A search for baryon-number violating $\Lambda \to m\ell$ decays using CLAS @ JLab

Michael E. McCracken[1,2], Matt Bellis[3]
for the CLAS Collaboration

[1]Washington & Jefferson College
Washington, Pa. 15301

[2]Carnegie Mellon University
Pittsburgh, Pa. 15213

[3]Siena College
Loudonville, New York 12211

27 June 2013
BARYONS '13
University of Glasgow, Scotland, UK

Motivation: Matter Asymmetry

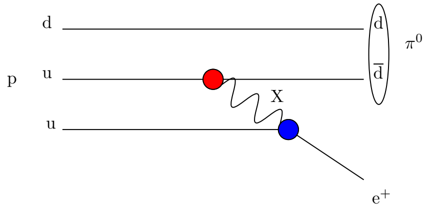
- We observe a matter-dominated (rather than symmetric) universe

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

- Likely that primordial universe began in a symmetric state
- Sakharov Conditions (1967) $\rightarrow$ To achieve current asymmetry, need:
  1. Violation of C and CP invariances
  2. B violation
  3. Interactions outside of thermal equilibrium
- Standard Model allows for B violation via *sphalerons* ≈ 10 TeV
- Observed CP violations in K and B mesons can't account for η
- Explanations:
  1. Undiscovered larger CP violations
  2. Undiscovered B violations

Motivation: Baryon Decay

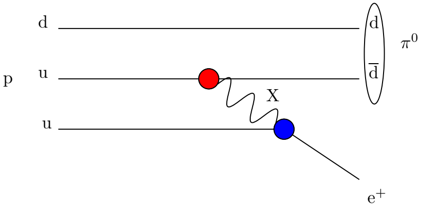
- Sakharov theorized a new boson that mixes quark and lepton flavors
- Such X bosons are features of many $SU(5)$ theories and GUTs
- X may have $q = \pm\frac{1}{3}$, $\pm\frac{2}{3}$, $\pm\frac{4}{3}$
- Example: p decay with X of $q = \frac{1}{3}$



- Relies on $q \to X + \bar{q}$ and $q + X \to \bar{\ell}$
- Experimental upper bound on p lifetime is $> 10^{33}$ y!

Motivation: Baryon Decay

- Non-observation of p decay:
  - large mass of X
  - flavor dependence of X coupling
- Parametrize X coupling (as in the CKM matrix)

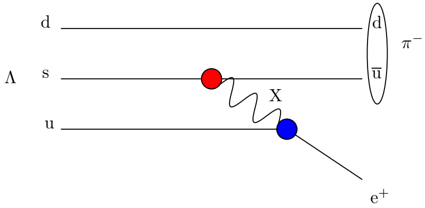


$$u \to X + \bar{d}$$
$$u + X \to e^+$$

$$\begin{pmatrix} X_{u\bar{d}} & X_{c\bar{d}} & X_{t\bar{d}} \\ X_{u\bar{s}} & X_{c\bar{s}} & X_{t\bar{s}} \\ X_{u\bar{b}} & X_{c\bar{b}} & X_{t\bar{b}} \end{pmatrix} \begin{pmatrix} X_{\bar{u}e} & X_{\bar{c}e} & X_{\bar{t}e} \\ X_{\bar{u}\mu} & X_{\bar{c}\mu} & X_{\bar{t}\mu} \\ X_{\bar{u}\tau} & X_{\bar{c}\tau} & X_{\bar{t}\tau} \end{pmatrix}$$

Motivation: Baryon Decay

- Non-observation of p decay:
  - large mass of X
  - flavor dependence of X coupling
- Parametrize X coupling (as in the CKM matrix)



$$s \rightarrow X + \bar{u}$$
$$u + X \rightarrow e^{+}$$

$$\begin{pmatrix} X_{u\bar{d}} & X_{c\bar{d}} & X_{t\bar{d}} \\ X_{u\bar{s}} & X_{c\bar{s}} & X_{t\bar{s}} \\ X_{u\bar{b}} & X_{c\bar{b}} & X_{t\bar{b}} \end{pmatrix} \begin{pmatrix} X_{\bar{u}e} & X_{\bar{c}e} & X_{\bar{t}e} \\ X_{\bar{u}\mu} & X_{\bar{c}\mu} & X_{\bar{t}\mu} \\ X_{\bar{u}\tau} & X_{\bar{c}\tau} & X_{\bar{t}\tau} \end{pmatrix}$$

