# $B_s \rightarrow \mu^+\mu^-$ At the Tevatron

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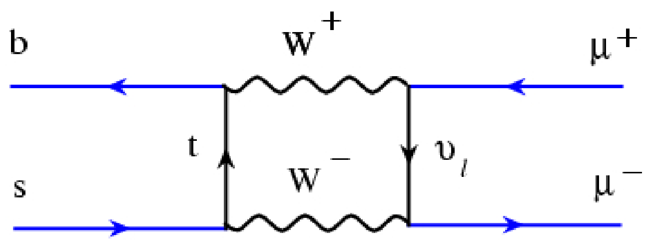
**(Fermilab)**

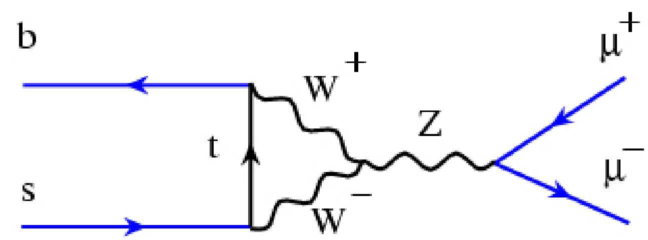
**Flavour in the Era of LHC**

**CERN**
**15 May 2006**

# $B \rightarrow \mu^+\mu^-$ Introduction

- In the Standard Model, the FCNC decay of $B \rightarrow \mu^+\mu^-$ is heavily suppressed




SM prediction → $BR(B_s \rightarrow \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$
(Buchalla & Buras, Misiak & Urban)

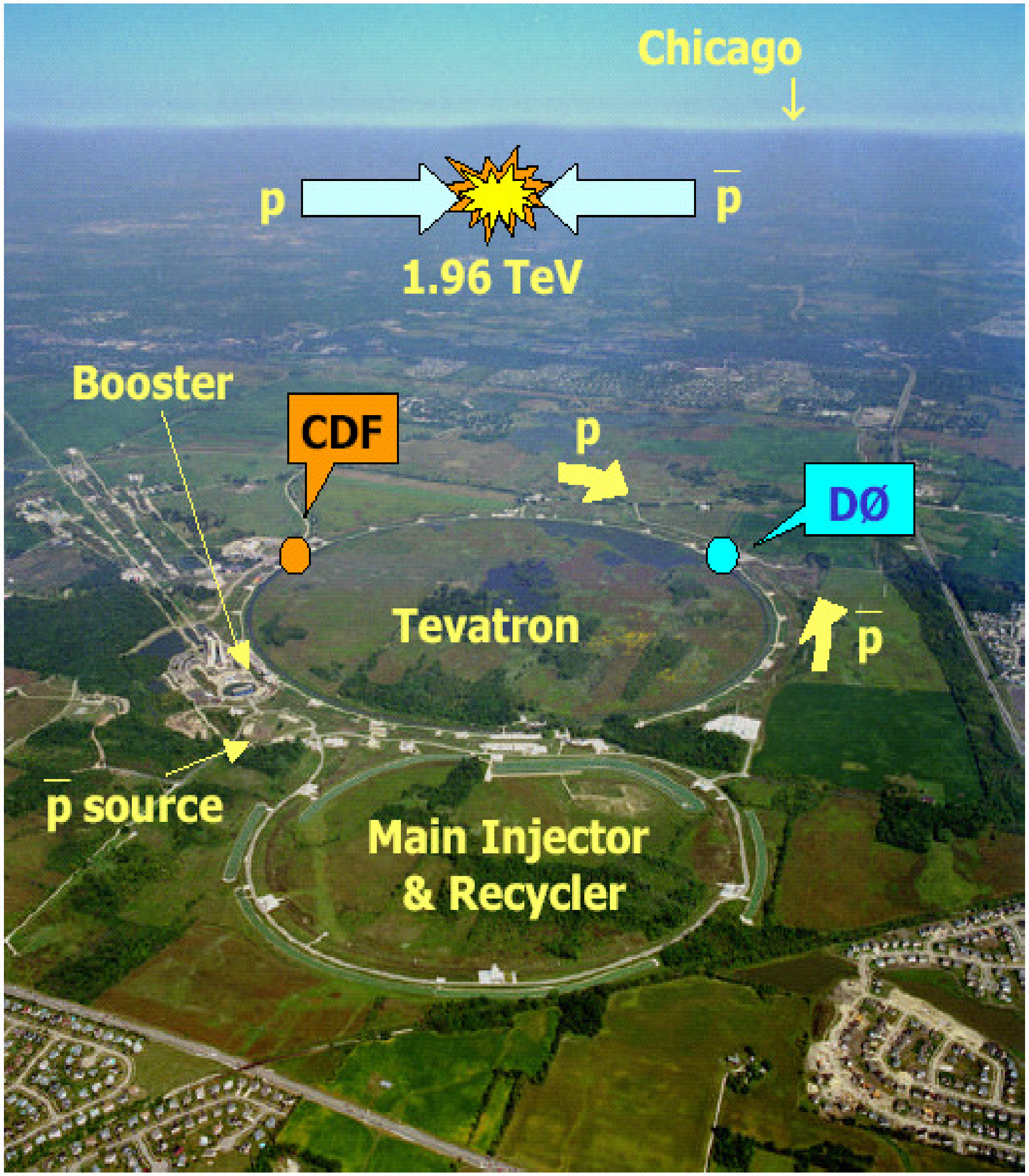
- $B_d \rightarrow \mu\mu$ is further suppressed by CKM factor $(v_{td}/v_{ts})^2$

- SM prediction is below the sensitivity of current experiments (CDF+D0): SM → Expect to see 0 events at the Tevatron

**Any signal at the Tevatron would indicate new physics!!**

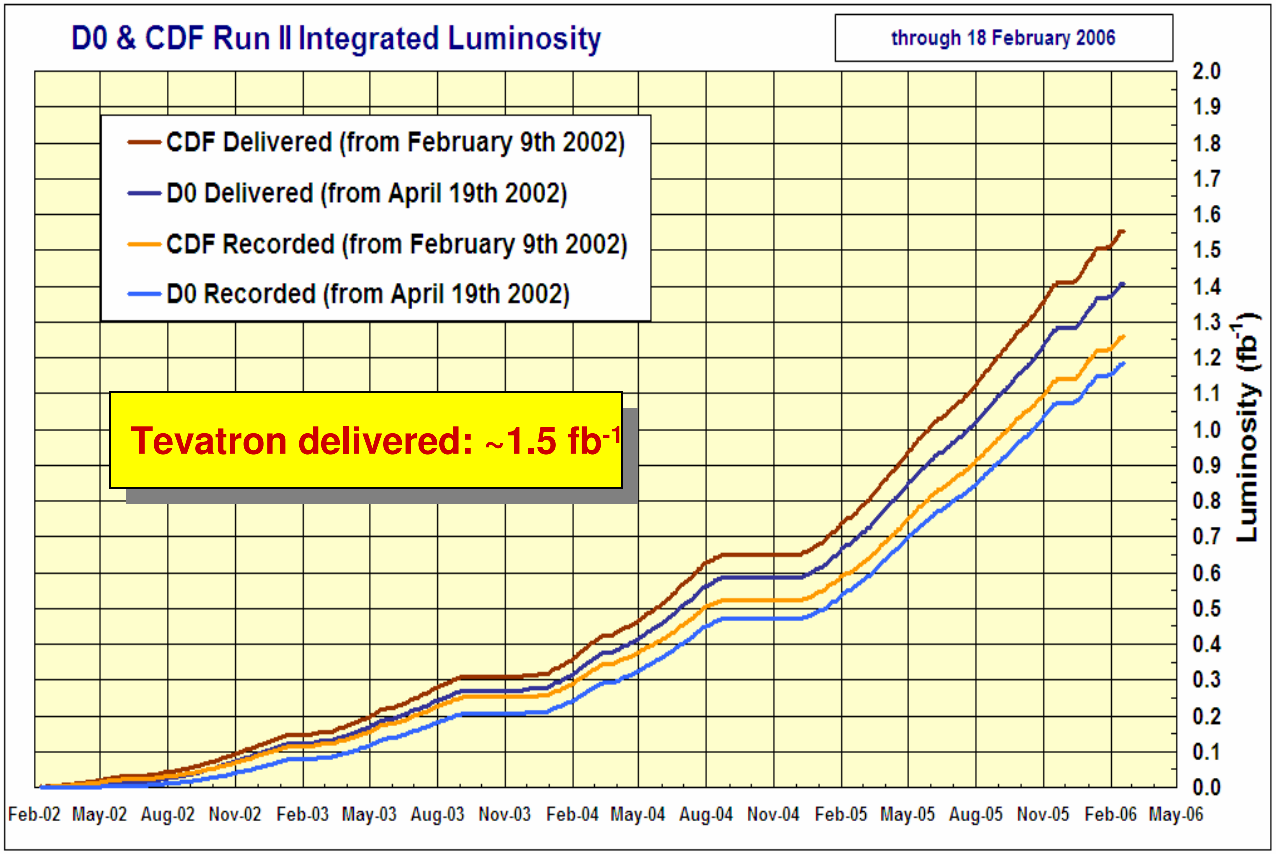
- See A. Dedes' talk next for new physics scenarios
(Also talks by C. Kao, G. Isidori, Y. Okada, and others)

