Wrong Sign Contamination in NOνA

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Fermilab New Perspectives 2019

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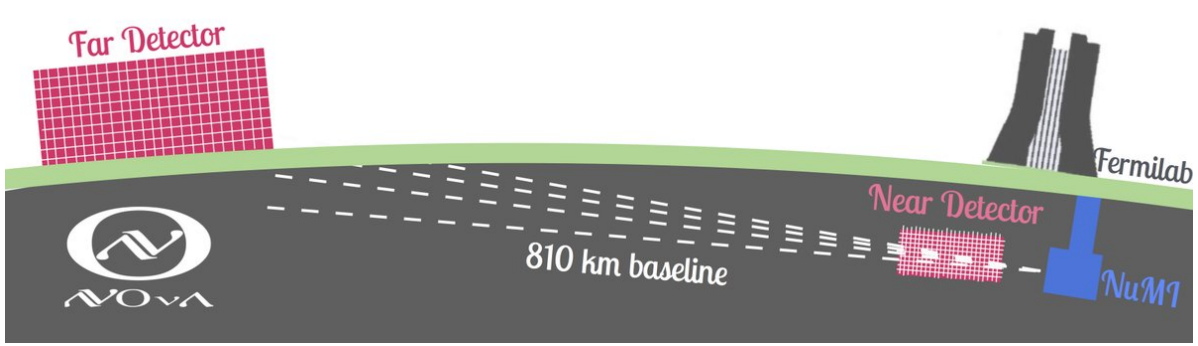
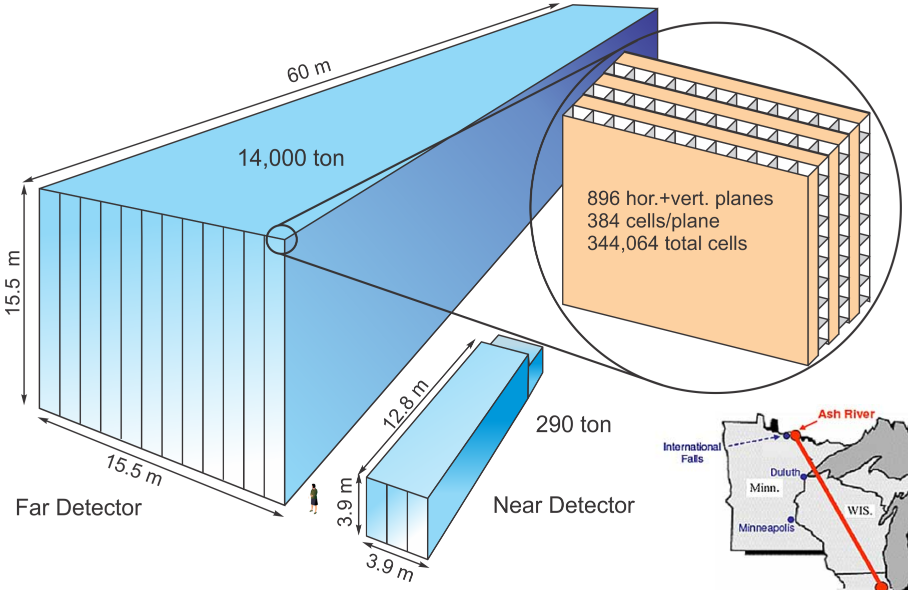
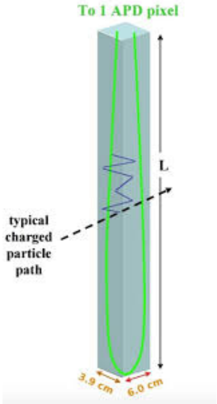
June 11, 2019

NOνA (NuMI Off-axis ν_e Appearance) experiment



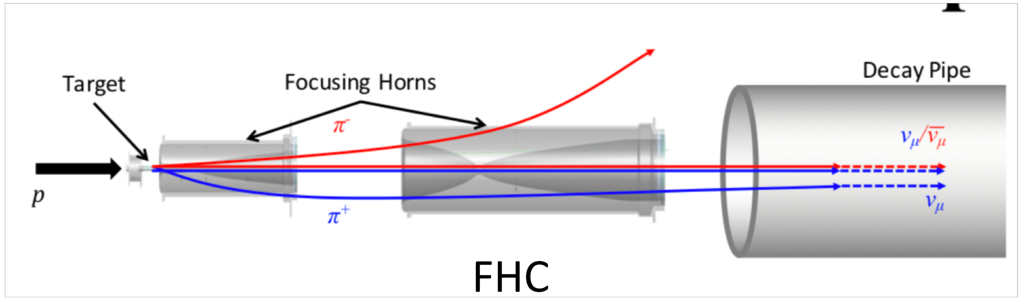


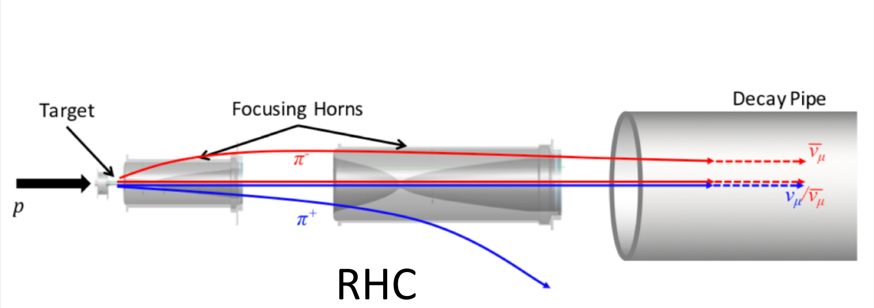


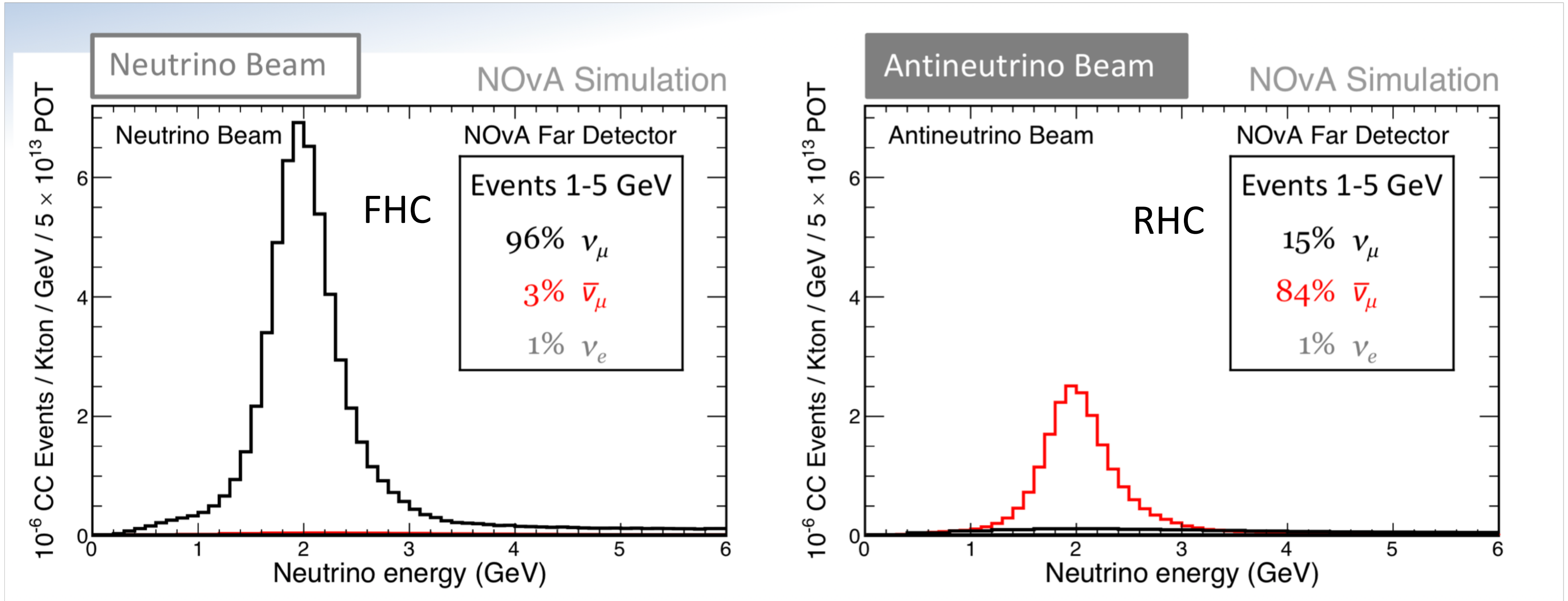
- NOνA is a precision neutrino experiment which uses NuMI (Neutrinos at Main Injector) beam of 740KW
- The detectors is built using highly reflective plastic PVC filled with liquid scintillator (mineral oil + pseudocumene + others)
- Far detector is off-axis by 14mrad because we find a large flux of neutrinos at an energy of 2 GeV, the energy at which oscillation from muon neutrinos to electron neutrinos is expected to be at a maximum.

Comparison of two modes of NuMI beam

Wrong Sign contamination in RHC is "fraction of neutrinos in antineutrino dominant beam"

