Heavy Flavor Rare Decays at the DØ Detector

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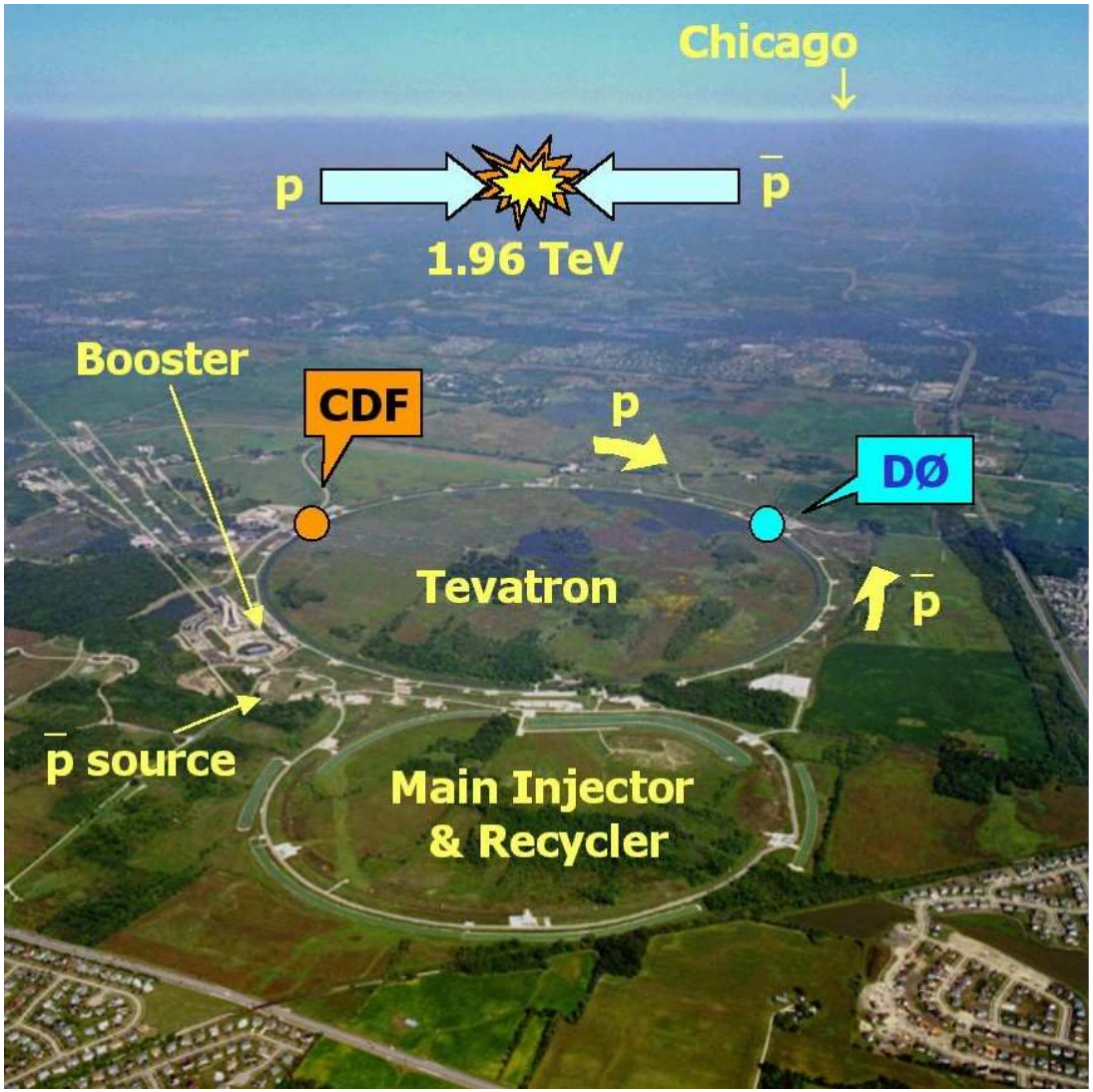
26th May, 2005

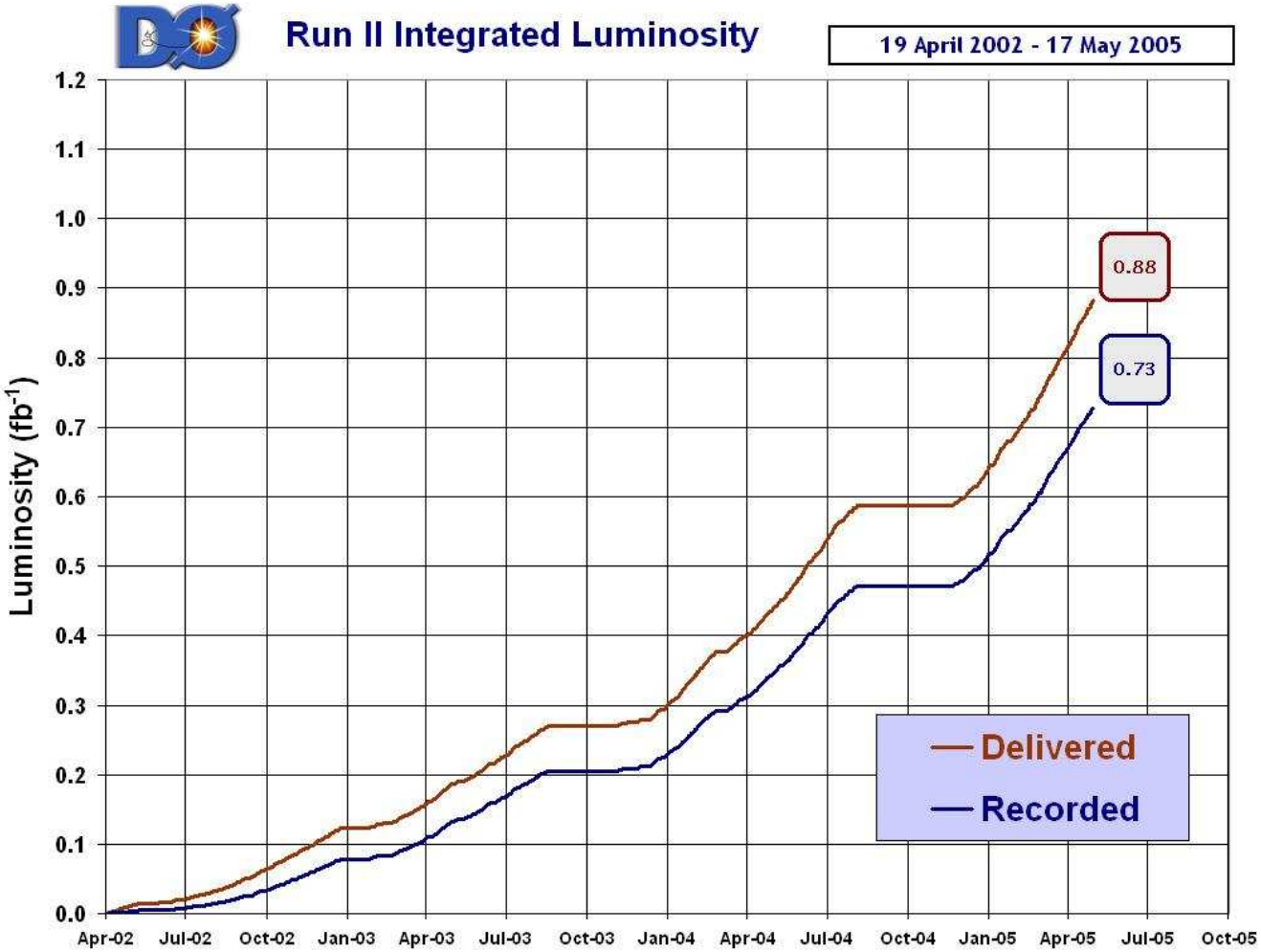
- The Tevatron
- DØ Experiment at the Tevatron
- Search for the Flavor Changing Neutral Current Decay $B_s^0 \to \mu^+\mu^-$
- Sensitivity study of $B_s^0 \to \mu^+\mu^-\phi$
- Observation of the $B_s \to \psi(2S)\phi$ decay
- Flavor Changing Neutral Current Charm Decays ($D_s \to \phi\pi \to \pi\mu^+\mu^-$ observation)
- Conclusions

The Fermilab Tevatron Collider



- New main injector and antiproton recycler
- Increase number of bunches ($6 \times 6 \rightarrow 36 \times 36$)
- Reduce bunch spacing ($3.5\mu s \rightarrow 396$ns)
- Increase beam energy 900 $\rightarrow$ 980 GeV (increase x-sections e.g. top production by 30-40 %)
- Projected integrated luminosity per experiment:
  - ≈ 2 fb^{-1} 2006
  - ≈ 8 fb^{-1} 2009
- Highest luminosity so far $117.57 \cdot 10^{30}$ cm^{-2} s^{-1}
- 0.75 fb^{-1} on tape per experiment
- Data taking efficiency: 85-90 %

Integrated Luminosity



Why rare B physics at the Tevatron ?

- Producing large numbers of $b\bar{b}$ pairs
  - $\sigma(p\bar{p} \to b\bar{b}) = 150\mu$b at 2 TeV
  - $\sigma(e^+e^- \to Z^0 \to b\bar{b}) = 7$ nb
  - $\sigma(e^+e^- \to \Upsilon(4S) \to b\bar{b}) = 1$ nb
- Expect 10^{10} $b\bar{b}$ pairs pairs/year at $4 \cdot 10^{31} cm^{-2} s^{-1}$
  - fragmenting into all B-species: $B_d, B_u, B_s, \Lambda_b, \ldots$
- Exploring the B_s sector

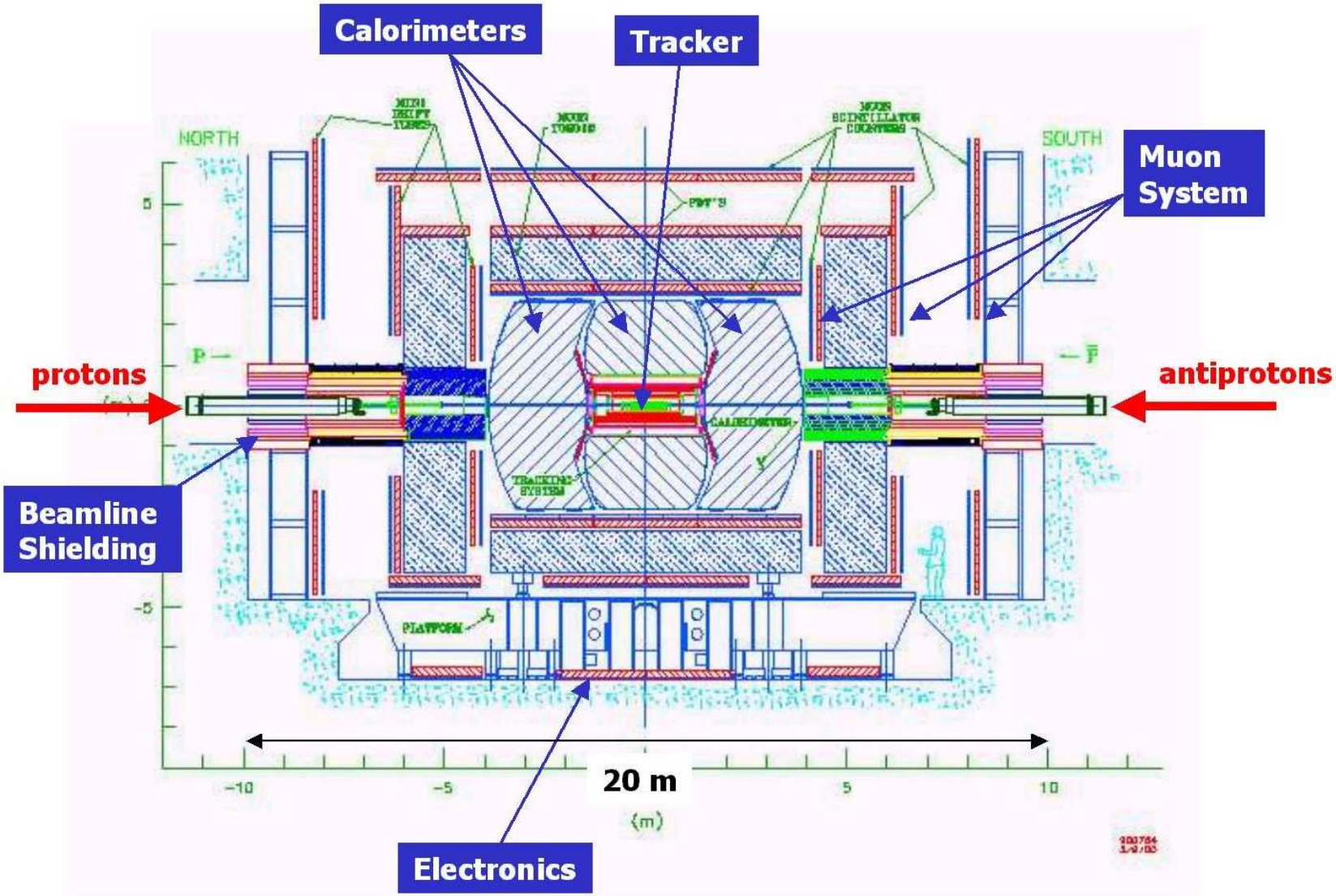
Con's

- QCD background overwhelming
- efficient trigger and reliable tracking necessary
- soft pt spectrum, smaller boost than LEP

