A Search for $B_d^0 / B_s^0 \to \mu^+\mu^-$ Decays at CDF with 7 fb^{-1}

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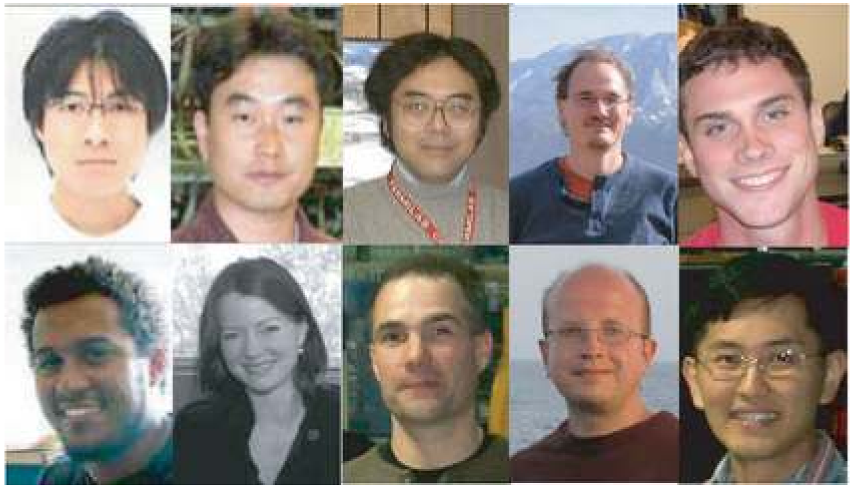
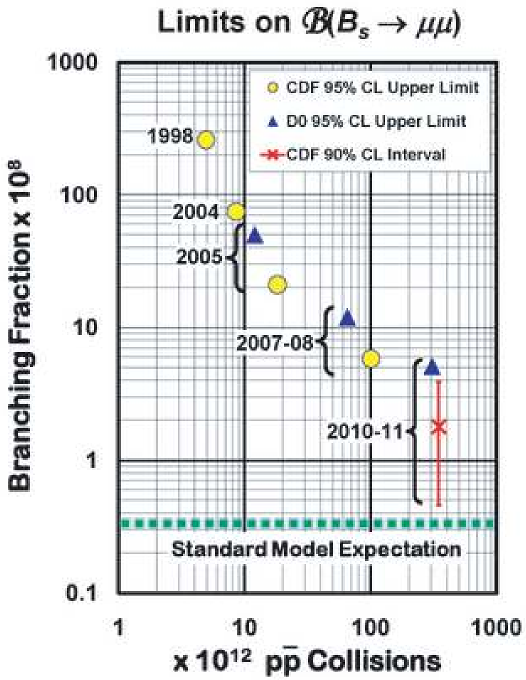
For the Bsmumu analysis group at CDF

July-27th 2011 KISTI seminar





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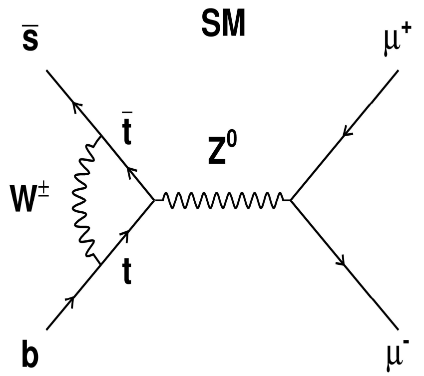
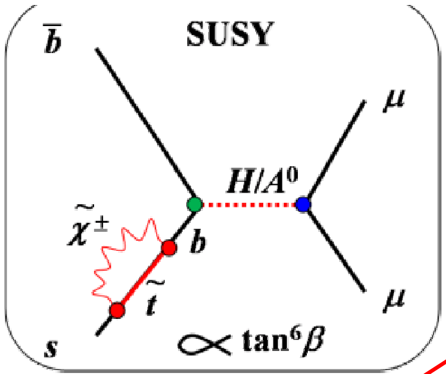
$B_s \to \mu\mu$ Physics Motivation

SM Expectation

$$Br : (3.2 \pm 0.2) \times 10^{-9}$$

JHEP 1009 (2010)106

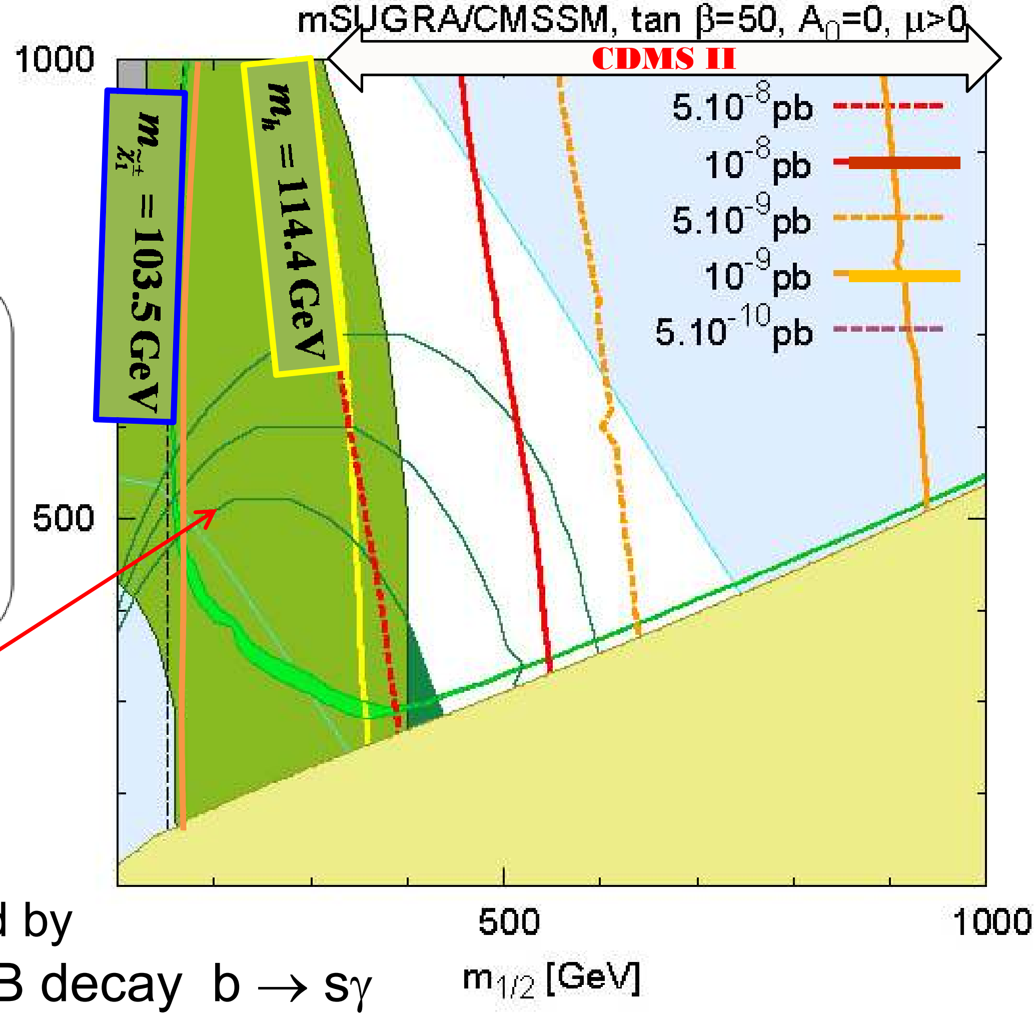




Br enhancement By New Physics

$$Br(B_s \to \mu\mu) = \begin{array}{l} 2\times10^{-8} \\ 3\times10^{-8} \\ 4.7\times10^{-8} \end{array}$$

Rouzbeh Allahverdi, Bhaskar Dutta, Yudi Santoso
arXiv:0912.4329



Excluded by

- a) Rare B decay $b \to s\gamma$
- b) No CDM candidate
- c) Muon magnetic moment

$B_s^0 \to \mu^+\mu^-$ for new Physics

Both in experiments And theories...

- CDF Public Note 9892 (2009)
- PRL 100 (2008) 101802
  → Cited 168 times
- CDF Public Note 8176 (2006)
- PRL 95 (2005) 221805
  → Cited 50 times
- PRL 93 (2004) 032001
  → Cited 77 times
- PRD 57 (1998) 3811

- PLB 693(2010) 539
  → Cited 10 times
- PRD 76 (2007) 092001
  → Cited 29 times
- PRL 94 (2005) 071802
  → Cited 81 times

- arXiv:1103.2465v1

Theory

- JHEP 1009 (2010)106
- ….
- JHEP 0502 (2005) 067
- …..
- PLB 538 (2002) 121
- ….
- ….

$B_s^0 \to \mu^+\mu^-$ for new Physics

How to ?

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

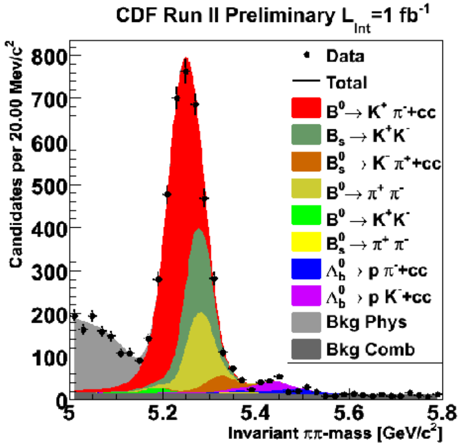
From Data, From MC, From PDG

- **Relative normalization search**
  - Measure the rate of $B_s \to \mu^+\mu^-$decays relative to $B \to J/\psi K^+$
  - Apply same sample pre-selection criteria
  - Uncertainties on Trigger and pre-selection efficiencies will cancel out in the ratios of the normalization
  - **$B_s \to \mu^+\mu^-$ sample is highly purified with Neural Network event selection**

$B_s^0 \to \mu^+\mu^-$ for new Physics

How difficult ?

- **Need to discriminate signal from background**
- **Need to retain decent signal**
  - **Reduce background by a factor of > 1000**
- **Signal**
  - **Final state fully reconstructed**
  - **B_s is long lived , B fragmentation is hard**
- **Background**
  - **Sequential semi-leptonic decay: b → cμ^-X → $\mu^+\mu^-$X**
  - **Double semileptonic decay: bb → $\mu^+\mu^-$X**
  - **Continuum $\mu^+\mu^-$, μ + fake, fake+fake**
  - **Peaking Background in signal region (B→hh)**

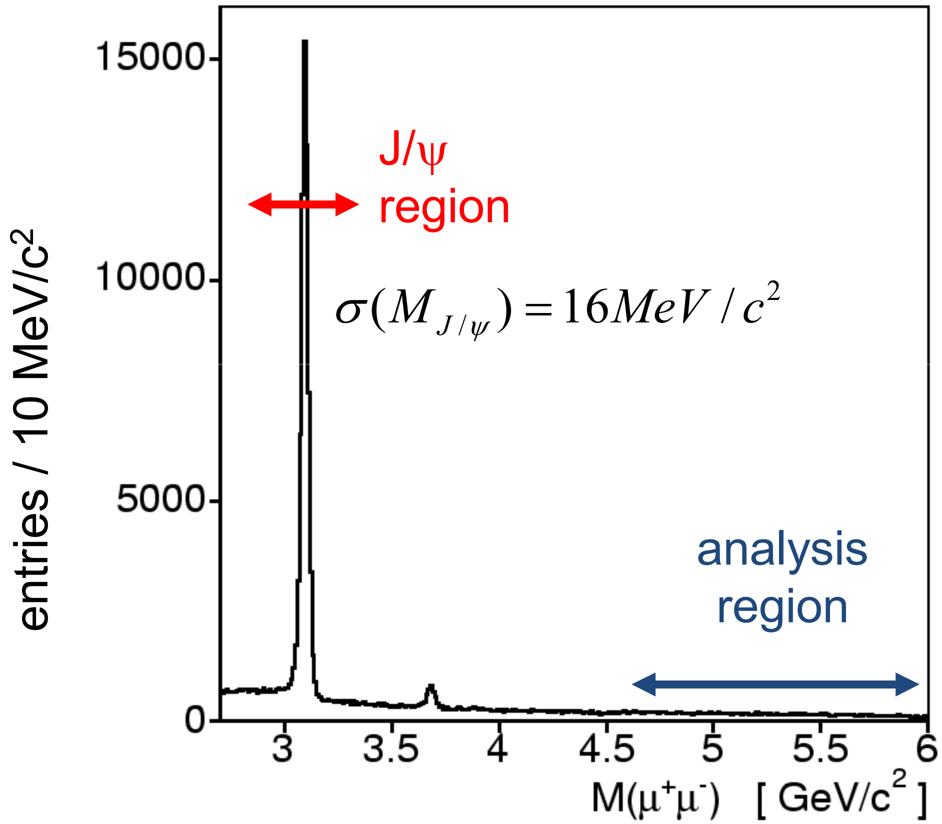


Trigger

Data collected using dimuon trigger

- "CC":
  - 2 central muons "CMU", $|\eta|<0.6$,
  - $p_T>1.5$ GeV
  - $2.7<M_{\mu\mu}<6.0$ GeV
  - $p_{T(\mu)}+ p_{T(\mu)} >4$ GeV

- "CF":
  - one central, one forward muon "CMX", $0.6<|\eta|<1.0$
  - $p_T>2$ GeV
  - other cuts same as above



Trigger efficiency same for muons from J/ψ or B_s (for muon of a given p_T)

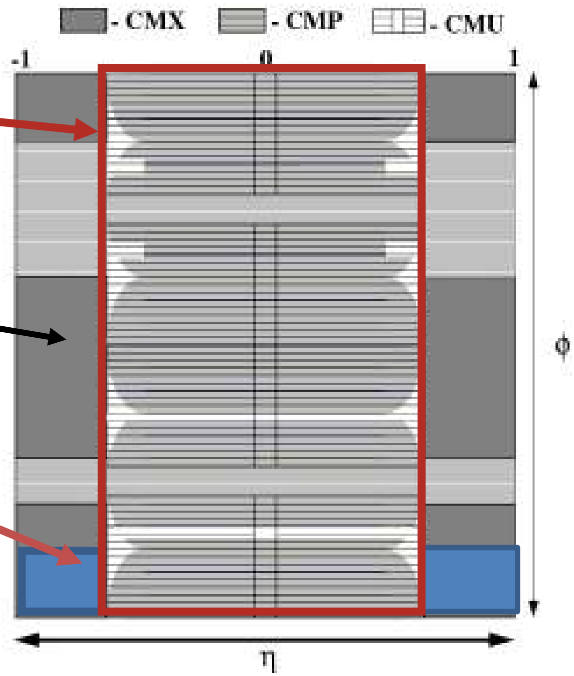
Improvements over previous $B_s(B^0) \to \mu^+\mu^-$ result from CDF

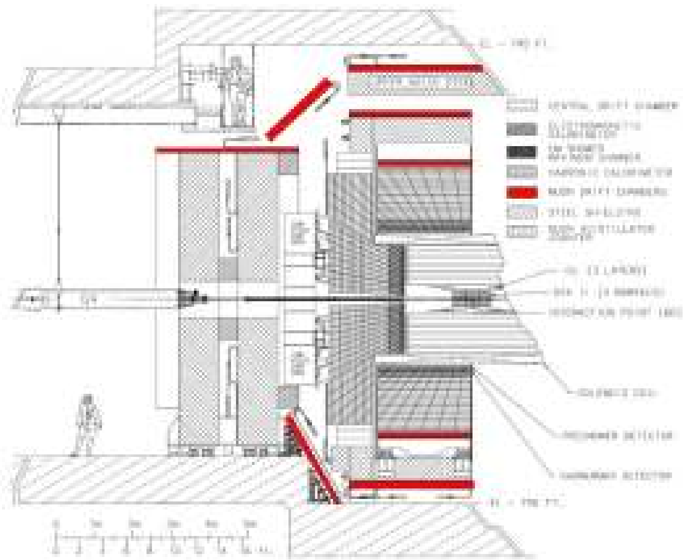
- Using twice the integrated luminosity (7 fb^{-1})
- Extended acceptance of events in the analysis by ~20%
  - muon acceptance includes forward muons detected in CMX miniskirts
  - 12% from tracking acceptance increase (using previously excluded "COT spacer region")
- Analysis improvements include an improved NN discriminant

Central muons (CMU)

Forward muons (CMX)

including "miniskirts"



