Atmospheric neutrino production height for ν_τ simulation

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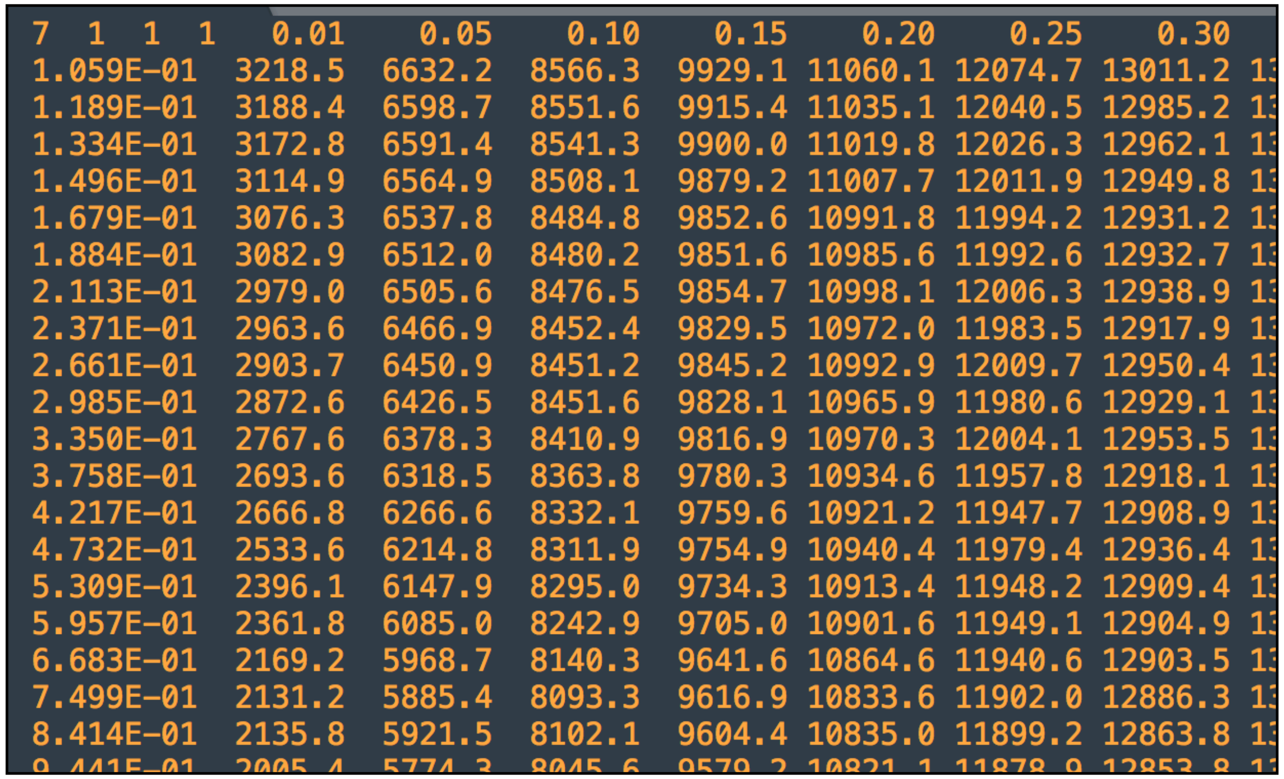
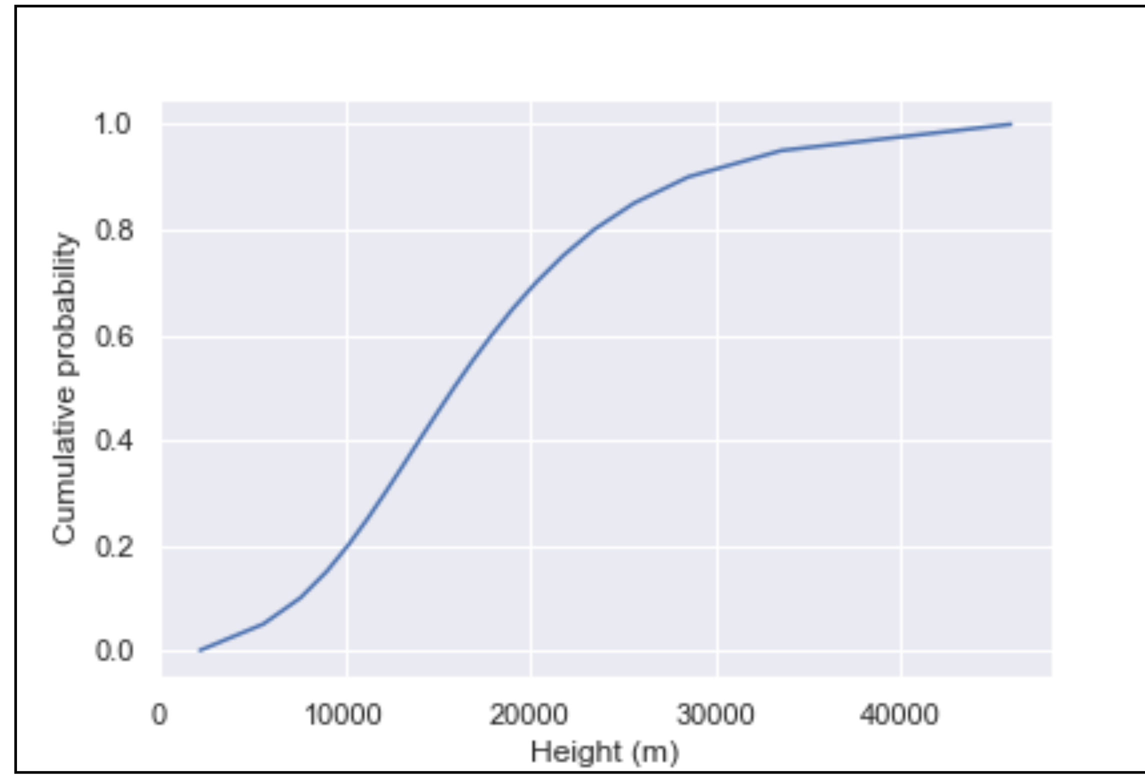
Atmospheric neutrino production height

