Rare Decays at the Tevatron

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Lattice QCD Meets Experiment
Workshop 2007

December 10, 2007

Outline

- Experimental Environment
- $B_S \rightarrow \mu\ \mu$ (CDF & D0)
- $B_S \rightarrow \mu\ \mu X$ (CDF & D0)
- $B, \Lambda_b \rightarrow hh$ (CDF)
- FCNC D Decay (D0)

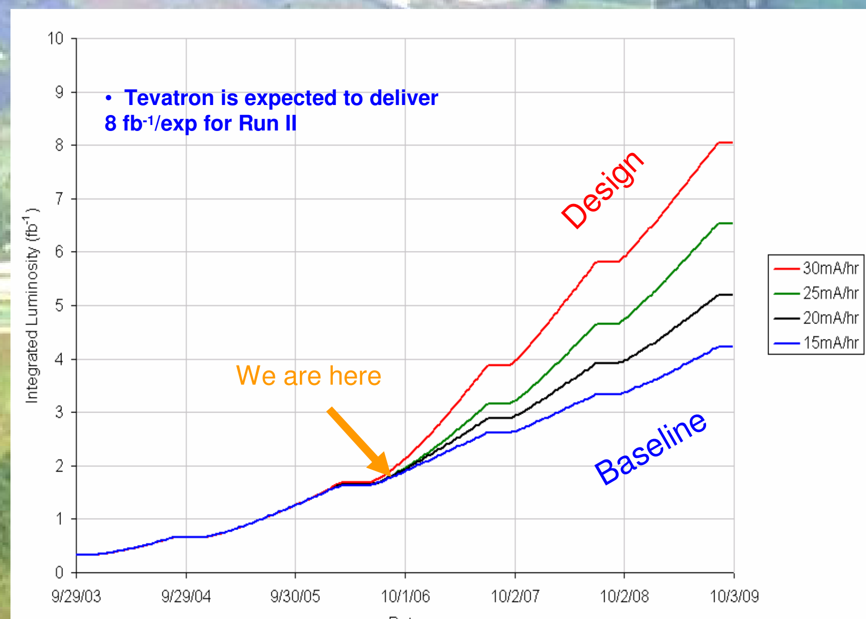
TEVATRON

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 with good purity level in hadronic environment**
- **Analyses presented today use**
  0.450 to 2 fb^{-1} of data



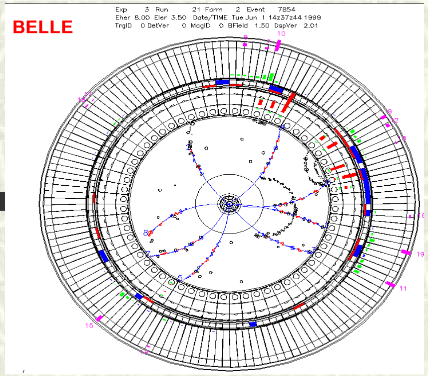
Tevatron Integrated Luminosity Projection

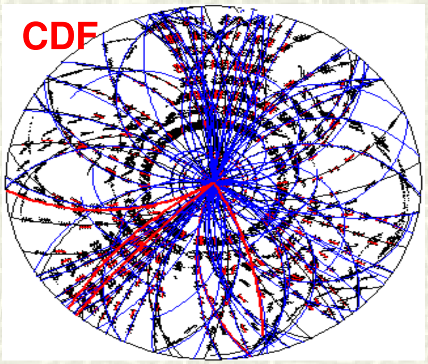
B Triggers

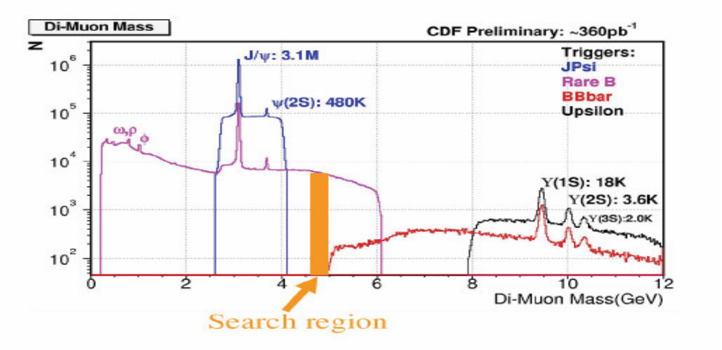
- **Trigger is the lifeline of B physics in a hadron environment**
- Rare B "Di-Muon" triggers:
  - Low single muon thresholds
  - Require Sum p_T or outer muon chambers
  - Di-muon trigger is the primary trigger

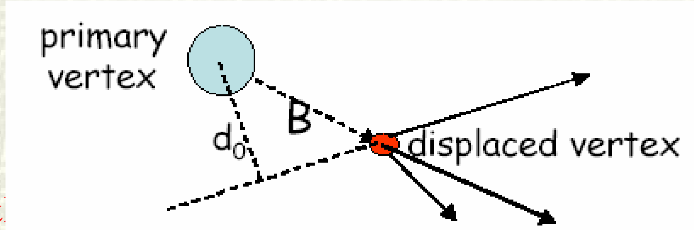
    for the CDF $B_s \rightarrow \mu^+\mu^-$ search

- "Hadronic" triggers using silicon vertex detectors:
  - Exploit long lifetime of heavy quarks
  - Two-track trigger
    - Two oppositely charged tracks with large impact parameters





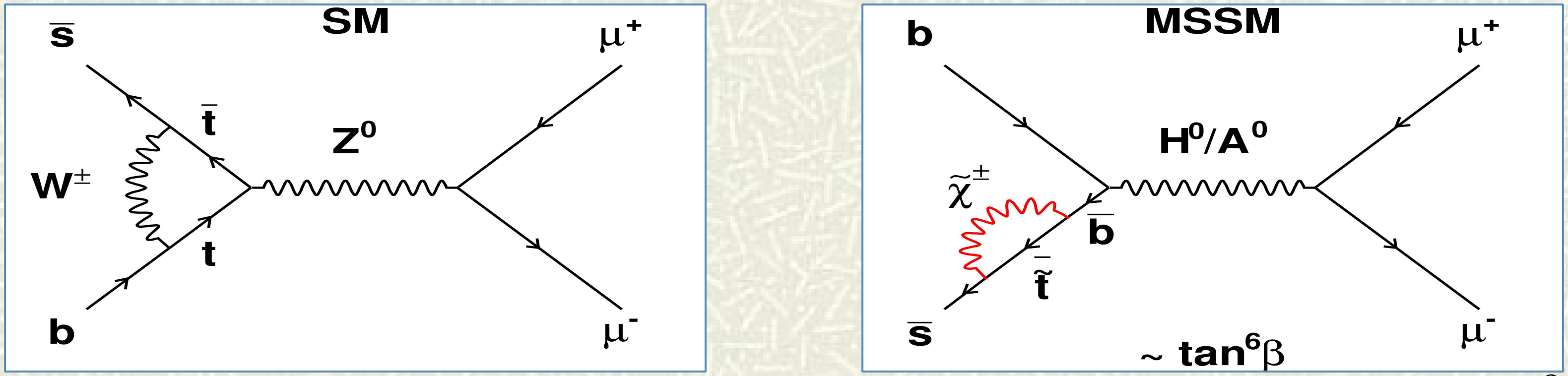




$B_{s(d)} \rightarrow \mu^+\mu^-$

BRIEF MOTIVATION

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



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

(Buchalla & Buras, Misiak & Urban)

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

- SM prediction is below the sensitivity of current experiments

  SM → Expect to see 0 events at the Tevatron

Any signal at the Tevatron would indicate new physics

•New limits place boundaries on theoretical models

Analysis Overview

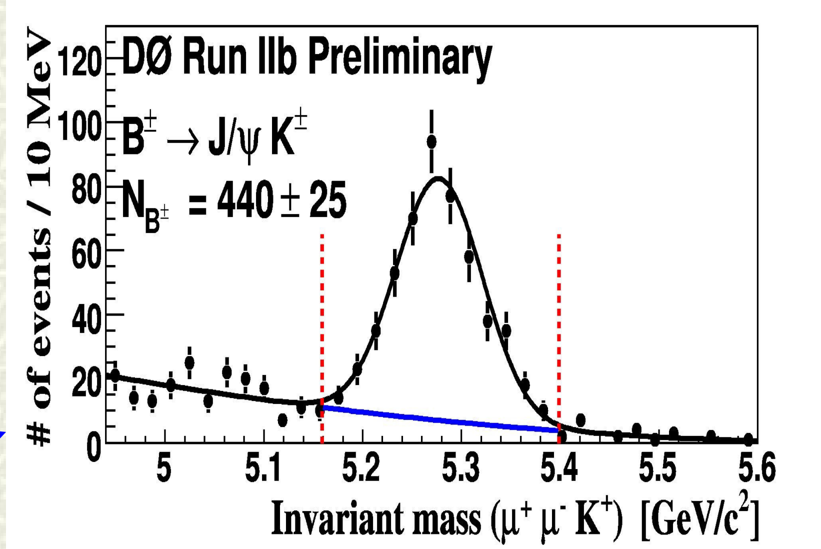
$$BR(B_s \to \mu^+\mu^-) = \frac{N_{Bs}}{N_{B+}} \frac{\alpha_{B+} \cdot \varepsilon_{B+}^{total}}{\alpha_{Bs} \cdot \varepsilon_{Bs}^{total}} \frac{f_{b\to B+}}{f_{b\to Bs}} BR(B^+ \to J/\psi K^+) BR(J/\psi \to \mu^+\mu^-)$$

Motto: reduce background and keep signal efficiency high

Step 1: Pre-selection cuts to reject obvious background

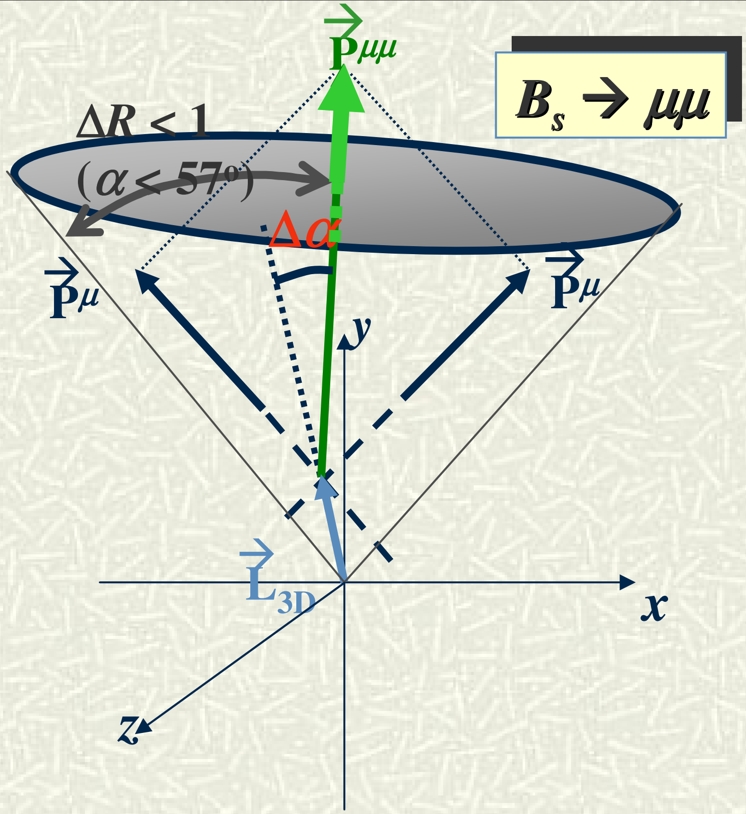
Step 2: Optimization (need to know signal efficiency and expected background)

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



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

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



- $\mu^+\mu^-$ mass ~ ±2.5σ mass window
- B vertex displacement: $\lambda = \frac{cL_{3D}M}{|\vec{p}(B)|}$
- 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)

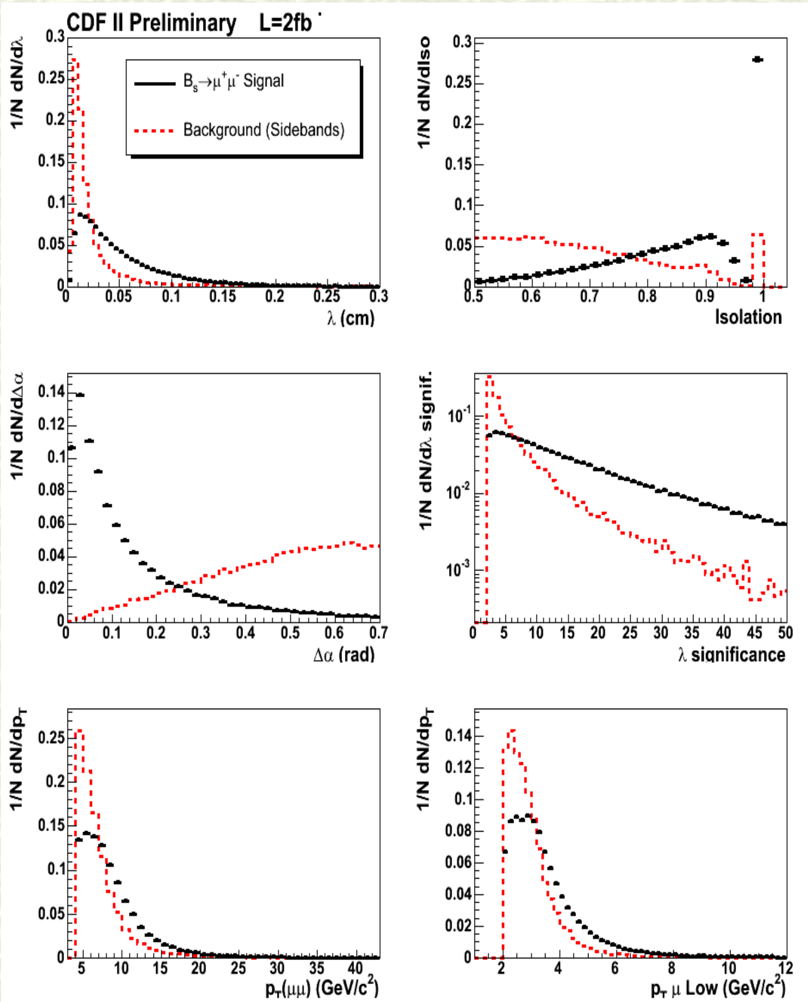
- "pointing (Δα)": $\Delta\alpha = \angle(\vec{p}(B) - \vec{L}_{3D})$

(angle between B_s momentum and decay axis)

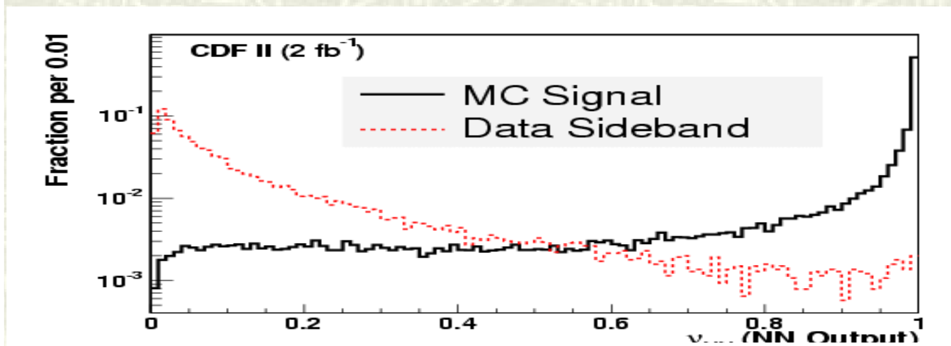
- λ/σ_λ: proper decay length significance
- $p_T(\mu\mu)$: transverse momentum of Bs
- $p_T(\mu)^{low}$: lower μ pT

