NEUTRINO ENERGY RECONSTRUCTION

NOvA detectors response and energy estimation techniques for signal events

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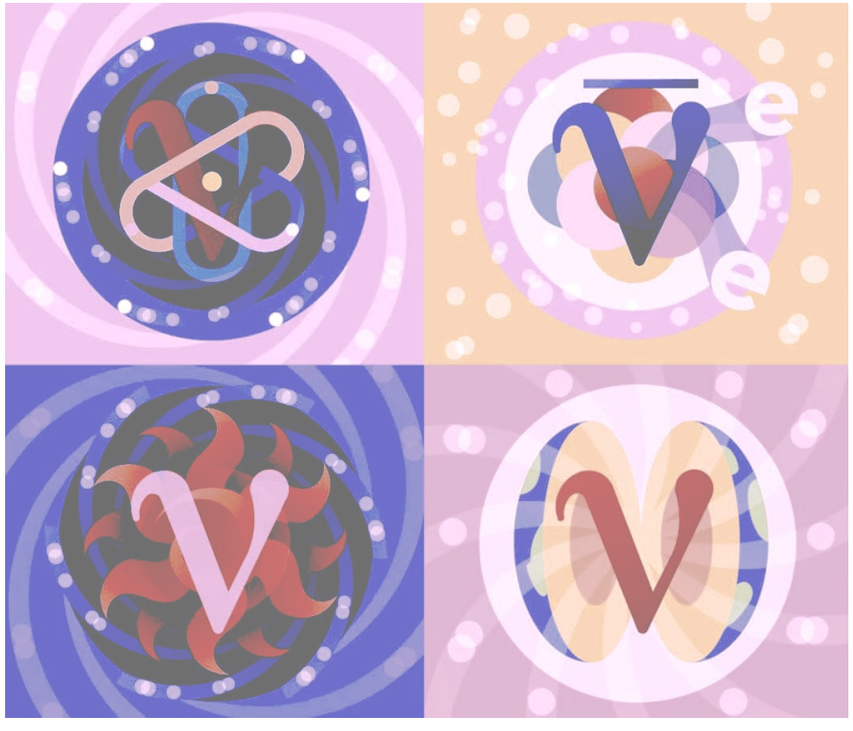
For the NOvA Collaboration

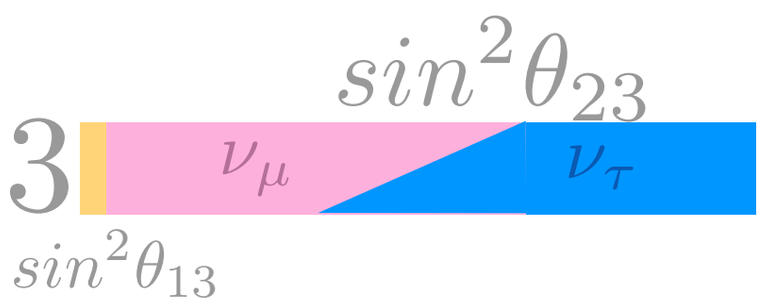


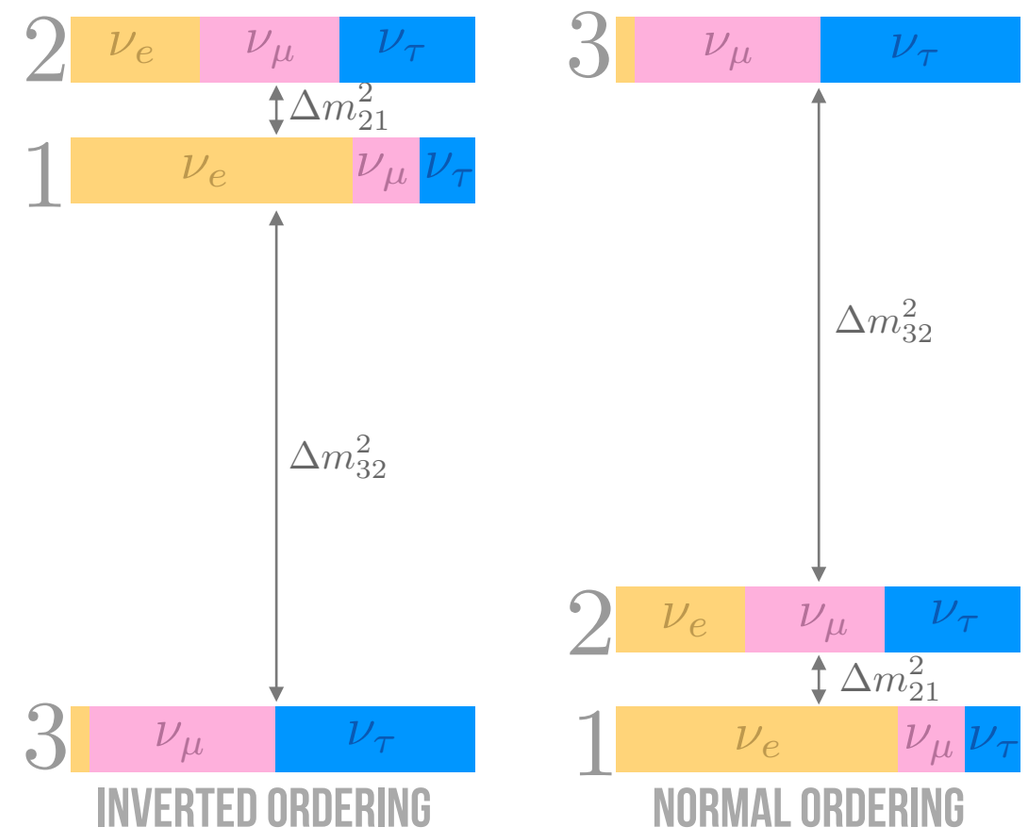
NOvA Physics Goals

$P(\nu_\mu \to \nu_\mu)$

Precision measurements of θ_{23}

Is this mixing maximal?