- A lot of the machinery to simulate atmospheric neutrinos in LArSoft is already in place.
  - GENIE comes with an atmospheric generator app, with flux drivers in place to interface with various fluxes (ie. Bartol, Honda).
  - Honda fluxes are most recent (2014), and include fluxes for the Homestake location (available here).
  - Art has a **GENIEHelper** class in the **nutools** package which can run this generator and produce atmospheric neutrinos in an art/ LArSoft output format.
- One piece is missing: Honda's neutrino production height tables, which have been made publicly available alongside the fluxes.
- Oscillations driven by L/E, so we have to know L!

Production height simulation



7 1 1 1	0.01	0.05	0.10	0.15	0.20	0.25	0.30
1.059E-01	3218.5	6632.2	8566.3	9929.1	11060.1	12074.7	13011.2
1.189E-01	3188.4	6598.7	8551.6	9915.4	11035.1	12040.5	12985.2
1.334E-01	3172.8	6591.4	8541.3	9900.0	11019.8	12026.3	12962.1
1.496E-01	3114.9	6564.9	8508.1	9879.2	11007.7	12011.9	12949.8
1.679E-01	3076.3	6537.8	8484.8	9852.6	10991.8	11994.2	12931.2
1.884E-01	3082.9	6512.0	8480.2	9851.6	10985.6	11992.6	12932.7
2.113E-01	2979.0	6505.6	8476.5	9854.7	10998.1	12006.3	12938.9
2.371E-01	2963.6	6466.9	8452.4	9829.5	10972.0	11983.5	12917.9
2.661E-01	2903.7	6450.9	8451.2	9845.2	10992.9	12009.7	12950.4
2.985E-01	2872.6	6426.5	8451.6	9828.1	10965.9	11980.6	12929.1
3.350E-01	2767.6	6378.3	8410.9	9816.9	10970.3	12004.1	12953.5
3.758E-01	2693.6	6318.5	8363.8	9780.3	10934.6	11957.8	12918.1
4.217E-01	2666.8	6266.6	8332.1	9759.6	10921.2	11947.7	12908.9
4.732E-01	2533.6	6214.8	8311.9	9754.9	10940.4	11979.4	12936.4
5.309E-01	2396.1	6147.9	8295.0	9734.3	10913.4	11948.2	12909.4
5.957E-01	2361.8	6085.0	8242.9	9705.0	10901.6	11949.1	12904.9
6.683E-01	2169.2	5968.7	8140.3	9641.6	10864.6	11940.6	12903.5
7.499E-01	2131.2	5885.4	8093.3	9616.9	10833.6	11902.0	12886.3
8.414E-01	2135.8	5921.5	8102.1	9604.4	10835.0	11899.2	12863.8
9.441E-01	2005.4	5774.3	8045.6	9579.2	10821.1	11878.9	12853.8