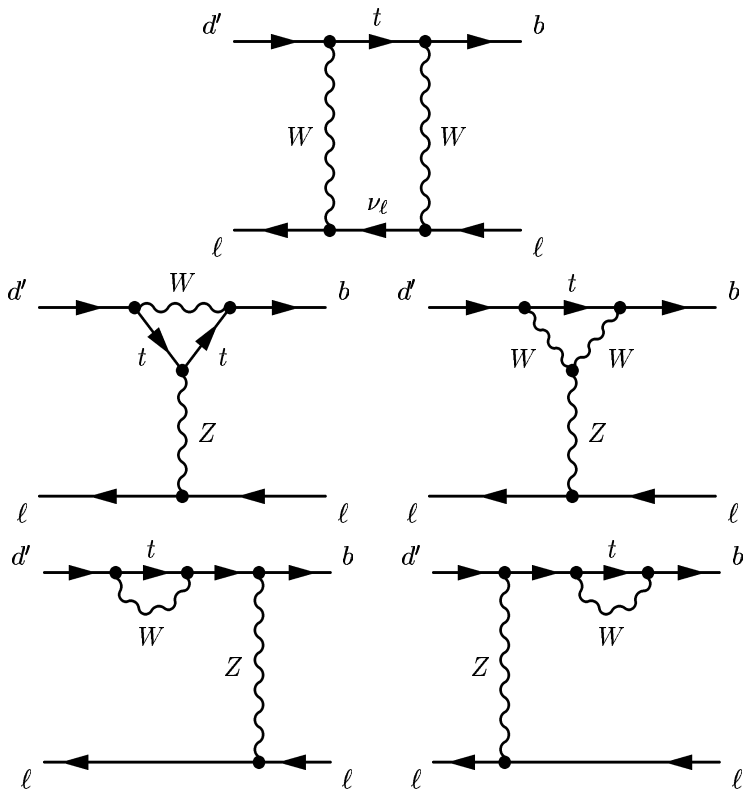
Key points for this analyses

- Muon system
- Muon trigger (single and dimuon triggers)
- Silicon Vertex + Tracker

DØ Detector


Calorimeters
Tracker
Muon System
protons
antiprotons
Beamline Shielding
Electronics
NORTH
SOUTH
20 m
(m)

Introduction to the $B_{d,s} \to l^+l^-$ decay I (SM)



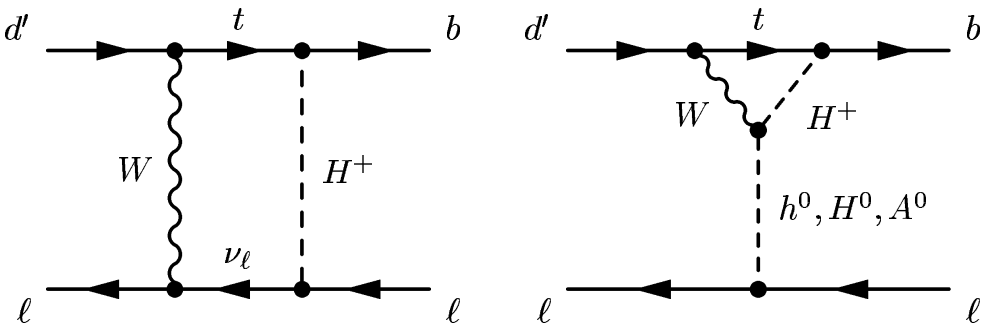
SM predictions

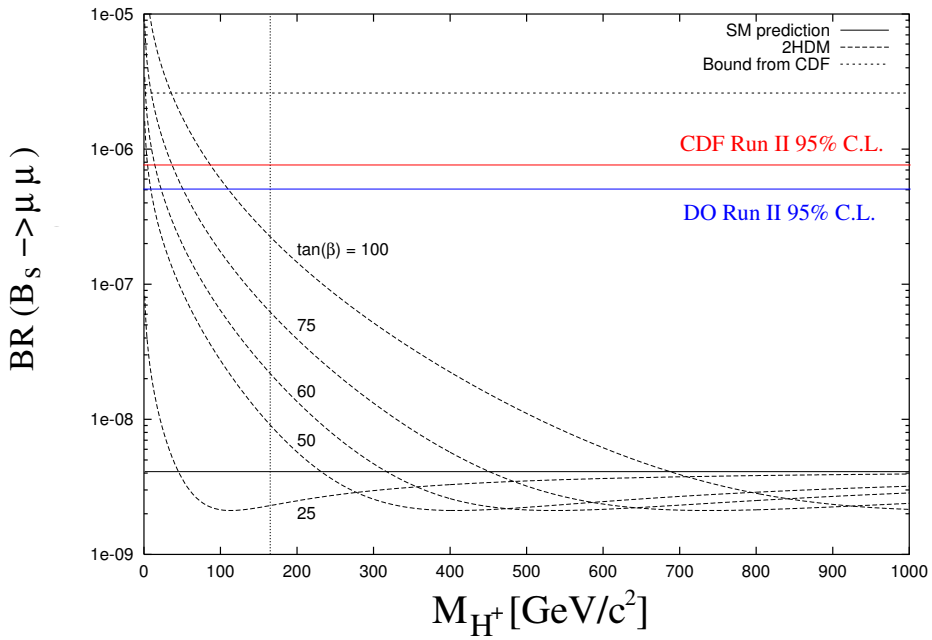
	$BR(B_d \to l^+l^-)$	$BR(B_s \to l^+l^-)$
l = e	$(3.4 \pm 2.3) \cdot 10^{-15}$	$(8.0 \pm 3.5) \cdot 10^{-14}$
l = μ	$(1.5 \pm 0.9) \cdot 10^{-10}$	$(3.4 \pm 0.5) \cdot 10^{-9}$
l = τ	$(3.1 \pm 1.9) \cdot 10^{-8}$	$(7.4 \pm 1.9) \cdot 10^{-7}$

Experimental upper limits at 90% (95%) CL

	$BR(B_d \to l^+l^-)$	$BR(B_s \to l^+l^-)$
l = e	$< 5.9 \cdot 10^{-6}$	$< 5.4 \cdot 10^{-5}$
l = μ	$< 8.3 \cdot 10^{-8}$	$< 4.1(5.0) \cdot 10^{-7}$
l = τ	$< 2.5\%$	$< 5.0\%$

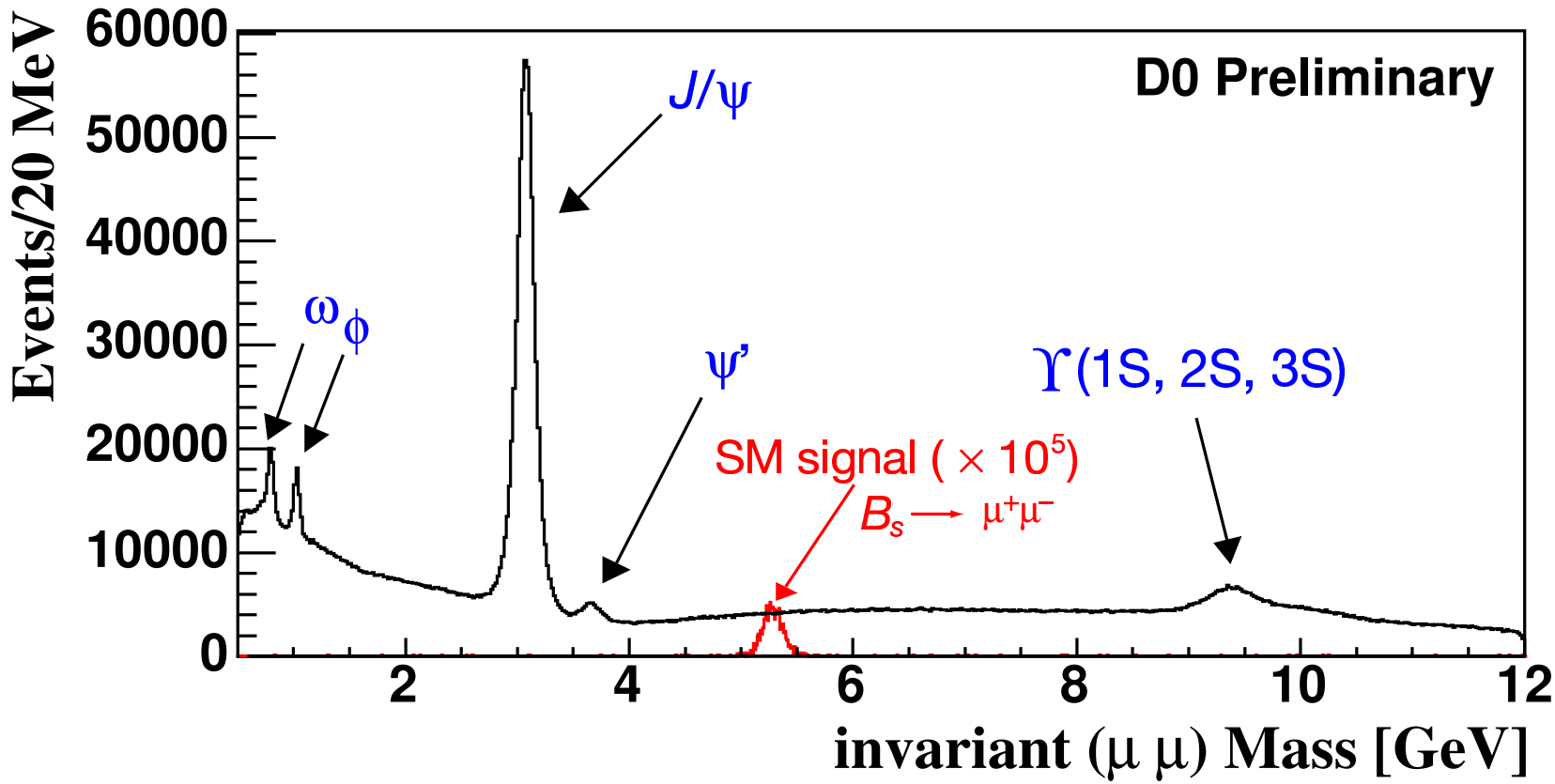
$B_s \to \mu^+\mu^-$ decay in the Two Higgs-Doublet Model





- Parameters of the neutral Higgs sector cancel out
- Branching fraction depends only on charged Higgs mass and $\tan\beta$
- Branching fraction increases like $\tan^4\beta$ ($\tan^6\beta$) in 2HDM (MSSM).
- Mode is complementary to $b \to s\gamma$
- R parity violating models can give tree level contributions

