Rare $B$ Decays for BSM at Tevatron and LHC

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$B_d/B_s \rightarrow \mu^+\mu^-$

$b \rightarrow s\mu^+\mu^-$

NP?
$B_{s(d)} \to \mu^+\mu^-$ for New Physics

- FCNC with EW loop diagram -> Highly suppressed in SM
  - $BR(B_s^0 \to \mu^+\mu^-) = (3.2 \pm 0.2) \times 10^{-9}$
  - $BR(B_d^0 \to \mu^+\mu^-) = (1.0 \pm 0.1) \times 10^{-10}$
  - Note: SM prediction could need additional scaling by -9%
- Experimentally clean & simple di-muon signal
- Sensitive for several NP contributions:
  - MSSM: $BR \sim \tan^6\beta$
  - 2HDM: $BR \sim \tan^4\beta$ with $H^+$
  - Br. Fraction could even be reduced than SM by unthought NP effects

![Diagram of $B_{s(d)} \to \mu^+\mu^-$ process]
\( \mathcal{B}_{s(d)} \rightarrow \mu^+\mu^- \) Method : Relative normalization counting

\[
\mathcal{BR}(B_s \rightarrow \mu^+\mu^-) = \frac{N_{B_s}}{N_{B_s}} \times \frac{\varepsilon_{\text{trig}}}{\varepsilon_{B_s}^{\text{trig}}} = \frac{\varepsilon_{\text{rec}}}{\varepsilon_{B_s}^{\text{rec}}} \frac{\alpha_{B^+}}{\alpha_{B_s}} \frac{1}{\varepsilon_{B_s}^{\text{NN}}} \cdot \mathcal{BR}(B^+ \rightarrow J/\psi K^+ \rightarrow \mu^+\mu^- K^+)
\]

From Data, From MC, Normalization mode, from PDG

- Measure the rate of \( B_{s(d)} \rightarrow \mu^+\mu^- \) decays relative to norm. mode \( B^+ \rightarrow J/\psi K^+ \)
- LHCb uses additional normalization modes \( B_s \rightarrow J/\psi \phi, B^0 \rightarrow K^+\pi^- \)
- Apply same sample pre-selection criteria
- Further purification of \( B_{s(d)} \rightarrow \mu^+\mu^- \) sample is done by cut-based / Neural Network (NN) / Boosted Decision Tree (BDT) / event selection

• Count events in signal regions
  – Signal region defined according to mass resolution
  – Note : \( \Delta m(B_s-B_d) = 86.8 \text{ MeV} \)
• BG estimation done by sideband events

<table>
<thead>
<tr>
<th>Mass resolutions [MeV]</th>
</tr>
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<tbody>
<tr>
<td>D0</td>
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<td>-------</td>
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<tr>
<td>120</td>
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</tbody>
</table>

MC simulation of \( B_s \) and \( B_d \rightarrow \mu^+\mu^- \) for CDF case
$B_{s(d)} \rightarrow \mu^+\mu^-$ Backgrounds

- **Dominant Backgrounds**
  - Sequential semi-leptonic decay: $b \rightarrow c\mu^-X \rightarrow \mu^+\mu^-X$
  - Double semileptonic decay: $bb \rightarrow \mu^+\mu^-X$
  - Continuum $\mu^+\mu^-$, $\mu$ + fake, fake+fake
  - Peaking Background in signal region ($B \rightarrow hh$)
Several kinematic parameters used to purify $B_{s(d)} \rightarrow \mu\mu$ signal

- $P_T(B)$, $P_T(\mu)$
- 2D/3D proper decay lengths and those significance
- Isolation
- 2D/3D Pointing angles ($\Delta \alpha_{3d}$)
- Impact parameter of $B_s(0)$ / muons and those significance
- Vertex Fitting $\chi^2$

Most of analyses use multi-variable discrimination parameter (BDT or NN) for S/B discrimination

$$I = \frac{p_T^{\mu\mu}}{p_T^{\mu\mu} + \sum_i p_T^{\mu_i}}$$

$R = 1$

Impact parameter $d_0, L_{xy}, L_{3d}, \lambda$
$M_{\mu\mu}$ for $B_d \rightarrow \mu^+\mu^-$ @CDF-II 9.7 fb$^{-1}$

- Events are binned according to NeuroBayes NN discriminant output
- Count events in each bin.

- Br. upper limit

\[ Br(B_d \rightarrow \mu^+\mu^-) < 4.6 \ (3.8) \times 10^{-9} \text{ at } 95\% \ (90\%) \text{ C.L.} \]

SM : (0.10 ± 0.01)×10$^{-9}$

- Observed events are fairly consistent with background.

