Atmospheric Neutrino and Nucleon Decay simulation tools in GENIE

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Outline

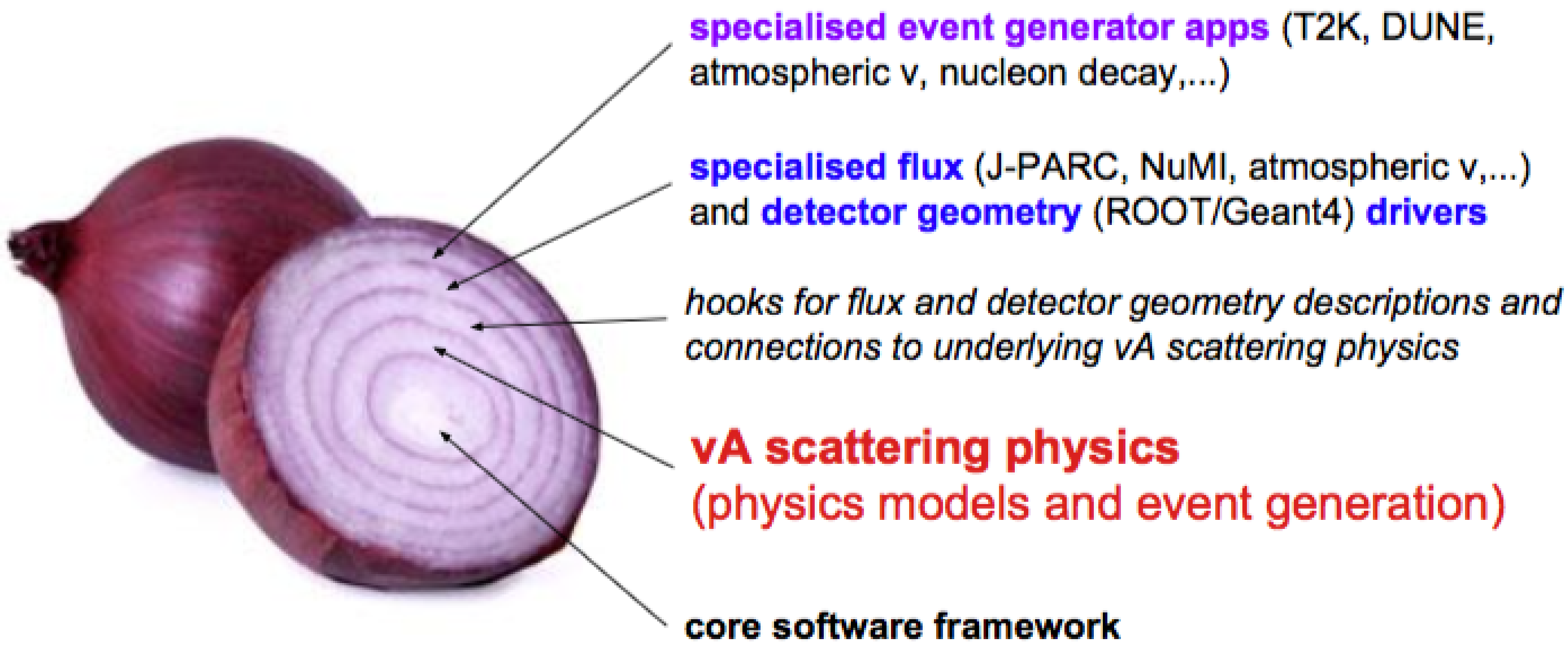
What is already available for the simulation of:

- atmospheric neutrino interactions,
- atmospheric neutrino induced upward-going muons,
- nucleon decay, and
- $n - \bar{n}$ osc. (not yet available in a public release, but see next talk).

Will highlight issues and areas for improvement.

GENIE structure

GENIE is organised in several layers, like an onion:



specialised event generator apps (T2K, DUNE, atmospheric ν, nucleon decay,...)

specialised flux (J-PARC, NuMI, atmospheric ν,...) and **detector geometry** (ROOT/Geant4) **drivers**

hooks for flux and detector geometry descriptions and connections to underlying νA scattering physics

νA scattering physics
(physics models and event generation)

core software framework

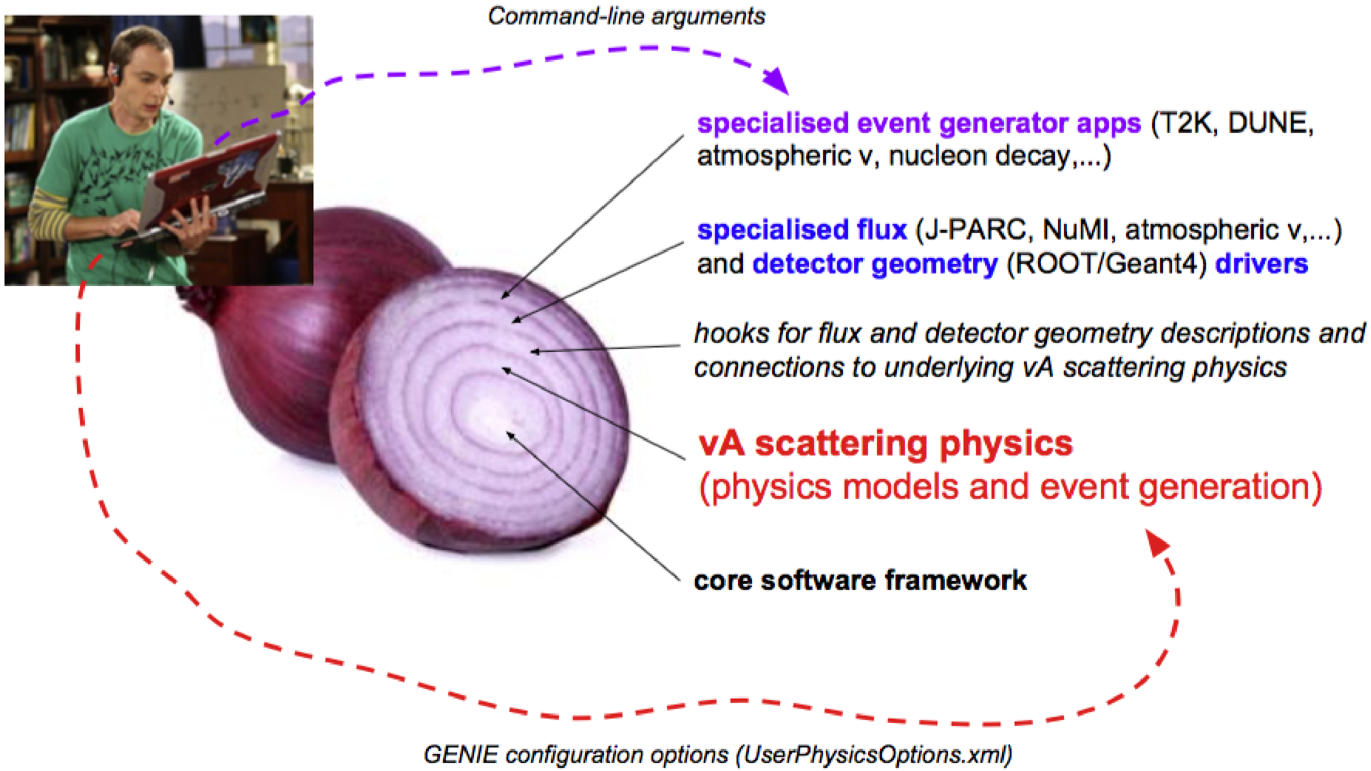
The **two outermost layers** are relevant to what I am discussing here.

GENIE vs GENIE wrapped by LArSoft

Typically, a user interacts with

- the physics layer using the GENIE configuration system, and
- the applications layers using command-line arguments

User experience *altered* by LArSoft. This doesn't concern me here: I will focus on what is in GENIE, not the specifics of running GENIE within other frameworks.



Command-line arguments

specialised event generator apps (T2K, DUNE, atmospheric ν, nucleon decay,...)

specialised flux (J-PARC, NuMI, atmospheric ν,...) and **detector geometry** (ROOT/Geant4) **drivers**

hooks for flux and detector geometry descriptions and connections to underlying νA scattering physics

νA scattering physics
(physics models and event generation)

core software framework

GENIE configuration options (UserPhysicsOptions.xml)

Overall status of atmospheric/PDK tools

Talking about onions, the following summarises the overall status of atmospheric/PDK tools in GENIE:

Overall status of atmospheric/PDK tools

- GENIE contains a **wealth of tools** for atmospheric ν / PDK studies
  - What is available goes **well beyond** what you can find in other well-established event generators.
- For GENIE, these tools are desireable but **not essential add-ons**.
  - They were never the focus of our development effort, and
  - they are not being validated before producing public releases.
- The atmospheric ν / PDK tools in GENIE are not quite at the same level of readiness and robustness as other GENIE tools you know of.

- It will take some development effort so that our users feel more like Chuck and less like the guy on the previous page.
- I hope this group can contribute.
- In the next slides, I will **highlight some areas for improvement**.

