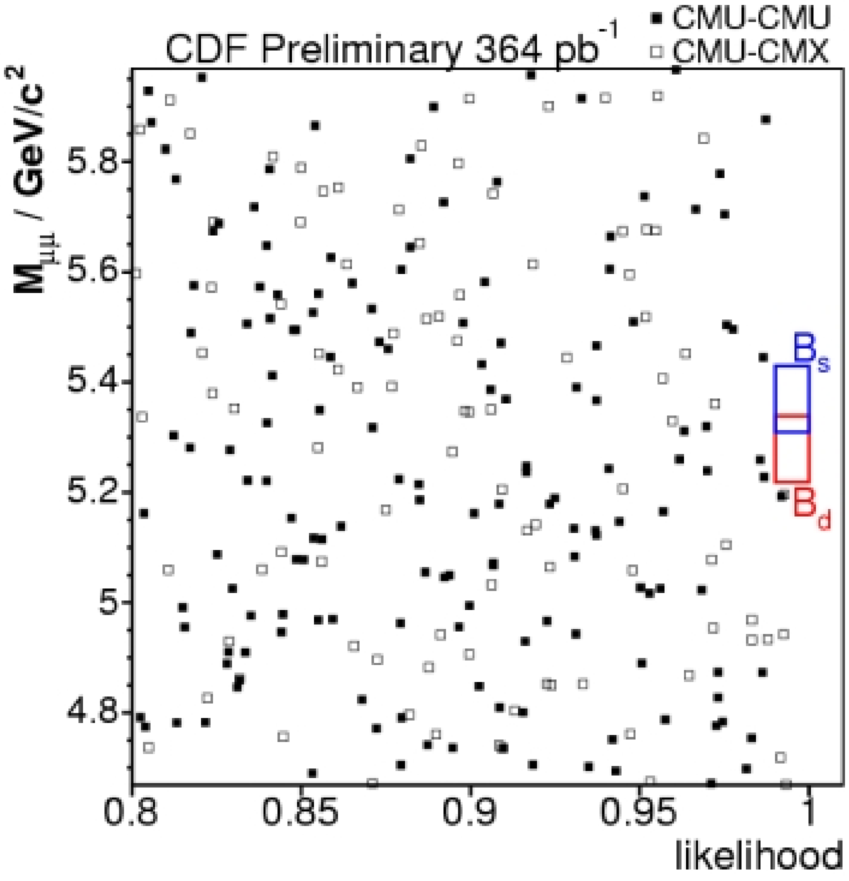
- Expected background: 4.3 ± 1.2
- Observed: 4

$BR(B_s \rightarrow \mu\mu) < 3.0\times10^{-7}$ @ 90% CL

$< 3.7\times10^{-7}$ @ 95% CL

Unblinded Results (CDF)

Results with $p_t(B)$>4GeV cut applied, Likelihood cut at 0.99:



No events found in B_s or B_d search windows in either muon pair type

Limits on BR($B_{d,s} \to \mu\mu$) (CDF)

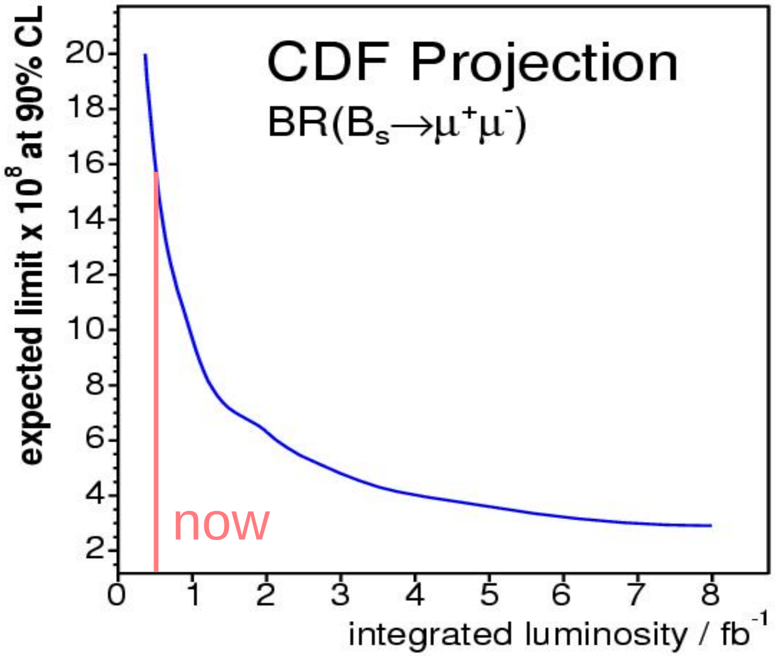
BR($B_s \to \mu\mu$) < 1.6×10^{-7} @ 90% CL
< 2.1×10^{-7} @ 95% CL

BR($B_d \to \mu\mu$) < 3.9×10^{-8} @ 90% CL
< 5.1×10^{-8} @ 95% CL

These are currently world best limits

The future for CDF:

- **use optimisation for $1fb^{-1}$**
- **need to reoptimise at 1fb-1 for best results**
- **assume linear background scaling**



$B^0_{d,s} \rightarrow \mu\mu\ K^+/K^*/\phi$

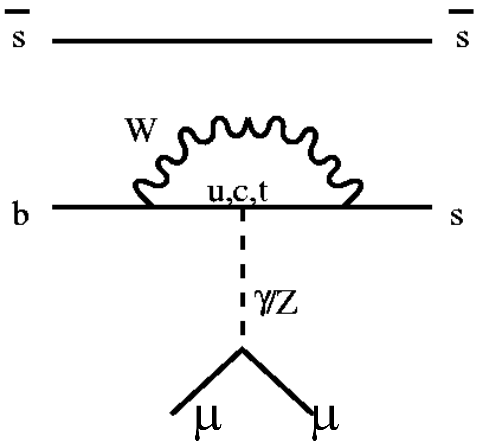
$B_{d,s} \to \mu\mu\ K^+/K^*/\phi$

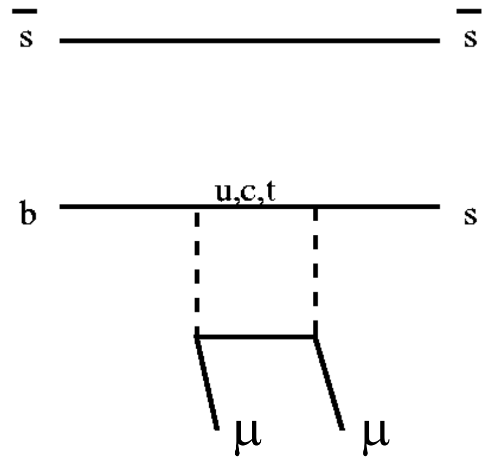
- **B Rare Decays**
  - $B^+ \to \mu\mu\ K^+$
  - $B^0 \to \mu\mu\ K^*$
  - $B_s \to \mu\mu\ \phi$
  - $\Lambda_b \to \mu\mu\ \Lambda$

