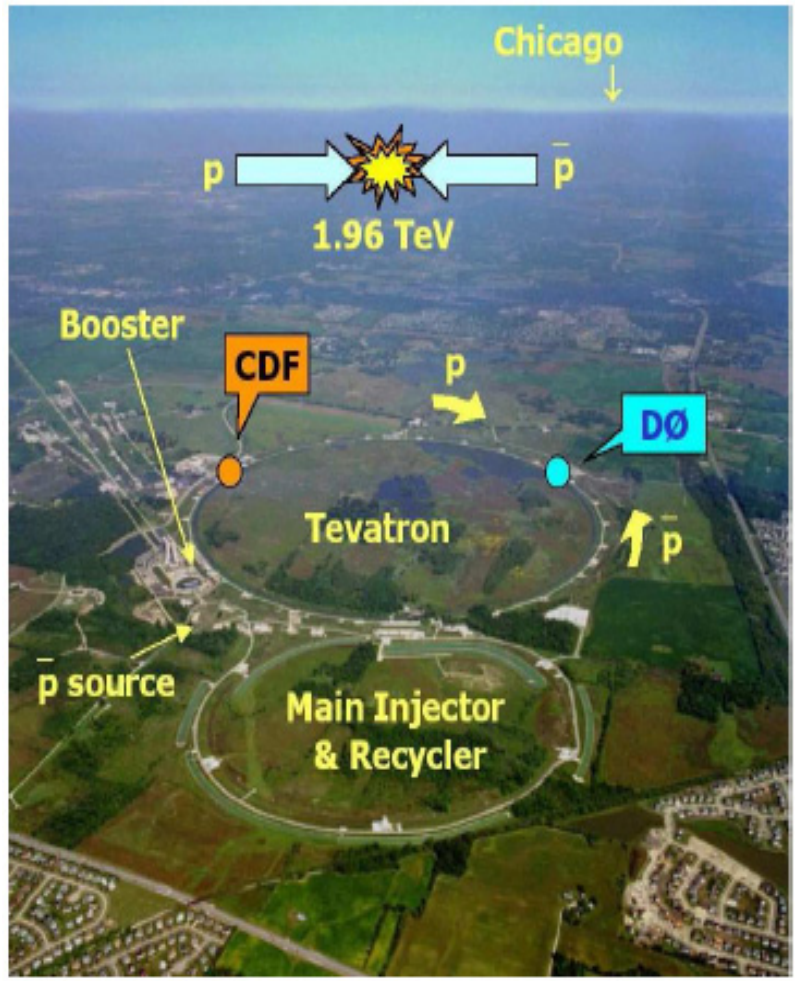
Rare decays of charm & bottom at Tevatron

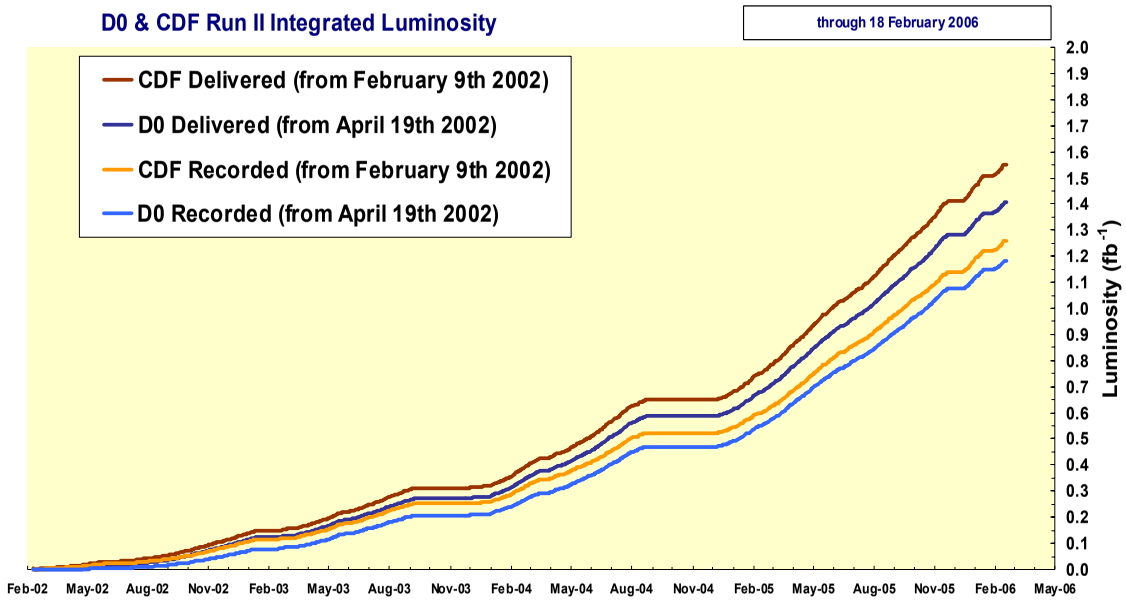
- Introduction
- Tevatron
- CDF & DØ Detector
- Rare charm decays
- Rare bottom beauty
- Summary & Conclusions



Frank Lehner
U Zurich
DIF '06, Frascati
28 Feb -03 March, 2006

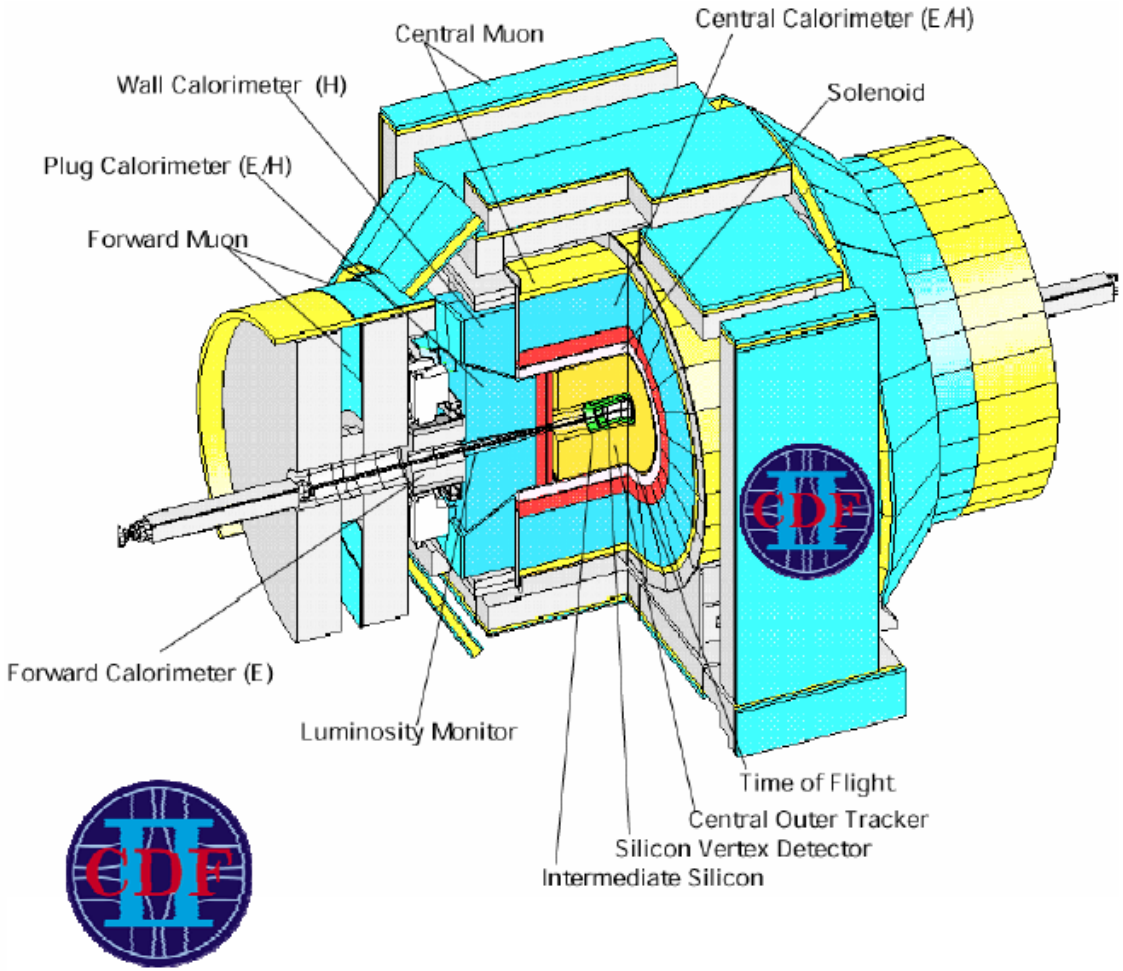
Tevatron performance

- excellent performance of Tevatron in 2005 and early 2006
- machine delivered more than 1500 pb^{-1} up to now !!
- recorded (DØ/CDF)
  - 1.2/1.4 fb^{-1}
  - record luminosity of 1.7×10^{32} cm^{-2}/s in January 2006
  - high data taking efficiency ~85%
- current dataset reconstructed and under analysis
  - ~1000 pb^{-1}
  - compare with ~100 pb^{-1} Run I