# TEVATRON



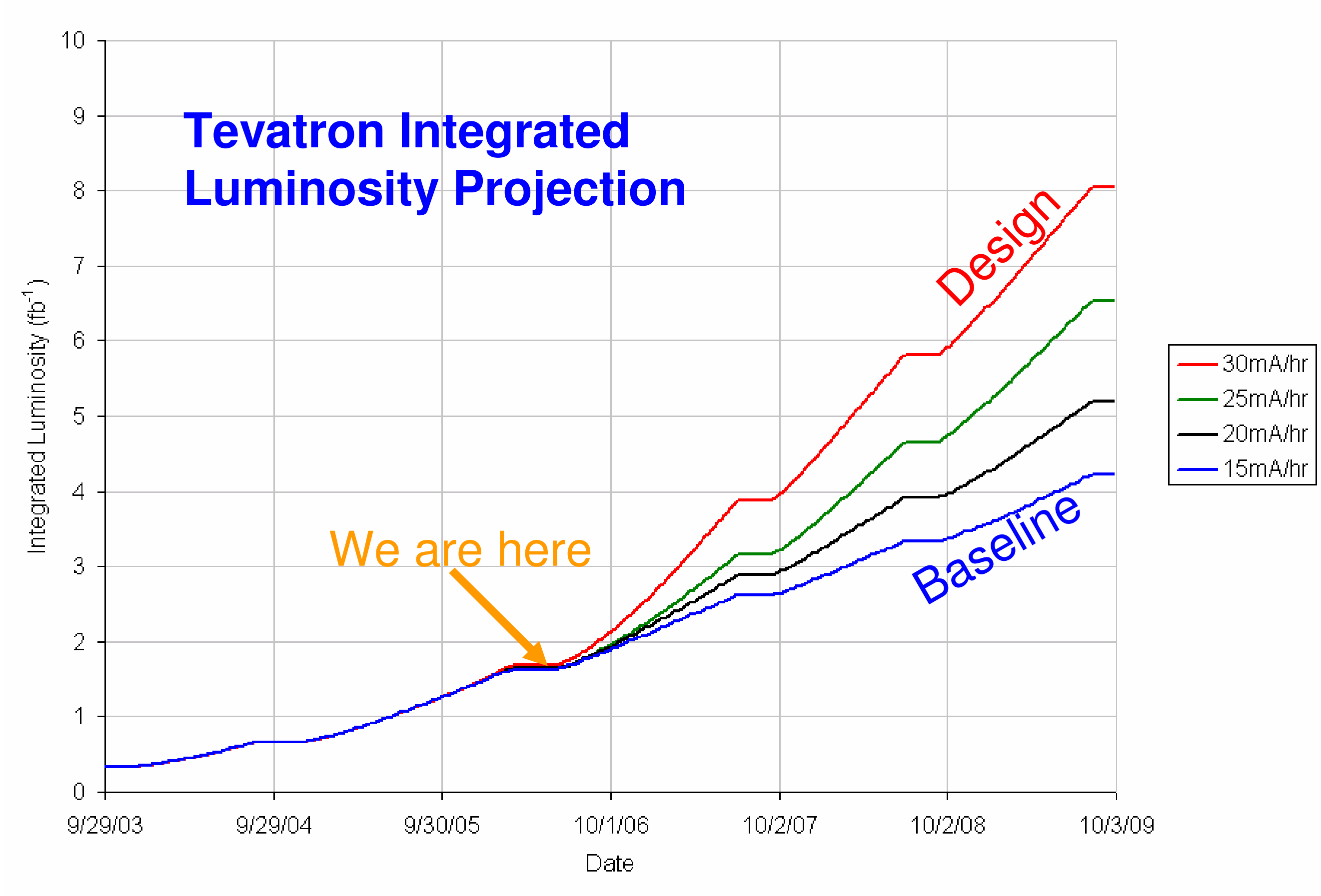

- Tevatron is the highest energy collider in operation
- Collide proton – antiproton at c.m.s = 1.96 TeV
- Record luminosity $\sim 1.8 \times 10^{32}$ cm$^{-2}$ s$^{-1}$
- Now in the middle of a 3-months shutdown for upgrade

# TEVATRON Performance



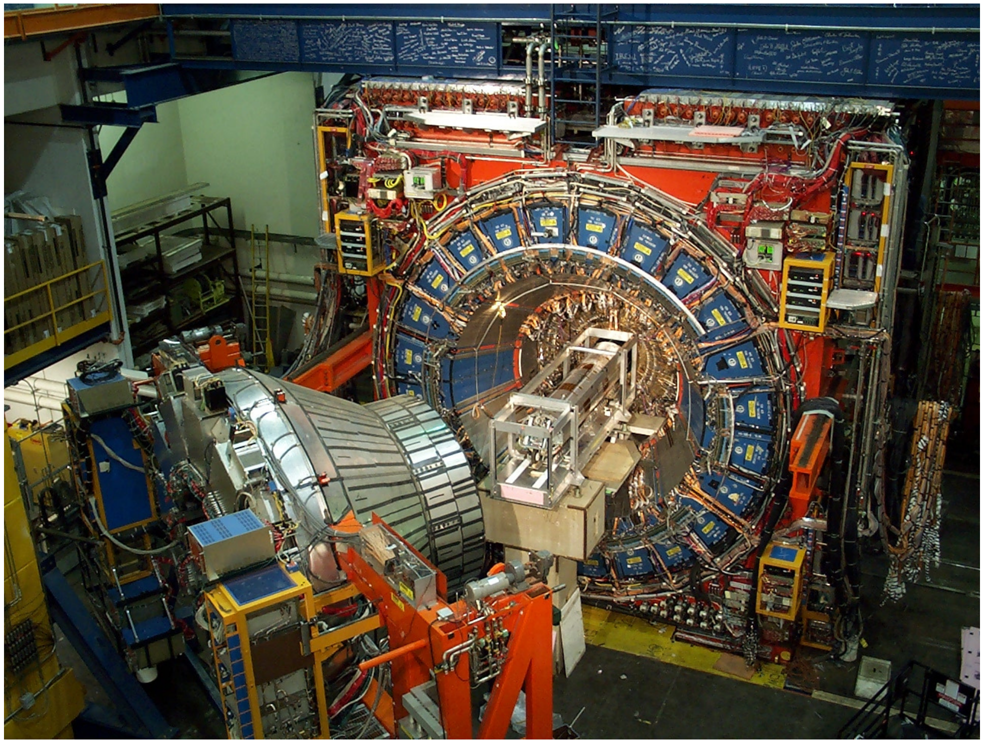

- CDF/D0 have collected > 1$fb^{-1}$/experiment. x10 more data than Run I
- Doubling dataset every year

