# Current Status for the Inclusive Neutral Current $\pi^0$ Production Cross Section Measurement with the NOvA Near Detector

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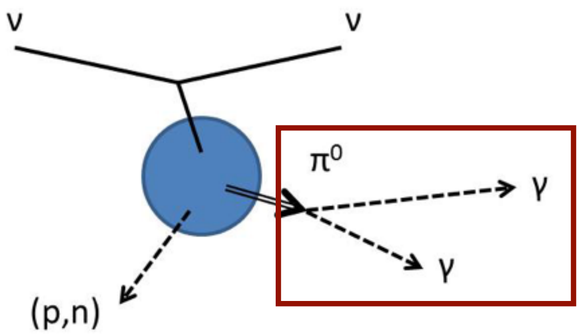
**38th Division of Particles and Fields Conference 2017**
**August 01, 2017**
**Fermi National Accelerator Laboratory, Batavia IL**

# Motivation

- Neutral Current (NC) interaction with a $\pi^0$ in the final state is the main background in $\nu_\mu \rightarrow \nu_e$ oscillation experiments as NOvA, DUNE.




*This interaction mode can fake the $\nu_e$ appearance signal in two ways:*
*a.) 2$\gamma$'s can merge together.*
*b.) one of them may escape detection.*

- Measuring NC $\pi^0$ production cross section is important in constraining this background.
- Most of the measurements are in the form of NC/CC cross section ratio e.g. K2K & SciBooNE.
- Absolute cross section measurement by MiniBooNE ~O(1 GeV) and limited number of these measurements ~O(2GeV).

arXiv:1305.7513v1 [hep-ex] 31 May, 2013

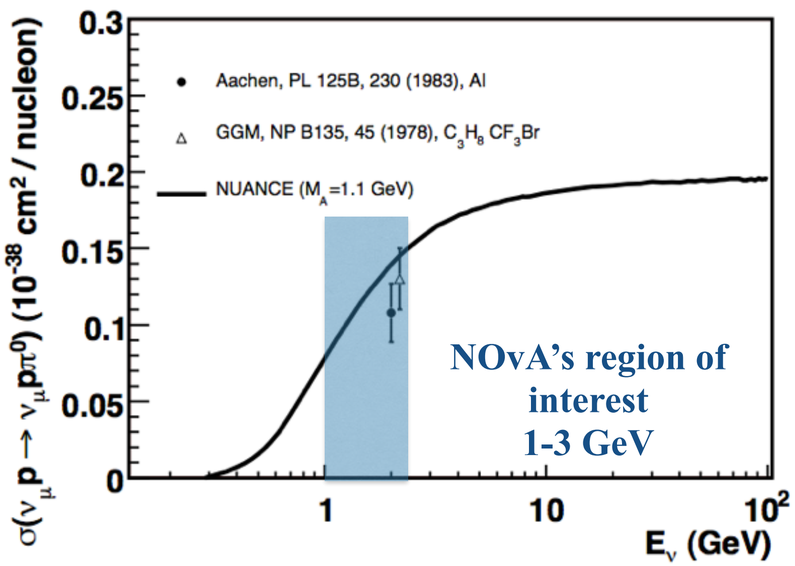


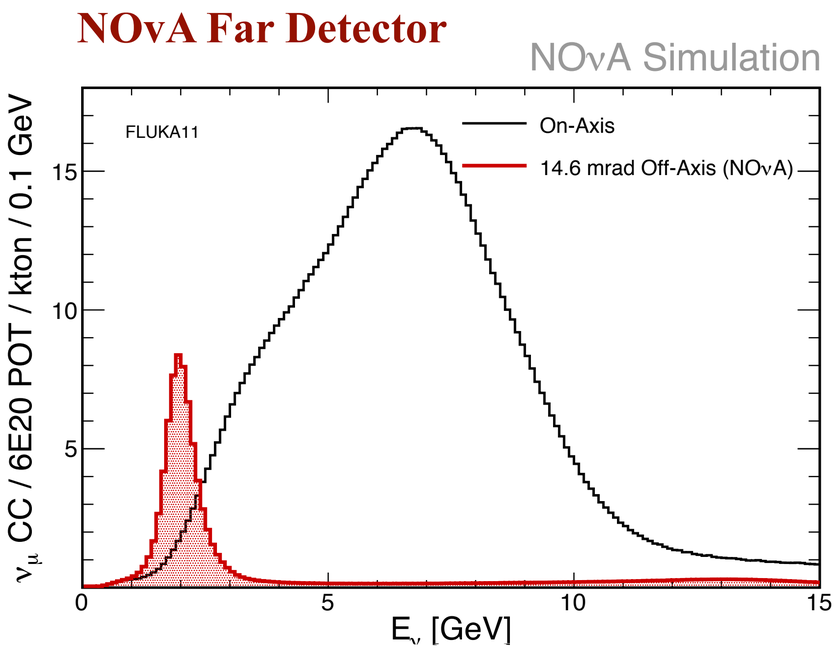

FIG. 16 Existing measurements of the cross section for the NC process, $\nu_\mu\, p \rightarrow \nu_\mu\, p\, \pi^0$, as a function of neutrino energy.

**We present here the current status of measuring NC $\pi^0$ production cross section with the NOvA Near Detector.**

# NOvA

## NuMI (Neutrinos at Main Injector) Off-axis $\nu_e$ Appearance

- NOvA study neutrino oscillations via $\nu_e$ appearance and $\nu_\mu$ disappearance channels with two detectors:
  the Near Detector (ND) at Fermilab.
  the Far Detector (FD) in Northern Minnesota.
- NOvA uses NuMI beam line, tuned to Medium Energy, to get an almost pure $\nu_\mu$ beam.
- NOvA detectors are sited 14 mrad off the NuMI beam axis



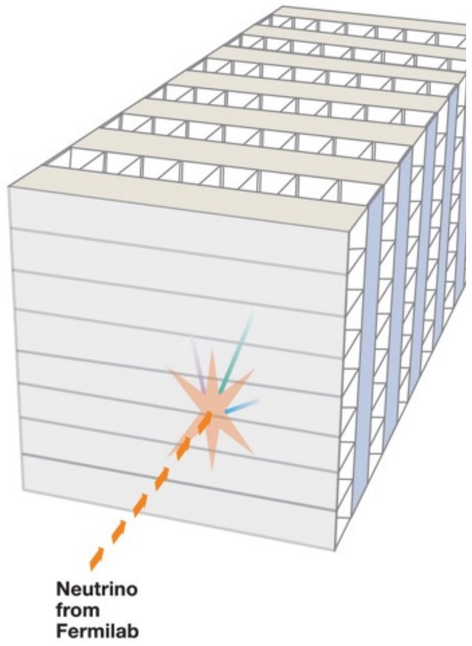

✔ Reduces Neutral Current (NC) background in oscillation analysis.

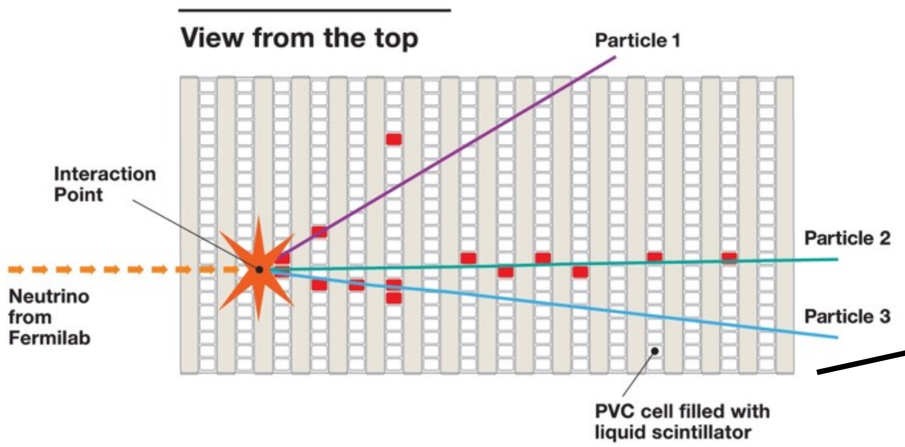
✔ Keeping high $\nu_\mu$ flux, peaked at 2 GeV in energy.

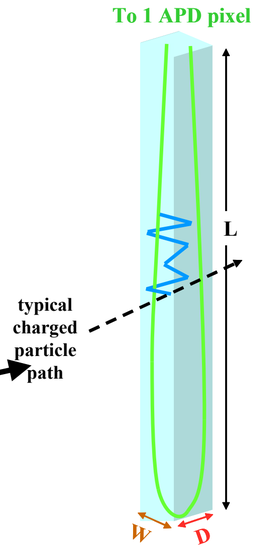
# NOvA Near Detector

- NOvA ND collects high statistics due to its close proximity to the target station.
- Provides an excellent opportunity for the measurement of various neutrino interactions.

**3d view of the detector**



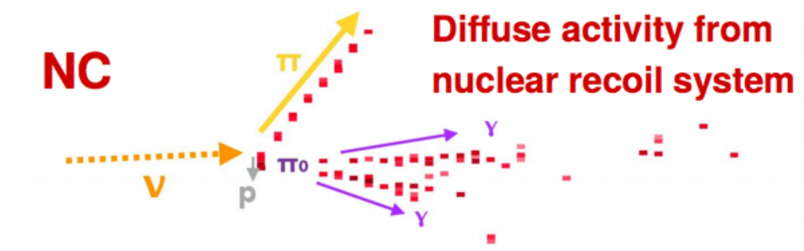



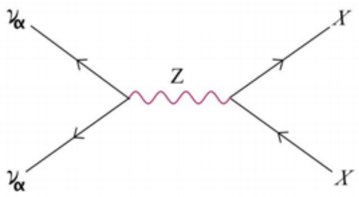




**<u>NOvA ND</u>** (193 ton)
3.9m X 3.9m X 12.67m

Low-z, highly active tracking calorimeters able to differentiate between muons (long tracks), electrons (EM showers) and <u>$\pi^0$</u>

<u>(leaves a gap before decaying to $\gamma$'s )</u>



# Monte Carlo (MC) study

- Study presented here uses Near Detector MC dataset with high statistics (x4 than the ND data).
- We use GENIE, an event generator, to simulate the neutrino interactions in the NOvA detectors.
- Data was collected in Forward Horn Current (FHC) beam configuration that focus $\pi^+$ to generate neutrinos.
- We normalize all the MC distributions and number of events to 8.09e20 POT that reflect our ND data.

# Cross section ($\sigma$) definition

$$\sigma_k = \frac{\Sigma_j \, U_{kj} \left( N_j^{sel} - N_j^{bkg} \right)}{T \, \phi \, \varepsilon_k}$$

**# of selected signal events**

**Unfolding matrix**

**# of selected background events**

**# of target nucleons**

**Neutrino flux**

**Efficiency of signal selection**

**This talk focus on the event selection part.**

# The Signal

$\nu_\mu$ induced NC interactions with at least 1 $\pi^0$ in the final state with kinetic energy above 0.5 GeV.

