Rare B decays at Tevatron and the B_c

- Introduction
- CDF & DØ Detector
- Results on rare B decays
- Results on B_c
- Summary

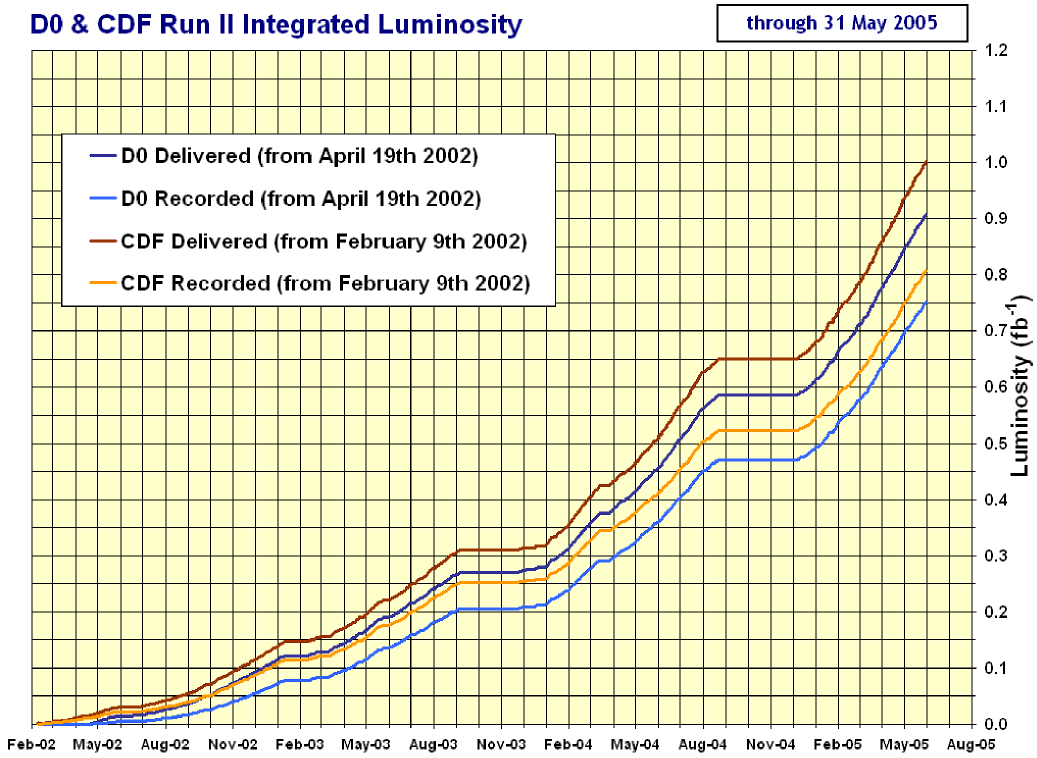
Pythia (not v6.1) sitting on the Delphic tripod cauldron and a priest.

Frank Lehner
U Zurich

WIN ’05, Delphi
06-11 June, 2005

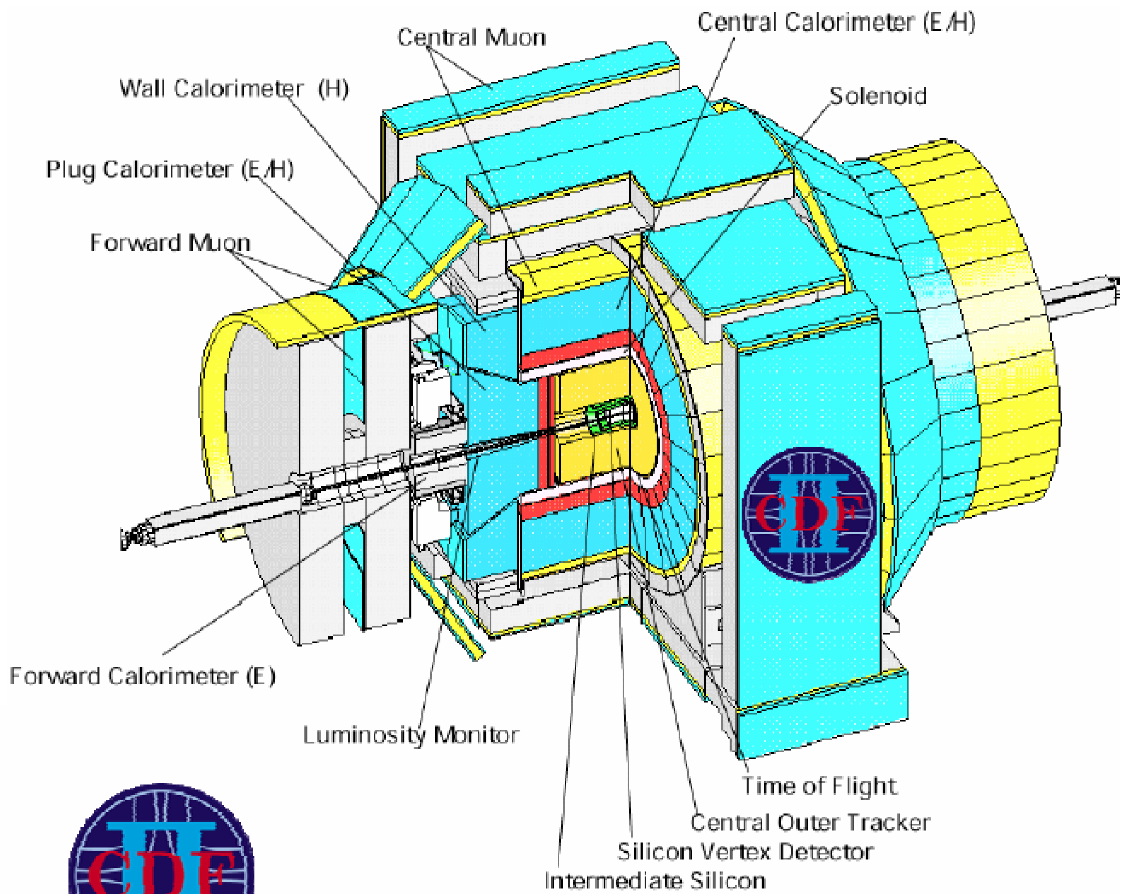
Tevatron performance

- excellent performance of Tevatron in 2004 and 2005
- machine delivered 900-1000 pb^{-1} up to now !!
- recorded (DØ, CDF)
  - ~480-530 pb^{-1} 2002-2004
  - ~270 pb^{-1} 2005
  - high data taking efficiency ~85%
- current datasets analyzed
  - ~200-500 pb^{-1} analyzed
  - compare with ~100 pb^{-1} Run I



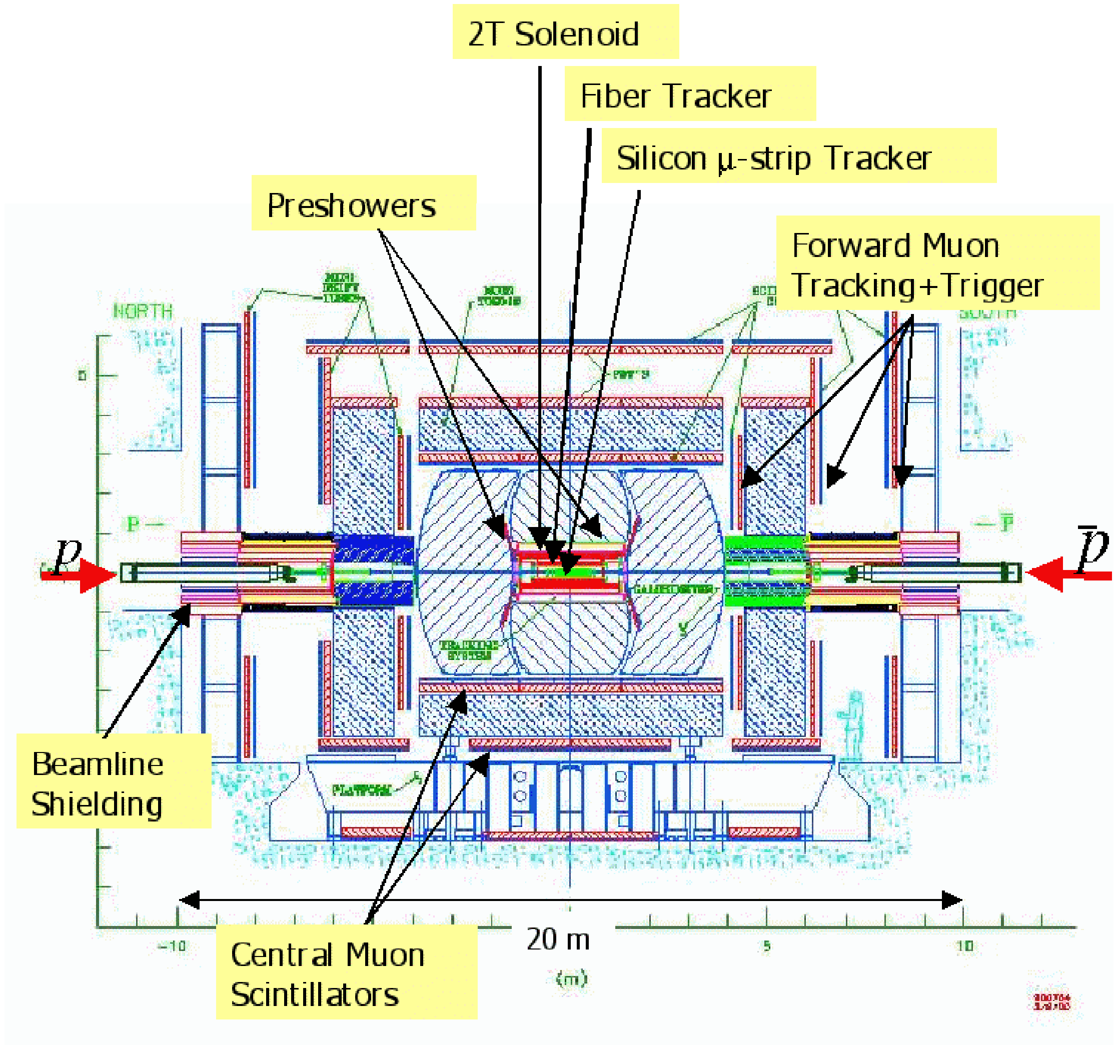
CDF detector

- Solenoid 1.4T
- 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
- Time of Flight
  - $\rightarrow$particle ID



