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Rare Decays at B-Factories

Recontres de Moriond EW 2009
La Thuile, March 7th-14th 2009

On behalf of the BaBar & Belle Collaborations
The SM has been able to explain in coherent framework (almost) all the experimental evidence of weak, strong and electromagnetic interactions.

CKM picture has been able to explain all the measurements in flavour sector.

BUT we know this is not the ultimate theory.

Everybody is eager for New Physics:
• Explore energy frontiers (Tevatron, LHC)
• Measure precisely virtual processes which can test high energy scales

Rare decays provide many clean probes:
• If a suppressed decay is observed, clear sign of NP
• If an UL is set, NP scenarios are constrained
Outline

From the (SM expected) less rare to the rarest.....

$B^\pm \rightarrow \tau^\pm \nu$

$B \rightarrow h^{(*)} \nu - \nu$

$B^\pm \rightarrow l^\pm \nu$ ($l = e, \mu$)

$B^0 \rightarrow J/\psi \phi$

$B^\pm \rightarrow K^\pm \pi^+ \pi^- / K^+ K^- \pi^\pm$

$B^\pm \rightarrow l^\pm \nu$

$B^0 \rightarrow J/\psi \phi$

$B^\pm \rightarrow K^\pm \pi^+ \pi^- / K^+ K^- \pi^\pm$

$B^\pm \rightarrow l^\pm \nu$ ($l = e, \mu$)

$B^0 \rightarrow J/\psi \phi$

$B^\pm \rightarrow K^\pm \pi^+ \pi^- / K^+ K^- \pi^\pm$

$tan\beta$ vs $m_{H^\pm}$

Dark Matter/SUSY

LFV (& $tan\beta$ vs $m_{H^\pm}$)

Rescattering effects

$b \rightarrow d\bar{d}d$ & $b \rightarrow s\bar{s}d$
Analyses Overview

Analyses with undetectable particles from signal B decay:

- Recoil technique: low efficiency (1% - 0.1%) but HIGH resolution --> necessary when more than one neutrino is present
- Semileptonic tagged recoil: higher efficiency but lower purity
- Hadronic tagged recoil: lower efficiency but higher purity

Totally inclusive reconstruction exploiting kinematic constraints:
HIGH efficiency but low resolution

Analyses with all detectable particles from signal B decay:

- Full kinematical reconstruction of the event possible

\[ B^\pm \rightarrow \tau^\pm \nu \ / B \rightarrow h^* \nu \nu \]

\[ B^\pm \rightarrow l^\pm \nu \ (l=e, \mu) \]

\[ B^\pm \rightarrow K^\mp \pi^+ \pi^- / K^+ K^- \pi^\pm \]

\[ B^0 \rightarrow J/\psi \phi \]
Theoretical calculations for these processes particularly reliable due to the absence of long distance interactions which affect $B \to h^*\ell\ell$
B → h(\*) \nu \nu analysis

\( h = K^+, K_S^0, K^{*0}, K^{*+}, \pi^+, \pi^0, \rho^+, \rho^0 \)

Hadronic recoil

\( B_{\text{sig}} \) selected with \( E_{\text{ECL}} = E_{\text{tot}} - E_{\text{reco}} < 0.3 \text{ GeV} \)

(Standard) Model dependence introduced applying cuts on signal \( h^* \) kinematics

Cut & count yield extraction

Feldman-Cousins UL extraction @ 90% CL

\[
\begin{array}{cccc}
\text{Mode} & N_{\text{obs}} & N_{\text{bkg}} & \text{eff}(\times 10^{-5}) \\
K^*0 \nu \nu & 7 & 4.2 \pm 1.4 & 5.1 \pm 0.3 \\
K^*+ \nu \nu & 4 & 5.6 \pm 1.8 & 5.8 \pm 0.7 \\
K^+ \nu \nu & 10 & 20.0 \pm 4.0 & 26.7 \pm 2.9 \\
K^0 \nu \nu & 2 & 2.0 \pm 0.9 & 5.0 \pm 0.3 \\
\end{array}
\]

492 fb\(^{-1}\)

PRL 99, 221802

K^*0 \nu \nu < 3.4 \times 10^{-4}
K^*+ \nu \nu < 1.4 \times 10^{-4}
K^+ \nu \nu < 1.4 \times 10^{-5}
K^0 \nu \nu < 1.6 \times 10^{-4}
**B → K^* γ γ analyses**