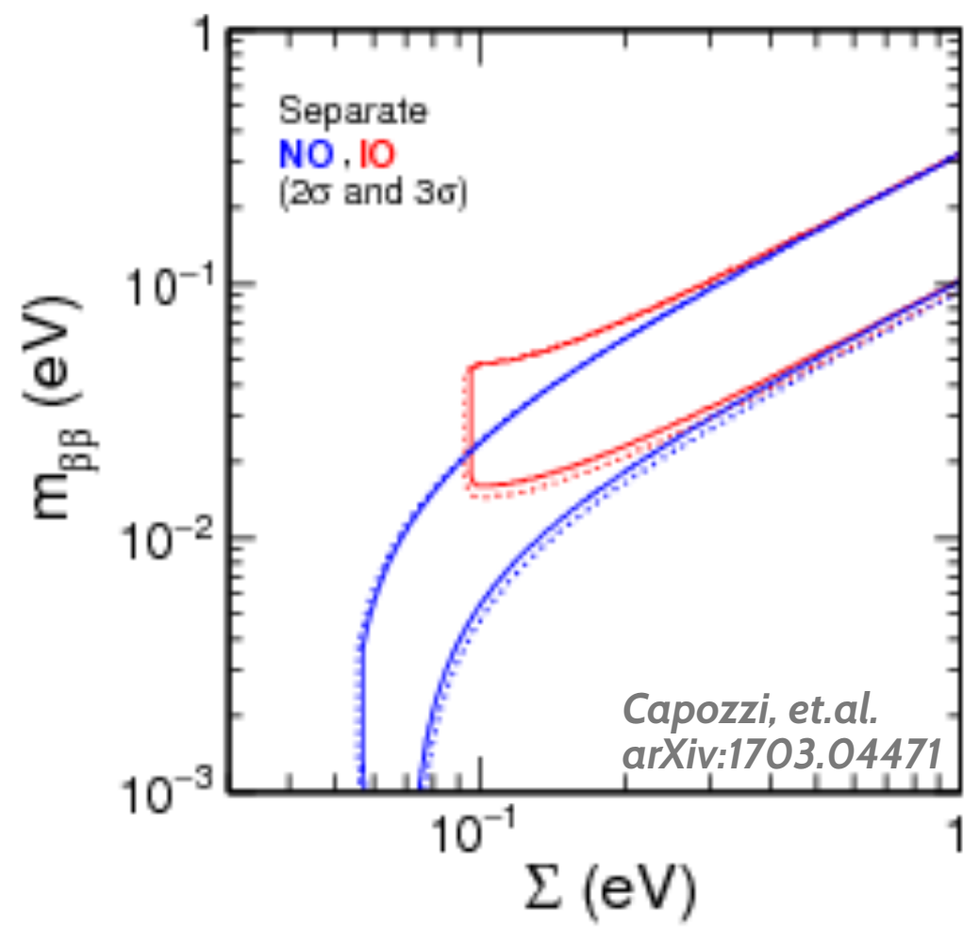




$P(\nu_\mu \to \nu_e)$

Measuring CP violation though δ_{CP} has implications in Leptogenesis (matter-antimatter asymmetry)

Measuring the neutrino mass hierarchy which also sets limits on the absolute mass scale.



The NOvA Experiment

Analyses:

Neutrino Oscillations

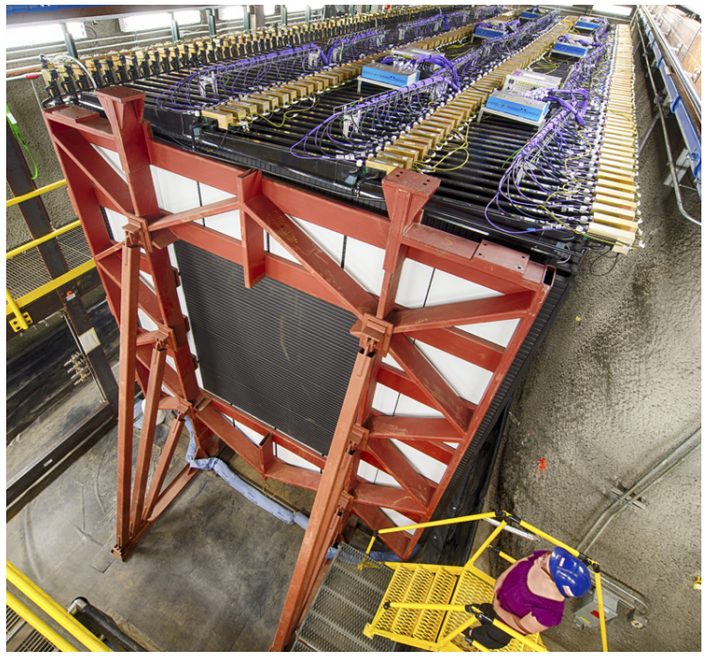
Steriles & NSI Searches

Cross Sections

Supernova Neutrinos,

Cosmic Ray Physics

Exotics Searches.



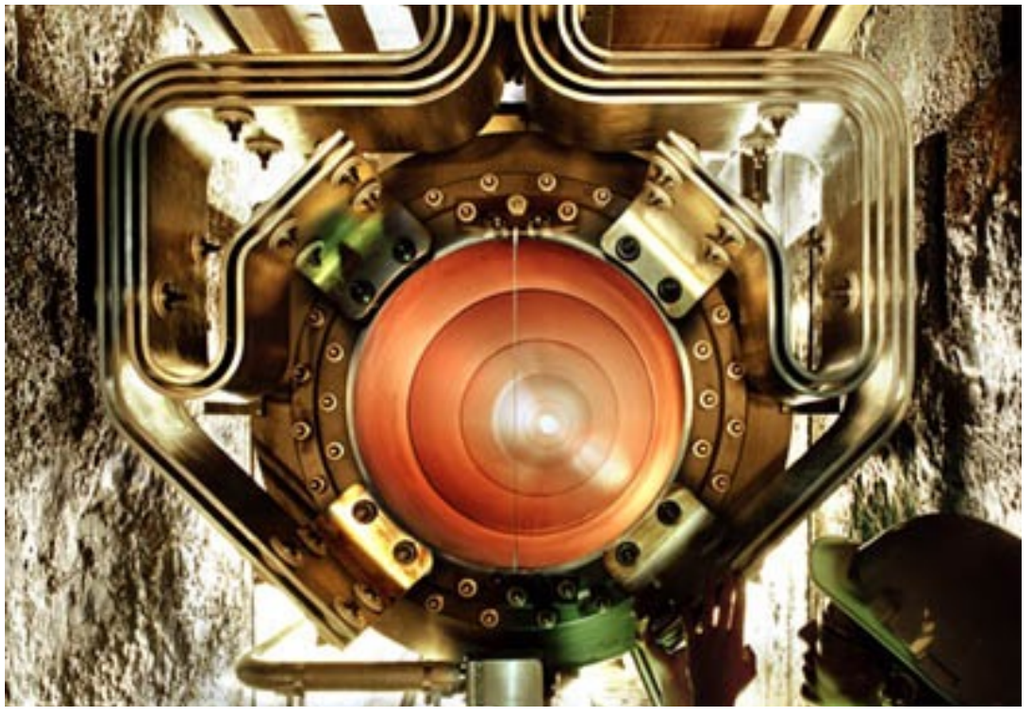
Measurable: A count or energy spectrum of each neutrino flavor.