Atmospheric neutrino event generation app

GENIE has an app (**gevgen_atmo**) for atmospheric ν event generation:

```
shell> gevgen_atmo
                <-n number_of_events, -e exposure_in_kton_x_yrs (not implemented)>
                -f flux
                -g geometry
                [-R rotation_from_topocentric_hz_frame]
                [-t geometry_top_volume_name]
                [-m max_path_lengths_xml_file]
                [-L geometry_length_units]
                [-D geometry_density_units]
                [-o output_event_file_prefix]
                [-r run_number]
                [-E energy_range]
                [–seed random_number_seed]
                [–cross-sections xml_file]
                [–event-generator-list list_name]
                [–message-thresholds xml_file]
                [–unphysical-event-mask mask]
                [–event-record-print-level level]
                [–mc-job-status-refresh-rate rate]
                [–cache-file root_file]
                [-h]
```

Flux and detector geometry drivers

```
shell> gevgen_atmo
           ...
           -f flux
           -g geometry
           ...
```

These two command-line arguments specify specific flux and geometry drivers to be used with the **gevgen_atmo** app, and set their mandatory arguments.

The flux driver implements the GENIE GFluxI interface:
https://genie.hepforge.org/trac/browser/generator/trunk/src/EVGDrivers/GFluxI.h
while the geometry driver implements the GENIE GeomAnalyzerI interface:
https://genie.hepforge.org/trac/browser/generator/trunk/src/EVGDrivers/GeomAnalyzerI.h

These interfaces define

- the operations that GENIE needs to perform on, and
- the information that needs to extract from

the flux and geometry descriptions in order to generate events.

Atmospheric neutrino flux drivers in GENIE

GENIE includes drivers for two atmospheric neutrino flux simulations (both 3-D simulations):

- **GFlukaAtmo3DFlux**:

  Interface to the FLUKA (A. Ferrari, P. Sala, G. Battistoni and T. Montaruli, Nucl. Phys. Proc. Suppl. 110 (2002) 336) atmospheric neutrino flux.

  Data files from: http://pcbat1.mi.infn.it/∼battist/neutrino.html

- **GBartolAtmoFlux**:

  Interface to the BGLRS (G. Barr, T.K. Gaisser, P. Lipari, S. Robbins and T. Stanev, Phys. Rev.D 70 (2004) 023006) atmospheric neutrino flux.

  Data files from: http://www-pnp.physics.ox.ac.uk/∼barr/fluxfiles

Atmospheric neutrino flux drivers in GENIE

Both drivers inherit all their functionallity from the **GAtmoFlux** base class and they just define the appropriate binning for each flux simulation:

- The FLUKA flux is given in 40 bins of $cos\theta$ (in [-1,1] range / bin width $=$ 0.05) and 61 equally log-spaced energy bins (20 bins per decade) with a minimum energy of 100 MeV.
- The BGLRS flux is given in 20 bins of $cos\theta$ (in [-1,1] range / bin width $=$ 0.1) and 70 log-spaced energy bins (20 bins per decade $<$ 10 GeV, 10 bins per decade $>$ 10 GeV (1-D)) with a minimum energy of 100 MeV.

To specify a specific simulation in **gevgen_atmo** and give the corresponding flux files use:

$$-\mathbf{f} \quad simulation\_name : /path/file[neutrino\_code], \ldots$$

For example, to specify the the FLUKA */data/sdave_numu07.dat* file will be used for the ν_μ flux and the */data/sdave_nue07.dat* file will be used for the ν_e flux, type

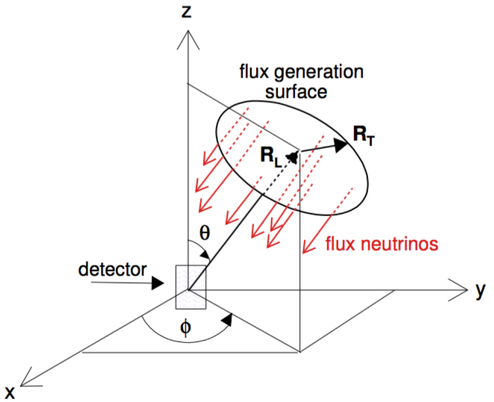
$$-\mathbf{f} \quad FLUKA : /data/sdave\_numu07.dat[14], /data/sdave\_nue07.dat[12]$$

To specify the the BGLRS */data/flux10_271003_z.kam_nue* file will be used for the ν_e flux, type

$$-\mathbf{f} \quad BGLRS : /data/flux10\_271003\_z.kam\_nue[12]$$

Atmospheric neutrino flux drivers in GENIE

For a given direction, determined by the zenith angle θ and the azimuth angle ϕ, the *flux generation surface* is a circular area, with radius R_T, which is tangent to a sphere of radius R_L.



R_T and R_L must be appropriately chosen so that the generation surface is always outside the input geometry volume and so that, for every given direction, the shadow of the generation surface covers the entire geometry.

To fix: No *gevgen_atmo* command-line arguments for R_T and R_L.

By default, the flux neutrino position and momentum 4-vectors are generated in the Topocentric Horizontal Coordinate System (+z: points towards the local zenith, +x: on same plane as local meridian and pointing south). A rotation to a user-defined topocentric coordinate system can be specified as:

$$-\mathbf{R} \quad \textit{convention} : \phi, \theta, \psi$$

For example, to set the Euler angles ϕ=3.14, θ=1.28, ψ=1.0 using the Y convention, type:

$$-\mathbf{R} \quad Y : 3.14, 1.28, 1.0$$

Atmospheric neutrino flux drivers in GENIE

Atmospheric neutrinos have a steep power-law spectrum:

$$\frac{d\Phi_{\nu_\mu}}{dE_\nu} \propto E_\nu^{-3.7}$$

Flux at 50 GeV is $\sim$6 orders of magnitudes lower than the flux at 1 GeV.

GENIE has an option to generate weighted atmospheric neutrino events.

The user can generate events with a different (less steep) power law spectrum, then a weight is calculated for each generated event.

To fix: Not toggled-on via *gevgen_atmo* command-line arguments.

Not validated (according to my memory).

A 3^{rd} atmospheric neutrino flux driver in GENIE

GENIE has an incubator project for the implementation of a driver for an additional atmospheric neutrino flux simulation:

- **GATMNCAtmo3DFlux**:

  An interface to the ATMNC (M. Sajjad Athar, M. Honda, T. Kajita, K. Kasahara and S. Midorikawa, Phys.Lett. B718 (2013) 1375) atmospheric neutrino flux.

  Data files from: http://www.icrr.u-tokyo.ac.jp/∼mhonda

Initial code was contributed by Gobinda Majumder, Ali Ajmi (INO experiment) but had a number of issues.

New flux has a ϕ dependence (unlike the FLUKA and BGLRS fluxes) which led to (relatively straightforward) structural changes affecting all atmospheric flux drivers ✓.

Expecting validation results (QMUL).

A 3^{rd} atmospheric neutrino flux driver in GENIE

Unlike the FLUKA and BGLRS simulations, the ATMNC simulation provides provides **azimuth angle dependent production height tables**.

The production height is not relevant information for GENIE, but GENIE should read-in the ATMNC information, generate a path-length for each flux ray and pass that information through.

For a full 3-flavour analysis the following samples are needed. Weighting with the corresponding oscillation probability requires the path-length L.