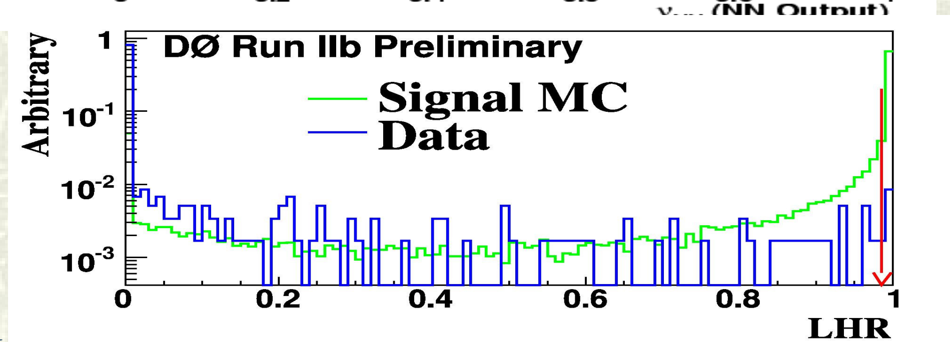
Isolation, pointing, and λ/σ_λ used by D0 Likelihood

Discriminating Variables



- Combine in Likelihood for D0 or NN (New Element) for CDF which takes into account the correlations between the variables
  - Removes 25% of the background
- Set limit by using 3 NN bins and 5 mass bins (New Element)
  - Improves expected limit by 25%
- Unbiased optimization
  - Based on simulated signal and data sidebands





CDF Control Samples

- Independent background control samples to cross check the combinatoric background estimate procedure

OS - : Opposite-sign dimuon sample with ct<0

SS+ : Same-sign dimuon sample with ct>0

SS- : Same-sign dimuon sample with ct<0

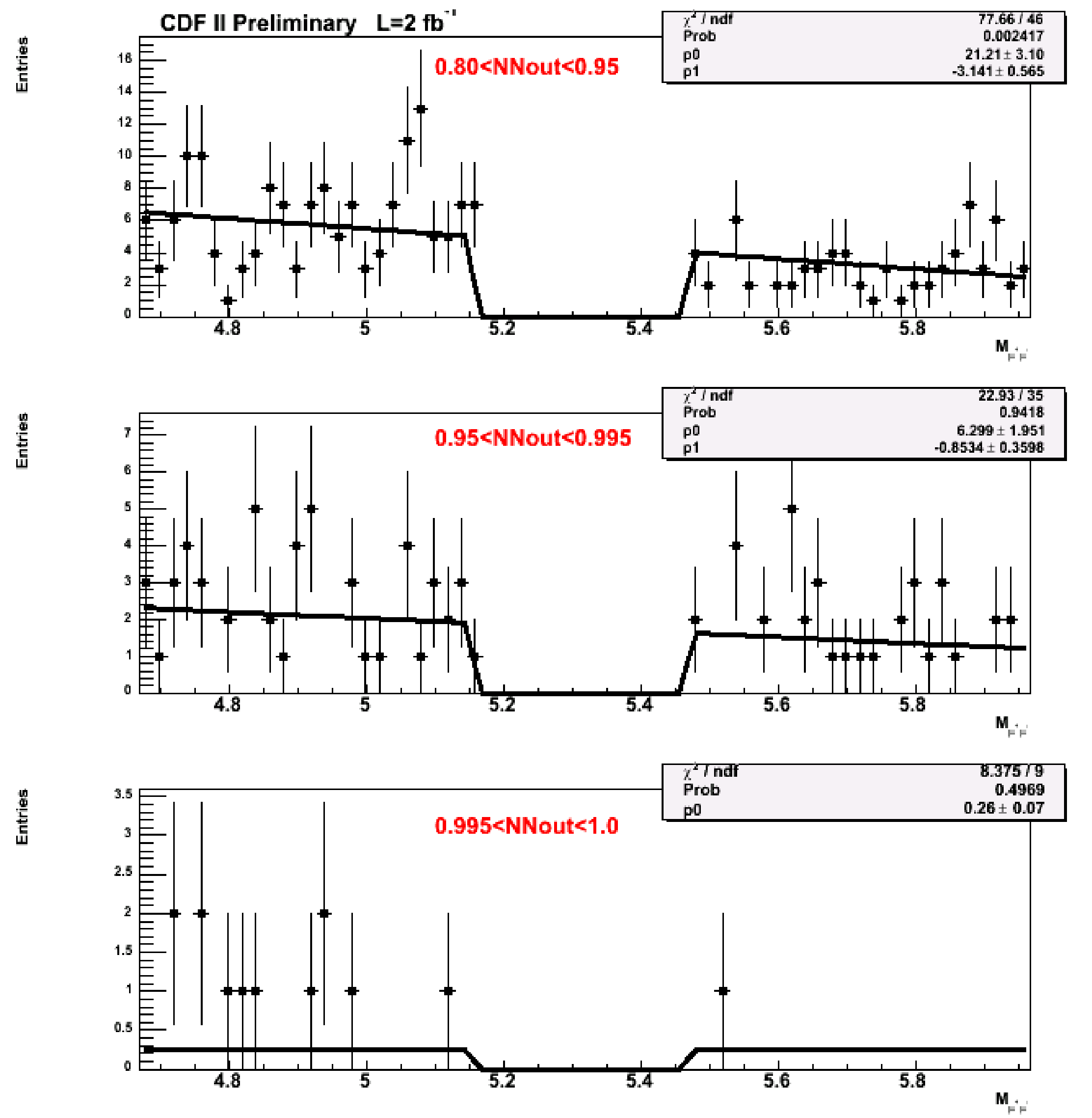
FM : Fake muon sample ct>0
(require at least one muon leg to fail our
muon likelihood and dE/dX requirement)

Checking Control Samples

NeuralNet cut		CMU-CMU pred	CMU-CMU obsv	CMU-CMU prob	CMU-CMX pred	CMU-CMX obsv	CMU-CMX prob
	>0.80	231±8	230	48%	254±9	278	10%
OS-	>0.90	133±6	137	37%	142±7	163	6%
	>0.995	23±3	21	41%	18±2	29	2%
	>0.80	1.2±0.6	0	34%	2.4±0.8	1	34%
SS+	>0.95	0.6±0.4	0	53%	1.2±0.6	1	66%
	>0.995	0.3±0.3	0	70%	0.3±0.3	0	70%
	>0.80	2.4±0.8	2	57%	7.5±1.5	6	40%
SS-	>0.90	1.2±0.6	2	34%	5.1±1.2	3	29%
	>0.98	0.3±0.3	0	70%	2.1±0.8	1	41%
	>0.80	26.1±2.8	25	48%	6.3±1.4	6	56%
FM	>0.95	8.4±1.6	5	19%	2.1±0.8	1	41%
	>0.995	3.3±1.0	3	58%	0.6±0.4	0	55%

- Using a wider ± 150 MeV signal window for cross-check

Combinatorial BKG (2/fb)

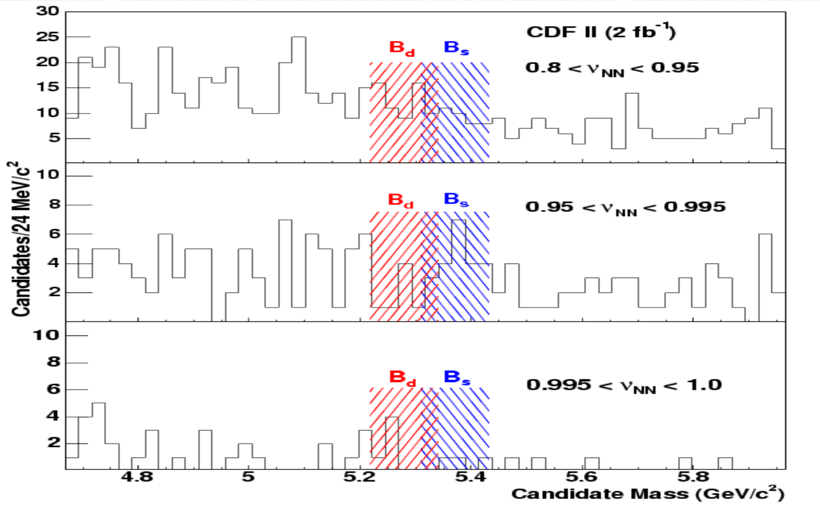


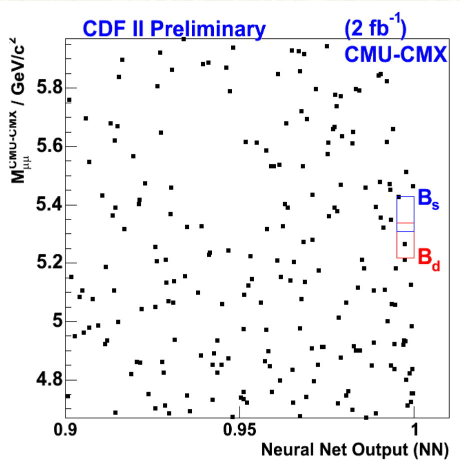
- Likelihood fit (polynomial) to sidebands
- Separate fit for 3 NN slices

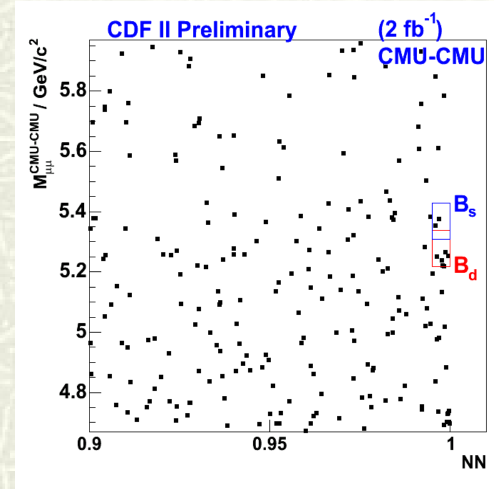
Use linear fit for NN>0.995 slice

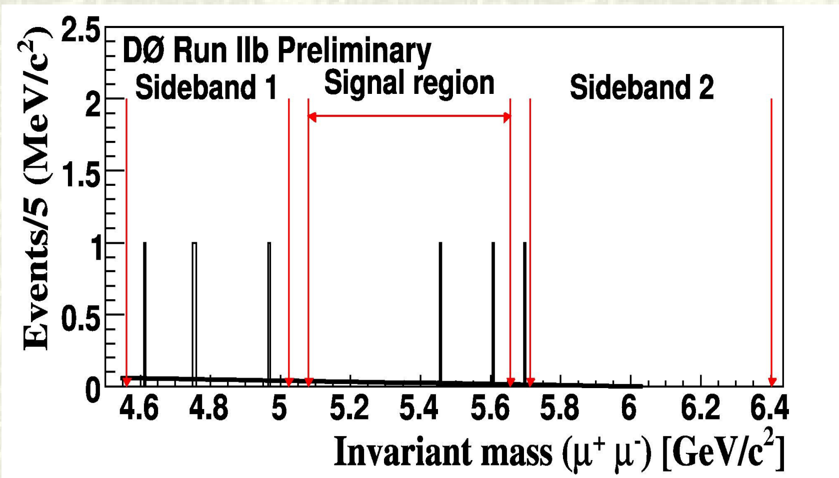
Also calculate the B->hh contributions which are added in to background estimate

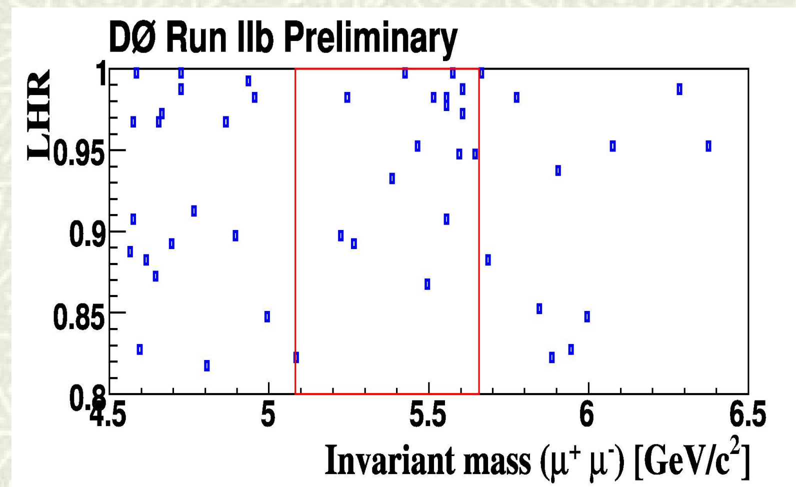
Unblinding the Signal Region











No significant excess observed!

Limit History

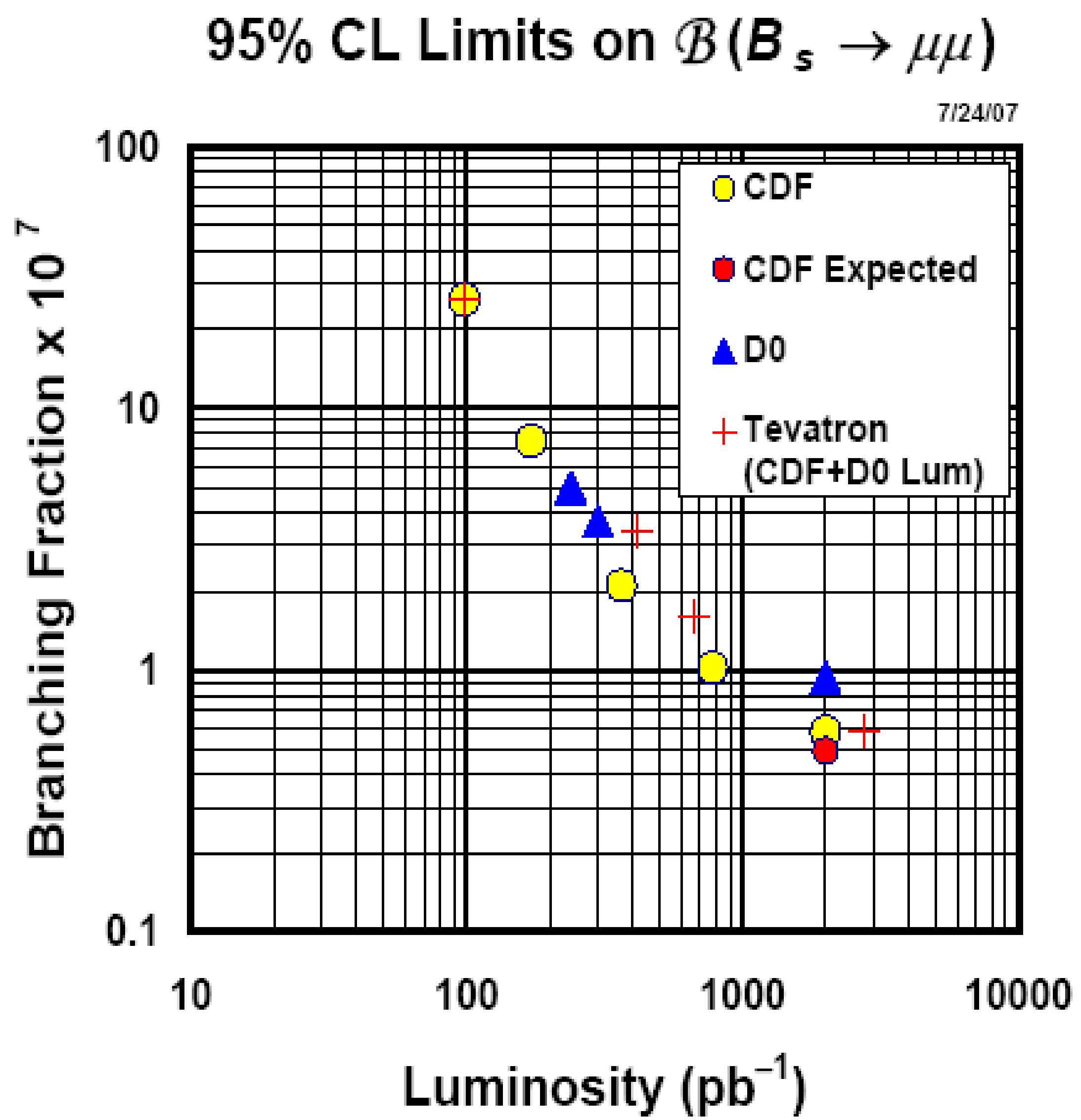
New Results are world's best limits

CDF:

$Br(B_s \rightarrow \mu\mu) < 4.7\times10^{-8}$ @ 90%CL
$< 5.8\times10^{-8}$ @ 95%CL

D0:

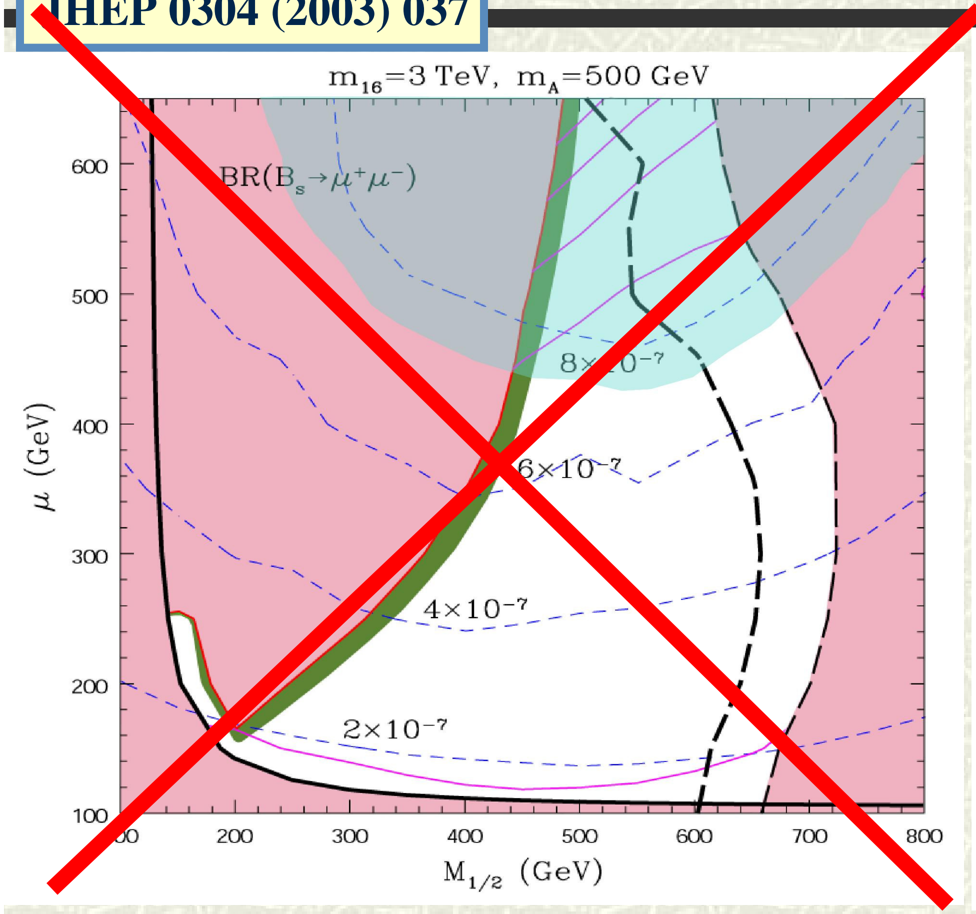
$Br(B_s \rightarrow \mu\mu) < 7.5\times10^{-8}$ @ 90%CL
$< 9.3\times10^{-8}$ @ 95%CL

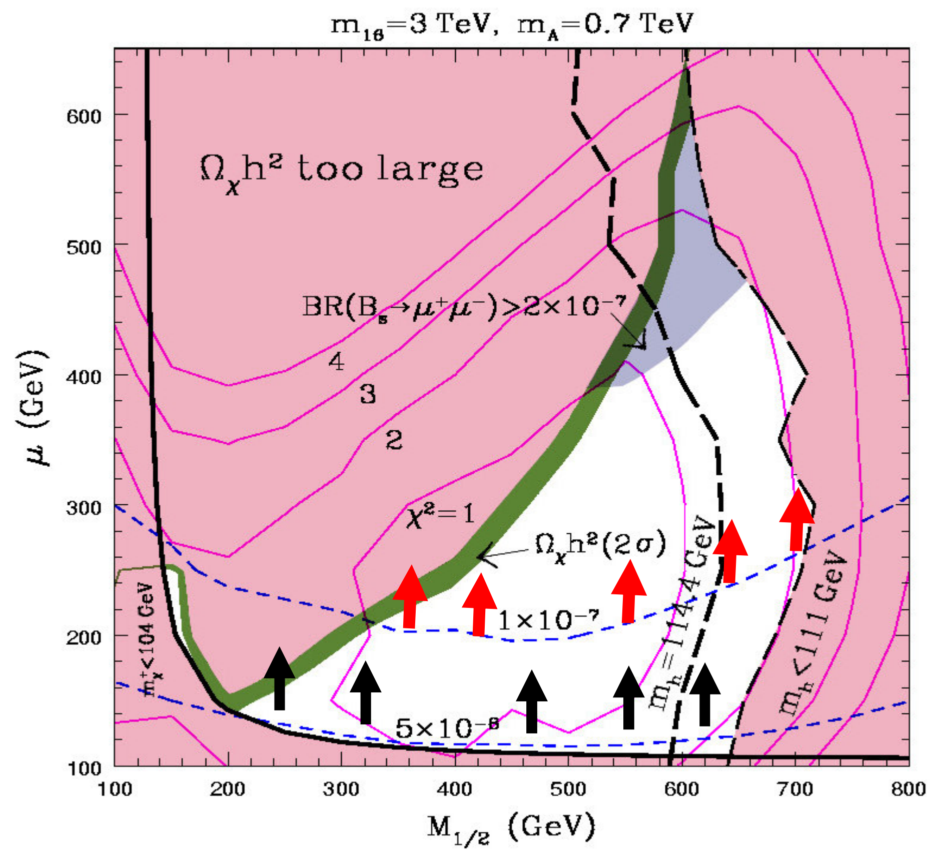


SO(10) Grand Unification Model

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

R. Dermisek *et al.*, hep-ph/0507233 (2005)





Pink regions are excluded by either theory or experiments

Green region is the WMAP preferred region

Blue dashed line is the Br(Bs→μμ) contour

Light blue region excluded by old Bs→μμ analysis

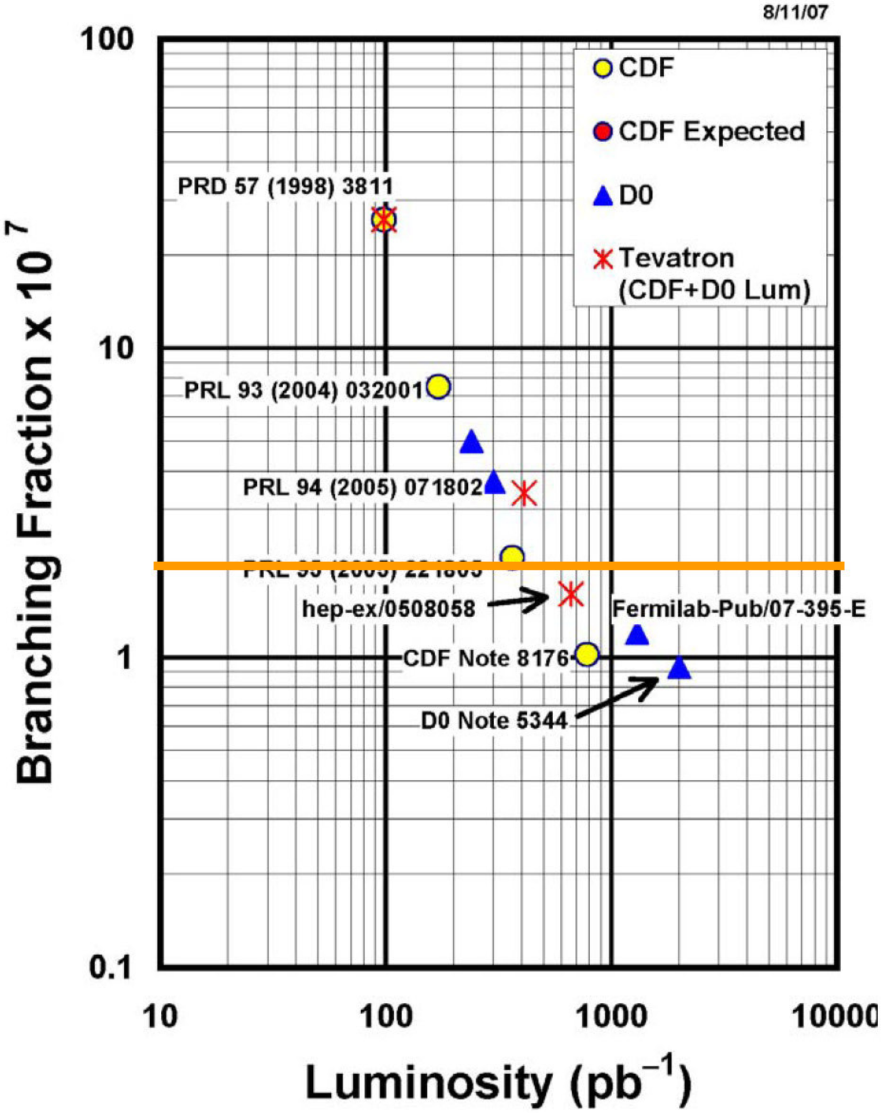
tan(β)~50 constrained by unification of Yukawa couplings

Our old result

New Limit

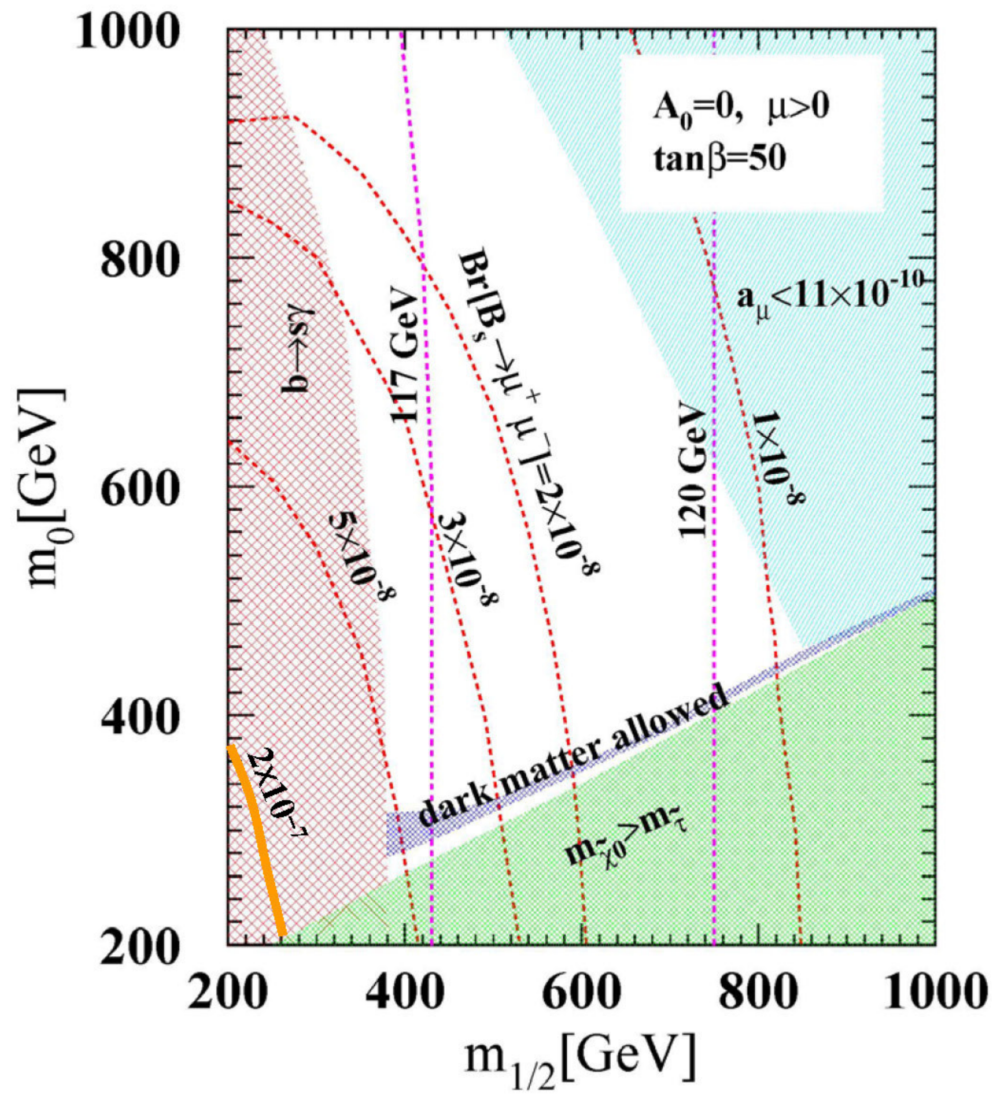
$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection

95% CL Limits on $\mathcal{B}(B_s \to \mu\mu)$

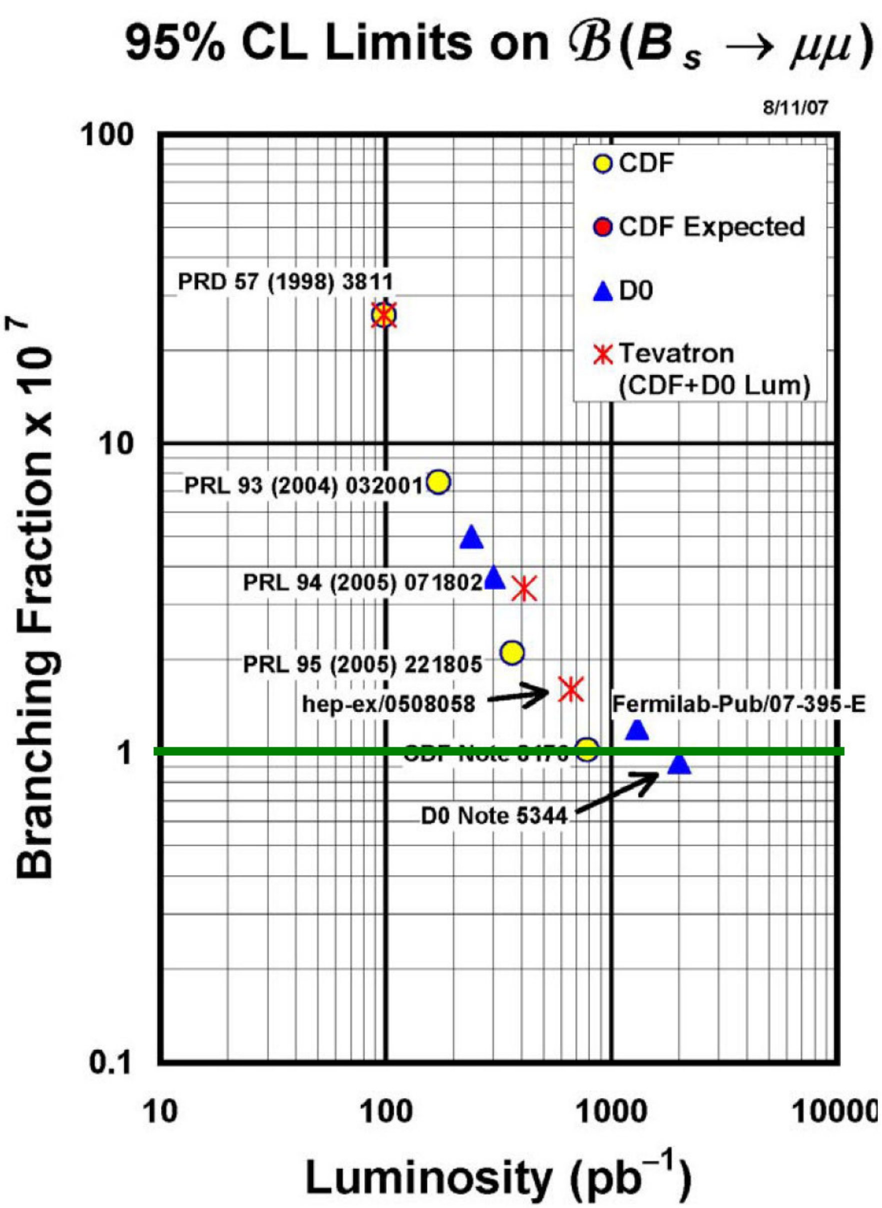


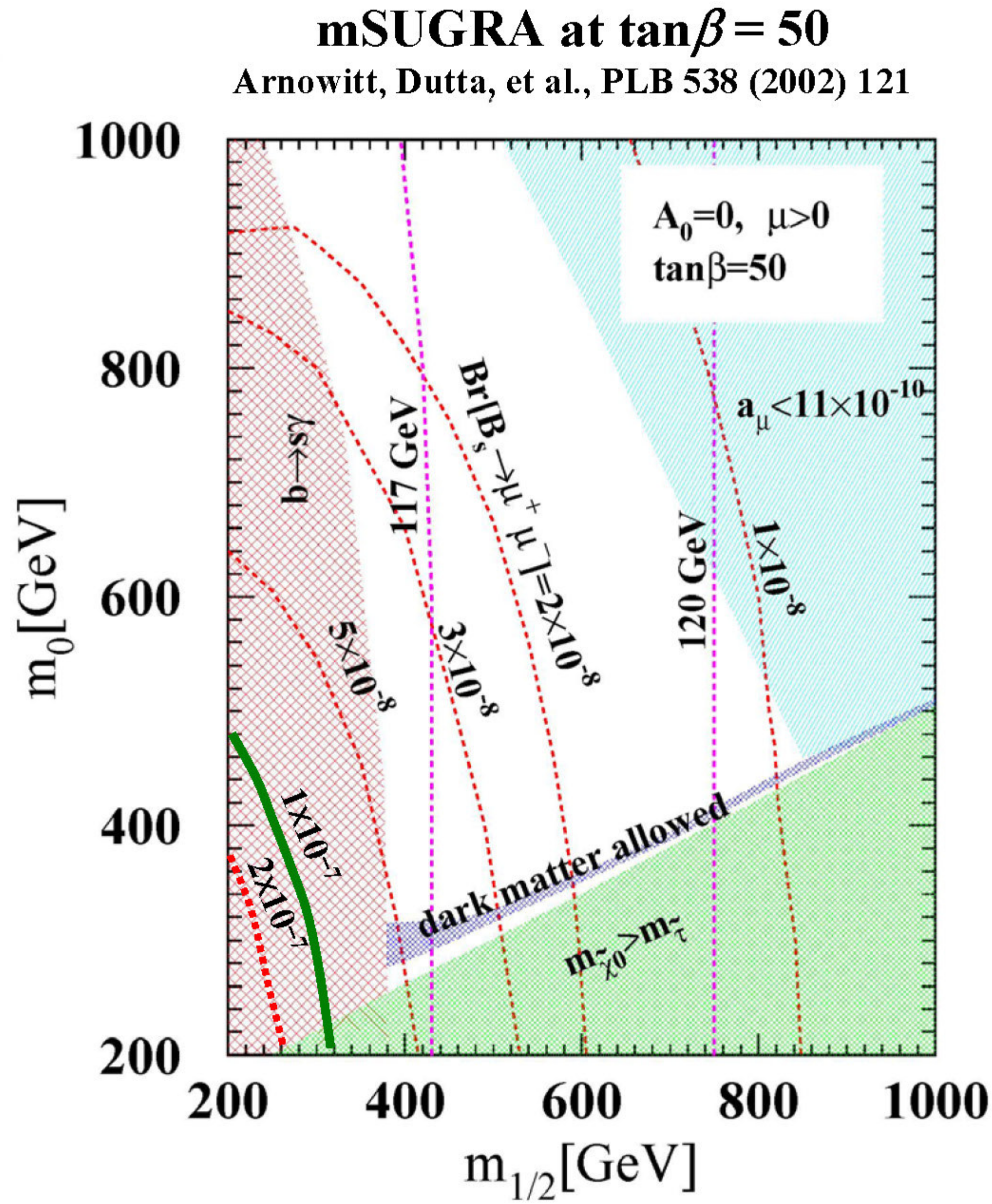
mSUGRA at $\tan\beta = 50$

Arnowitt, Dutta, et al., PLB 538 (2002) 121



$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection





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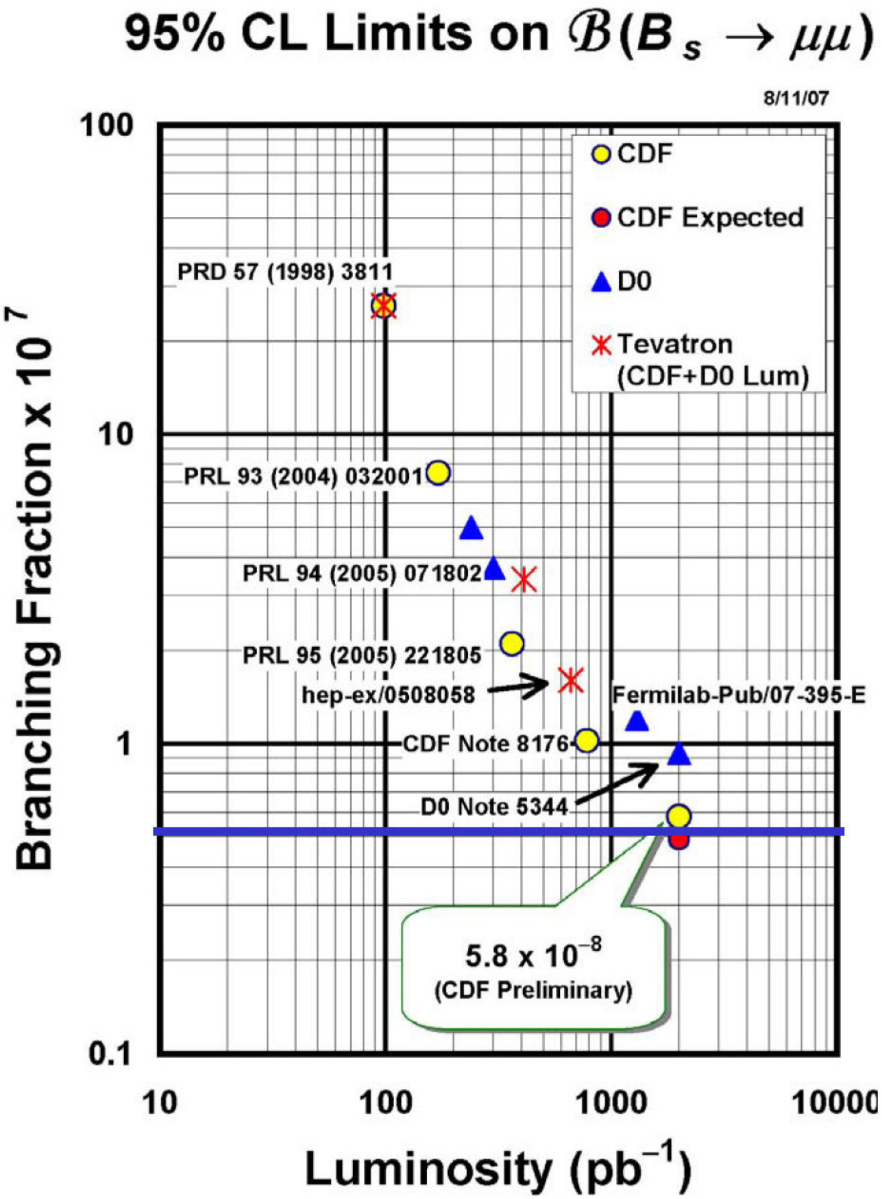
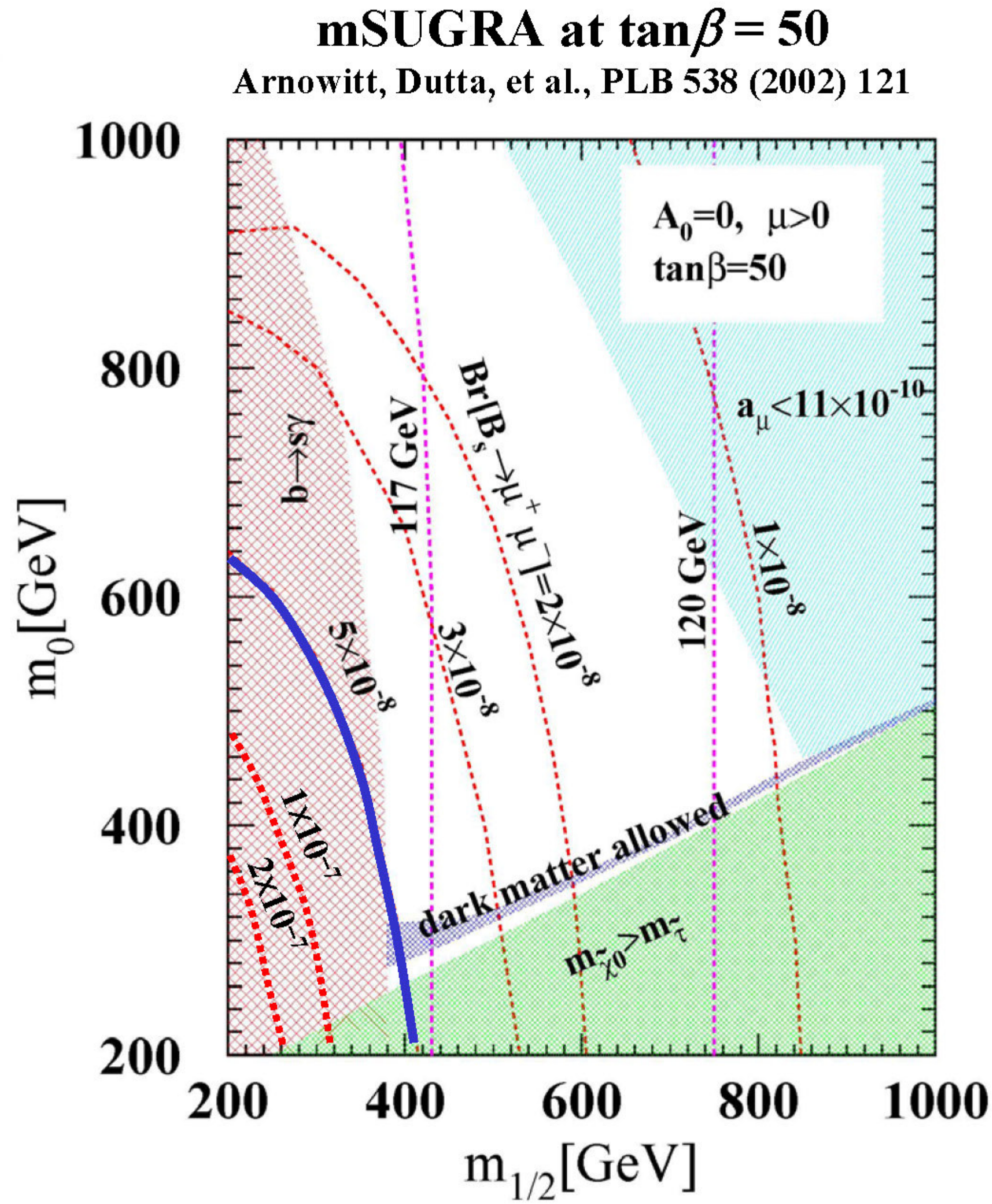
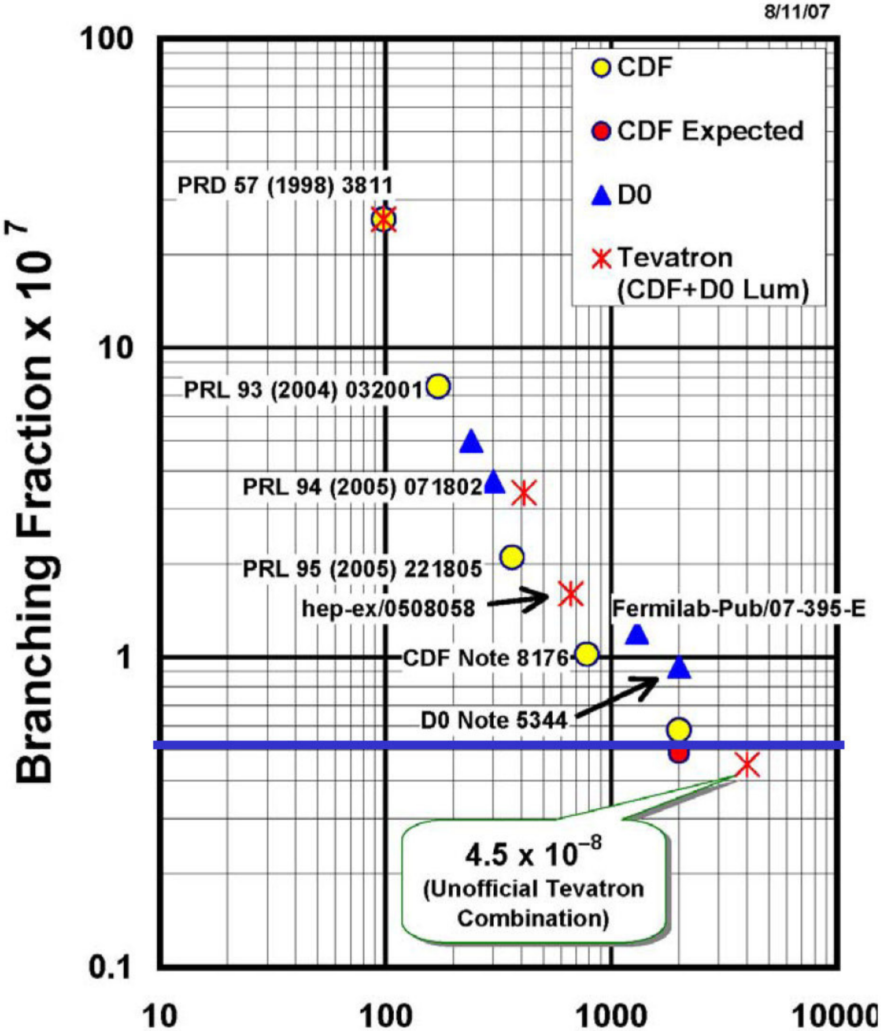
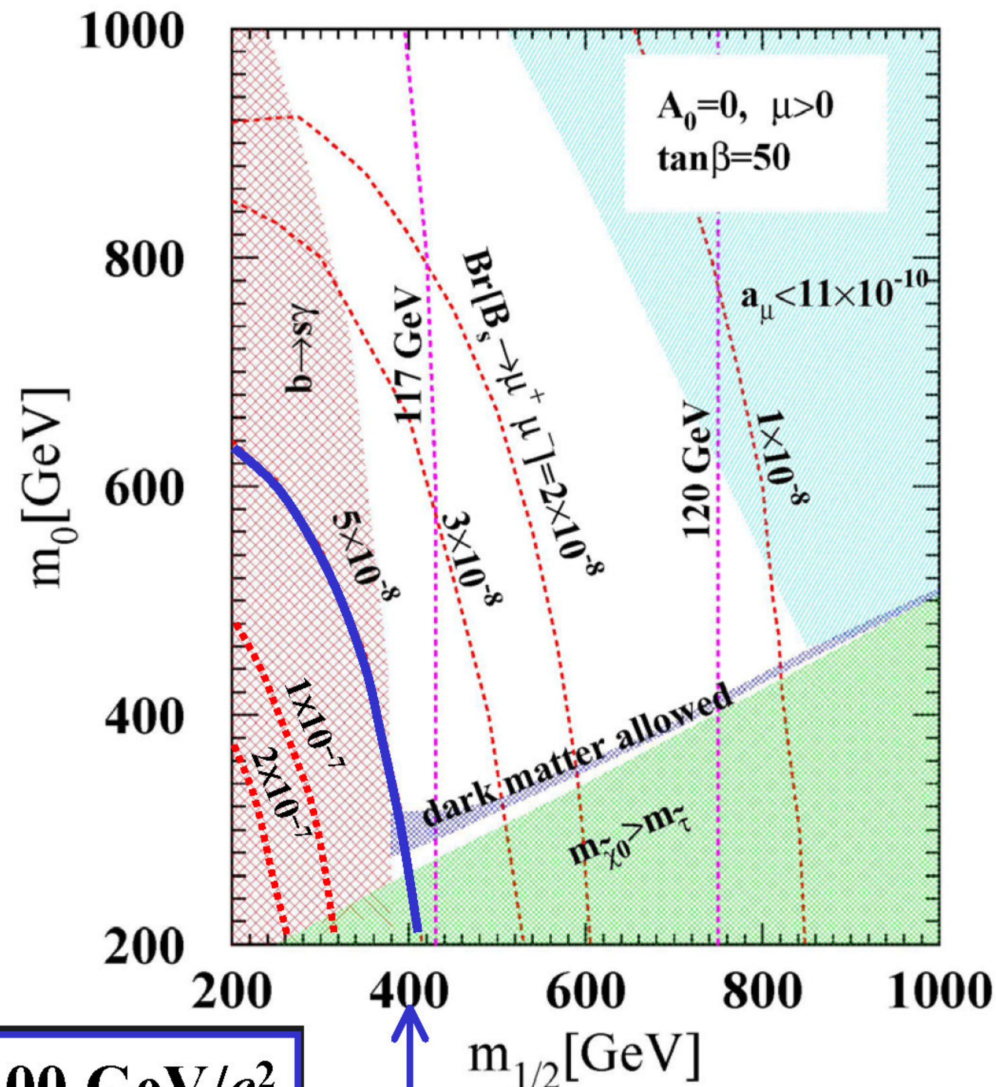




