NEUTRON PRODUCTION IN NEUTRINO-NUCLEUS INTERACTIONS WITH T2K

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XXI International Workshop on Neutrino Telescopes

DFG Deutsche Forschungsgemeinschaft

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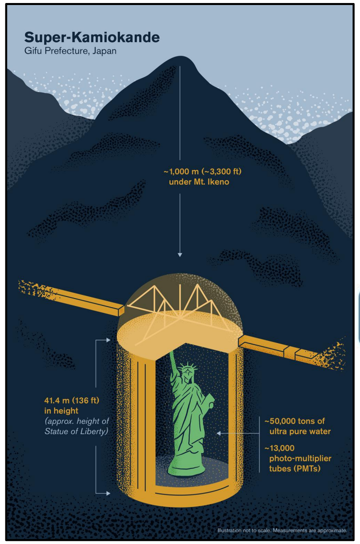
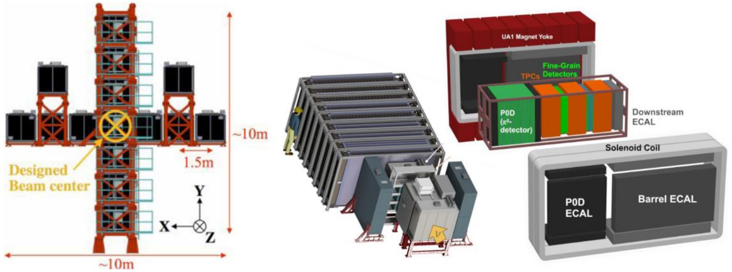
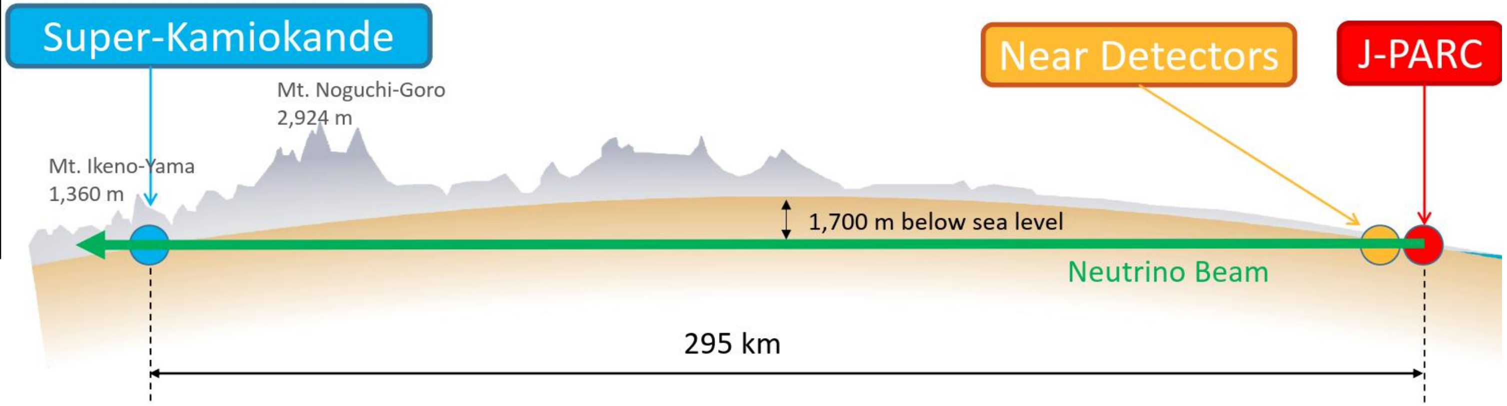
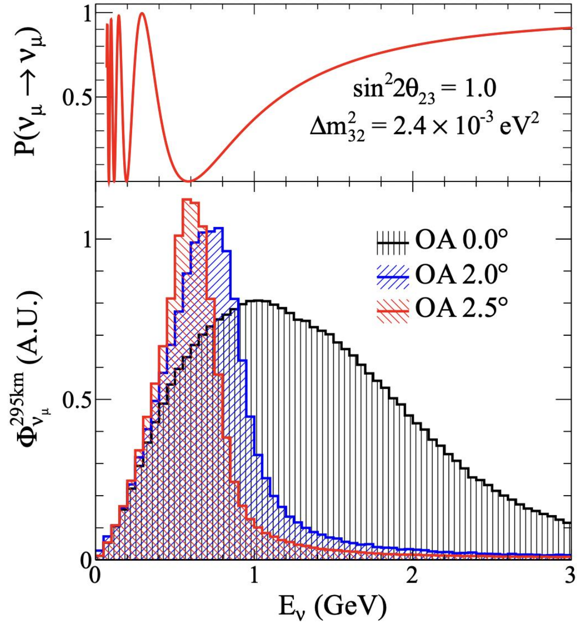
The T2K Experiment







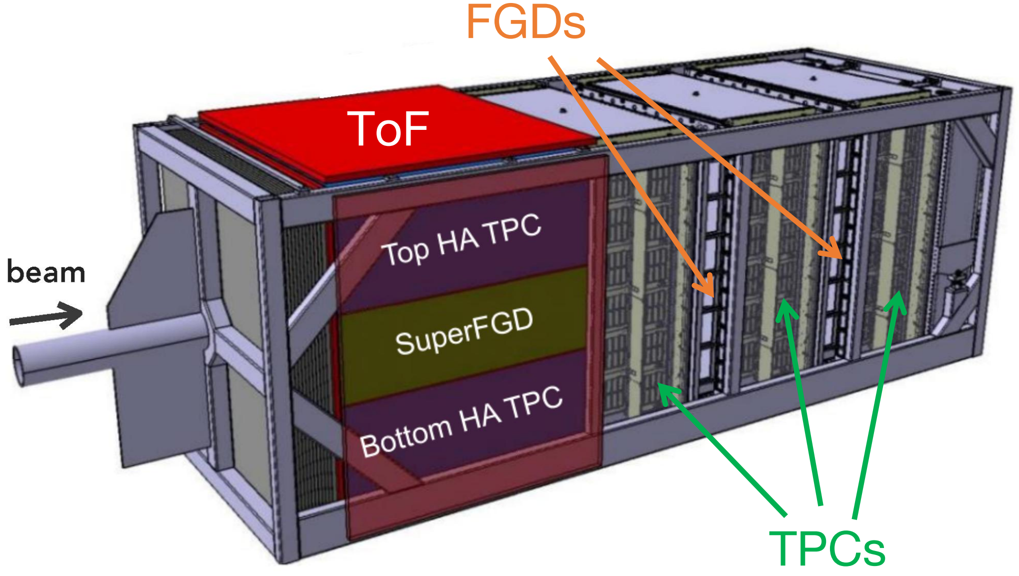


Phys.Rev.D 87,012001 (2013)

- Long-baseline experiment (295 km)
- Near detectors (ND280, INGRID, WAGASCI-BabyMIND) at 280m from J-PARC
- E_ν peaks at 0.6 GeV at ND280 (2.5° off-axis)

Related Talks: S. King, L. Machado

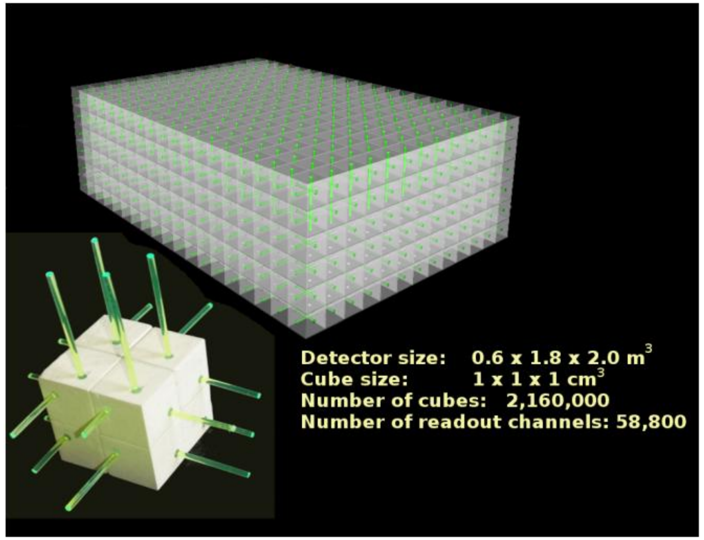
Near Detector ND280 Upgrade



- HA-TPC does the identification and reconstruction of particles traveling at high angles.

- TOF, along with SFGD, can differentiate between incoming and outgoing particles

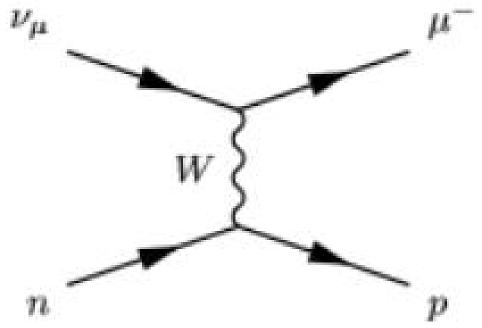
- Super-FGD is made of ~ 2 million scintillator cubes of size 1 cm which provide sub-ns timing resolution.

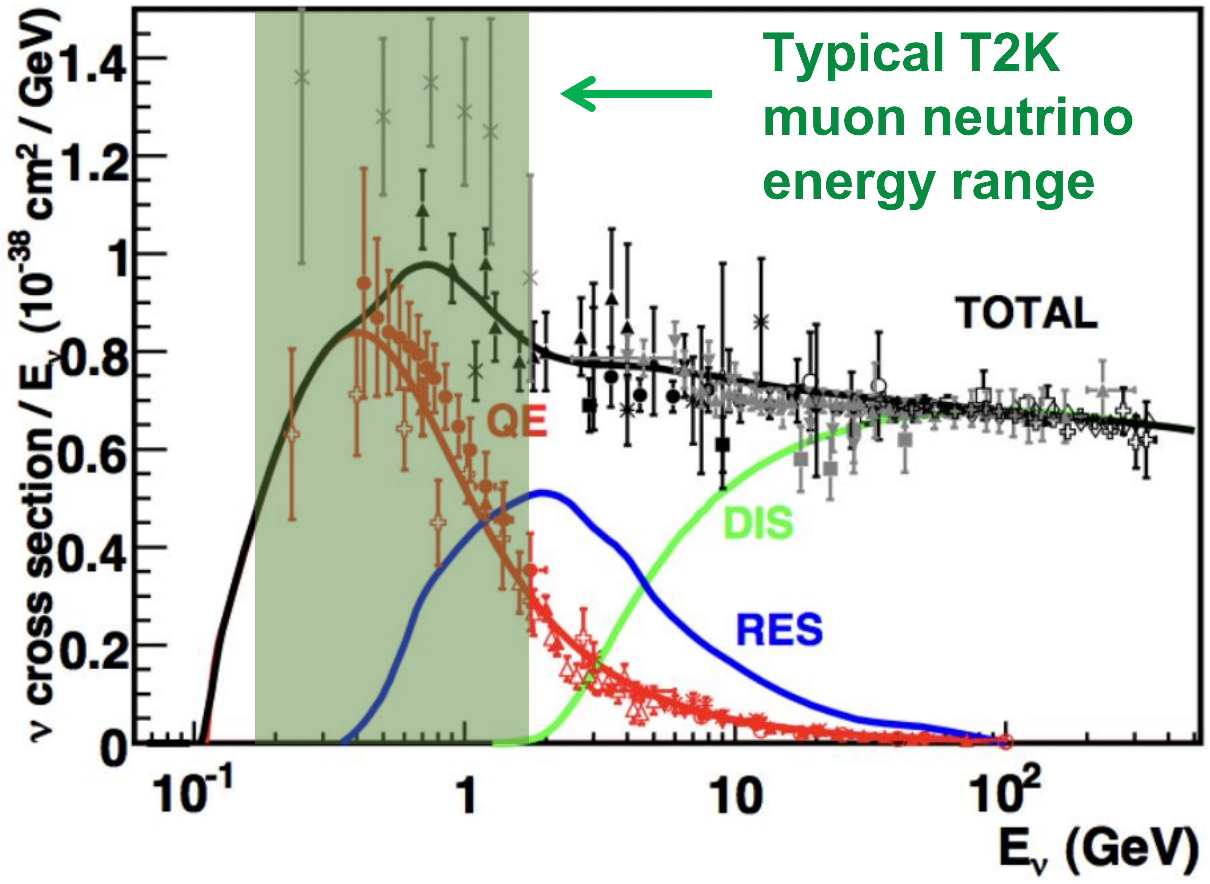


Related Talks: G. Reina, M. Feltre, W. Okinaga-san

Neutrino-Nucleus Interactions

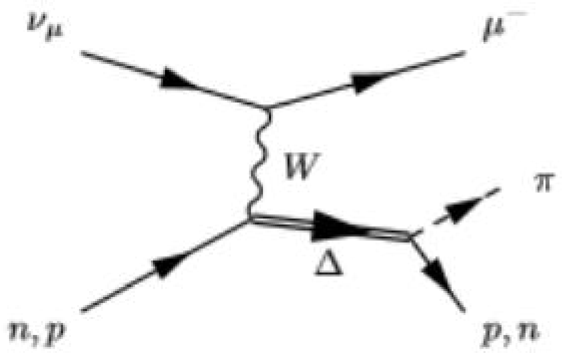
Quasi-Elastic Scattering (CCQE)





