LANL Neutron Beam Test and the sFGD

Stony Brook Neutron Workshop

Abraham Teklu, June 19th 2023

Overview

- The Neutron Particle Gun Studies with the ND280 Software
  - Simulation Overview
  - Reconstruction Steps
  - Effective ways to improve kinetic energy resolution
- The preliminary Neutron Selection for the RHC mode in the sFGD
  - Simulation Overview
  - Selection Steps
  - Studies in progress

Simulation Overview

ND280 Software Configuration

Package	Branch
oaEvent	master
oaGeomInfo	master
eventCalib	master
eventRecon	master
trackerRecon	master
sfgRecon	master
trexRecon	master
recPackRecon	master

ND280 Software Configuration

Package	Branch
eventAnalysis	master
oaAnalysisReader	master
nd280Geant4Sim	7.3
detResponseSim	master

- Current configuration is master branches for 14.5, except for nd280Geant4Sim
- The PGUN used this configuration

Stony Brook University

ND280 Software Configuration

- Running a neutron particle gun:
  - Generated 1M neutrons starting from the center of sFGD and along z and with uniform energy from 0 to 1 GeV

```
# To get help for a command use runND280 --command=""

[software]
cmtpath = environment
cmtroot = environment

[configuration]
module_list = nd280Geant4Sim detResponseSim eventCalibMC eventRecon eventAnalysis

[filenaming]
run_number = 0000
subrun = 0003

[nd280Geant4Sim]
num_events = 4000
mc_type = ParticleGun
mc_particle = neutron
mc_position = Point -0.5 3.0 -193.894
mc_energy = uniform 0 1000
mc_direction = Beam 0 0 1
random_seed = 533

#geometries in ~/nd280sw/nd280Geant4Sim_master/Linux-Debian_11-gcc_9-x86_64
[geometry]
baseline = 2022

[electronics]
random_seed = 4987
```

Stony Brook University

Reconstruction Steps

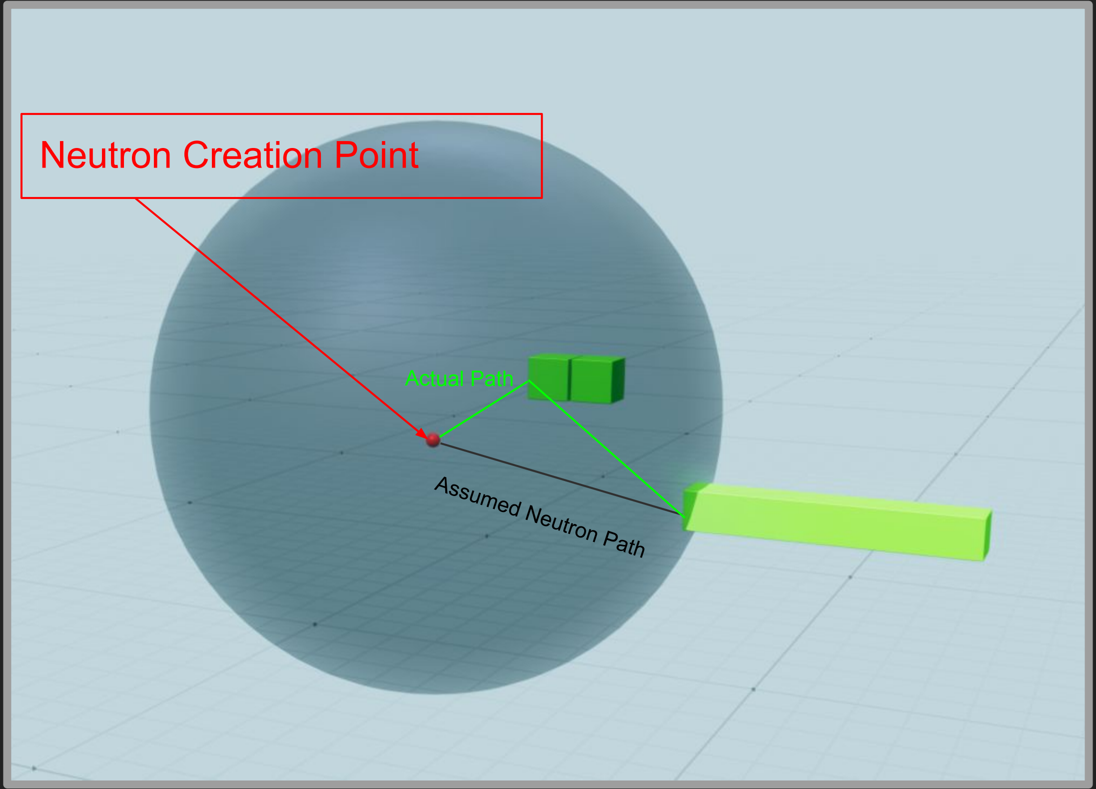
Reconstruction Steps

1. Select Events with a Track in the SFGD
2. Remove Events with reconstructed neutron velocity > c
3. Cluster Cut

Cluster Cut

- If there is a cluster in the event that happened before the track then the path of the neutron to the track is not straight.

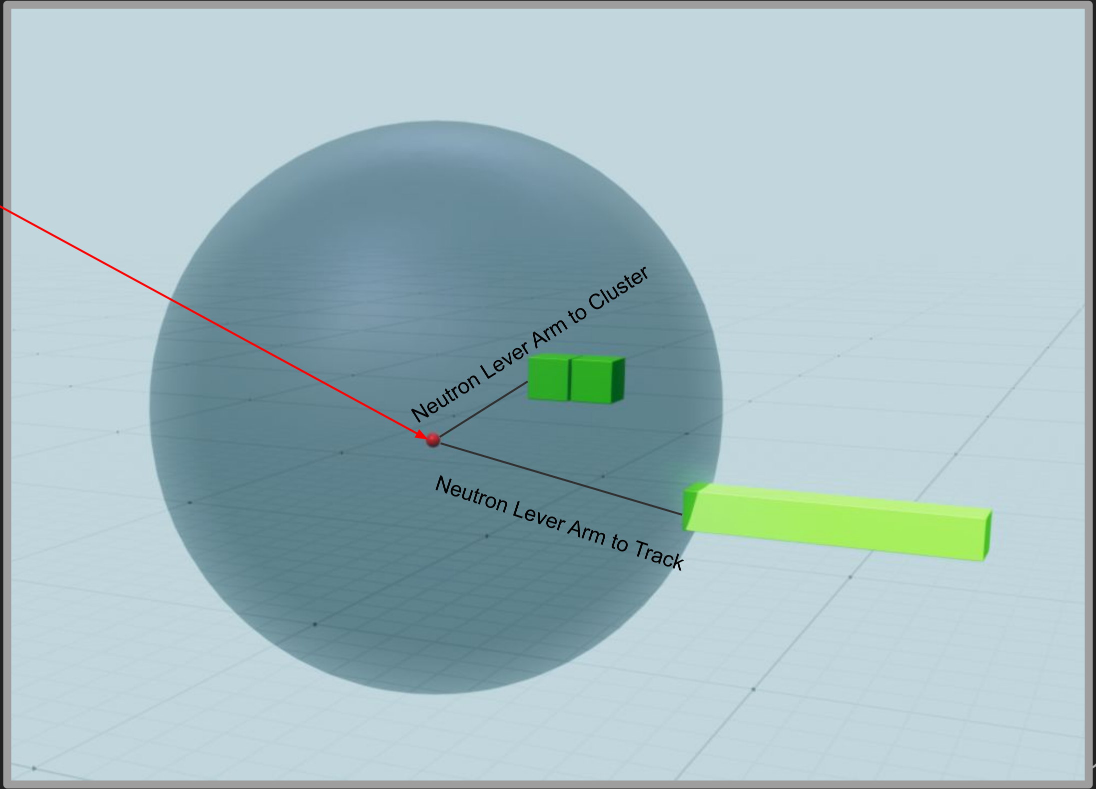
- This will ruin the neutron energy calculation.



Cluster Cut

- A lever arm from the neutron creation point for the closest track and cluster is compared.

- If there exists a cluster with a **shorter lever arm** and **the same or earlier timing info**, the event is removed.



*Using clusters is also something to look into

Stony Brook University

Effective Ways to Improve KE Resolution

Getting Reconstructed Energy

The reconstructed energy for the neutron can be calculated using the neutron lever arm and the difference in time between the neutron creation time in the simulation and the reconstructed vertex hit time, which I refer to as the vertex time.

$$v_{reco} = \frac{L}{t_{vert}}$$

L is the lever arm of the neutron and t_{vert} is the vertex time of the most upstream reconstructed particle.

$$\gamma = \frac{1}{\sqrt{1-(v_{reco}/c)^2}}$$

$$KE_{reco} = m_n c^2(\gamma - 1)$$

m_n is the neutron mass and c is the speed of light. This is the same as E_{reco} - $m_n c^2$

$$KE_{true} = E_{true} - m_n c^2$$

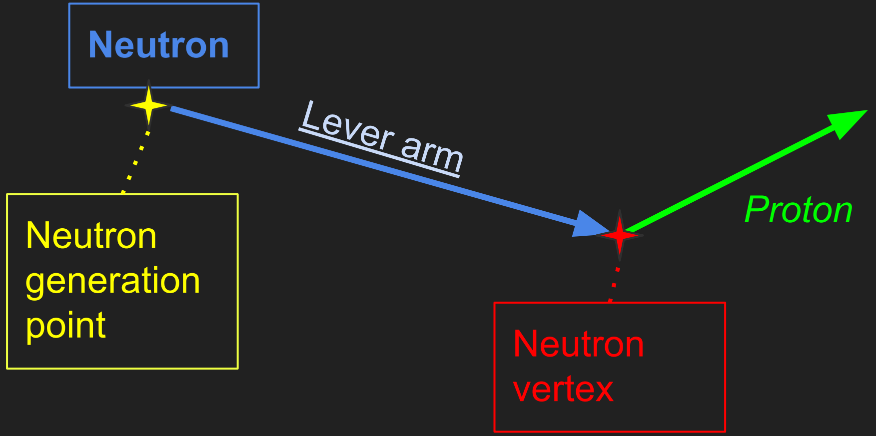
*notice t_vert is a true variable minus a reco variable. This will slightly bias our energy for the particle gun, but we won't run into this in the neutrino studies

Time of Flight Effect on KE Resolution

C(cm/ns)	Lever arm (cm)	Vertex time (ns)	Velocity (cm/ns)	gamma	KE (MeV)	Mn - neutron mass
29.9792	25	1.5	16.66666667	1.203048406	190.6624534	939
29.9792	25	1	25	1.811928457	762.4008214	939

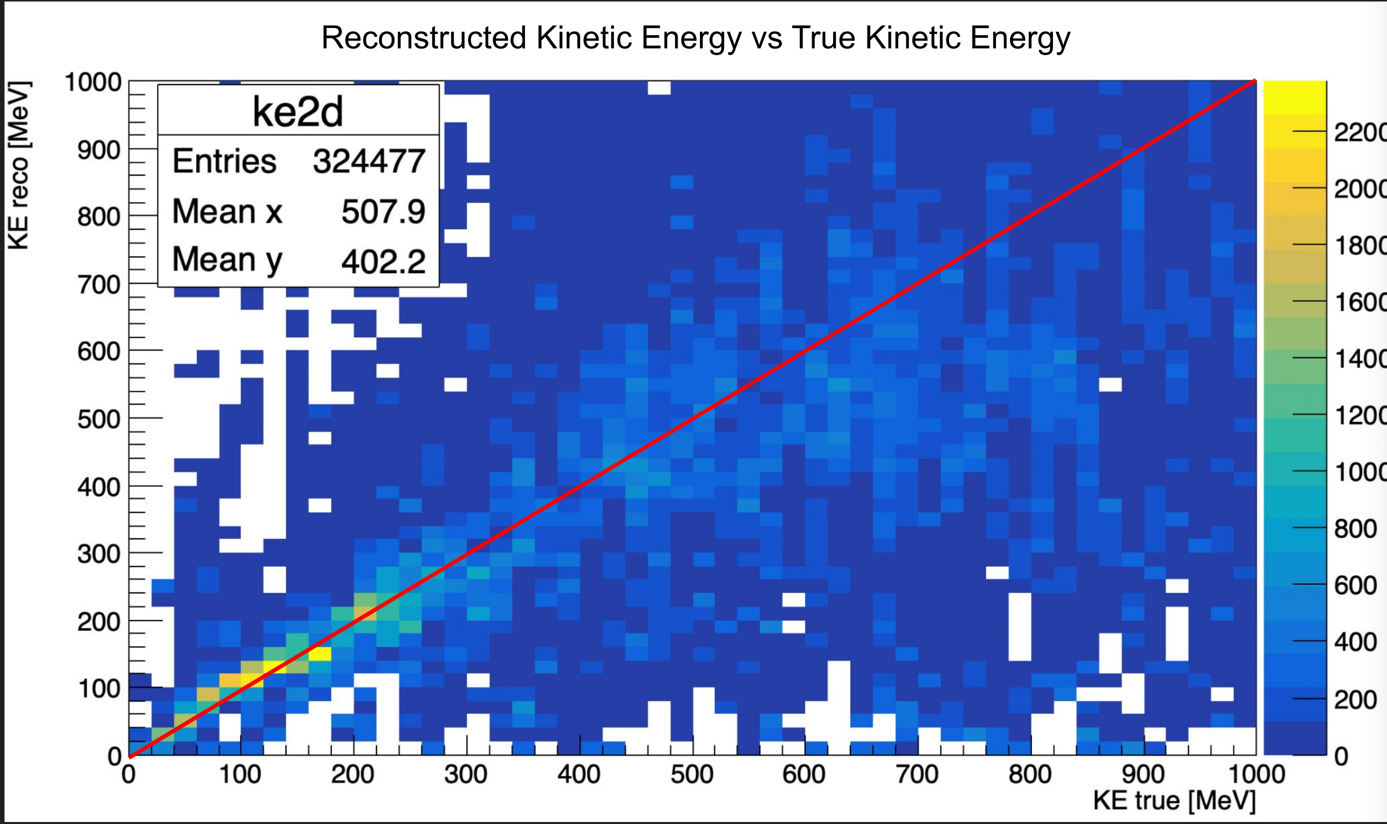
Time is the limiting factor on neutron energy resolution!

