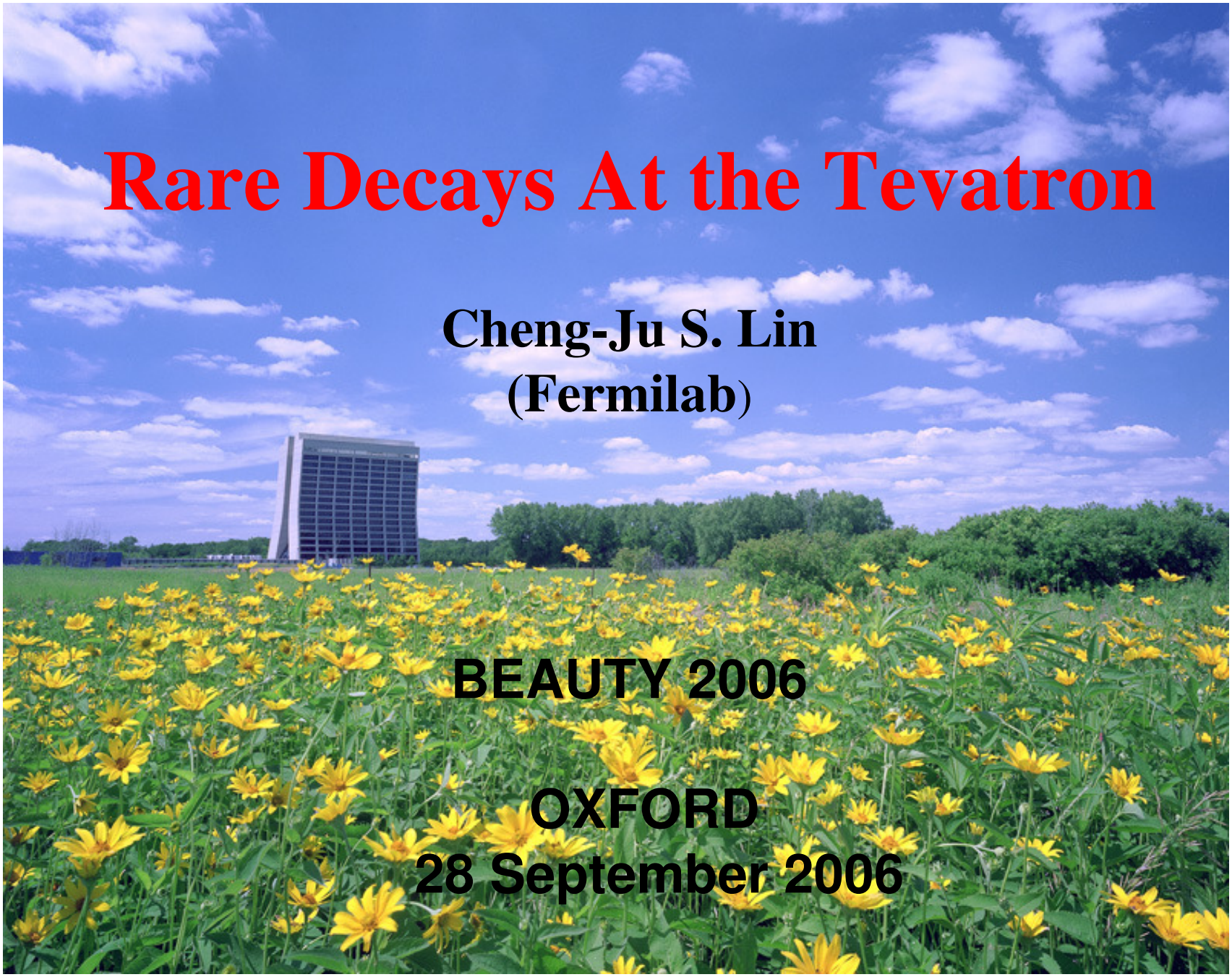


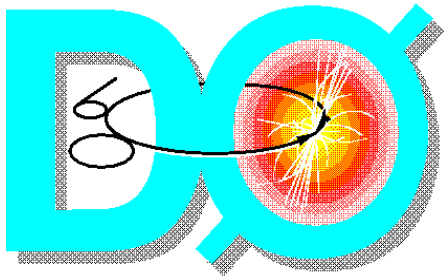
Rare Decays At the Tevatron

Cheng-Ju S. Lin
(Fermilab)

BEAUTY 2006

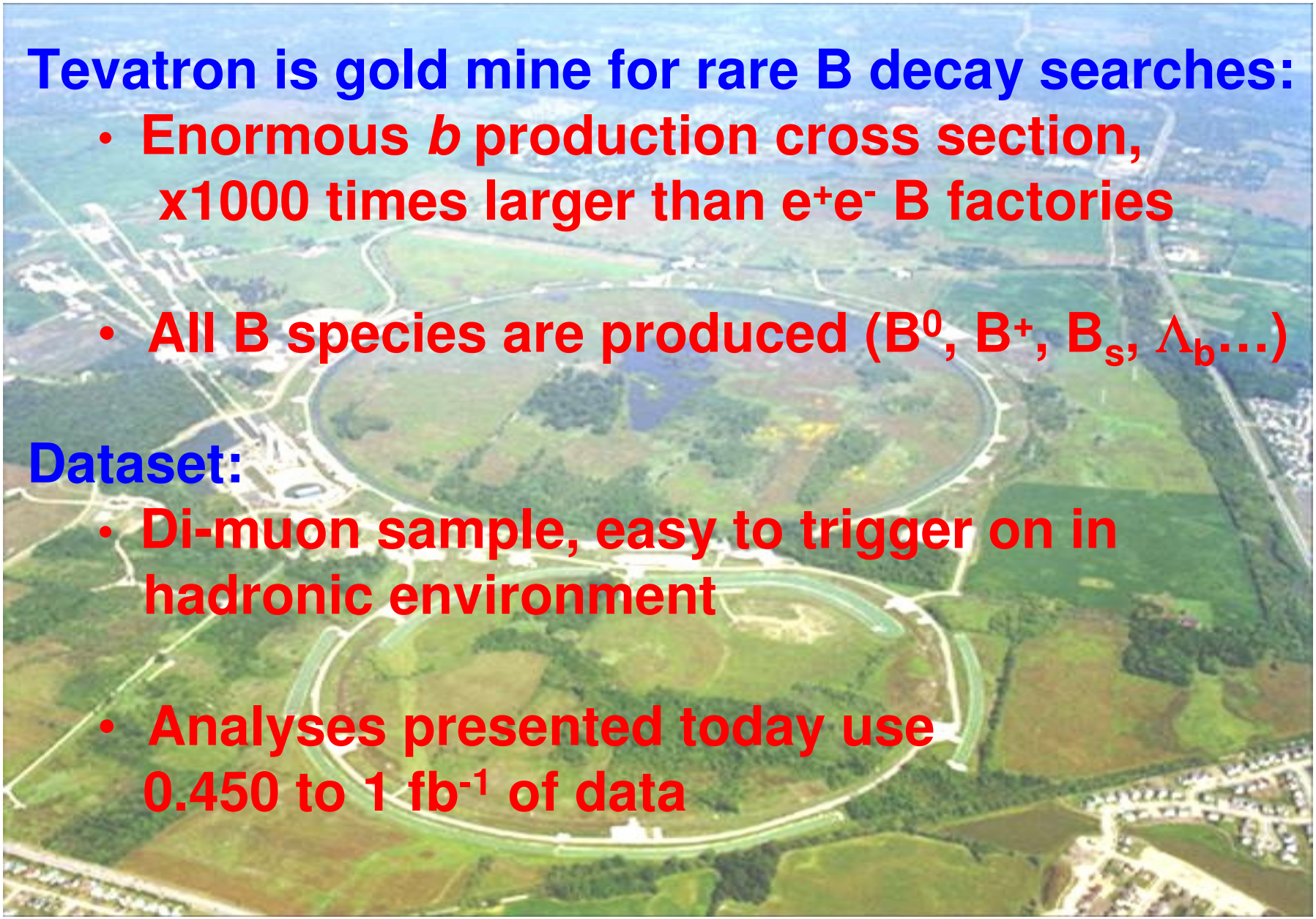
OXFORD
28 September 2006

OUTLINE



- Experimental Issues For Rare Decay Searches
- $B_{s(d)} \rightarrow \mu^+\mu^-$ Status and Prospects
- Non-resonant Rare Decays:
  - $B_d \rightarrow \mu\mu K^{*0}$
  - $B^+ \rightarrow \mu\mu K^+$
  - $B_s \rightarrow \mu\mu\phi$

TEVATRON



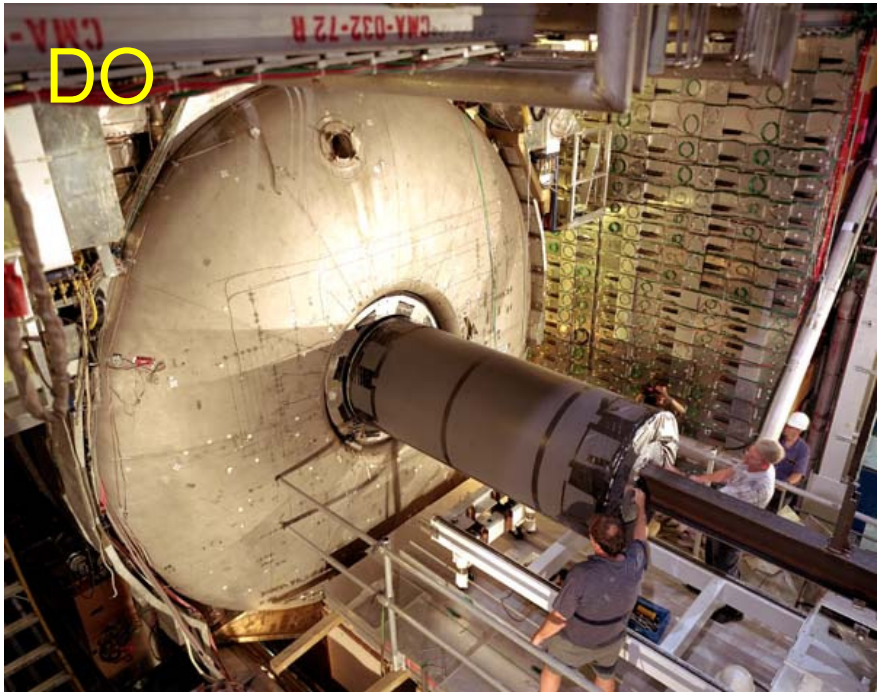
Tevatron is gold mine for rare B decay searches:

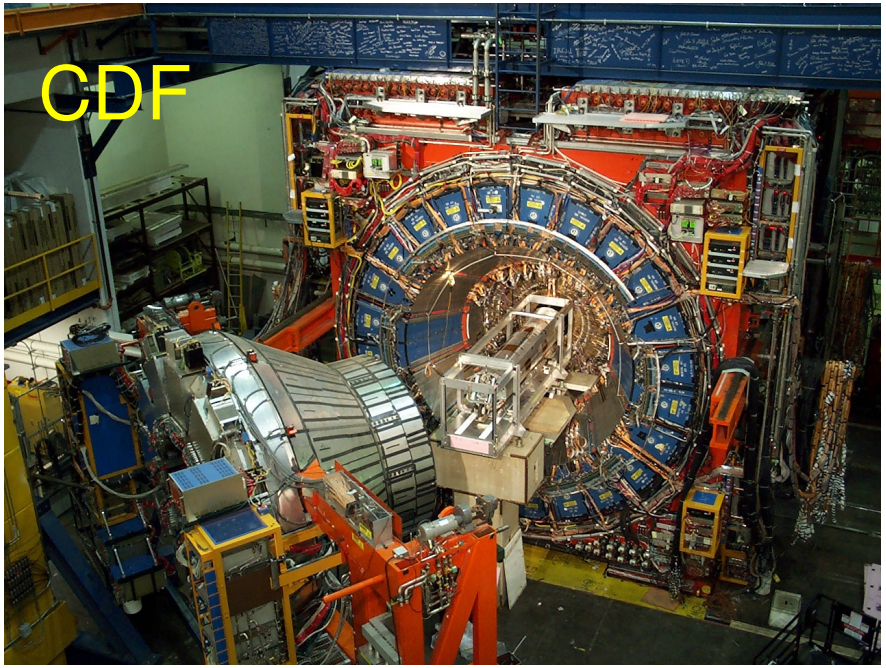
- **Enormous *b* production cross section, x1000 times larger than e^+e^- B factories**
- **All B species are produced (B^0, B^+, B_s, Λ_b…)**

Dataset:

- **Di-muon sample, easy to trigger on in hadronic environment**
- **Analyses presented today use 0.450 to 1 fb^{-1} of data**

CDF + D0 DETECTORS





Key elements for rare decay searches:

- Good muon coverage
  D0: $|\eta|<2.2$

- Good track momentum resolution → mass resolution
  CDF: can resolve $B_s \rightarrow \mu\mu$ from $B_d \rightarrow \mu\mu$ decays

- Good B vertexing resolution
  CDF: L00 (r_{inner}~1.4cm)
  D0: L0 upgrade(r_{inner}~1.6cm)

- Particle ID
  CDF: dE/dx and TOF

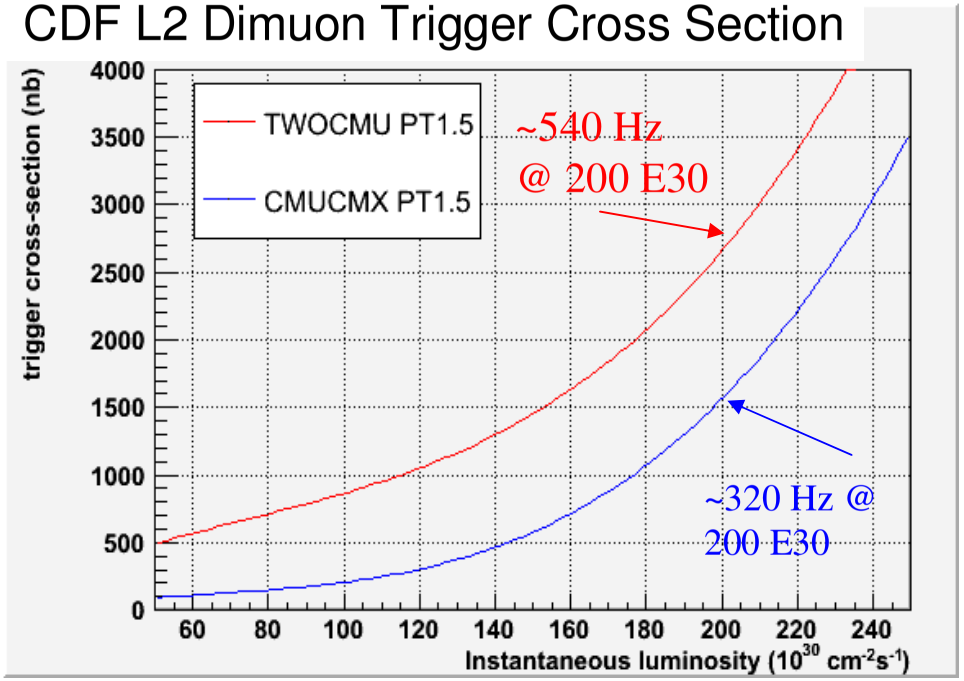
RARE B TRIGGERS AT TEVATRON

- **Trigger is the lifeline of B physics in a hadron environment !!!**

- Inelastic QCD cross section is about 1000x larger than b cross section

- Primary triggers:
  - Di-muons + kinematic requirements
  - Single muon for calibration

- **Main issue: trigger rate blows up rapidly vs. luminosity ☹**



For illustration, these two low pT di-muon triggers alone would take up ~100% of L2 trigger bandwidth at 200E30

KEEPING RARE B TRIGGERS ALIVE

- Handles to control rates:
  - Tighter selection cuts (e.g. pT of muon)
  - Apply prescales (DPS, FPS, UPS, etc.)
  - Improving trigger algorithm
  - Upgrading trigger hardware

  } Non-optimal for rare searches

- We've been using a combination of all four handles to control the trigger rate→ trading efficiency for purity

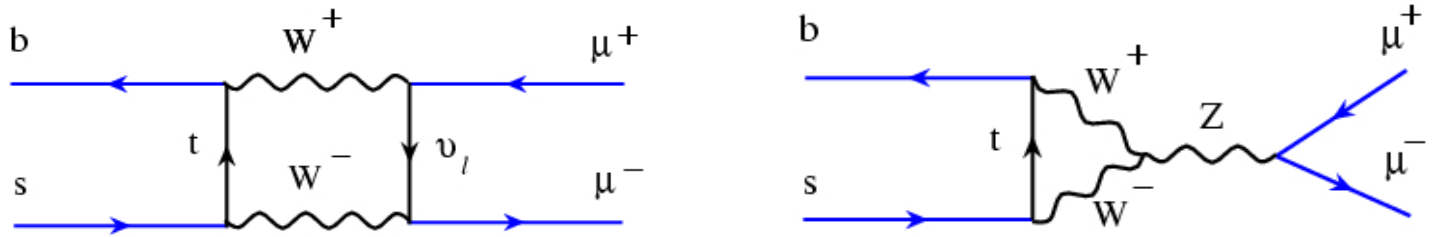
- It's been a great challenge keeping B triggers alive at Tevatron

- It'll be an even greater challenge at the LHC !!

$B \rightarrow \mu^+\mu^-$ SEARCH AT THE TEVATRON

BRIEF MOTIVATION

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



SM prediction → $BR(B_s \to \mu^+\mu^-) = (3.5 \pm 0.9) \times 10^{-9}$

(Buchalla & Buras, Misiak & Urban)

- B_d→μμ is further suppressed by CKM factor $(v_{td}/v_{ts})^2$

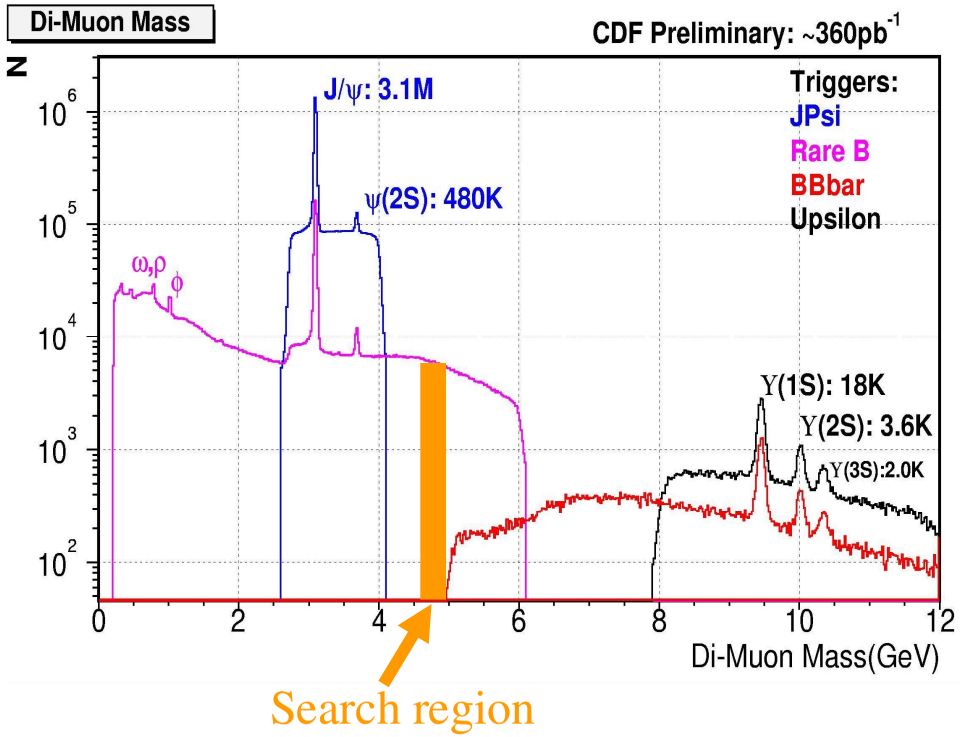
- SM prediction is below the sensitivity of current experiments (CDF+D0): SM → Expect to see 0 events at the Tevatron

Any signal at the Tevatron would indicate new physics!!