$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection

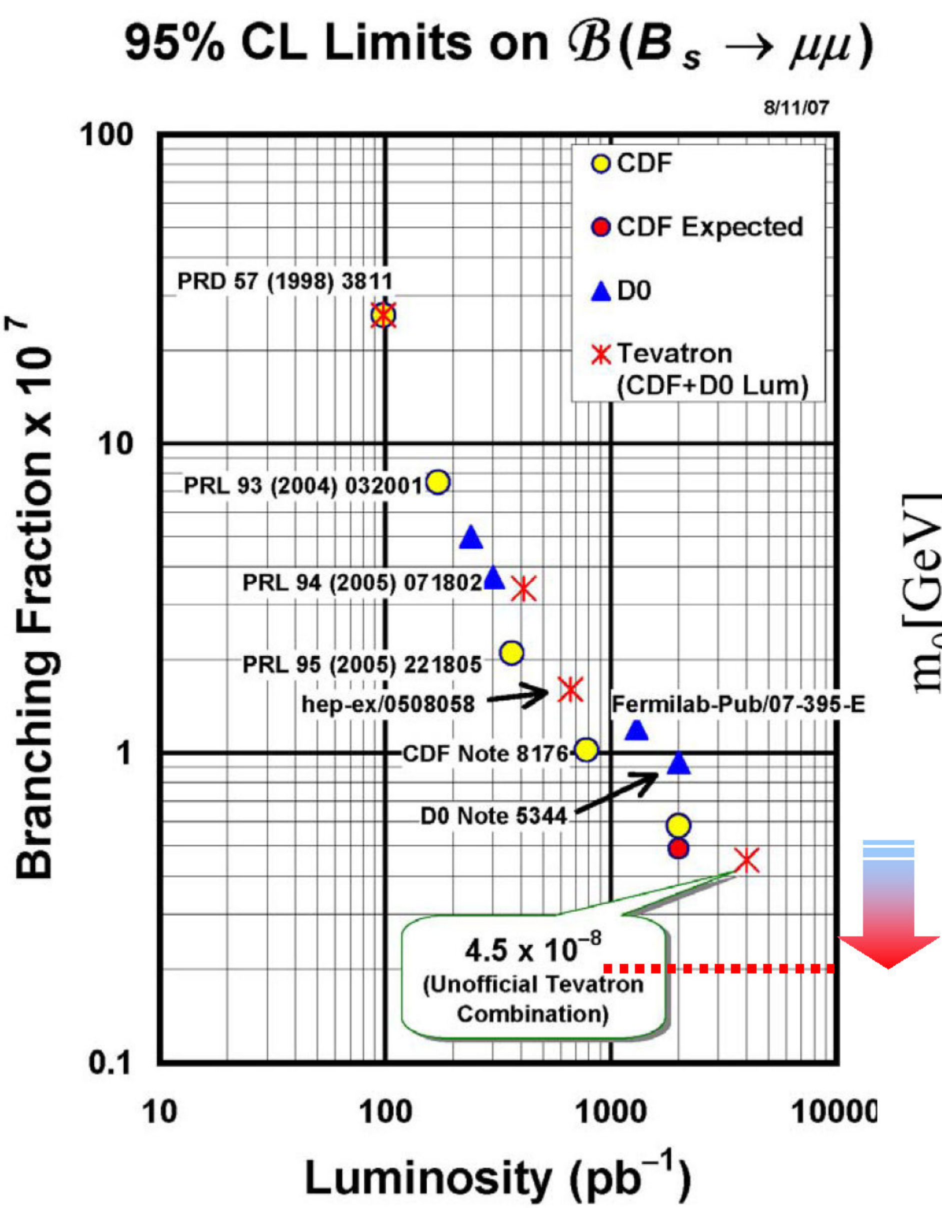


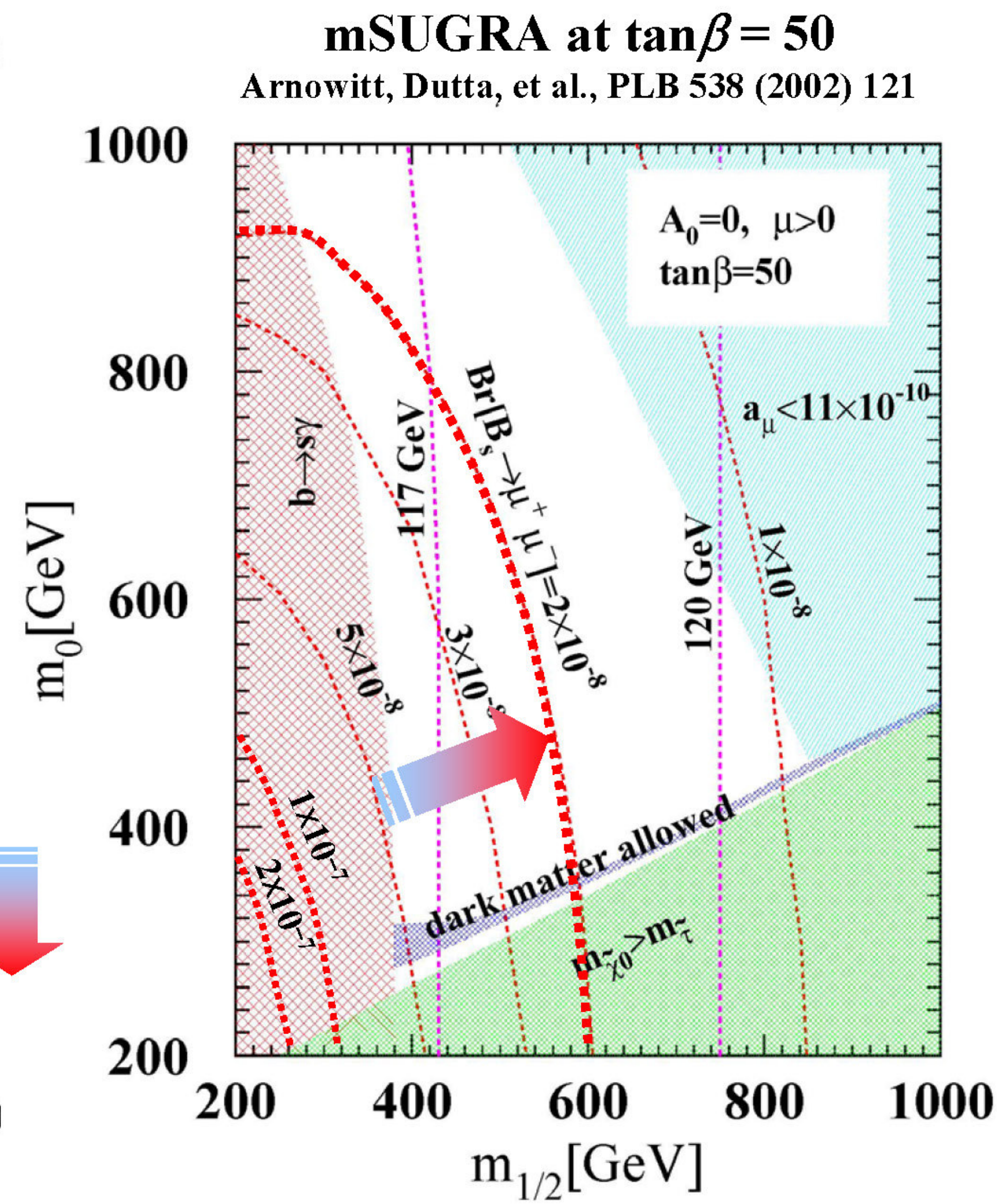


Competitive to the LHC ☺

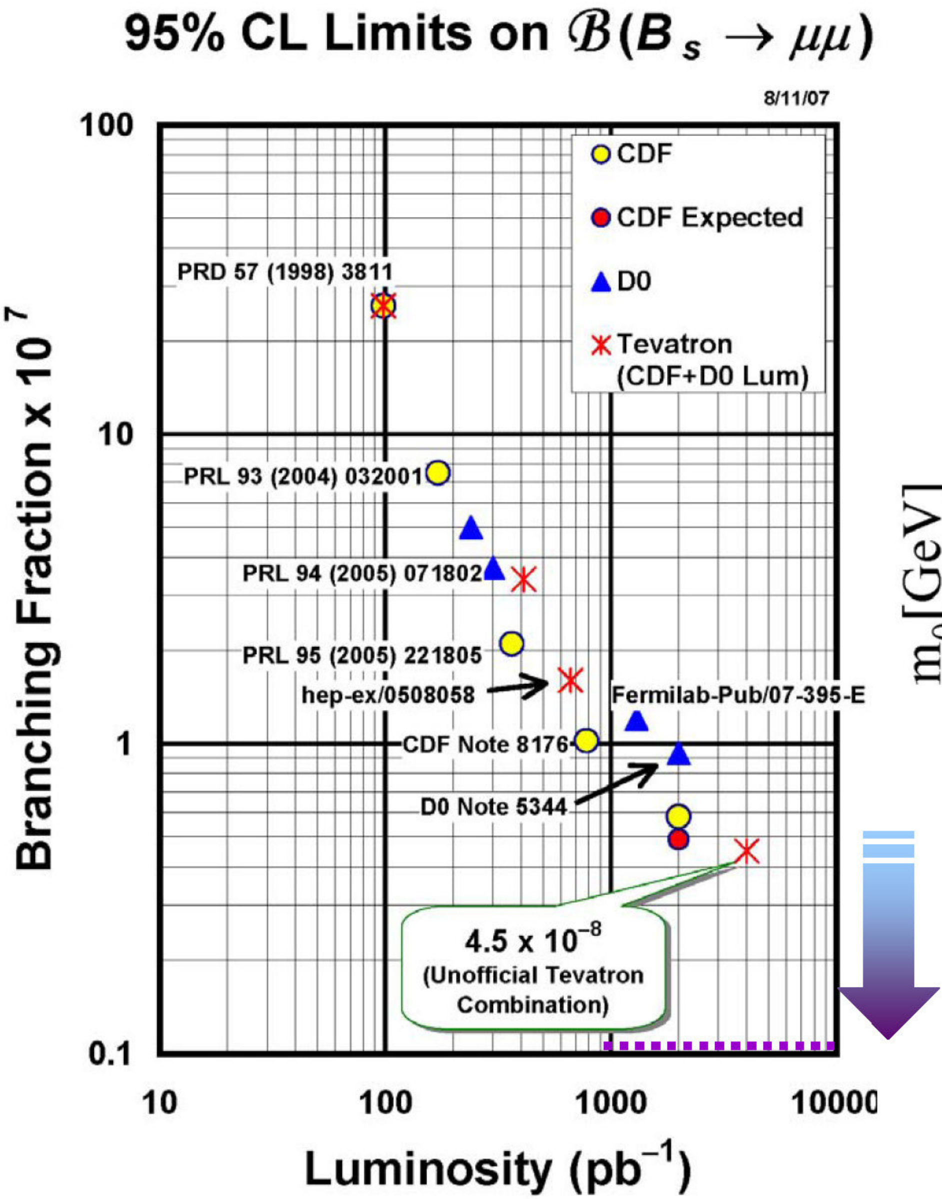
$M_{\tilde{g}} \sim 1100\ \mathrm{GeV}/c^2$

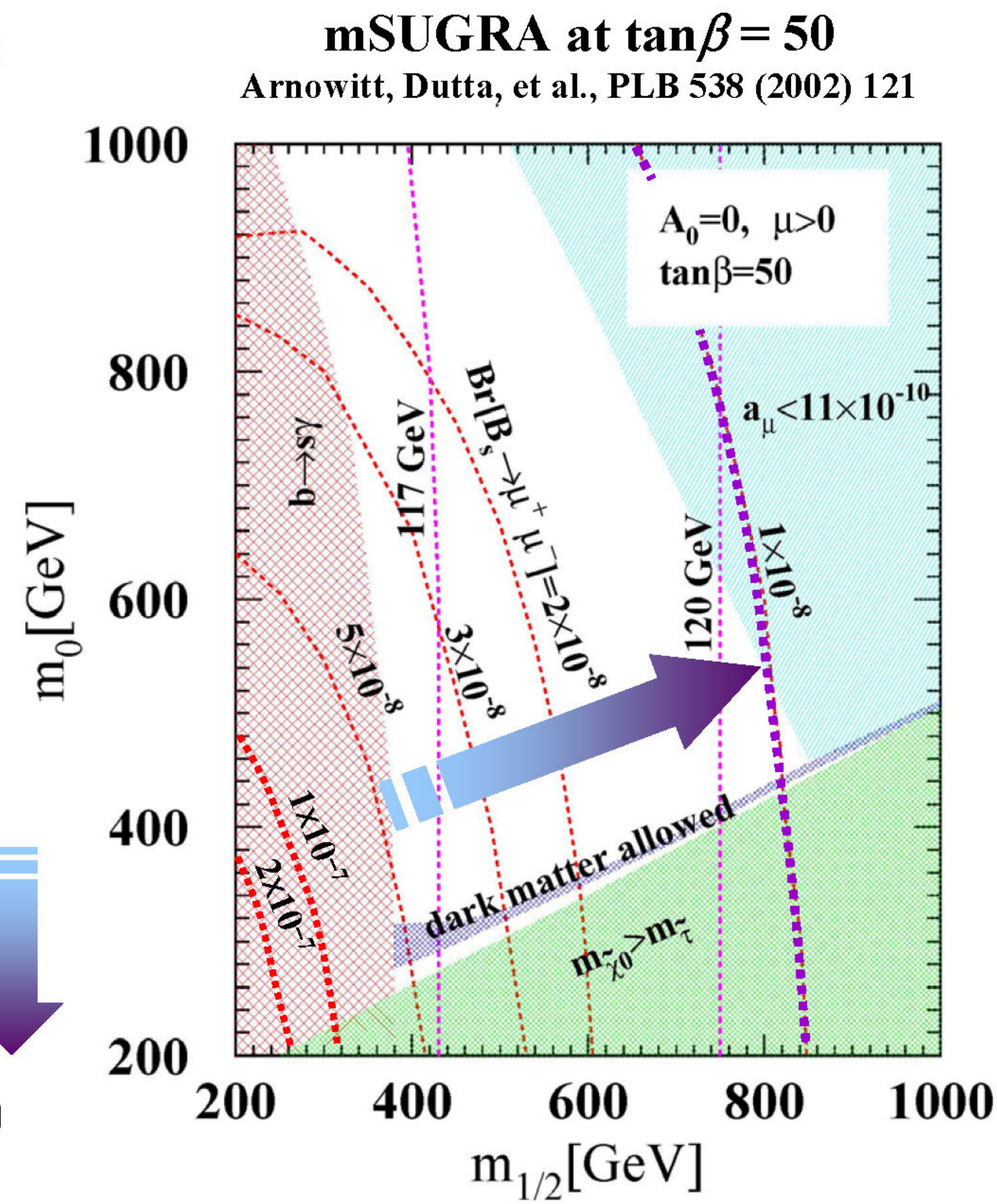
$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection