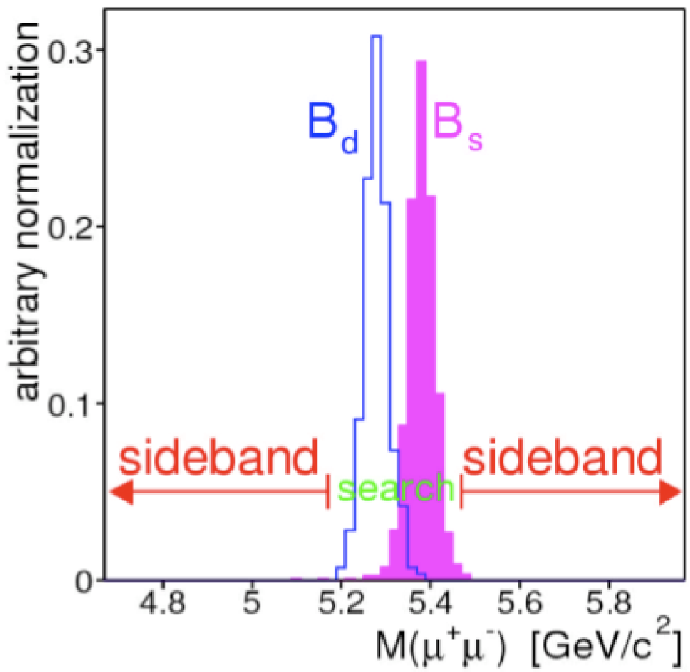


"Blind" search region

- Search region: $5.169 < M_{\mu\mu} < 5.469$ GeV
  - corresponds to $\pm 6 \times \sigma_m$, where $\sigma_m \approx 24$MeV (2-track invariant mass resolu tion)

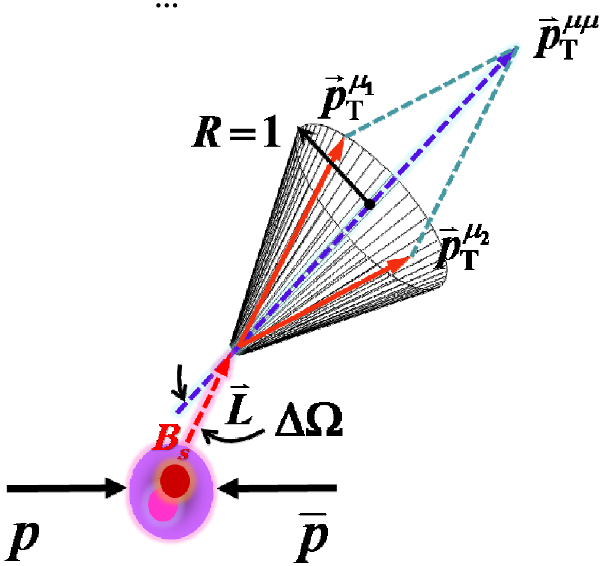
- Sideband regions: additional 0.5 GeV on either side
  - Used to understand background

MC simulation of B_s and $B^0 \rightarrow \mu^+\mu^-$ mass peaks



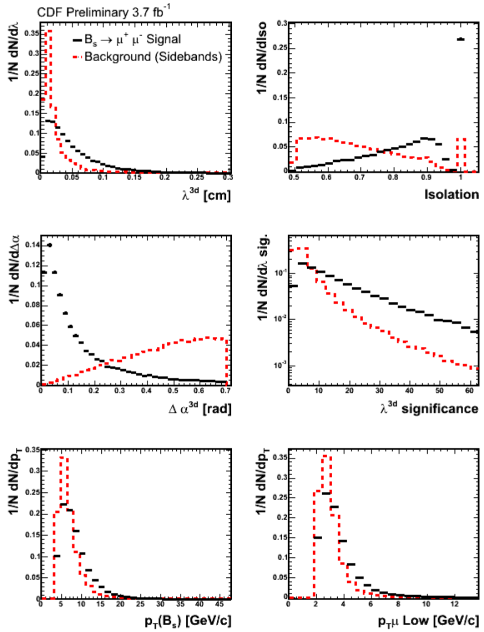
Signal Optimization

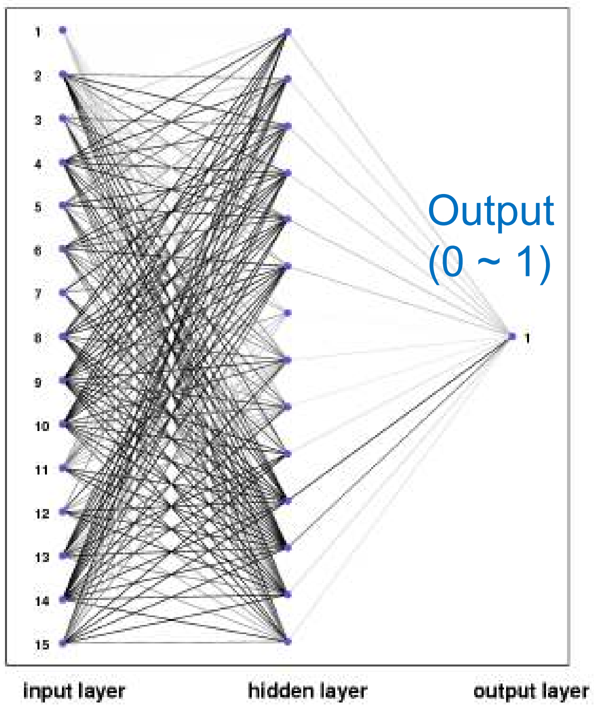
- **NN input variables**
- **3D pointing angle**
- **Isolation**
- **Proper decay length**
- **Proper decay length sig.**
- **P_T(Bs)**
- **$P_T(\mu)$**
- **Etc…**



- Multi-variable analysis : Neural Network
- Unbiased optimization based on MC signal and data sidebands

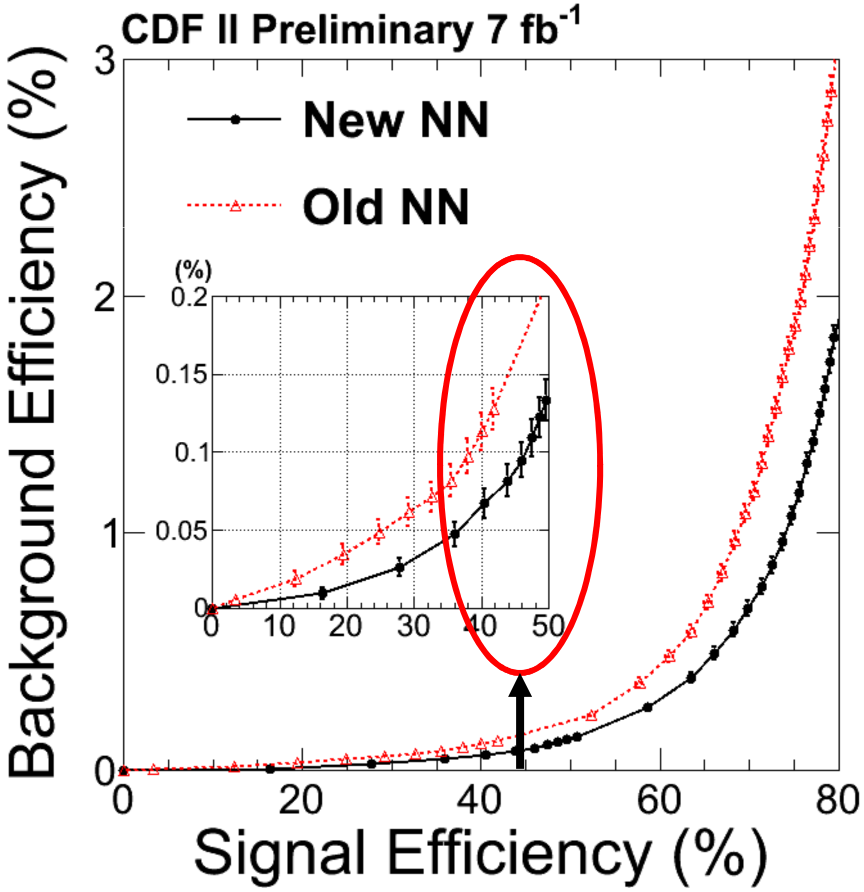
Discriminating variables

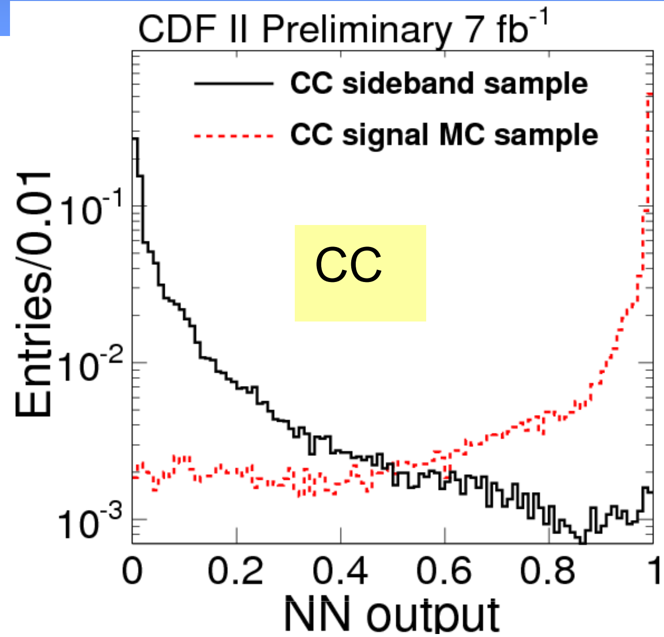


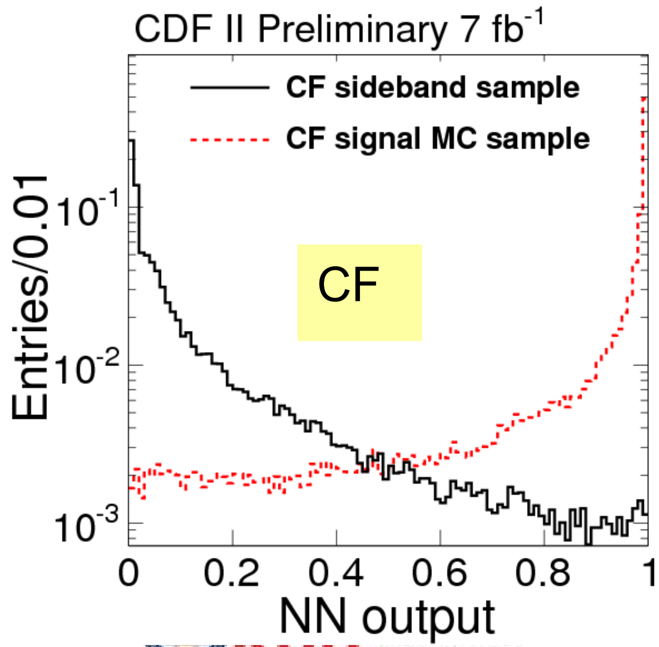


Signal Optimization

- Systematic study has been done to optimize NN event selection
- Excellent improvement achieved by using 14 discriminating variables!







1) Combinatoric background

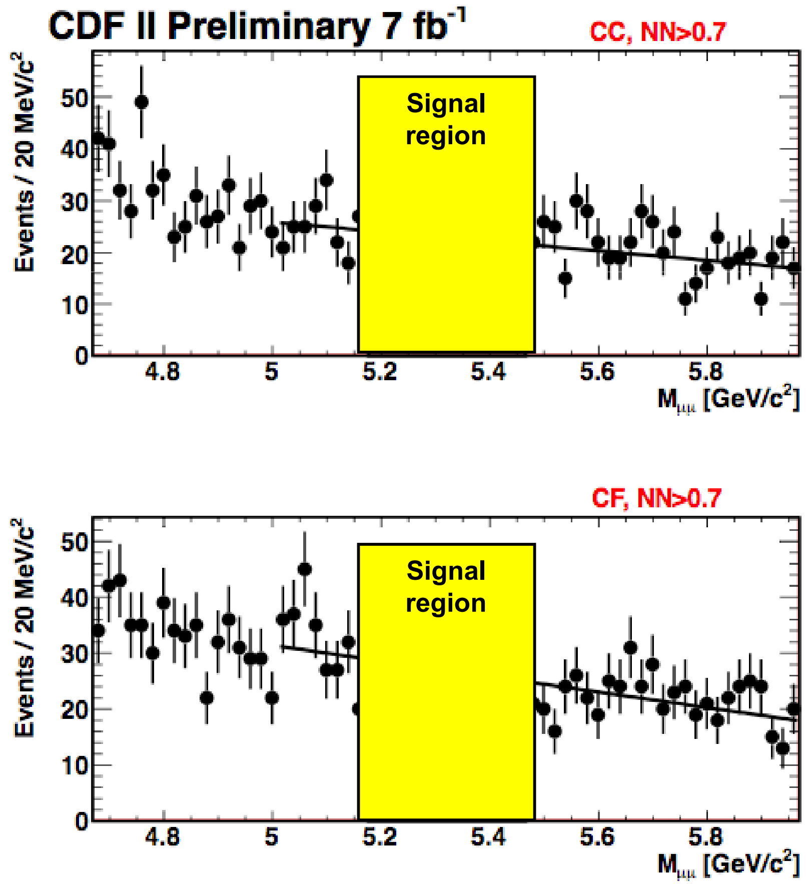
Using our background dominated data sample, fit $M_{\mu\mu}$ to a linear function.

- use distributions of sideband events with NN output >0.7

- only events with $M_{\mu\mu}$>5 GeV used to suppress contributions from $b \rightarrow \mu\mu X$

- slopes then fixed and normalization determined for each NN bin

- systematic uncertainty determined by studying effects of various fit functions and fit ranges
  - between 10-50%



2) Background from two-body hadronic B decays

Two-body $B \rightarrow hh$ decays where h produces a fake muon can contribute to the background

- fake muons dominated by π^+, π^-,K^+, K^-
- fake rates are determined separately using D*-tagged $D \rightarrow K^-\pi^+$ events

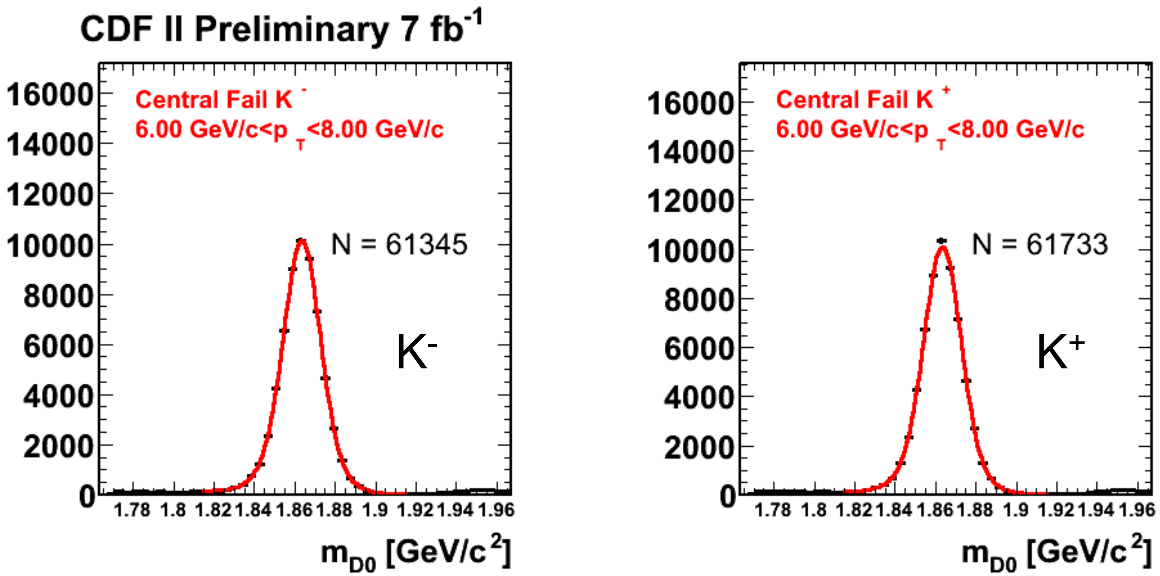
Estimate contribution to signal region by:

- take acceptance, M_{hh}, $p_T(h)$ from MC samples. Normalizations derived from known branching fractions
- convolute $p_T(h)$ with p_T and luminosity-dependent μ-fake rates. Double fake rate ~0.04%