} observed at Babar, Belle

hep-ex/0109026,
hep-ex/0308042,
hep-ex/0503044

- **FCNC $b \to s\gamma^*$**
- **Penguin or box processes in the Standard Model:**





- **Rare processes: Latest Belle measurement**

$$\mathcal{B}(B \to K\ell^+\ell^-) = (5.50^{+0.75}_{-0.70} \pm 0.27 \pm 0.02) \times 10^{-7}$$

Motivations

1) Would be first observations in B_s and Λ_b channels

2) Tests of Standard Model
   - branching ratios
   - kinematic distributions (with enough statistics)

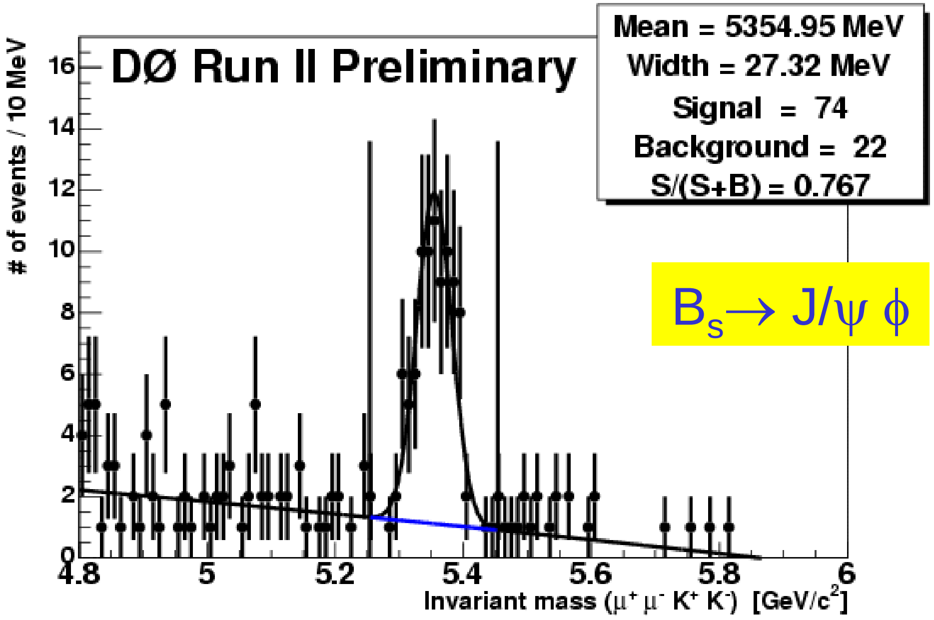
- Effective field theory for $b \to s$ (Operator Product Expansion)

$$\mathcal{H}_{\text{eff}} = -4\frac{G_F}{\sqrt{2}} V_{ts}^* V_{tb} \sum_{i=1}^{10} C_i(\mu) O_i(\mu)$$

- Rare decay channels are sensitive to Wilson coefficients which are calculable for many models (several new physics scenarios e.g. SUSY, technicolor)
- Decay amplitude: C_9
- Dilepton mass distribution: C_7, C_9
- Forward-backward asymmetry: C_{10}

Analysis Outline (CDF,D0)

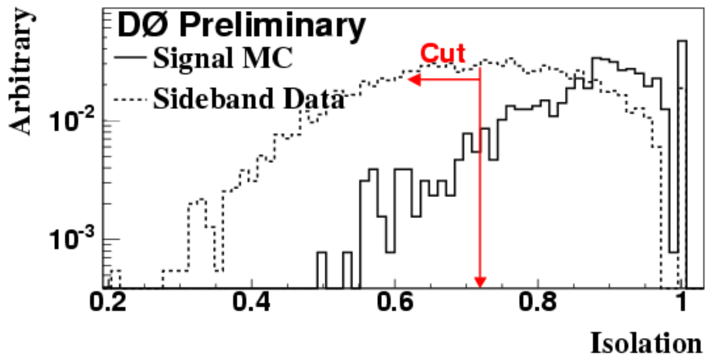
- **Use $B \to J/\psi X$ channels as control channels**
  - **exactly the same signature ($J/\psi \to \mu\mu$)**
  - **use MC to obtain relative efficiency**

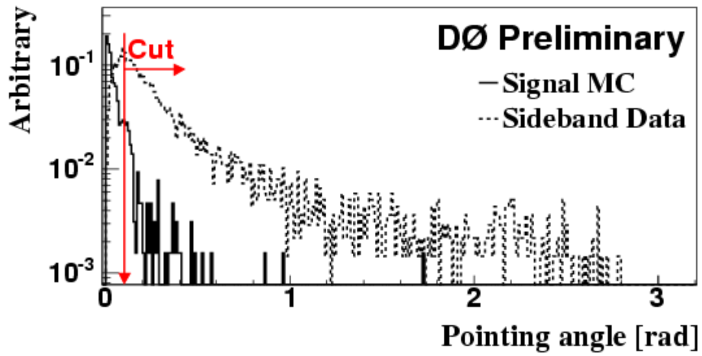


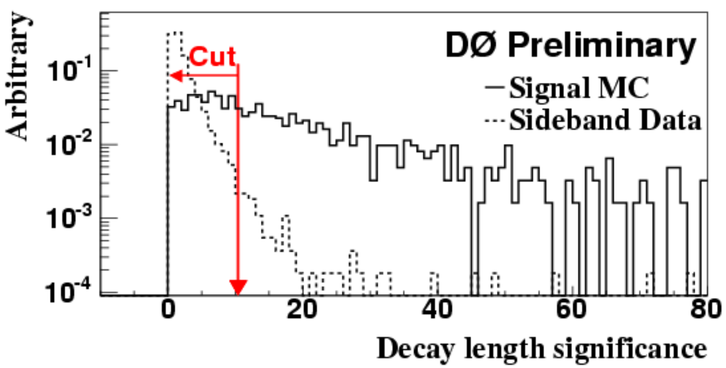
- **Most likely confirm observation $B^+ \to \mu\mu K^+$ and measure BR**
- **Then either**
  - **make first observations in B_s and Λ_b** or
  - **set strong branching ratio limits**