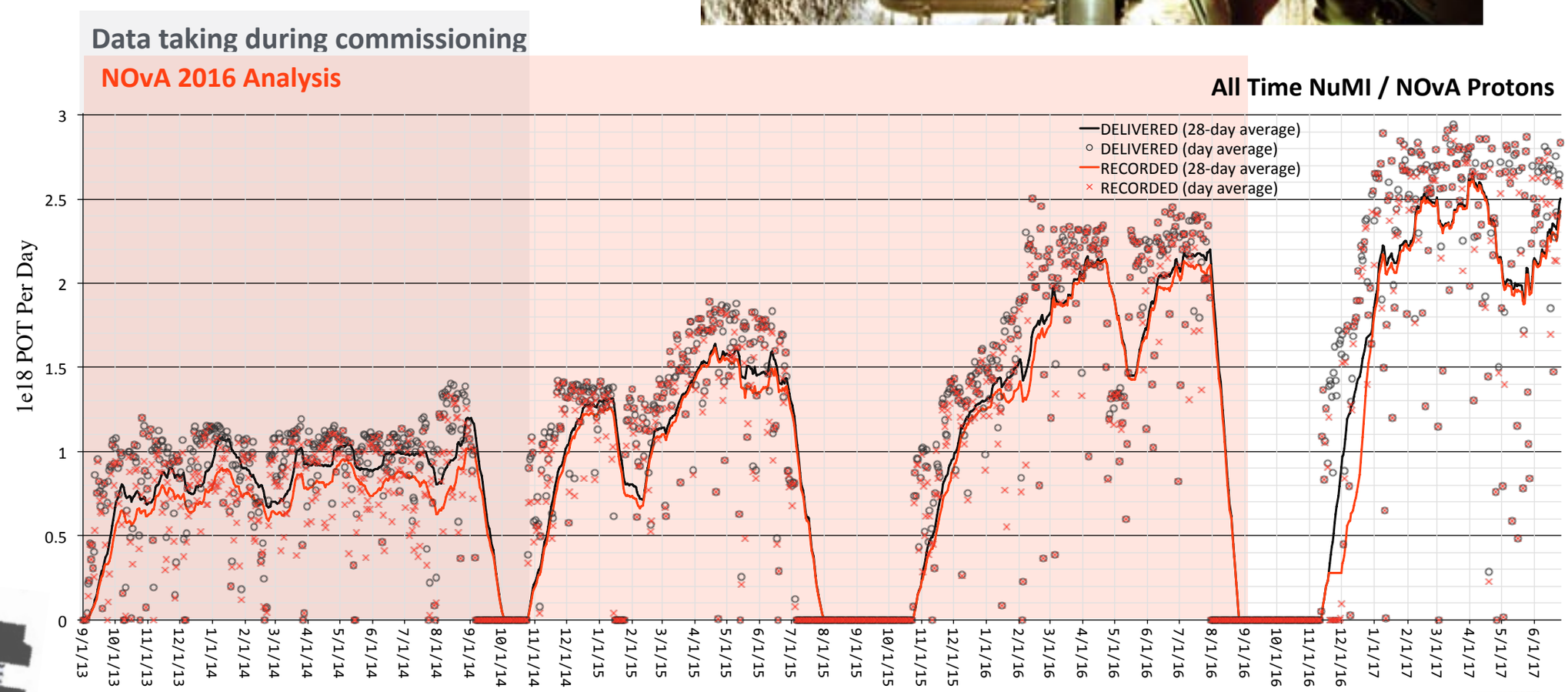
Technology: Two functionally equivalent calorimeters.

The world's most intense neutrino beam

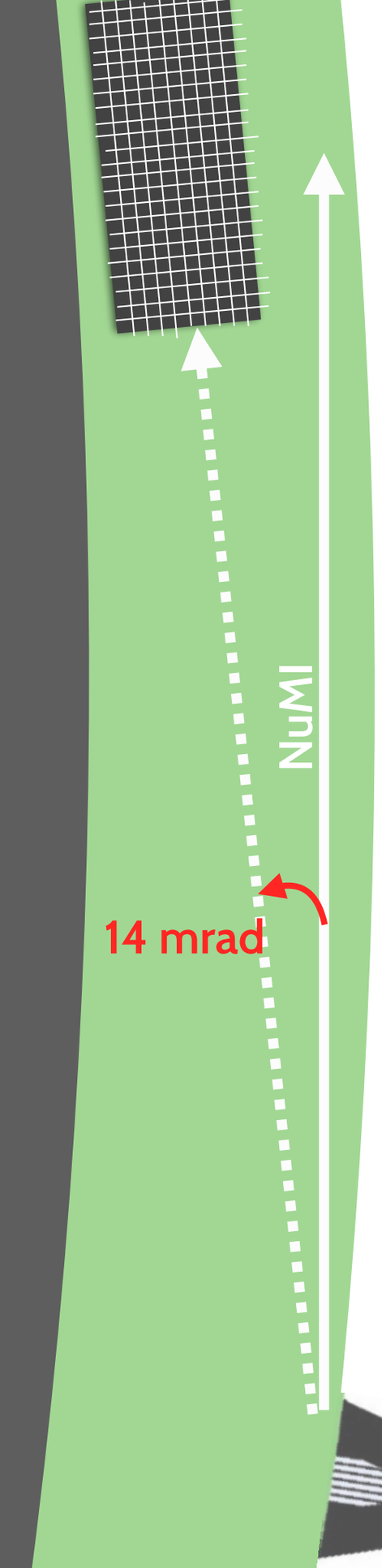
NuMI delivers neutrinos at over 700kW

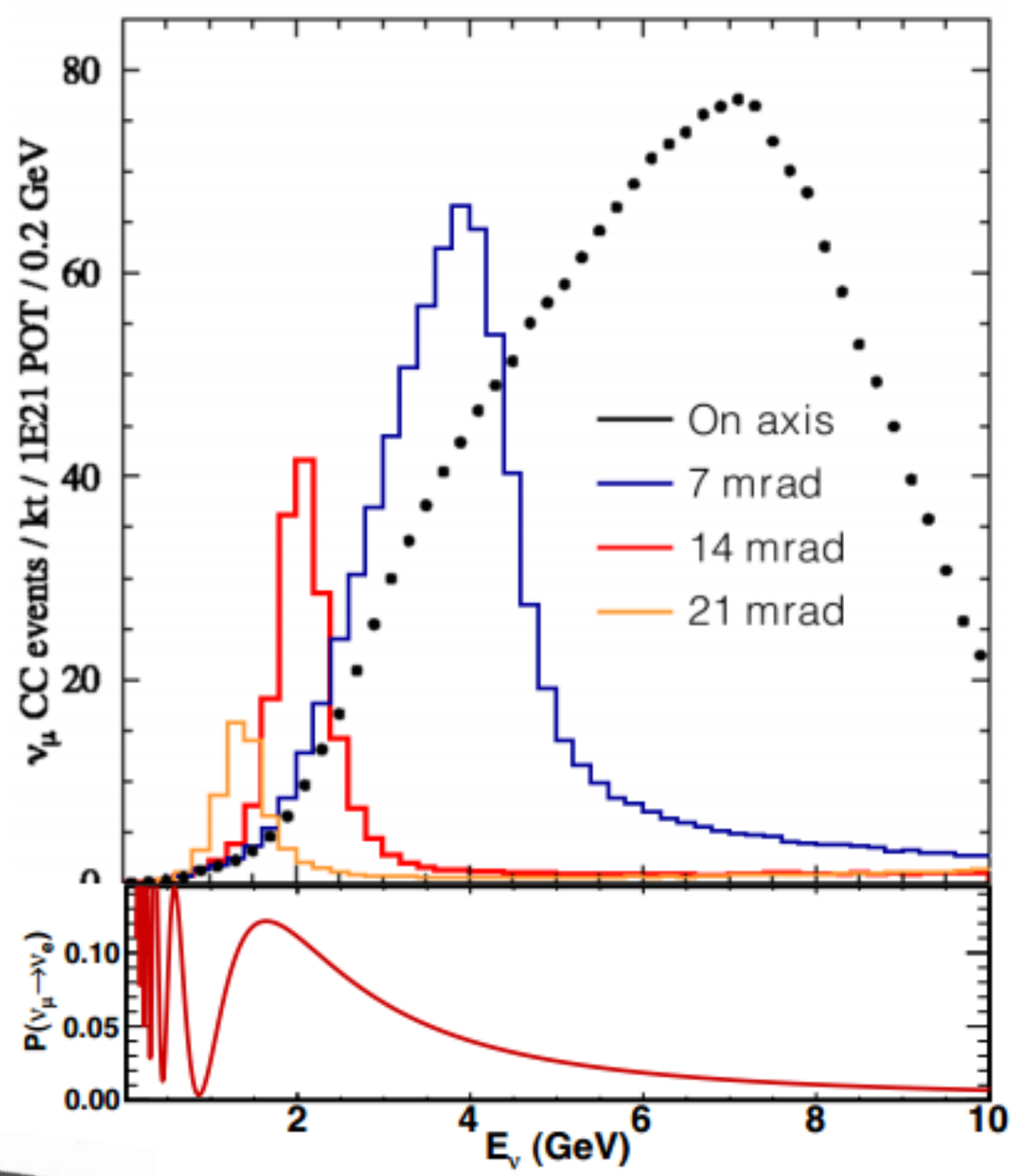
NOvA records NuMI events with > 95% uptime