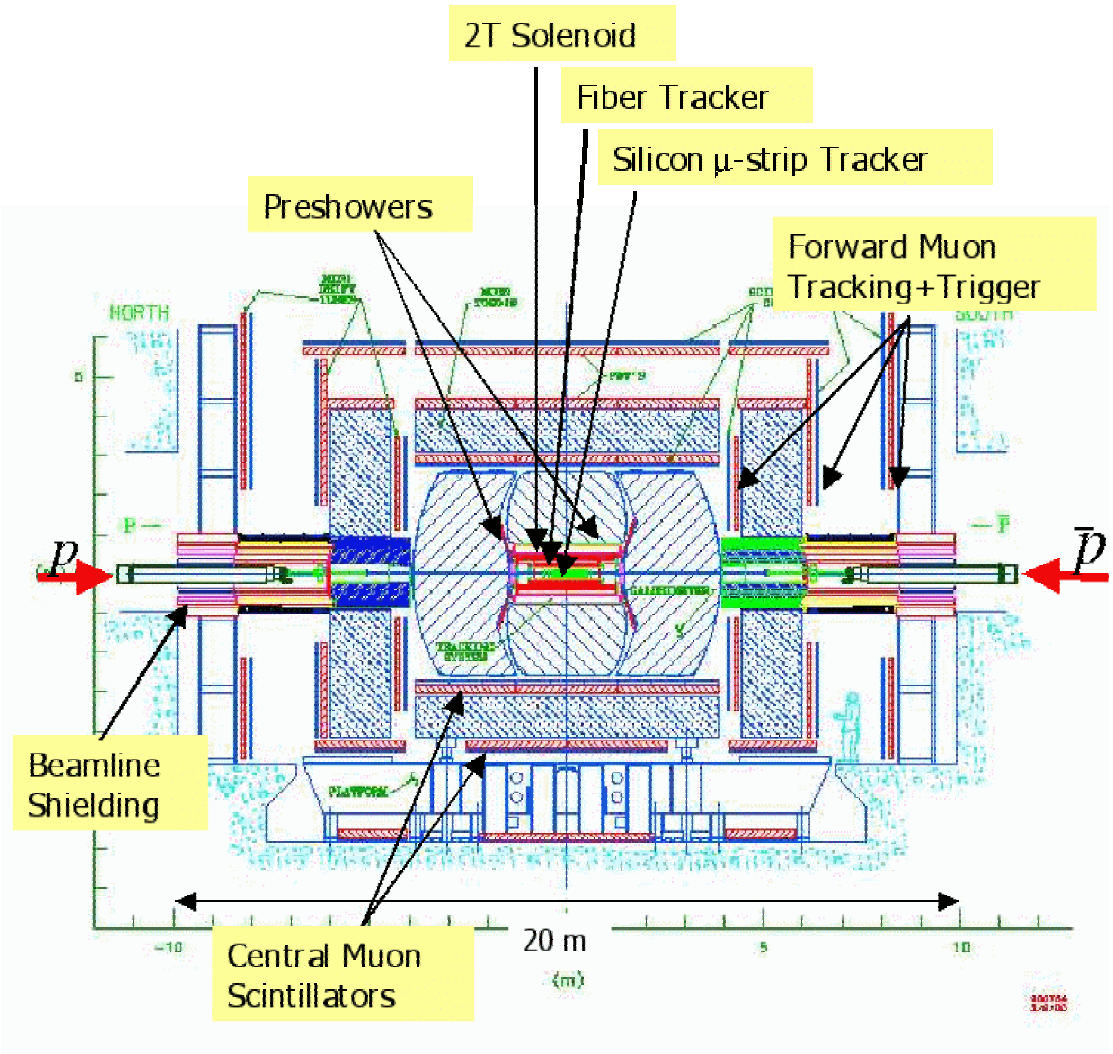
CDF detector

- Silicon Tracker SVX
  - up to $|\eta|<2.0$
  - SVX fast r-ϕ readout for trigger
- Drift Chamber
  - 96 layers in $|\eta|<1$
  - particle ID with dE/dx
  - r-ϕ readout for trigger
- tracking immersed in Solenoid 1.4T
- Time of Flight
  - $\rightarrow$particle ID



DØ detector

- 2T Solenoid
- hermetic forward & central muon detectors
  - excellent coverage $|\eta|<2$
- Fiber Tracker
  - 8 double layers
- Silicon Detector
  - up to $|\eta|<2.5$



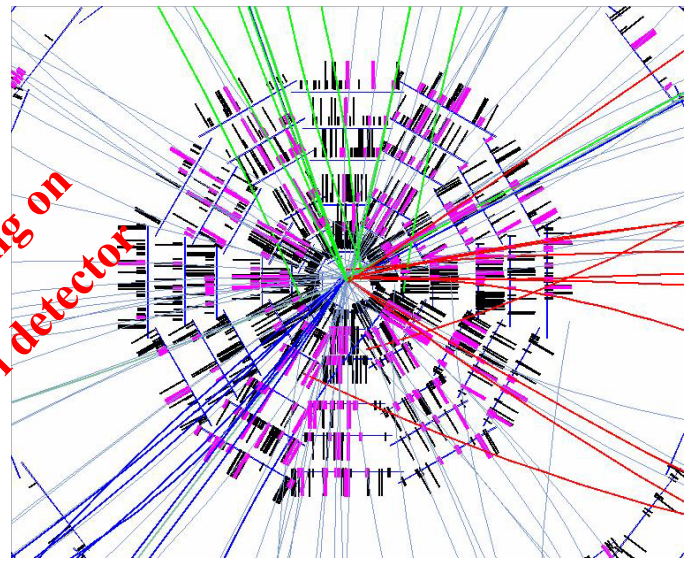
Charm and bottom production at Tevatron

- bb cross section orders of magnitude larger than at B-factories $\Upsilon(4S)$ or Z
- all kinds of b hadrons produced:
  - B_d, B_s, B_c, B^{**}, Λ_b, Ξ_b, …
- charm cross section even higher, about 80-90% promptly produced
- However:
  - QCD background overwhelming, b-hadrons hidden in 10^3 larger background
  - events complicated, efficient trigger and reliable tracking necessary
- crucial for bottom and charm physics program:
  - good vertexing & tracking
  - triggers w/ large bandwidth, strong background rejection
  - muon system w/ good coverage

e.g., integrated cross sections for $|y|<1$:

$\sigma(D^0, p_T \geq 5.5\ \text{GeV/c}) \sim 13\ \mu b$

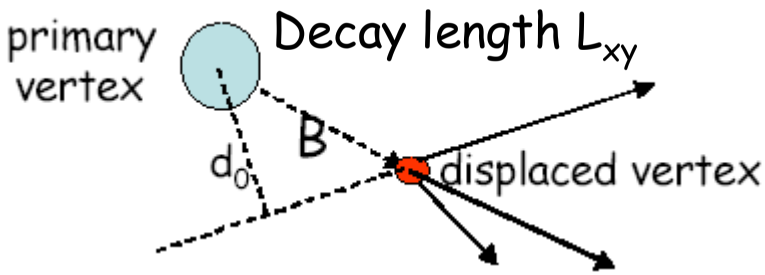
$\sigma(B^+, p_T \geq 6\ \text{GeV/c}) \sim 4\ \mu b$



Triggers for bottom & charm physics

- "classical" triggers:
  - robust and quiet di-muon and single-muon triggers
  - working horse for masses, lifetimes, rare decays etc.
  - keys to B physics program at DØ

- "advanced" triggers using silicon vertex detectors
  - exploit long lifetime of heavy quarks
  - displaced track + leptons for semileptonic modes
  - two-track trigger (CDF) – all hadronic mode
    - two oppositely charged tracks with impact parameter
    - 2-body charmless B decays etc.
    - charm physics



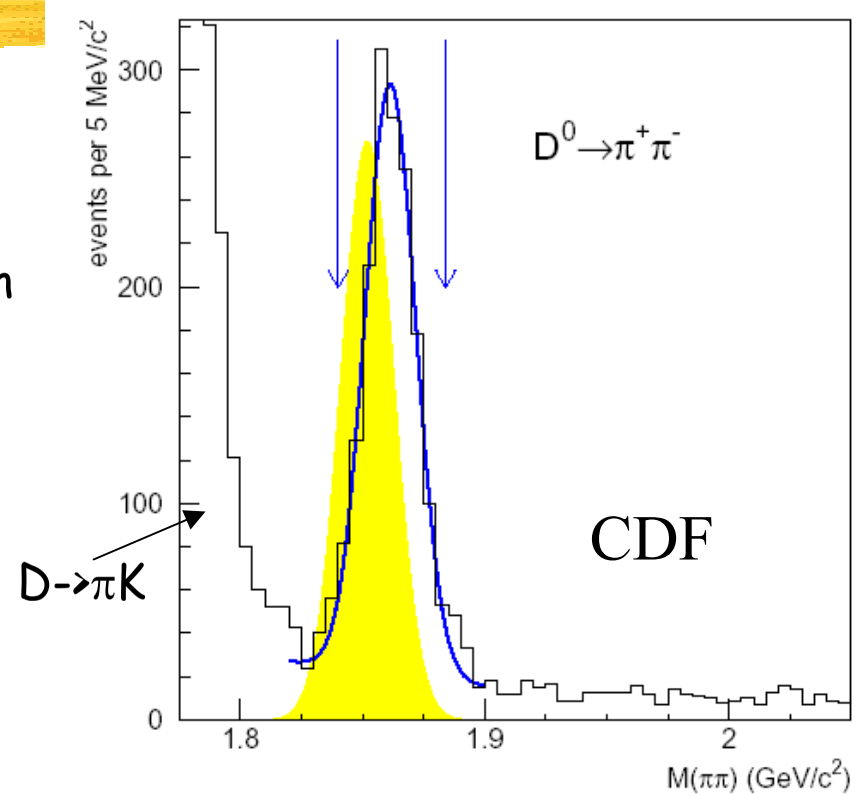
$p_T(B) \geq 5$ GeV
$L_{xy} \geq 450\ \mu m$

FCNC & new physics

- flavor-changing neutral current processes
  - in SM forbidden at tree level
  - at higher order occur through box- and penguin diagrams
  - sensitive to virtual particles in loop, thus can discern new physics
- GIM-suppression for down-type quarks relaxed due to large top mass
  - observable SM rates lead to tight constraints of new physics
- corresponding charm decays are less scrutinized and largely unexplored
  - smaller BRs, more suppressed by GIM-mechanism, long-distance effects also dominating
  - nevertheless large window to observe new physics beyond SM exists: R_p-violating models, little Higgs models w/ up-like vector quark etc.