DØ detector

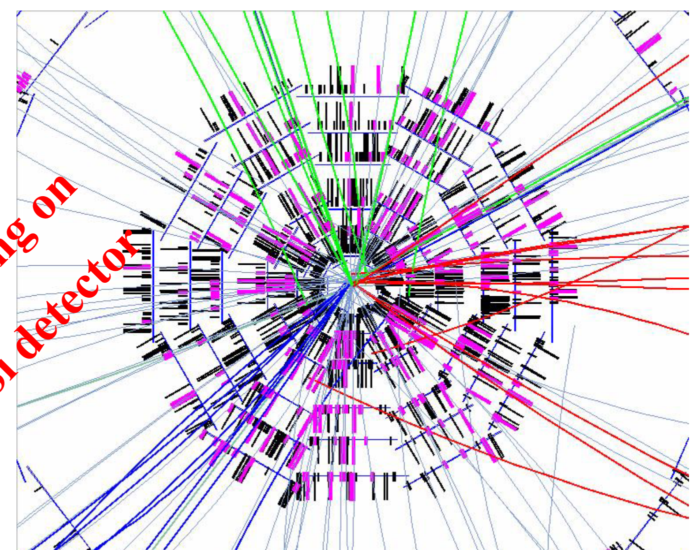
- 2T Solenoid
- beamline shielding
  - reduce background
- forward Muon + Central Muon detectors
  - excellent coverage $|\eta|<2$
- Fiber Tracker
  - 8 double layers
- Silicon Detector
  - up to $|\eta|<2.5$



B production at Tevatron

- Pro's:
  - large cross section >10^4 x larger than at present B-factories $\Upsilon(4S)$
  - all kinds of b hadrons produced:
    - B_d, B_s, B_c, B**, Λ_b, Ξ_b, …
- Con's:
  - QCD background overwhelming
  - efficient trigger and reliable tracking necessary
  - soft p_t spectrum, smaller boost than LEP
- Key for B physics program:
  - Muon system
  - Muon trigger (single and dimuon triggers)
  - Silicon Vertex + Tracker
  - trigger on displaced vertices/tracks

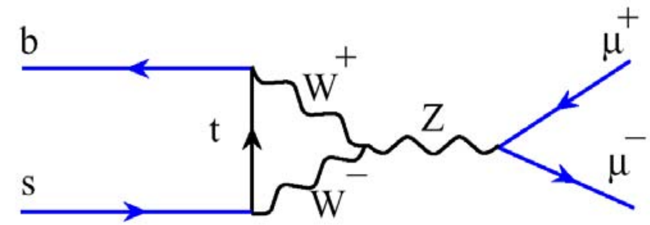
$$\sigma(p\bar{p} \to b\bar{b}) \approx 150\,\mu b$$
$$@\sqrt{s} = 2\text{TeV}$$

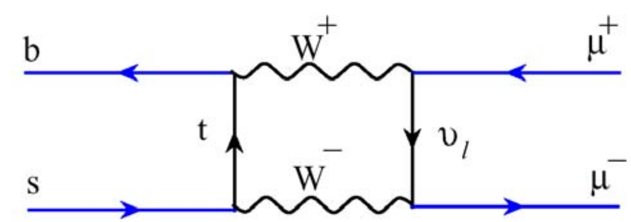


Lots going on in Si detector

Purely leptonic B decay

- purely leptonic **B->l+ l-** decay is a flavor changing neutral current (FCNC)
- in SM forbidden at tree level
- proceeds thru penguin/box diagrams, helicity suppressed
- SM: $BR(B_s \rightarrow \mu^+\mu^-) \sim 3.4\times10^{-9}$
- 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





SM expectations:

	$Br(B_d\rightarrow l^+l^-)$	$Br(B_s\rightarrow l^+l^-)$
$l = e$	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}

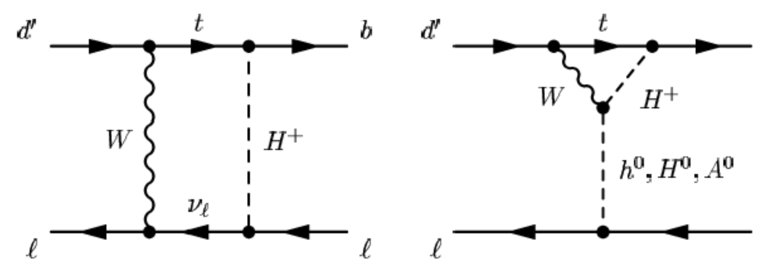
Current published limits:

C.L. 90%	$Br(B_d\rightarrow l^+l^-)$	$Br(B_s\rightarrow l^+l^-)$
$l = e$	$< 6.1 \cdot 10^{-8}$	$< 5.4 \cdot 10^{-5}$
$l=\mu$	$< 8.3 \cdot 10^{-8}$	**$< 4.1 \cdot 10^{-7}$**
$l=\tau$	< 2.5%	< 5.0%

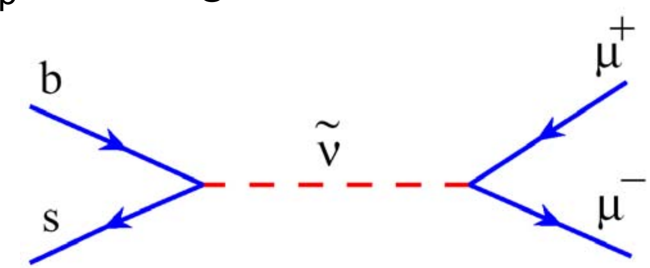
Purely leptonic B decay

- excellent probe for 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:



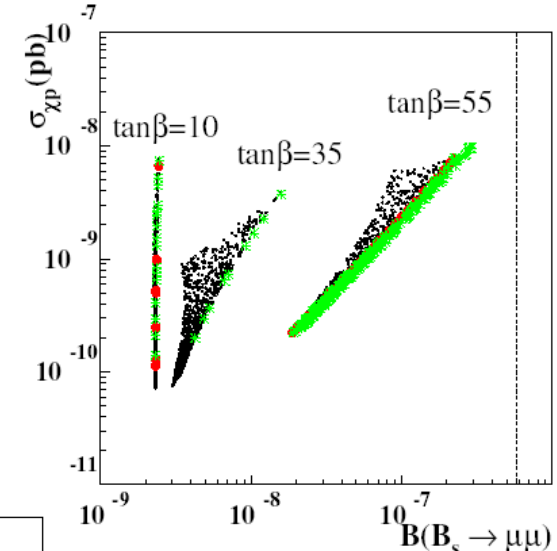
R_p violating:

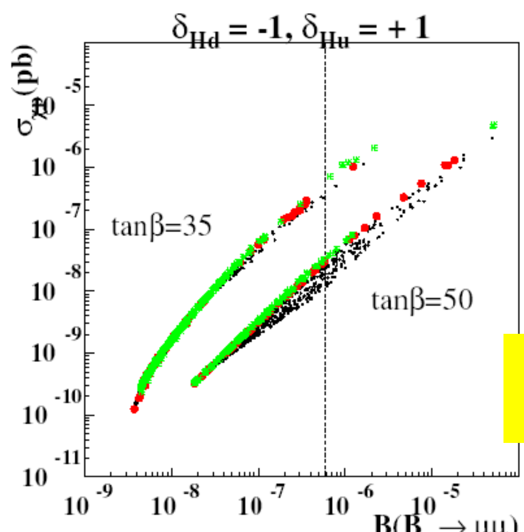


Constraining dark matter

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

universal Higgs mass parameters



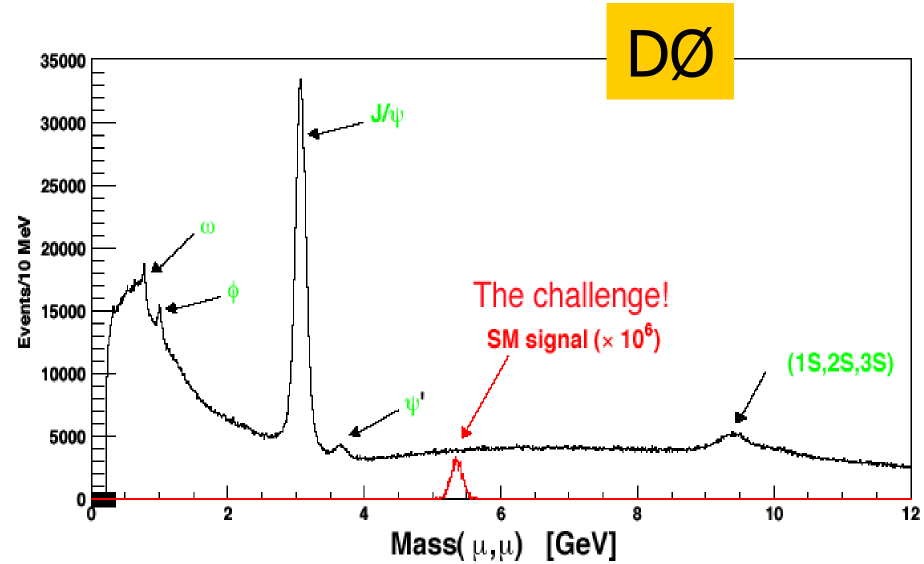


non-universal Higgs mass Parameters, $\delta H_u=1$, $\delta H_d=-1$

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

Experimental search

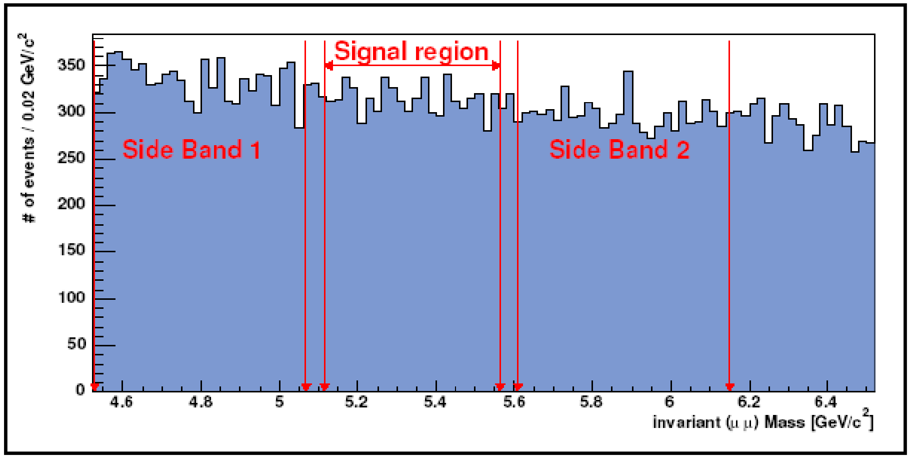
- **CDF:**
  - 364 pb^{-1} di-muon triggered data
  - two separate search channels
    - central/central muons
    - central/forward muons
  - extract B_s and B_d limit
- **DØ:**
  - 240 pb^{-1} (update 300 pb^{-1}) di-muon triggered data
- **both experiments:**
  - blind analysis to avoid experimenter's 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 Bd and Bs; 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

