Search for the rare decay
$B^+ \rightarrow K^+ \tau^+ \tau^-$ at BaBar

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Outline

• $B^+ \rightarrow K^+\tau^+\tau^-$ Theoretical Motivation
• BaBar Analysis Details
• Signal selection
• Background Estimate
• Expected Results and sensitivity
B$^+ \to K^+ \ell^+ \ell^-$: Electroweak FCNC

$b \to s \ell^+ \ell^-$:

$C_7, C_9$ (vector), and $C_{10}$ (axial).
Observables: branching fraction, $A_{CP}, A_{FB}$.

$$H_{eff} = \frac{4G_F}{\sqrt{2}} \sum_i C_i(\mu, M)O_i$$

Operator Matrix Elements
Encode long-distance contributions, calculated by
heavy quark expansion in powers of $m_b$ or SCET.

Wilson Coefficients
Calculated perturbatively,
describe short-distance physics.

New Physics can alter physical observables.
B$^+ \rightarrow K^+ \ell^+ \ell^-$:

- $B \rightarrow K^+ \ell^+ \ell^-$, where $\ell = e$ or $\mu$.
- FCNC process with branching fraction of $O(10^{-6})$.
- BaBar results: Consistent with SM.

**Phys. Rev. D 86, 032012**
$B^+ \rightarrow K^+ \tau^+ \tau^-$:

- Third generation extension of $B \rightarrow K^+ \ell^+ \ell^-$.

<table>
<thead>
<tr>
<th>$\ell$</th>
<th>$4x \leq \hat{s} \leq 1$</th>
<th>$0.6 \leq \hat{s} \leq 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e$</td>
<td>$1.2 \times 10^{-5}$</td>
<td>$8.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\mu$</td>
<td>$1.0 \times 10^{-5}$</td>
<td>$8.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>$\tau$</td>
<td>$5.4 \times 10^{-7}$</td>
<td>$4.3 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

- New physics could enter the loop and alter the branching fraction

- No long distance contribution from $J/\psi \rightarrow \tau^+ \tau^-$. $B(\psi(2S) \rightarrow \tau^+ \tau^-) = 3.0 \times 10^{-4}$
BaBar Experiment:

- Located at SLAC National Accelerator Laboratory
- $e^+e^-$ collisions at CM energy of 10.58 GeV ~ mass of $\Upsilon(4S)$.

Data Collection: 1999 to 2008
Total integrated luminosity, at the $\Upsilon(4S)$ resonance, of 429 fb$^{-1}$.
471 million $\bar{B}B$ pairs.
Analysis Tools:

• Full BaBar dataset: 429 fb\(^{-1}\).
  – Data, in the region of interest, is **blinded** until analysis is finalized.

• Signal Monte Carlo:
  – Dedicated MC samples where \( B^+ \rightarrow K^+ \tau^+ \tau^- \) governed by Ali Model (Phys Rev D 61, 074024)

\[ B^+ \rightarrow K^+ \tau^+ \tau^- : \text{Consider only leptonic final states.} \]

<table>
<thead>
<tr>
<th>Mode</th>
<th>( \tau ) decay</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>( \tau^+ \rightarrow e^+ \bar{\nu}<em>e \nu</em>\tau ), ( \tau^- \rightarrow e^- \bar{\nu}<em>e \nu</em>\tau )</td>
</tr>
<tr>
<td>Muon</td>
<td>( \tau^+ \rightarrow \mu^+ \bar{\nu}<em>\mu \nu</em>\tau ), ( \tau^- \rightarrow \mu^- \bar{\nu}<em>\mu \nu</em>\tau )</td>
</tr>
<tr>
<td>Electron-Muon</td>
<td>( \tau^+ \rightarrow \mu^+ \bar{\nu}<em>\mu \nu</em>\tau ), ( \tau^- \rightarrow e^- \bar{\nu}<em>e \nu</em>\tau )</td>
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**Background Monte Carlo**

