Some results on Bs→μμ and other FCNC decays from the CDF experiment

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OUTLINE

- **Flavor Changing Neutral Current B decays**

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

  $D^0 \rightarrow \mu^+\mu^-$

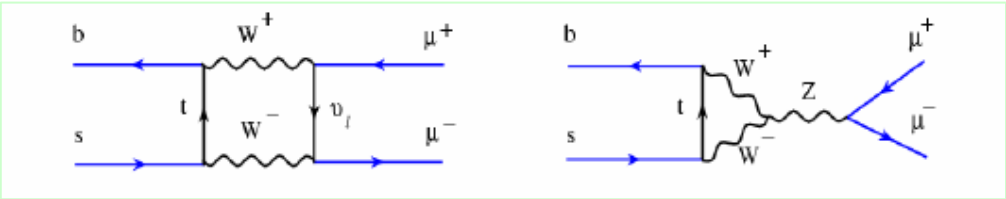
  $B_{s,d} \rightarrow e^+e^-$

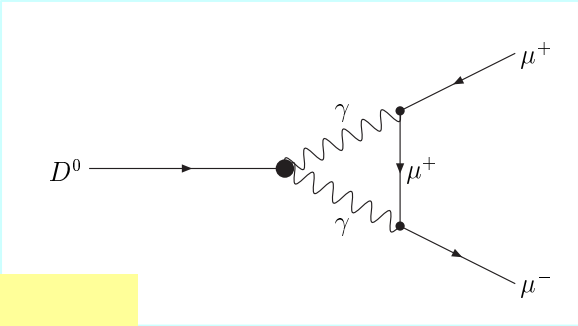
- **Lepton Flavor Violation**

  $B_{s,d} \rightarrow e\mu$

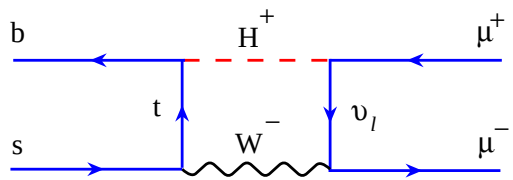
FCNC B,D decays

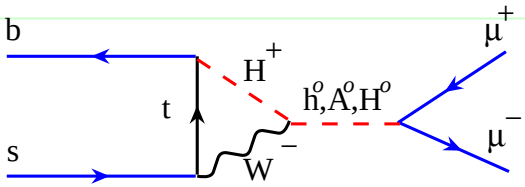
FCNC decays are suppressed at tree level. For D^0 it is also very much suppresed by GIM mechanism. The basic SM Feynman diagrams are:



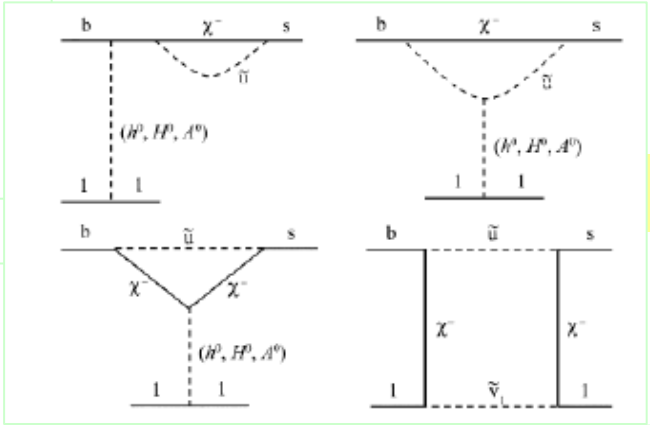


NSM effects can enhance the BR, through loops :



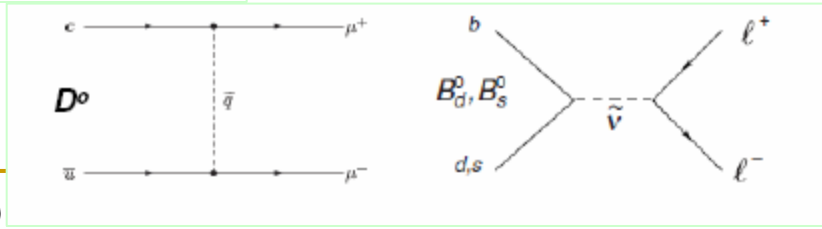


MFV, 2HDM

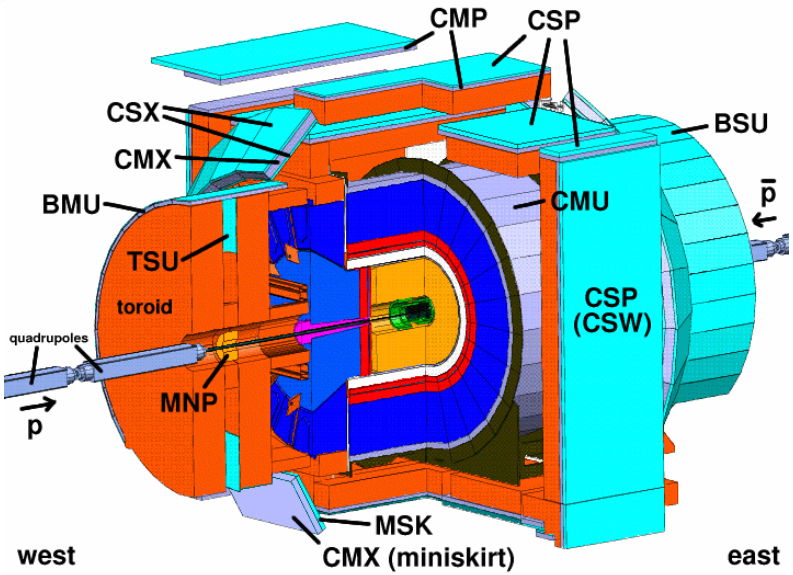


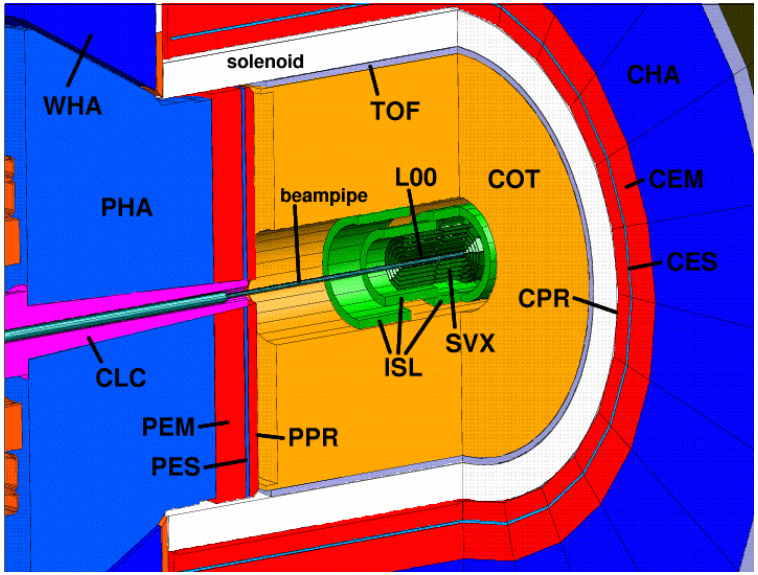
MSSM, BR (B) α $\tan^6\beta$

Or trough RPV:



The CDF detector





- Good tracking resolution, $\sigma(p_T)/p_T^2 \sim 0.1\%\ \mathrm{GeV}^{-1}$
  - Precise mass resolution
- Silicon Vertex Detector
  - Excellent vertex resolution
  - Crucial for triggering
- Large acceptance and good ID for leptons
- Kaon/pion separation
  - dE/dX in the COT
  - Time of Flight

$B_{s,d} \rightarrow \mu\mu$

$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{N_{B_s}}{N_{B^+}} \cdot \frac{\alpha_{B^+}}{\alpha_{B_s}} \cdot \frac{\epsilon^{trig}_{B^+}}{\epsilon^{trig}_{B_s}} \cdot \frac{\epsilon^{reco}_{B^+}}{\epsilon^{reco}_{B_s}} \cdot \frac{1}{\epsilon^{NN}_{B_s}} \cdot \frac{f_u}{f_s} \cdot BR(B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+)$$

	CMU-CMU		CMU-CMX	
$(\alpha_{B^+}/\alpha_{B_s})$	0.297 ± 0.020	$(\pm 7\%)$	0.191 ± 0.013	$(\pm 7\%)$
$(\epsilon^{trig}_{B^+}/\epsilon^{trig}_{B_s})$	0.9930 ± 0.0002	(-)	0.9956 ± 0.0004	(-)
$(\epsilon^{reco}_{B^+}/\epsilon^{reco}_{B_s})$	0.89 ± 0.04	$(\pm 4\%)$	0.88 ± 0.04	$(\pm 4\%)$
$\epsilon^{NN}_{B_s}(NN > 0.80)$	0.779 ± 0.047	$(\pm 6\%)$	0.790 ± 0.047	$(\pm 6\%)$
N_{B^+}	8117 ± 137	$(\pm 2\%)$	3270 ± 90	$(\pm 3\%)$
f_u/f_s	3.86 ± 0.59	$(\pm 15\%)$	3.86 ± 0.59	$(\pm 15\%)$
$BR(B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+)$	$(5.94 \pm 0.21) \times 10^{-5}$	$(\pm 4\%)$	$(5.94 \pm 0.21) \times 10^{-5}$	$(\pm 4\%)$
ses	$(9.5 \pm 0.7) \times 10^{-9}$	$(\pm 18\%)$	$(1.5 \pm 1.0) \times 10^{-8}$	$(\pm 18\%)$

Single event sensitivity: BR with N_{Bs}=1

W. M. Yao et al.[Particle Data Group], J. Phys. G **33**, 1(2006).

Neural Net

Acceptances

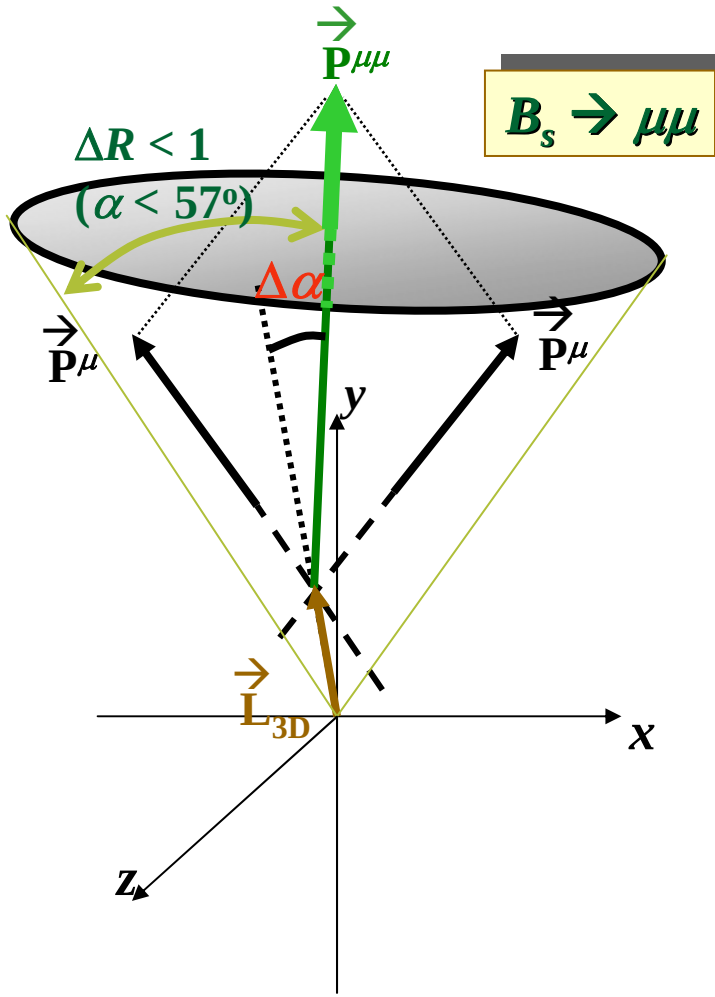
B→ μμ

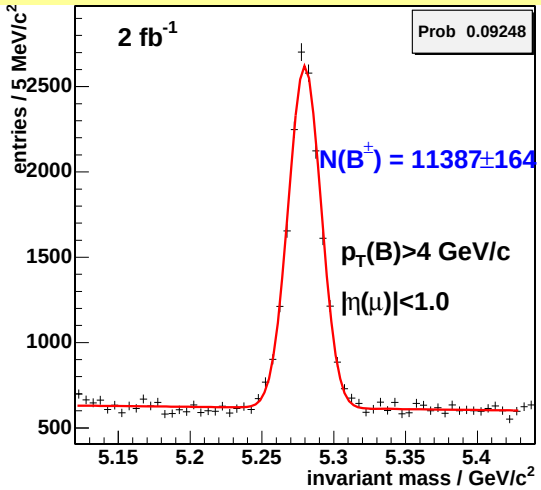
Trigger: Di-muon for rare decays (Dynamic pre-scale for a fraction of data)

Common pre-Selection to $B_{s,d}$,B^+: trigger match, good run, track and muon quality, silicon vertex quality, fiducial requirements to avoid regions of rapidly changing trigger efficiencies, kinematical cuts of B-hadron

$B_{s,d}$→μμ selection: 3D-vertex quality of dimuon, isolation, pointing angle of the B flight direction to the collision point, proper decay length significance

B^+→J/ψ K selection: Invariant mass of dimuons, K track quality, three track vertex quality, isolation, pointing angle



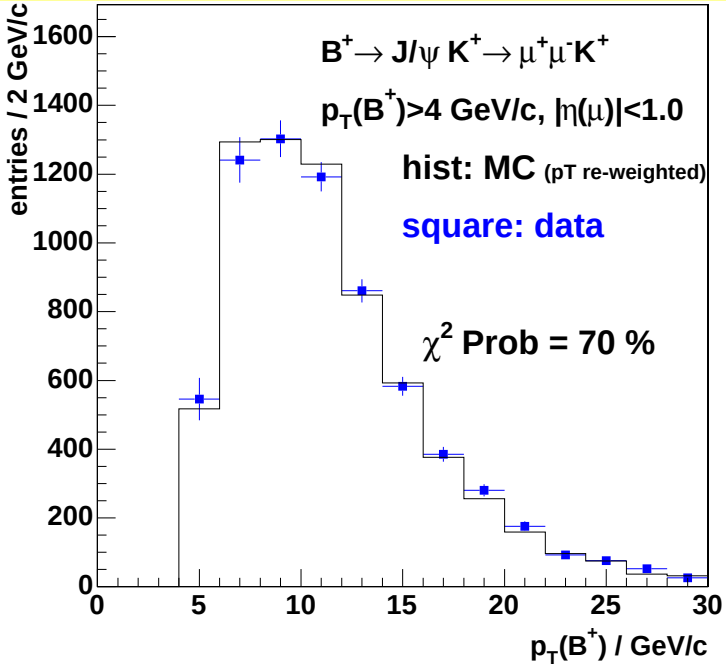


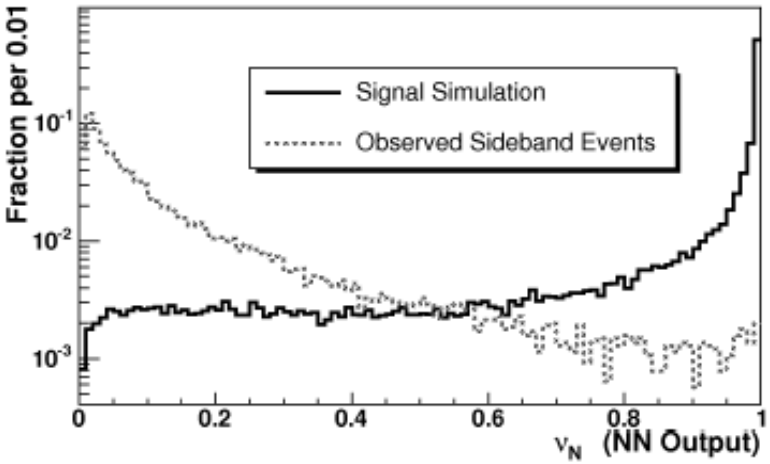
$B \rightarrow \mu\mu$

Monte Carlo Samples: $B_s \rightarrow \mu\mu$, to estimate the signal efficiency and train the NN, and $B^+ \rightarrow J/\psi K^+$ to estimate some selection requirements and cross-check MC modeling of NN discriminant, both tuned Pythia+EvtGen