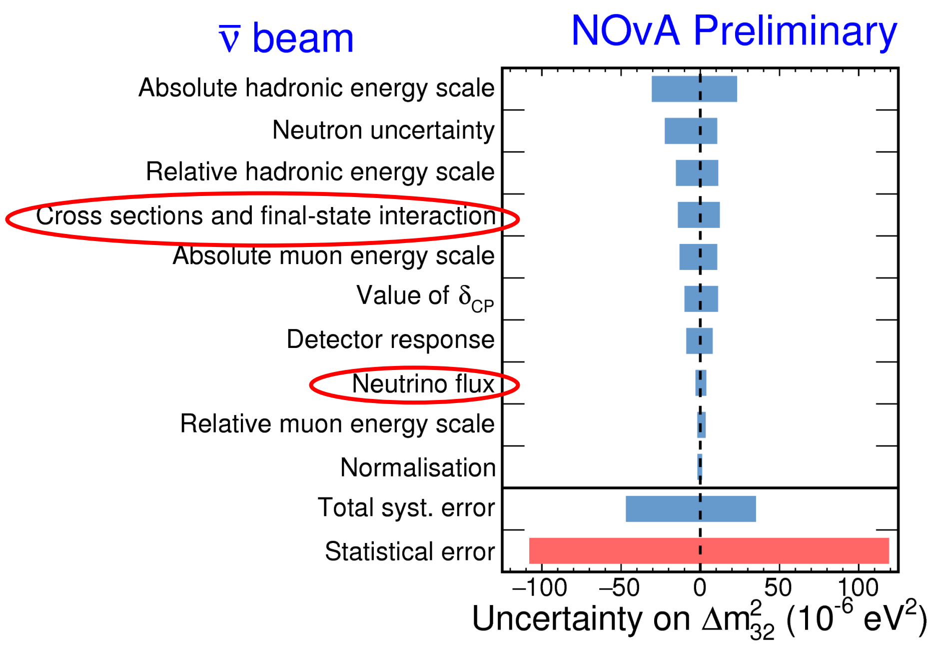


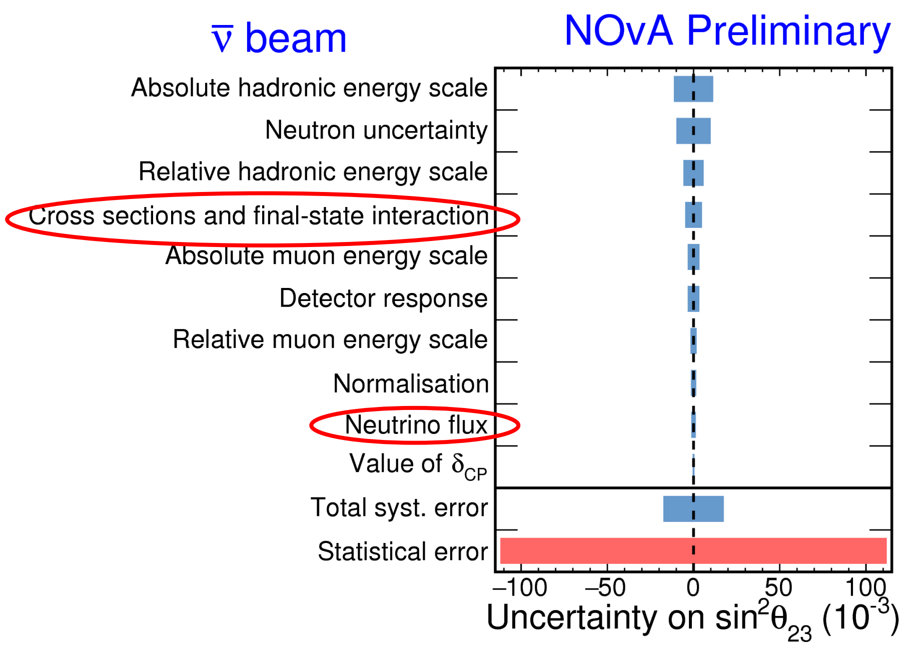




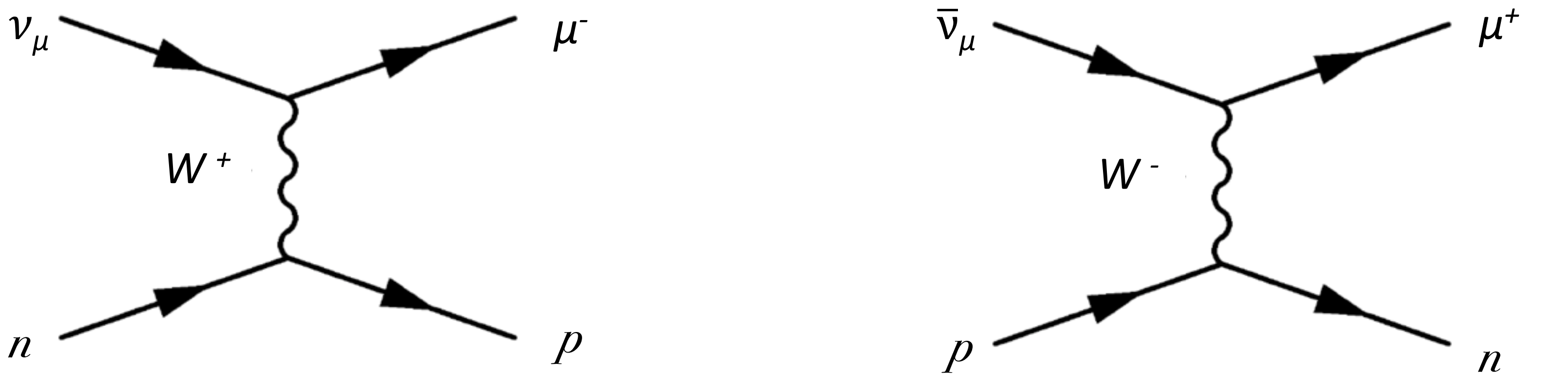
Why should we estimate wrong sign contamination precisely

- If we don't estimate neutrinos and antineutrinos in the beam precisely it throws off our mass hierarchy and δ_{cp} measurements because these are done based on difference between ν_e and $\bar{\nu}_e$ appearance.





ν_μ CC interactions



- Neutrinos produce μ^- and more likely proton as end product
- Antineutrinos produce μ^+ and more likely neutron as end product

Different approaches in NOνA

Data-driven methods used for providing a cross check of the simulated wrong-sign component of the antineutrino (RHC) beam using ν_e and ν_μ near detector (ND) selections.

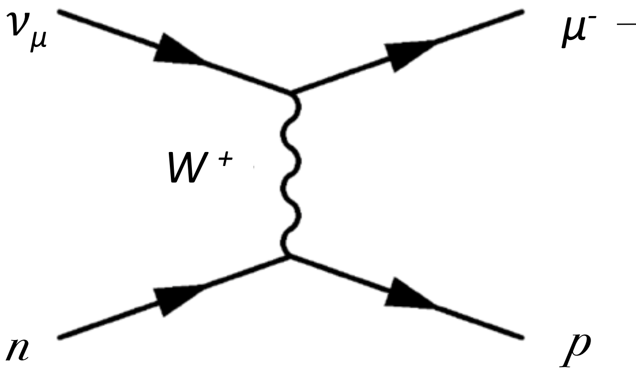
1. **Neutron Capture method**

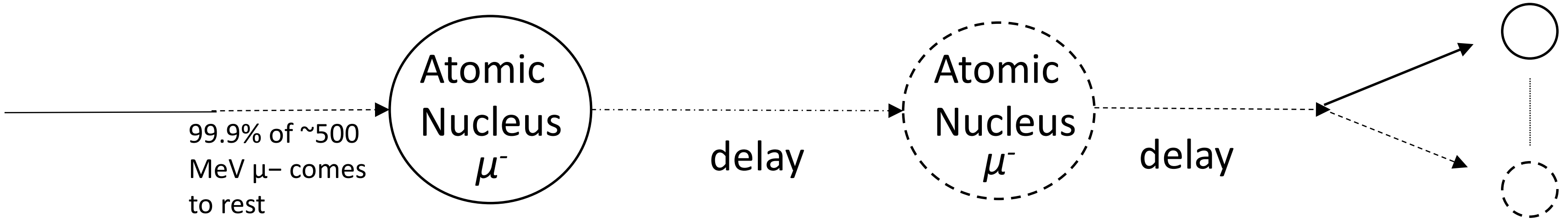
2. **Event level classification** of proton and non-proton events using machine learning (Event CVN Proton ID)

3. **Proton track identification** using machine learning (Prong CVN Proton ID)

4. **Boosted Decision Tree** (BDT): ν and $\bar{\nu}$ classification

Wrong Sign using neutron capture



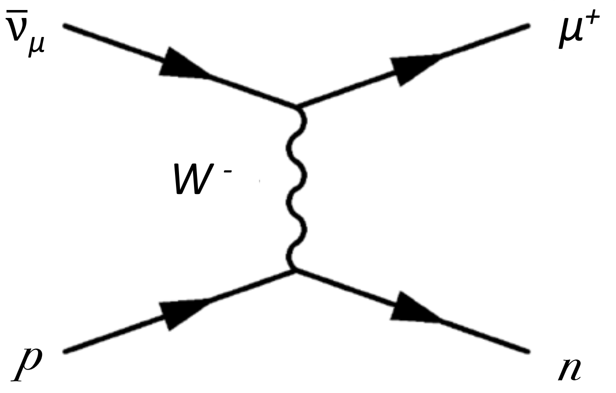


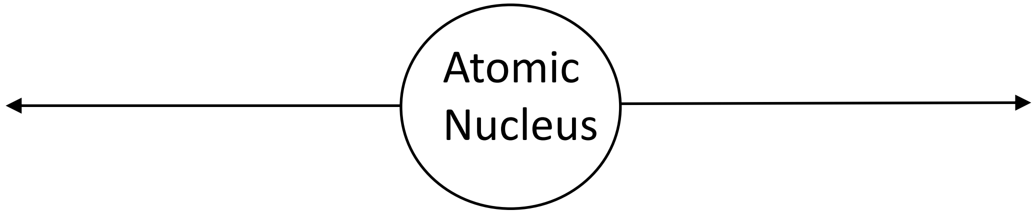
Muons captured in nucleus

~1-10 MeV
Neutrons are released

Catch:

1. π⁻ get captured and produce neutrons too.
2. Pile up



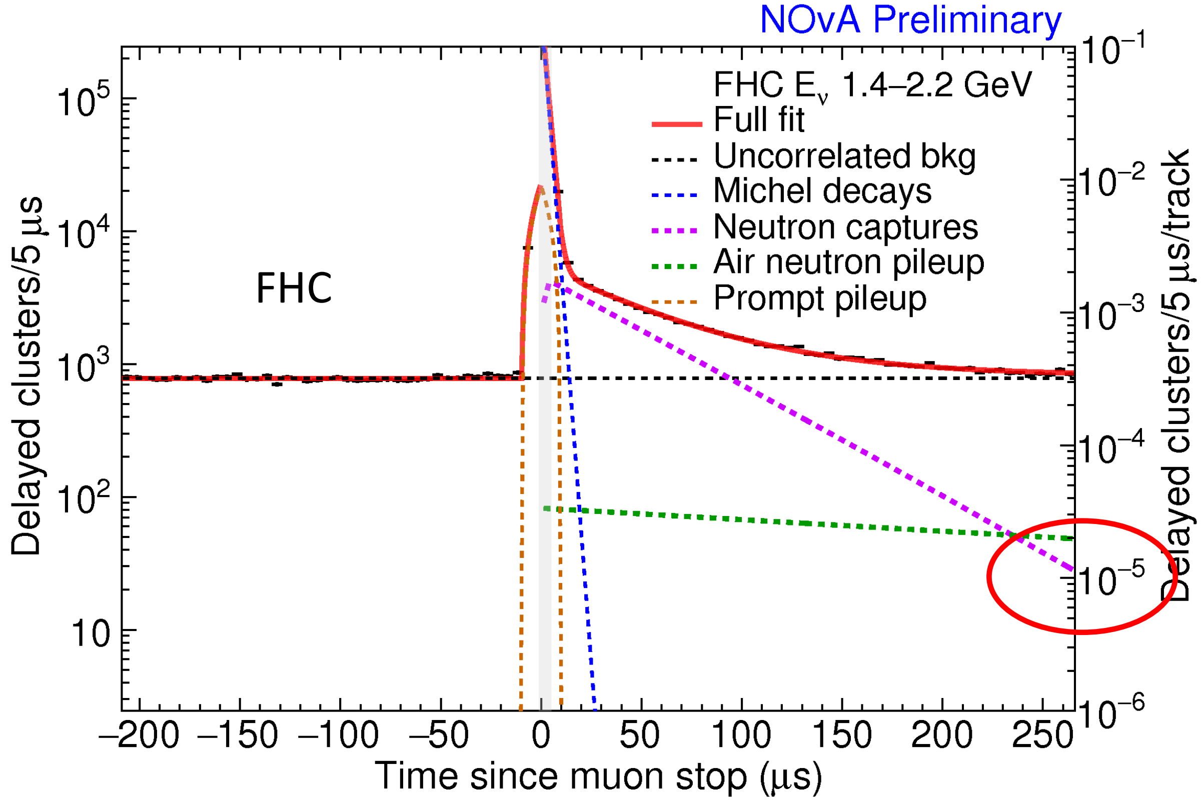


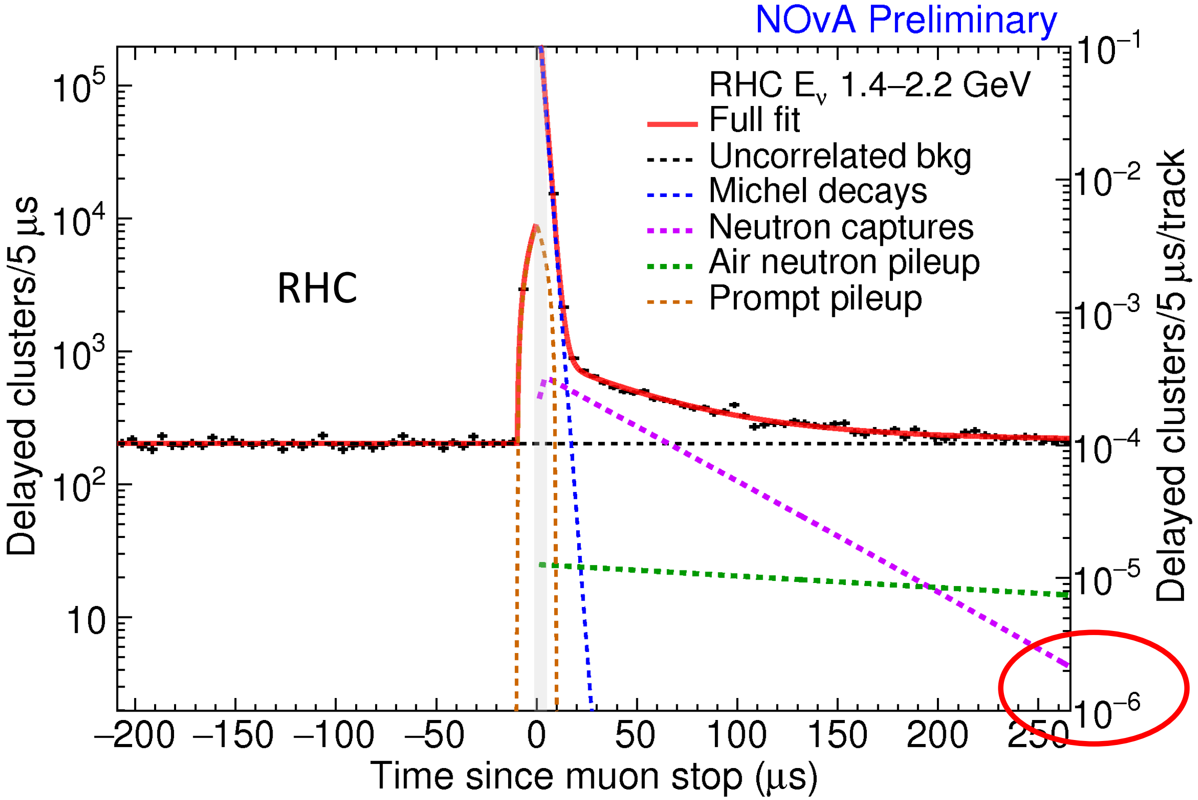
Muons repelled by nucleus
Because of positive charge

Prompt neutron

Wrong Sign using neutron capture

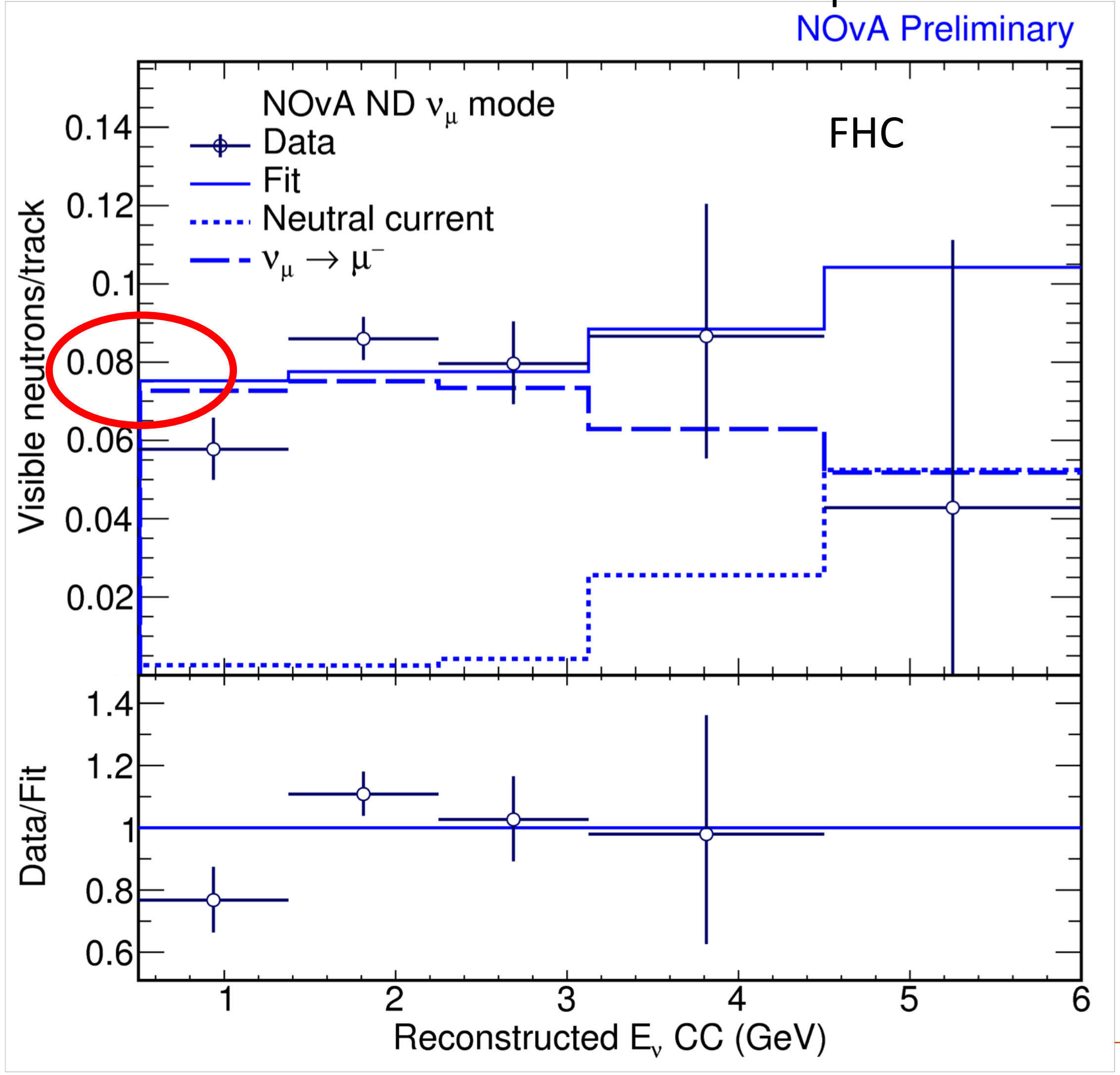
Relatively small number of neutrons are produced per selected track in RHC data, because μ^{+} are not captured by nuclei.