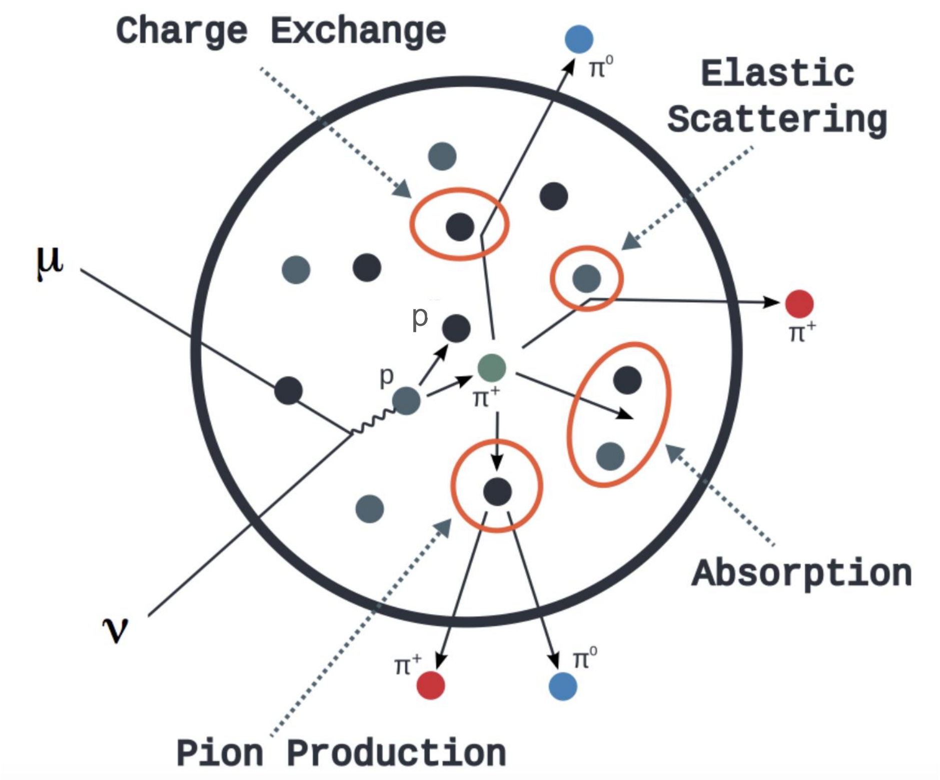
https://doi.org/10.2172/1042577

Delta Resonance



Related Talk: E. Sandford

Final State Interactions (FSI)



Picture Credits: T. Golan

- Particles produced after neutrino-nucleus interaction can undergo FSI.
- This makes identification of specific interactions in detector difficult.
- Identifying topology is a better choice as it reduces model dependence.

Some topologies:

CC0π, CC1π, CC-multi π, **CC0πNn**

Interactions in CC0πNn Topology

CCQE ($\nu_\mu n \rightarrow \mu^- p$) : With FSI

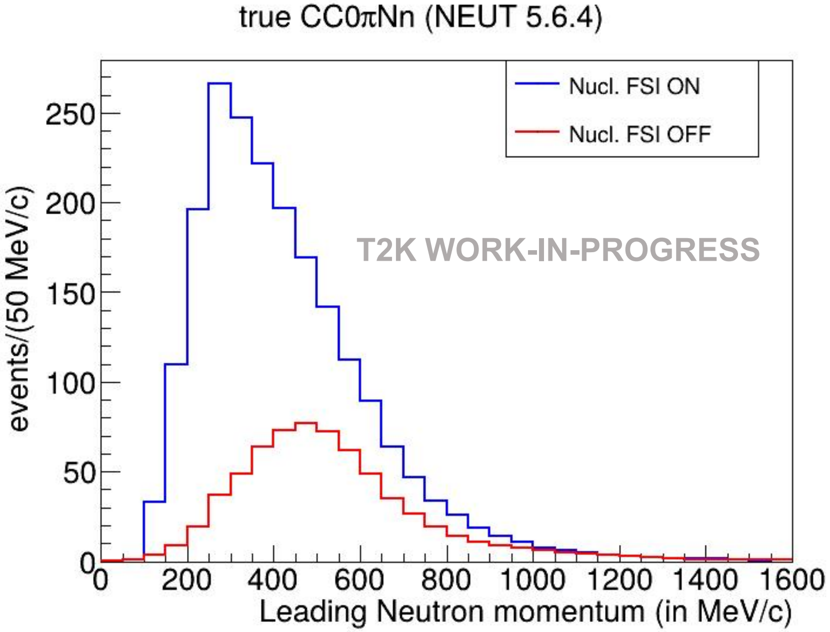
2p2h ($\nu_\mu nn \rightarrow \mu^- np$) : With or without FSI

($\nu_\mu np \rightarrow \mu^- pp$) : With FSI

Delta resonance : With or without FSI

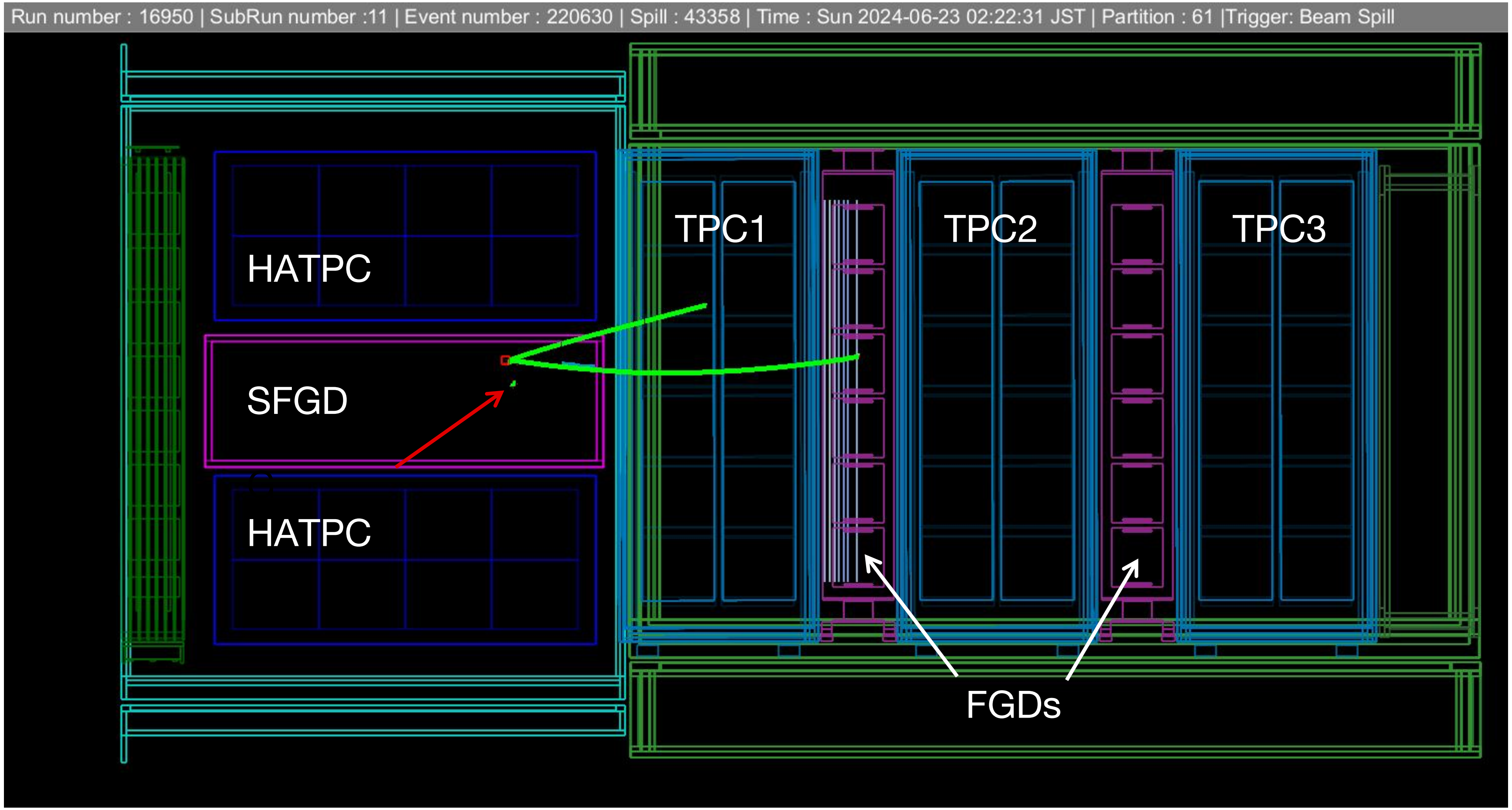
Type of interaction	% in CC0πNn (before FSI*)	% in CC0πNn (after FSI*)
CCQE	0% (0)	54.80% (1119)
2p2h	36.08% (245)	22.82% (466)
Delta res.	59.65% (405)	21.11% (431)
Others	4.27% (29)	1.27% (26)

*FSI turned ON or OFF here is Nucleon FSI



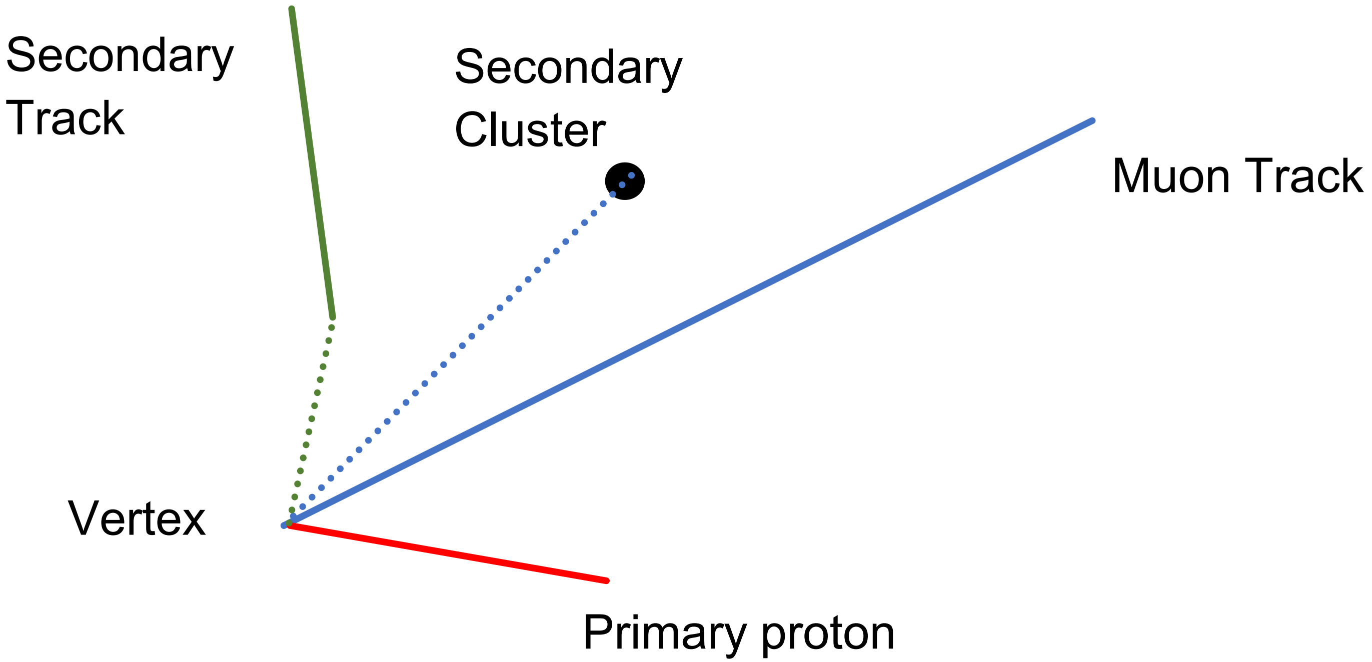
- Large increase in events due to CCQE and 2p2h undergoing FSI
- CC0πNn topology can be used to test FSI models

