Search for $B_{s,d} \to \mu^+\mu^-$ Decays at CDF II

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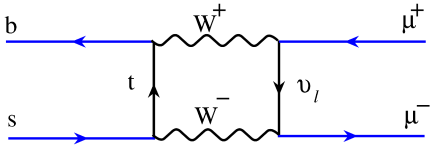
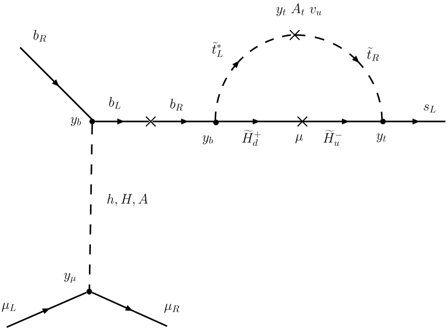
Oct 2011

for the CDF Collaboration

Motivation

- $B_s \to \mu^+\mu^-$ can only occur through higher order FCNC diagrams in Standard Model (SM)
- Suppressed by the GIM Mechanism and helicity
- SM predicts very low rate with little SM background ($\mathcal{BR}(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$, $\mathcal{BR}(B_d \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$, E.Gamiz et al. (HPQCD Collaboration), A.J. Buras et al.
- BSM models predict enhancement
- Ratio of $\mathcal{BR}(B_s \to \mu^+\mu^-)$ and $\mathcal{BR}(B_d \to \mu^+\mu^-)$ is important to discriminate amongst BSM models
- Clean experimental signature





Analysis Description

Simple Analysis

- 2 Muons
- Identify methods of suppressing background and keep signal
- Look for bump in di-muon mass distribution

Analysis Strategy

- Blind ourselves to di-muon signal mass region
- Use mass sidebands to estimate dominant background in signal region
- Optimize selection criteria a priori
- Build confidence in background estimates by employing same methods on control regions

What do we measure?

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

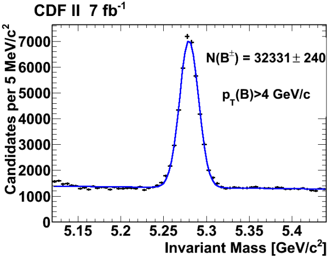
From Data, From MC, From PDG

$N_{B^+} \sim 2 \times 10^4$, $\frac{\epsilon^{trig}_{B^+}}{\epsilon^{trig}_{B_s}} \sim 1$

$\frac{\epsilon^{reco}_{B^+}}{\epsilon^{reco}_{B_s}} \sim 1$, $\frac{\alpha_{B^+}}{\alpha_{B_s}} \sim 0.5$, $\frac{1}{\epsilon^{NN}_{B_s}} \sim 1$

$\frac{f_u}{f_s} \sim 3$, $\mathcal{B}(B^+ \to J/\Psi K^+ \to \mu^+\mu^- K^+) \sim 5 \times 10^{-5}$

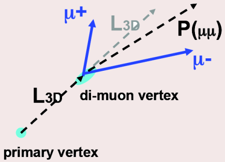
- Measure rate of $B_s \to \mu^+\mu^-$ relative to $B^+ \to J/\Psi K^+$, $J/\Psi \to \mu^+\mu^-$
- Apply same selection to find $B^+ \to J/\Psi K^+$
- Systematic uncertainties will cancel in ratio, e.g. dimuon trigger efficiency is the same for both modes



Signal vs. Background

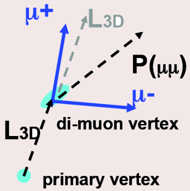
Signal Properties

- Final state fully reconstructed
- B_s is long lived ($c\tau =\sim 450\mu$m)
- b fragmentation is hard: few additional tracks



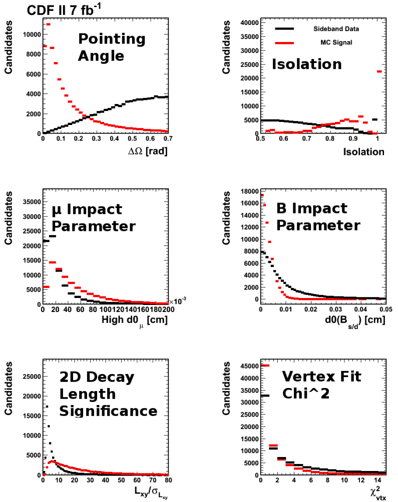
Background contributions & characteristics