- Neutrino production height tables are provided as cumulative probability distributions binned in energy and azimuth & zenith angles.
- 101 log-uniform bins in energy, twelve 30° bins in ϕ and twenty 0.1 bins in $\cos\theta_z$. Probability distribution sampled in intervals of 0.05, with 0.01 and 0.99 at extremes.
- Wrote a class **HondaProdHeight** to parse this text file and throw a production height for each neutrino generated in GENIEHelper.

Production height simulation

- Construct one of these tables for each neutrino flavour provided (ν_e, ν_μ, ν_e, ν_μ).
- Properly account for flavour mixing! This is especially important since we're considering ν_τ events.
    - The code has to look back before the simulated neutrino's flavour and determine what flavour the neutrino was prior to flavour-mixing.
- After GENIE simulates the event, the production height code finds the appropriate height probability distribution, throws a random number and linearly interpolates between the two closest points in the distribution to read off a height value.
    - For ease, the endpoints of the probability distribution 0.01 and 0.99 are set to 0 and 1.

Coordinate transformation

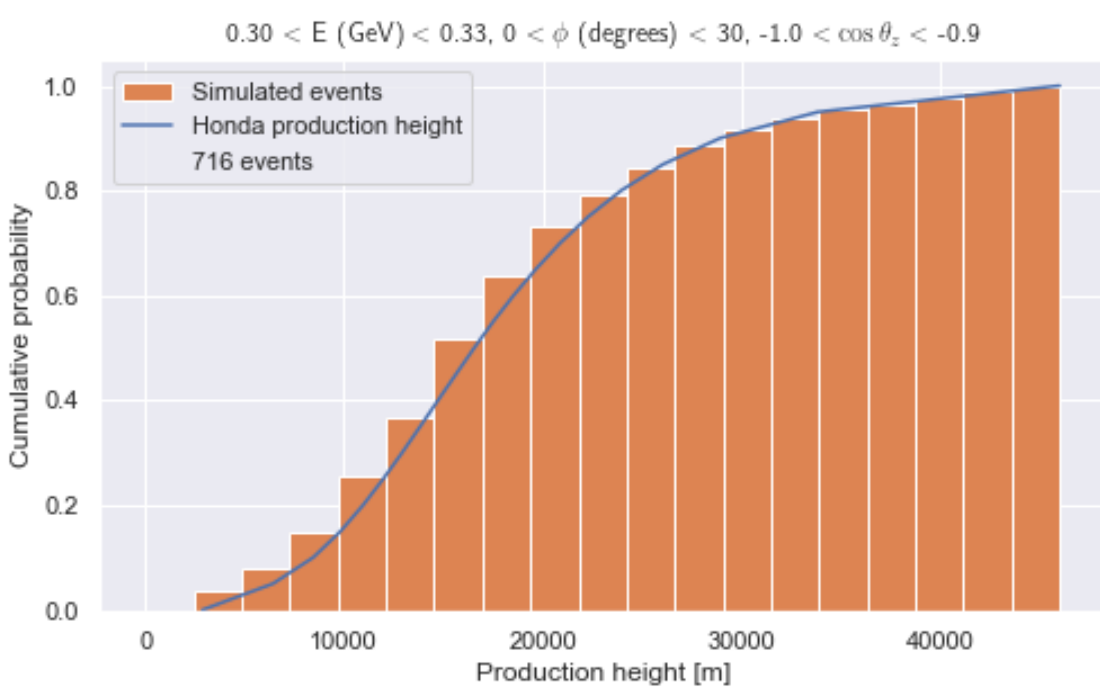
- Honda and DUNE use different coordinate systems, and this has to be accounted for as a rotational correction to the neutrino direction when simulating events:

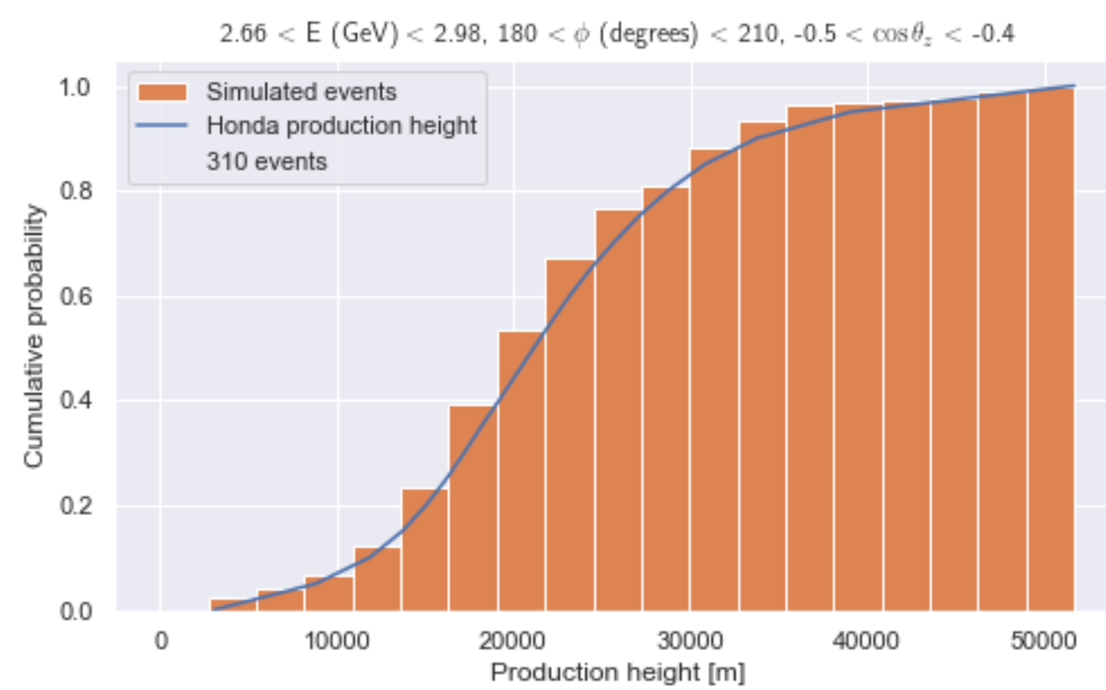
Honda coordinate system	DUNE coordinate system
Z points down	Z points away from FNAL
Y points East	Y points up
X points South	X points SSW

- Apply a rotational correction: transform nu direction from DUNE into Honda coordinate system and then look it up in Honda's production height table.
- Phi is not handled properly yet due to a bug in GENIE, for which a fix is incoming. For now ϕ distribution of generated neutrinos is incorrect.