Neutron candidate in an actual event



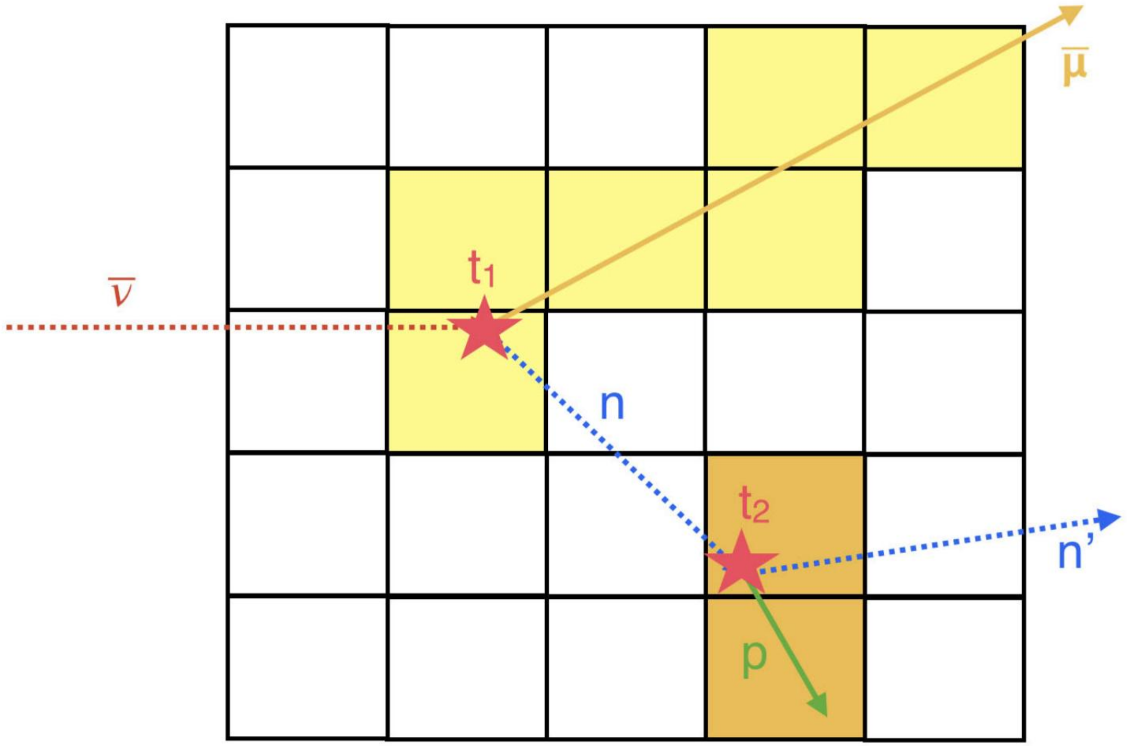
One neutron candidate in this event

Selection of CC0π events



- One muon track
- No pion track
- Any number of proton tracks

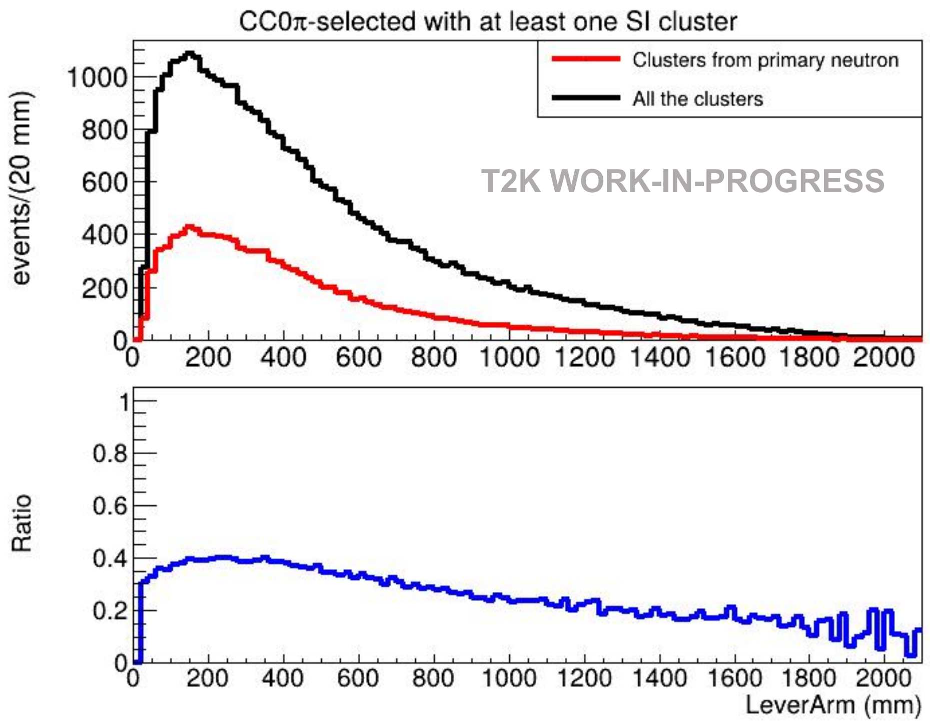
Reconstructing a neutron

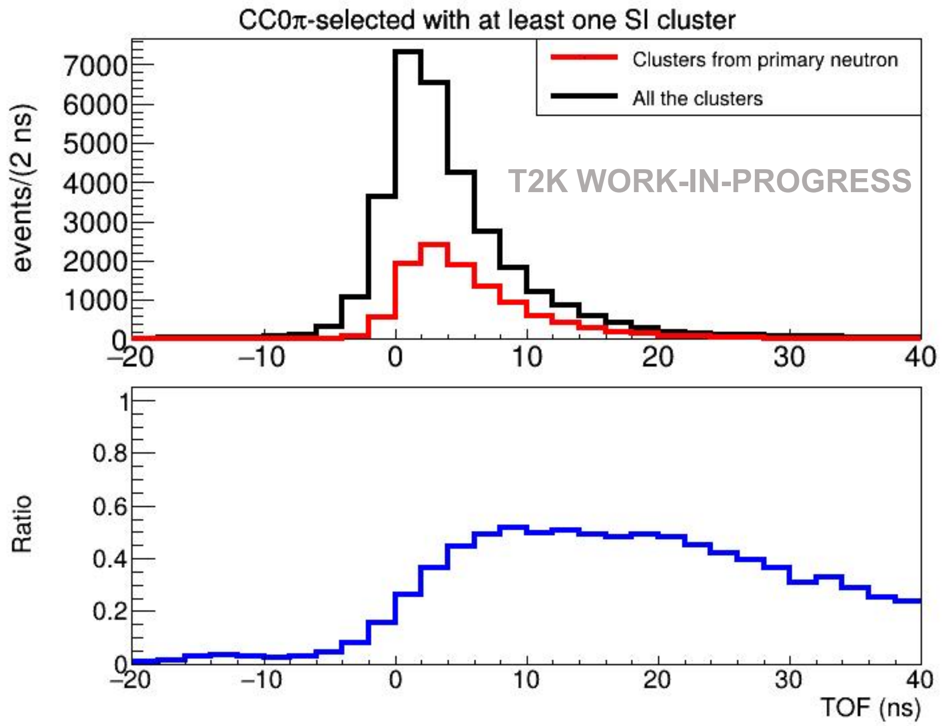


Phys. Rev. D 101, 092003 (2020)

- Neutrons deposit energy away from the vertex.
- Lever arm and Time-of-flight are tools to identify a neutron and reconstruct its energy.

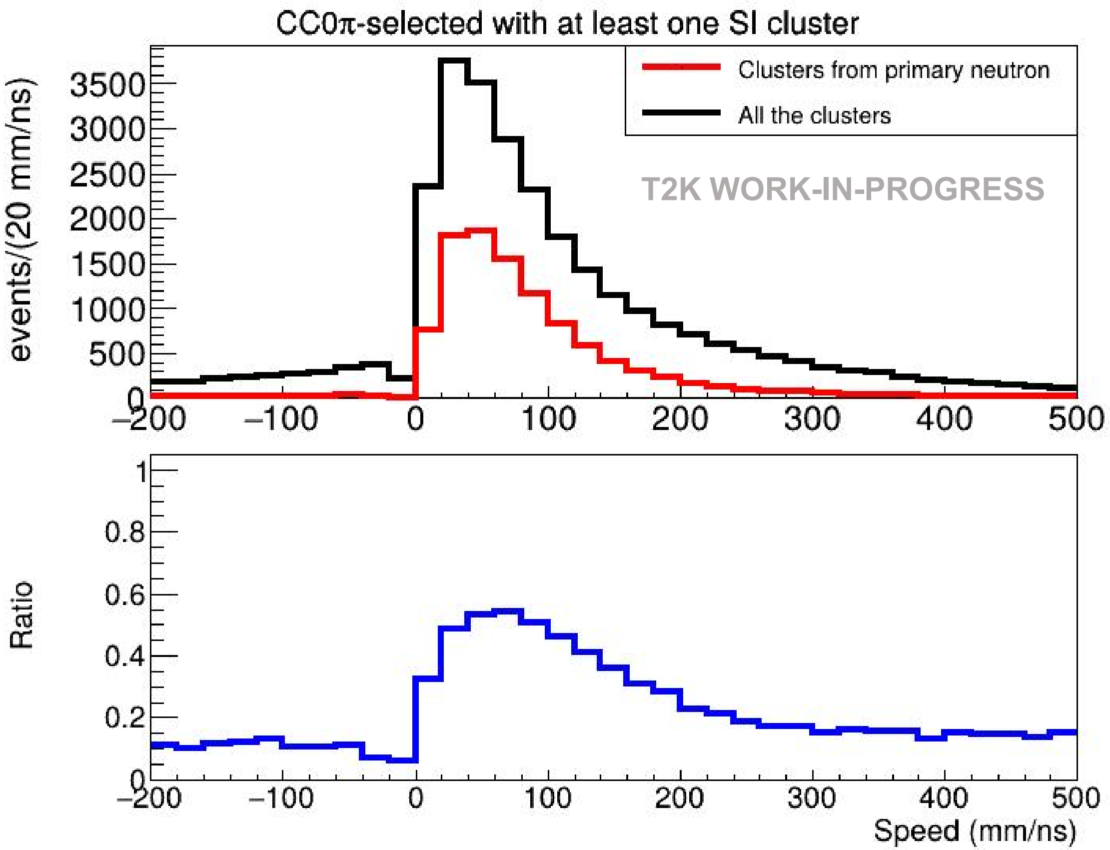
CC0π pre-selected with secondary clusters

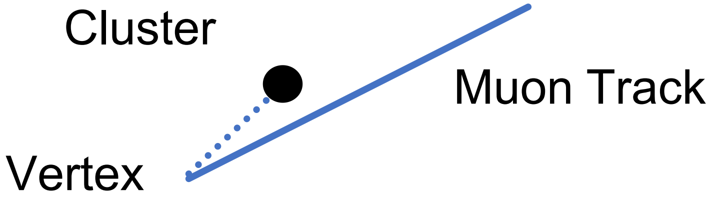




- Neutron (and background) cluster distribution peaks around 15 cm from the neutrino vertex.
- Time-of-flight can be negative due to timing resolution of SFGD. Applying a cut on the distribution, such as 0 < TOF (ns) < 20, can provide a pure sample of neutrons.

