Searching for baryon number violation in the BaBar dataset and elsewhere

LEPP Journal Club
Cornell University

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Siena College

Katherine Ollier / Flickr

http://www.techvalleyconnect.com
http://maps.google.com
Jim was my thesis advisor.
1 Motivation

2 BaBar

3 Blind analyses

4 Our search

5 Other places to look

6 Summary
Motivation
Motivation

• Our universe is matter...not anti-matter.
Motivation

- Our universe is **matter**...not **anti-matter**.
- \( t = \) early universe:
  - matter = anti-matter
Motivation

- Our universe is **matter**...not **anti-matter**.
- \( t = \) early universe:
  - matter = anti-matter
- \( t = \) now:
  - matter \( \neq \) anti-matter
- How do we know?
  - Cosmic ray's are mostly matter.
  - \( \gamma \)-ray spectrum.
- Universe is compartmentalized?
  - Very difficult theoretically.
Sakharov conditions

- Andrei Sakharov (1967)
- "Violation of CP Invariance, c Asymmetry, and Baryon Asymmetry of the Universe."
- Three conditions required for matter (baryon) asymmetry. [Sak67]
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  1. Early universe is out of thermal equilibrium.
     - Rate for $\psi_{B=0} \rightarrow \psi_{B\neq 0}$ is different than for $\psi_{B\neq 0} \rightarrow \psi_{B=0}$.
     - The universe is cooling!

- C and CP-violation
- Baryon number violation
  - Implies sum of baryons + anti-baryons is a non-conserved quantity.
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     • Decay rates are different for matter and anti-matter.
  3. Baryon number violation
     • Implies sum of baryons + anti-baryons is a non-conserved quantity.

• Let’s look at these last two...
Direct CP-violation

- Direct CP-violation
  - $B^0 \rightarrow K^+\pi^-$
  - $\bar{B}^0 \rightarrow K^-\pi^+$

Decay rates are different!

Sakharov condition # 2!

Preliminary

BABAR

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Direct CP-violation

- Direct CP-violation
  - $B^0 \rightarrow K^+\pi^-$
  - $\bar{B}^0 \rightarrow K^-\pi^+$
- Decay rates are different!
- $A_{CP} \approx -0.1$
- Sakharov condition # 2!
Baryon number violation

- Baryon number violation actually *does* exist in the Standard Model.
  - Sphaleron, a non-perturbative process.
  - Occurs at very high temperatures. $T = 100\text{GeV}$. ($10^{15}\text{K}$)
  - Only found immediately after the big bang.

- **Sakharov condition # 3!**
Motivation

• Does this predict our asymmetric universe?
  • $B$ for baryon
  • $B + \bar{B}$ annihilations in the early universe produced photons.
  • Asymmetry parameter ($\eta$).

\[ \eta = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx 10^{-9} \]
Motivation

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  • \( B + \bar{B} \) annihilations in the early universe produced photons.
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\[
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• Combination of observed \textit{CP} violation and theoretical BNV in Standard Model is insufficient by 10 orders of magnitude!!!
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- Combination of observed \textit{CP}-violation and and theoretical BNV in Standard Model is insufficient by 10 orders of magnitude!!!
- Additional \textit{CP} violation? \textit{Much work out there...no smoking gun}.
- Additional BNV?
- 1974, "\textit{Unity of All Elementary Particle Forces}," Georgi and Glashow
  - Proton decay mediated by heavy bosons ($X$ & $Y$) which couple to \textit{quarks} and \textit{leptons}.
- Many Grand Unified Theories $\Rightarrow$ BNV
- How would proton decay work?
Proton decay

New interaction with new gauge bosons.

- $X$ has charge $q = +\frac{1}{3}$
  - $X \rightarrow q + q$
  - $X \rightarrow q + \ell$
- B-L is the conserved quantity
Leptoquark limits and predictions

Experimental work
Super-Kamiokande
Proton lifetime $> 10^{29}$ years!

Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo [KO]
Proton decay

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- $X \to q + q$
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Proton decay

• $X$ is $q = \frac{1}{3}$
  • $X \rightarrow q + q$
  • $X \rightarrow q + \ell$

• B-L is conserved quantity.