Validation

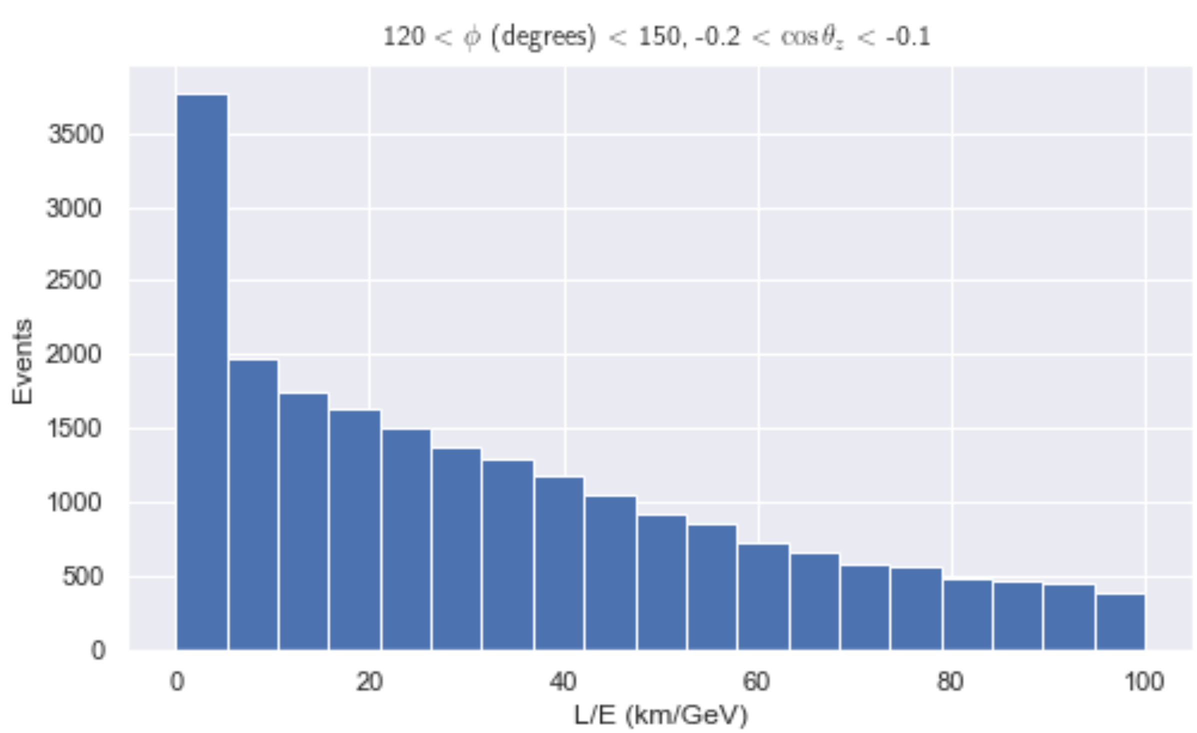
- Simple in-and-out test using a $\nu_\mu \rightarrow \nu_\tau$ flux swap:
  - Produce a large-statistics sample, split it out into energy & direction bins, and then compare production height distribution to the Honda input!
- After a few iterations, simulated events are now in good agreement with the Honda production height inputs.

