Expanding GENIE's Nucleon Decay Tools

Michel Sorel

(IFIC Valencia)

DUNE NDK/Atmos/Cosmo Physics WGs Meeting

2016-07-20

Current NDK Simulation Capabilities in GENIE

- GENIE currently generates 11 single nucleon, exclusive, decay modes
- All are 2-body, anti-lepton + meson, decay modes
- GENIE can generate NDK events within any nucleus, Ar included
- Same modes can now be simulated directly within a LArSoft module calling GENIE, see Tingjun's talk
- However, there's more…

From GENIE Physics & User Manual (arXiv:1510.05494)

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

Table 8.1: Nucleon decay modes simulated in GENIE.

Current status of NDK searches

Numbering scheme and limits in PDG

	Mode	Partial mean life (10^{30} years)	Confidence level
	Antilepton + meson		
τ_1	$N \to e^+\pi$	> 2000 (n), > 8200 (p)	90%
τ_2	$N \to \mu^+\pi$	> 1000 (n), > 6600 (p)	90%
τ_3	$N \to \nu\pi$	> 1100 (n), > 390 (p)	90%
τ_4	$p \to e^+\eta$	> 4200	90%
τ_5	$p \to \mu^+\eta$	> 1300	90%
τ_6	$n \to \nu\eta$	> 158	90%
τ_7	$N \to e^+\rho$	> 217 (n), > 710 (p)	90%
τ_8	$N \to \mu^+\rho$	> 228 (n), > 160 (p)	90%
τ_9	$N \to \nu\rho$	> 19 (n), > 162 (p)	90%
τ_{10}	$p \to e^+\omega$	> 320	90%
τ_{11}	$p \to \mu^+\omega$	> 780	90%
τ_{12}	$n \to \nu\omega$	> 108	90%
τ_{13}	$N \to e^+K$	> 17 (n), > 1000 (p)	90%
τ_{14}	$p \to e^+K^0_S$		
τ_{15}	$p \to e^+K^0_L$		
τ_{16}	$N \to \mu^+K$	> 26 (n), > 1600 (p)	90%
τ_{17}	$p \to \mu^+K^0_S$		
τ_{18}	$p \to \mu^+K^0_L$		
τ_{19}	$N \to \nu K$	> 86 (n), > 5900 (p)	90%
τ_{20}	$n \to \nu K^0_S$	> 260	90%
τ_{21}	$p \to e^+K^*(892)^0$	> 84	90%
τ_{22}	$N \to \nu K^*(892)$	> 78 (n), > 51 (p)	90%
	Antilepton + mesons		
τ_{23}	$p \to e^+\pi^+\pi^-$	> 82	90%
τ_{24}	$p \to e^+\pi^0\pi^0$	> 147	90%
τ_{25}	$n \to e^+\pi^-\pi^0$	> 52	90%
τ_{26}	$p \to \mu^+\pi^+\pi^-$	> 133	90%
τ_{27}	$p \to \mu^+\pi^0\pi^0$	> 101	90%
τ_{28}	$n \to \mu^+\pi^-\pi^0$	> 74	90%
τ_{29}	$n \to e^+K^0\pi^-$	> 18	90%
	Lepton + meson		
τ_{30}	$n \to e^-\pi^+$	> 65	90%
τ_{31}	$n \to \mu^-\pi^+$	> 49	90%
τ_{32}	$n \to e^-\rho^+$	> 62	90%
τ_{33}	$n \to \mu^-\rho^+$	> 7	90%
τ_{34}	$n \to e^-K^+$	> 32	90%
τ_{35}	$n \to \mu^-K^+$	> 57	90%
	Lepton + mesons		
τ_{36}	$p \to e^-\pi^+\pi^+$	> 30	90%
τ_{37}	$n \to e^-\pi^+\pi^0$	> 29	90%
τ_{38}	$p \to \mu^-\pi^+\pi^+$	> 17	90%
τ_{39}	$n \to \mu^-\pi^+\pi^0$	> 34	90%
τ_{40}	$p \to e^-\pi^+K^+$	> 75	90%
τ_{41}	$p \to \mu^-\pi^+K^+$	> 245	90%
	Antilepton + photon(s)		
τ_{42}	$p \to e^+\gamma$	> 670	90%
τ_{43}	$p \to \mu^+\gamma$	> 478	90%
τ_{44}	$n \to \nu\gamma$	> 28	90%
τ_{45}	$p \to e^+\gamma\gamma$	> 100	90%
τ_{46}	$n \to \nu\gamma\gamma$	> 219	90%
	Three (or more) leptons		
τ_{47}	$p \to e^+e^+e^-$	> 793	90%
τ_{48}	$p \to e^+\mu^+\mu^-$	> 359	90%
τ_{49}	$p \to e^+\nu\nu$	> 170	90%
τ_{50}	$n \to e^+e^-\nu$	> 257	90%
τ_{51}	$n \to \mu^+e^-\nu$	> 83	90%
τ_{52}	$n \to \mu^+\mu^-\nu$	> 79	90%
τ_{53}	$p \to \mu^+e^+e^-$	> 529	90%
τ_{54}	$p \to \mu^+\mu^+\mu^-$	> 675	90%
τ_{55}	$p \to \mu^+\nu\nu$	> 220	90%
τ_{56}	$p \to e^-\mu^+\mu^+$	> 6	90%
τ_{57}	$n \to 3\nu$	> 0.0005	90%
τ_{58}	$n \to 5\nu$		

GENIE Incubator Project

From GENIE's webpage: www.genie-mc.org

Incubator Projects

[Currently in incubation] - [Graduated from incubation] - [Retired from incubation]

Incubator projects are in-house development activities or community development efforts led by the GENIE WG Coordinators and overseen by the GENIE board. An incubator project is the unique route for any physics or software development into any of the GENIE suite products (Generator, Comparisons, Tuning).