$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection

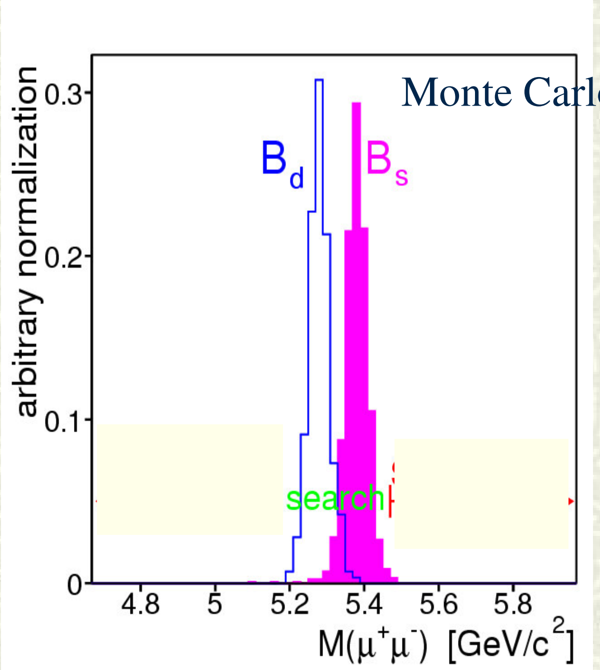




B_d->μμ Results at CDF

- CDF's analysis is also sensitive to B_d->μμ
  - Due to excellent mass resolution
  - ~25 MeV/c^2

- Expected limit 1.3 x 10^{-8} at 90% confidence level



Gives new world's best limit of:

$$BR(B_d \to \mu^+\mu^-) < 1.5\times10^{-8}\,(1.8\times10^{-8})\ \text{at}\ 90\%(95\%)\ \text{C.L.}$$

$B \to \mu\mu h$

Search for $B \to \mu\mu h$

- Non-resonant decays $B \to \mu\mu h$ via box or penguin diagrams
  - → new physics may be observable through interference with SM amplitudes

- Already observed (BaBar, Belle):
  - $B_u \to \mu\mu K$
  - $B_d \to \mu\mu K^*$

PRD 73, 092001 (2006)
PRL 96, 251801 (2006)

- Missing:
  - $B_s \to \mu\mu \phi$
  - prediction: $BR(B_s \to \mu\mu\phi)=1.6x10^{-6}$

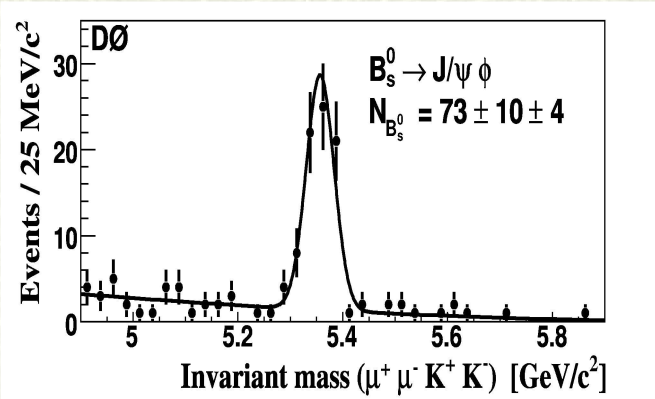
C.Q. Geng and C.C. Liu, J. Phys. G 29, 1103 (2003)

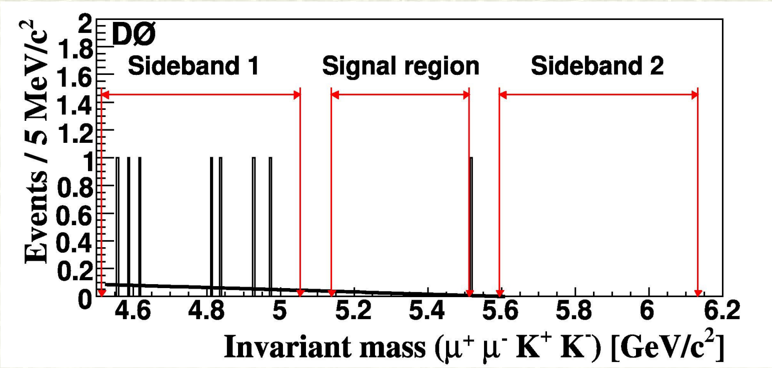
Search Methodology

- Similar method as used for $B_s \to \mu\mu$
- Unbiased (blinded) selection optimization using
  - signal event sample: MC simulation
  - background sample: data sidebands
- Normalize to analogous resonant $B \to J/\psi\ h$ decay

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

- Apply cuts on search mode and normalization mode
- Remove resonant $\mu\mu$ by cutting out J/ψ / $\psi(2S)$ mass ranges
- Unblind

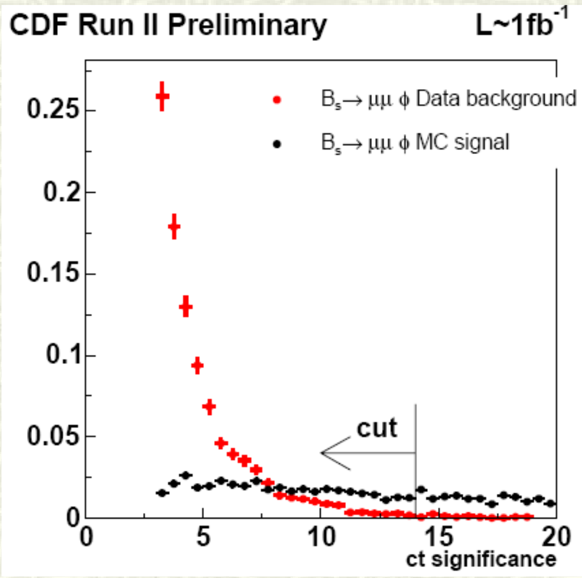


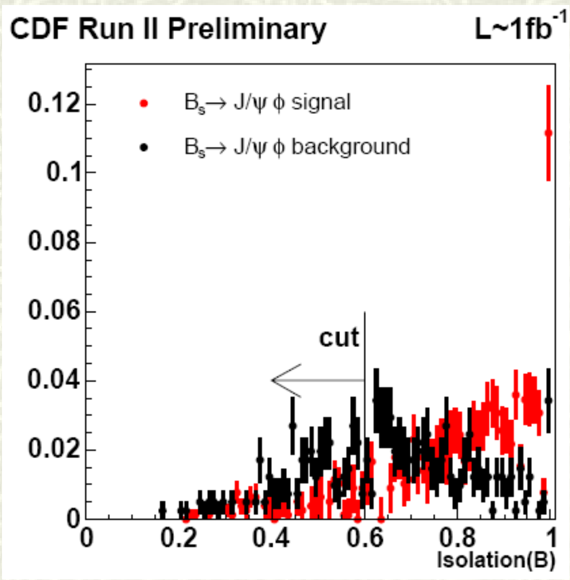


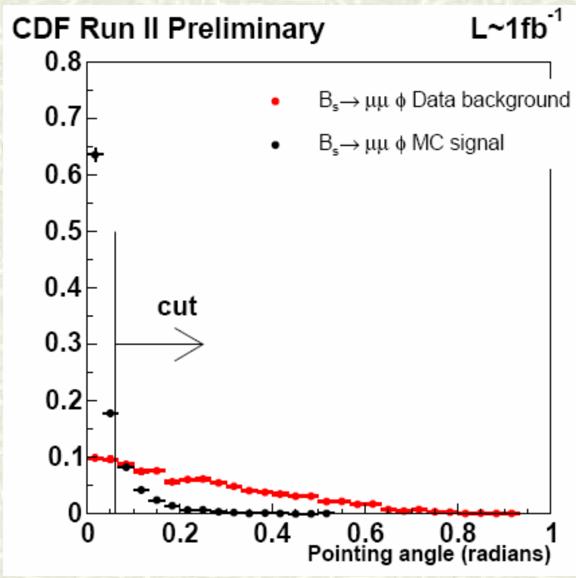
Selection Strategy

Optimize selection based on cuts on similar quantities as used for $B_s \rightarrow \mu\mu$ (decay length, isolation, pointing angle)

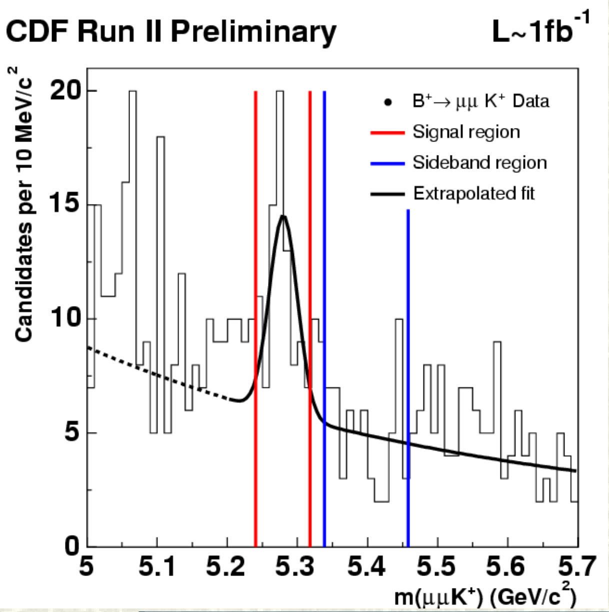
Optimize on best value for $\frac{S}{\sqrt{S+B}}$

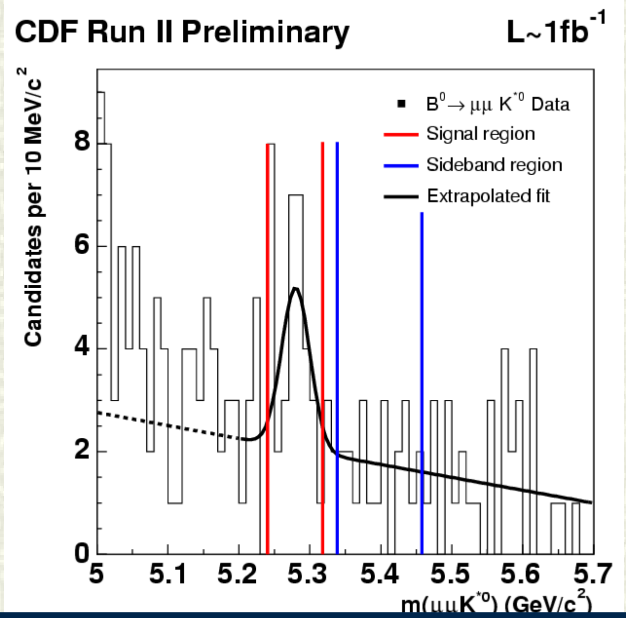


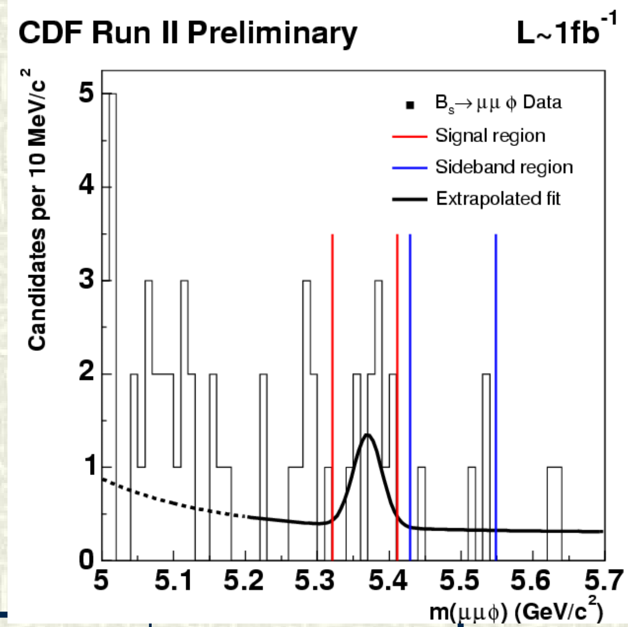




Observations





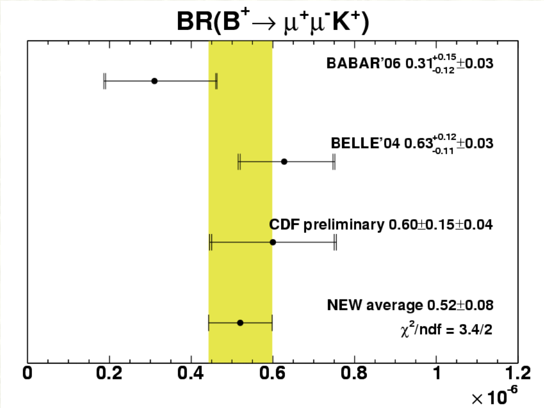


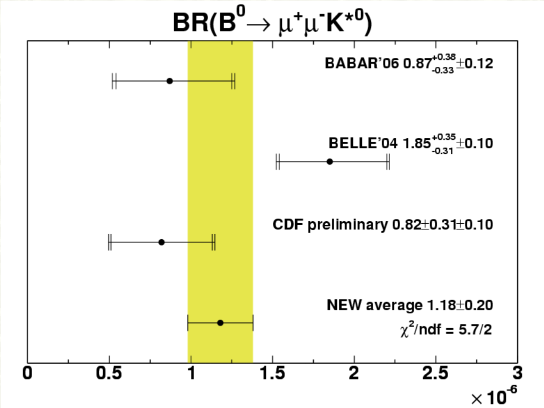
	$B_u \to \mu\mu K$	$B_d \to \mu\mu K^*$	$B_s \to \mu\mu \phi$
# events signal range	90	35	11
# estim. BG events	45.3 ± 5.8	16.5 ± 3.6	3.5 ± 1.5
Significance	4.5 σ	2.9 σ	2.4 σ

Results (World's Best)

BR($B^+ \rightarrow \mu\mu K^+$) = [0.72 ± 0.15(stat.) ± 0.05(syst.)]x10^{-6}

BR($B^0 \rightarrow \mu\mu K^*$) = [0.82 ± 0.31(stat.) ± 0.10(syst.)]x10^{-6}





- D0: $$\frac{BR(B_s \rightarrow \mu^+\mu^-\phi)}{BR(B_s \rightarrow J/\psi\phi)} < 4.4 \cdot 10^{-3} \text{ @ } 95\% C.L.$$ 0.45 fb^{-1}

