This is one of interesting rare decays to test new physics such as SUSY:
\[ \text{Br}(B_s \to \mu \mu)_{\text{SM}} \sim 3 \times 10^{-9} \]
\[ \text{Br}(B_s \to \mu \mu)_{\text{SUSY}} \sim \text{Br}(B_s \to \mu \mu)_{\text{SM}} \times (10 \sim 1000) \]
- Within the SM, we will not see any events even with \( 100 \times 10^{12} \) collisions at the Tevatron.
- In the SUSY models (large \( \tan \beta \)), the decay can be enhanced by up to 1,000.

But the SUSY particle masses are expected to be of order of 1000 GeV. But the \( B_s \) mass is ~5 GeV.

How can one possibly test SUSY models using \( B_s \) meson decays? This is a main topic of this lecture.

We focus on a rare decay of \( B_s \) today.

**Why \( B_s \to \mu \mu \)?**

- [1990’s] LEP results on the measurements of couplings indicate SUSY with two Higgs doublets gives a possibility of unification of fundamental forces.
  - This motivates me to work on a particular channel ("trilepton") at the Tevatron.
- [1998] There were two SUSY/Higgs workshops at Fermilab to explore a feasibility and a potential of discovery of Higgs and SUSY at the Tevatron. An importance of large \( \tan \beta \) SUSY scenarios is highlighted.
  - This motivated me to work on large \( \tan \beta \) scenario of SUSY where tau leptons are the key in SUSY discovery.
- [2002] The WMAP measurement of the dark matter content (23%) in the universe strongly indicates a few SUSY scenarios. One of them is a scenario at large \( \tan \beta \) where one can explore at the Tevatron using the \( B_s \to \mu \mu \) decays.
  - This is the beginning of my PPC program.

**My Brief History toward \( B_s \to \mu \mu \)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
</table>
The goal of this lecture is to understand Flavor Changing Neutral Currents (FCNCs) and its power in probing new physics.

But, FCNC...

Recap: “Penguin” Diagrams

Note: those types of “loop diagrams” are very important to search effects beyond the standard model, because any undiscovered particles can contribute in the loop as a virtual state!

Recap: Weak Isospins in the SM

\[ q = +2/3 \quad (u), \quad (c), \quad (t) \quad I_w = +1/2 \]
\[ q = -1/3 \quad (d), \quad (s), \quad (b) \quad I_w = -1/2 \]

Recap: Kobayashi-Maskawa Matrix

KM is a generalization of Cabibbo-GIM for three generations of quarks. The weak interaction quark generations:

\[ \left( \begin{array}{c}
    u \\
    d \\
    s \\
    c \\
    t \\
    b \\
\end{array} \right) \]

They are related to the physical quark states by Kobayashi-Maskawa (KM) matrix:

\[ U_{ud} u_d \quad U_{ub} u_b \quad U_{cd} c_d \quad U_{tb} t_b \quad U_{sd} s_d \quad U_{sb} s_b \]

for example:

Canonical form of \( U_i \) depend only on three generalized Cabibbo angles and one phase factor:

\[ U = \begin{pmatrix}
    c_t & s_t \\
    -s_t & c_t \\
\end{pmatrix} \]

\[ c_t = \cos \theta_t, \quad s_t = \sin \theta_t \]
Recap: Kobayashi-Maskawa Matrix

The full matrix:

$$U = \begin{pmatrix}
\cos \theta_1 & \sin \theta_1 \\
-\sin \theta_1 \cos \delta_1 & \cos \theta_1 \cos \delta_1 - \sin \theta_1 \sin \delta_1 e^{i \phi_1} & \sin \theta_1 \sin \delta_1 e^{i \phi_1} \\
-\sin \theta_1 \sin \delta_1 & \cos \theta_1 \sin \delta_1 \cos \phi_1 + \sin \theta_1 \cos \delta_1 & \cos \theta_1 \sin \delta_1 \sin \phi_1 - \sin \theta_1 \cos \delta_1
\end{pmatrix}$$

Using the experimental values:

$$|U_{ij}| = \begin{pmatrix}
0.9705 \ldots 0.9770 & 0.21 \ldots 0.24 & 0.0 \ldots 0.014 \\
0.21 \ldots 0.24 & 0.971 \ldots 0.973 & 0.036 \ldots 0.070 \\
0.0 \ldots 0.024 & 0.036 \ldots 0.069 & 0.997 \ldots 0.999
\end{pmatrix}$$