Sensitivity Analysis (D0)

- Cuts analysis using same variables as $B_s \rightarrow \mu\mu$ analysis

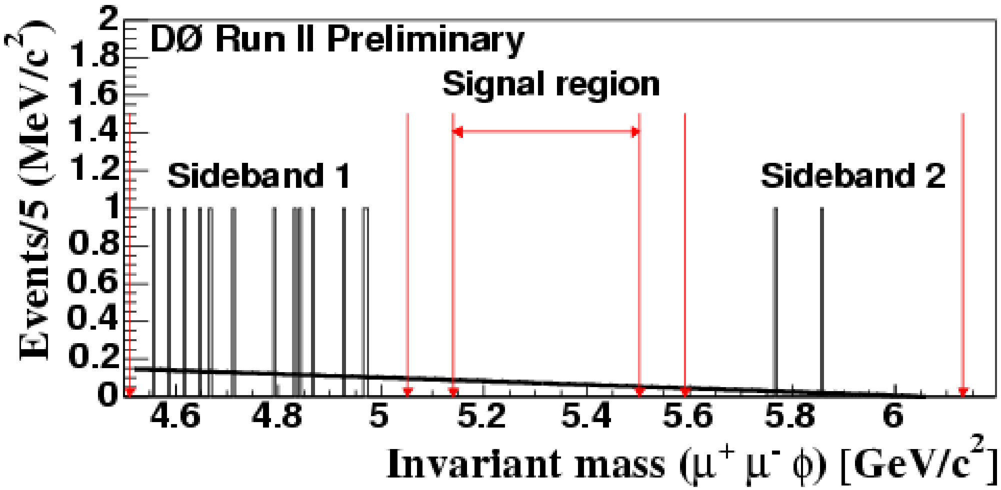






- Remove the dimuon mass regions corresponding to J/ψ, ψ', ϕ
- Contribution from rare decays not well understood under resonances

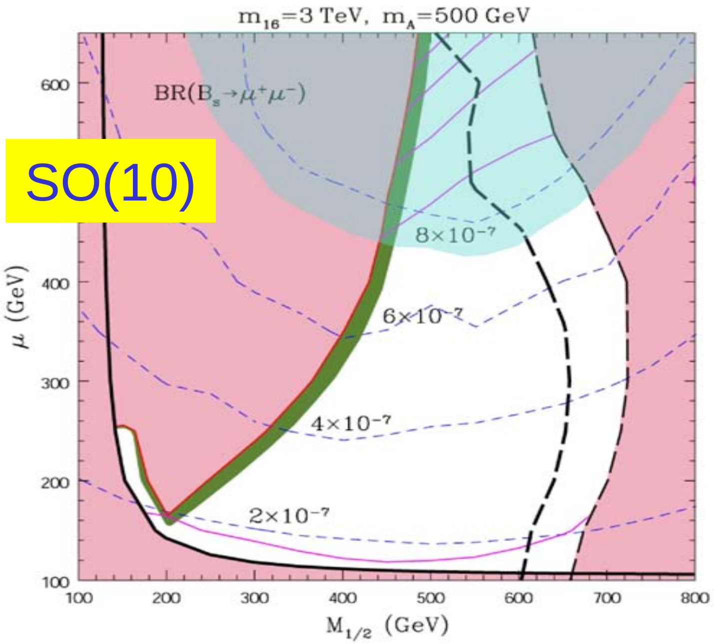
Sensitivity Analysis (D0)

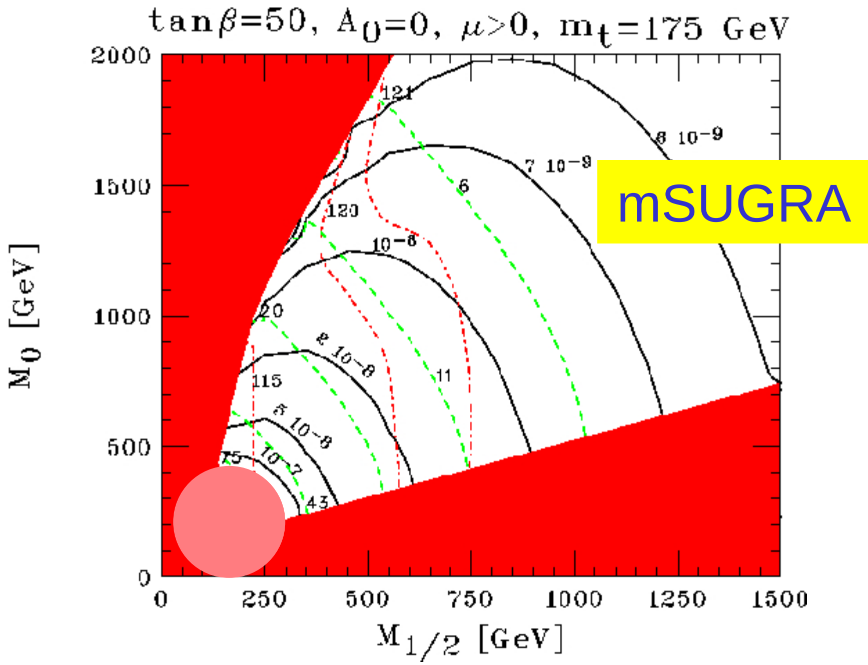


- Box is unopened
- Expected background: 5.1 ± 1.0 events
- Sensitivity for 90% C.L. limit calculated: BR($B_s \rightarrow \mu\mu\ \phi$)<1.2 x$10^{-5}$