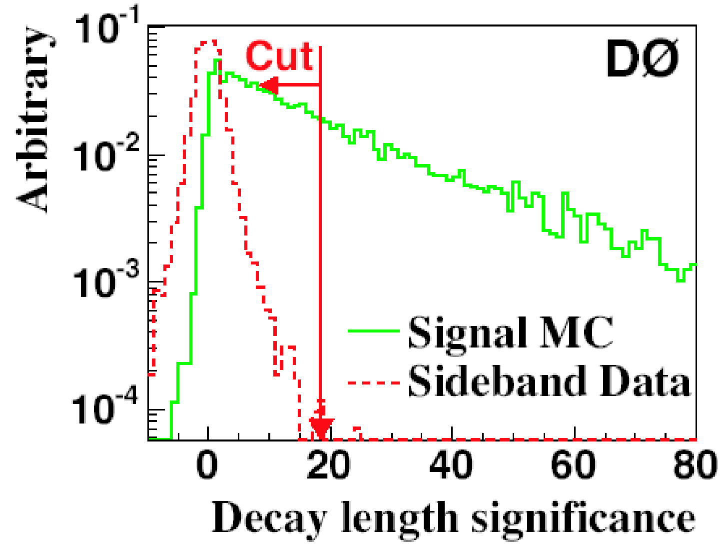


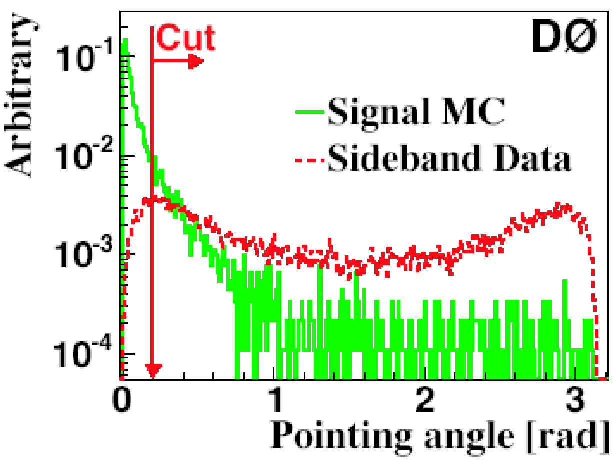
e.g. DØ: about 38k events after pre-selection

Potential sources of background:
- continuum μμ Drell-Yan
- sequential semi-leptonic b->c->s decays
- double semi-leptonic bb-> μμX
- b/c->μx+fake
- fake + fake

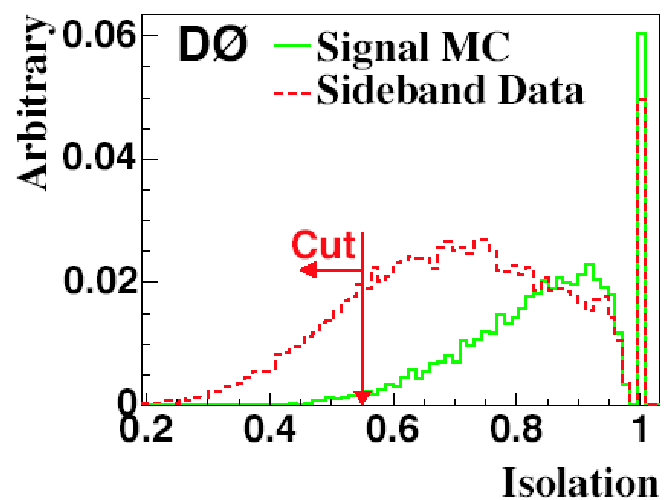
Optimization I

- 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



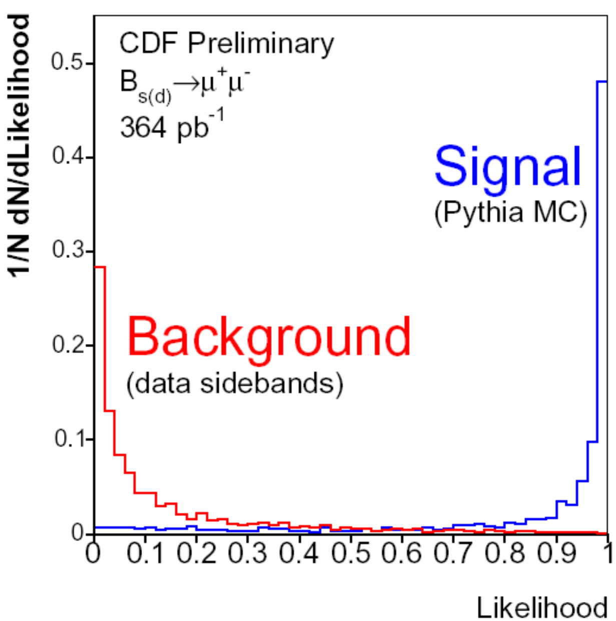


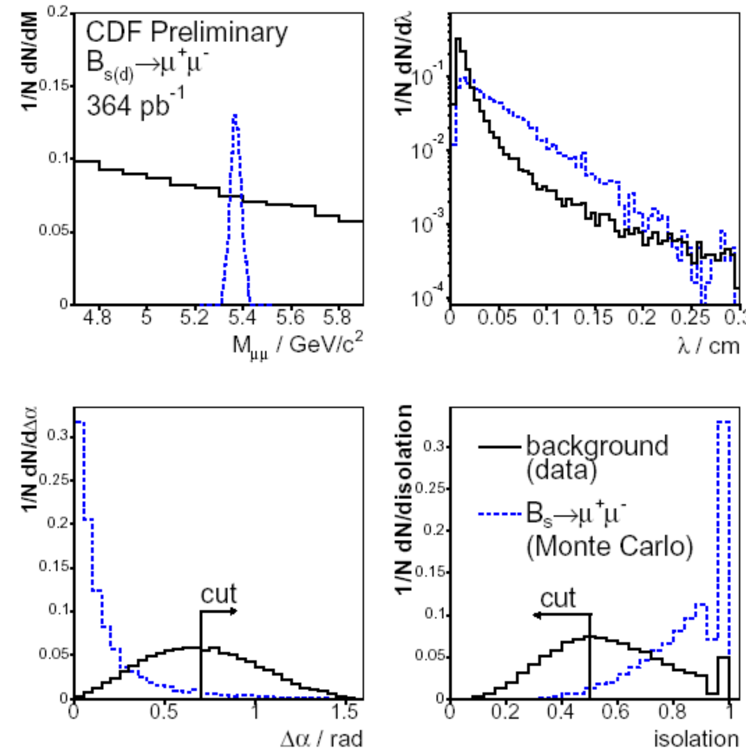
- use signal MC and 1/3 of (sideband) data for optimiz
- random grid search
- maximize $\varepsilon/(1.+\sqrt{B})$
- total efficiency w.r.t 38k p selection criteria: 38.6%



Optimization II

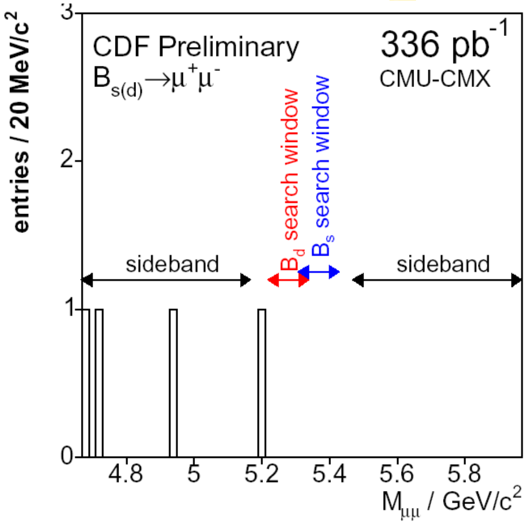
- CDF: discriminating variables
  - pointing angle between $\mu^+\mu^-$ and decay length vector
  - isolation in cone around B_s candidate
  - proper decay length probability $p(\lambda) = \exp(-\lambda/\lambda_{Bs})$