Selection: Neural network, inputs: proper decay length, 3D opening angle between B flight direction and decay vertex, Isolation, proper decay length significance, transverse momentum of B and μ

- We performed an unbiased optimization using signal MC and sideband data for background
- We made a separate estimate of the background for two-body hadronic decays, for each mass and NN bin. It is about ten times smaller

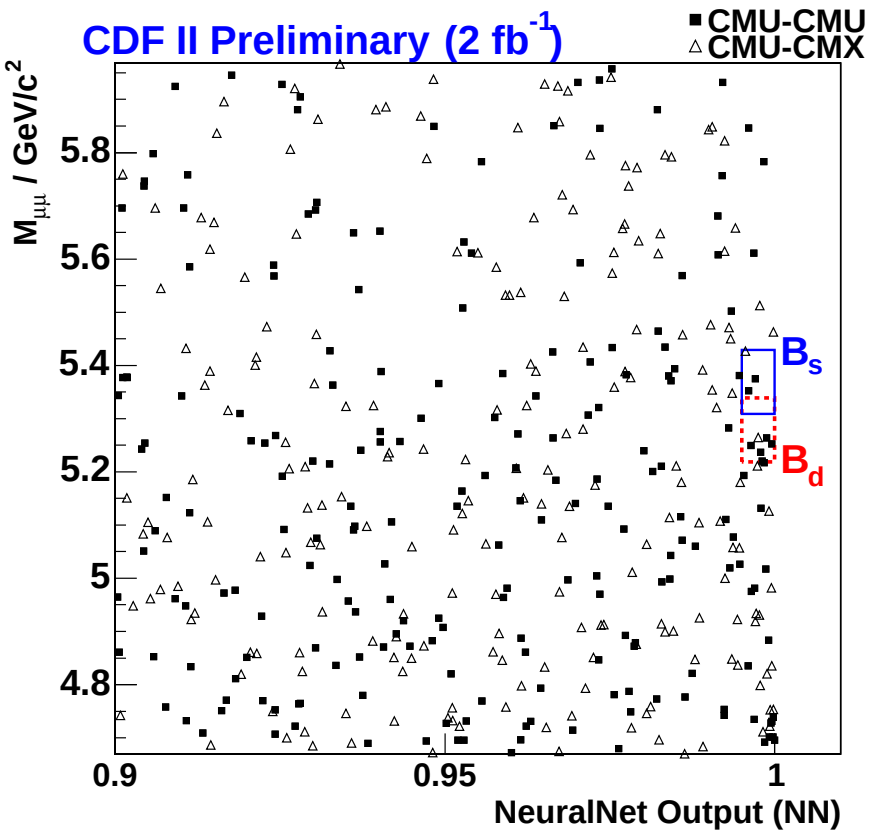


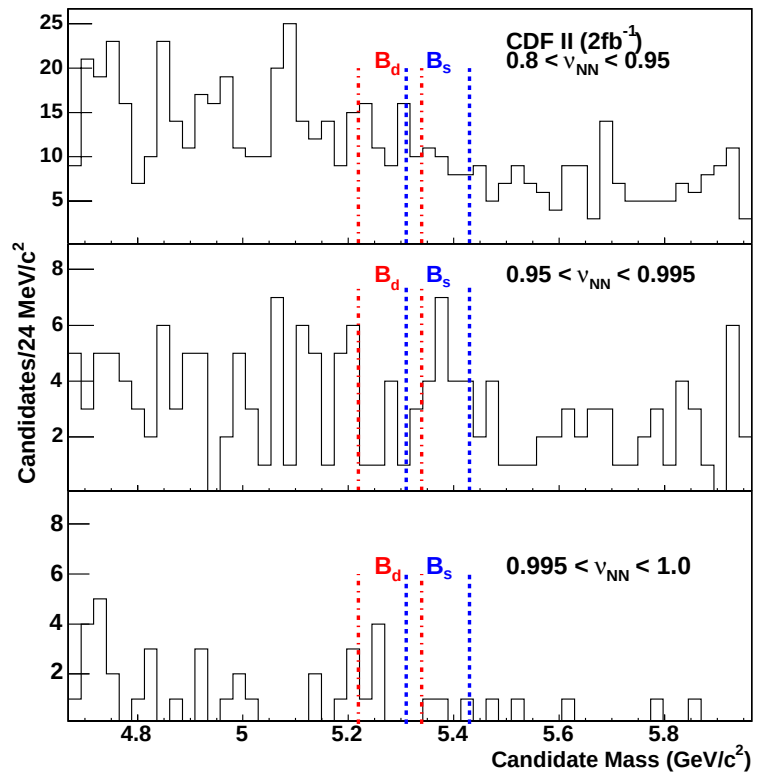


B→ μμ results (PRL 100,101802 (2008))

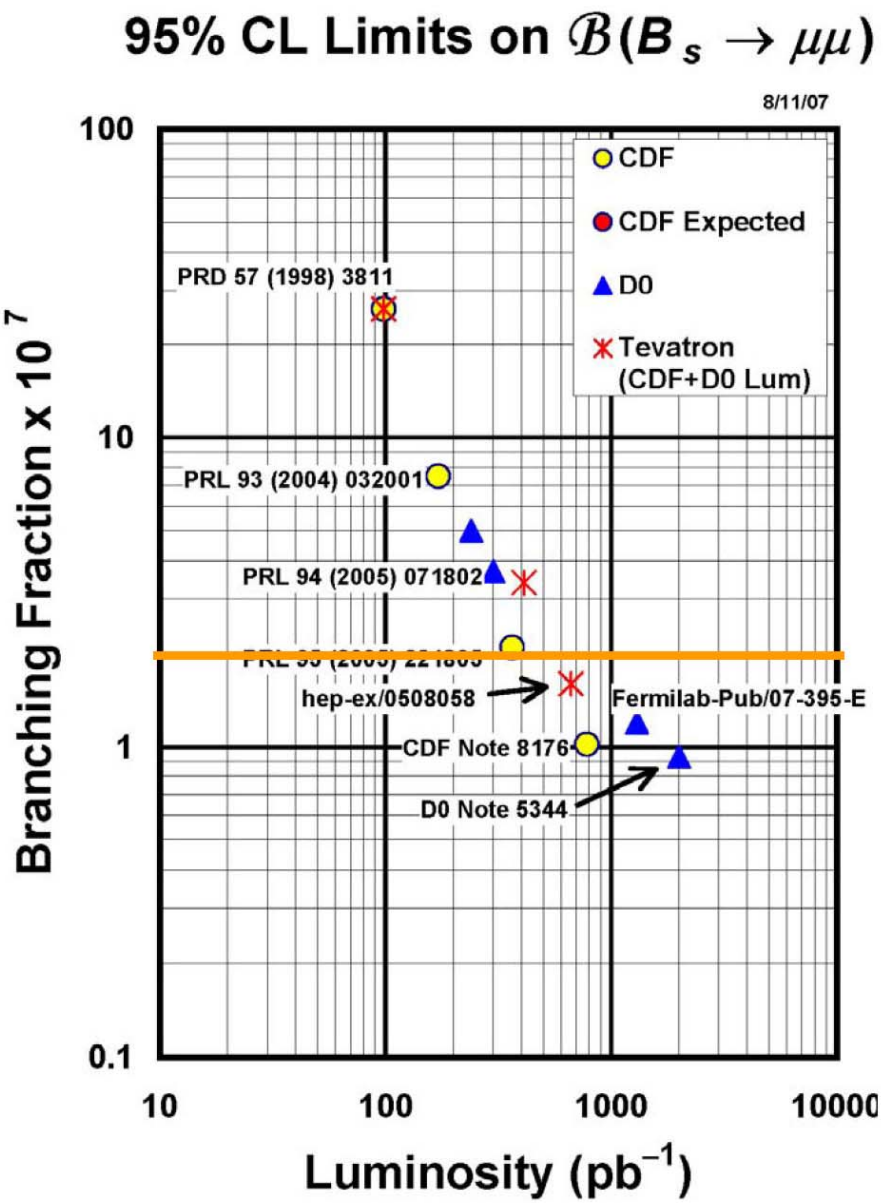
$$\mathrm{BR}(B_s \to \mu^+\mu^-) = \frac{N_{B_s}}{N_{B^+}} \cdot \frac{\alpha_{B^+}}{\alpha_{B_s}} \cdot \frac{\epsilon^{trig}_{B^+}}{\epsilon^{trig}_{B_s}} \cdot \frac{\epsilon^{reco}_{B^+}}{\epsilon^{reco}_{B_s}} \cdot \frac{1}{\epsilon^{NN}_{B_s}} \cdot \frac{f_u}{f_s} \cdot BR(B^+ \to J/\psi K^+ \to \mu^+\mu^- K^+)$$

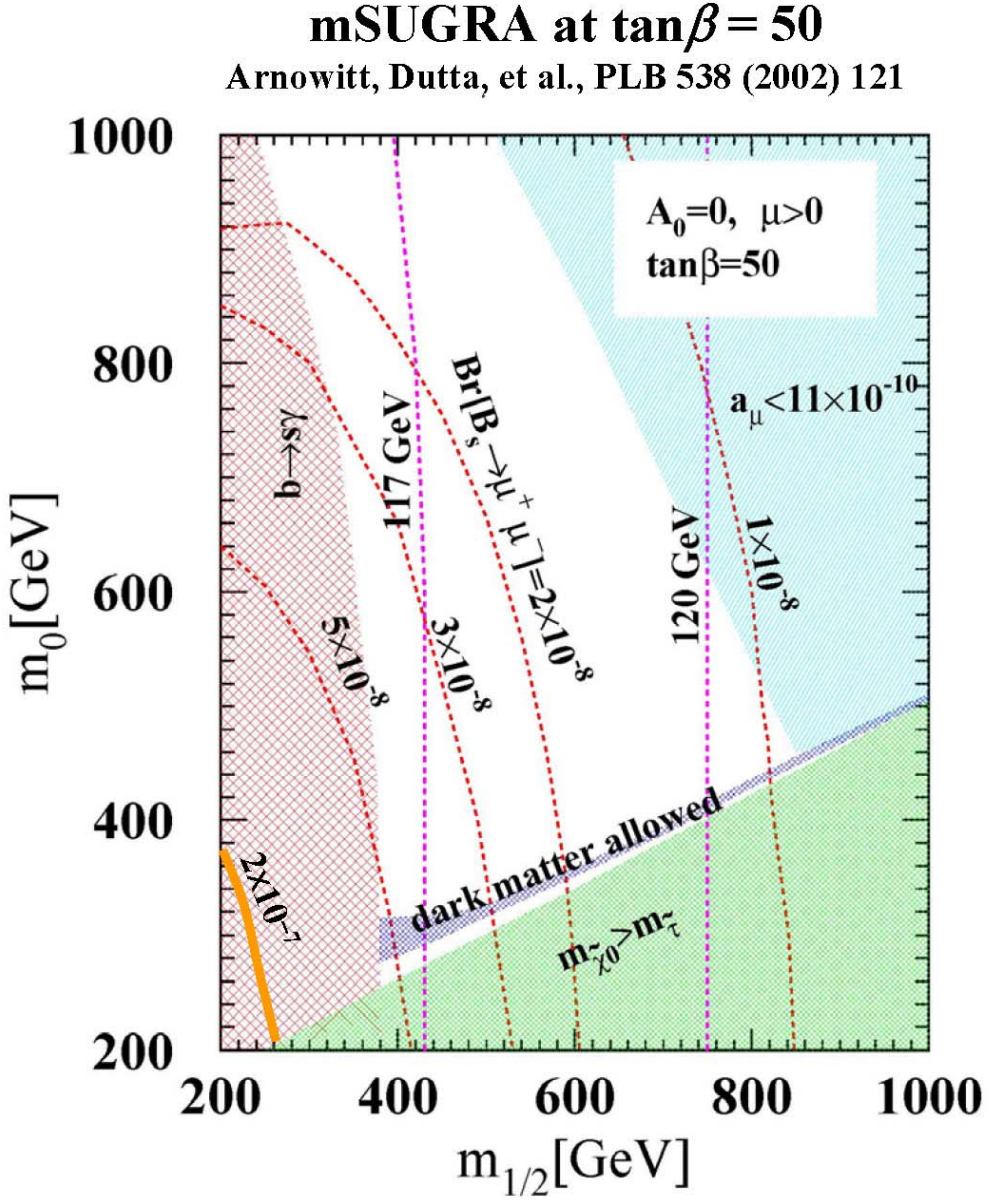
Two-dimensional fitter. Each NN-mass bin is a single-bin counting experiment (shape templates from: MC for signal and data sidebands fitting + B→hh, for background)