Strategically positioned detectors





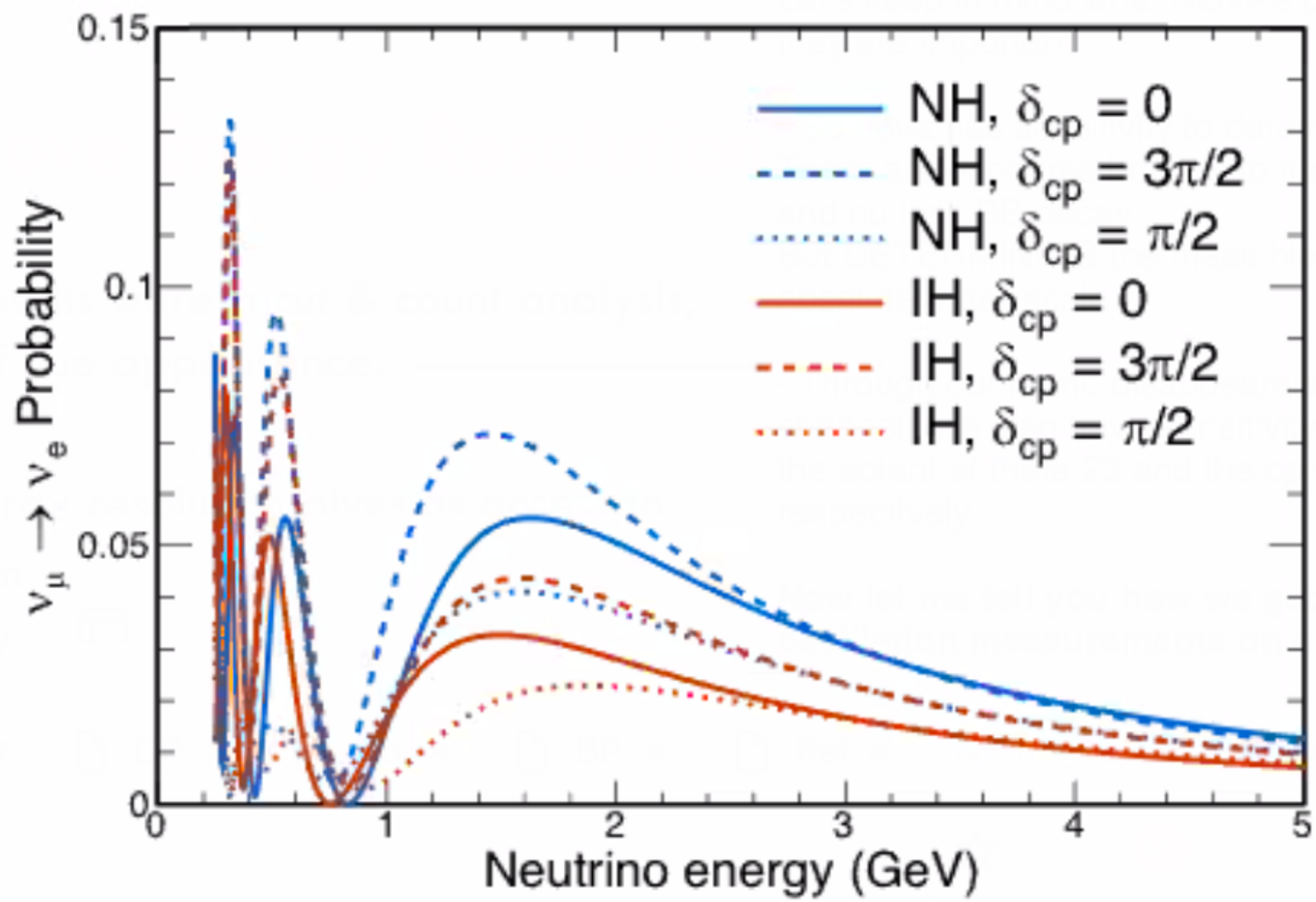
From decay kinematics, the Off-Axis placement constrains NOvA's energy spectrum.

The oscillation maximum at L=810 km is ~2GeV

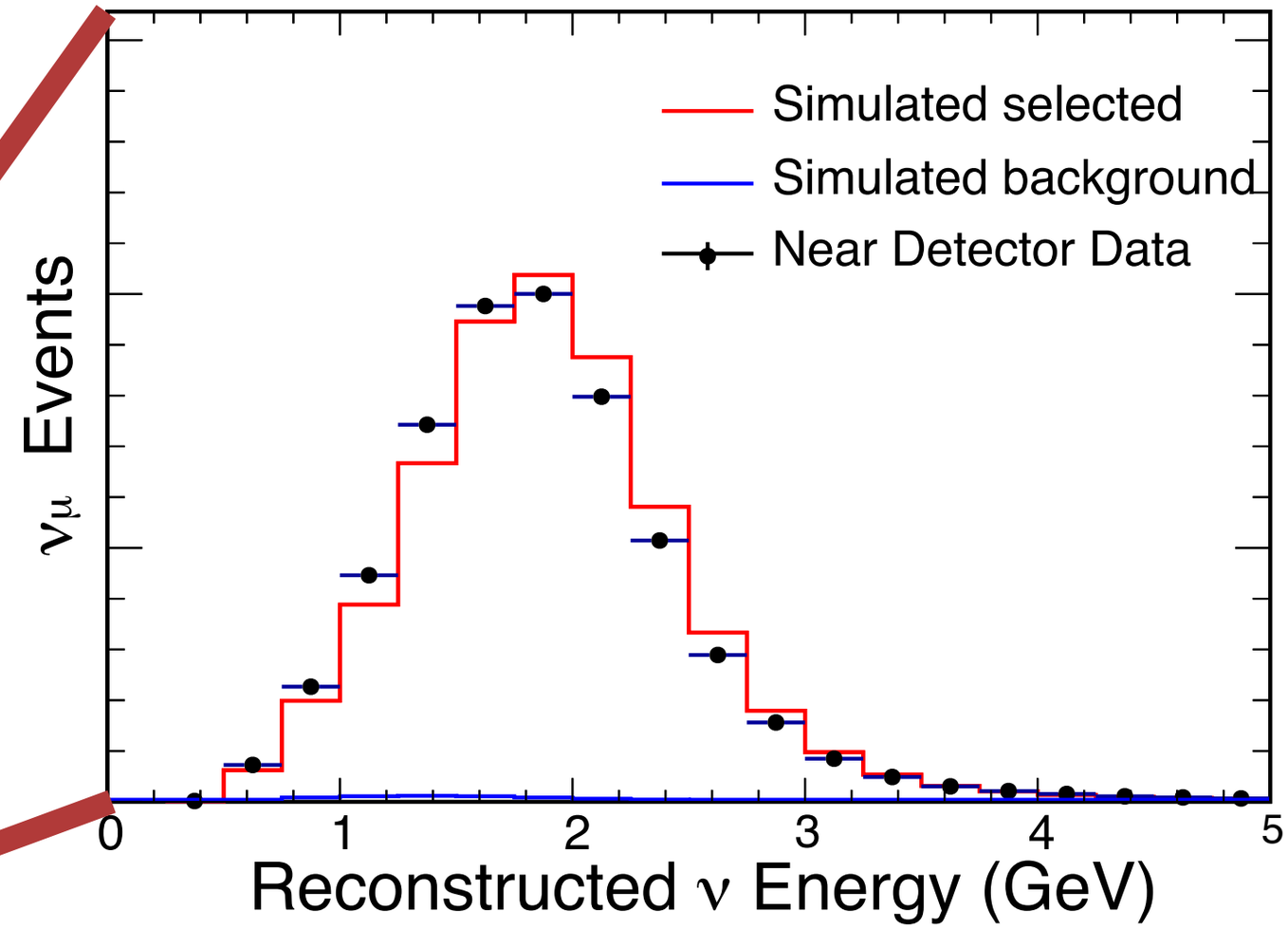
Constraining the energy improves background rejection.