Motivation: $\Lambda \to m\ell$

- The Λ presents a long-lived strange state ($c\tau = 7.89$ cm)
- Current uncertainties on Γ allow for discovery at our sensitivities
- Opportunity to observe rare decays
- Differs from p decay by access to $X_{s\bar{q}}$
- CLAS has lots of them, easily separable from background
- Hyperon photoproduction in CLAS is understood
  - $d\sigma$, polarization from $\gamma p \to K^+ Y$ published
  - $\gamma p \to K^+ \Lambda$ PRC **81**, 025201 (2010)
  - $\gamma p \to K^+ \Sigma^0$ PRC **82**, 025202 (2010)
  - forthcoming papers on Y^* arXiv:1305.6776 [nucl-ex]
- First measurement; upper-bound is worst-case scenario

Analysis Overview

- We search for B-violating $\Lambda \to m\ell$ decays in nine final states:
  - K^+e^-
  - K^-e^+
  - π^+e^-
  - π^-e^+
  - $K^+\mu^-$
  - $K^-\mu^+$
  - $\pi^+\mu^-$
  - $\pi^-\mu^+$
  - $K_s^0\nu$
- Chosen for:
  - $\Delta B = -1$
  - $\Delta L = \pm 1$
  - $\Delta(B - L) = 0,\ 2$
  - Reconstructability in CLAS
  - Conservation of angular momentum
  - Conservation of charge

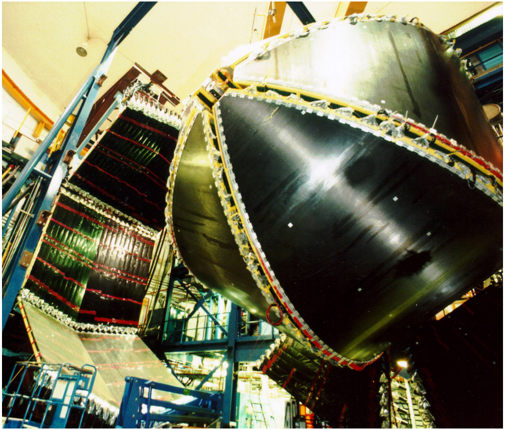
Analysis Overview

- We search for B-violating $\Lambda \to m\ell$ decays in nine final states:
  - K^+e^-
  - K^-e^+
  - π^+e^-
  - π^-e^+
  - $K^+\mu^-$
  - $K^-\mu^+$
  - $\pi^+\mu^-$
  - $\pi^-\mu^+$
  - $K_s^0\nu$

Reaction	ΔB	ΔL	$\Delta(B-L)$	X charge (e)	quark couplings	lepton-quark couplings
$\Lambda \to K^+\ell^-$	-1	$+1$	-2	$\frac{2}{3}$	$d\bar{s}$, $s\bar{s}$	$s\ell$, $d\ell$
$\Lambda \to K^-\ell^+$	-1	-1	0	$-\frac{4}{3}$, $-\frac{1}{3}$	$u\bar{u}$, $d\bar{u}$	$s\bar{\ell}$, $d\bar{\ell}$
$\Lambda \to \pi^+\ell^-$	-1	$+1$	-2	$\frac{2}{3}$	$d\bar{d}$, $s\bar{d}$	$s\ell$, $d\ell$
$\Lambda \to \pi^-\ell^+$	-1	-1	0	$-\frac{1}{3}$, $-\frac{4}{3}$	$s\bar{u}$, $u\bar{u}$	$u\bar{\ell}$, $s\bar{\ell}$
$\Lambda \to K^0\nu$	-1	±1	0, -2	$-\frac{1}{3}$, $\frac{2}{3}$	$u\bar{s}$, $s\bar{s}$	$s\nu$, $u\nu$
					$d\bar{d}$, $u\bar{d}$	$d\nu$

CLAS Detector @ JLab

- CEBAF Large Acceptance Spectrometer
- Toroidal $\vec{B}$
- Wire tracking chambers
- Scintillator timing detectors
- Tagged γ from bremsstrahlung of 4.023 GeV e^- beam
- Dataset collected in 2005