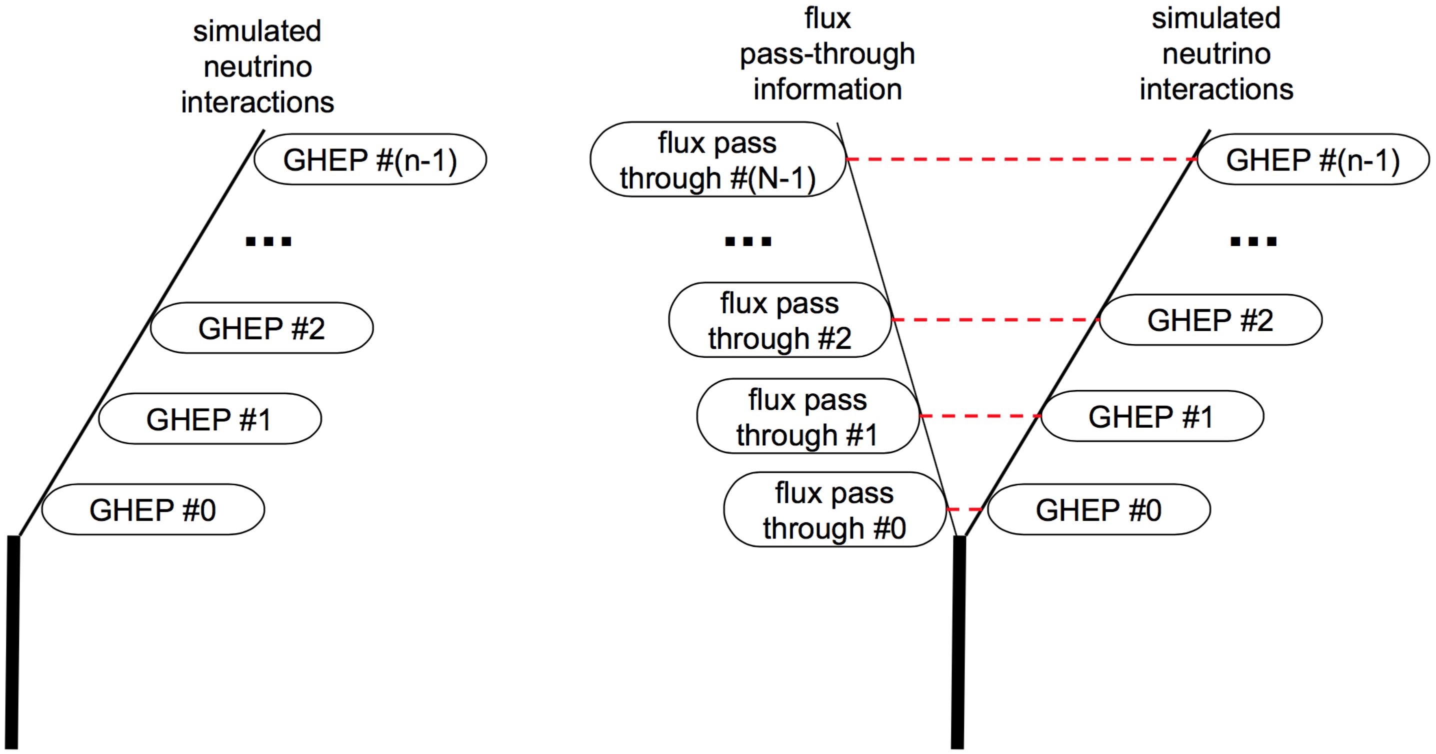
- ν_e sample (ν_e flux, ν_e interaction physics): Analysis weights with $P(\nu_e \to \nu_e)$
- ν_μ sample (ν_μ flux, ν_μ interaction physics): Analysis weights with $P(\nu_\mu \to \nu_\mu)$
- $\bar{\nu}_e$ sample ($\bar{\nu}_e$ flux, $\bar{\nu}_e$ interaction physics): Analysis weights with $P(\bar{\nu}_e \to \bar{\nu}_e)$
- $\bar{\nu}_\mu$ sample ($\bar{\nu}_\mu$ flux, $\bar{\nu}_\mu$ interaction physics): Analysis weights with $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$

- Osc. ν_e sample (ν_μ flux, ν_e interaction physics): Analysis weights with $P(\nu_\mu \to \nu_e)$
- Osc. $\bar{\nu}_e$ sample ($\bar{\nu}_\mu$ flux, $\bar{\nu}_e$ interaction physics): Analysis weights with $P(\bar{\nu}_\mu \to \bar{\nu}_e)$
- ...

Atmospheric neutrino flux driver pass-through info

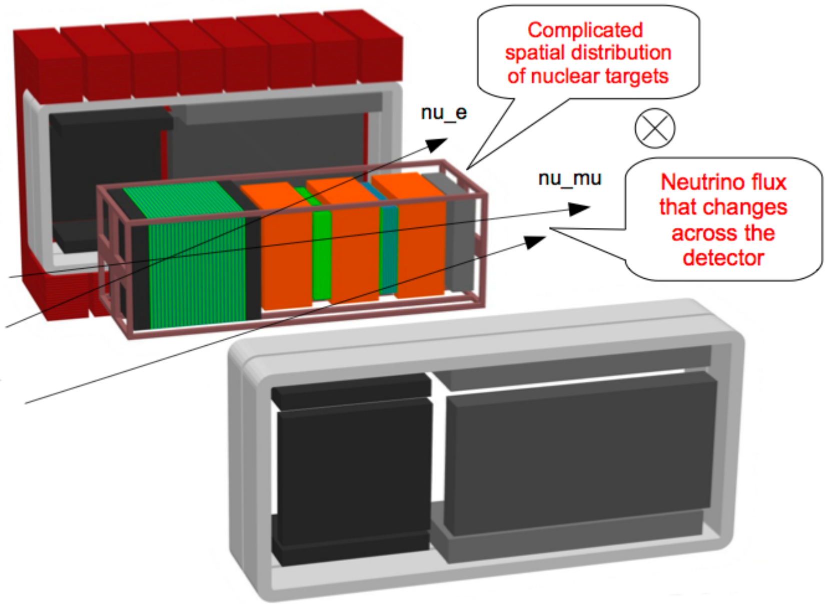
TODO: GENIE should read-in the additional ATMNC information, generate a path-length for each flux ray and pass that information through.

A similar scheme is already in use for GENIE event generation apps for accelerator experiments. Additional branches get added to the output event tree to pass through additional flux simulation data for every flux ray that interacts.
This scheme will have to be adapted for atmospheric neutrinos.



Generating events within a detector

GENIE was setup to solve the very CPU-intensive problem of generating events within a detector geometry. Generally:



- Detectors not uniform, with a complex distribution of nuclear targets.
- Neutrino fluxes also not uniform for detector locations close to the neutrino target. Flux changes across the detector.
- Need to be able to generate events in specific volumes only, sometimes not related with any actual geometry volume.
- Need to keep track of the absolute sample normalization (usually in terms of protons on target).

GENIE has tools to solve this problem without taking shortcuts.

Generating events within a detector

The fundamental problem here is to compute a complex multi-dimensional integral

$$N_{ev} \propto \int dE_{\nu} dcos\theta_{\nu} d\phi_{\nu} dxdydt \sum_{f(lavor)} \frac{d^6\Phi_f(E_{\nu}, cos\theta_{\nu}, \phi_{\nu}, x, y, t)}{dE_{\nu} dcos\theta_{\nu} d\phi_{\nu} dxdydt} \int_0^{\infty} ds \sum_{i(sotope)} \frac{\rho(\vec{r}) w_i(\vec{r}) \sigma^{tot}_{f;i}(E_{\nu})}{A_i(\vec{r})}$$

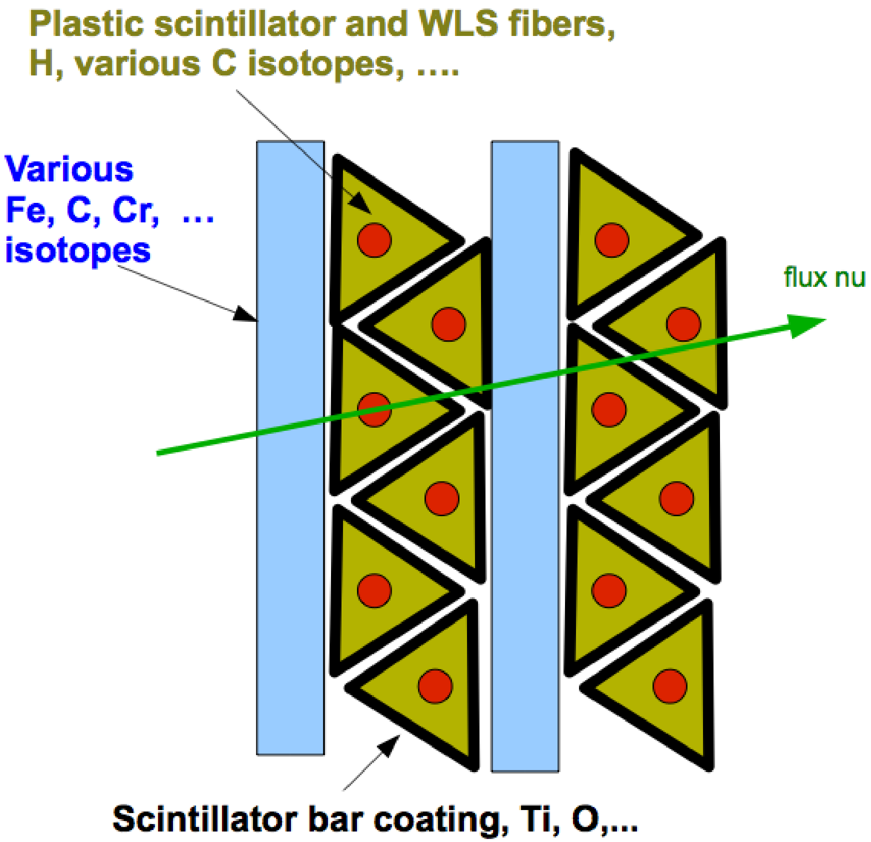
for which an analytical answer is not possible.