Feynman Diagrams for $B_s \rightarrow \mu \mu$

Cont'd

Cont'd

FCNC in $B_s \rightarrow \mu \mu$

$$\text{Br}(B_s \rightarrow \mu \mu) \propto$$

$2b$ SUSY

$2s$ $\text{SM}$

$\frac{1}{3}$ $\frac{2}{3}$ $\frac{2}{3}$ $\frac{2}{3}$

Recap: Fermi's Theory

Amplitude

$$A_i = \frac{\lambda}{f} \int \frac{d^4 \pi}{2 \pi^3} \text{Tr} ( \epsilon_i \cdot \epsilon_f )$$

$$A_i = \frac{\lambda}{f} \int \frac{d^4 \pi}{2 \pi^3} \text{Tr} ( \epsilon_i \cdot \epsilon_f )$$

CKM Matrix in $B_s \rightarrow \mu \mu$

$$V_{tb} \ldots \text{transition between } t \text{ and } b$$

$$V_{ts} \ldots \text{transition between } t \text{ and } s$$

$$\text{CKM matrix}$$
[Ref.] Amplitude of $B_s(d)\rightarrow \mu^+\mu^-$

Recap: Universality

$m_{1/2}$ for gaugino masses

$m_0$ for squarks and sleptons

$\tan^2\theta \approx (\tilde{\chi}_1^\pm, \tilde{\tau}_1) \Rightarrow (m_{1/2}, m_0) \Rightarrow (\tilde{\chi}_1^0, \tilde{\tau}_1)$

Cosmologically Allowed Region

Testing the Same SUSY Model (★)

3 Particle-Physics Experiments
Tevatron

$\sqrt{s} = 1.96 \text{ TeV}$

Proton ($p$) Antiproton ($\bar{p}$)

B$_{(s,d)} \rightarrow \mu^+ \mu^-$ Candidate

Run 198082 Event 8264441:
- $M(\mu\mu) = 5.375 \text{ GeV}$
- $c_t = 236 \text{ m}$
- $p_t(\mu^+) = 4.6 \text{ GeV}$
- $p_t(\mu^-) = 2.4 \text{ GeV}$

Anatomy of $B_s \rightarrow \mu\mu$

$\Gamma = \frac{p_T^{\mu\mu}}{p_T^{\mu\mu} + \sum p_T^i}$

$\Delta R = 1$

Experimentally, ...

$N_{\mu\mu} = N_{\mu\mu} + N_{\bar{\mu}\bar{\mu}} + N_{ef}$

- Identification of $\mu$
  $\mu \rightarrow \mu$
  $\mu \rightarrow \text{ something else}$
  $\Gamma_{\mu}$

-fake rate
  We need to prepare pure samples of $\pi$'s and $K$'s

Samples of $\pi$'s and $K$'s

$D'(cd) \rightarrow K^- \pi^+$

Decay-In-Flight

$\Gamma_{\mu} = \Gamma_{\mu} + \Gamma_{\bar{\mu} \bar{\mu}}$

<table>
<thead>
<tr>
<th>$p_T$</th>
<th>$p_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$2 \text{ GeV}$</td>
<td>$3 \text{ GeV}$</td>
</tr>
</tbody>
</table>
**Impact Parameter**

- Silicon layer 1
- Impact parameter $S < 20 \mu m$
- Impact parameter $D > 20 \mu m$

---

**$B_s(d) \rightarrow \mu^+ \mu^-$ at CDF**

- A powerful indirect search to probe cosmologically consistent SUSY at large $\tan \beta$ e.g.,
  - Amorosit et al., PLB 538 (2002) 121 for mSUGRA


- Goal: $2 \times 10^9$ with 6.9 fb$^{-1}$ and two challenging updated methods:
  1. Event selection by Neural Network (NN)
  2. Improved study of muon ID & fake rate

- Publication plan: PRL in early 2011

---

**1st Round Analysis**


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**9:30 am Central Time, Nov. 18, 2010 (0:30 am KT, Nov. 19, 2010)**

**Report on $B_s \rightarrow \mu \mu$ Analysis**

Salu Uozumi
Kyungpook National University, Korea
Exotic Group Meeting, Nov-16th 2010

For the $B_s \rightarrow \mu \mu$ group

D. Glinzinski$^1$, M. Handon$^2$, W. Hopkins$^3$, T. Kwon$^{4,5}$, D. Kang$^6$, V. Kratovly$^7$, C. J. Lin$^8$, J. Thom$^9$