- No model dependent cuts on K^* kinematic
- First completely model independent analyses!!
- Most important variable $E_{\text{extra}}$: ML fit to $E_{\text{extra}}$ distribution
- HAD: fit to NN output
  - **NN variables:** $R_2$, $\cos\theta_{B\text{tag/T}}$, $E_{\text{miss}} + p_{\text{miss}}$, $\cos\theta_{\text{miss}}$, $M_{K^*}$, $M_{K_S}$, $E_{\text{extra}}$
- HAD and SL results combined
- UL extraction in Bayesian approach @ 90% CL

### SL
- $K^{*0} \gamma \gamma < 18 \times 10^{-5}$
- $K^{*+} \gamma \gamma < 9 \times 10^{-5}$

### HAD
- $K^{*0} \gamma \gamma < 11 \times 10^{-5}$
- $K^{*+} \gamma \gamma < 21 \times 10^{-5}$

### Combined
- $K^{*0} \gamma \gamma < 12 \times 10^{-5}$
- $K^{*+} \gamma \gamma < 8 \times 10^{-5}$

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PRD 78, 072007

413 fb$^{-1}$
Let's suppose there is a light (<2.5 GeV) scalar dark matter candidate $S$.

The UL can be translated into $S$ mass & coupling constraint.

N.B. the $H \rightarrow SS$ decay would saturate the Higgs decay rate, making impossible the Higgs discovery at LHC!!

From BaBar UL (using for SM Buchalla, Hiller & Isidori PRD 63, 014015)

Burgess et al. Nucl.Phys. B619, 709

$\kappa^2 = \lambda^2 \left( \frac{100 \text{ GeV}}{m_h} \right)^4$

$\sim O(1)$ from cosmological constr.
$B^\pm \rightarrow l^\pm \nu$

In the SM

$$B(B^+ \rightarrow \ell^+ \nu_\ell) = \frac{G_F^2 m_B m_\ell^2}{8\pi} \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 \left| f_B^2 |V_{ub}|^2 \right|_{\tau_B}$$

- $\tau \, \nu = (1.2 \pm 0.4) \times 10^{-4}$
- $\mu \, \nu = (5.6 \pm 0.4) \times 10^{-7}$
- $e \, \nu = (1.3 \pm 0.4) \times 10^{-11}$

Annihilation process: helicity suppression allows charged Higgs to be competitive with SM
Directly test Yukawa interactions

* In a general SUSY scenario

$$\frac{B(B^+ \rightarrow l^+ \nu_\ell)}{B(B^+ \rightarrow l^+ \nu_\ell)}_{\text{SM}} \approx (1 - \tan^2 \beta \frac{m_B^2}{M_H^2})^2.$$  

W.S. Hou  
Phy.Lett. D 48, 2342

* In a particular MFV scenario with non minimal LFV

$$R^B_{\mu\tau} = \frac{\Gamma(B \rightarrow \mu^+ \nu)}{\Gamma(B \rightarrow \tau^+ \nu)} \quad R^B_{e\tau} = \frac{\Gamma(B \rightarrow e^+ \nu)}{\Gamma(B \rightarrow \tau^+ \nu)}$$

$$\Delta \sim 10\% \left(R^B_{\mu\tau}\right)_{\text{SM}} \quad \sim 10^3 \times \left(R^B_{e\tau}\right)_{\text{SM}}$$

G.Isidori & P.Paradisi  
Phy.Lett. B 639, 499

See A. Bozek's talk for Belle results on $B \rightarrow \tau \, \nu$
B$^{\pm} \rightarrow l^\pm \nu$ with SL recoil

- Most powerful variables: $E_{\text{extra}}$ and momentum of signal lepton in $B$ rest frame ($p_T^{\text{REST}}$)
- Remaining variables considered for likelihood ratios (LHRs) of PDFs separated for continuum and $B\bar{B}$ background
- Cuts optimized separately for each mode
- Background estimate from $E_{\text{extra}}$ sideband data rescaled with $MC$
$B^\pm \rightarrow l^\pm \nu$ with SL recoil