Summary

- $B_{d,s} \to \mu^+\mu^-$ are a powerful probe of new physics
  - Could give first hint of new physics at the Tevatron
  - World best limits coming from Tevatron experiments
  - Combinations of D0 and CDF results by Lepton Photon 05





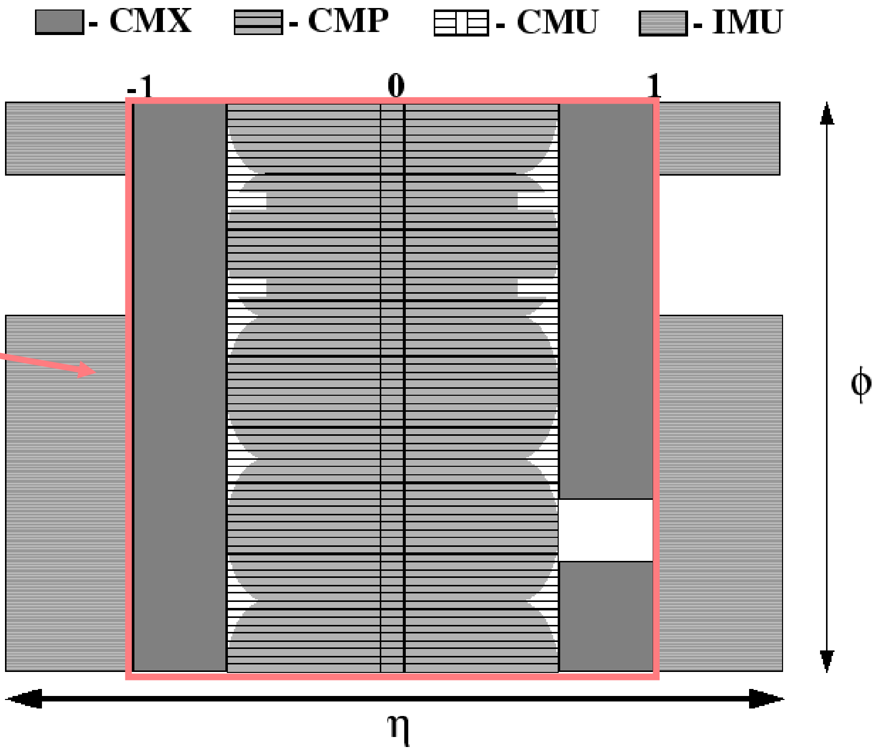
- $B_{d,s} \to \mu^+\mu^- K/K^*/\phi$ should be observable in Run II
  - Also a test of the Standard Model
  - Sensitivity analysis performed, awaiting results

Backup

Samples (CDF)

- Dedicated rare B triggers
  - in total six Level 3 paths
  - Two muons + other cuts
  - using all chambers to $|\eta|\leq 1.1$

  - Use two types of dimuons:
    CMU-CMU
    CMU-CMX



  - Additional cuts in some triggers:
    - $\Sigma p_t(\mu)$>5 GeV
    - L_{xy}>100μm
    - mass($\mu\ \mu$)<6 GeV
    - mass($\mu\ \mu$)>2.7 GeV

Background estimate (CDF)

	LH cut	CMU-CMU pred	CMU-CMU obsv	CMU-CMX pred	CMU-CMX obsv
	>0.50	236+/-4	235	172+/-3	168
OS-	>0.90	37+/-1	32	33+/-1	36
	>0.99	2.8+/-0.2	2	3.6+/-0.2	3
	>0.50	2.3+/-0.2	0	2.8+/-0.3	3
SS+	>0.90	0.25+/-0.03	0	0.44+/-0.04	0
	>0.99	<0.10	0	<0.10	0
	>0.50	2.7+/-0.2	1	3.7+/-0.3	4
SS-	>0.90	0.35+/-0.03	0	0.63+/-0.06	0
	>0.99	<0.10	0	<0.10	0
	>0.50	84+/-2	84	21+/-1	19
FM+	>0.90	14.2+/-0.4	10	3.9+/-0.2	3
	>0.99	1.0+/-0.1	2	0.41+/-0.03	0

1.) OS- : opposite-charge dimuon, $\lambda < 0$

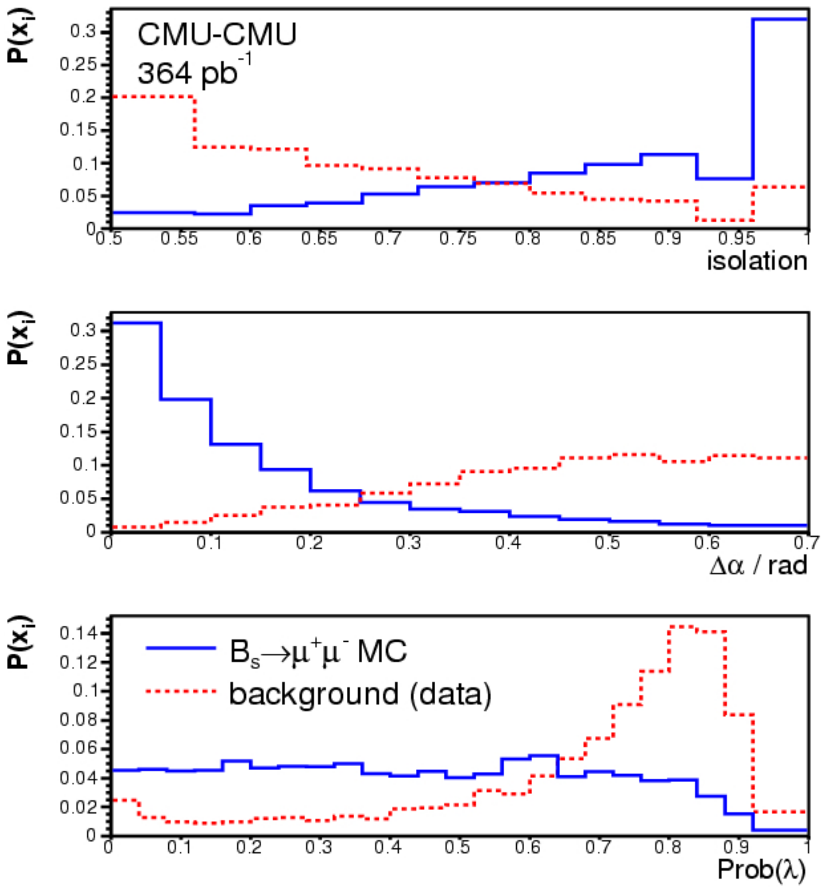
2.) SS+ : same-charge dimuon, $\lambda > 0$