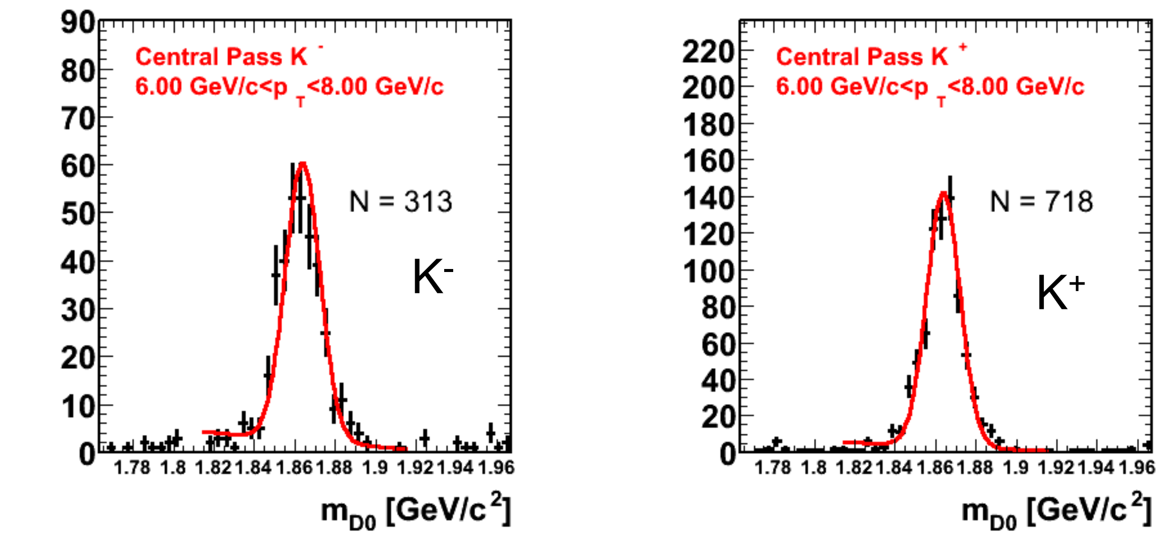
Fake rates from D*-tagged $D^0 \rightarrow K^-\pi^+$ events

Example of D^0 peaks in one bin of p_T, used to extract a p_T and luminosity-dependent fake rate

for K^+ and K^-



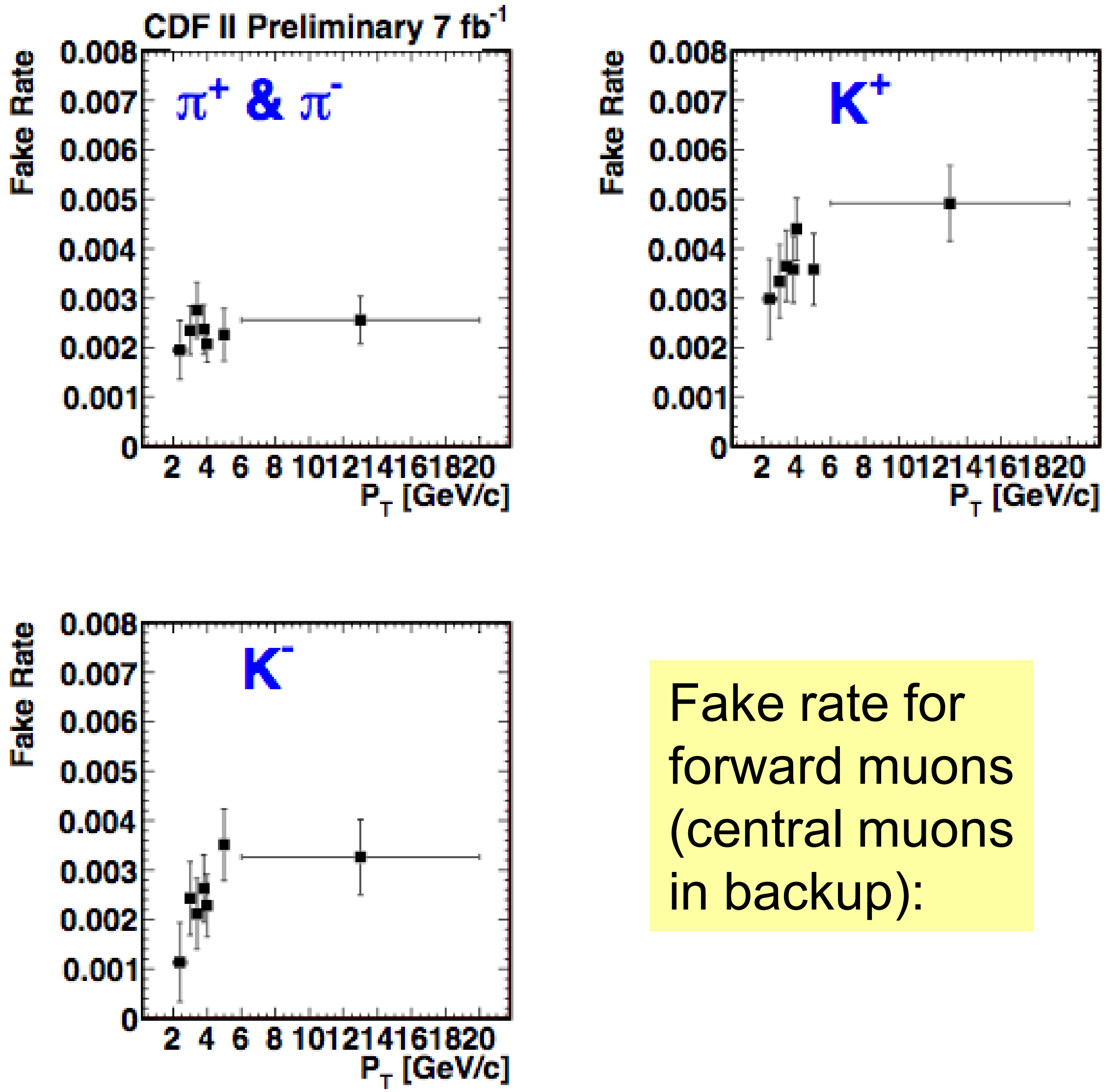
Kaons passing muon selection:



Muon fake rates

- Variations with p_T and luminosity are taken into account

- Total systematic uncertainty (due to both muon legs) dominated by residual run-dependence: ~35%



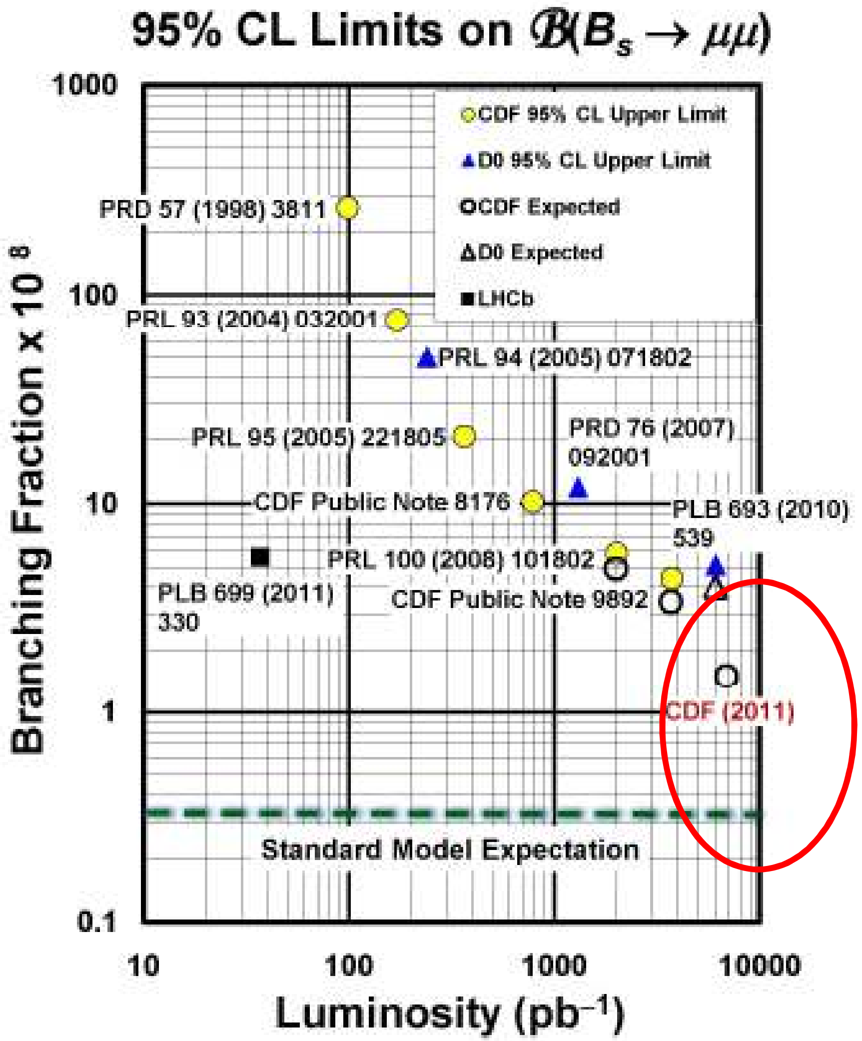
Fake rate for forward muons (central muons in backup):

Expected limits

$BR(B_s \to \mu^+\mu^-) < 1.5\times10^{-8}$ @ 95%CL

$BR(B^0 \to \mu^+\mu^-) < 4.6\times10^{-9}$ @ 95%CL

Significant improvement in sensitivity over all previous analyses

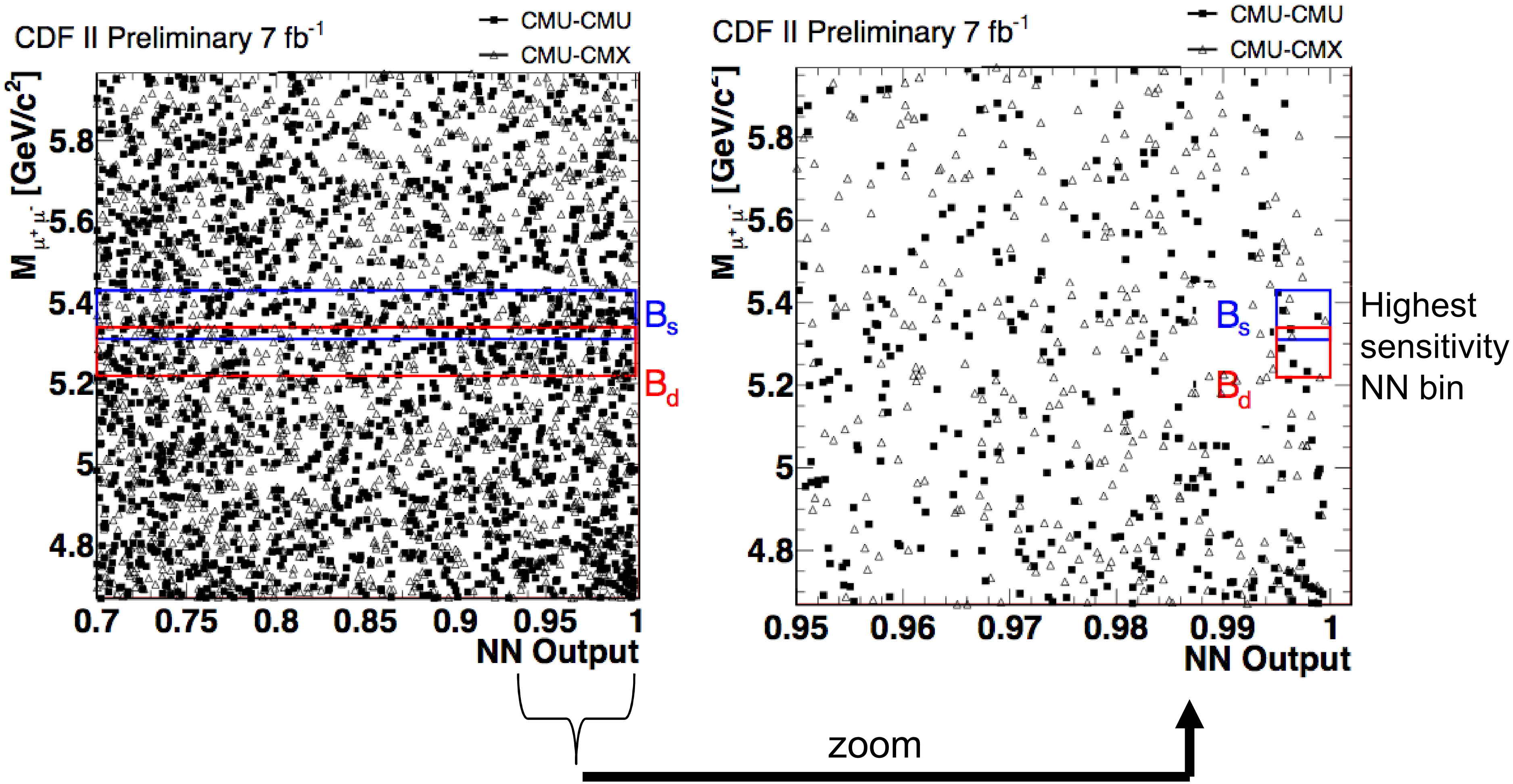


For $BR(B_s \to \mu^+\mu^-)$:

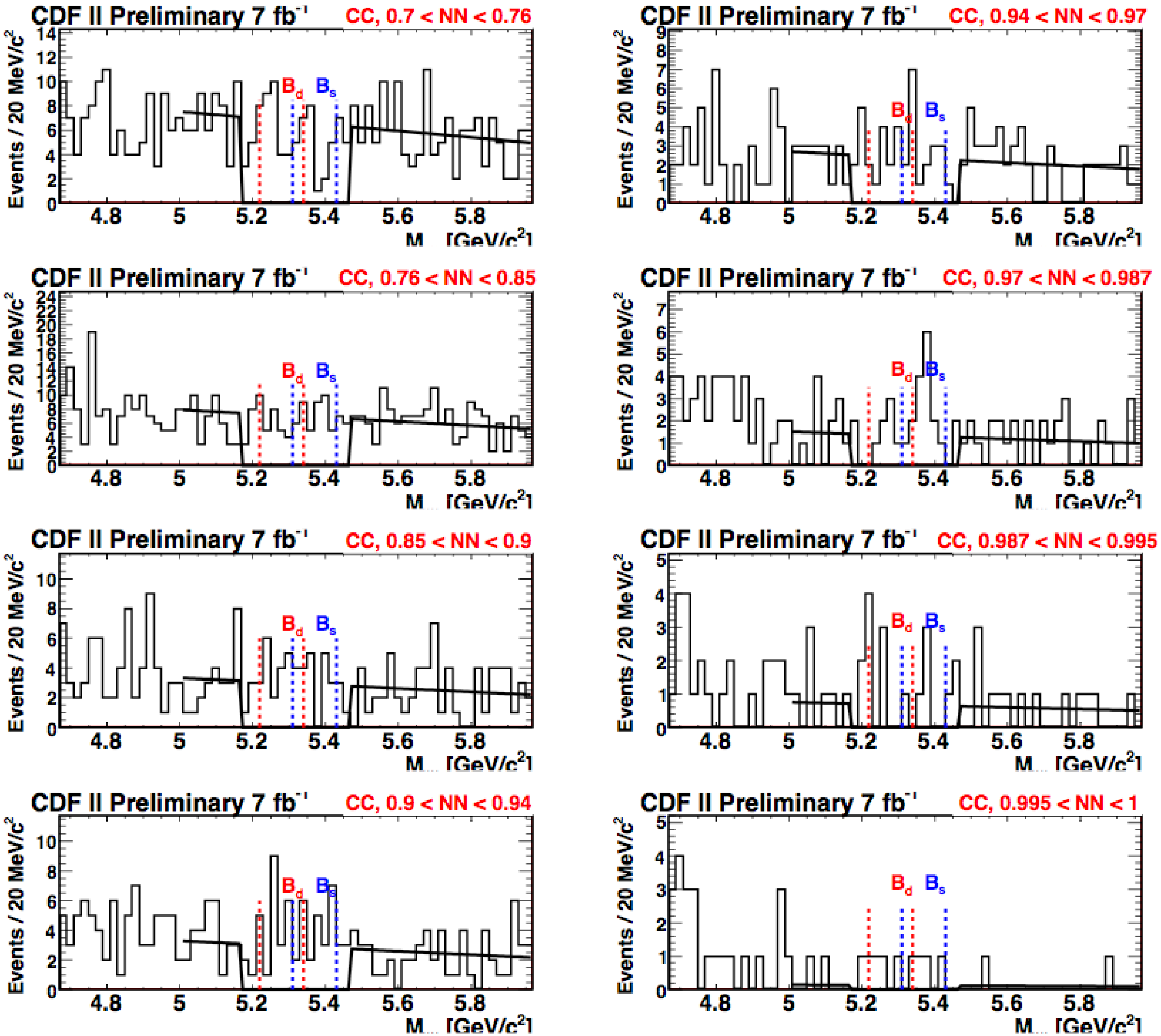
	Expected	Observed
2.0 fb^{-1}	: 4.9×10^{-8}	5.8×10^{-8}
3.7 fb^{-1}	: 3.4×10^{-8}	4.4×10^{-8}
7 fb^{-1}	: 1.5×10^{-8}	

Opening “the box”