1 Fermilab National Accelerator Laboratory, 2 University of Wisconsin, Madison, 3 Cornell University, 4 Texas A&M University, 5 Kyungpook National University, Korea, 6 University of California, Santa Barbara, 7 Lawrence Berkeley National Laboratory
Pre-selection: $B_s(B^0)$ Search Samples

- ~100k candidates in $B_s(B^0)$ search sample,
- Huge background events!
- We need a power tool to reject background events

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

Pre-selection: $B_s(B^0)$ Search Samples

Neural Net (NN)

Neural Net (NN)

New Neural Network

Signal Optimization

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 ($\Delta \alpha_{\mu}$)
  - Lower $|p_T(Bs)|$
  - 3D proper decay length significance
  - Larger $|d_0(B)$
  - Smaller $|d_0(B)$ significance
  - Larger $|d_0(B)$ significance
  - Vertex Fitting $\chi^2$
  - Decay length ($L_{\mu}$)
  - 2D pointing angle ($\Delta \alpha_{d0}$)
  - $L_{d_0}$ significance
  - $|d_0(Bs)|$

Multi-variable analysis: Neural Network
- Unbiased optimization based on MC signal and data sidebands
- Discriminating variables:
  - Output (0 ~ 1)
Systematic study has been done to optimize NN event selection. Excellent improvement achieved by using 14 discriminating variables.

Results

Bias Check from NN Event Selection

Mass Bias Check with Sideband region

NO correlation between NN and Mass

[Q] Do you see any difference?

2 pm Central Time, July 15, 2011
(4 am KT, July 16, 2011)

First two-sided limit of the $B_s \rightarrow \mu^+\mu^-$ decay rate

Wine and Cheese Seminar
Fermilab, 7/15/2011
Julia Thom-Levy, Cornell University

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

S. Uozumi, D. Kong, T. Kamon
For the CDF Bsmumu analysis group

July-27th 2011 KISTI seminar

Both in experiments And theories...

Theory

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

- PLB 693(2010) 539
- PRD 76 (2007) 092001
- PRL 94 (2005) 071802
- arXiv:1103.2465v1
How to?

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

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: $b \rightarrow c\mu X \rightarrow \mu^+\mu^-X$
  - Double semileptonic decay: $b \rightarrow 2\mu X$
  - Continuum $\mu^+\mu^-$, $\mu$ + fake, fake+fake
  - Peaking Background in signal region ($B \rightarrow hh$)

Trigger

Data collected using dimuon trigger

- "CC":
  - 2 central muons
  - "CMU", $|##|<0.6,$
  - $p_T>1.5$ GeV
  - $2.7 < M_{\mu\mu} < 6.0$ GeV
  - $P_{T_{\mu}} + P_{T_{\mu>>}} > 4$ GeV
- "CF":
  - one central, one forward muon
  - "CMX", $0.6 < |##| < 1.0$
  - $P_T > 2$ GeV
  - other cuts same as above

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

Improvements over Previous Search

- Using twice the integrated luminosity (7 $\text{fb}^{-1}$)
- Extended acceptance of events in the analysis by $\sim 20\%$
  - 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

"Blind" Search Region

- Search region: $5.169 < M_{\mu\mu} < 5.469$ GeV
  - corresponds to $\pm 6 \times \sigma_{M_{\mu\mu}}$ where $\sigma_{M_{\mu\mu}} = 24$ MeV (2-track invariant mass resolution)
- Sideband regions: additional 0.5 GeV on either side
  - Used to understand background

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 $\pi^+, \pi^0, K^+, K^-$
- fake rates are determined separately using $D^*-tagged \rightarrow K\pi^+$ 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 $\mu$-fake rates. Double fake rate $\sim 0.04\%$

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: $\sim 35\%$

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:

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

Expected limits

$BR(B_s \rightarrow \mu^+\mu^-) < 1.5 \times 10^{-8}$ @ 95%CL
$BR(B^0 \rightarrow \mu^+\mu^-) < 4.6 \times 10^{-9}$ @ 95%CL

Significant improvement in sensitivity over all previous analyses

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

<table>
<thead>
<tr>
<th>Luminosity (fb)</th>
<th>Expected</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>$4.9 \times 10^{-8}$</td>
<td>$5.8 \times 10^{-8}$</td>
</tr>
<tr>
<td>3.7</td>
<td>$3.4 \times 10^{-8}$</td>
<td>$4.4 \times 10^{-8}$</td>
</tr>
<tr>
<td>7</td>
<td>$1.5 \times 10^{-8}$</td>
<td></td>
</tr>
</tbody>
</table>

