Updated Search for Non-SM Physics in $B \rightarrow K(*)\mu^+\mu^-$ Decays at CDF

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for the CDF collaboration

DPF11, August 10, 2011
Brown University, Providence, Rhode Island
Outline of Talk (6.8/fb Update):

- Introduction / Total BR’s for B->K(*)μ⁺μ⁻
- Differential BR’s (distributions in q² = M_{μμ})
- Angular Analysis from dBR’s (variables A_{FB}, F_L, A_T^{(2)}, A_{im})


- First dBR Measurements of B →φμ⁺μ⁻ and Λ_b → Λμ⁺μ⁻
- First Observation of Λ_b → Λμ⁺μ⁻ at CDF (!)
  (Hideki Miyake @ EPS-HEP 2011)


Previous results:
  (B → φμμ 4.4/fb)     PRL 106, 161801 (2011)
**b → sμμ decays**

Promising tool to pursue new physics

Decay amplitude might be affected by heavy NP particles

Use μ⁺ μ⁻ trigger, 1 or 2 hadrons @ displaced vertex

**Signal Channels, BR \(\sim O(10^{-6})\)**

- \(B^0 \rightarrow K^*0 \, \mu \mu\)
- \(B^+ \rightarrow K^{*+} \, \mu \mu\)
- \(B^+ \rightarrow K^+ \, \mu \mu\)
- \(B^0 \rightarrow K_s \, \mu \mu\)
- \(B_s \rightarrow \phi \, \mu \mu\)
- \(\Lambda_b \rightarrow \Lambda \, \mu \mu\)

**Ref. Channels**

- \(B^0 \rightarrow K^*0 \, J/\psi\)
- \(B^+ \rightarrow K^{*+} \, J/\psi\)
- \(B^+ \rightarrow K^+ \, J/\psi\)
- \(B^0 \rightarrow K_s \, J/\psi\)
- \(B_s \rightarrow \phi \, J/\psi\)
- \(\Lambda_b \rightarrow \Lambda \, J/\psi\)
Total BR Analysis

\[ \frac{\mathcal{B}(H_b \rightarrow h\mu^+\mu^-)}{\mathcal{B}(H_b \rightarrow J/\psi h)} = \frac{N_{h\mu^+\mu^-}}{N_{J/\psi h}} \times \frac{\mathcal{B}(J/\psi \rightarrow \mu^+\mu^-)}{\varepsilon_{\text{rel}}} \]

- Rare channel yield
- Control channel yield
- Relative efficiency \( (=\varepsilon(h\mu\mu)/\varepsilon(J/\psi h)) \)

\( H_b = B^0, B^+, B_s, \Lambda_b \)

\( h = K^{*0}, K^{*+}, K^+, K_s, \Phi, \Lambda \)

Trigger on \( \mu^+ \mu^- \): Rare (Signal) Channels

Reference Channels (e.g. \( J/\psi \rightarrow \mu^+ \mu^- \))

Charmonium Veto Bands ➔
Fitted Events in Signal and Reference Modes

Analysis dates back to CDF Run I. New CDF results have:
- higher luminosity, additional triggers, better particle ID,
- loosened selection, better Neural Network optimization,
- more physics channels.


NEW RESULTS:

<table>
<thead>
<tr>
<th>Mode</th>
<th>$N_{h\mu^+\mu^-}$</th>
<th>$s$ ($\sigma$)</th>
<th>$N_{J/\psi}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+$</td>
<td>$K^+\mu^+\mu^-$</td>
<td>234 ± 19 (345)</td>
<td>13.7 72156 ± 272 (83773)</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$K^0\mu^+\mu^-$</td>
<td>164 ± 15 (234)</td>
<td>13.7 28299 ± 233 (40320)</td>
</tr>
<tr>
<td>$B^0_S$</td>
<td>$\phi\mu^+\mu^-$</td>
<td>49 ± 7 (66)</td>
<td>9.0 4555 ± 79 (5656)</td>
</tr>
<tr>
<td>$B^0$</td>
<td>$K_S^0\mu^+\mu^-$</td>
<td>28 ± 9 (63)</td>
<td>3.5 9470 ± 90 (10699)</td>
</tr>
<tr>
<td>$B^+$</td>
<td>$K^{*+}\mu^+\mu^-$</td>
<td>20 ± 6 (36)</td>
<td>3.5 4557 ± 79 (5709)</td>
</tr>
<tr>
<td>$\Lambda^0$</td>
<td>$\Xi\mu^+\mu^-$</td>
<td>24 ± 5 (34)</td>
<td>5.8 1736 ± 53 (2523)</td>
</tr>
</tbody>
</table>
$b \rightarrow s \mu \mu$ signals (CDF 6.8 fb$^{-1}$)
$\Lambda_b \rightarrow \Lambda \mu\mu$ observation

First experimental search for baryonic $b \rightarrow s \mu\mu$ decay

Reduce possible $K_s \mu\mu$ contamination
Momentum imbalance of $V^0$ daughters

First observation!