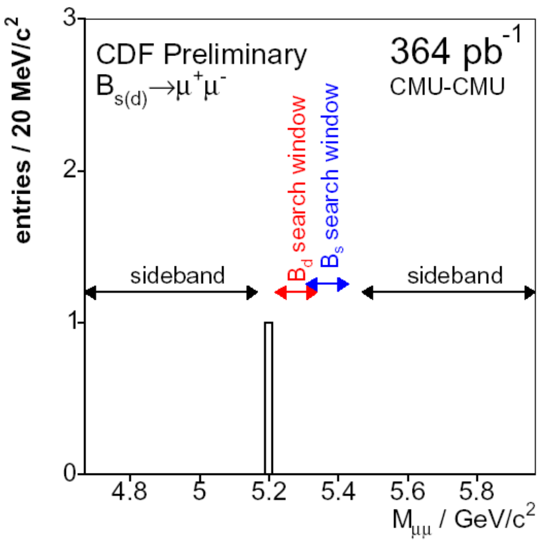


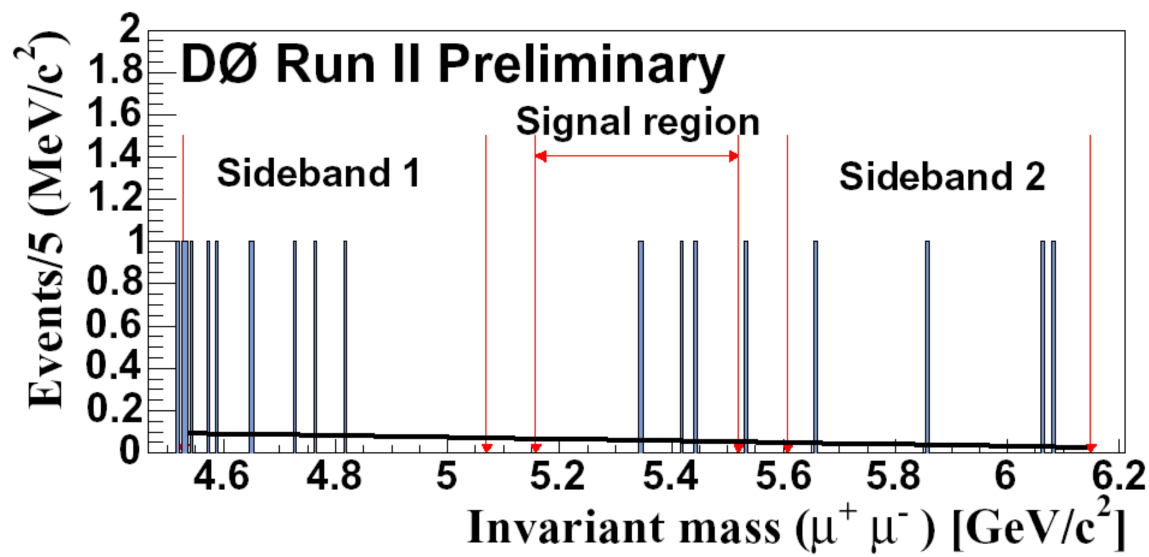
- construct likelihood ratio for optimization on "expected upper limit"
- LH cut efficiency w.r.t pre-selection criteria: 34.8%

Unblinding the signal region



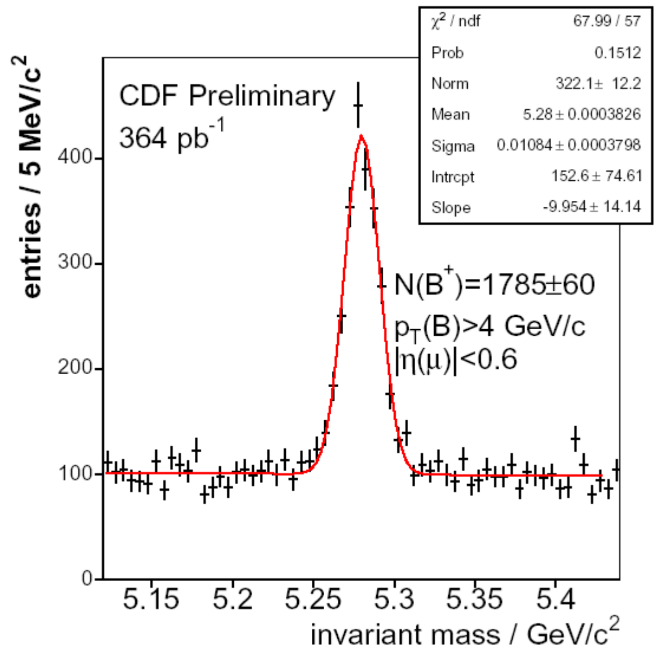
- CDF:
  - central/central: observe 0, expect 0.81 ± 0.12
  - Central/forward: observe 0, expect 0.66 ± 0.13
- DØ:
  - PRL: observe 4, expect 3.7 ± 1.1
  - update: observe 4, expect 4.3 ± 1.2

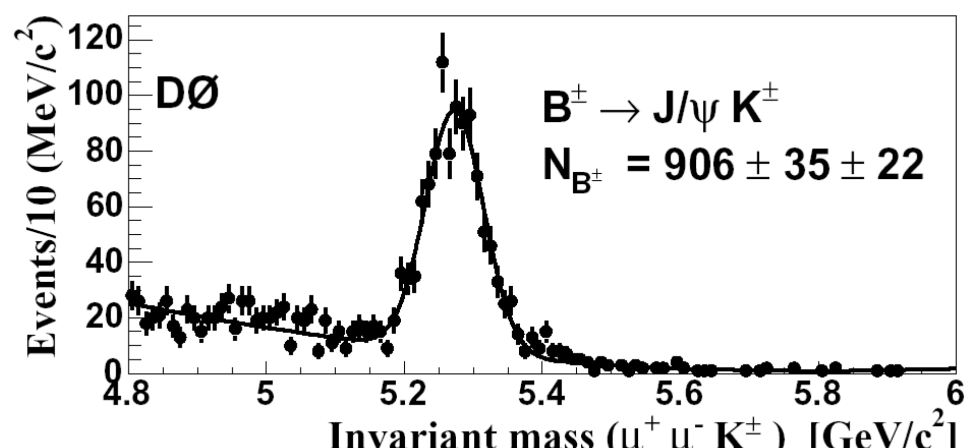




Normalization

- 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





The Limits

- $BR(B_s \to \mu^+\mu^-) = N_{ul}/N_{B+} \times \varepsilon_{B+}/\varepsilon_{Bs} \times f_u/f_s \times BR(B^+ \to J/\psi K^+) \cdot BR(J/\psi \to \mu^+\mu^-)$
  - $\varepsilon_{B^+}/\varepsilon_{Bs}$ relative efficiencies
  - f_u/f_s fragmentation ratio (in case of B_s limit) – use world average value with 15% uncertainty
- N.B.:
  - DØ mass resolution is not sufficient to separate B_s from B_d. Assume no B_d contribution (conservative)
  - CDF sets limit 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}	Prelim
CDF $B_d \to \mu\mu$	364 pb^{-1}	4.9×10^{-8}	Prelim

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

Limits

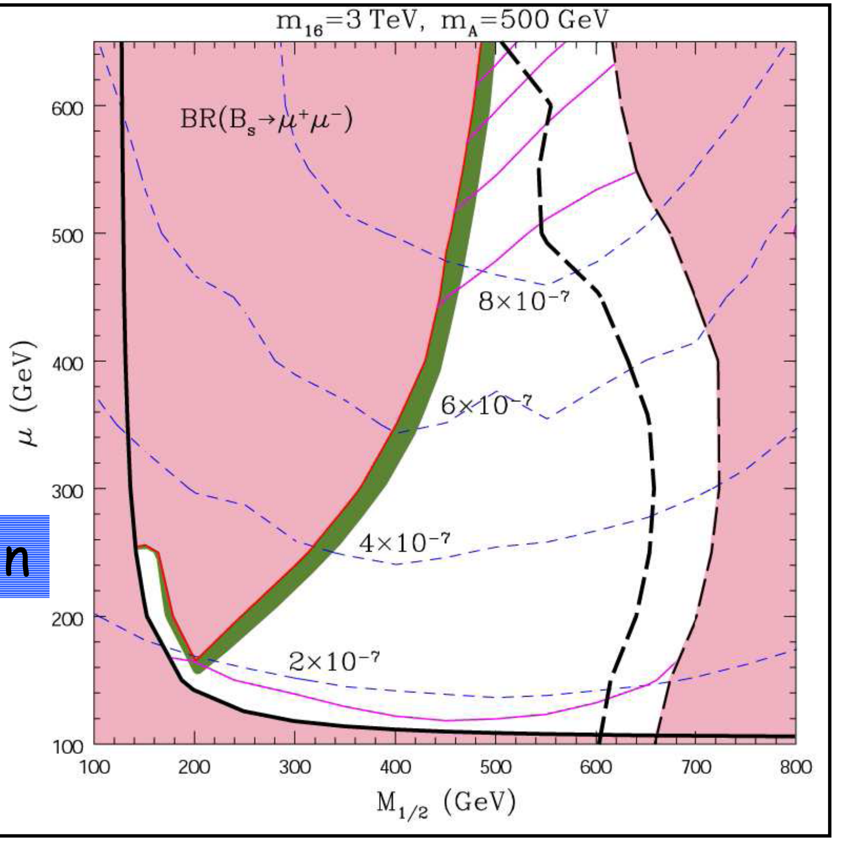
Example: SO(10) symmetry breaking model

best limit from CDF:

$BR(B_s \to \mu^+\mu^-) < 2.0 \times 10^{-7}$ @95% C.L

constraints SO(10) model severely

stay tuned for Tevatron limit combination

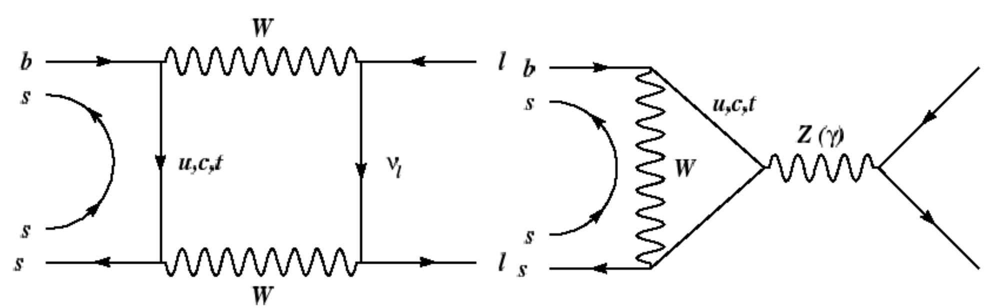


Contours of constant $Br(B_s \to \mu^+\mu^-)$

R. Dermisek et al.
JHEP 0304 (2003) 037

Sensitivity analysis $B_s \to \mu^+\mu^-\phi$

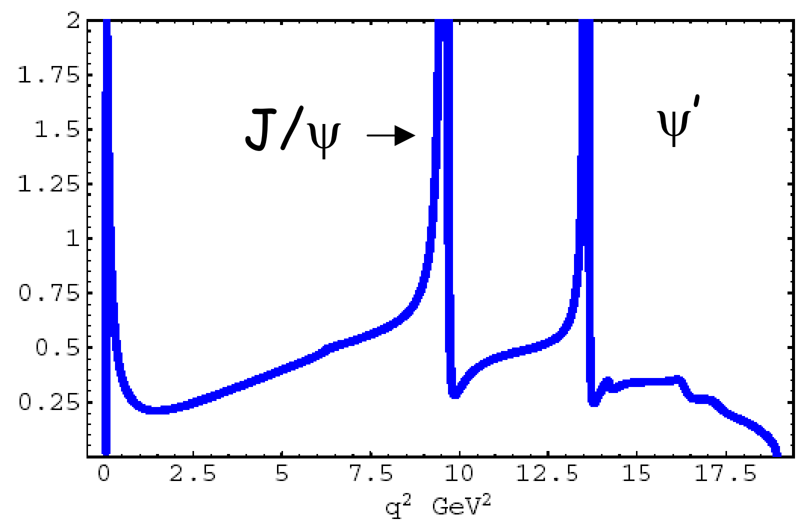
- long-term goal: investigate $b \to s\, l^+ l^-$ FCNC transition in B_s meson
- exclusive decay: $B_s \to \mu^+\mu^-\phi$
- SM prediction:
  - short distance BR: $\sim 2\times10^{-6}$
  - about 30% uncertainty due to $B \to \phi$ form factor
- 2HDM: enhancement possible, depending on parameters for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



