# Dark Neutrino Simulations with GENIE on SBND


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# BSM Physics on SBND

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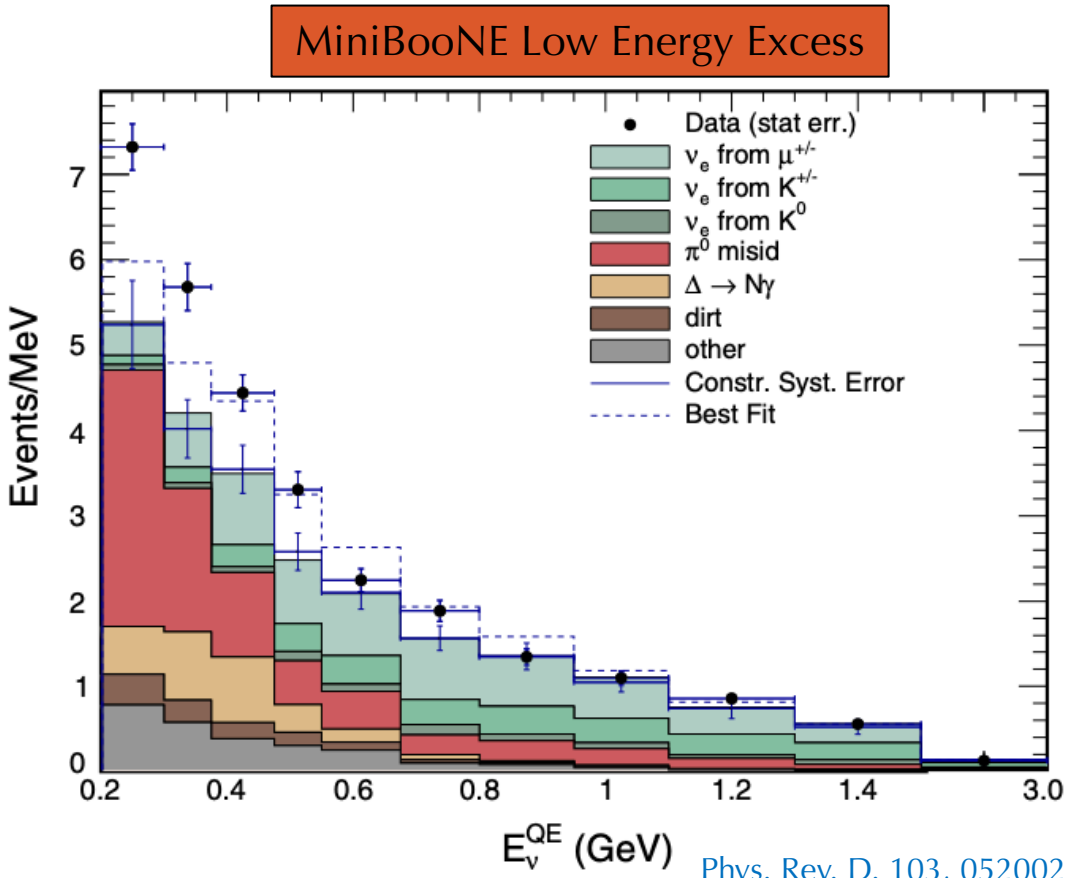
- One of the outstanding puzzles in neutrino physics are the ~1 $eV^2$ anomalies, particularly the Low Energy Excess observed by MiniBooNE.
- It merits different avenues of research, Beyond Standard Model physics one of them.

SBND qualities that enable a rich program of new exotic searches:

- ~1mm special resolution
- Excellent particle identification
- Fine calorimetry sampling
- High yield photon detection system
- High flux beam and large statistics



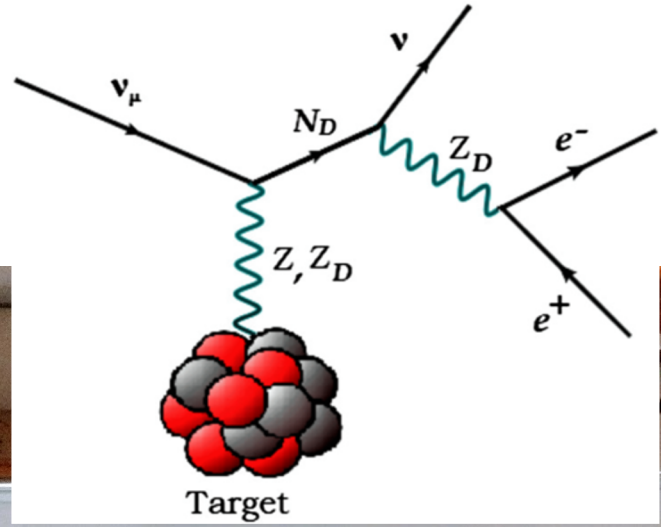

Phys. Rev. D. 103, 052002

# Dark Neutrino Portal to Explain MB

- New Dark Sector with a **dark neutrino** and **dark gauge boson**
- Both with masses in the range of ~10 to ~100 MeV
- The process goes:
  - beam neutrino $\nu$ interacts **coherent quasi elastically** with **Ar** nucleus
  - upscatters to **dark neutrino** $N_D$, which in turn decays to
  - neutrino $\nu$ and **dark boson** $Z_D$, this last one decays to
  - $e^+ e^-$, aka *the signal*
  - small hadronic interaction, if at all detectable
- Explain MiniBooNE Low Energy Excess:

  ee is highly boosted such that MB can't distinguish them and are construe as $\nu_e$ CCQE-like
- Main reference paper

  https://doi.org/10.1103/PhysRevLett.121.241801



# Cross Section and Free Parameters

$$\frac{d\sigma}{dT_T} = \frac{2\pi\alpha_{EM}\alpha_D FF^2\varepsilon^2|U_{\mu 4}|^2|U_{D4}|^2 Z_T^2\left(M_N^2(T_T - 2E_\nu - M_T) + 2M_T(2E_\nu^2 - 2T_T E_\nu + T_T(T_T - M_T)\right)}{E_\nu^2\left(M_{Z_D}^2 + 2T_T M_T\right)^2}$$

| Categories | Symbol | Property | Default Value |
|---|---|---|---|
| Masses | $M_{Z_D}$ | Dark Mediator | 0.420 GeV |
| | $M_N$ | Dark Neutrino | 0.03 GeV |
| Mixings | $\varepsilon$ | Kinetic Mixing | 1.66e-4 |
| | $U_{\alpha 4}$ | (Squared) Flavour Mixing | (1e-10, 9e-7, 1e-10) |
| | $\alpha_D$ | Dark Gauge Coupling | 0.25 |