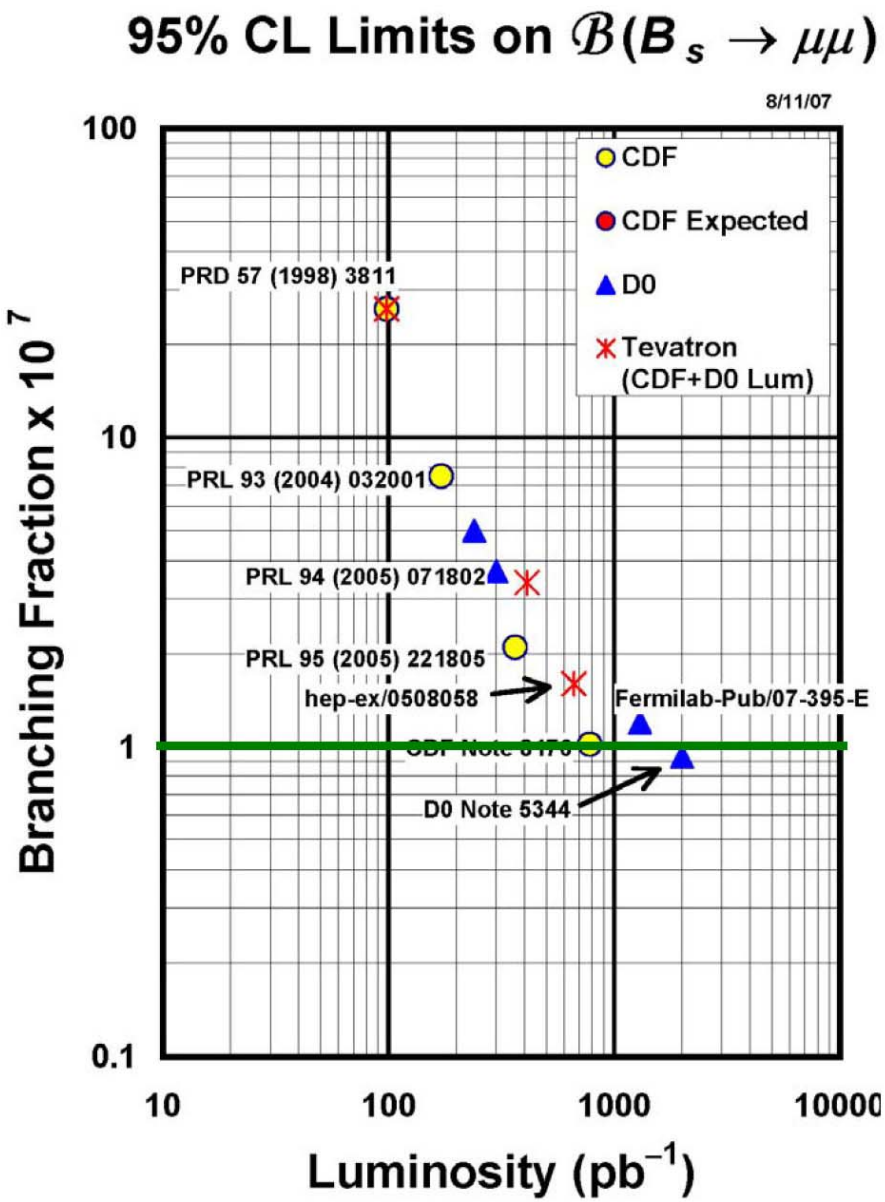


$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection



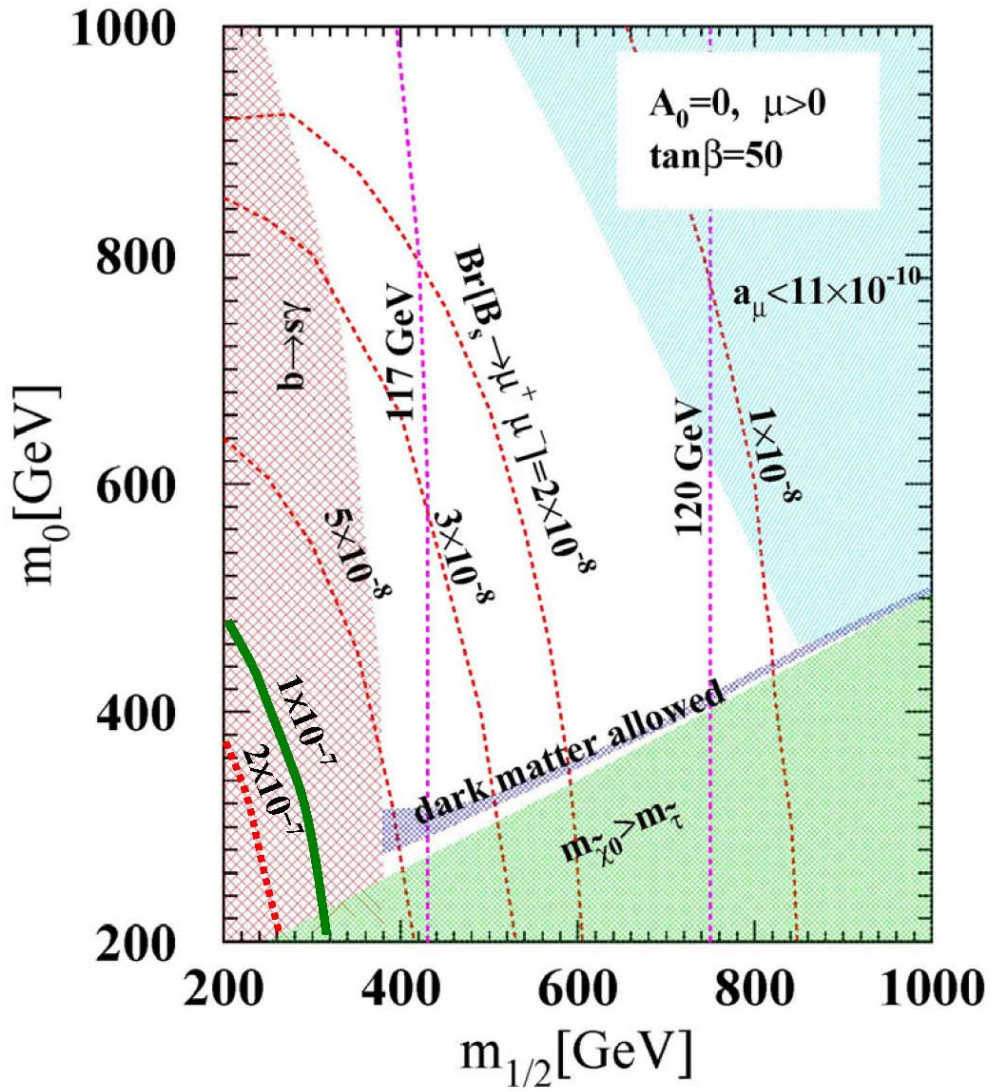


$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection

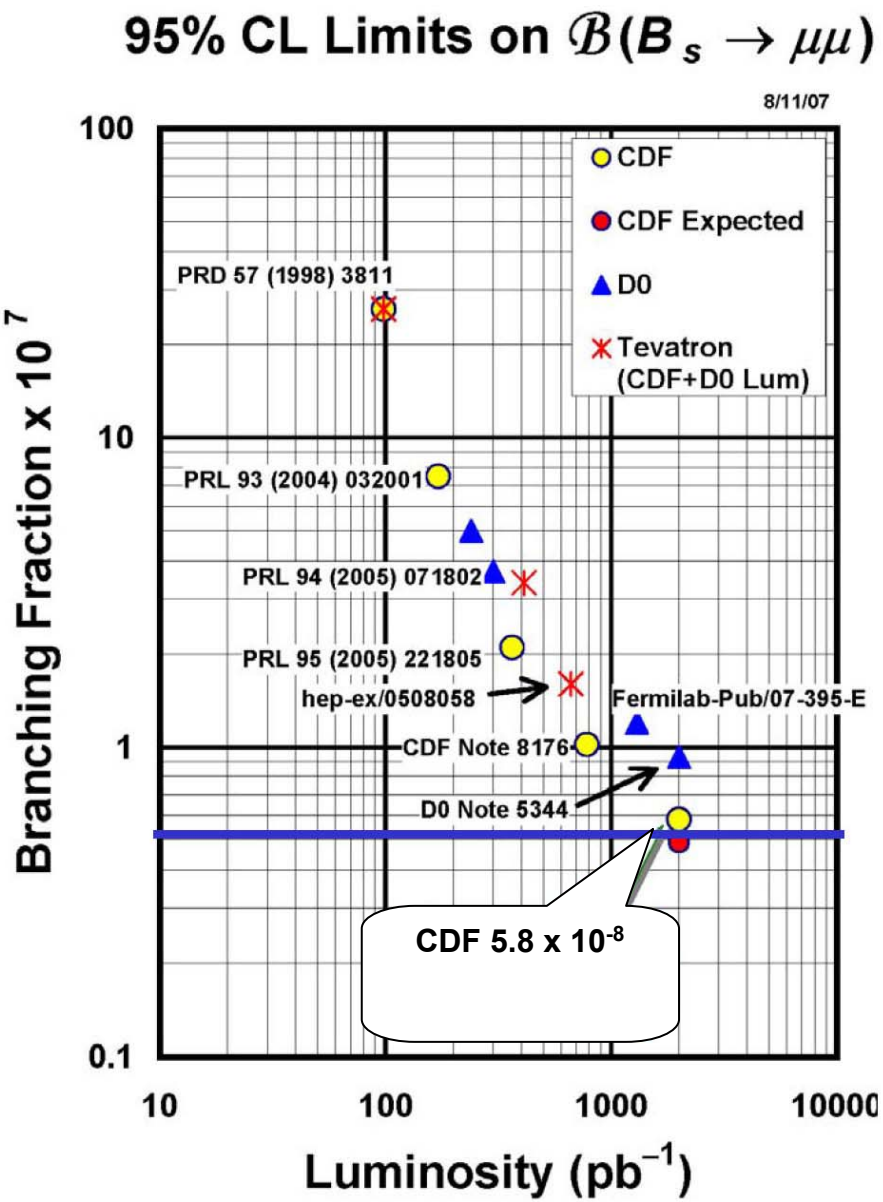


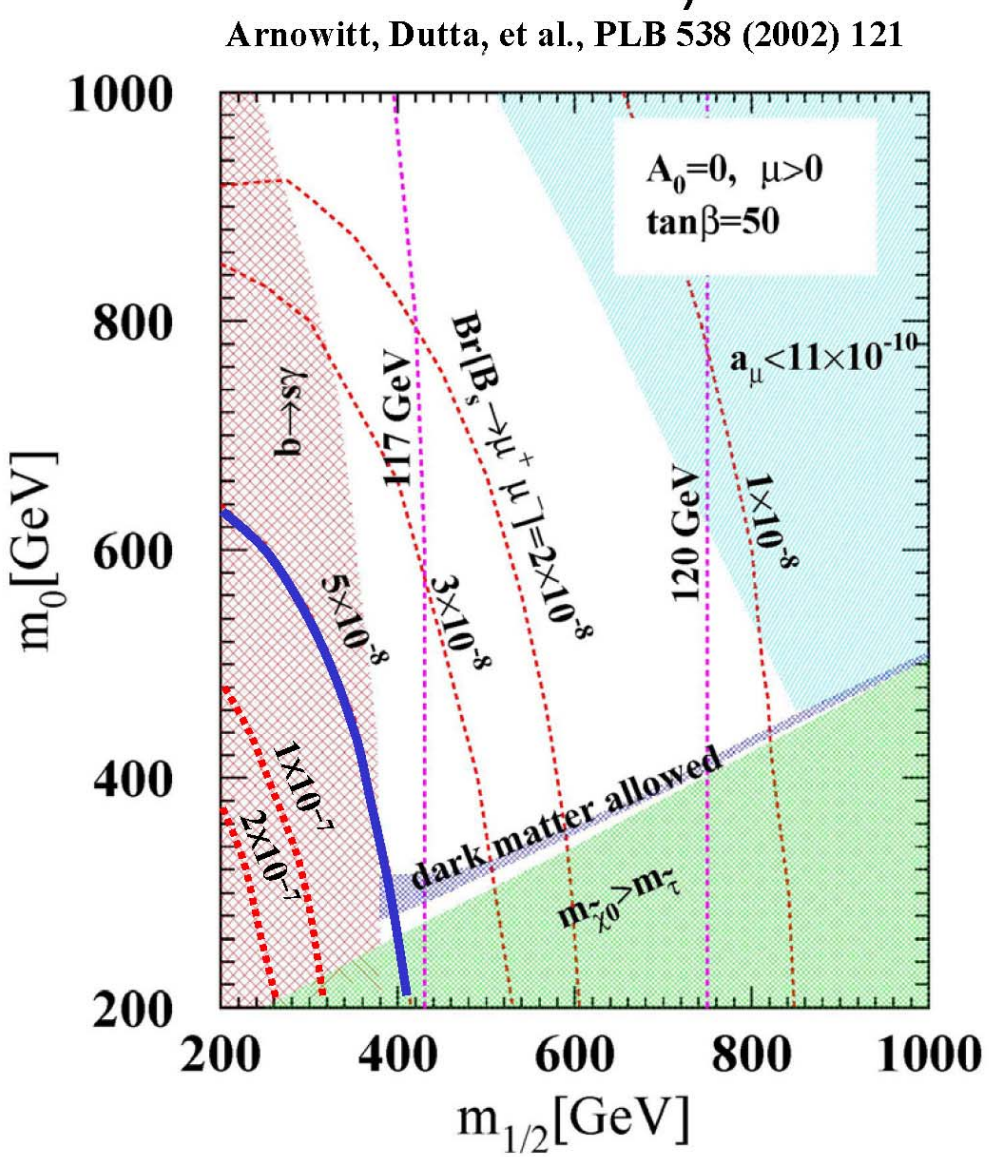
mSUGRA at $\tan\beta = 50$

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

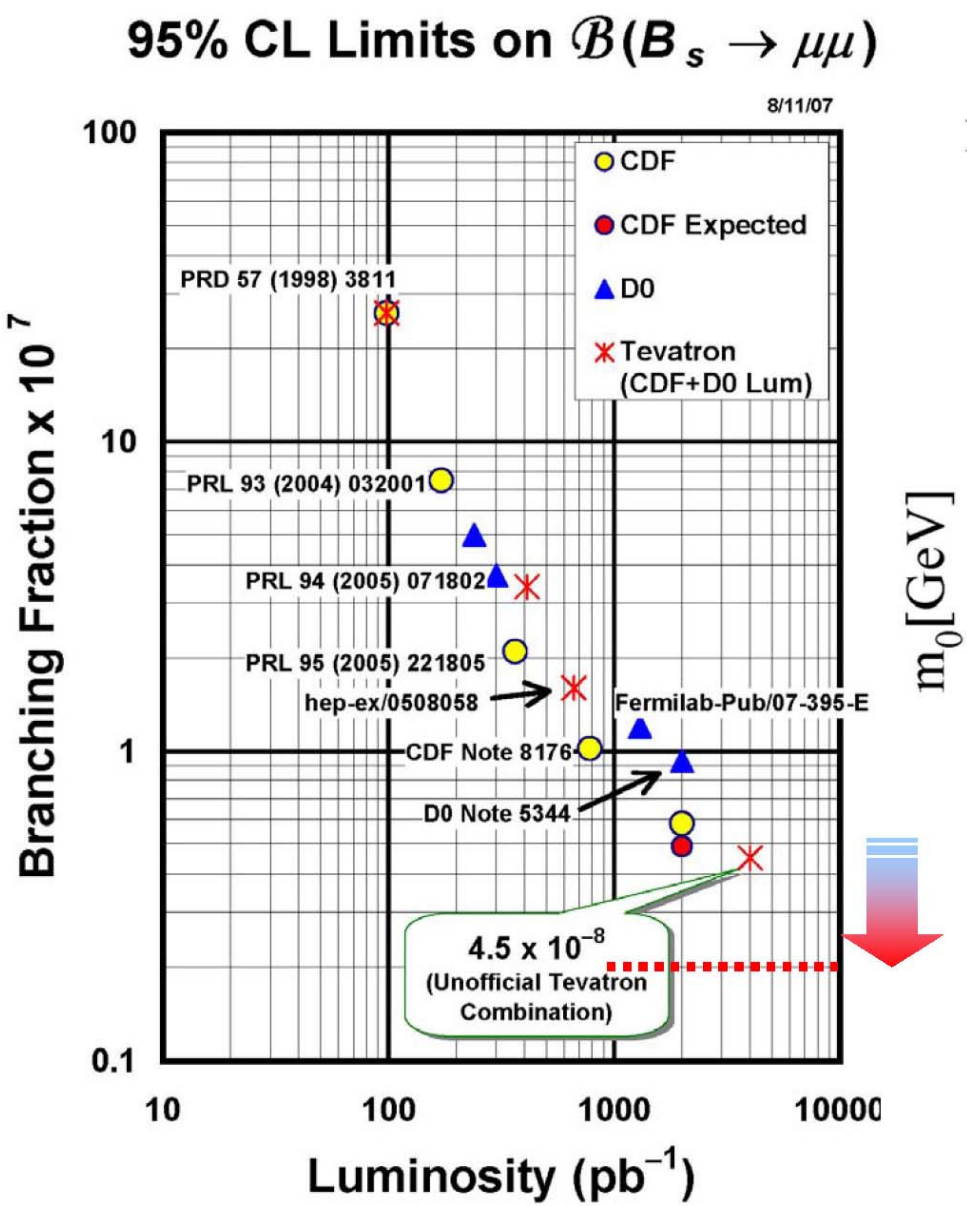


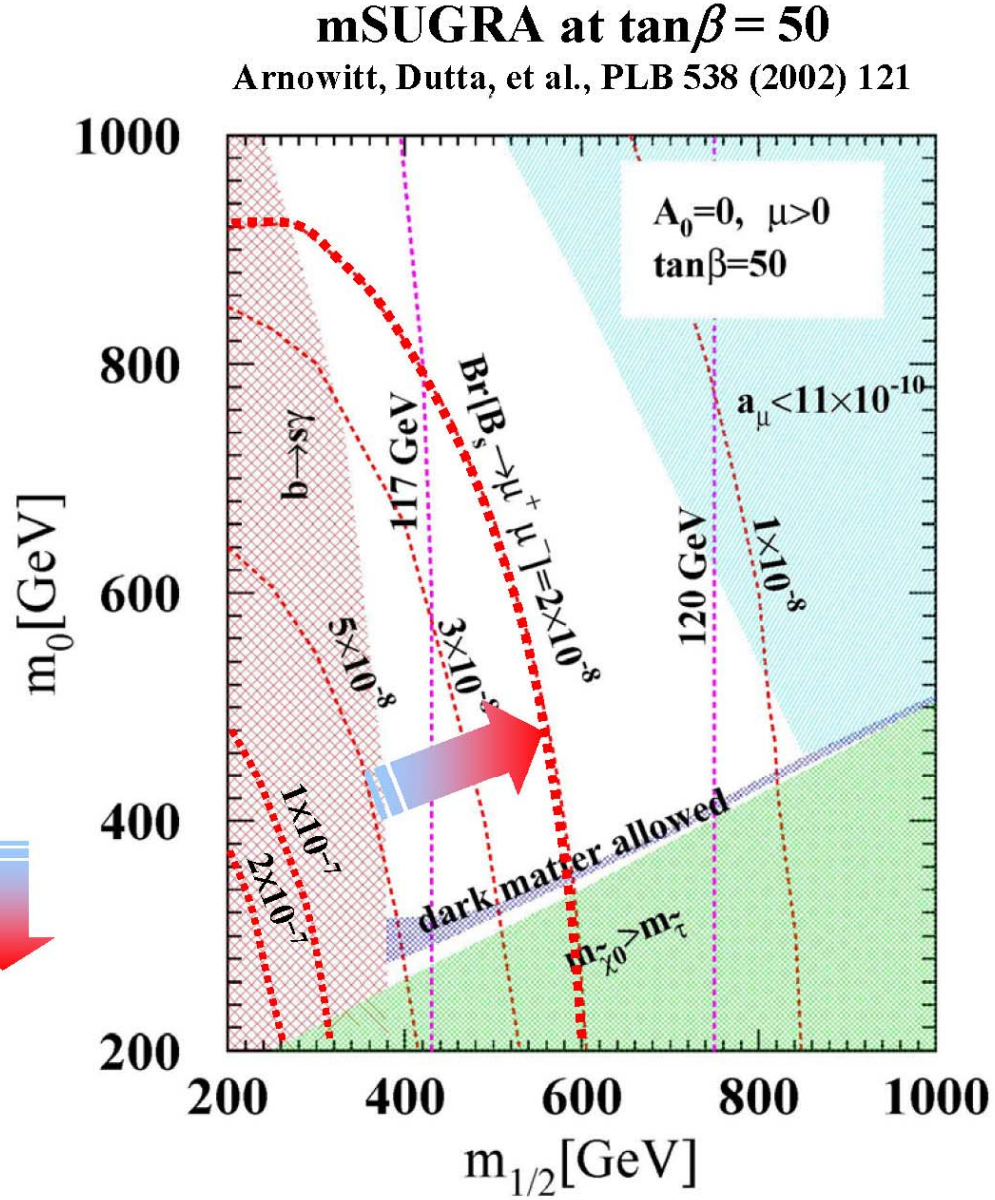
$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection



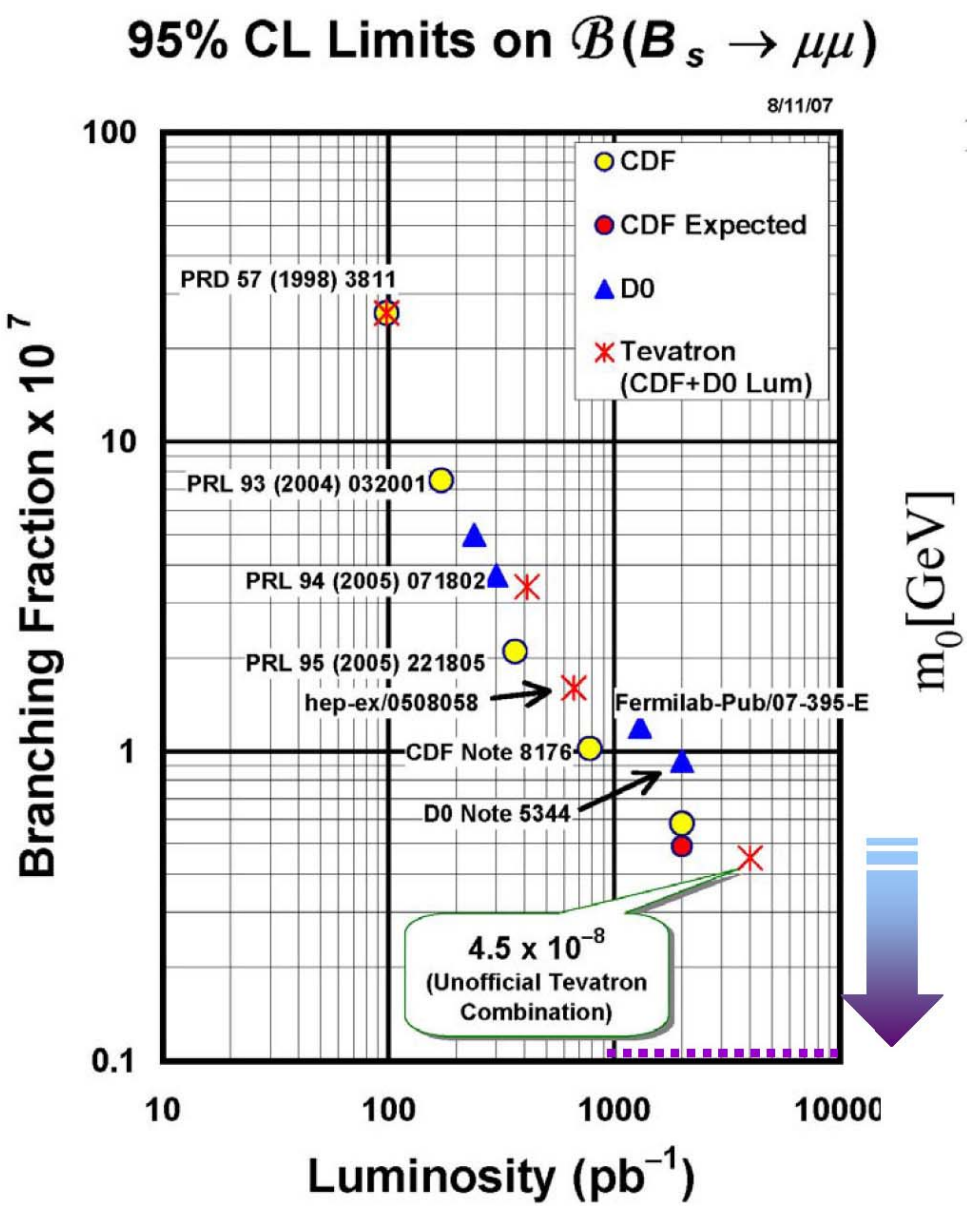


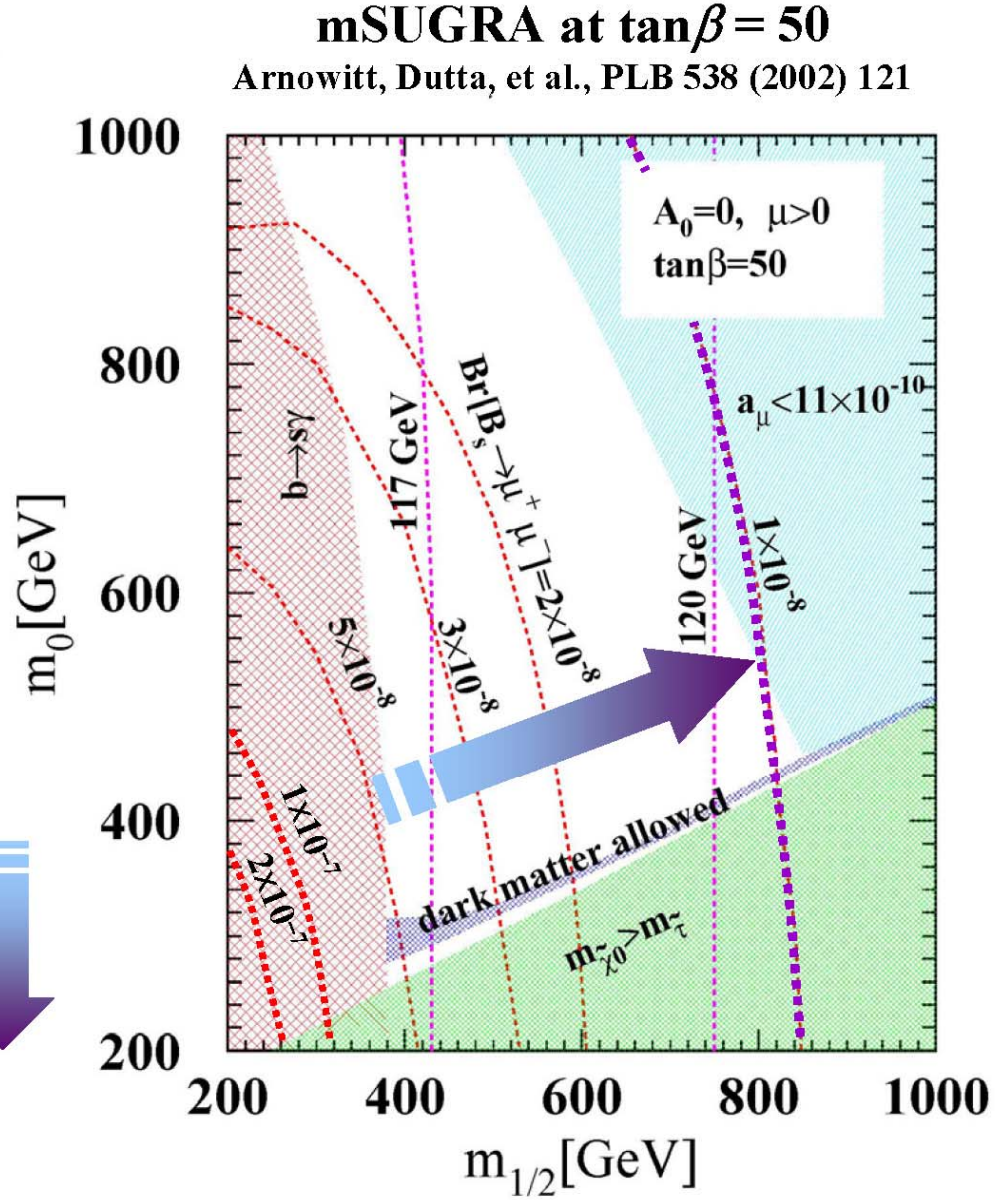
$\mathcal{B}(B_s \to \mu\mu)$ and Cosmological Connection





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

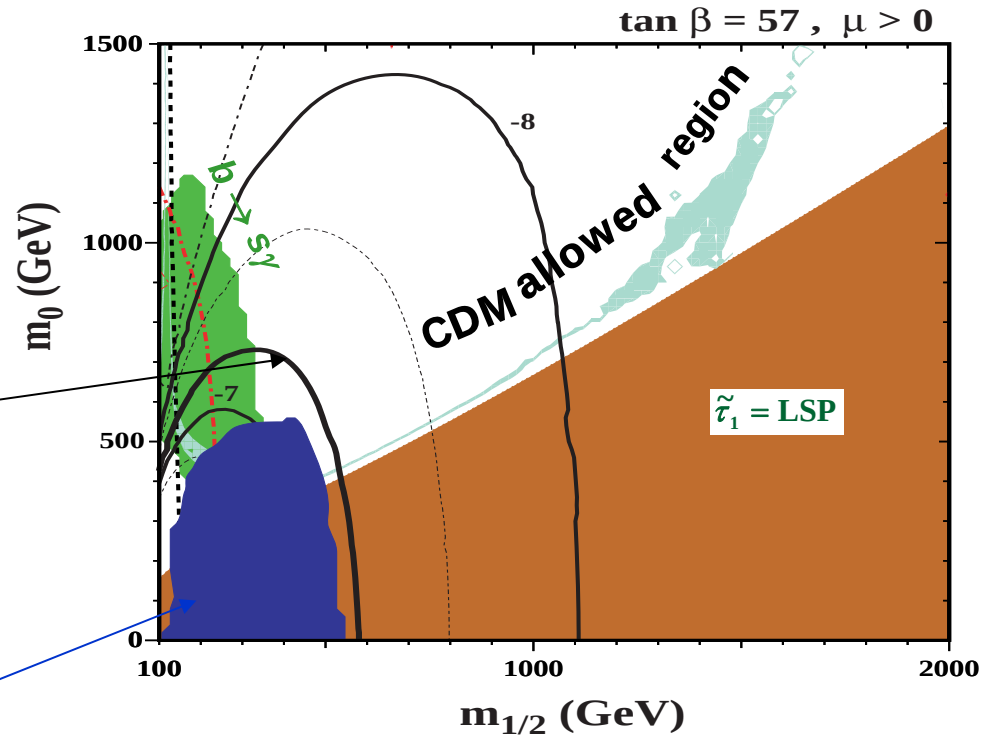




Limits in $B_s \rightarrow \mu\mu$ CMSSM

5.8 x10^{-8} (CDF, 2 fb^{-1})

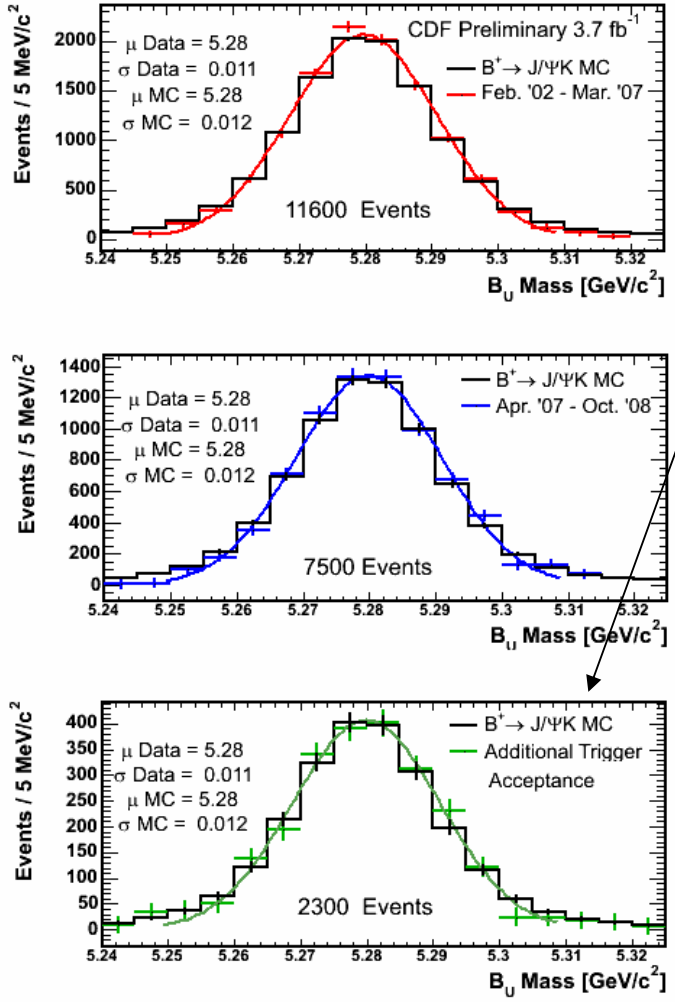
Disallowed region , taking into account all uncertainties (A_0=0, μ>0)

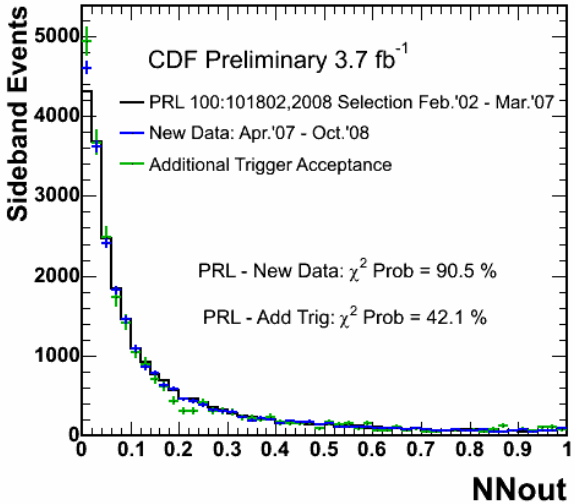


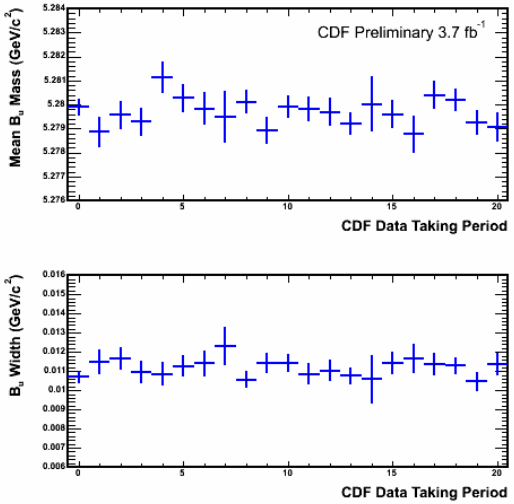
J. Ellis et al. hep-ph/0504196v2 (Nov 2005)