  -> Works as an important check on BG estimation also for $B_s \rightarrow \mu^+\mu$ case
$B_s \to \mu^+\mu^-$ Double-sided Br. Limit @ CDF-II 9.7 fb$^{-1}$

Double-sided limit:
$Br(B_s \to \mu^+\mu^-) = 13^{+9}_{-7} \times 10^{-9}$

Single-sided upper limit (95% CL):
$Br(B_s \to \mu^+\mu^-) < 27 \times 10^{-9}$

$p$-values assuming
$B_s$ background only: 0.94%
$B_s$ SM+background: 7.1%

$\rightarrow \sim 2\sigma$ away from SM ($3.2 \pm 0.2 \times 10^{-9}$)
ATLAS $B_{s(d)} \rightarrow \mu^+ \mu^-$ Result (PLB 713 (2012), pp. 387-407)

- 2.4 fb$^{-1}$ @ 7 TeV pp collision data
- Utilize BDT analysis with 14 variables
- Events are binned in 3 rapidity regions
- Signal counting is done in each bin

$95\% CL : Br(B_{s(d)} \rightarrow \mu^+ \mu^-) < 22 \times 10^{-9}$

Median expected (95% CL): $Br(B_{s(d)} \rightarrow \mu^+ \mu^-) < 25 \times 10^{-9}$

SM : $(3.2 \pm 0.2) \times 10^{-9}$
- 5 fb⁻¹ @ 7 TeV, cut-based analysis optimized for barrel and endcap regions separately
- $B^0$ and $B_s$ are separated thanks to good mass resolution

<table>
<thead>
<tr>
<th></th>
<th>$B_s \to \mu^+\mu^-$ barrel</th>
<th>$B_s \to \mu^+\mu^-$ endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N^{\exp}_{signal}$</td>
<td>2.70± 0.41</td>
<td>1.23± 0.18</td>
</tr>
<tr>
<td>$N^{\exp}_{bg}$</td>
<td>0.77± 0.50</td>
<td>1.22± 0.53</td>
</tr>
<tr>
<td>$N^{obs}$</td>
<td>2</td>
<td>4</td>
</tr>
</tbody>
</table>

95% CL: $Br(B^0 \to \mu^+\mu^-) < 1.8 \times 10^{-9}$
95% CL: $Br(B_s \to \mu^+\mu^-) < 7.7 \times 10^{-9}$

Median expected (95% CL):

- $Br(B^0 \to \mu^+\mu^-) < 1.6 \times 10^{-9}$
- $Br(B_s \to \mu^+\mu^-) < 8.4 \times 10^{-9}$

SM ($B_d \to \mu\mu$): $(0.10 \pm 0.01) \times 10^{-9}$
($B_s \to \mu\mu$): $(3.2 \pm 0.2) \times 10^{-9}$
LHCb $B_{s(d)} \rightarrow \mu^+\mu^-$ (PRL 108, 231801 (2012))

- Data is from 1 fb$^{-1}$ in 2011 runs
- RICH detector available for fake Kaon ID
- BDT analysis separated into 2 stages:
  - 1$^{\text{st}}$ stage ... based on 6 variables
  - 2$^{\text{nd}}$ stage ... Event classification using BDT output with 9 variable
- Count number of events in each bin of BDT output value
LHCb $B_{s(d)} \rightarrow \mu^+ \mu^-$ Result

95% CL: $Br(B^0 \rightarrow \mu^+ \mu^-) < 1.03 \times 10^{-9}$
95% CL: $Br(B_s \rightarrow \mu^+ \mu^-) < 4.5 \times 10^{-9}$

Median expected (95% CL):
$Br(B_s \rightarrow \mu^+ \mu^-) < 7.2 \times 10^{-9}$
$Br(B^0 \rightarrow \mu^+ \mu^-) < 1.13 \times 10^{-9}$

Unbinned likelihood fit to $M_{\mu\mu}$
Projection with 8 BDT bins give
$Br(B_s \rightarrow \mu^+ \mu^-) = 0.8^{+1.8}_{-1.3} \times 10^{-9}$

SM ($B_d \rightarrow \mu\mu$): $(0.10 \pm 0.01) \times 10^{-9}$
($B_s \rightarrow \mu\mu$): $(3.2 \pm 0.2) \times 10^{-9}$
$B_s \rightarrow \mu^+\mu^-$ LHC combined Result

- Three LHC results are combined as of June-2012 (CMS PAS BPH-12-009)

LHC combined upper limit at 95% CL:

$\text{Br}(B^0 \rightarrow \mu^+\mu^-) < 0.81 \times 10^{-9}$

$\text{Br}(B_s \rightarrow \mu^+\mu^-) < 4.2 \times 10^{-9}$

SM ($B_d \rightarrow \mu\mu$) : $(0.10 \pm 0.01) \times 10^{-9}$

($B_s \rightarrow \mu\mu$) : $(3.2 \pm 0.2) \times 10^{-9}$

<table>
<thead>
<tr>
<th>Mode</th>
<th>Limit</th>
<th>ATLAS</th>
<th>CMS</th>
<th>LHCb 2010</th>
<th>LHCb 2011</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0_s \rightarrow \mu^+\mu^-$ ($10^{-9}$)</td>
<td>Bkg Only</td>
<td>23</td>
<td>(3.6)</td>
<td>65</td>
<td>3.4</td>
<td>2.3</td>
</tr>
<tr>
<td></td>
<td>Bkg+SM</td>
<td>22</td>
<td>8.4</td>
<td>56</td>
<td>4.5</td>
<td>4.2</td>
</tr>
<tr>
<td></td>
<td>Obs</td>
<td>22</td>
<td>7.7 (7.2)</td>
<td>56</td>
<td>4.5</td>
<td>4.2</td>
</tr>
</tbody>
</table>
$B_s \rightarrow \mu^+\mu^-$ Results summary

- Measured upper limits are very close to SM prediction value
- Clear “observation” expected soon followed by “measurement”.
- Precise comparison with SM will be strong tool for BSM search!
$b \to s\mu^+\mu^-$ for New Physics

- Strongly suppressed in SM due to 2\textsuperscript{nd} order weak interaction
- New physics in a loop can change event shapes from SM

- Many channels with different spectator quark flavors available to explore $b \to s\mu^+\mu^-$ decays for BSM
- CDF, LHCb and B factories have measurements of several parameters in $b \to s\mu^+\mu^-$ decays
  - differential Br. Fraction ($d\text{Br}/dq^2$)
  - Forward-backward asymmetry ($A_{FB}$)
  - Angular parameters ($F_L$, $A_T^{(2)}$, $A_{im}$)
  - Isospin asymmetry ($A_I$)

• Another exciting stage to search BSM!
$b \rightarrow s \mu^+ \mu^-$ decays @ CDF 9.6 fb$^{-1}$
$b \rightarrow s \mu^+ \mu^-$ diff. $\text{Br}$ fraction @ CDF

- Measurement of $\text{Br}$. fraction as a function of $q^2 = M_{\mu\mu}^2$
- SM prediction well matches to data

J/$\psi$, $\psi'$ veto
$b \to s \mu^+ \mu^-$ diff. Br fraction @LHCb

- Beautiful consistency with SM (LHCb-CONF-2012-008/003)
  (except slight deficit in $B^0 \to K^0 \mu\mu$ low $q^2$ region,
  correlating with discrepancy on low-$q^2$ isospin asymmetry)
$b \to s \mu^+ \mu^-$ angular analysis

- There are various event-shape parameters in $b \to s \mu^+ \mu^-$ angular analysis to access physics beyond the SM ([arXiv:1108.0695](arXiv:1108.0695)).

**Forward-backward asymmetry $A_{FB}$**

\[
A_{FB}(q^2) = \frac{\Gamma(q^2, \cos \theta_\mu > 0) - \Gamma(q^2, \cos \theta_\mu < 0)}{\Gamma(q^2, \cos \theta_\mu > 0) + \Gamma(q^2, \cos \theta_\mu < 0)}
\]

**$K^*$ polarization parameter $F_L$**

\[
d\sigma/d\theta_K \propto \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L) (1 - \cos^2 \theta_K)
\]

**Transverse polarization asymmetry $A_T^{(2)}$**

**T-odd CP asymmetry $A_{im}$**

\[
d\sigma/d\phi \propto \frac{1}{2\pi} \left[ 1 + \frac{1}{2} (1 - F_L) A_T^{(2)} \cos 2\phi + A_{im} \sin 2\phi \right]
\]

**Isospin asymmetry $A_I$**

\[
A_I = \frac{B(B^0 \to K^{(*)0} \mu^+ \mu^-) - \frac{\tau_0}{\tau^+} B(B^{\pm} \to K^{(*)\pm} \mu^+ \mu^-)}{B(B^0 \to K^{(*)0} \mu^+ \mu^-) + \frac{\tau_0}{\tau^+} B(B^{\pm} \to K^{(*)\pm} \mu^+ \mu^-)}
\]
**b → sμ⁺μ⁻ A_{FB} results**

- CDF (9.6 fb⁻¹), LHCb (1 fb⁻¹) and B factories have B^0→K(∗)μμ A_{FB} results
- Every result is consistent with SM prediction.