- Fairly simple cross section equation
- Economically computed and integrated
- Currently set to the values used in the reference paper
- These parameters modify the cross section formula and ultimately the relevant observable kinematic variables
  - **Reweighting is not straightforward**

# DNus in GENIE

- With the guidance of M. Roda (U. Liverpool), I have created a fully functional module which generates Dark Neutrinos.
- Decays of $N_{\mathcal{D}}$ and $Z_{\mathcal{D}}$ handled within GENIE, with the 3+10 decay channels relevant to the energy range implemented.
- Form Factor suitable for this interaction (Phys. Lett. B. 1191.264:114-119)
- 7 model parameters integrated and controlable
- Extensively stress tested:
  - 100+ isotopes,
  - 6 neutrinos
  - Energies up to 1PeV
- Available in GENIE v3.2.

Nucl.Instrum.Meth.A614 (2010) 87-104

UNIVERSAL NEUTRINO GENERATOR & GLOBAL FIT

GENIE GHEP Event Record [print level: 3]

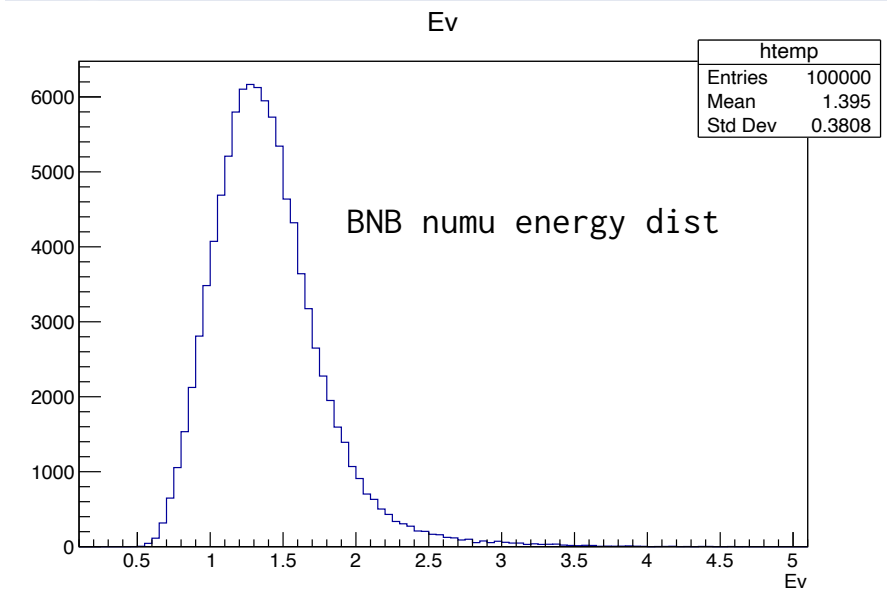
| Idx | Name | Ist | PDG | Mother | Daughter | Px | Py | Pz | E | m |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | nu_mu | 0 | 14 | -1 | -1 | 2 | 2 | 0.000 | 0.000 | 1.000 | 1.000 | 0.000 |
| 1 | Ar40 | 0 | 1000180400 | -1 | -1 | 3 | 3 | 0.000 | 0.000 | 0.000 | 37.216 | 37.216 |
| 2 | nu_D | 3 | 2000030000 | 0 | -1 | 4 | 5 | 0.061 | 0.018 | 0.905 | 1.000 | 0.420 |
| 3 | Ar40 | 1 | 1000180400 | 1 | -1 | -1 | -1 | -0.061 | -0.018 | 0.095 | 37.216 | 37.216 |
| 4 | nu_mu | 1 | 14 | 2 | -1 | -1 | -1 | 0.128 | -0.071 | 0.079 | 0.166 | 0.000 |
| 5 | Z_D | 3 | 2000030001 | 2 | -1 | 6 | 7 | -0.067 | 0.089 | 0.826 | 0.834 | 0.030 |
| 6 | e- | 1 | 11 | 5 | -1 | -1 | -1 | -0.045 | 0.069 | 0.682 | 0.687 | 0.001 |
| 7 | e+ | 1 | -11 | 5 | -1 | -1 | -1 | -0.022 | 0.019 | 0.144 | 0.147 | 0.001 |
| | Fin-Init: | | | | | | | -0.000 | 0.000 | 0.000 | -0.000 | |