This page serves the purpose of informing the community for the scope and breadth of the GENIE development programme. Community members that have a wish to contribute to GENIE and identify the need for a new project are strongly encouraged to contact the GENIE WG Coordinators who, upon fully defining the scope and specification, can launch new incubator projects.

Currently in incubation

Project: ***ndec_channel_additions***
Description: An upgrade all GENIE's nucleon decay tool to include all 2-body and 3-body decay channels listed in PDG and adoption of PDG decay mode numbering scheme. All decays implemented as phase space decays decays at the moment.
Developers: Michel Sorel (IFIC), Elena Gramellini (Yale), Jennifer Raaf (Fermilab).
Reporting: TCWG.
Target release: GENIE/Generator v2.12?
Documentation: internal wiki

Current status of the GENIE Incubator Project

Requirements

- All single-nucleon exclusive decay channels listed in the 2015 update of the PDG will be included → **68 modes**
- Decay modes include 2, 3, or 5 generated particles. **Approximation**: use phase space decays for all
- For stand-alone GENIE applications, keep using **gevgen_ndcy** executable, now expanded
    - Decay mode ID (-m command-line argument) will now range from 1 to 58, to match PDG numbering
    - Some mode IDs have both a proton and a neutron sub-mode, to be specified with the decayed nucleon PDG argument (-N)
- **Note**: corresponding change also needed in LArSoft's **NucleonDecay_module**, once these changes make it to a GENIE's production release
- Full list of requirements under review by GENIE's team

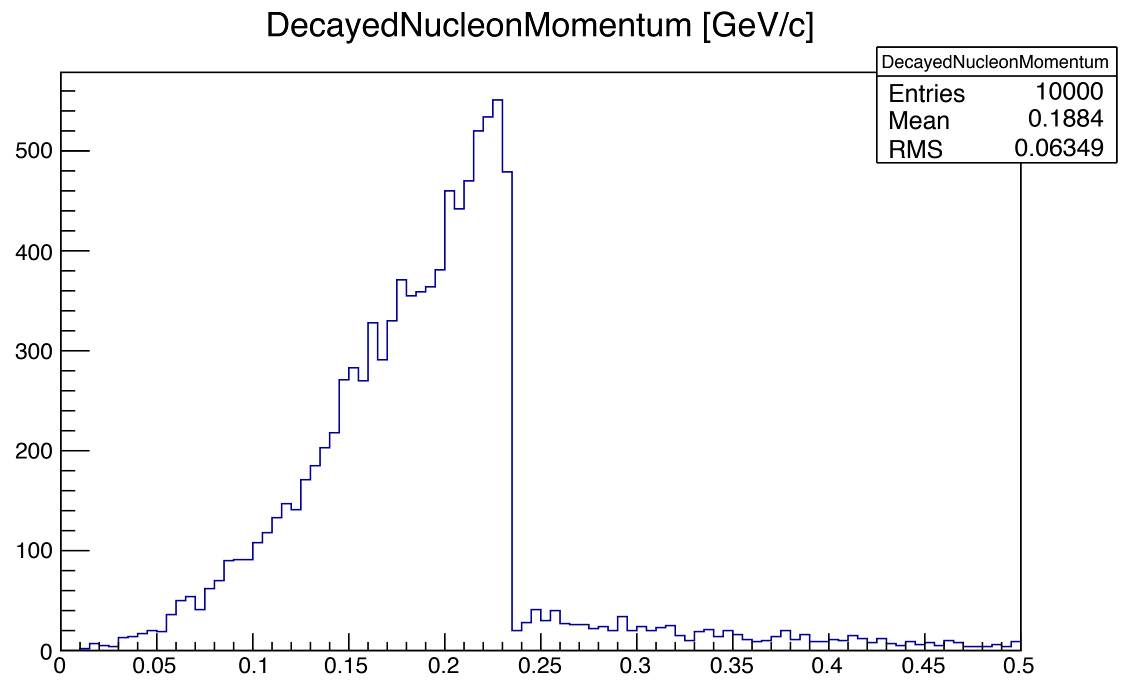
Current status of the GENIE Incubator Project