Search for $D^0 \to \mu^+ \mu^-$

- FCNC decay with $c \to u\, l^+ l^-$ quark transition as short distance physics
- in SM BR~3×10^{-13}, but dominated by long-distance two-photon contribution
- R_p-violating SUSY may enhance BR of this mode considerably
- present exp. limit: 1.3×10^{-6} @90% C.L. (BaBar)
- CDF analysis:
  - PRD68 (2003) 091101
  - data (65 pb^{-1}) collected with two-track trigger to search for $D \to \mu^+ \mu^-$
  - normalization of search to topological similar $D \to \pi\pi$, trigger efficiency and acceptance cancel
  - mass resolution for two-body decays σ = 10 MeV/c^2

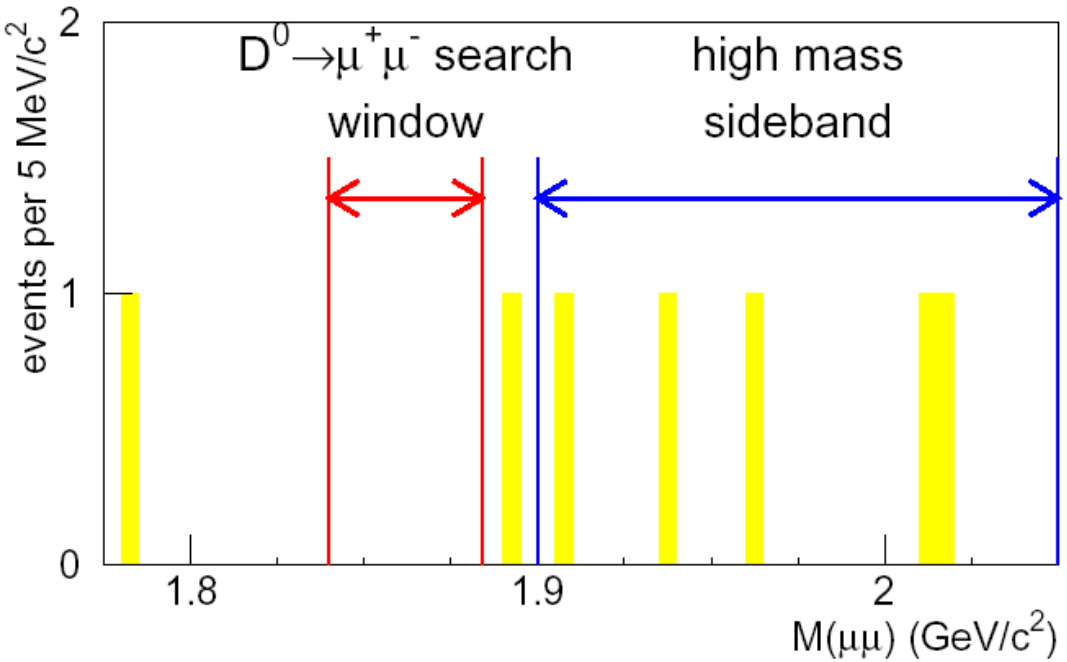


$D \to \pi\pi$ almost completely overlap with the $\mu^+ \mu^-$ search window, good understanding of $\pi \to \mu$ fake rate, determined from a sample of D* tagged $D \to \pi K$ decays. Misidentification: 1.3±0.1%

Search for $D^0 \to \mu^+ \mu^-$

- optimization of analysis on discriminating variables keeping the signal box hidden
- combinatorial background estimated from high mass sideband: 1.6±0.7
- fake background from #D-> ππ events reconstructed in signal window multiplied with misidentification probability π->μ: 0.22 ±0.02
- total expected background: 1.8±0.7 events
- zero events found -> limit
- updated analysis from CDF with much more data coming soon, will also look into ee and eμ channel

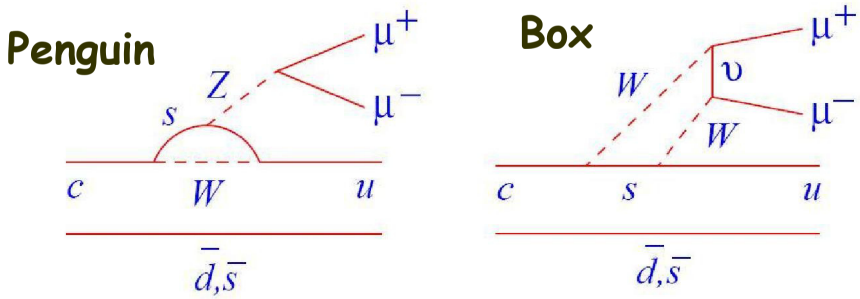
CDF



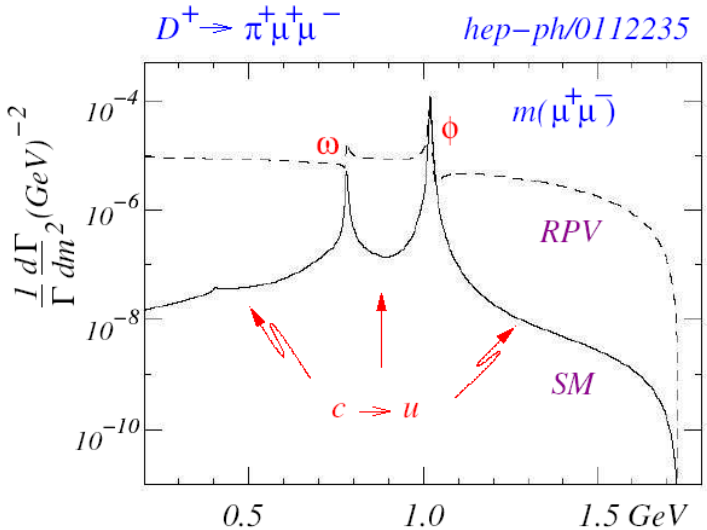
CDF:
BR($D^0 \to \mu^+ \mu^-$)<2.5×10^{-6} @90% C.L.

towards $D^{\pm} \to \pi^{\pm} \mu^{+}\mu^{-}$

- non-resonant $D^{\pm} \to \pi^{\pm} \mu^{+}\mu^{-}$ is a good place to search for new physics in up-type FCNC - enhanced in R_p-violating models or little Higgs models (see talk by S. Fajfer)
- Strategy at DØ: establish first resonant $D_s^{\pm} \to \phi\, \pi^{\pm} \to \mu^{+}\mu^{-}\, \pi^{\pm}$ and search then for D^{+} candidates in the continuum for non-resonant decay
- DØ analysis based on ~500 pb^{-1} of di-muon triggered data, select:
  - $\mu^{+}\mu^{-}$ consistent with $m(\phi)$
  - combine $\mu^{+}\mu^{-}$ with track p_t>0.18 GeV/c in same jet for $D_{(s)}$ candidates with $1.3 < m(\mu^{+}\mu^{-}\, \pi^{\pm}) < 2.5$ GeV/c^2
  - in average 3.3 candidates => apply vertex-χ^2 criterion to select correct one in 90% of cases (MC)

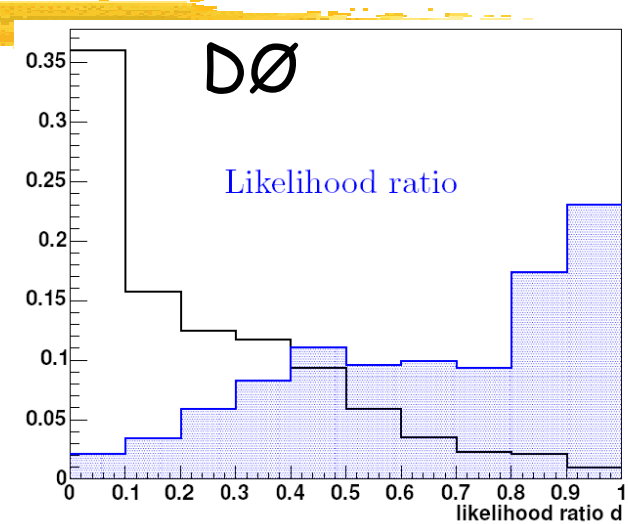


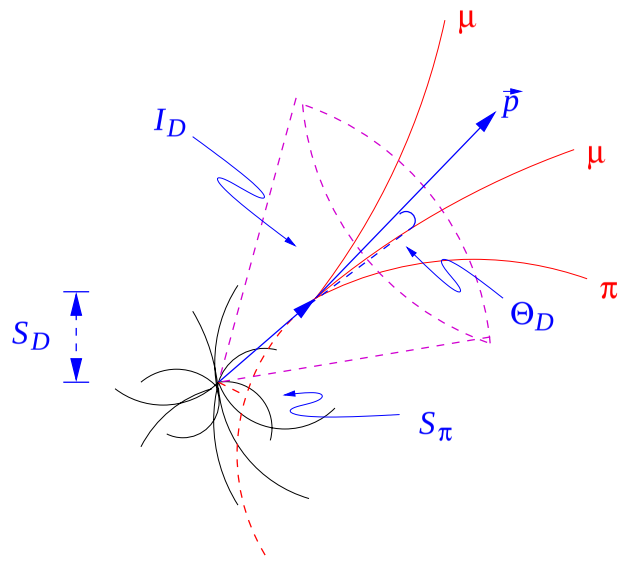
SM: BR ~10^{-8}



Optimization

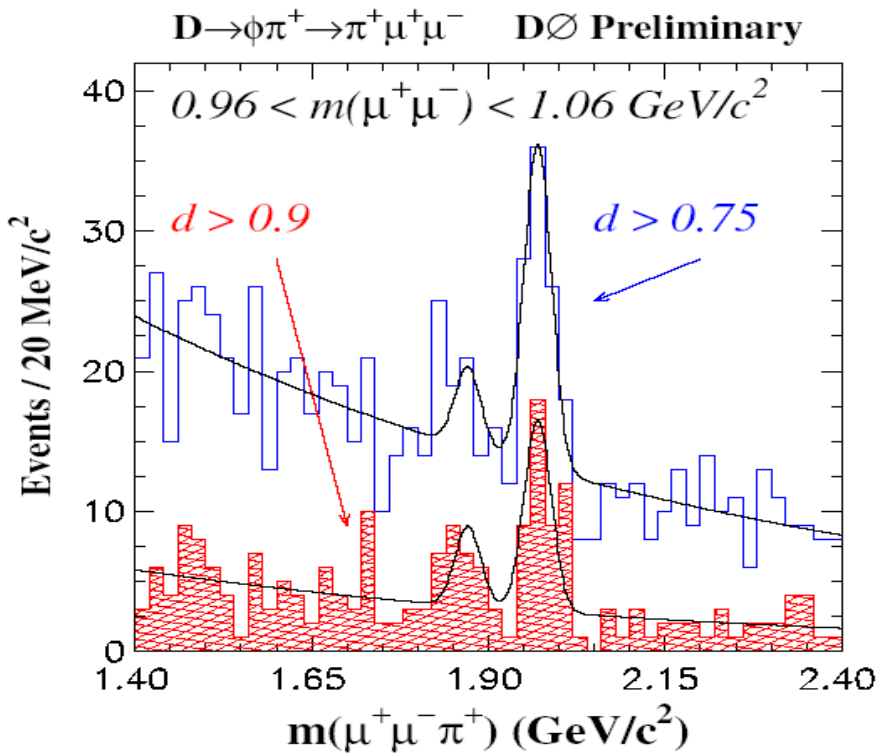
- to further minimize background:
- construct likelihood ratio for signal (MC) and background (sideband) events based on
  - isolation of D candidate I_D
  - transverse decay length significance S_D
  - collinearity angle between D momentum and vector between prim. & sec. Vertex θ_D
  - significance ratio R_D = impact parameter of $\pi^{\pm}$ / S_D
  - correlations taken into account
- Likelihood cut chosen to maximize $\varepsilon_S/\sqrt{\varepsilon_B}$ with background modeled from sidebands