3.) SS- : same-charge dimuon, $\lambda < 0$

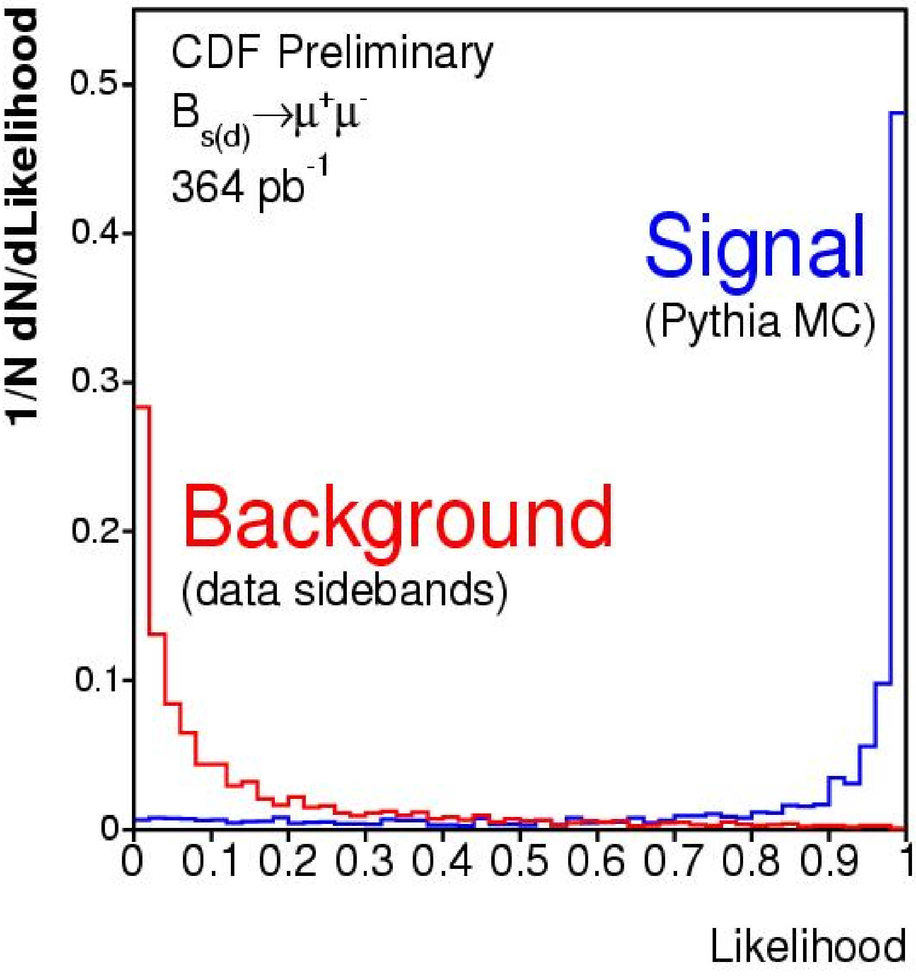
4.) FM : fake muon sample (at least one leg failed muon stub chi2 cut)

Likelihood p.d.f.s (CDF)

Input p.d.f.s:



Likelihood ratio discriminant:



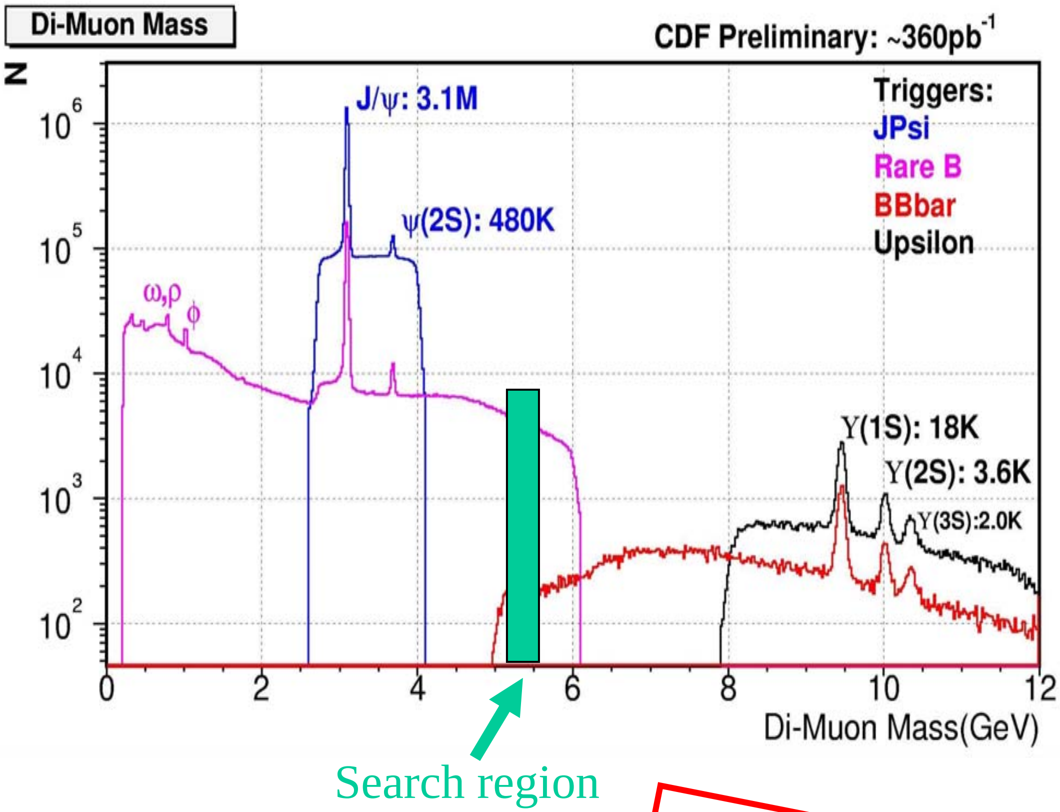
Methodology (CDF)