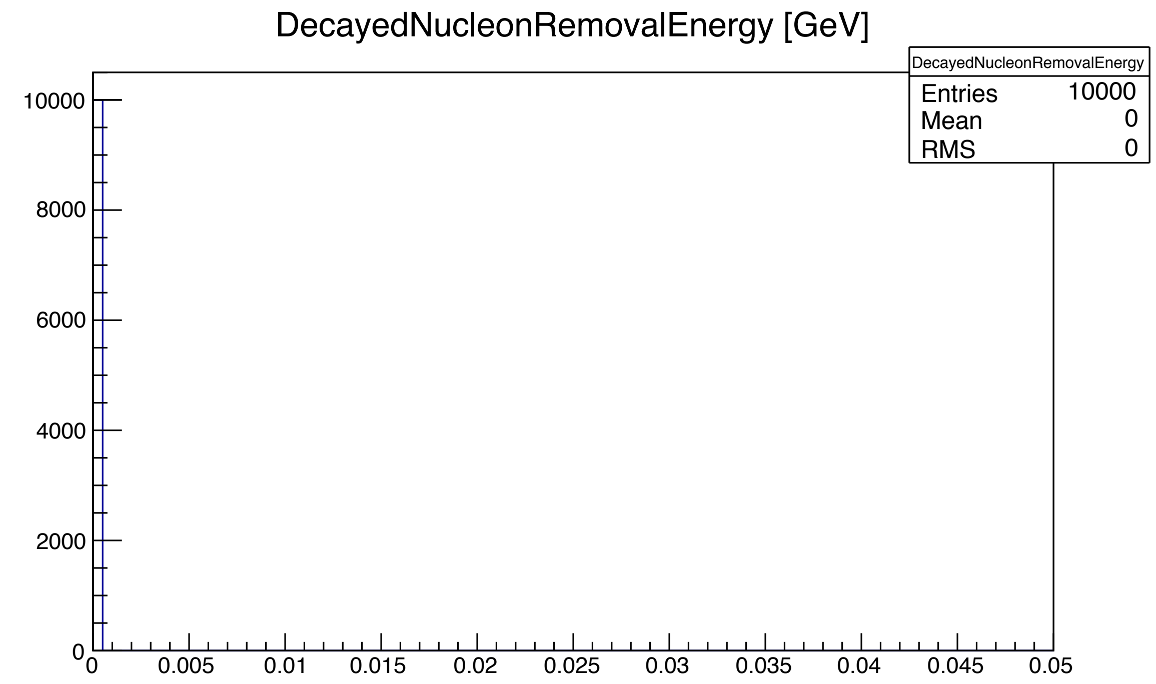
Code implementation

- Code changes already implemented in a development branch of GENIE
- GENIE packages affected: Apps, contrib, Interaction, **NucleonDecay**, PDG
  - ~1,000 lines of (highly repetitive) code
- Code changes under review by GENIE’s team
- Hope to have branch merged with GENIE’s trunk in time for GENIE v2.12
- Now looking at some validation plots → following slides

Example validation plots for mode with K^0 daughter

$p \to \mu^+ K^0$, decayed nucleon histograms



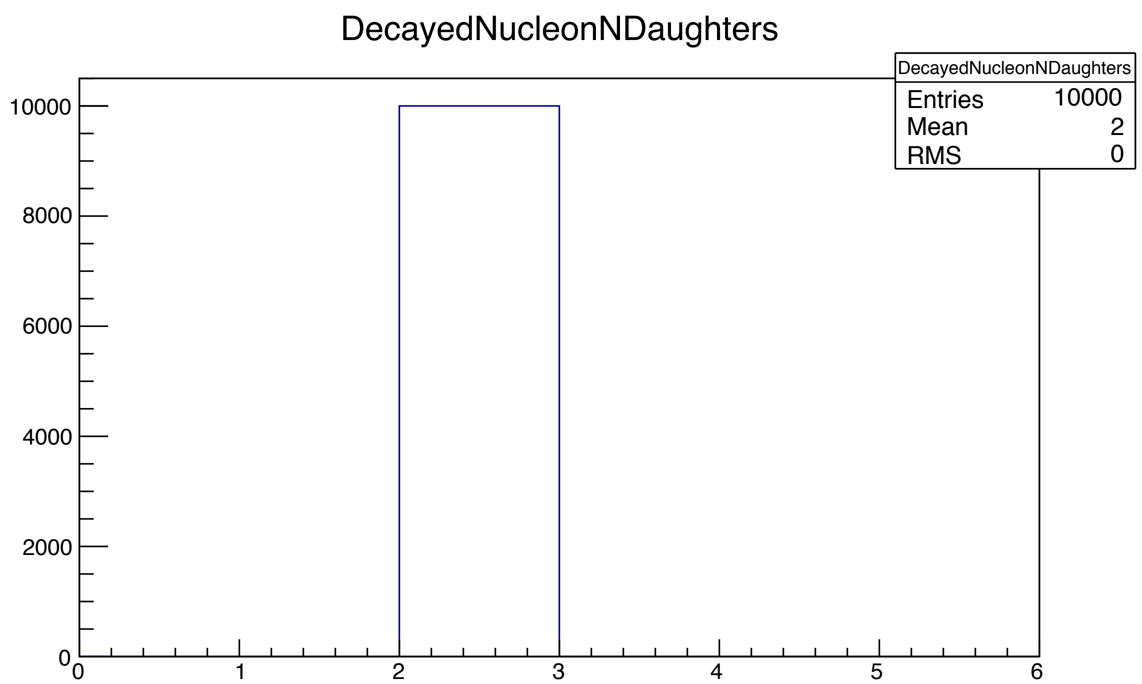


- Proton momentum distribution typically up to Fermi momentum, 0.242 GeV in GENIE's RFG model for Ar
- Small fraction of events at higher momenta?