Blind Analysis Overview

1. Identify number of $\gamma p \to K^+\Lambda$, $\Lambda \to p\pi^-$ events
   - Fiducial, particle ID, and analysis cuts applied
   - Acceptance correct to get the number of $\Lambda \to p\pi^-$ produced
2. Develop cuts to select bnv signal
   - optimize cuts using signal MC and blinded data
3. Investigate effect of bnv cuts on background MC
4. Un-blind data, identify N_{bnv}
5. Calculate Γ_{bnv} or set upper limit

Blind Analysis Overview

- We use a naïve estimate of the significance of a measurement

$$\varsigma = N_s/\sqrt{N_s + N_b} \tag{1}$$

- We set confidence levels for bnv observation to 4σ
- ϵ is the efficiency for a given bnv channel (acceptance *and* cuts)
- $\Gamma_{p\pi^-} = 0.639$ is the $\Lambda \to p\pi^-$ branching fraction
- $N_{p\pi^-}$ is the number of $\Lambda \to p\pi^-$ decays in dataset
- N_{bnv} is the observed number of bnv events after unblinding
- Then we can calculate Γ_{bnv}

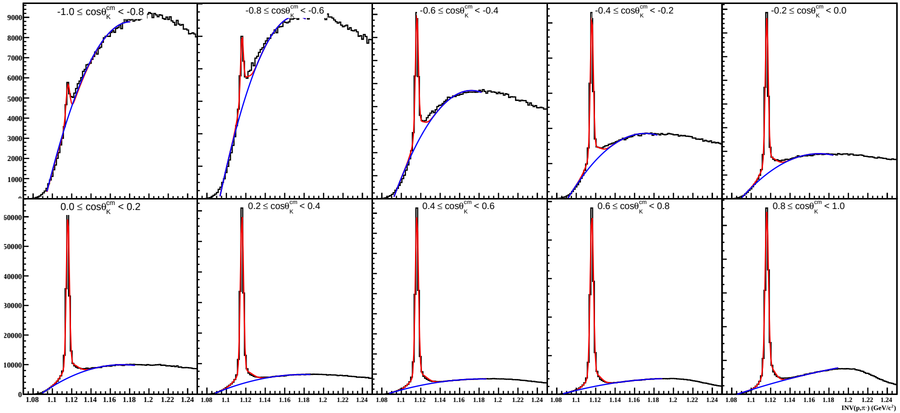
$$\Gamma_{\text{bnv}} = (\Gamma_{p\pi^-})\frac{N_{\text{bnv}}}{\epsilon \cdot N_{p\pi^-}} \tag{2}$$

$\Lambda \to p\pi^-$ Counting

- Identify data SM decays using a $K^+p\pi^-$ final state
- Generate 3×10^6 MC $\gamma p \to K^+\Lambda \to K^+p\pi^-$
  - distributed according to brem. spectrum and published $d\sigma/d\Omega$
  - Process with detector simulation
- Apply loose missing mass and timing cuts, detector cuts
- Extract number of events from $(p_p + p_\pi)^2$ histograms, binned in $\cos\theta_K^{cm}$
- 3.01×10^6 events after all cuts
- Acceptance correct for analysis cuts and detector acceptance
- $N_{p\pi^-} = 3.23 \times 10^7$ $\Lambda \to p\pi^-$ produced during data taking

Counting $\Lambda \to p\pi^-$ events

Invariant mass of $p\pi^-$ system for all data events, binned in $\cos\theta_K^{cm}$



$\Lambda \to m\ell$ EVENT SELECTION

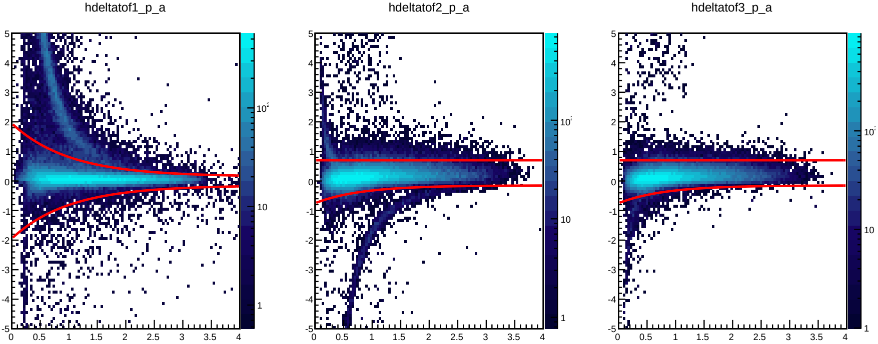
- Begin with timing-based PID cuts specific to final-state particles
  - Cutting out proton is a strong constraint
- Tune additional cuts on MM^2 and $MM(K^+)$
- Use $inv(m_d, \ell)$ spectrum to identify signal
- Select optimal cuts based on (reduced) Punzi figure of merit arXiv:physics/0308063 [data-an]
- For a given set of cuts, C,