- Also interesting measurement is crossing point at A_{FB}=0, since theory predicts the crossing point accurately.
- LHCb performed world’s first measurement:
  \[ q_0^2 = 4.9^{+1.1}_{-1.3} \text{GeV}^2 \]
  Again consistent with SM prediction (arXiv:1105.0376).
\[ b \rightarrow s\mu^+\mu^- \] other angular analysis result

- CDF full 9.6 fb\(^{-1}\) analysis
- No significant deviation from SM found in every parameters…
$b \rightarrow s\mu^+\mu^-$ other angular analysis result

$LHCb$ Preliminary

$S_3 \propto A_T^{(2)}(1-F_L)$: the asymmetry in $K^{*0}$ transverse polarization

- LHCb 1 fb$^{-1}$ analysis
- Again, No significant deviation from SM.
\[ b \to s\mu^+\mu^- \text{ Isospin asymmetry} \]

SM expectation is zero for any \( q^2 \) value.

- LHCb \( B \to K \mu\mu \) channel shows 4.4\( \sigma \) deviation from zero.
  (B factories have also shown asymmetry)
- CDF result is consistent with SM (\( =0 \)).

LHCb-PAPER-2012-011
Summary

• Heavy flavor sector has been taken an important rule for various SM measurements for a long time.

• Also to explore BSM, Rare B decays are very interesting stage to see possible NP contribution through SM-suppressed loop diagrams.

• Now Tevatron passes the torch to LHC experiments.

• Rapidly growing LHC data is remarkably improving several B rare decay measurements.
  - $b \rightarrow d \mu \mu$ decay : LHCb already has $5\sigma$ measurement of Br. Fraction (LHCb-CONF-2012-006)
  - Measurement of CP asymmetry in radiative B decays $b \rightarrow s \gamma$ : LHCb reported current world”s best result

• As well as discovery of the Higgs-like boson, heavy flavor sector is also entering to very exciting era. **Stay tuned !!**
Backups
$B_s \rightarrow \mu^+\mu$ Results summary
D0 $B_s^{(0)} \rightarrow \mu^+\mu^-$ Result

- Use 6.1 fb$^{-1}$ in D0 runII data
- Final event selection done by Bayesian Neural Network
- Mass resolution $120 \text{ MeV} > \Delta m(B_s-B^0)$
- \( \rightarrow \) measure admixture of $B_s/B^0$ signal

Red : SM x 100

95%CL : $\text{Br}(B_s^{(0)} \rightarrow \mu^+\mu^-) < 51 \times 10^{-9}$

Median expected (95% CL):
$\text{Br}(B_s^{(0)} \rightarrow \mu^+\mu^-) < 40 \times 10^{-9}$

Update with full 10 fb$^{-1}$ will come soon!
$B_{s/d} \rightarrow \mu^+\mu^-$ Method: Relative normalization counting

- Same method with previous 6.9 fb$^{-1}$ results last summer (PRL 107, 191801)
- This analysis updates results with whole 9.7 fb$^{-1}$ of CDF Run-II data

- Measure the rate of $B_{s/d} \rightarrow \mu^+\mu^-$ decays relative to $B^+ \rightarrow J/\psi K^+$ control sample
  1. Apply same event pre-selection to both sample
  2. $B_s \rightarrow \mu^+\mu^-$ sample is highly purified by Neural Network (NN) event selection
  3. NN takes 14 kinematic variables and output value ranging 0 (BG like)~1 (signal like)
  4. $B_s \rightarrow \mu^+\mu^-$ candidates are categorized into 8 different NN value bins for counting
  5. BG shape is determined from di-muon mass sideband fitting

Original $B_s \rightarrow \mu^+\mu^-$ and $B^+ \rightarrow J/\psi K^+$ samples

Pre-selected $B^+ \rightarrow J/\psi K^+$

Pre-selected $B_s \rightarrow \mu^+\mu^-$ sample

Final $B_s \rightarrow \mu^+\mu^-$ sample

$\begin{align*}
\text{NN out} &= 0.700-0.760 \\
\text{NN out} &= 0.987-0.995 \\
\text{NN out} &= 0.995-1.000
\end{align*}$

