Rare B decay searches with BABAR using hadronic tag reconstruction

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PEP-II Asymmetric B Factory produced e+e- interactions at the $\Upsilon(4S)$ resonance (~10.5 GeV)

$$\sigma(B\bar{B}) \sim 1.1\text{nb} \Rightarrow 1.1\text{M}/\text{fb}^{-1}$$

Total of 430 fb$^{-1}$ collected by BABAR between 1999 – 2008:

$$\sim 500 \text{ million } B\bar{B} \text{ pairs}$$

$B^0\bar{B}^0$ pair is produced in a coherent $L=1$ state

See talk by Tom Mattison on Weds afternoon
Rare decay searches with BABAR

Substantial potential for New Physics searches in rare B decays

- non-SM contributions can be comparable to or larger than (suppressed) SM contribution:

\[ r_H^{\text{SUSY}} = \left[ 1 - \left( \frac{m_B^2}{m_{H^\pm}^2} \right) \frac{\tan^2 \beta}{(1 + \epsilon_0 \tan \beta)} \right]^2 \]

- Experimental challenge is to identify rare signal decays with missing energy or limited kinematic information
Rare decay searches with BABAR

How can we distinguish particles associated with the “interesting” signal event from those arising from the decay of the second B meson in a Υ(4S) → BB event?

- Reconstruct the other B instead, then check if whatever is left looks like a signal decay

\[ B^+ \rightarrow l^+ \nu \gamma \] signal simulation
Hadronic “tag” reconstruction

Reconstruct a large sample of hadronic (or semileptonic) B decays in specific “clean” decay modes

- method based on a D(*) “seed”, to which individual charged and neutral pions and kaons are added until a B candidate is identified
- exploit knowledge of CM energy and tag B kinematics

Advantages:

- clean separation of signal and tag decay products
- improved determination of missing energy and signal B 4-vector
- strong suppression of (and precise determination of) continuum backgrounds

Disadvantage:

- efficiency \(~0.3\%\)

\[ B^- \rightarrow D^{(*)0} X^- \]

\[ K^- \pi^+ \]

\[ K^- \pi^+ \pi^0 \]

\[ K^- \pi^+ \pi^- \pi^+ \]

\[ K^0_s \pi^+ \pi^- \]

\[ m_{ES} (GeV/c^2) \]
Leptonic B decays

Helicity suppressed SM process with potential sensitivity to tree-level New Physics contributions

\[ \mathcal{B}_r(B^+ \to \ell^+ \nu_{\ell}) = \frac{G_f^2}{8\pi} |V_{ub}|^2 f_B^2 m_B m_\ell \tau_B \left(1 - \frac{m_\ell^2}{m_B^2}\right)^2 \]

- SM BFs scale with final state lepton mass squared, hence \( \tau \) mode is most prominent (BF \( \sim 10^{-4} \)), but \( \mu \) mode is within statistical reach of B current factories (BF \( \sim 10^{-7} \)),

In MSSM (or generic 2HDM), charged Higgs boson gives equal relative enhancement/suppression in all modes

- At one-loop level, large (Higgs mediated) lepton flavour violating effects can break hierarchy imposed by helicity suppression

i.e. NP constrained by measuring ratios of branching fractions of leptonic modes

**Standard Model Rates**
- \( B(B^+ \to \tau^+ \nu) \sim 1 \times 10^{-4} \)
- \( B(B^+ \to \mu^+ \nu) \sim 4 \times 10^{-7} \)
- \( B(B^+ \to e^+ \nu) \sim 10^{-12} \)
Results of hadronic and semileptonic tag searches for $B^+ \rightarrow \tau^+ \nu$ have been reported by both BABAR and Belle

- Resulting charged Higgs bound is fairly model-independent and substantially constrains region of parameter space accessible to LHC experiments

**Tagged $B^+ \rightarrow l^+ \nu$ ($l = e, \mu$)**

Can use the hadronic $B$ reconstruction method to search for other leptonic modes ($e, \mu$) as well as $\tau$ mode

- only 1 neutrino, so reconstruction of tag $B$ completely constrains event kinematics
- Signal $B$ rest frame estimated from tag $B$ 4-vector, permitting 2-body signal kinematics to be exploited
Tagged $B^+ \rightarrow l^+\nu$ ($l = e, \mu$) and LFV