Five types:

\( B^+ \rightarrow K^+ \tau^+ \tau^- \)

\( Y(4S) \rightarrow B \bar{B} \) occurs, but \( B \) does not decay via \( B^+ \rightarrow K^+ \tau^+ \tau^- \)

No \( Y(4S) \) formed, \( e^+e^- \rightarrow l^+l^- \) or \( q\bar{q} \)
Hadronic $B_{\text{tag}}$ Reconstruction:

- Reconstruct first $B$, $B_{\text{tag}}$, from hadronic modes, using $B \rightarrow D + X$.
- The remaining tracks and clusters are attributed to $B_{\text{sig}}$.

Isotropc $B\bar{B}$ events

Jet-like continuum events

Ratio $> 0.5$
Signal Selection: $B_{\text{sig}}$ side

- $E_{\text{miss}} > 0$.
  - $E_{\text{miss}} = p_Y - p_{\text{Btag}} - p_{\text{tracks}} - p_{\text{clusters}}$.
- $Q_{\text{tot}} = -Q_{\text{Btag}}$.
- Exactly 3 tracks, passing Particle Identification (PID) for one Kaon and two leptons.
- $\pi^0$ veto
  - Any 2 clusters with $E > 30 \text{ MeV}$, $E_{\text{sum}} > 200 \text{ MeV}$ and $0.1 < M_{\text{sum}} < 0.16 \text{ GeV}$.

Look at mass combinations of tracks at this point to identify potential backgrounds.
Signal Selection:

Leptonic Modes:

- **J/ψ peak**
- **D^0 peak:** muons mis-ID as pions.

- Photon conversions

O~ 50 events

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Signal Selection:

- Exactly three tracks.
- One kaon: $Q_k = -Q_{\text{btag}}$
- Two Oppositely charged Leptons ($e^+e^-$ or $\mu^+\mu^-$ or $e^+\mu^-$) 
- $\pi^0$ veto
  - Any 2 clusters with $E>30$ MeV, $0.1<l_m<0.8$, $E_{\text{sum}}>200$ MeV and $0.1<M_{\text{sum}}<0.16$ GeV.
- $J/\psi$ veto
  - Sum of 2 leptons does not lie $3.00<M_{l+l^-}<3.194$ GeV.
- Photon conversions veto
  - Require sum of $e^+$ with any other oppositely charged track has a mass $>50$ MeV.
- $D^0$ veto
  - Require sum of Kaon with any oppositely charged lepton does not lie within the mass region $1.80<M_{K+l^-}<1.90$ GeV.
$S_B$ Cut:

$$S_B = \frac{q^2}{m_B^2} = \frac{p_{Bsig}^2 - p_K^2}{m_B^2}$$

Kaon Momentum in Signal MC

Heavy tau mass impose upper limit on kaon momentum.

Large number of B+B- events surviving signal cuts

$s_B > 0.45$
Signal Selection: Dominant Background

Use TMVA to suppress dominant backgrounds using a set of discriminating variables.

Angle between Kaon and oppositely charged lepton in di-tau frame.

di-tau frame defined as the frame recoiling against the Kaon
Signal Selection: Dominant Background

9 Input variables:
• 3 calorimeter
• 2 Kinematic
• 4 angular

\[ E_{\text{miss}} = \vec{p}_B - (\vec{p}_K + \vec{p}_{l+} + \vec{p}_{l-}) \]

\[ \cos(\theta_{l+l}) \]
TMVA Cut:

**Electron**
- MLP > 0.70

**Muon**
- MLP > 0.75

**Elec-Muon**
- MLP > 0.75
Control Study:

\[ B^+ \rightarrow \bar{D}^0 l^+ \nu \quad \bar{D}^0 \rightarrow K^+ \pi^- \]

- Need to verify data-MC agreement after TMVA cut.
- Reverse TMVA cut on control sample in increments of 0.05.