Typical BG fitting

For one NN output bin
Central-Central muons

Central-Forward muons

$M_{\mu\mu}$ for $B_s \rightarrow \mu^+\mu^-$ with CDF-II 9.7 fb$^{-1}$

- Best fit estimates a $2\sigma$ excess of signal over background yielding

$$B_{T}(B_s \rightarrow \mu^+\mu^-) = 13^{+9}_{-7} \times 10^{-9}$$
CDF $B_s \rightarrow \mu^+\mu^-$ Double-sided Br. Limit with 9.7fb$^{-1}$

$$Br(B_s \rightarrow \mu^+\mu^-) = 13^{+9}_{-7} \times 10^{-9}$$

90% CL: $2.2 \times 10^{-9} < Br(B_s \rightarrow \mu^+\mu^-) < 30 \times 10^{-9}$

95% CL: $0.8 \times 10^{-9} < Br(B_s \rightarrow \mu^+\mu^-) < 34 \times 10^{-9}$

$p$-values assuming
$B_s$ background only: 0.94%
$B_s$ SM+background: 7.1% ... ~2\sigma away from SM

Single-sided upper limit: $Br(B_s \rightarrow \mu^+\mu^-) < 27 \times 10^{-9}$ at 95% C.L.
\( B_s \rightarrow \mu^+\mu^- \) Prospects at LHC

- LHC is entering to era of Br. measurement order of \( 10^{-9} \)!
- What we will see?
  - Br. Enhancement in order of \( 10^{-9} \) ?
  - Consistent Br. with SM?
  - Decrease of Br. by NP?

Exciting stage to search NP in heavy flavor sector!
$B_s \rightarrow \mu^+\mu^- : an \, MSSM \, case$

SM Expectation

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

Possible large Br enhancement by $\tan^6 \beta$

$Br(B_s \rightarrow \mu\mu) =
\begin{align*}
&2 \times 10^{-8} \\
&3 \times 10^{-8} \\
&4.7 \times 10^{-8}
\end{align*}$

Excluded by

- Rare B decay $b \rightarrow s\gamma$
- No CDM candidate
- Muon magnetic moment

mSUGRA/CMSSM, $\tan \beta = 50$, $A_0 = 0$, $\mu > 0$
Reconstructed $b \rightarrow s \mu^+ \mu^-$ events and Br. fractions

CDF II 6.7 fb$^{-1}$, Phys. Rev. Lett 107, 201802 (2011)

Br($\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$)
$= [1.73 \pm 0.42 \text{ (stat)} \pm 0.55 \text{ (syst)}] \times 10^{-6}$

Br($B_s^0 \rightarrow \phi \mu^+ \mu^-$) $= [1.47 \pm 0.24 \pm 0.46] \times 10^{-6}$

Br($B^+ \rightarrow K^+ \mu^+ \mu^-$) $= [0.46 \pm 0.04 \pm 0.02] \times 10^{-6}$

Br($B^0 \rightarrow K^0 \mu^+ \mu^-$) $= [1.02 \pm 0.10 \pm 0.06] \times 10^{-6}$

Br($B^0 \rightarrow K^0 \mu^+ \mu^-$) $= [0.32 \pm 0.10 \pm 0.02] \times 10^{-6}$

Br($B^+ \rightarrow K^*+ \mu^+ \mu^-$) $= [0.95 \pm 0.32 \pm 0.08] \times 10^{-6}$

World’s first observation !!

Other $B^0/\rightarrow K \mu^+ \mu^-$ channels have comparably large statistics with B factories & LHC.
Summary & Conclusions

• B rare decays are excellent stage to search for New Physics effect.
• Using full 9.7 fb\(^{-1}\) of CDF Run-II data sample, we measured:

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching Ratio</th>
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<tbody>
<tr>
<td>(B_s \rightarrow \mu^+\mu^-)</td>
<td>(1.3^{+0.9}_{-0.7} \times 10^{-8})</td>
</tr>
<tr>
<td>90% CL</td>
<td>(2.2 \times 10^{-9})</td>
</tr>
<tr>
<td>95% CL</td>
<td>(0.8 \times 10^{-9})</td>
</tr>
</tbody>
</table>

• Latest CDF result stays \(\sim 2\sigma\) from SM \(Br(B_s \rightarrow \mu^+\mu^-)_{SM} = (3.2 \pm 0.2) \times 10^{-9}\)