Sensitivity analysis
$B_s \to \mu^+\mu^-\phi$

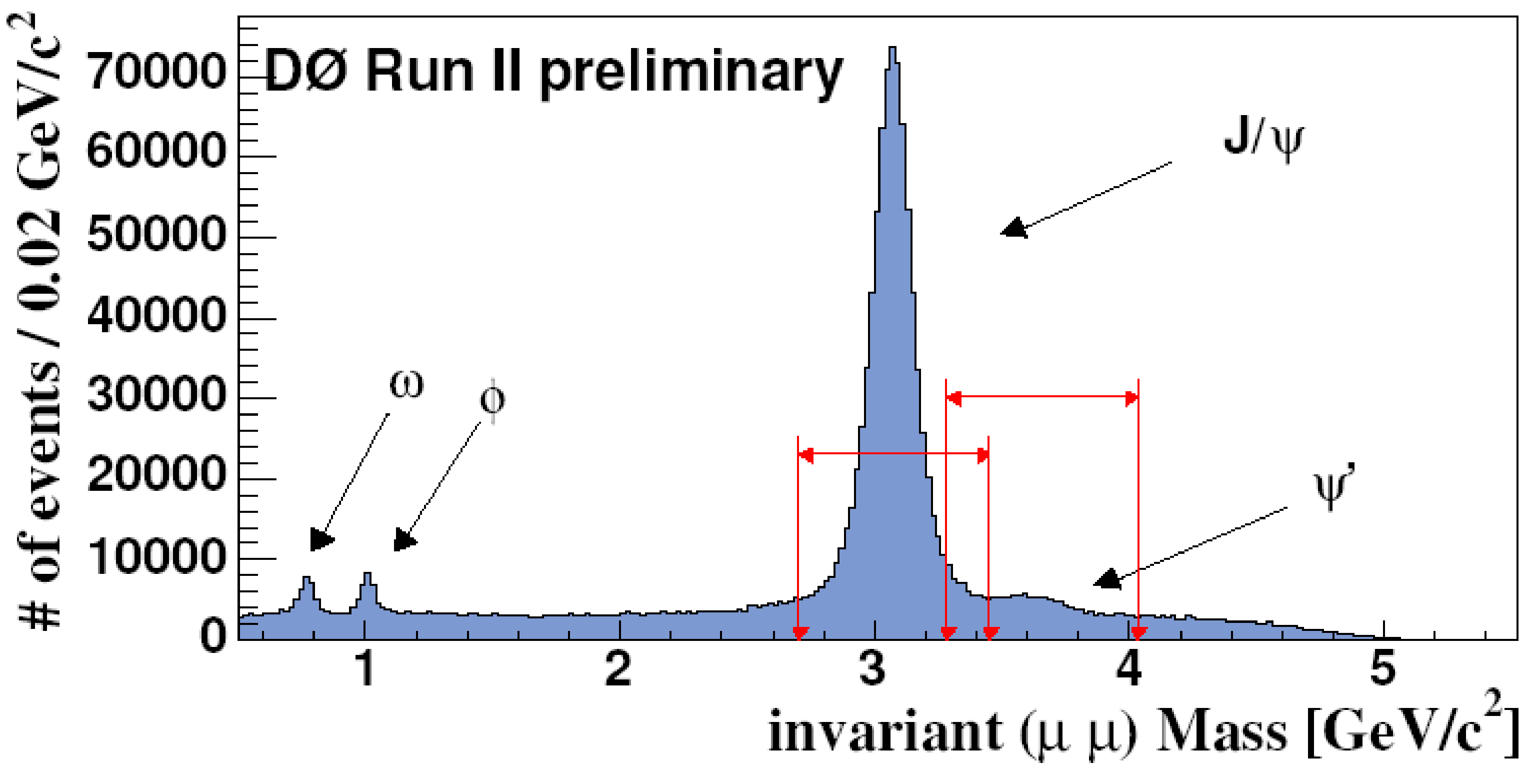
- DØ: 300 pb^{-1} of dimuon data
- normalize to resonant decay $B_s \to J/\psi\ \phi$
- cut on mass region $0.5 < M(\mu\mu) < 4.4\ GeV/c^2$ excluding J/ψ & ψ'
- two good muons, $p_t > 2.5\ GeV/c$
- two additional oppositely charged tracks $p_t > 0.5\ GeV/c$ for ϕ
- ϕ candidate in mass range $1.008 < M(\phi) < 1.032\ GeV/c^2$
- good vertex
- $p_t(B_s$ cand.$) > 5\ GeV/c$
- B_s collinearity > 0.95

Dilepton mass spectrum in b -> s l l decay



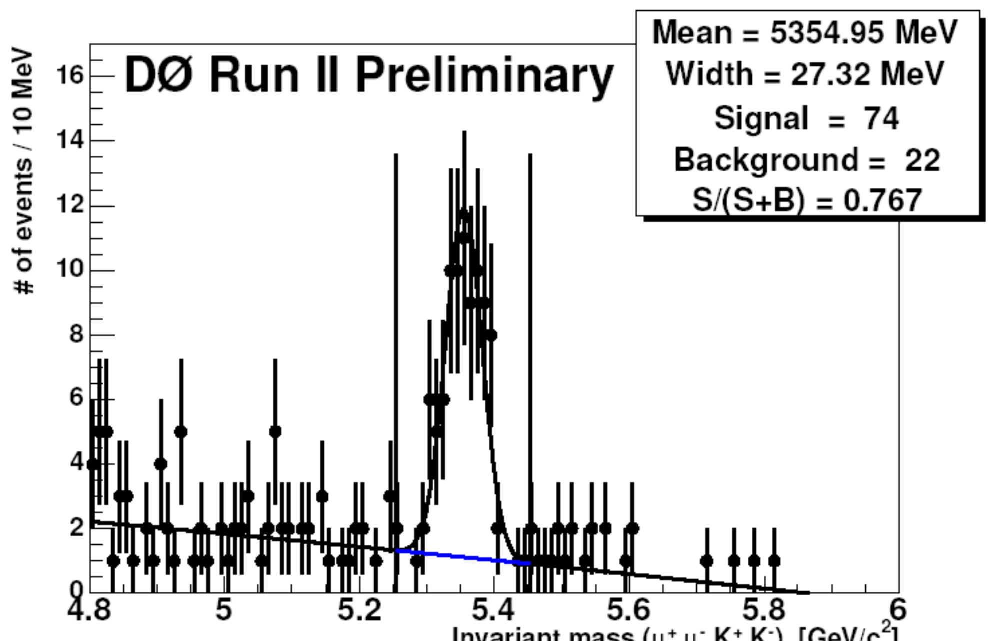
Sensitivity analysis
$B_s \rightarrow \mu^+\mu^-\phi$

- dimuon candidates combined with additional ϕ candidate (looser selection)



Sensitivity analysis
$B_s \to \mu^+\mu^-\phi$

- Optimization with following variables in random grid search
  - pointing angle
  - decay length significance
  - isolation
- use resonant decay $B_s \to J/\psi\ \phi$ with same cuts as normalization
- gaussian fit with quadratic background: 74 ± 11 $B_s \to J/\psi\ \phi$



Expected Limit

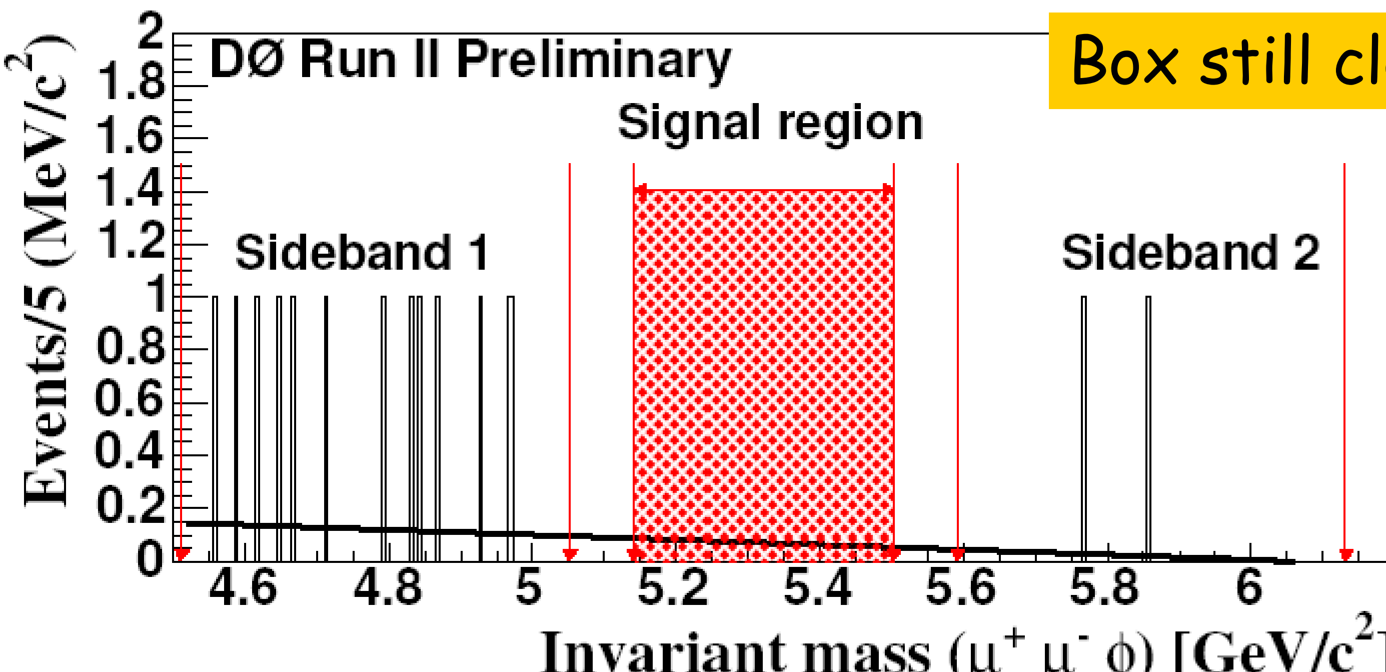
- expected background from sidebands: 5.1 ± 1.0 events
- sensitivity/average expected limit (@95% C.L):