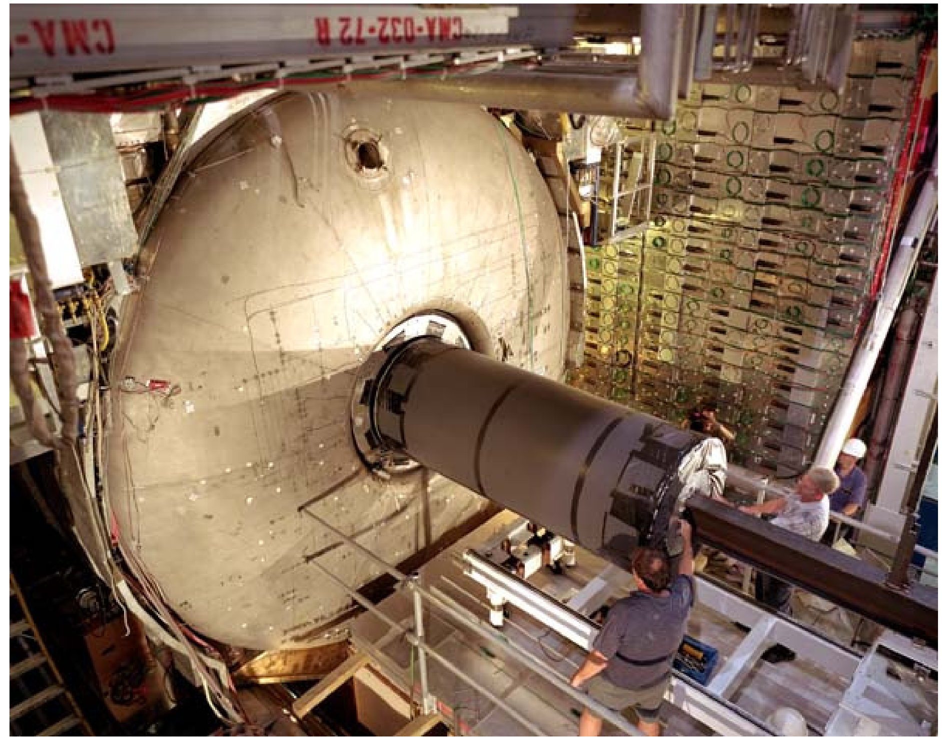
# TEVATRON Projection




**Tevatron is expected to deliver 8 $fb^{-1}$/exp for Run II**

# CDF and D0 Detectors





**CDF:**

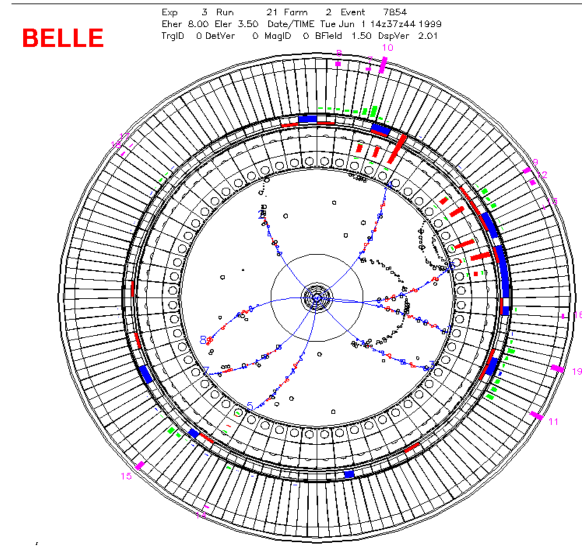
- Excellent silicon vertex detector
- Good particle identification (K,$\pi$)
- Good momentum and track impact parameter resolutions

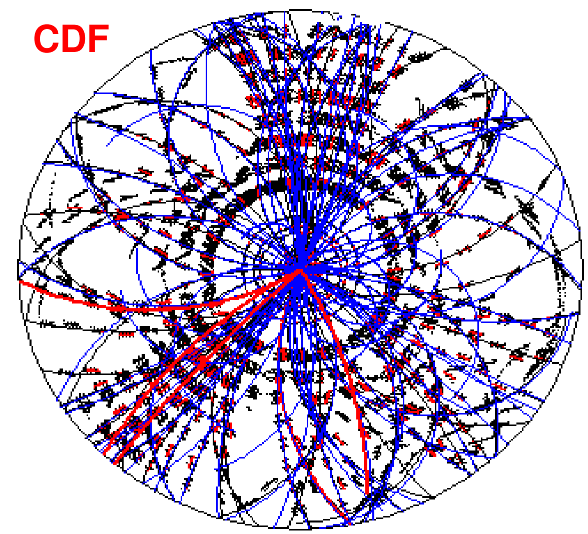
**D0:**

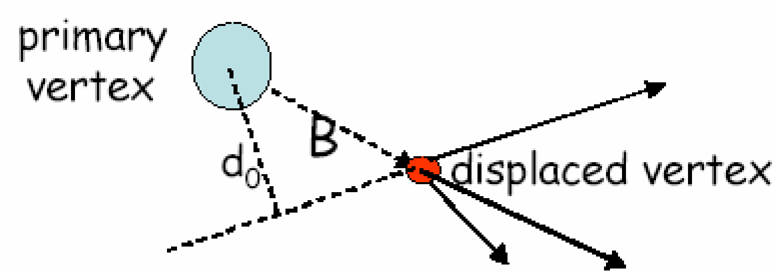
- Extended tracking and muon coverage
- Good electron identification
- New innermost-layer silicon detector installed

# B Triggers at Tevatron

- **Trigger is the lifeline of B physics in a hadron environment !!!**
- "Muon" triggers:
  - Requiring single-muon or di-muons (very clean)
  - working horse for masses, lifetimes, rare decays etc.
  - keys to B physics program at DØ
- "Hadronic" triggers using silicon vertex detectors:
  - exploit long lifetime of heavy quarks
  - Two-track trigger (CDF) –
    - Two oppositely charged tracks with large impact parameters
    - Important for Bs mixing

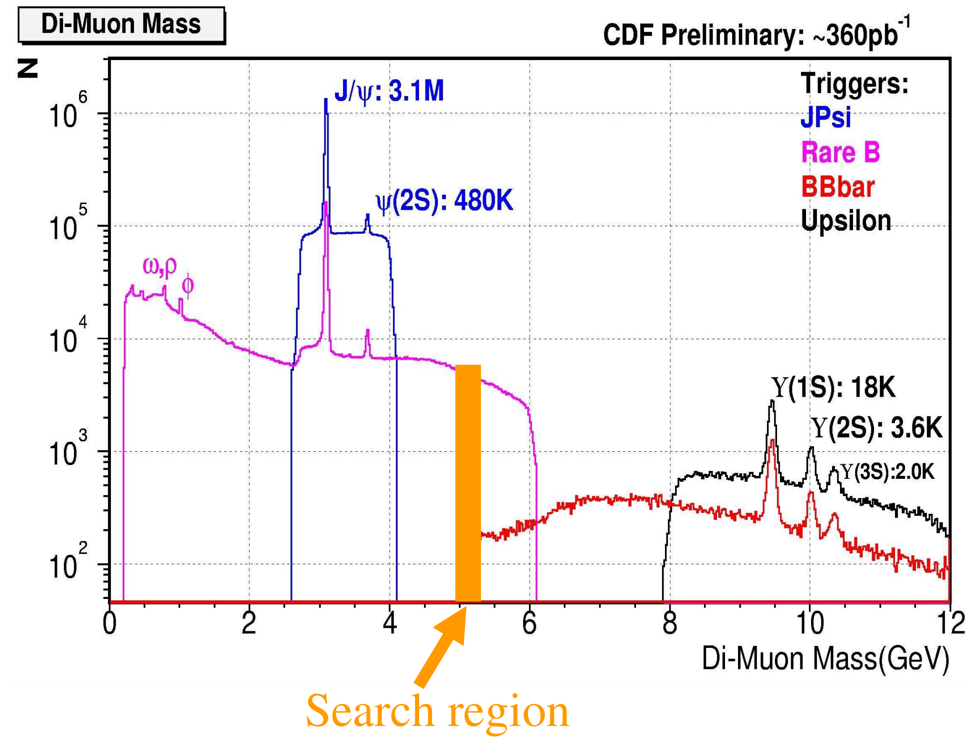


# Rare B Dataset

- **CDF:**
  - 780 $pb^{-1}$ di-muon triggered data
  - Two separate search channels
    - Central/central muons (CMU-CMU)
    - Central/forward muons (CMU-CMX)
  - Extract $B_s$ and $B_d$ limit




- **DØ:**
  - First 300 $pb^{-1}$ di-muon triggered data with box opened → limit
  - 400 $pb^{-1}$ data still blinded
  - Combined sensitivity for 700 $pb^{-1}$ of recorded data (300 $pb^{-1}$ + 400 $pb^{-1}$ )

S/B is expected to be extremely small. Effective bkg rejection is the key to this analysis!!