$D_{(s)}^{\pm} \to \phi\, \pi^{\pm} \to \mu^{+}\mu^{-}\, \pi^{\pm}$

- after cuts a signal of 51 D_s resonant decay candidates with expected background of 18 are observed
  - excess with (>7σ) significance
- first observation of resonant decay $D_s^{\pm} \to \phi\, \pi^{\pm} \to \mu^{+}\mu^{-}\, \pi^{\pm}$ as benchmark
- the number of (resonant) $D^{+} \to \phi\, \pi^{\pm} \to \mu^{+}\mu^{-}\, \pi^{\pm}$ is determined in fit with parameters fixed in looser selection
- fit yields 13±5 $D^{\pm}$ events (significance: 2.7σ), set either limit or calculate BR
- accomplished first major step in FCNC three-body charm decay program
- analysis will be updated with more statistics soon (~1fb^{-1})
- as future goal: search for excess in non-resonant continuum region

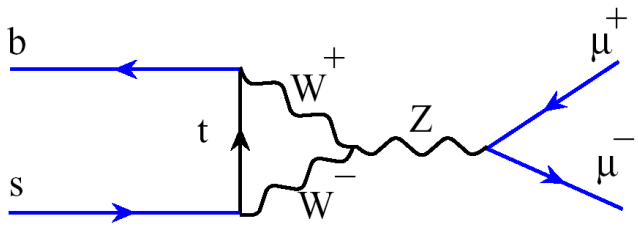


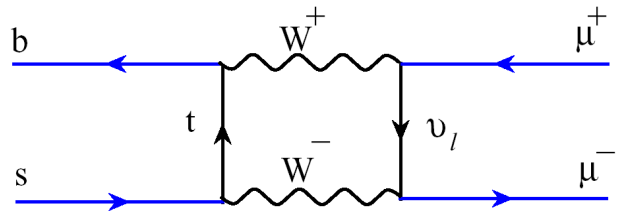
$Br(D^{\pm} \to \phi\pi^{\pm} \to \mu^{+}\mu^{-}\pi^{\pm}) = (1.70^{+0.08+0.06}_{-0.73\ -0.82})\times 10^{-6}$

$Br(D^{\pm} \to \phi\pi^{\pm} \to \mu^{+}\mu^{-}\pi^{\pm}) < 3.14\times 10^{-6}$ (90% C.L)

Purely leptonic B decay

- **$B \to l^+ l^-$** decay is helicity suppressed FCNC
- SM: $BR(B_s \to \mu^+\mu^-) \sim 3.4\times10^{-9}$
- depends only on one SM operator in effective Hamiltonian, hadronic uncertainties small
- B_d relative to B_s suppressed by $|V_{td}/V_{ts}|^2 \sim 0.04$ if no additional sources of flavor violation
- reaching SM sensitivity: present limit for $B_s \to \mu^+\mu^-$ comes closest to SM value





SM expectations:

	$Br(B_d \to l^+l^-)$	$Br(B_s \to l^+l^-)$
$l = e$	3.4×10^{-15}	8.0×10^{-14}
$l=\mu$	1.0×10^{-10}	3.4×10^{-9}
$l=\tau$	3.1×10^{-8}	7.4×10^{-7}

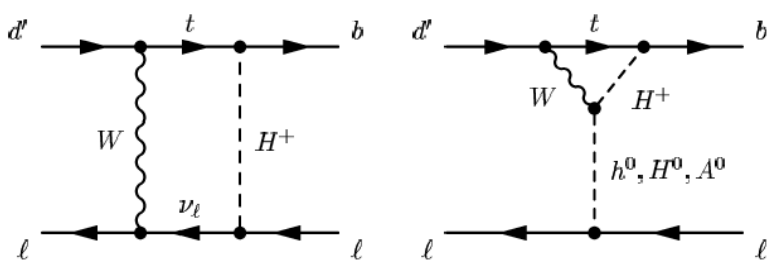
Current published limits:

C.L. 90%	$Br(B_d \to l^+l^-)$	$Br(B_s \to l^+l^-)$
$l = e$	$< 6.1 \cdot 10^{-8}$	$< 5.4 \cdot 10^{-5}$
$l=\mu$	$< 8.3 \cdot 10^{-8}$	$< 1.5 \times 10^{-7}$
$l=\tau$	< 2.5%	< 5.0%

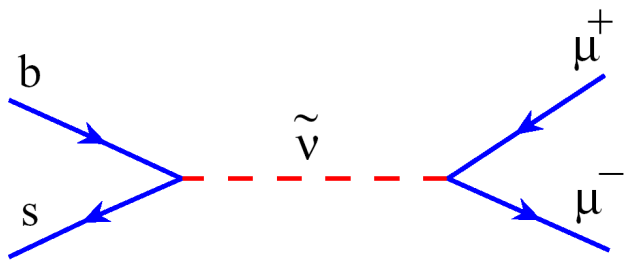
Purely leptonic B decay

- excellent probe for many new physics models
- particularly sensitive to models w/ extended Higgs sector
  - BR grows ~$\tan^6\beta$ in MSSM
  - 2HDM models ~ $\tan^4\beta$
  - mSUGRA: BR enhancement correlated with shift of $(g-2)_\mu$
- also, testing ground for
  - minimal SO(10) GUT models
  - R_p violating models, contributions at tree level
  - (neutralino) dark matter …

Two-Higgs Doublet models:

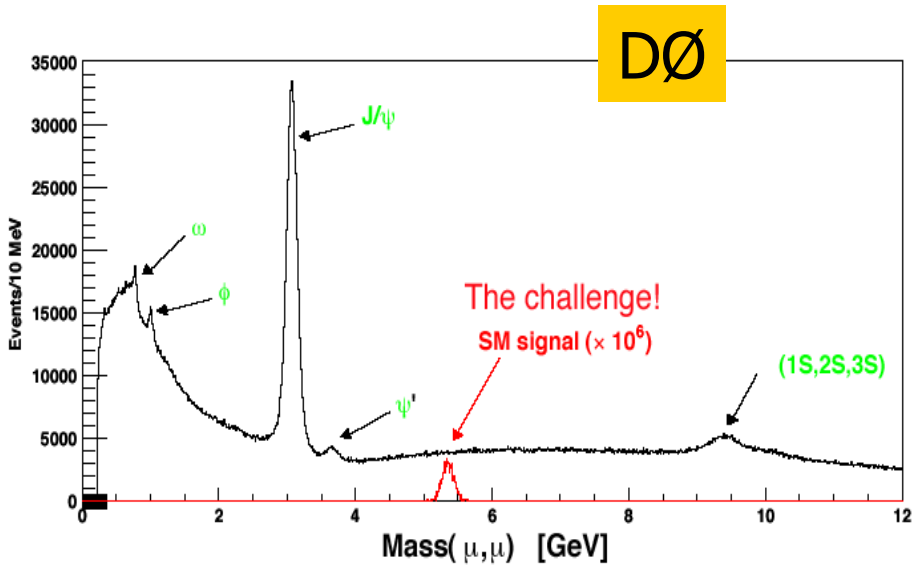


R_p violating:



Experimental search

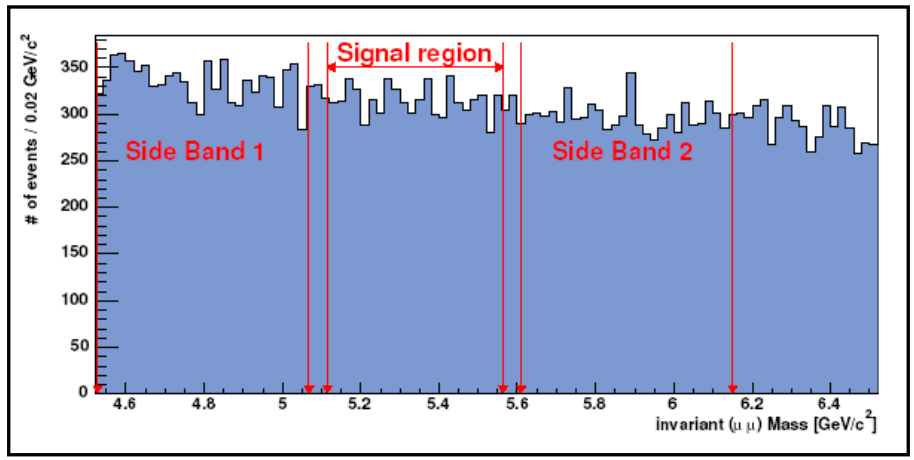
- **CDF:**
  - 364 pb^{-1} di-muon triggered data
  - two separate search channels
    - central/central muons
    - central/forward muons
  - extract B_s and B_d limit
- **DØ:**
  - 240 pb^{-1} (update 300 pb^{-1}) di-muon triggered data
- **both experiments:**
  - blind analysis to avoid experimenter's bias
  - side bands for background determination
  - use $B^+ \to J/\psi\ K^+$ as normalization mode
    - $J/\psi \to \mu^+\mu^-$ cancels $\mu^+\mu^-$ selection efficiencies



blinded signal region:
DØ: $5.160 < m_{\mu\mu} < 5.520$ GeV/c^2;
$\pm 2\sigma$ wide, σ=90 MeV
CDF: $5.169 < m_{\mu\mu} < 5.469$ GeV/c^2;
covering B_d and B_s; σ=25 MeV

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 vertex
- **Pre-Selection CDF:**
  - $4.669 < m_{\mu\mu} < 5.969$ 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