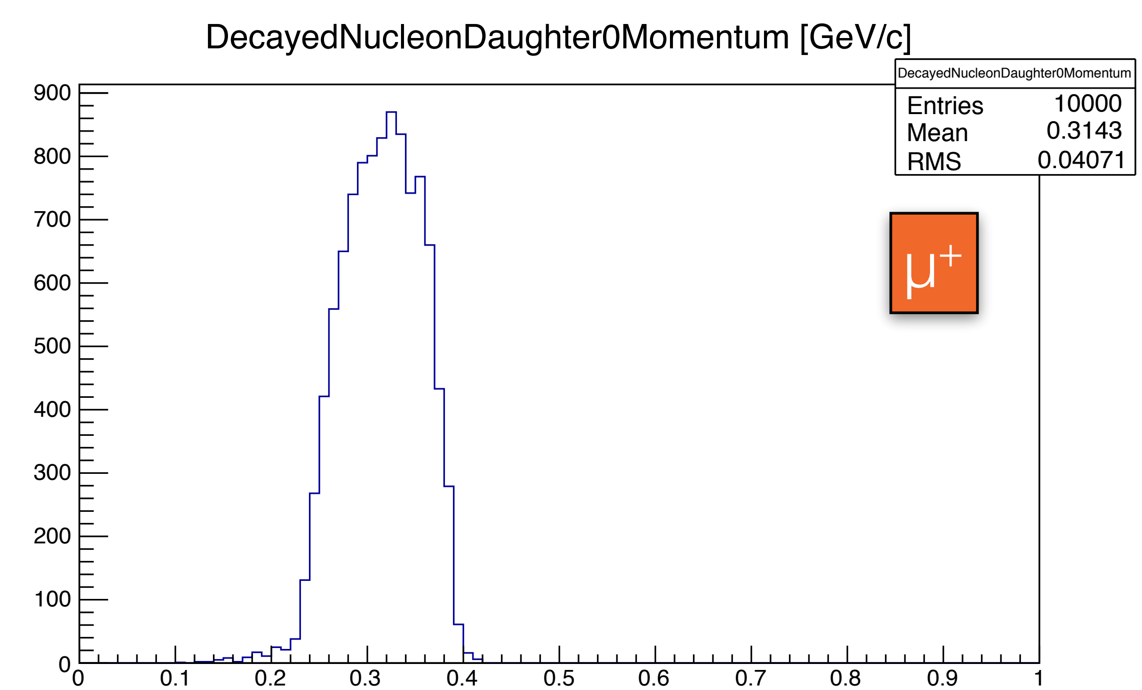
- If I understood GENIE output correctly, proton binding energy always set to zero
- Correct? (Binding energy accounted for in Super-K NDK searches)

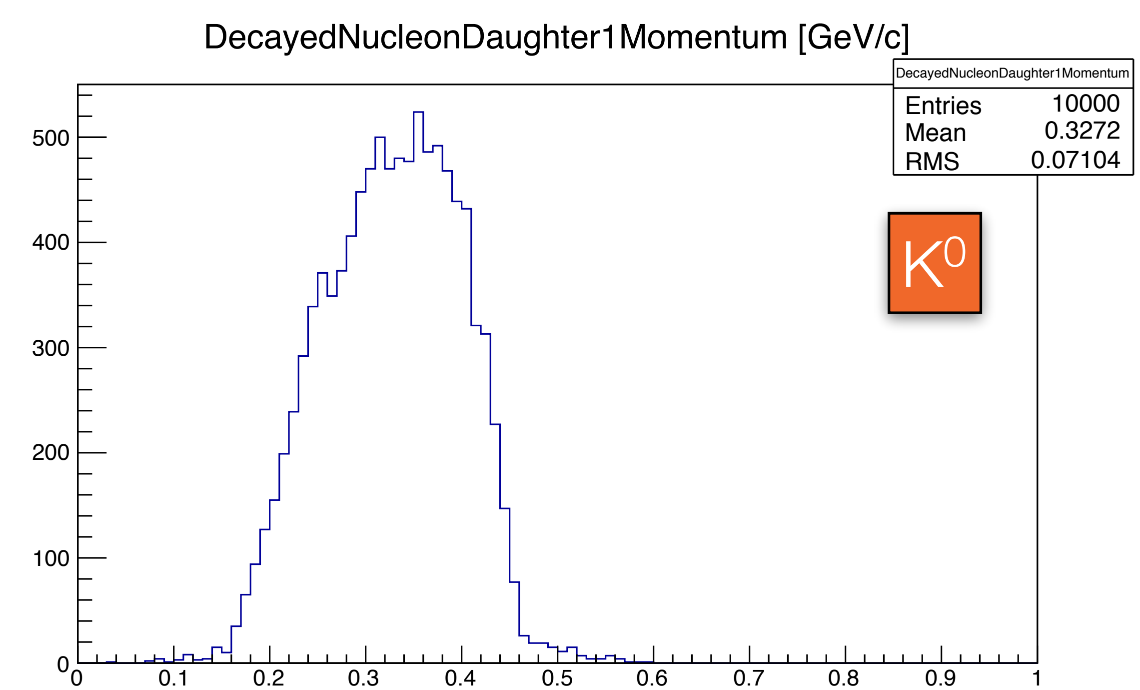
Example validation plots for mode with K^0 daughter