- TOF resolution of this type of detector is around 1 ns
- Most events have a TOF of 5 ns or less so binning based on TOF is going to be an effective tool



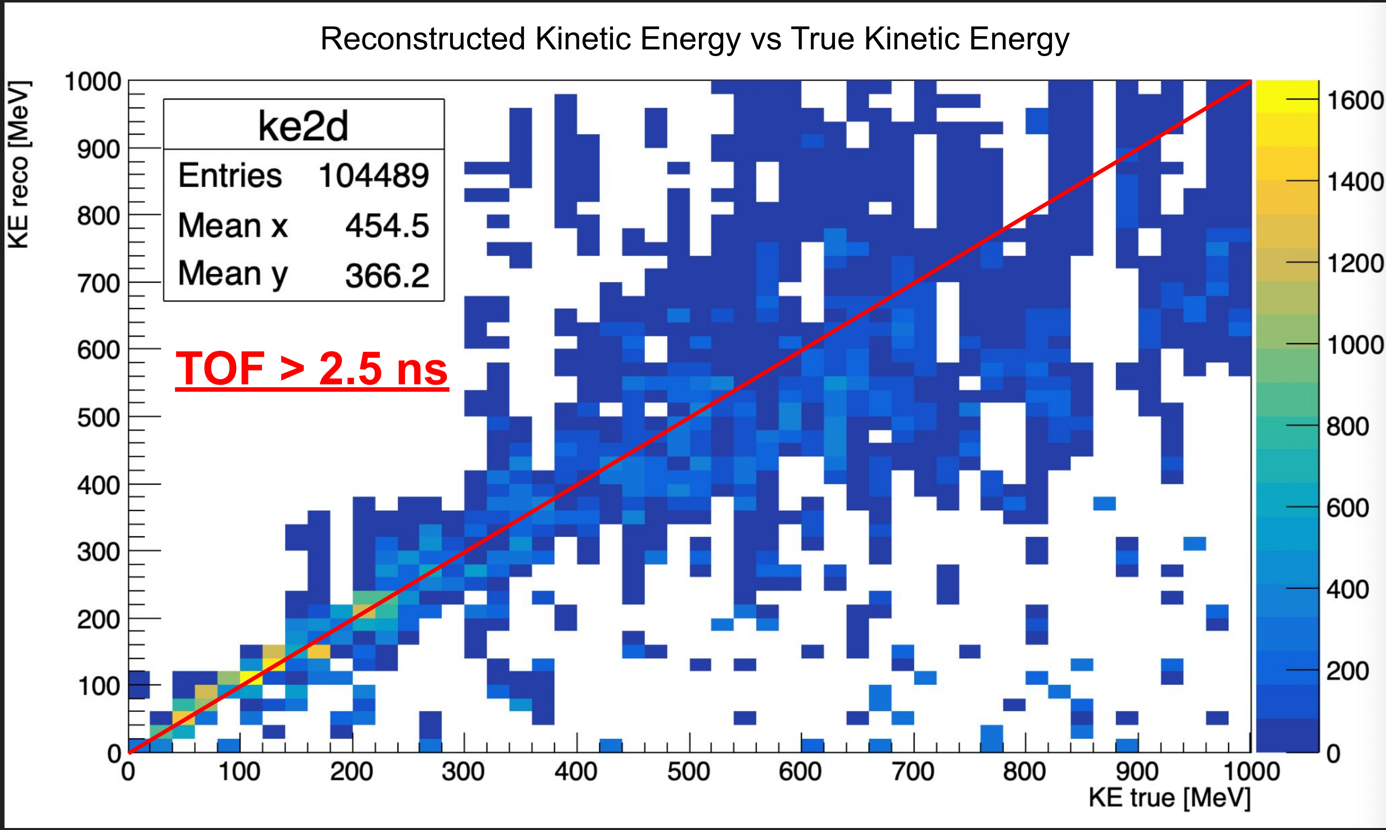
Time of Flight Effect on KE Resolution

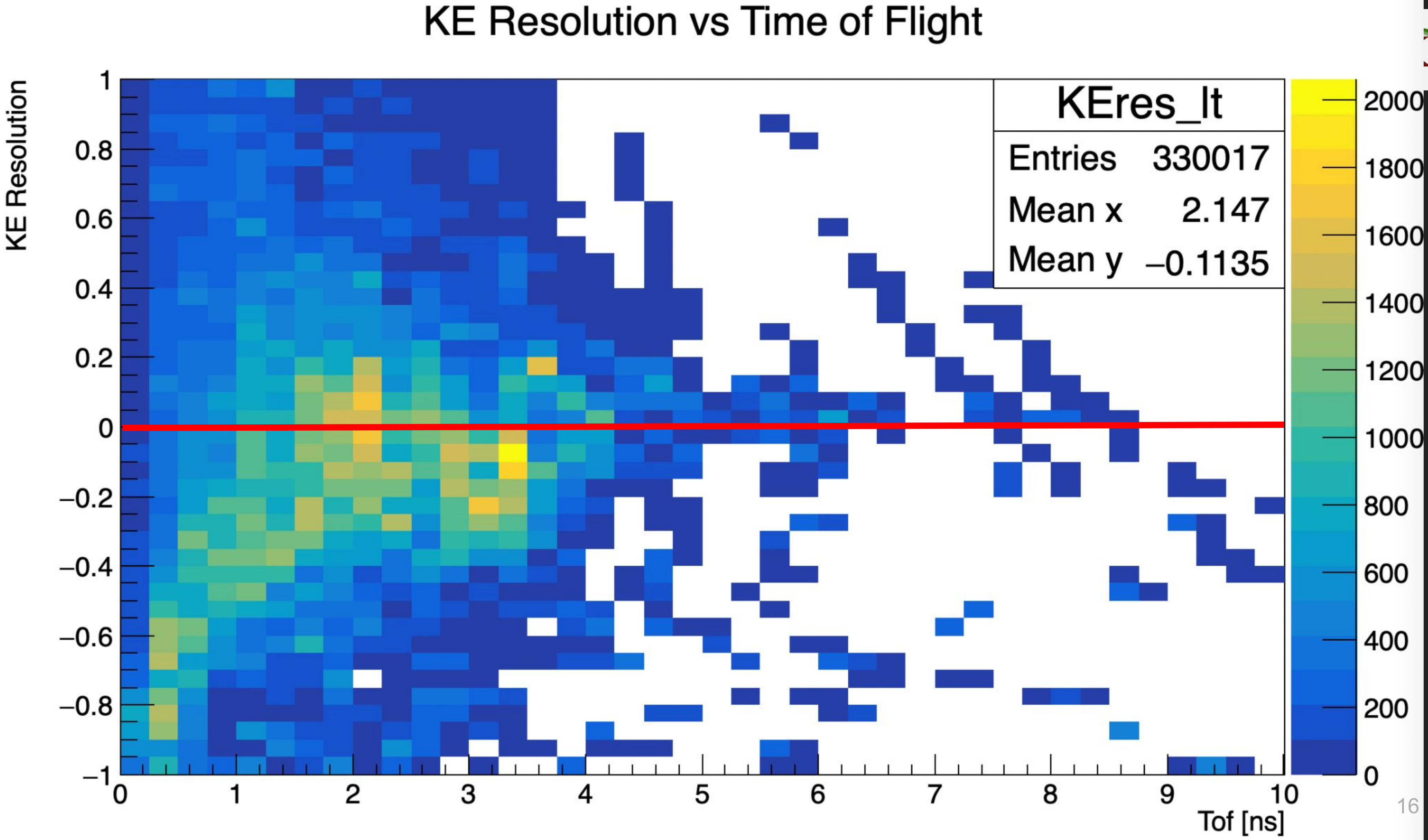
- These are all the events that passed the reconstruction steps
- A number of events left no track in the SFGD



Time of Flight Effect on KE Resolution

- About ⅓ of the events have a TOF of 2.5 ns or more
- The resolution still gets worse at higher energies because more complicated multitrack events happen more often.



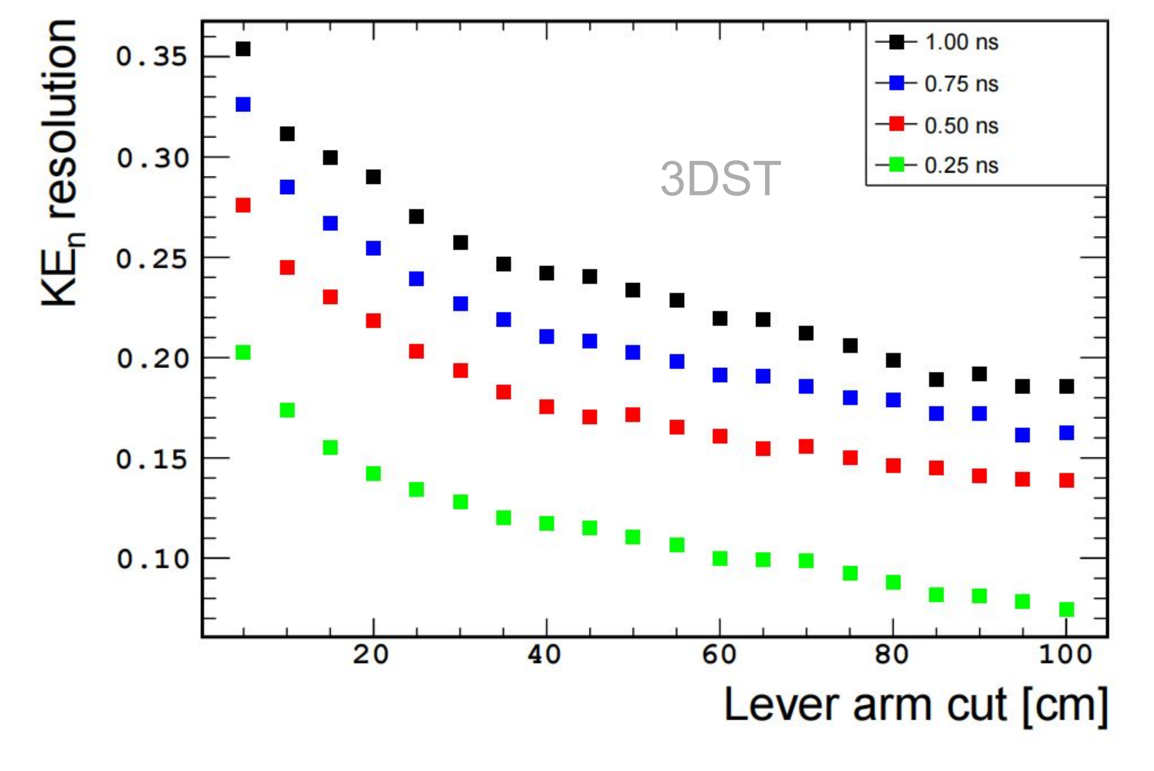

KE Resolution vs Time of Flight
KE Resolution
Tof [ns]
KEres_lt
Entries 330017
Mean x 2.147
Mean y −0.1135
1
0.8
0.6
0.4
0.2
0
−0.2
−0.4
−0.6
−0.8
−1
0
1
2
3
4
5
6
7
8
9
10
2000
1800
1600
1400
1200
1000
800
600
400
200
0

Comparison to study in 3DST

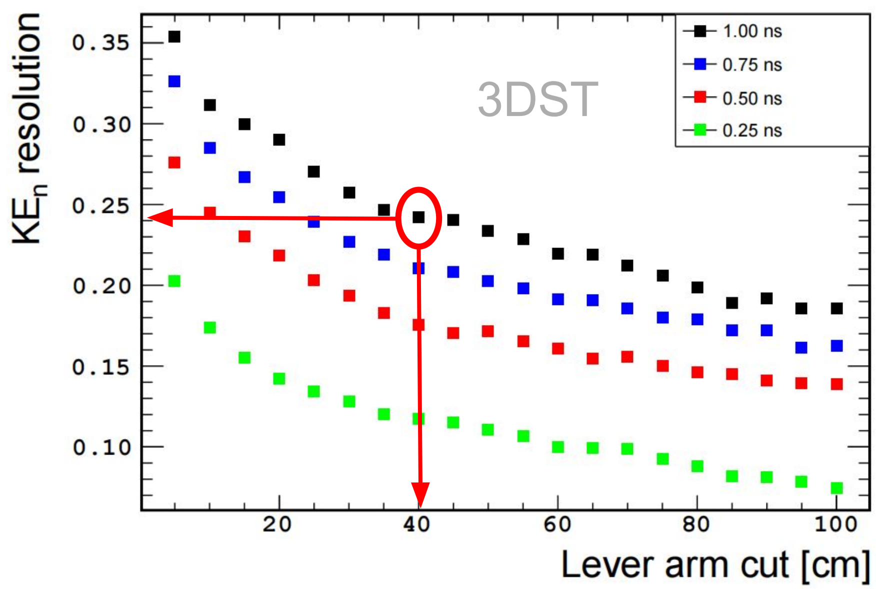
The lever arm cut studies done for 3DST (detector proposed for DUNE ND).

This is a plot performed for 3DST studies of neutron energy resolution as a function of the lever-arm cut for various time resolutions for 3DST.