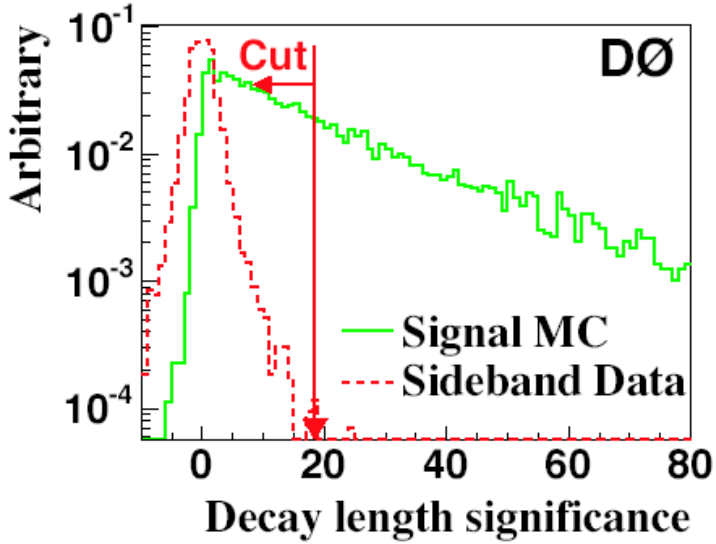


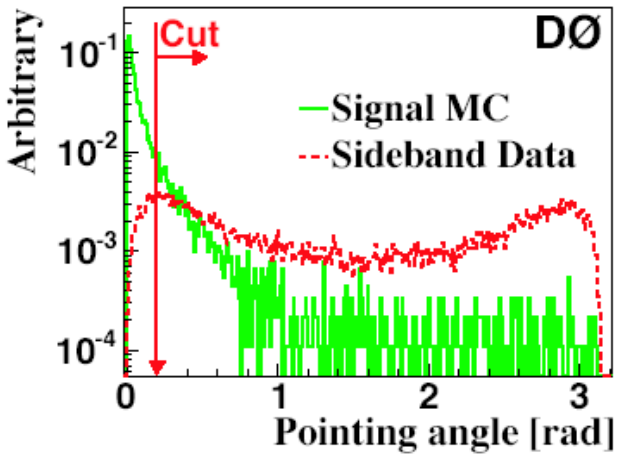
e.g. DØ: about 38k events after pre-selection

Potential sources of background:
- continuum $\mu\mu$ Drell-Yan
- sequential semi-leptonic b->c->s decays
- double semi-leptonic bb-> $\mu\mu$X
- b/c->μx+fake
- fake + fake

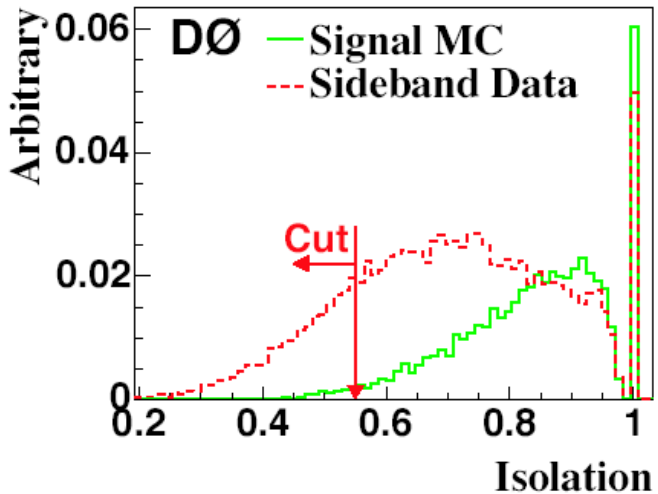
Optimization I

- DØ:
- optimize cuts on three discriminating variables
  - angle between $\mu^+\mu^-$ and decay length vector (pointing consistency)
  - transverse decay length significance (B_s has lifetime): $L_{xy}/\sigma(L_{xy})$
  - isolation in cone around B_s candidate



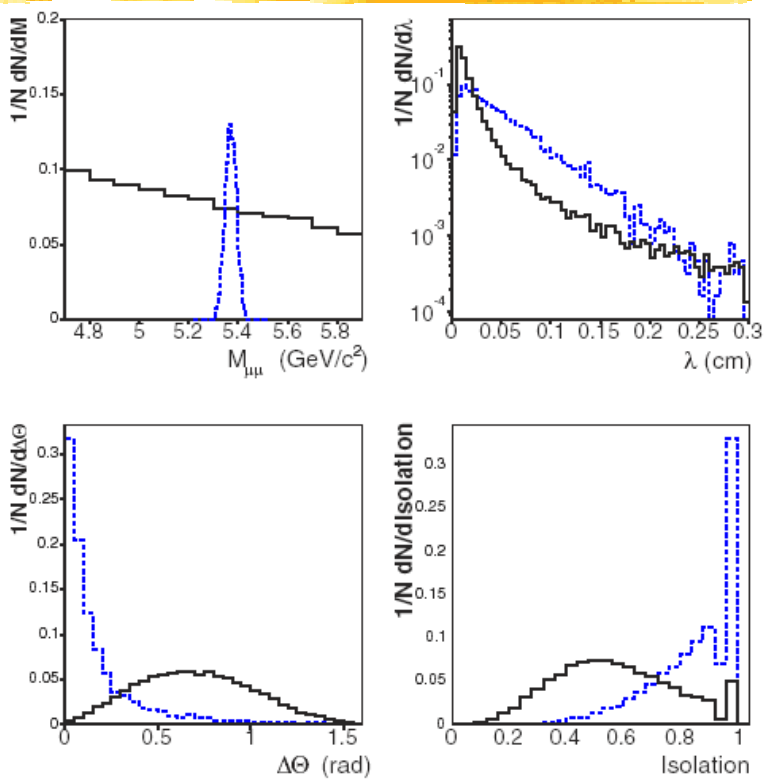


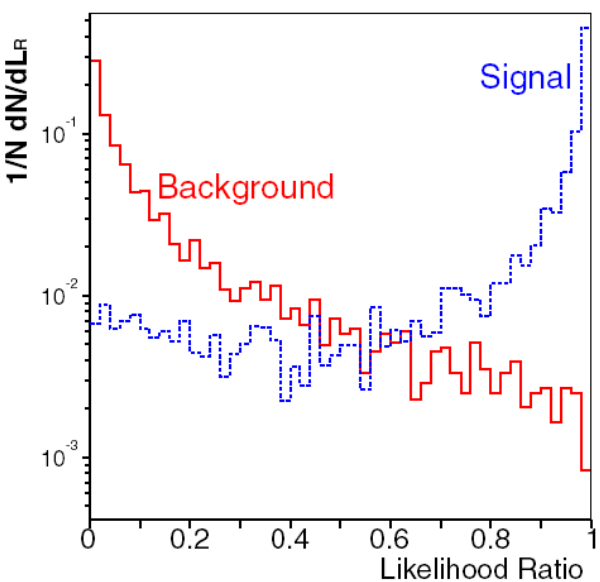
- use signal MC and 1/3 of (sideband) data for optimizc
- random grid search
- maximize $\varepsilon/(1.+\sqrt{B})$
- total efficiency w.r.t 38k p selection criteria: 38.6%



Optimization II

- CDF: discriminating variables
  - pointing angle between $\mu^+\mu^-$ and decay length vector
  - isolation in cone around B_s candidate
  - proper decay length probability $p(\lambda) = \exp(-\lambda/\lambda_{Bs})$

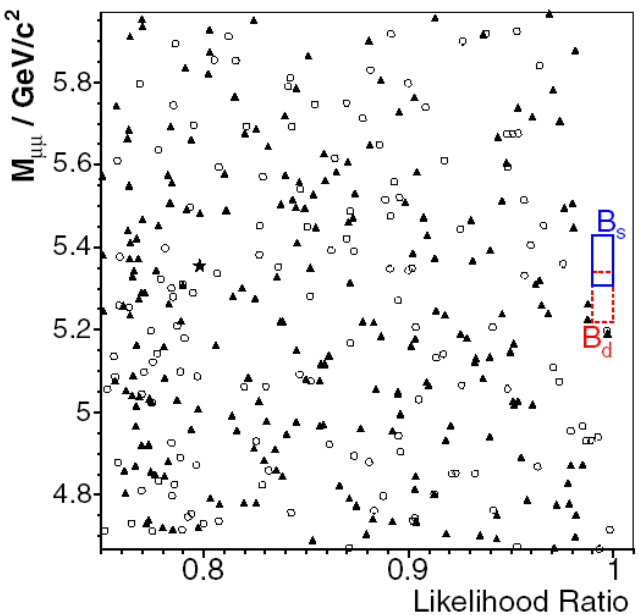




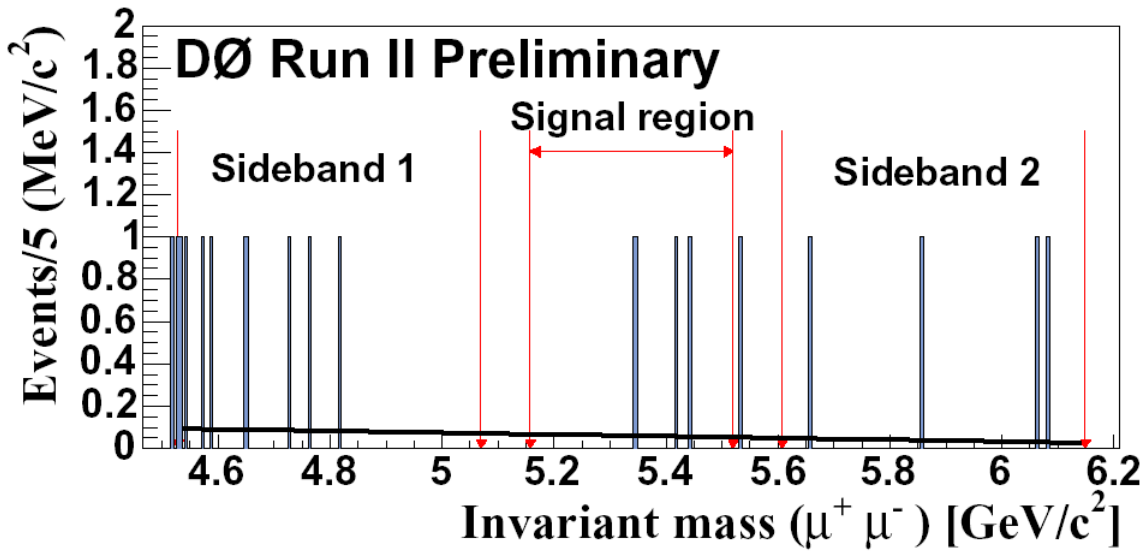
- construct likelihood ratio to optimize on "expected upper limit"