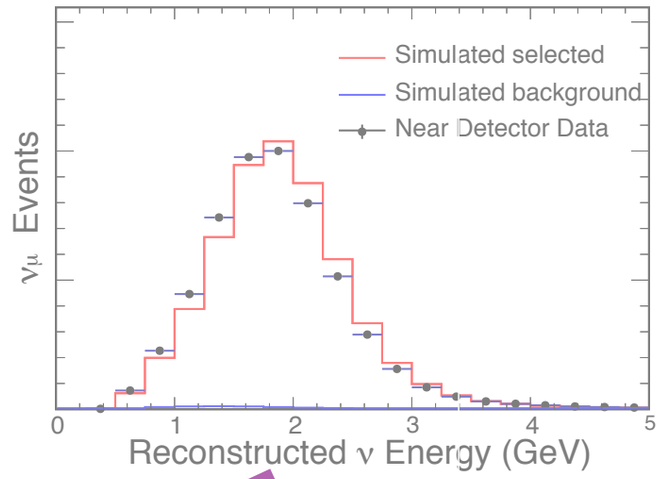
Shape of the Oscillation Probability

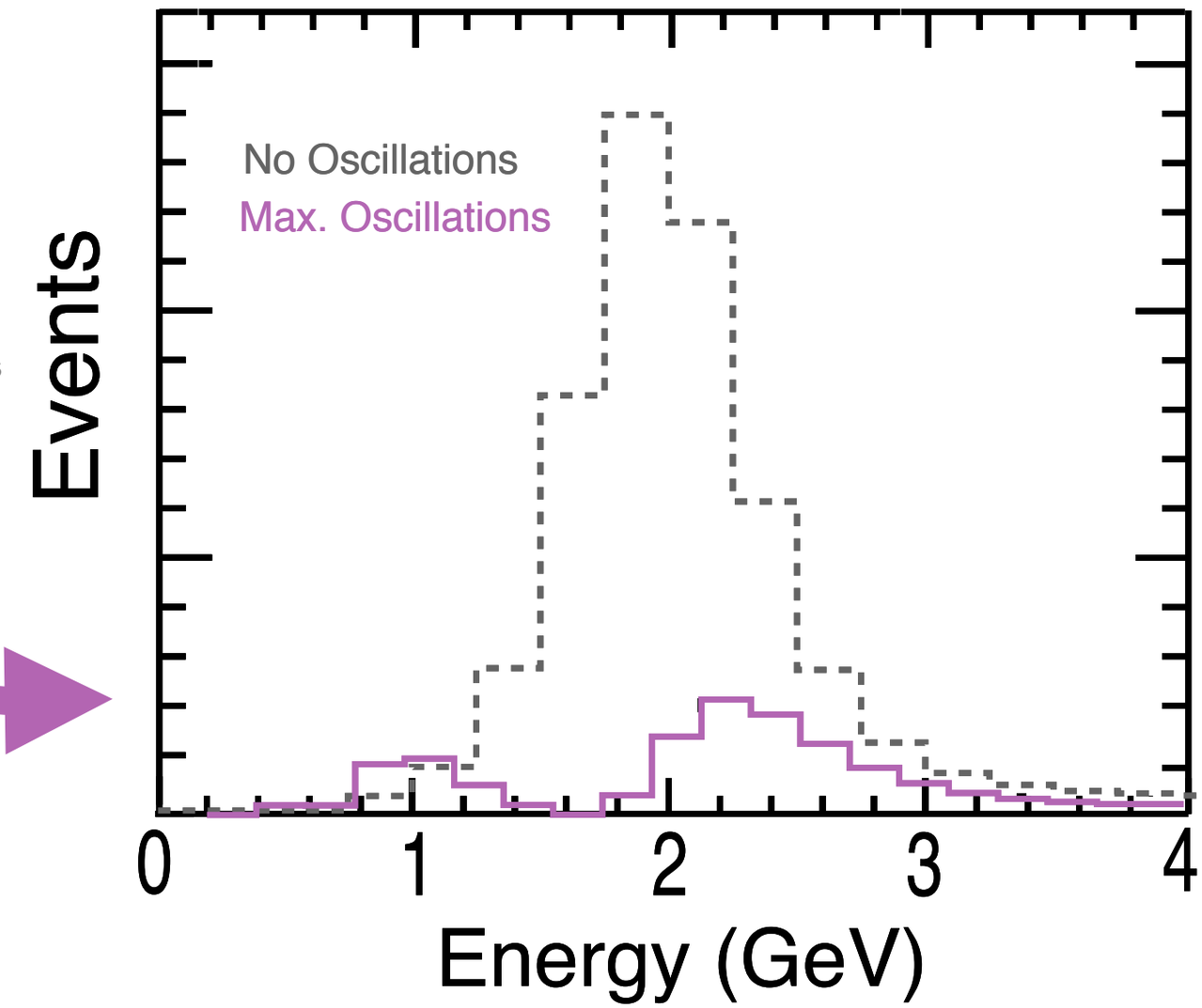
The value of δ and the hierarchy also change the shape oscillation probability as a function of E.