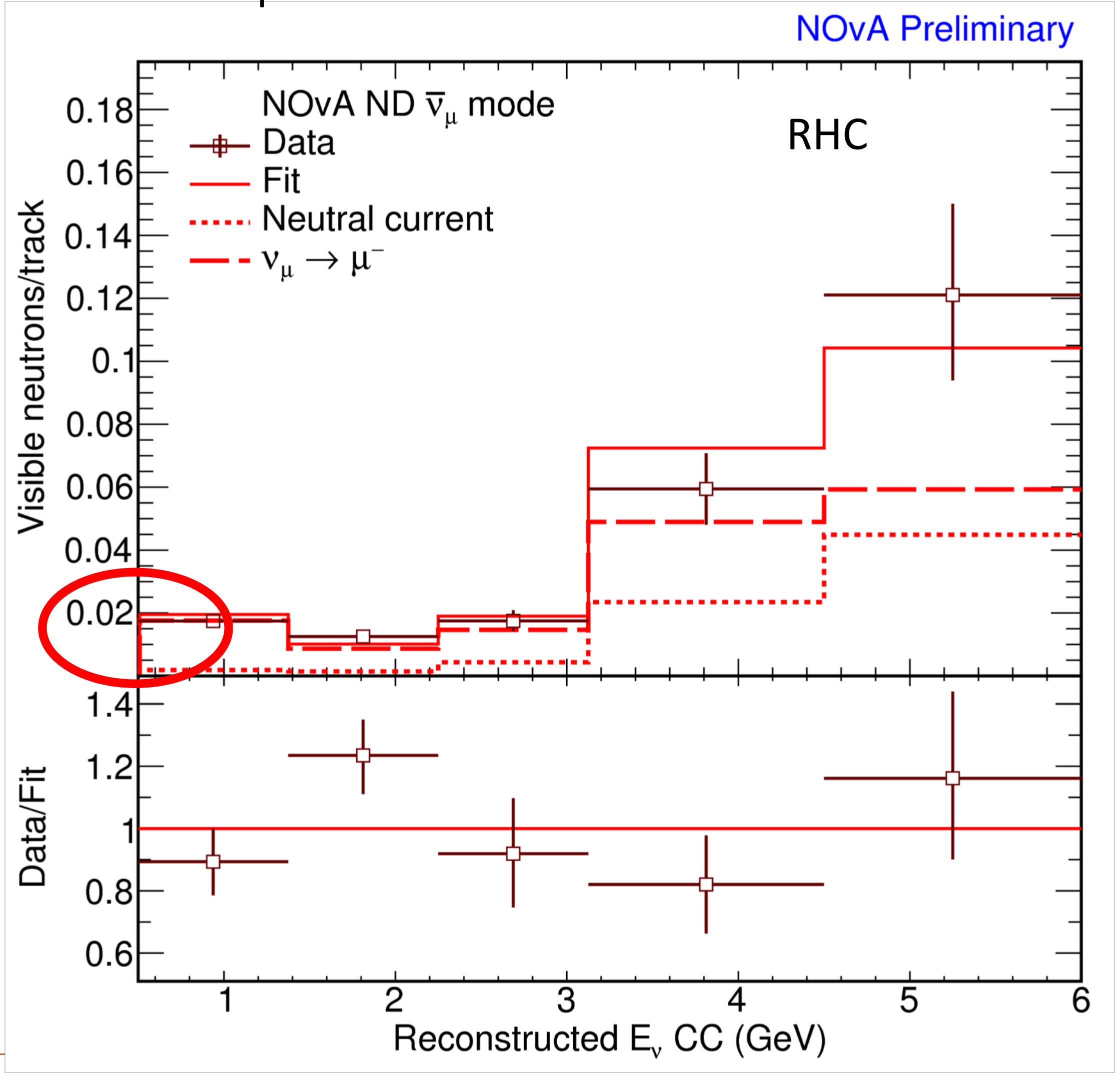




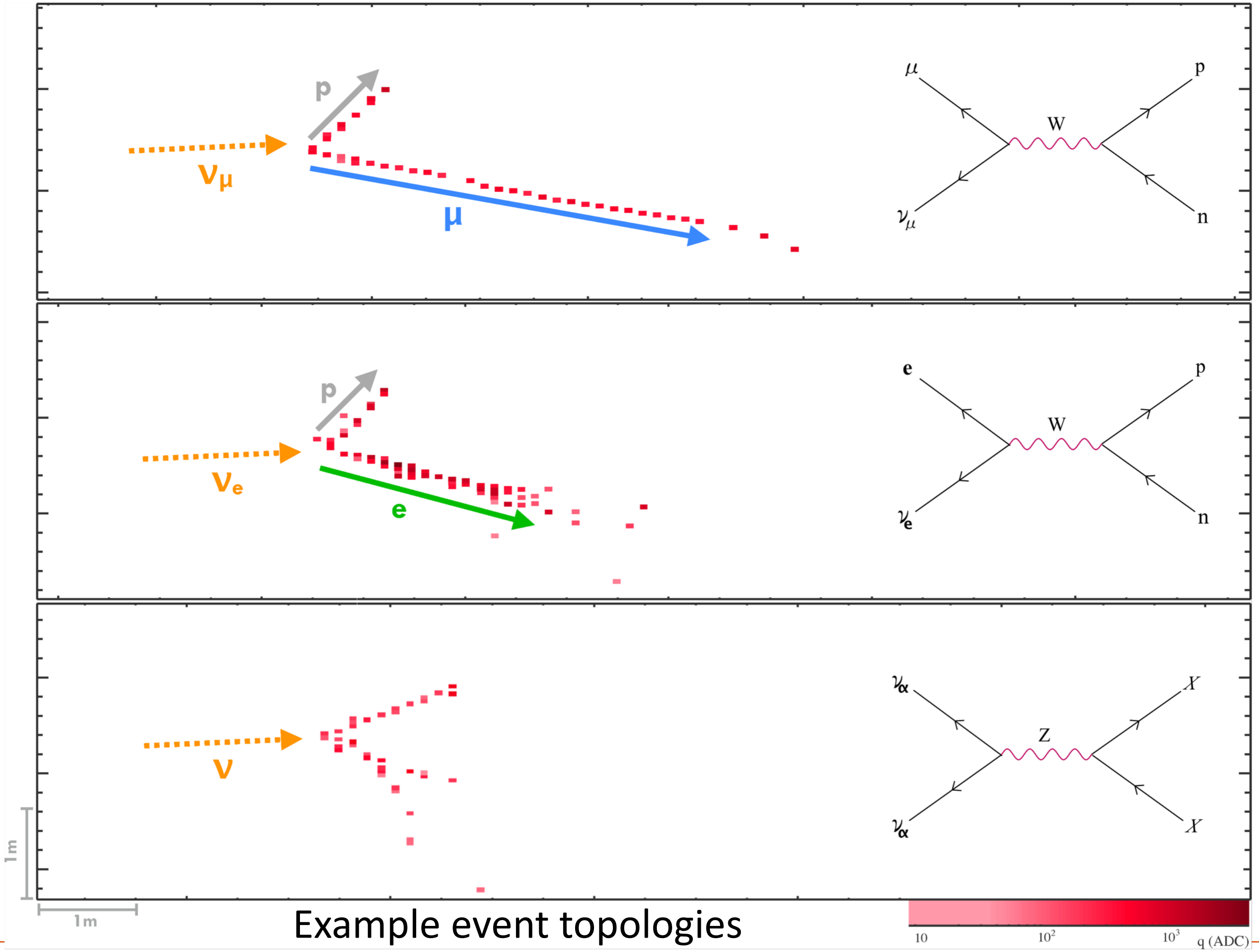
Wrong Sign using neutron capture

Monte Carlo template fit with data for Neutrons per track



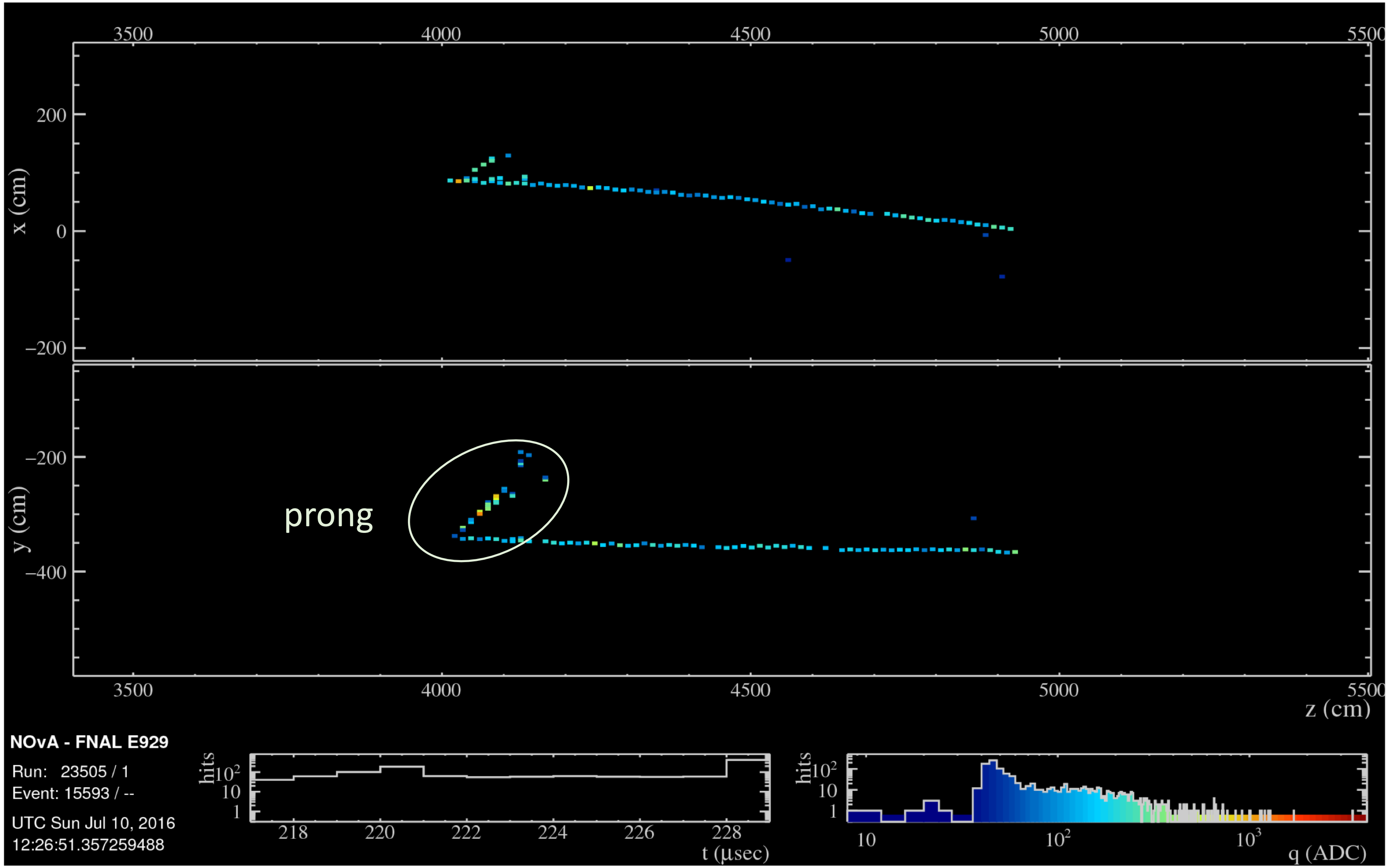


Wrong Sign estimation using Event level classification



Example event topologies

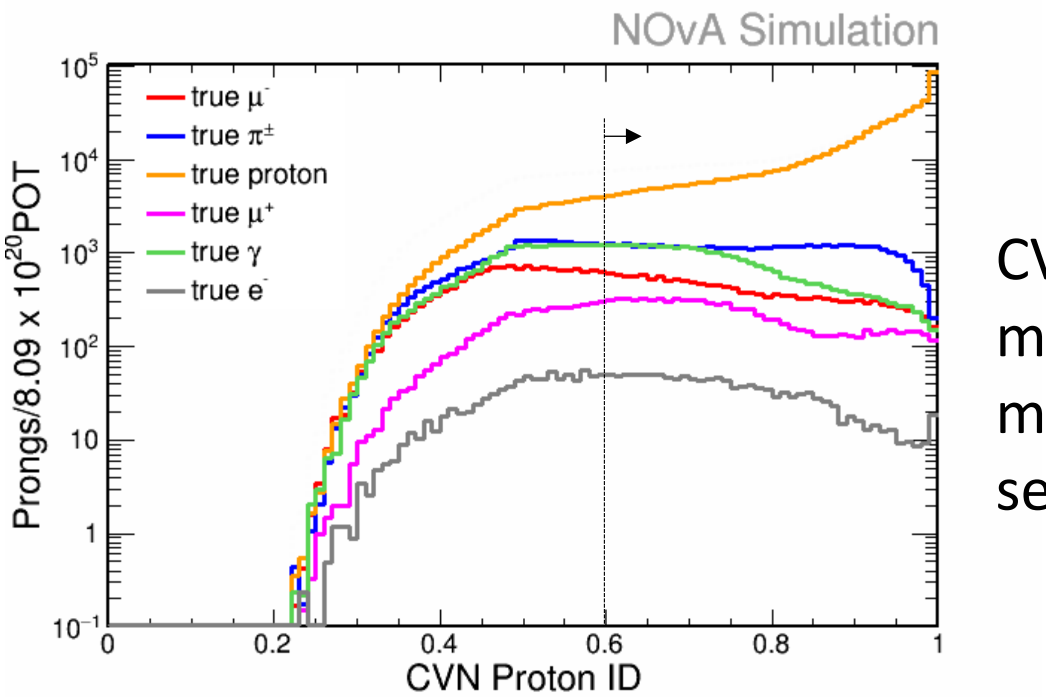
What is a Prong?



Example of selected RHC event

Proton track identification using machine learning (Prong CVN Proton ID)

- We can also use CVN deep learning classification algorithm to classify prongs based on particle type rather than events neutrino topology
- Sample is broken into events with 0 protons and those with one or more proton.



CVN distribution of protons selected by the maximum cvn value after the standard muon-neutrino charged-current inclusive selection.