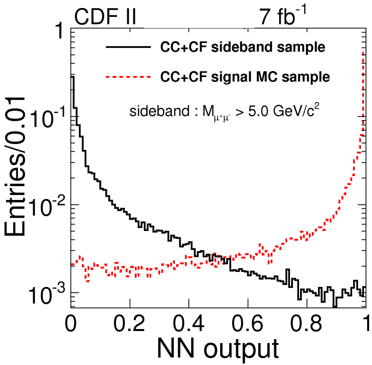
- Sequential semi-leptonic decay: $b \to c\mu^- X \to \mu^+\mu^- X$
- Double semi-leptonic decay: $bb \to \mu^-\mu^+ X$
- Continuum $\mu^-\mu^+$
- μ + fake and fake+fake
  - Partially reconstructed
  - Softer
  - Short lived
  - Less isolated
- $B \to hh$: peaking in signal region



Signal Discrimination

- 14 Discriminating variables
- Invariant mass of muons with 2.5σ window, σ=24 MeV

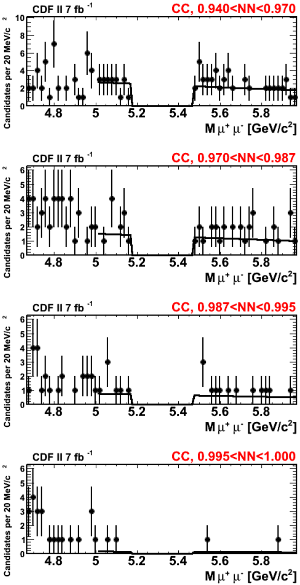




- Combined in NN, optimized with signal MC and data mass sideband
- Optimize NN a priori with data mass sideband and signal MC
- Validated NN with normalization mode and control region

Combinatorial background

- Fit common slope to all sidebands of NN bins
- Exclude region of $B \to \mu^+\mu^- X$ decays from sidebands
- Estimate systematics due to shape uncertainty
- Expect about 0.8 events in most sensitive bin



Peaking $B \to hh$ background

- Peaking in signal region
- Estimated using MC and D^*-tagged $D^0 \to \pi^+ K^-$ data
  - MC for p_T and mass distibution
  - D^*-tagged for fake rate: Ratio of pions/kaons passing muon ID
  - D^*-tagged sample large enough to bin in p_T and luminosity
- Only 10% of combinatorial background in B_s
- 10x larger in B_d

NN Bin	CC	CF
$0.700 < NN < 0.970$	0.03 ± 0.01	$0.01 \pm <0.01$
$0.970 < NN < 0.987$	$0.01 \pm <0.01$	$0.01 \pm <0.01$
$0.987 < NN < 0.995$	$0.02 \pm <0.01$	$0.01 \pm <0.01$
$0.995 < NN < 1.000$	0.08 ± 0.02	0.03 ± 0.01

Table: B$\to$hh B_s background for the 3 highest NN bins and the lower 5 bins combined.

Background Estimate Check

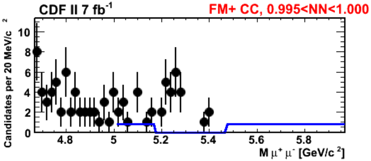
- Check background estimates with background dominated control samples
  - Signal has two opposite sign muons with positive lifetime
  - Control samples have opposite sign negative lifetime, same-sign positive/negative lifetime, and reverse muon ID
  - Total of 64 samples
- Apply same background methods on control sample that we can unblind

	CC		
NN cut	pred	obsv	prob(%)
0.700<NN<0.760	217.4±(12.5)	203	77.7
0.760<NN<0.850	262.0±(14.1)	213	99.1
0.850<NN<0.900	117.9±(8.6)	120	44.7
0.900<NN<0.940	112.1±(8.4)	116	39.4
0.940<NN<0.970	112.7±(8.4)	108	64.2
0.970<NN<0.987	80.2±(6.9)	75	68.3
0.987<NN<0.995	67.6±(6.3)	41	99.8
0.995<NN<1.000	32.5±(4.2)	35	37.5