# Analysis Overview

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

Motto: reduce background and keep signal eff high

Step 1: pre-selection cuts to reject obvious bkg

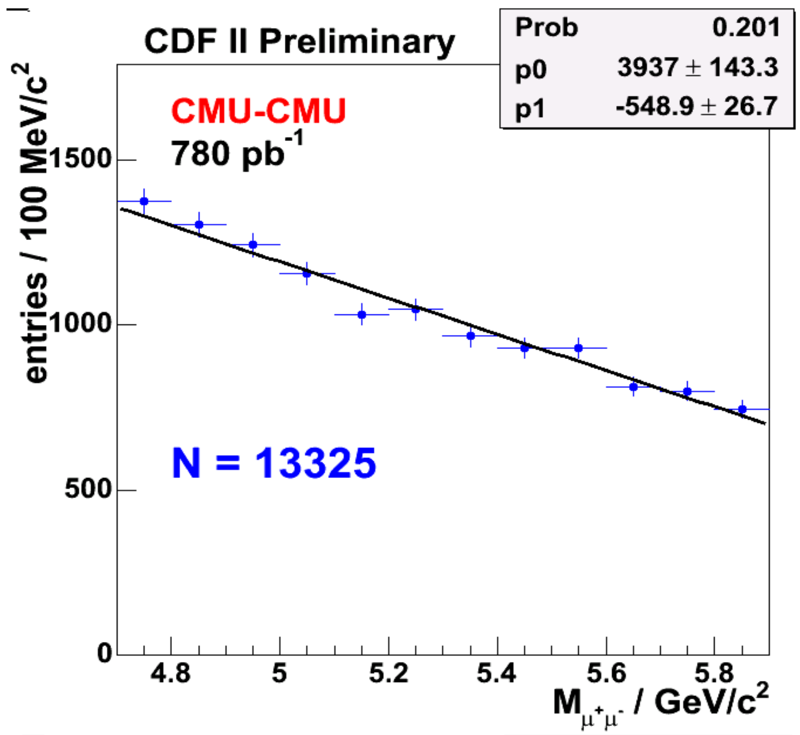
Step 2: optimization (need to know signal efficiency and expected bkg)

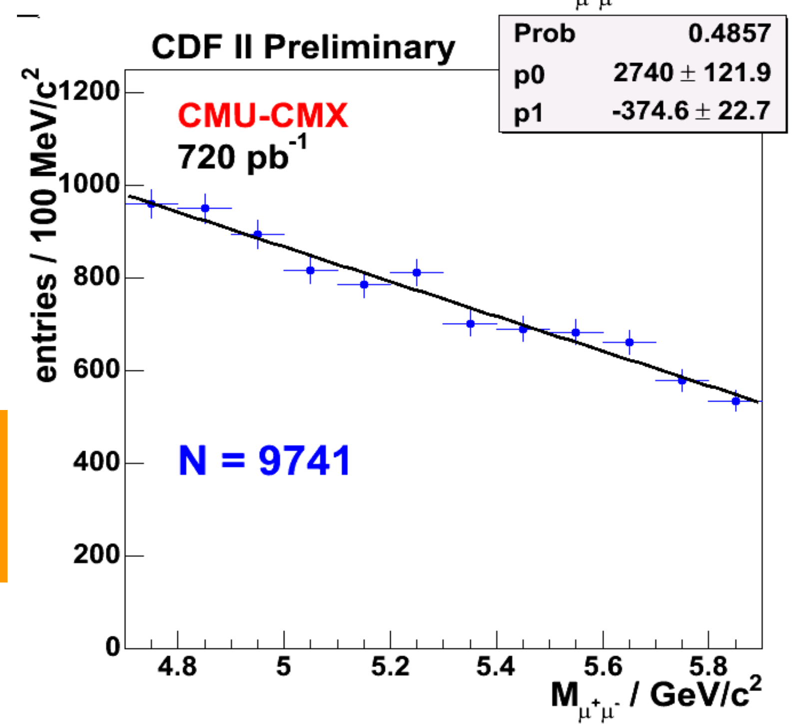
Step 3: reconstruct $B^+ \to J/\psi K^+$ normalization mode

Step 4: open the box → compute branching ratio or set limit

# CDF Pre-selection

- **Pre-Selection cuts:**
  - $4.669 < m_{\mu\mu} < 5.969$ GeV/$c^2$
  - muon quality cuts
  - $p_T(\mu)>2.0$ (2.2) GeV/c CMU (CMX)
  - $p_T(B_s$ cand.)>4.0 GeV/c
  - $|\eta(B_s)| < 1$
  - good vertex
  - 3D displacement $L_{3D}$ between primary and secondary vertex
  - $\sigma(L_{3D})<150$ μm
  - proper decay length $0 < \lambda < 0.3$cm

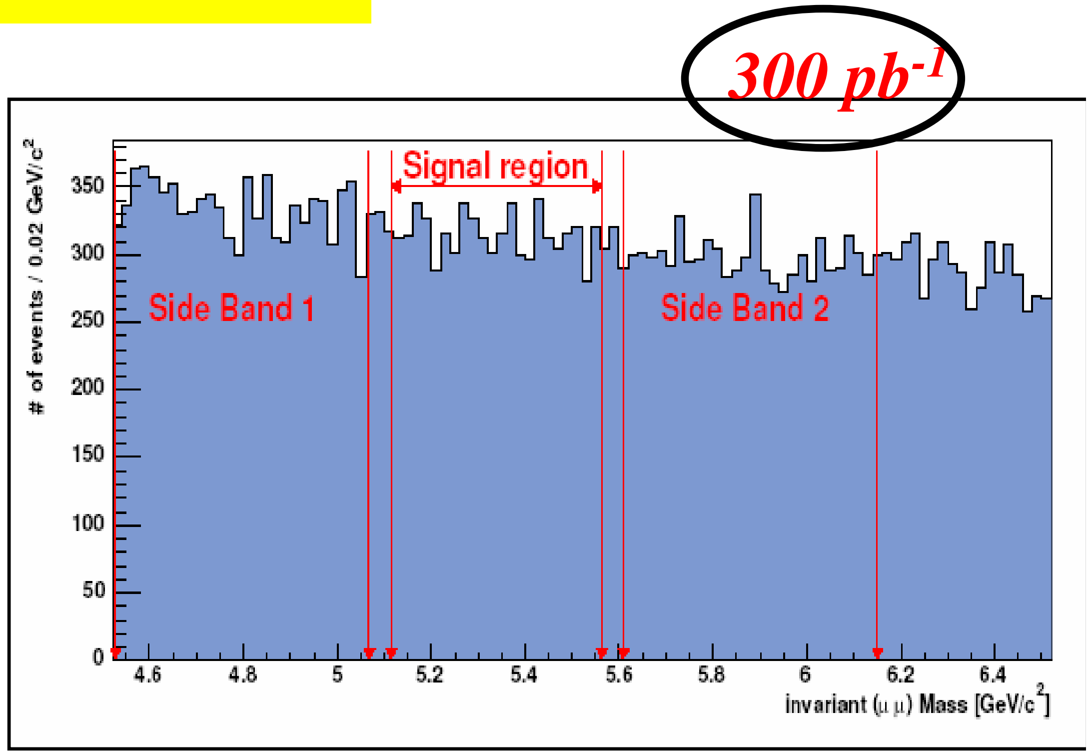



**Bkg substantially reduced but still sizeable at this stage**

# D0 Pre-selection

- **Pre-selection DØ:**
  - $4.5 < m_{\mu\mu} < 7.0$ GeV/c$^2$
  - muon quality cuts
  - $p_T(\mu)>2.5$ GeV/c
  - $|\eta(\mu)| < 2$
  - $p_T(B_s$ cand$)>5.0$ GeV/c
  - good di-muon vertex