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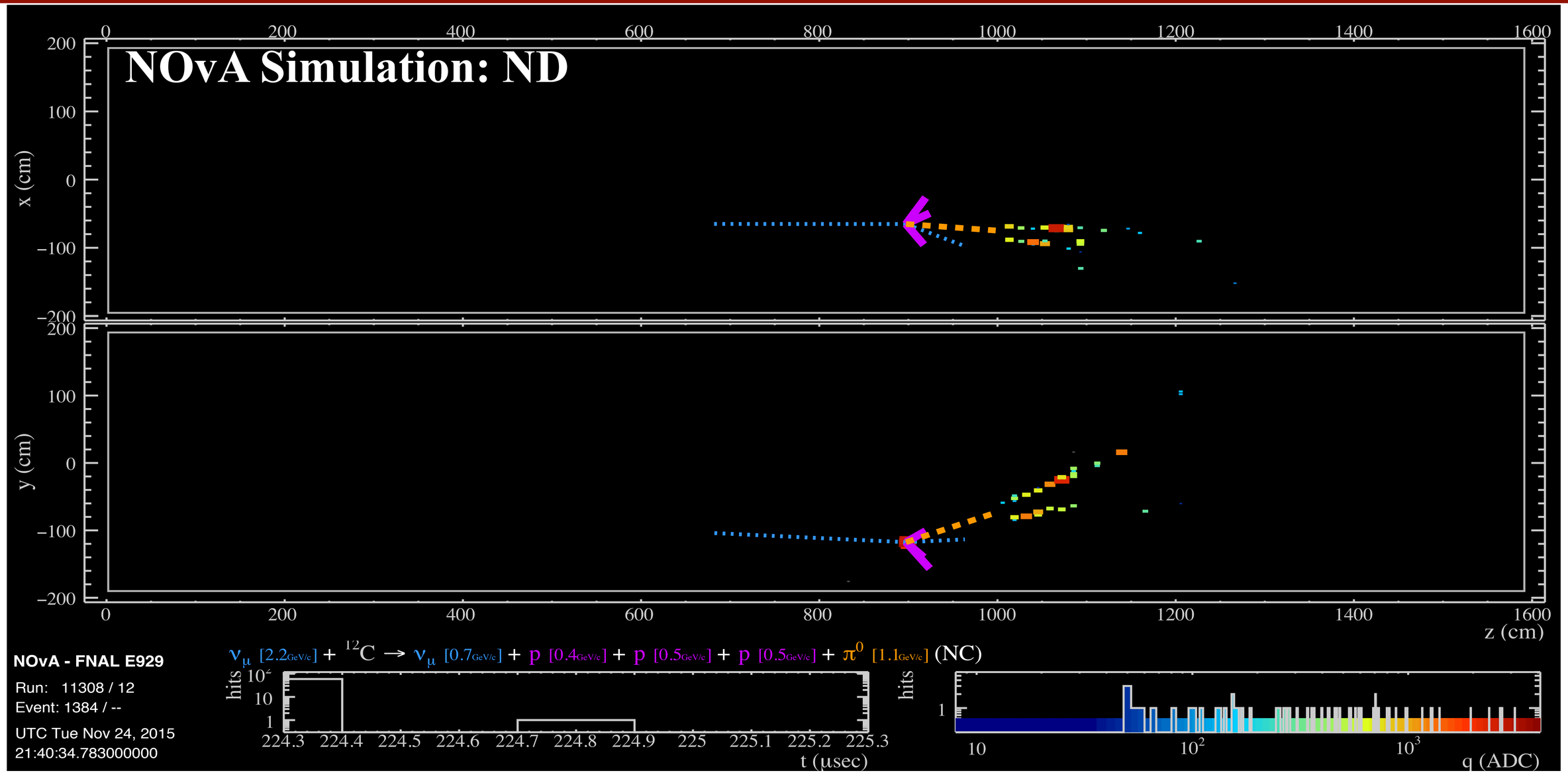
Top View

Beam →

Side View



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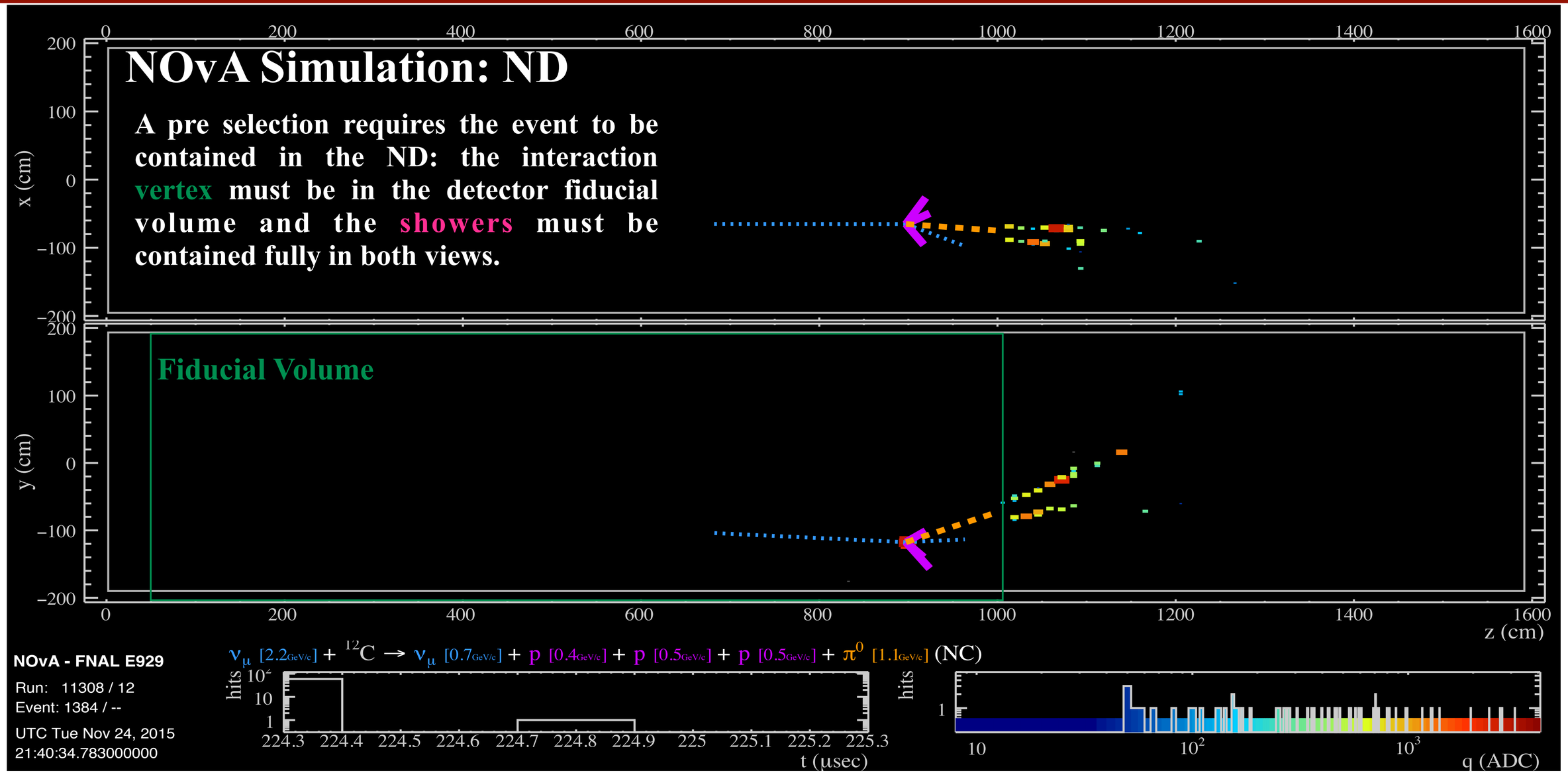

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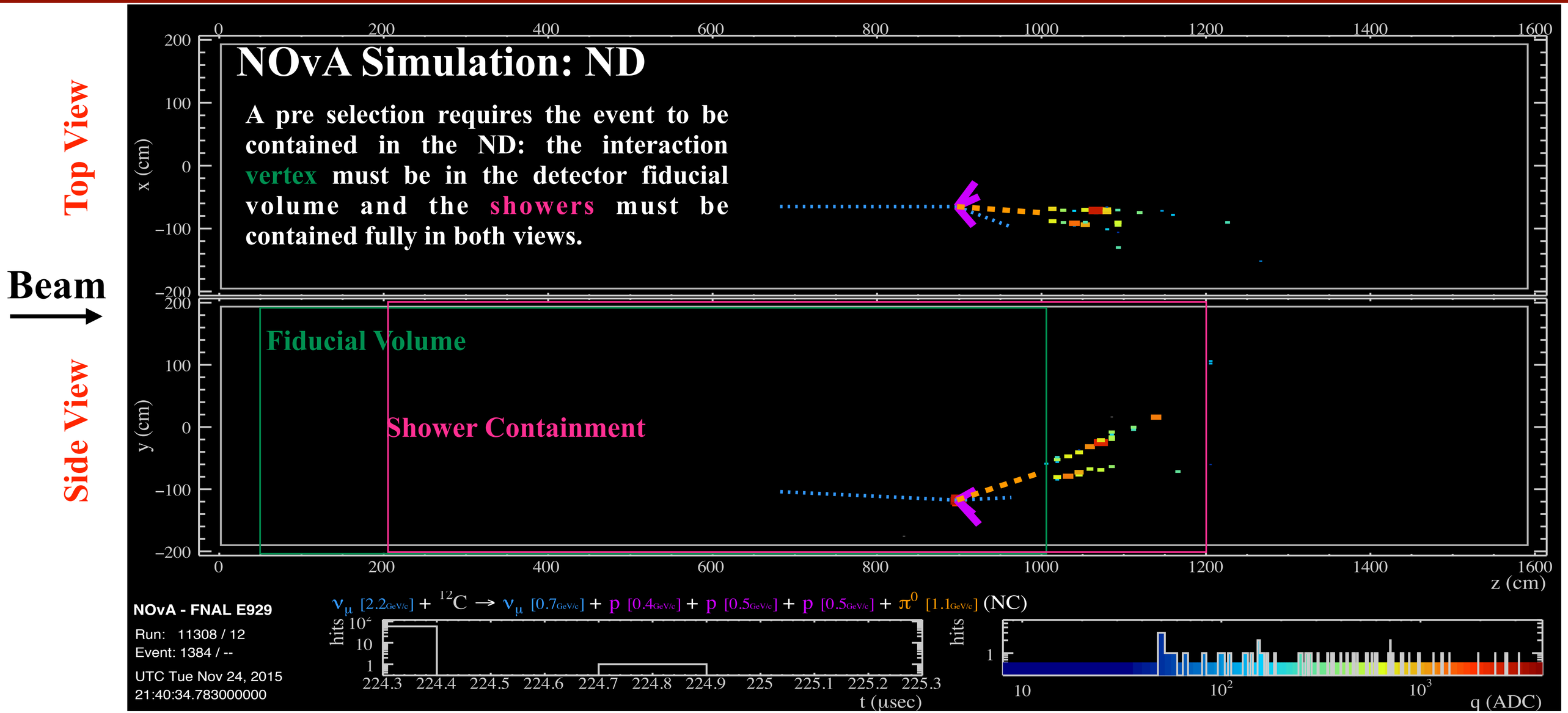