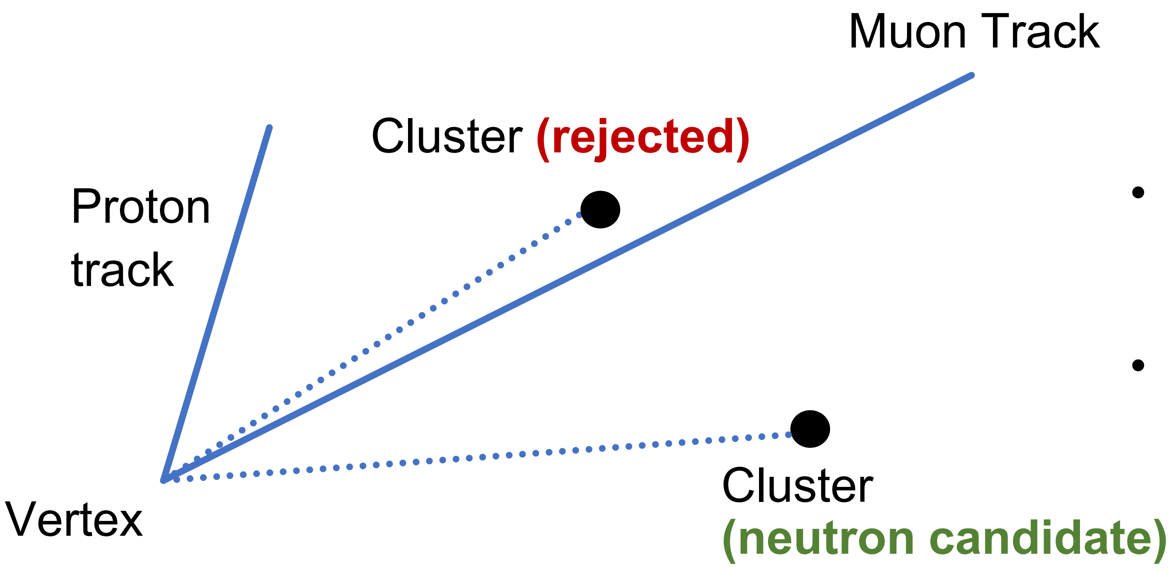
CC0π pre-selected with secondary clusters
(speed)





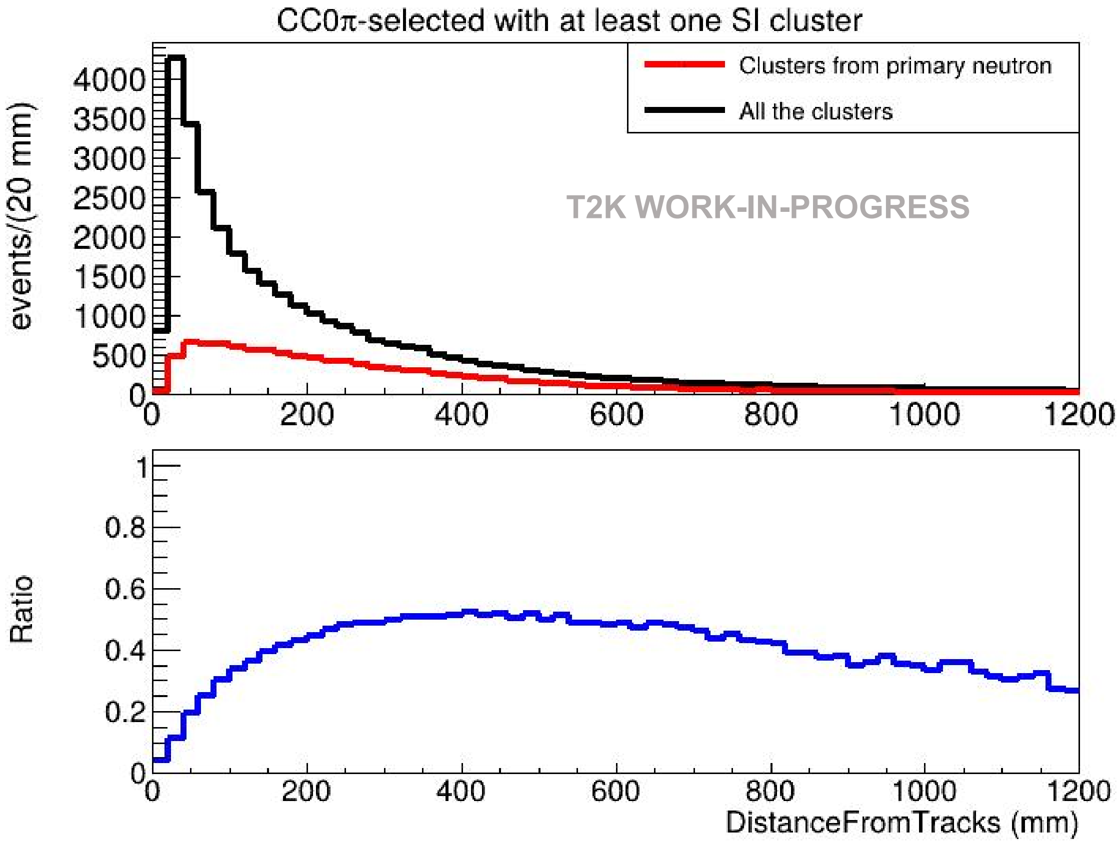
- Speed = Lever Arm / Time-of-Flight
- Reconstructed speed would not be more than 300 mm/ns (speed of light) if the detectors were perfect.
- Neutrons are heavy particles with low momentum, so speed peaks at around 20% of the speed of light (~200 MeV/c momentum) and significantly drops around 67% of the speed of light (~850 MeV/c momentum) for T2K flux.

Minimum distance from all tracks in SFGD



- Clusters close to any track could be produced by that track and not primary neutrons.
- They should be rejected as neutron candidates.

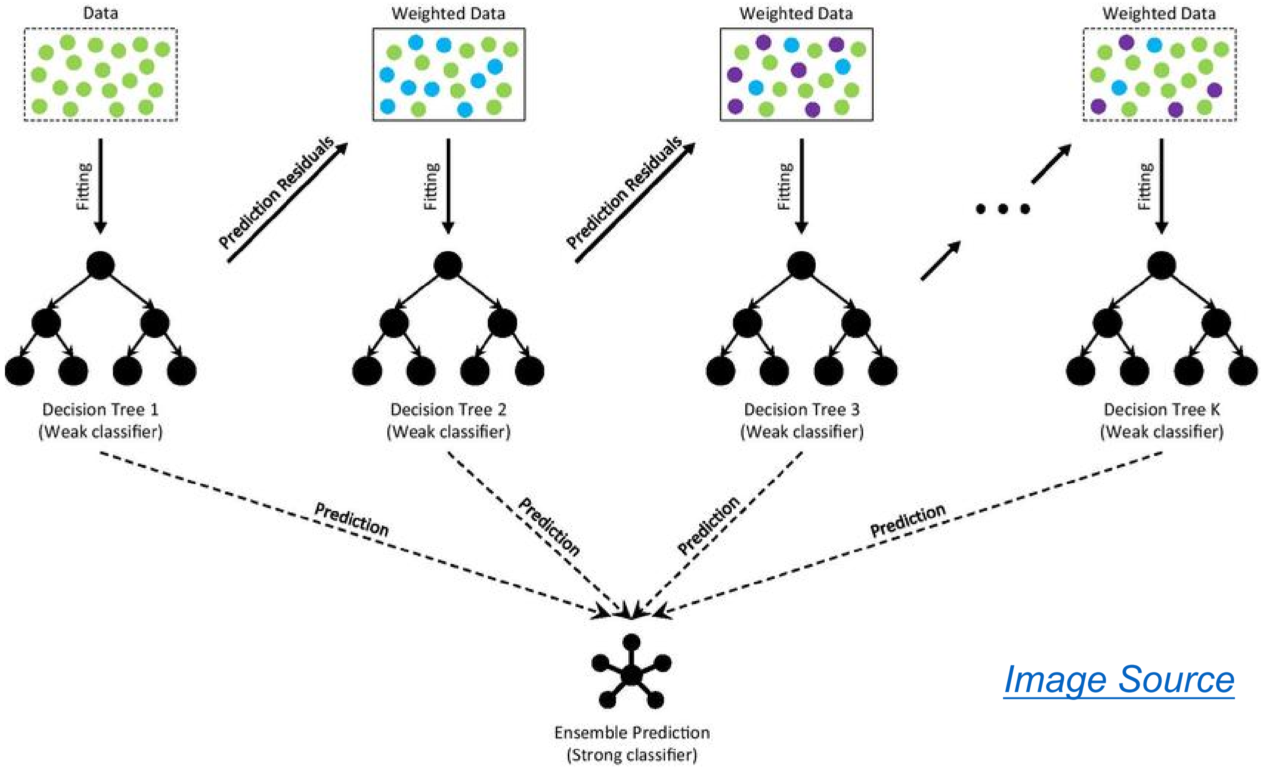
CC0π pre-selected with secondary clusters (minimum distance from all tracks)



- Background distribution peaks for clusters close to other tracks (~5 cm) and leads to impure neutron sample.
- These are primarily due to muon hits not used in track reconstruction and delta electrons produced by primary muons.

Boosted Decision Trees (BDTs)

- Training: Trees are trained sequentially, and each new tree focuses on correcting the errors made by the previous one.



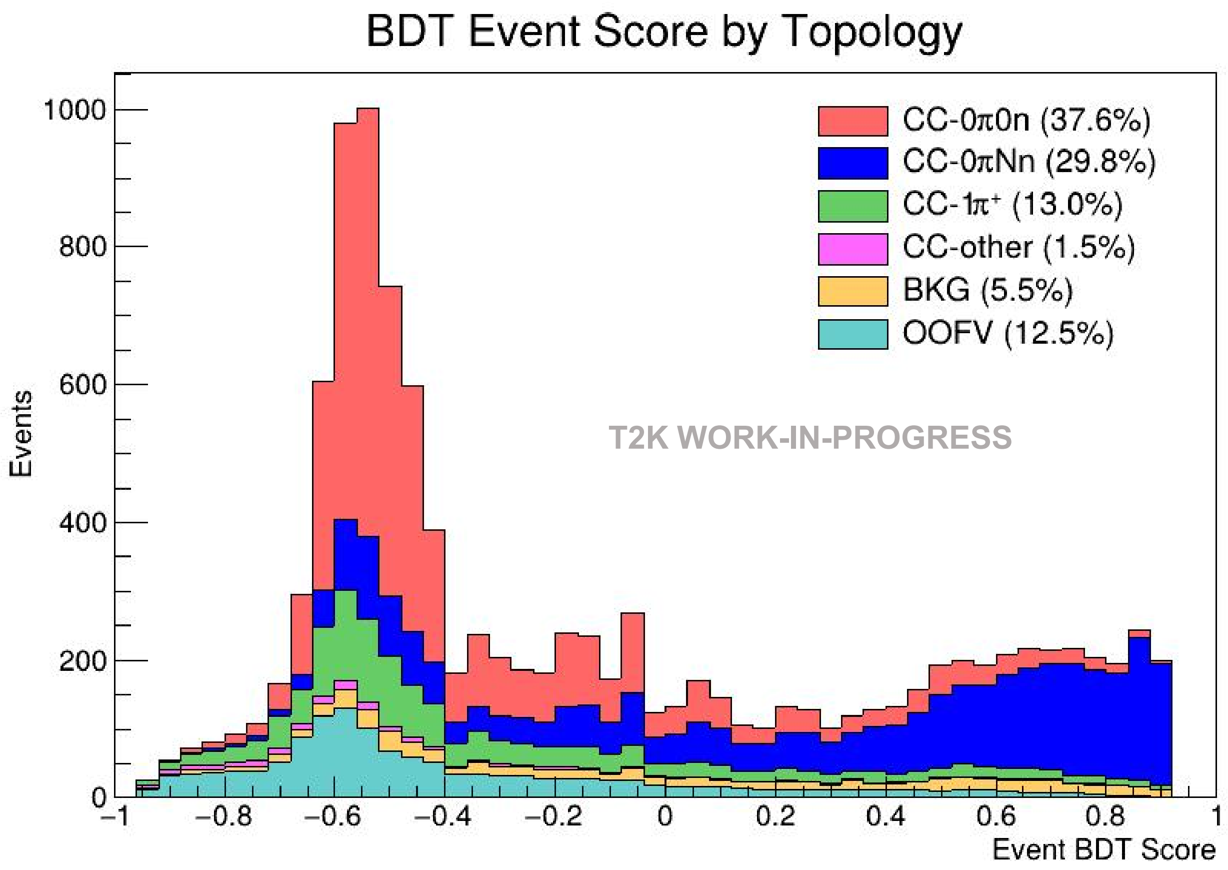
Gradient BDT

Image Source

BDT to Select CC0πNn events

- BDT1: Cluster training (Signal: clusters from neutrons)
- BDT2: Track training (Signal: tracks from neutrons)
- BDT3: Event level to find CC0πNn events (takes inputs from BDT1 and BDT2)