• Various \(b \rightarrow s\mu^+\mu^-\) decay channels are observed with 6.8 fb\(^{-1}\) of data:

\[
Br(\Lambda_b^0 \rightarrow \Lambda \mu^+\mu^-) = [1.73 \pm 0.42\text{(stat)} \pm 0.55\text{(syst)}] \times 10^{-6} \text{... world’s first!!}
\]

\[
Br(B_s^0 \rightarrow \phi \mu^+\mu^-) = [1.47 \pm 0.24 \pm 0.46] \times 10^{-6}
\]

\[
Br(B^+ \rightarrow K^+ \mu^+\mu^-) = [0.46 \pm 0.04 \pm 0.02] \times 10^{-6}
\]

\[
Br(B^0 \rightarrow K^*0 \mu^+\mu^-) = [1.02 \pm 0.10 \pm 0.06] \times 10^{-6}
\]

\[
Br(B^0 \rightarrow K^0 \mu^+\mu^-) = [0.32 \pm 0.10 \pm 0.02] \times 10^{-6}
\]

\[
Br(B^+ \rightarrow K^{**} \mu^+\mu^-) = [0.95 \pm 0.32 \pm 0.08] \times 10^{-6}
\]

• \(A_{FB}\) result with full CDF Run-II data analysis will come out soon!
$B^+ \rightarrow J/\psi K^+$ Control sample

- Roughly selected with pre-selection cuts same with ones for $B_s \rightarrow \mu^+\mu^-$ pre-selection

- Control sample used for Br. normalization and cross checks for background modeling.

Opposite-sign $\mu\mu$, $B$ decay length < 0 (OS-)

Same-sign $\mu\mu$, $B$ decay length > 0 (SS+)

Same-sign $\mu\mu$, $B$ decay length < 0 (SS-)

One $\mu$ is tagged as fake, $B$ decay length > 0 (FM+)

<table>
<thead>
<tr>
<th>Prediction</th>
<th>Nobs</th>
<th>Prob(N$\geq$Nobs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2665.2$\pm$61.4</td>
<td>2552</td>
<td>90%</td>
</tr>
<tr>
<td>26.4$\pm$4.0</td>
<td>36</td>
<td>9%</td>
</tr>
<tr>
<td>61.8$\pm$6.1</td>
<td>69</td>
<td>25%</td>
</tr>
<tr>
<td>727.9$\pm$28.9</td>
<td>760</td>
<td>21%</td>
</tr>
<tr>
<td><strong>3481.3$\pm$68.3</strong></td>
<td><strong>3417</strong></td>
<td><strong>76%</strong></td>
</tr>
</tbody>
</table>

Prediction from $B^+ \rightarrow J/\psi K^+$ sample

Observed in $B_s \rightarrow \mu\mu$ BG control sample
Further BG discrimination by Neural Network

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

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

Discriminating variables

Input nodes

Output (0 ~ 1)

NeuroBayes with 14 discriminating parameters strongly distinguish signal and BG.
BG shape modeling from $M_{\mu\mu}$ Sideband

- Events are separated in each NN output bins
- In each bin, continuum BG is estimated from SB polynomial fitting
- $< 5$ GeV is rejected from the fit to avoid $B \rightarrow \mu^+\mu^- +$ neutrinos events)
$M_{\mu\mu}$ distributions for $B_d / B_s$ signal region

Completely consistent with BG For $B_d \rightarrow \mu^+\mu^-$ channel.

On $B_s \rightarrow \mu^+\mu^-$ channel, No evident excess observed, while best fit result is sizeable (SMx4.1) in highest NN bin.
$B_s \rightarrow \mu^+\mu^-$ Branching fraction limit

$$\Delta \chi^2$$

CDF II Preliminary 9.7 fb$^{-1}$

**SM prediction**

- **90% Bound**
- **68% Bound**

**Pseudoexperiments**

CDF II Preliminary 9.7 fb$^{-1}$

- **Bkg Only MC**
- **Data**

- **$B_s \rightarrow \mu^+\mu^-$**
- **p-value=0.94%**

$$Br(B_s \rightarrow \mu^+\mu^-) = 1.3^{+0.9}_{-0.7} \times 10^{-8}$$

- **90%CL : 2.2 \times 10^{-9} < Br(B_s \rightarrow \mu^+\mu^-) < 3.0 \times 10^{-8}**

- **95%CL : 0.8 \times 10^{-9} < Br(B_s \rightarrow \mu^+\mu^-) < 3.4 \times 10^{-8}**

**p-values assuming**

- **$B_s$ background only : 0.94%**
- **$B_s$ SM+background : 7.1%**

Again with SM prediction

$$Br : (3.2 \pm 0.2) \times 10^{-9}$$
$b \rightarrow s\mu^+\mu^-$ Branching fraction measurement
- Again Relative normalization counting -