$$\mathcal{P}(C) = \frac{\epsilon(C)}{a/2 + \sqrt{B(C)}} \tag{3}$$

- Attractive features:
  - a is confidence level (sigmas)
  - finite as $B(C) \to 0$
  - does NOT depend on amount of signal or production cross section

Example: $\Lambda \to \pi^+\mu^-$ event selection

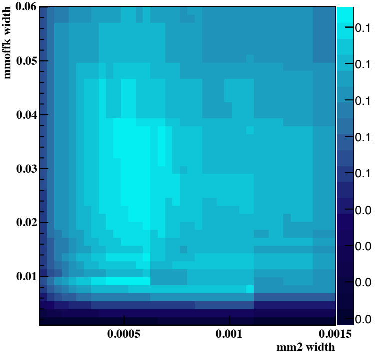
- $\gamma p \to K_r^+ \Lambda \to K_r^+ \pi^+ \mu^-$
- Choose positive track assignment using $inv(\pi^+, \mu^-)$
- Generate 10^6 $\Lambda \to K^+\pi^+\mu^-$ MC events
- timing cuts vetted on MC; skim dataset

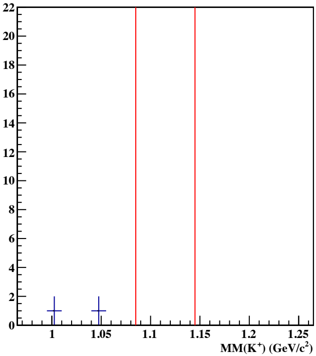


Δtof v $|\vec{p}|$ for final-state tracks

$\Lambda \to \pi^+\mu^-$ EVENT SELECTION

- Apply cuts on MM^2 and $MM(K_r^+)$
- Vary widths, choose pair with optimal $\mathcal{P}$
  - MM^2: $w_1 \in [0.0001, 0.004]$ GeV^2/c^4
  - $MM(K_r^+)$: $w_2 \in [0.001, 0.2]$ GeV/c^2

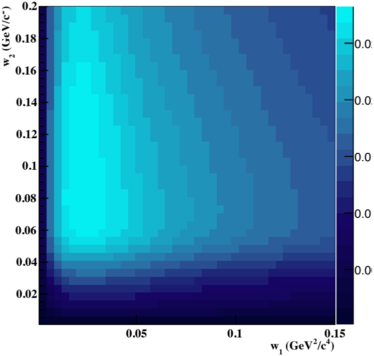


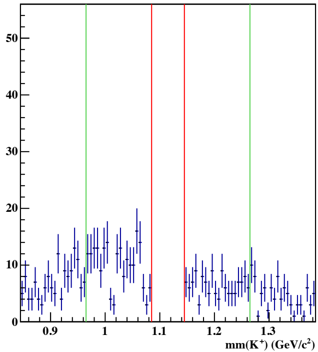


$\mathcal{P}(C)$ for all cut combinations

$\Lambda \rightarrow K_s^0 \nu$ EVENT SELECTION

- Apply cuts on MM^2 and 2-d cut based on $\pi^+\pi^-$ opening angle and $|\vec{p}_{K^0}|$
- Vary widths, choose pair with optimal $\mathcal{P}$
- Due to missing $\vec{p}_\nu$, background persists

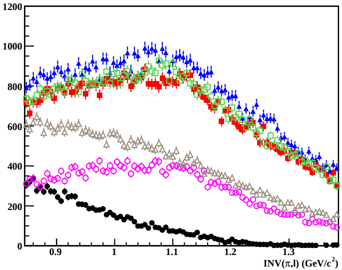


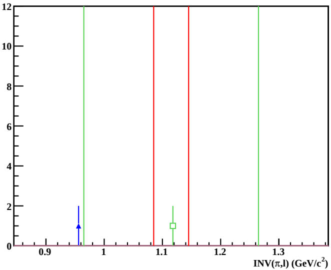


$\mathcal{P}(C)$ for all cut combinations

Assessing background signatures

- Assess whether cuts give background some signal-like shape
- Generate 5×10^5 MC events for the following final states
  - pe^+e^-
  - $p\mu^+\mu^-$
  - $p\pi^+\pi^-$
  - pK^+K^-
  - $p\pi^+\pi^-\pi^0$
- Apply optimal cuts to each reaction. Very few events pass.