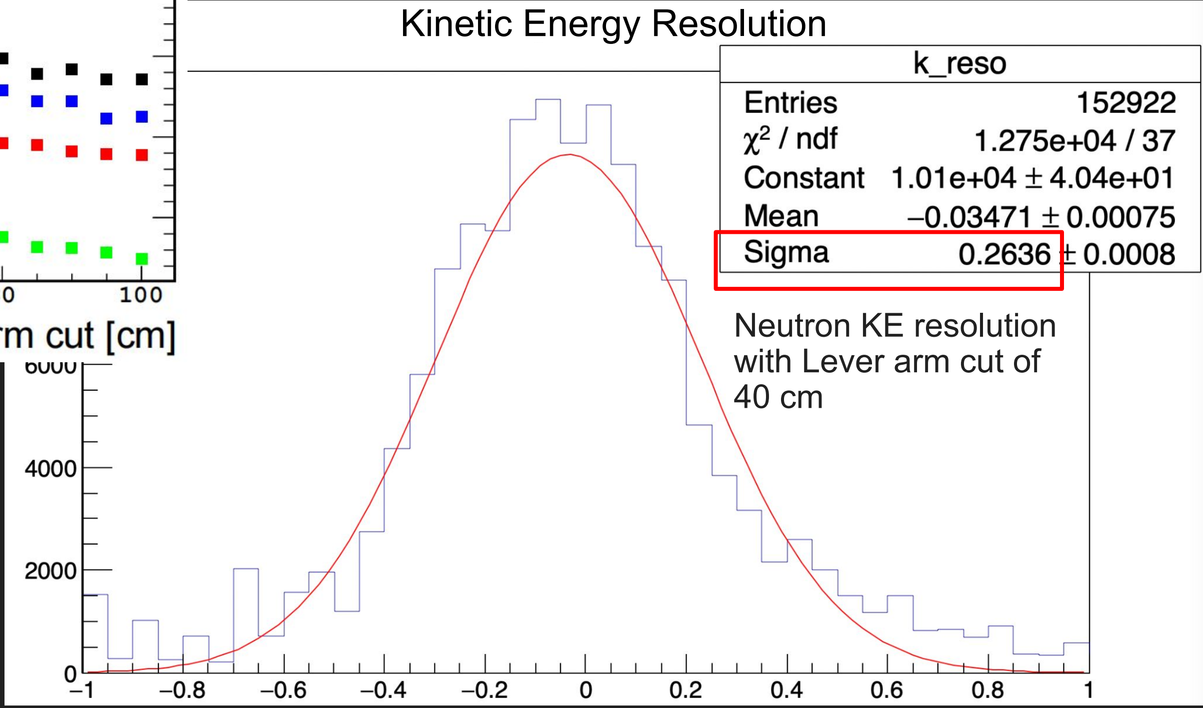
Inspiration for TOF cut



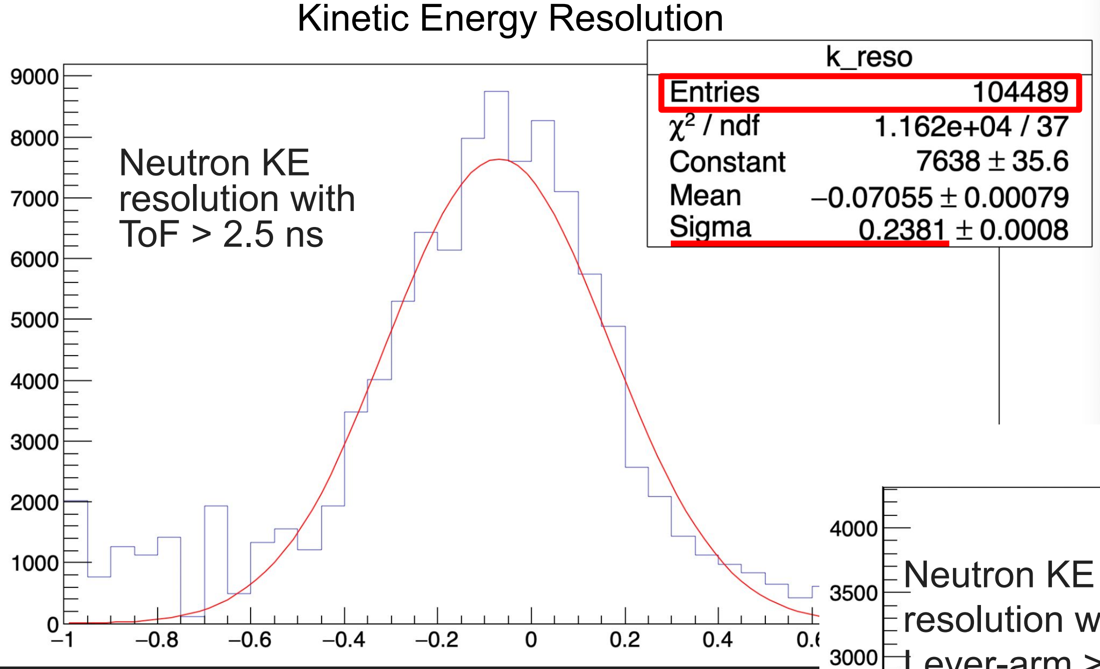
Gwon, S., et al. "Neutron detection and application with a novel 3D-projection scintillator tracker in the future long-baseline neutrino oscillation experiments." arXiv preprint arXiv:2211.17037 (2022).



Gwon, S., et al. "Neutron detection and application with a novel 3D-projection scintillator tracker in the future long-baseline neutrino oscillation experiments." arXiv preprint arXiv:2211.17037 (2022).

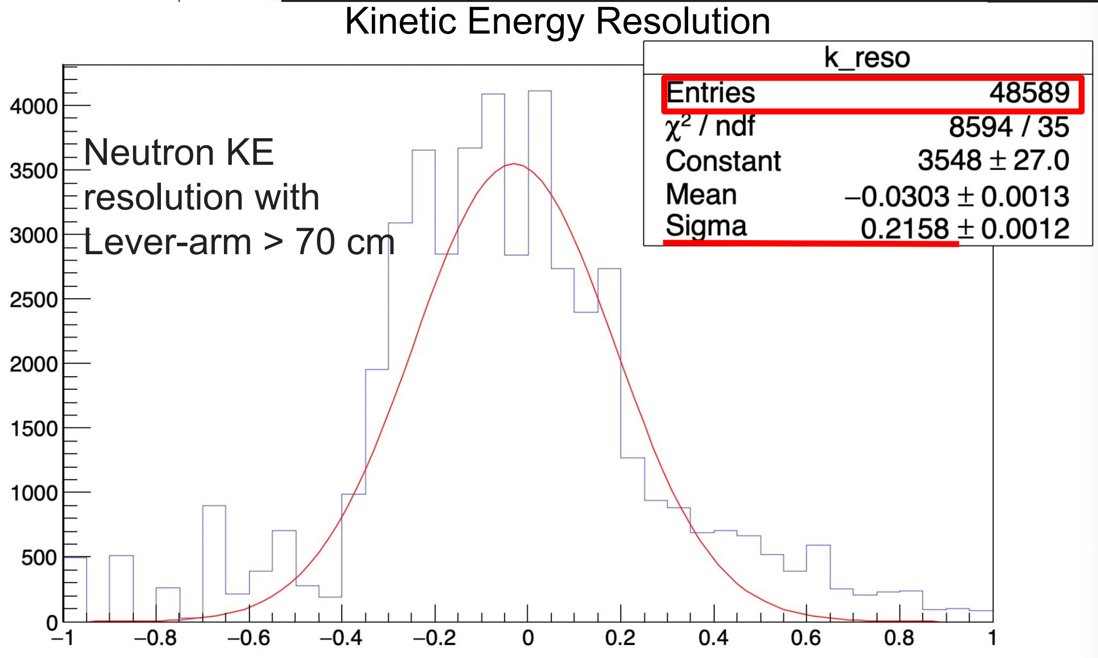


Of course these studies are totally different, but even with the energy range and selection differences the ND280 simulation seems to have a similar resolution.



In general TOF cut keeps more statistics to achieve a similar KE resolution.

This is because the limiting factor on KE resolution is timing resolution not spatial resolution.



Lever-arm cut is essentially raising the average TOF of the neutrons.

Numu RHC Studies in Highland

Highland Software Configuration

Package name	base tag	branch for upgrade
eventAnalysis	~~7.0~~ 7.2	feature/upgrade_highland
highland2SoftwarePilot	stable	
oaAnalysisReader	2.23	feature/upgrade_global
psycheCore	3.45	
psycheEventModel	3.41	feature/upgrade_global
psycheUtils	3.34	
psycheND280Utils	3.63	feature/upgrade_global
psycheIO	3.34	feature/upgrade_global
psycheSelection	3.51	feature/upgrade_global
psycheSystematics	3.54	
highlandCore	2.40	feature/upgrade_global
highlandEventModel	2.34	feature/upgrade_global
highlandUtils	2.36	feature/upgrade_global
highlandTools	2.29	
highlandCorrections	2.25	
highlandIO	2.45	feature/upgrade_global
upgradeAnalysis	main	main

The suggested nd280 software configuration is 14.4 but I am using 14.5

Ston
Uni

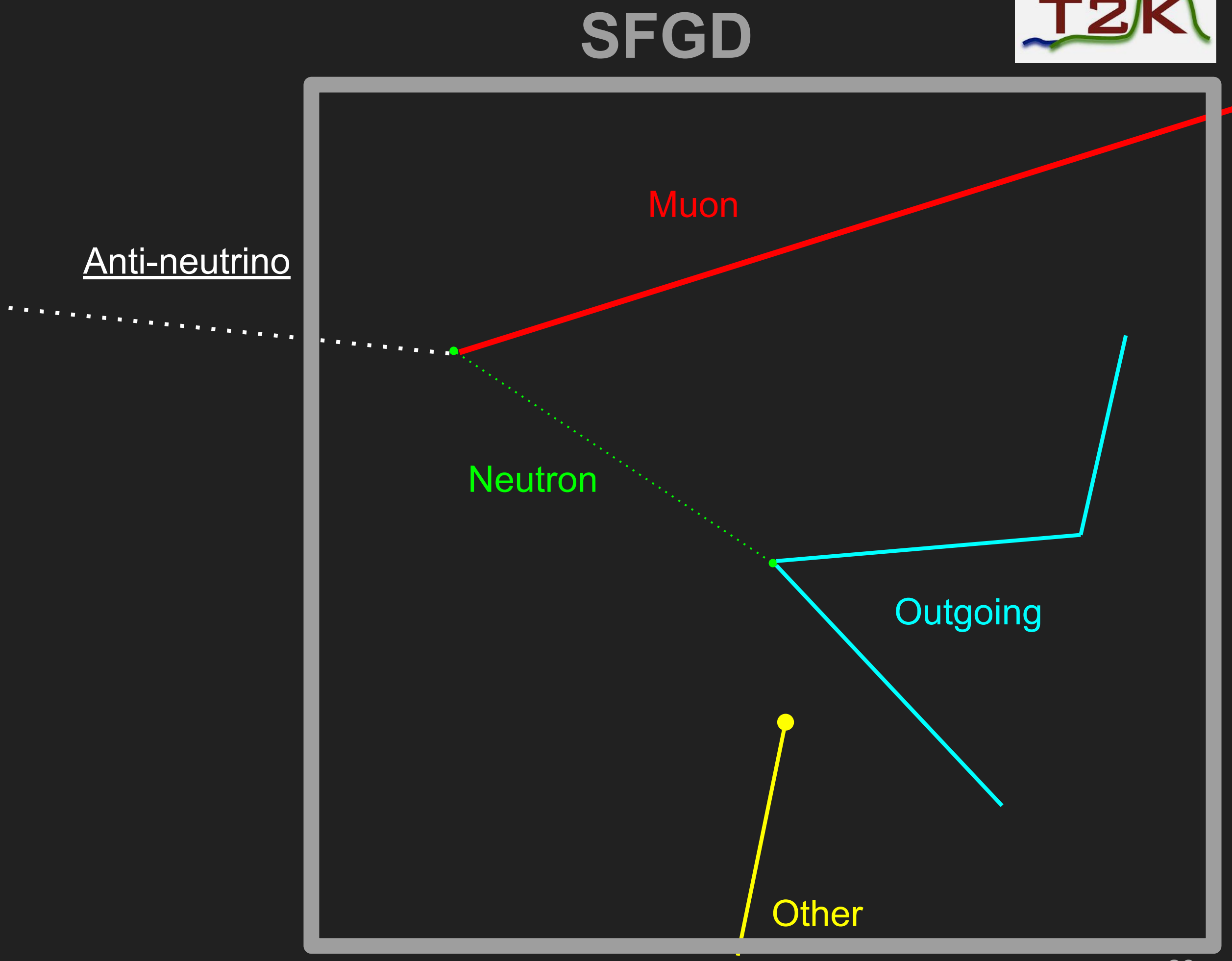
Current Plan for Neutron Selection

- Currently I am using numu_selection_neutron
  - This will be where I am building the first neutron selection CC0p0pi1n
  - This is going to have simpleset topology to identify, a clean muon track and a remote track in the SFGD
- The selection will look for a lone muon track.
- Then group the remote tracks in the SFGD if they are connected.
- Then compare the vertex of the muon and primary remote tracks to see if it is possible for a neutron with reasonable energy.
- Maybe a cylinder cut around muon track to reject gammas
- Pi0 cut to remove gammas
- …
- After this we can implement the neutron reconstruction used in the particle gun and see if the results are comparable.

Lone Muon : Cut 1

- The first cut for CC0pi0p1n is a looking for a muon track in the SFGD with no other connected tracks

- Then look for disconnected tracks in the SFGD

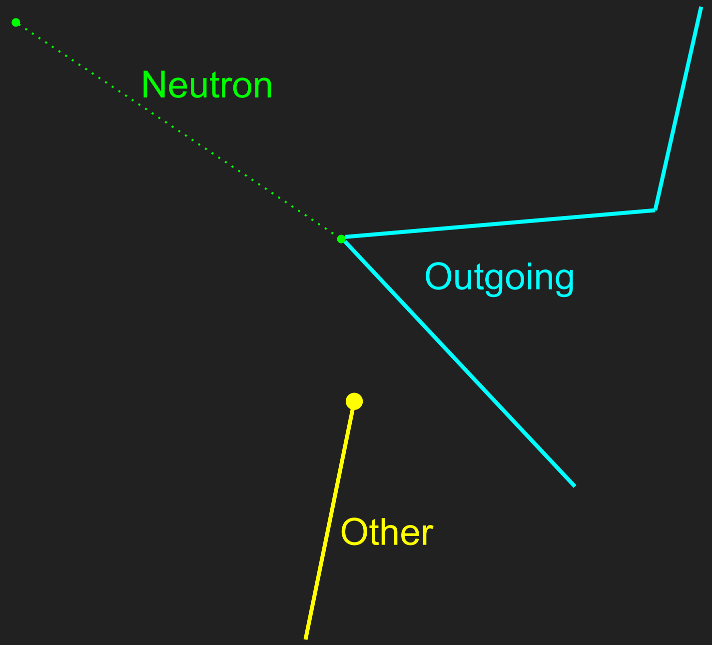


Connected Track Algorithm : Cut 2

Make a list of distances between the head of each reco track and the head and tail of every other reco track. *Ignoring the muon!*

If the number of distances that equal zero match the number of tracks, everything is connected.