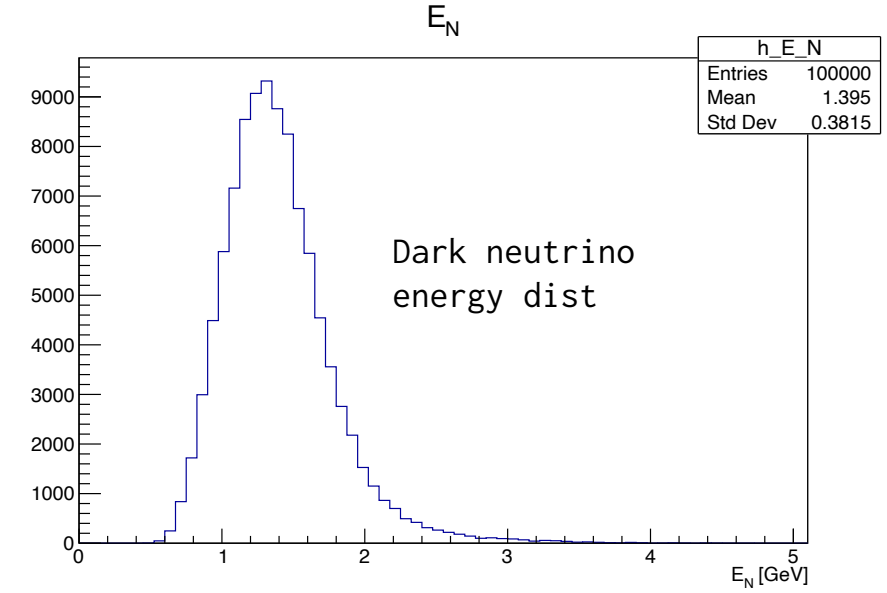
Vertex: nu_mu @ (x = 0.00000 m, y = 0.00000 m, z = 0.00000 m, t = 0.000000e+00 s)

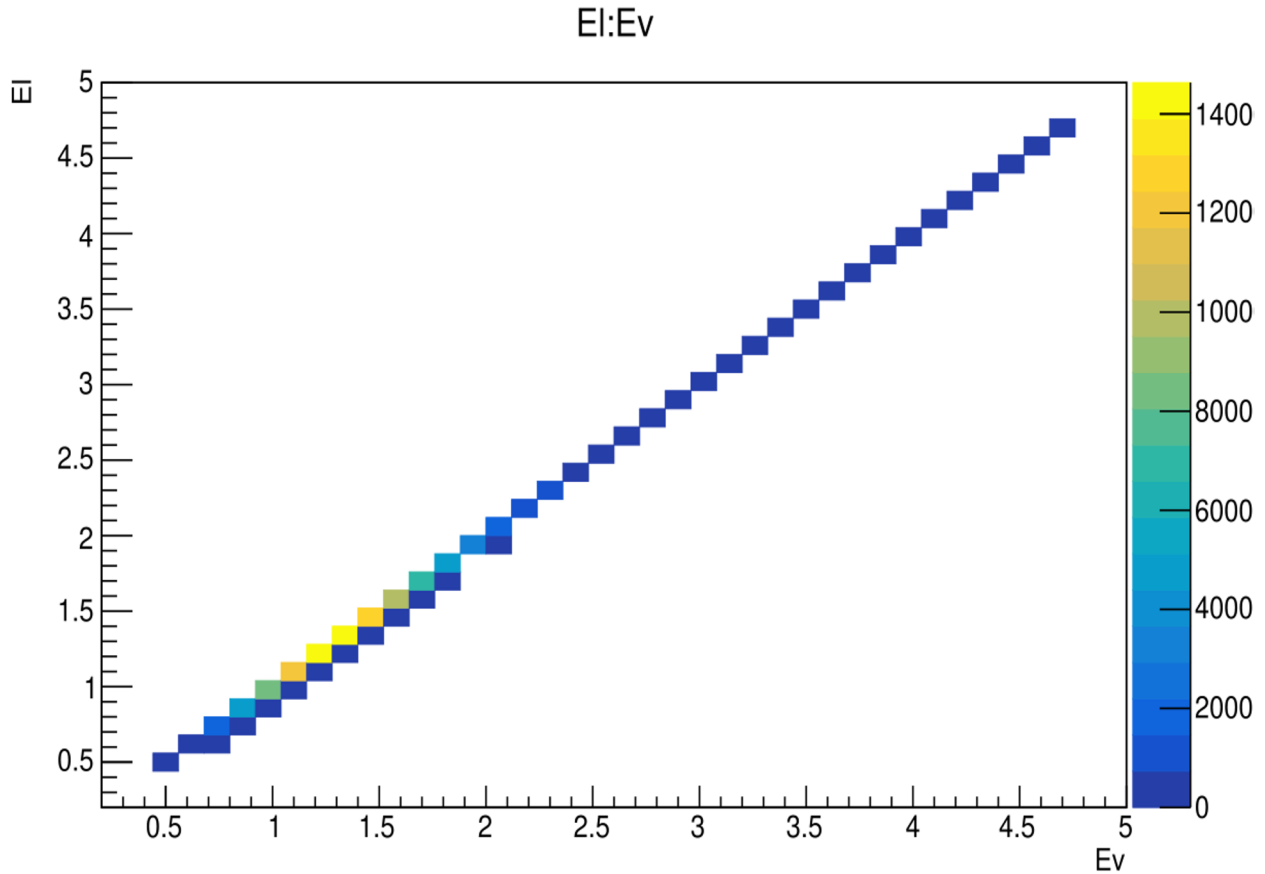
Err flag [bits:15->0] : 0000000000000000 | 1st set: none
Err mask [bits:15->0] : 1111111111111111 | Is unphysical: NO | Accepted: YES

sig(Ev) = 5.24919e-42 cm^2 | dsig(Ev;{K_s})/dK = 3.00880e-38 cm^2/{K} | Weight = 1.00000