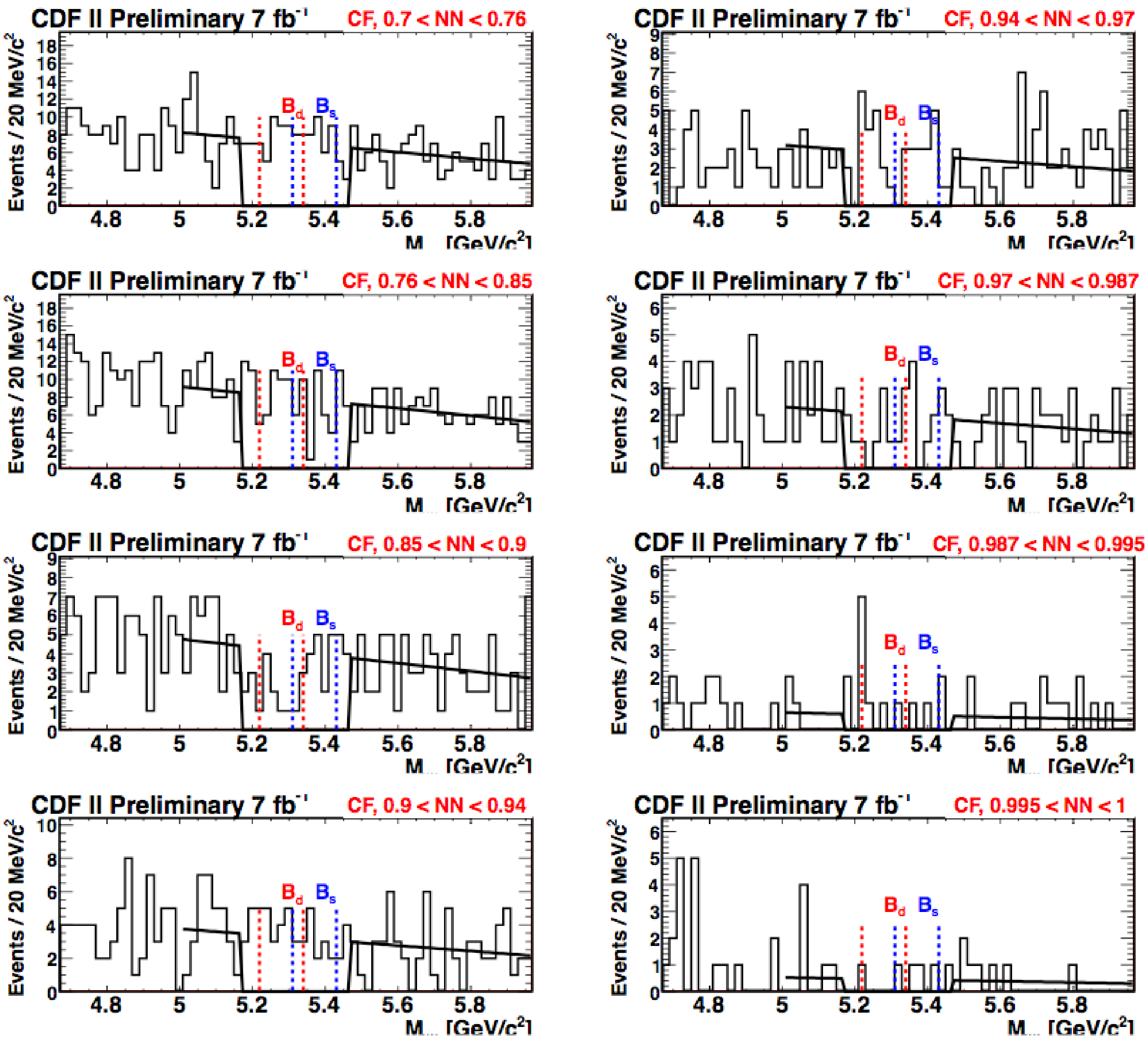
$B_s \rightarrow \mu^+\mu^-$ search: opening the box



CC only


CDF II Preliminary 7 fb⁻¹
CC, 0.7 < NN < 0.76
CC, 0.94 < NN < 0.97
CC, 0.76 < NN < 0.85
CC, 0.97 < NN < 0.987
CC, 0.85 < NN < 0.9
CC, 0.987 < NN < 0.995
CC, 0.9 < NN < 0.94
CC, 0.995 < NN < 1
Events / 20 MeV/c²
[GeV/c²]
Bd
Bs

CF only

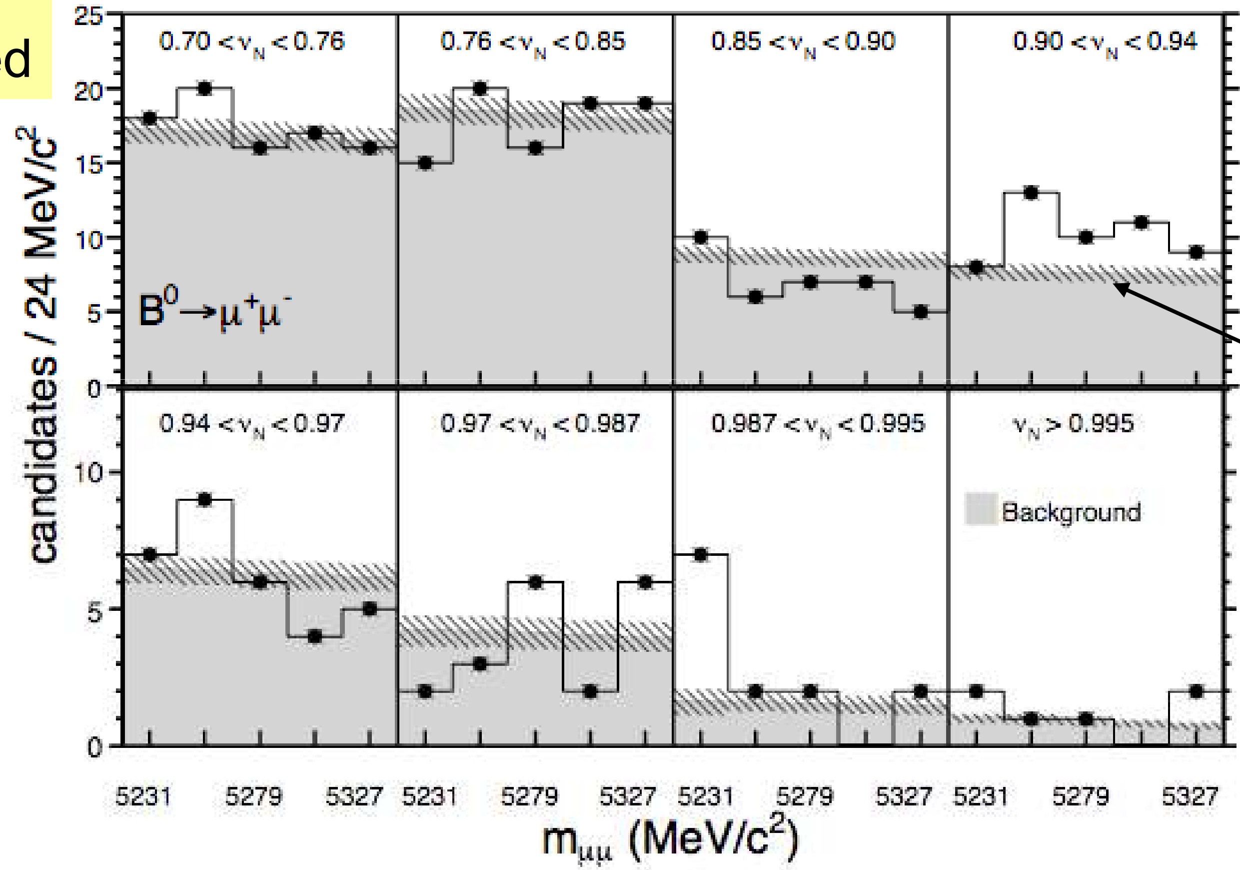


CDF II Preliminary 7 fb⁻¹
CF, 0.7 < NN < 0.76
CF, 0.76 < NN < 0.85
CF, 0.85 < NN < 0.9
CF, 0.9 < NN < 0.94
CF, 0.94 < NN < 0.97
CF, 0.97 < NN < 0.987
CF, 0.987 < NN < 0.995
CF, 0.995 < NN < 1
Events / 20 MeV/c²
M [GeV/c²]
Bd
Bs

Focus on B^0 signal window first

B^0 signal window, comparison of observation and background prediction

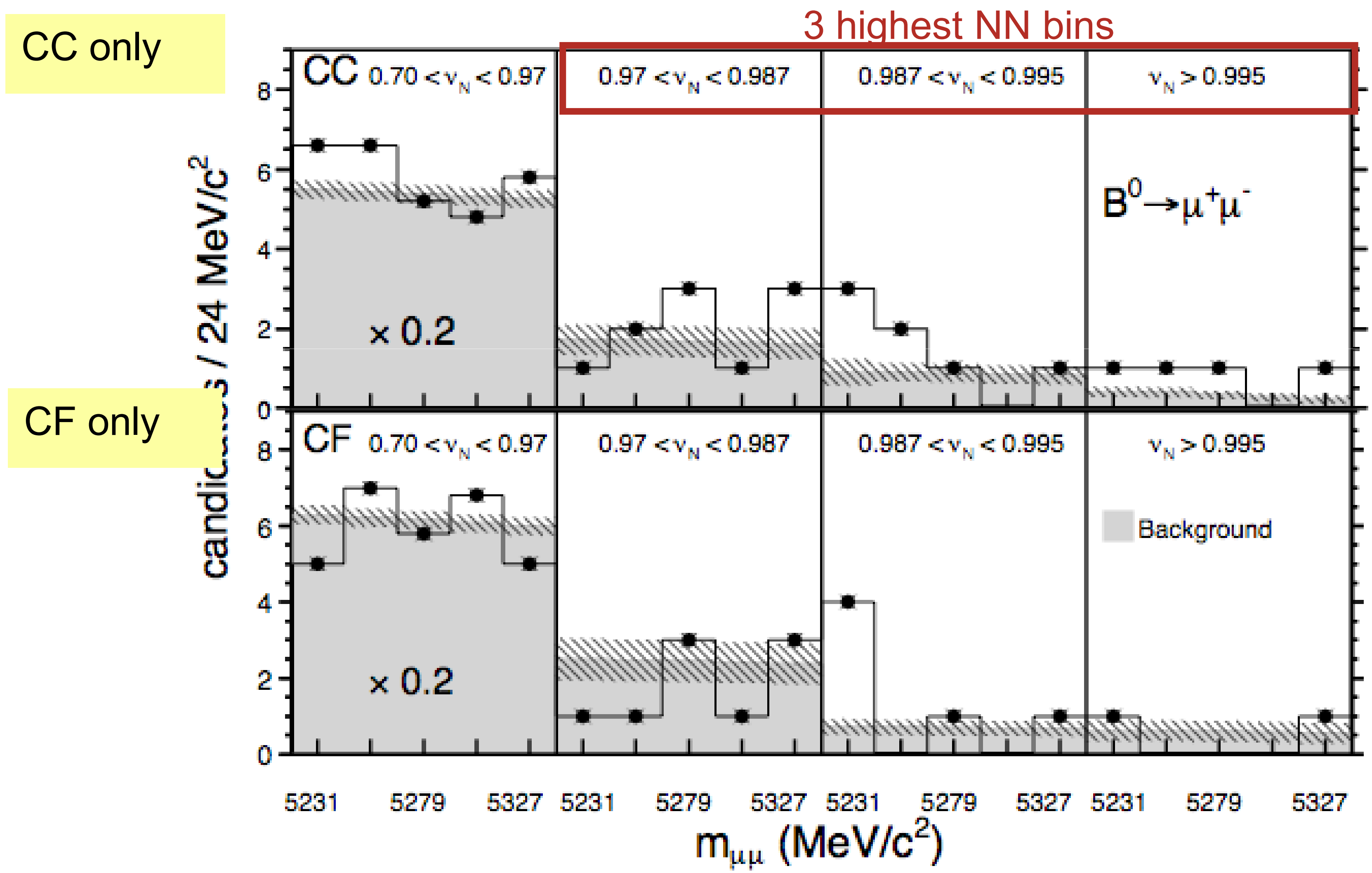
CC, CF combined



Dark hatched band shows uncertainty on the mean background prediction

Data and background expectation are in good agreement

B^0 signal window, comparison of observation and background prediction



B^0 signal window, comparison of observation and background prediction

3 most sensitive NN bins only

CC only

NN Bins	CC	Mass bins [GeV/c^2] 5.219-5.243	5.243-5.267	5.267-5.291	5.291-5.315	5.315-5.339
0.970<NN<0.987	Exp	3.00±0.65	2.97±0.64	2.93±0.64	2.90±0.63	2.86±0.62
	Obs	2	3	4	3	4
0.987<NN<0.995	Exp	0.90±0.28	0.89±0.28	0.86±0.27	0.84±0.27	0.81±0.27
	Obs	3	2	1	0	1
0.995<NN<1.000	Exp	0.40±0.21	0.38±0.20	0.32±0.17	0.25±0.15	0.20±0.14
	Obs	1	1	1	0	1

CF only

	CF					
0.970<NN<0.987	Exp	2.50±0.59	2.47±0.58	2.44±0.58	2.40±0.57	2.37±0.56
	Obs	1	4	3	1	2
0.987<NN<0.995	Exp	0.71±0.25	0.70±0.25	0.69±0.25	0.68±0.24	0.67±0.24
	Obs	4	0	1	0	1
0.995<NN<1.000	Exp	0.62±0.42	0.62±0.42	0.60±0.41	0.57±0.40	0.55±0.39
	Obs	1	0	0	0	1

Data and background expectation are in good agreement

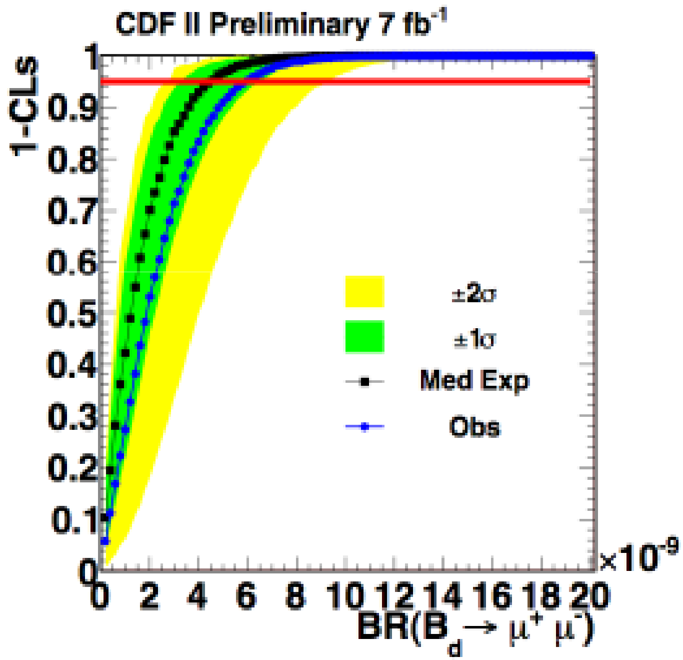
$B^0 \to \mu^+\mu^-$ search, observed limit

We set a limit (using CLs method) of

$$BR(B^0 \to \mu^+\mu^-) < 6.0 \times 10^{-9}$$

at 95% C.L.