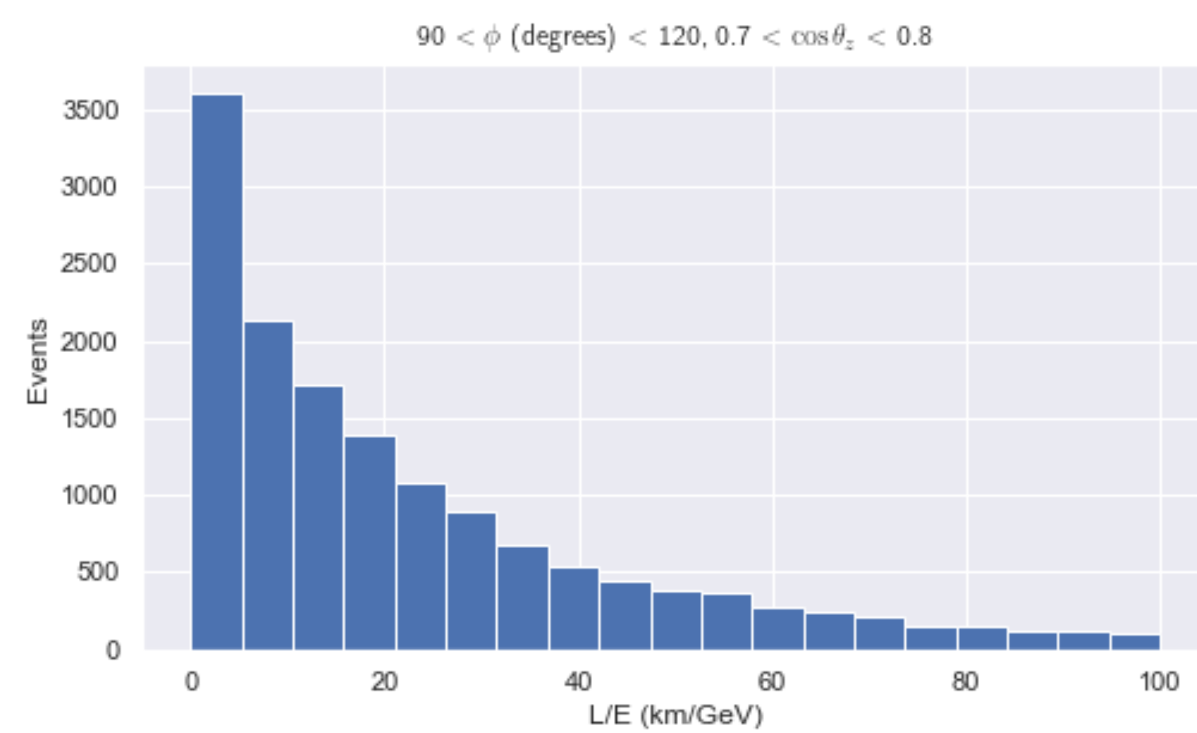




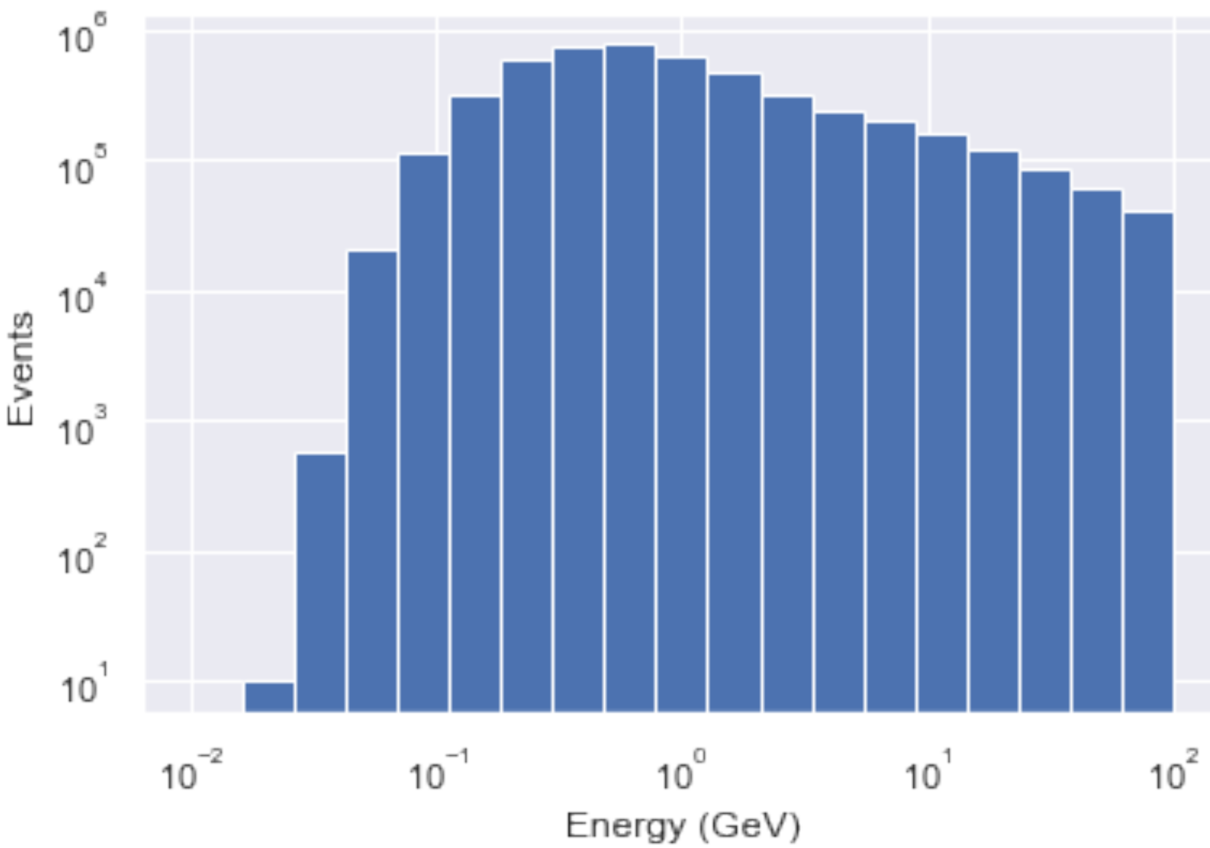
L/E spectra

- The neutrino path length is set as the **fdktogen** (ie. distance between decay and generation) in the **MCFlux** data product of the art event.
- Can use this information to construct true L/E spectra:

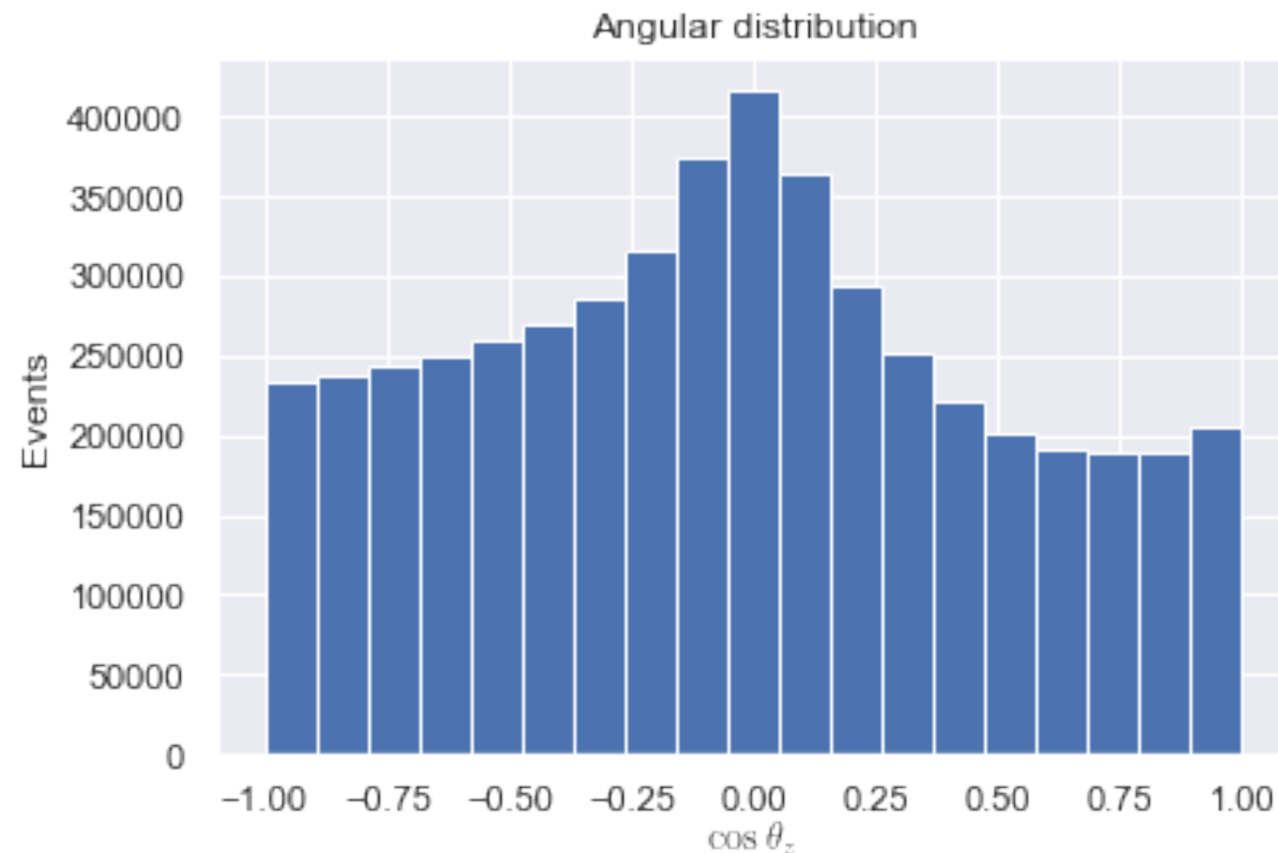




Other distributions



Energy



Zenith angle

Access to files

- I have generator-level MC files available for all four initial flavours, which I'm happy to share.
- In addition to the art files, I also have a flat tree containing neutrino energy, production height and direction for each event, which I can provide as a ROOT tree or a Pandas data frame.

Next steps

- After producing these true distributions for all four initial flavours, the next step is to push these samples through the full G4, detsim, reco chain.
    - Starting with 100k events in each initial flavour, with a view to possibly topping up afterwards if necessary.
- Using the full detector geometry will allow us to quantify things like containment and energy & angular resolution.
- Also thinking about how to apply oscillations — need to better understand how a changing matter density affects how oscillations are applied.
- For an early approximation we could try using nuCraft, a tool I found which calculates oscillation probabilities for changing matter density.
    - It has an option to average over neutrino production heights, although I don't know where those numbers come from and how accurate they are.