DØ dimuon sample of $\approx 240\text{pb}^{-1}$



- Signal region is $m_{B_s^0} \pm 2\sigma = 5.160 < m_{B_s} < 5.520$ GeV/c^2

Pre-Selection Cuts

- Normalize to the $B^+ \to J/\psi K^+$ decay
- Cut on Mass region of DiMuon sample $4.5 < m_{\mu\mu} < 7$ GeV/c^2
- Two good muons with a net charge of zero and p_T greater than 2.5 GeV
- The triggered muons have reconstructed tracks in the tracker
- Good reconstructed vertex
- A minimum p_T of the B_s candidate of 5 GeV is required
- Cut on the uncertainty of the transverse decay length $\sigma(L_{xy}) < 150\mu m$

38k events remain

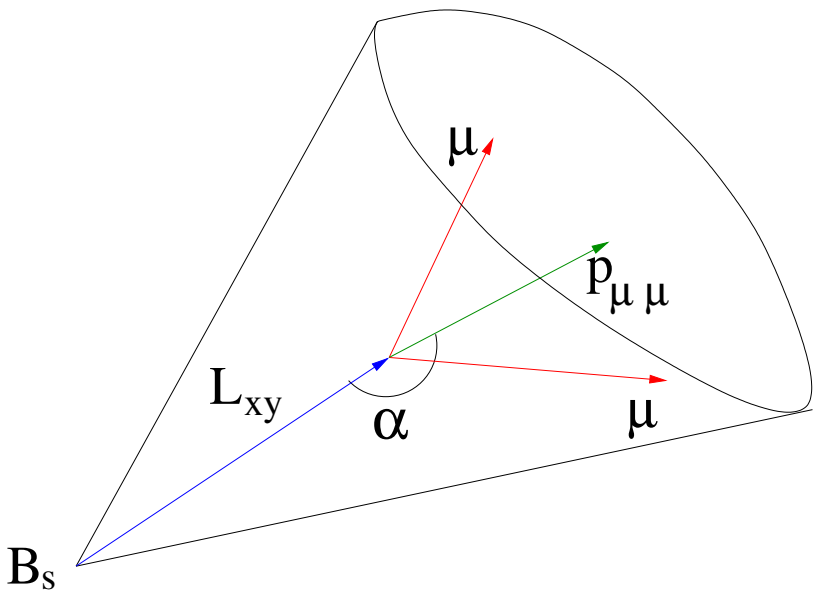
Discriminating variables

- ⊕ Opening angle α between the vertex direction and the muon pair "Pointing consistency"
- ⊕ Decay length significance $(L_{xy}/\sigma(L_{xy}))$
- ⊕ Isolation of the muon pair

$$\text{Iso} = \frac{p_{B_s}}{p_{B_s} + \sum_{\text{allTracks}\Delta R \leq 1} p}$$

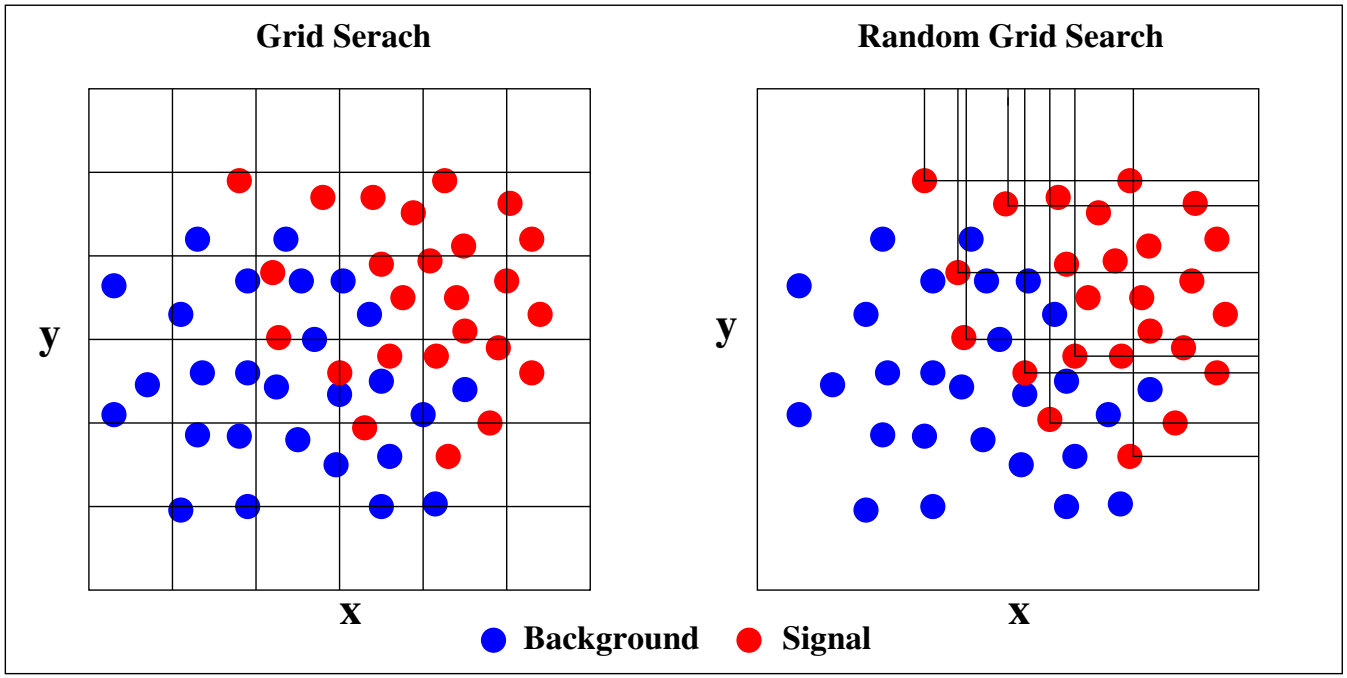
with

$$\Delta R = \sqrt{(\Delta\Phi)^2 + (\Delta\eta)^2} \leq 1$$



Optimization procedure

- To optimize cuts on a small data subset and keep signal region as a blind box
- Performed random grid search of the 3 discriminating variables

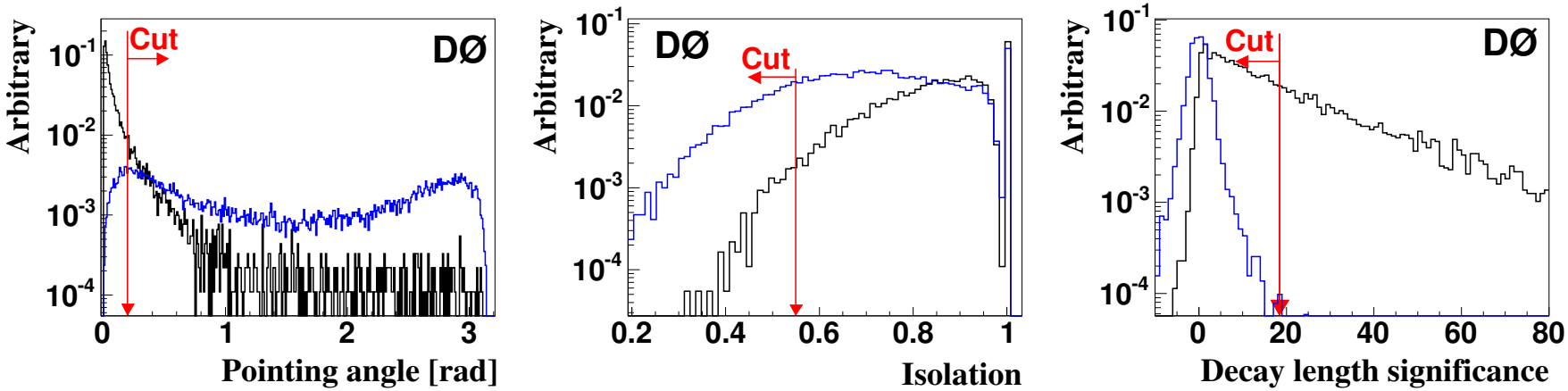


- Maximize sensitivity of searches for new signals

$$P = \frac{\epsilon_{\mu^+\mu^-}}{a/2 + \sqrt{B}}$$

define α as significance of the test
a is the number of sigmas for α(i.e 95% $\rightarrow$ 2 σ $\rightarrow$ a=2)

Discriminating variables - Optimization results



Pointing angle
$\alpha < 0.2$ radians

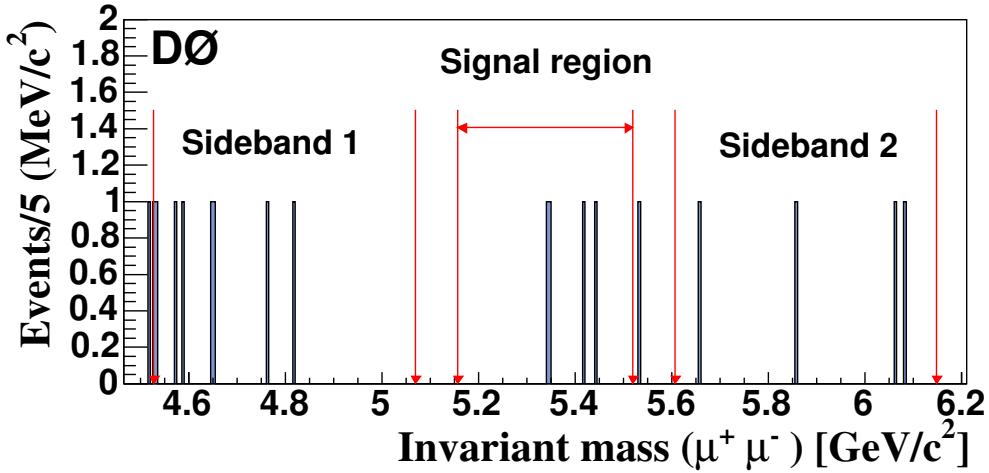
Isolation > 0.56

Transverse decay length
significance > 18.5

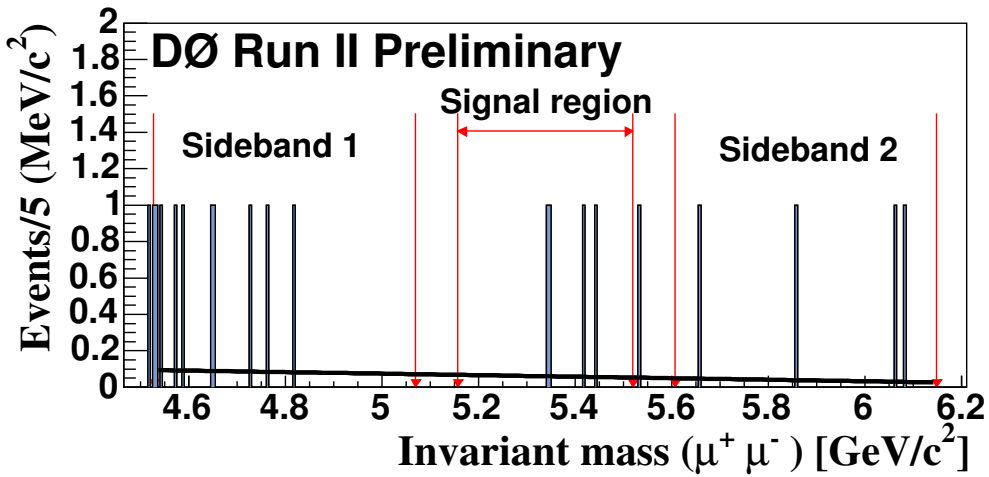
Cut	MC efficiency [%]	Signal MC	ex. Background
Pointing angle	83.4	8016	573 ± 14
Decay length sig	47.5	3847	4.3 ± 1.2
Isolation	97.4	3746	3.7 ± 1.1