Wrong Sign using BDT (ν_e)

One can also look at isolating ν_e CC events by using certain event topology characteristics with enough separation power and using them as inputs to a Boosted Decision Tree. Several variable are used as input :

1. CVN Final State Proton Score
2. Reconstructed Shower Inelasticity
3. Stretch Factor : $$\Sigma = \frac{\rho_{max,z} - \rho_{mean,z}}{\rho_{mean,z} - \rho_{min,z}}$$
4. dE/dx energy deposition in first few planes
5. Max. Prong CVN Proton Score (For 2+ prong events)
6. Gap from Vertex (for Max. Prong CVN Proton Score Prong – For 2+ prong events)

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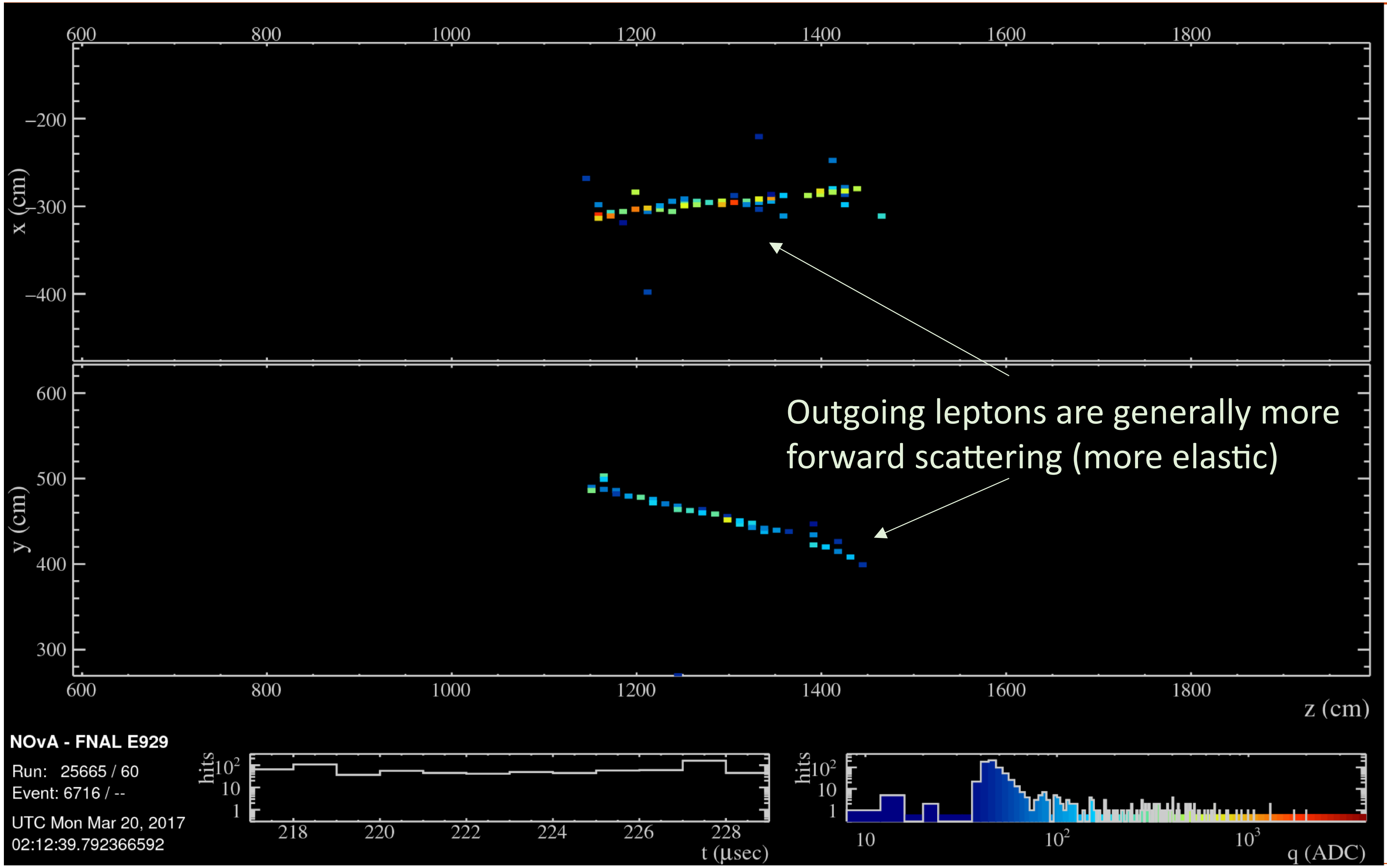
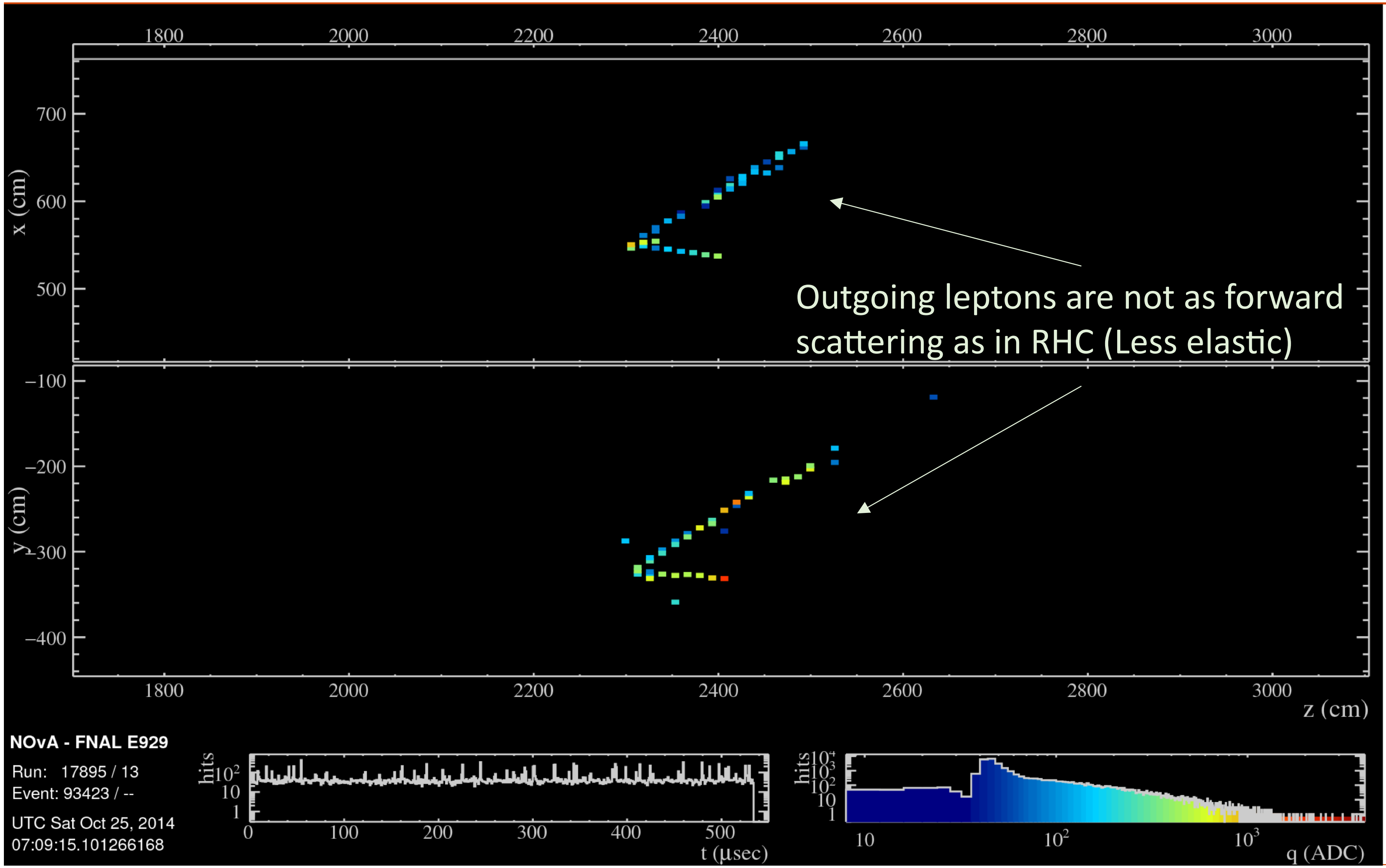
Example: RHC event display



Example: FHC event display



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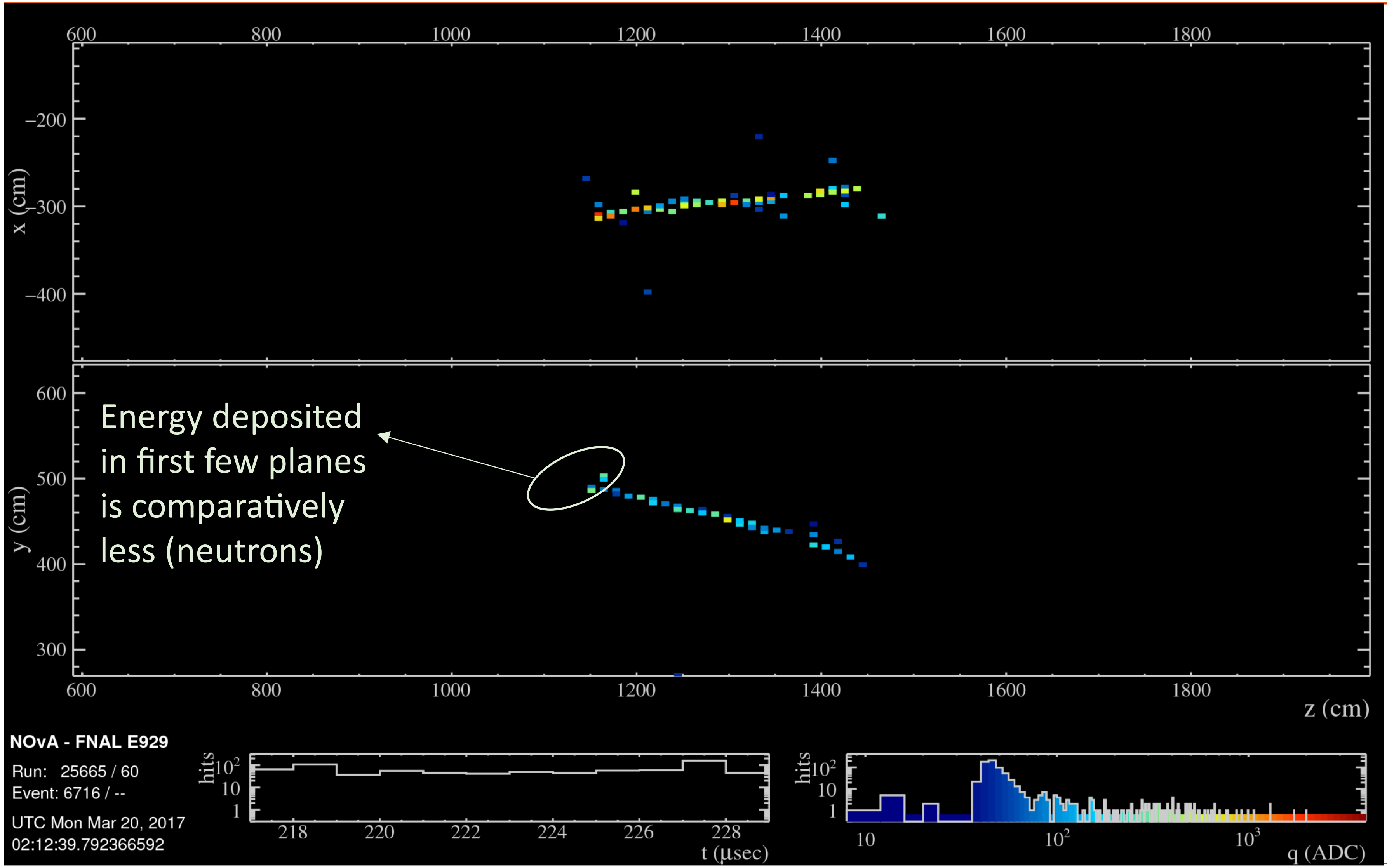