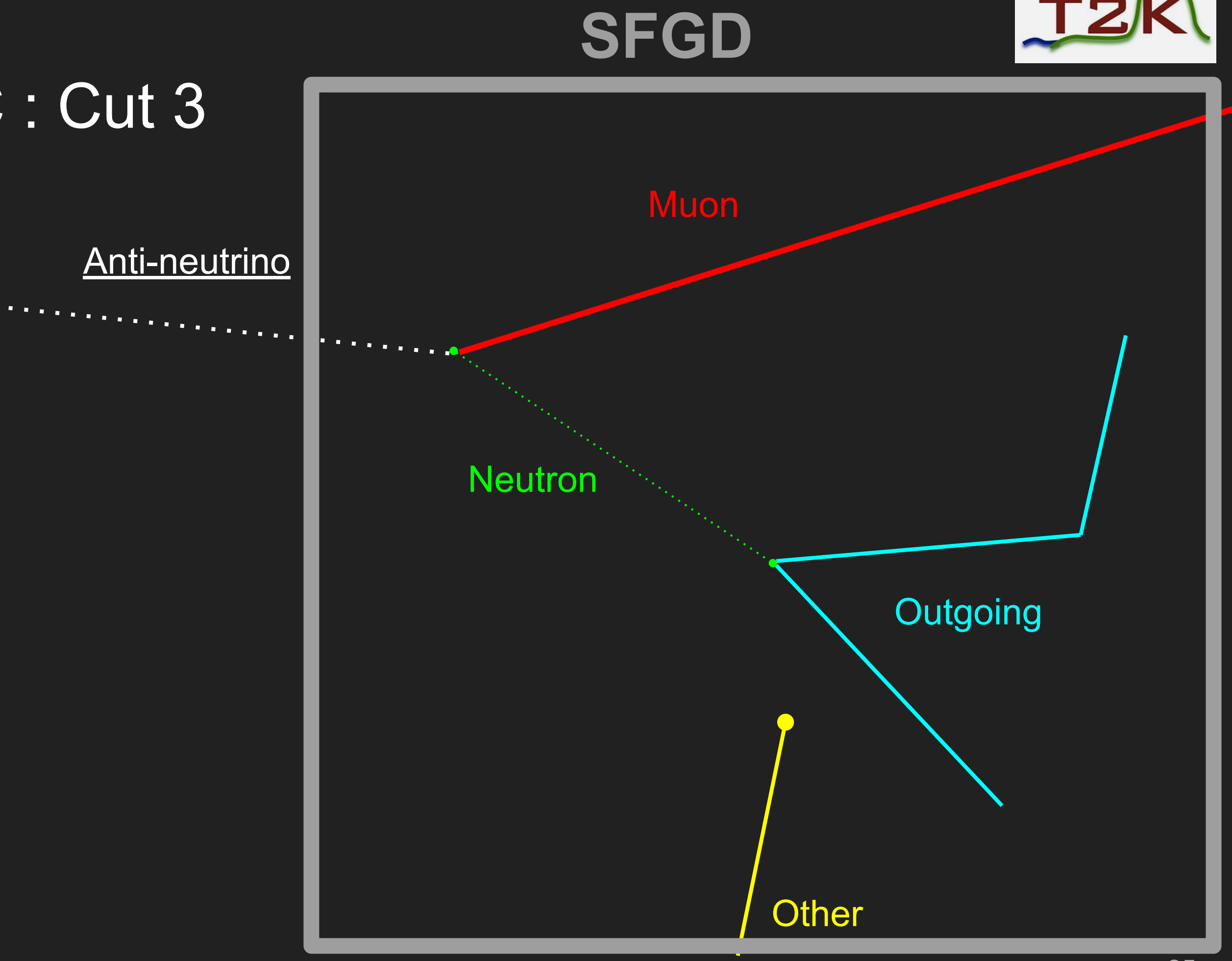
If the number of distances that equal zero is less then the number of tracks, everything isn't connected.



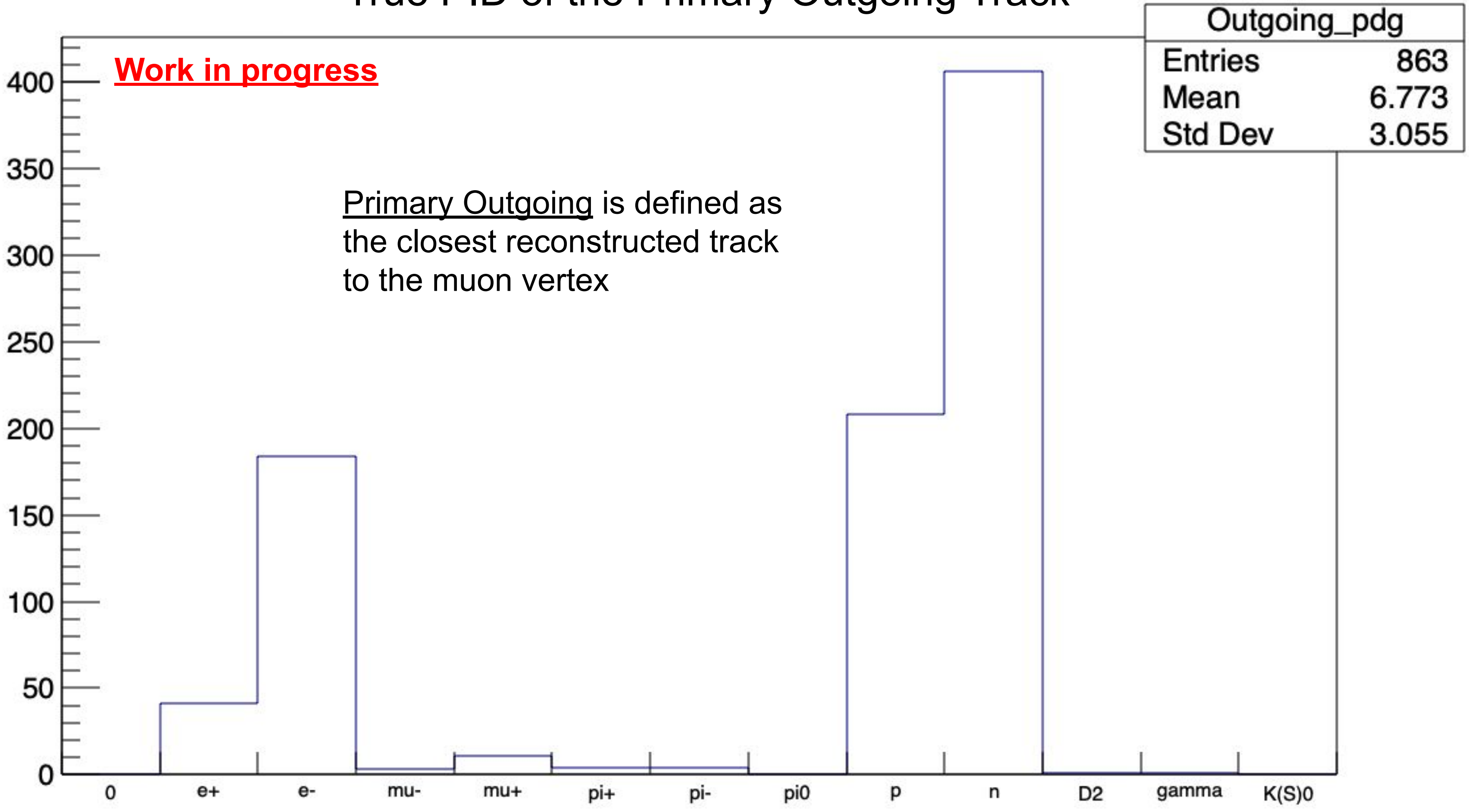
Stony Brook University

Neutron Velocity < C : Cut 3

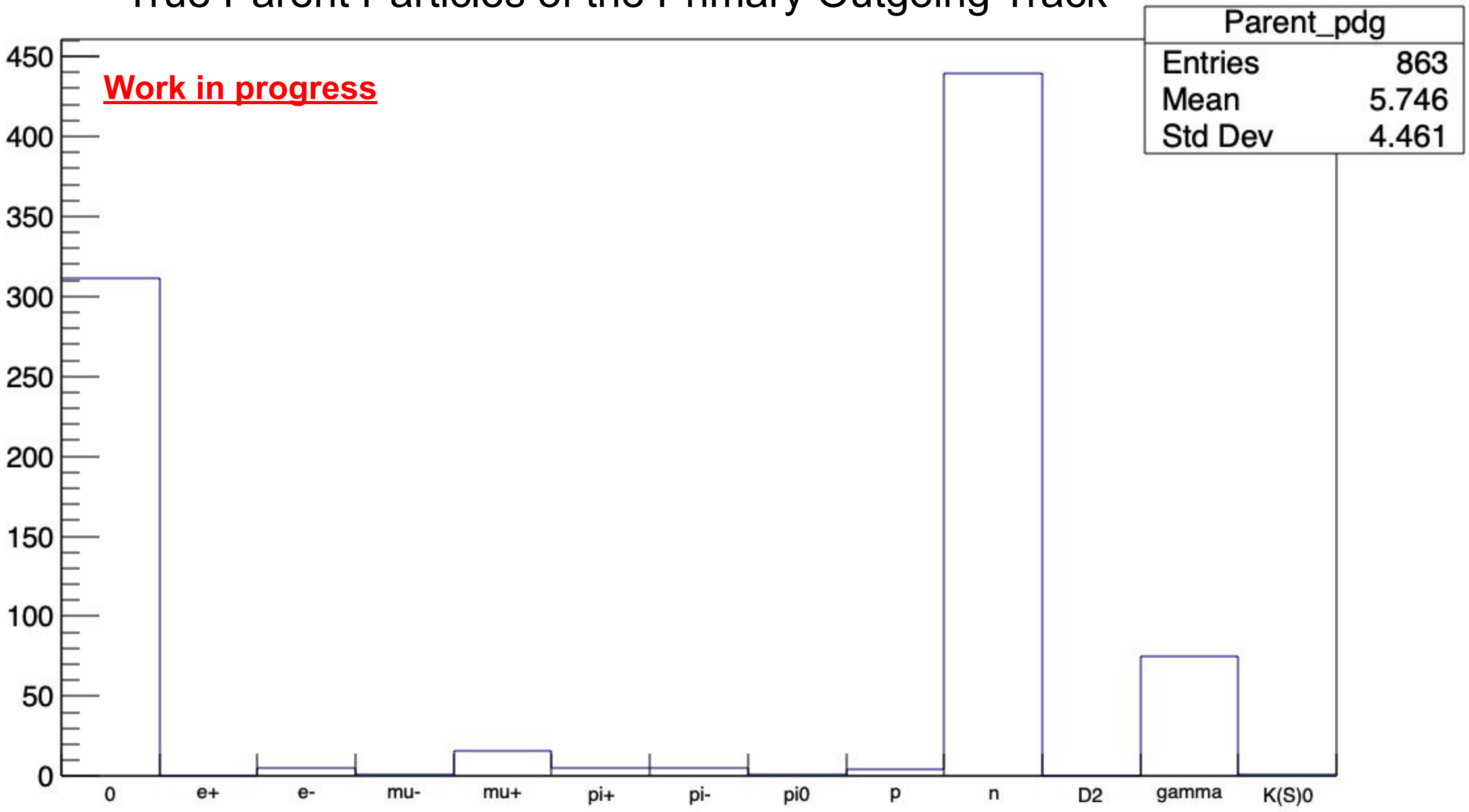
- Lastly use the timing and distance between the muon vertex and the outgoing track vertex to calculate the neutron velocity. And make sure V < C