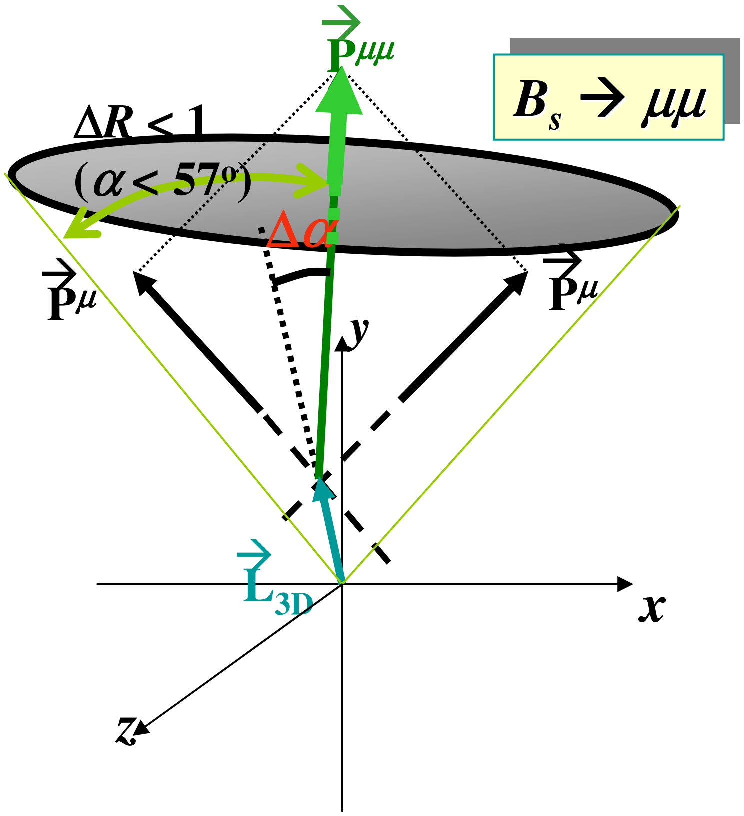



**~ 38k events after pre-selection**

Potential sources of background:

- continuum μμ Drell-Yan
- sequential semi-leptonic b→c→s decays
- double semi-leptonic bb→ μμX
- b/c→μx+fake
- fake + fake

# B→ $\mu^+\mu^-$ Signal vs Bkg Discrimination




- $\mu^+\mu^-$ mass

- B vertex displacement:

  CDF → $\lambda = \frac{cL_{3D}M}{|\vec{p}(B)|}$

  D0 → $L_{xy} / \sigma_{Lxy}$

- Isolation (Iso):

$$Iso = \frac{p_T(B)}{p_T(B) + \sum_i p_T^i(\Delta R_i < 1)}$$

(fraction of $p_T$ from B→μμ within $\Delta R=(\Delta\eta^2+\Delta\phi^2)^{1/2}$ cone of 1)

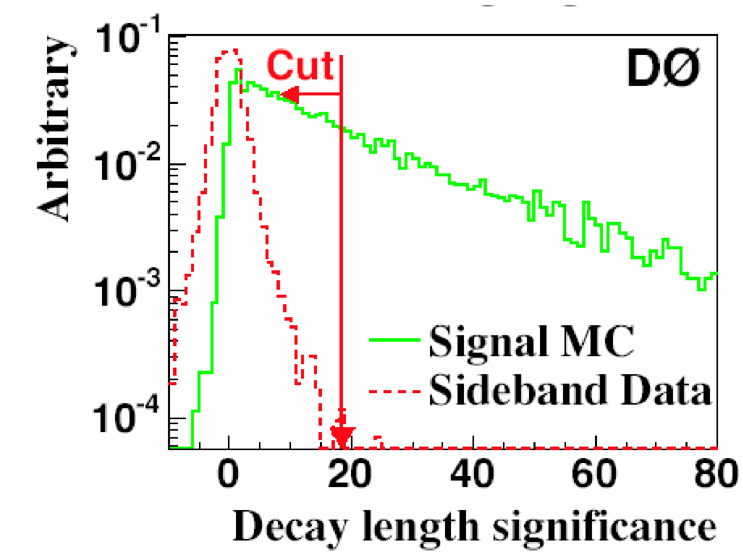
- "pointing ($\Delta\alpha$)":

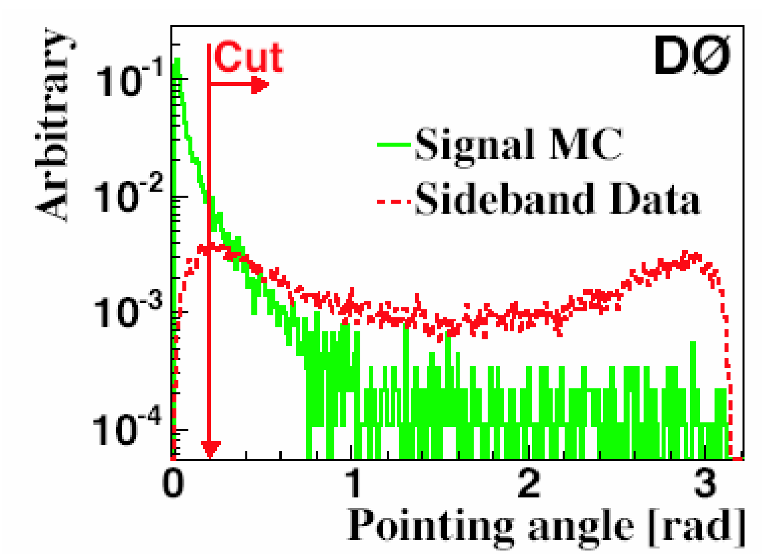
$$\Delta\alpha = \angle(\vec{p}(B) - \vec{L}_{3D})$$

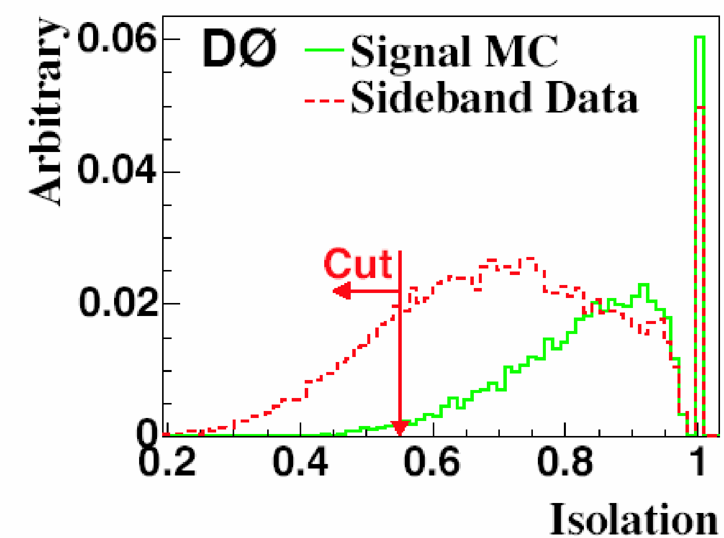
(angle between $B_s$ momentum and decay axis)

# D0 Optimization

- Optimize cuts on three discriminating variables
  - Pointing angle
  - 2D decay length significance
  - Isolation
- Random Grid Search
- Maximize S/(1+sqrt(B))