# Truth Variables of DNus in Ar

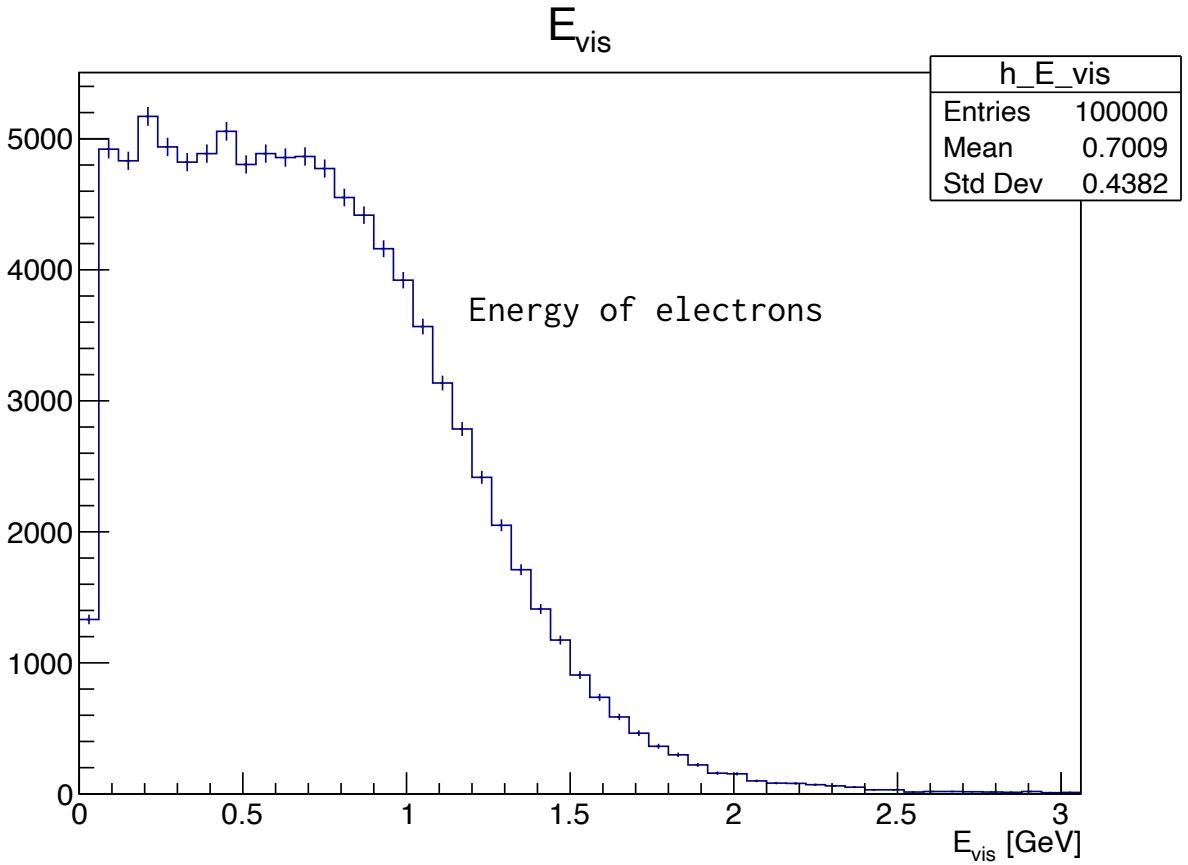


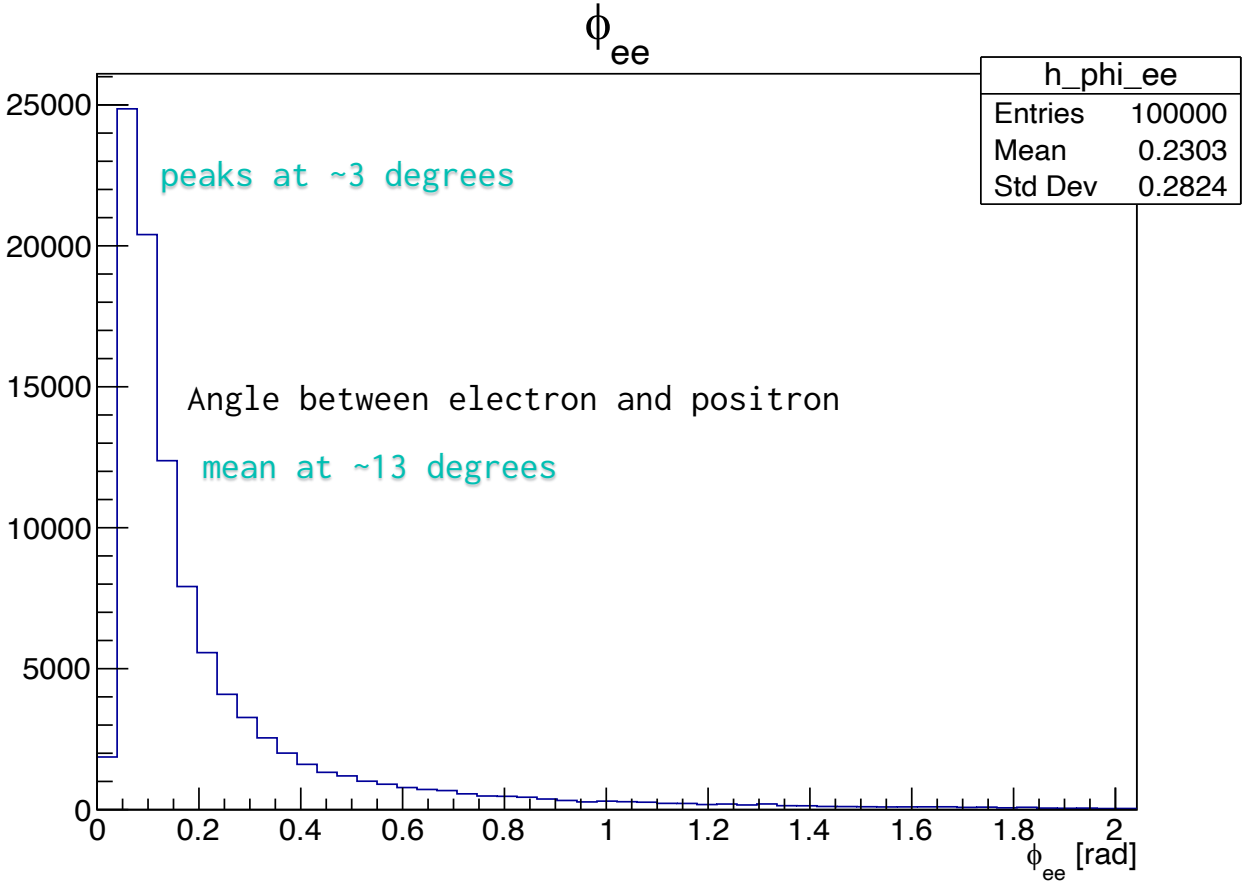




The dark neutrino energy is very close to the initial neutrino energy

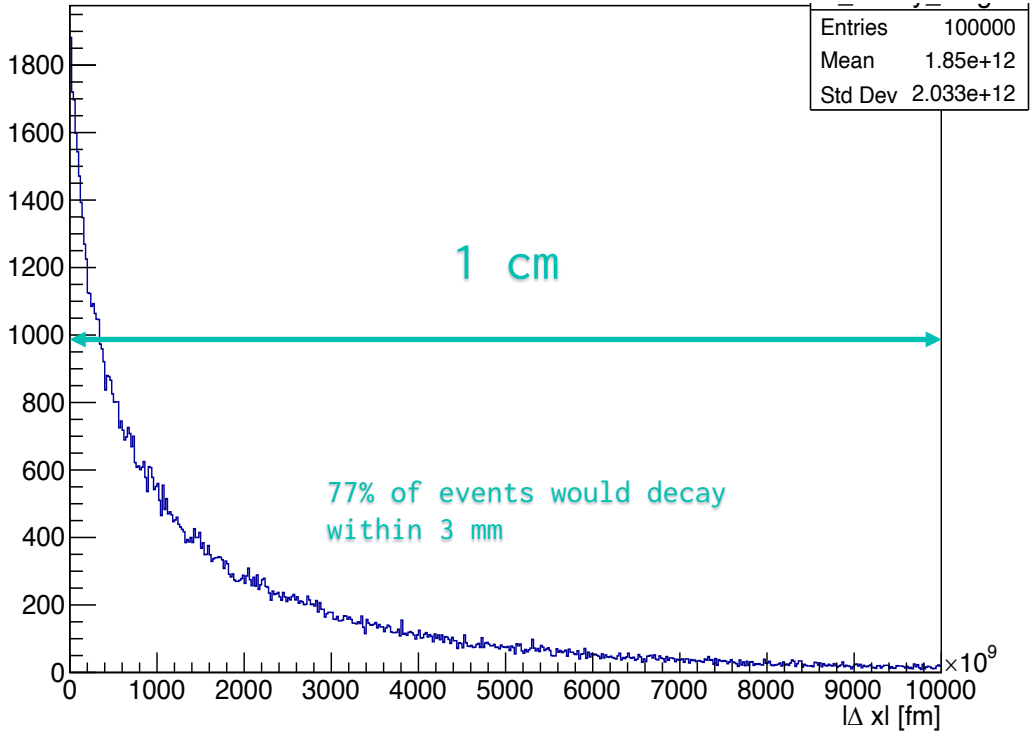