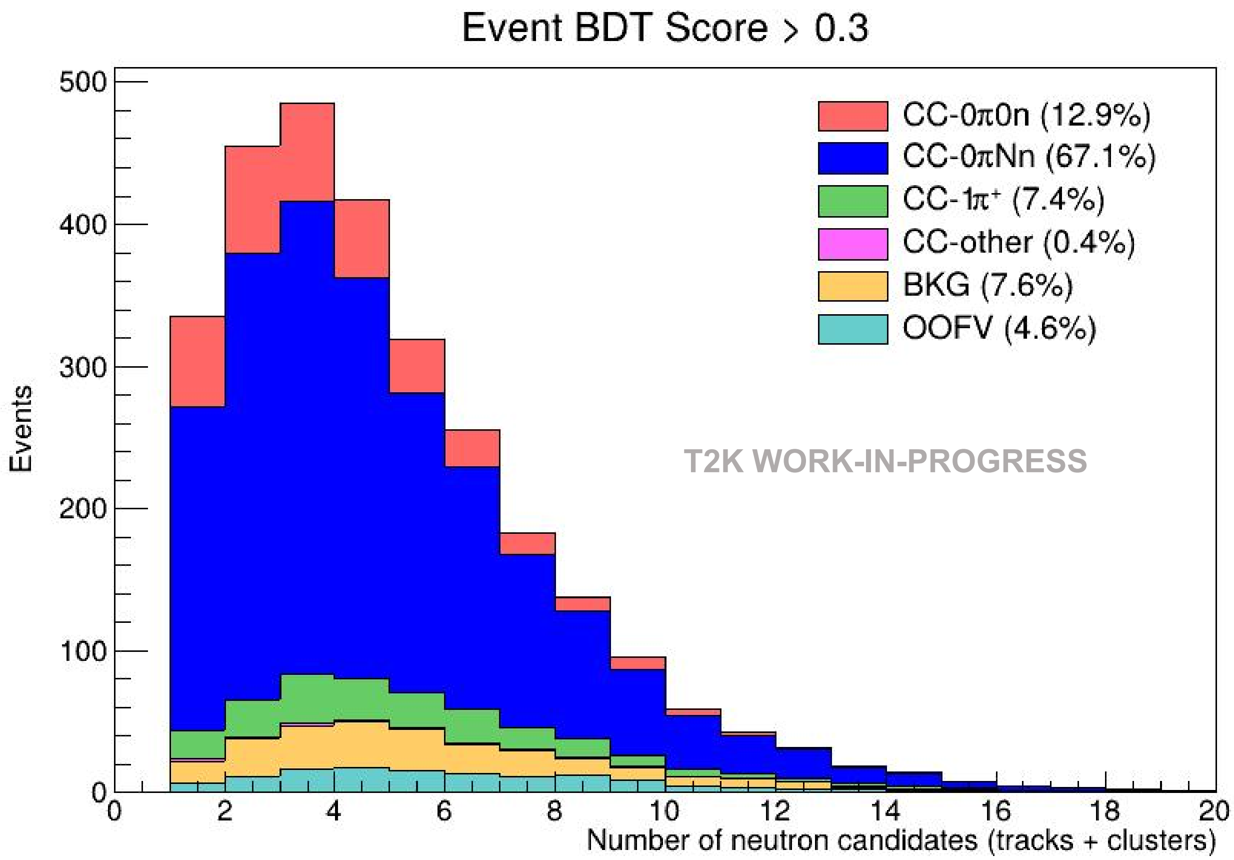
Event BDT Score



Initial purity of CC0πNn: ~ 30%

With high BDT scores, ~ 90% purity is achievable.

Number of neutron candidates



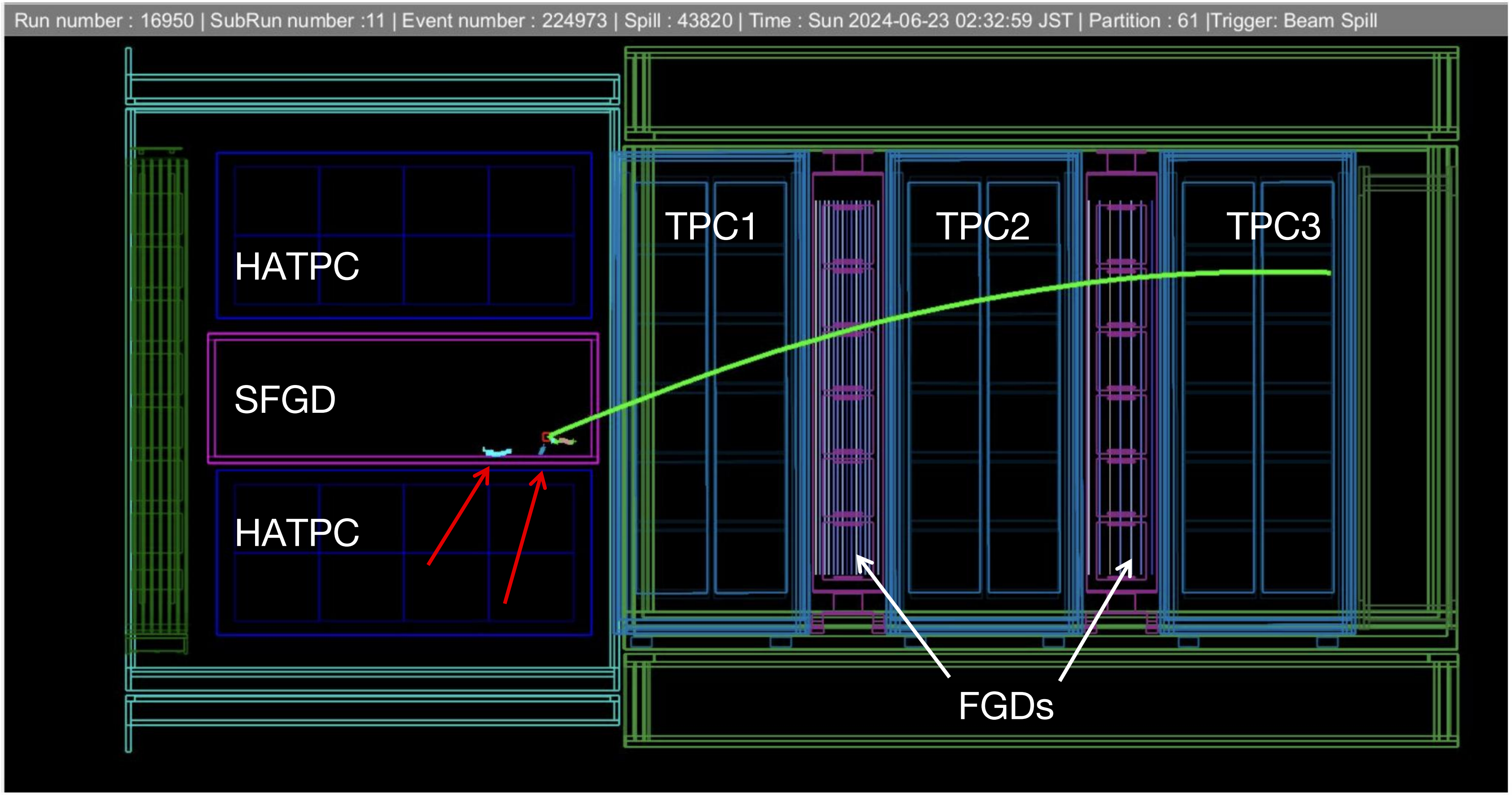
Distribution of neutron candidates (tracks + clusters) peaks around 2 - 4 neutron candidates.

Summary

- ND280 upgrade has made **reconstruction of particles with shorter tracks** or smaller energies even better.
- CC0πNn topology can be instrumental in **testing FSI models.**
- Neutrons leave an energy deposit in the form of a track or a cluster **away from the vertex**.
- To identify neutron events, BDTs are trained and they give **high signal purity**.
- Currently, work is in progress to **develop systematics** and **study model dependence** in CC0πNn selection.

Thanks for your attention!

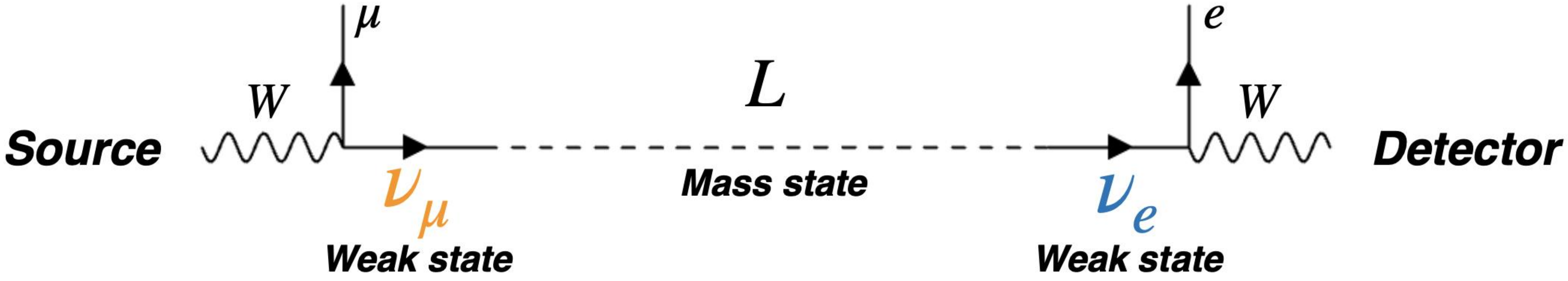
Neutron candidate in an actual event



Two neutron candidates in this event

Backup

Neutrino Oscillations

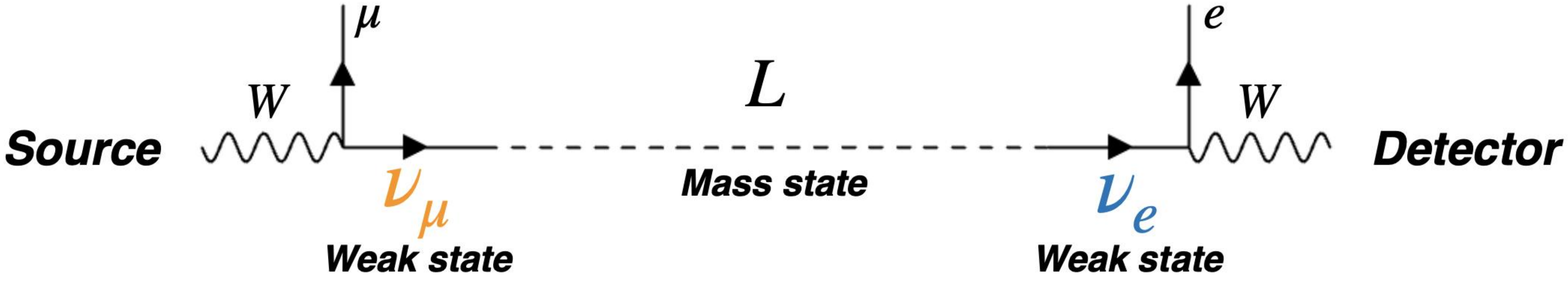


- Neutrinos produced in a specific flavor state (ν_μ) with energy E
- After traveling a distance L,

  ν_μ decrease in number $\Longrightarrow$ ν_μ disappearance
  ν_e increase in number $\Longrightarrow$ ν_e appearance