Data/MC Yield:
- MLP<0.75: 0.979 +/- 0.029
- MLP<0.70: 0.978 +/- 0.030

Good agreement between data and MC
Background Estimate: $m_{ES}$ sideband substitution

Two types of background:
• Combinatorial background: $cc, \tau^+\tau^-, q\bar{q}$, and mis-reconstructed $B\bar{B}$.
• Peaking background: Properly reconstructed $B\bar{B}$.

- Estimate combinatorial background using data in $m_{ES}$ sideband region.
- Correct peaking background to match peaking data component.
Unblinded Data in MLP<0.5:

Before $m_{ES}$ sideband substitution:

After $m_{ES}$ sideband substitution:
# Systematic Errors

<table>
<thead>
<tr>
<th>Source</th>
<th>Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical Uncertainty</td>
<td>~2-3%</td>
</tr>
<tr>
<td>$B_{\text{tag}}$ Yield</td>
<td>~3-5%</td>
</tr>
<tr>
<td>Kaon PID</td>
<td>~2-4%</td>
</tr>
<tr>
<td>Lepton PID</td>
<td>~5-7%</td>
</tr>
<tr>
<td>$\pi^0$ Reconstruction</td>
<td>~3%</td>
</tr>
<tr>
<td>Background BFs</td>
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<tr>
<td>TMVA Cut</td>
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- **Source**
  - **Theoretical Uncertainty**: ~2-3%
  - **$B_{\text{tag}}$ Yield**: ~3-5%
  - **Kaon PID**: ~2-4%
  - **Lepton PID**: ~5-7%
  - **$\pi^0$ Reconstruction**: ~3%
  - **Background BFs**: ~2-3%
  - **TMVA Cut**: ~9%

- **Compare signal efficiency between signal MC generated with BALL model and phasepace.**
- **Vary the shape of the combinatorial $m_{ES}$ (continuum instead of mis-charged BB).**
- **Data-MC comparison using information from PID performance plots.**
- **Apply $\pi^0$ reconstruction on control sample and calculate the difference in relative efficiency.**
- **Use TMVA output in TMVA sideband region: MLP<0.5 to estimate data-MC difference.**
- **Vary background BFs by their PDG uncertainty and determine the difference in bkg estimate.**
## Expected Sensitivity

<table>
<thead>
<tr>
<th>Mode</th>
<th>Signal Efficiency (x 10⁻⁶)</th>
<th>Non-Peaking Bkg</th>
<th>Peaking Bkg</th>
<th>Central Limit (x 10⁻⁴)</th>
<th>Upper Limit (x 10⁻⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>11.2 ± 1.8</td>
<td>4.44 ± 0.83</td>
<td>37.4 ± 1.9</td>
<td>0.38</td>
<td>20.1</td>
</tr>
<tr>
<td>Muon</td>
<td>11.5 ± 1.9</td>
<td>4.75 ± 0.87</td>
<td>21.9 ± 1.6</td>
<td>0.69</td>
<td>18.5</td>
</tr>
<tr>
<td>Elec-Muon</td>
<td>21.2 ± 2.5</td>
<td>6.82 ± 1.0</td>
<td>47.5 ± 2.3</td>
<td>0.70</td>
<td>12.1</td>
</tr>
<tr>
<td>Combined</td>
<td>---</td>
<td>----</td>
<td>----</td>
<td>0.64</td>
<td>8.26</td>
</tr>
</tbody>
</table>

Systematic Errors are NOT included.

Limits calculated assuming $N_{\text{obs}} \sim N_{\text{bkg}}$. 
Conclusion

• $B^+ \rightarrow K^+\tau^+\tau^-$ : FCNC process, stringent test of the Standard Model.
• Current expected sensitivity of $O(10^{-4})$.
• Analysis to be published in the upcoming year (after finalizing systematics.)
BACK UP SLIDES
Signal Selection: $B_{\text{tag}}$ Side

Continuum likelihood suppression using event shape variables.