Good agreement between observed and expected background

$B \to hh$ Background Check

- Used control sample with reversed muon ID cuts: enhanced in hadrons
  - Total of 16 samples
- Estimated fake rates for this sample using D^*-tagged for fake rate: Ratio of pions/kaons failing muon ID



Conclusion

- Checked combinatorial and peaking background estimates with control samples
- Good agreement between predicted and observed

Expected Sensitivity

$B_s \to \mu^+\mu^-$ CC

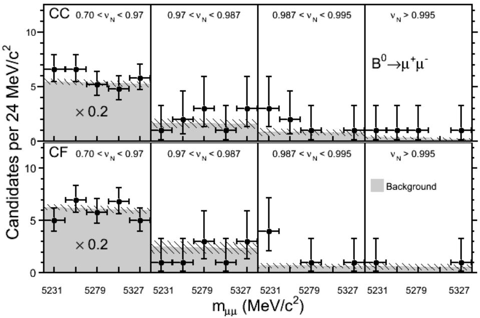
NN Bin	ϵ_{NN}	B→hh Bkg	Total Bkg	Exp SM Signal
$0.700 < NN < 0.970$	20%	0.03	129.24±6.50	0.26±0.05
$0.970 < NN < 0.987$	8%	< 0.01	7.91±1.27	0.11±0.02
$0.987 < NN < 0.995$	12%	0.02	3.95±0.89	0.16±0.03
$0.995 < NN < 1.000$	46%	0.08	0.79±0.40	0.59±0.11

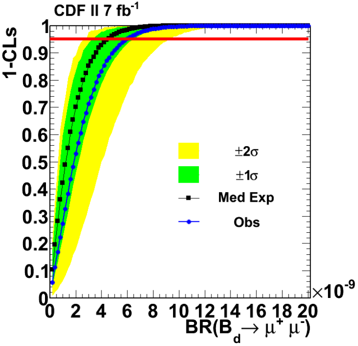
- $\sim$ 80% signal efficiency for NN
- Small contribution of peaking background compared to combinatorial (B_s)
- Expect $\sim$2 SM signal event (CC and CF)

Expected Limits

B_s: 1.5×10^{-8} **at 95% CL**
B_d: 4.6×10^{-9} **at 95% CL**

Results: B_d

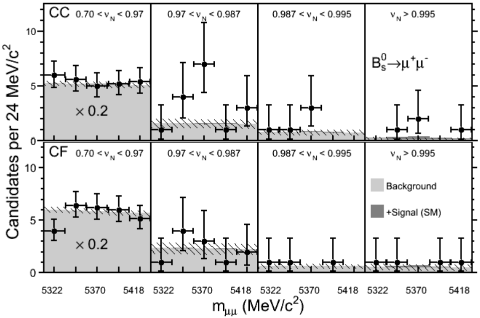


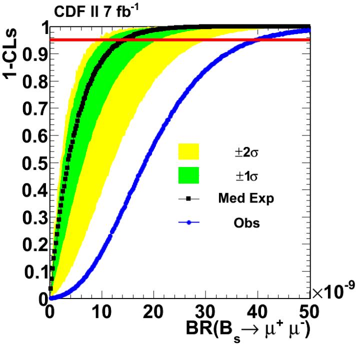


- Five mass bins
- Five lowest NN bins combined
- Light gray: Background estimates
- Hashed: Systematic errors on background
- Error bars on points: Poisson error on mean
- **No excess in B_d mass region (p-value=23%)**

B_d limit: $\mathcal{B}(B_d \to \mu^+\mu^-) < 6.0 \times 10^{-9}$ @ 95% C.L.

Results: B_s



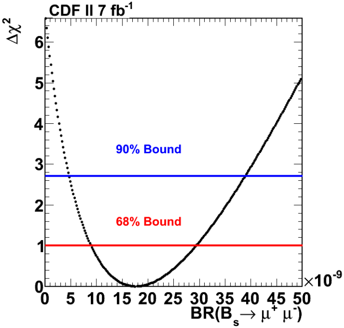


- Dark gray: Expected SM signal
- **Excess in in CC**
  - p-value for background only hypothesis: 0.27%
  - p-value for SM+background hypothesis: 1.92%

B_s **limit:** $\mathcal{B}(B_s \to \mu^+\mu^-) < 4.0 \times 10^{-8}$ **@ 95% C.L. (**$> 2\sigma$ **from expected)**