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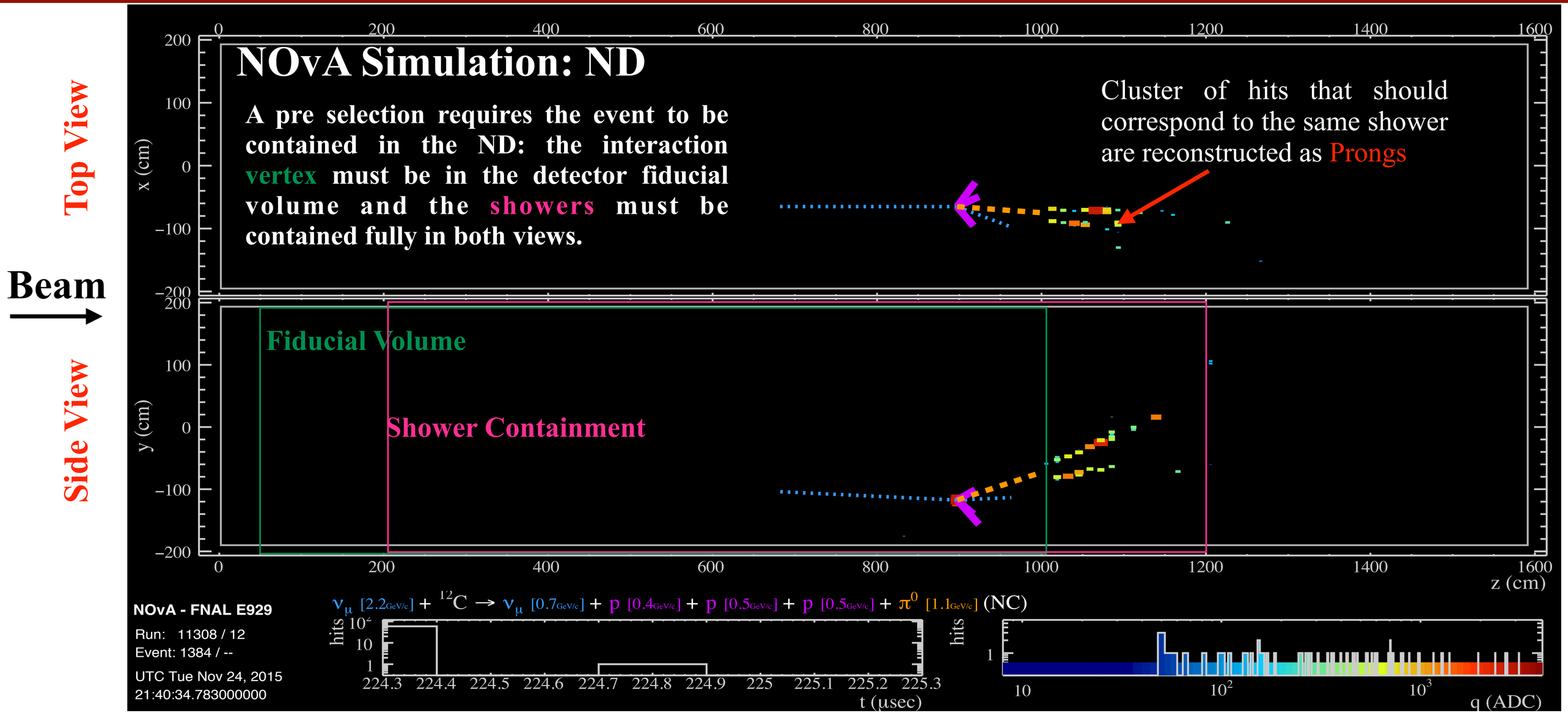

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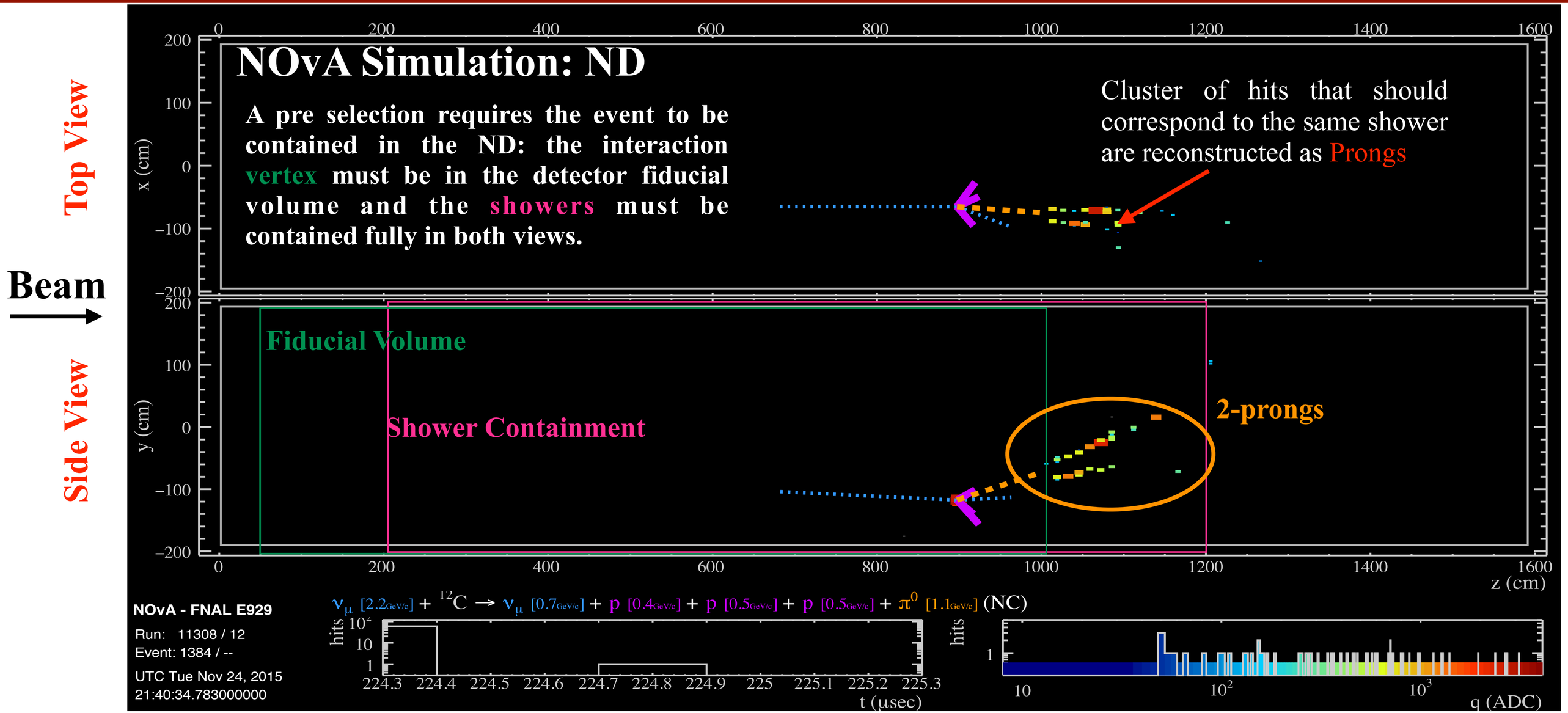

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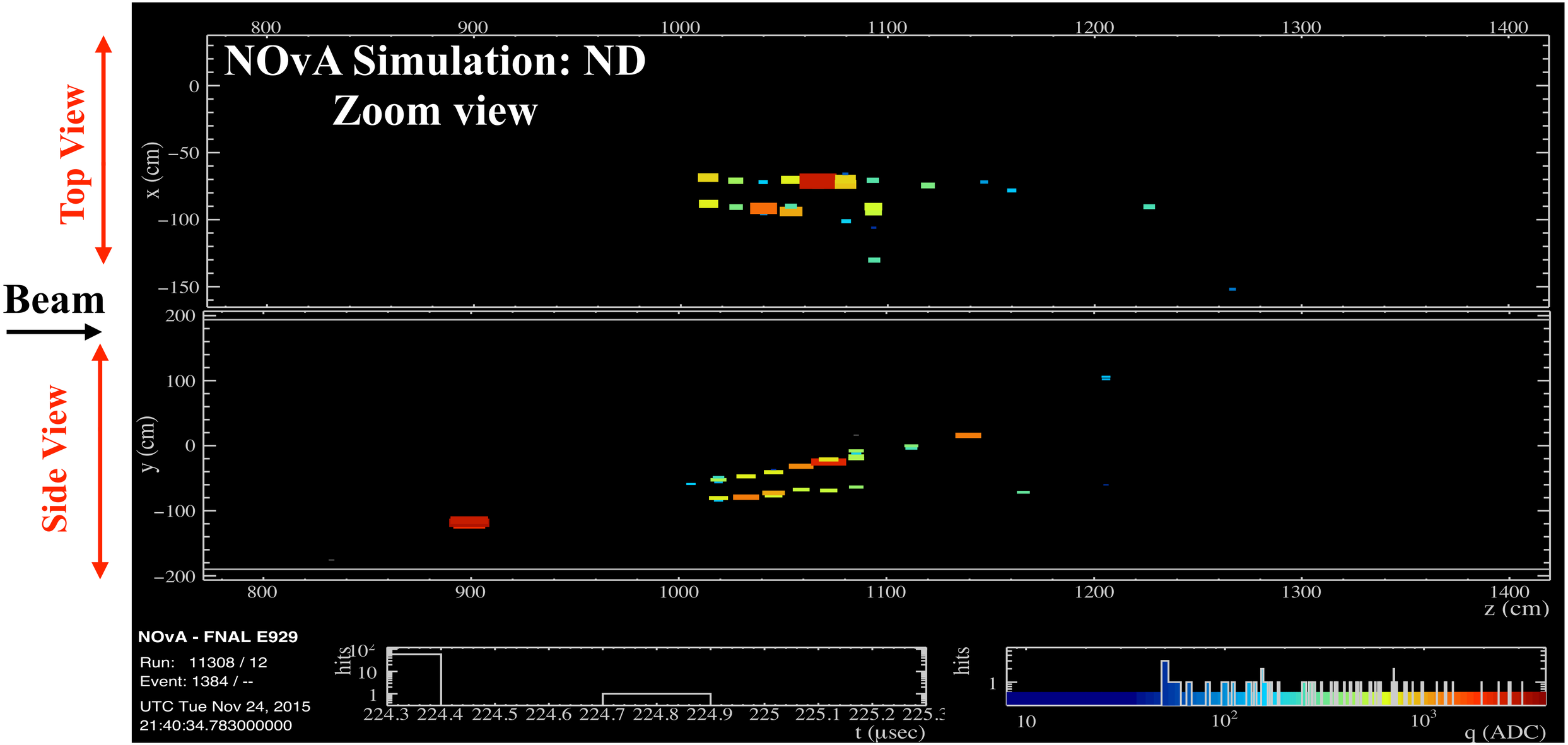
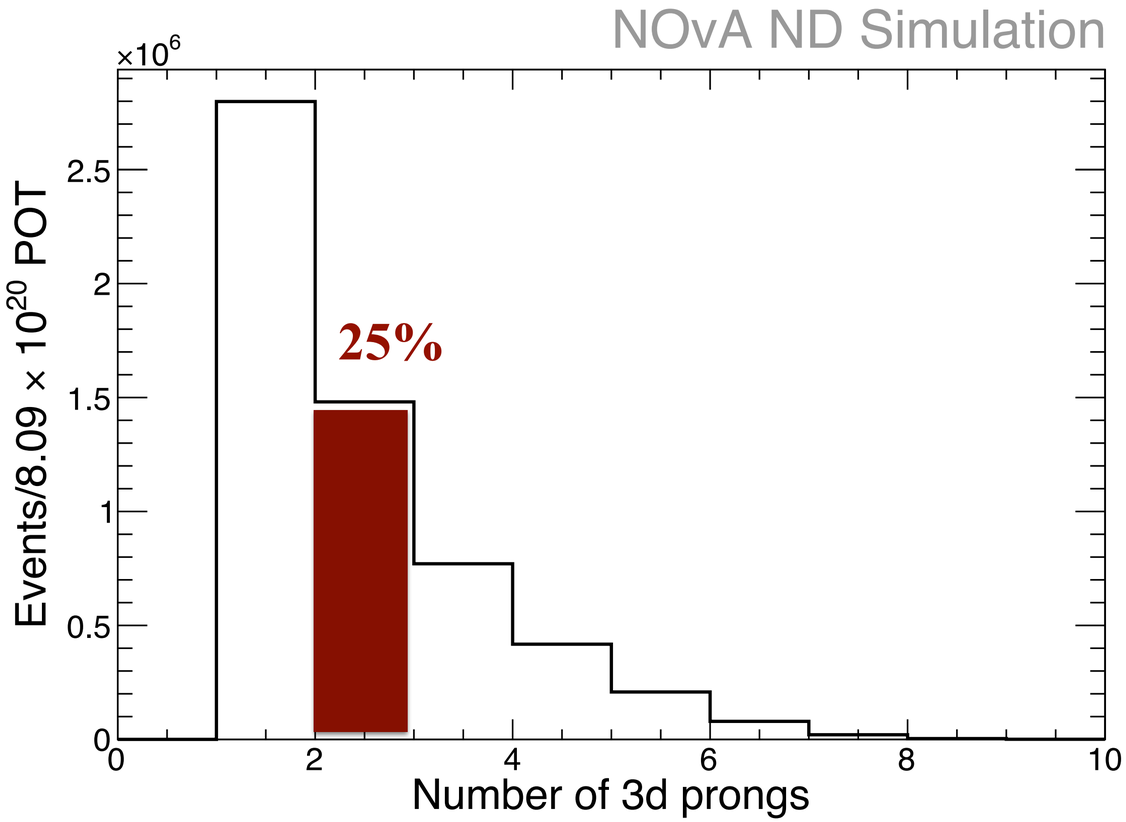
$\nu_\mu$ induced NC interactions with at least 1 $\pi^0$ in the final state with kinetic energy above 0.5 GeV.