- E_{ν}: neutrino energy
- $cos\theta_{\nu}$: flux neutrino zenith angle
- ϕ_{ν}: flux neutrino azimuthal angle
- $dxdy$: unit area in some surface upstream of any volume where we consider interactions
- t: time
- ds: infinitesimal step along the neutrino direction
- $\vec{r} = \vec{r}(s, cos\theta_{\nu}, \phi_{\nu}, x, y)$: position along the neutrino ray in the detector coordinate system
- $\frac{d^6\Phi_f}{dE_{\nu} dcos\theta_{\nu} d\phi_{\nu} dxdydt}$: differential flux of neutrinos of flavour f
- $\rho(\vec{r})$: detector density at position $\vec{r}$ (typically a mixture)
- $w_i(\vec{r})$: weight fraction for isotope i, in the mixture at position $\vec{r}$
- $A_i(\vec{r})$: mass number for isotope i, in the mixture at position $\vec{r}$
- $\sigma^{tot}_{f;i}(E_{\nu})$: total cross-section for interactions of neutrinos of flavour f with isotope i, at energy E_{ν}.

Generating events within a detector

The numerical integration involves:

- Pulling random rays from the neutrino flux description and "throwing" them towards the detector.
- Following the ray, stepping through the geometry and, in the absence of external fiducial cuts, getting all segments described by the entry and exit points of the flux ray in every single volume it passes through.
- For each segment, which is purely within a volume, figure out the corresponding mixture information (density, isotopic composition, weight fraction for each isotope) and calculate the density-weighted path length for each isotope seen along the trajectory.



Detector geometry drivers in GENIE

GENIE has two geometry drivers:

- one that is able to handle detailed detector geometry description in ROOT format (TGeoManager), and
- one that is handling a simple "target mix" (no detailed geometry).

gevgen_atmo is able to use both geometry drivers.

To use a ROOT detector geometry description, one simply needs to specify an input ROOT file containing the geometry:

$$-\mathbf{g} \quad /some/path/dune\_far\_detector.root$$

To use a simple "target mix" one needs to supply a comma-separated list of targets and their weight fractions. For example, to use a target mix of 88.79% (weight fraction) O^{16} and 11.21% H (sometimes also called "water") type:

$$-\mathbf{g} \quad 1000080160[0.8879], 1000010010[0.1121]$$

Detector geometry drivers in GENIE

The latter option is probably reasonably sufficient for most DUNE studies.

However, with a ROOT geometry, one will hit the following problem: The current implementation of the ROOT geometry driver, although correct and appropriate in other contexts (near detectors of accelerator neutrino experiments), is **inefficient for atmospheric neutrinos**.

Indeed, since all parts of the detector see the same spectrum, we don't need to propagate each flux ray individually into the detector.

TODO: For atmospheric ν, we need a new driver which is a hybrid of the current detailed ROOT geometry driver and the simple "target mix" driver. Mainly:

- Instead of calculating path-lengths for each target material along the path of a flux ray, return the mass of each target material in the part of the geometry that is being considered.
- Distribute vertices uniformly (by weight) in volumes that contain the selected target.

Atmospheric neutrino event sample normalization

In GENIE accelerator neutrino event generation apps, one typically sets the exposure either in **number of events** or in **protons on target (POT)**.

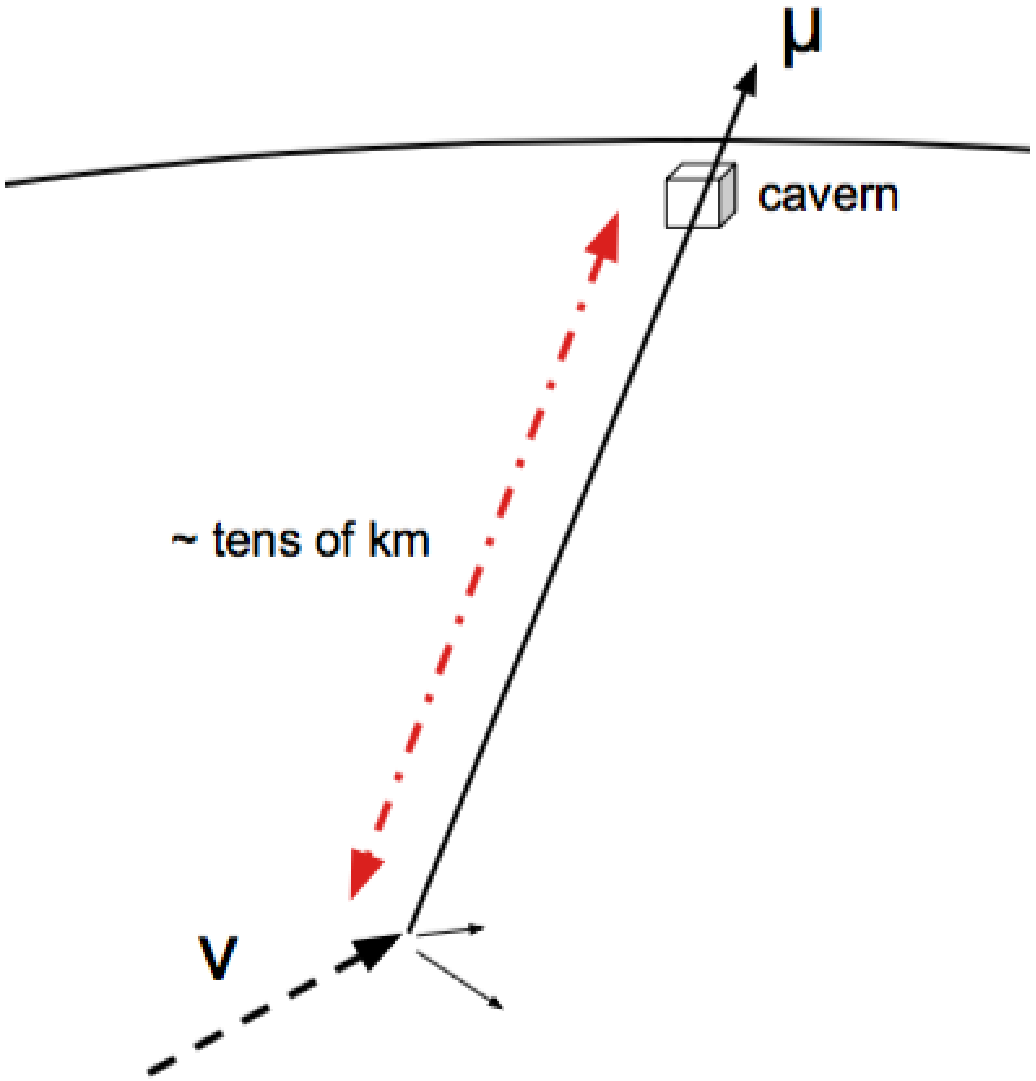
- It is very difficult, if not impossible, to calculate the POT exposure after the event generation job is finished, so it is essential that we do this within the event generation app.

In GENIE atmospheric neutrino event generation apps, one typically sets the exposure either in **number of events** or in **kton · years**.

- **kton · years** calculation not implemented just yet.
- It is relatively trivial to calculate.
- But, one of the most common GENIE questions I get...
- Here is an GENIE example from T2K that can be easily adapted:
  https://genie.hepforge.org/trac/browser/generator/trunk/src/contrib/t2k/sk_sample_norm_abs.C

TODO: Calculate the kton · years exposure within **gevgen_atmo**

Atmospheric neutrino induced up-going muons



For neutrino-induced up-going muons, the usual event generation schemes would be terribly inefficient.

A muon entering the detector could originate from a multi-TeV atmospheric neutrino interaction several km below the detector.

One would need to consider an *enormous* volume, with the vast majority of events not registering any activity in the detector.

Atmospheric neutrino induced up-going muons

Typically, then, one converts the atmospheric neutrino flux to a muon flux as follows:

$$\frac{dN_\mu}{dE_\mu} = \int_{E_\mu}^{\infty} dE_{\nu_\mu} \Big(\frac{dN_{\nu_\mu}}{dE_{\nu_\mu}} \cdot \frac{dP(E_{\nu_\mu}, E_\mu)}{dE_\mu} \Big)$$

where:

$$\frac{dP(E_{\nu_\mu}, E_\mu)}{dE_\mu} = N_A \int_{E_\mu}^{E_{\nu_\mu}} dE'_\mu \int_0^{\infty} dX \; g(X, E_\mu, E'_\mu) \cdot \frac{1}{E_{\nu_\mu}} \int_0^1 dx \; \frac{d^2\sigma_{CC}}{dxdy} \Big|_{y=1-\frac{E'_\mu}{E_{\nu_\mu}}}$$

is the probability that a neutrino of energy E_{ν_μ} interacting anywhere in the rock below the detector gives a muon with energy E_μ *in the detector*.

The quantity $g(X, E_\mu, E'_\mu)$ is the probability that a muon of energy E'_μ will have energy E_μ after a propagating in the rock for a distance X (gr/cm^2).

Muon energy loss

A collection of semi-empirical / phenomenological formulas, for describing muon energy loss processes in the energy range from 1 GeV to several TeV can be found in the CERN Yellow Report of W. Lohman, R. Kopp and R. Voss [CERN 85-03].