- Search for muon pairs in B_d/B_s mass windows
- D0 search for only Bs and correct for Bd decays
- Approximately $360pb^{-1}$ integrated luminosity
- Blind analysis
- Aim to measure BR or set limit

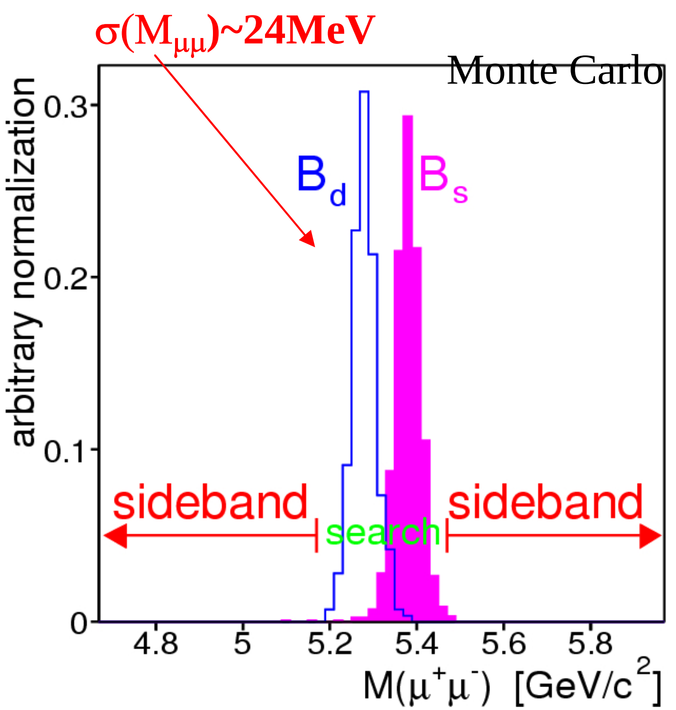
$$BR(B_s \rightarrow \mu^+\mu^-) = \frac{N_{Bs}}{N_{B+}} \frac{\alpha_{B+} \cdot \varepsilon_{B+}^{total}}{\alpha_{Bs} \cdot \varepsilon_{Bs}^{total}} \frac{f_u}{f_s} BR(B^+ \rightarrow J/\psi K^+) BR(J/\psi \rightarrow \mu^+\mu^-)$$

- Reconstruct normalization mode ($B^+ \rightarrow J/\psi K^+$)
- Construct discriminant to select B signal and suppress dimuon background
- Measure background
- Measure the acceptance and efficiency ratios

Signal and Side-band Regions



- Use events from same triggers for B^+ and Bs(d) →μμ reconstruction.
- Search region:
  - 5.169 < Mμμ < 5.469 GeV
  - Signal region not used in optimization procedure

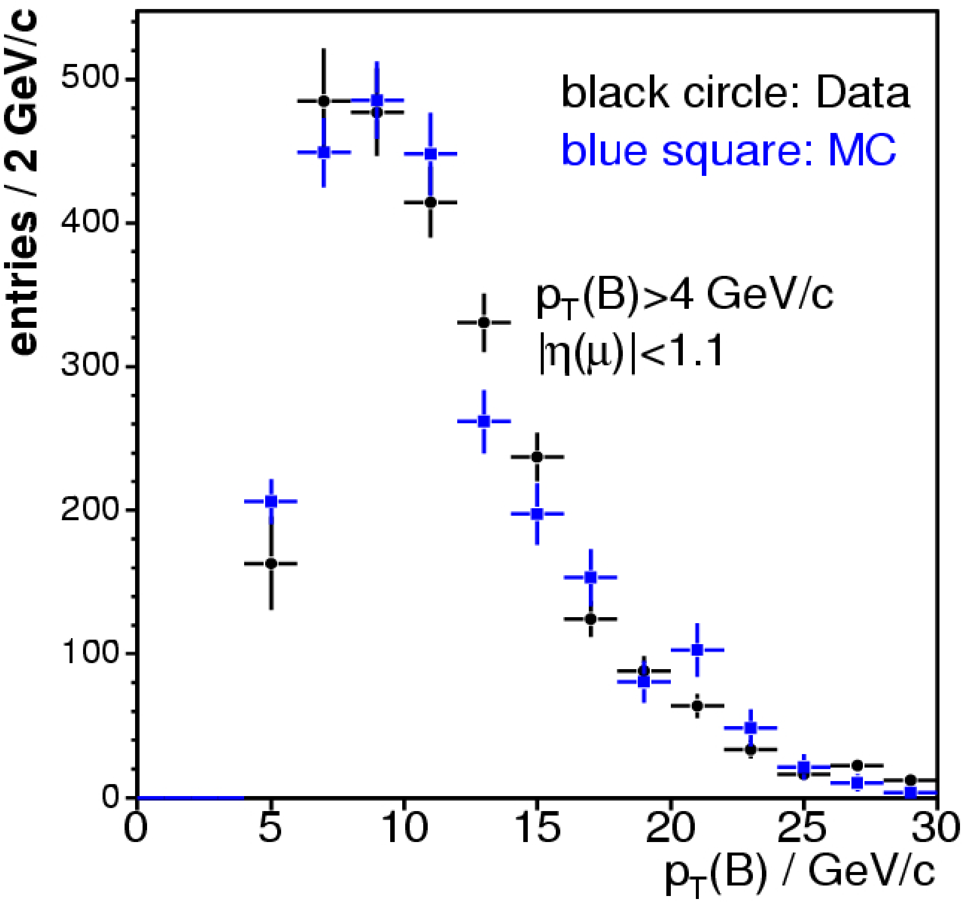


- Sideband regions:
  - 500MeV on either side of search region
  - For background estimate and analysis optimization.