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

The rarest $\Lambda_b$ decay to date

Expectations

✓ $(4.0\pm1.2)\times10^{-6}$  
✓ $4.4\times10^{-6}$  
✓ $2.08\times10^{-6}$

Phys.Rev.D64,074001 (2001)
**FCNC in $b \rightarrow s\mu\mu$ decays (CDF 6.8 fb$^{-1}$)**

- Rare decays with BR $\sim O(10^{-6})$ in SM are good probes of NP

<table>
<thead>
<tr>
<th>Mode</th>
<th>Relative $B(10^{-3})$</th>
<th>Absolute $B(10^{-6})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0 \rightarrow \Lambda \mu^+ \mu^-$</td>
<td>$2.45 \pm 0.59 \pm 0.29$</td>
<td>$1.73 \pm 0.42 \pm 0.55$</td>
</tr>
<tr>
<td>$B_s^0 \rightarrow \phi \mu^+ \mu^-$</td>
<td>$1.13 \pm 0.19 \pm 0.07$</td>
<td>$1.47 \pm 0.24 \pm 0.46$</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^+ \mu^+ \mu^-$</td>
<td>$0.46 \pm 0.04 \pm 0.02$</td>
<td>$0.46 \pm 0.04 \pm 0.02$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^0 \mu^+ \mu^-$</td>
<td>$0.77 \pm 0.08 \pm 0.03$</td>
<td>$1.02 \pm 0.10 \pm 0.06$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^*0 \mu^+ \mu^-$</td>
<td>$0.37 \pm 0.12 \pm 0.02$</td>
<td>$0.32 \pm 0.10 \pm 0.02$</td>
</tr>
<tr>
<td>$B^0 \rightarrow K^- \mu^+ \mu^-$</td>
<td>$0.67 \pm 0.22 \pm 0.04$</td>
<td>$0.95 \pm 0.32 \pm 0.08$</td>
</tr>
</tbody>
</table>

*first observed by CDF:*

- $B_s \rightarrow \Phi \mu\mu$ (PRL106,161801 (2011))
- $\Lambda_b \rightarrow \Lambda \mu\mu$ (arXiv:1107.3753)

- Most precise BR measurements

- BR theoretical calculations of $\Lambda_b \rightarrow \Lambda \mu\mu$

(4.0$\pm$1.2)$\times$10$^{-6}$

4.4$\times$10$^{-6}$

2.08$\times$10$^{-6}$


Phys.Rev.D64,074001 (2001)

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Comparison with Other Experiments

(*) All BRs except CDF@6.8 fb⁻¹ are taken from HFAG 2010 August

World’s most precise $b \rightarrow s \mu \mu$ BR measurements!
$b \rightarrow s\mu\mu$ differential BR (CDF 6.8 $fb^{-1}$)

- Enhanced sensitivity to NP from differential BR (dBR) dependence on $q^2$.
- dBR as function of $\mu\mu$ squared invariant mass ($q^2$) in good agreement with theory:

Red curves: SM predictions; (a) based on $4.0 \times 10^{-6}$

Blue curve(a): rescaled SM prediction to our total BR $(1.73/4.0)$

Green bands: charmonium veto

(a) and (b) are first measurements!
Differential BR’s (2)

Results for $K_s$ (left) and $K^{*+} \rightarrow K_s \pi^+$ (right).
- New!

Combined results for $K$ (left) and $K^*$ (right).
- Assume isospin symmetry.
$B^0 \rightarrow K^{*0} \mu^+ \mu^-$ Decay Variables

Asymmetries provide most powerful probe for New Physics.

- Four angular observables: $F_L, A_{FB}, A_T^{(2)}, A_{im}$ which depend on $K^*$ Polarization Amplitudes.
- Small theoretical uncertainties. Asymmetries can be accessed with current data (Belle, BaBar, CDF, early LHCb.)
Angular analysis

One can extract various information from the decay angular distribution

\[ \cos \theta_K \]

\[ \cos \theta_\mu \]

\[ \phi \]

\[ \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_K). \]

**NEW**

\[ A_T^{(2)} \] Transverse polarization asymmetry

\[ A_{im} \] Triple product asymmetry

\[ \frac{1}{2\pi} \left[ 1 + \frac{1}{2} (1 - F_L) A_T^{(2)} \cos 2\phi + A_{im} \sin 2\phi \right] \]
Muon Forward-Backward Asymmetry ($A_{FB}$)

Belle claimed 2.7σ discrepancy with SM.