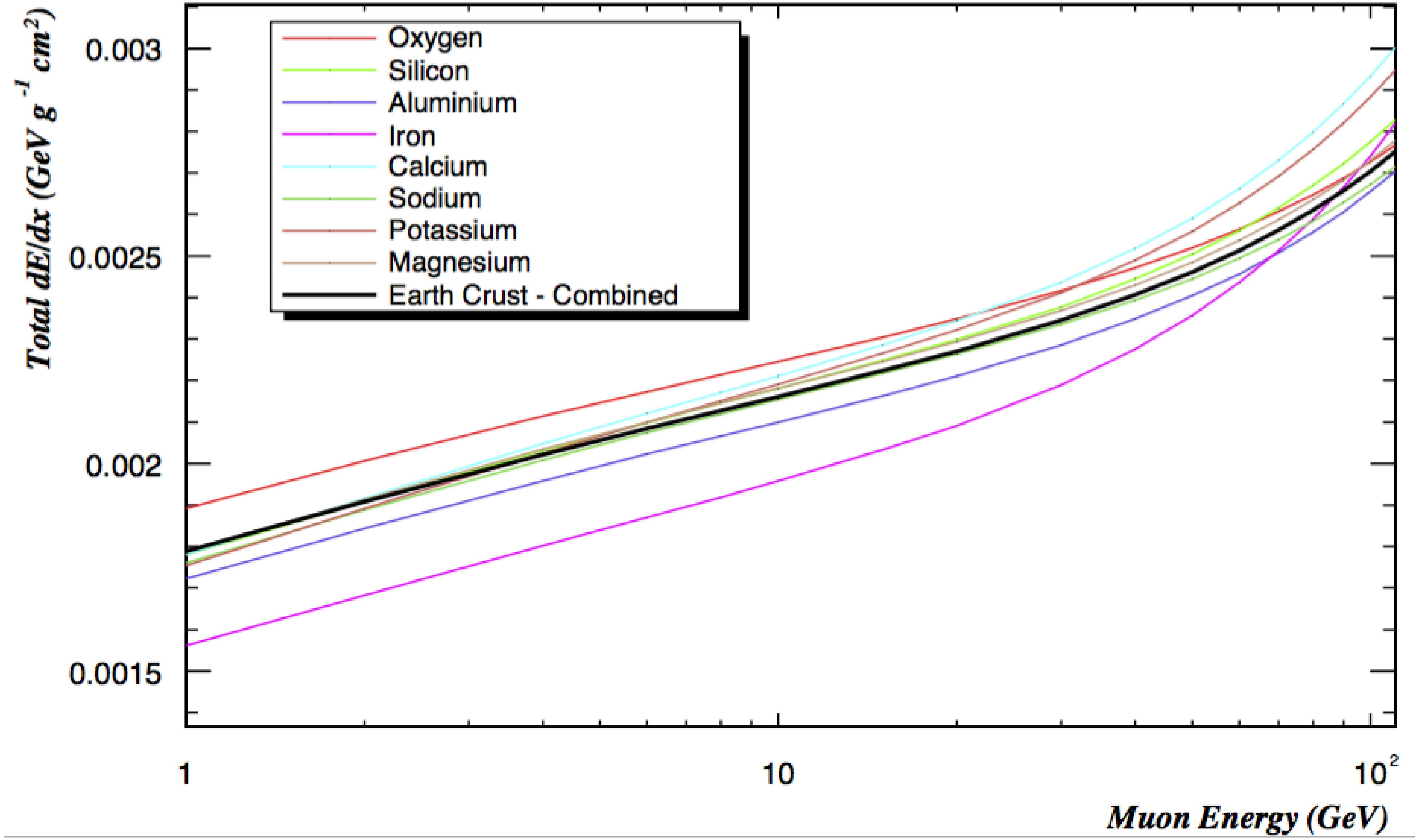
The following energy loss processes are implemented in GENIE (*):

- **Ionization**: modeled with the known formula of Bethe-Bloch.
- **Muon bremsstrahlung**: modeled through the Bethe-Heitler expression with the Petrukhin-Shestakov form factors.
- **Direct electron pair production**: described from the semi-empirical Kokulin-Petrukhin formula based on the work of Kelner-Kotov.
- **Photonuclear interaction**: described using the phenomenological model of Bezrukov-Bugaev.

(*) https://genie.hepforge.org/trac/browser/generator/trunk/src/MuELoss

Muon energy loss

Total $\frac{dE_{mu}}{dx}$ (due to ionization, bremsstrahlung, electron pair production and photonuclear interactions) for all Earth crust elements:



Atmospheric neutrino induced up-going muon flux app

GENIE has an app (**gevgen_upmu**) to generate up-going muon passing through a box volume surrounding a detector:

```
shell> gevgen_upmu
             -n number_of_muons
             -f flux
             -d detector_bounding_box_size
             -g rock_composition (not implemented)

             [-r run_number]
             [--seed random_number_seed]
             [--cross-sections xml_file]
             [--message-thresholds xml_file]
```

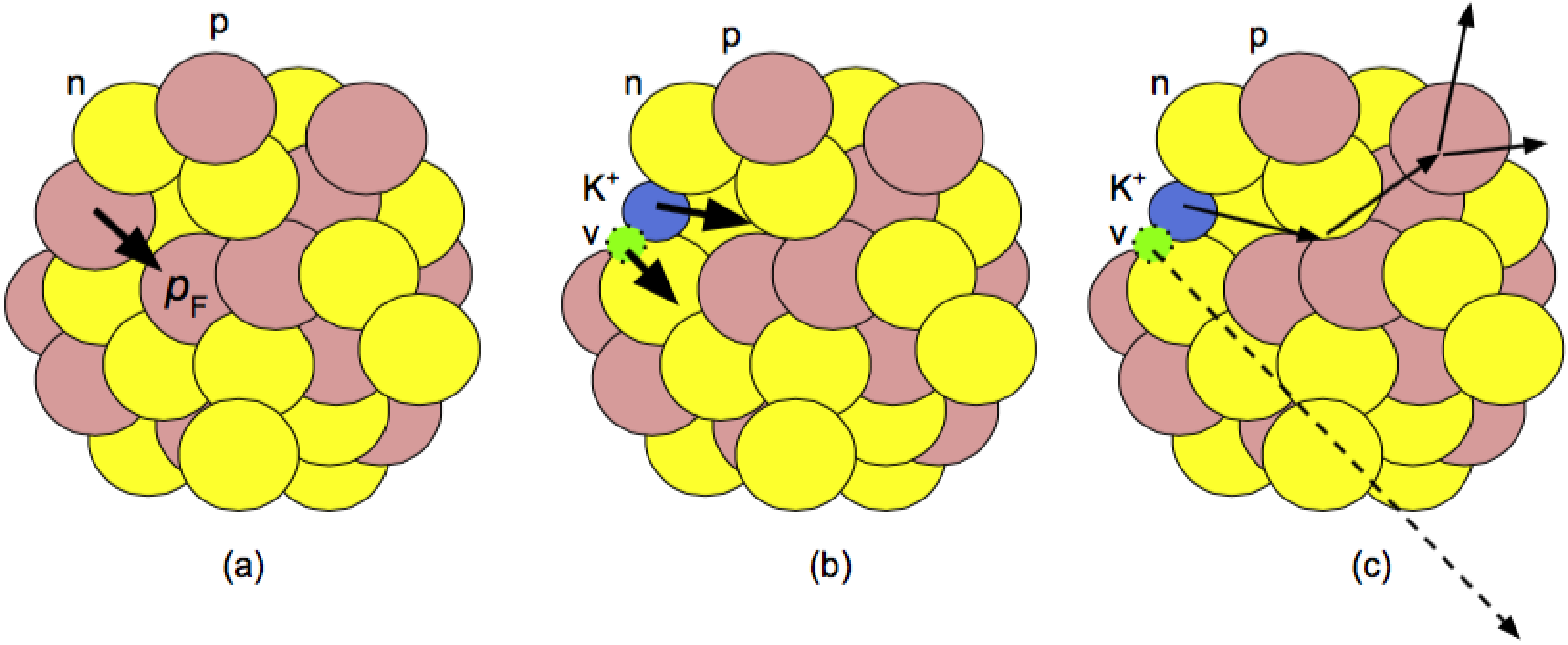
This app was never tested / validated.

Also, it contains a hardcoded rock composition and a simplistic muon dE/dx model. The -g option needs to be impemented and **gevgen_upmu** needs to be connected to the MuELoss package.

Nucleon decay simulation

Nucleon decay is a process that fits nicely within GENIE:

- The GENIE framework is generic enough to easily accomodate non-neutrino events
- There are physics modelling complementarities:
    - nuclear initial state (Fermi momentum, binding etc), and
    - intranuclear hadron transport.



Nucleon decay app

GENIE has an app (**gevgen_ndcy**) for nucleon decay simulation:

```
shell> gevgen_ndcy
              -n number_of_events
              -m nucleon_decay_mode
              -g geometry

              [-t geometry_top_volume_name]
              [-L geometry_length_units]
              [-D geometry_density_units]
              [-o output_event_file_prefix]
              [-r run_number]
              [--seed random_number_seed]
              [--message-thresholds xml_file]
              [--event-record-print-level level]
              [--mc-job-status-refresh-rate rate]
              [-h]
```

For the time being, a ROOT geometry is not supported for use in **gevgen_ndcy** - Only a simple target mix.