• Hypothesize a flavour/generation dependance to this interaction...

\[
\begin{pmatrix}
X_{ud} & X_{cd} & X_{td} \\
X_{us} & X_{cs} & X_{ts} \\
X_{ub} & X_{cb} & X_{tb}
\end{pmatrix}
\]

\[
\begin{pmatrix}
X_{\bar{u}e} & X_{\bar{c}e} & X_{\bar{t}e} \\
X_{\bar{u}\mu} & X_{\bar{c}\mu} & X_{\bar{t}\mu} \\
X_{\bar{u}\tau} & X_{\bar{c}\tau} & X_{\bar{t}\tau}
\end{pmatrix}
\]

• $B^0 \rightarrow \Lambda_c^+ \ell^-$
• $B^+ \rightarrow \Lambda^0 \ell^+$

$\ell = \mu$ or $e$
Experimental and theoretical constraints

Experimental work

- Tevatron, HERA, LHC searches for leptoquarks.
  \[ M_{LQ} > 300 - 1000 \text{ GeV}/c^2 \]

- "Baryon number violation involving higher generations."
  [HNS05]

- Uses proton decay to constrain upper limits.

- \[ B(B_0) \rightarrow +c\ell < 4 \times 10^{-29} \]

- "Despite our findings, we believe it is still worth to look for BNV processes in charm, \( B \), and maybe in the future in top decays."

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\( B \text{ mixing} \)
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Experimental work

- Tevatron, HERA, LHC searches for leptoquarks.
  \[ M_{LQ} > 300 - 1000 \text{ GeV}/c^2 \]

Theoretical work

- “Baryon number violation involving higher generations.”, Hou, et.al. [HNS05]
  - Uses proton decay to constrain upper limits.
  - \( B(B^0) \rightarrow \Lambda_c^+ \ell^- < 4 \times 10^{-29} \)
  - “Despite our findings, we believe it is still worth to look for BNV processes in \( \tau \), charm, \( B \), and maybe in the future in top decays.”
BaBar and SLAC
- BaBar at SLAC
- 1999-2008

BaBar

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BaBar

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- PEP-II asymmetric $e^+e^-$ collider
  - Ran on $\Upsilon(4S)$
  - Instantaneous $\mathcal{L} = 10^{-34}$ cm$^{-2}$ s$^{-1}$
- 1 billion $B$ mesons

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- PEP-II asymmetric $e^+e^-$ collider
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- 1 billion $B$ mesons
- Backgrounds (or other physics!)
  - $e^+e^- \rightarrow u\bar{u}/d\bar{d}/s\bar{s}/c\bar{c}$
  - $e^+e^- \rightarrow e^+e^-/\mu^+\mu^-/\tau^+\tau^-$
- 400+ papers and counting.
- Excellent momentum and spatial resolution.
Layers of detectors
- Sophisticated particle ID.
- Inner silicon vertex detector.
  - Energy, spatial position (momentum)
- Drift chambers.
  - Energy, momentum
- Cerenkov detector (DIRC)
  - Velocity ($\pi/K$ ID)
- Muon detection in outer region
  - Timing, spatial position
- All fed into a neural net algorithm.
- Gives analysts 6 levels.
  - For each particle type ($e, \mu, p, \pi, K$)
  - Vary purity/efficiency.
  - Function of kinematics.
$b$ quark production at an $e^+ e^-$ collider
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b quark production at an $e^+ e^- \text{ collider}$
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$e^+ \rightarrow b \bar{q} \rightarrow q \bar{b}$
b quark production at an $e^+ e^-$ collider
\[ B^0 \rightarrow \Lambda_c \ell^- \]
\[ B^- \rightarrow \Lambda \ell^- \]
\[ B^- \rightarrow \bar{\Lambda} \ell^- \]
Our search

\[ \ell = \mu \text{ or } e \]

\[ B^0 \rightarrow \Lambda^+_c \ell^- \]

\[ \rightarrow \]

\[ e^- \rightarrow e^+ \]

Experimental requirements:

• Cleanly identify 3-4 charged particles.
• Demonstrate they came from a B meson.

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B mixing 25 / 52
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\[ B^0 \rightarrow \Lambda_c^+ \ell^- \]
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\[ B^- \rightarrow \Lambda^0 \ell^- \]
\[ \Lambda^0 \rightarrow p\pi^- \]

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Blind analyses
Blind searches

Blind searches (Roodman, [Roo03])
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- *Experimenter’s bias.*
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- Medical field: double blind trials.
- Electron $e/m$, Dunnington (1933)
Blind searches

Blind searches (Roodman, [Roo03])

- *Experimenter’s bias.*
- Medical field: double blind trials.
- Electron $e/m$, Dunnington (1933)
- *History of measurements?*
- How do you guard against this?
- Don’t look!