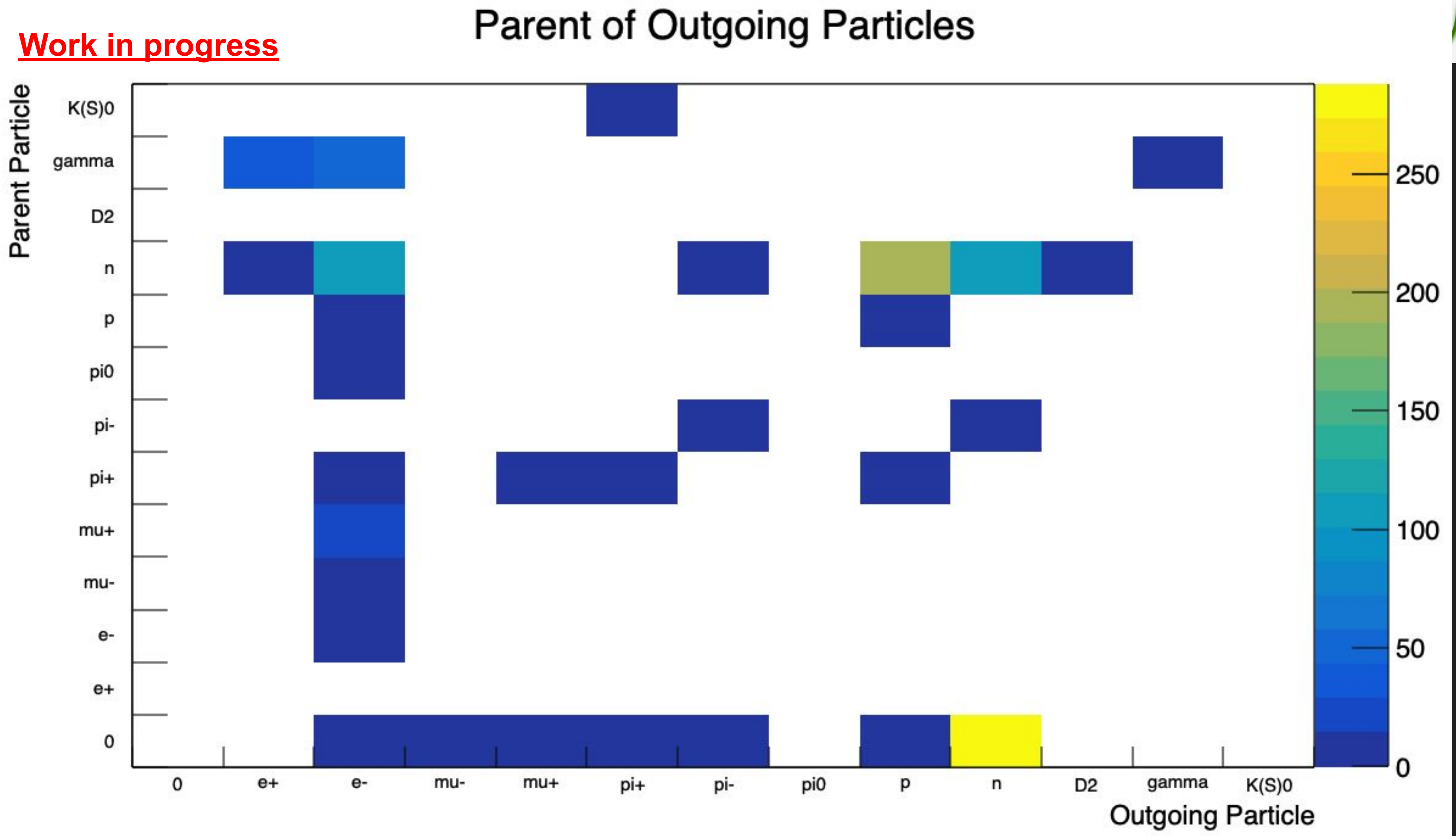
True PID of the Primary Outgoing Track



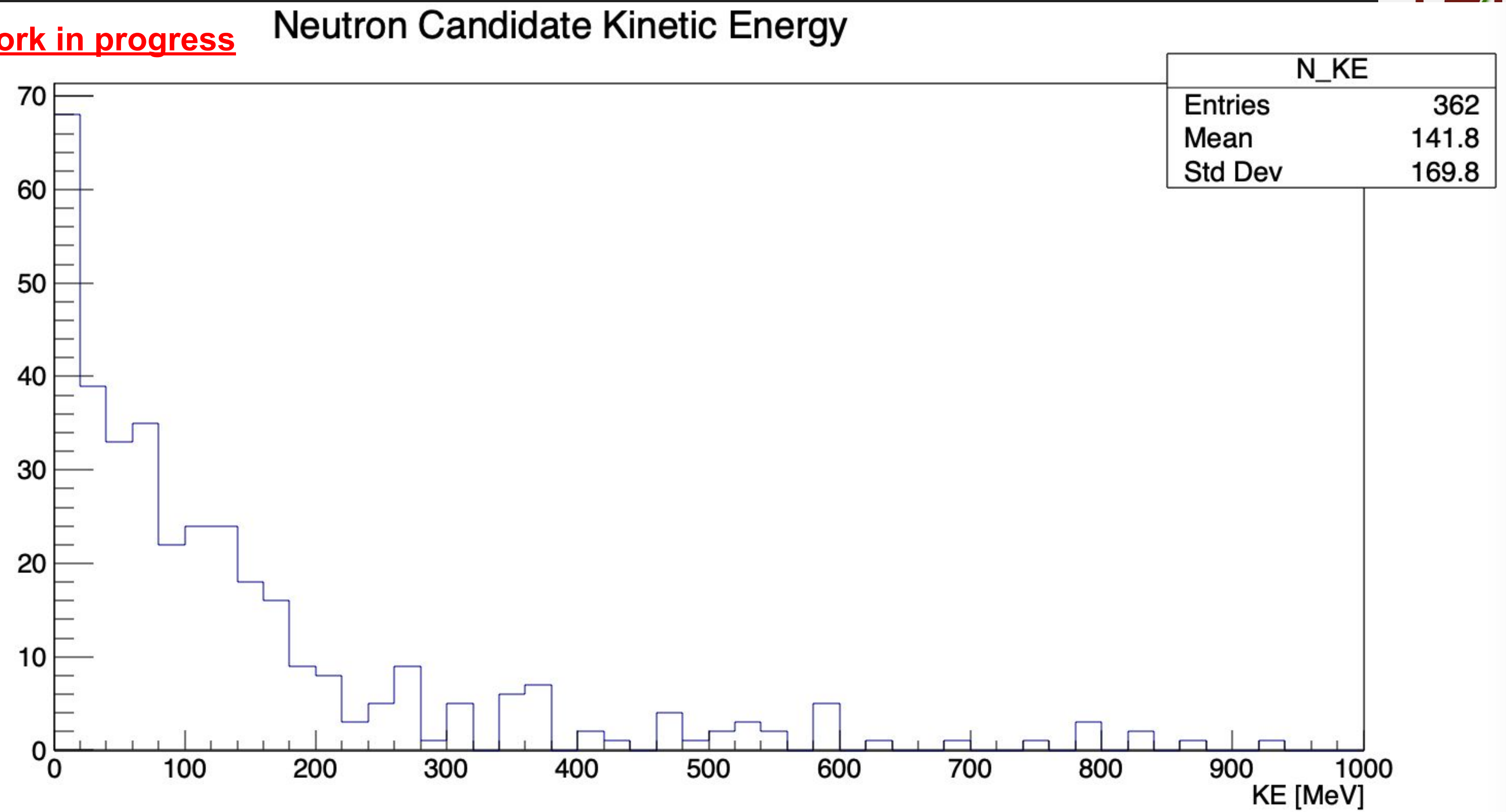
True Parent Particles of the Primary Outgoing Track



Work in progress



Work in progress



Stony Brook University

Connection between Neutron Test Beam and sFGD Neutron Selection

Overview

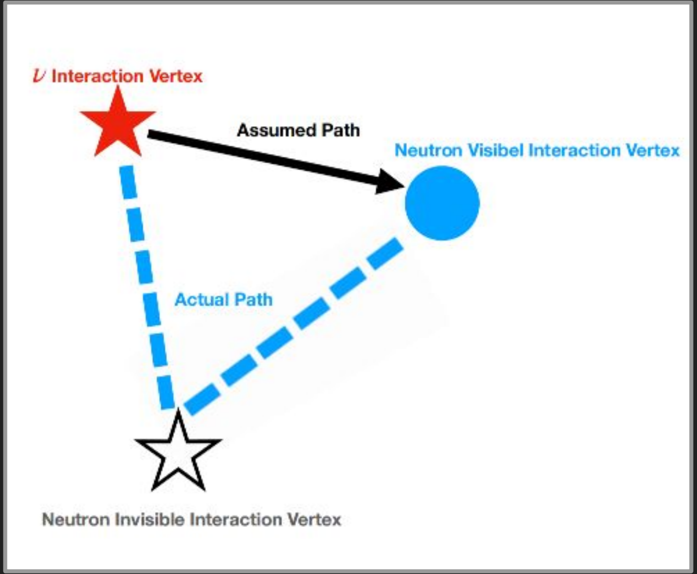
- The LANL Neutron Beam Test was a major effort
  - We should try to use all parts of the buffalo so to speak
- There a two major categories that would be useful for the SFGD
  - MC Tunes base on the Neutron Beam Test
  - Data to data Selection Comparisons

MC Tuning!

- There are 3 main areas where the Neutron Beam Test can improve the sFGD MC
  - Invisible Scattering
  - Cross-Section
  - Track/Cluster distributions

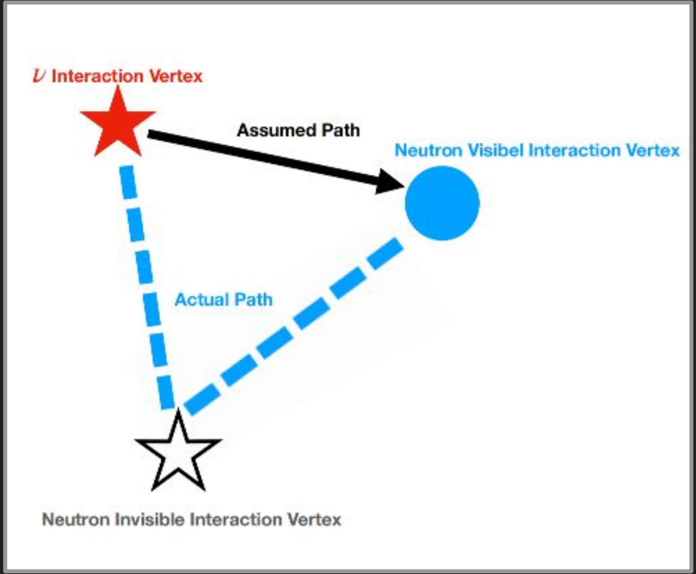
MC Tune for Invisible Scattering

- sFGD will use TOF from the neutrino vertex to calculate the energy of the neutron.
- This is the only way because the deposit energy isn't very correlated with the neutron energy
- Depending on the amount of invisible scattering the neutron energy can be miscalculated if the shortest path is assumed



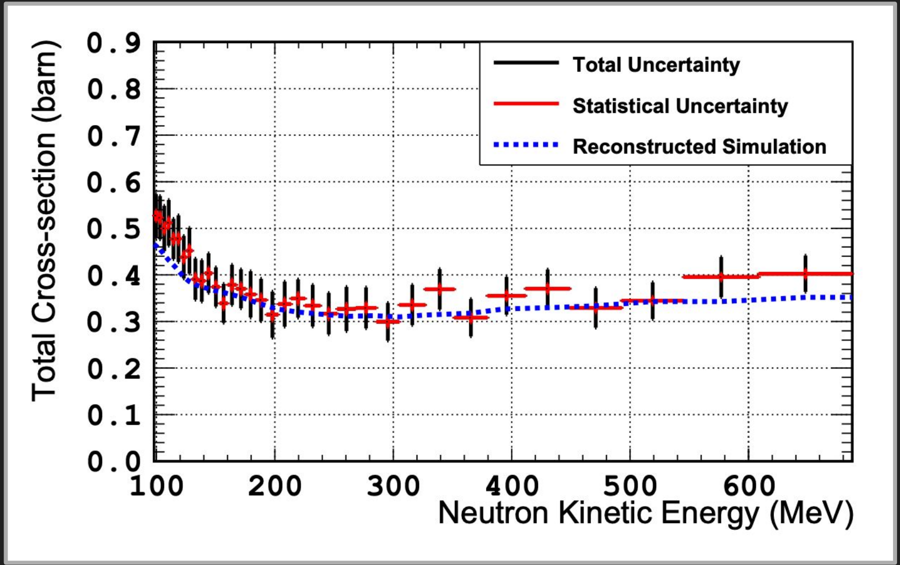
MC Tune for Invisible Scattering

- The tune itself can take many different forms.
  - There can be a tune based on the lever-arm. Giving a PDF of the number of elastic scatters parameterized by the lever-arm. This would need to be based on spread of the vertex. This can be used as a systematic on the energy.
  - This could be a straight tune on the MC if we believe the accuracy of the data to predict the invisible scattering.



MC Tune for Cross-Section

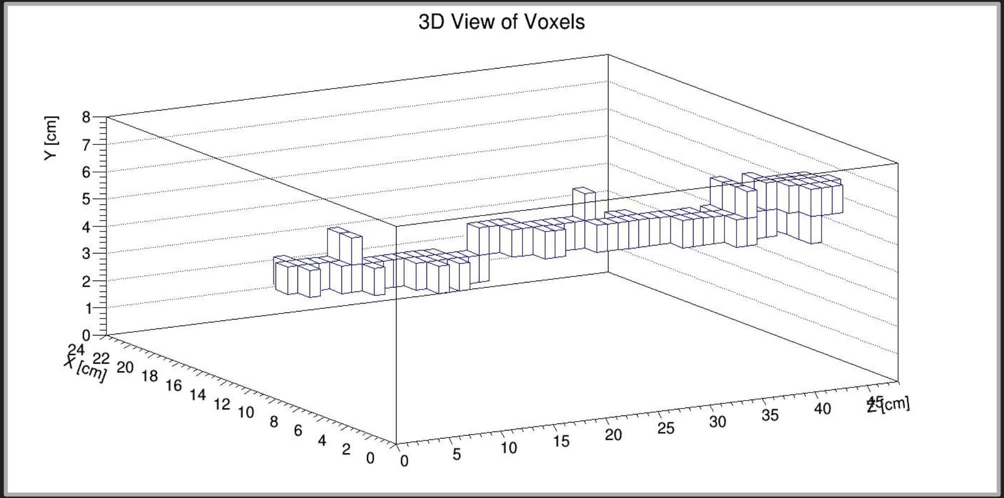
- This is essentially being done by Joel already, but he is comparing Minerva simulation to the ND280 simulation and checking the physics list to make sure there are no weird discrepancies.
  - This tune could also include the total cross-section.



Budd, H., Capo, J., Chaves, J., Chong, P., Christodoulou, G., Danilov, M., ... & Zilberman, P. (2022). Total Neutron Cross-section Measurement on CH with a Novel 3D-projection Scintillator Detector. *arXiv preprint arXiv:2207.02685*.