MC Samples

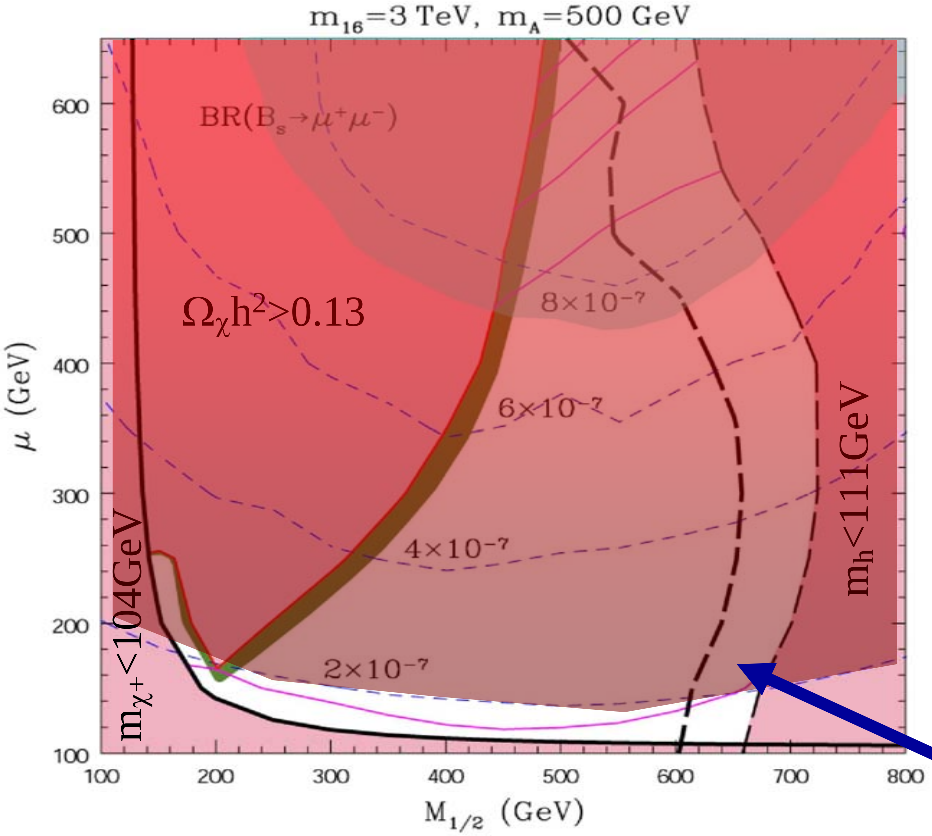
Pythia MC

- Tune A
- default cdfSim tcl
- realistic silicon and beamline
- pT(B) from Mary Bishai
- pT(b)>3 GeV && |y(b)|<1.5
  - $B_s \rightarrow \mu^+\mu^-$ (signal efficiencies)
  - $B^+ \rightarrow JK^+ \rightarrow \mu^+\mu^- K^+$ (nrmlztn efncy and xchks)
  - $B^+ \rightarrow J\pi^+ \rightarrow \mu^+\mu^-\pi^+$ (nrmlztn correction)



SO(10) Unification Model

R. Dermisek *et al.*, hep-ph/0304101

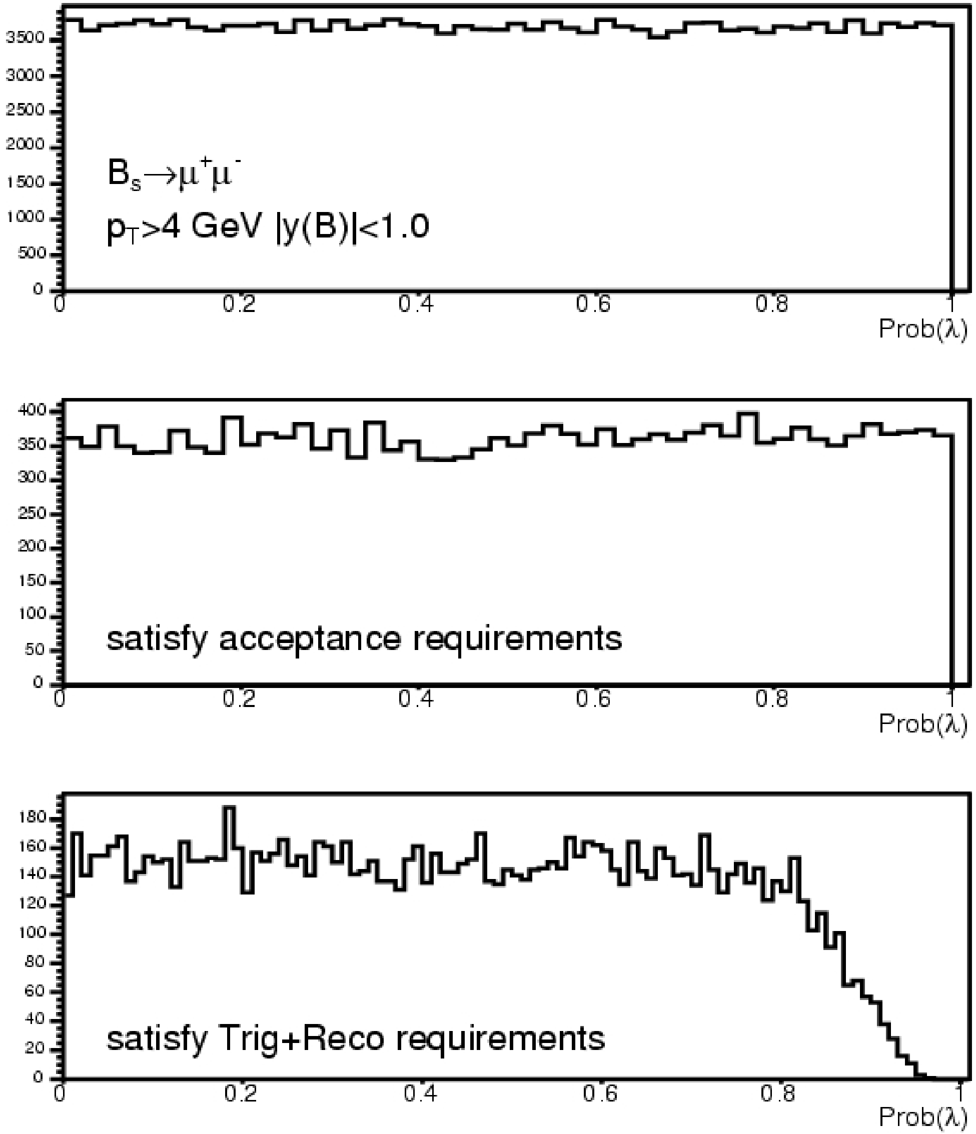


- tan(β)~50 constrained by unification of Yukawa coupling
- All previously allowed regions (white) are excluded by this new measurement
- Unification valid for small $M_{1/2}$ (~500GeV)
- New Br(Bs→μμ) limit strongly disfavors this solution for m_A= 500 GeV