Br($B_s \rightarrow \mu\mu$): “Prospects in 2002” and Now

Run II Prospect: 95% CL Limits

Opening “the box”
**B_s → μ⁺μ⁻ Search: Opening the Box**

Focus on $B^0$ signal window first

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

Data and background expectation are in good agreement
**B₀ signal window, comparison of observation and background prediction**

3 most sensitive NN bins only

<table>
<thead>
<tr>
<th>CC only</th>
<th>CC</th>
<th>Mass bins [GeV/c²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN Bin</td>
<td>Exp</td>
<td>Obs</td>
</tr>
<tr>
<td>0.976 &lt; NN &lt; 1.017</td>
<td>3.30 ± 0.02</td>
<td>3.31 ± 0.02</td>
</tr>
<tr>
<td>0.976 &lt; NN &lt; 0.999</td>
<td>3.40 ± 0.02</td>
<td>3.40 ± 0.02</td>
</tr>
<tr>
<td>0.999 &lt; NN &lt; 1.000</td>
<td>3.40 ± 0.02</td>
<td>3.40 ± 0.02</td>
</tr>
</tbody>
</table>

Data and background expectation are in good agreement

---

**B₀ → μ⁺μ⁻ Search, Observed Limit**

We set a limit (using CLs method)

\[ BR(B₀ → μ⁺μ⁻) < 6.0 \times 10^{-9} \]

at 95% C.L.

- world's best limit
- consistent with the expected limit

\[ BR(B₀ → μ⁺μ⁻) < 4.6 \times 10^{-9} \]

Compare to the SM BR calculation of

\[ BR(B₀ → μ⁺μ⁻) = (1.0 ± 0.1) \times 10^{-10} \]

---

**Now on Bₕ signal window**

Data in Bₕ signal window

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

<table>
<thead>
<tr>
<th>CC only</th>
<th>CC</th>
<th>Mass bins [GeV/c²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NN Bin</td>
<td>Exp</td>
<td>Obs</td>
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<td>3.40 ± 0.02</td>
<td>3.40 ± 0.02</td>
</tr>
</tbody>
</table>

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

---

**Bₕ → μ⁺μ⁻ Search, Observed Limit**

Using the CLs method, we observe

\[ BR(Bₕ → μ⁺μ⁻) < 4.0 \times 10^{-8} \]

at 95% C.L.

- Compare to the expected limit

\[ BR(Bₕ → μ⁺μ⁻) < 1.5 \times 10^{-8} \]

- 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 Bₕ search window yield?
Using the log-likelihood fit, we set the first two-sided limit of $B_s \to \mu^+\mu^-$ decay:

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

Our central value is:

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

Compare to SM calculation of:

$$BR(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

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

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

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:

$$BR(B^0 \to \mu^+\mu^-) < 6.0(5.0) \times 10^{-8} \text{ at 95\% (90\%) C.L.}$$

Our central value is:

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

Compare to SM calculation of:

$$BR(B_s \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$$

Conclusion

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:

$$BR(B^0 \to \mu^+\mu^-) < 6.0(5.0) \times 10^{-8} \text{ at 95\% (90\%) C.L.}$$

What we will see beyond our horizon?

Stay tuned!
**BS → μμ Physics Motivation**

**SM Expectation**

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

JHEP 1009 (2010)106

**Br enhancement By New Physics**

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

Excluded by

- \[ Br(B_s \to \mu\mu) = 2 \times 10^{-8} \]
- \[ 3 \times 10^{-8} \]
- \[ 4.7 \times 10^{-8} \]

**Probing New Physics**

- “Smoking gun” of some Flavor Violating NP models:
  - ratio \( Br(B \to \mu\mu\gamma) / Br(B \to \mu\mu\pi^-) \) highly informative about whether NP violates flavor significantly or not
  - clear correlation between CP violating mixing phase from \( B_s \to J/\psi \phi \) and \( Br(B \to \mu\mu\pi^-) \)

- Important complementarity with direct searches at Tevatron and LHC
  - Indirect searches can access even higher mass scales than LHC COM energies

**New bounds on \( Br(B_s \to \mu\mu\pi^-) \) and \( Br(B \to \mu\mu\pi^-) \) are of crucial importance, and are a top priority at the Tevatron and LHC.**

**Pre-selection: B⁺ normalization sample**

- \( B^+ \to J/\psi K \to \mu^+\mu^- K^+ \)
  - \( \sim 30k \) candidates.