$<BR(B_s \to \phi\, \mu^+\mu^-)/BR(B_s \to J/\psi\, \phi)> = 1.3 \times 10^{-2}$

if $BR(B_s \to J/\psi\, \phi) = 9.3\times10^{-4}$ PDG2004 is used:

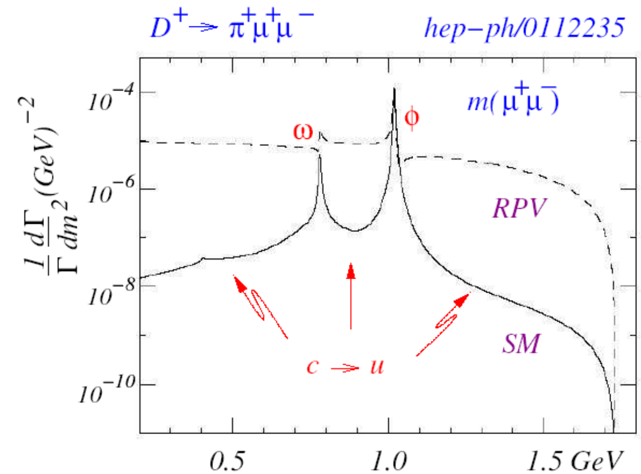
$<BR(B_s \to \phi\, \mu^+\mu^-)> = 1.2\times10^{-5}$

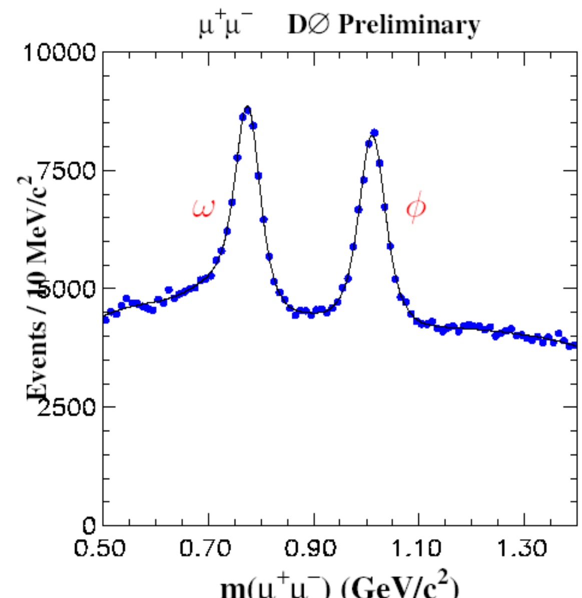
expect x5 improvement w.r.t previous limit



Study of FCNC charm decays

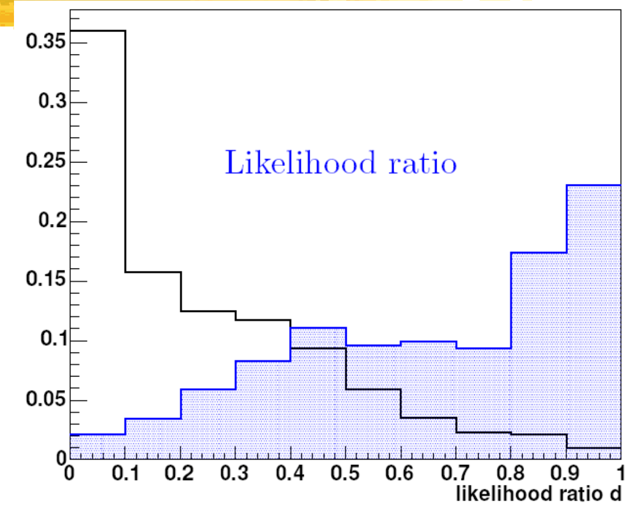
- FCNC in up-type flavor sector:
  - large areas of parameter space for new physics still unexplored
  - e.g. R_p violating models could enhance c->u l^+l^- transitions
- Strategy: establish first resonant $D_s^\pm$ -> $\phi\ \pi^\pm$ -> $\mu^+\mu^-\ \pi^\pm$ then search in continuum for non-resonant decay
- DØ: select in 508 pb^{-1} of dimuon data
  - $0.96 < m(\phi \to \mu\mu) < 1.06$ GeV/c^2
  - 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/c2,
  - average 3.3 candidates/event
    - choose best vertex-χ^2

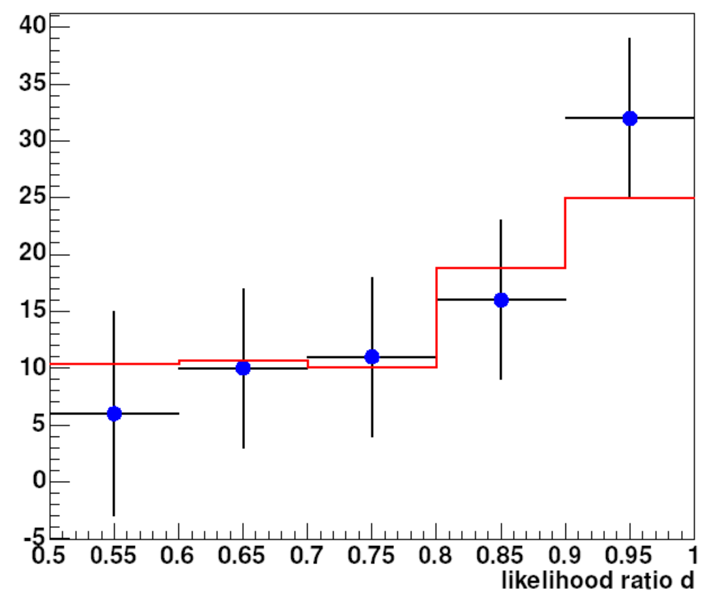




Optimization

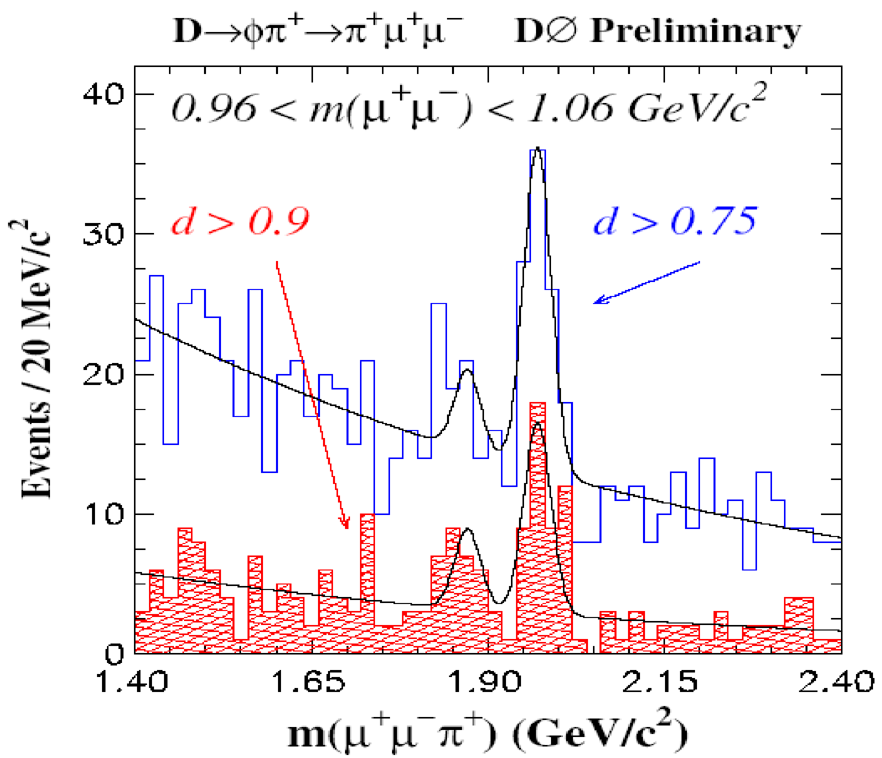
- construct likelihood ratio for signal (MC) and background (sideband) events based on
  - isolation of D candidate I_D
  - transverse decay length significance S_D
  - collinearity angle between D momentum and vector between prim. & sec. Vertex θ_D
  - significance ratio R_D = impact parameter of $\pi^{\pm}$ / S_D
  - correlations taken into account
- good agreement in D_s yield between data and MC for different LH ratio cuts
- Likelihood cut chosen to maximize $\varepsilon_S/\sqrt{\varepsilon_B}$