B_s: Central Values, Bounds and P-Values

- Used $\Delta\chi^2$ method
- Cross checked with Bayesian Posterior method
- Includes all systematics
- 90% Bound:
  $4.6 \times 10^{-9} < \mathcal{B}(B_s \to \mu^+\mu^-) < 3.9 \times 10^{-8}$
- Stable: No large deviation when only using subset of bins



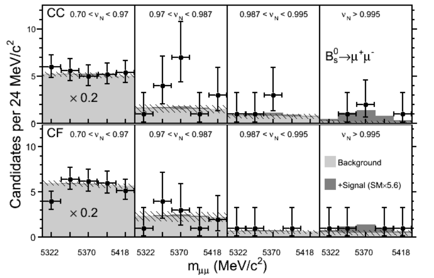
Summary of p-values and limits

	All Bins	2 Highest NN Bins
Central Value ($\times10^{-8}$)	$1.8^{+1.1}_{-0.9}$	$1.4^{+1.0}_{-0.8}$
90% Bounds ($\times10^{-8}$)	$0.46 < \mathcal{B} < 3.9$	$0.33 < \mathcal{B} < 3.3$
Bkg Only p-value	0.27%	0.66%
SM+Bkg p-value	1.92%	4.14%

Third NN Bin Excess

Background Estimate Problem

- Combinatorial Background Problem
  - B_d Uses same sideband as B_s $\Rightarrow$ No excess in B_d
- Peaking Backgound Problem
  - Only peaking background is $B \to hh$
  - 10x larger in B_d region
  - No excess in B_d $\Rightarrow$ good fake rates

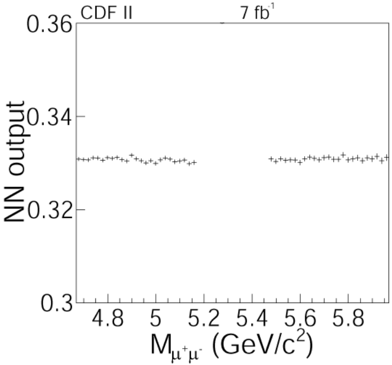


Neural Network Problem

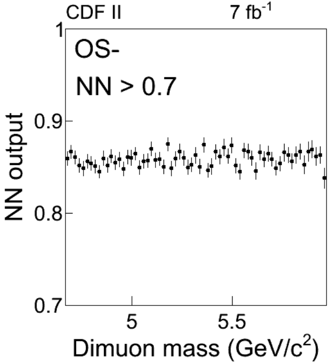
- Mass bias?
- Overtrained?
- Mismodels data?

NN Studies: Mass bias

NN Output vs Dimuon Mass for Signal Sample (blinded)



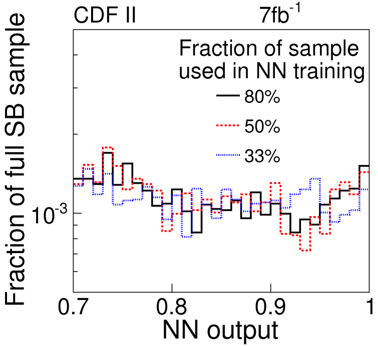
NN Output vs Dimuon Mass for Control Sample



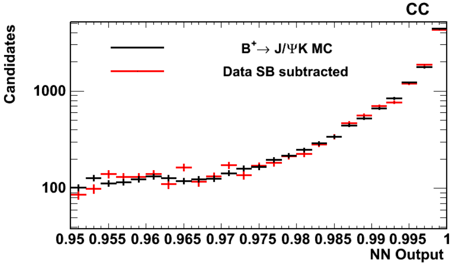
Unlikely to be cause of excess in 3rd NN bin of CC