# The signal

**$\nu_\mu$ induced NC interactions with at least 1 $\pi^0$ in the final state with kinetic energy above 0.5 GeV.**

- Analysis considers 2-prong events originating from a common vertex.
- Prongs are the cluster of hits that should correspond to the same shower.
- 2 of the reconstructed 3D prongs should be associated with the 2ɣ from the $\pi^0$ decay.

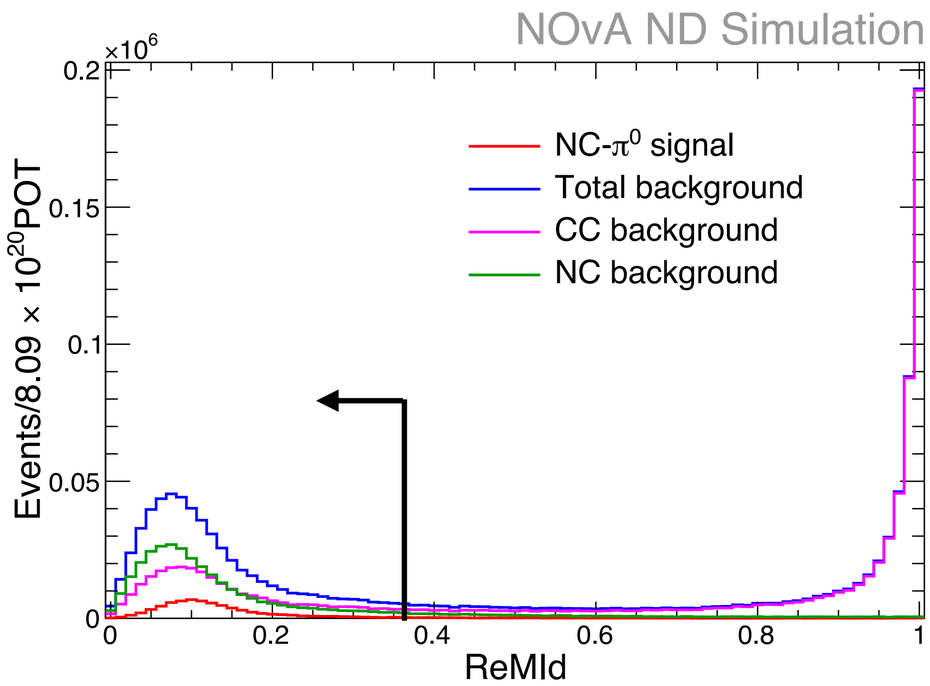


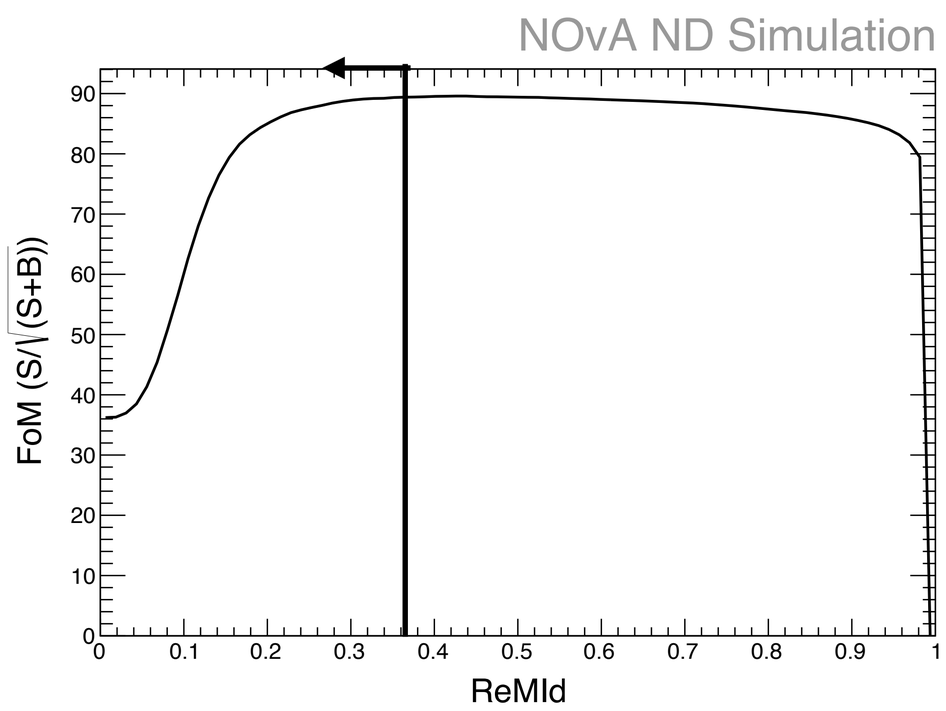
# The background

- $\nu_\mu$ Charge Current interactions (with and without $\pi^0$ in the final state) ➔ CC-background
- $\nu_\mu$ NC interactions without a $\pi^0$ in the final state and with a $\pi^0$ in the final state below energy threshold (K.E < 0.5 GeV) ➔ **NC-background**
- $\nu_e$: Intrinsic beam contamination (Negligible!)

# Preliminary steps towards background rejection

## Reconstructed Muon Identification (ReMId)



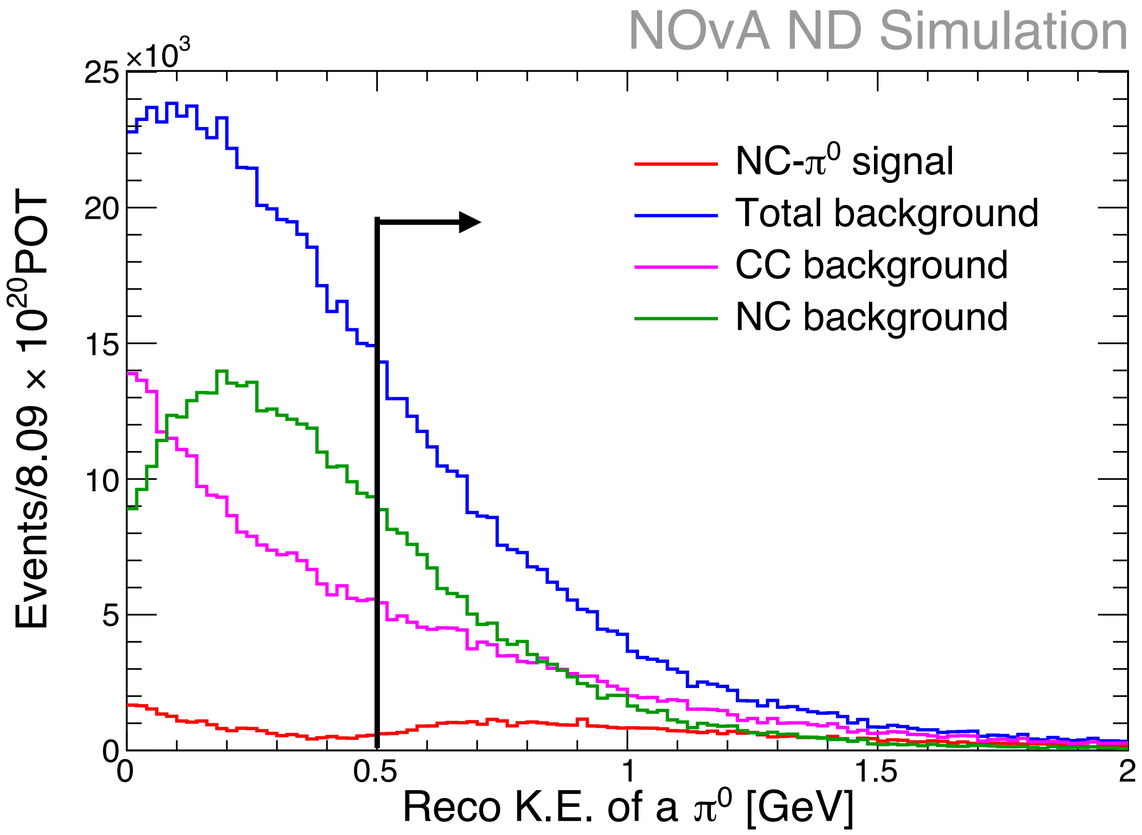

- ReMId is a Particle Identification (PID) algorithm, specifically based on muon tracks, that has been developed to be used in $\nu_\mu$ disappearance analysis.
- Select muons from $\nu_\mu$ CC interactions.
- It gives a value 0 to 1 to an event, where 1 is for CC like events.