Expect 3.7±1.1 background events in 240pb^{-1}

Surviving events



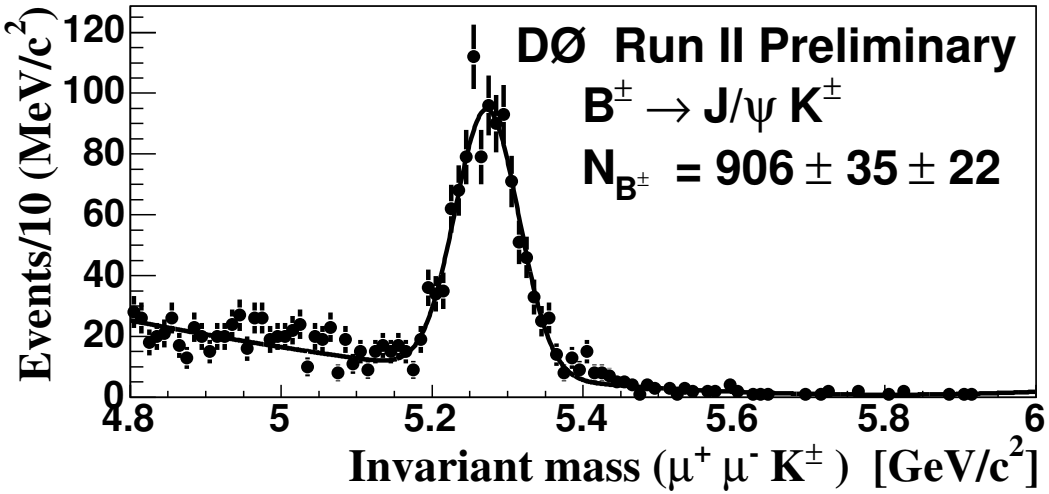
Published! – Expect 3.7 ± 1.1 events in 240pb^{-1} and observe 4



Update! – Expect 4.3 ± 1.2 events in 300pb^{-1} and observe 4

Normalizing channel $B^{\pm} \to J/\psi K^{\pm}$

- Use the decay of the $J/\psi \to \mu\mu$ to cancel $\mu\mu$ efficiencies (Apply same cuts to J/ψ like above.)
- Vertex an additional track to the J/ψ
- Additional cuts on the Kaon and $B^{\pm}$
  - Kaon pt of .9 Gev is required
  - χ^2 of the vertex fit contribution not more than 10, together not more than 20
  - Collinearity of .9 is required



Fit of a gaussian with a quadratic background

Calculating the upper Limit

$$\mathcal{B}(B_s \to \mu^+\mu^-) \leq \frac{N_{UL}(n_{obs}, n_B)}{N_{B^\pm}} \cdot \frac{\epsilon^{B^\pm}_{\mu\mu K}}{\epsilon^{B_s}_{\mu\mu}} \cdot \frac{\mathcal{B}(B^\pm \to J/\psi K^\pm) \cdot \mathcal{B}(J/\psi \to \mu\mu)}{\frac{f_{b\to B_s}}{f_{b\to B_{u,d}}} + R \cdot \frac{\epsilon^{B_d}_{\mu\mu}}{\epsilon^{B_s}_{\mu\mu}}}$$

- $N_{UL}(n_{obs}, n_B)$ is the Upper Limit calculated using the Feldman-Cousins method
  4 events observed and 4.3 $\pm$1.2 background expected
- $N_{B^\pm}$ is the number of accepted $B^\pm \to J/\psi K^\pm$ events
  $N_{B^\pm} = 906 \pm 35 \pm 22$ events
- $\varepsilon_{\mu\mu}$ and $\varepsilon_{\mu\mu K}$ are reconstruction efficiencies
  $\varepsilon_{\mu\mu K}/\varepsilon_{\mu\mu} = 0.247 \pm 0.009 \pm 0.017$
- Correction factor for fragmentation $f_{b\to B_s}/f_{b\to B_{u,d}} = 0.270 \pm 0.034$ PDG
- Assume no B_d contribution i.e. R=0 due to its suppression by $|V_{td}/V_{ts}|^2$
  valid in all MFV models

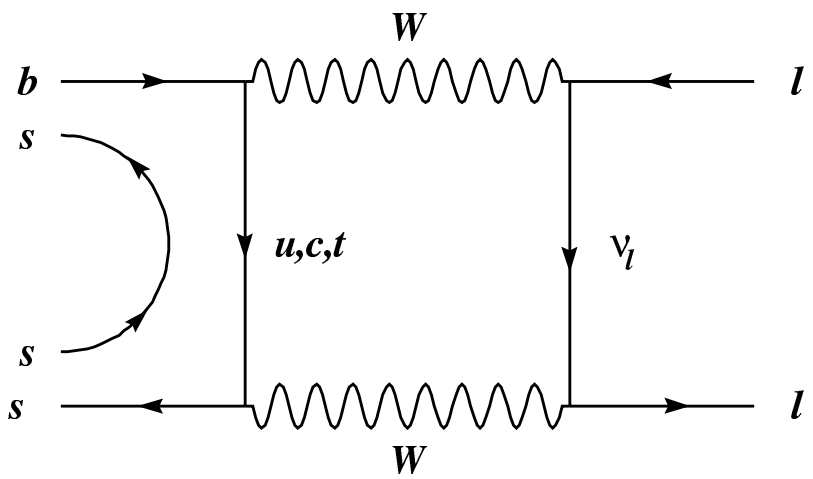
$$\mathcal{B}(B_s \to \mu^+\mu^-) \leq 3.7 \cdot 10^{-7} (3.0 \cdot 10^{-7}) \text{ at } 95\% \ (90\%) \text{ C.L.}$$

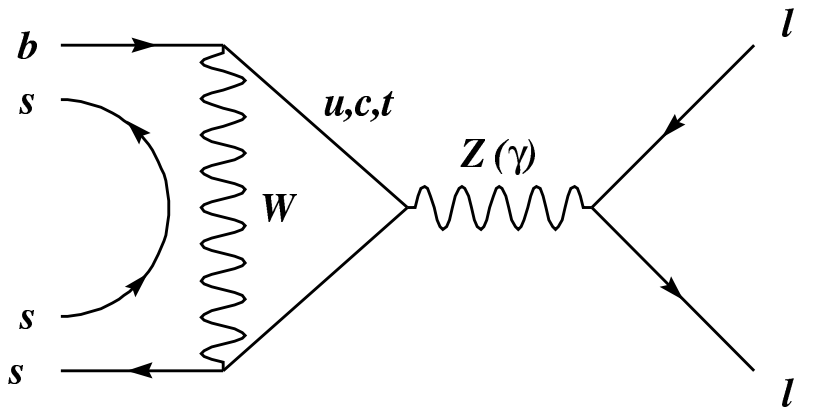
Published in Phys.Rev.Lett.94:071802,2005 is

$$\mathcal{B}(B_s \to \mu^+\mu^-) \leq 5.0 \cdot 10^{-7} (4.1 \cdot 10^{-7}) \text{ at } 95\% \ (90\%) \text{ C.L.}$$

Introduction to the $B_s \to l^+l^-\phi$ decay (SM)

One-loop diagrams in the Standard Model



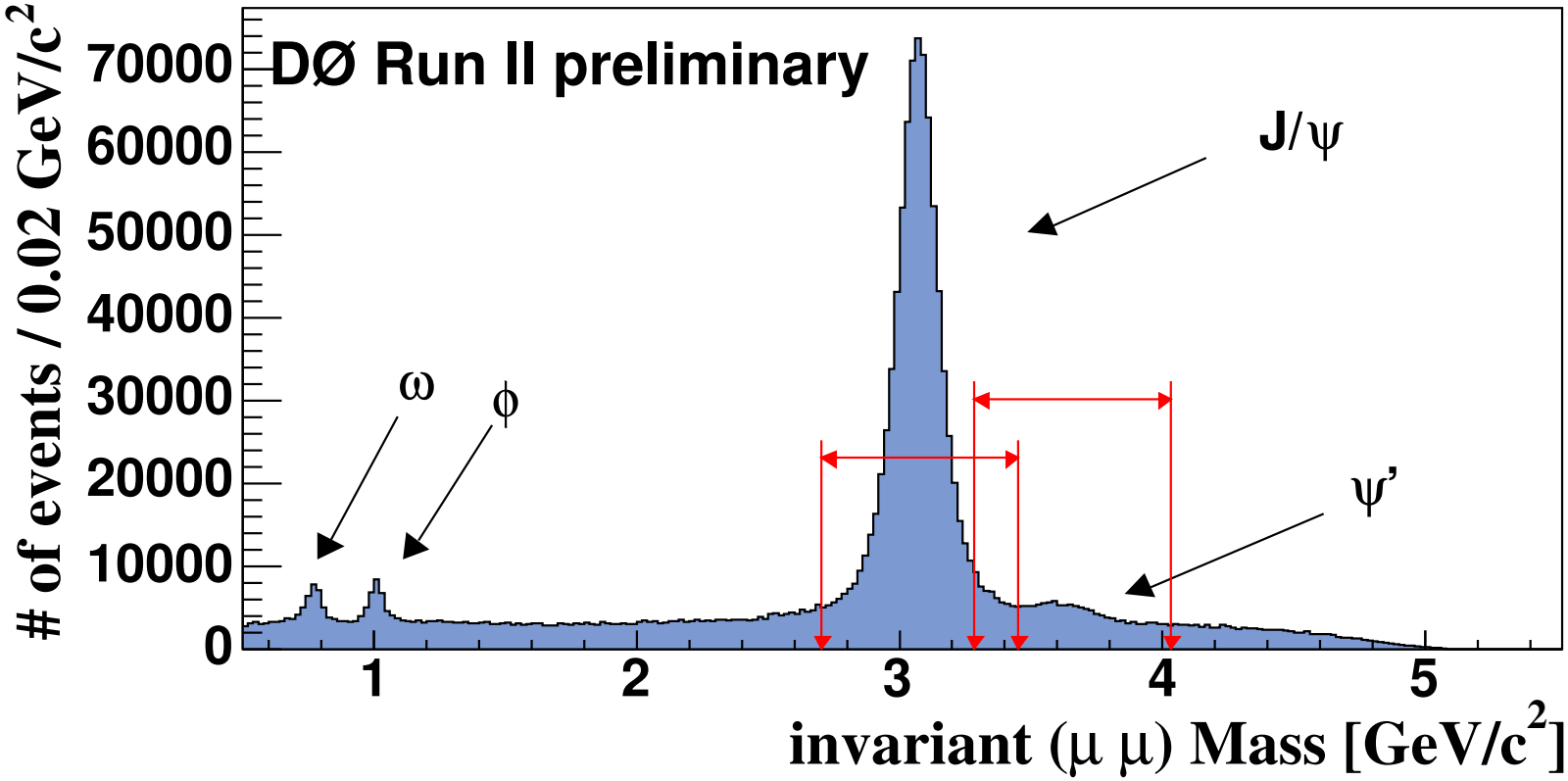


- FCNC suppressed but induced by electroweak pinguin and box diagrams
- Inclusive $B \to X_s l^+l^-$ measured by B-factories (l either μ or e) $\mathcal{B} = 4.46 \pm^{+0.98}_{-0.96} \times 10^{-6}$
- Exclusive modes $B \to K^* l^+l^-$ and $B \to K l^+l^-$ have also been measured and agree within SM
- SM prediction of $B_s^0 \to \mu^+\mu^-\phi) \approx 1.6 \times 10^{-6}$
- Potential enhancements in SUSY-models.
- Only existing bound CDF Run I $\mathcal{B}(B_s^0 \to \mu^+\mu^-\phi) < 6.7 \times 10^{-5}$