Jet-like continuum events

Isotropic BB events

<table>
<thead>
<tr>
<th>R2All</th>
<th>Thrust$_z$</th>
<th>cos$\theta_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
</tbody>
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<table>
<thead>
<tr>
<th>cos$\theta_{\text{Pmiss}}$</th>
<th>Thrust Magnitude</th>
<th>cos$\theta_B$</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image4.png" alt="Graph" /></td>
<td><img src="image5.png" alt="Graph" /></td>
<td><img src="image6.png" alt="Graph" /></td>
</tr>
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Signal BF of 0.1
Discriminating variables

Angle between Vector Recoiling against the Kaon and low momentum lepton in CM frame.

Angle between Bs and oppositely charged lepton in CM frame.
Discriminating variables:

- **Kaon Momentum**
- **Missing Energy** \( E_{\text{miss}} = p_B - (p_K + p_{l+} + p_{l-}) \)
- **Lepton Momentum**

Leptons with charge opposite to Kaon.
Background Estimate: mES sideband substitution

Two types of background:
• Combinatorial background: c\bar{c}, \tau^+\tau^-, uds, and mis-reconstructed B\bar{B}.
• Peaking background: Properly reconstructed B\bar{B}.

Combinatorial background is determined using data in the sideband m_{ES} region.
Sideband data is scaled by a cumulative Ratio:

\[ R = \frac{\text{Number of MC combinatorial events in } m_{ES} \text{ signal region}}{\text{Number of events in the } m_{ES} \text{ sideband region}} \]

B+B- MC combinatorial component is assumed to be the same as B^0B^0 for charged modes:

\[ R_{B^0B^0} = \frac{N_{B^0B^0}^{\text{signal}}}{N_{B^0B^0}^{\text{sideband}}} \]
$m_{ES}$ sideband substitution:

Two types of background:
- Combinatorial background: $c\bar{c}$, $\tau^+\tau^-$,uds, and mis-reconstructed $B\bar{B}$.
- Peaking background: Properly reconstructed $B\bar{B}$.

Peaking component is estimated using $B^+\bar{B}^-$ or $B^0\bar{B}^0$ MC, depending on the charge of the signal mode. Peaking component of $B^+\bar{B}^-$ or $B^0\bar{B}^0$ is isolated and scaled by a correction factor, $CF$, to match the peaking data.

$$CF = \frac{N_{data}}{N_{BB}}$$

Before:

After:
Ratio and Correction Factor

Ratio for $B \rightarrow K^+ \tau^+ \tau^-$ Signal Selection

- Chosen after applying PID cuts

Correction Factor for $B \rightarrow K^+ \tau^+ \tau^-$ Signal Selection

- Chosen after applying PID cuts

Ratio used to scale sideband data and estimate non-peaking background.  
**0.352 +/- 0.006**

Correction factor used to correct differences between Monte Carlo peaking background and peaking data.  
**0.868 +/- 0.012**
TMVA: Neural Network

• Use a Neural Network to separate between signal and background.

• 9 Input variables: 5 calorimeter and 4 angular.

• Both signal and background samples are randomly split in half for training and testing.
Signal Selection: $B_{tag}$ side

Purity:

Fraction of properly reconstructed $B_{tag}$'s within a decay mode.

For each decay mode, the daughter *tracks* of the $B_{tag}$ are truth-matched:

- The number of pions, kaons, and $K_{s0}$ is determined for each mode.
- This number is compared with the actual number of each particle type originating from the $B_{tag}$ according to MC truth.
Control Study:

\[ B^+ \rightarrow \bar{D}^0 l^+ \nu \bar{D}^0 \rightarrow K^+ l^- \nu \]

Apply TMVA on control and data sample, and then reverse TMVA Cut in increments of 0.05.

Data/MC Yield:

MLP < 0.75: 0.979 +/- 0.029
MLP < 0.70: 0.978 +/- 0.030