In addition to baseline cuts, \( B^+ \) sample passes

- \( J/\psi \) mass constraint for dimuons
- \( K \) quality cuts, and \( J/\psi \) and \( K \) constrained to common vertex

**Data in Bₛ signal window**

**BS → μ⁺μ⁻**

Rare decay \( B^0_s \to \mu^+\mu^- : \) FCNCs, forbidden at tree level

**SM Expectation**

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

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**NP Expectation**

**Br enhancement**

**Strong Probe to New Physics**

**Maximal Enhancements of \( S_{mix} \), \( Br(B \to \mu\mu\pi^-) \) and \( K^- \to \pi^+\nu\bar{\nu} \)**

(without taking correlation between them)

<table>
<thead>
<tr>
<th>Model</th>
<th>Upper Bound on ( S_{mix} )</th>
<th>Enhancement of ( Br(B_\to \mu\mu\pi^-) )</th>
<th>Enhancement of ( Br(K^- \to \pi^+\nu\bar{\nu}) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMFV</td>
<td>0.04</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>MFV</td>
<td>0.04</td>
<td>1000%</td>
<td>30%</td>
</tr>
<tr>
<td>LHT</td>
<td>0.30</td>
<td>30%</td>
<td>150%</td>
</tr>
<tr>
<td>RS</td>
<td>0.75</td>
<td>10%</td>
<td>60%</td>
</tr>
<tr>
<td>4G</td>
<td>0.80</td>
<td>400%</td>
<td>300%</td>
</tr>
<tr>
<td>AC</td>
<td>0.75</td>
<td>1000%</td>
<td>2%</td>
</tr>
<tr>
<td>RVV</td>
<td>0.50</td>
<td>1000%</td>
<td>10%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Large B̄b Currents</th>
<th>RS = RS with custodial protections</th>
<th>AC = Agashe, Carone</th>
<th>B̄b→N̄b2</th>
<th>SM_{sppns}</th>
<th>V_{tb}^{-1}</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.94</td>
<td>0.87</td>
<td>0.87</td>
<td>0.87</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>ε_{b}</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
</tr>
</tbody>
</table>

**Plenary talk A.Buras, Beauty 2011:**

**Probing New Physics**

**Important complementarity with direct searches at Tevatron and LHC**

**Indirect searches can access even higher mass scales than LHC COM energies**
**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:
  \[ 2 \ln(Q) = \frac{L(x + b) \mid \text{data}}{L(b) \mid \text{data}} \]

- In the denominator, the “signal” is fixed to zero (i.e., we assume background only), and in the numerator it floats.

- \( L(h \mid x) \) is the product of Poisson probabilities over all NN and mass bins.

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

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

---

**P value for background-only hypothesis**

Observed p-value: 0.27%.

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

---

**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 \( B \to hh \) 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. It needs a different set of \( K/\pi \) fake rates since the muon ID requirements are different than used in the signal sample. Same method as before is used.

---

**Result of background checks in control samples**

<table>
<thead>
<tr>
<th>Control Sample</th>
<th>Prediction</th>
<th>Nobs</th>
<th>Prob(N ≥ Nobs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS-</td>
<td>2140.0±53.9</td>
<td>1999</td>
<td>98%</td>
</tr>
<tr>
<td>SS+</td>
<td>19.7±3.4</td>
<td>25</td>
<td>19%</td>
</tr>
<tr>
<td>SS-</td>
<td>46.8±5.3</td>
<td>53</td>
<td>25%</td>
</tr>
<tr>
<td>FM+</td>
<td>567.8±25.4</td>
<td>593</td>
<td>24%</td>
</tr>
<tr>
<td>Sum</td>
<td>2774.3±59.9</td>
<td>2670</td>
<td>91%</td>
</tr>
</tbody>
</table>

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

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

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.

Does the fluctuation in this bin drive the result?
Check how the answer changes if we only look at the two highest NN bins.

Residual $B \rightarrow hh$ background

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

$$\begin{array}{c|c|c}
\text{CC} & 0.08\pm0.2 & 0.03\pm0.1 \\
\text{CF} & 0.72\pm0.2 & 0.2\pm0.05 \\
\end{array}$$

Factor 10 higher contribution in $B^0$ signal window because $B \rightarrow hh$ 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 $B \rightarrow hh$ decays (FM+ sample, at least one "muon" has to fail our muon selection)

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 $B \rightarrow hh$
  - 0.08 residual events, carefully checked modeling