# Truth Variables of DNus in Ar



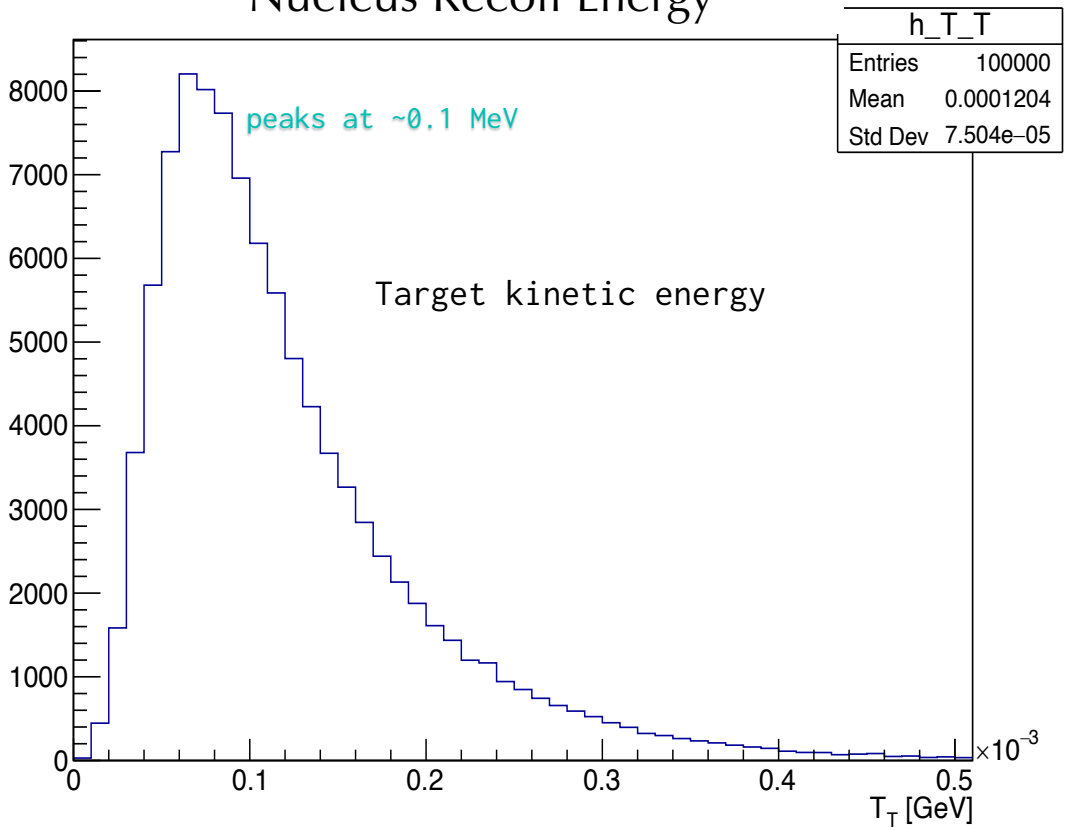



# Truth Variables of DNus in Ar

Gap between initial interaction and start of $e^-e^+$ tracks



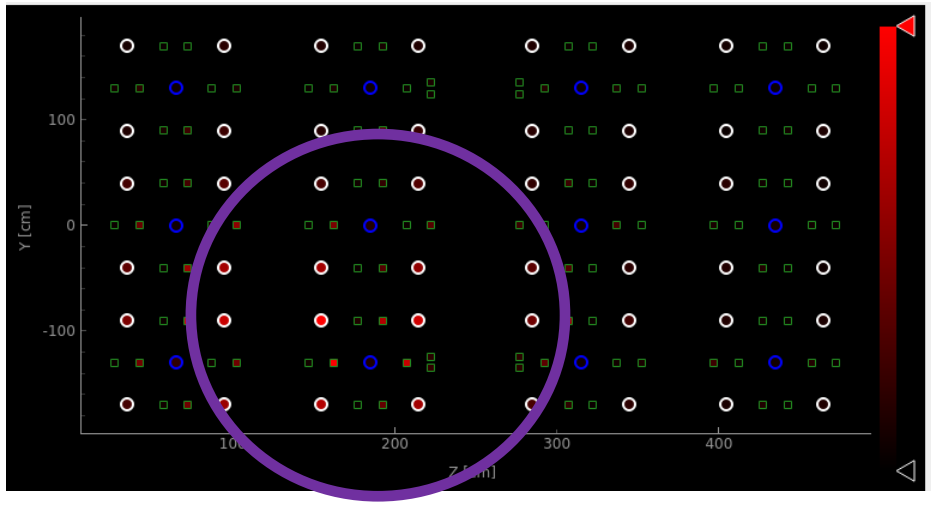