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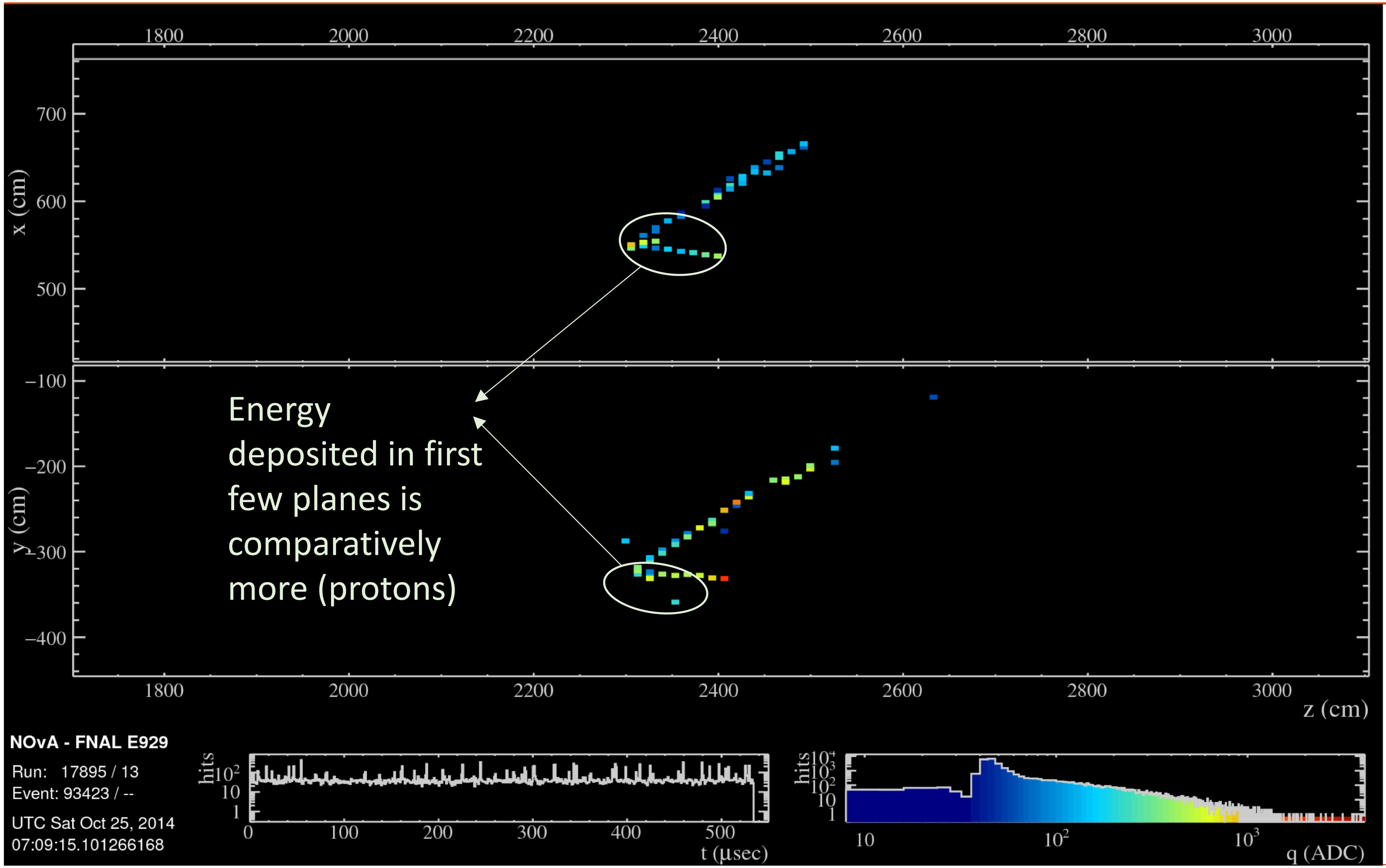

Wrong sign in BDT (ν_μ) - Ongoing

One can also look at isolating ν_μ CC events by using certain variables with enough separation power by using them as inputs to a Boosted Decision Tree.

Two sets of variables are used: Raw hits and calibrated hits . This was done to see if calibration has influence on our Wrong Sign estimate.

1. Hadronic energy or hadronic hits

2. Direction cosine angle of muons compare to direction of beam

3. Total energy or total hits

4. Muon energy or muon hits

5. Orphan hits (hits not grouped into any clusters)

6. Michel electrons

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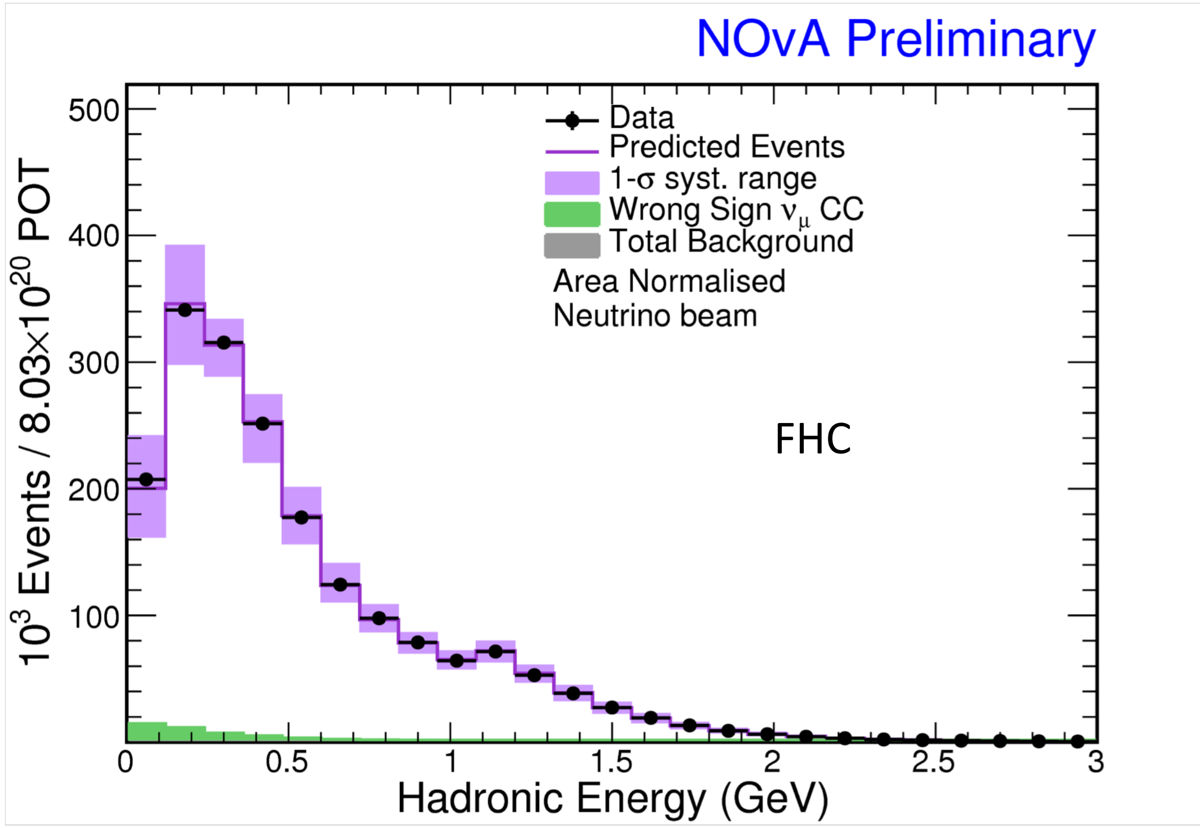
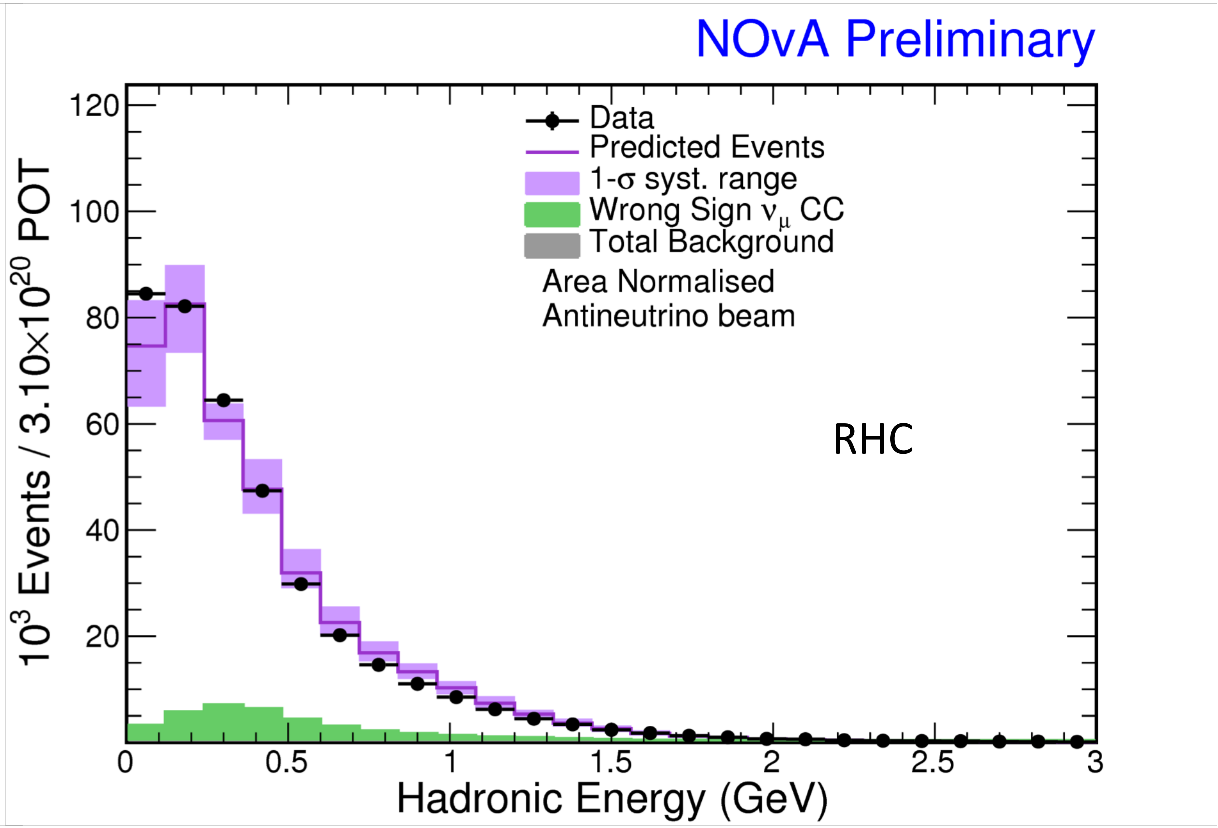
Hadronic Energy