CDF data are among world’s most accurate and do not yet suggest non-SM effects.

Red Curve: SM prediction (note zero crossing point prediction).
Blue curve: NP could swap the sign of $A_{FB}$ at low $q^2$ (and give no crossing point).
**K* Longitudinal Polarization Fraction**

$F_L$ determined from angular distribution of $K^*$ decay products (e.g. $K^+\pi^-$ or $K_s\pi^+$).

Simultaneous fit to all $K^*$ modes.

Green bands: charmonium veto
Transverse Polarization Asymmetry ($A_T^{(2)}$)

- First time anyone looks at this variable.
- Magnitude grows as $q^2$ increases (SM).
- Obtained from fits to $\phi$ angular distribution.
- Sensitive to CP-conserving RH currents (not just swapped sign of $C_7$).
- Data in reasonably good agreement with SM predictions.
- Swapped sign has little effect, but different predictions from other BSM models.
T-odd CP asymmetry ($A_{\text{im}}$)

Obtained from fits to $\phi$ angular distribution.

$A_{\text{im}}$ is sensitive to CP-violating Right-Handed currents.

Measuring $A_{T}^{(2)}$ and $A_{\text{im}}$

More statistics needed!

SM predicts the T-odd CP asymmetry $A_{\text{im}}$ to be $\sim$ zero.
New probes: $A_T^{(2)}$ and $A_{\text{im}}$

Right-handed current sensitive observables
Small in SM ($A_T^{(2)}$ is negatively large in high $q^2$)
Strongly affected by RH current up to $\mathcal{O}(\pm 1)$
Provide unique discrimination of NP models
No experimental result so far

BSM: $\sim \pm 1$

SM: $\sim 0$

$A_T^{(2)}$

arXiv:1006.5013
C. Bobeth, G. Hiller, D. van Dyk
Conclusions

• Updated B → K(*)μ⁺μ⁻ analysis with 6.8/fb of data.
  Nearly 2x statistics. New channels (K_s,K*+).
• More precise Total BR’s for exclusive b → sμμ decays.
• First measurement of dBR in B_s → φμμ.
  First observation of Λ_b → Λμμ.
  
• First measurements of A_T^{(2)} and A_{im} (add. probes for NP).
• Precision of A_{FB} and F_L competitive with other experiments, and among world’s most accurate.
  
BACKUP
Angular Dependence of Decay Rates

\[
\frac{1}{\Gamma} \frac{d\Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{d \cos \theta_K} = \frac{3}{2} F_L \cos^2 \theta_K + \frac{3}{4} (1 - F_L)(1 - \cos^2 \theta_K) \quad F_L
\]

\[
\frac{1}{\Gamma} \frac{d\Gamma(B^0 \rightarrow K^{*0} \mu^+ \mu^-)}{d \cos \theta_\mu} = \frac{3}{4} F_L (1 - \cos^2 \theta_\mu) + \frac{3}{8} (1 - F_L)(1 + \cos^2 \theta_\mu) + A_{FB} \cos \theta_\mu \quad F_L, A_{FB}
\]

\[
\frac{1}{\Gamma} \frac{d\Gamma(B \rightarrow K^* \mu^+ \mu^-)}{d\phi} = \frac{1}{2\pi} [1 + \frac{1}{2} (1 - F_L) A^{(2)}_T \cos 2\phi + A^{im} \sin 2\phi]. \quad A^{(2)}_T, A^{im}
\]
Observables

\[
A_{FB} = \frac{3 \text{Re}(A_{\perp L} A_{\parallel L}^*) - \text{Re}(A_{\perp R} A_{\parallel R}^*)}{2 |A_0|^2 + |A|^2 + |A_\perp|^2},
\]

\[
F_L = \frac{|A_0|^2}{|A_0|^2 + |A|^2 + |A_\perp|^2},
\]

\[
A_T^{(2)} = \frac{|A_\perp|^2 - |A|^2}{|A_\perp|^2 + |A|^2},
\]

\[
A_{\text{im}} = \frac{\text{Im}(A_{\perp L} A_{\parallel L}^*) + \text{Im}(A_{\perp R} A_{\parallel R}^*)}{|A_0|^2 + |A|^2 + |A_\perp|^2}.
\]