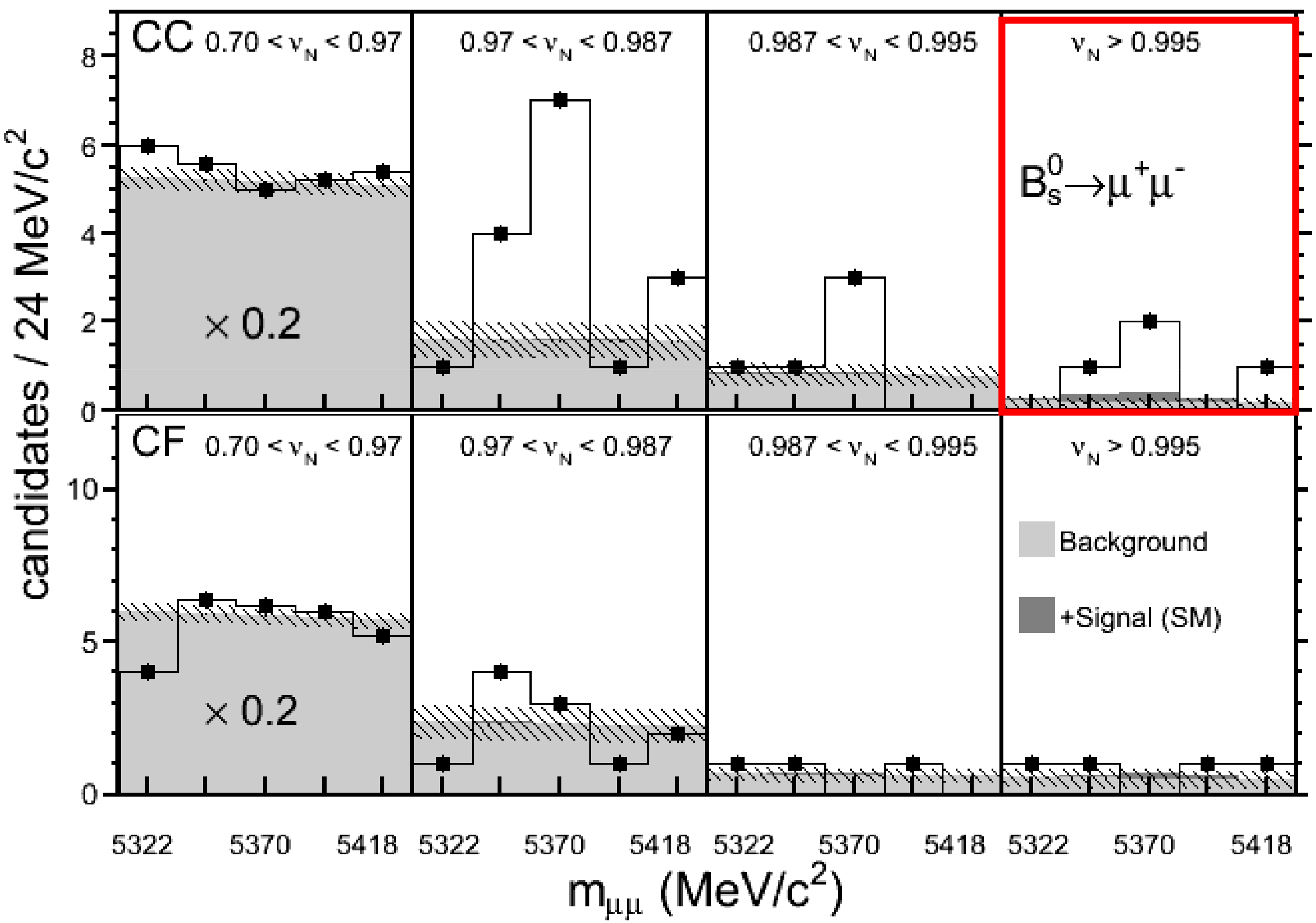
- world's best limit
- consistent with the expected limit $BR(B^0 \to \mu^+\mu^-) < 4.6 \times 10^{-9}$



Compare to the SM BR calculation of

$$BR(B^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$$

Data in B_s signal window



B_s signal window, comparison of observation and background prediction

Shown is the total expected background and total uncertainty, as well as number of observed events

CC		Mass bins [GeV/c^2]				
NN Bins		5.310-5.334	5.334-5.358	5.358-5.382	5.382-5.406	5.406-5.430
0.970<NN<0.987	Exp	1.62±0.49	1.6±0.48	1.58±0.47	1.57±0.47	1.55±0.46
	Obs	1	4	7	1	3
0.987<NN<0.995	Exp	0.82±0.27	0.8±0.27	0.79±0.26	0.78±0.26	0.78±0.26
	Obs	1	1	3	0	0
0.995<NN<1.000	Exp	0.21±0.14	0.18±0.13	0.16±0.12	0.16±0.12	0.16±0.12
	Obs	0	1	2	0	1
CF						
0.970<NN<0.987	Exp	2.38±0.56	2.34±0.55	2.31±0.54	2.28±0.54	2.25±0.53
	Obs	1	4	3	1	2
0.987<NN<0.995	Exp	0.67±0.24	0.66±0.24	0.65±0.24	0.64±0.23	0.63±0.22
	Obs	1	1	0	1	0
0.995<NN<1.000	Exp	0.56±0.39	0.54±0.38	0.53±0.38	0.52±0.37	0.51±0.36
	Obs	1	1	0	1	1

Observe an excess, concentrated in the 3 highest NN bins of the CC sample, over background expectation

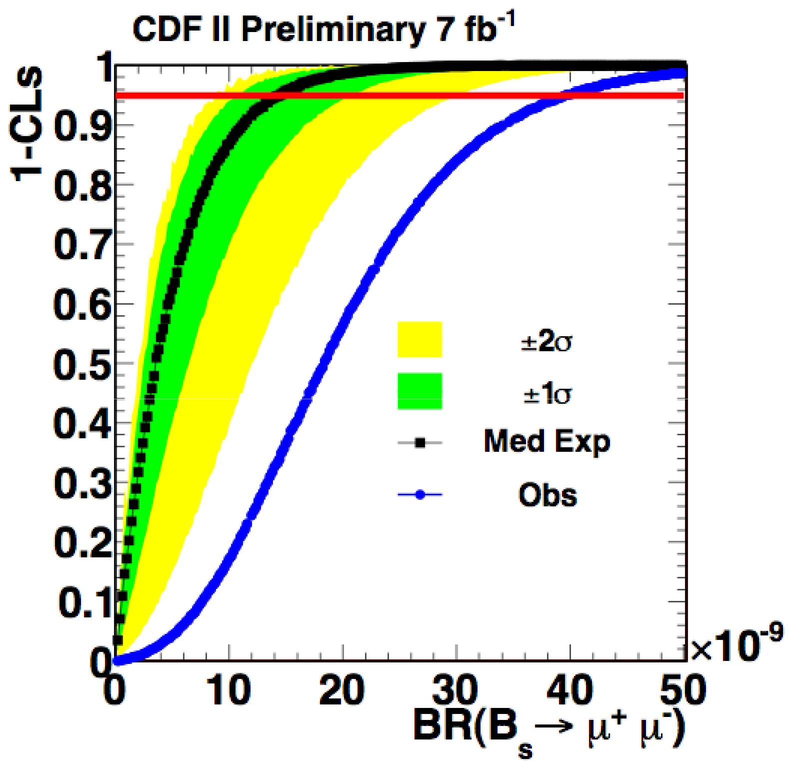
$B_s \to \mu^+\mu^-$ search, observed limit

Using the CLs method, we observe

$BR(B_s \to \mu^+\mu^-) < 4.0\times10^{-8}$

at 95% C.L.

- Compare to the expected limit $BR(B^0 \to \mu^+\mu^-) < 1.5\times10^{-8}$
- outside the 2σ consistency band



Need statistical interpretation of the observed excess:

- what is the level of inconsistency with the background?
- what does a fit to the data in the B_s search window yield?

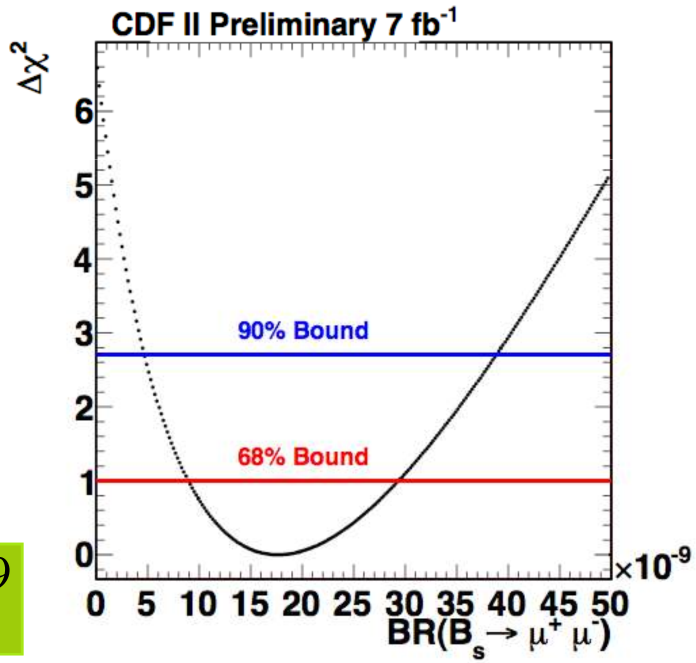
Fit to the data in the B_s search window

Using the log-likelihood fit, we set the first two-sided limit of $B_s \to \mu^+\mu^-$ decay

$$4.6\times10^{-9} < BR(B_s \to \mu^+\mu^-) < 3.9\times10^{-8}$$ @90% C.L.

Our central value is

$$BR(B_s \to \mu^+\mu^-) = 1.8^{+1.1}_{-0.9}\times10^{-8}$$



Compare to SM calculation of

$$BR(B_s \to \mu^+\mu^-) = (3.2\pm0.2)\times10^{-9}$$

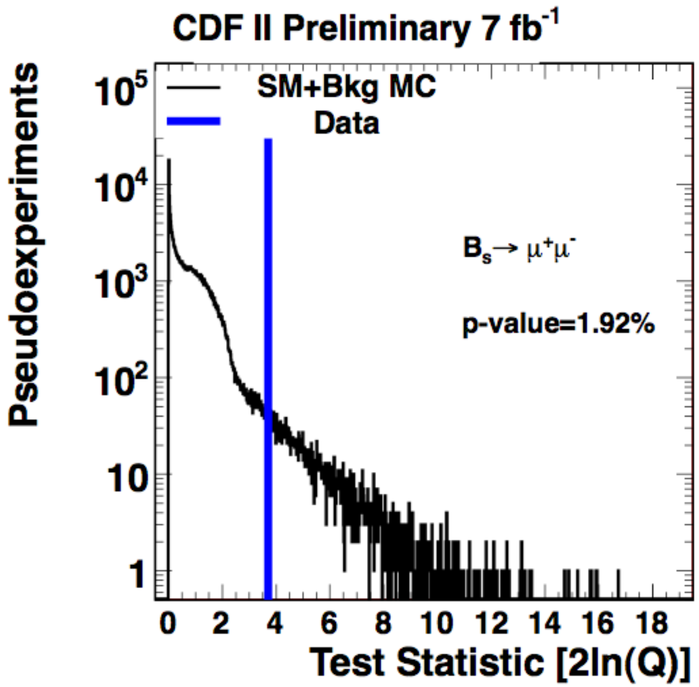
Consistency with the SM prediction of $B_s \to \mu^+\mu^-$ decays

reminder: SM prediction: BR($B_s \to \mu^+\mu^-$)=$(3.2\pm0.2)\times10^{-9}$

A. J. Buras et al., JHEP 1010:009,2010

"Background" hypothesis now includes the SM expectation of BR($B_s \to \mu\mu$)

If we include the SM BR($B_s \to \mu^+\mu^-$) in the background hypothesis, we observe a p-value of 1.9%



taking into account the small theoretical uncertainty on the SM prediction by assuming +1σ: p-value: 2.1%

Conclusions

We see an excess over the background-only expectation in the B_s signal region and have set the first two-sided bounds on $BR(B_s \to \mu^+\mu^-)$

$$4.6 \times 10^{-9} < BR(B_s \to \mu^+\mu^-) < 3.9 \times 10^{-8}$$ at 90% C.L.

A fit to the data, including all uncertainties, yields

$$BR(B_s \to \mu^+\mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$$

Data in the B^0 search window are consistent with background expectation, and the world's best limit is extracted:.

$$BR(B^0 \to \mu^+\mu^-) < 6.0(5.0) \times 10^{-9}\, at 95\%(90\%) C.L.$$

http://www.fnal.gov/pub/today/archive_2011/today11-07-15_CDFraredecay.html

Fermilab *Today*

Friday, July 15, 2011

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Special Result of the Week

Rare or medium rare?

When particles decay, they frequently do so in only a few different ways. However, once in a while, particles can decay in an unusual way. It is in these rare instances that scientists can catch a glimpse of something that they normally wouldn't otherwise see.

These decays are important because they can shed light on subatomic processes that scientists cannot observe directly, either here at the Tevatron or at the LHC. One example of such a rare decay is the decay of a B_s meson, which is composed of a b quark and an s quark, into a pair of muons ($B_s \rightarrow \mu^+$ and μ^-). The Standard Model predicts that the rate of this decay is so infrequent (3.2×10^{-9}) that it would take more than 350 trillion collisions for scientists to see it.

So why look for it? The presence of new particles or new interactions can substantially increase how often these rare decays occur, making them worth studying. In fact, the Bs decay ($B_s \rightarrow \mu^+$ and μ^-) is sensitive to contributions from a wide variety of new physics. This makes this rare decay an excellent place to look for deviations from the Standard Model.

The earlier results of this important experiment appeared in Fermilab Today in March 2004 and September 2007 and in International Science Grid This Week in February 2008. In 2009, CDF set the upper limit on these rare B_s decays at 43 out of a billion. With the newest result, CDF has further reduced that upper limit to 39 decays per billion and has set for the first time a lower limit of more than 4.6 B_s meson decays per billion.

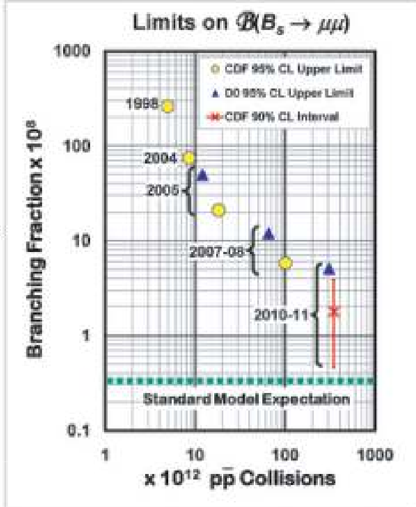
To get this result, a team of CDF physicists sifted through 7 inverse femtobarns of data searching for B_s mesons decaying into muon pairs. **CDF physicists saw a slight excess in the data, which may provide us with the first hints of this elusive decay. If the excess is real, it would correspond to a decay rate that is somewhat larger than, but not inconsistent with the Standard Model prediction.**

With the Tevatron and LHC experiments collecting more data, we'll soon see if this excess stands the test of time.

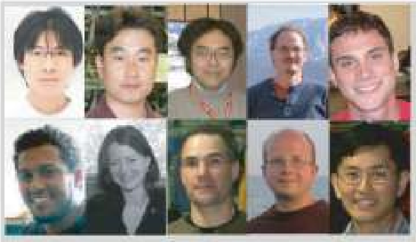
A special Wine & Cheese seminar on this topic will take place at 2 p.m. today in the auditorium.

Click here to learn more about today's CDF result.
http://arxiv.org/abs/1107.2304

- edited by Andy Beretvas and Doug Glenzinski



The figure shows limits on the Bs decay rates at the Tevatron. CDF found at a 90 percent confidence level the rate is between 0.46 and 3.9×10^{-8}. The central value is more than five times than predicted by the Standard Model.



These physicists were responsible for this analysis. Top row, from left: Satoru Uozumi and Daejung Kong, Kyungpook National University, Korea; Teruki Kamon, Texas A&M/KNU; Matthew Herndon and David Sperka, Wisconsin University. Bottom row, from left: Walter Hopkins and Julia Thom, Cornell University; Doug Glenzinski, Fermilab; Slava Krutelyov, University of California - Santa Barbara; and Cheng-Ju Kin, Lawrence Berkeley National Laboratory.

Fermi National Accelerator Laboratory Office of Science/U.S. Department of Energy | Managed by Fermi Research Alliance, LLC

Fermilab-Today July-15^{th}

Results submitted to PRL

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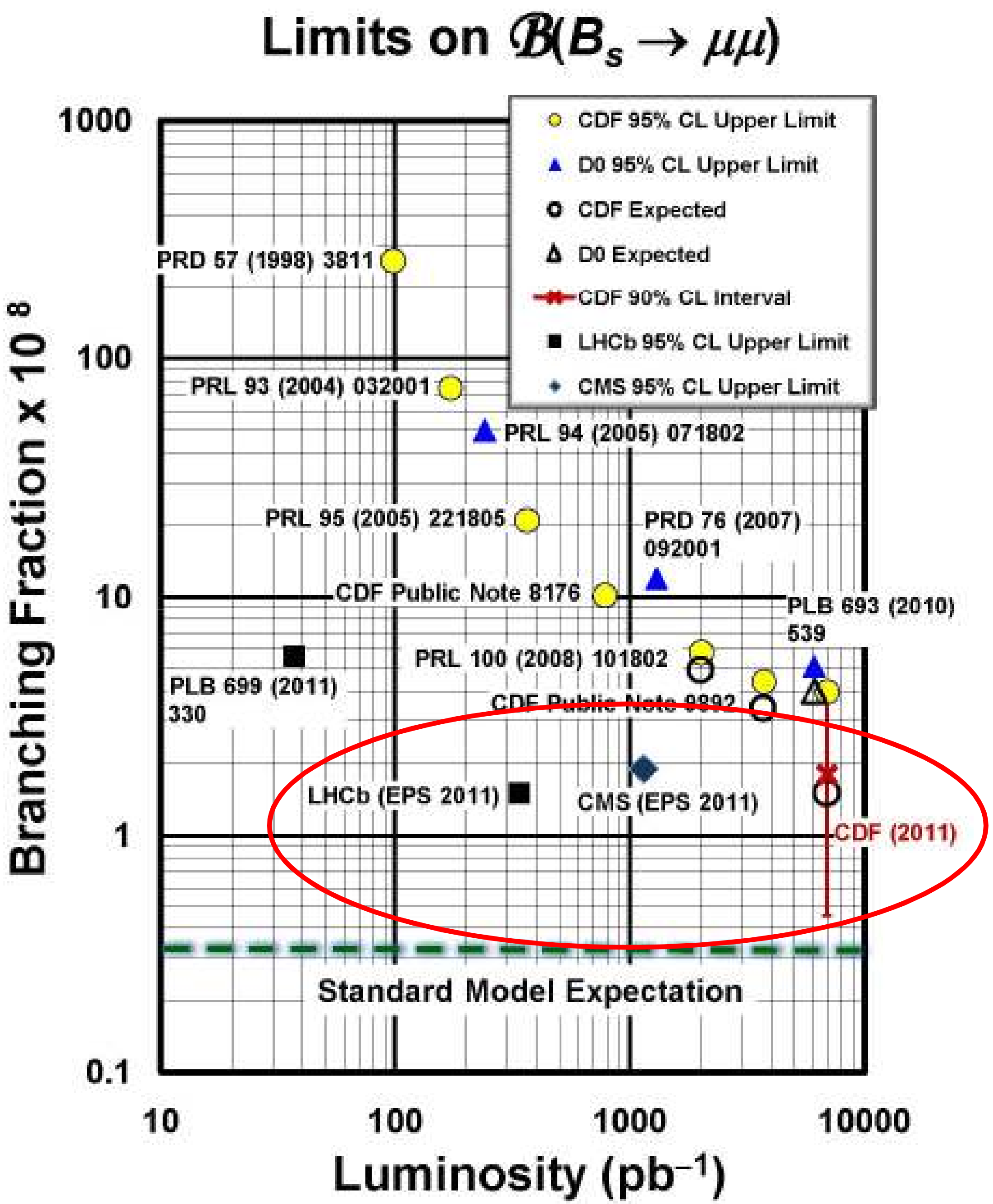


What we will see beyond our horizon ?