$B_s^0 \to \mu\mu\phi$ Selection Cuts

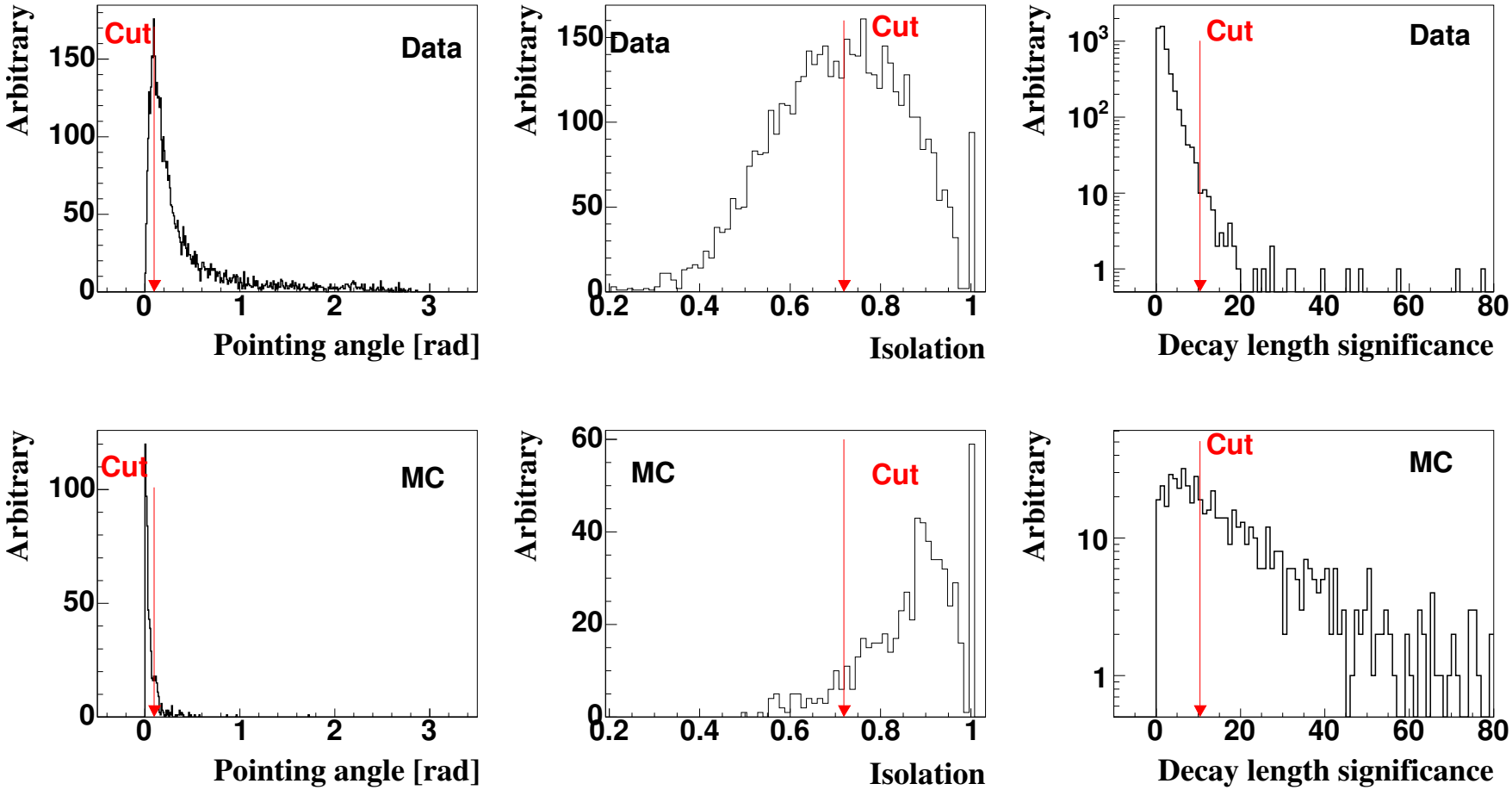
- Use 300pb^{-1} of data
- Normalize to the $B_s^0 \to J/\psi\phi$ decay
- Cut on Mass region $0.5 < m_{\mu\mu} < 4.4$ GeV/c^2 excl. J/ψ,Ψ'
- Two good muons with a net charge of zero and p_T greater than 2.5 GeV
- The triggered muons have reconstructed tracks in the tracker
- Good reconstructed vertex
- A minimum p_T of the B_s candidate of 5 GeV is required
- Cut on the uncertainty of the transverse decay length $\sigma(L_{xy}) < 150\mu m$
- B_s collinearity > 0.95
- A ϕ candidate mass $1.008 < m_\phi <$1.032 GeV/c^2

DØ dimuon sample of $\approx 300\text{pb}^{-1}$



- Dimuon candidates combined with an additional ϕ candiate in the range $0.980 < m_\phi < 1.080$ GeV/c^2

Discriminating variables - Optimization results



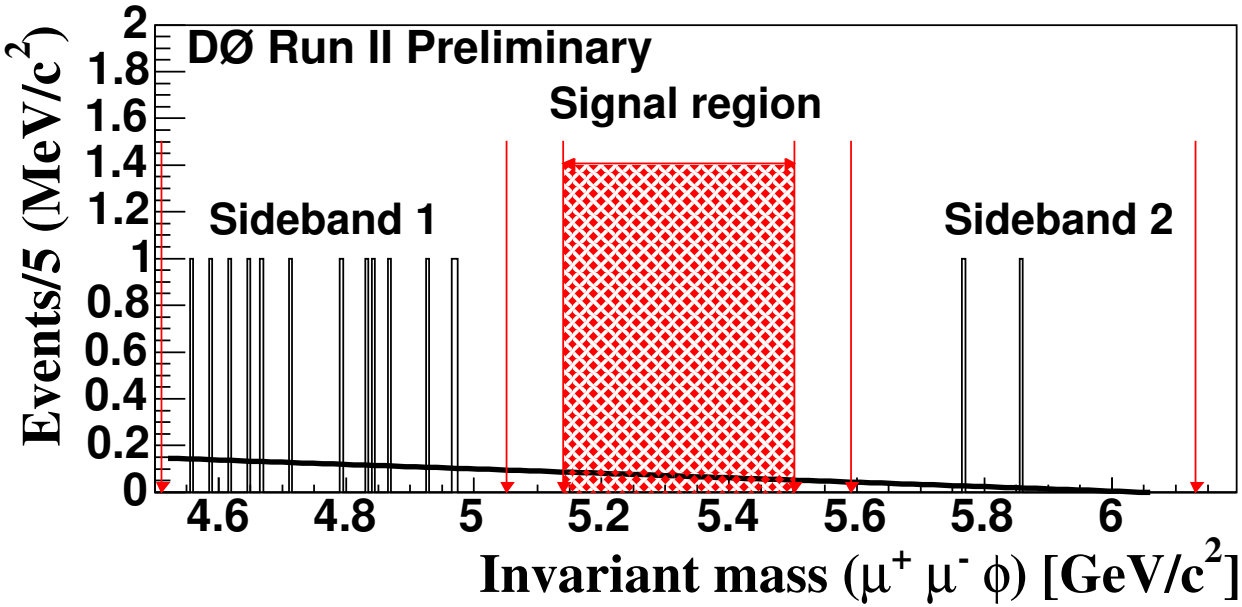
Pointing angle
$\alpha < 0.1$ radians

Isolation > 0.72

Transverse decay length
significance > 10.5

After the final cuts

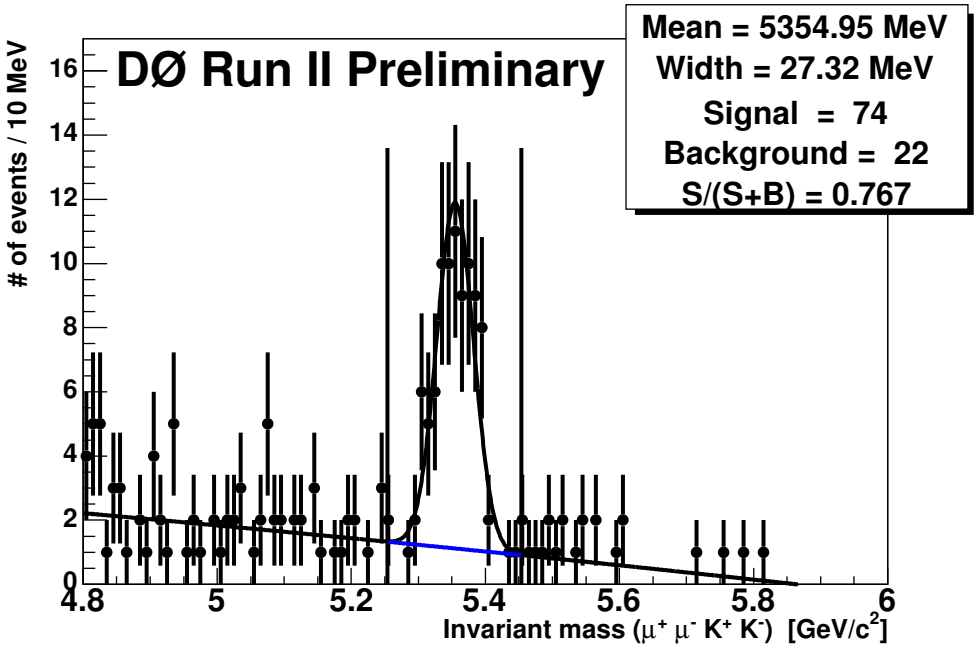
Cut	MC efficiency [%]	ex. Background
Pointing angle	81	291 ± 10
Decay length	71	8.7 ± 1.6
Isolation	92	5.1 ± 1.0



Box kept closed!

Normalizing channel $B_s \to J/\psi\phi$

- Invariant Dimuon mass at J/ψ and use of mass constraint



Fit of a gaussian with a quadratic background
$N_{B_s} = 74 \pm 11$ (stat)

Calculating the 'Limit' for the B_s normalization

$$\frac{\mathcal{B}(B_s \to \mu^+\mu^-\phi)}{\mathcal{B}(B_s \to J/\psi\phi)} = \frac{N_{UL}(n_{obs}, n_{back})}{N_{B_s}} \cdot \frac{\epsilon_{J/\psi\phi}}{\epsilon_{\mu\mu\phi}} \cdot \mathcal{B}(J/\psi \to \mu\mu)$$

- $N_{UL}(n_{obs}, n_{back})$ is the Upper Limit calculated using a Feldman-Cousins ordering scheme $n_{back} = 5.1 \pm 1.0$ events
- N_{B_s} is the number of accepted $B_s \to J/\psi\phi$ events
  $N_{B_s} = 74 \pm 11$ events
- $\varepsilon_{J/\psi\phi}$ and $\varepsilon_{\mu\mu\phi}$ are reconstruction efficiencies from MC
  $\varepsilon_{J/\psi\phi}/\varepsilon_{\mu\mu\phi} = 2.19 \pm 0.13(stat)$

Expected statistical average upper limit is calculated via

$$< \frac{\mathcal{B}(B_s \to \mu^+\mu^-\phi)}{\mathcal{B}(B_s \to J/\psi\phi)} >= \sum_{n_{obs}=0}^{\infty} \frac{\mathcal{B}(n_{obs}, n_{back})}{\mathcal{B}(B_s \to J/\psi\phi)} \cdot \frac{n_{back}^{n_{obs}}}{(n_{obs})!} \cdot \exp(-n_{back})$$

$$< \frac{\mathcal{B}(B_s \to \mu^+\mu^-\phi)}{\mathcal{B}(B_s \to J/\psi\phi)} > \; = 1.3 \cdot 10^{-2} \text{ at } 95\% \text{ CL}$$

if $\mathcal{B}(B_s \to J/\psi\phi)$ is taken to be $9.3 \cdot 10^{-4}$

$$< \mathcal{B}(B_s \to \mu^+\mu^-\phi) > \; = 1.2 \cdot 10^{-5} \text{ at } 95\% \text{ CL}$$

Motivation for the $B_s \to \psi(2S)\phi$ decay

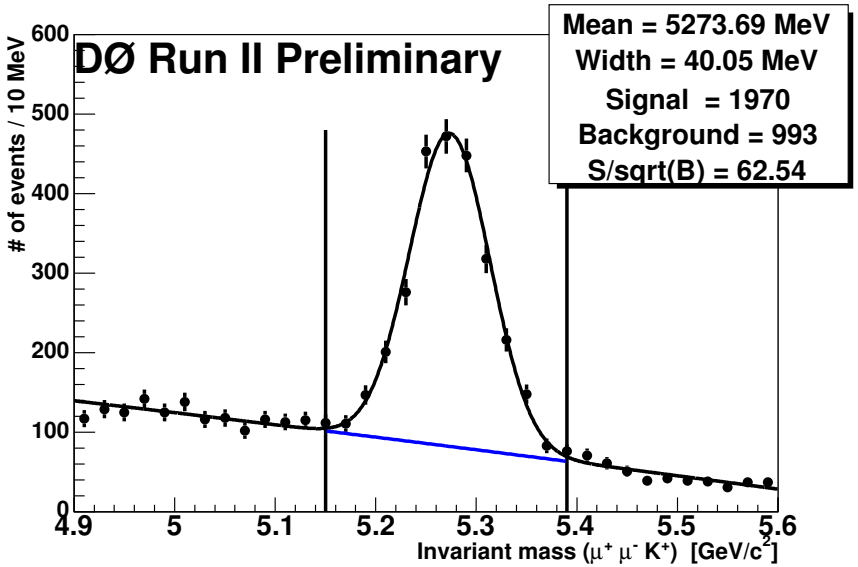
- PDG says the decay has been "seen" (1 event by ALEPH in 1992 where they measured the B_s mass)
- Historically
  - The decay $B^+ \to \psi(2S)K^+$ was observed at ARGUS in 1990
  - $B^0 \to \psi(2S)K^{*0}$ was observed at CDF (Run I) in 1998
  - $B^0 \to \psi(2S)K_s$ and $B^+ \to \psi(2S)K^{*+}$ in the year 2000 be CLEO
- Measurements show that the rates of B^+ and B^0 mesons decay to the $\psi(2S)$ final states is approximately 60% of the rates of the analogues decay to the J/ψ.
- The relative branching ratio $B_s^0 \to \psi(2S)\phi / B_s^0 \to J\psi\phi$ has not yet been measured.