$p \rightarrow \mu^+ K^0$, histograms for decayed nucleon daughters



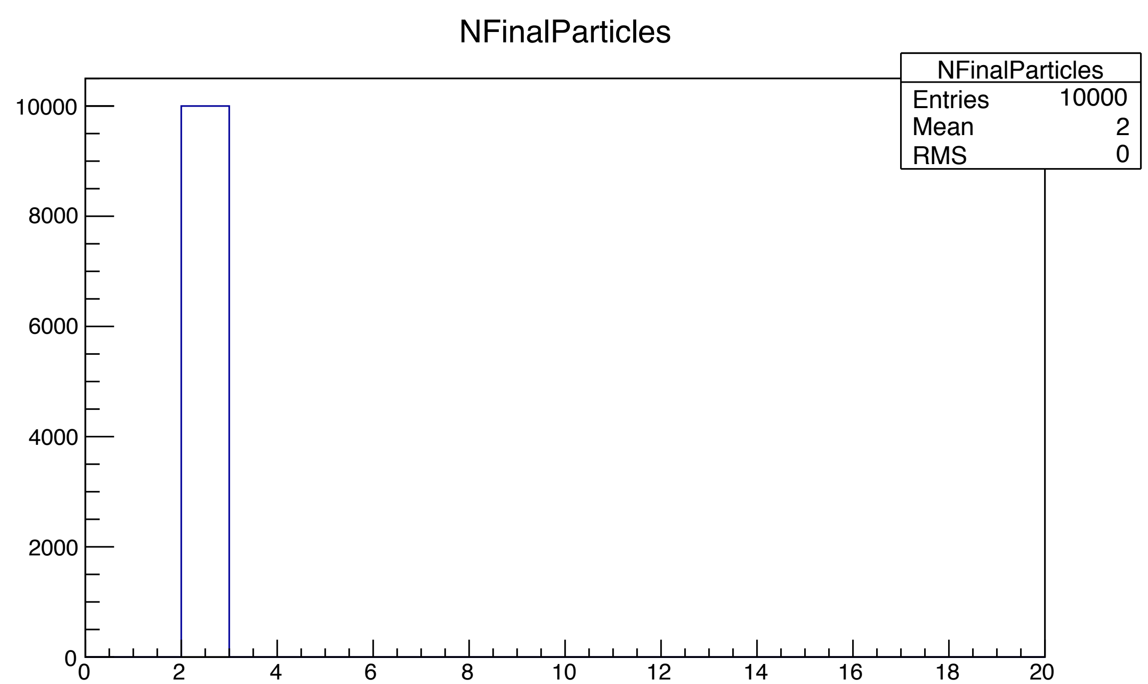
- Always two proton decay daughters, as expected
- Average momenta as expected, smearing due to Fermi momentum