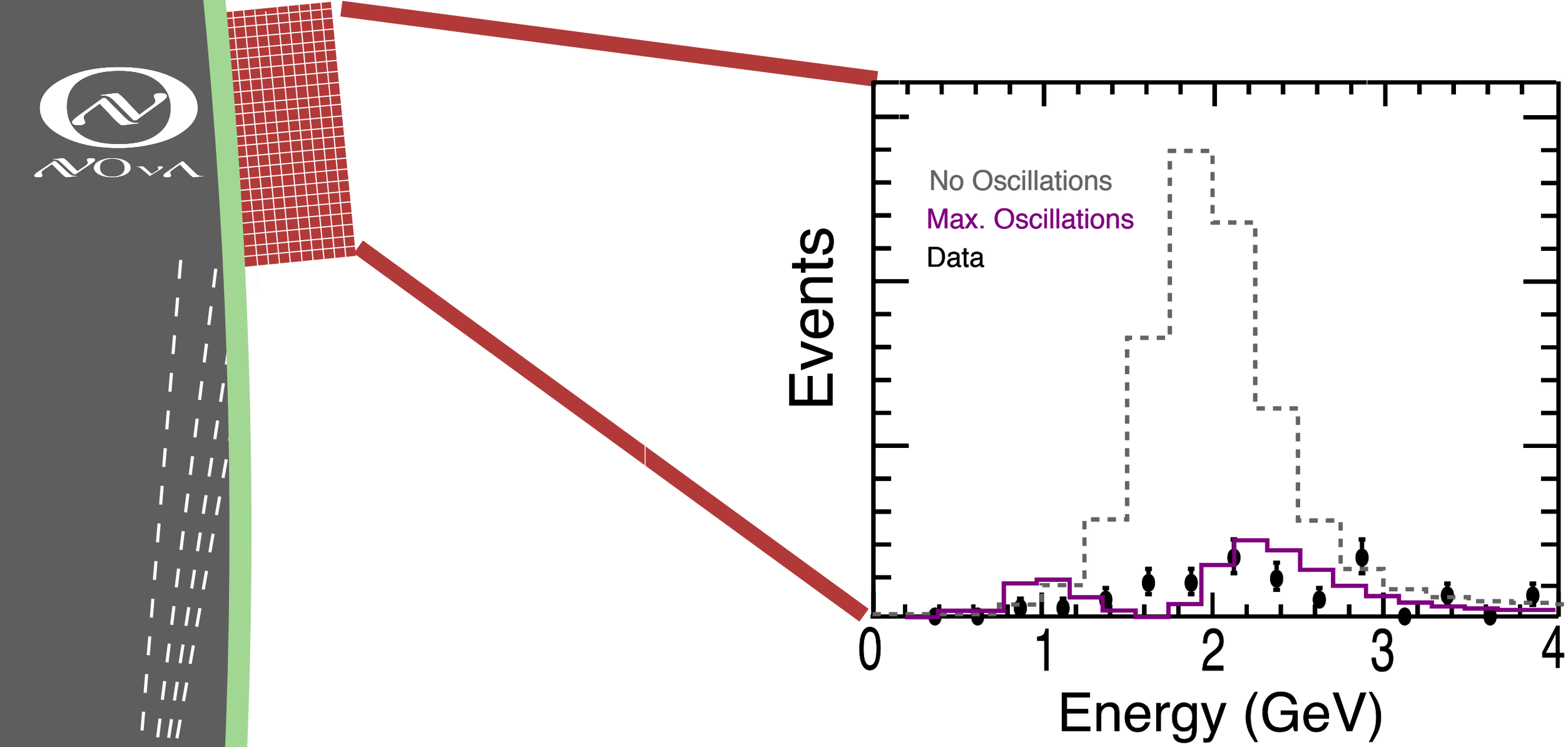
Measure the flux at the Near Detector



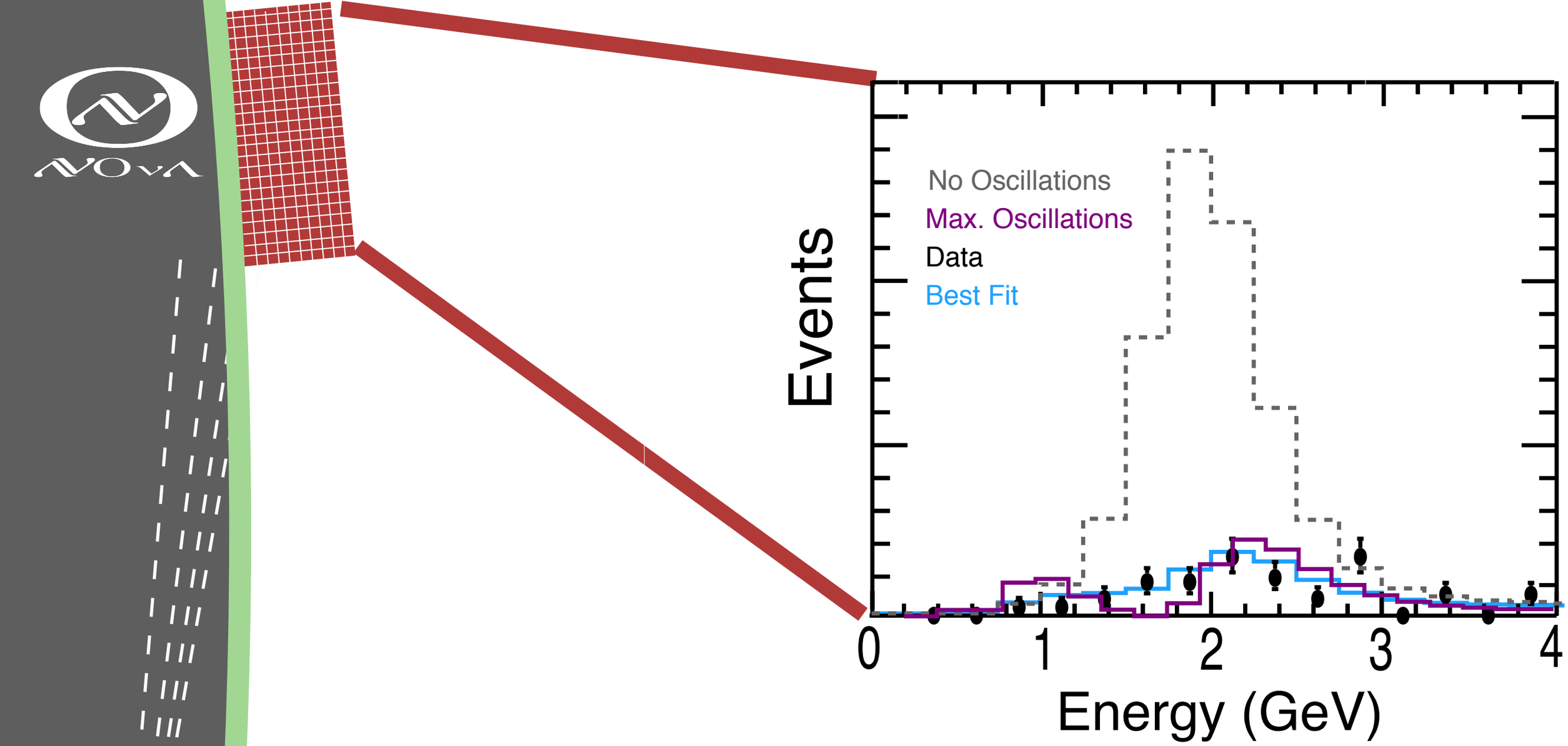




Extrapolate to a Prediction