- See Tobias Hurth talk this morning for new physics scenarios

RARE B DATASETS

- **CDF:**
  - 780 pb^{-1} di-muon triggered data
  - Two separate search channels
    - Central/central muons (CMU-CMU)
    - Central/forward muons (CMU-CMX)
  - CMU $|\eta|<0.6$, CMX $0.6 < |\eta| < 1$
  - 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!!

METHODOLOGY

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

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)

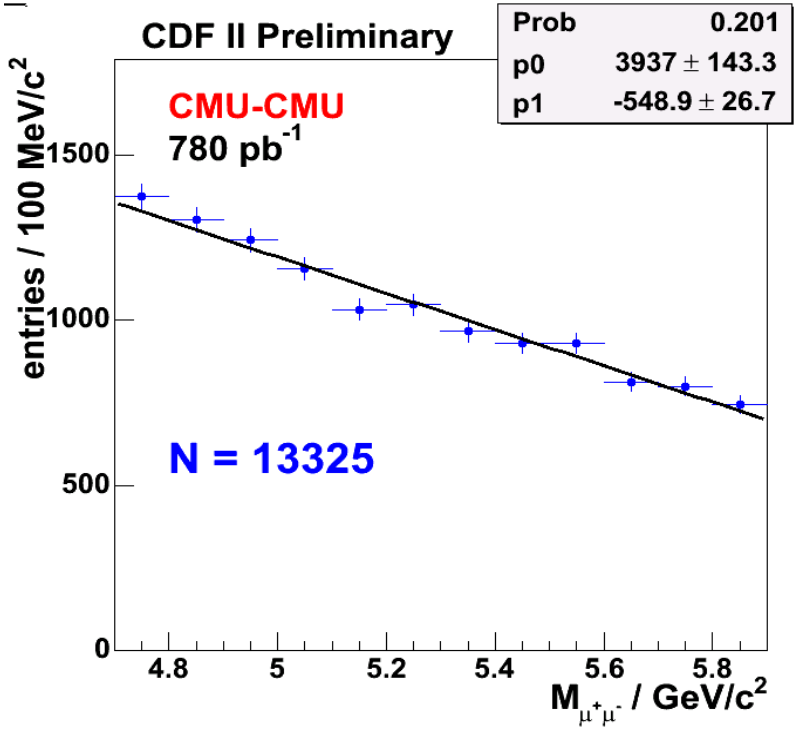
Step 3: reconstruct $B^+ \to J/\psi\, K^+$ normalization mode

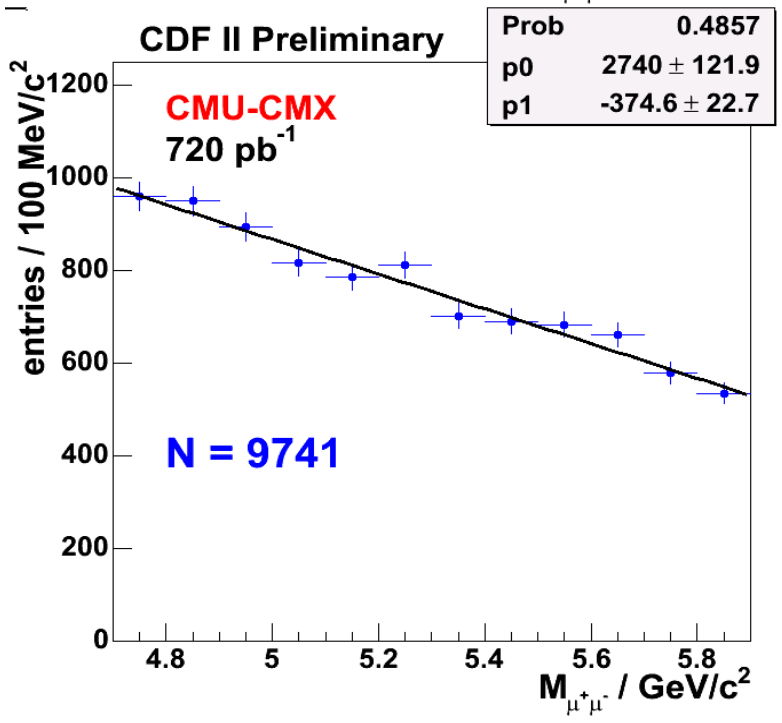
Step 4: open the box → compute branching ratio or set limit

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
  - $|y(B_s)| < 1$
  - good vertex
  - 3D displacement L_{3D} between primary and secondary vertex
  - $\sigma(L_{3D})<150$ μm
  - proper decay length $0 < \lambda < 0.3$cm

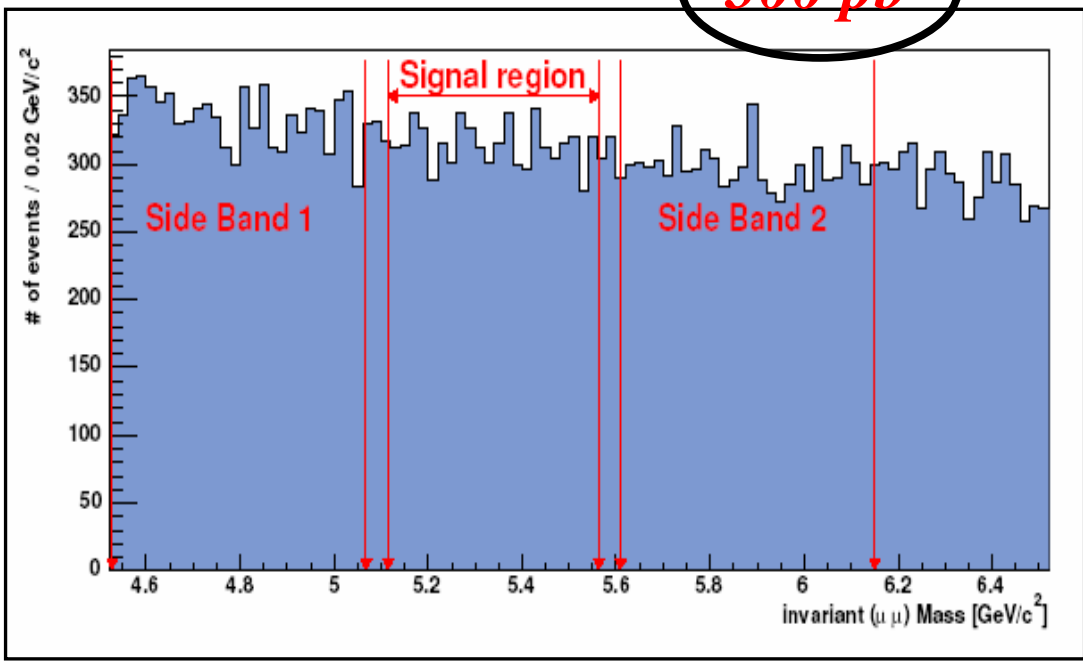
Bkg substantially reduced but still sizeable at this stage





D0 PRE-SELECTION

- **Pre-selection DØ:**
  - $4.5 < m_{\mu\mu} < 7.0$ GeV/c²
  - muon quality cuts
  - $p_T(\mu) > 2.5$ GeV/c
  - $|\eta(\mu)| < 2$
  - $p_T(B_s \text{ cand}) > 5.0$ GeV/c
  - good di-muon vertex

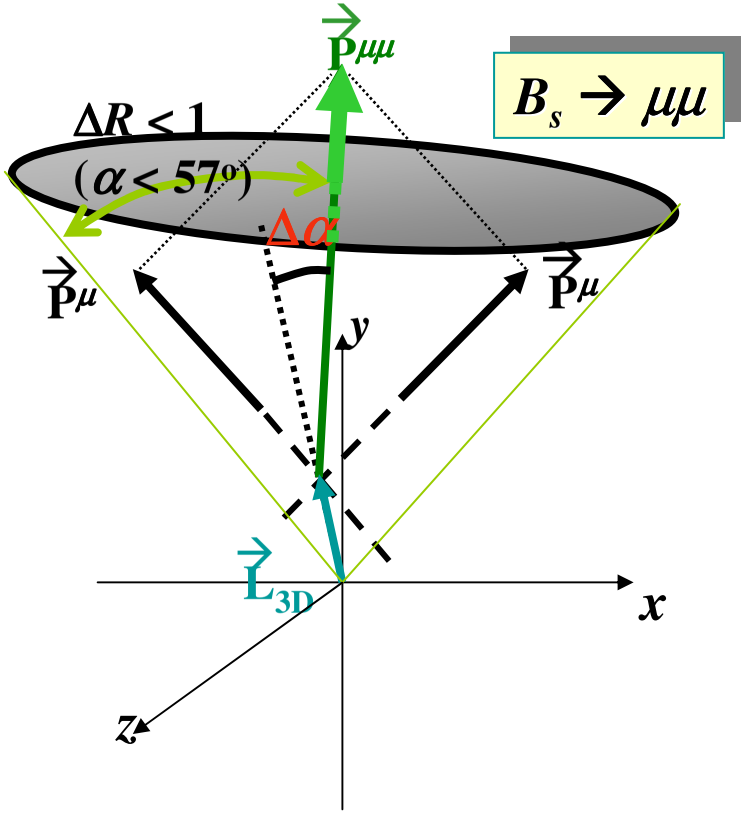


~ 38k events after pre-selection

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

~±2.5σ mass window

– B vertex displacement:

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

D0 → L_{xy} / σ_{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 (Δα)":

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

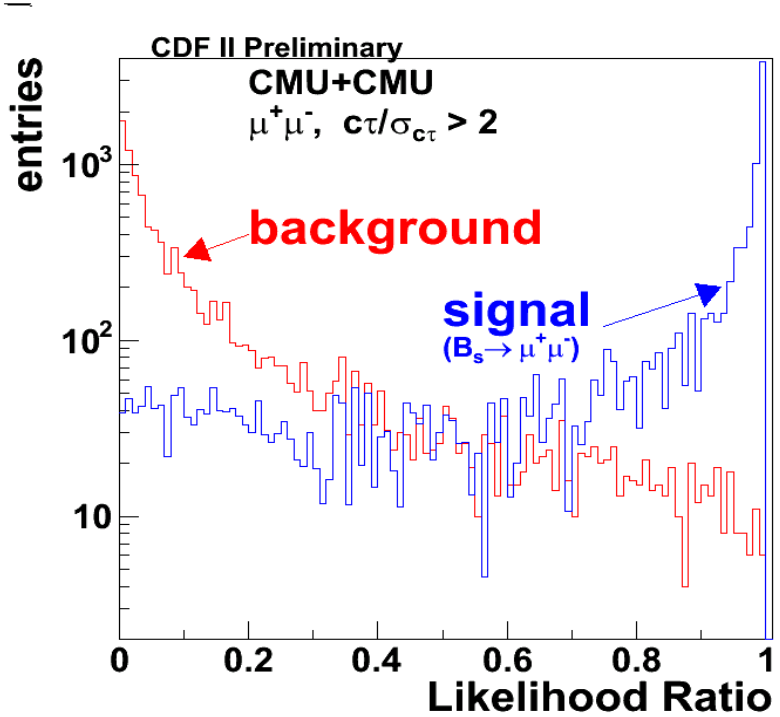
(angle between B_s momentum and decay axis)

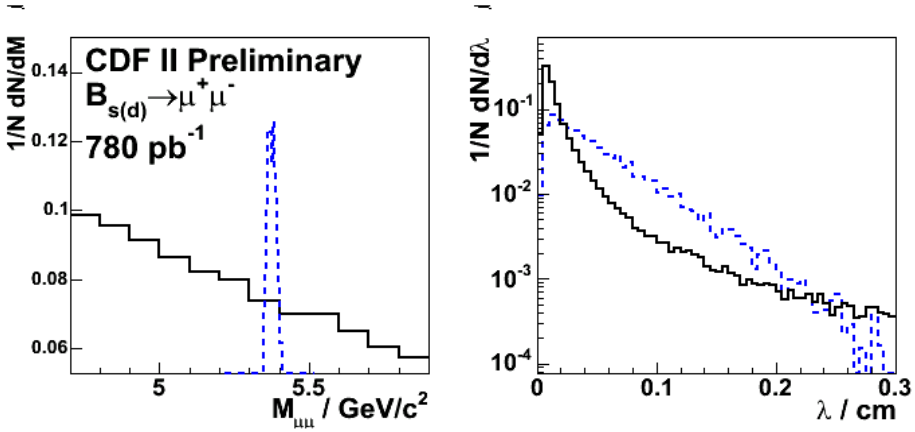
CDF OPTIMIZATION

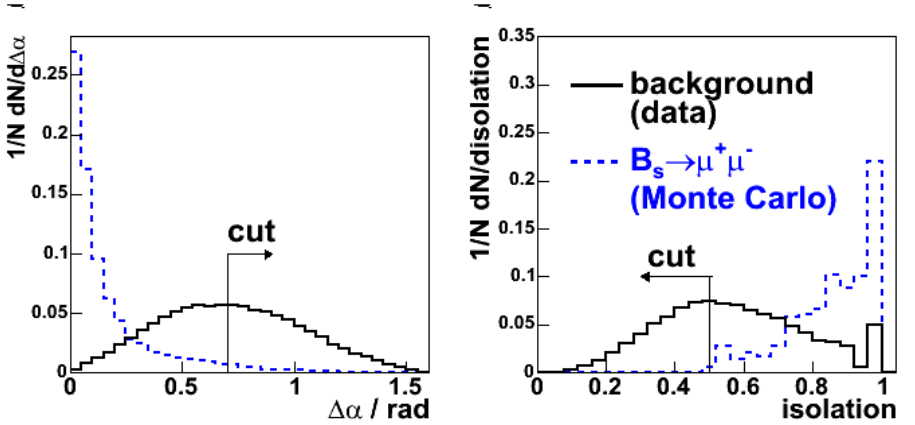
- CDF constructs a likelihood ratio using discriminating variables λ, Δα, Iso

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

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



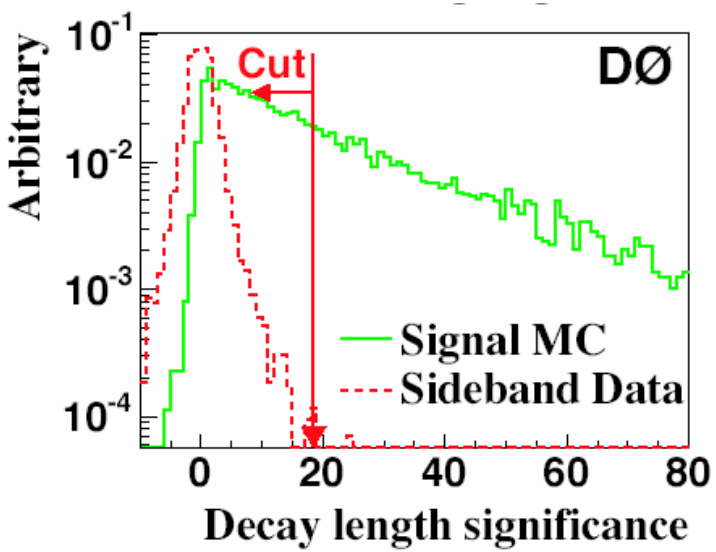


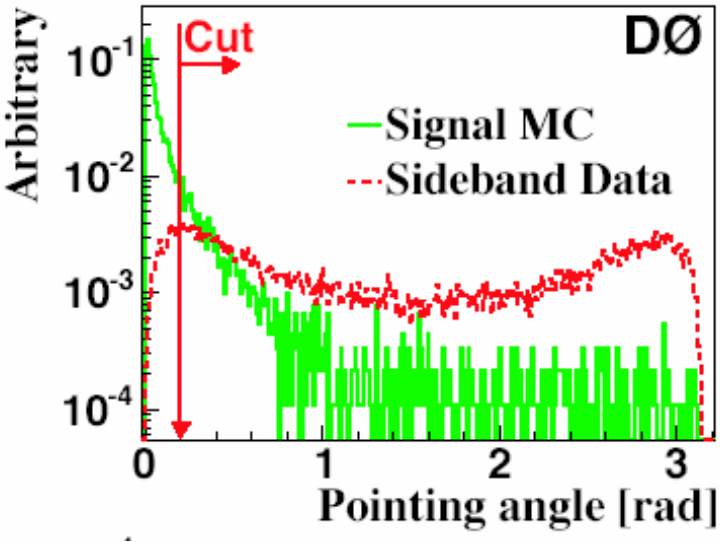


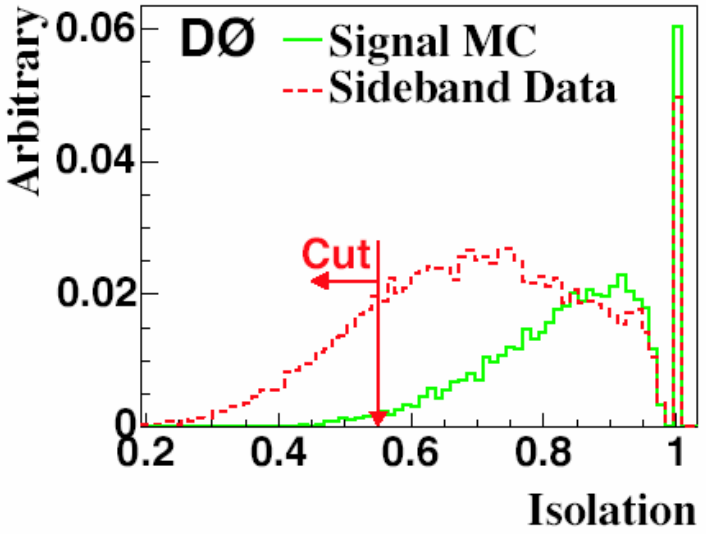
- Optimize on expected upper limit
- L_R(optimized)>0.99

