Nucleon Decay Studies

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Proton Decay FSI Studies in GENIE

FSI studies in GENIE v2.12.8 for $p \rightarrow K^+\nabla$

- **hA default** model (data driven model)
- **hA2014** an improve version of hA default with more data (much less extrapolation) if no data for a particular nucleus an $A^{2/3}$ scaling is used
- **hN2015** (theory driven model) includes K charge exchange
- **No FSI**
FSI hA default

- hA default model (data driven model)
FSI hA2014

hA2014 an improve version of hA default with more data (much less extrapolation) if no data for a particular nucleus an $A^{2/3}$ scaling is used
FSI hN2015

hN2015 Improvement of treatment of K FSI. (theory driven model) includes K charge exchange ($K^+ n \rightarrow K^0 p$)
No FSI

Diagram showing:
- KE (GeV) vs. Counts (left)
- KE (GeV) vs. Probability (right)
- Final state vs. Primary ratio (bottom)

Graphs indicate:
- Proton and Neutron distributions
- Primary and Final state KE variations

Legend:
- Primary
- Final state
- Proton
- Neutron
Kaon Tracking Efficiency (Golden Channel)

Tracking Eff

<table>
<thead>
<tr>
<th></th>
<th>Tracking Eff</th>
</tr>
</thead>
<tbody>
<tr>
<td>hA Default</td>
<td>55.6%</td>
</tr>
<tr>
<td>hA2014</td>
<td>55.8%</td>
</tr>
<tr>
<td>hN2015</td>
<td>54.8%</td>
</tr>
<tr>
<td>noFSI</td>
<td>71.9%</td>
</tr>
</tbody>
</table>

Are GENIE FSI models too destructive?
FSI models on BDT Response

\[ p \rightarrow K^+ \bar{\nu} \]

Signal:
proton decay with \( K \rightarrow \mu^+ + \nu_\mu \) only

Background:
Atmospheric neutrinos

**Graphs:**
- **Signal:** \( p \rightarrow K^+ \bar{\nu} \)
- **Background:** Atmospheric neutrinos
- **Comparison of background rejection:**
  - **hA Default**
  - **hA2014**
  - **hN2015**
  - **noFSI**

**Table:**

<table>
<thead>
<tr>
<th>Model</th>
<th>Background Expectation @ 50% eff (10kt-y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>hA Default</td>
<td>8.08</td>
</tr>
<tr>
<td>hA2014</td>
<td>7.8</td>
</tr>
<tr>
<td>hN2015</td>
<td>8.4</td>
</tr>
<tr>
<td>noFSI</td>
<td>5.1</td>
</tr>
</tbody>
</table>
FSI on other decay modes (Default FSI model)

\[ p \rightarrow K^+ \nabla \]

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

\[ n \rightarrow K^+ \mu^- \]
Comments on FSI studies

Kaon FSI has a significant impact on the analysis

How do we quantify this in terms of a systematic error on the lifetime limits?

Do we use noFSI ± 20% sys? ±10% sys ± 5%?

Any decay mode w/Kaon in the final state needs to address this
Part II
Neutron Decay Analysis \((n \rightarrow \mu^- K^+)\)

Others nucleon decay modes include also kaon + charged lepton and our sensitivity may be better for these modes

\(n \rightarrow \mu^- K^+\)

This decay mode has an muon and kaon

Topology is different from the golden channel
Neutron Decay Analysis ($n \rightarrow \mu^- K^+$)

$n \rightarrow \mu^- K^+$ We are using TMVA with a Boosted Decision Tree (BDT) to estimate background/signal separation

Signal:
neutron decay with $K \rightarrow \mu^+ + \nu_\mu$ only

Background:
Atmospheric neutrinos

Using same BDT as $p \rightarrow K^{+\nu}$ trained with different sample
Neutron Decay Analysis ($n \rightarrow \mu^- K^+$)

$n \rightarrow \mu^- K^+$  We are using TMVA with a Boosted Decision Tree (BDT) to estimate background/signal separation

Signal:
neutron decay with $K \rightarrow \mu^+ + \nu_\mu$ only

Background:
Atmospheric neutrinos

31.5% selection efficiency

*Using same BDT as $p \rightarrow K^+\nu$ trained with different sample*
Update on Neutron Decay Analysis (n→e⁻ K⁺)

At the collaboration was shown a similar study using the same BDT trained on different sample.