- Choose ReMId cut value which maximizes the Figure of Merit (FoM=S/√S+B)
- So, we include **ReMId < 0.36 as a preselection cut.**

# Preliminary steps towards background rejection

## Reconstructed kinetic energy (Reco K.E.)

- We include a cut on reconstructed $\pi^0$ K.E. in preselection.
- **Reco K.E > 0.5 GeV** rejects 80% of the background w.r.t the background events with fiducial & containment and thus **improves Signal (S) to Background (B) ratio.**
- It still **maximizes the FoM (S/√S+B)**




**Reco K.E with fiducial, containment & ReMId < 0.36**

# Approach for final event selection

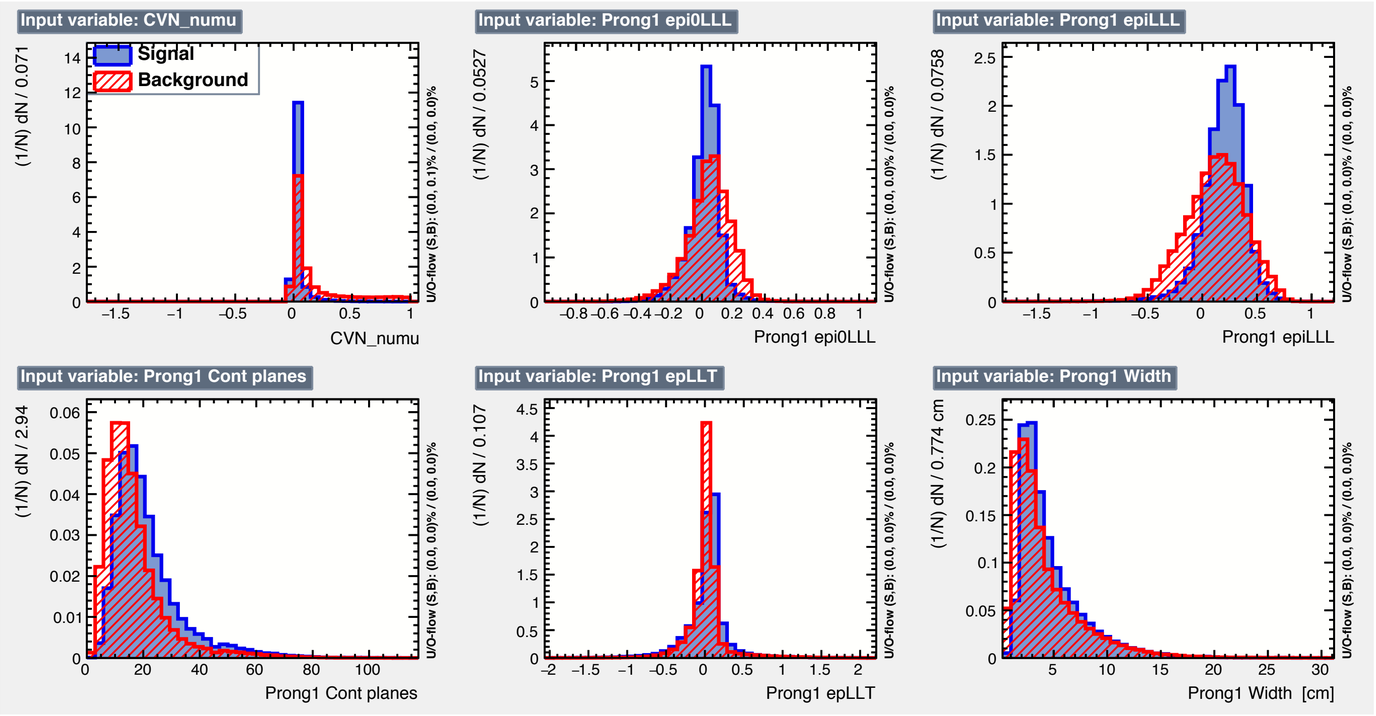
## MultiVariate (MV) method

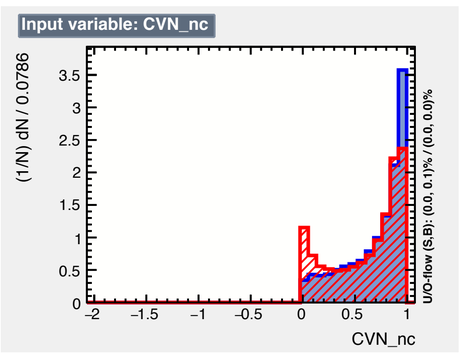
- Pre Selection: ***Fiducial* + *Containment* + *ReMId* < *0.36* + *Reco K.E* > *0.5 GeV***
- For the final selection, we studied various MV methods.
- Performance with **GradientBoost** method (a type of Boosted Decision Tree (BDT): "BDTG") was better compared to other algorithms.
- Tried different sets of variables and among all those best result was given by 9 input variables.

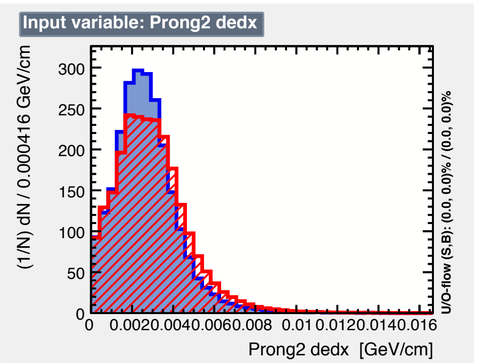
# Input variables

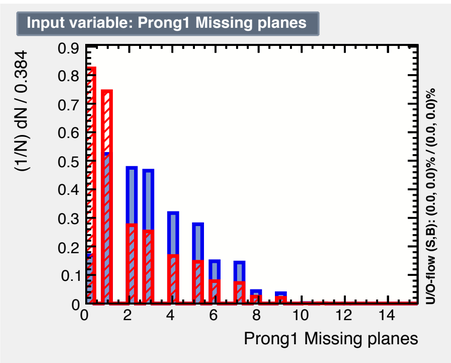
| Rank | Variable | Separation |
|---|---|---|
| 1 | CVN_numu | 1.524e-01 |
| 2 | Prong1 Missing planes | 1.406e-01 |
| 3 | Prong1 epi0LLL | 8.832e-02 |
| 4 | Prong1 epiLLL | 8.293e-02 |
| 5 | Prong1 Cont planes | 8.248e-02 |
| 6 | Prong1 epLLT | 6.322e-02 |
| 7 | Prong1 Width | 5.794e-02 |
| 8 | CVN_nc | 3.129e-02 |
| 9 | Prong2 dedx | 1.150e-02 |

Separation is zero for identical signal and background and it is one for shapes with no overlap