D0 OPTIMIZATION

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

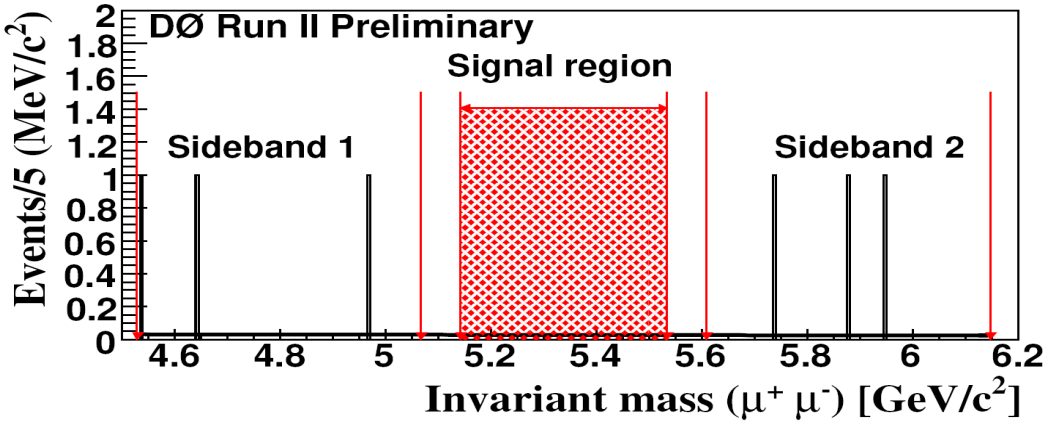






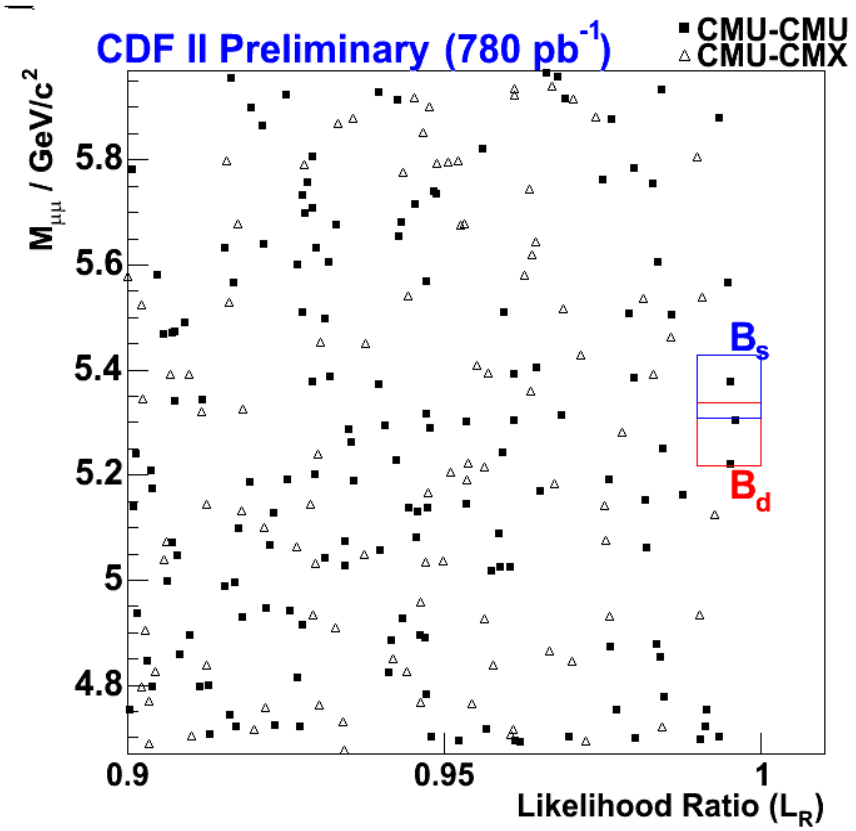
BACKGROUND ESTIMATES

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

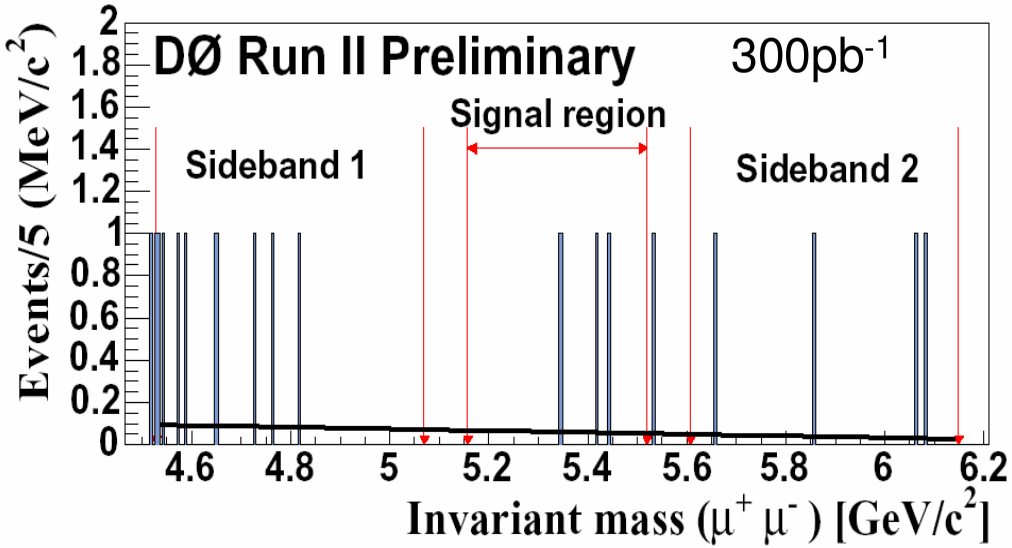


- CDF signal region is also contaminated by $B \rightarrow h^+h^-$ (e.g. $B \rightarrow K^+K^-$, $K^+\pi^-$, $\pi^+\pi^-$)
  - $K,\pi \rightarrow$ muon fake rates measured from data
  - Convolute fake rates with expected $Br(B \rightarrow h^+h^-)$ to estimate #
    - B_s signal window = 0.19 ± 0.06
    - B_d signal window = 1.37 ± 0.16
  - Total bkg = combinatoric + $(B \rightarrow hh)$

BOXES OPENED



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



- DØ $B_s \rightarrow \mu\mu$ (300 pb^{-1}):
  - observe 4, expect 4.3 ± 1.2
- DØ (blinded, 400 pb^{-1}):
  - <Nbkg> = 2.2 ± 0.7

BRANCHING RATIO LIMITS

- Evolution of limits (in 95%CL):

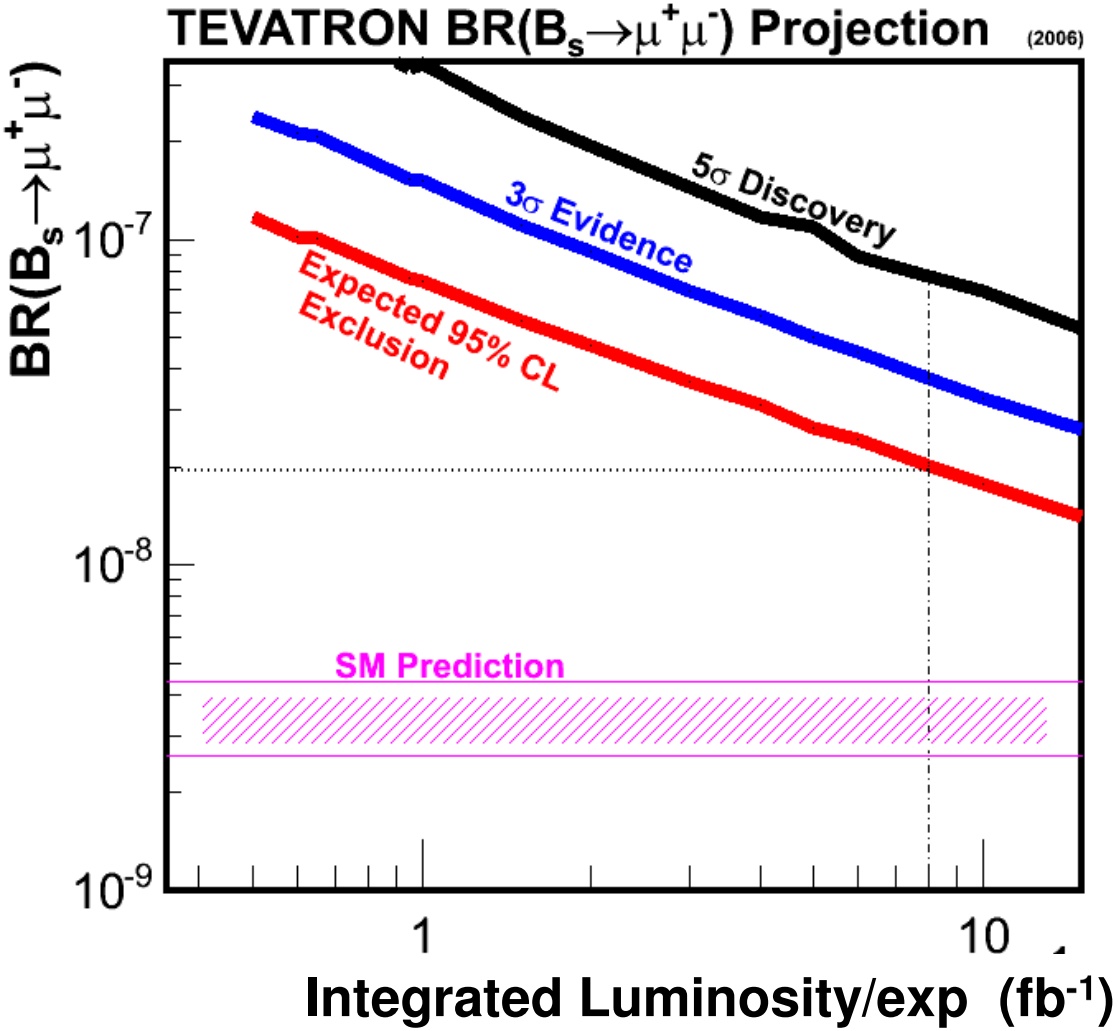
CDF $B_s \to \mu\mu$	176 pb^{-1}	7.5×10^{-7}	Published
DØ $B_s \to \mu\mu$	240 pb^{-1}	5.1×10^{-7}	Published
DØ $B_s \to \mu\mu$	300 pb^{-1}	4.0×10^{-7}	Prelim.
DØ $<B_s \to \mu\mu>$	700 pb^{-1}	$<2.3\times10^{-7}>$	Prelim. Sensitivity
CDF $B_s \to \mu\mu$	364 pb^{-1}	2.0×10^{-7}	Published
CDF $B_s \to \mu\mu$	780 pb^{-1}	1.0×10^{-7}	Prelim.

World's best limits

90% CL

Babar $B_d \to \mu\mu$	111 fb^{-1}	8.3×10^{-8}	Published
CDF $B_d \to \mu\mu$	364 pb^{-1}	4.9×10^{-8}	Published
CDF $B_d \to \mu\mu$	780 pb^{-1}	3.0×10^{-8}	Prelim.