Results opened at EPS 2011

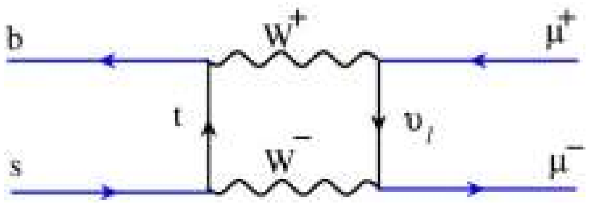
Stay tuned !

KNU KYUNGPOOK NATIONAL UNIVERSITY

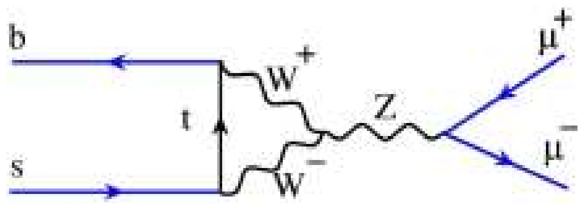
$B_s^0 \to \mu^+\mu^-$

Rare decay $B_s^0 \to \mu^+\mu^-$: FCNCs, forbidden at tree level

SM Diagrams



Box Diagram



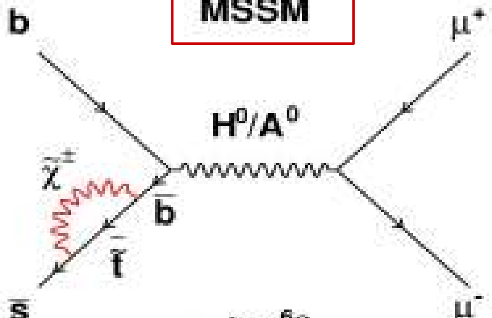
Penguin Diagram

SM Expectation

$Br : (3.2 \pm 0.2) \times 10^{-9}$

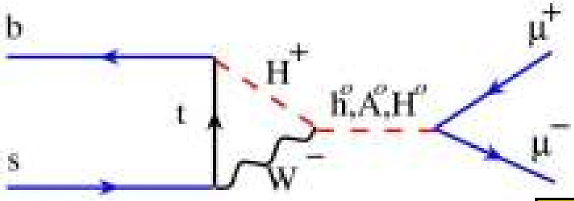
JHEP 1009 (2010)106

MSSM



$\sim \tan^6\beta$

2HDM



Penguin Diagram

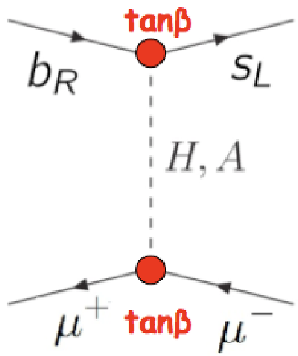
NP Expectation

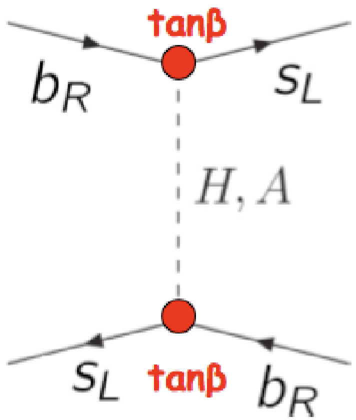
Br enhancement

Powerful Probe to New Physics

Probing New Physics

- “Smoking gun” of some Flavor Violating NP models:
  - ratio BR($B_s \to \mu^+\mu^-$)/ BR($B^0 \to \mu+\mu-$) highly inform
    ative about whether NP violates flavor significantly
    or not
  - clear correlation between CP violating mixing pha
    se from $B_s \to J/\psi\phi$ and BR($B_s \to \mu^+\mu^-$)
    Altmannshofer, Buras, Gori, Paradisi, Straub, Nucl.Phys.B830:17-94,2010





- Important complementarity with direct se
  arches at Tevatron and LHC
  - Indirect searches can access even higher mass s
    cales than LHC COM energies

New bounds on BR($B^0 \to \mu^+\mu^-$) and BR($B_s \to \mu^+\mu^-$) are of crucial importance, and are a top priority at the Tevatron and LHC.

Probing New Physics

Plenary talk
A.Buras, Beauty 2011:

Maximal Enhancements of $S_{\psi\varphi}$, $Br(B_s \to \mu^+\mu^-)$ and $K^+ \to \pi^+\nu\bar{\nu}$

(without taking correlation between them)

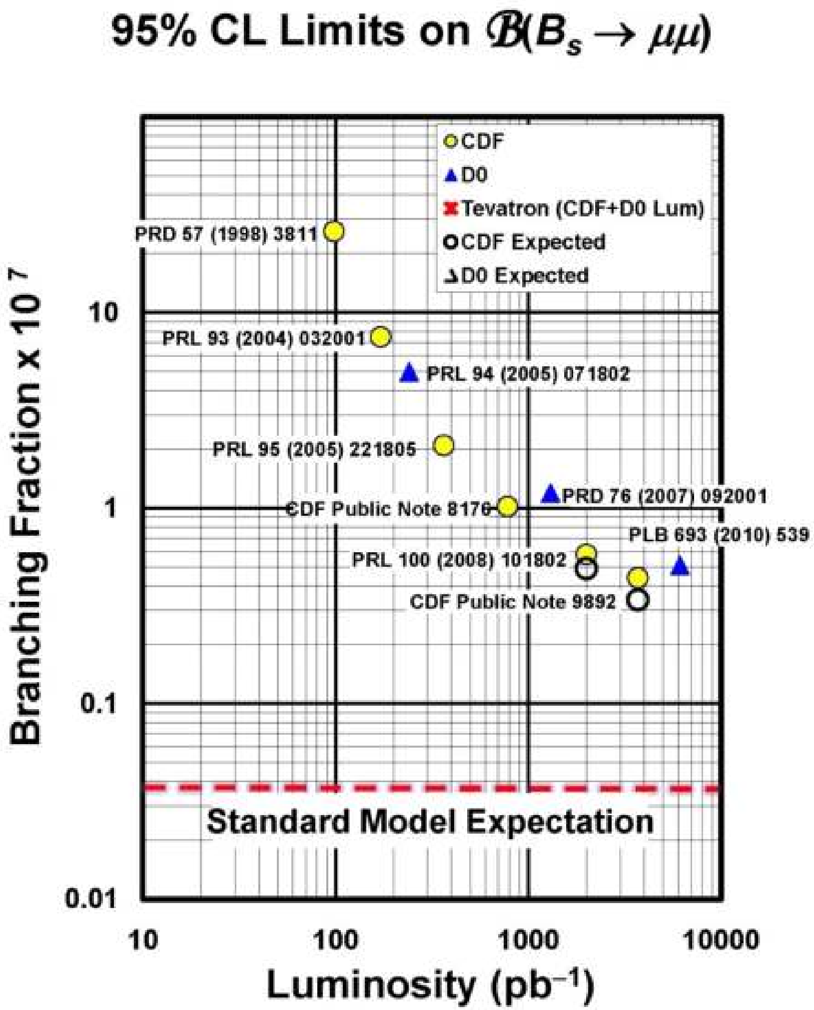
Model	Upper Bound on ($S_{\psi\varphi}$)	Enhancement of $Br(B_s \to \mu^+\mu^-)$	Enhancement of $Br(K^+ \to \pi^+\nu\bar{\nu})$
CMFV	0.04	20%	20%
MFV	0.04	1000%	30%
LHT	0.30	30%	150%
RS	0.75	10%	60%
4G	0.80	400%	300%
AC	0.75	1000%	2%
RVV	0.50	1000%	10%

Large RH Currents

RS = RS with custodial protections
AC = Agashe, Carone $U(1)_F$
RVV = Ross, Velaso-Sevilla, Vives (04) $SU(3)_F$

$B_s \to \mu\mu$ at CDF

- ❑ A powerful indirect search to probe cosmol ogically consistent SUSY at large tan*b*. e.g.,
  - Arnowitt et al., PLB 538 (2002) 121 for mSUGRA;
  - S. Baek, Y.G. Kim, and P. Ko, JHEP 0502, 067 (2005) for non-universal Higgs sce nario.



- ❑ 3 PRLs (2004, 2005, 2008)
  → Producing the best limits on SUSY

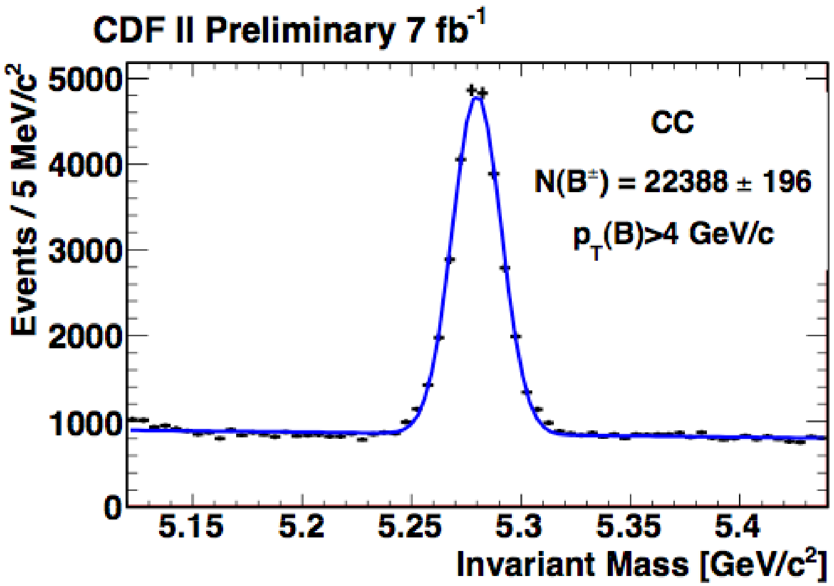
- ❑ Goal: 2×10^{-8} with 6.9 fb^{-1} and two challenging updated methods :

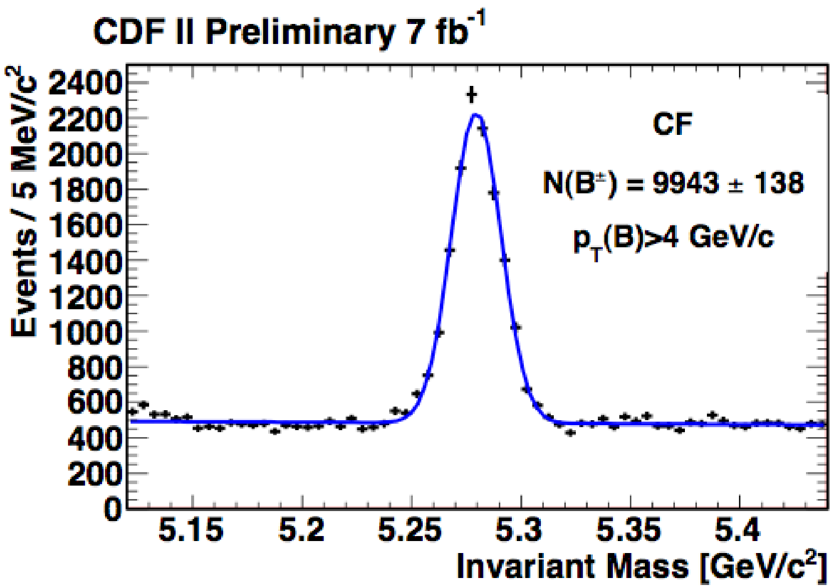
Pre-selection: B^+ normalization sample

$B^+ \rightarrow J/\psi K \rightarrow \mu^+\mu^- K$,
~30k candidates.

In addition to baseline cuts, B^+ sample passes

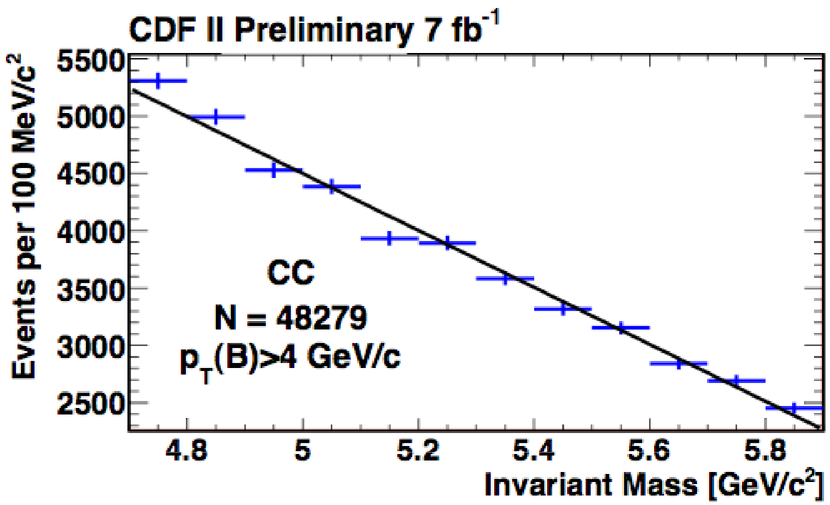
- J/ψ mass constraint for dimuons
- K quality cuts, and K and J/ψ constrained to common vertex