B→μμ analysis progress

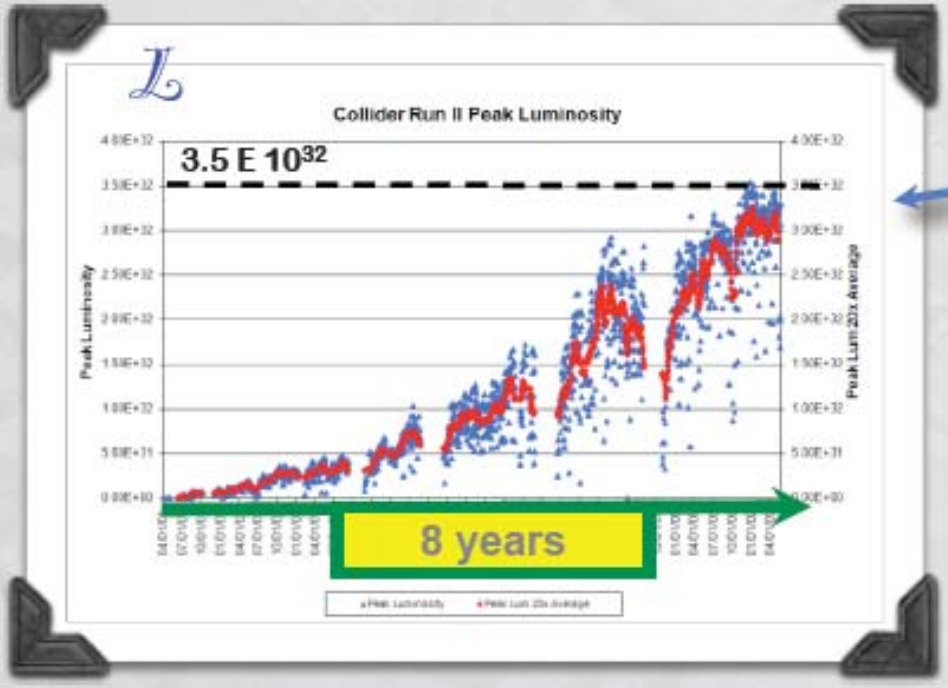
- Increasing statistics (4 fb^{-1} well advanced)
- Improving trigger acceptance (two-track trigger, 15% more statistics)
- Improving dimuon trigger acceptance (12% more statistics)
- Detector effects studied. Normalization mode well understood







Run 2 Luminosity Progress



Record peak inst. luminosity

$3.6\ E\ 10^{32}\ cm^{-2}\ s^{-1}$

Record luminosity/week

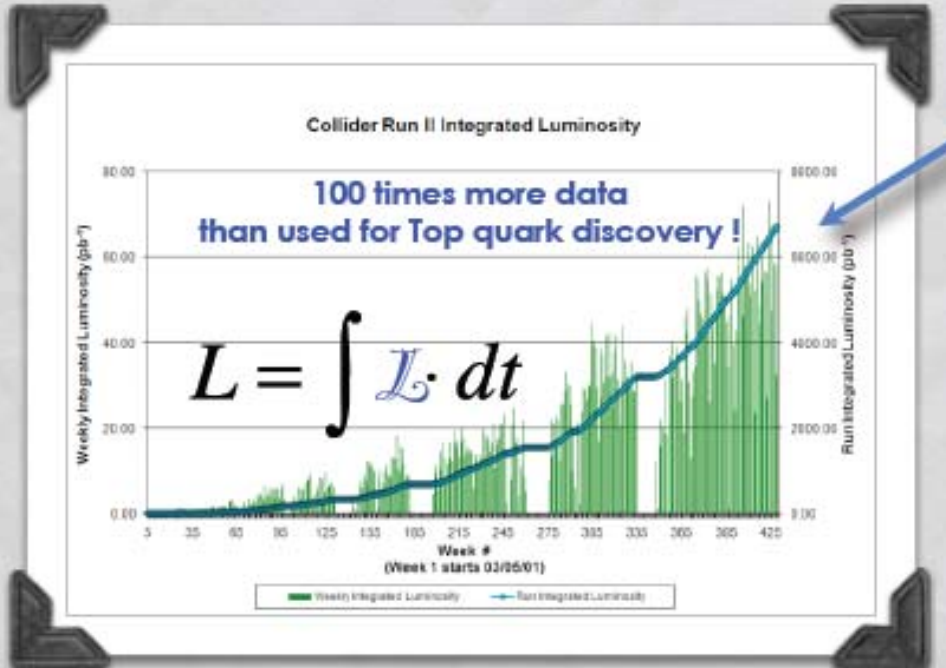
$73\ pb^{-1}$

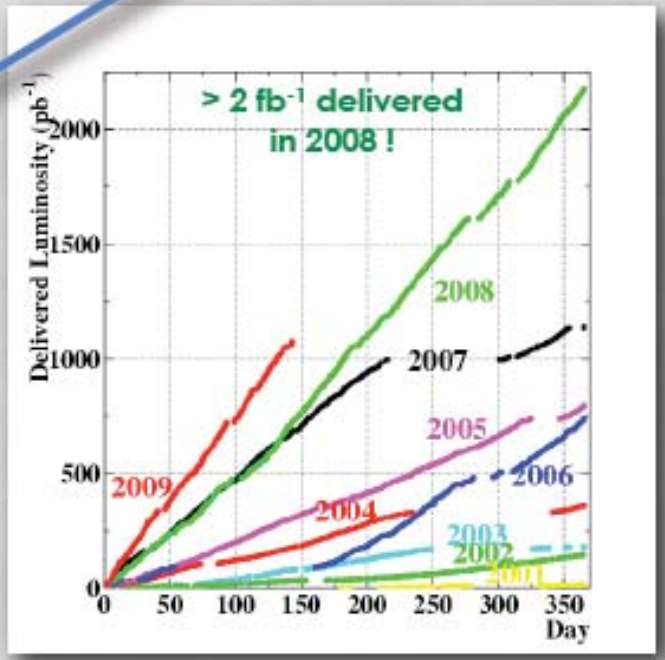
Record luminosity/month

$250\ pb^{-1}$

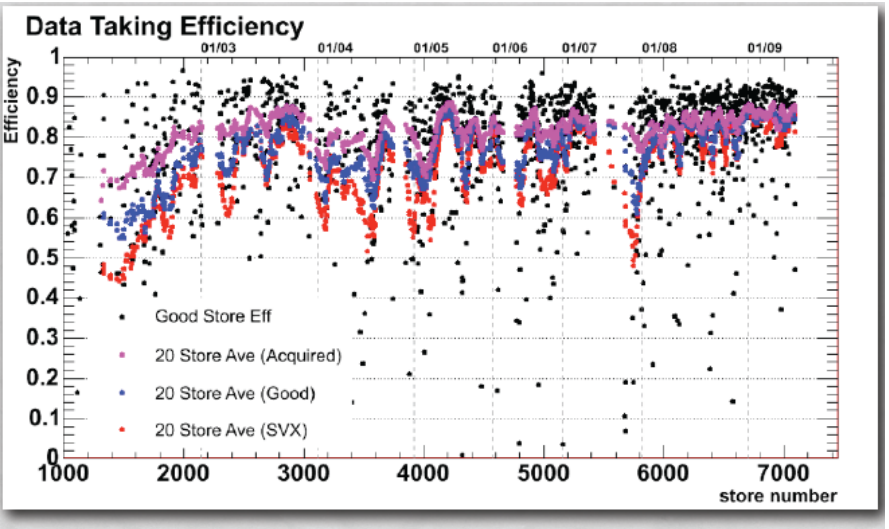
Total Luminosity delivered

$6.8\ fb^{-1}$

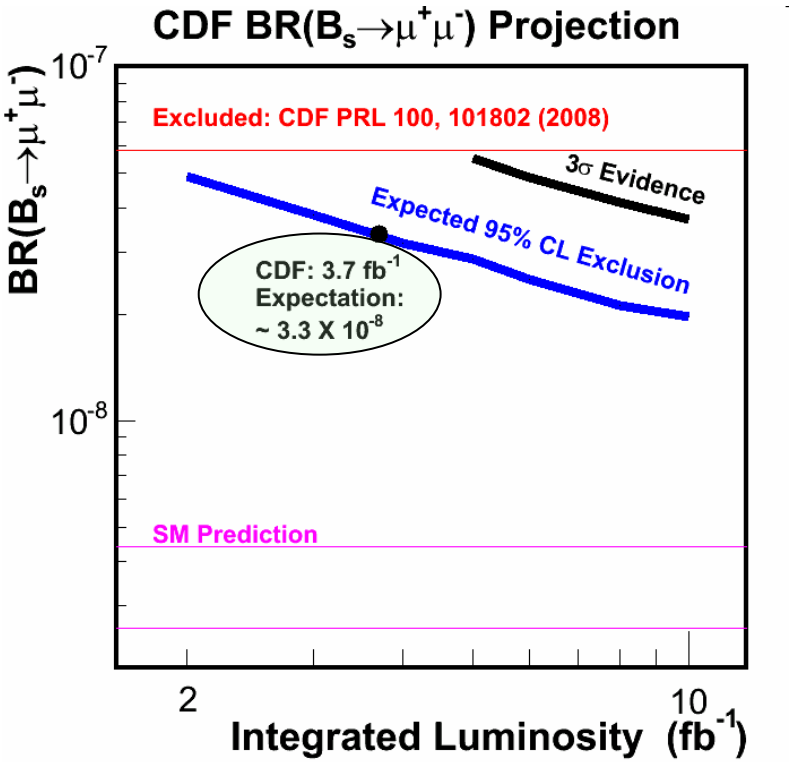




Expectations



6.8 fb^{-1} delivered => 5.6 fb^{-1} recorded (83%)
Good with Silicon = 5.1 fb^{-1}



Expected limits calculated using published CLs based method and scaling of normalization mode and backgrounds linearly.
May be slightly conservative since NN binning could be reoptimized and new dE/dx calibration is improved

$B_{s,d} \rightarrow e\mu$ (ee) strategy

Events (or Events @ limit)
surviving all selection criteria (incl. Lepton ID)

World average

$$Br(B_s^0 \to e^+\mu^-) = \frac{N(B_s^0 \to e^+\mu^-) \cdot Br(B_d^0 \to K^+\pi^-) \cdot f_{B_d^0}/f_{B_s^0}}{\epsilon^{rel}_{B_s^0 \to e^+\mu^-} \cdot N(B_d^0 \to K^+\pi^-)}.$$

The Result

Fit to B->hh spectrum of evts. surviving all but lepton ID selection

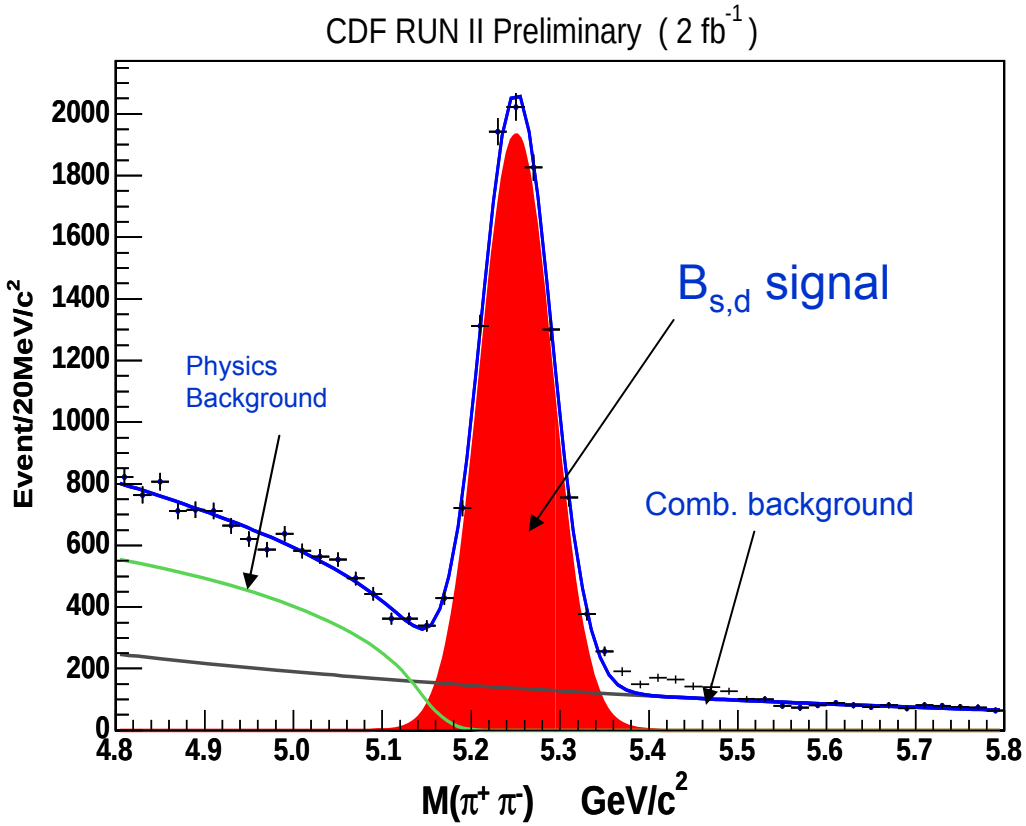
Bs only:
biggest contribution to systematic uncertainty

Relative efficiency:
MC for kinematics and mass window efficiency
CDF measurements (J/Psi,photon conversions) for lepton ID efficiency and acceptance

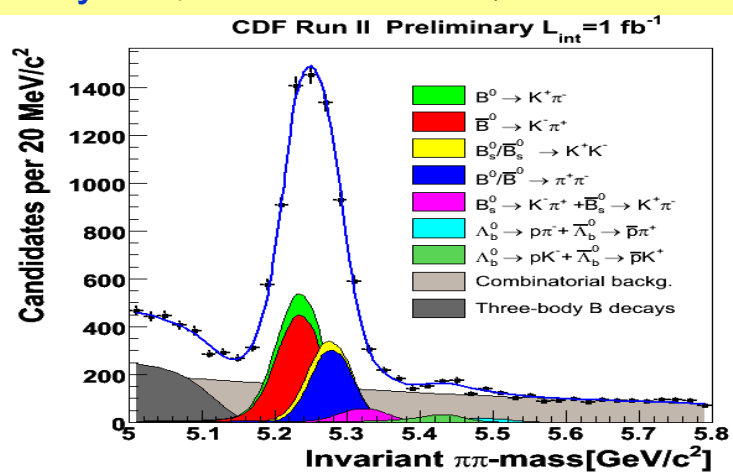
$B_{s,d} \rightarrow ee, e\mu$

Trigger: Two-track trigger

Common pre-Selection to $B_{s,d}$: trigger match, good run, track quality, silicon vertex quality, fiducial requirements, kinematical cuts of B-hadron, 3D-vertex quality of B-hadron candidate, isolation, pointing angle of the B flight direction to the collision point



Same procedure as in B→hh analysis (PRL 97, 211802 2006)

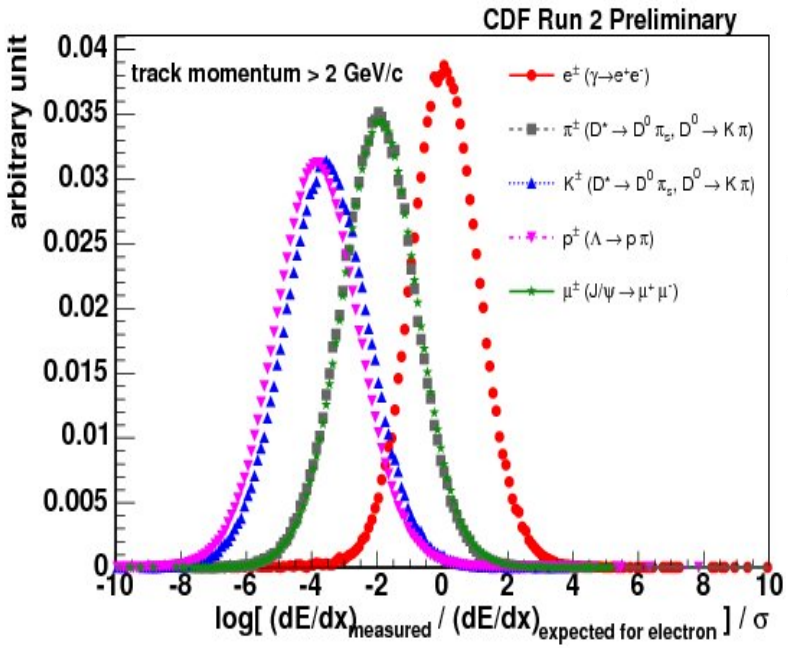


$B_{s,d} \rightarrow ee, e\mu$

Electron, muon identification:

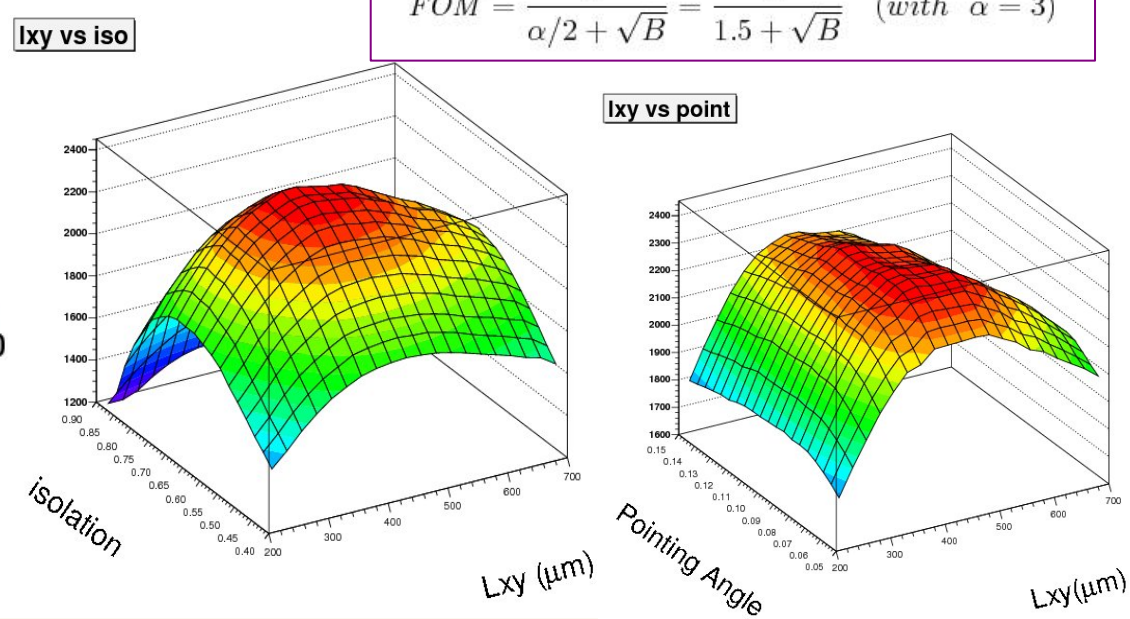
Electrons: dE/dX in the drift chamber, E_{had}/E_{em},E/P,matching to the calorimeter towers, shower profile,…

Muons: Track-muon chambers matching, ..