NN Studies: Overtraining and Mismodeling

NN SB background eff for NN's trained on different fractions of SB



$B^+ \to J/\psi K^+$ MC and Data Signal NN Output Distribution



Unlikely to be cause of excess in 3rd NN bin of CC
MC models data well

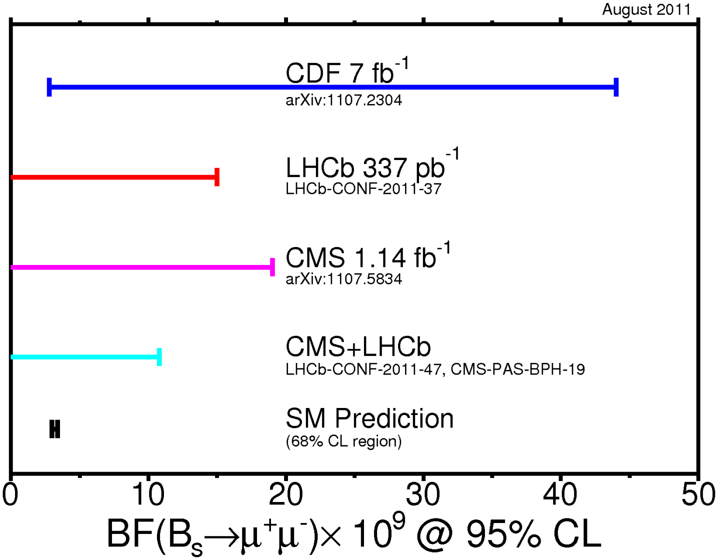
Conclusion on 3rd NN bin

- Not due to any NN mismodeling
- Not due to background mismodeling
- **Only explanation left: Not unlikely statistical fluctuation in 80 bins**

From PRL:

In short, there is no evidence that the excess in this bin is caused by a mistake or systematic error in our background estimates or our modeling of the ν_{NN} performance and distribution. The most plausible remaining explanation is that this is a statistical fluctuation.

Current Experimental Status



Conclusion

- CDF updated the $B_s \to \mu^+\mu^-$ search with doubled dataset $(7\mathrm{fb}^{-1})$ and improved analysis technique
- CDF has excess of $B_s \to \mu^+\mu^-$ events at the level of 2.7σ relative to background only hypothesis
- Set the first two-sided bound on the rate: $4.6 \times 10^{-9} < \mathcal{B}(B_s \to \mu^+\mu^-) < 3.9 \times 10^{-8}$ at the 90% CL, compatible with SM and other experiments
- Update analysis with full CDF dataset is ongoing

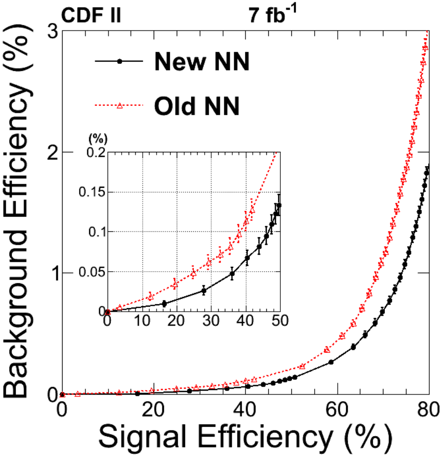
Backup Slides

Signal Discrimination

- Optimize NN a priori using data mass sideband and signal MC
- Validated NN with normalization mode and control region
  - Checked for Overtraining
  - Checked for Mass bias
  - Checked MC modeling of data
- Divide data sample into several bins
  - Two muon topologies: Central-Central (CC) and Central-Forward (CF)
  - 8 NN bins ranging between $0.7 < NN < 1.0$
  - 5 mass bins: Allows mass shape determination

Analysis Improvements

- $\sim$50% more data
- 20% Increase in acceptance by including CMX miniskirts and COT spacer regions
- Using new dE/dx calibration for better μ ID
- Improved fake rates for peaking background estimates
- New neural network with 2x better background rejection



Combinatorial Background

NN Bin	CC	CF
$0.700 < NN < 0.970$	129.2±6.5	146.3±7.0
$0.970 < NN < 0.987$	7.9±1.9	11.6±1.8
$0.987 < NN < 0.995$	4.0±1.1	3.3±1.0
$0.995 < NN < 1.000$	0.79±0.52	2.6±1.5

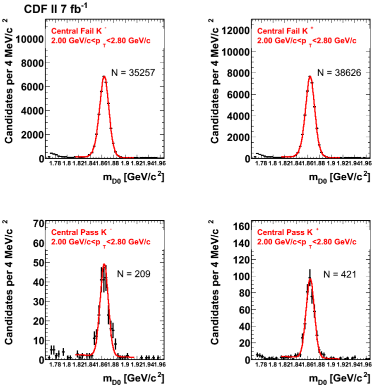
Table: Combinatorial B_s background for the 3 highest NN bins and the lower 5 bins combined.