- Sensitivity to maximum oscillation depends on L/E

Neutrino Oscillations



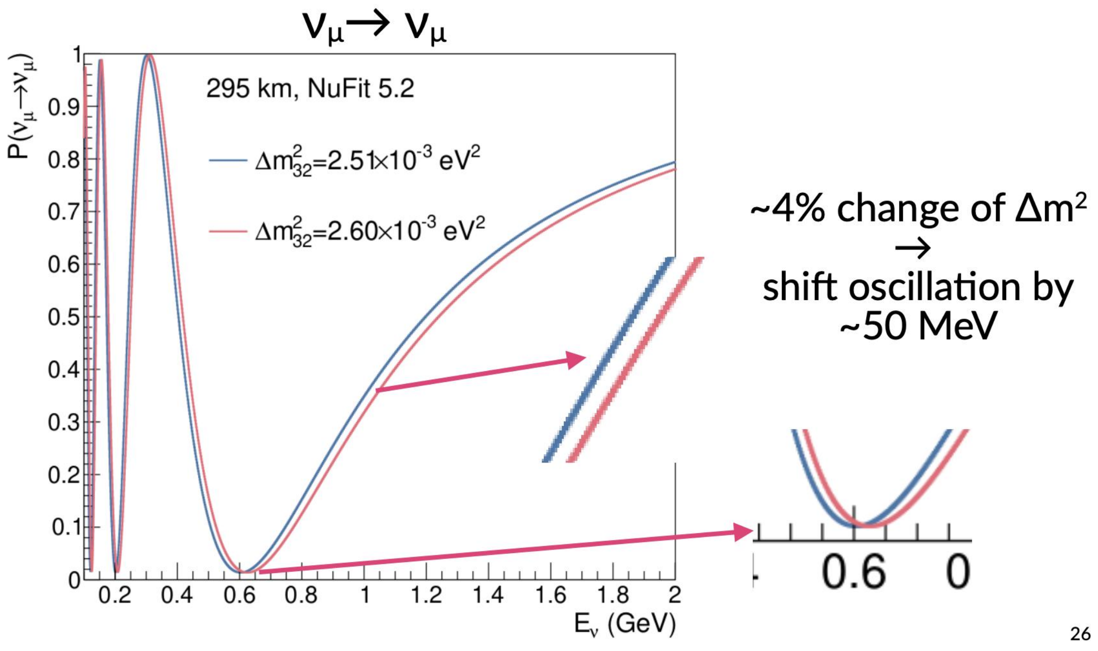
- Neutrinos produced in a specific flavor state (ν_μ) with energy E

- Oscillation probability depends on:
  - Neutrino energy — **Need to know**
  - Travelling distance ("baseline") — **Known**
  - PMNS mixing parameters
  - Difference between mass states — **What is measured**

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Parameters in PMNS matrix
$(\theta_{23}, \theta_{13}, \theta_{12}, \delta_{CP})$

Neutrino Energy as Uncertainty



[C. Wret, NuSTEC2024](#)

- For precise measurement of oscillation parameters, neutrino energy must be well-reconstructed.
- One of the leading sources of uncertainty in neutrino energy reconstruction are neutrons (calorimetric) and interaction models (kinematic).
- They have a high chance of escaping the detector without depositing any energy, hence, creating a problem in reconstructing neutrino energy.

PONTECORVO- MAKI-NAKAGAWA-SAKATA (PMNS) MATRIX

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} \text{PMNS} \\ \text{matrix} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$\begin{aligned} U &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} P \\ &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\rm CP}} \\ -s_{12}c_{23} - c_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{\rm CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & -c_{12}s_{23} - s_{12}s_{13}c_{23}e^{i\delta_{\rm CP}} & c_{13}c_{23} \end{pmatrix} P\,. \end{aligned}$$

- PMNS matrix describes mixing between flavour states and mass states
- Six parameters in PMNS matrix
  $(\boldsymbol{\theta_{23}}, \boldsymbol{\theta_{13}}, \boldsymbol{\delta_{CP}}, \theta_{12}, \alpha_1, \alpha_2)$

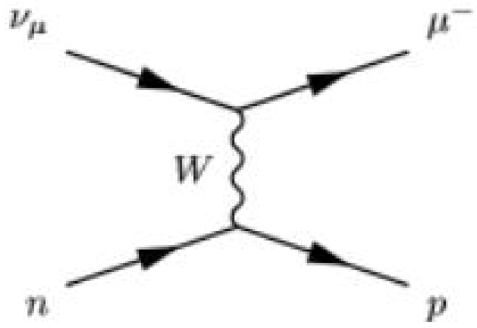
T2K is sensitive to these three parameters

$$P_{\rm Majorana} = \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

- CP phase (or "Dirac phase") δ_{CP}: a measure of asymmetry between neutrino and antineutrino oscillations
- Majorana phase (α_1, α_2): Plays a role in neutrinoless double beta decay but not in neutrino oscillations

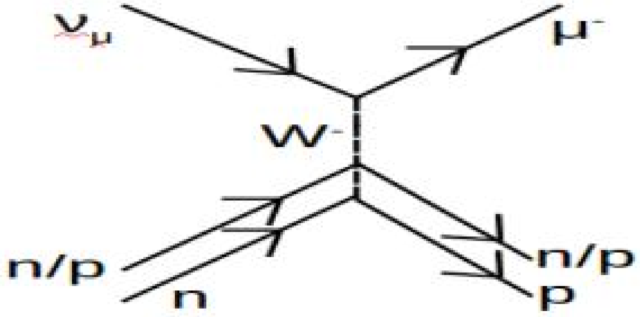
NEUTRINO-NUCLEUS INTERACTIONS

Quasi-Elastic Scattering (CCQE)



$$\nu_\mu n \rightarrow \mu^- p$$

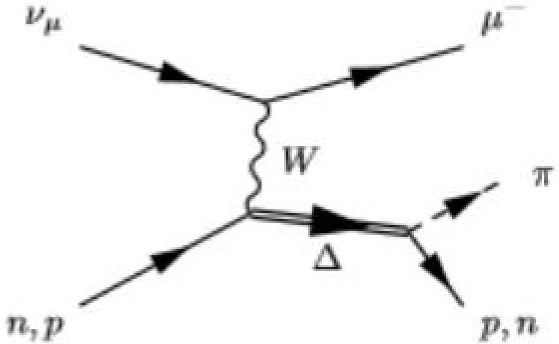
Two-particle two-hole process (2p2h)



$$\nu_\mu n n \rightarrow \mu^- n p$$

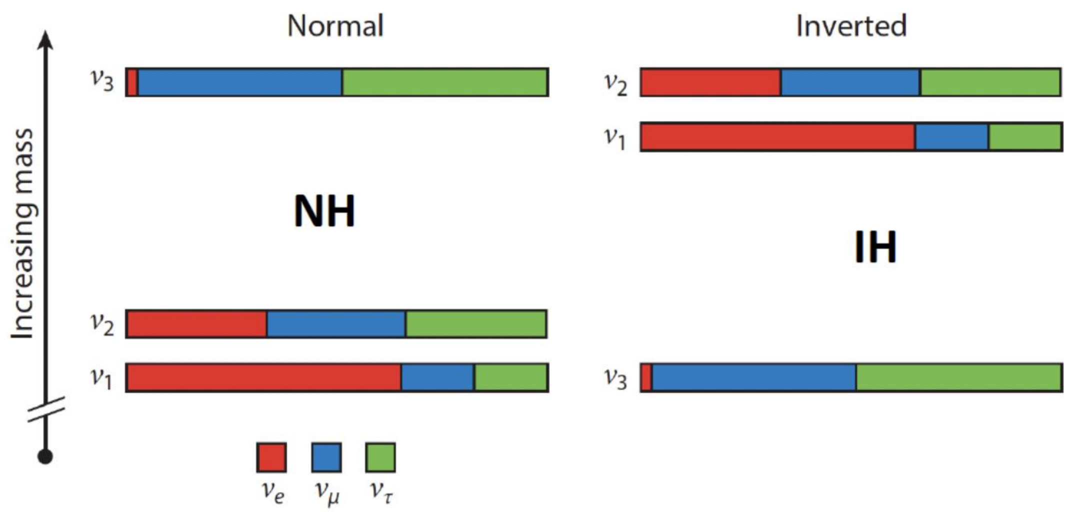
$$\nu_\mu n p \rightarrow \mu^- p p$$

Delta Resonance



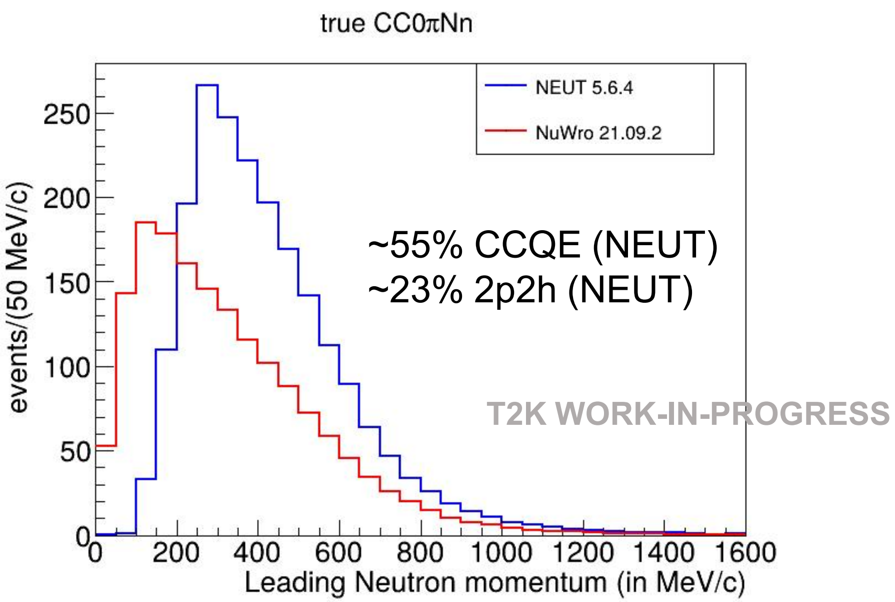
$$\nu_\mu n \rightarrow \mu^- \Delta^+ \rightarrow \mu^- \pi^+ n$$
$$\rightarrow \mu^- \pi^0 p$$
$$\nu_\mu p \rightarrow \mu^- \Delta^{++} \rightarrow \mu^- \pi^+ p$$

Neutrino Mass Ordering



https://arxiv.org/pdf/1610.05533.pdf

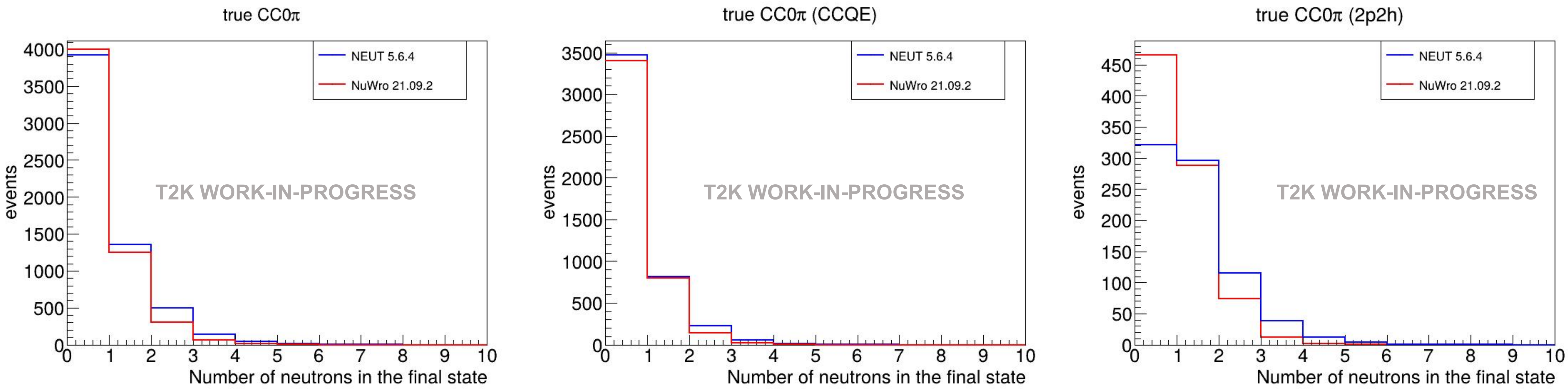
Comparison between NEUT and NuWro



- All the CCQE events enter this topology through FSI only.

- This topology can differentiate between FSI models in NEUT and NuWro using T2K data.

Neutron Multiplicity in NEUT and NuWro



- NEUT 5.6.4 and NuWro 21.09.2 use the same 2p2h model but the fraction pp/np is different between the two which has an impact on neutron multiplicity.