Unblinding the signal region

CDF

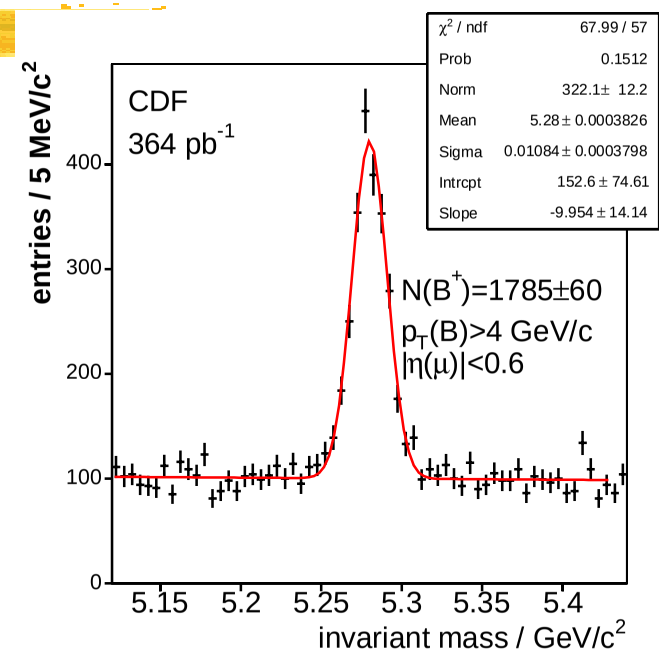


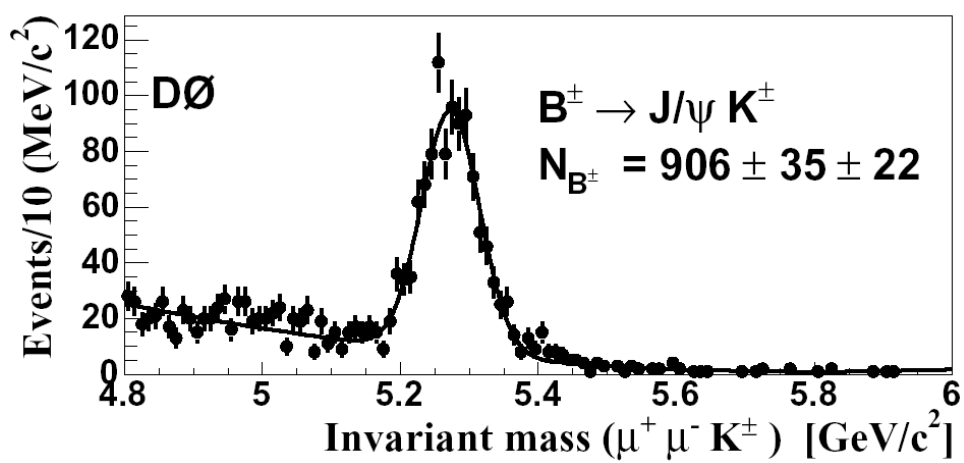
- CDF:
  - central/central: observe 0, expect 0.81 ± 0.12
  - Central/forward: observe 0, expect 0.66 ± 0.13
- DØ:
  - observe 4, expect 4.3 ± 1.2



Normalization

- relative normalization is done to $B^+ \to J/\psi\ K^+$
- advantages:
  - $\mu^+\mu^-$ selection efficiency same
  - high statistics
  - BR well known
- disadvantages:
  - fragmentation $b \to B_u$ vs. $b \to B_s$
- DØ: apply same values of discriminating cuts on this mode
- CDF: no likelihood cut on this mode





Master equation

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq \frac{N_{\rm ul}}{N_{B^\pm}} \cdot \frac{\epsilon_{\mu\mu K}^{B^\pm}}{\epsilon_{\mu\mu}^{B_s^0}} \cdot \frac{\mathcal{B}(B^\pm \to J/\psi(\mu^+\mu^-)K^\pm)}{\frac{f_{b\to B_s}}{f_{b\to B_{u,d}}} + R \cdot \frac{\epsilon_{\mu\mu}^{B_d^0}}{\epsilon_{\mu\mu}^{B_s^0}}}, \quad (2)$$

- R = BR(B_d)/BR(B_s) is small due to $|V_{td}/V_{ts}|$^2
- $\varepsilon_{B^+}/\varepsilon_{Bs}$ relative efficiency of normalization to signal channel
- $\varepsilon_{Bd}/\varepsilon_{Bs}$ relative efficiency for $B_d \to \mu^+\mu^-$ versus $B_s \to \mu^+\mu^-$ events in B_s search channel (for CDF~0, for DØ ~0.95)
- f_s/f_u fragmentation ratio (in case of B_s limit) - use world average with 15% uncertainty

The present (individual) limits

- DØ mass resolution is not sufficient to separate B_s from B_d. Assume no B_d contribution (conservative)
- CDF sets separate limits on B_s & B_d channels
- all limits below are 95% C.L. Bayesian incl. sys. error, DØ also quotes FC limit

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.
CDF $B_s \to \mu\mu$	364 pb^{-1}	2.0×10^{-7}	Published
CDF $B_d \to \mu\mu$	364 pb^{-1}	4.9×10^{-8}	Published

B_d limit x2 better than published Babar limit w/ 111 fb^{-1}

updates on limits/sensitivities expected soon

Tevatron limit combination I

- fragmentation ratio $b \to B_s / b \to B_{u,d}$
  - standard PDG value as default
  - Tevatron only fragmentation (from CDF) improves limit by 15%
- uncorrelated uncertainties:
  - uncertainty on eff. ratio
  - uncertainty on background
- correlated uncertainties:
  - BR of $B^{\pm} \to J/\psi(\to\mu\mu) K^{\pm}$
  - fragmentation ratio $b \to B_s / b \to B_{u,d}$
- quote also an average expected upper limit and single event sensitivity

hep-ex/0508058

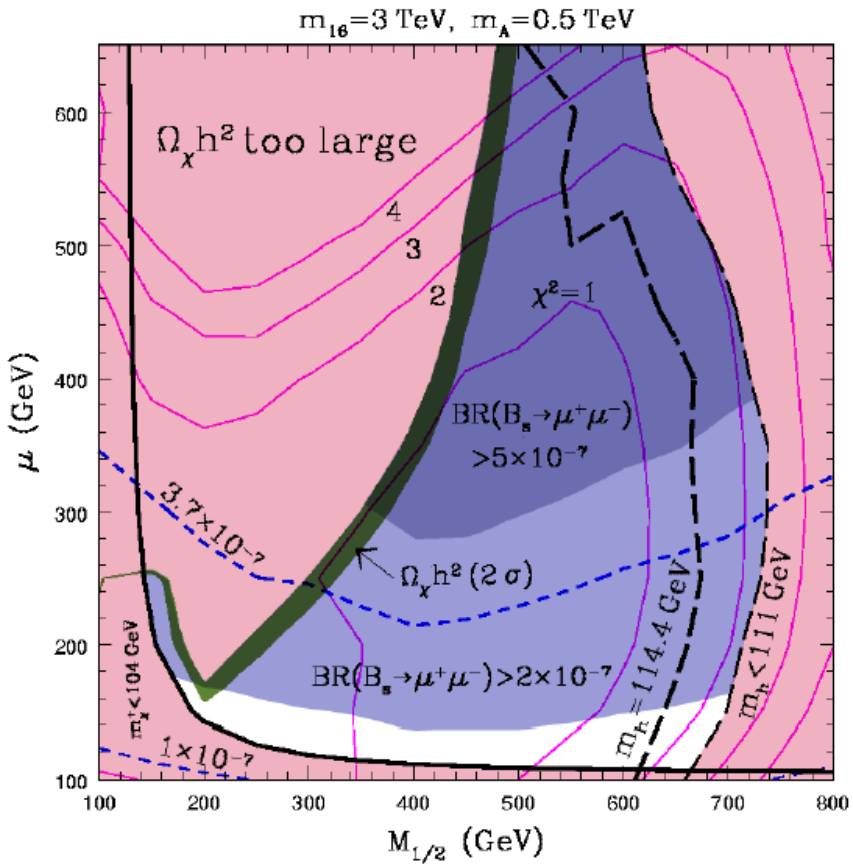
	CDF U-U	CDF U-X	DØ
Luminosity	$364\ \mathrm{pb}^{-1}$	$336\ \mathrm{pb}^{-1}$	$300\ \mathrm{pb}^{-1}$
$(A_{B^+}/A_{B_s^0})$	0.852 ± 0.084	0.485 ± 0.048	0.247 ± 0.019
N_{B^+}	1785 ± 60	696 ± 39	906 ± 41
N_b	0.81 ± 0.12	0.66 ± 0.13	4.3 ± 1.2
N_o	0	0	4
$ses\ (\times 10^7)$	1.04 ± 0.16	1.52 ± 0.25	0.59 ± 0.09
	(0.62 combined)		
expect. limit 90% C.L.	3.5×10^{-7}	5.6×10^{-7}	3.5×10^{-7}
	(2.0×10^{-7} combined)		
obsvd. limit 90% C.L.	(1.5×10^{-7} combined)		3.2×10^{-7}

DØ has larger acceptance due to better η coverage,
CDF has greater sensitivity due to lower background expectations

Combination II

- combined CDF & DØ limit:
- $BR(B_s \to \mu^+ \mu^-) < 1.2\ (1.5) \times 10^{-7}$ @ 90% (95%) C.L.
- world-best limit, only factor 35 away from SM
- important to constrain models of new physics at tanβ
- e.g. mSO(10) model is severely constraint