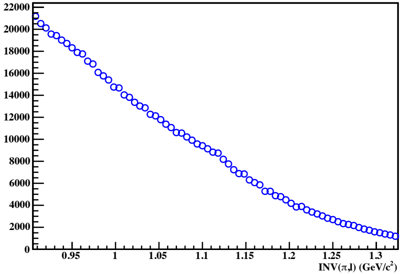


$INV(\pi^-, e^+)$ before and after analysis cuts

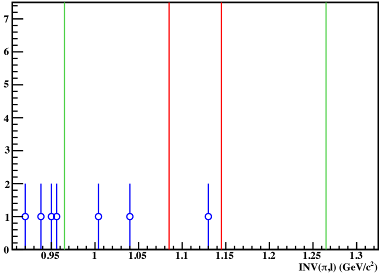
Unblinding

- Effects of cuts on signal and background MC are understood
- Unblind the signal region of identification plots

Unblinding



$INV(\pi^+, \mu^-)$ before cuts...



... and after optimal cuts.

A single event in signal region...

Unblinding

- In all but the $K_s^0\nu$ channel, there are 0 or 1 events in signal region
- We estimate the upper-bound on N_{bnv} using the Feldman-Cousins method PRD 57, 3873-3889 (1998)
- At 95% confidence, what is the maximum N_{bnv} given expected background B_{B} and observed N_{O}?
- Example: for $\Lambda \to \pi^+\mu^-$
  - $N_{\mathrm{B}} = 0.5$
  - $N_{\mathrm{O}} = 1$
  - $\to N_{\mathrm{bnv}} < 4.64$

Unblinding

- In all but the $K_s^0\nu$ channel, there are 0 or 1 events in signal region
- We estimate the upper-bound on $N_{\rm bnv}$ using the Feldman-Cousins method PRD 57, 3873-3889 (1998)
- At 95% confidence, what is the maximum $N_{\rm bnv}$ given expected background $B_{\rm B}$ and observed $N_{\rm O}$?
- Example: for $\Lambda \to \pi^+\mu^-$
  - $N_{\rm B} = 0.5$
  - $N_{\rm O} = 1$
  - $\to N_{\rm bnv} < 4.64$
- We use this upper bound and calculate a maximum $\Gamma_{\rm bnv}$

$$\Gamma_{\rm bnv} = (\Gamma_{p\pi^-})\frac{N_{\rm bnv}}{\epsilon \cdot N_{p\pi^-}} < (0.639)\frac{4.64}{0.105 \cdot 6.23 \times 10^7} = 1.61 \times 10^{-6} \quad (4)$$

PRELIMINARY

Preliminary results

We use the FC method for all of the charged decay modes

decay	N_{B}	N_{O}	FC N_{bnv} upper bound	Γ_{bnv} upper bound ($\times 10^{-7}$)
K^+e^-	0.25	0	< 2.63	< 5.26
$K^+\mu^-$	0.0	0	3.09	8.13
K^-e^+	0.5	0	2.63	5.35
$K^-\mu^+$	0.25	0	< 2.63	< 5.65
π^+e^-	0.0	0	3.09	3.32
$\pi^+\mu^-$	0.5	1	4.64	4.53
π^-e^+	0.0	0	3.09	3.44
$\pi^-\mu^+$	0.0	0	3.09	3.65
$K_s^0\nu$	82.5	58	to come	to come

PRELIMINARY

Conclusions

- $\Lambda \to m\ell$ is useful as a test of B conservation
- Provides search similar to that for nucleon decay
- CLAS data set provides $\approx 10^{-7}$ sensitivities
- We find no appreciable signal at these sensitivities
- MC studies are necessary to estimate Γ for $\Lambda \to K_s^0\nu$