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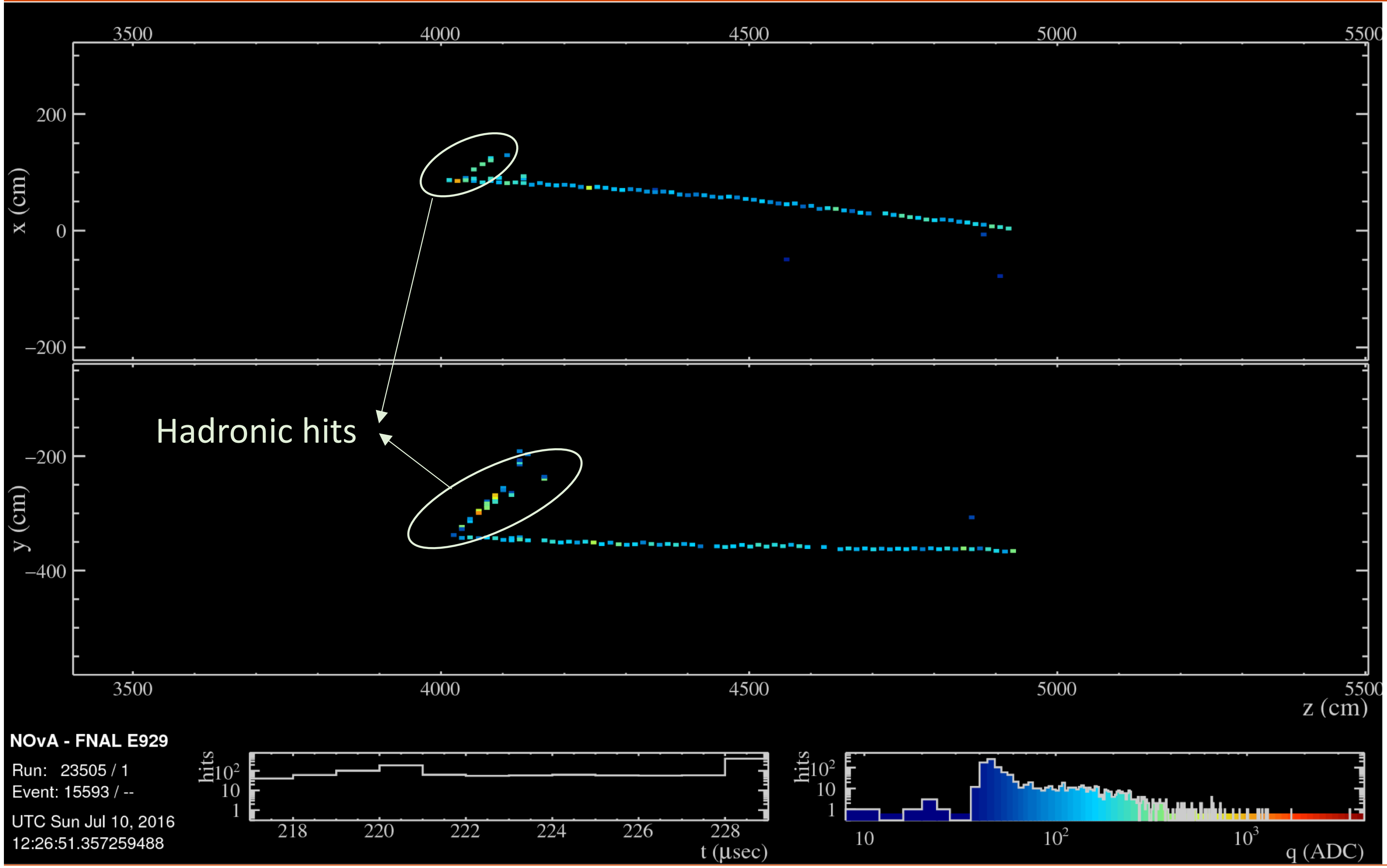

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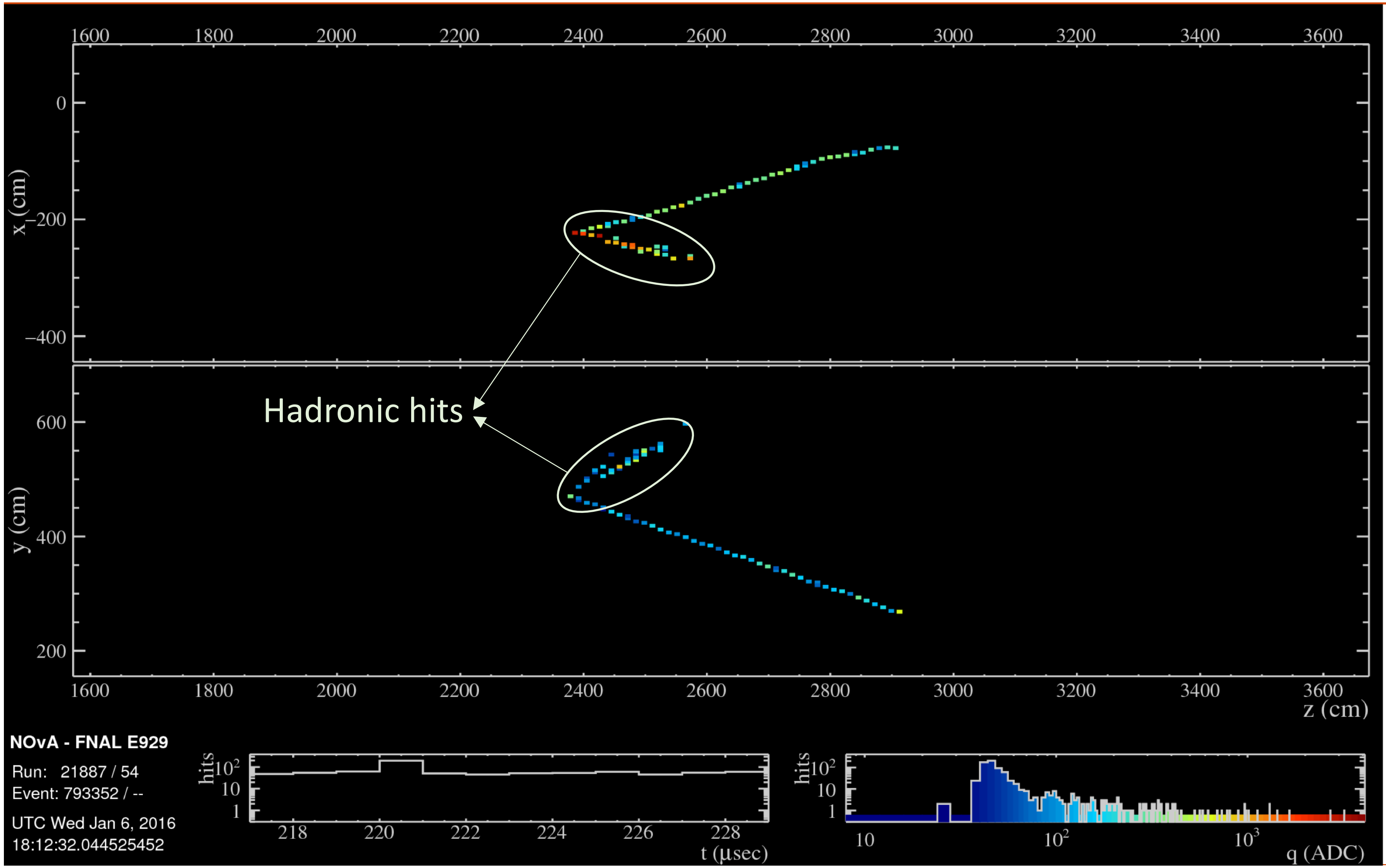

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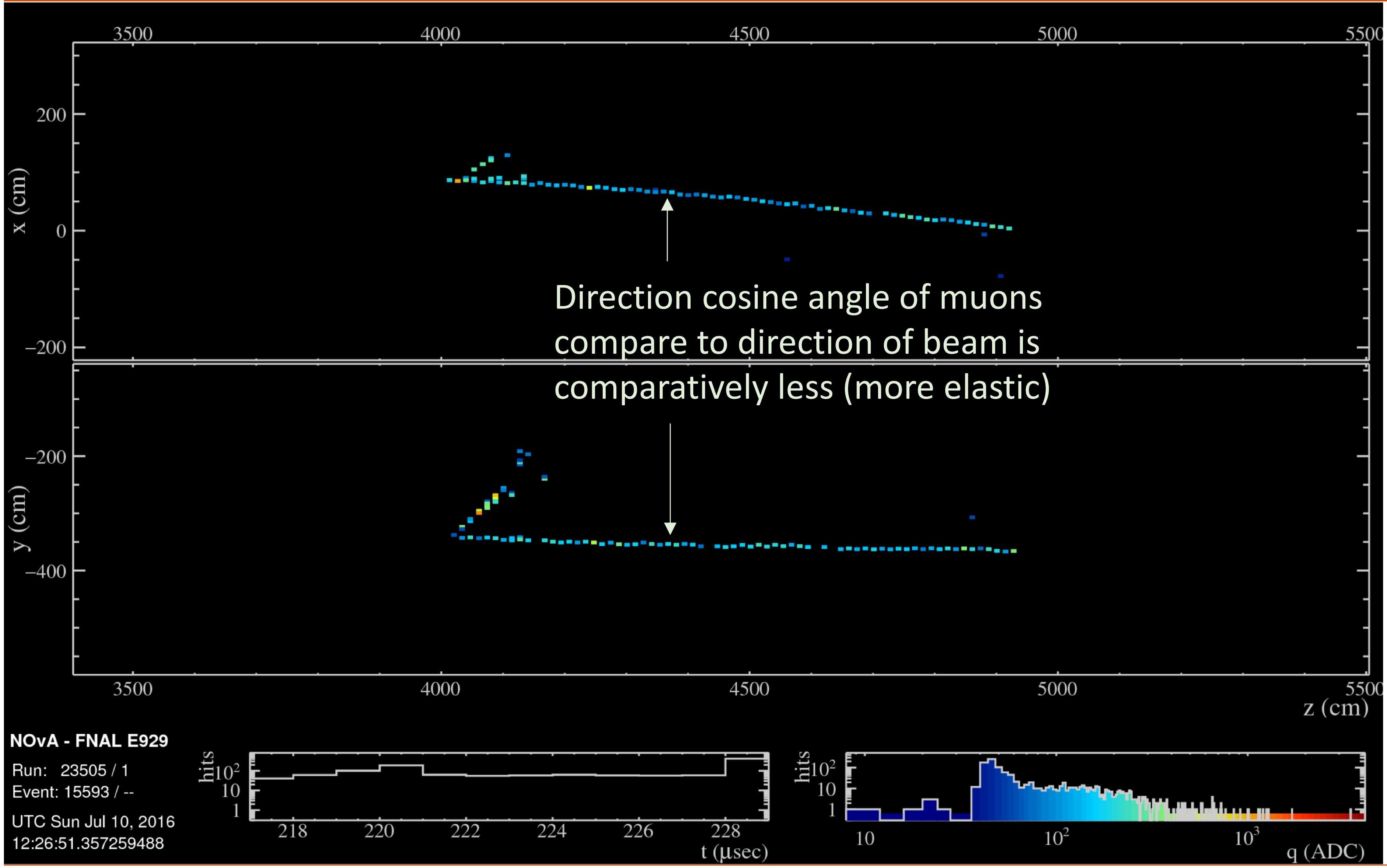