Hadronic tag reconstruction method used for first time for this search by BABAR (thesis work of M. Klemetti, McGill)

- Sensitivity limited by statistics with BABAR data sample but excellent control of kinematics and background suppression would make this a slam-dunk for SuperB

<table>
<thead>
<tr>
<th>Mode</th>
<th>Data Sample</th>
<th>90% CL limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow \mu^+\nu$</td>
<td>378 M</td>
<td>$5.6 \times 10^{-6}$</td>
</tr>
<tr>
<td>$B^+ \rightarrow e^+\nu$</td>
<td></td>
<td>$5.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow \mu^+\tau^-$</td>
<td></td>
<td>$2.2 \times 10^{-6}$</td>
</tr>
<tr>
<td>$B^0 \rightarrow e^+\tau^-$</td>
<td></td>
<td>$2.8 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

PRD-RC 77, 091104 (2008)

- also placed limits on LFV neutral B modes
$B^+ \rightarrow l^+ \nu \gamma \quad (l = e, \mu)$

Presence of (hard) photon removes helicity suppression in purely leptonic decay modes, but adds factor of $\alpha$ and form factor uncertainties:

$$\frac{d\Gamma}{dE_\gamma} = \frac{\alpha G_F^2 |V_{ub}|^2}{48\pi^2} m_B^4 \left[ f_A^2(E_\gamma) + f_V^2(E_\gamma) \right] x(1-x)^3$$

$B(B^+ \rightarrow l^+ \nu \gamma) \sim (1-5) \times 10^{-6}$ for all three modes

- In practice, can extract $\lambda_B$ which is related to $B$ light cone wave function

$$\Gamma(B^+ \rightarrow l^+ \nu \gamma) = \frac{G_F^2 |V_{ub}|^2 m_B^5}{288\pi^2} f_B^2 \left( \frac{Q_u}{m_b} - \frac{Q_b}{m_b} \right)^2$$

Model uncertainties make it desirable to provide model-independent measurement...

G. Korchemsky, D. Pirjol, T.-M. Yan
Tagging provides precise measurement of tag $B$ (and hence signal $B$) 4-vector

- in combination with lepton and photon, neutrino 4-vector is fully determined

- strong suppression of (dominant) $b \rightarrow u \ell \nu$ decay background

- no additional particles should be present in the event

Work by Dana Lindemann (McGill)
Non-B backgrounds are strongly suppressed by tag reconstruction procedure, and remaining background can be estimated directly from data.

- Only B “peaking” backgrounds rely on MC, and this can be explicitly verified against data.

reconstructed invariant mass of tag B candidate
**B^+ → ℓ^+νγ results**

Unblinded data revealed slight excess over expectation, but consistent with no signal.

<table>
<thead>
<tr>
<th></th>
<th>B→eνγ</th>
<th>B→μνγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>N_{bkg}</td>
<td>2.8 ± 0.6</td>
<td>3.4 ± 0.9</td>
</tr>
<tr>
<td>N_{obs}</td>
<td>4</td>
<td>7</td>
</tr>
</tbody>
</table>

Model independent branching fraction results:

<table>
<thead>
<tr>
<th></th>
<th>B^+→ e^+ν_εγ</th>
<th>B^+→ μ^+ν_μγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>B_{combined}</td>
<td>(6.5^{+7.6}<em>{-4.7}^{+2.8}</em>{-0.8}) × 10^{-6}</td>
<td></td>
</tr>
<tr>
<td>Model-ind. Limits</td>
<td>&lt; 17×10^{-6}</td>
<td>&lt; 26×10^{-6}</td>
</tr>
<tr>
<td>Limits</td>
<td>&lt; 15.6×10^{-6}</td>
<td></td>
</tr>
</tbody>
</table>

**BABAR preliminary**

To be submitted to PRL
Summary

Tag reconstruction techniques provide an extremely clean analysis environment for studies of rare B decay processes which would otherwise lack sufficient kinematic constraints

- tag efficiency is low, but large B factory datasets still make these methods viable
- very interesting sensitivity for high luminosity SuperB factory!