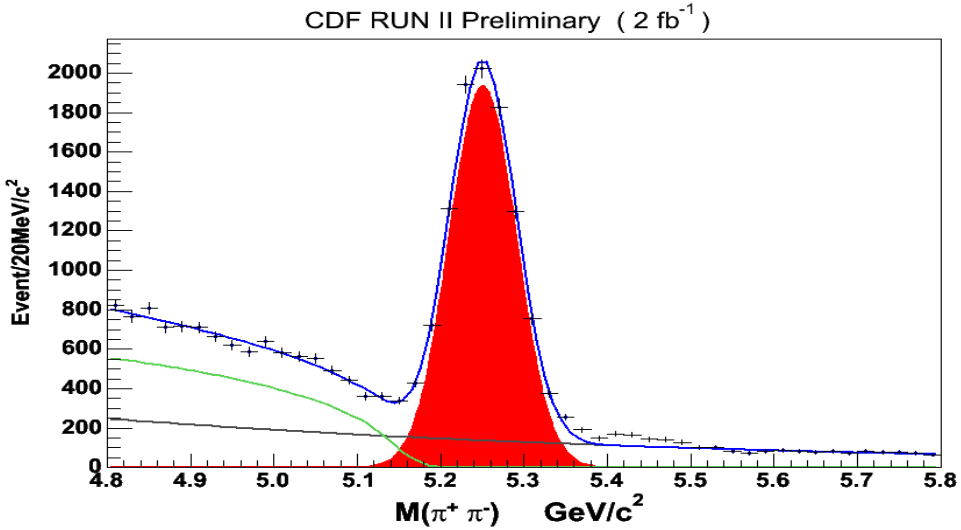
Cut optimization: made with data for background (sidebands) and MC or fitting data for signal

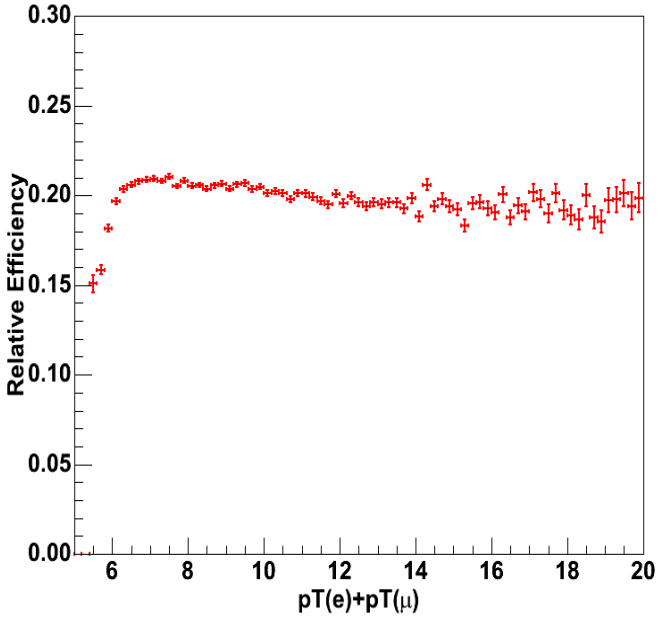
$$FOM = \frac{S}{\alpha/2 + \sqrt{B}} = \frac{S}{1.5 + \sqrt{B}} \quad (with \ \ \alpha = 3)$$



$B_{s,d} \rightarrow e\mu$

B→hh with optimized cuts





$\varepsilon(B \rightarrow e\mu)/e(B \rightarrow K\pi)$

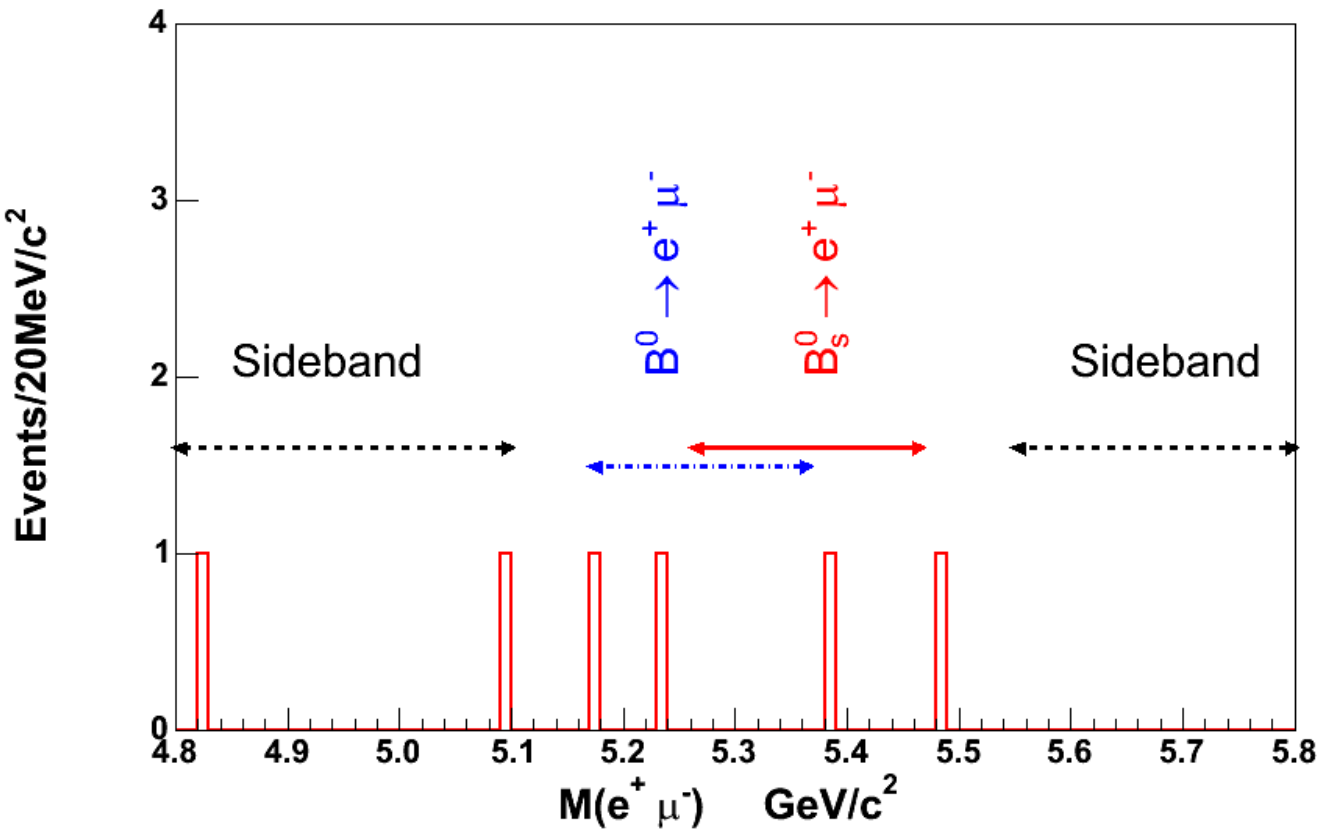
Efficiency and acceptance studied relative to that of B→Kπ.

Detector and kinematic acceptance from MC

Fiducial coverage from data

$B_{s,d} \rightarrow e\mu$ search

Search for $e\mu$ candidates, in the + - 3σ mass window around the $B_{s,d}$ mass, by using the identification cuts



Background estimation (combinatorial from the sidebands, double fake from B→hh):

0.8 +- 0.6, B_s

0.9 +- 0.6, B_d

$B_{s,d} \rightarrow e\mu$ results

PRL 102, 201801 (2009)

Source	values	$\Delta Br(B_s^0 \rightarrow e^+\mu^-)$	$\Delta Br(B_d^0 \rightarrow e^+\mu^-)$
$N(B^0 \rightarrow K^+\pi^-)$	6387.0 ± 214.4	3.4%	3.4%
$BR(B^0 \rightarrow K\pi)$	$(19.4 \pm 0.6) \times 10^{-6}$	3.1%	3.1%
$f_{B_d^0}/f_{B_1^0}$	3.86 ± 0.59	15.3%	-
$\epsilon^{Rel}_{B_s^0 \rightarrow e^+\mu^-}$	0.2071 ± 0.0158	7.6%	-
$\epsilon^{Rel}_{B_d^0 \rightarrow e^+\mu^-}$	0.2097 ± 0.0123	-	5.9%
Total		17.7%	7.5%

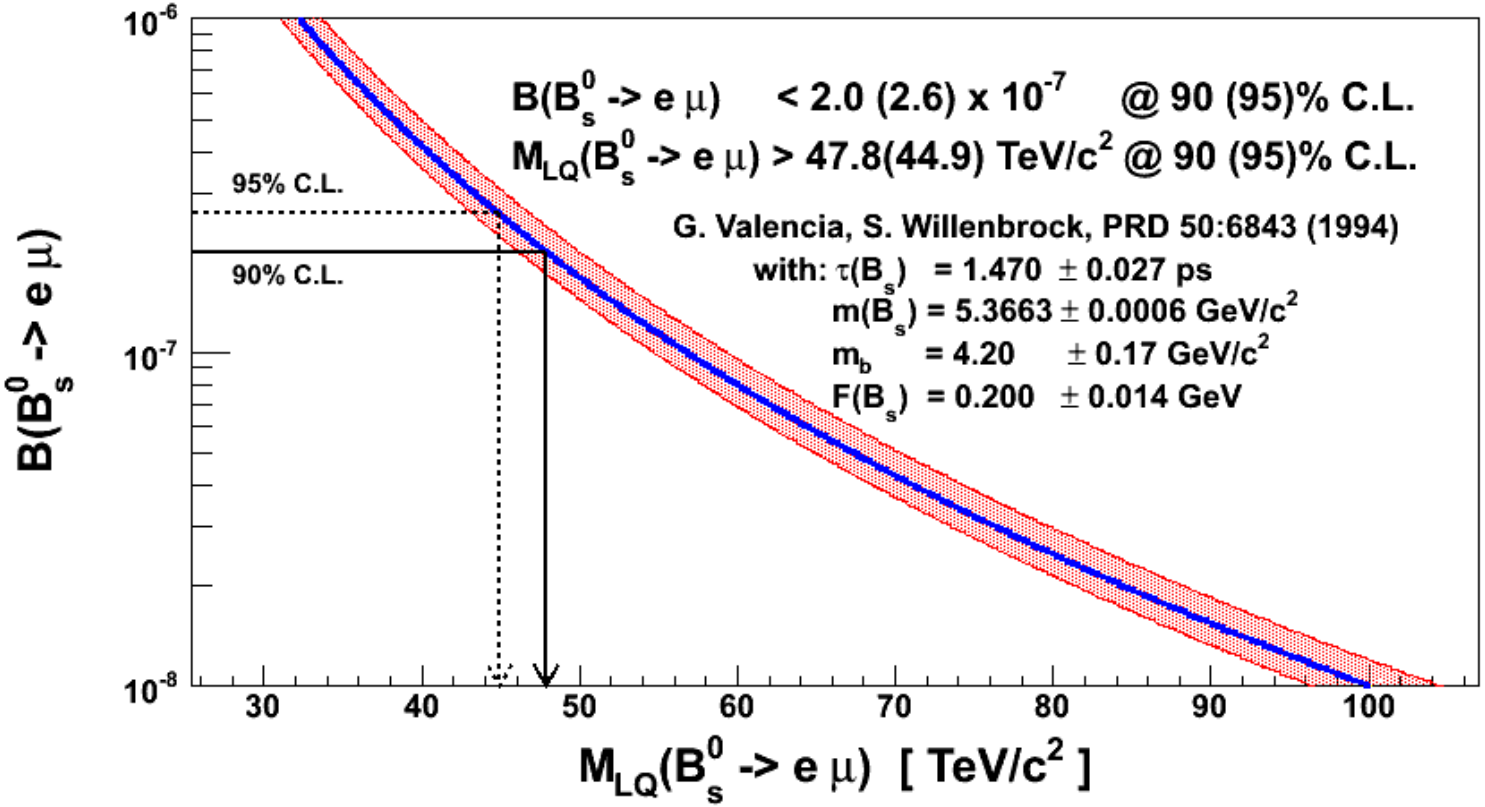
Systematic uncertainties on the limits of BR ($B_{s,d} \rightarrow e\mu$)

Run II (L= 2fb^{-1}) results at 90 (95) % CL:
$Br(B_s \rightarrow e^+\mu^-) < 2.0\ (2.6)\ \times 10^{-7}$
$Br(B_d \rightarrow e^+\mu^-) < 6.4\ (7.9)\ \times 10^{-8}$

$B_{s,d} \rightarrow e\mu$ limits on Pati-Salam leptoquark masses

$B(B_s \rightarrow e\mu) = \pi\, \alpha_s^2(M_{LQ})\, M_{LQ}^{-4}\, F^2_{Bs}\, m^3_{Bs}\, R^2\, \tau_{Bs} \hbar^{-1}$

$$R = \frac{m_{B_s}}{m_b}\left(\frac{\alpha_s(M_{LQ})}{(\alpha_s(m_t)}\right)^{-4/7}\left(\frac{\alpha_s(m_t)}{(\alpha_s(m_b)}\right)^{-12/23}$$