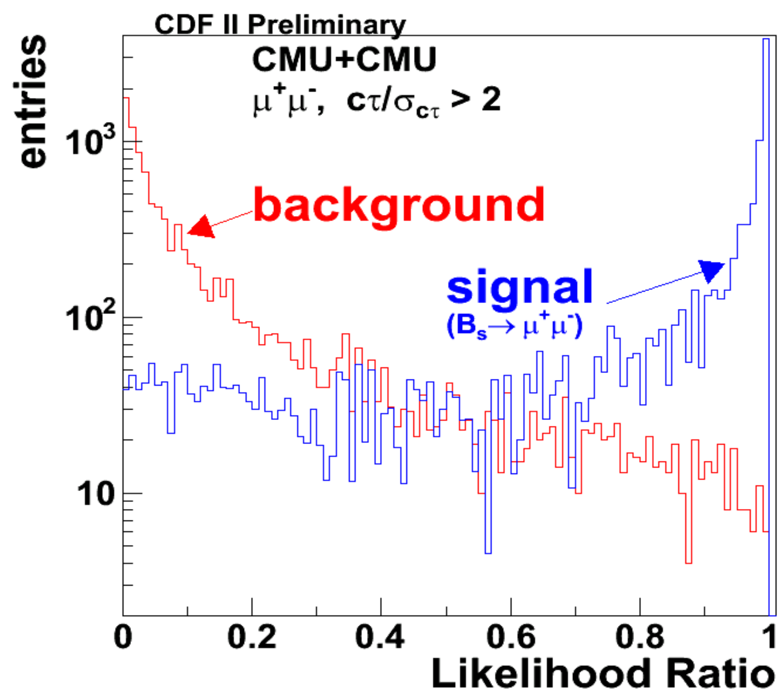



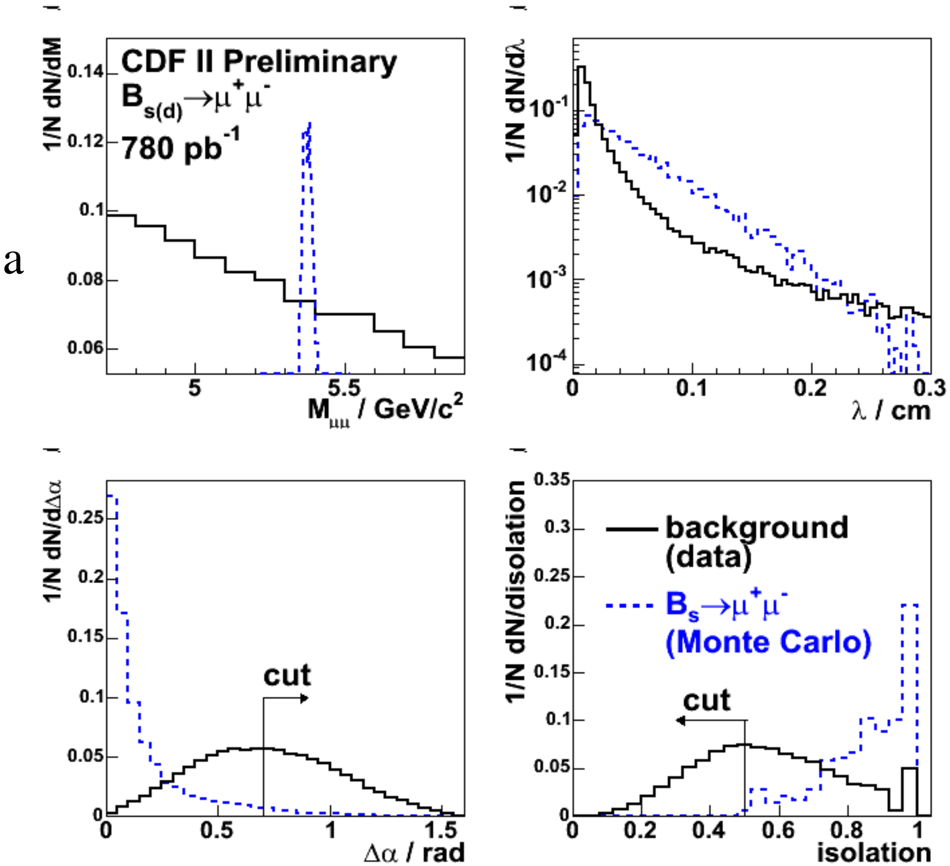
# CDF Optimization

- CDF constructs a likelihood ratio using discriminating variables $\lambda$, $\Delta\alpha$, Iso

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

$P_{s/b}$ is the probability for a given sig/bkg to have a value of $x$, where $i$ runs over all variables.

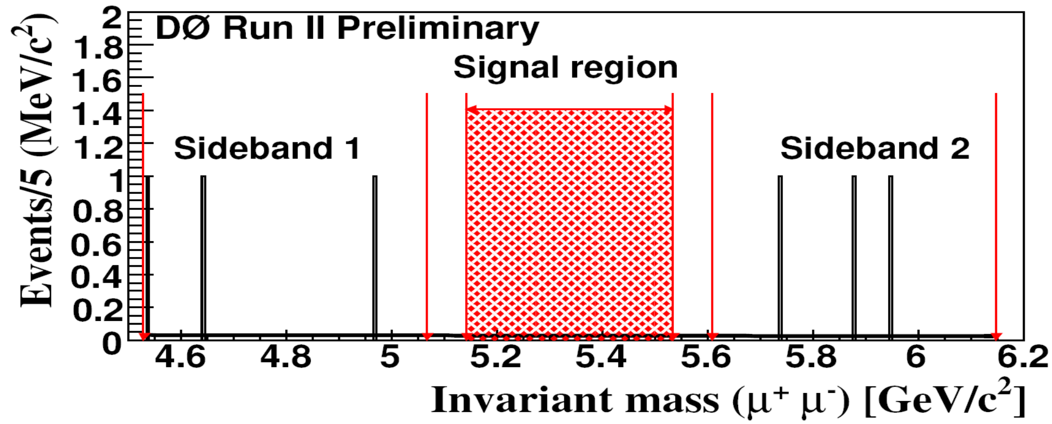



- Optimize on expected upper limit
- $L_R$(optimized)>0.99

# Background Estimate

- Extrapolated bkg from side-bands to signal region assume linear shape

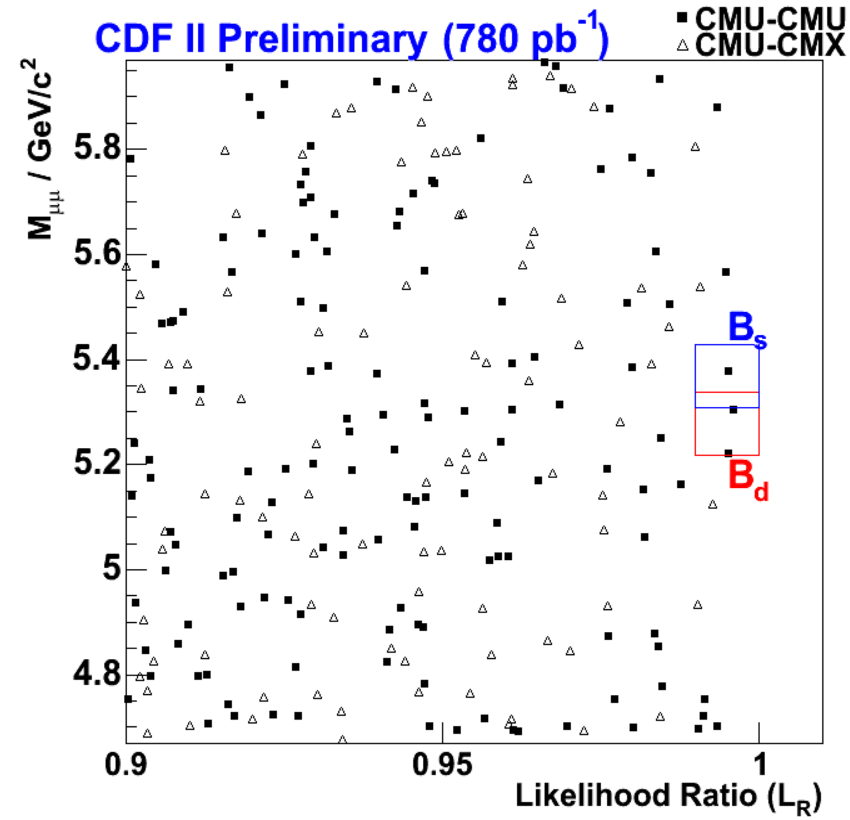



- CDF signal region is also contaminated by $B \rightarrow h^+h^-$ (e.g. $B \rightarrow K^+K^-$, $K^+\pi^-$, $\pi^+\pi^-$)
  - $K,\pi \rightarrow$ muon fake rates measured from data
  - Convolute fake rates with expected $Br(B \rightarrow h^+h^-)$ to estimate #