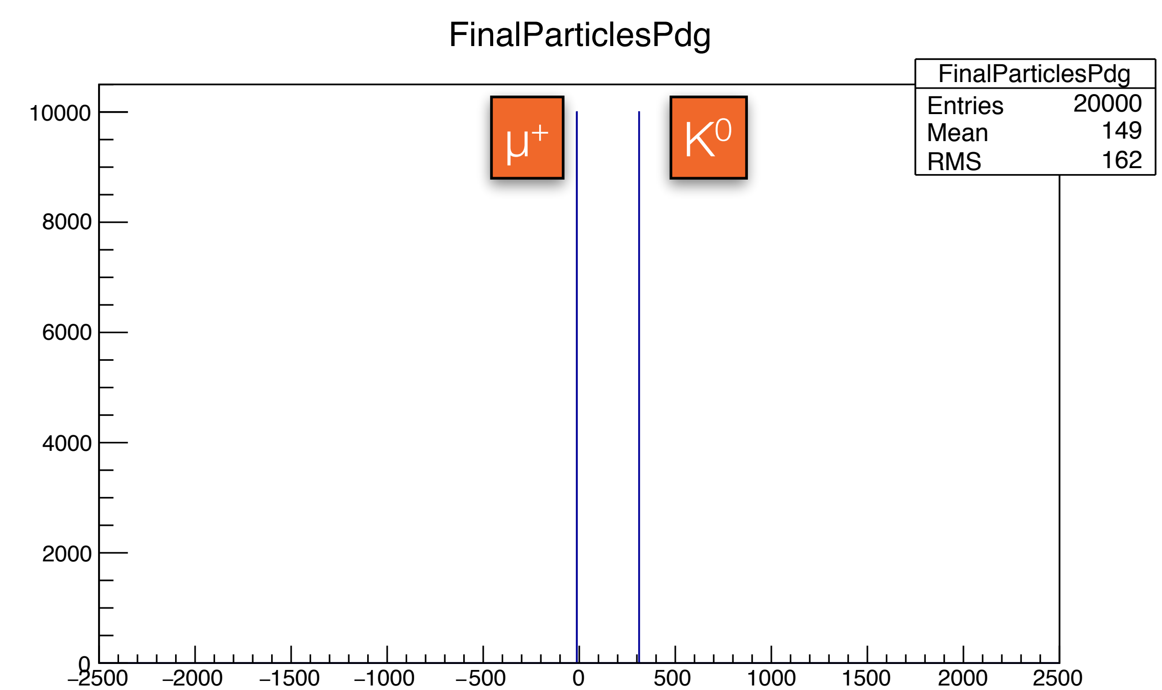




Example validation plots for mode with K^0 daughter

$p \rightarrow \mu^+ K^0$, histograms for GENIE's stable final state particles

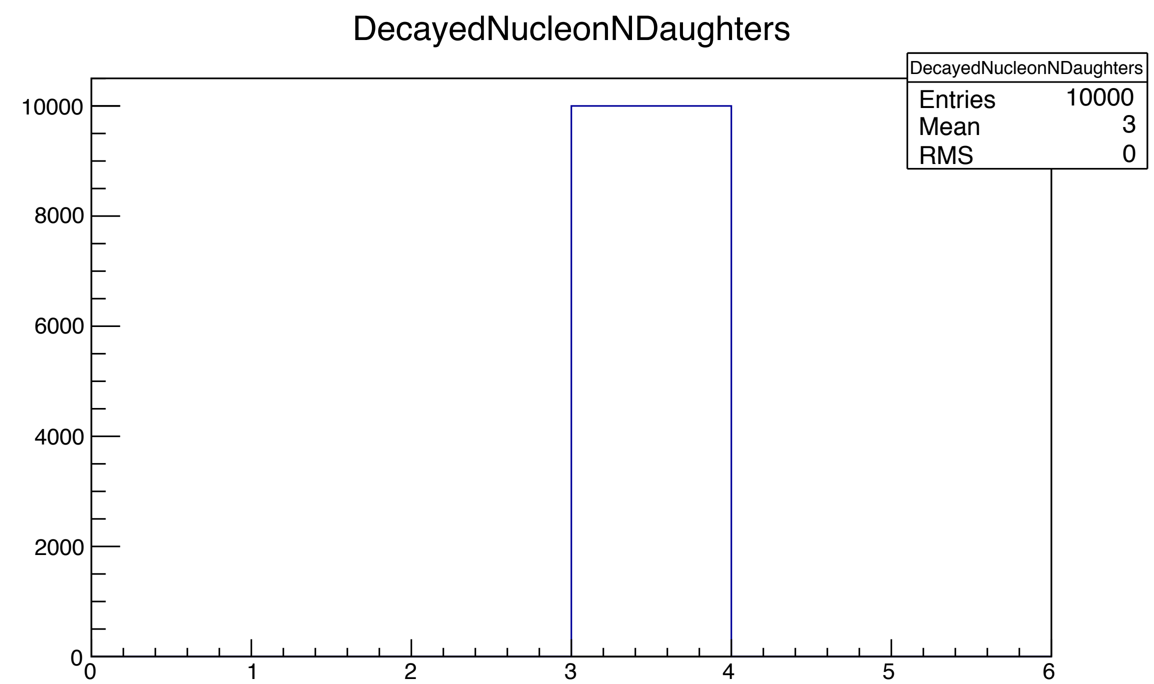


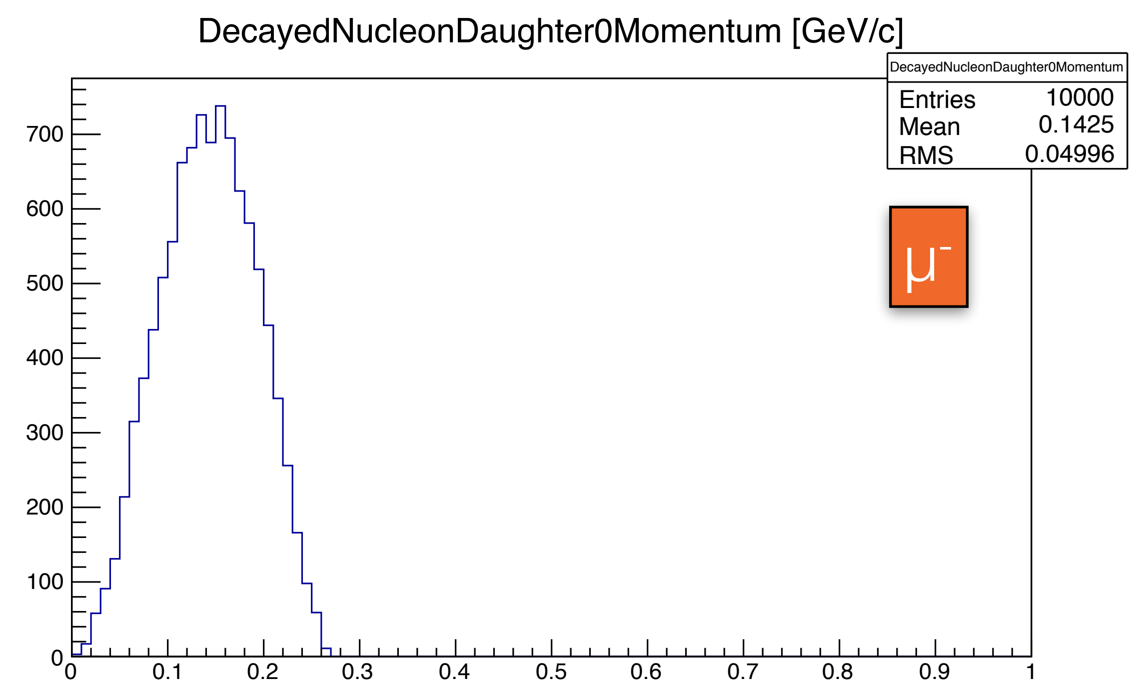


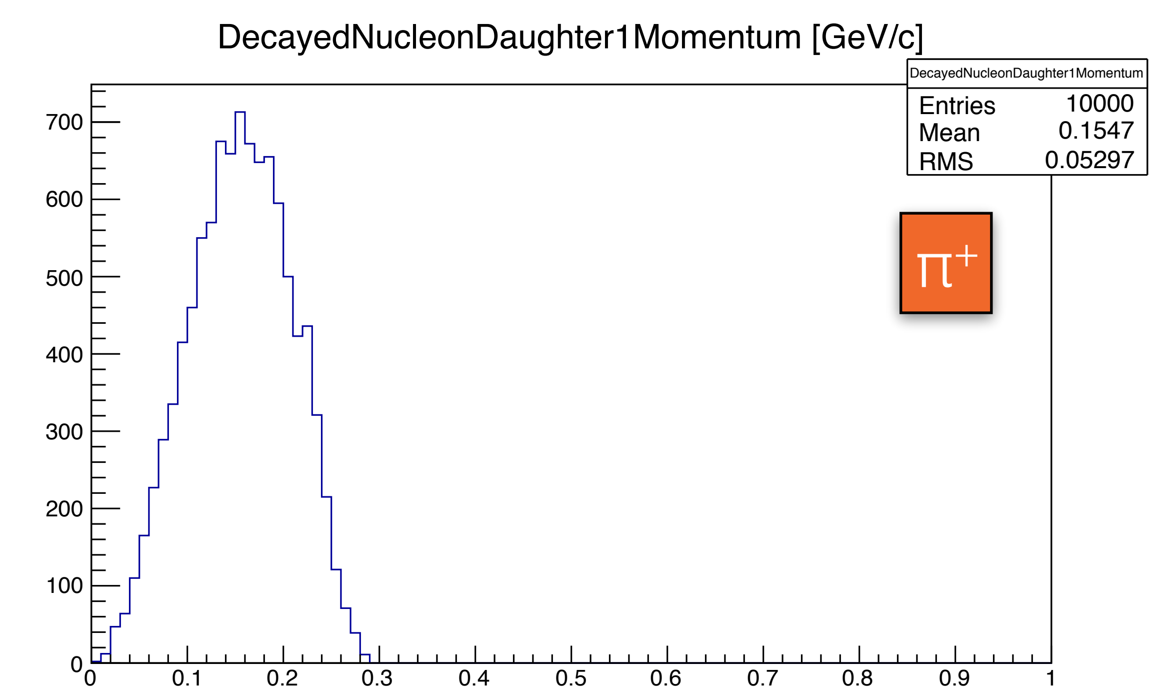
- Same number of GENIE's stable final state particles as number of proton decay daughters, and always μ^+ and K^0
- Reason: no FSI within nucleus for K^0 in GENIE, hence pre-FSI = post-FSI
- GENIE currently has meson FSI only for $\pi^\pm$, π^0, K^+.
- This is a list we'd like to help the GENIE team expand, for our NDK studies in DUNE