Strategy

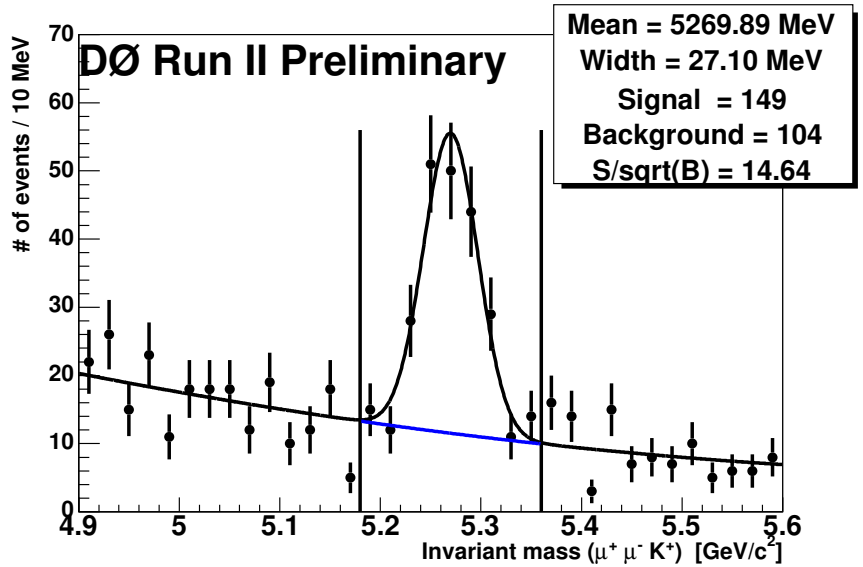
- Use $B^+ \to (J/\psi/\psi(2S))K^+$ as control channel
- Reconstruct the $B_s^0 \to J\psi\phi$ decay.
- Move Di-Muon mass window to the $\psi(2S)$ resonance ($3.45 < m_{\mu^+\mu^-} < 3.95$)
- Constrain the Di-Muon mass candidate to the $\psi(2S)$ mass

$B^+ \to (J/\psi, \psi(2S))K^+$ mass plots

$B^+ \to J/\psi K^+$



$B^+ \to \psi(2S)K^+$



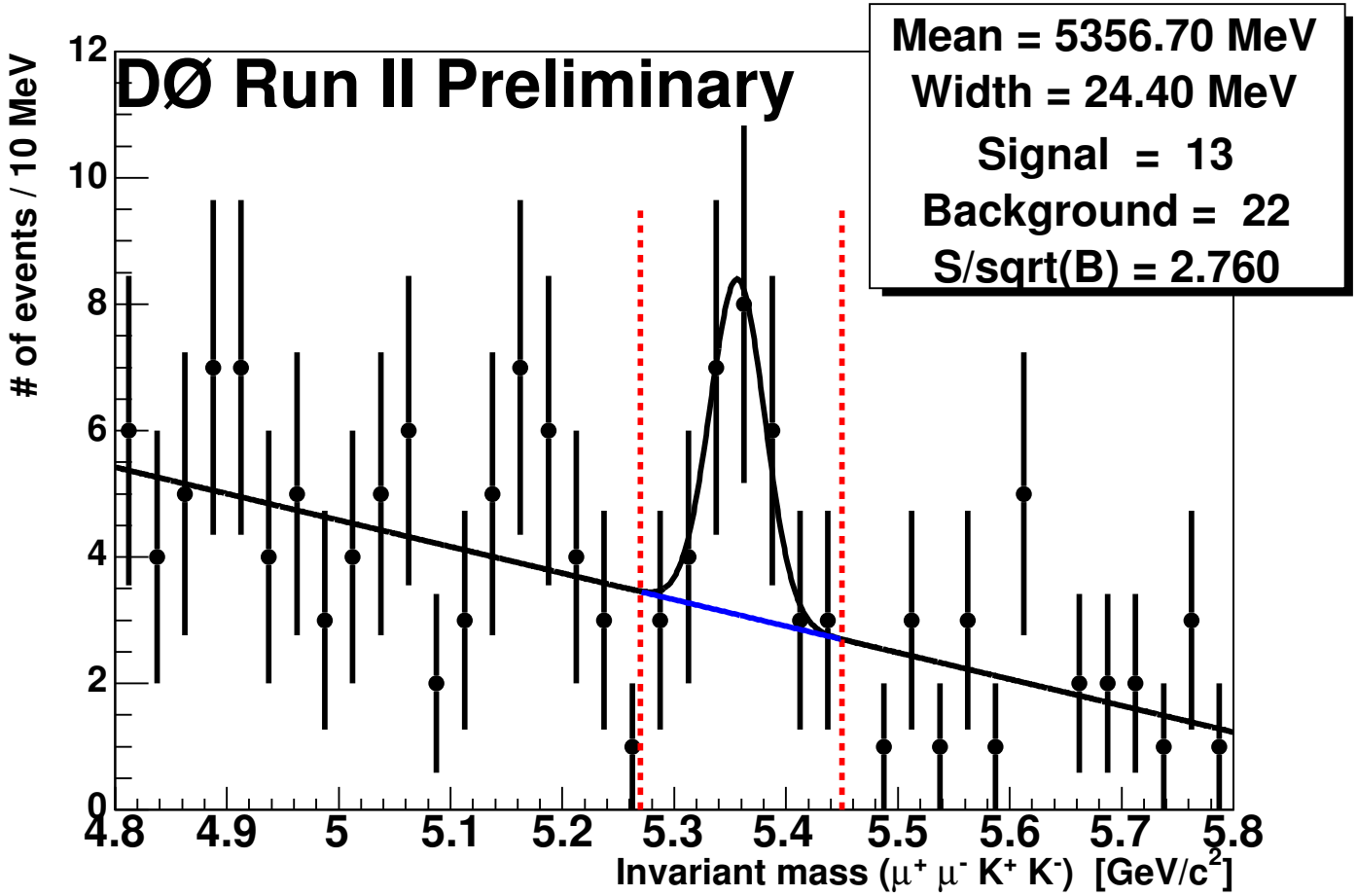
$$\frac{\mathcal{B}(B^+ \to \psi(2S)K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = \frac{N_{\psi(2S)K^+}}{N_{J\psi K^+}} \times \frac{\varepsilon_{\psi(2S)K^+}}{\varepsilon_{J\psi K^+}} \times \frac{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}{\mathcal{B}(J\psi \to \mu^+\mu^-)}$$

$$= 0.60 \pm 0.05(\text{stat}) \pm 0.04(\text{sys}) \pm 0.06(\text{BR})$$

Preliminary!

$$\frac{\mathcal{B}(B^+ \to \psi(2S)K^+)}{\mathcal{B}(B^+ \to J/\psi K^+)} = 0.64 \pm 0.06(\text{stat}) \pm 0.06(\text{sys})[\text{BaBar 02}]$$

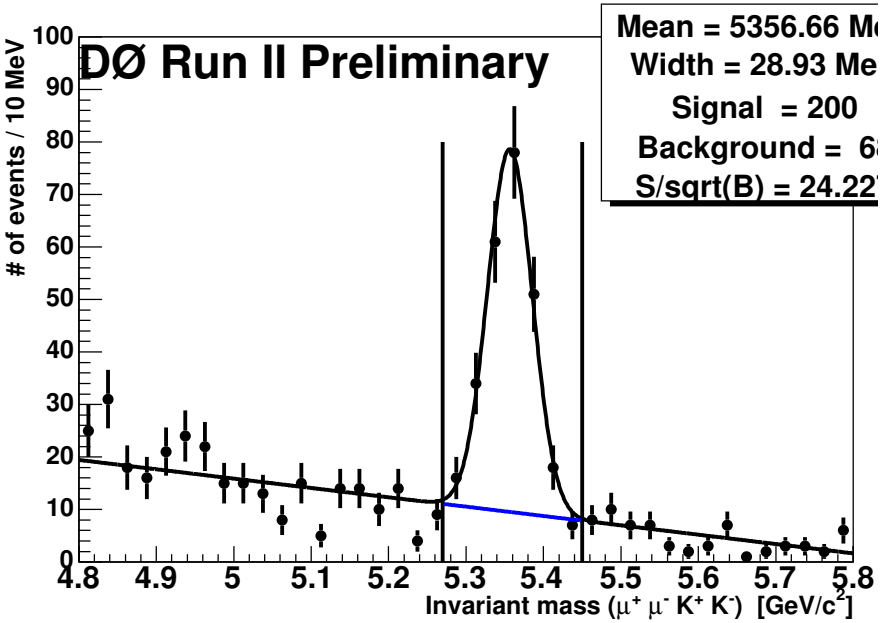
First look at the mass plot



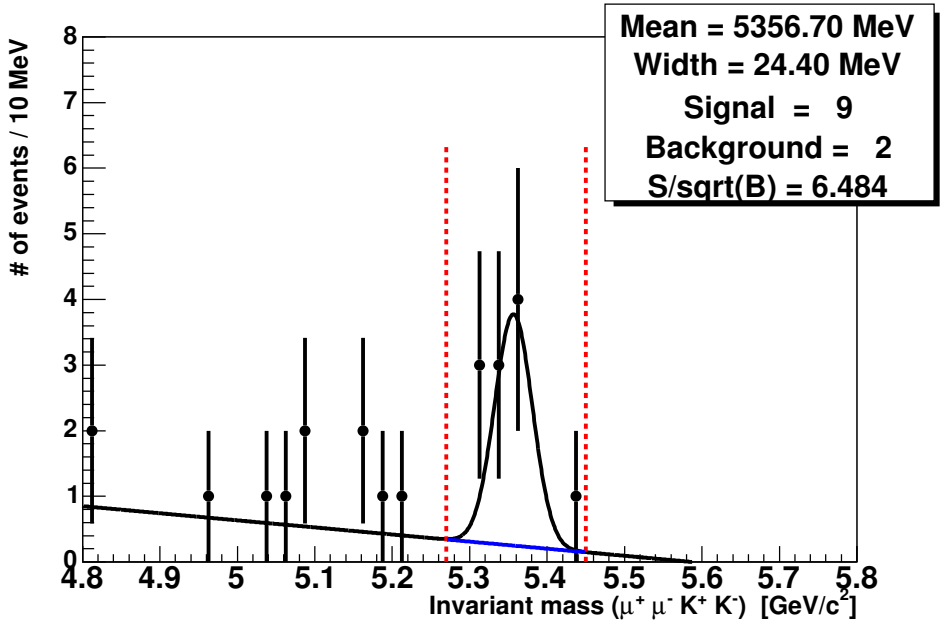
Decay length significance > 4

$B_s^0 \to (J/\psi, \psi(2S))\phi$ mass plots

$B_s^0 \to J/\psi\phi$



$B_s^0 \to \psi(2S)\phi$



$$\frac{\mathcal{B}(B_s^0 \to \psi(2S)\phi)}{\mathcal{B}(B_s^0 \to J/\psi\phi)} = \frac{N_{\psi(2S)\phi}}{N_{J\psi\phi}} \times \frac{\varepsilon_{\psi(2S)\phi}}{\varepsilon_{J\psi\phi}} \times \frac{\mathcal{B}(\psi(2S) \to \mu^+\mu^-)}{\mathcal{B}(J\psi \to \mu^+\mu^-)}$$