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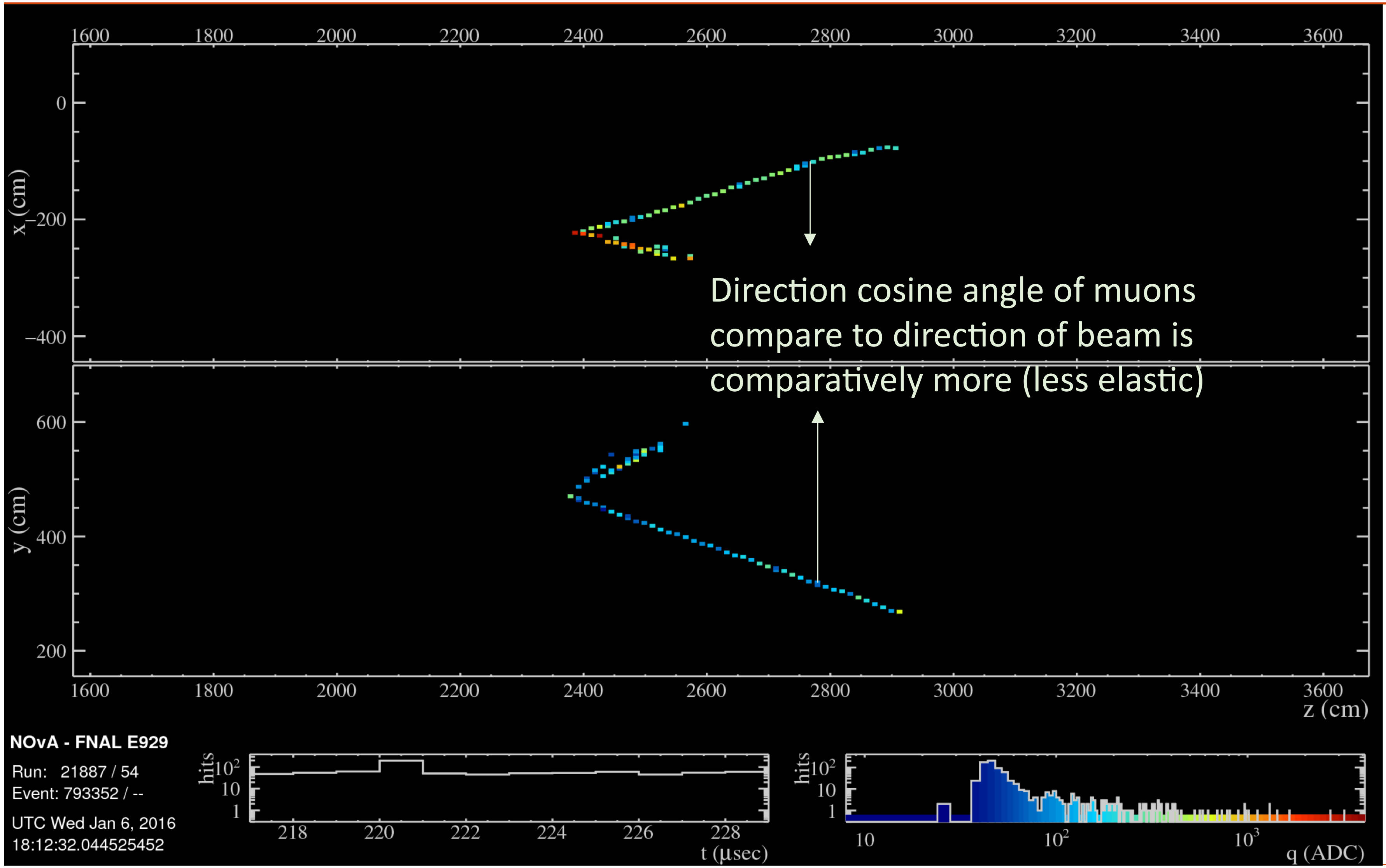
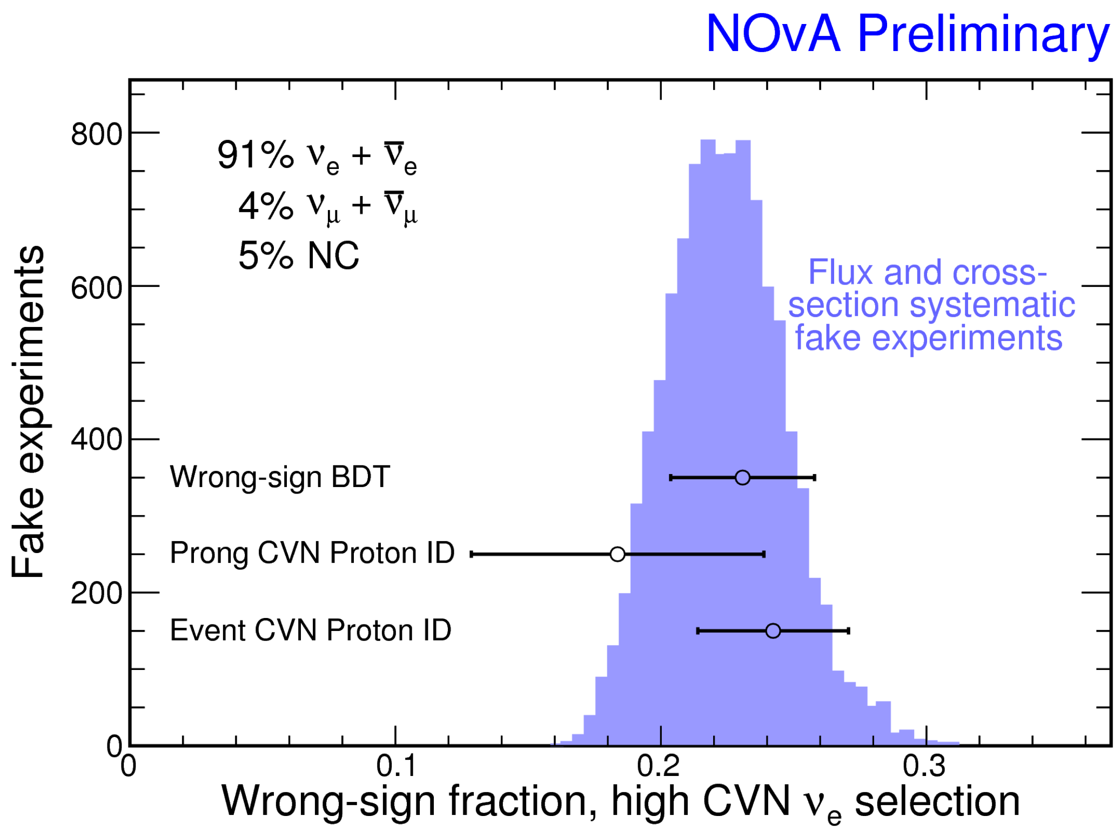
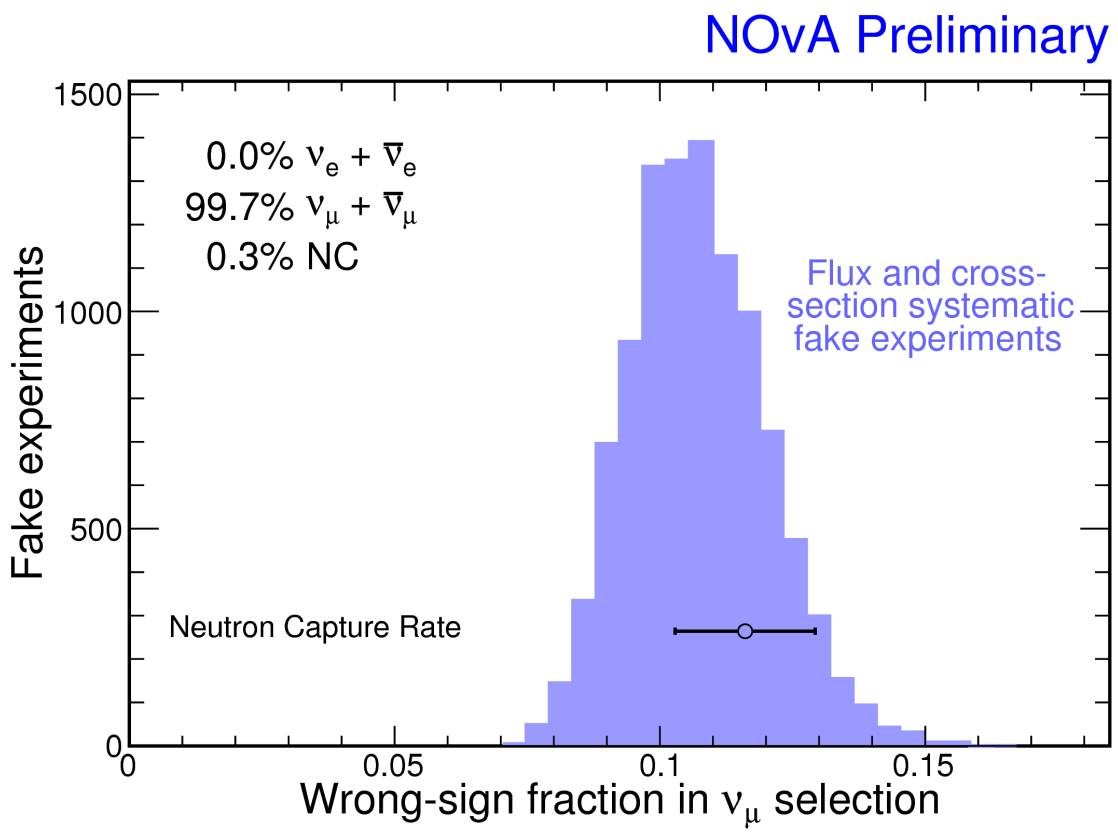


Results


NOvA Preliminary
91% $\nu_e + \bar{\nu}_e$
4% $\nu_\mu + \bar{\nu}_\mu$
5% NC
Flux and cross-section systematic fake experiments
Wrong-sign BDT
Prong CVN Proton ID
Event CVN Proton ID
Fake experiments
0
200
400
600
800
0
0.1
0.2
0.3
Wrong-sign fraction, high CVN ν_e selection


NOvA Preliminary
0.0% $\nu_e + \bar{\nu}_e$
99.7% $\nu_\mu + \bar{\nu}_\mu$
0.3% NC
Flux and cross-section systematic fake experiments
Neutron Capture Rate
Fake experiments
0
500
1000
1500
0
0.05
0.1
0.15
Wrong-sign fraction in ν_μ selection

Conclusion

- It is important to estimate the Wrong sign contamination to get neutrino oscillation parameters right
- An Event can be classified into neutrino or antineutrino event by looking at their end products and kinematic variables
- Various data-driven cross checks has been done to estimate wrong sign contamination in RHC
- Results show that the estimated wrong sign contamination from different methods agree with each other and our simulation

Thank you for your patience.

Questions ??

Backup slides

Computing wrong sign fraction

1. S = integrated νe+ νμ + NC(ν)
2. B = integrated ν̄e + ν̄μ + NC(ν̄)
3. D = integrated selected data
4. RS = right-sign enhanced selection (falls to one side of method)
5. WS = wrong-sign enhanced selection (falls to other side of method)

$$\alpha B_{RS} + \beta S_{RS} = D_{RS}$$
$$\alpha B_{WS} + \beta S_{WS} = D_{WS}$$

→

$$\mathcal{M} = \begin{bmatrix} B_{RS} & S_{RS} \\ B_{WS} & S_{WS} \end{bmatrix}$$

→

$$\mathcal{C} = \mathcal{M}^{-1} \begin{bmatrix} \sigma_{data,RS} & 0 \\ 0 & \sigma_{data,WS} \end{bmatrix} \mathcal{M}^T$$

Wrong sign fraction is computed using :

$$f = \frac{\Sigma_i \beta_i WS_i}{\Sigma_i(\beta_i WS_i + \alpha_i RS_i)}$$

Wrong sign fraction for neutron capture:

$$f = \frac{\gamma WSCC + \epsilon WSNC}{\gamma WSCC + \epsilon(WSNC + RSNC) + \rho RSCC}$$