Searches for exotica at \textit{BaBar}

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- Search for lepton-number violating (LNV) processes  
  \[ B^+ \rightarrow X^- l^+ l'^+ \]

- Search for a dark photon in  
  \[ e^+ e^- \rightarrow \gamma A', \quad A' \rightarrow e^+ e^-, \mu^+ \mu^- \]
Data taking period: 1999-2008

\( \Upsilon(4S): \ 424 \text{ fb}^{-1} \)

\( \Upsilon(3S): \ 28 \text{ fb}^{-1} \)

\( \Upsilon(2S): \ 14 \text{ fb}^{-1} \)

corresponding to: \( 471 \times 10^6 B \bar{B} \)

between the \( b \bar{b} \) resonances: \( 48 \text{ fb}^{-1} \)

\[ E(e^+e^-) = \sqrt{s} \sim 10.58 \text{ GeV} = m(\Upsilon(4S)) \sim 2 \cdot m(B) \]

\[ \Delta E = E^*(B) - \sqrt{s}/2 \]

\[ m_{ES} = \frac{1}{c^2}\sqrt{s/4 - p'^*2(B) \cdot c^2} \]
\[ B^+ \rightarrow X^- l^+ l'^+ \]

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\[ B^+ \rightarrow K^- e^+ e^+ \]
\[ B^+ \rightarrow K^- e^+ \mu^+ \]
\[ B^+ \rightarrow K^- \mu^+ \mu^+ \]
\[ B^+ \rightarrow \rho^- e^+ e^+ \]
\[ B^+ \rightarrow \rho^- e^+ \mu^+ \]
\[ B^+ \rightarrow \rho^- \mu^+ \mu^+ \]
\[ B^+ \rightarrow D^- e^+ e^+ \]
\[ B^+ \rightarrow D^- e^+ \mu^+ \]
\[ B^+ \rightarrow D^- \mu^+ \mu^+ \]
\[ B^+ \rightarrow K^- e^+ \mu^+ \]
\[ B^+ \rightarrow \pi^- e^+ \mu^+ \]

charge-conjugated modes are implied for this analysis
Motivation

- Matter-Antimatter asymmetry in the universe requires LNV processes
- Neutrinos should have a mass due to observed neutrino oscillations
- Majorana type neutrinos could make LNV possible
- LNV also introduced in many other New Physics scenarios

\[ \bar{b} \rightarrow W^+ \nu/\bar{\nu} \rightarrow W^+ l^+ \bar{b} \]
Selection criteria

- **Particle identification** for all tracks

- **$e^+$ and $e^-$ from photon conversions are removed**

- **Momentum requirements** on the lepton tracks

- **$K^*^- \rightarrow K^0_S \pi^-$, $K^- \pi^0$$\rho^- \rightarrow \pi^- \pi^0$$D^- \rightarrow K^+ \pi^- \pi^-$$**

  (with usual requirements on invariant mass, flight length, ...)

- **Boosted decision tree (BDT) discriminant used to suppress background**

- **$B$ candidate vertex fit**: If there are more than one $B$ candidate per event, use only the one with the highest fit probability
Signal extraction

- Unbinned maximum likelihood fit in $\Delta E$, $m_{ES}$, and BDT output
  - for modes with resonances, the invariant resonance mass is included in the fit too

- Signal shape parameters are fixed using Monte Carlo distributions

$$B^+ \rightarrow \pi^- e^+ \mu^+$$

line: signal+background fit
dashed line: background PDF
solid histogram: signal PDF
## Results