Event Rate Calculation

Number of ν_e events at Super-Kamiokande

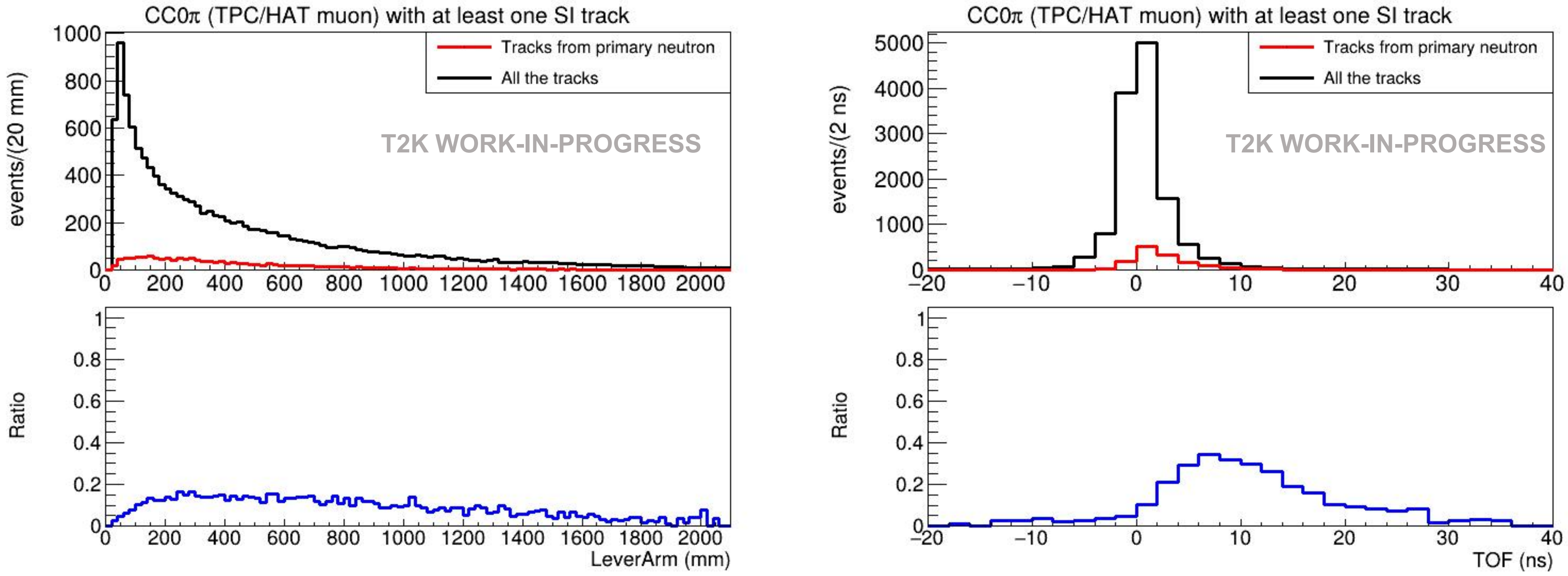
$$N(E_{reco}) = \int dE_{true} P(\nu_\mu \rightarrow \nu_e)(E_{true}) \sigma(E_{true}) \Phi(E_{true}) S(E_{true}, E_{reco})\, \epsilon(E_{true})$$

$N(E_\nu)$ = Event rate
$P(\nu_\mu \rightarrow \nu_e)(E_\nu)$ = Oscillation probability
$\sigma(E_\nu)$ = Interaction cross-section
$\Phi(E_\nu)$ = Neutrino flux
$S(E_{true}, E_{reco})$ = Smearing matrix
$\epsilon(E_\nu)$ = Detector efficiency

Reconstructed energy can be different from true energy

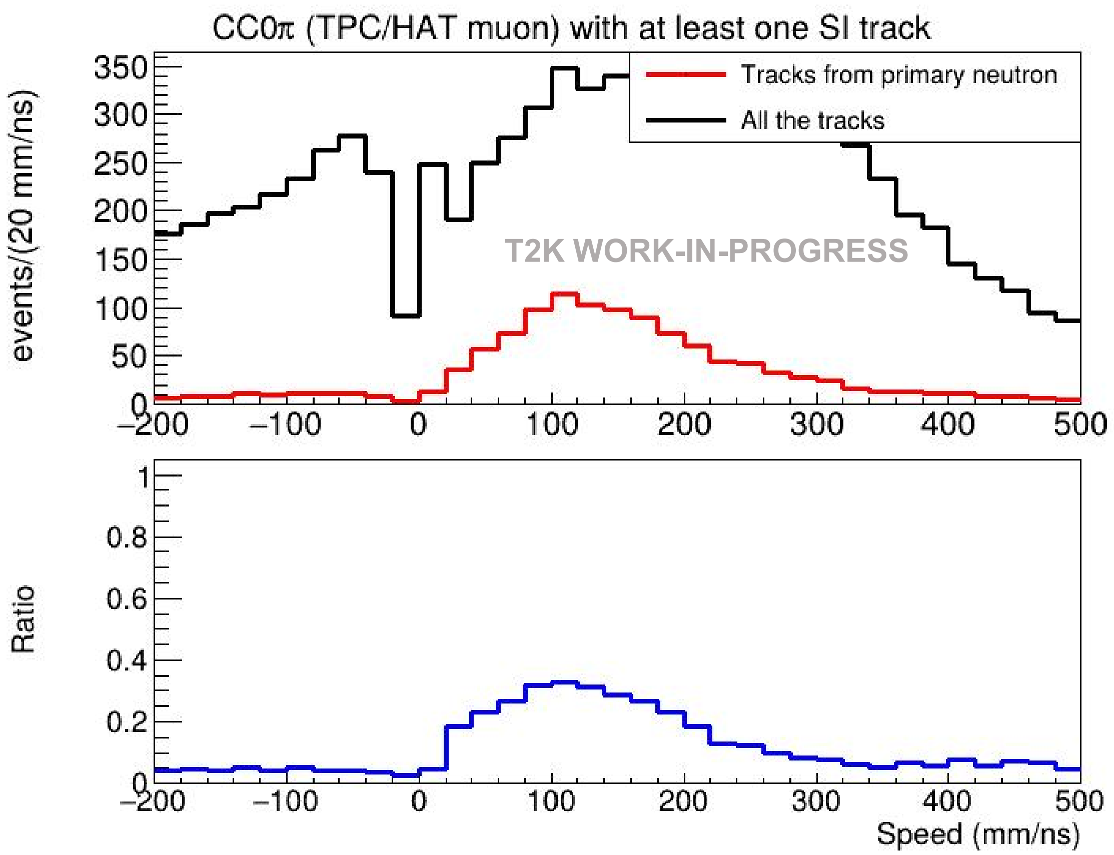
Neutrino-nucleus interaction models

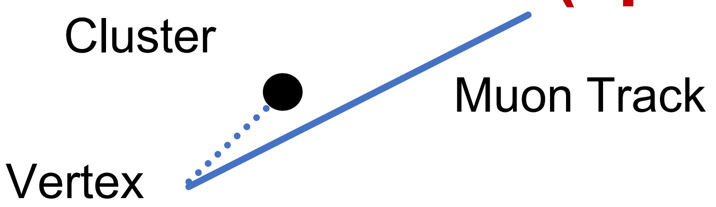
CC0π pre-selected with secondary tracks



- Neutron (and background) cluster distribution peaks around 50-60 cm from the neutrino vertex.
- Time-of-flight can be negative due to timing resolution of SFGD. Applying a cut on the distribution, such as 0 < TOF (ns) < 10, can provide a pure sample of neutrons.

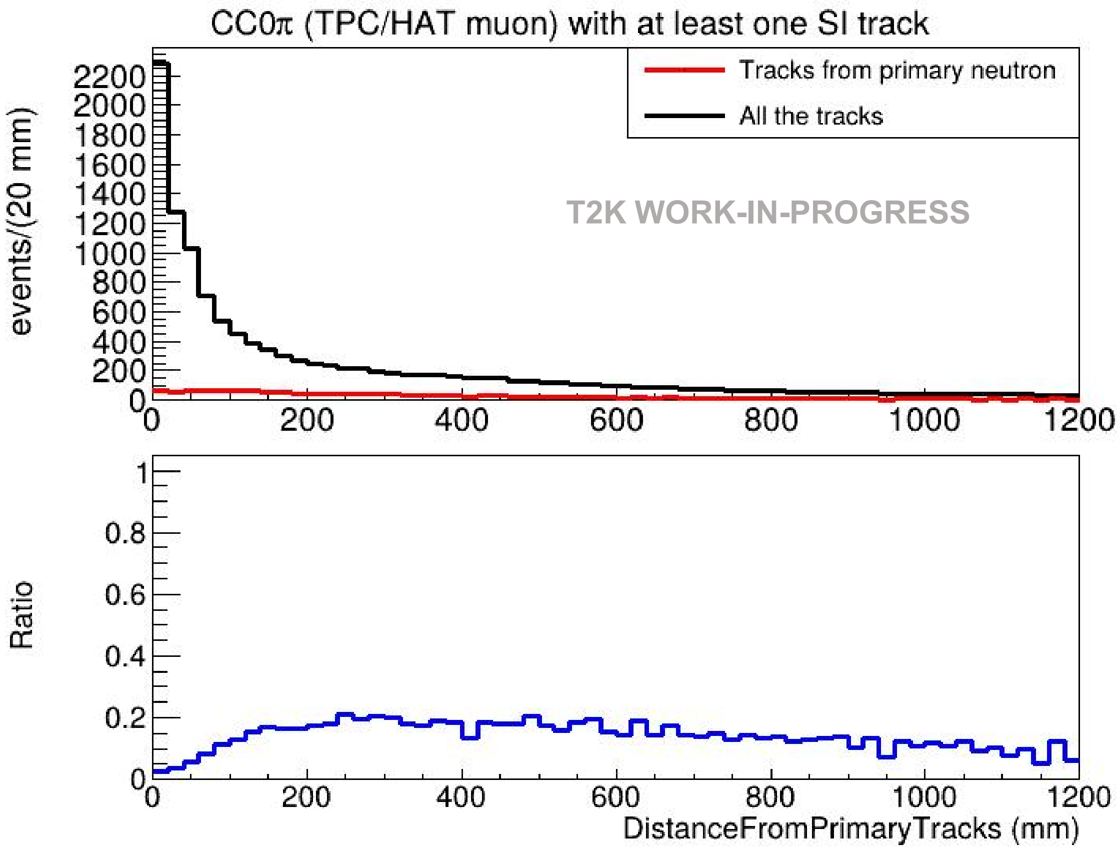
CC0π pre-selected with secondary tracks (speed)





- Speed = Lever Arm / Time-of-Flight
- Reconstructed speed would not be more than 300 mm/ns (speed of light) if the detectors were perfect.
- Speed drops around the speed of light and peaks around 40% of the speed of light.
- This is higher than cluster distribution since tracks are generally produced by high momentum neutrons.

CC0π pre-selected with secondary tracks (minimum distance from all tracks)



- Background distribution peaks for clusters close to other tracks (~5 cm) and leads to impure neutron sample.
- These are primarily due to muon hits not used in track reconstruction and delta electrons produced by primary muons.