Figure 2: A historical perspective of values of a few particle properties tabulated in this Review as a function of date of publication of the Review. A full error bar indicates the quoted error; a thick-lined portion indicates the same but without the “scale factor.”

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Blind searches

Hidden signal box.

- $K_L^0 \rightarrow \mu^\pm e^\mp$
- Ariska, *PRL* 70, 1993
- FNAL, E791

**Kinematics dictates region of interest.**

**Other approaches: hidden answer, random noise.**
Blind search

CDMS (2009), dark matter search
Our search
Signal and backgrounds

\[ \text{Signal} \]
\[ e^+ e^- \rightarrow B \bar{B} \]
\[ B \rightarrow \Lambda_{(c)} \ell \]
**Signal and backgrounds**

**Signal**

\[ e^+ e^- \rightarrow B\bar{B} \]

\[ B \rightarrow \Lambda_{(c)} \ell \]

**Backgrounds**

**Standard Model decays**

\[ e^+ e^- \rightarrow q\bar{q} \quad (q = c, s, u, d) \]

\[ e^+ e^- \rightarrow \ell^+ \ell^- \quad (\ell = \tau, \mu, e) \]
Particle Identification (PID)

- Optimize PID for kinematics.
- e.g. $\Lambda_c^+ \rightarrow pK^-\pi^+$
- Loose PID
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- Optimize PID for kinematics.
- e.g. $\Lambda_c^{+} \rightarrow pK^-\pi^+$
- Loose PID
- Some set of PID criteria.

\[ M(pK^-\pi^+) \text{ GeV/c}^2 \]

\[ \text{events/MeV} \]

\[ B \text{ mixing} \]

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- Use $\Lambda_c^+$ efficiency and background rejection to optimize selection.

![Histogram of $M(pK^-\pi^+)$]
Particle Identification (PID)

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- Loose PID
- Some set of PID criteria.
- Use $\Lambda_c^+$ **efficiency** and **background rejection** to optimize selection.
- $\Lambda$: $ct = 7.89$ cm
- Select transverse flight length $> 0.2$ cm and loose PID criteria.
Multivariate discriminator

TMVA http://tmva.sourceforge.net/

- Six variables: $B \cos(\theta)$ CM and 5 shape variables
- Neural network algorithm was used.

Figure: $\Lambda_{c\mu^-}$ Comparison between signal MC and $q\bar{q}$ MC.
Optimization of candidate selection.

- Punzi figure of merit. (*PHYSTAT 2003*) [?]
  - Strike a balance between *setting upper limit for null results* and *observation of a small signal*.

\[
f.o.m. = \frac{\epsilon_S}{\sqrt{B + a/2}}
\]

- \(a\) is significance (# of \(\sigma\)).
  - For this analysis, \(a = 5\).
- \(\epsilon_S\) is the efficiency of the signal.
- \(B\) is the number of background candidates.
Discriminating variables

- $B$ mass
- **Beam energy** resolution is better than $B$ energy.

![Signal process (Monte Carlo)](image1)

![All background processes (Monte Carlo)](image2)
Discriminating variables

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- $m_{ES} = \sqrt{\frac{1}{4}s - (p_B^*)^2}$
- $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$
- Discriminating power in 2D plane.
- Signal region is blinded during candidate selection optimization!

Signal process (Monte Carlo)

All background processes (Monte Carlo)
Fitting procedure

- Optimized PID selection and neural net selection with blinded data and MC samples.
- Determine probability density functions (PDFs) used to describe signal and background.
- Fit using unbinned extended likelihood method.
- Define criteria for quoting upper limits and significance of signal.
- Many (~ 100k) Monte Carlo studies to determine sensitivity and possible bias.

