# Proton Decay Unidoc

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***Abstract*—Currently, this is empty but will contain the specific language we'll be using in future papers.**

## I. Introduction

Conservation of baryon number is accidental, i.e does not correspond to any known symmetry: its violation is predicted by almost all GUTs

TODO: Need citation here

Proton (or bounded neutron) decay can occur only as a violation of baryon number, pointing to an indirect evidence for GUTs

TODO: Once again, citation

The golden channels:

1) $p \rightarrow \overline{\nu}_\tau + K^+$
2) $p \rightarrow e^+ + \pi^0$

Different GUTs use different decay modes, and LAr may have different sensitivities to these.

## II. Previous Work

### A. T2K

The summary of results can be found in the collaboration paper [1].

A much more detailed paper can be found in B. Viren's PhD thesis[2].

Best limits on $\tau_{p\rightarrow e^+ + \pi^0}/B$ set by Super-Kamiokande at $5.4 \times 10^{33}$ years (90%C.L.).

This roughly goes as:

$$\tau/B = \frac{N_0 \Delta t \epsilon}{n_{obs} - n_{bg}} \tag{1}$$

Where $N_0$ is the number of decay centers, $\Delta t$ is the amount of time being measured, and $n_{obs} - n_{bg}$ is the number of observed decays divided by the number of observed bg events. Efficiency is measured as $\epsilon$ for the decay mode.

Brett's thesis prefers to use the decay rate or inverse of this

$$\Gamma = \frac{n}{NT\epsilon} \tag{2}$$

The language here differs a little.

### B. $\mu$BooNE

The previous researcher leading up proton decay studies was Elena Gramellini. She frequently references Ed Kearns who has a ton of informative plots.

This will a more comprehensive search of the microboone docdb.

## III. Referencing the Software

This section will be used to develop the language we'll be using to properly reference the software in LArSoft[3].

## IV. The Goal

This is done following Brett Virren's thesis.

The confidence level for the limit on the decay rate, $\Gamma_{lim}$ can be calculated as,

$$CL = A \int_0^{\Gamma_{lim}} d\Gamma \int_0^\infty db \int_0^\infty db_{MC} \int_0^\infty d\lambda \int_0^1 d\epsilon I(...) \tag{3}$$

Where,

$$I(...) = \frac{b_{MC}^{n_b}(\Gamma\lambda\epsilon + b)^n}{b} e^{-b_{MC} - \frac{(b_{MC} - bC)^2}{2\sigma_b^2} - \frac{(\lambda-\lambda_0)^2}{2\sigma_\lambda^2} - (\Gamma\lambda\epsilon + b)} \tag{4}$$

Where

- $b_{MC}$, the true mean MC background rate.
- $\Gamma$, the true decay rate of interest (integration parameter)
- $\lambda = NT$, the true exposure
- $b$, the true background rate (decay parameter)
- $n$, the number of events observed
- $\lambda_0$, the estimated exposure
- $\sigma_\lambda$, the uncertainty in the estimated exposure
- $C$, the ratio of MC events to data events.
- $n_b$, the number of MC events passing the the proton decay selection criteria
- $\epsilon$ The efficiency of detecting the decay products of this mode.

Specifically, the parameters that need to be measured are:

- $n$, the number of events observed
- $n_b$, the number of MC events passing the the proton decay selection criteria
- $\sigma_b$ The estimated uncertainty in the MC background rate
- $\lambda_0$, the estimated exposure
- $\sigma_\lambda$, the uncertainty in the estimated exposure
- $C$, the ratio of MC events to data events.$\equiv n/(n_b + n_o)$
- $\epsilon_0$ Estimated efficiency
- $\sigma_\epsilon$ Uncertainty in estimated efficiency

The constant of proportionality, $A$ is found by setting $CL = 1$ and $\Gamma_{lim}$ to $\infty$.

The efficiency term missing from his paper is:

$$P(\epsilon|\vec{I}) = e^{-(\epsilon-\epsilon_0)^2/2\sigma_\epsilon^2} \tag{5}$$

which should be in the integrand. The estimated efficiency for each mode is found by dividing the number of proton decay MC events which pass all cuts by the number which pass the event sample cuts.

For a given CL, evaluate the integral numerically using a minimization routine to obtain $\Gamma_{lim}$

## V. General Method

This part follows Elena's reasoning

1) Pick a decay mode (topology).
2) Evaluate the background processes that can contribute to identifying the decay products.
3) Define cuts for a given process which maximize the efficiency.
4) For these cuts, obtain:
   - The MC background rate and uncertainty
   - The estimated exposure (fiducial cuts?)
   - The number of events in the data
   - The number of background events passing selection criteria in MC
   - the ratio of all MC events to all data events which pass selection criteria
   - The estimated efficiency
5) Evaluate integral

## VI. Backgrounds

The big aspect behind this will be background identification. The cuts that were mentioned are:

- production PID
- No additional vertex activity
- Proximity
- Planarity
- Total Energy deposited
- Total Net Momentum
- Fiducialization

Elena's work was based around examining the MCC5 cosmics generation data sets. A year ago, she was working on cuts.

## VII. Conclusion

This section summarizes the paper.

## References

[1]T. S.-K. Collaboration, : and M. Shiozawa, "Search for Proton Decay via p- e+ pi0 in a Large Water Cherenkov Detector", (1998) 10.1103/PhysRevLett.81.3319.

[2]B. Viren, "A Search for the Decay of Protons to e+pi0 and mu+pi0", PhD (State University of New York, Stony Brook, 2000).

[3]E. Snider, G. ( Zeller, M. Thomson, P. Spentzouris, D. Schmitz, A. Rubbia, J. Raaf, O. Palamara, B. Fleming, F. Cavanna, and S. Brice, *LArSoft*, 2016.