Decision Tree

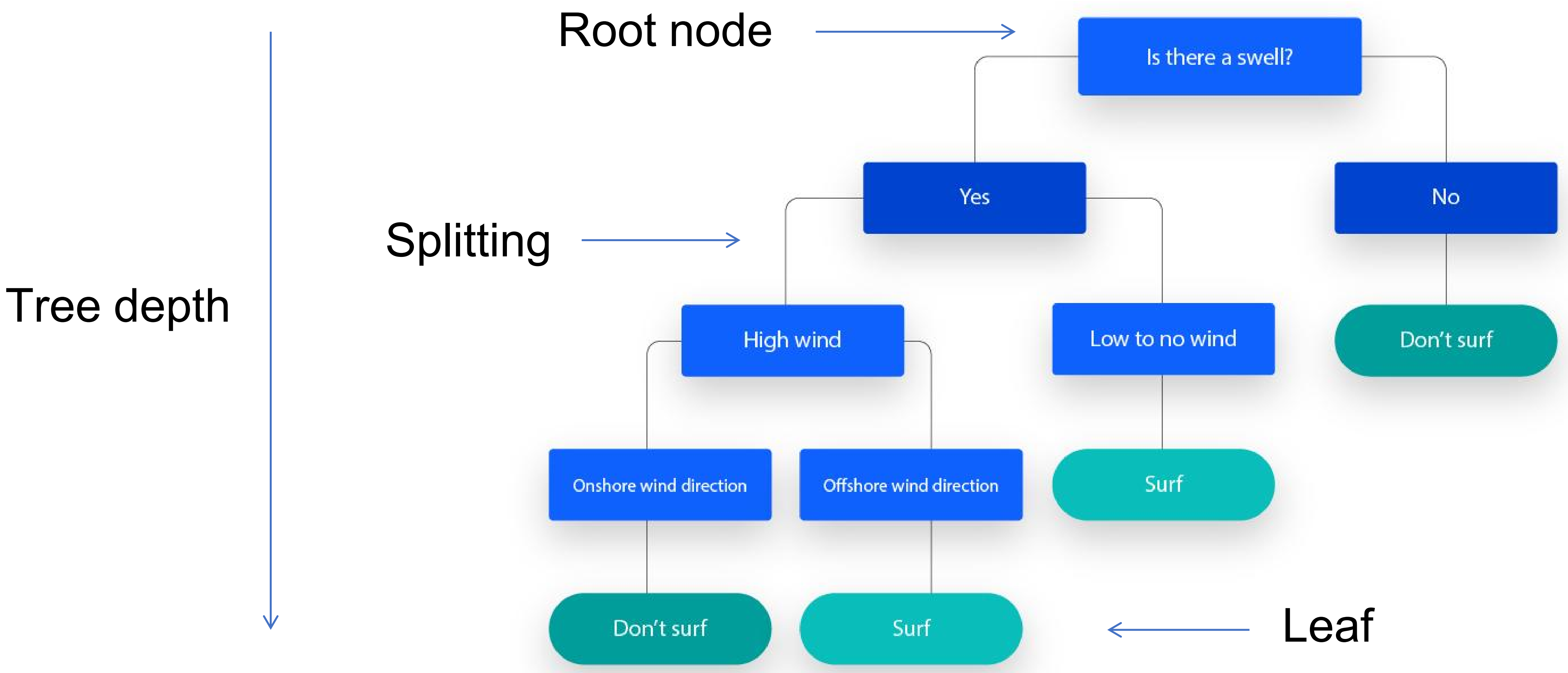


Image Source

Problems with Single Decision Trees

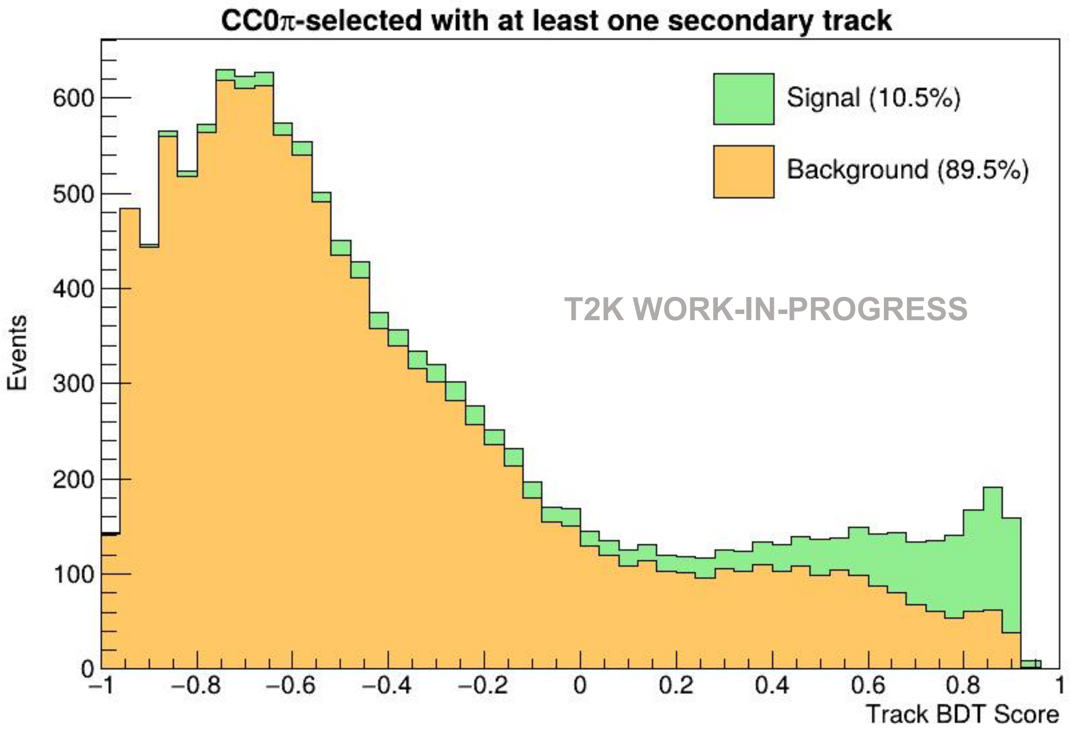
- Single decisions tree are fast and easy but have problems:

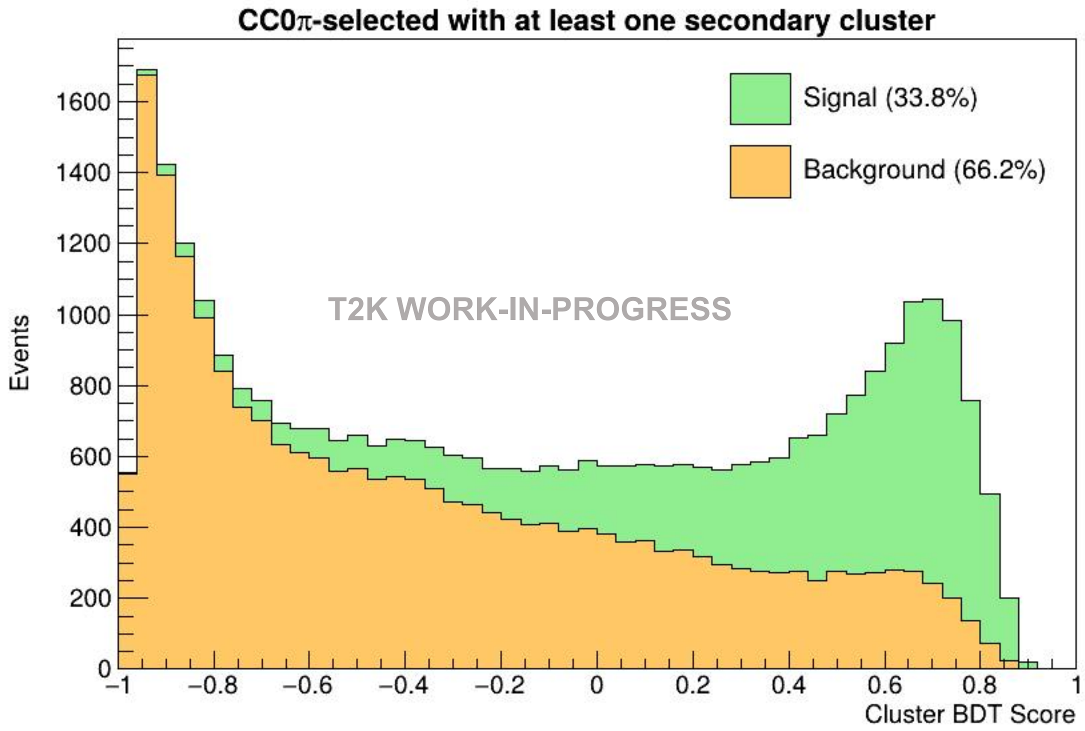
1. Can lead to overfitting, especially if deep, which means difficult to generalize to new events.

2. Might not describe the data very well if shallow.

3. Instability: Small changes in data can change the whole tree.

Track and Cluster BDT Score

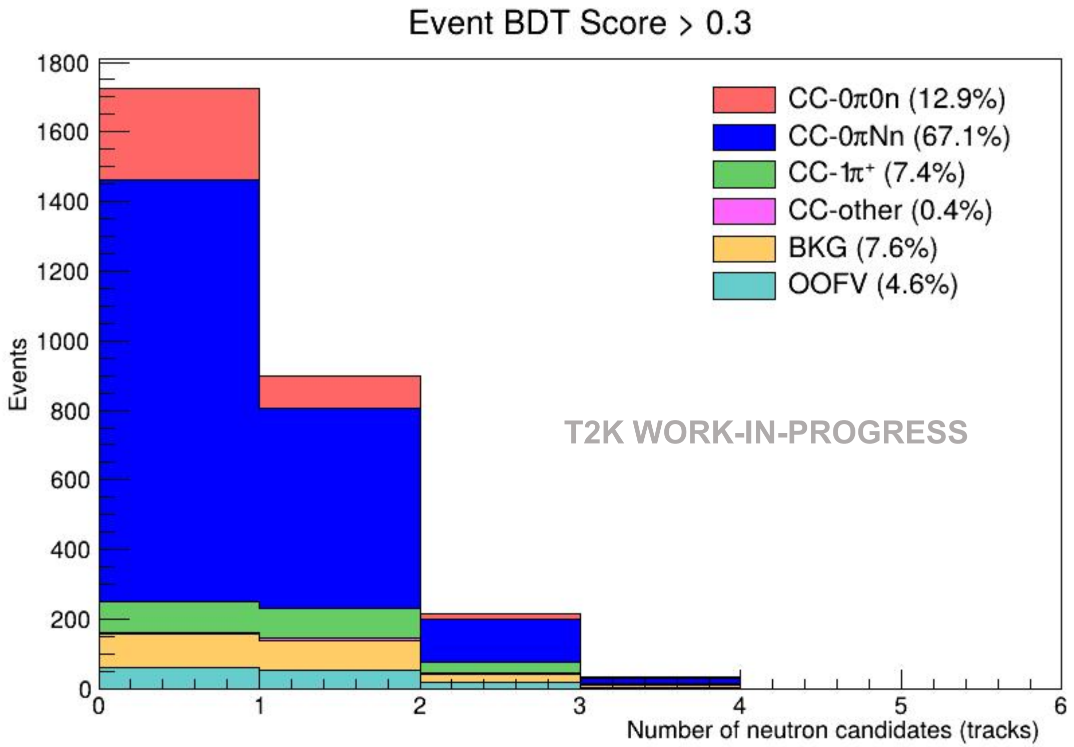


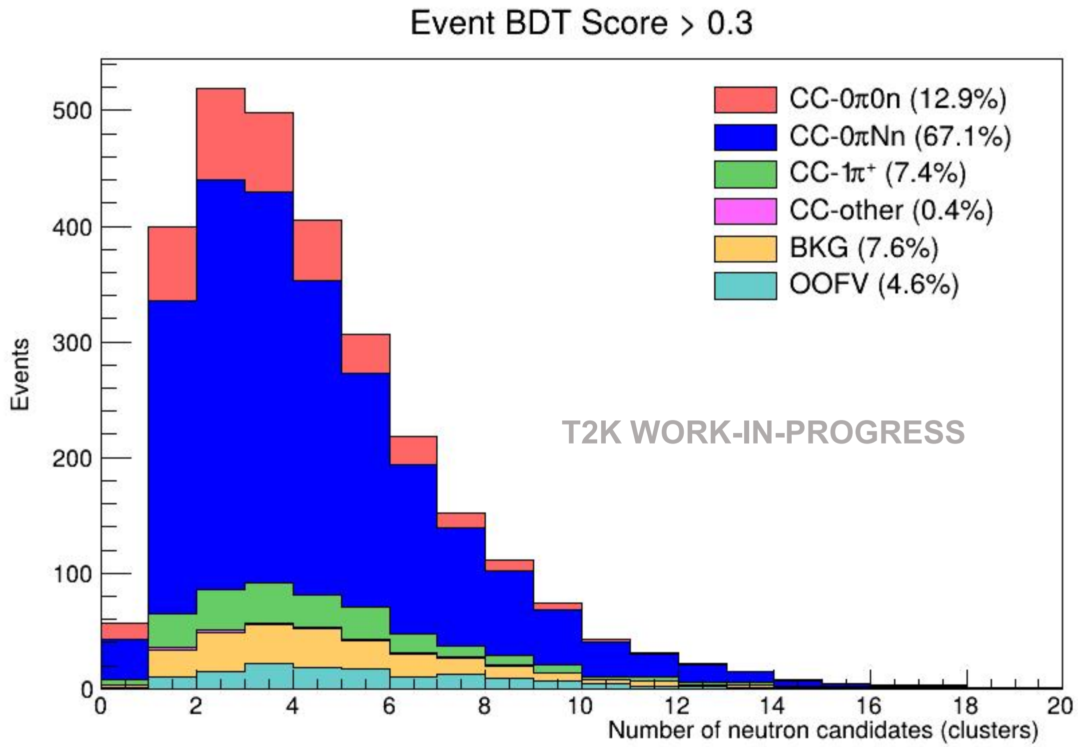


Track BDT score is for all the secondary tracks (at least 3 cm from the reconstructed primary vertex) in all CC0π-selected events. Same for clusters.

Signal means that the secondary object is connected to a primary neutron through one or more scatterings and that neutron has the same vertex as that of the muon.

Number of neutron (track and cluster) candidates





There is at least one neutron candidate in these events. So, no cluster means that there is at least one track and vice versa.