TEVATRON REACH ON $B_s \rightarrow \mu\mu$



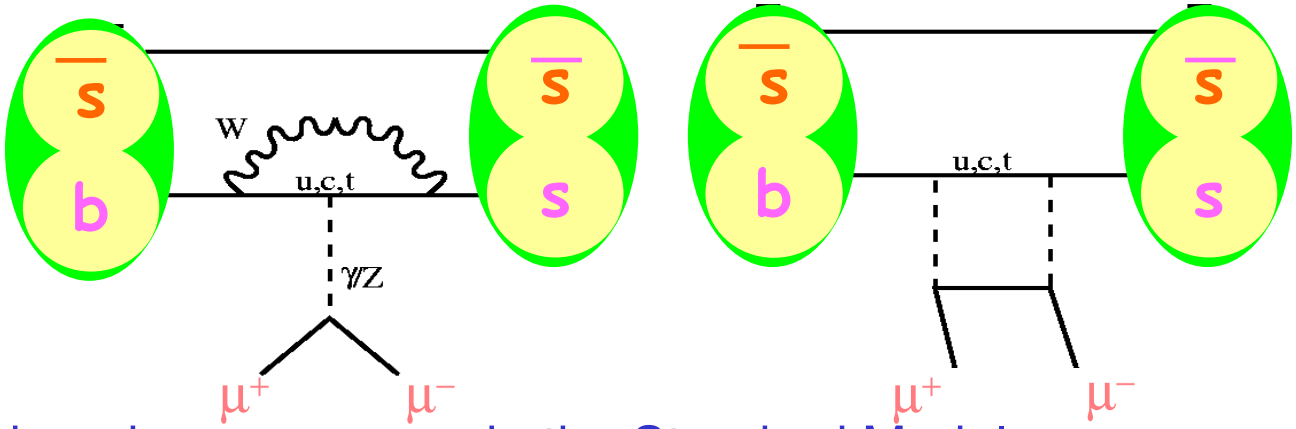
Conservative projection based on sensitivity of current analyses

Ongoing efforts to significantly improve sensitivity of the analyses

Tevatron can push down to at least low 10^{-8} region

B→ $\mu^+\mu^-$ h DECAYS AT THE TEVATRON

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



- Penguin or box processes in the Standard Model
- New physics could interfere with the SM amplitudes
- Can look for new physics via decay rates and decay kinematics
- B Rare Decays $B \to \mu^+\mu^- h$:
  - $B^+ \to \mu\mu\ K^+$ } observed at Babar, Belle
  - $B^0 \to \mu\mu\ K^*$ } observed at Babar, Belle
  - $B_s \to \mu\mu\ \phi$ } not seen

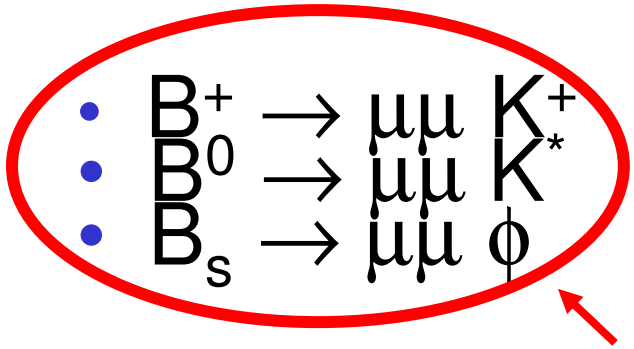
PRD 73, 092001 (2006)
hep-ex/0410006

- Rare processes: predicted $BR(B_s \to \mu\mu\ \phi) = 16.1 \times 10^{-7}$

C. Geng and C. Liu, J. Phys. G 29, 1103 (2003)

B→J/ψh DATASETS

- **CDF:**
  - 1 fb^{-1} di-muon trigger data
  - Search in all three modes:



New RunII results

- **DØ:**
  - 450 pb^{-1} di-muon data
  - Published $B_s \to \mu\mu\phi$ result

METHODOLOGY

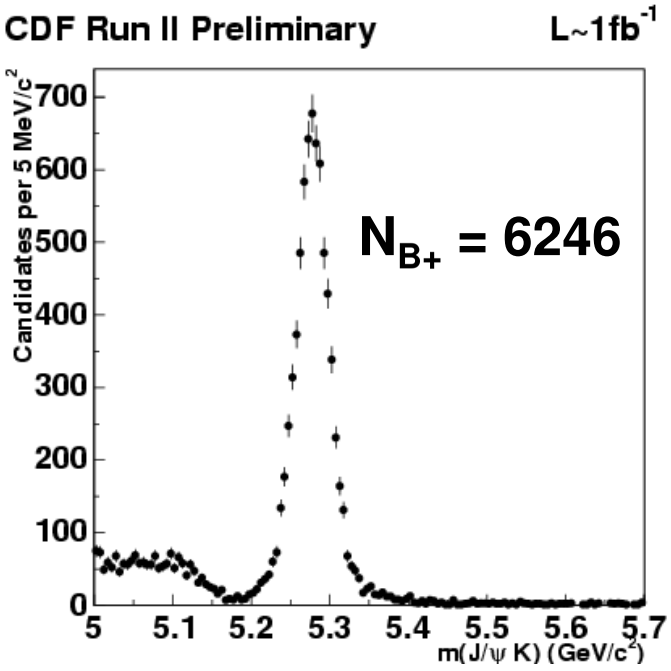
- Experimental method similar to $B_s \rightarrow \mu\mu$ analysis
- Measure branching ratio (or set limit) relative to the reference $B \rightarrow J/\psi$ h resonance decay

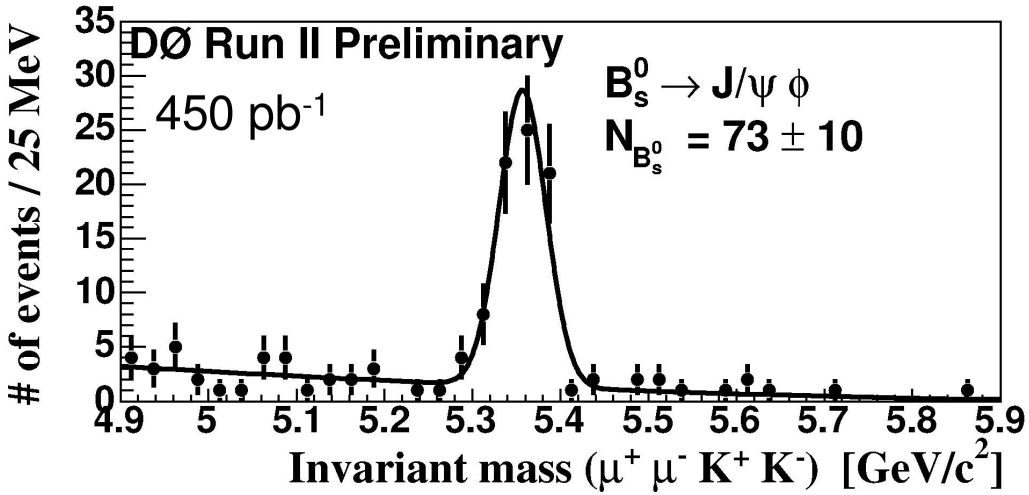
$$\frac{BR(B \to \mu^+\mu^- h)}{BR(B \to J/\psi h)} = \frac{N_{\mu\mu h}}{N_{J/\Psi h}} \frac{\varepsilon^{total}_{J/\Psi h}}{\varepsilon^{total}_{\mu\mu h}} BR(J/\psi \to \mu^+\mu^-)$$

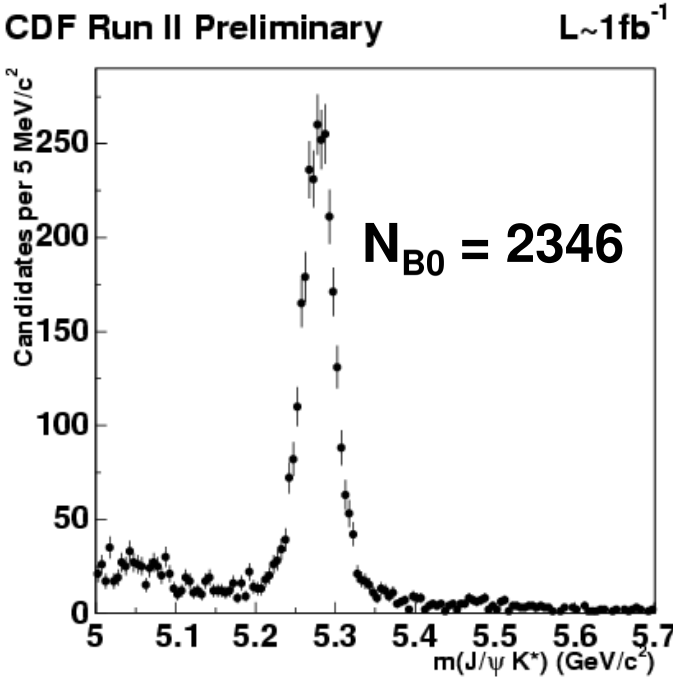
- Exclude ψ and ψ' invariant mass regions for non-resonant decays
- Relative efficiency determined from a combination of data and Monte Carlo
- Bkg estimated from mass side-band(s). Feed-down contribution estimated from MC