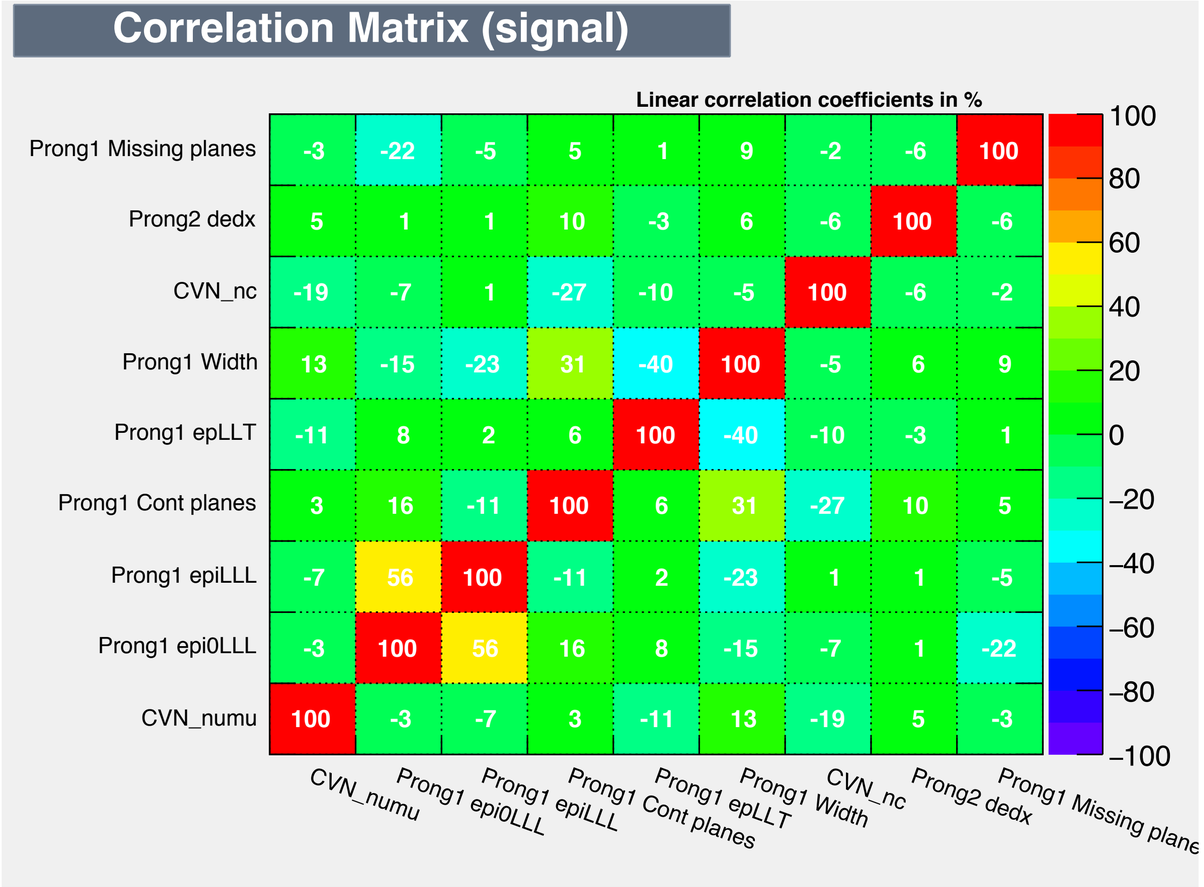



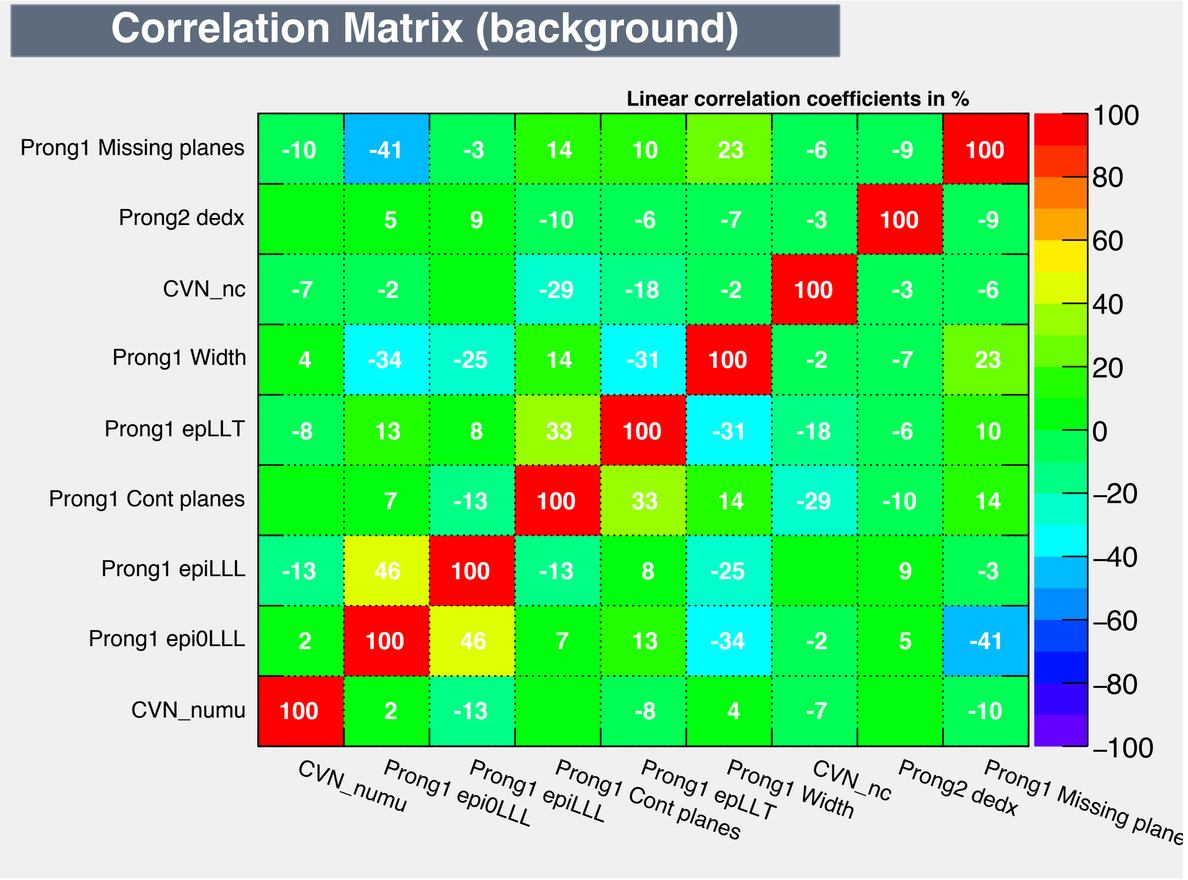



# Correlation matrix

## Signal

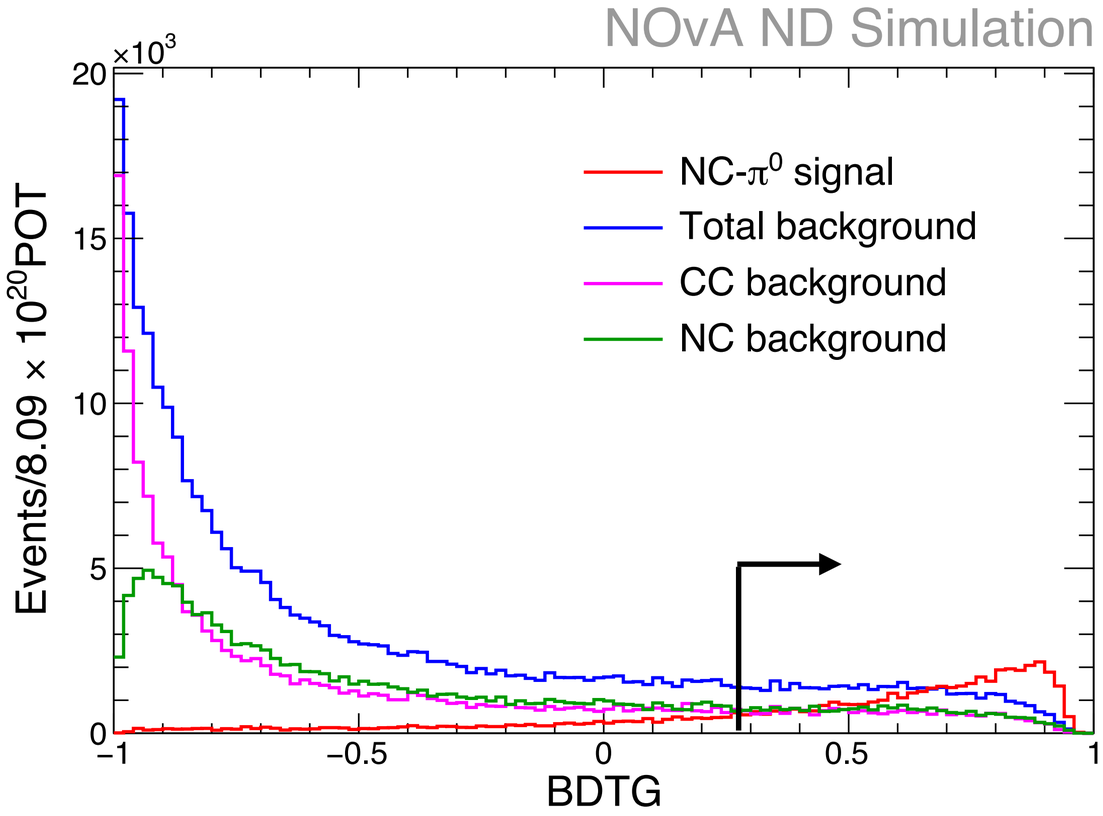



## Background

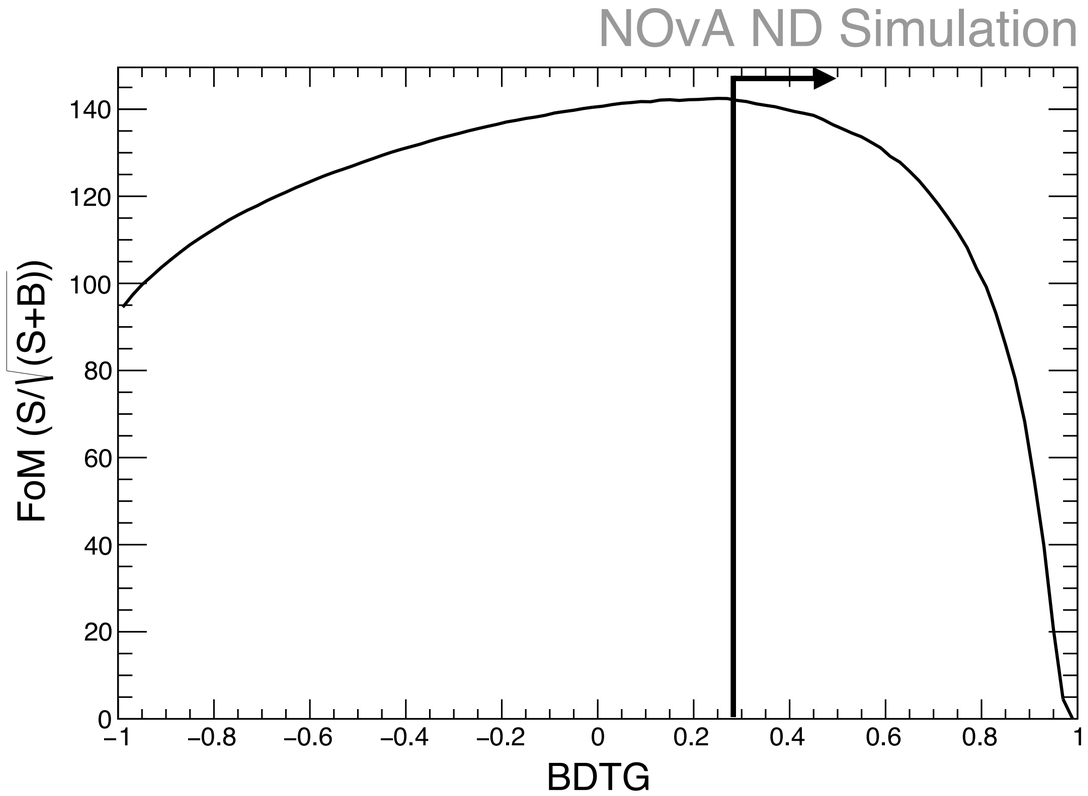



Variables are not correlated to each other.

# BDTG distribution




**FoM from BDTG distribution after evaluation**




Maximum FoM with BDTG @0.27

# Events

| | Signal (S) | Background (B) | S/B | FoM S/sqrt(S+B) | ε Signal w.r.t events with Fid + Cont) | Purity |
|---|---|---|---|---|---|---|
| **Fiducial + Containment** | 91007 | 1389929 | 0.06 | 74.8 | | |
| **ReMId < 0.36** | 85829 | 876124 | 0.09 | 87.5 | | |
| **Reco K.E > 0.5** | 55192 | 285675 | 0.2 | 94.5 | | |
| **BDTG > 0.27** | **43634** | **44361** | **0.98** | **147.09** | **48%** | **49.6%** |

**Signal is: 60% DIS**
**27% RES**
**11% COH**

**Bkg is: 53% NC**
**47% CC**

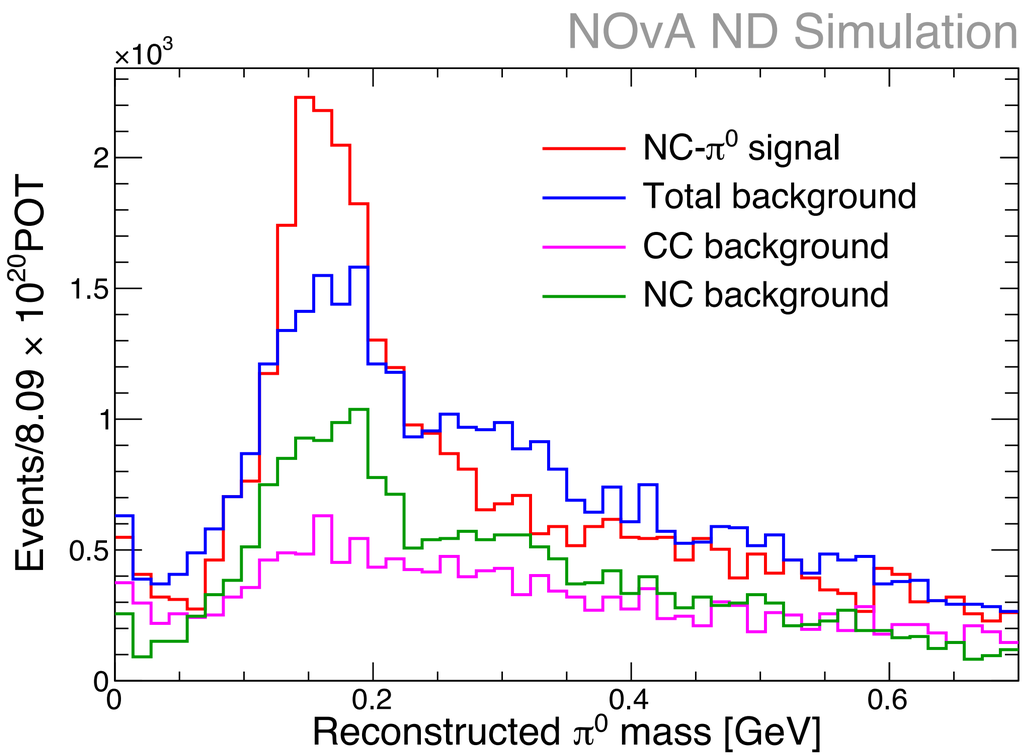
**Signal efficiency is 15% w.r.t the events with fiducial.**

Event numbers corresponds to 8.09e20 POT which reflects our ND data.