$$= 0.60 \pm 0.21(\text{stat}) \pm 0.06(\text{sys}) \pm 0.07(\text{BR})$$

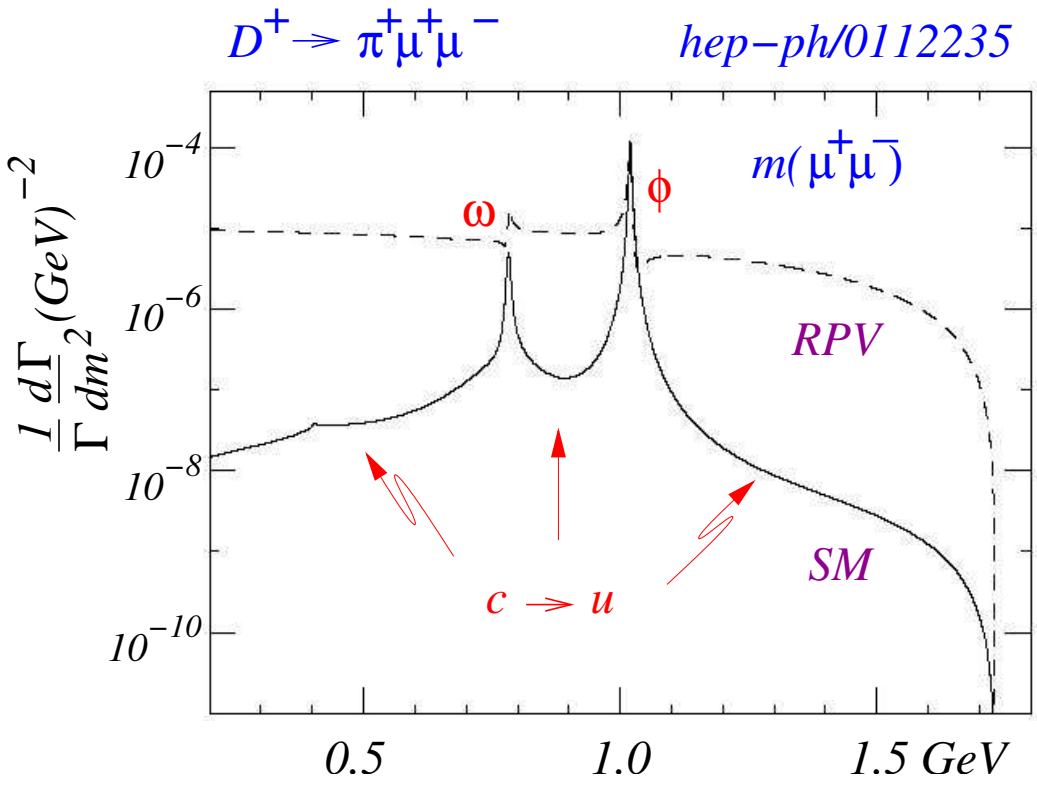
Preliminary!

Motivation for $c \to u l^+ l^-$ decays

FCNC processes $\Rightarrow$ ideal testing ground for new phenomena.

Strict limits already from:
$b \to s$ processes in B decay,
$s \to d$ processes in K decay.

However, large areas of parameter space still untapped in
up sector: $c \to u$, $t \to c$...



Kinematic distributions in three body $c \to u l^+ l^-$ decays can be used w/o to minimize uncertainties related to long distance contributions.

Strategy: First find resonances: $D_s^+ \to \phi\pi^+ \to \pi^+\mu^+\mu^-$, then search for excess in continuum region.

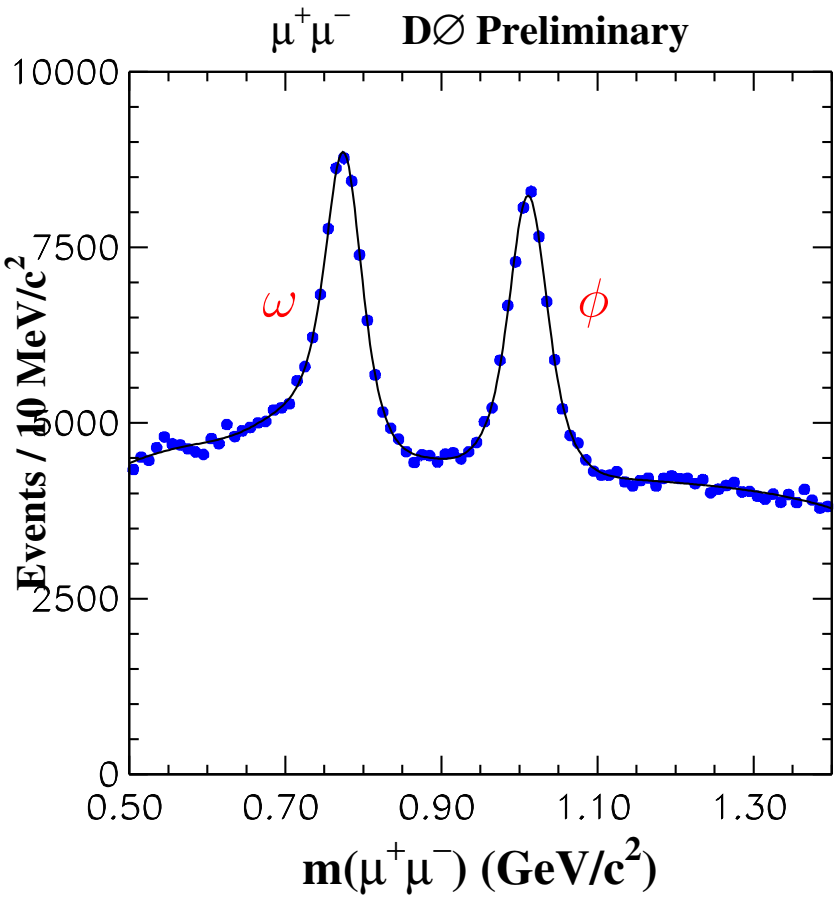
D Selection

508 pb^{-1}

select $\phi \to \mu^+\mu^-$:
$0.96 < m(\mu^+\mu-) < 1.06$ GeV

combine $\mu^+\mu^-$
with a track in the same jet
$p_T > 180$ MeV

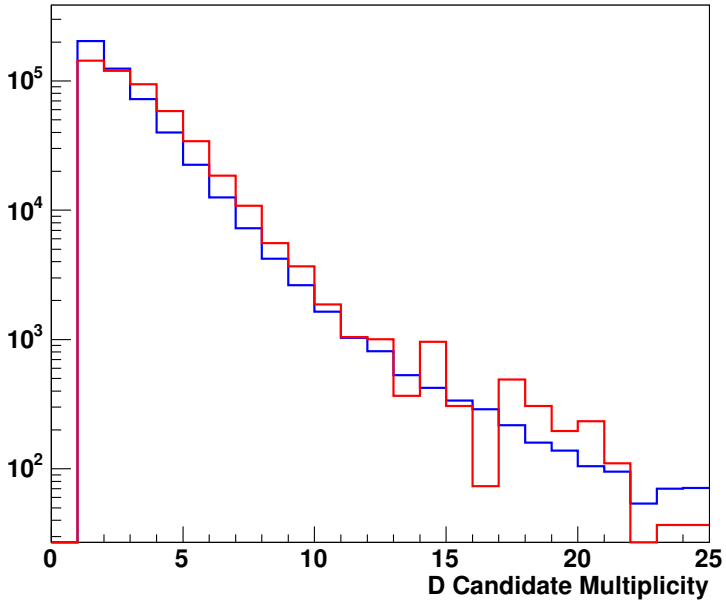
Select D: $1.4 < m(\pi^+\mu^+\mu^-) < 2.4$ GeV



Best Track Selection

large track mult. $\Rightarrow$ several D candidates per event

$\langle n_{cand} \rangle = 2.5/\text{evt}$



choose minimum:

$\mathcal{M} = \chi^2_{\text{vtx}} + (1/p_T(\pi))^2 + \Delta R^2_\pi$

	ϵ
ΔR	0.70
χ^2	0.83
p_T	0.88
$\mathcal{M}$	0.90

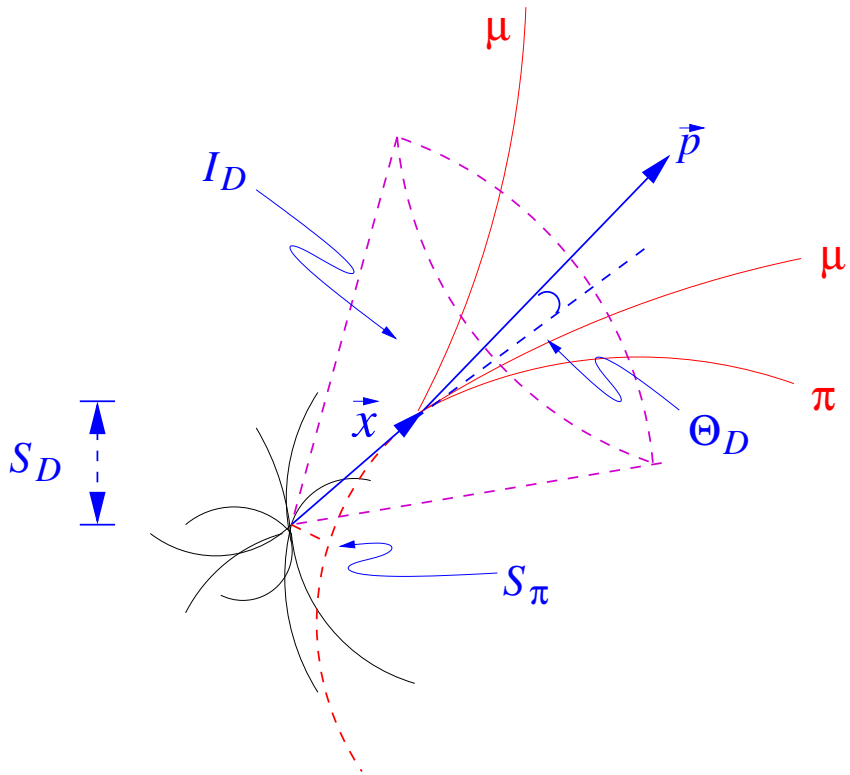
correct track typically:

- forms good vtx with $\mu^+\mu^-$,
- has higher p_T,
- is close to $\mu^+\mu^-$ ($\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$)

retain 90% of true signal
remove 60% of background

Background Suppression

Signal:	large $c\tau$, good vtx, points to IP, contains most of jet energy
uds:	$c\tau = 0$, good vtx, random pointing, contains fraction of jet energy
$c\bar{c}$, $b\bar{b}$:	large $c\tau$, poor vtx, random pointing, contains fraction of jet energy

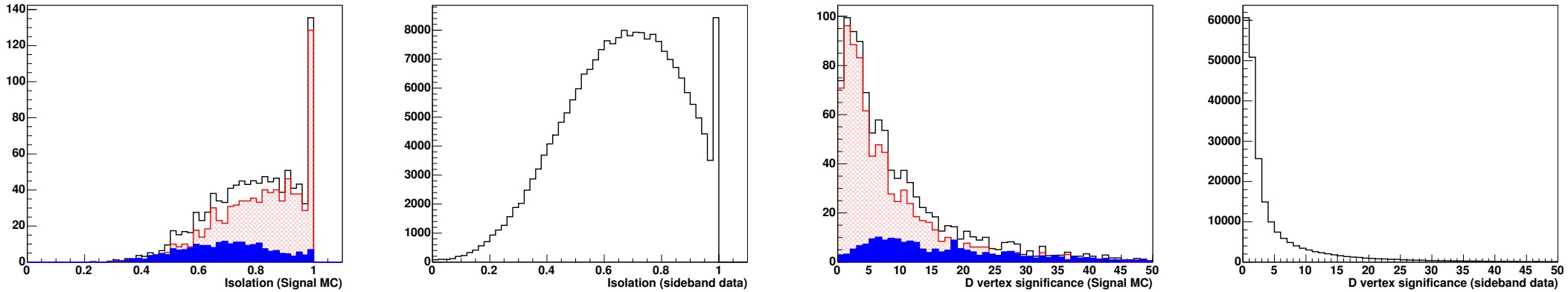


$\mathcal{I}_D$:	D isolation
$\mathcal{S}_D$:	D ct significance
Θ_D:	D collinearity angle
$\mathcal{R}_\mathcal{S}$:	Ratio of π impact parameter sig. to $\mathcal{S}_D$