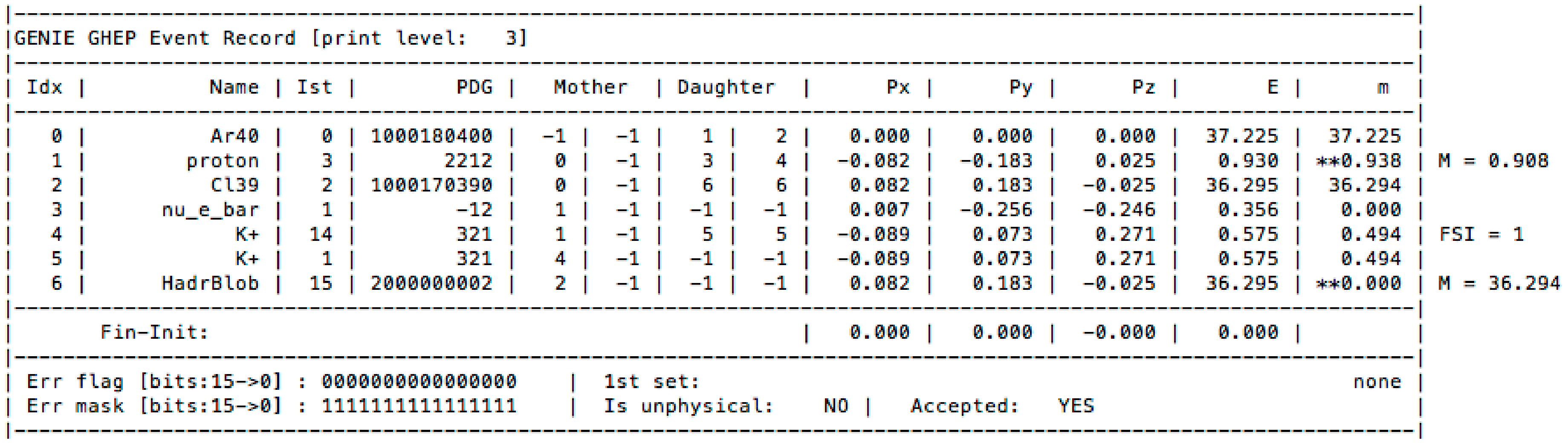
Nucleon decay modes

The following two-body nucleon decay modes are implemented:

ID	**Decay channel**	**Current limit ($\times 10^{34}$ yrs)**
0	$p \rightarrow e^+\pi^0$	1.3
1	$p \rightarrow \mu^+\pi^0$	1.1
2	$p \rightarrow e^+\eta^0$	0.42
3	$p \rightarrow \mu^+\eta^0$	0.13
4	$p \rightarrow e^+\rho^0$	0.07
5	$p \rightarrow \mu^+\rho^0$	0.02
6	$p \rightarrow e^+\omega^0$	0.03
7	$p \rightarrow \mu^+\omega^0$	0.08
8	$n \rightarrow e^+\pi^-$	0.2
9	$n \rightarrow \mu^+\pi^-$	0.1
10	$p \rightarrow \bar{\nu}K^+$	0.4

Nucleon decay modes

Typical event:



```
|------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                        |
|------------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |      m  |
|------------------------------------------------------------------------------------------------------------------|
|   0 |          Ar40 |   0 | 1000180400 |  -1 |  -1 |   1 |   2 |   0.000 |   0.000 |   0.000 |  37.225 |  37.225 |
|   1 |        proton |   3 |       2212 |   0 |  -1 |   3 |   4 |  -0.082 |  -0.183 |   0.025 |   0.930 | **0.938 | M = 0.908
|   2 |          Cl39 |   2 | 1000170390 |   0 |  -1 |   6 |   6 |   0.082 |   0.183 |  -0.025 |  36.295 |  36.294 |
|   3 |      nu_e_bar |   1 |        -12 |   1 |  -1 |  -1 |  -1 |   0.007 |  -0.256 |  -0.246 |   0.356 |   0.000 |
|   4 |            K+ |  14 |        321 |   1 |  -1 |   5 |   5 |  -0.089 |   0.073 |   0.271 |   0.575 |   0.494 | FSI = 1
|   5 |            K+ |   1 |        321 |   4 |  -1 |  -1 |  -1 |  -0.089 |   0.073 |   0.271 |   0.575 |   0.494 |
|   6 |      HadrBlob |  15 | 2000000002 |   2 |  -1 |  -1 |  -1 |   0.082 |   0.183 |  -0.025 |  36.295 | **0.000 | M = 36.294
|------------------------------------------------------------------------------------------------------------------|
|       Fin-Init:                                                |   0.000 |   0.000 |  -0.000 |   0.000 |          |
|------------------------------------------------------------------------------------------------------------------|
| Err flag [bits:15->0] : 0000000000000000     |  1st set:                                                     none |
| Err mask [bits:15->0] : 1111111111111111     |  Is unphysical:    NO |   Accepted:   YES                          |
|------------------------------------------------------------------------------------------------------------------|
```

New nucleon decay modes

It is trivial to add additional two-body decay channels.

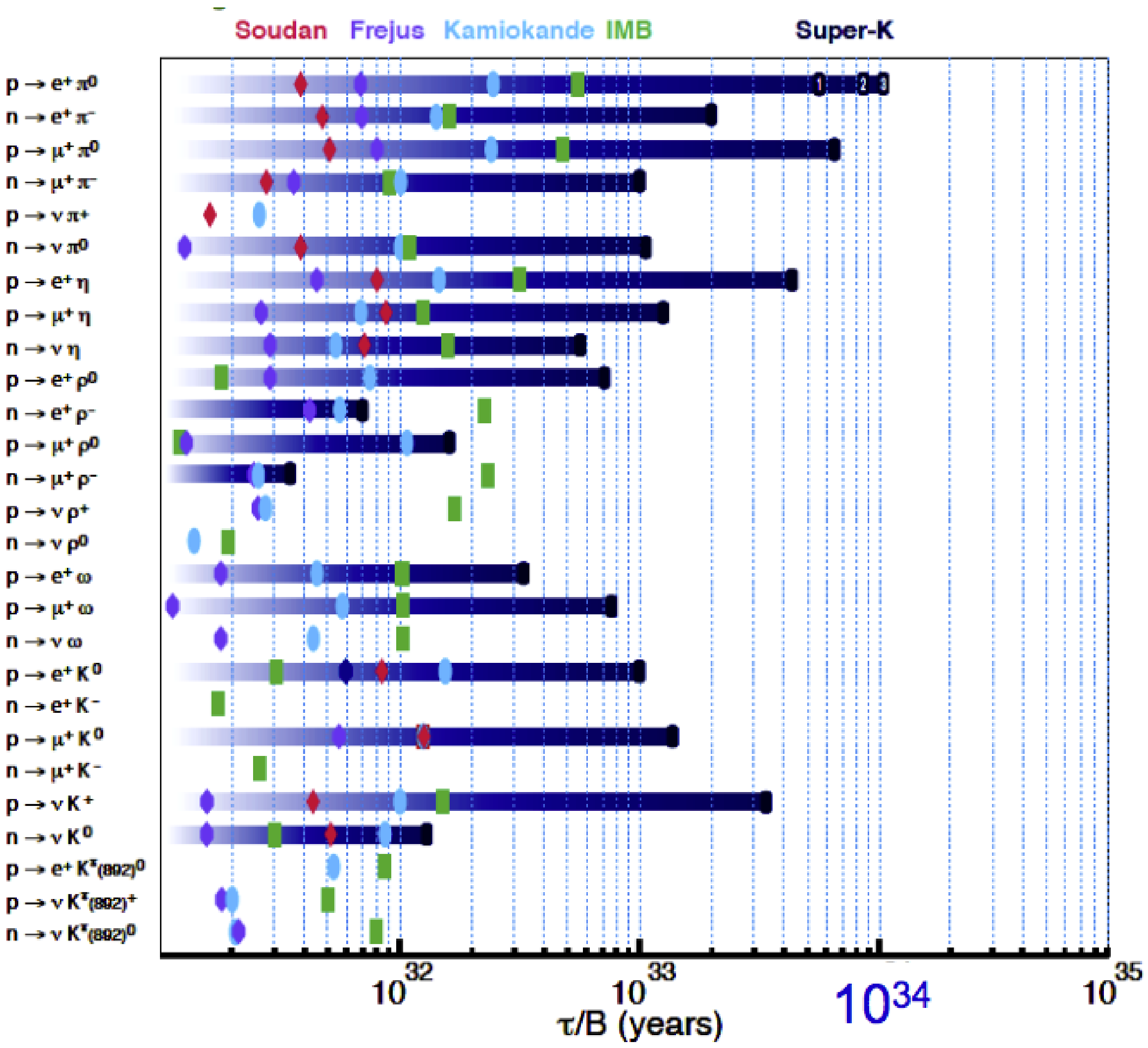
Recently, Elena Gramellini (Yale/MicroBooNE) contributed code to add some additional channels:

- $p \to \bar{\nu}\pi^+$
- $p \to \gamma e^+$
- $p \to \gamma \mu^+$
- $p \to K^0_L e^+$
- $p \to K^0_s e^+$
- $p \to K^0_L \mu^+$
- $p \to K^0_s \mu^+$
- $n \to \bar{\nu}\pi^0$
- $n \to e^- K^+$

Although this was a very positive step, several channels for which experimental studies and limits exist, were not included in the MicroBooNE update.

