NuLeptonSim: A practical use of a neutrino propagation code as an event generator

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What Has Been Done?

- Modelling of in-ice cascades induced by neutrino-sourced muons and $\tau$-leptons
  - Events weighted by neutrino survival probability
  - Leptons propagated with PROPOSAL
  - NuRadioMC calculates radio emission from induced cascades

- Radiative losses improve instrument sensitivity with respect to purely neutrino interactions
  - Increasing number of observable cascades with increasing energy
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  - Energy losses due to neutral current interactions
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- Charged leptons sourced from secondary channels:
  - $\nu_\tau \rightarrow \tau \rightarrow \mu + \nu_\tau + \bar{\nu}_\mu$
  - $\bar{\nu}_e + e^- \rightarrow W^-$
  - $W^- \rightarrow \ell^- + \bar{\nu}_\ell$
## Existing Neutrino Propagation Tools

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<th>Software</th>
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<th>Cross-Section</th>
<th>Energy Loss</th>
<th>Decay</th>
<th>Secondaries</th>
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NuTauSim

- C++ based monte carlo that models the Earth-emergent flux of tau leptons given monoenergetic fluxes of primary tau neutrinos and Earth emergence angles
  - Earth emergence probability
  - Energy distribution

- Includes NC and CC neutrino interactions, tau decays, regeneration

- Using average energy losses along a propagation step allows for comparatively fast speeds

- Physical models are modular and can be easily changed
NuLeptonSim

- Upgrade to NuTauSim, but same basic layout

- New features:
  - Muon & muon neutrino propagation
  - Glashow Resonance events
  - Multiple particle tracking
  - Inclusion of detector volumes and arbitrary trajectories
Propagation of Charged Leptons (without PROPOSAL)

- From particle starting point, sample interaction length from exponential with mean:
  \[ X_{\text{int}} = \frac{A m_N}{\sigma} \]
  - Propagated distance:
    \[ \Delta R = X_{\text{int}} / \rho \]

- Determine interaction type by ratio of cross sections at particle energy and a random number

- Sample energy of interaction \( \Delta E \)
  - Using inverse transform sampling on CDFs of interaction cross sections (see bonus slide)

- Increment energy:
  \[ E = E - \Delta E \]

- Continue until exiting volume or reaching threshold
Event Generation for ARA

1. Isotropically throw trajectories through the Earth
2. Accept trajectories that pass through the cylinder
   - For ARA: 15km radius, 2.8km depth
3. For each passing trajectory, throw $N_{\nu}$ neutrinos using NuLeptonSim and save events which occur inside the volume
   - Charged current
   - Neutral current
   - $\tau$ decays
   - Glashow Resonance
   - Charged leptons
     - Propagate further using custom code
4. Output passing events:
   $[E(\text{shower}) + \text{inelasticity, } x, y, x', y', z', \text{type, weight}]$

Characteristics of showers can be approximated by:
- $\gamma$'s (e's from CC, e's and $\pi^0$s from decays, e's from GR, e's from pair production, $\gamma$'s from Bremsstrahlung)
- Hadrons (CC, NC, $\pi^+$s from decays, nucleons from photonuclear interactions)
5-Station ARA Layout

- 5 stations simulated in deployed positions
- Radio emission from showers initialized by neutrino interactions or charged lepton radiative losses are calculated and propagated by PYREX
  - Event detection considered for 3 triggered antennas with $3-6\sigma$
- Searching for:
  - Coincident events for potential lowered thresholds
  - Effect of regeneration on effective volume
  - Effect of secondaries on effective volume
5-Station ARA Performance

- Effective volume calculated only using primary neutrino interaction vertices matches well to A2 (2 station ARA) in Phys. Rev. D 102, 043021 (2020)
- Effect of $\tau$-leptons matches well to results of Phys. Rev. D 102, 083011 (2020)
  - Decay topology makes up a few percent of observed events (stronger effect at lower energies)
  - Radiative losses $\sim\frac{1}{3}$ of neutrino curve at 1EeV, increases to $\sim\frac{2}{3}$ at 100EeV
    - Closer to $\sim\frac{1}{2}$ in PRD at 100EeV
Conclusion

- Robust simulation pipeline:
  - Isotropically throw trajectories
  - Propagating neutrinos through the Earth (NuLeptonSim)
    - Record any interactions
  - Propagate showers and calculate radio emission using PYREX

- Initial results match well with previous studies
  - First hints of an increase in effective area from radiative losses due to increased propagation range at high energies

- Muon neutrinos currently running

- Higher statistics runs coming soon
Discussion & Questions
**Bonus Slide: Neutrino Interaction in the Earth**

- Calculate grammage profile along neutrino trajectory:

\[ X_E(L) = \int_0^L \rho(r(L)) \, dL \]

- Sample neutrino interaction grammage from exponential distribution with mean:

\[ X_{int}^\nu(E_\nu) = \frac{m_N}{\sigma_{CC}(E_\nu) + \sigma_{NC}(E_\nu)} \]