<table>
<thead>
<tr>
<th>Mode</th>
<th>Expected Background ($N_{BG}$)</th>
<th>Observed Events ($N_{obs}$)</th>
<th>Overall Efficiency ($\varepsilon$)</th>
<th>Branching Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau^+ \rightarrow e^- \nu_e \bar{\nu}_e$</td>
<td>$91 \pm 13$</td>
<td>148</td>
<td>$(3.08 \pm 0.14) \times 10^{-4}$</td>
<td>$(4.0 \pm 1.2) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \mu^- \nu_\mu \bar{\nu}_\mu$</td>
<td>$137 \pm 13$</td>
<td>148</td>
<td>$(2.28 \pm 0.11) \times 10^{-4}$</td>
<td>$(1.0 \pm 1.2) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \pi^+ \nu_\tau \bar{\nu}_\tau$</td>
<td>$233 \pm 19$</td>
<td>243</td>
<td>$(3.89 \pm 0.15) \times 10^{-4}$</td>
<td>$(0.6 \pm 0.3) \times 10^{-4}$</td>
</tr>
<tr>
<td>$\tau^+ \rightarrow \pi^0 \nu_\tau \bar{\nu}_\tau$</td>
<td>$59 \pm 9$</td>
<td>71</td>
<td>$(1.30 \pm 0.07) \times 10^{-4}$</td>
<td>$(2.0 \pm 1.3) \times 10^{-4}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow \tau^+ \nu_\tau$</td>
<td>$521 \pm 31$</td>
<td>610</td>
<td>$(10.54 \pm 0.41) \times 10^{-4}$</td>
<td>$(1.8 \pm 0.8 \pm 0.1) \times 10^{-4}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow \mu^+ \nu_\mu$</td>
<td>$15 \pm 10$</td>
<td>11</td>
<td>$(27.1 \pm 1.2) \times 10^{-4}$</td>
<td>&lt; $11 \times 10^{-6}$ at 90% CL</td>
</tr>
<tr>
<td>$B^+ \rightarrow e^+ \nu_e$</td>
<td>$24 \pm 11$</td>
<td>17</td>
<td>$(36.9 \pm 1.5) \times 10^{-4}$</td>
<td>&lt; $7.7 \times 10^{-6}$ at 90% CL</td>
</tr>
</tbody>
</table>

Using $|V_{ub}| = (4.43 \pm 0.54) \times 10^{-3}$

Latest lattice QCD:

$f_B = 230 \pm 57$ MeV

Combined with previous BaBar measurement with HAD recoil:

$B^+ \rightarrow \tau^+ \nu = (1.8 \pm 0.6) \times 10^{-4}$

New B-Factory: $B^+ \rightarrow \mu^+ \nu$

PRD 77, 011107

arXiv:0809.4027

A. Gray et al.,PRL 95, 212001
Look for the highest momentum lepton in the event and use all other tracks and neutral to reconstruct $B_{\text{tag}}$.

Tight requirement on lepton PID and momentum.

Typical background:

- $q\bar{q}, B\to X_u l \nu$

$B_{\text{tag}}$ requirement on $\Delta E$.

Background suppression: modified $R_2$ in Fisher, $p_T^{\text{miss}}>1.75$ GeV and $\cos \theta^{\text{miss}}<0.84$ (0.82).

ML fit to $B_{\text{tag}} m_{BC}$.

UL extraction integrating 90% of likelihood.

$B^\pm \to l^\pm \nu (l=e, \mu)$ inclusive

$253\text{ fb}^{-1}$

$B^+\to \mu^+ \nu$

Efficiency $(2.2 \pm 0.1)\%$

Yield $4.1 \pm 3.1$

$B^+\to e^+ \nu$

Efficiency $(2.4 \pm 0.1)\%$

Yield $-1.8 \pm 3.3$

$B^\pm \to l^\pm \nu < 1.7 \times 10^{-6}$

$B^\pm \to e^\pm \nu < 9.8 \times 10^{-7}$

Reconstruction technique similar to Belle’s

Additional background from two photon processes for electron mode

$B_{tag}$ requirement on $\Delta E$ (and $p_T$)

Background suppression: topological and kinematical Fisher optimized separately for each mode on 5 different variables

ML fit to $B_{tag} m_{ES}$ and linear combination of signal lepton momentum in B rest frame and c.m. frame

UL extraction in Bayesian approach

\[ B^\pm \rightarrow l^\pm \nu \quad (l=\text{e, } \mu) \text{ inclusive} \]

Efficiency (6.1 ± 0.2)%
Yield 1.4 ± 17.2

Efficiency (4.7 ± 0.3)%
Yield 17.9 ± 17.6

$B^\pm \rightarrow \mu^\pm \nu \quad < 1.0 \times 10^{-6}$

$B^\pm \rightarrow e^\pm \nu \quad < 1.9 \times 10^{-6}$

arXiv:0903.1220
Preliminary, submitted to Phys.Rev. D

\[ B^+ \rightarrow \mu^+ \nu \]

\[ B^+ \rightarrow e^+ \nu \]

\[ B^± \rightarrow \mu^\pm \nu \]

\[ B^± \rightarrow e^\pm \nu \]
$\mathbf{B}^{\pm} \rightarrow \mu^{\pm} \nu$ constraint