Example: SO(10) symmetry breaking model

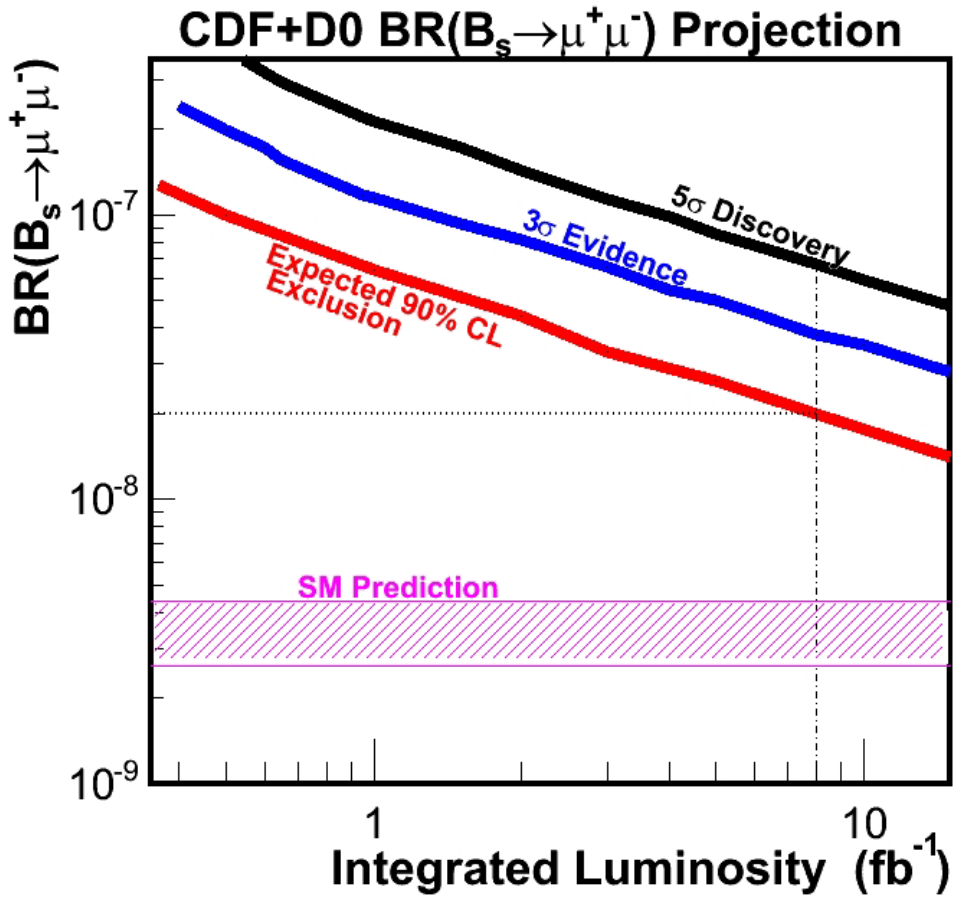


R. Dermisek et al.
hep-ph/0507233

Contours of constant $Br(B_s \to \mu^+\mu^-)$

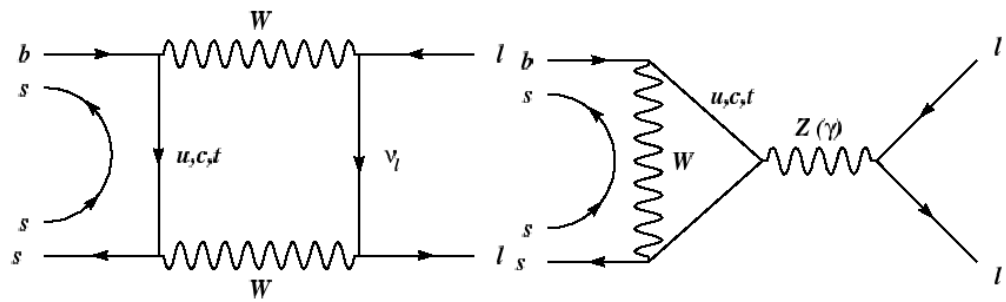
Future Prospects for $B_s \to \mu^+\mu^-$

- assuming unchanged analysis techniques and reconstruction and trigger efficiencies are unaffected with increasing luminosity
- for $8 fb^{-1}$/experiment an exclusion at 90%C.L. down to 2×10^{-8} is possible
- both experiments pursue further improvements in their analysis



Search for $B_s \to \mu^+\mu^-\phi$

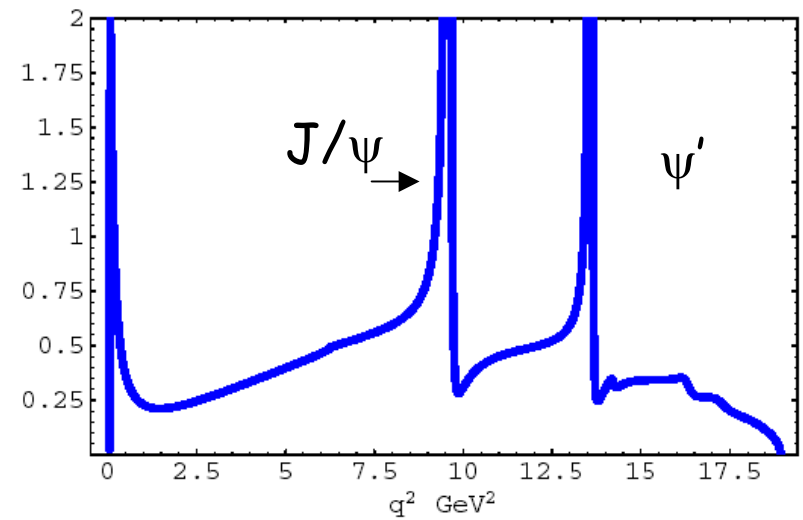
- long-term goal: investigate $b \to s\, l^+ l^-$ FCNC transitions in B_s meson
- exclusive decay: $B_s \to \mu^+\mu^-\phi$
- SM prediction:
  - short distance BR: $\sim 1.6\times10^{-6}$
  - about 30% uncertainty due to $B\to\phi$ form factor
- 2HDM: enhancement possible, depending on parameters for $\tan\beta$ and M_{H+}
- presently only one published limit
  - CDF Run I: 6.7×10^{-5} @ 95% C.L.

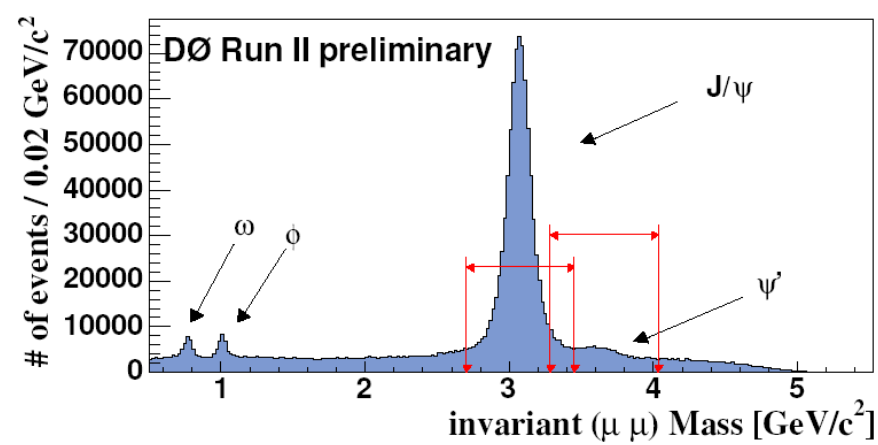


Search for $B_s \to \mu^+\mu^-\phi$

- DØ: 300 pb^{-1} of dimuon data
- normalize to resonant decay $B_s \to J/\psi\ \phi$
- cut on mass region $0.5 < M(\mu\mu) < 4.4$ GeV/c^2 excluding J/ψ & ψ'
- two good muons, $p_t > 2.5$ GeV/c
- two additional oppositely charged tracks $p_t > 0.5$ GeV/c for ϕ
- ϕ candidate in mass range $1.008 < M(\phi) < 1.032$ GeV/c^2
- good vertex
- $p_t(B_s$ cand.$) > 5$ GeV/c
- non-resonant decay: cut out J/ψ and ψ'

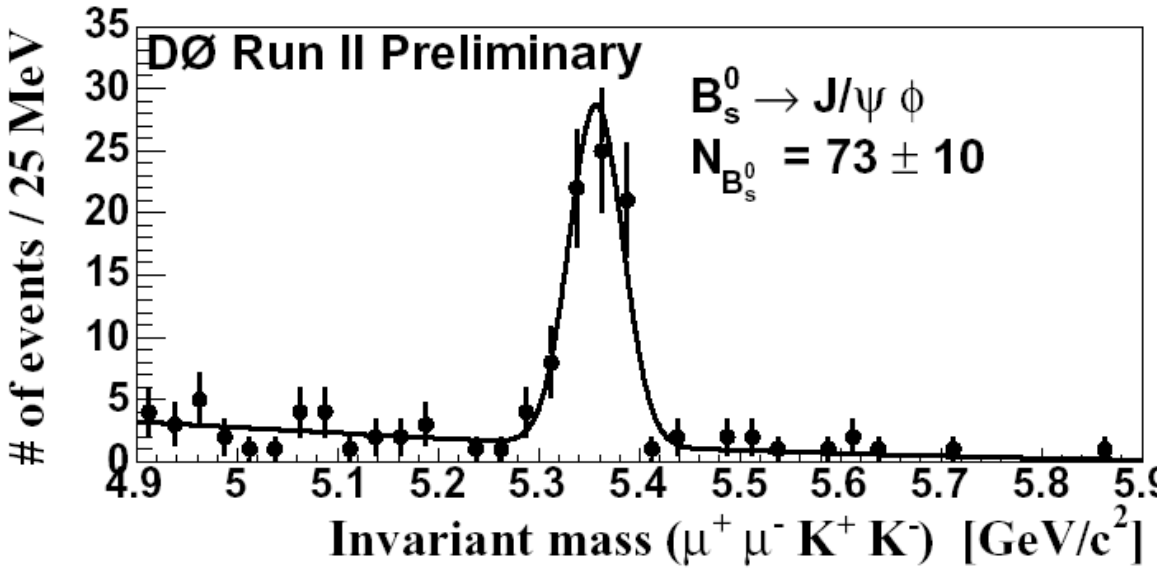
Dilepton mass spectrum in b -> s l l decay





Search for $B_s \to \mu^+\mu^-\phi$

- blind analysis: optimization with following variables in random grid search
  - pointing angle
  - decay length significance
  - Isolation
- background modeled from sidebands
- use resonant decay $B_s \to J/\psi\ \phi$ with same cuts as normalization
- gaussian fit with quadratic background: 73 ± 10 $B_s \to J/\psi\ \phi$ resonant decays