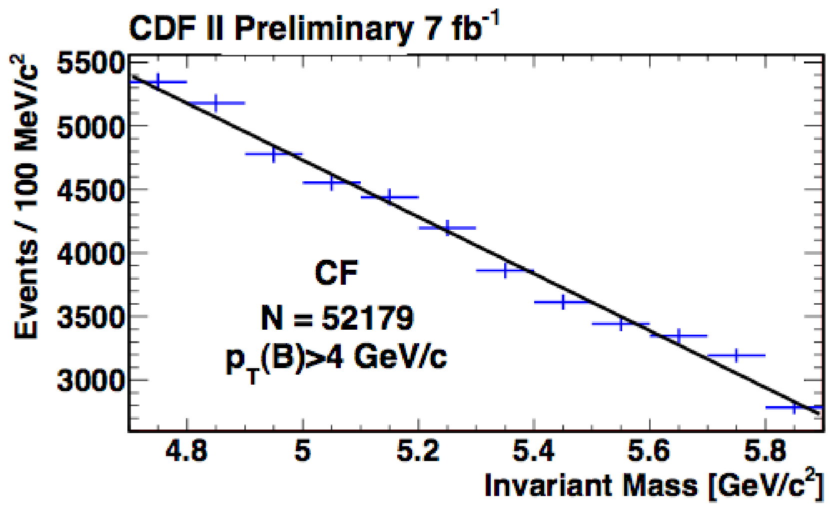




Pre-selection: $B_s(B^0)$ search samples

$B_s(B^0)$ search sample,
~100k candidates





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New Neural Network

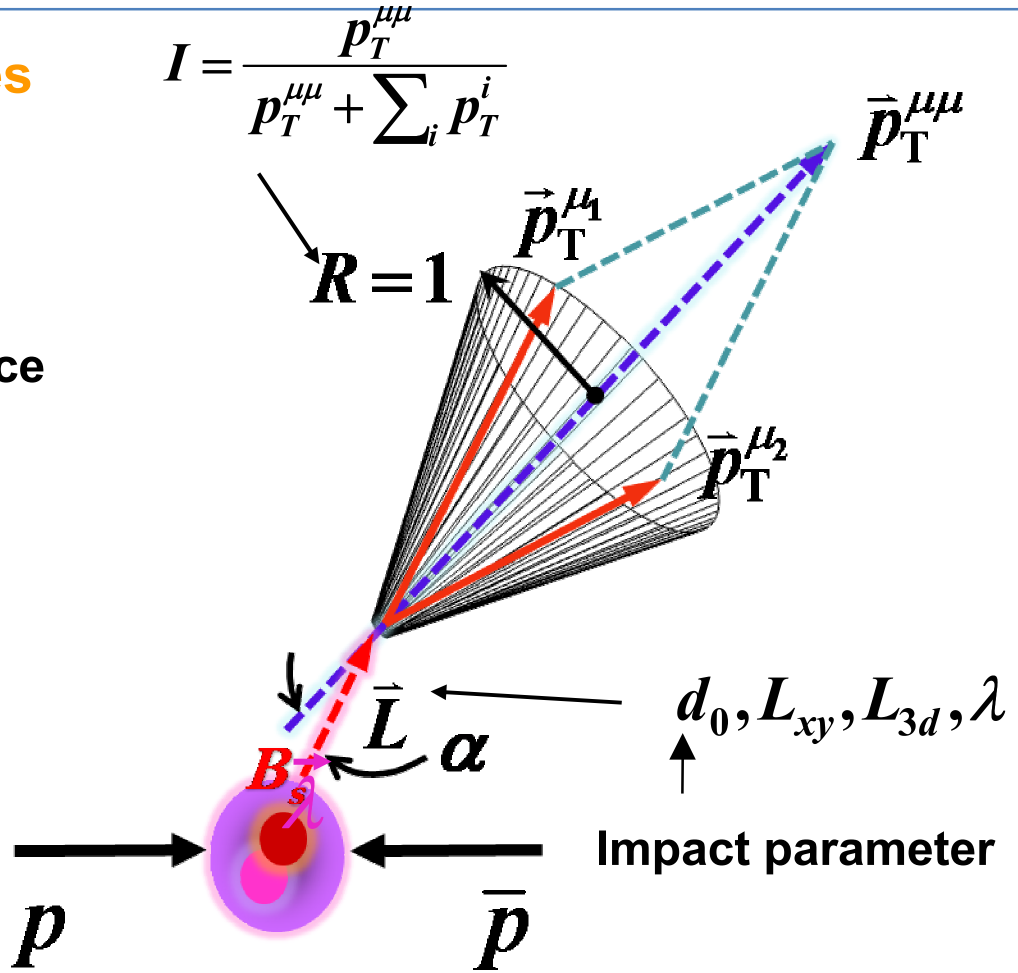
✓ New 14 variable NN to increase S/B

✓ Carefully chose input variables to avoid bias for di-muon mass shape

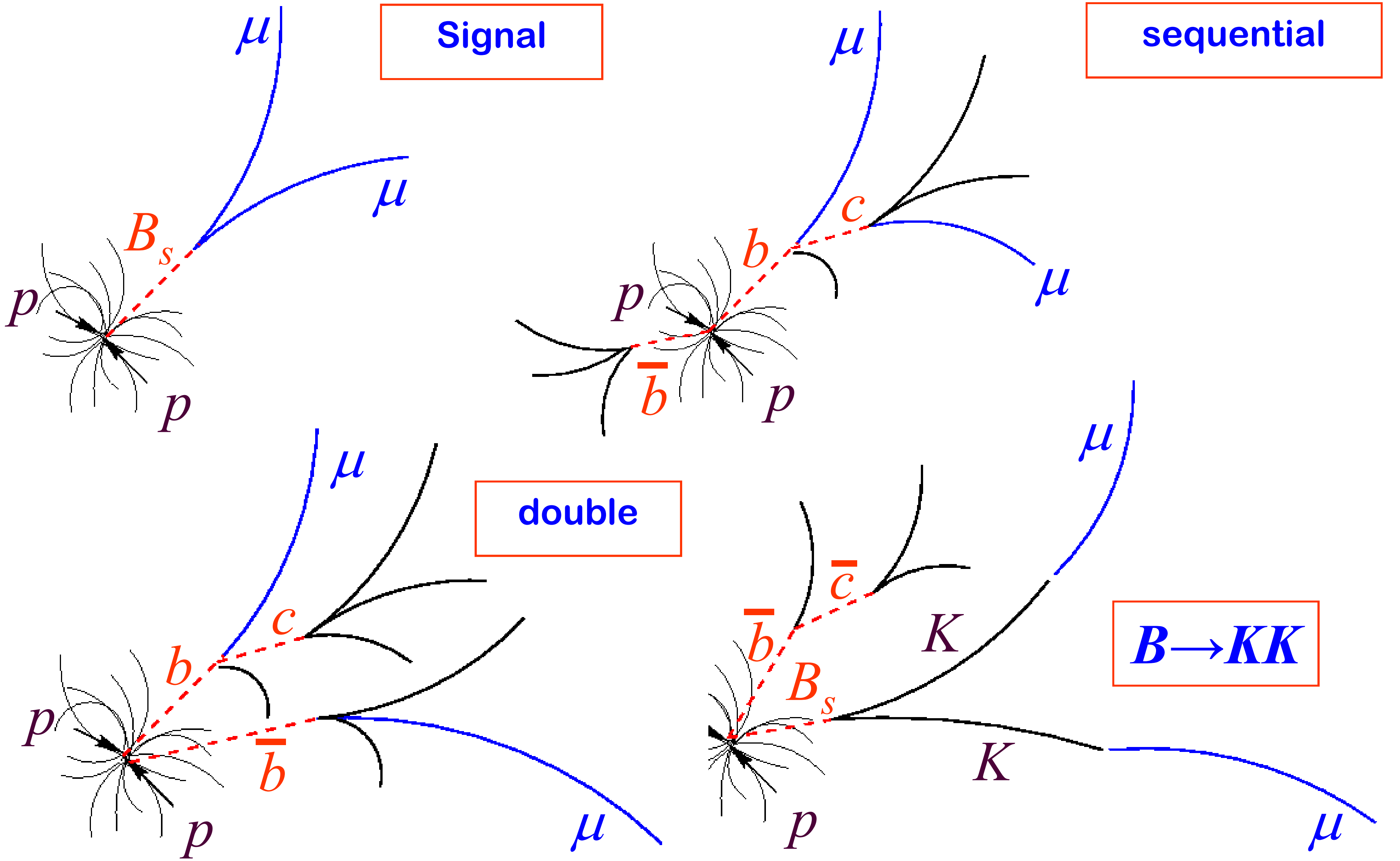
Neural Network Input Variables

- 3D proper decay length
- Isolation
- Pointing angle ($\Delta\alpha_{3d}$)
- Lower $|p_T(\mu)|$
- 3D proper decay length significance

- Larger $|d_0(\mu)|$
- Smaller $|d_0(\mu)|$
- Smaller $|d_0(\mu)|$ significance
- Larger $|d_0(\mu)|$ significance
- Vertex Fitting χ^2
- Decay length (L_{3d})
- 2D pointing angle ($\Delta\alpha_{2d}$)
- L_{xy} significance
- $|d_0(Bs)|$



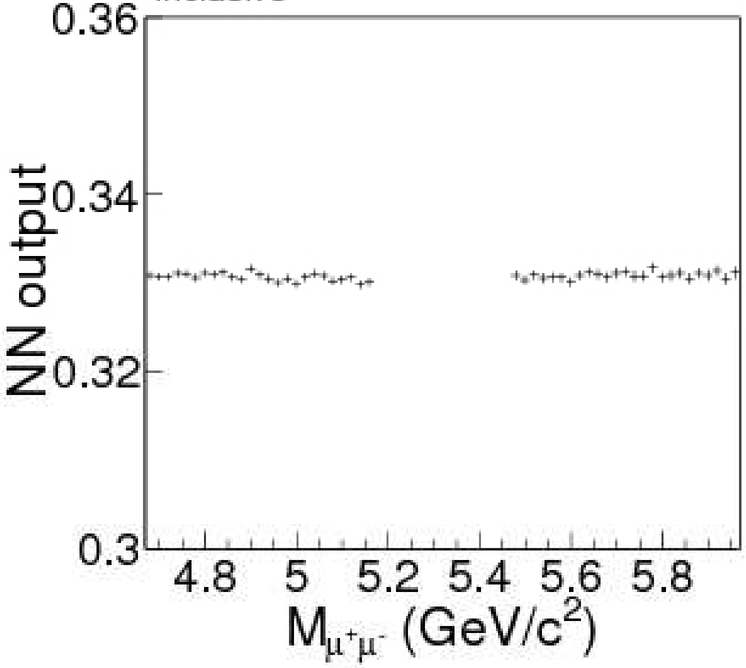
$B_s(B^0)$ Signal vs. Background



From B. Casey, ICHEP2010

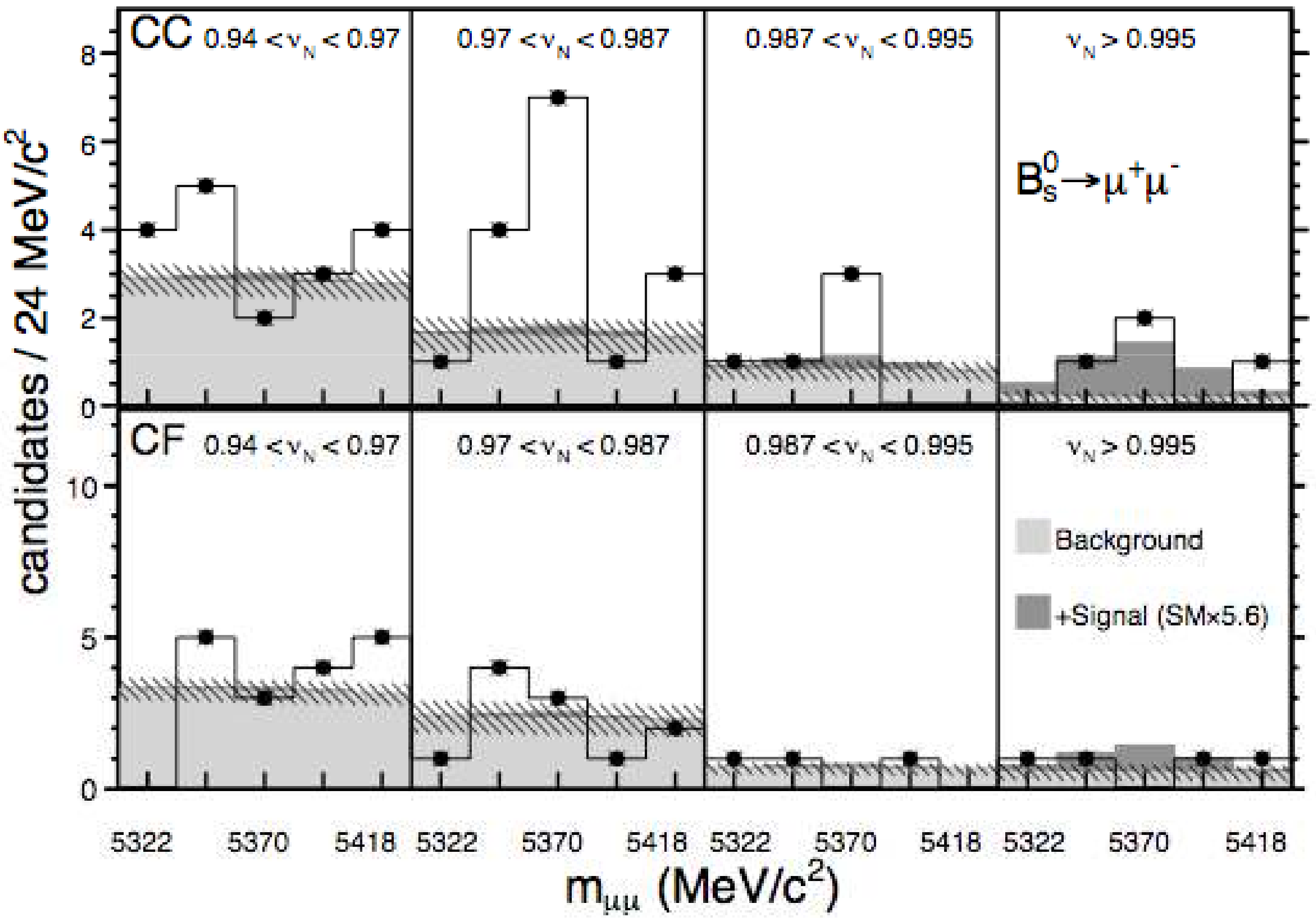
Bias Check from NN event selection

Mass Bias Check with Sideband region



NO correlation b/w NN and Mass

Data in B_s signal window



Determination of the p-value

Ensemble of background-only pseudo-experiments is used to determine a p-value for a given hypothesis

- for each pseudo-experiment, we do two fits and form the log-likelihood ratio

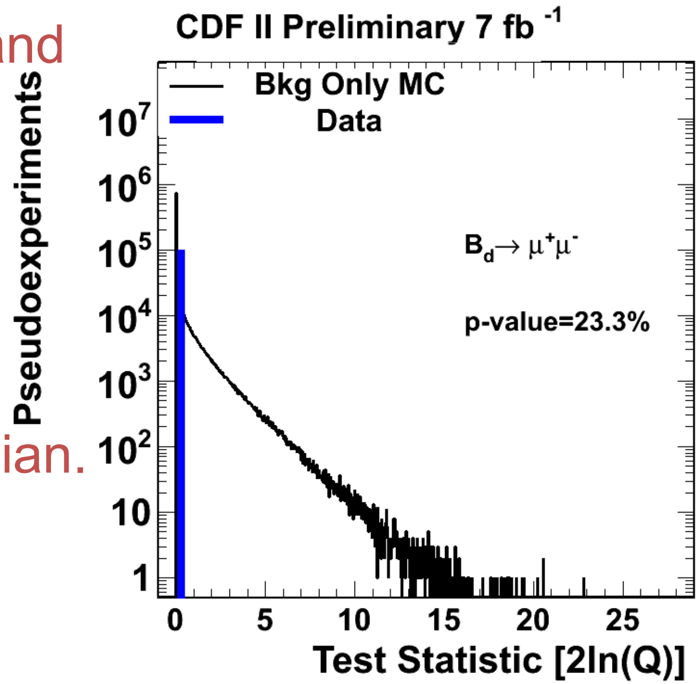
$$2\ln(Q) \quad \text{with} \quad Q = \frac{L(s+b\,|\,data)}{L(b\,|\,data)}$$

- in the denominator, the "signal" is fixed to zero (I.e. we assume background only), and in the numerator s floats

- *L(h|x)* is the product of Poisson probabilities over all NN and mass bins

- systematic uncertainties included as nuisance parameters, modeled as Gaussian.

Log Likelihood Distribution of pseudo-experiments for background-only hypothesis for $B^0 \rightarrow \mu^+\mu^-$ signal window



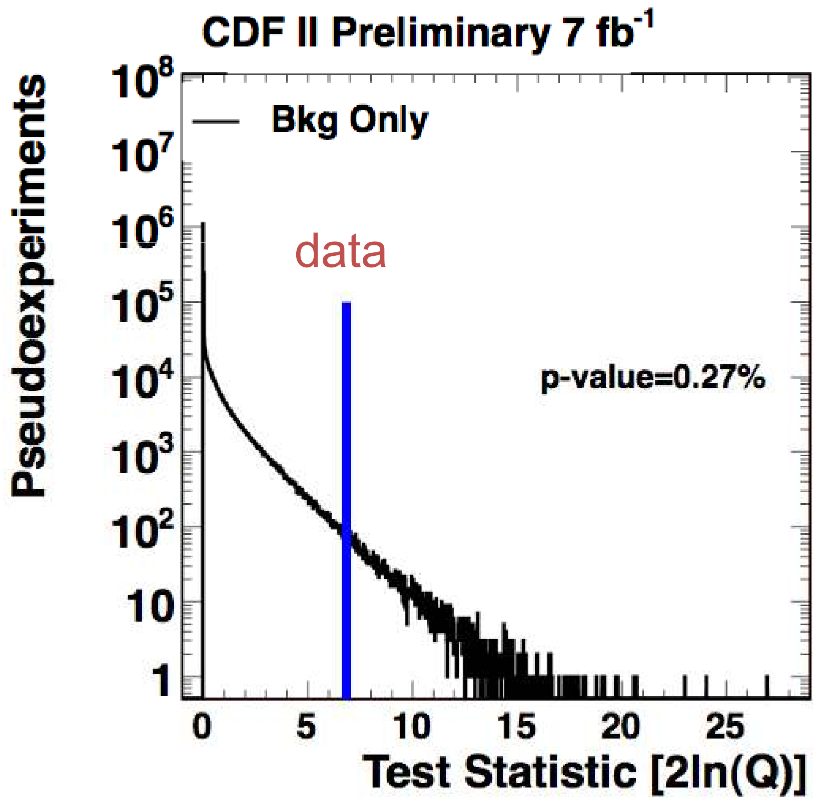
Result: the p-value for the background-only hypothesis is 23.3%

P value for background-only hypothesis

Log Likelihood Distribution
of pseudo-experiments
for background hypothesis

Observed p-value: 0.27%.