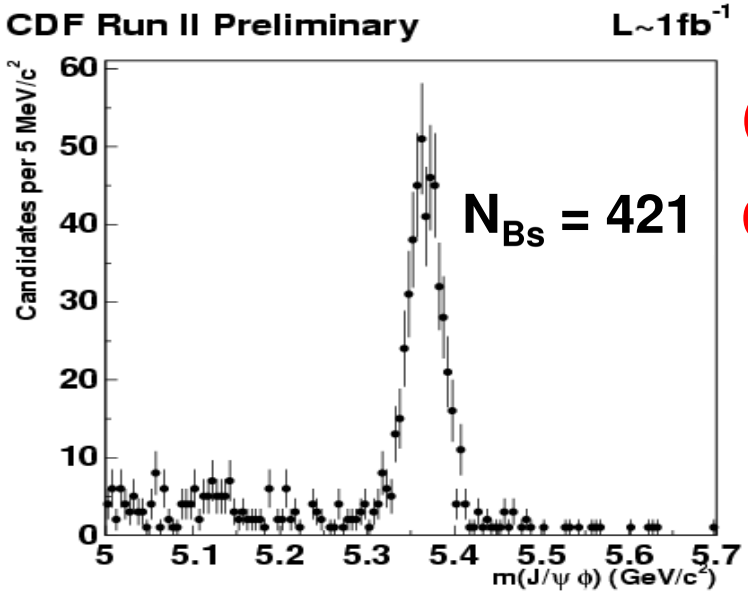
NORMALIZATION MODES

Apply similar pre-selection requirements as B→μμ analysis





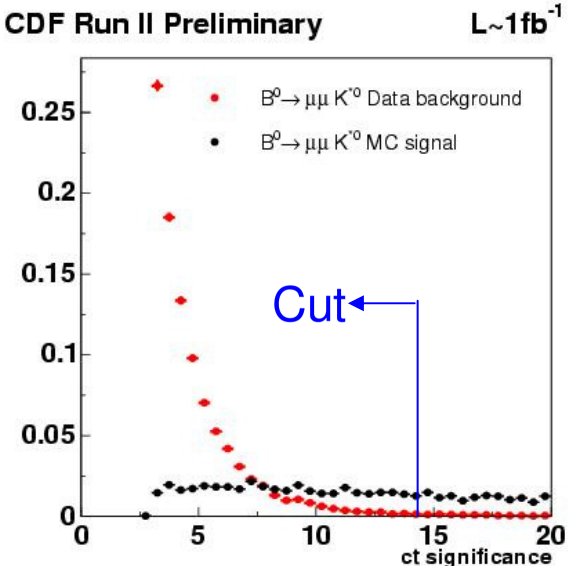


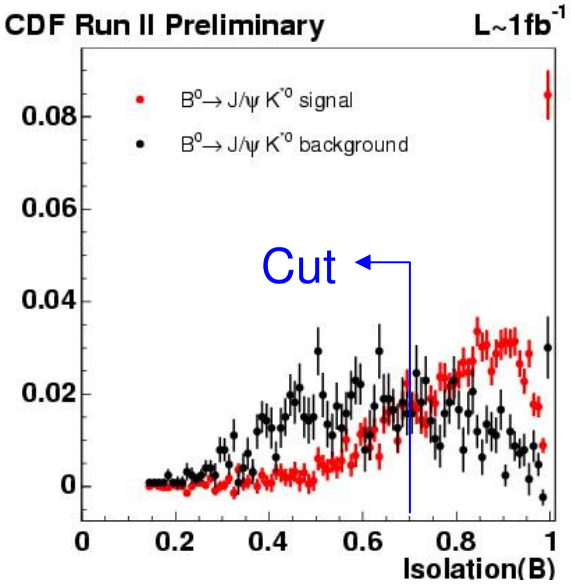


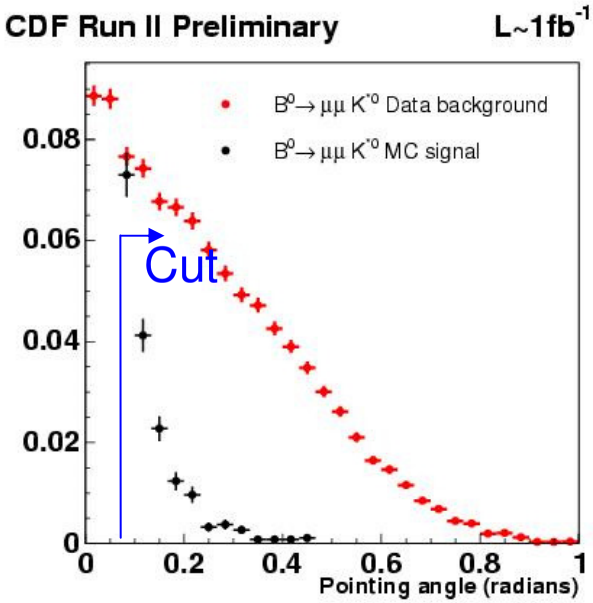
Clean samples of norm events

B→ $\mu^+\mu^-$h SIGNAL VS BKG DISCRIMINATION

- CDF and DØ use three similar variables







- Decay length significance

$$\frac{L_{XY}}{\sigma(L_{XY})}$$

- 2D Pointing $|\phi_B - \phi_{vtx}|$
- Isolation

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

(DØ uses |P|, instead of p_T)

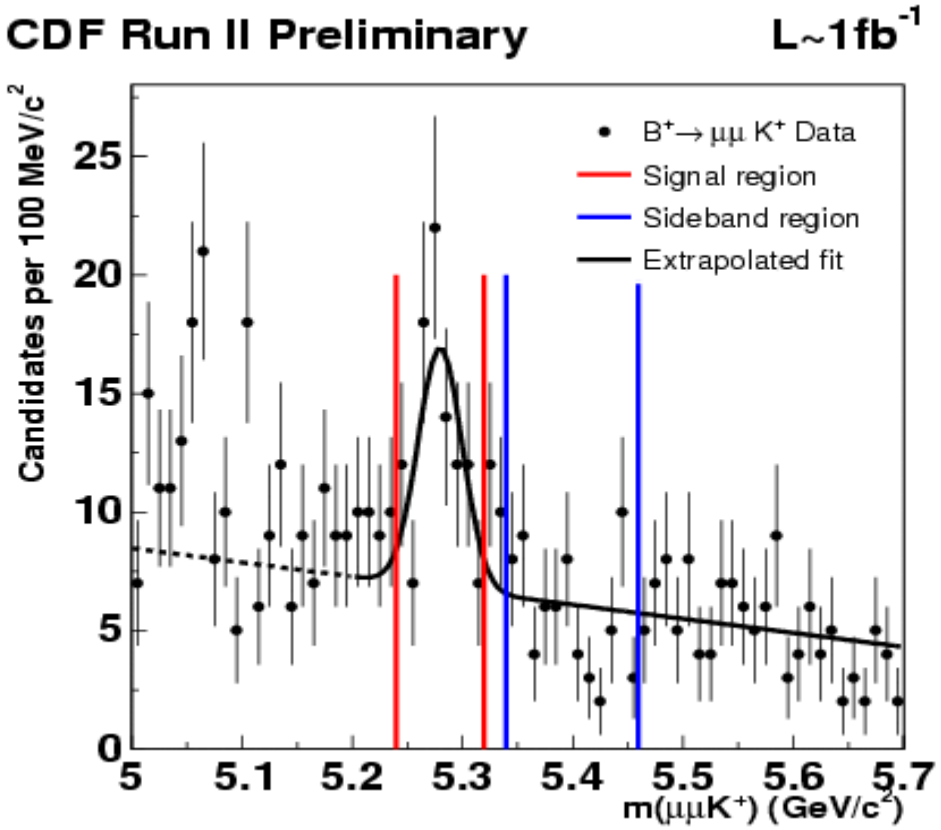
Optimization:

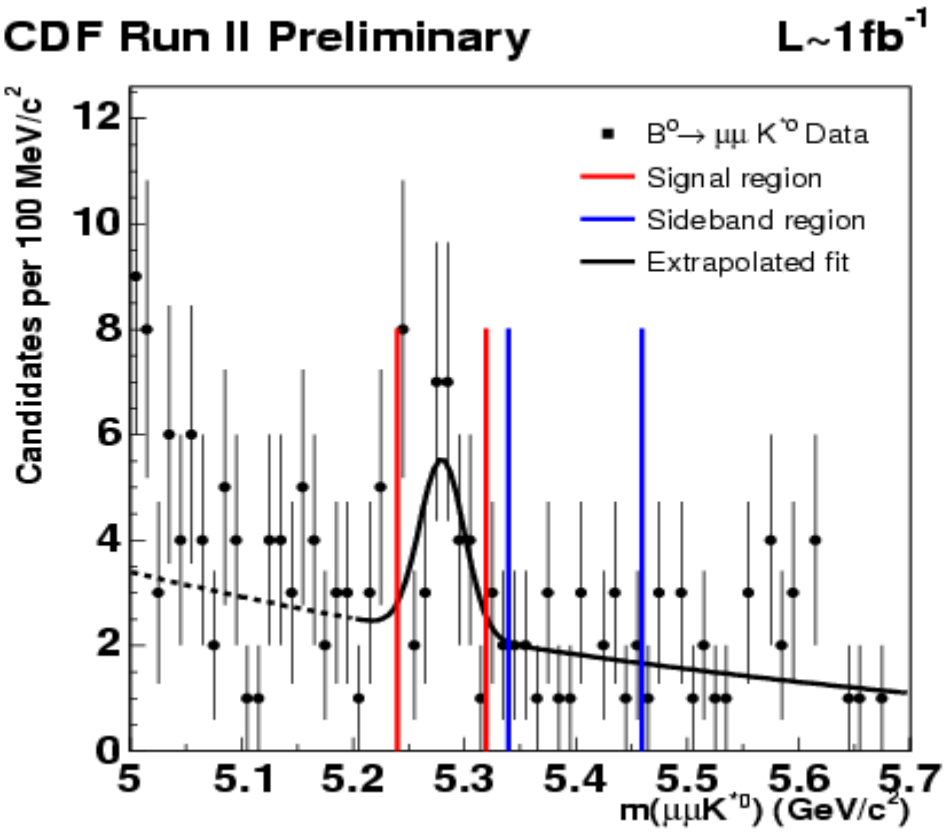
Using data sidebands and MC to avoid introducing biases

CDF → f.o.m. = N_{sig} / sqrt(N_{sig}+N_{bkg})