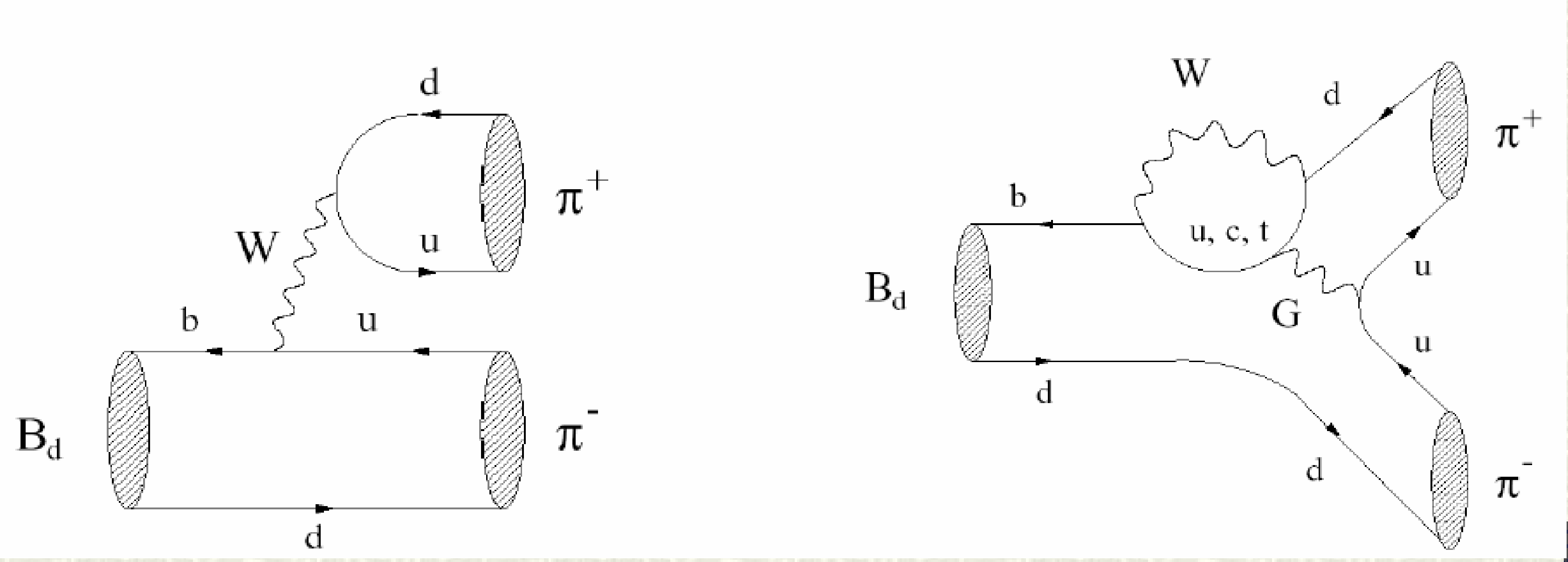
- CDF: $$\frac{BR(B_s \rightarrow \mu^+\mu^-\phi)}{BR(B_s \rightarrow J/\psi\phi)} < 2.61 \cdot 10^{-3} \text{ @ } 95\% C.L.$$ 1 fb^{-1}

New World's Best Limit

B, $\Lambda_b \rightarrow hh$

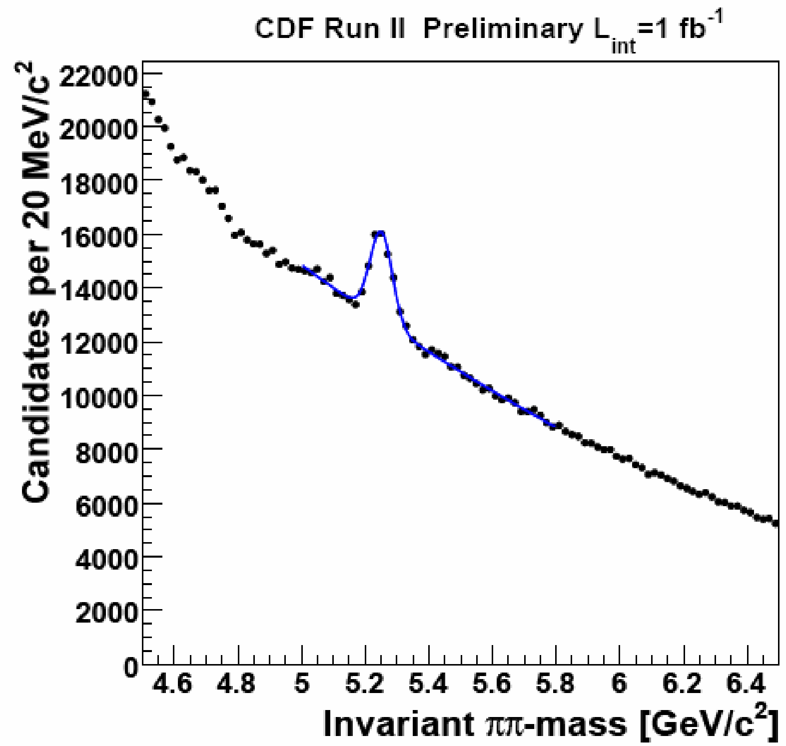
B^0, $B_{S,}$ $\Lambda_b \rightarrow \pi\pi$, $K\pi$, KK

- $B \rightarrow hh$ decays are the most used B decays for study of CPV because only two light bodies --> plenty of final states to measure same observables allowing multiple constraints on interesting parameters as CKM angle gamma.
- The fact that penguin diagrams (bottom-right) participate gives sensitivity to new physics.
- CDF already obtained important results such as: first observation of $B_S \longrightarrow KK$, and measurement of direct CPV asymmetries in $B^0 \longrightarrow K^+\pi^-$



$B \rightarrow hh'$ Trigger

- Hard to trigger, only two "stable" hadrons in final state
- Exploit long lifetime of the *B*-hadrons

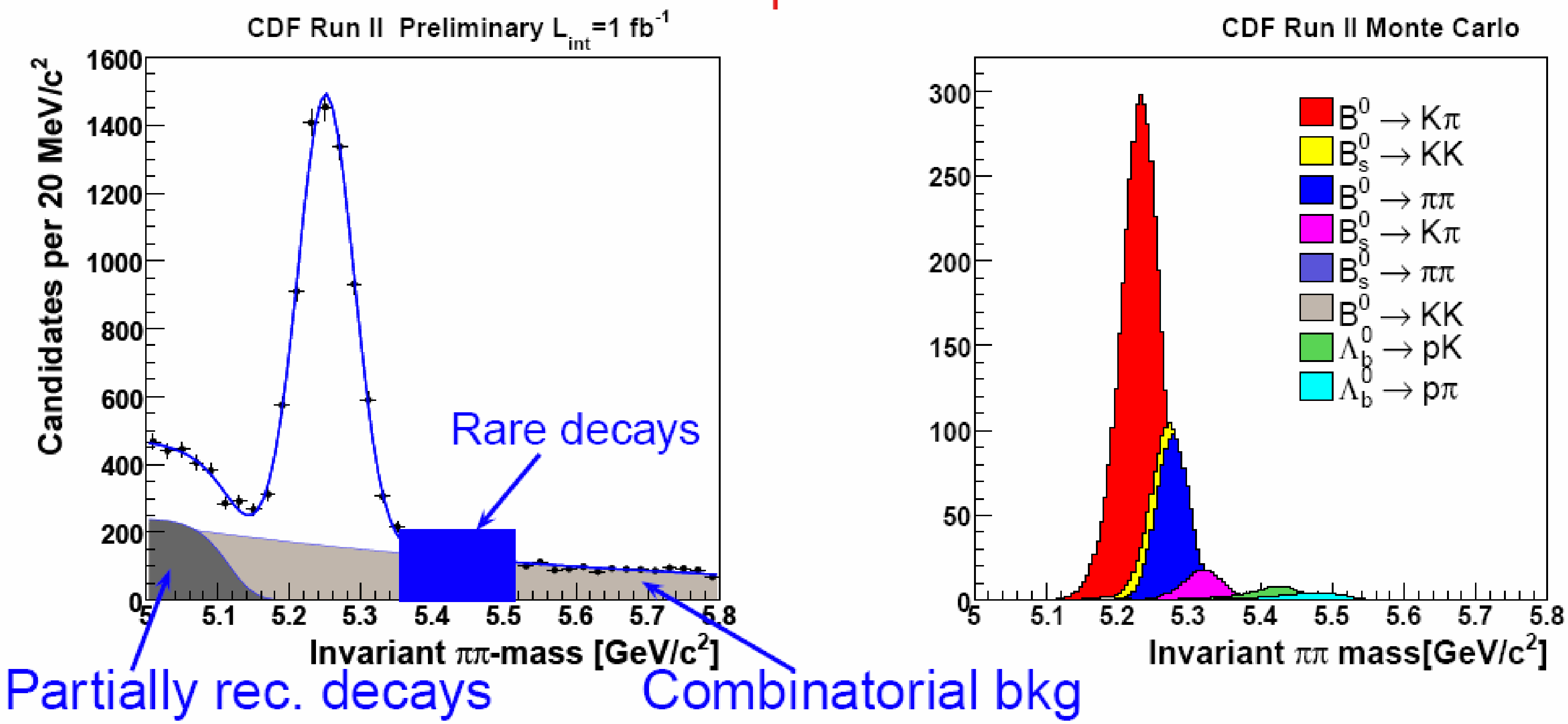


Confirm trigger cuts offline
Peak already visible

Disentangling modes

- Despite excellent mass resolution ($\approx 22\text{MeV}/c^2$) different decays overlaps
- Event-by-event particle ID not sufficient to separate modes

$\Rightarrow$ Combined kinematics and particle ID fit



Fit Yields

- Large yields for known modes

Signal events:

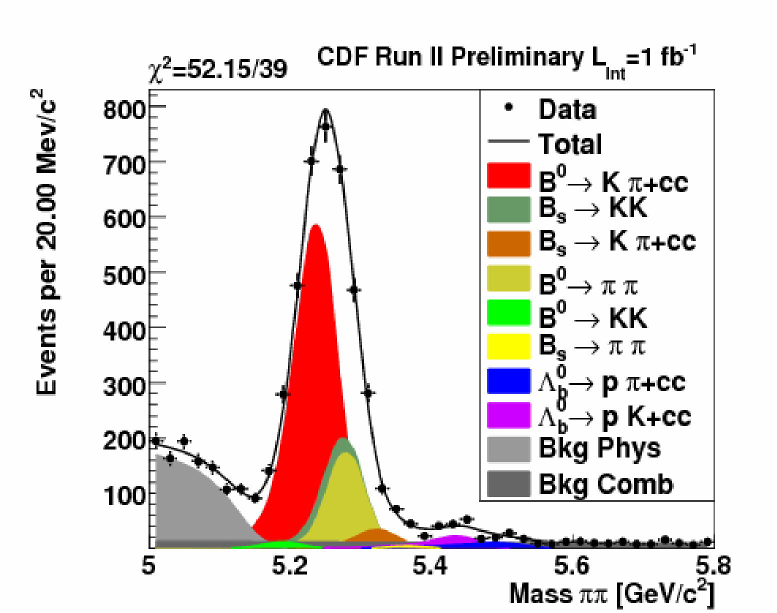
$B^0 \to \pi^+\pi^-$	1121 ± 63
$B^0 \to K^+\pi^-$	4045 ± 84
$B_s \to K^+K^-$	1307 ± 64

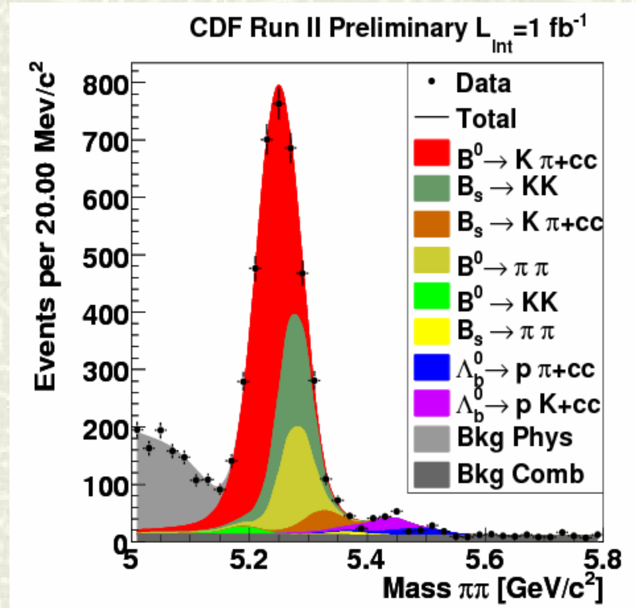
$\frac{\mathcal{B}(B^0\to\pi^+\pi^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$	$0.259 \pm 0.017 \pm 0.016$
$\mathcal{B}(B^0 \to \pi^+\pi^-)$	$(5.10 \pm 0.33 \pm 0.36) \cdot 10^{-6}$
$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s\to K^+K^-)}{\mathcal{B}(B^0\to K^+\pi^-)}$	$0.324 \pm 0.019 \pm 0.041$
$\mathcal{B}(B_s \to K^+K^-)$	$(24.4 \pm 1.4 \pm 4.6) \cdot 10^{-6}$

- Three New Modes

$B_s \to K^-\pi^+$	$230 \pm 34 \pm 16$	8σ
$\Lambda_b \to p\pi^-$	$110 \pm 18 \pm 16$	6σ
$\Lambda_b \to pK^-$	$156 \pm 20 \pm 11$	11σ

First measurement of direct CP violating asymmetries in $\Lambda_b \rightarrow ph$ decays





$$A_{\mathrm{CP}}(\Lambda_b^0 \rightarrow p\pi^-) = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow p\pi^-) - \mathcal{B}(\overline{\Lambda}_b^0 \rightarrow \overline{p}\pi^+)}{\mathcal{B}(\Lambda_b^0 \rightarrow p\pi^-) + \mathcal{B}(\overline{\Lambda}_b^0 \rightarrow \overline{p}\pi^+)} = 0.03 \pm 0.17\ (stat.) \pm 0.05\ (syst.),$$

$$A_{\mathrm{CP}}(\Lambda_b^0 \rightarrow pK^-) = \frac{\mathcal{B}(\Lambda_b^0 \rightarrow pK^-) - \mathcal{B}(\overline{\Lambda}_b^0 \rightarrow \overline{p}K^+)}{\mathcal{B}(\Lambda_b^0 \rightarrow pK^-) + \mathcal{B}(\overline{\Lambda}_b^0 \rightarrow \overline{p}K^+)} = 0.37 \pm 0.17\ (stat.) \pm 0.03\ (syst.).$$

First measurement of Branching Ratios in $\Lambda_b \to ph$ decays

$$\frac{\sigma(p\bar{p} \to \Lambda_b^0 X, p_T > 6\ \mathrm{GeV}/c)}{\sigma(p\bar{p} \to B^0 X, p_T > 6\ \mathrm{GeV}/c)} \frac{\mathcal{B}(\Lambda_b^0 \to p\pi^-)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.0415 \pm 0.0074\ (stat.) \pm 0.0058\ (syst.)$$

$$\frac{\sigma(p\bar{p} \to \Lambda_b^0 X, p_T > 6\ \mathrm{GeV}/c)}{\sigma(p\bar{p} \to B^0 X, p_T > 6\ \mathrm{GeV}/c)} \frac{\mathcal{B}(\Lambda_b^0 \to pK^-)}{\mathcal{B}(B^0 \to K^+\pi^-)} = 0.0663 \pm 0.0089\ (stat.) \pm 0.0084\ (syst.).$$

Using $Br(B \to K^+\pi^-)$ and ratios of fragmentation functions, can extract Λ_b branching ratios:

$$\mathcal{B}(\Lambda_b^0 \to p\pi^-) = (3.1 \pm 0.6\ (stat.) \pm 0.7\ (syst.)) \times 10^{-6},$$
$$\mathcal{B}(\Lambda_b^0 \to pK^-) = (5.0 \pm 0.7\ (stat.) \pm 1.0\ (syst.)) \times 10^{-6}.$$

PDG fragmentation functions

$$\mathcal{B}(\Lambda_b^0 \to p\pi^-) = (1.4 \pm 0.2\ (stat.) \pm 0.6\ (syst.)) \times 10^{-6},$$
$$\mathcal{B}(\Lambda_b^0 \to pK^-) = (2.2 \pm 0.3\ (stat.) \pm 1.0\ (syst.)) \times 10^{-6}.$$

CDF fragmentation functions

All results agree with the Standard Model Predictions

First Observation and BR Measurement of $B_S \rightarrow K\pi$

$$\frac{f_s}{f_d}\frac{\mathcal{B}(B_s \rightarrow K^-\pi^+)}{\mathcal{B}(B^0 \rightarrow K^+\pi^-)} = 0.066 \pm 0.010 \pm 0.010$$