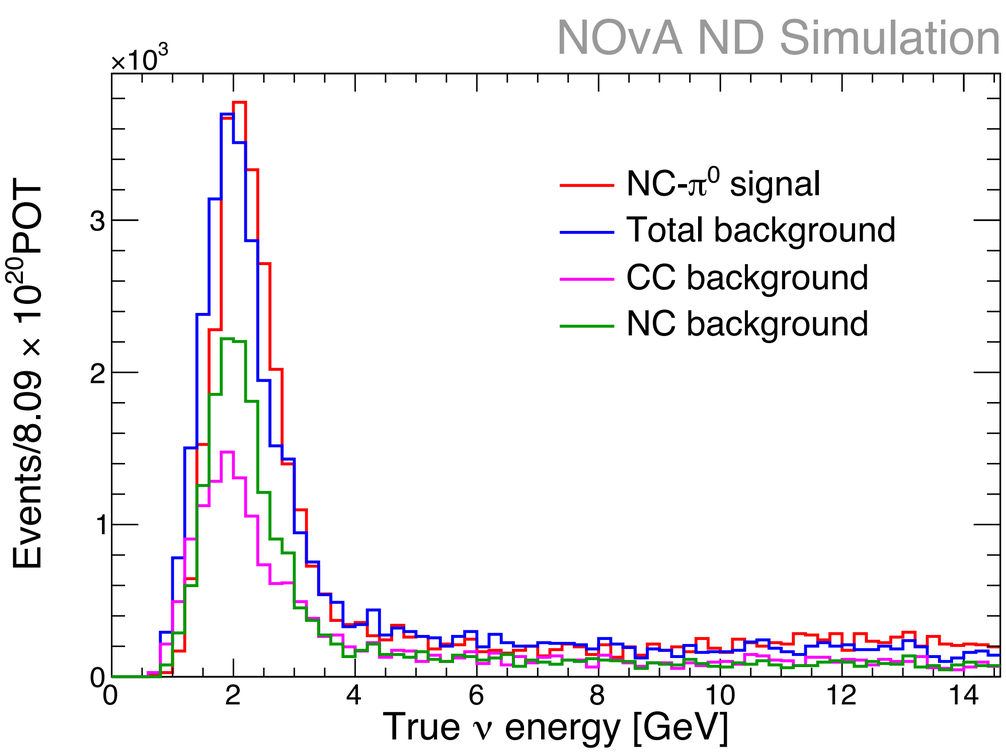
# Variables distribution

**Fiducial + Containment + ReMId < 0.36 + Reco K.E. > 0.5GeV + BDTG > 0.27**

**Reconstructed $\pi^0$ mass**




**True ν energy**

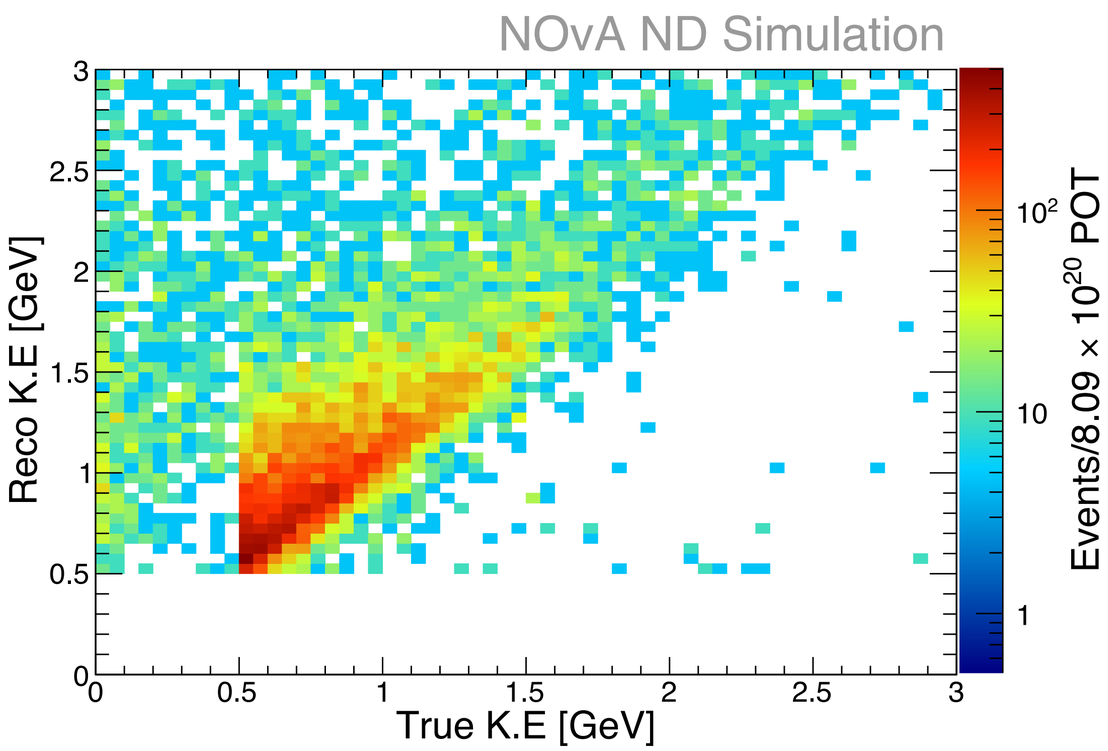



**Background is dominated with NC component and the $\pi^0$ 's below threshold (< 0.5GeV) is giving a peak in NC background.**

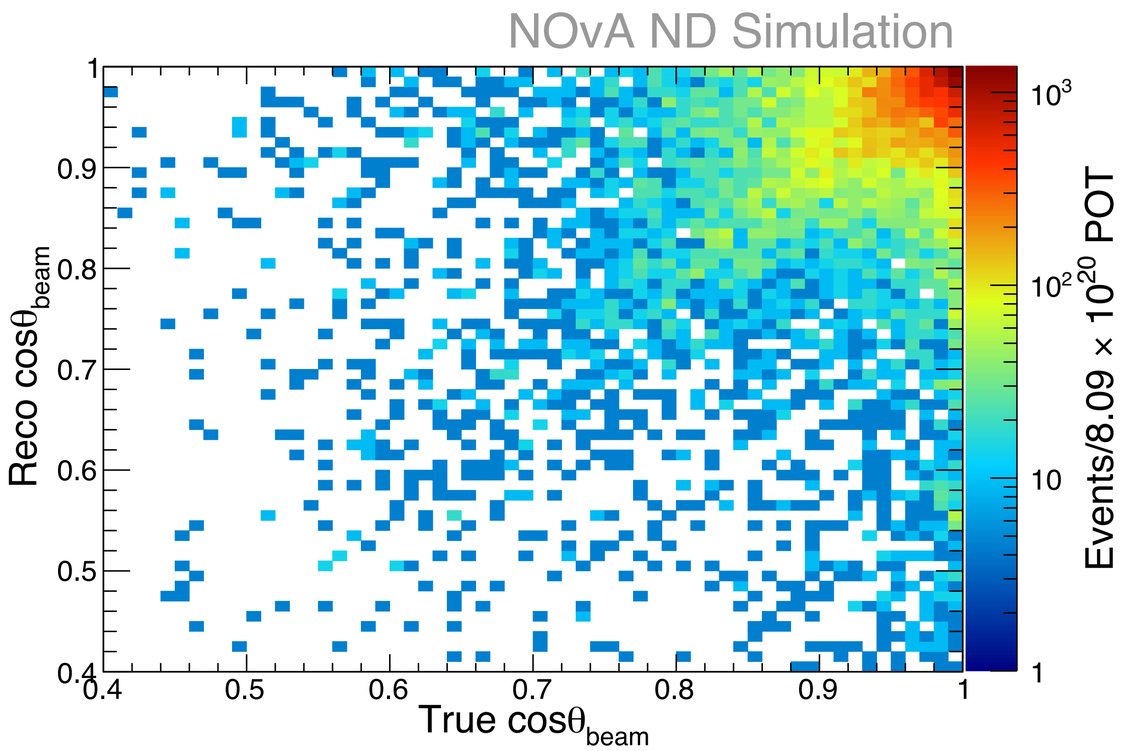
# Variables distribution

**Fiducial + Containment + ReMId < 0.36 + Reco K.E. > 0.5GeV + BDTG > 0.27**

**Reco vs True $\pi^0$ Kinetic energy: Log scale**



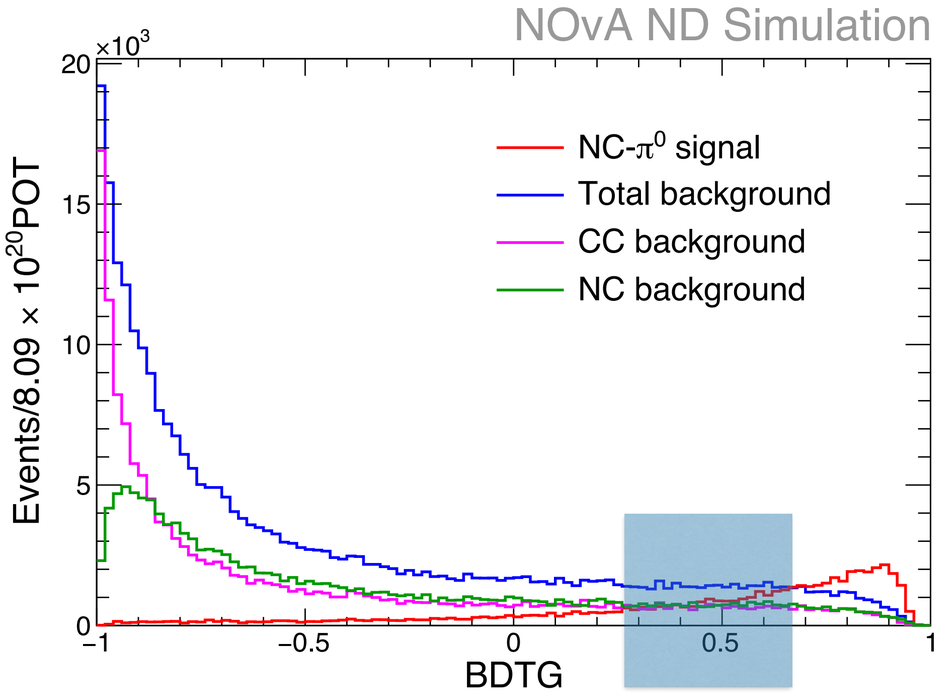

**Reco vs True $\pi^0$ beam angle : Log scale**



# Look at systematics

- BDTG cut has rejected ~97% of the background w.r.t the background events that pass fiducial & containment cuts.
- Still, we have a lot of background.
- We can still get rid of some of the background by choosing harder cut on BDTG.