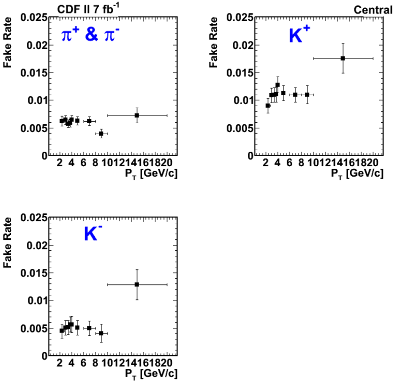
NN Bin	CC	CF
$0.700 < NN < 0.970$	134.0±6.6	153.4±7.3
$0.970 < NN < 0.987$	8.2±2.0	12.1±1.9
$0.987 < NN < 0.995$	4.1±1.2	3.4±1.1
$0.995 < NN < 1.000$	0.8±0.5	2.8±1.6

Table: Combinatorial B_d background.

Fake rates

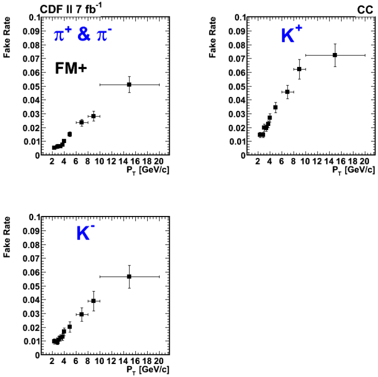
- Binned in p_T and instantenous luminosity





Fake rates: Pion and Kaon Enhanced Control Sample

- Same procedure as with signal sample but now reversing muon ID cuts (dE/dx and muon likelihood function)



Expected Sensitivity

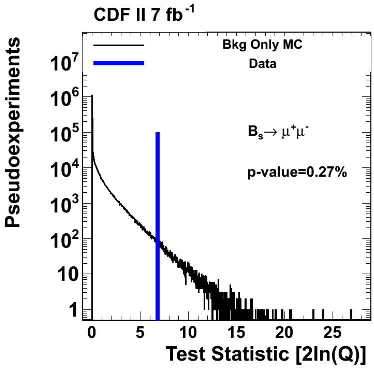
	CC		CF	
$(\alpha_{B+}/\alpha_{B_s})$	0.307 ± 0.018	$(\pm 6\%)$	0.197 ± 0.014	$(\pm 7\%)$
$(\epsilon^{trig}_{B+}/\epsilon^{trig}_{B_s})$	0.99935 ± 0.00012	$(< 1\%)$	0.97974 ± 0.00016	$(< 1\%)$
$(\epsilon^{reco}_{B+}/\epsilon^{reco}_{B_s})$	0.85 ± 0.06	$(\pm 8\%)$	0.84 ± 0.06	$(\pm 9\%)$
$\epsilon^{NN}_{B_s}(NN > 0.70)$	0.915 ± 0.042	$(\pm 4\%)$	0.864 ± 0.040	$(\pm 4\%)$
$\epsilon^{NN}_{B_s}(NN > 0.995)$	0.461 ± 0.021	$(\pm 5\%)$	0.468 ± 0.022	$(\pm 5\%)$
N_{B+}	22388 ± 196	$(\pm 1\%)$	9943 ± 138	$(\pm 1\%)$
f_u/f_s	3.59 ± 0.37	$(\pm 13\%)$	3.59 ± 0.37	$(\pm 13\%)$
$B(B^+ \to \mu^+\mu^- K^+)$	$(6.01 \pm 0.21) \times 10^{-5}$	$(\pm 4\%)$	$(6.01 \pm 0.21) \times 10^{-5}$	$(\pm 4\%)$
SES (All bins)	$(2.9 \pm 0.5) \times 10^{-9}$	$(\pm 18\%)$	$(4.0 \pm 0.7) \times 10^{-9}$	$(\pm 18\%)$

Combined Single Event Sensitivity (CC+CF) = 1.7×10^{-9}

Single Event Sensitivity is now to level of SM

Background only

- Estimated p-values for background only and SM+background hypothesis
- Compare observed with the distribution expected from ensembles of pseudo-experiments
  - background-only
  - background + signal at SM level
- All systematics included in pseudo-experiments



B_s **background only p-value = 0.27%**
B_s **SM+background p-value = 1.92%**
B_d **background only p-value = 23%**