<table>
<thead>
<tr>
<th>Mode</th>
<th>Events</th>
<th>Yield</th>
<th>$\eta$(%)</th>
<th>$\Pi B_i$(%)</th>
<th>$S(\sigma)$</th>
<th>$B \times 10^{-7}$</th>
<th>$B_{UL} \times 10^{-7}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^{*-} e^+ e^+$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K^{*-} \rightarrow K^- \pi^0$</td>
<td>63</td>
<td>3.8 ± 3.3</td>
<td>11.5 ± 0.1</td>
<td>33.3</td>
<td>1.2</td>
<td>1.7 ± 1.4 ± 0.1</td>
<td>4.0</td>
</tr>
<tr>
<td>$K^{*-} \rightarrow K_S^0 \pi^-$</td>
<td>91</td>
<td>0.8 ± 3.9</td>
<td>12.3 ± 0.1</td>
<td>22.8</td>
<td>0.3</td>
<td>0.6 ± 2.9 ± 0.2</td>
<td>6.0</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*-} e^+ \mu^+$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.0</td>
<td>−4.5 ± 2.6 ± 0.4</td>
</tr>
<tr>
<td>$K^{*-} \rightarrow K^- \pi^0$</td>
<td>117</td>
<td>−1.9 ± 4.7</td>
<td>7.9 ± 0.1</td>
<td>33.3</td>
<td>0.0</td>
<td>−1.5 ± 3.8 ± 0.4</td>
<td>6.5</td>
</tr>
<tr>
<td>$K^{*-} \rightarrow K_S^0 \pi^-$</td>
<td>172</td>
<td>−5.1 ± 2.6</td>
<td>8.5 ± 0.1</td>
<td>22.8</td>
<td>0.0</td>
<td>−6.0 ± 2.8 ± 0.7</td>
<td>4.2</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^{*-} \mu^+ \mu^+$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.3</td>
<td>2.4 ± 1.8 ± 0.4</td>
</tr>
<tr>
<td>$K^{*-} \rightarrow K^- \pi^0$</td>
<td>85</td>
<td>2.3 ± 1.8</td>
<td>6.1 ± 0.1</td>
<td>33.3</td>
<td>1.3</td>
<td>2.0 ± 1.8 ± 0.2</td>
<td>7.0</td>
</tr>
<tr>
<td>$K^{*-} \rightarrow K_S^0 \pi^-$</td>
<td>98</td>
<td>2.0 ± 1.8</td>
<td>5.8 ± 0.1</td>
<td>22.8</td>
<td>1.0</td>
<td>3.1 ± 2.9 ± 0.9</td>
<td>9.8</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^- e^+ e^+$</td>
<td>411</td>
<td>−2.1 ± 5.7</td>
<td>12.1 ± 0.1</td>
<td>100.0</td>
<td>0.0</td>
<td>−0.4 ± 1.0 ± 0.1</td>
<td>1.7</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^- e^+ \mu^+$</td>
<td>1651</td>
<td>4.6 ± 11.4</td>
<td>10.3 ± 0.1</td>
<td>100.0</td>
<td>0.4</td>
<td>1.0 ± 2.4 ± 0.2</td>
<td>4.7</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^- \mu^+ \mu^+$</td>
<td>936</td>
<td>2.9 ± 6.8</td>
<td>7.3 ± 0.1</td>
<td>100.0</td>
<td>0.5</td>
<td>0.9 ± 2.0 ± 0.3</td>
<td>4.2</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^- e^+ e^+$</td>
<td>401</td>
<td>3.9 ± 4.8</td>
<td>10.2 ± 0.1</td>
<td>9.13</td>
<td>1.0</td>
<td>8.8 ± 8.6 ± 1.5</td>
<td>26</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^- e^+ \mu^+$</td>
<td>549</td>
<td>1.1 ± 3.2</td>
<td>7.7 ± 0.1</td>
<td>9.13</td>
<td>0.5</td>
<td>3.4 ± 9.4 ± 1.1</td>
<td>21</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^- \mu^+ \mu^+$</td>
<td>229</td>
<td>−1.7 ± 2.5</td>
<td>5.7 ± 0.1</td>
<td>9.13</td>
<td>0.0</td>
<td>−6.5 ± 9.9 ± 0.9</td>
<td>17</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^- e^+ \mu^+$</td>
<td>117</td>
<td>5.5 ± 3.5</td>
<td>15.2 ± 0.1</td>
<td>100.0</td>
<td>1.8</td>
<td>0.6 ± 0.5 ± 0.1</td>
<td>1.6</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^- e^+ \mu^+$</td>
<td>464</td>
<td>3.8 ± 3.5</td>
<td>16.4 ± 0.2</td>
<td>100.0</td>
<td>1.2</td>
<td>0.5 ± 0.5 ± 0.1</td>
<td>1.5</td>
</tr>
</tbody>
</table>

ULs at the 90% C.L.

($B^+ \rightarrow K^- e^+ e^+$, $B^+ \rightarrow K^- \mu^+ \mu^+$, $B^+ \rightarrow \pi^- e^+ e^+$, and $B^+ \rightarrow \pi^- \mu^+ \mu^+$ previously analyzed, used in this analysis as a crosscheck only)
## Results