Nucleus Recoil Energy

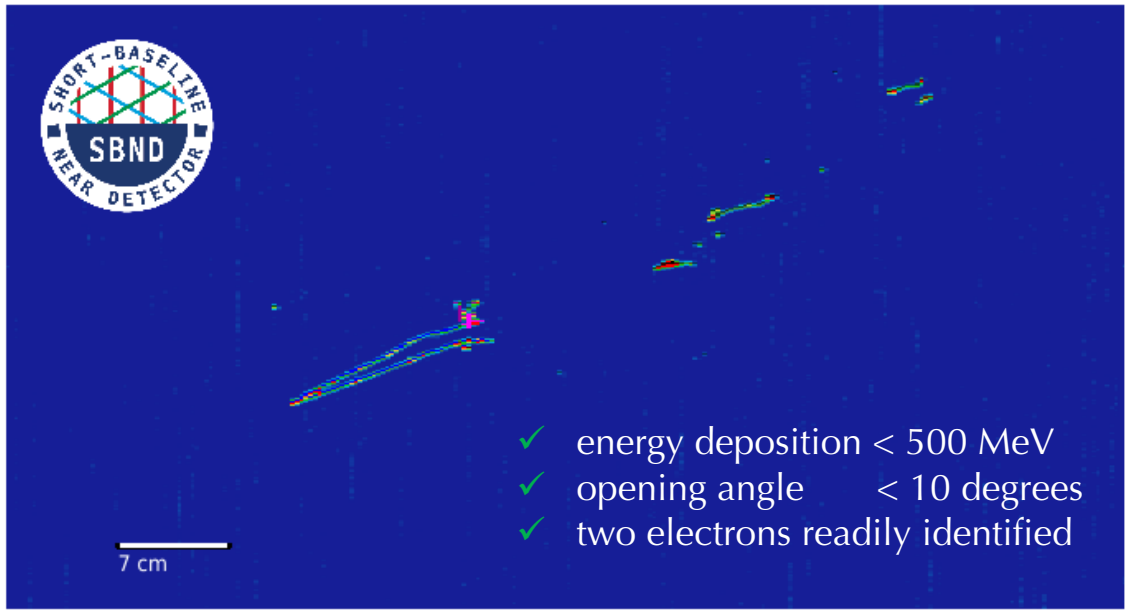


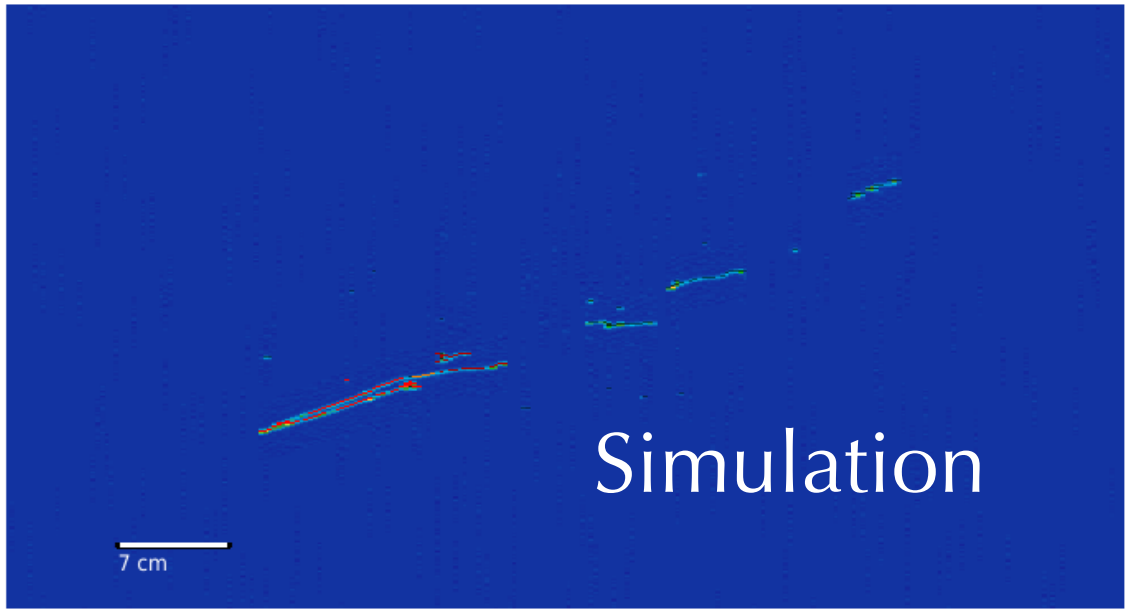

There's a fraction of events where displaced tracks from a tiny blip, are an extra handle for identifying DNu events