Recent BABAR results on rare leptonic B decays $B^+ \rightarrow l^+ \nu(\gamma)$ provide interesting constraints on New Physics which are fully competitive with expected direct LHC sensitivity
**B⁺/- tag reconstruction**

Realistic tagging efficiency (per B⁺/-) of ~0.24% in events containing a low-multiplicity “signal” event

- typically “signal-side” selection is fairly efficient (~10% - 70%)

Assuming ~30% efficiency gives “single-event sensitivity” at

\[
\text{Br}(B \to \text{rare}) \sim 2 \times 10^{-8} \quad \text{with } 75 \text{ ab}^{-1}
\]

No combinatorial background in signal events!

After continuum background suppression

\[m_{ES} (\text{GeV}/c^2)\]
BABAR analysis (optimized for $\sim$0.5$\text{ab}^{-1}$) can be naively extrapolated to SuperB luminosities

- Simple cut-and-count with no kinematic or angular constraints on the signal lepton or photon

Sensitive to entire SM range with 75$\text{ab}^{-1}$

- Ultimate limitation will likely be $b \rightarrow u \ell \nu$ form factors needed for “peaking” background estimate

Dedicated SuperB study currently in progress
Neutral B tags

Realistic tagging efficiency (per $B^0$) of $\sim 0.16\%$ in events containing a low-multiplicity “signal” event

- Assuming 30\% efficiency gives “single-event sensitivity” at
  \[
  \text{Br}(B \to \text{rare}) \sim 3 \times 10^{-8} \quad \text{with 75 ab}^{-1}
  \]

Obviously, actual sensitivity depends on the level of background...

After continuum background suppression
Run 7

- Data taken between December 16, 2007 and April 7, 2008
  - 30.2 fb\(^{-1}\) at \(\Upsilon(3S)\)
  - 14.5 fb\(^{-1}\) at \(\Upsilon(2S)\)
  - ~5 fb\(^{-1}\) above \(\Upsilon(4S)\) scan
- Several \(\Upsilon(3S)\) analyses and above \(\Upsilon(4S)\) scan presented at ICHEP 2008
Tagged $B^+ \rightarrow l^+ \nu$ ($l = e, \mu$)

- Signal lies at kinematic endpoint in lepton $p^*$ for $B$ decays, hence essentially no $B$ background
- Continuum background can produce high $p^*$ leptons, but this background can be directly determined from data using the tag $B_{ES}$ sideband
- Narrow signal peak would lead to a very compelling signal with a very small number of events

<table>
<thead>
<tr>
<th></th>
<th>$e^+ \nu$</th>
<th>$\mu^+ \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\epsilon_{tot} \times 10^5$</td>
<td>$135 \pm 4$</td>
<td>$120 \pm 4$</td>
</tr>
<tr>
<td>$n_b \text{ MC}$</td>
<td>$2.66 \pm 0.13$</td>
<td>$5.74 \pm 0.25$</td>
</tr>
<tr>
<td>$n_b^*$</td>
<td>$2.67 \pm 0.19$</td>
<td>$5.67 \pm 0.34$</td>
</tr>
<tr>
<td>$n_s^*$</td>
<td>$-0.07 \pm 0.03$</td>
<td>$-0.11 \pm 0.05$</td>
</tr>
<tr>
<td>$B \times 10^{-6}$</td>
<td>$-0.1^{+2.6}_{-1.7}$</td>
<td>$-0.2^{+2.7}_{-1.8}$</td>
</tr>
<tr>
<td>$B^{90% \text{ C.L.}}$</td>
<td>$5.2 \times 10^{-6}$</td>
<td>$5.6 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
Experimentally challenging due to presence of multiple neutrinos:

- Search for 1-prong $\tau$ decays: $\tau \rightarrow e\nu\nu$, $\tau \rightarrow \mu\nu\nu$, $\tau \rightarrow \pi\nu$ and $\tau \rightarrow \pi\pi\pi^0\nu$

- “Topological” signal candidate selection, then require residual calorimeter energy to be consistent with “noise”

BABAR searches based on $383 \times 10^6$ B meson pairs

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (0.9 \pm 0.6\text{(stat.)} \pm 0.1\text{(syst.)}) \times 10^{-4}$$

(SL tag)

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (1.8_{-0.8}^{+0.9} \pm 0.4 \pm 0.2) \times 10^{-4}$$

(Had tag)