Figure: Fit to simulated data
Our blind data

Entries: 18220

$M_{ES} \text{ GeV}/c^2$

$\Delta E \text{ GeV}$

$\Delta E$ vs. $M_{ES}$

Entries: 18220

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Results!
Results

\[ B \rightarrow \Lambda_c^+ \mu^- \]

\[ B \rightarrow \Lambda_c^+ e^- \]
$B \rightarrow \Lambda^0 \mu^-$

$B \rightarrow \Lambda^0 e^-$
Results

\[ B \rightarrow \bar{\Lambda}^0 \mu^- \]

\[ B \rightarrow \bar{\Lambda}^0 e^- \]
Results

No significant signal is observed

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Upper limit (90% CL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to \Lambda^+_c \mu$</td>
<td>$180 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B^0 \to \Lambda^+_c e$</td>
<td>$520 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B^- \to \Lambda^0 \mu$</td>
<td>$6.2 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B^- \to \Lambda^0 e$</td>
<td>$8.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B^- \to \overline{\Lambda}^0 \mu$</td>
<td>$6.1 \times 10^{-8}$</td>
</tr>
<tr>
<td>$B^- \to \overline{\Lambda}^0 e$</td>
<td>$3.2 \times 10^{-8}$</td>
</tr>
</tbody>
</table>

Most significant branching fraction:

$$\mathcal{B}(B^0 \to \Lambda^+_c e^-) = (190^{+130}_{-90}) \times 10^{-8} \text{ at } 2.4\sigma$$

First experimental upper limits on these processes. [dAS$^+11$]
Other places to look
Rubin, et al. (CLEO Collaboration, 2009) “Search for $D^0 \rightarrow \bar{p}e^+$ and $D^0 \rightarrow pe^-$” \cite{R09}

\begin{center}
\includegraphics[width=0.5\textwidth]{diagram}
\end{center}
Lambda decays (Jefferson Lab)

Current analysis...

\[ \Lambda \rightarrow s d \rightarrow \pi^+ d u \rightarrow e^+ \]

- Jefferson Lab (CLAS)
- \( \gamma p \rightarrow K^+ \Lambda \)
- \( \Lambda \rightarrow \text{meson} + \text{lepton} \)
- Mike McCracken at Washington & Jefferson College, and CMU colleagues. Blind analysis!
- Parallel analysis: ROOT and python
  
  https://github.com/mattbellis/lichen
Jefferson Lab (CLAS)

$\gamma p \rightarrow K^+ \Lambda$

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t-quark decays (LHC)

Davidson and Verdier, (2011)
“Leptoquarks decaying to a top quark and a charged lepton at hadron colliders” [DV11]

Dong, et al. (2011)
“Baryon number violation at the LHC: the top option” [DDG⁺12]

Decays of top quark to leptoquarks?
Standard Model decays

\[ t \rightarrow q = (b) \]

\[ W^+ \rightarrow \ell^+ + \nu_\ell \]

\[ t \rightarrow q = (b) \]

\[ W^+ \rightarrow q + \bar{q} \]

Baryon-/Lepton-number violating decays

\[ t \rightarrow q = (\bar{b}, \bar{s}, \bar{d}) \]

\[ X^+(q = +\frac{1}{3}) \rightarrow \ell^+ \]

\[ \bar{q} = (\bar{c}, \bar{u}) \]

\[ t \rightarrow q = (b, \bar{s}, \bar{d}) \]

\[ X^+(q = +\frac{1}{3}) \rightarrow \nu \]

\[ \bar{q} = (b, \bar{s}, \bar{d}) \]

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Summary
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• Experimentally, there’s still a lot of places left to look!
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• Experimentally, there’s still a lot of places left to look!
• Regardless of outcome, these searches provide an excellent training ground for students.

Thanks for your time!
P. del Amo Sanchez et al.
Searches for the baryon- and lepton-number violating decays $B^0 \rightarrow \Lambda_c^+ \ell^-$, $B^- \rightarrow \Lambda \ell^-$, and $B^- \rightarrow \bar{\Lambda} \ell^-$. 

Zhe Dong, Gauthier Durieux, Jean-Marc Gerard, Tao Han, and Fabio Maltoni.
Baryon number violation at the LHC: the top option.

Sacha Davidson and Patrice Verdier.
Leptoquarks decaying to a top quark and a charged lepton at hadron colliders.

Wei-Shu Hou, Makiko Nagashima, and Andrea Soddu.
Baryon number violation involving higher generations.

(Institute of Astrophysics of Andalucia Spain) J. Maiz Appelaniz.

The University of Tokyo Kamioka Observatory, ICRR (Institute for Cosmic Ray Research).
P. Rubin et al.
Search for $D_0 \to \bar{p} \, e^+$ and $D_0 \to p \, e^-$. 

Aaron Roodman.
Blind Analysis in Particle Physics.
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Violation of CP Invariance, $c$ Asymmetry, and Baryon Asymmetry of the Universe. 
Reprinted in *Kolb, E.W. (ed.), Turner, M.S. (ed.): The early universe* 371-373, and in 
Backup slides