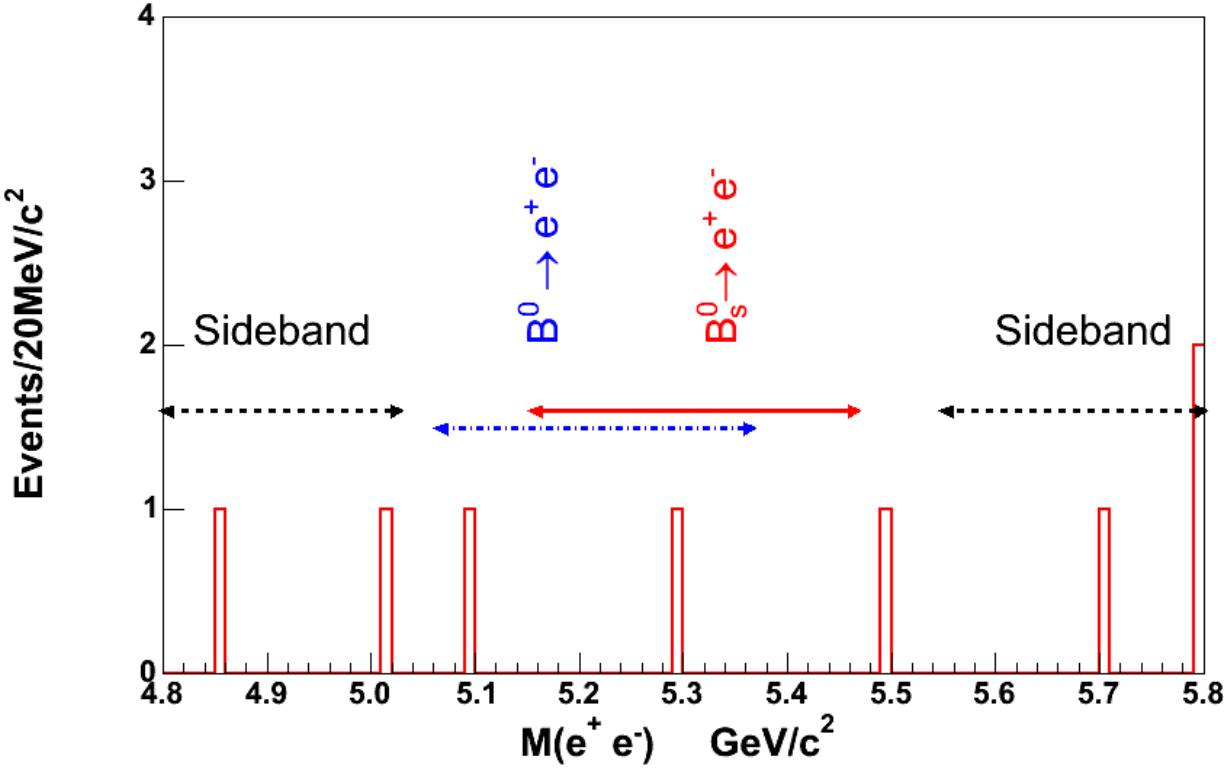


M_{LQ} ($B_s \rightarrow e\mu$) >47.8(44.9) TeV/c^2 , at 90(95)% CL

M_{LQ} ($B_d \rightarrow e\mu$) >59.3(56.3) TeV/ c^2, at 90(95)% CL

$B_{s,d} \rightarrow ee$ search

Search for candidates, in the (+3, –6)σ_{mass} window around the $B_{s,d}$ mass, by using the identification cuts



Background estimation (combinatorial from the sidebands, double fake from B→hh): 2.7+-1.8, Bs or Bd

$B_{s,d} \rightarrow ee$ results

PRL 102, 201801 (2009)

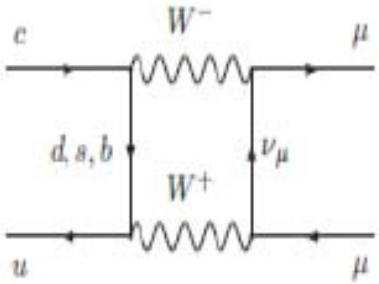
Source	values	$\Delta Br(B_s^0 \rightarrow e^+e^-)$	$\Delta Br(B_d^0 \rightarrow e^+e^-)$
$N(B^0 \rightarrow K^+\pi^-)$	6387.0 ± 214.4	3.4%	3.4%
$BR(B^0 \rightarrow K\pi)$	$(19.4 \pm 0.6) \times 10^{-6}$	3.1%	3.1%
$f_{B_d^0}/f_{B_1^0}$	3.86 ± 0.59	15.3%	-
$\epsilon^{Rel}_{B_s^0 \rightarrow e^+e^-}$	0.1290 ± 0.011	8.9%	-
$\epsilon^{Rel}_{B_d^0 \rightarrow e^+e^-}$	0.1278 ± 0.011	-	8.9%
Total		18.3%	10.0%

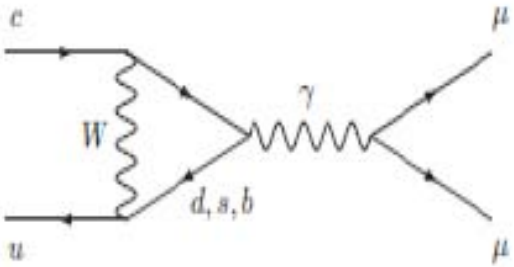
Systematic uncertainties on the limits of BR ($B_{s,d} \rightarrow ee$)

Run II (L= 2fb^{-1}) results at 90 (95) % CL:
$Br(B_s \rightarrow e^+e^-) < 2.8\ (3.7) \times 10^{-7}$
$Br(B_d \rightarrow e^+e^-) < 8.3\ (10.6) \times 10^{-8}$

$D^0 \rightarrow \mu\mu$

Very suppressed in SM by the GIM mechanism (m_q^2/m_W^2, no top loop)

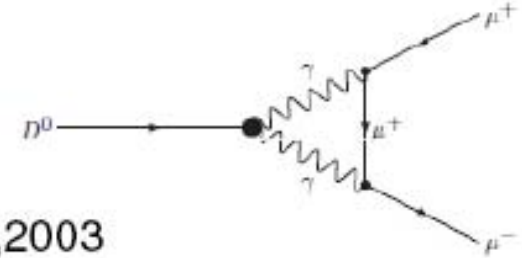




Decay rate dominated by long distance contributions

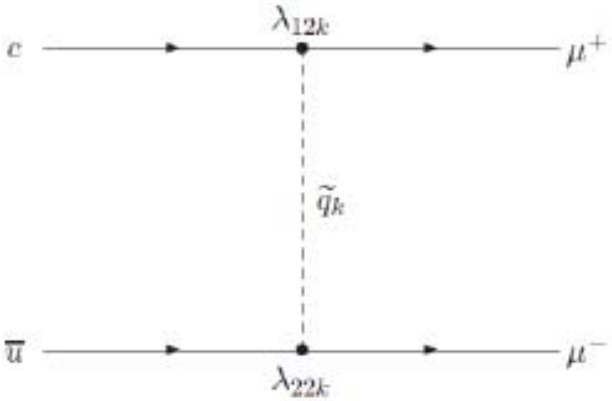
$$B_{SM}^{LD}(D^0 \rightarrow \ell^+\ell^-) \cong 3\times10^{-13}$$

Burdman-Shipsey, Ann.Rev.Nucl.Part.Sci.53:431-499,2003



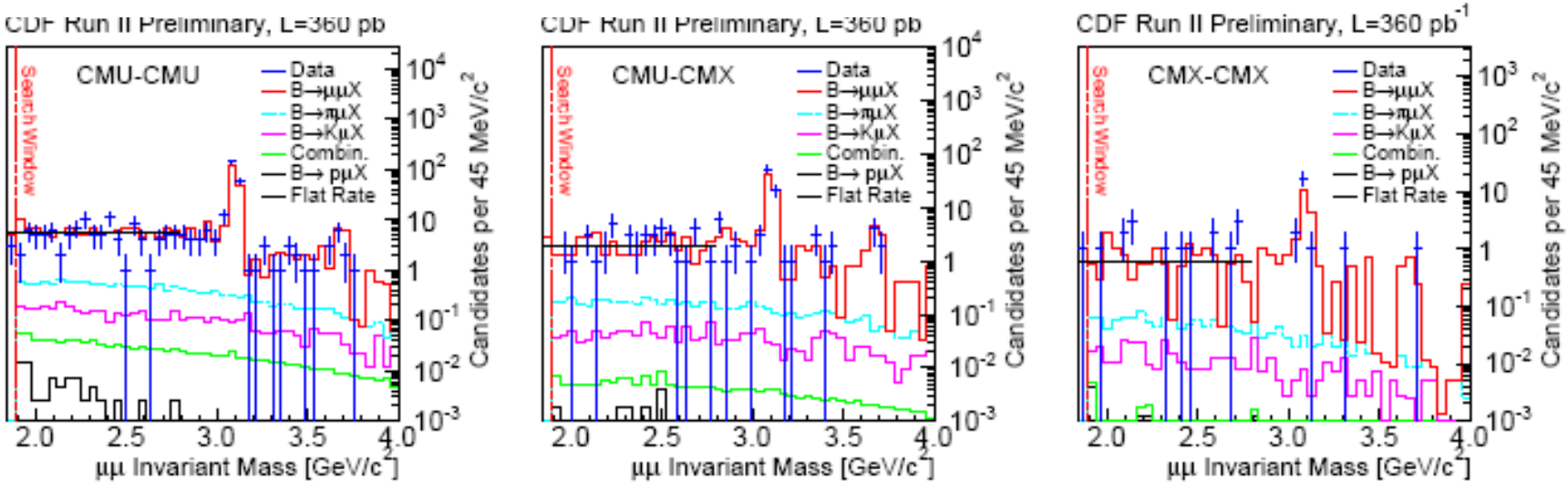
Enhancements are possible in R-parity violating SUSY models

$$B^{\not{R}_p}(D^0 \rightarrow \mu^+\mu^-) = \tau_{D^0} f_D^2 m_\mu^2 m_D \sqrt{1-\frac{4m_\mu^2}{m_D^2}} \frac{\left(\tilde{\lambda}'_{22k}\tilde{\lambda}'_{21k}\right)^2}{64\pi\, m_{\tilde{d}_k}^4}$$



$D^0 \rightarrow \mu\mu$ results

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N(\mu^+\mu^-)}{N(\pi^+\pi^-)} \cdot \frac{\epsilon(\pi^+\pi^-)}{\epsilon(\mu^+\mu^-)} \cdot \mathcal{B}(D^0 \to \pi^+\pi^-)$$



	CMU-CMU	CMU-CMX	CMX-CMX
Exp. Bkg	4.9 ± 1.3	2.74 ± 0.96	1.04 ± 0.48
Observed	3	0	1

Dominant BG: $B \rightarrow \mu\mu X$

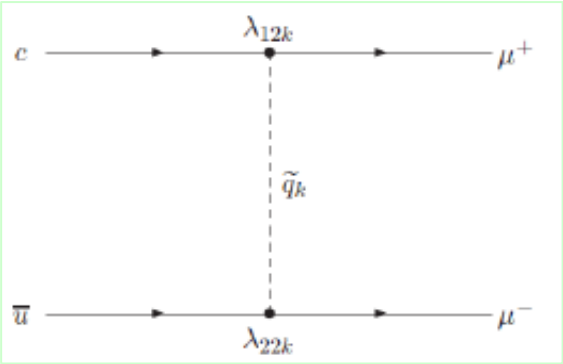
Bayesian approach to set CLs combining channels and including uncertainties

$D^0 \rightarrow \mu\mu$ results

Limits

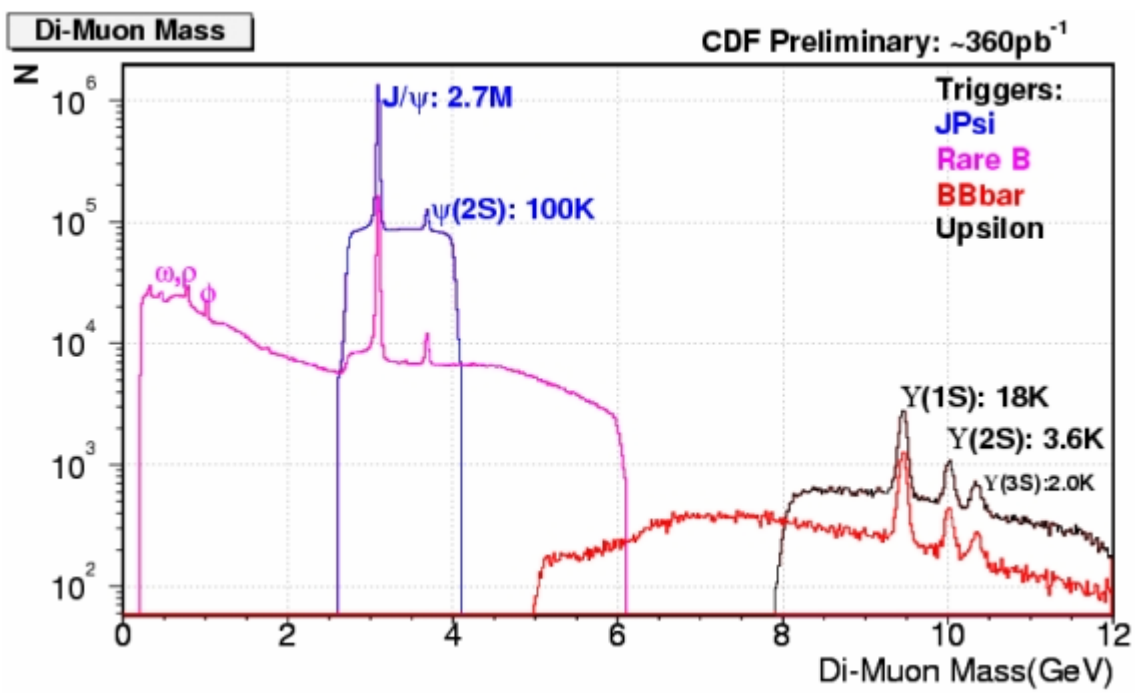
- A Bayesian calculation yields the following limits
  - 4.3×10^{-7} at the 90% credibility level or
  - 5.3×10^{-7} at the 95% credibility level (CL).
- This translates into a limit on R-parity-violating squark couplings, at the 90% CL:

$$\lambda_{21k}\lambda_{22k} < 1.5\sqrt{\mathcal{B}(D^0 \rightarrow \mu^+\mu^-)} = 9.8 \times 10^{-4}$$



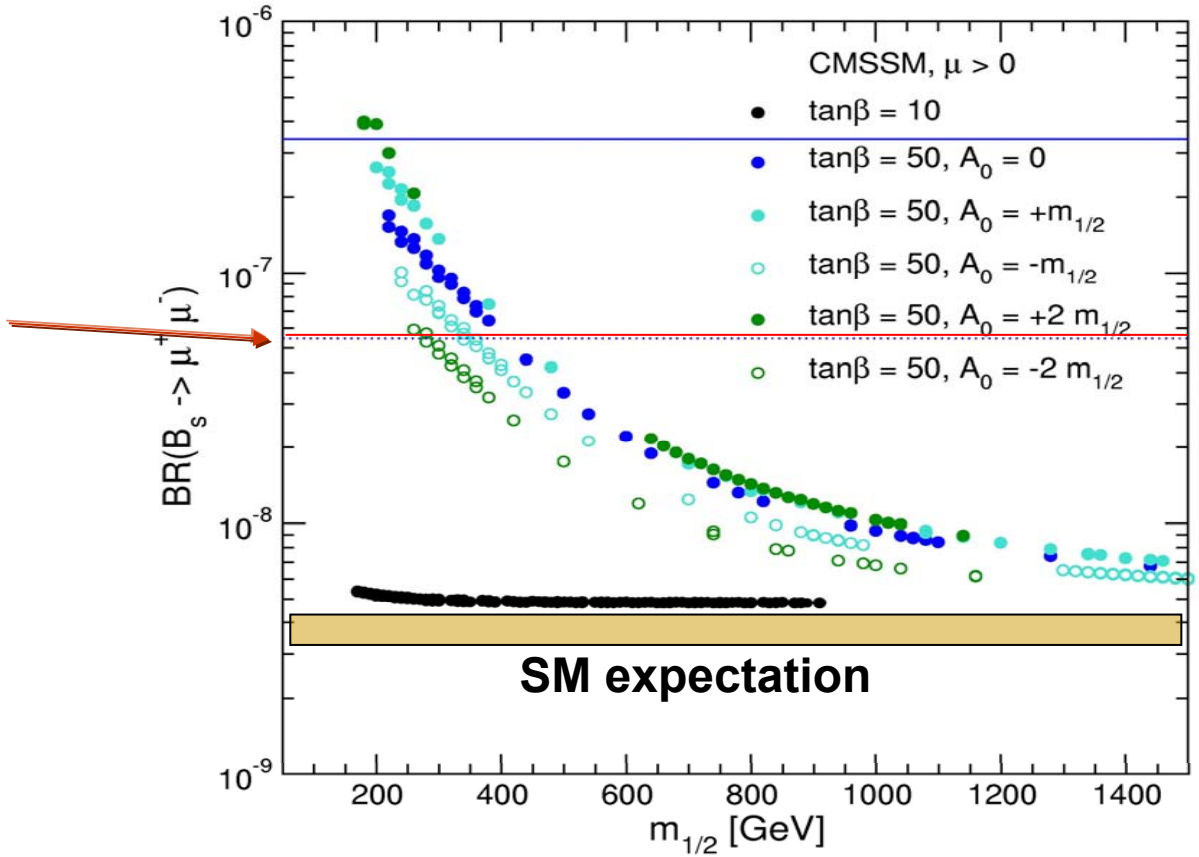
BACKUP

JPsi: Di-Muon events in the mass range around the JPsi and the Psi(2S).
Either two triggered CMU muons or a CMU muon and a CMX muon.
Rare B: Di-Muon events in an expanded mass range from 0 to 6GeV with tighter cuts.
Either two CMU muons or a CMU muon and a CMX muon with cuts on Lxy or SumPt or alternatively
as CMU or CMX muon and a CMUP(CMU and CMP) muon without requirements on Lxy or SumPt .
Note the two CMU muon version of the trigger has a mass cut of greater than 2.7GeV for part of the data taking period.
BBBar: Di-Muon events in an expanded mass range from 5 to 12GeV. Both muons must be CMUP muons.
Upsilon: Di-Muon events in a mass range around the Upsilon. Either a CMU or CMX muon and a CMUP muon.