Combined result: (2.6σ significance)

$$\mathcal{B}(B^+ \rightarrow \tau^+ \nu) = (1.2 \pm 0.4_{\text{stat.}} \pm 0.3_{\text{bkg.}} \pm 0.2_{\text{syst.}}) \times 10^{-4}.$$
In limit of zero photon energy (actually, below a few 100 MeV) “signal” is helicity suppressed leptonic modes

- KPY model only valid down to ~few hundred MeV

- Difference in models mainly impacts angular distributions
\[ B^+ \rightarrow l^+ \nu \gamma \quad (l = e, \mu) \]
**B→X_uℓν Backgrounds**

Background primarily from $B→π^0ℓν$ with one missing $γ$

Using $B→π^0ℓν$ MC, we’ve categorized the problematic background events for further study:

1. Ineffective $π^0$ veto
   Mis-detected $γ$ energy from detector resolution, split clusters, or pair prod.

2. Either one or both $γ$’s lost down Beam-pipe

3. Mis-reconstructed $B_{tag}$
   1 or both $γ$’s missing from signal-side clusters

4. Combined Cluster of both $γ$’s

5. 2$^{nd}$ $γ$’s Energy Too Low

$π^0$ decays with one $γ$ moving in the same direction as the $π^0$ in the lab frame
Results in a $γ$ whose lab-frame energy is too low for detection (<20 MeV) and a high energy $γ$ that kinematically mimics the signal $γ$.


NP @ tree level and beyond

Tree-level charged Higgs (Type-II 2HDM or MSSM) contribution has the same relative effect on all leptonic modes:

\[ B(B^+ \to l^+ \nu)^{\text{MSSM}} = B(B^+ \to l^+ \nu)^{\text{SM}} \times \left[ 1 - \left( \frac{m_B^2}{m_{H^+}^2} \right) \tan^2 \beta / (1 + \epsilon_0 \tan \beta) \right]^2 \]

- “Universality” preserved at tree level

At one-loop level, potentially large Lepton Flavour Violation (LFV) effects entering from e.g. SUSY in grand unification scenarios:

i.e. \( B^+ \to l^+ \nu_{l'} \) where \( l' \neq l \) via effective \( l H^+ \nu \) coupling

- Observable effects in ratios, \( R_{b \ell/\tau} \), of B leptonic branching ratios:

\[
(R_{B}^{\ell/\tau})_{\text{MSSM}} = (R_{B}^{\ell/\tau})_{\text{SM}} \left[ 1 + \frac{1}{R_{B\tau\nu}} \left( \frac{m_B^4}{M_{H^+}^4} \right) \left( \frac{m_\tau^2}{m_\ell^2} \right) \left[ \Delta_{R}^{\ell/\tau} \right]^2 \frac{\tan^6 \beta}{(1 + \epsilon_0 \tan \beta)^2} \right]
\]

- Uncertainties from \( V_{ub} \) and \( f_B \) cancel in ratio of modes!

\[ \Rightarrow \text{NEED DETERMINATION OF BOTH } \tau \text{ AND } \mu \text{ MODES} \]

Lepton Flavour Violation

• In Standard Model, lepton flavour conservation is not associated with any underlying symmetry principle
  • LFV generally permitted in New Physics models containing more than one Higgs doublet
    • In SUSY seesaw models, flavour changing insertions arise from Yukawa couplings in the slepton mass RGEs:

\[
\begin{align*}
\tau \rightarrow l \gamma \quad (l = e, \mu)
\end{align*}
\]

• \(\Rightarrow\) New Physics effects in \(\tau \rightarrow l \gamma \quad (l = e, \mu)\) can saturate experimental bounds in natural and well-motivated models
  • MSSM with heavy right-handed neutrinos and seesaw mechanism: \(\text{Br} \sim 10^{-7}\)
  • heavy Dirac neutrinos, RPV SUSY models, flavour changing \(Z'\) models...
Higgs mediated LFV

- Higgs mediated LFV present in MSSM at loop level given that there is a source of LFV among sleptons:

\[ \text{Effective SUSY} \]

\[ \tan^2 \beta \]

- Predicts LFV effects in a variety of \( \tau \) and B decay modes (with preference for 3\textsuperscript{rd} generation couplings):

From A. Dedes, Super B Factory proceedings: hep-ph/0503261