An error was found in the background rate therefore the sensitivity calculation was bogus.
Update on Neutron Decay Analysis (n→e⁻ K⁺)

Update on n→e⁻ K⁺

New strategy: Remove obvious background events and then use TMVA (BDT) to do the “nitty gritty” of the selection

• Assume that the event is n→ K⁺ + EM energy
• Then calculate Kaon total energy
• Sum up all the energy in the event \( E_{\text{total}} = E_K + E_{\text{em}} \) (\( E_{\text{em}} \) visible EM energy)
• Make a 2D cut of \( E_K \) vs \( E_{\text{total}} \)
• Then TMVA with BDT (reco variables)

Signal: neutron decay n→e⁻ K⁺
Background: Atmospheric neutrinos
Update on Neutron Decay Analysis (n→e⁻ K⁺)

Update on n→e⁻ K⁺

- Assume that the event is n→ K⁺ + EM energy
- Then calculate Kaon total energy
- Sum up all the energy in the event $E_{total} = E_K + E_{em}$ (E_{em} visible EM energy)
- Make a 2D cut of $E_K$ vs $E_{total}$
Update on Neutron Decay Analysis (n→e⁻ K⁺)
**Update on Neutron Decay Analysis (n→e⁻ K⁺)**

- Then TMVA with BDT (reco variables)

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**TMVA overtraining check for classifier: BDT**

- Signal (test sample) vs. Background (test sample)
- Signal (training sample) vs. Background (training sample)

Kolmogorov-Smirnov test: signal (background) probability = 0 (0.001)

**Very Preliminary**

35.6% selection efficiency
w/ 1.8 bkgd events per 10kton-year

**Current limit**

1e33

Lifetime Sensitivity

Exposure kton-year
How are we going to handle FSI?

There other decay modes (e.g. $n \rightarrow e^- K^+$, $n \rightarrow \mu^- K^+$) where our current performance is “good” for TDR material

Need to optimize event selector for $n \rightarrow \mu^- K^+$ topology

What about an inclusive measurement of nucleon decay $n/p \rightarrow K^+ X$?
The End
Proton Decay Analysis (Golden Channel)

\[ p \rightarrow K^+ \bar{\nu} \]

Signal:
proton decay with \( K \rightarrow \mu^+ + v_\mu \) only

Background:
Atmospheric neutrinos

![Signal efficiency vs. BDT response](image)

TMVA overtraining check for classifier: BDT
Neutron Decay Analysis ($n \rightarrow e^- K^+$)

$n \rightarrow e^- K^+$

**Signal:**
neutron decay with $K \rightarrow \mu^+ + \nu_\mu$ only

**Background:**
Atmospheric neutrinos

$$\begin{align*}
\text{Signal eff} & = 4 \times 10^{-3} - 0.2 \\
\text{Background Rejection} & = 23 \times 10^{-3}
\end{align*}$$

**Neutron Decay Analysis ($n \rightarrow e^- K^+$)**

<table>
<thead>
<tr>
<th>Signal (test sample)</th>
<th>Signal (training sample)</th>
<th>Background (test sample)</th>
<th>Background (training sample)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expected Stats</td>
<td></td>
<td></td>
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</table>

**TMVA overtraining check for classifier: BDT**

Kolmogorov-Smirnov test: signal (background) probability = 0.031 (0.05)

**UO-flow (S,B):** (0.0, 0.0)%/ (0.0, 0.0)%

**BDT response**

$\frac{1}{N} dN/dx$

$0.1 \rightarrow 0.4$

**Signal eff**

$0.1 \rightarrow 1$

**Backgr Rejection**

$0.1 \rightarrow 10^{-1}$
Neutron Decay Analysis ($n \rightarrow \mu^- K^+$)

$n \rightarrow \mu^- K^+$

Signal:
neutron decay with $K \rightarrow \mu^+ + \nu_\mu$ only

Background:
Atmospheric neutrinos

**Signal eff**

$10^{-4}$  $10^{-3}$  $10^{-2}$  $10^{-1}$  0  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1
Backgr Rejection

**Backgr Rejection**

$10^{-4}$  $10^{-3}$  $10^{-2}$  $10^{-1}$  0  0.1  0.2  0.3  0.4  0.5  0.6  0.7  0.8  0.9  1
Signal eff

**MVA_BDT**

**TMVA overtraining check for classifier: BDT**

Kolmogorov-Smirnov test: signal (background) probability = 0.082 (0.013)