  \( \sigma_{CC}/\sigma_{NC} \approx 2.6 \)

- Charged lepton energy = \((1-y)\) E\(_\nu\)
  
  - Average \( y \approx 20\% \)
Bonus Slide: Charged Lepton Propagation (continuous)

- Assume continuous energy losses inside the Earth:
  \[
  \left\langle \frac{dE_\tau}{dX} \right\rangle = -a(E_\tau) - b(E_\tau)E_\tau
  \]

  \(a(E_\tau)\) corresponds to constant ionization losses
  \(b(E_\tau)\) corresponds to radiative losses
  ○ Bremsstrahlung
  ○ Electron-positron pair production
  ○ Photonuclear interactions

- Propagated in steps \(\Delta L\) such that 0.1\% of the primary energy is lost

- Check for decay with probability:
  \[
  P_{\text{decay}}(E_\tau) = 1 - e^{-\Delta L/\gamma(E_\tau)ct_\tau}
  \]
  ○ Sample neutrino energy from decay spectra
Bonus Slide: Modeling Neutrino Propagation

- Must properly consider:
  - Charged-current and neutral-current neutrino interactions
    - Uncertainties at the highest energies disagree by an order of magnitude
  - Energy losses of charged leptons
    - Similar uncertainties within a factor of 5
    - Continuous versus stochastic losses
  - Charged lepton decay
    - Polarization state uncertainty
  - Multiple particle tracking/reinteraction
Bonus Slide: Shower Initiation via Radiative Energy Losses

- Radiative energy losses proportional to primary energy
  - Even a small fraction lost can trigger a detectable shower if the primary is energetic enough
  - Tau losses ~1/10 Muon losses, but have characteristically higher primary energies

- Losses to consider:
  - Pair production (model as $\gamma$ shower)
  - Bremsstrahlung (model as $\gamma$ shower)
  - Photonuclear (model as hadronic shower)

- For each Earth-emergent charged lepton, provide:
  - Energy of deposition
  - Location of deposition
  - Interaction type

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Bonus Slide: Cross Section Behavior

- Must consider energy dependence of cross sections
**Bonus Slide: Radiative Energy Sampling of Charged Leptons**

- Integrate cross sections to recover cumulative distribution function:

\[
\text{CDF}(v) = \int_{v_{\text{min}}}^{v} \frac{d\sigma}{dv} / \int_{v_{\text{min}}}^{v_{\text{max}}} \frac{d\sigma}{dv}
\]

- Use inverse transform sampling to recover depositions in an interaction

- Resample the CDF values over a regular grid from [0,1]

- Build 2-D interpolation table (charged lepton energy, random sample)

Curves are normalized! Only shape is important

Bonus Slide: Cutoff for low inelasticities?

- Lower bound for inelasticity for Bremsstrahlung emission is 0

- Consider a lower bound cutoff for inelasticity where interactions below do not contribute significantly to energy loss processes

- Energy losses can be approximated as:

$$-\left\langle \frac{dE}{dX} \right\rangle = \alpha + \beta E$$

where

$$\beta^i(E) = \frac{N}{A} \int_{y_{\text{min}}}^{y_{\text{max}}} dy \, y \frac{d\sigma^i(y, E)}{dy}$$

Lines correspond to values of lower bound cutoff inelasticity:
- Solid: $1 \times 10^{-11}$
- Dotted: $1 \times 10^{-9}$
- Dashed: $1 \times 10^{-7}$
- Dot-dashed: $1 \times 10^{-5}$

$y = 1 \times 10^{-9}$ is a good approximation for the lower bound!
Input leptons cluster near bedrock at the bottom of the viewing region whereas primary neutrinos cluster near the surface at the top of the viewing region.
5-Station ARA Performance - Angular
5-Station ARA Performance - Lepton Energies

Leptons from 1e10 GeV Neutrinos
Trigger: 3 antennas triggering on -7 σ on 1 station(s)

Weighted Counts

Energy (GeV)

$10^8 \quad 10^9 \quad 10^{10} \quad 10^{11} \quad 10^{12}$
PyREx Detector Simulations

- Simulates Askaryan radiation from neutrino interactions with the Askaryan model developed by Jamie Alvarez-Muñiz, Andrés Romero-Wolf, and Enrique Zas: https://arxiv.org/abs/1106.6283
- Using an south pole based ice model based on south pole ice properties parameterized by Matt Newcomb
- Noiseless simulations were used in this study (no additional noise was added to signals, thermal noise was only simulated to calculate trigger thresholds)

- Triggering:
  - ARA uses tunnel diodes in their signal chain
  - An antenna triggers if signal is below $\bar{n} - P\sigma_n$ where $\bar{n}$ is the average noise signal, $\sigma_n$ is the RMS value of noise in the antenna, and $P$ is an integer

- Code used in this study is open source and can be found here: https://github.com/abigailbishop/pyrex/tree/secondaries/analyses/secondaries