<table>
<thead>
<tr>
<th>$B$ decay mode</th>
<th>$\text{BABAR}$ result (@90% CL)</th>
<th>previous UL</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+ \rightarrow K^*-e^+e^+$</td>
<td>4.0</td>
<td>28 (CLEO, @90% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^*-e^+\mu^+$</td>
<td>3.0</td>
<td>44 (CLEO, @90% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^*-\mu^+\mu^+$</td>
<td>5.9</td>
<td>83 (CLEO, @90% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^-e^+e^+$</td>
<td>1.7</td>
<td>26 (CLEO, @90% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^-e^+\mu^+$</td>
<td>4.7</td>
<td>33 (CLEO, @90% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow \rho^-\mu^+\mu^+$</td>
<td>4.2</td>
<td>50 (CLEO, @90% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^-e^+e^+$</td>
<td>26</td>
<td>26 (BELLE, @90% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^-e^+\mu^+$</td>
<td>21</td>
<td>18 (BELLE, @90% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow D^-\mu^+\mu^+$</td>
<td>17</td>
<td>6.9 (LHCb, @95% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow K^-e^+\mu^+$</td>
<td>1.6</td>
<td>20 (CLEO, @90% CL)</td>
</tr>
<tr>
<td>$B^+ \rightarrow \pi^-e^+\mu^+$</td>
<td>1.5</td>
<td>13 (CLEO, @90% CL)</td>
</tr>
</tbody>
</table>
Search for a dark photon in

\[ e^+e^- \rightarrow \gamma A', \quad A' \rightarrow e^+e^-, \mu^+\mu^- \]

arXiv:1406.2980, submitted to PRL
Motivation

- Dark matter particles don’t interact much with Standard Model (SM) particles

- Possibility: new $U(1)'$ with corresponding dark photon $A'$
  - could couple to the SM hypercharge via kinetic mixing
  - mixing strength: $\epsilon$
  - effective interaction between dark photon and electromagnetic current: $\epsilon e A'_\mu J^\mu_{EM}$
  - these dark photons would mediate annihilation of dark matter particles into SM fermions

- If such $A'$ is the reason for observed anomalies in cosmic rays, the mass of $A'$ should be in the range of MeV/$c^2$ to about 2 GeV/$c^2$ (Positron excess and lack of antiprotons)

  We can probe $0.02 \text{ GeV}/c^2 < m_{A'} < 10 \text{ GeV}/c^2$
• Events with 2 oppositely charged tracks and a single photon are selected

• Particle ID requirements for the charged tracks

• Fitted with a beam-energy constraint and charged tracks coming from a common vertex

• Neural network used to suppress $e^+e^- \rightarrow \gamma e^+e^-$ SM interactions

• Resonant regions in $m_{ll}$ are excluded in the search
  $(\omega, \phi, J/\psi, \psi(2S), \Upsilon(2S), \text{and } \Upsilon(3S))$
Signal extraction

- $m_{e^+e^-}$ and reduced muon mass $m_R = \sqrt{m_{\mu\mu}^2 - 4m_\mu^2}$ are divided in intervals
  - 20$\sigma$ to 30$\sigma$ of the expected signal resolution in $m(A')$ wide
    signal resolution between 1.5 MeV/$c^2$ and 8 MeV/$c^2$

- Fit performed in each interval

- Data taken at different beam energies are fitted separately and results combined

- All of BABAR data is used
Results

Grey bands show excluded mass regions due to resonances

\[ S_S = \sqrt{2 \log(\mathcal{L}/\mathcal{L}_0)} \]

Can be translated to the mixing strength as a function of \( m_{A'} \)…
• *BABAR* 2009 based on search for light CP-odd Higgs boson using only a subsample of data used in this analysis

• Range of the parameter space motivated by interpretation of the discrepancy between measured and calculated $(g-2)_\mu$ mostly excluded

\[ 15 \text{ MeV}/c^2 \lesssim m_{A'} \lesssim 30 \text{ MeV}/c^2 \] remains
Summary

- 11 Lepton Number Violating modes analyzed
  - For $B^+ \rightarrow K^- l^+ l'^+$, $B^+ \rightarrow K^*^- l^+ l'^+$, and $B^+ \rightarrow \rho^- l^+ l'^+$ UL improved by an order of magnitude
  - UL for $B^+ \rightarrow D^- l^+ l'^+$ in agreement with Belle and LHCb measurements

- Searched for a dark photon in the region $0.02 \text{ GeV}/c^2 < m_{A'} < 10 \text{ GeV}/c^2$
  - Significant improvements over previous constraints obtained by different experiments
  - Upper limits for mixing strength $\epsilon$ are set at the level of $10^{-4} - 10^{-3}$
  - Almost all of the remaining parameter regions favored by the discrepancy between measured and calculated $(g - 2)_\mu$ is excluded
Many talks and posters presented by *BABAR* at ICHEP.

Two are related to this topic:

- “Poster presentation on Dark Photon search at *BABAR*” presented by Prof. David Hitlin

- “Search for low-mass CP odd Higgs boson” by Rocky So

Thank you for your attention!