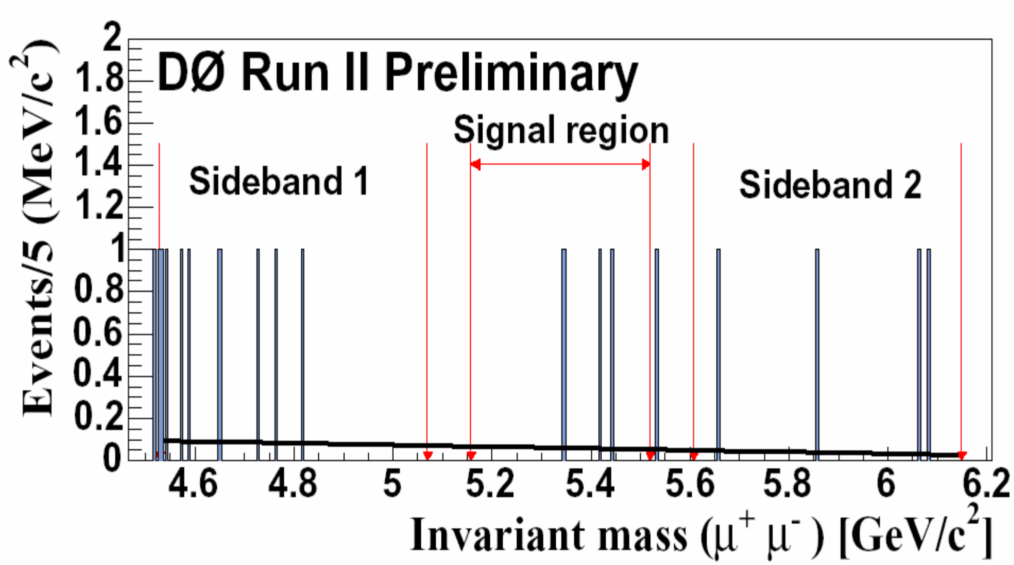
    Bs signal window = $0.19 \pm 0.06$

    Bd signal window = $1.37 \pm 0.16$
  - Total bkg = combinatoric + ($B \rightarrow hh$)

# Box Opened

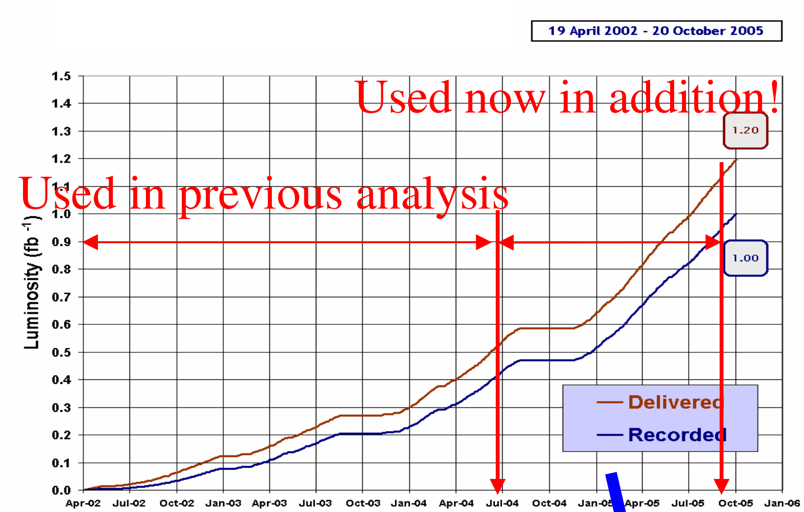



- CDF (780 pb$^{-1}$):
  - central/central: observe 1, expect 0.88 ± 0.30
  - Central/forward: observe 0, expect 0.39 ± 0.21

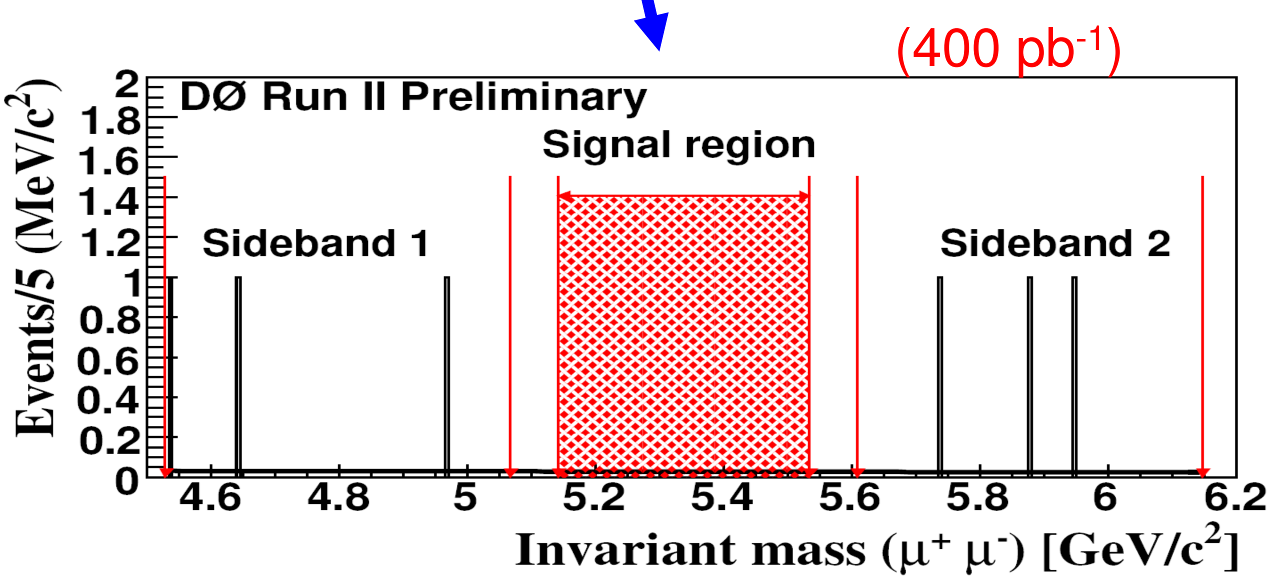



- DØ (300 pb$^{-1}$):
  - observe 4, expect 4.3 ± 1.2

# D0 Sensitivity for 700 $pb^{-1}$




- Obtain a sensitivity (w/o unblinding) w/o changing the analysis
- Combine "old" Limit with obtained sensitivity

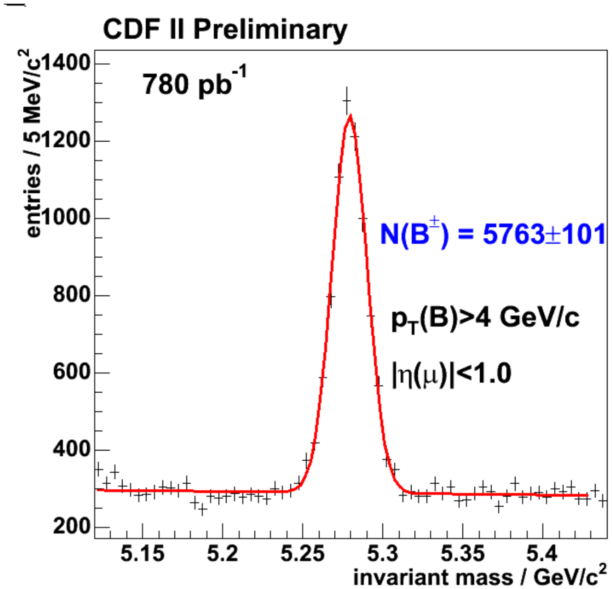



Cut Values changed only slightly!