This corresponds to a 2.8σdiscrepancy
with a background-only null hypothesis
(one-sided gaussian)



Cross Checks

Cross checks of the total background prediction

Apply background model to statistically independent control samples and compare result with observation. We have investigated 2 groups of samples:

1) Control samples composed mainly of combinatorial backgrounds
   - **OS-**: $\mu^+\mu^-$ events with negative proper decay length
   - **SS+**: loose pre-selection* and same sign muon pairs
   - **SS-**: like SS+ but negative proper decay length

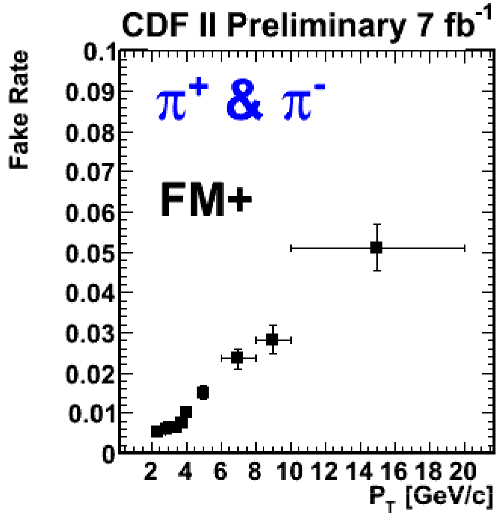
2) Control sample with significant contribution from B->hh background
   - **FM+**: loose pre-selection and at least one muon fails quality requirements

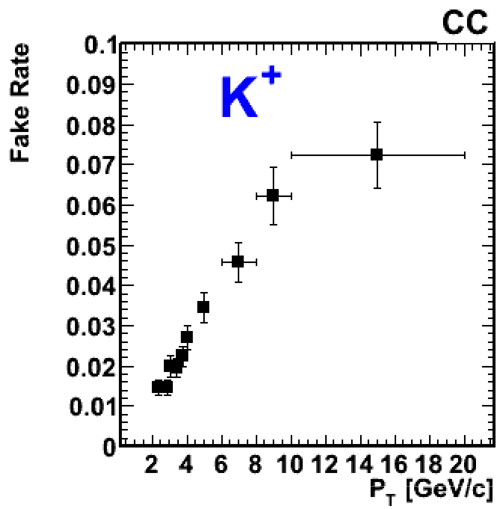
* Loose pre-selection = $p_T(\mu)$>1.5 and $p_T(\mu\mu)$> 4 GeV

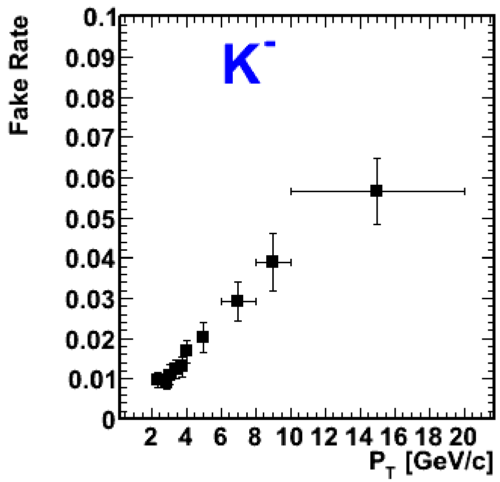
Aside: The FM+ control sample

The FM+ control sample has at least one muon which fails our muon quality requirements

→need a different set of K/π fake rates since the muon ID requirements are different than used in the signal sample. Same method as before is used







Fake rate for central muons (FM+ selection)

Result of background checks in control samples

Control Sample	Prediction	Nobs	Prob(N>=Nobs)
OS-	2140.0 ± 53.9	1999	98%
SS+	19.7 ± 3.4	25	19%
SS-	46.8 ± 5.3	53	25%
FM+	567.8 ± 25.4	593	24%
Sum	2774.3 ± 59.9	2670	91%

Shown are total number of events in all NN bins.

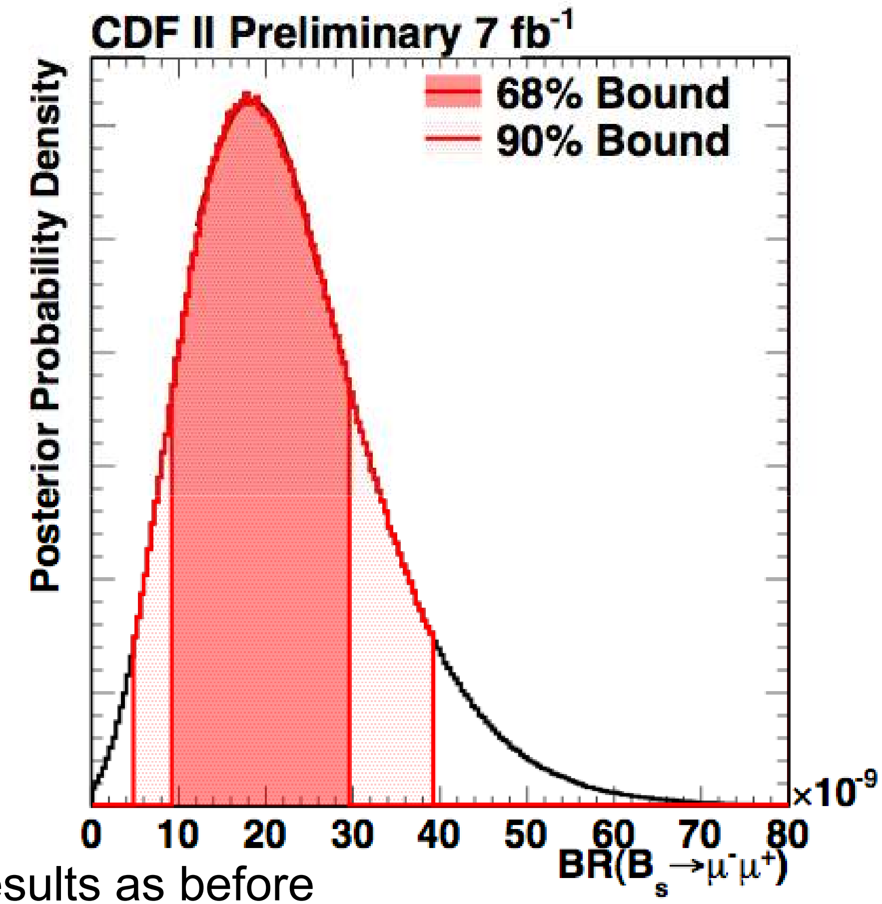
- "Prob(N>=Nobs)" is the Poisson probability for making an observation at least as large given the predicted background

✓ Good agreement across all control samples.

Fit to the data: cross checks

Use Bayesian binned likelihood technique

- assumes a flat prior for BR>0
- integrates over all sources of systematic uncertainty assuming gaussian priors
- best fit value taken at maximum, uncertainty taken as shortest interval containing 68% of the integral.



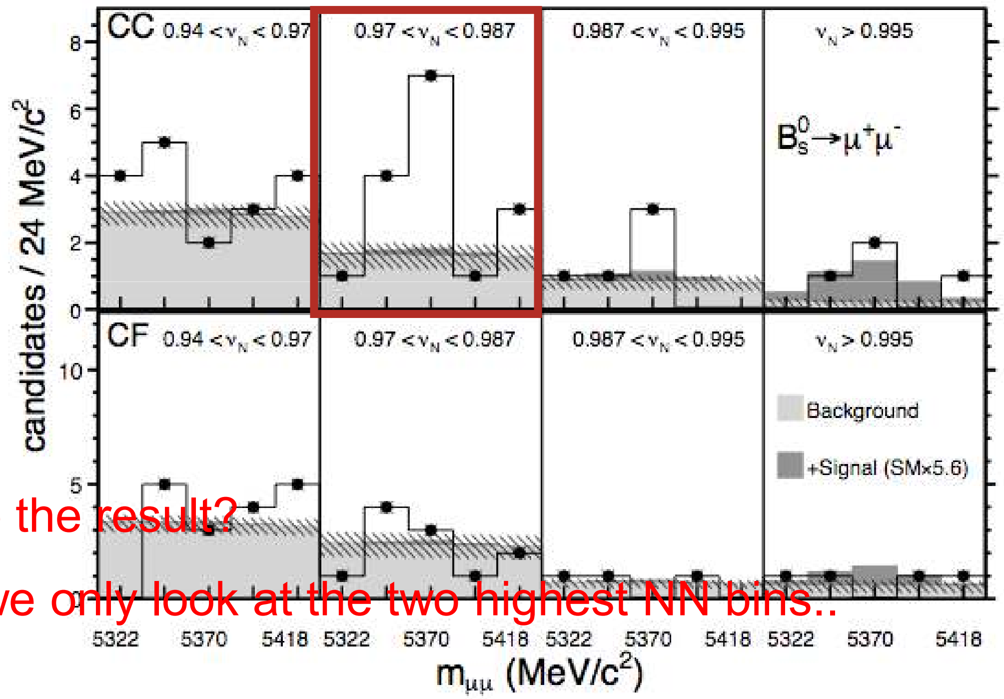
Best fit to the data yields almost identical results as before

$$BR(B_s \to \mu^+ \mu^-) = 1.8^{+1.1}_{-0.9} \times 10^{-8}$$

A closer look at the data

- excess observed in CC muons
- in most sensitive NN bin: data looks signal-like
- see a fluctuation in 0.97<NN<0.987- little signal sensitivity in this bin.

B_s signal window, CC and CF separate
Showing only the most sensitive 4 highest NN bins



Does the fluctuation in this bin drive the result?

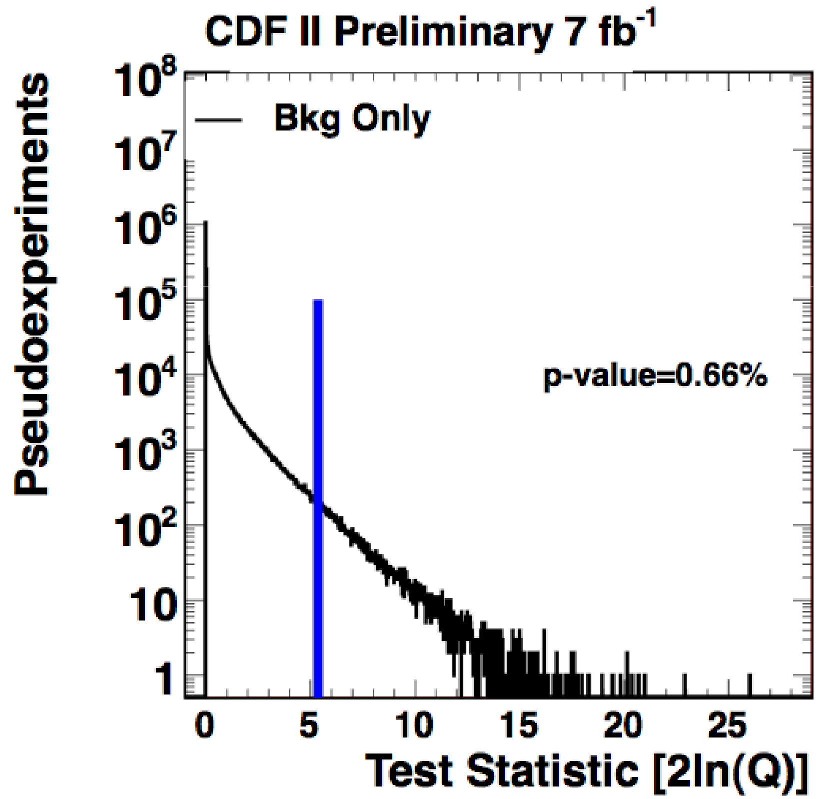
Check how the answer changes if we only look at the two highest NN bins..

Fit to the data, only considering the 2 highest NN bins

- Background-only hypothesis:
  Observed p-value: 0.66%
  (compare to 0.27%)

- Background + SM hypothesis:
  Observed p-value: 4.1%
  (compare to 1.9%)

- Conclusion: "fluctuation" in the lower sensitivity bin adds to the observed discrepancy, but is not the driving contribution.



Residual $B \to hh$ background

The number of residual $B \to hh$ events are very small. E.g. for the highest NN bins:

	CC	CF
B_s signal window	0.08±0.2	0.03±0.01
B^0 signal window	0.72±0.2	0.2±0.05

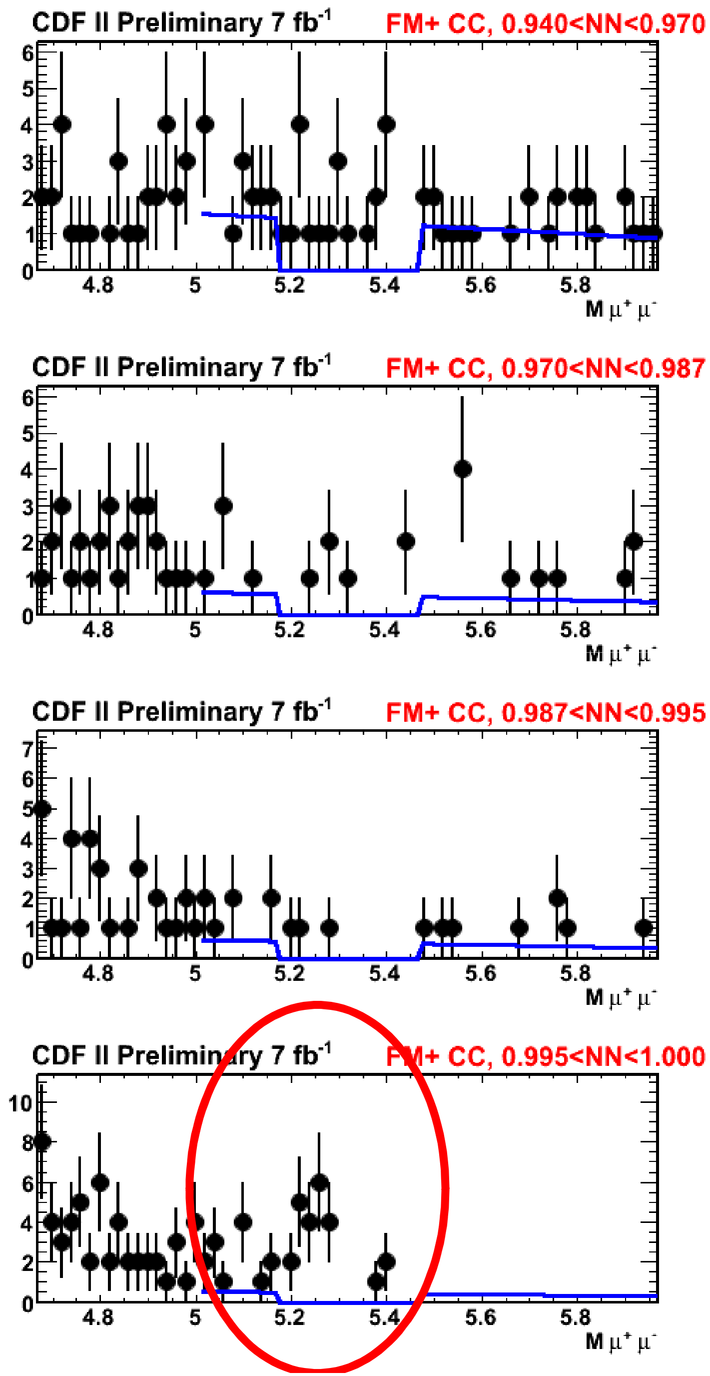
Factor 10 higher contribution in B^0 signal window because $B \to hh$ peaks closer to the B^0 mass

- and we see no excess over the prediction in the B^0 signal window

We carefully checked our predictions in a control region enhanced in $B \to hh$ decays (FM+ sample, at least one "muon" has to fail our muon selection)

	Predicted total events	observed	Prob.(%)
$0.700 < NN < 0.760$	$118.3 \pm (8.6)$	136	11.1
$0.760 < NN < 0.850$	$110.5 \pm (8.3)$	121	22.3
$0.850 < NN < 0.900$	$52.0 \pm (5.4)$	37	96.3
$0.900 < NN < 0.940$	$37.3 \pm (4.5)$	37	53.0
$0.940 < NN < 0.970$	$20.1 \pm (3.3)$	20	52.3
$0.970 < NN < 0.987$	$8.3 \pm (2.0)$	6	77.1
$0.987 < NN < 0.995$	$8.7 \pm (2.0)$	3	97.5
$0.995 < NN < 1.000$	$20.8 \pm (3.5)$	24	30.7

Observation in FM+ sample, highest NN bins



In our highest NN bin we clearly select $B \rightarrow hh$ and can predict it accurately with our background estimate method.

Summary- Cross checks

We have performed cross checks (some shown in the backup slides) to confirm that

✓The results are stable w.r.t. variations in error shape assumptions

- have compared poisson to gaussian statistics for shapes of systematic uncertainties

✓The results are independent of the statistical treatment

- we get the same answers using Bayesian and Likelihood fit

✓The results are not driven by a fluctuation that is observed in the 3rd highest NN bin

- somewhat smaller significance when the 3rd highest NN bin is excluded

✓The excess is not from B→hh

- 0.08 residual events, carefully checked modeling