The contributed code was not included in GENIE, and a more comprehensive literature search and GENIE upgrade is required.

New nucleon decay modes



[Y.Hayato, GLA2011]

Additional studied channels that may be included:

- $n \to \nu \eta^0$
- $n \to \nu \gamma$
- $n \to e^+ \rho^-$
- $n \to \mu^+ \rho^-$
- $p \to \nu \rho^+$
- $n \to \nu \rho^0$
- $n \to \nu \omega^0$
- $n \to e^+ K^-$
- $n \to \nu K^0$

New nucleon decay modes

In particular, I would like to see work to upgrade the GENIE nucleon decay generator trivial addition of two-body decay channels.

For example [J. C. Pati and A. Salam, Phys.Rev. D10 (1974) 275]:

- $p \to e^+\bar{\nu}\nu$, and
- $p \to e^+e^+e^-$

For these channels, a phase space decay can be a poor approximation.

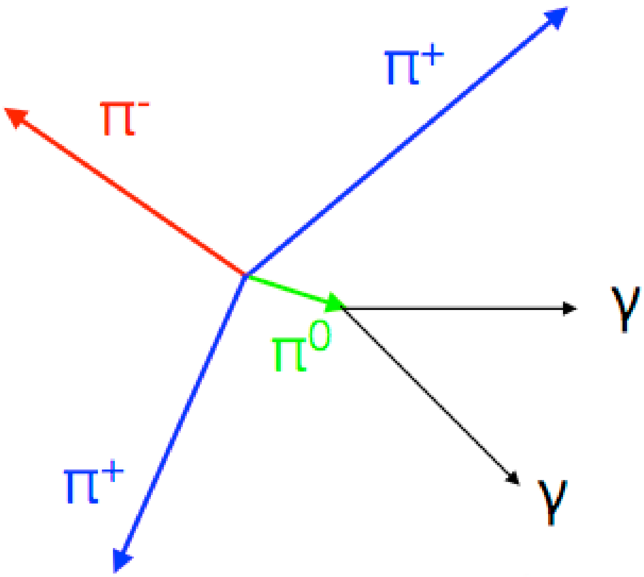
However these nucleon decay channels share final states with SM processes (e.g μ decay), and reasonably model-independent improvements to simple phase decays exist in literature [M.-C. Chen and V. Takhistov, Phys.Rev. D89 (2014) 9, 095003].

$n - \bar{n}$ oscillation app

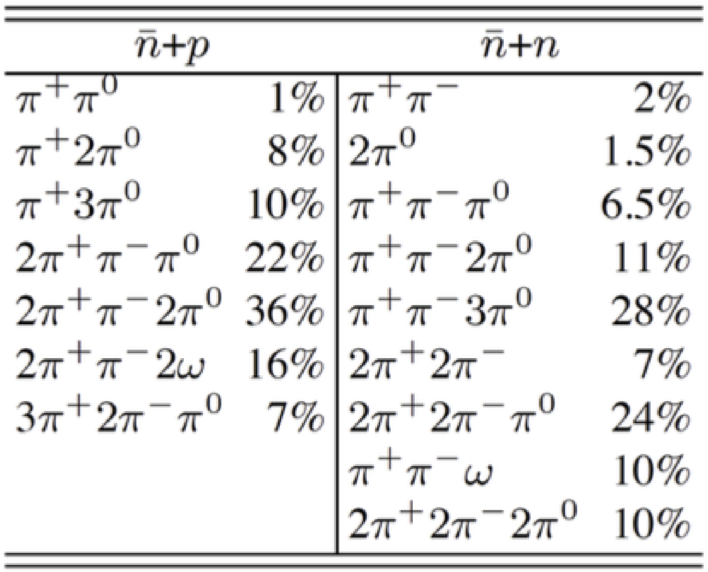
GENIE has an active incubator project (developers: J.Hewes, G. Karagiorgi (Manchester)) to simulate $n - \bar{n}$ oscillations.

Neutron spontaneously oscillates into antineutron and annihilates with a nearby nucleon. The final state is a spherical cascade of pions.

The code is modelled on GENIE's existing proton decay event generator.



[J.Hewes]



$\bar{n}+p$		$\bar{n}+n$	
$\pi^+\pi^0$	1%	$\pi^+\pi^-$	2%
$\pi^+2\pi^0$	8%	$2\pi^0$	1.5%
$\pi^+3\pi^0$	10%	$\pi^+\pi^-\pi^0$	6.5%
$2\pi^+\pi^-\pi^0$	22%	$\pi^+\pi^-2\pi^0$	11%
$2\pi^+\pi^-2\pi^0$	36%	$\pi^+\pi^-3\pi^0$	28%
$2\pi^+\pi^-2\omega$	16%	$2\pi^+2\pi^-$	7%
$3\pi^+2\pi^-\pi^0$	7%	$2\pi^+2\pi^-\pi^0$	24%
		$\pi^+\pi^-\omega$	10%
		$2\pi^+2\pi^-2\pi^0$	10%

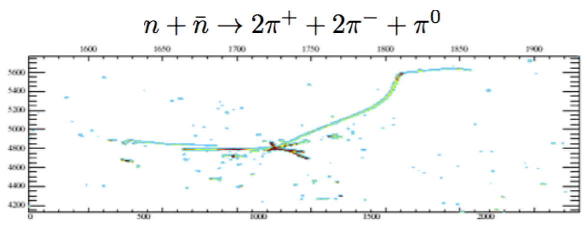
Super-Kamiokande branching ratios

[J.Hewes]

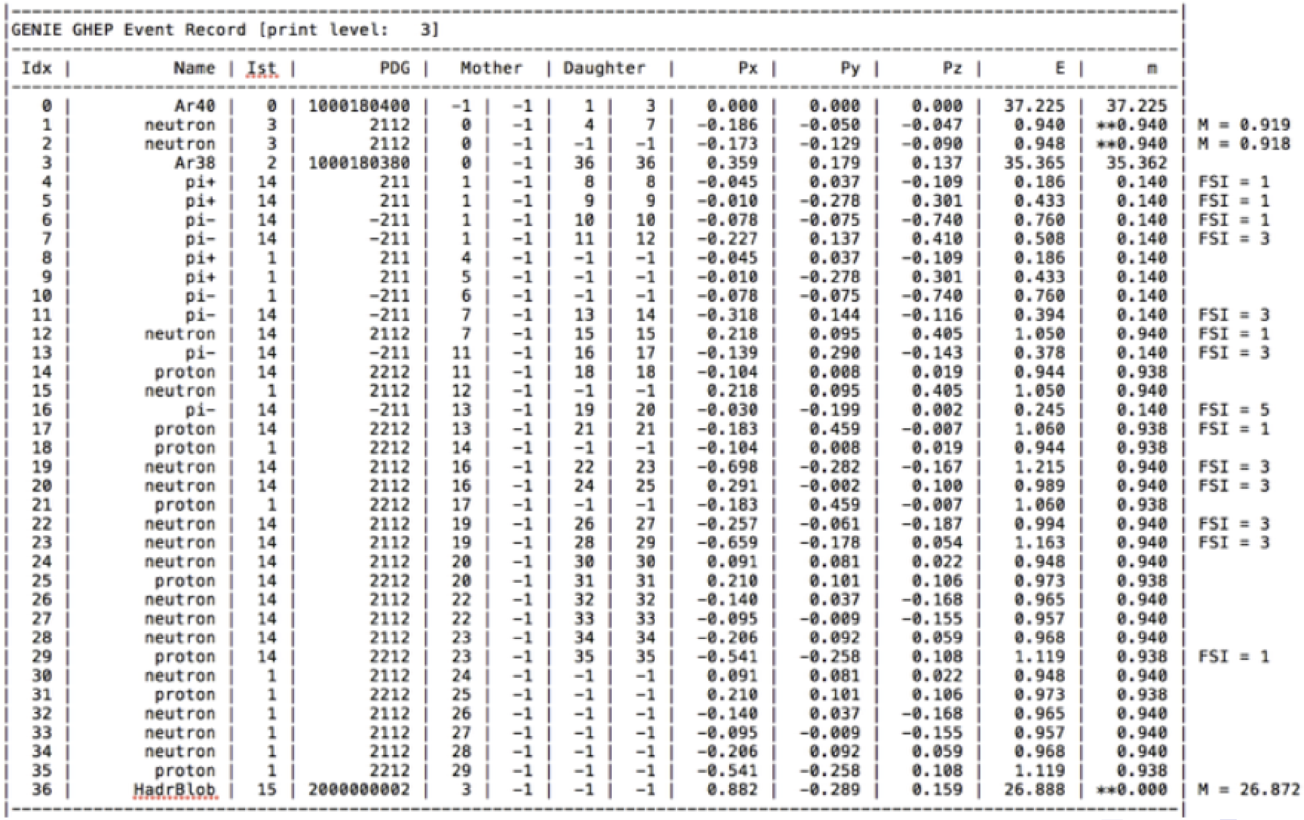
$n - \bar{n}$ oscillation app

Code appears to be in good order (GENIE review and formal project graduation pending).