$M = \pi, K, D, B, ...$

$$R_{\mathcal{M}}^{i/k} = \frac{\sum \Gamma(M \rightarrow l_j \nu_i)}{\sum \Gamma(M \rightarrow l_k \nu_i)} \quad i, j, k = e, \mu, \tau.$$ 

$$R_{\mathcal{M}}^{i/k}_{\text{MSSM}} = (R_{\mathcal{M}}^{j/k})_{\text{SM}} [1 + \frac{1}{R_{mk\nu}} \left( \frac{m_{M}^{4}}{m_{H^{\pm}}^{4}} \right) \left( \frac{m_{k}^{2}}{m_{j}^{2}} \right) |\Delta_{R}^{ij}|^{2} \frac{\tan^{6} \beta}{(1 + \cot \beta \tan \beta)^{2}}]$$

**With K decays,** tau not accessible so only $\Delta_{13}$

$R_{K}$ measured at $O(1\%)$ accuracy

**With B decays,**

$\Delta_{13} \text{ AND } \Delta_{23}$

Only UL on $R_{B}$ but similar constraint!!!

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Isidori & Paradisi

Phys.Lett. B 639, 499

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With BaBar UL

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Probe for rescattering effect

Important to understand patterns of CP asymmetries for charmless 2-body B decays

Selection cuts:

\[-150 \text{ (–60)} \text{ MeV}/c^2 < M_{e^+e^–(\gamma)(\mu^+\mu^–)} - m_{J/\psi} < 36 \text{ (36)} \text{ MeV}/c^2\]

\[|m_{K^+K^-} - m_{\phi}| < 10 \text{ MeV}/c^2\]

\[5.27 \text{ GeV}/c^2 < M_{bc} < 5.29 \text{ GeV}/c^2\]

Dominant backgrounds (taken into account in the ML fit):

\[B^0 \rightarrow J/\psi K^{*0}(892) [\rightarrow K^-\pi^+]\]

\[B^{0/-} \rightarrow J/\psi K_1(1270) [\rightarrow K^-\pi^+\pi^0/\pi^-]\]

| Event yield | 4.6 $\pm$ 3.1 $\pm$ 2.5 |
| Significance | 2.3$\sigma$ |
| Upper limit of signal yield ($Y_{90}$) | 9.5 |
| Detection efficiency ($\epsilon$) | 26.2% |
| Upper limit of branching fraction | $< 9.4 \times 10^{-7}$ |
\[ B^+ \rightarrow K^- \pi^+ \pi^- / K^- K^+ \pi^- \]

\[ b \rightarrow q q \bar{s} / b \rightarrow q q \bar{d} \approx (V_{td} V_{ts}^* \sim \lambda^5 \sim 3 \cdot 10^{-5}) \cdot b \rightarrow q \bar{q} s / b \rightarrow q \bar{q} d \]

\[ \sim O(10^{-11}) \]

\[ \sim O(10^{-14}) \]

\[ \mathcal{H}_{\text{eff.}} = \sum_{n=1}^{5} [C_n \mathcal{O}_n + \tilde{C}_n \tilde{\mathcal{O}}_n], \]

\[ \mathcal{O}_1 = \bar{d}_L^i \gamma^\mu b_L^j d_R^j R \gamma_\mu s_R^j, \]

\[ \mathcal{O}_2 = \bar{d}_L^i \gamma^\mu b_L^j d_R^j R \gamma_\mu s_R^j, \]

\[ \mathcal{O}_3 = \bar{d}_L^i \gamma^\mu b_L^j d_R^j L \gamma_\mu s_L^j, \]

\[ \mathcal{O}_4 = \bar{d}_R^i b_L^j d_L^j s_R^j, \]

\[ \mathcal{O}_5 = \bar{d}_R^i b_L^j d_L^j s_L^j, \]

\[ \Gamma^{(MS)SM}_{\pi \pi K} = |C_3^{(MS)SM}|^2 \times 2.0 \times 10^{-3} \text{ GeV}^5, \]

\[ \Gamma^{RPV}_{\pi \pi K} = |C_4^{RPV} + \tilde{C}_4^{RPV}|^2 \times 9.2 \times 10^{-3} \text{ GeV}^5, \]

\[ \Gamma^{Z'}_{\pi \pi K} = |C_1^{Z'} + \tilde{C}_1^{Z'}|^2 \times 1.0 \times 10^{-2} \text{ GeV}^5, \]

\[ + |C_3^{Z'} + \tilde{C}_3^{Z'}|^2 \times 1.3 \times 10^{-3} \text{ GeV}^5, \]

\[ + \text{Re} \left[ \left( \left( C_1^{Z'} + \tilde{C}_1^{Z'} \right) \left( C_3^{Z'} + \tilde{C}_3^{Z'} \right) \right)^* \right] \times 6.7 \times 10^{-3} \text{ GeV}^5. \]