MC Tune for Track/Cluster Distribution

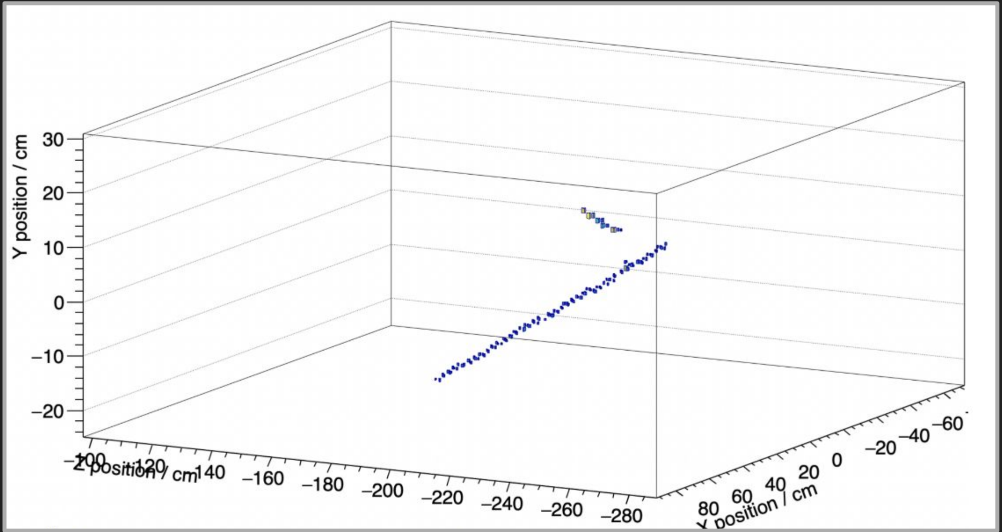
- sFGD is quite new so the MC might not be simulating the dE/dx properly. There have most likely been tunes based on the CERN beam test, but those events were only a single energy things might change at different MeV.
- This can also affect the topology of the events and what gets categorized as Tracks vs Clusters



Selection Comparison

- We can now use a data sample from the Neutron Beam Test to compare to the sFGD neutron selection, along with an MC neutron sample
  - Of course this comparison won't be an apple to apples comparison but it could provide valuable information to update the selection in the early stages.

Ideal CCQE RHC Event



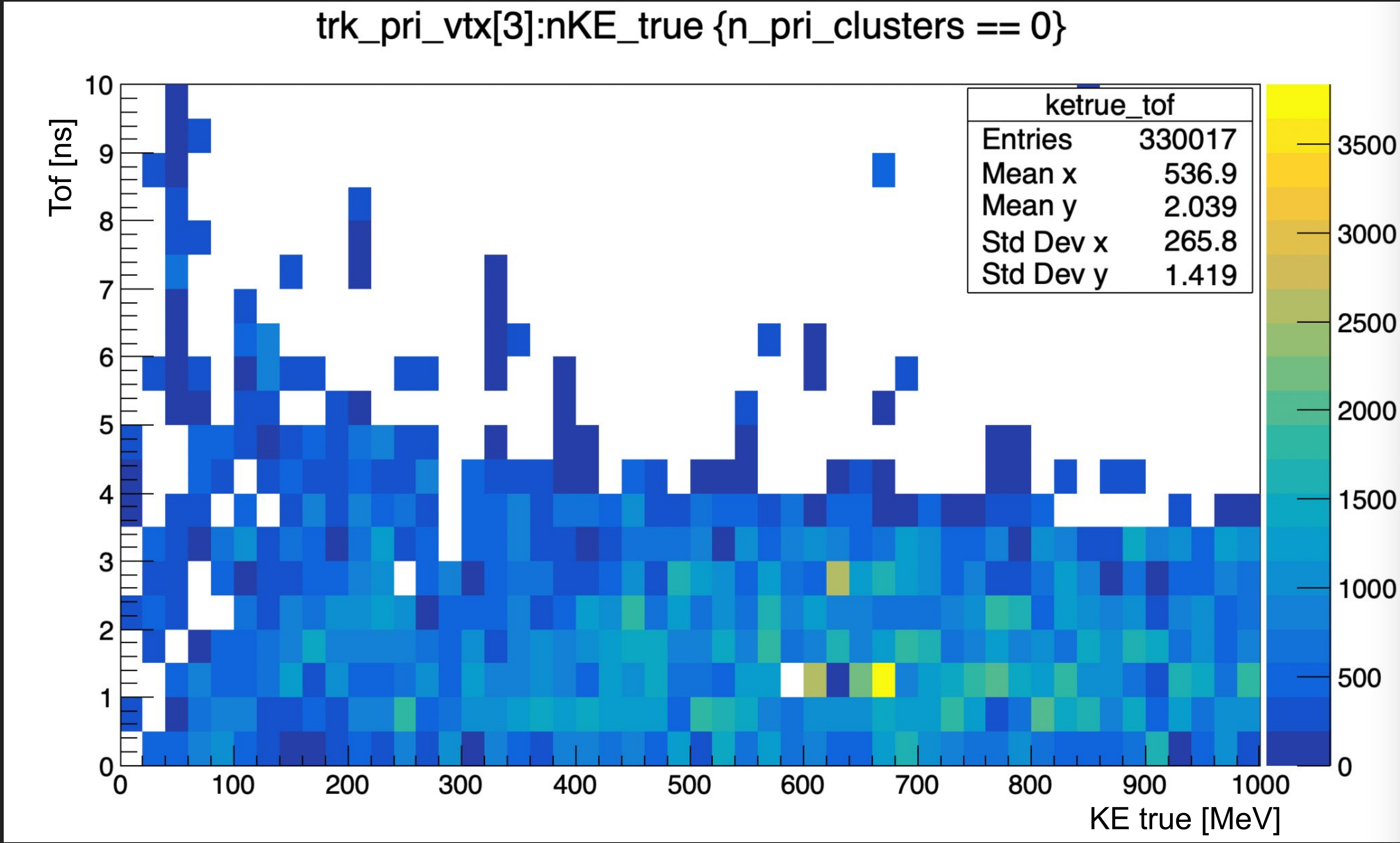
Summary

- Particle gun study had some insights
  - Neutron energy resolution around 20% is possible
  - Using TOF over Lever-arm for event binning has double the statistics for the highest energy resolution events
- Currently working in Highland on RHC

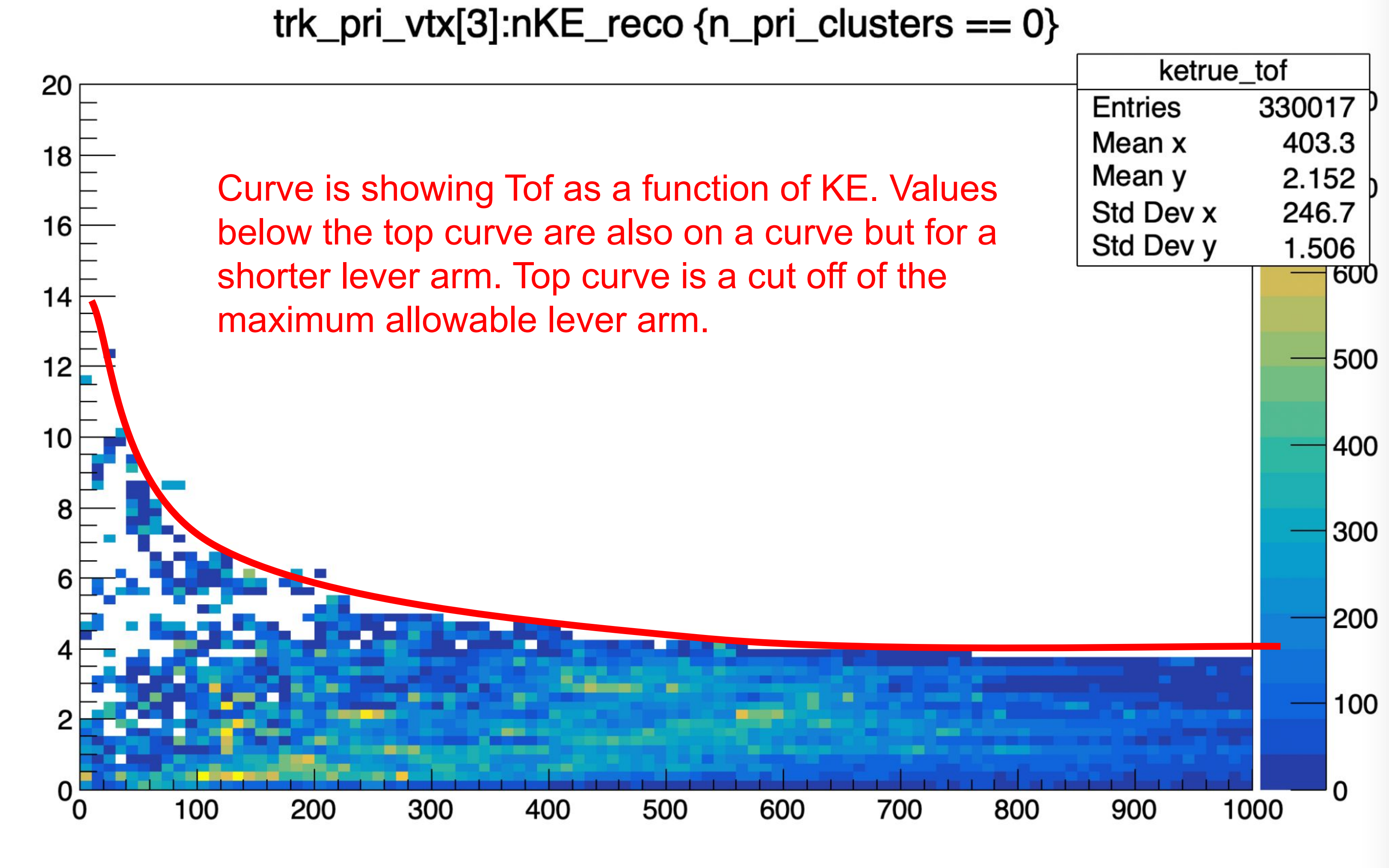
  AntiNuMu CC0π0p-1n selection
  - Out of FV Neutron Background Study is in progress
  - Most of the selection seems to be neutrons
  - There are some background that needs to be quantified
  - There are some adjustments to the selection just based on these plots
  - A gamma cut might need to be implemented

- MC Tune for invisible scattering is going to be really helpful.
  - Especially if you consider using other variables besides just beam spread
  - There is also a possibility of looking into theoretical work
- MC Tune for cross-section is being worked on by Joel but it doesn't currently include total cross-section
- MC tune of dE/dX should be checked and updated if the beam test data shows discrepancies
- Data to data comparison is also possible.