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

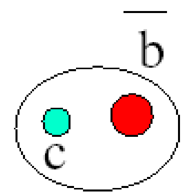
- observe 51 D_s candidates with expected background of 18
  - excess with (>7σ) significance
- first observation of resonant decay $D_s^{\pm} \to \phi\,\pi^{\pm} \to \mu^+\mu^-\,\pi^{\pm}$ as benchmark
- fit yields 13 ± 5 $D^{\pm}$ events (2.7σ)
- limit on $D^{\pm} \to \phi\,\pi^{\pm} \to \mu^+\mu^-\,\pi^{\pm}$ almost factor 3 better than previous experiments
- accomplished first major step in FCNC three-body charm decay program
- Future: search for excess in non-resonant continuum region



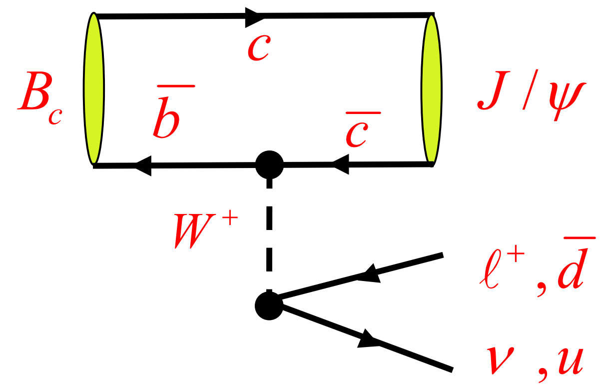
$$\mathcal{B}(D^+ \to \phi\pi^+ \to \pi^+\mu^+\mu^-) < 3.14 \times 10^{-6}\ \ (90\%\ \text{C.L.})$$

$B^{\pm}_c$ meson

- least well known ground state B meson
- theory: large mass and shortest life time
- measurement of B_c properties are good test of quark model
- both quarks can decay semi-leptonically
- first observation of B_c in semileptonic decay in Run I (CDF): 20 ± 6 events



B_c meson



PDG 2004	B_c	Compare to B^0
m [GeV/c2]	6.4 ± 0.4	5.2793 ± 0.0007
τ [ps]	0.46 ± 0.17	1.536 ± 0.014

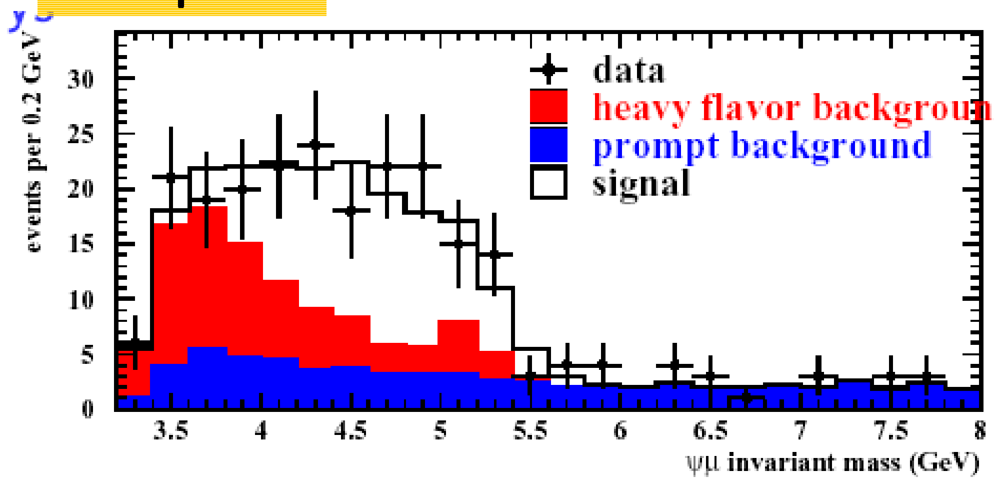
Semileptonic B_c decay I

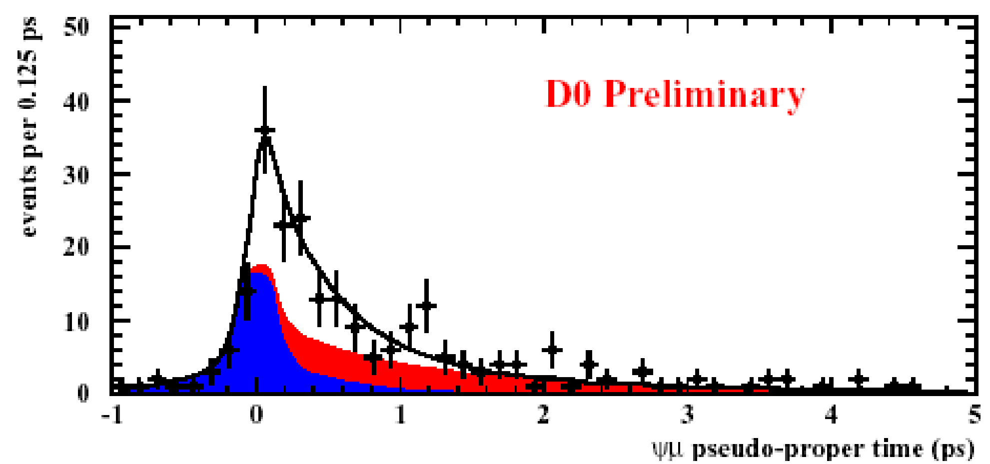
- $B_c^{\pm} \to J/\psi \, l^{\pm} \, \nu$
- DØ: 210 pb-1 of dimoun data
- combine J/ψ ($\to \mu^+\mu^-$) with extra high-quality muon in event
- perform simultaneous fit to $J/\psi + \mu$ mass and (pseudo-) proper decay time
- average correction factor to account for missing ν momentum:
- 231 candidates, signal of 95 ± 11 ± 12

$$m = 5.95 \pm 0.14 \pm 0.34 \; GeV/c^2$$

$$\tau = 0.448^{+0.123}_{-0.096} \pm 0.121 ps$$

DØ prel



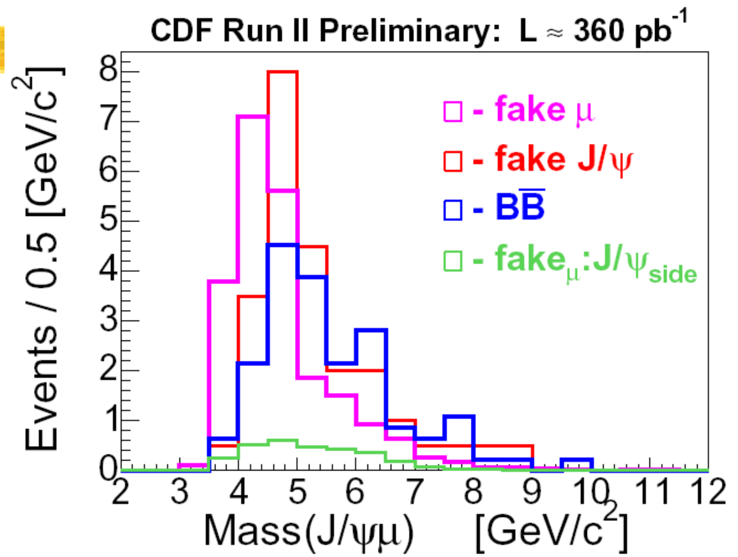


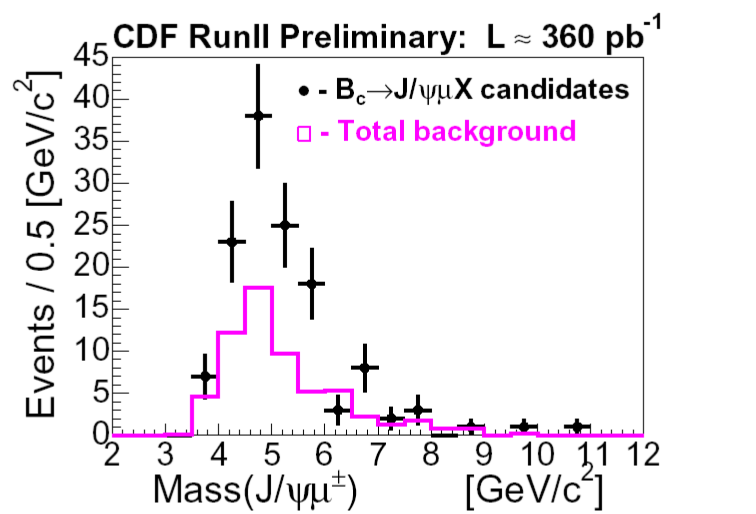
Semileptonic B_c decay II

- $B_c^{\pm} \to J/\psi + l^{\pm} + \nu$
- CDF: 360 pb^{-1} of dimoun data
- combine J/ψ ($\to \mu^+\mu^-$) with extra high-quality muon in event
- detailed study of background sources
  - fake “third” muon or fake J/ψ
  - b [$\to J/\psi$] b [$\to \mu$]
- 60.0 ± 12.6 signal events above background
- measure BR·σ relative to $B^{\pm} \to J/\psi\ K^{\pm}$ for $p_T(B) > 6$ GeV/c:

$$\frac{\sigma(B_c^{\pm})\times BR(B_c^{\pm} \to J/\psi + \mu^{\pm} + \upsilon)}{\sigma(B^{\pm})\times BR(B^{\pm} \to J/\psi + K^{\pm})} =$$

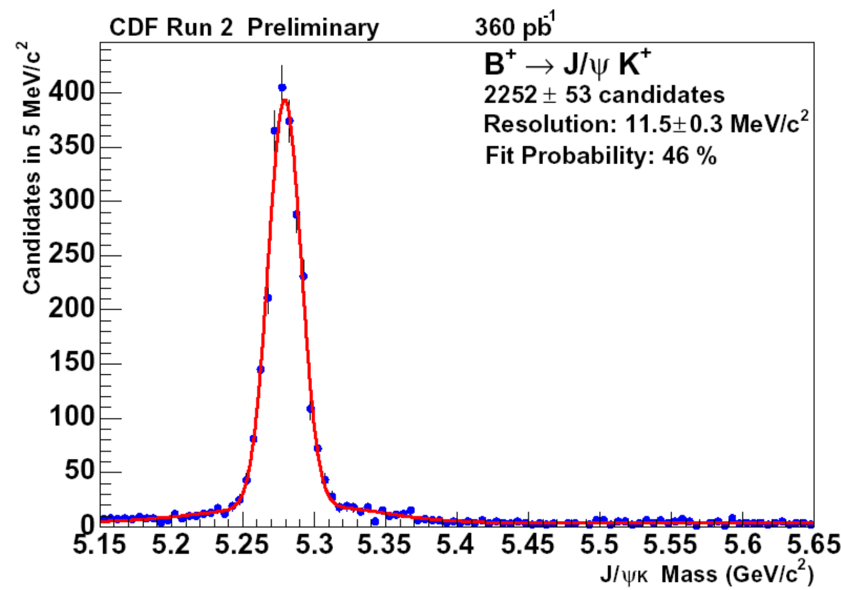
$$0.249 \pm 0.045(\text{stat.}) \pm 0.069(\text{sys.})^{+0.080}_{-0.032}(\text{life.})$$