for the Far Detector

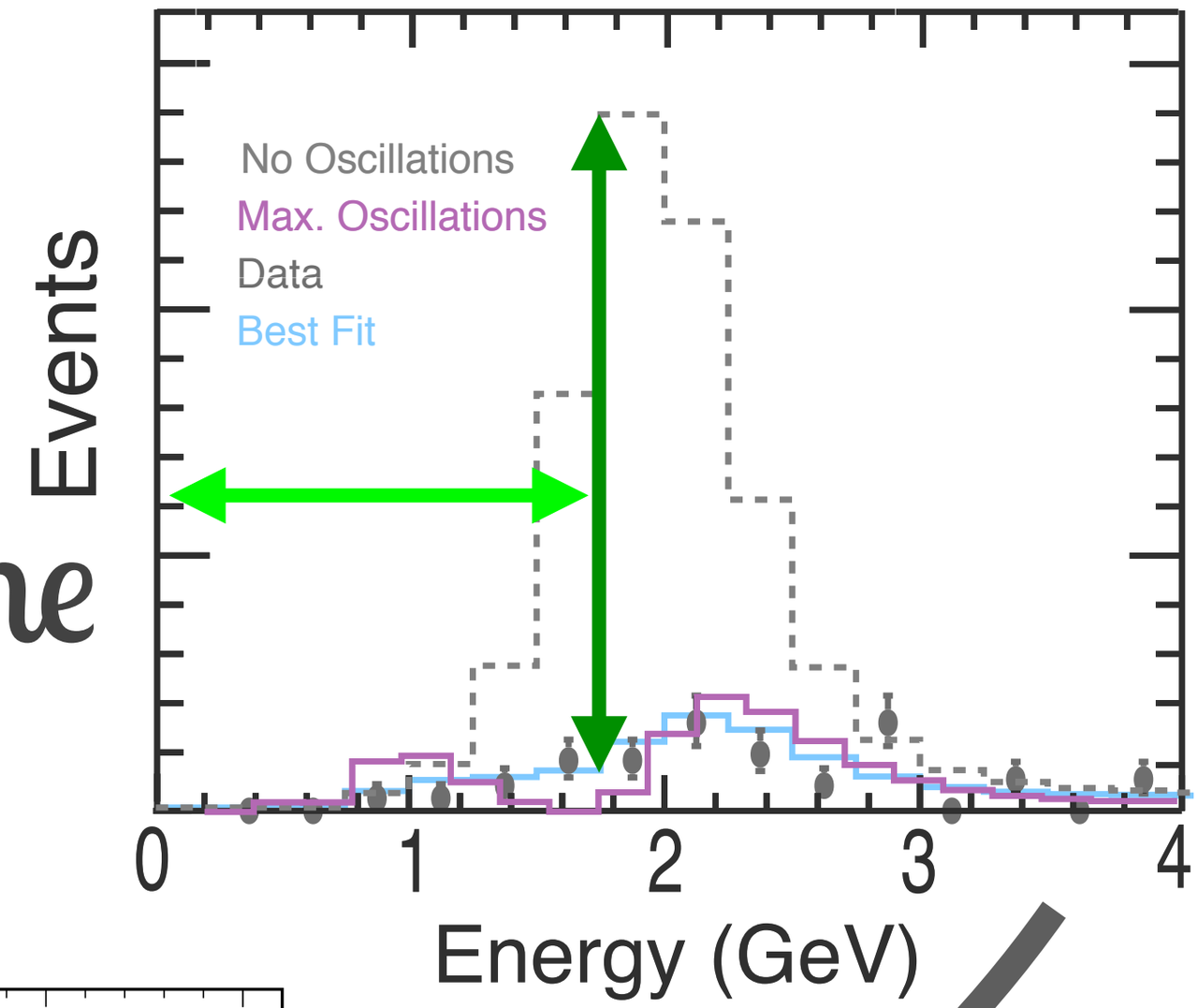


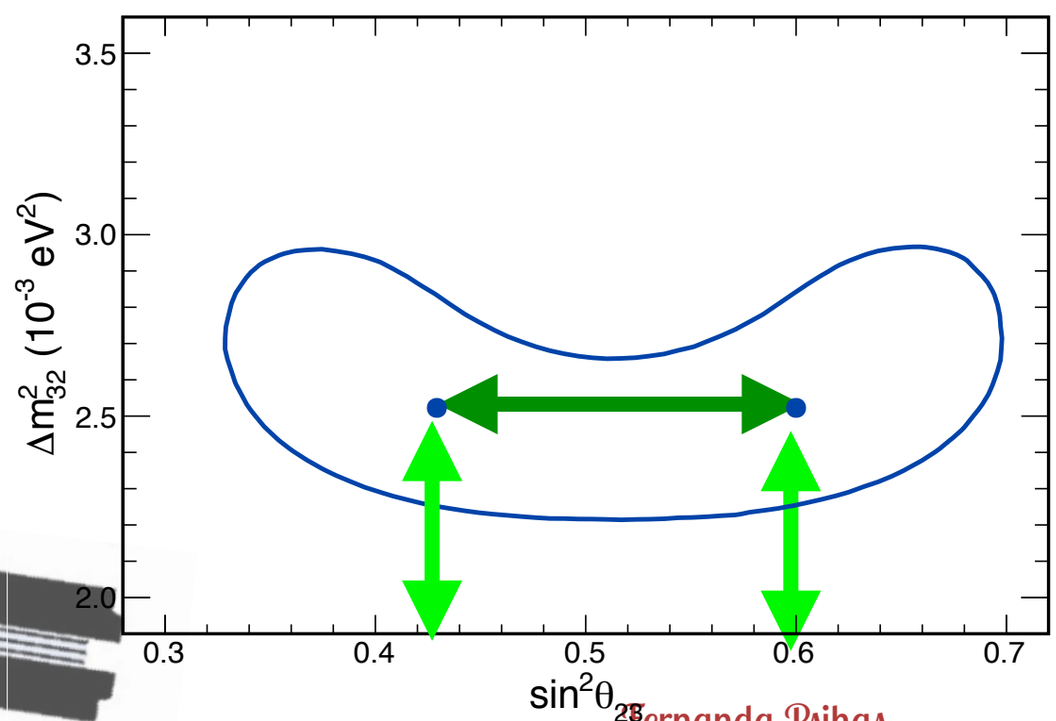
Measure the Spectrum at the Far Detector