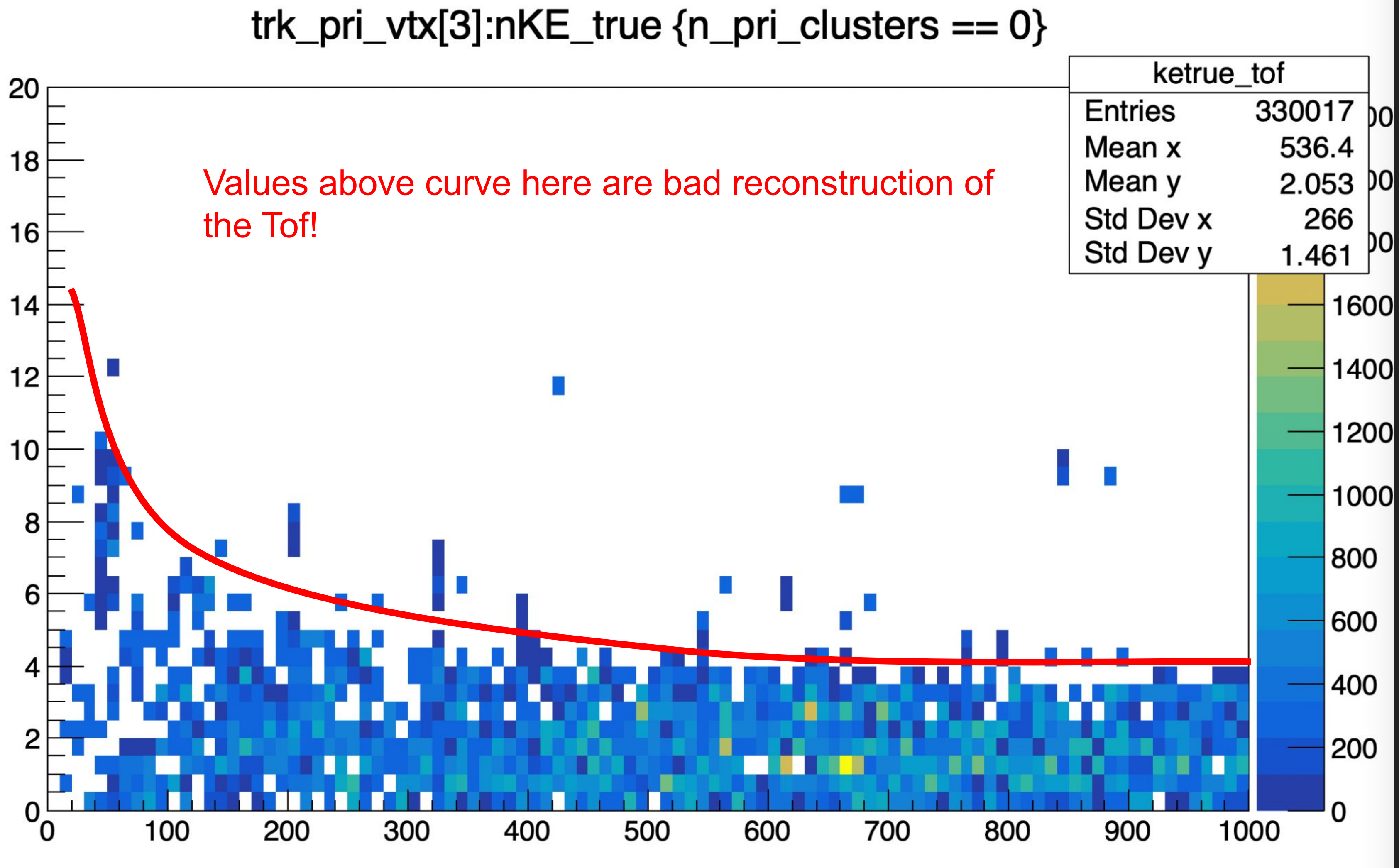
Backup

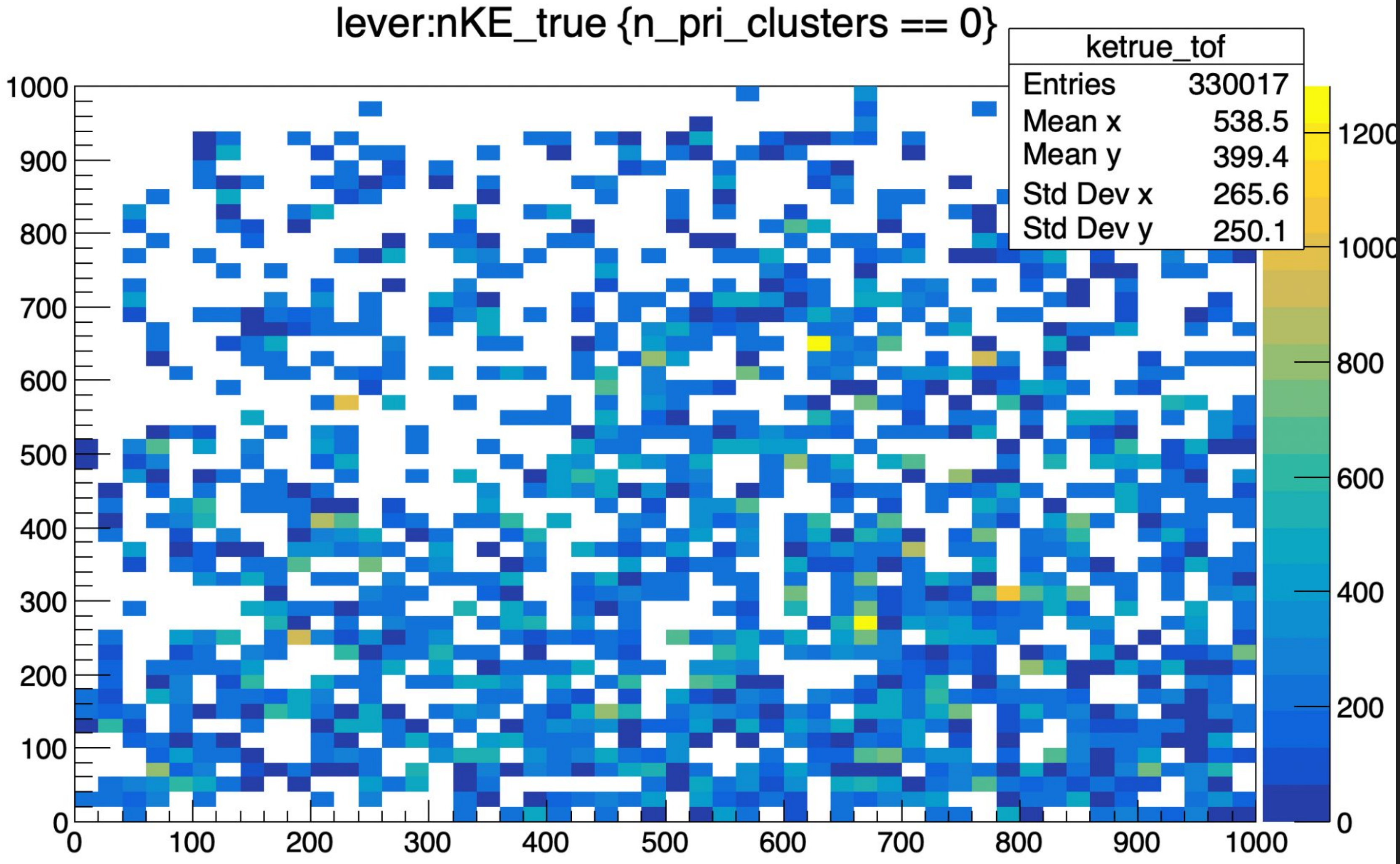


trk_pri_vtx[3]:nKE_true {n_pri_clusters == 0}
ketrue_tof
Entries 330017
Mean x 536.9
Mean y 2.039
Std Dev x 265.8
Std Dev y 1.419
Tof [ns]
KE true [MeV]



trk_pri_vtx[3]:nKE_reco {n_pri_clusters == 0}
ketrue_tof
Entries 330017
Mean x 403.3
Mean y 2.152
Std Dev x 246.7
Std Dev y 1.506
Curve is showing Tof as a function of KE. Values below the top curve are also on a curve but for a shorter lever arm. Top curve is a cut off of the maximum allowable lever arm.
0 100 200 300 400 500 600 700 800 900 1000
0 2 4 6 8 10 12 14 16 18 20
0 100 200 300 400 500 600


trk_pri_vtx[3]:nKE_true {n_pri_clusters == 0}
ketrue_tof
Entries 330017
Mean x 536.4
Mean y 2.053
Std Dev x 266
Std Dev y 1.461
Values above curve here are bad reconstruction of the Tof!
0
2
4
6
8
10
12
14
16
18
20
0
100
200
300
400
500
600
700
800
900
1000
0
200
400
600
800
1000
1200
1400
1600


lever:nKE_true {n_pri_clusters == 0}
ketrue_tof
Entries 330017
Mean x 538.5
Mean y 399.4
Std Dev x 265.6
Std Dev y 250.1
0
100
200
300
400
500
600
700
800
900
1000
1200

Why **Tof vs KE** shows a cut off and **Lever vs KE** doesn't show a cut off.

$$\gamma = \frac{1}{\sqrt{1-(L/c*t_{vert})^2}}$$

$$KE_{reco} = m_n c^2(\gamma - 1)$$

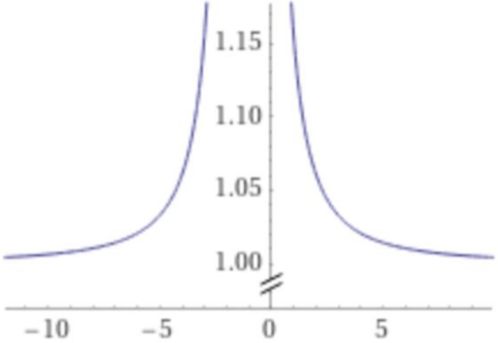
$$(KE_{reco}/m_n c^2 + 1)^2 = \frac{1}{1-(L/c*t_{vert})^2}$$

$$\sqrt{\frac{-1}{(KE_{reco}/m_n c^2+1)^2}+1} = (L/c*t_{vert})$$

Input

$$y = \frac{1}{\sqrt{1-\frac{1}{(x+1)^2}}}$$

Plots



(x from -11.9 to 9.9)

Why **Tof vs KE** shows a cut off and **Lever vs KE** doesn’t show a cut off.

$$\gamma = \frac{1}{\sqrt{1-(L/c*t_{vert})^2}}$$

$$KE_{reco} = m_n c^2(\gamma - 1)$$

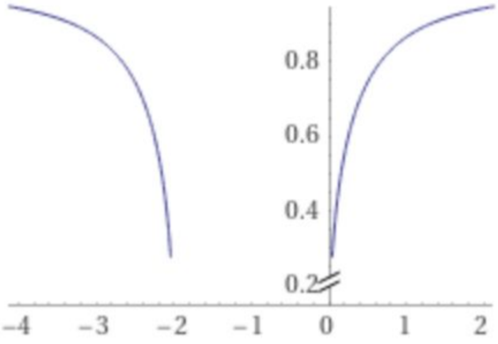
$$(KE_{reco}/m_n c^2 + 1)^2 = \frac{1}{1-(L/c*t_{vert})^2}$$

$$\sqrt{\frac{-1}{(KE_{reco}/m_n c^2+1)^2}+1} = (L/c*t_{vert})$$

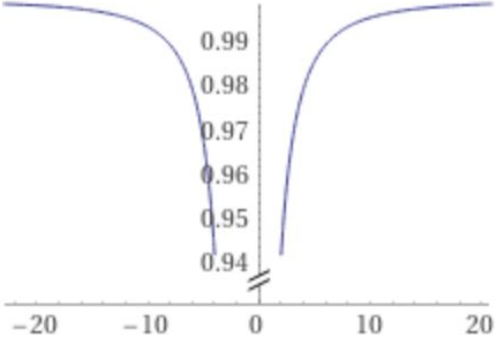
Input

$$y = \sqrt{1 - \frac{1}{(x+1)^2}}$$

Plots



(x from −4.1 to 2.1)

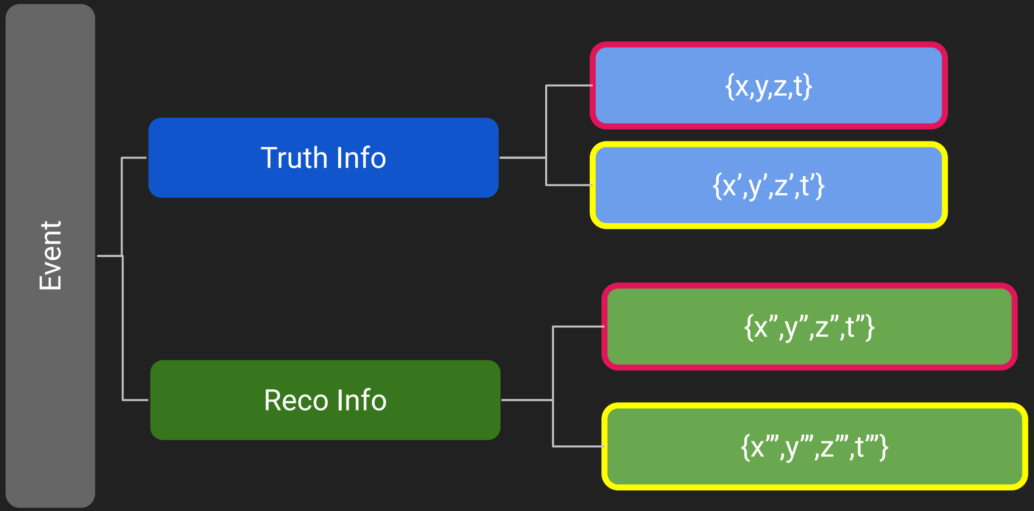


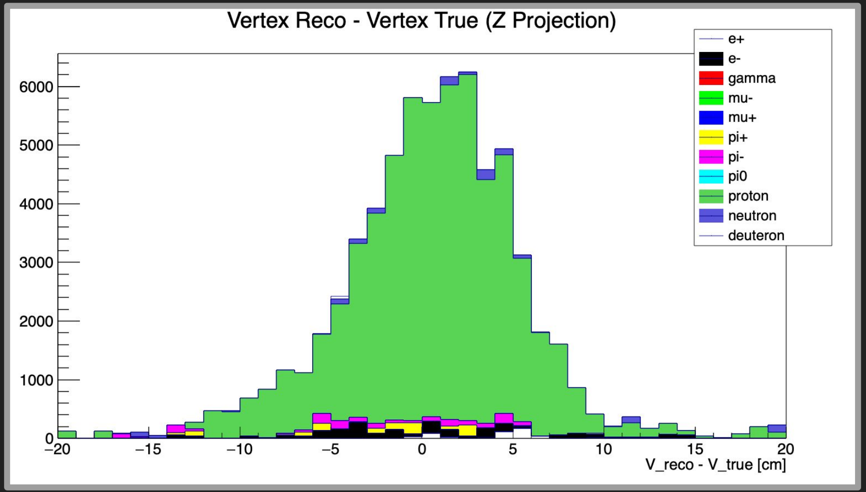
(x from −22.8 to 20.8)

Truth Particle Info

The truth information doesn’t know what will be reconstructed and what won’t.

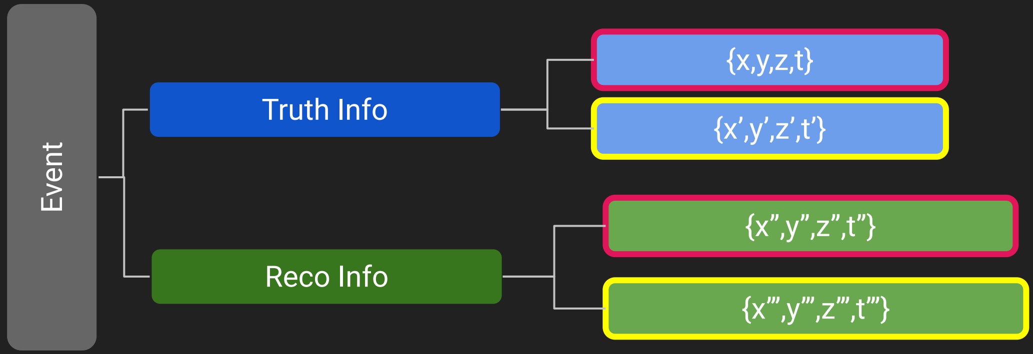
The way the true info and the reco info are associated are by the ND280 software comparing the true and reco events and taking the most likely pairings of reco and true info.

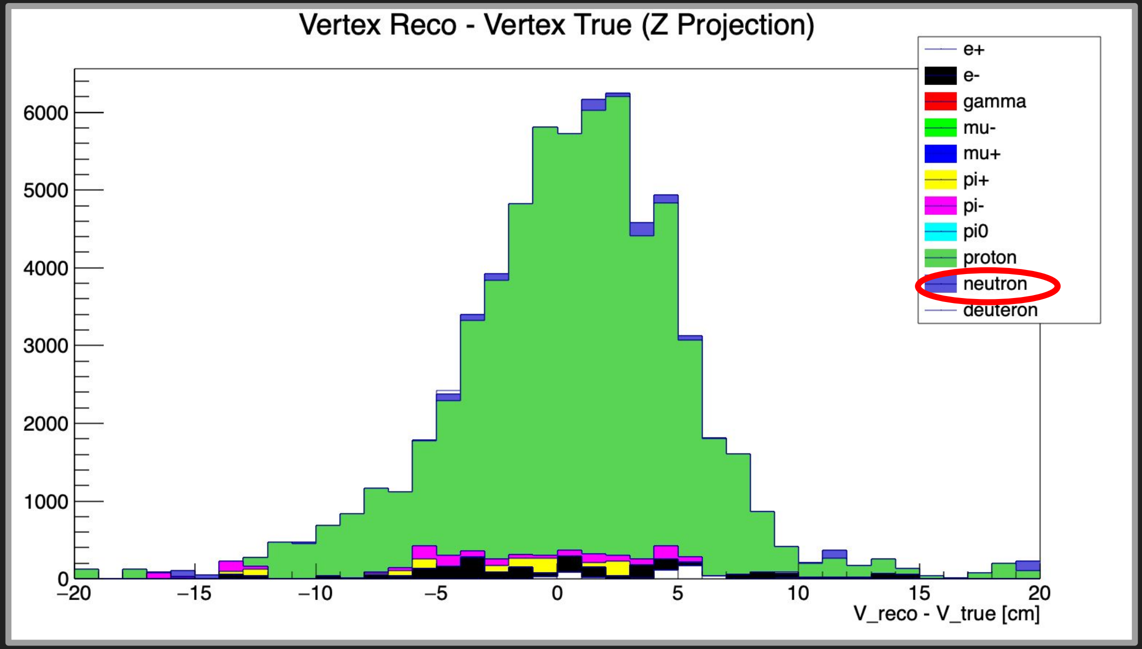




Truth Particle Info

This is how some of the true particle types end up being neutrons. Many neutrons are produced in these neutron particle gun events and it could be mistaken as the reconstructed track if it had similar parameters.