Excluded by this new result

Red regions are excluded by either theory or experiments
Green region is the WMAP preferred region
Blue dashed line is the Br(Bs→μμ) contour
Light blue region excluded by old Bs→μμ analysis

Method: Likelihood Variable Choice

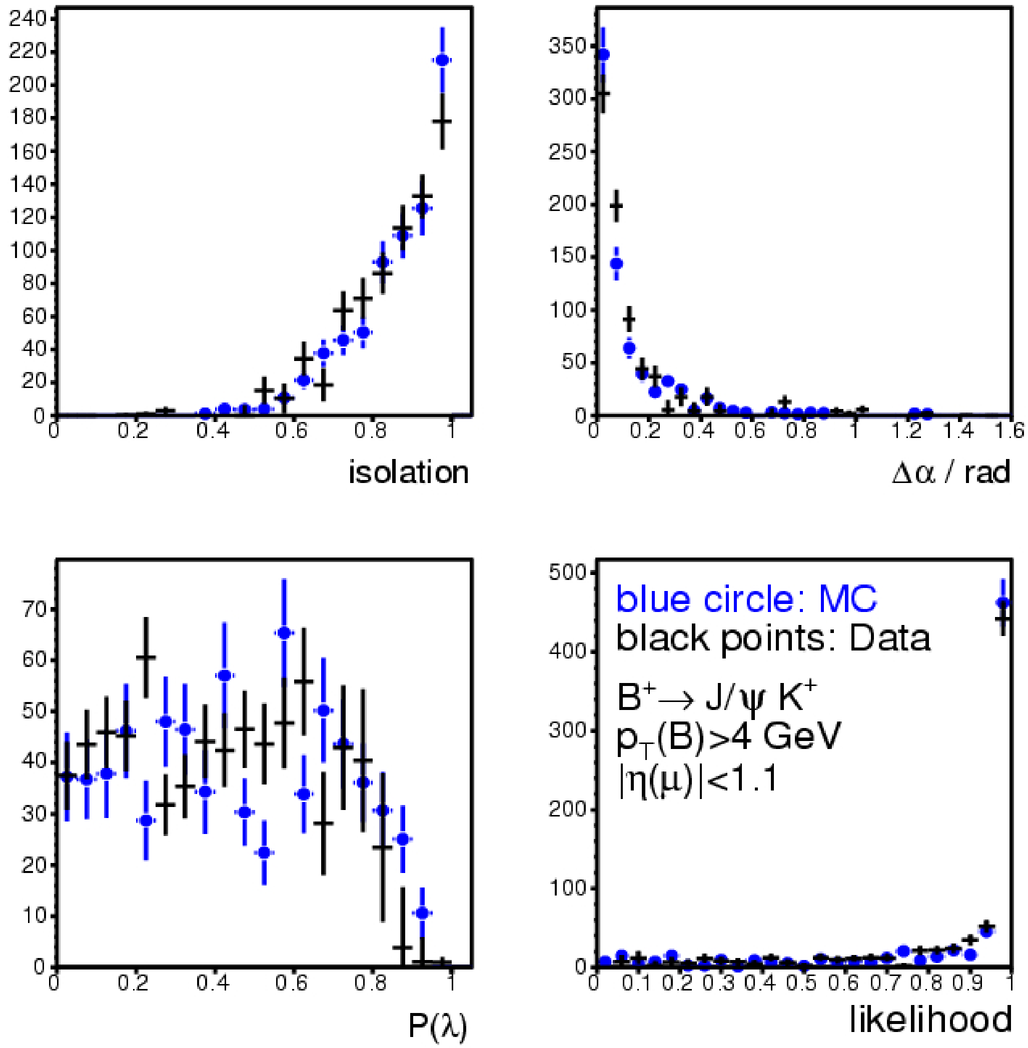


Prob(λ) = probability of $B_s \to \mu\mu$ yields $\lambda > \lambda_{obs}$
(ie. the integral of the cumulative distribution)

Prob(λ) = exp($-\lambda$/438 μm)

- yields flat distribution
- reduces sensitivity to MC modeling inaccuracies (e.g. L00, SVX-z)

Method: Checking MC Modeling of Signal LH



For CMU-CMX:

- MC reproduces Data efficiency vs LHood cut to 5% or better
- Assign 5% (relative) systematic for CMU-CMX

Step 4: Compute Acceptance and Efficiencies

$$\left(\frac{\alpha_{B+}}{\alpha_{Bs}}\right)\cdot\left(\frac{\varepsilon_{B+}^{trig}}{\varepsilon_{Bs}^{trig}}\right)\cdot\left(\frac{\varepsilon_{B+}^{reco-\mu\mu}}{\varepsilon_{Bs}^{reco-\mu\mu}}\right)\cdot\left(\frac{\varepsilon_{B+}^{vtx}}{\varepsilon_{Bs}^{vtx}}\right)\cdot\varepsilon_{B+}^{reco-K}\cdot\frac{1}{\varepsilon_{Bs}^{LH}}$$

- Most efficiencies are determined directly from data using inclusive $J/\psi \rightarrow \mu\mu$ events. The rest are taken from Pythia MC.

- $\alpha(B+/Bs)$ = 0.297 +/- 0.008 (CMU-CMU)
  = 0.191 +/- 0.006 (CMU-CMX)

- $\varepsilon^{LH}(Bs)$: ranges from 70% for LH>0.9 to
  40% for LH>0.99

- $\varepsilon^{trig}(B+/Bs)$ = 0.9997 +/- 0.0016 (CMU-CMU)
  = 0.9986 +/- 0.0014 (CMU-CMX)

- $\varepsilon^{reco-\mu\mu}(B+/Bs)$ = 1.00 +/- 0.03 (CMU-CMU/X)

- $\varepsilon^{vtx}(B+/Bs)$ = 0.986 +/- 0.013 (CMU-CMU/X)

- $\varepsilon^{reco-K}(B+)$ = 0.938 +/- 0.016 (CMU-CMU/X)

Red = From MC

Green = From Data

Blue = combination of MC and Data