D0 → f.o.m. = N_{sig} / (1 + sqrt(N_{bkg}))

UNBLINDED B^0 AND B^+ RESULTS





$B^+ \rightarrow \mu\mu\ K^+$:

$N_{obs} = 107$

<bkg> = 51.6 ± 6.1

Significance = 5.2σ

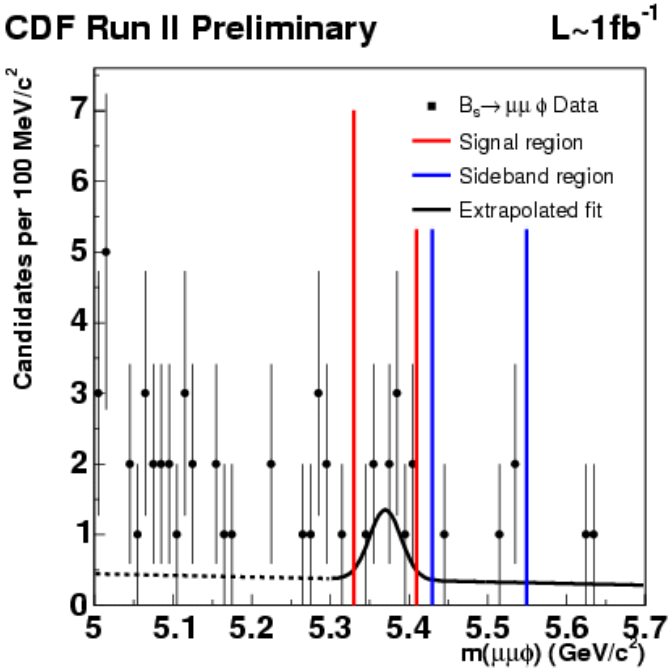
$B^0 \rightarrow \mu\mu\ K^{*0}$:

$N_{obs} = 35$

<bkg> = 16.5 ± 3.6

Significance = 2.9σ

UNBLINDED B_s RESULTS



CDF $B_s \rightarrow \mu\mu\,\phi$:

$N_{obs} = 9$

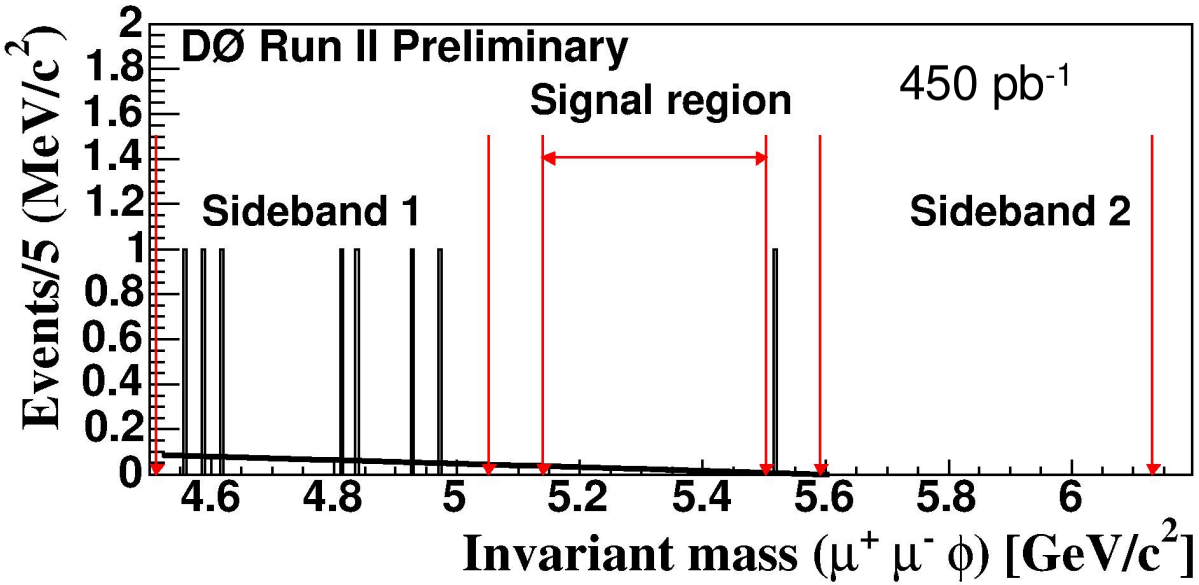
<bkg> = 3.5 ± 1.5

Significance = 1.8σ

D0 $B_s \rightarrow \mu\mu\,\phi$:

$N_{obs} = 0$

<bkg> = 1.6 ± 0.6



No $B_s \rightarrow \mu\mu\,\phi$ signal observed

B→J/ψh RESULTS

CDF 1fb^{-1}	$B^+ \to \mu\mu K^+$	$B^0 \to \mu\mu K^{*0}$	$B_s \to \mu\mu\phi$
Rel BR± stat ± syst 10^{-3}	0.71 ± 0.15 ± 0.04	0.62 ± 0.23 ± 0.07	0.91 ± 0.55 ± 0.11
Abs BR ± stat ± syst 10^{-6}	0.72 ± 0.15 ± 0.05	0.82 ± 0.31 ± 0.10	0.85 ± 0.51 ± 0.31
Rel BR 95% CL Limit x10^{-3}	-	-	2.3
Rel BR 90% CL limit x10^{-3}	-	-	2.0

D0 0.45fb^{-1}	$B_s \to \mu\mu\phi$
Rel BR 95% CL Limit x10^{-3}	4.4
Rel BR 90% CL limit x10^{-3}	3.5

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SUMMARY

- CDF and D0 have analyzed first ~800 pb^{-1} of data to search for $B \rightarrow \mu\mu$. No signal is seen in the CDF data. D0 has not opened the box for the later half of data.

- Current limit already severely constrain new physics models

- Both CDF and DO are significantly improving the sensitivity for the 1 fb^{-1} update. The expected combined sensitivity for 1 fb^{-1} is in the mid 10^{-8} level.

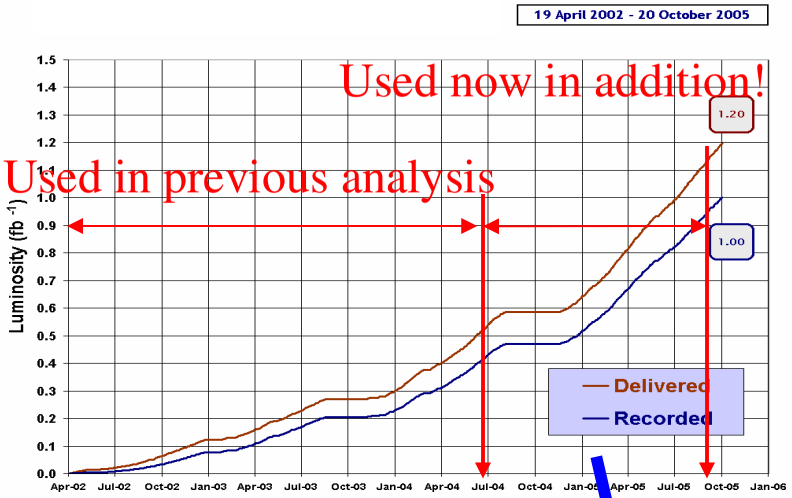
- Tevatron is now getting into B^+ and $B^0 \rightarrow \mu\mu h$ terrority. Preliminary results are consistent with B factories.

- No $B_s \rightarrow \mu\mu\phi$ signal. New CDF result improves limit by x2. Tevatron closing in on SM prediction.

- Still have ~ x8 more data to be collected. Plenty of room for discoveries !!!

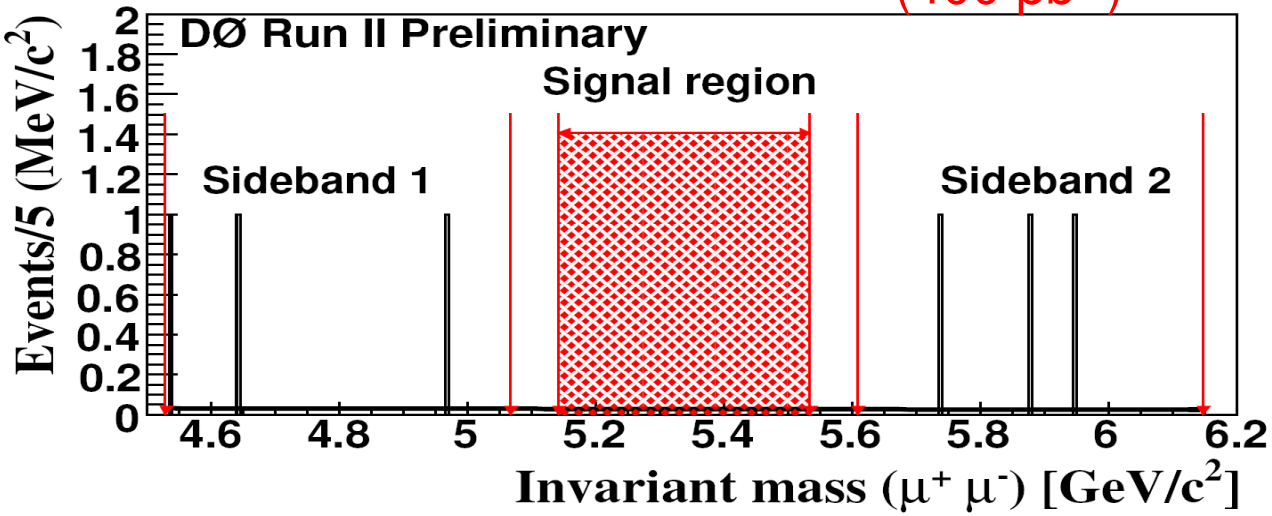
BACKUP

D0 SENSITIVITY FOR 700 pb^{-1}



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

(400 pb^{-1})



Cut Values changed only slightly!

Expect 2.2 ± 0.7 background events