1 Getting the trigger time

The reconstructed hit time is a sum of the electronics and light simulation timing as well as the trigger time and the bunch time. The truth hit time has the event time relative to the neutron being created. The neutron creation time includes a bunch time because the particle gun simulation produces the neutrons in six bunches like a neutrino simulation.

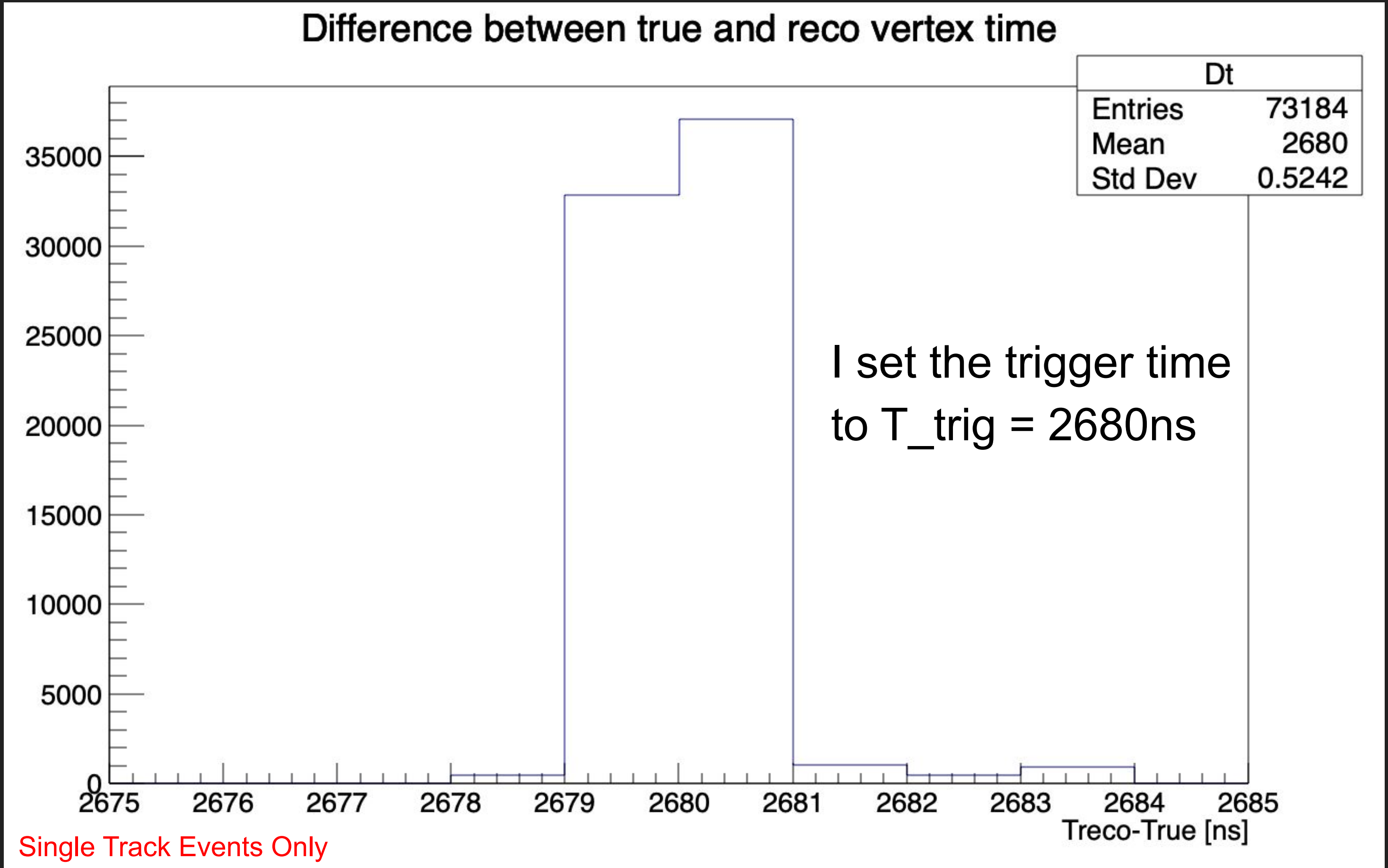
$$t_{reco} = t_{event} + t_{sim} + t_{trig} + t_{bunch}$$

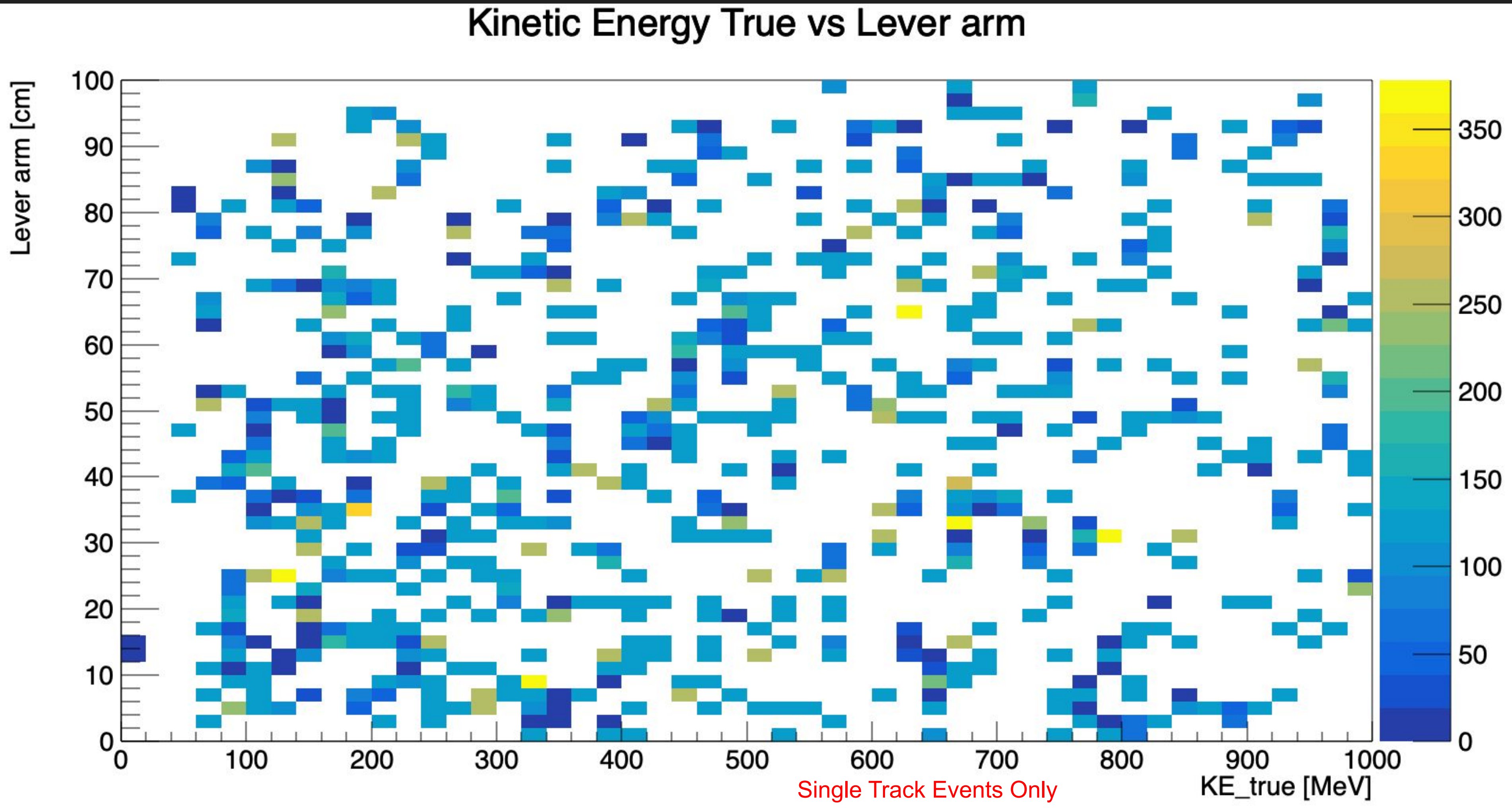
$$t_{true} = t_{event} + t_{bunch}$$

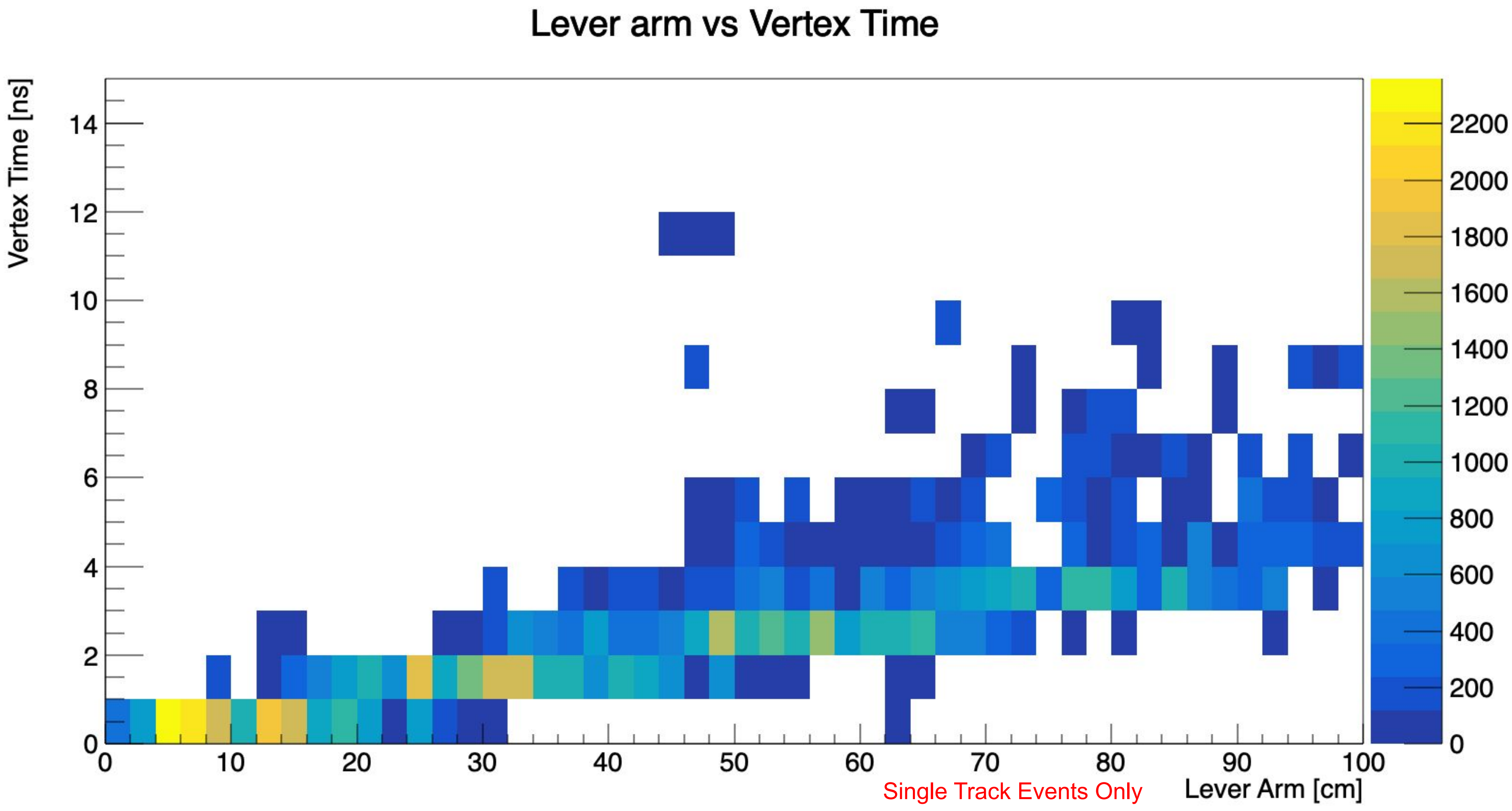
$$t_{reco} - t_{true} = t_{trig} + t_{sim}$$

What I did to get the trigger time is select single particle events, particle meaning track in the reconstruction, to not miss identify the vertex. Then take the vertex hit, the earliest hit in time, from that track. Then subtract the true time of the vertex hit from that particle and it left a distribution produced by the electronic and light simulation, as well as a shift due to the trigger.

Getting the trigger time




Kinetic Energy True vs Lever arm
Lever arm [cm]
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600
700
800
900
1000
KE_true [MeV]
0
50
100
150
200
250
300
350
Single Track Events Only



Lever arm vs Vertex Time
Vertex Time [ns]
Lever Arm [cm]
Single Track Events Only
0
2
4
6
8
10
12
14
0
10
20
30
40
50
60
70
80
90
100
0
200
400
600
800
1000
1200
1400
1600
1800
2000
2200