App should be available in a near future release.


$n + \bar{n} \rightarrow 2\pi^{+} + 2\pi^{-} + \pi^{0}$

[J.Hewes]



```
|------------------------------------------------------------------------------------------------------------------------|
|GENIE GHEP Event Record [print level:   3]                                                                              |
|------------------------------------------------------------------------------------------------------------------------|
| Idx |          Name | Ist |        PDG |   Mother  | Daughter  |      Px |      Py |      Pz |       E |        m |
|------------------------------------------------------------------------------------------------------------------------|
|   0 |          Ar40 |   0 | 1000180400 |  -1 |  -1 |   1 |   3 |   0.000 |   0.000 |   0.000 |  37.225 |   37.225 |
|   1 |       neutron |   3 |       2112 |   0 |  -1 |   4 |   7 |  -0.186 |  -0.050 |  -0.047 |   0.940 | **0.940 | M = 0.919
|   2 |       neutron |   3 |       2112 |   0 |  -1 |  -1 |  -1 |  -0.173 |  -0.129 |  -0.090 |   0.948 | **0.940 | M = 0.918
|   3 |          Ar38 |   2 | 1000180380 |   0 |  -1 |  36 |  36 |   0.359 |   0.179 |   0.137 |  35.365 |   35.362 |
|   4 |           pi+ |  14 |        211 |   1 |  -1 |   8 |   8 |  -0.045 |   0.037 |  -0.109 |   0.186 |    0.140 | FSI = 1
|   5 |           pi+ |  14 |        211 |   1 |  -1 |   9 |   9 |  -0.010 |  -0.278 |   0.301 |   0.433 |    0.140 | FSI = 1
|   6 |           pi- |  14 |       -211 |   1 |  -1 |  10 |  10 |  -0.078 |  -0.075 |  -0.740 |   0.760 |    0.140 | FSI = 1
|   7 |           pi- |  14 |       -211 |   1 |  -1 |  11 |  12 |  -0.227 |   0.137 |   0.410 |   0.508 |    0.140 | FSI = 3
|   8 |           pi+ |   1 |        211 |   4 |  -1 |  -1 |  -1 |  -0.045 |   0.037 |  -0.109 |   0.186 |    0.140 |
|   9 |           pi+ |   1 |        211 |   5 |  -1 |  -1 |  -1 |  -0.010 |  -0.278 |   0.301 |   0.433 |    0.140 |
|  10 |           pi- |   1 |       -211 |   6 |  -1 |  -1 |  -1 |  -0.078 |  -0.075 |  -0.740 |   0.760 |    0.140 |
|  11 |           pi- |  14 |       -211 |   7 |  -1 |  13 |  14 |  -0.318 |   0.144 |  -0.116 |   0.394 |    0.140 | FSI = 3
|  12 |       neutron |  14 |       2112 |   7 |  -1 |  15 |  15 |   0.218 |   0.095 |   0.405 |   1.050 |    0.940 | FSI = 1
|  13 |           pi- |  14 |       -211 |  11 |  -1 |  16 |  17 |  -0.139 |   0.290 |  -0.143 |   0.378 |    0.140 | FSI = 3
|  14 |        proton |  14 |       2212 |  11 |  -1 |  18 |  18 |  -0.104 |   0.008 |   0.019 |   0.944 |    0.938 |
|  15 |       neutron |   1 |       2112 |  12 |  -1 |  -1 |  -1 |   0.218 |   0.095 |   0.405 |   1.050 |    0.940 |
|  16 |           pi- |  14 |       -211 |  13 |  -1 |  19 |  20 |  -0.030 |  -0.199 |   0.002 |   0.245 |    0.140 | FSI = 5
|  17 |        proton |  14 |       2212 |  13 |  -1 |  21 |  21 |  -0.183 |   0.459 |  -0.007 |   1.060 |    0.938 | FSI = 1
|  18 |        proton |   1 |       2212 |  14 |  -1 |  -1 |  -1 |  -0.104 |   0.008 |   0.019 |   0.944 |    0.938 |
|  19 |       neutron |  14 |       2112 |  16 |  -1 |  22 |  23 |  -0.698 |  -0.282 |  -0.167 |   1.215 |    0.940 | FSI = 3
|  20 |       neutron |  14 |       2112 |  16 |  -1 |  24 |  25 |   0.291 |  -0.002 |   0.100 |   0.989 |    0.940 | FSI = 3
|  21 |        proton |   1 |       2212 |  17 |  -1 |  -1 |  -1 |  -0.183 |   0.459 |  -0.007 |   1.060 |    0.938 |
|  22 |       neutron |  14 |       2112 |  19 |  -1 |  26 |  27 |  -0.257 |  -0.061 |  -0.187 |   0.994 |    0.940 | FSI = 3
|  23 |       neutron |  14 |       2112 |  19 |  -1 |  28 |  29 |  -0.659 |  -0.178 |   0.054 |   1.163 |    0.940 | FSI = 3
|  24 |       neutron |  14 |       2112 |  20 |  -1 |  30 |  30 |   0.091 |   0.081 |   0.022 |   0.948 |    0.940 |
|  25 |        proton |  14 |       2212 |  20 |  -1 |  31 |  31 |   0.210 |   0.101 |   0.106 |   0.973 |    0.938 |
|  26 |       neutron |  14 |       2112 |  22 |  -1 |  32 |  32 |  -0.140 |   0.037 |  -0.168 |   0.965 |    0.940 |
|  27 |       neutron |  14 |       2112 |  22 |  -1 |  33 |  33 |  -0.095 |  -0.009 |  -0.155 |   0.957 |    0.940 |
|  28 |       neutron |  14 |       2112 |  23 |  -1 |  34 |  34 |  -0.206 |   0.092 |   0.059 |   0.968 |    0.940 |
|  29 |        proton |  14 |       2212 |  23 |  -1 |  35 |  35 |  -0.541 |  -0.258 |   0.108 |   1.119 |    0.938 | FSI = 1
|  30 |       neutron |   1 |       2112 |  24 |  -1 |  -1 |  -1 |   0.091 |   0.081 |   0.022 |   0.948 |    0.940 |
|  31 |        proton |   1 |       2212 |  25 |  -1 |  -1 |  -1 |   0.210 |   0.101 |   0.106 |   0.973 |    0.938 |
|  32 |       neutron |   1 |       2112 |  26 |  -1 |  -1 |  -1 |  -0.140 |   0.037 |  -0.168 |   0.965 |    0.940 |
|  33 |       neutron |   1 |       2112 |  27 |  -1 |  -1 |  -1 |  -0.095 |  -0.009 |  -0.155 |   0.957 |    0.940 |
|  34 |       neutron |   1 |       2112 |  28 |  -1 |  -1 |  -1 |  -0.206 |   0.092 |   0.059 |   0.968 |    0.940 |
|  35 |        proton |   1 |       2212 |  29 |  -1 |  -1 |  -1 |  -0.541 |  -0.258 |   0.108 |   1.119 |    0.938 |
|  36 |     HadrBlob |  15 | 2000000002 |   3 |  -1 |  -1 |  -1 |   0.882 |  -0.289 |   0.159 |  26.888 | **0.000 | M = 26.872
|------------------------------------------------------------------------------------------------------------------------|
```

Possible new GENIE incubator projects

- Add a more efficient ROOT geometry driver for atmospheric ν interactions.
- Set **gevgen_atmo** exposure in terms of kton·yrs.
- Add atmospheric flux pass-through info (e.g. production height).
- ATMNC flux validation (on going progress?).
- Validate the neutrino-induced upgoing-mu app **gevgen_upmu**
- **gevgen_upmu** rock composition / interface to MuELoss package
- Remaining two-body decay channels in **gevgen_ndcy**
- Three-body decay channels in **gevgen_ndcy**
  - Literature search - most well motivated channels?
  - Beyond phase space decays (model-independent or specific BSM models)
- Add detector geometry support in **gevgen_ndcy** and **gevgen_nnbar**
- Validation, validation, validation
  - GENIE views these tools as desireable but not essential add-ons
  - We don't validate the atmospheric flux drivers before a release
  - We don't validate the atmospheric neutrino apps before a release
  - We don't validate the nucleon decay apps before a release
  - Unlikely that we will write validation programs for these any time soon
  - Will plug-in any contributed validation program to our suite of tests
  - You can help us guarantee the integrity of the tools you use most