Can constrain RPV:

\[ \sum_{n=1}^{3} \left( \frac{100 \text{ GeV}}{m_{\nu_n}} \right)^2 |\chi_{n21} \chi_{n13}^*| < 8.9 \times 10^{-5}, \]
B⁺→K⁻π⁺π⁻/K⁻K⁺π⁻ analysis

J/ψ, D⁰ and ψ(2S) vetos

Efficiencies: 21.6% / 17.8%

NN variables: \( L_2/L_0, |\cos \theta_{\text{beam}}|, |\cos \theta_{\text{thrust}}|, \)

B\( ^\pm \rightarrow K^{\mp}\pi^{\mp}\pi^{\mp} < 7.4 \times 10^{-7} \)

B\( ^\pm \rightarrow K^{\mp}K^{\mp}\pi^{\mp} < 4.2 \times 10^{-7} \)


Phys.Rev.D 78 091102

426 fb⁻¹


Phys.Rev.D 78 091102

426 fb⁻¹

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Conclusion & Outlook

Rare decays are standard probes for NP searches given the low decay rates.

They are complementary to the direct exploration of energy frontier and can access even higher scales.

Thanks to the improved analysis techniques and the huge integrated luminosity, today is possible to reach $O(10^{-6}-10^{-7})$ in sensitivity.

Even if only UL, rare decays are already able to impose interesting constraints on various NP scenarios.

Nonetheless, decays with undetectable particles in the final state will not be measurable at the LHC and a Super Flavour Factory will be needed in order to obtain improved measurements.
Backup Slides
Detectors & Datasets

BaBar Recorded Luminosity: 531.43 fb
BaBar Recorded Y(4s): 432.89 fb
BaBar Recorded Y(3s): 30.23 fb
BaBar Recorded Y(2s): 14.45 fb
Off Peak Luminosity: 53.85 fb

~900 fb⁻¹
Recoil Technique

Powerful technique providing a pure and clean B sample which you pay with a low efficiency $\sim O(0.01) - O(0.001)$
B → K^* ν ν Model Un-dependence

Selection and Fit Variables chosen in order to minimize the dependence on the kinematical model
(i.e. use variables with NO correlation to \( s = m_{\nu \nu}^2 / m_B^2 \))

missing 4-momentum:

\[ p_{\text{miss}} = p_{\text{beams}} - p_{\text{D}} - p_K \]

\[ E_{\text{miss}} \text{ vs. } s \]

\[ E_{\text{miss}} + |p_{\text{miss}}| \text{ vs. } s \]
\( B \rightarrow K^* \nu \bar{\nu} \) and MFV SUSY

- Assume a Minimal Flavor Violation (MFV) scenario:
  - NP enters only through modifications of the functions \( B(x_t) \) and \( C(x_t) \);

- NP in \( B(x_t) \) expected to give small contributions;

- Set a limit on \( \Delta C = C - C_{SM} \) assuming \( B = B_{SM} \).

All the most recent results for \( B \rightarrow K(*) \nu \bar{\nu} \) are used.

NP in \( C \) as large as 6 times the SM can be excluded at 95\% C.L.
$B^\pm \rightarrow l^\pm \nu$ with SL recoil

- Large excess in first 3 bins gives:
  $\text{BF}(B \rightarrow \tau\nu(\tau \rightarrow e\nu\nu)) = (4.0 \pm 1.2) \times 10^{-4}$

- Many sideband/control sample studies performed:
  - two photon fusion QED events: where a fake D0 is reconstructed and the $e^+, e^-$ are reconstructed as the tag or signal leptons. No excess seen in the D0 sidebands.
  - events that contain overlapping $e^+e^-$ collisions: study the separation of the reconstructed B vertices, $\Delta z$: possible excess at high $\Delta z$, however no excess found.
  - other samples studied include photon pair production and Bremstrahlung recovered electrons
  - Same number of electrons, muons from the tag B: expected for true signal
$B^\pm \rightarrow l^\pm \nu$ with SL recoil
Photon Fusion Event

Not detected
$B^\pm \rightarrow \mu^\pm \nu$ constraint

At SuperB with 5% error in the ratio
$B^\pm \rightarrow l^\pm \nu$ ($l=e, \mu$) inclusive

**BR Likelihoods**

**BR Likelihood from $N_{\text{observed}}$**

**Bayesian Posterior BR Likelihood**