Limit on $B_s \to \mu^+\mu^-\phi$

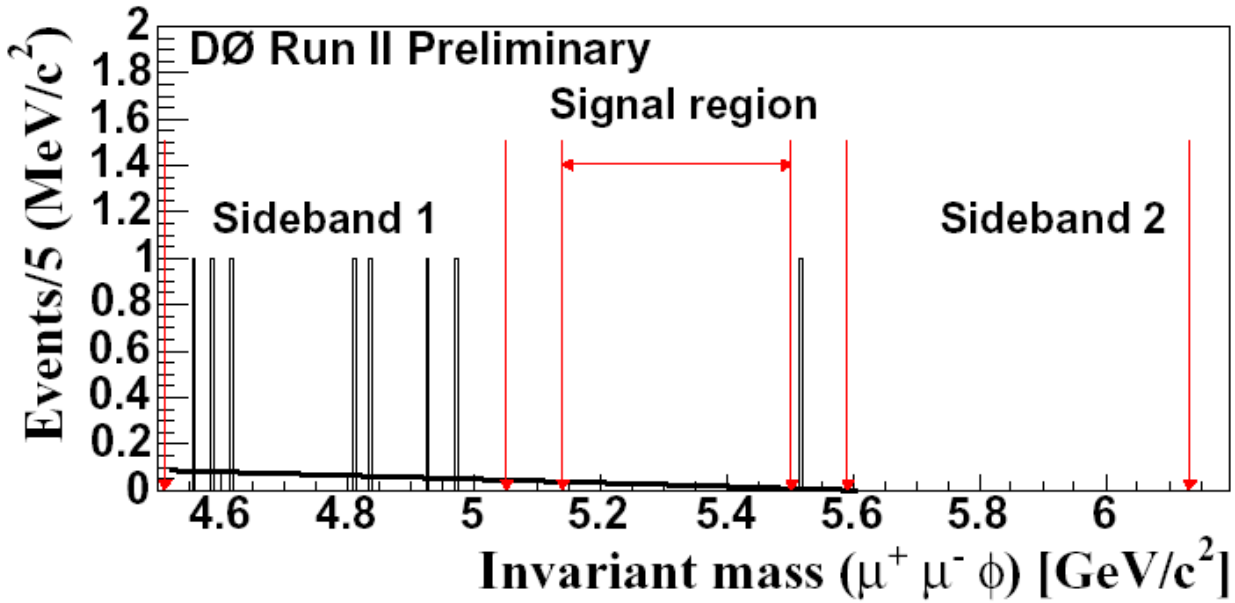
- expected background from sidebands: 1.6 ± 0.4 events
- observe zero events in signal region

$BR(B_s \to \phi\, \mu^+\mu^-)/BR(B_s \to J/\psi\, \phi) < 4.4 \times 10^{-3}$ @ 95% C.L.

Using central value for $BR(B_s \to J/\psi\, \phi) = 9.3\times10^{-4}$ PDG2004:

$BR(B_s \to \phi\, \mu^+\mu^-) < 4.1\times10^{-6}$ @ 95% C.L.

x10 improvement w.r.t previous limit



Conclusions

- Tevatron is also a charm & bottom production factory for probing new physics in rare charm and bottom decays
- CDF limit on D-> $\mu^+ \mu^-$ decay already competitive with only 65 pb^{-1}, improved limit will come soon…
- first DØ observation of benchmark channel $D_s^\pm$ -> $\phi \pi^\pm$ -> $\mu^+\mu^- \pi^\pm$ as first step towards a charm rare FCNC decay program
- CDF & DØ provide world best limits on purely leptonic decays $B_{d,s}$ -> $\mu^+\mu^-$, limit important to constrain new physics
- with more statistics to come enhance exclusion power/discovery potential for new physics
- improved DØ limit on exclusive B_s -> $\mu^+\mu^-\phi$ decay shown, about 2x above SM
- Tevatron is doubling statistics every year - stay tuned for many more exciting results on charm & bottom

SPARE

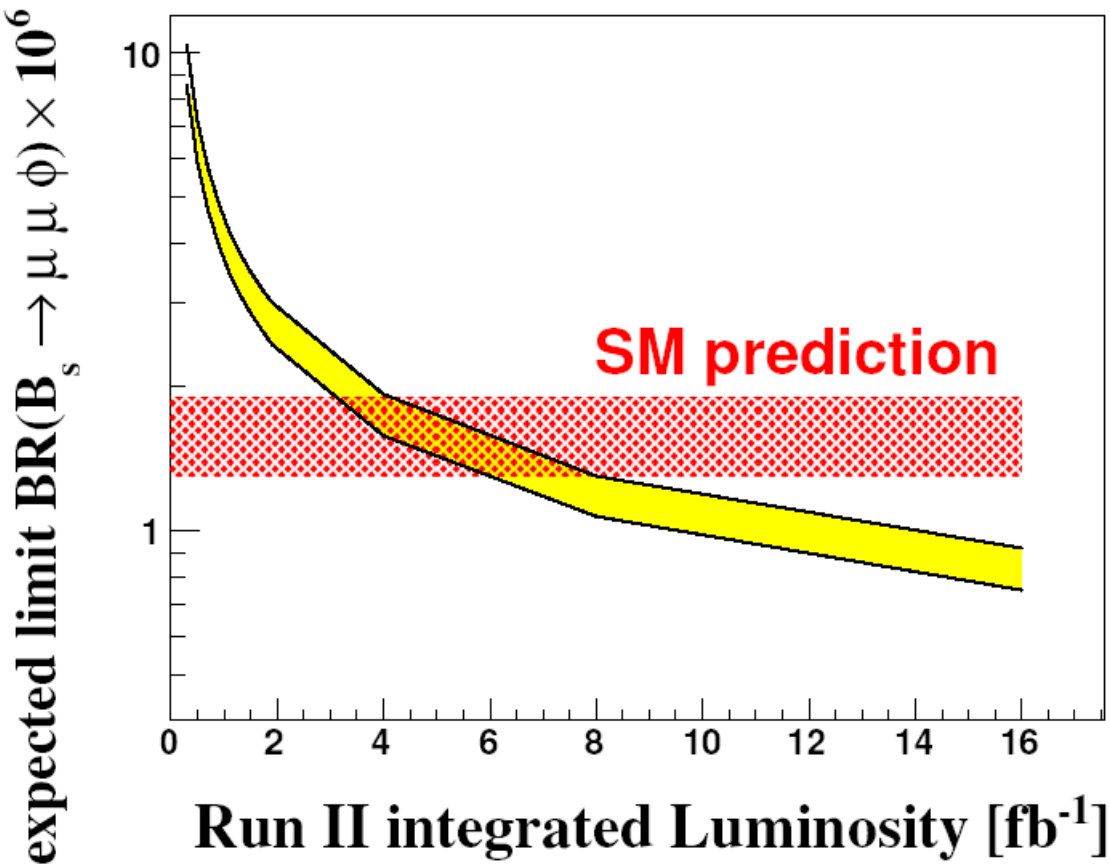
Systematic uncertainties

- systematics for DØ (CDF very similar)
- efficiency ratio determined from MC with checks in data on trigger/tracking etc.
- large uncertainty due to fragmentation ratio
- background uncertainty from interpolating fit

Source	Relative Uncertainty [%]
$\epsilon^{B^\pm}_{\mu\mu K}/\epsilon^{B^0_s}_{\mu\mu}$	7.7
Number of $B^\pm \to J/\psi K^\pm$ events	5.1
$\mathcal{B}(B^\pm \to J/\psi K^\pm)$	4.0
$\mathcal{B}(J/\psi \to \mu^+\mu^-)$	1.7
$f_{b\to B^0_s}/f_{b\to B^0_{u,d}}$	12.7
Background uncertainty	29.7

expected limit $B_s \to \mu^+\mu^-\phi$

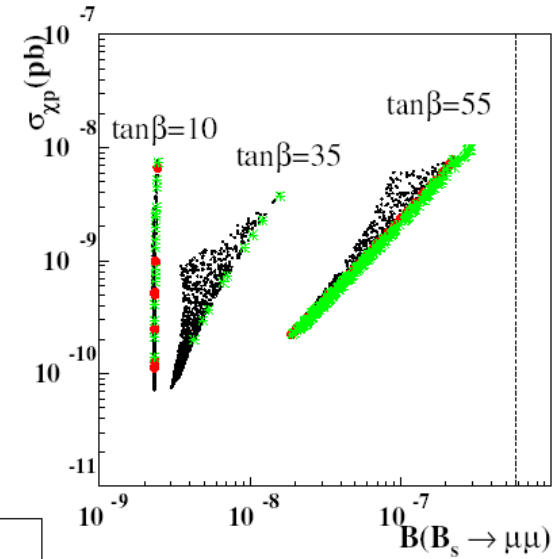
- expected limit at 95% C.L. for $B_s \to \mu^+\mu^-\phi$

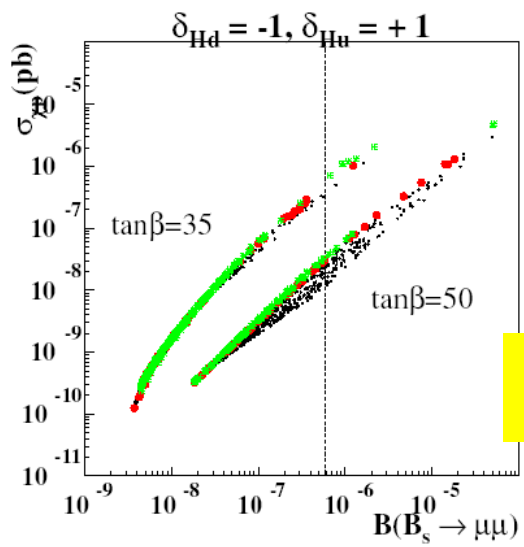


Constraining dark matter

- mSUGRA model: strong correlation between BR($B_s \to \mu^+\mu^-$) with neutralino dark matter cross section especially for large tanβ
- constrain neutralino cross section with less than, within and greater than 2σ of WMAP relic density

universal Higgs mass parameters





non-universal Higgs mass Parameters, δH_u=1, δH_d=-1

S. Baek et al., JHEP 0502 (2005) 067