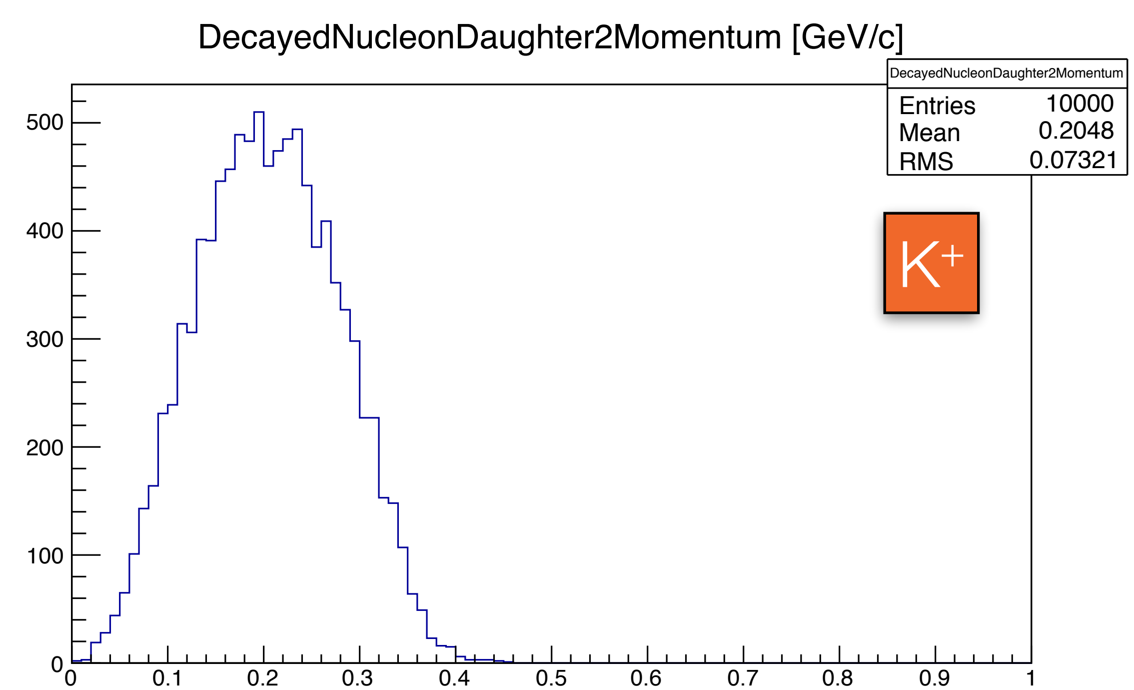
Example validation plots for 3-body decay mode

$p \rightarrow \mu^- \pi^+ K^+$, histograms for decayed nucleon daughters



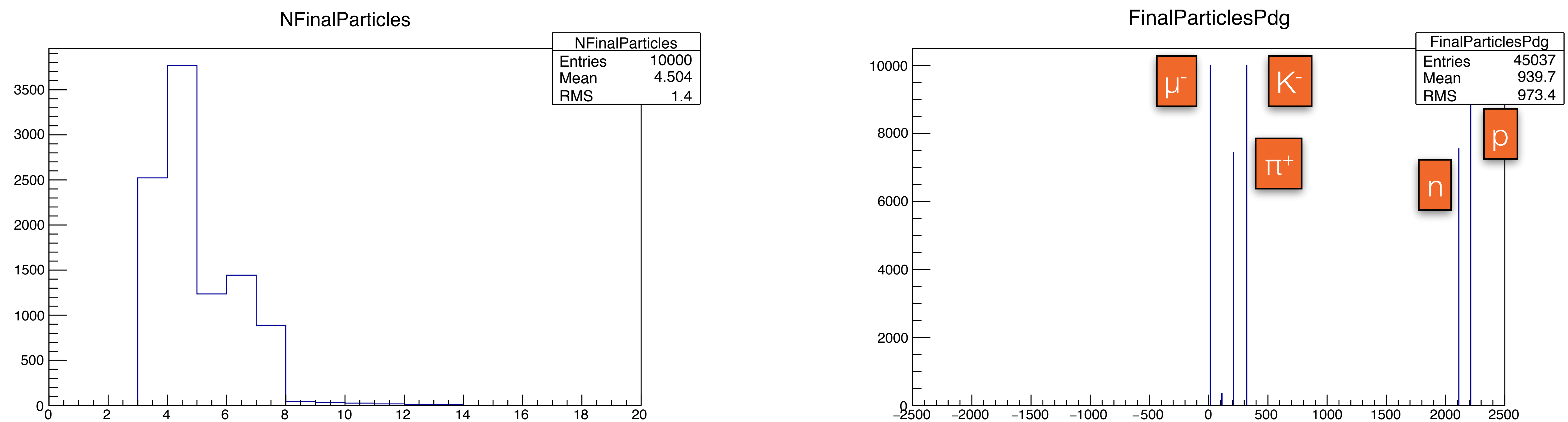






Example validation plots for 3-body decay mode

$p \rightarrow \mu^- \pi^+ K^+$, histograms for GENIE's stable final state particles



- Large fraction of π^+'s undergo FSI, producing protons and neutrons
- No K^+ absorbed in 10,000 simulated decays
  - <0.01% at 0.20 GeV/c. To be compared with 0.2% at 0.34 GeV/c. As expected?
- Also, no π^-'s nor gamma rays
  - Do we expect <0.01% π charge exchange or nuclear de-excitation gamma rays, at these momenta?

Conclusions

- GENIE being extended to be able to simulate all single-nucleon, exclusive, decay modes that have ever been searched for (according to PDG)
  - 68 modes (current GENIE: 11 modes)
  - Should include all "DUNE-promising modes" according to Maury +Lisa's definition (DUNE-doc-1220)
- Code already exists, now under GENIE review, hopefully will make it into GENIE v2.12 → LArSoft
- This process useful to unveil / re-discover some limitations of GENIE nuclear models for NDK searches?
  - Intra-nuclear transport for mesons other than $\pi^{\pm,0}$, K^{+}, nuclear de-excitation gamma rays?