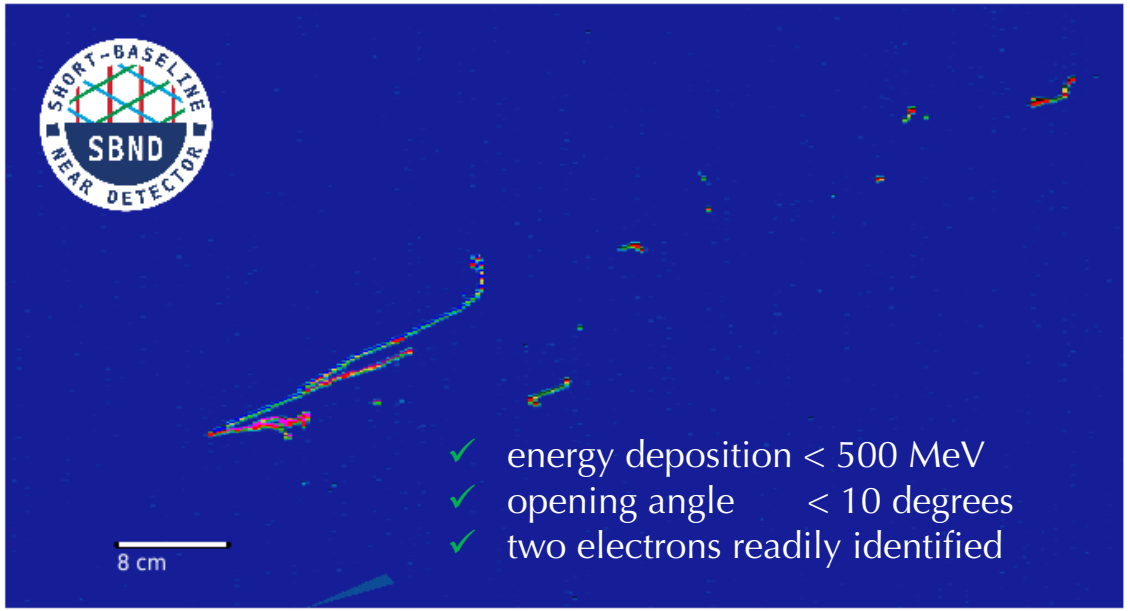
# Dark Neutrino Event in SBND

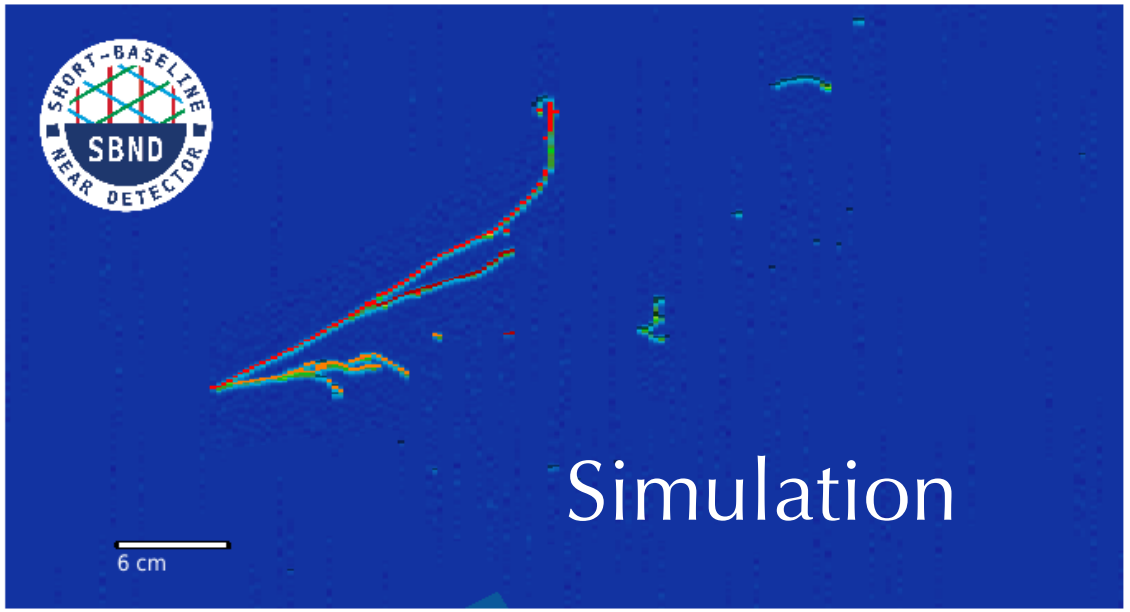
- All technical challenges related to the integration of the generator module to our simulation framework have been overcome and I can routinely simulate DNu events, on their own or along with standard neutrino interactions.
- The goal is for this process to be part of the suit of simulations available for the broader LArTPC and neutrino community.