B_c mass from fully reconstructed decay mode

- so far large exp. uncertainty on mass
  - -> use fully reconstructed mode for better resolution
- two-body decay mode $B_c \to J/\psi\ \pi^{\pm}$ best choice
- CDF: analysis uses 360 pb^{-1}
- $B^{\pm}$ -> $J/\psi\ K^{\pm}$ as control sample (topological similar)
- perform blind analysis search
  - mass region $5.6 < M(J/\psi\ \pi^{\pm}) < 7.2$ GeV/c2, 100× wider than expected resolution
  - cut optimize on signal MC (S) and background data (B) in mass window
  - maximize $\Sigma = S/(1.5+\sqrt{B})$ as balanced score function for "discovery" and limit-setting
  - 390 candidates in window remain

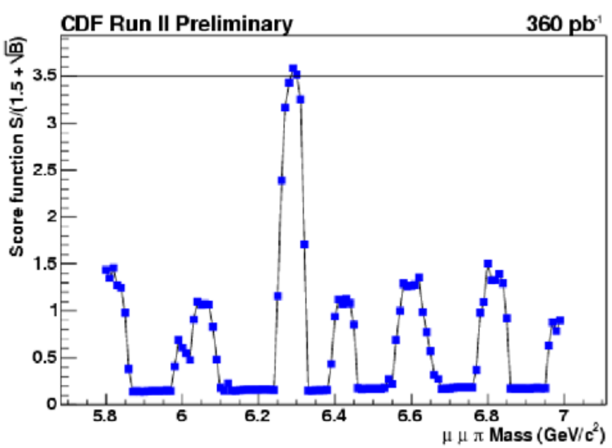


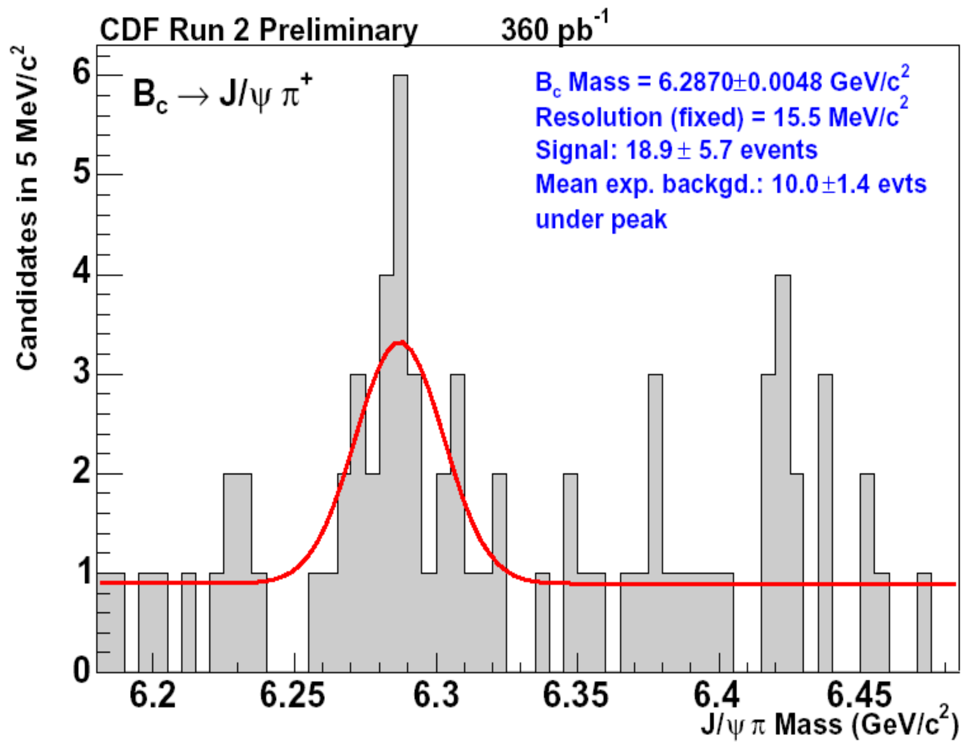
Summary of cut values used:

1. $p_T(\pi)$ > 1.8 GeV/c
2. $L_{xy}/\sigma(L_{xy})$ > 4.4
3. $\chi^2(3D)$ < 9.0
4. $d_0(B_c)$ $< 65\ \mu m$
5. pointing angle < 0.4 radians
6. $\chi^2_{vtx}(\pi)$ < 2.6
7. ct $< 750\ \mu m$

B_c mass from fully reconstructed decay mode

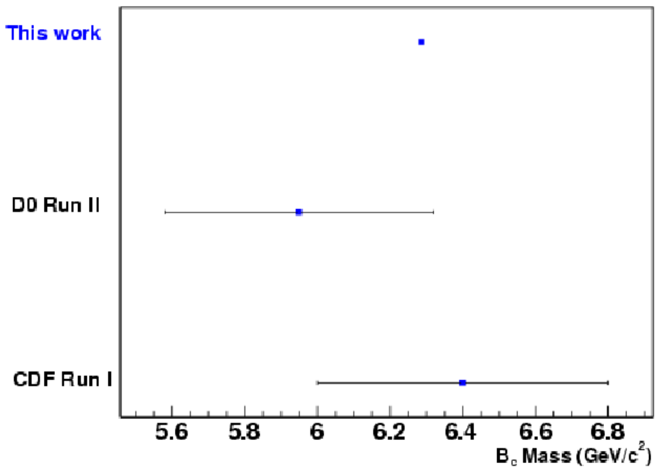
- before unblinding
  - define in advance procedure for signal peak search
  - define in advance level of acceptable “false” probability that background fluctuates into signal: p=0.1%
  - deploy toy MC with background only to define score function value corresponding to p=0.1%
- apply procedure & score function to data

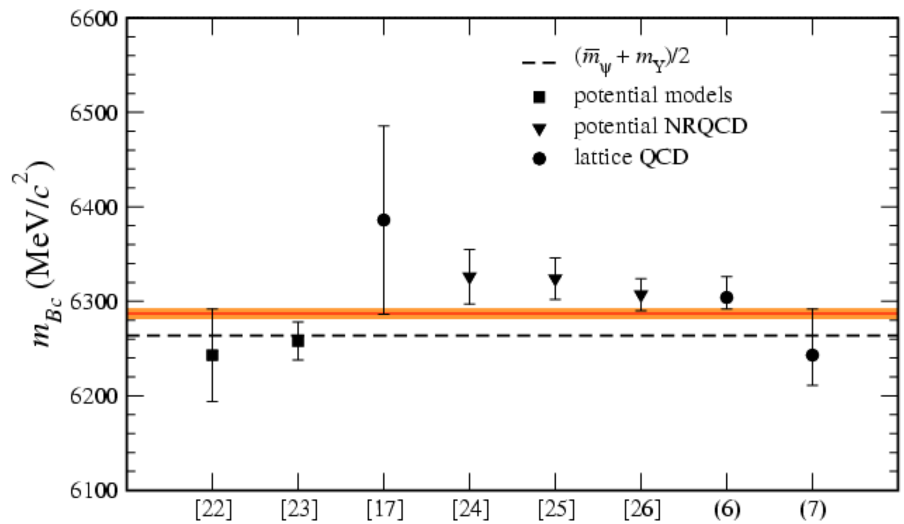




signal of 18.9 ± 5.7 events found

B_c mass from full reconstructed decay mode





$$M(B_c) = (6287.0 \pm 4.8_{stat.} \pm 1.1_{syst.})\,\mathrm{MeV}/c^2$$

- precision on $M(B_c)$ improved by a factor 100 !
- main systematic uncertainty from background shape given by low statistics
- good agreement with theory

Conclusions

- CDF & DØ provide world best limits on purely leptonic decay $B_{d,s} \to \mu^+\mu^-$
- with more statistics to come enhance exclusion power/discovery potential for new physics
- current sensitivity for b -> s l+ l- transition in exclusive $B_s \to \mu^+\mu^-\phi$ decay shown, still factor 5 away from SM
- first observation of benchmark channel $D_s^{\pm} \to \phi\,\pi^{\pm} \to \mu^+\mu^-\,\pi^{\pm}$ as first step towards a charm rare FCNC decay program
- clear signals for $B_c^{\pm} \to J/\psi + l^{\pm} + \nu$, allowing to study mass & lifetime of B_c
- most precise mass measurement from fully reconstructed $B_c \to J/\psi\,\pi^{\pm}$

Knowledge must come through action; you can have no test which is not fanciful, save by trial.

Sophocles, *Trachiniae*
Greek tragic dramatist (496 BC - 406 BC)

Experimental status

- previous experimental results on $B_s \to \mu\mu$ (@95% C.L)
- CDF (100 pb^{-1}, Run I): 2.6×10^{-6} PRD57(1998)3811
- CDF (171 pb^{-1}): 7.5×10^{-7} PRL93(2004)032001
- DØ (240 pb^{-1}): 5.0×10^{-7} PRL94(2005)071802
- DØ prel. (300 pb^{-1})
- CDF prel. (360 pb^{-1})

Will cover these results

Triggering on B's

- single lepton triggers
  - semileptonic B decays
  - variety of triggers with raised p_t threshold, pre-scaled and/or supported with track/displaced vertex triggers
- two-muon triggers
  - from J/ψ
  - tracks $\leftrightarrow$ matched μ
  - $p_t(\mu) > 1.5$ GeV/c
- two track triggers
  - displaced tracks & vertex
  - fully hadronic reconstructed modes, e.g. two body charmless decays