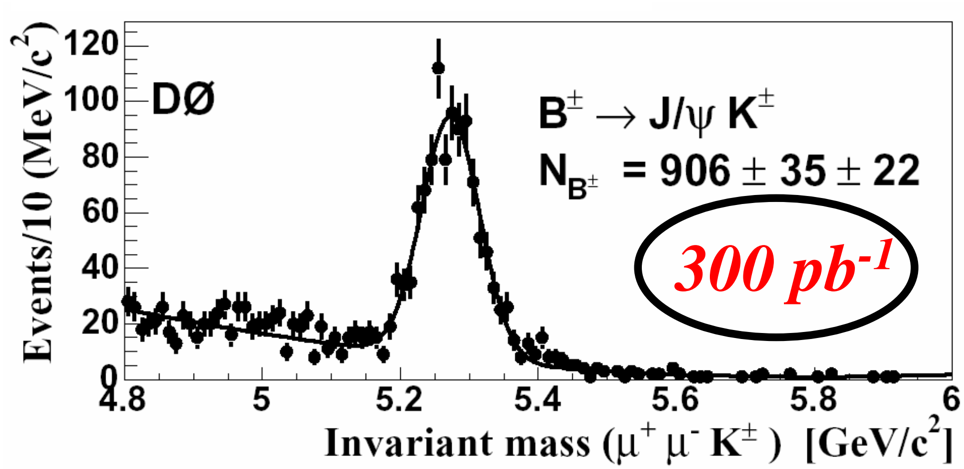
Expect 2.2 ± 0.7 background events

# Setting Limits

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




- $B^+$ reconstructed using similar selection criteria as Bs
- Acceptance and efficiency ratios are obtained from combination of data and Monte Carlo
- Fragmentation ratio (fs/fu) from world average with ~12% uncertainty




- Branching ratios of norm mode taken from world average

# Branching Ratio Limits

- Using Bayesian methods (flat prior) and including stat+syst errors
- Time evolution of limits (in 95%CL):

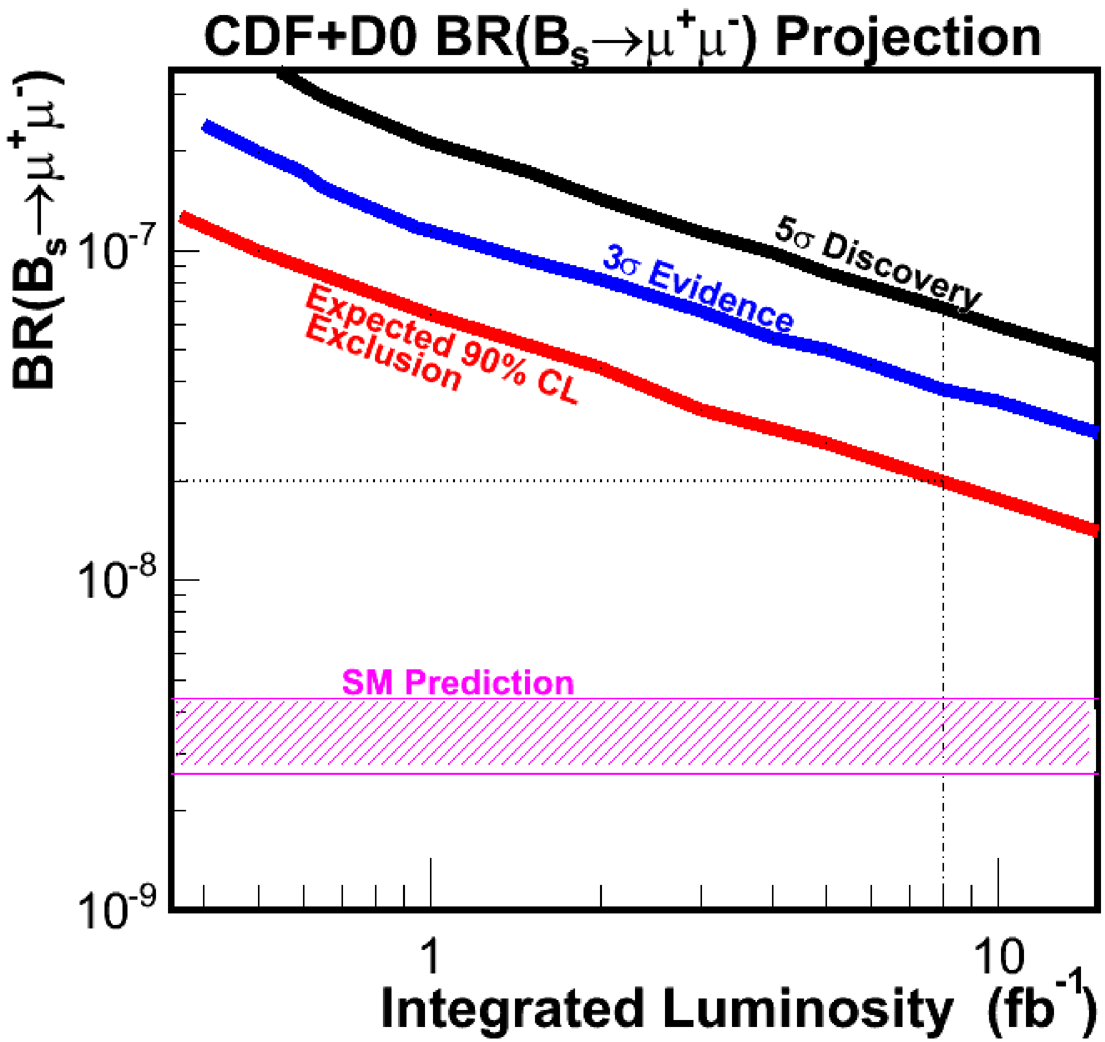
| | | | |
|---|---|---|---|
| CDF $B_s$->$\mu\mu$ | 176 $pb^{-1}$ | $7.5\times10^{-7}$ | Published |
| DØ $B_s$->$\mu\mu$ | 240 $pb^{-1}$ | $5.1\times10^{-7}$ | Published |
| DØ $B_s$->$\mu\mu$ | 300 $pb^{-1}$ | $4.0\times10^{-7}$ | Prelim. |
| DØ <$B_s$->$\mu\mu$> | 700 $pb^{-1}$ | <$2.3\times10^{-7}$> | Prelim. Sensitivity |
| CDF $B_s$->$\mu\mu$ | 364 $pb^{-1}$ | $2.0\times10^{-7}$ | Published |
| CDF $B_s$->$\mu\mu$ | 780 $pb^{-1}$ | $1.0\times10^{-7}$ | Prelim. |
| CDF $B_d$->$\mu\mu$ | 364 $pb^{-1}$ | $4.9\times10^{-8}$ | Published |
| CDF $B_d$->$\mu\mu$ | 780 $pb^{-1}$ | $3.0\times10^{-8}$ | Prelim. |

World's best limits

**Combine CDF + D0 (expected limit) improves result by ~20%**

**→ $Br(B_s \to \mu\mu) <\sim 0.8\times10^{-7}$ @ 95%C.L.**

# TEVATRON Reach on $B_s \rightarrow \mu\mu$




Projection was made about a year ago

So far we are doing slightly better than the projection

Based on current projection, Tevatron can push down to low $10^{-8}$ region

# Summary

- CDF and D0 have analyzed first ~800 $pb^{-1}$. No signal is seen in the CDF data. D0 has not opened the box for the later data.
- A full Tevatron $B_s \rightarrow \mu\mu$ analysis update for 1 $fb^{-1}$ is planned for this summer. The expected sensitivity is in the mid $10^{-8}$ level
- Based on conservative estimate, Tevatron will be able to reach down to the low $10^{-8}$. However, if $BR(B_s \rightarrow \mu\mu)$ is at the SM value ☹ Then we will need to wait for LHC for observation.