# Tagging Dark Neutrino Events in SBND

Agnostic Approach:

- Look for events that have two clear electron interactions coming from a common neutrino vertex
- Require little to no hadronic interaction
- Expect more on this soon

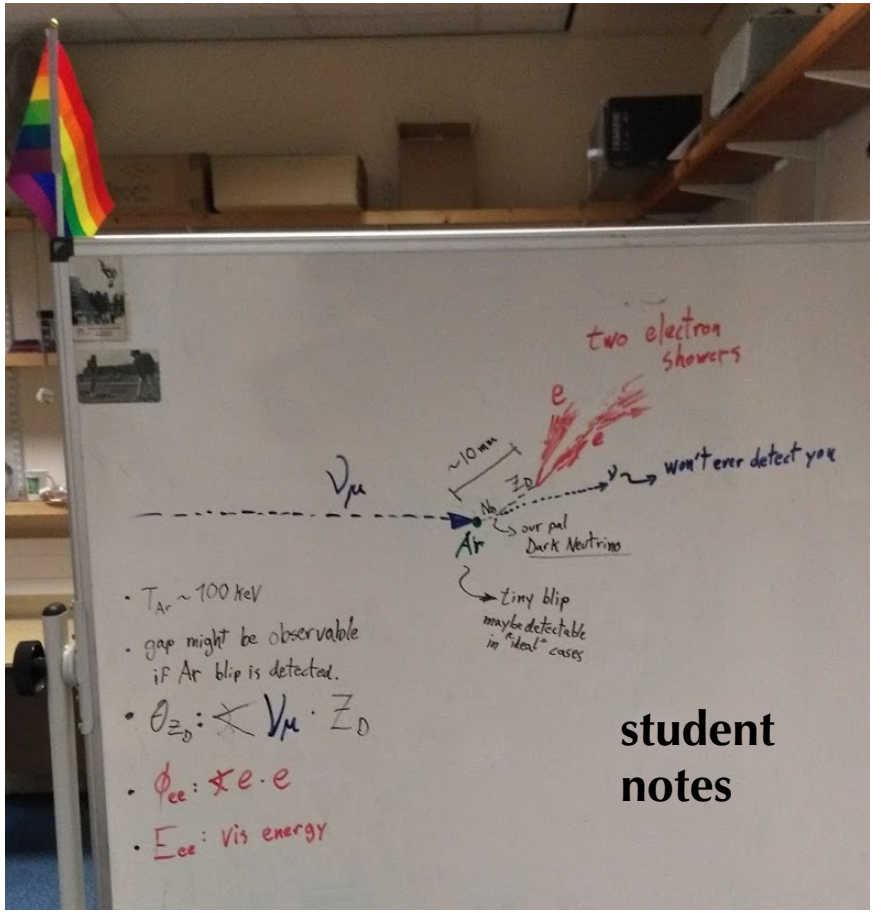
# Summary and Next Steps

- Fully working Dark Neutrino module implemented in GENIE available in v3.2.
- Infrastructure in place to expand model to have more interactions types and other energy ranges and physics outcomes.
- Breaking ground on SBND and creating technical expertise to integrate new BSM models with our simulations framework.
- Ongoing: reconstruction and selection analysis of ee pairs in SBND simulations, that is agnostic to specific model parameters.
- Dark Neutrinos search is a good prospect for SBN program, specially SBND, as it leverages the superb qualities of LArTPCs and the high flux of interactions.

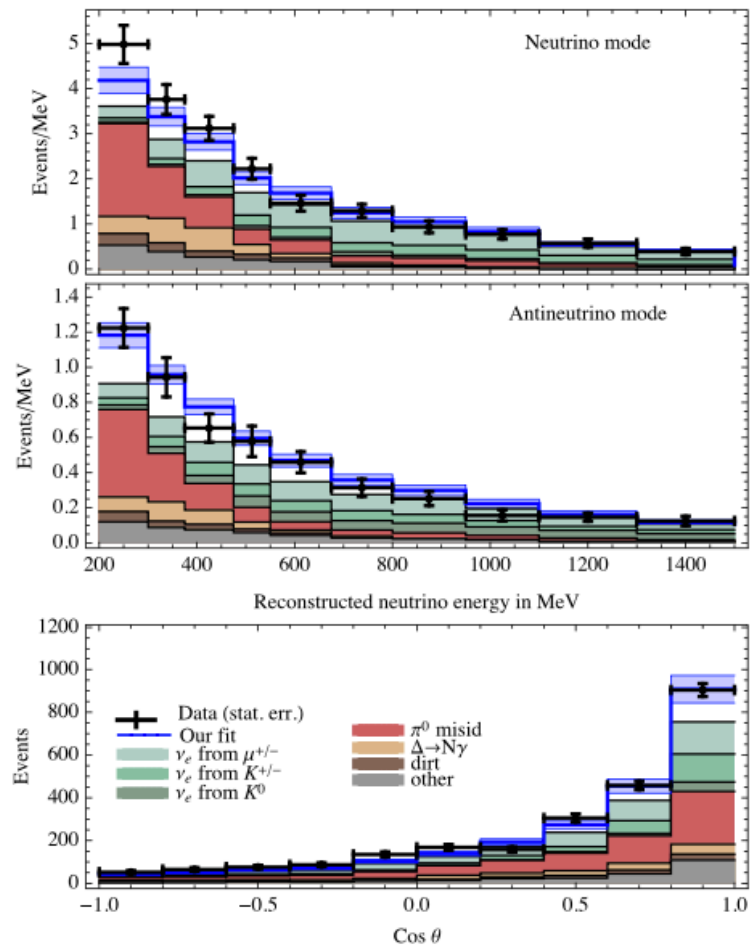
# Backup

# Additional observations

- It has several routes to be expanded:
  - Neutrino masses model, might become relevant for DUNE energies
  - Similar observables but through other internal mechanism
  - Add NC, RES interactions which are relevant for other energy ranges
- None of which I plan to tackle for the foreseeable future
- Unlike oscillations, there's no L/E dependence so it's observable in SBND and ICARUS. Will be much more common in SBND due to the high flux
- The decay of $\pi^0$ are a source of background, but can be suppressed by requiring the absence of a gap between vertex and showers and no hadronic interaction



# Dark Neutrinos on mineral oil




- Reference paper provides a set of parameters values that closely follows the shape of MB LEE
- By default my module runs with these values