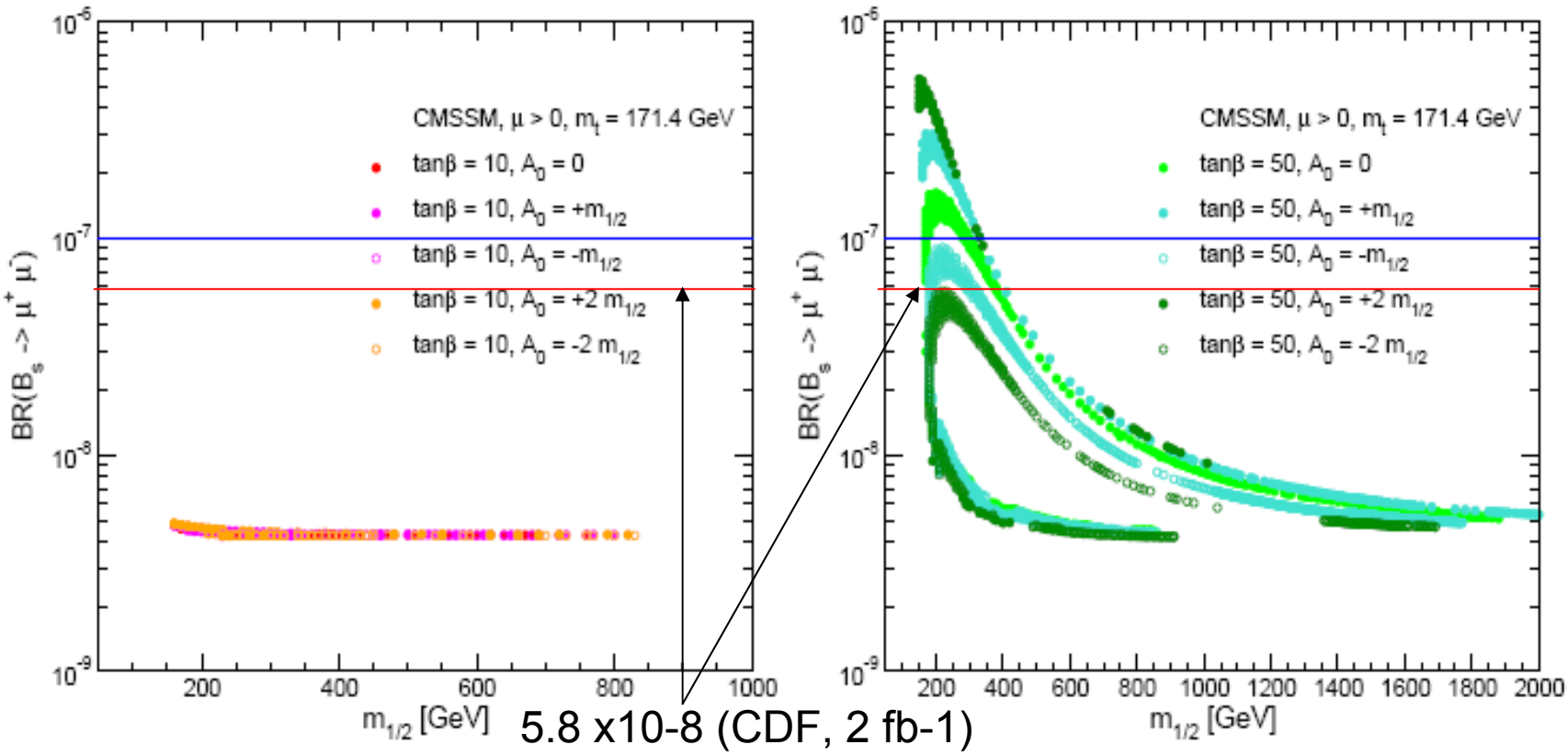
Limits in $B_s \rightarrow \mu\mu$ CMSSM

95% CL Limits:
CDF: 5.8x10^{-8} (2 fb-1)



hep-ph/0411216

Limits in Bs→μμ CMSSM



5.8 x10-8 (CDF, 2 fb-1)

arXiv:0706.0652v1 [hep-ph] 4 Jun 2007

J. Ellis[1], S. Heinemeyer[2], K.A. Olive[3], A.M. Weber[4] and G. Weiglein[5]

Analysis Outline (cont.)

1.) "Baseline" Selection

- Trigger Matching
- COT/Muon/SVX Quality
- Muon Likelihood and dE/dx
- Vertex Quality

$$\chi^2_{\mathrm{vtx}} < 15$$

$$\sigma_{\mathrm{L_{3D}}} < 0.0150 \text{ cm}$$

$$\mathrm{L_{3D}} < 1.0 \text{ cm}$$

$$0 < \lambda < 0.3 \text{ cm}$$

$$\lambda/\sigma(\lambda) > 2$$

2.) 6 Variable Neural Net

Proper decay length $\lambda = \frac{cL_{3D}M_{vtx}}{|\vec{p}(B)|}$

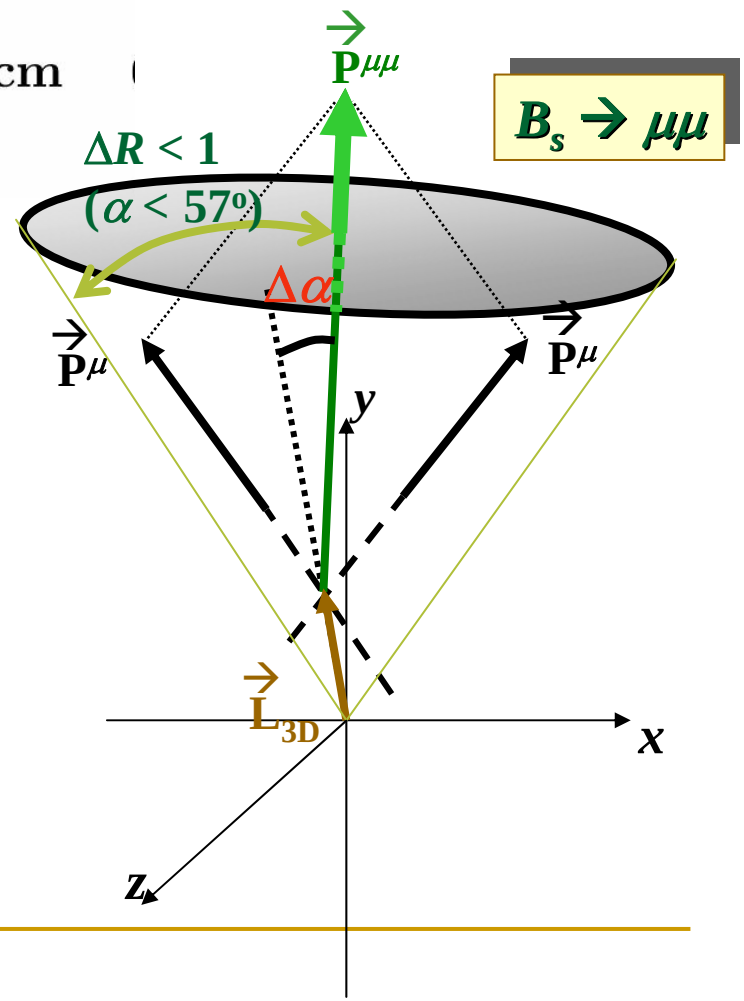
Isolation $Iso = \frac{p_T(B)}{p_T(B) + \sum_i p_T^i(\Delta R_i < 1.0)}$

Pointing $\Delta\alpha$ (3D opening angle between the Bs momentum and the decay axis)

λ significance = λ/σ_λ

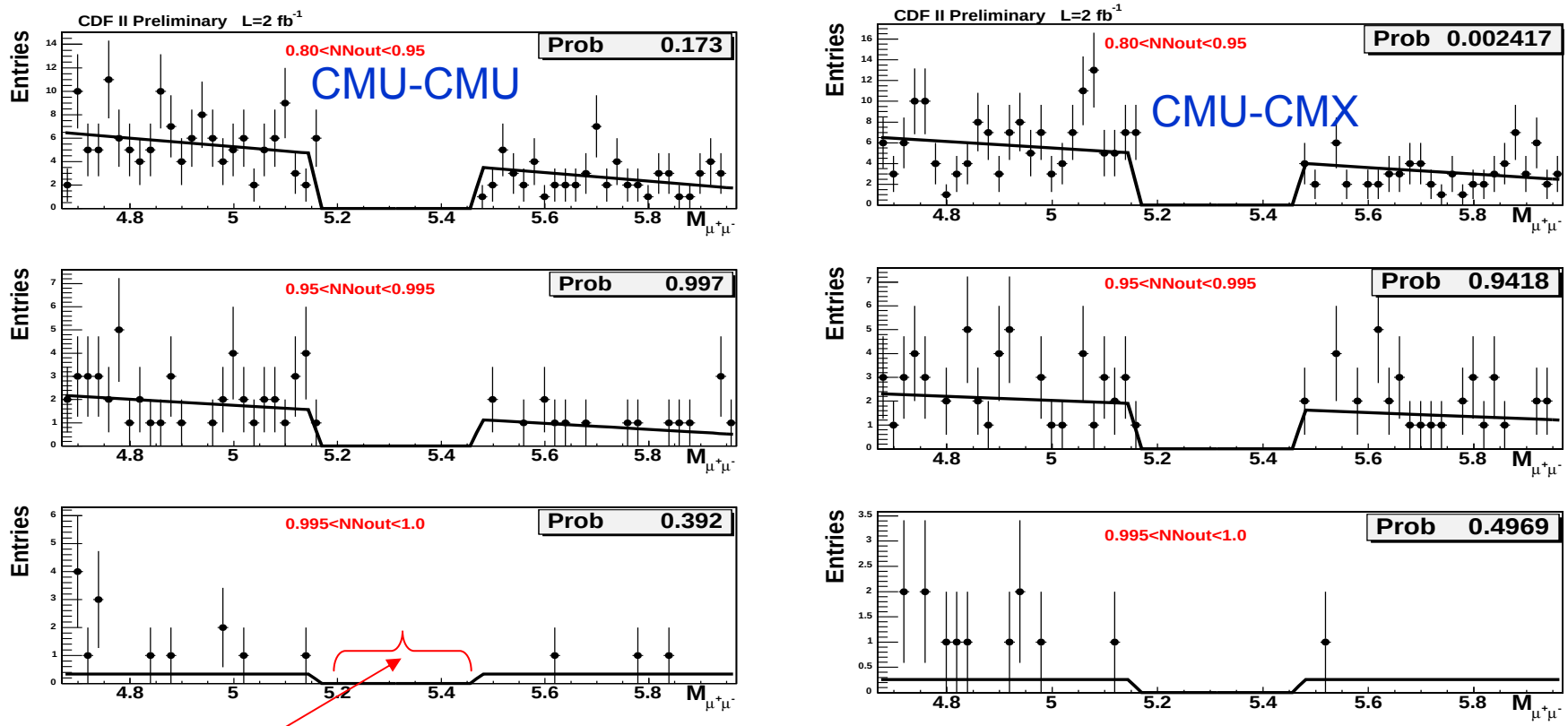
$p_T(B_S)$ = transverse momentum of the B_S candidate

$p_T(\mu)$ = transverse momentum of the lower momentum muon daughter



B→ μμ

Background estimation: Blind analysis(both B_s and B_d), from the sidebands of the dimuon mass distribution data (also used for optimization)



+-150 MeV/c^2, centered on the world average of B_s and B_d masses

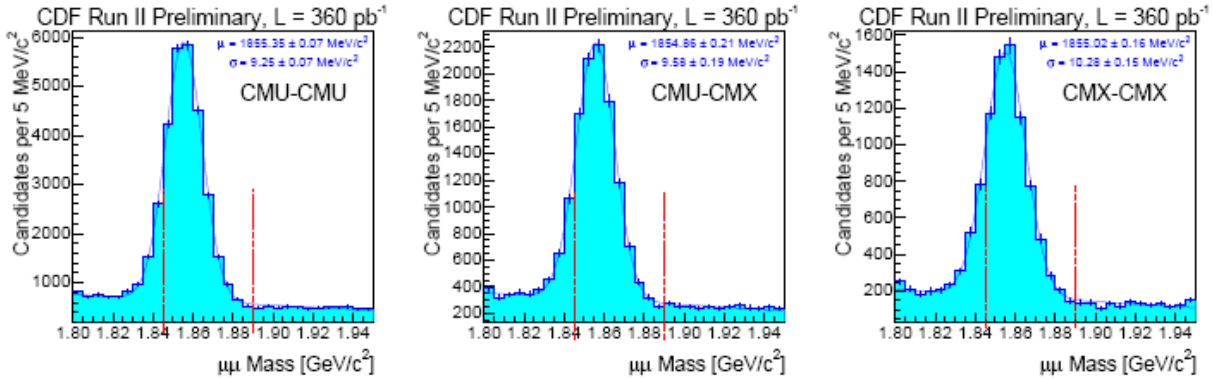
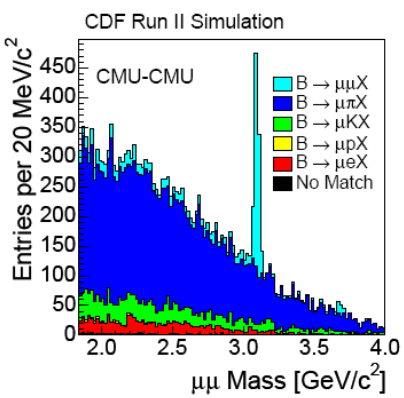
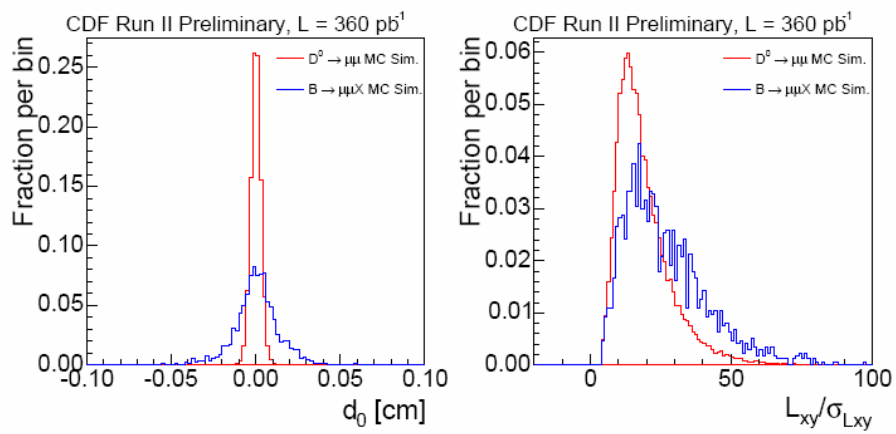
- Separate estimate of the background for two-body hadronic decays, for each mass and NN bin.

It is about ten times smaller

$D^0 \rightarrow \mu\mu$

$$\mathcal{B}(D^0 \to \mu^+\mu^-) = \frac{N(\mu^+\mu^-)}{N(\pi^+\pi^-)} \cdot \frac{\epsilon(\pi^+\pi^-)}{\epsilon(\mu^+\mu^-)} \cdot \mathcal{B}(D^0 \to \pi^+\pi^-)$$

- Normalization to $D^0 \rightarrow \pi^+\pi^-$.
- Tag to $D^{*-} \rightarrow D^0\pi^-$ with $\Delta M(D^{*-}, D^0) = 0.144\text{-}0.147$
- Muon identification methods to reduce fakes, estimated from D* tagged $D^0 \rightarrow K^+\pi^-$ data
- Background from MC



Reduced by probability ratio discriminant using impact parameter and decay length significance