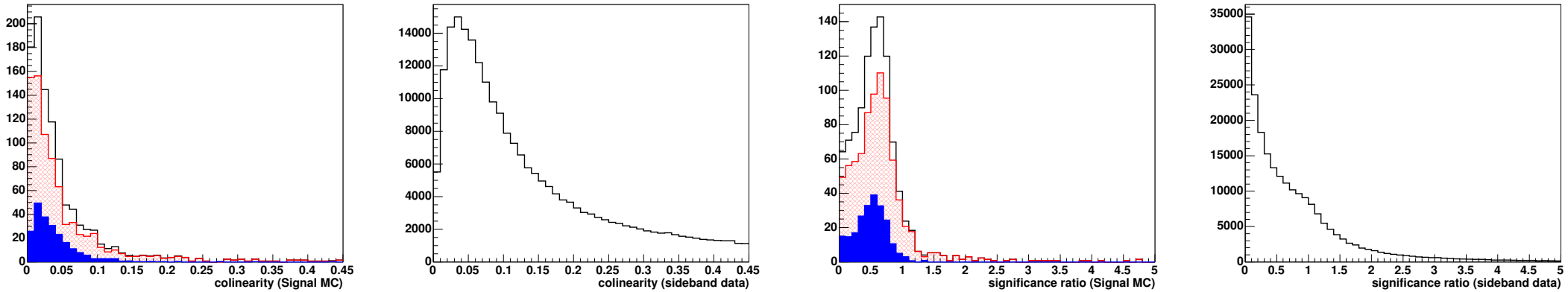
Suppression Variables

MC: red: $p\bar{p} \to c\bar{c}$, blue: $p\bar{p} \to b\bar{b}$, $b \to c$; data from D mass sidebands

MC | data sidebands | MC | data sidebands



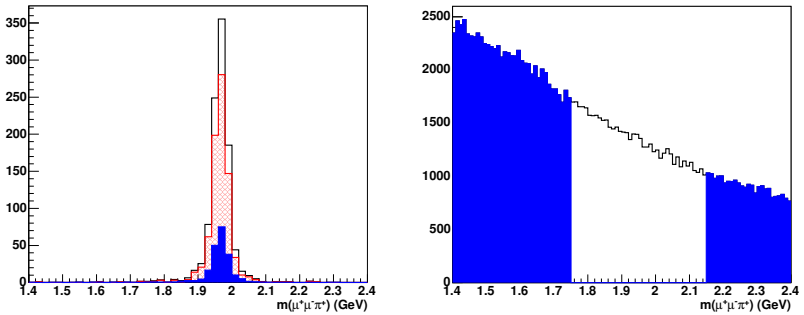
D isolation $\mathcal{I}_D$ | D flight length significance $\mathcal{S}_D$



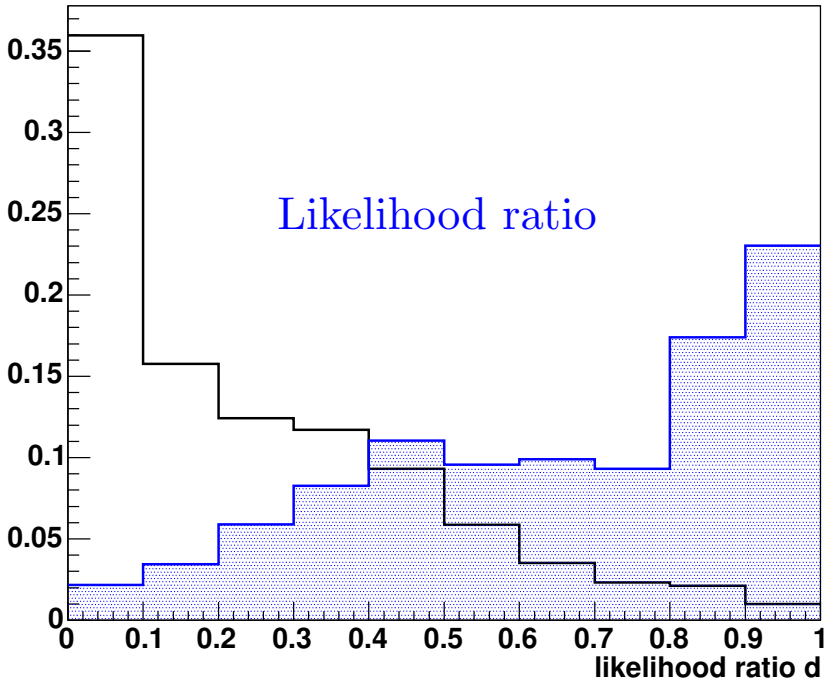
D collinearity angle Θ_D | significance ratio $\mathcal{R}_\mathcal{S}$

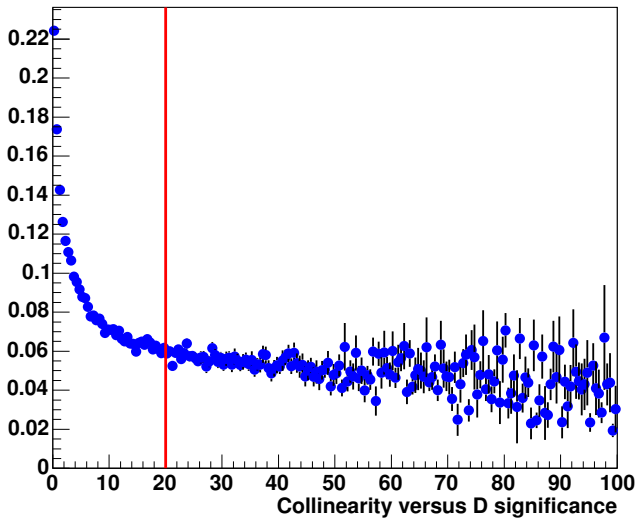
Combined Likelihood

Form a combined likelihood



sig PDF: MC, back PDF: sidebands



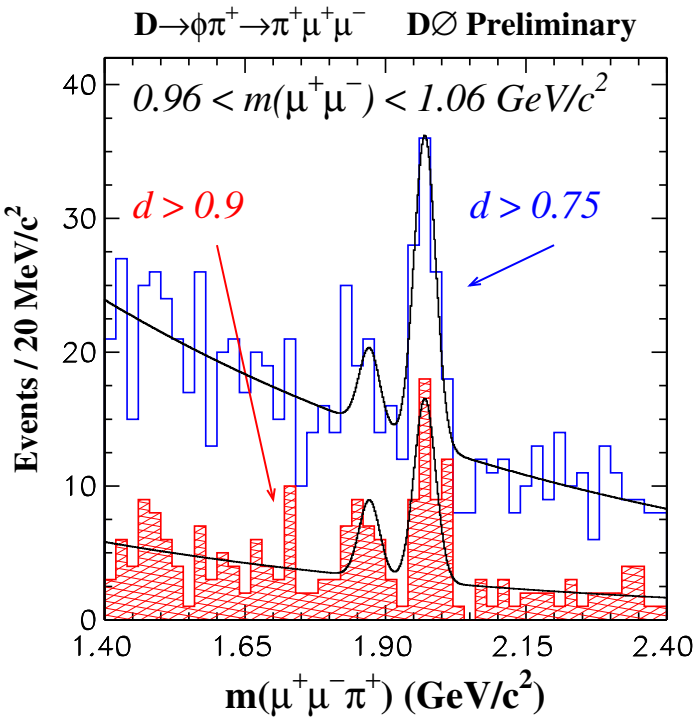


include correlations

$\mathcal{S}_D < 20$:
$\mathcal{L} = \mathcal{L}(\mathcal{I}_D) \times \mathcal{L}(\mathcal{S}_D, \Theta_D, \mathcal{R}_\mathcal{S})$

$\mathcal{S}_D \geq 20$:
$\mathcal{L} = \mathcal{L}(\mathcal{I}_D) \times \mathcal{L}(\mathcal{S}_D) \times \mathcal{L}(\Theta_D) \times \mathcal{L}(\mathcal{R}_\mathcal{S})$

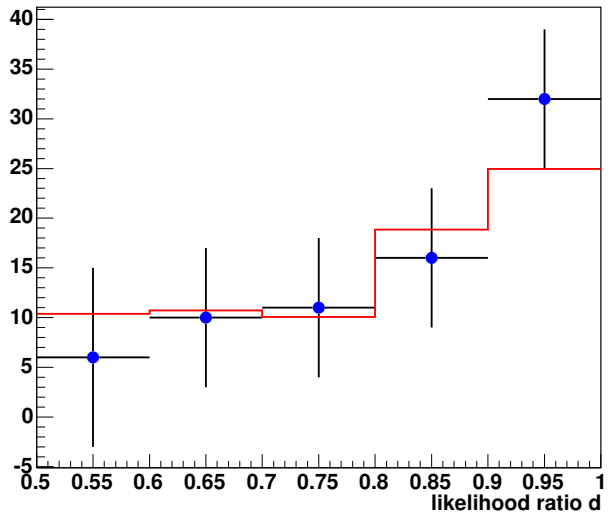
Results



Fit: 33 ± 7 D_s cand. ($> 7\sigma$)

13 ± 5 D^+ cand. (2.7σ)

D_s yield as a function of likelihood ratio



good agreement between data and MC for background suppression variables.

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

Conclusions

Limit on FCNC decay $B_s \to \mu^+\mu^-$

- Published limit on $B_s \to \mu^+\mu^-$ (with ≈ 240 pb^{-1} of data)
  Published in Phys.Rev.Lett.94:071802,2005
  $\mathcal{B}(B_s \to \mu^+\mu^-) \leq 5.0 \cdot 10^{-7}(4.1 \cdot 10^{-7})$ at 95% (90%) C.L.
- Update of limit on $B_s \to \mu^+\mu^-$ (with ≈ 300 pb^{-1} of data)
  $\mathcal{B}(B_s \to \mu^+\mu^-) \leq 3.7 \cdot 10^{-7}(3.0 \cdot 10^{-7})$ at 95% (90%) C.L. (Preliminary!)

Serach for FCNC $B_s \to \mu^+\mu^-\phi$

- Expected statistical average upper limit is at 95%CL is
  $< \mathcal{B}(B_s \to \mu^+\mu^-\phi) > \; = 1.2 \cdot 10^{-5}$
  if we use $\mathcal{B}(B_s \to J/\psi\phi) = 9.3 \cdot 10^{-4}$ (Preliminary!)
- This should Improve the best published limit by a factor 6
- But still $\approx \mathcal{O}(1)$ away from the SM (with ≈ 300 pb^{-1} of data)

Observation of $B_s^0 \to \psi(2S)\,\phi$

- $B_s^0 \to \psi(2)\,\phi$ events have been observed.
- The relative branching ratio $B_s^0 \to \psi(2S)\,\phi / B_s^0 \to J/\psi\phi$ has been measured to be $0.60 \pm 0.21(\text{stat}) \pm 0.06(\text{sys}) \pm 0.07(\text{BR})$ (Preliminary!)
- Also $B^\pm \to \psi(2S)K^\pm / B^\pm \to J\psi K^\pm$ has been measured to be $0.60 \pm 0.05(\text{stat}) \pm 0.04(\text{sys}) \pm 0.06(\text{BR})$ (Preliminary!)

Flavor Changing Neutral Current Charm Decays

- First obs.of the benchmark channel $D_s \to \phi\pi \to \pi\mu^+\mu^-$
  - first step in program to study 3-body FCNC c decays.
- Limit on $\mathcal{B}(D^+)$ of 3.14×10^{-6} (Preliminary!) indicates DØ has the best sensitivity due to enormous charm x-sections at the Tevatron and excellent DØ muon ID.