**We look at the effect of systematics on BDTG distribution to optimize the event selection.**

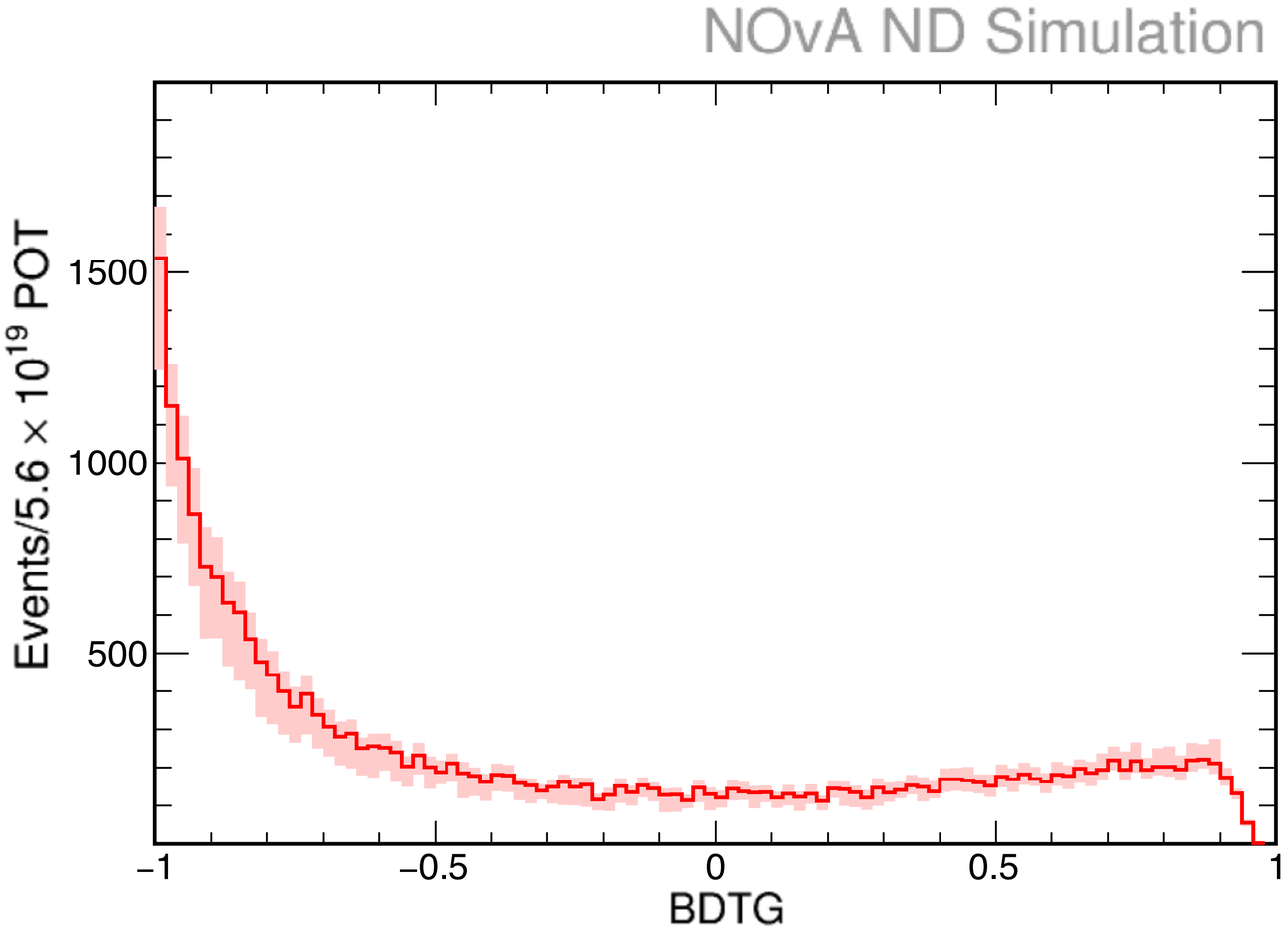


# Cross section & FSI systematic uncertainty

- We study the effect of cross section and Final State Interactions (FSI) systematic uncertainties on BDTG distribution.

- Error band represents $\pm 1\sigma$ uncertainty.

- It stays almost constant in BDTG range 0.2 - 0.7, means we are not biasing our selection too much by choosing higher cut value for BDTG.



# Summary & Future plans

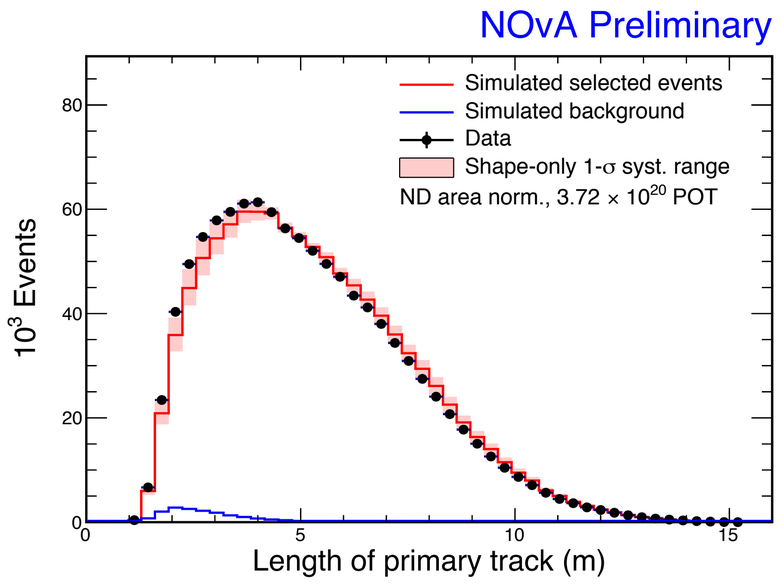
- NOvA ND collects high statistics data.
- We are exploring to make differential cross section measurement with the NOvA ND.
- Plan is to optimize the final event selection based on systematics.
- We started looking at cross section and FSI systematic uncertainties.
- Study is underway.
- Stay tuned for the exciting results!

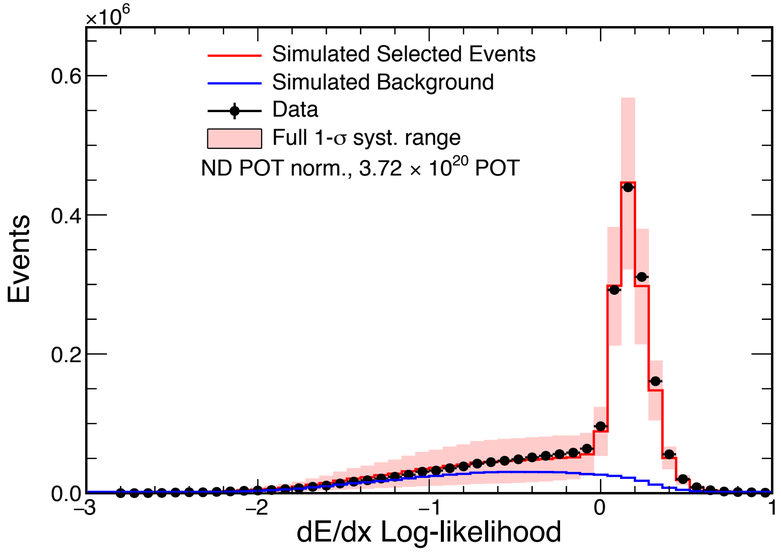
Thank you
Fermilab

# Back-up

# ReMId

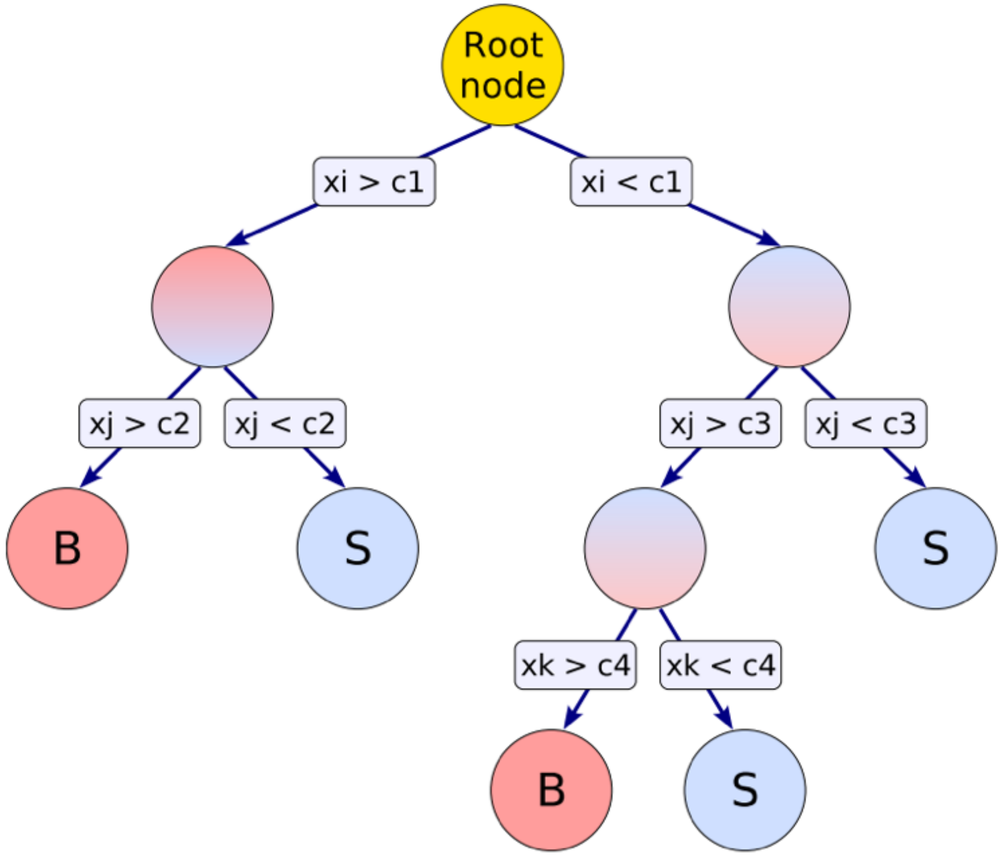
- ReMId is a Particle Identification (PID) algorithm, specifically based on muon tracks, that has been used in $\nu_\mu$ disappearance analysis.
- It separates muons from hadronic background using k-Nearest Neighbors (kNN) algorithm trained with 4 variables:
  - track length
  - longitudinal energy profile (dE/dx)
  - scattering along the track and
  - fraction of energy in the neutrino event associated with the track.



# Boosted Decision Tree

- BDT is a binary tree structured classifier where the event will get more weight if it is classified and vice versa if the event is mis classified.
- It will go through all the variables to find the best variable and value to split events.
- Repeat the procedure until a stop criteria is fulfilled.



# Modeling systematics - Multiverse

- We use Multi-universe approach to treat cross section modeling systematic uncertainties.
- With this approach, all the GENIE parameters can be varied at a same time.
- Create ensemble of universes, each with a different set of relevant GENIE parameters.
- Allow bin to bin correlations.