- Starts with di-muon trigger datasets with 6.8 fb$^{-1}$

- Control sample events are pre-selected by kinematical cuts

- Signal candidates are selected by Neural Network in addition to pre-selection for further purification

<table>
<thead>
<tr>
<th>Signal mode</th>
<th>Control sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \rightarrow K^{*0}\mu\mu$</td>
<td>$B^0 \rightarrow J/\psi K^{*0}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+\mu\mu$</td>
<td>$B^+ \rightarrow J/\psi K^+$</td>
</tr>
<tr>
<td>$B_s \rightarrow \phi\mu\mu$</td>
<td>$B_s \rightarrow J/\psi \phi$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*+}\mu\mu$</td>
<td>$B^+ \rightarrow J/\psi K^{*+}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K_s\mu\mu$</td>
<td>$B^0 \rightarrow J/\psi K_s$</td>
</tr>
<tr>
<td>$\Lambda_b \rightarrow \Lambda\mu\mu$</td>
<td>$\Lambda_b \rightarrow J/\psi \Lambda$</td>
</tr>
</tbody>
</table>

- Ratio of Br. Fraction of signal and control sample is determined by

\[
\mathcal{B}(B \rightarrow h\mu^+\mu^-) = \frac{N_{h\mu^+\mu^-}^{\text{NN}}}{N_{h\mu^+\mu^-}^{\text{pre}}} \epsilon_{h\mu^+\mu^-}^{\text{pre}} \epsilon_{J/\psi h}^{\text{pre}} \frac{1}{\epsilon_{h\mu^+\mu^-}^{\text{NN}} \epsilon_{J/\psi h}^{\text{NN}}} \times \mathcal{B}(J/\Psi \rightarrow \mu^+\mu^-),
\]

From PDG

Control sample yield (only with pre-selection) Efficiencies ratio

Pre-selection

From PDG
Reconstructed $b \rightarrow s \mu^+ \mu^-$ events and Br. fractions

$$Br(\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-) = [1.73 \pm 0.42 \, \text{(stat)} \pm 0.55 \, \text{(syst)}] \times 10^{-6}$$

$$Br(B_s^0 \rightarrow \phi \mu^+ \mu^-) = [1.47 \pm 0.24 \pm 0.46] \times 10^{-6}$$

$$Br(B^+ \rightarrow K^+ \mu^+ \mu^-) = [0.46 \pm 0.04 \pm 0.02] \times 10^{-6}$$

$$Br(B^0 \rightarrow K^0 \mu^+ \mu^-) = [1.02 \pm 0.10 \pm 0.06] \times 10^{-6}$$

$$Br(B^0 \rightarrow K^*0 \mu^+ \mu^-) = [0.32 \pm 0.10 \pm 0.02] \times 10^{-6}$$

$$Br(B^+ \rightarrow K^*+ \mu^+ \mu^-) = [0.95 \pm 0.32 \pm 0.08] \times 10^{-6}$$

World’s first observation!!

Other $B^{0/+} \rightarrow K \mu^+ \mu^-$ channels have comparably large statistics with B factories.
Event-shape ($A_{FB}$) analysis for $b \rightarrow s \mu^+\mu^-$ decay

- There are various event-shape parameters to access physics beyond the SM (arXiv:1108.0695).
- Most interesting parameter is FB asymmetry as a function of $q^2=M_{\mu\mu}^2$ compared with muon polar angle in $B$ rest frame:

$$A_{FB}(q^2) = \frac{\Gamma(q^2, \cos\theta_\mu > 0) - \Gamma(q^2, \cos\theta_\mu < 0)}{\Gamma(q^2, \cos\theta_\mu > 0) + \Gamma(q^2, \cos\theta_\mu < 0)}$$

$A_{FB} > 0$ even at low $q^2$

CDF: comparable resolution as Belle

$N(K^{*}\Pi) \sim 250$ (Belle)  
$N(K^{*}\mu\mu) \sim 100$ (CDF)

Now we have 6.8 fb$^{-1}$ from CDF Run II!!
$A_{FB}$ analysis with 6.8 fb$^{-1}$

$B \to K^* \mu^+ \mu^-$
(simultaneous fit of $K^0$ and $K^+$ channels)

$B^+ \to K^+ \mu^+ \mu^-$

CDF Run II Preliminary L=6.8fb$^{-1}$

- CDF provides $b \to s \mu^+ \mu^-$ $A_{FB}$ measurement comparable with $B$ factories!
Summary & Conclusions

• B rare decays are excellent stage to search for New Physics effect.
• Using full 9.7 fb⁻¹ of CDF Run-II data sample, we measured:

<table>
<thead>
<tr>
<th>Decay</th>
<th>Branching</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_s \rightarrow \mu^+\mu^- )</td>
<td>1.3±0.42(stat)±0.55(syst) × 10⁻⁸</td>
<td></td>
</tr>
</tbody>
</table>

90% CL : 2.2 × 10⁻⁹ < \( B_s \rightarrow \mu^+\mu^- \) < 3.0 × 10⁻⁸
95% CL : 0.8 × 10⁻⁹ < \( B_s \rightarrow \mu^+\mu^- \) < 3.4 × 10⁻⁸

Latest CDF result stays ~2σ from \( Br(B_s \rightarrow \mu^+\mu^-)_{SM} = (3.2±0.2) \times 10⁻⁹ \)

• Various \( b \rightarrow s\mu^+\mu^- \) decay channels are observed with 6.8 fb⁻¹ of data:

\[
\begin{align*}
Br(\Lambda_b^0 \rightarrow \Lambda\mu^+\mu^-) & = [1.73±0.42(stat)±0.55(syst)] \times 10⁻⁶ \ldots \text{world’s first!!} \\
Br(B_s^0 \rightarrow \phi\mu^+\mu^-) & = [1.47±0.24±0.46] \times 10⁻⁶ \\
Br(B^+ \rightarrow K^+\mu^+\mu^-) & = [0.46±0.04±0.02] \times 10⁻⁶ \\
Br(B^0 \rightarrow K^{*0}\mu^+\mu^-) & = [1.02±0.10±0.06] \times 10⁻⁶ \\
Br(B^0 \rightarrow K^0\mu^+\mu^-) & = [0.32±0.10±0.02] \times 10⁻⁶ \\
Br(B^+ \rightarrow K^{*+}\mu^+\mu^-) & = [0.95±0.32±0.08] \times 10⁻⁶
\end{align*}
\]

• Observed \( A_{FB} \) is comparable with \( B \) factories.
$B_S^0 \rightarrow \mu^+ \mu^-$

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

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

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NP Expectation

Br enhancement

Powerful Probe to New Physics
The CDF Detector

- Silicon Vertex Detector (precise position measurement)
- Tracking Chamber (momentum measurement)
- 1.4 Tesla Solenoidal magnet
- Calorimeter (red and blue) (energy measurement)
- Muon Detector (yellow & blue)

General purpose collider detector for many physics

- $B$ physics
- QCD / Top quark properties
- Electroweak physics ($W$, $Z$ bosons)
- Higgs / Exotic physics
The CDF Detector

A detector cross-section, showing particle paths

- Beam Pipe (center)
- Tracking Chamber
- Magnet Coil
- E-M Calorimeter
- Hadron Calorimeter
- Magnetized Iron
- Muon Chambers
- Neutron
- Photon
- Electron
- Proton
- Muon

\( \eta = 1.0 \)
CDF 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 $J/\psi$ or $B_s$
(for muon of a given $p_T$)
Background from two-body hadronic B decays

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

- fake muons dominated by $\pi^+, \pi^-, K^+, K^-$
- 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 $\mu$-fake rates. Double fake rate ~0.04%
Fake rates from D*-tagged D⁰ → K⁻π⁺ events

Example of D⁰ 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:
Probing New Physics

• “Smoking gun” of some Flavor Violating NP models:
  - ratio $\frac{BR(B_s \rightarrow \mu^+ \mu^-)}{BR(B^0 \rightarrow \mu^+ \mu^-)}$ highly informative about whether NP violates flavor significantly or not
  - clear correlation between CP violating mixing phase from $B_s \rightarrow J/\psi \phi$ and $BR(B_s \rightarrow \mu^+ \mu^-)$

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

New bounds on $BR(B^0 \rightarrow \mu^+ \mu^-)$ and $BR(B_s \rightarrow \mu^+ \mu^-)$ 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 $S_{\psi\phi}$, $\text{Br}(B_s \to \mu^+\mu^-)$ and $K^+ \to \pi^+\nu\bar{\nu}$

(without taking correlation between them)

<table>
<thead>
<tr>
<th>Model</th>
<th>Upper Bound on ($S_{\psi\phi}$)</th>
<th>Enhancement of $\text{Br}(B_s \to \mu^+\mu^-)$</th>
<th>Enhancement of $\text{Br}(K^+ \to \pi^+\nu\bar{\nu})$</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>

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

\[ 2 \ln(Q) \text{ with } Q = \frac{L(s + b|\text{data})}{L(b|\text{data})} \]

- 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.

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