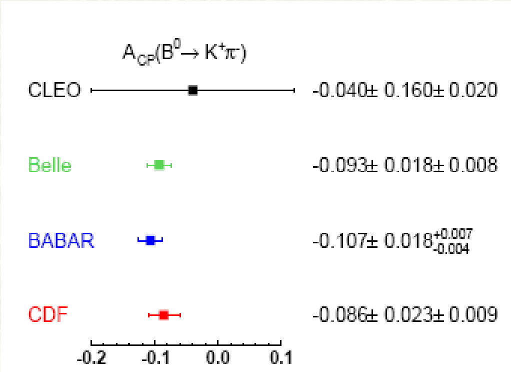
Using input from HFAG

$$\Rightarrow \mathcal{B}(B_s \rightarrow K^-\pi^+) = (5.0 \pm 0.75 \pm 1.0) \cdot 10^{-6}$$

Direct CP Violation

$$A_{CP} = \frac{N(\overline{B}^0 \to K^-\pi^+) - N(B^0 \to K^+\pi^-)}{N(\overline{B}^0 \to K^-\pi^+) + N(B^0 \to K^+\pi^-)}$$
$$= -0.086 \pm 0.023 \pm 0.009$$

- Only significant difference in K^+/K^- interaction with material
- Calibrate with $D^0 \to h^+h^-$ with assumption $A_{CP}(D^0 \to K\pi) = 0$
- Dominant systematic uncertainty
  - Particle ID model
  - WA B meson masses



$$A_{CP} = \frac{N(\overline{B}_s \to K^+\pi^-) - N(B_s \to K^-\pi^+)}{N(\overline{B}_s \to K^+\pi^-) + N(B_s \to K^-\pi^+)}$$
$$= +0.39 \pm 0.15 \pm 0.08$$

2.5σ Significance

- First indication of CP violation in B_s system
- Sign and size agree with SM expectation

$\Rightarrow$ No evidence for 'exotic' sources of CP violation

- Will repeat with more data (already 2.5fb^{-1} on tape)

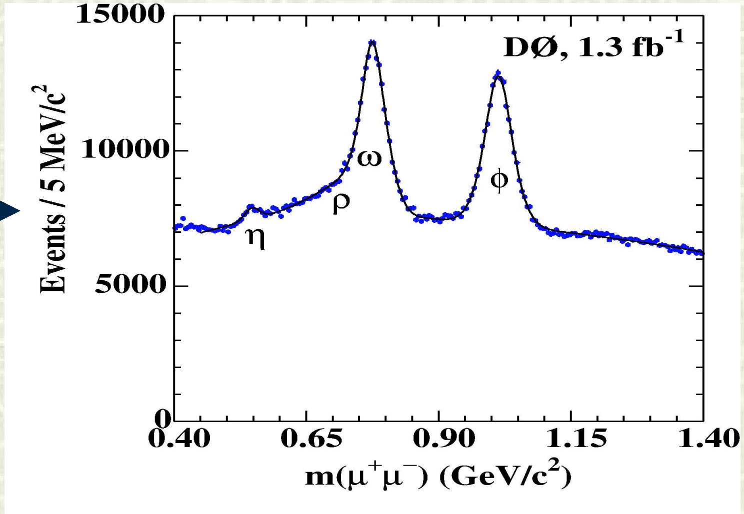
FCNC D Decays at D0

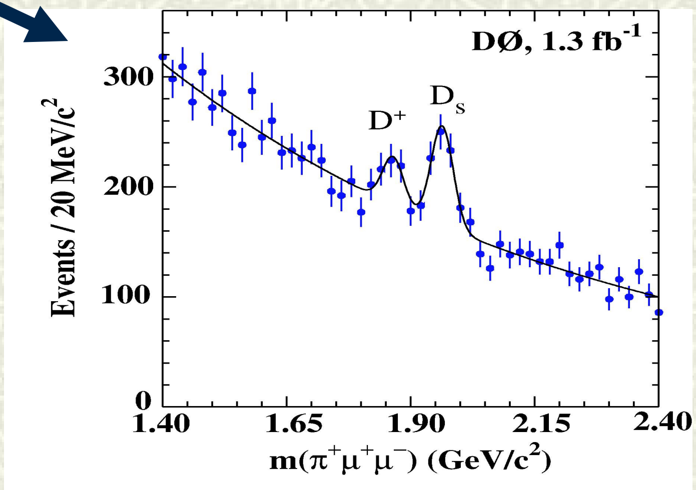
General Description

- Another place where the SM is highly suppressed and a signal would be indication of new physics
- Uses 1.3 fb-1
- Search for D_S^+ and $D^+ \rightarrow \varphi\pi^+ \rightarrow \mu\mu\pi^+$
- Also looks at continuum decay $D^+ \rightarrow \mu\mu\pi^+$ away from φ resonance
- SM predictions at 10^{-9}

Methodology for Direct Decay

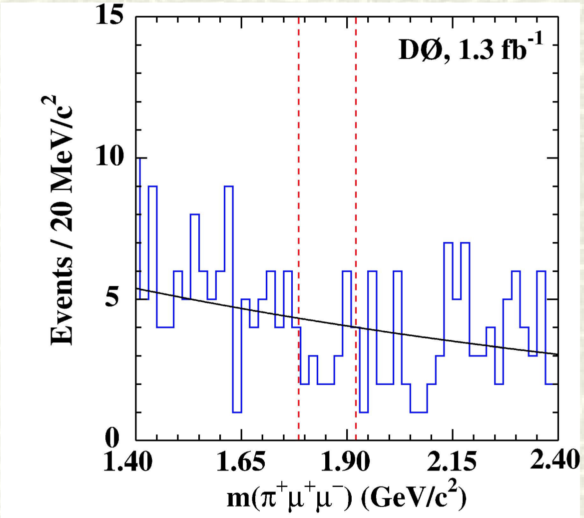
- Uses Dimuon trigger
- Reconstruct the dimuon spectrum
- Add in track
  - Use long lifetime properties to separate signal from background
  - Also uses kinematic properties of decay
    - Fits of daughters and decay angles





Continuum $D^+ \to \mu\mu\pi^+$

- Exclude $0.96 < \text{Mass}(\mu\mu\pi^+) < 1.06$ resonant peak
- Use same cuts as resonant decays, add in isolation
- 19 signal events seen
- Sideband background => 25.8+-4.6
- Probability of background fluctuation is 14%
- Set limit on $D^+ \to \varphi\pi^+ \to \mu\mu\pi^+$
  - Br = $3.9\text{x}10^{-6}$ at 90% c.l. New World's best limit



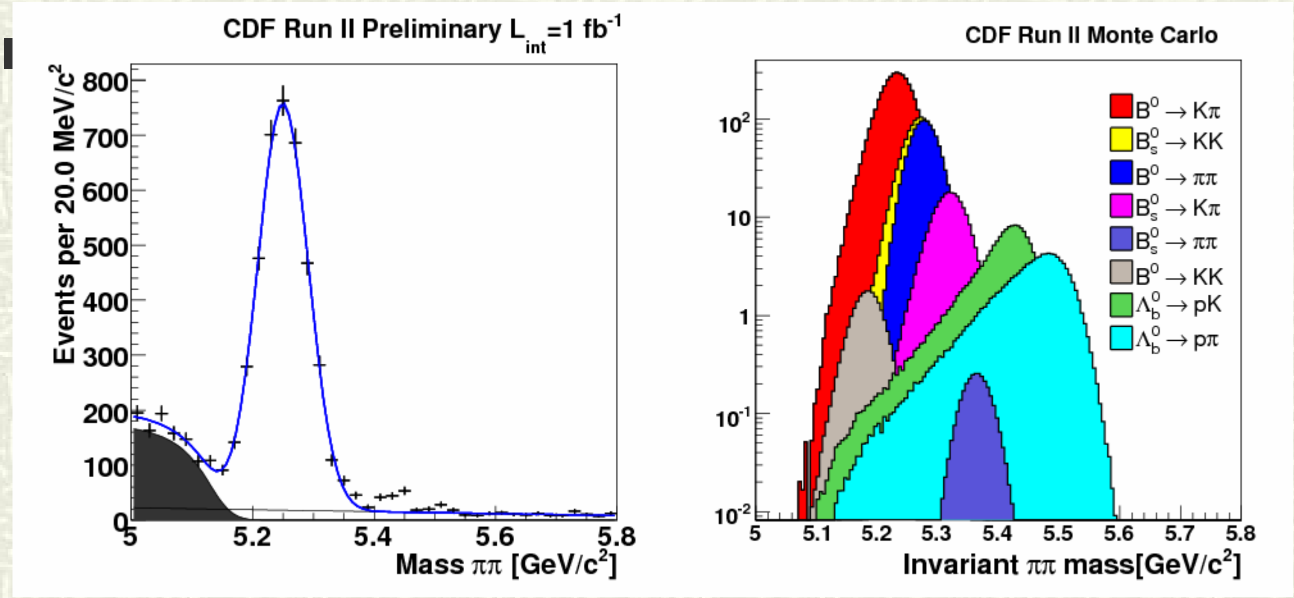
Conclusions

- Rare decays are highly suppressed in the SM allowing for very sensitive probes of new physics at the Tevatron
- A lot of work is being done to improve the analyses, in addition to just adding luminosity, to push closer to the SM predictions

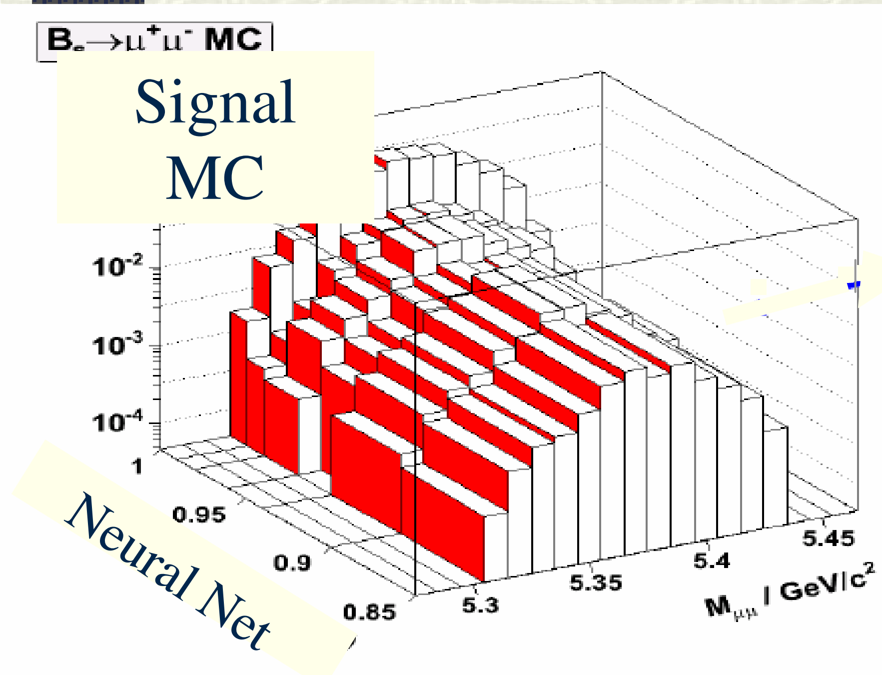
Backup Slides

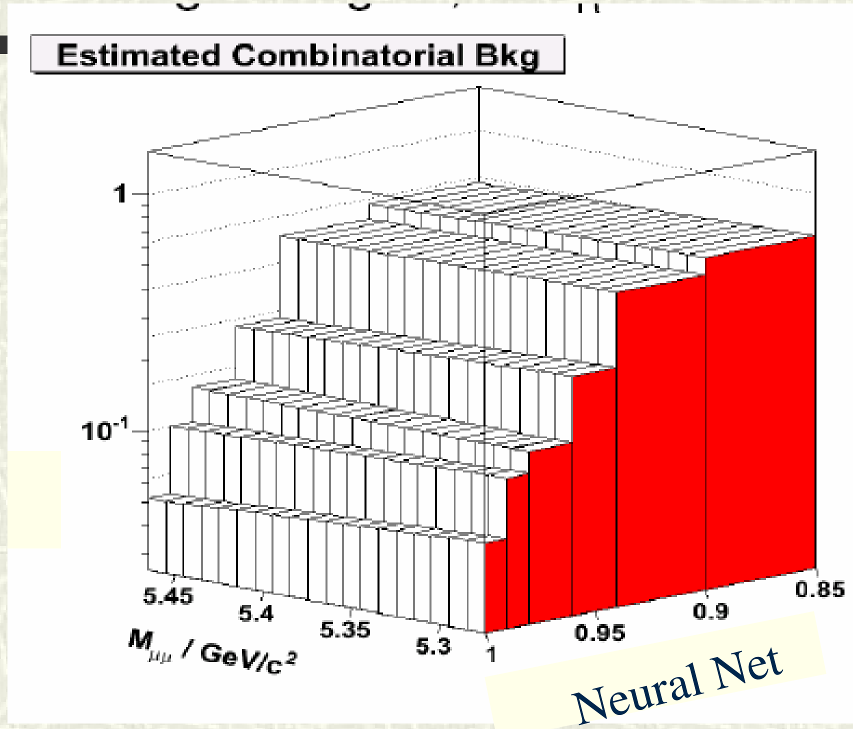
Search for Λ_b

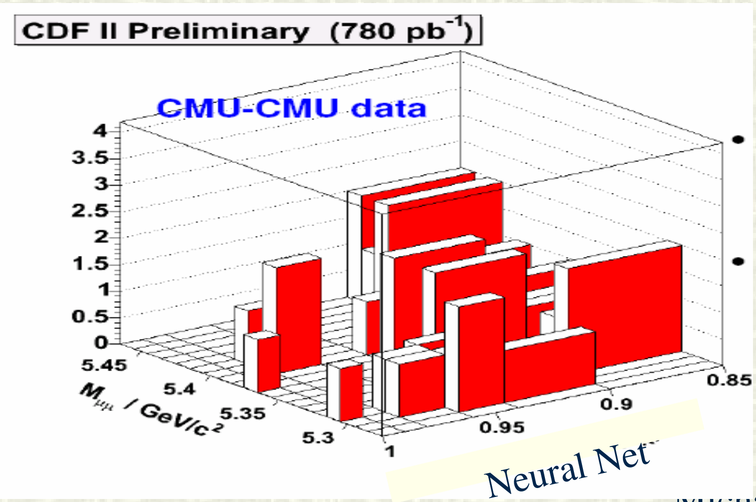
- No asymmetry previously seen in hadron decays
- Uses unbinned multivariate Likelihood fit
  - Uses PID



2D Fitter (an example)







B->hh is calculated and added to plot before fitting

Expected Bkg vs Observed Events

- For B_S signal window
- Bkg includes B->hh backgrounds
- Combine all bins in a 2d fit

CMU-CMU

	Mass Bin (GeV)	5.310-5.334	5.334-5.358	5.358-5.382	5.382-5.406	5.406-5.430
NN bin 0.80-0.95	Expected BKG	4.9±0.3	4.8±0.3	4.7±0.3	4.6±0.3	4.5±0.3
	Observed	3	3	7	3	2
NN bin 0.95-0.995	Expected BKG	1.6±0.2	1.6±0.2	1.5±0.2	1.5±0.2	1.5±0.2
	Observed 1	1	4	2	2	
NN bin 0.995-1.0	Expected BKG	0.43±0.1	0.42±0.1	0.41±0.1	0.41±0.1	0.41±0.1
	Observed	0	1	1	0	0

CMU-CMX

	Mass Bin (GeV)	5.310-5.334	5.334-5.358	5.358-5.382	5.382-5.406	5.406-5.430
NN bin 0.80-0.95	Expected BKG	5.4±0.4	5.3±0.3	5.2±0.3	5.1±0.3	5.0±0.3
	Observed	8	6	3	6	3
NN bin 0.95-0.99	Expected BKG	2.1±0.2	2.1±0.2	2.1±0.2	2.0±0.2	2.0±0.2
	Observed	3	2	2	4	0
NN bin 0.995-1.0	Expected BKG	0.32±0.09	0.31±0.09	0.31±0.09	0.31±0.09	0.31±0.09
	Observed 0	0	0	0	0	1