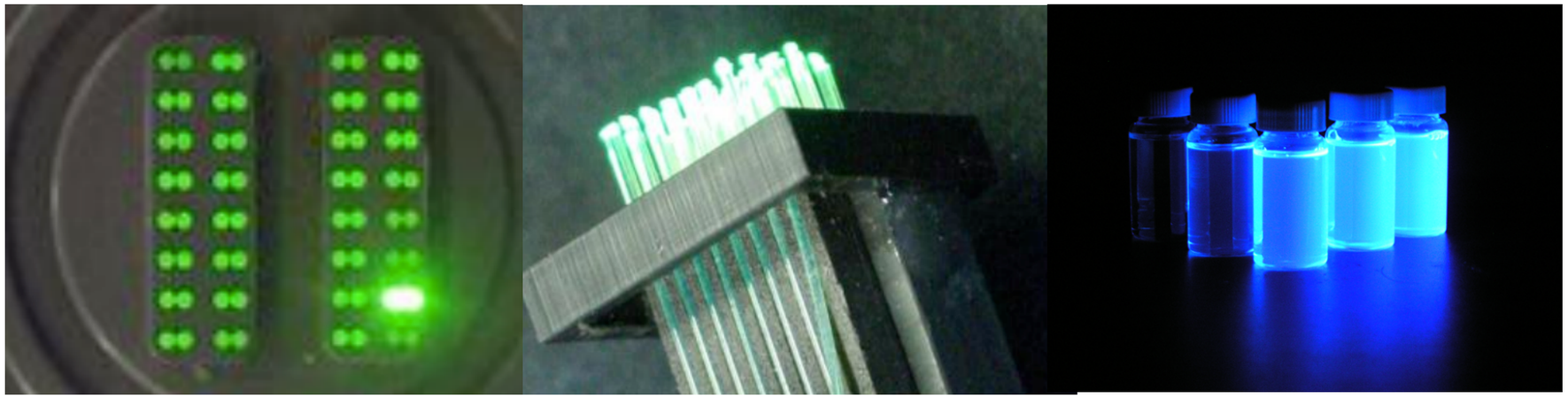


Measure the Spectrum at the Far Detector ... and fit

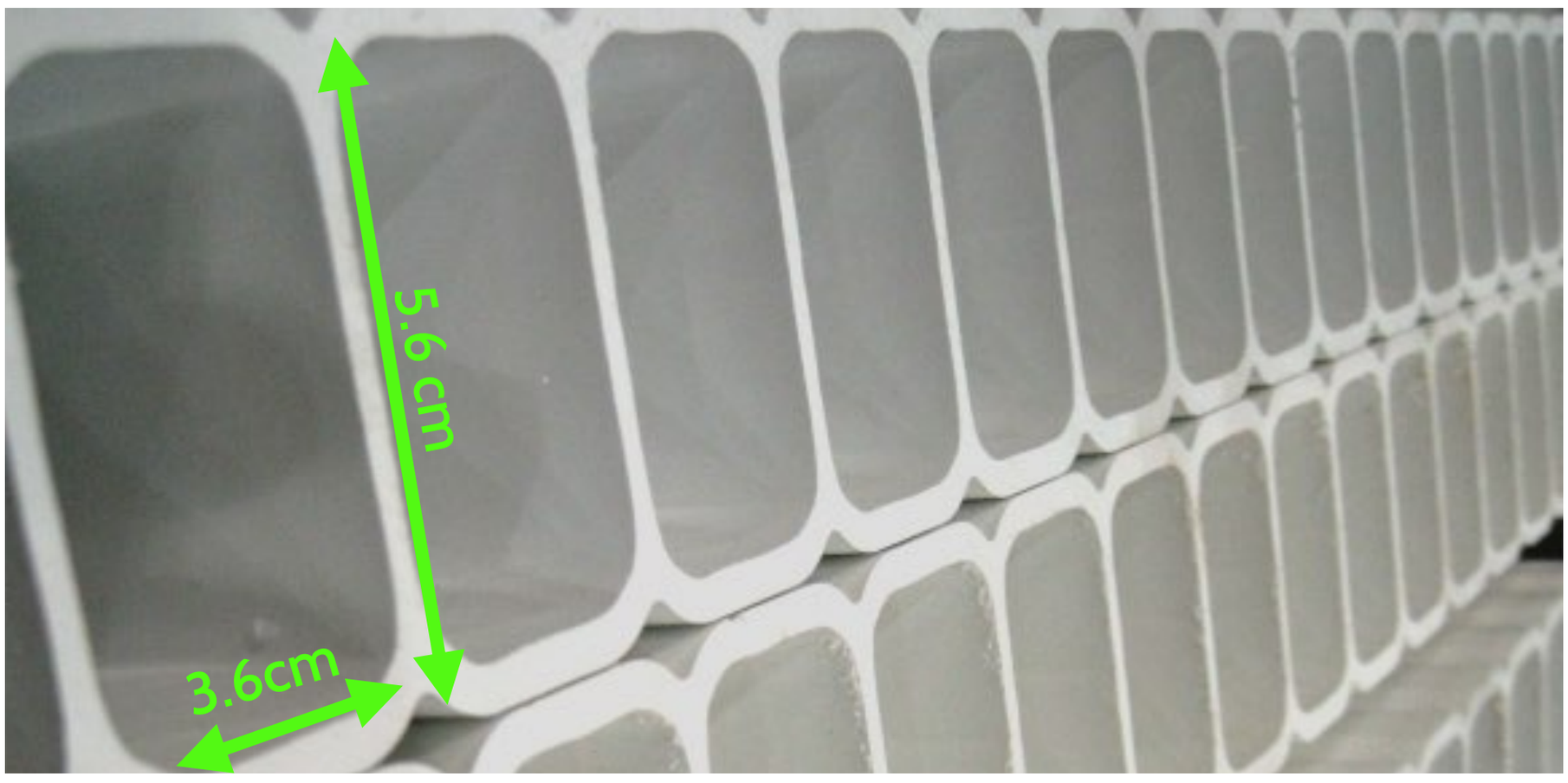
The fit constraints the parameters

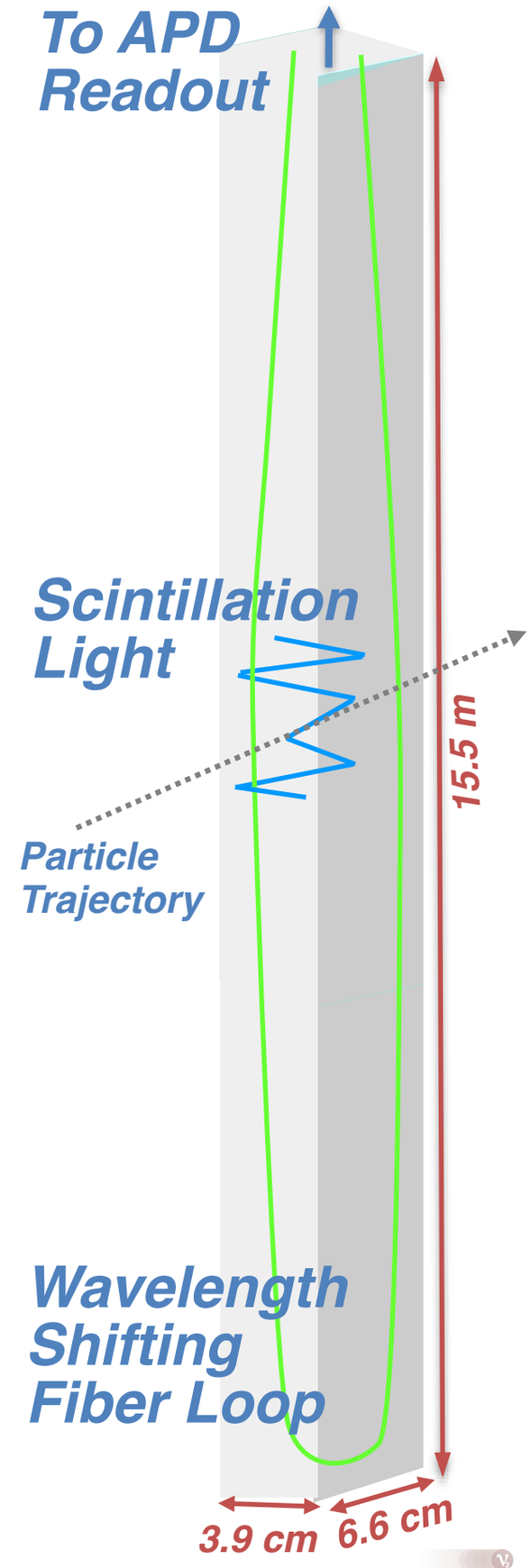






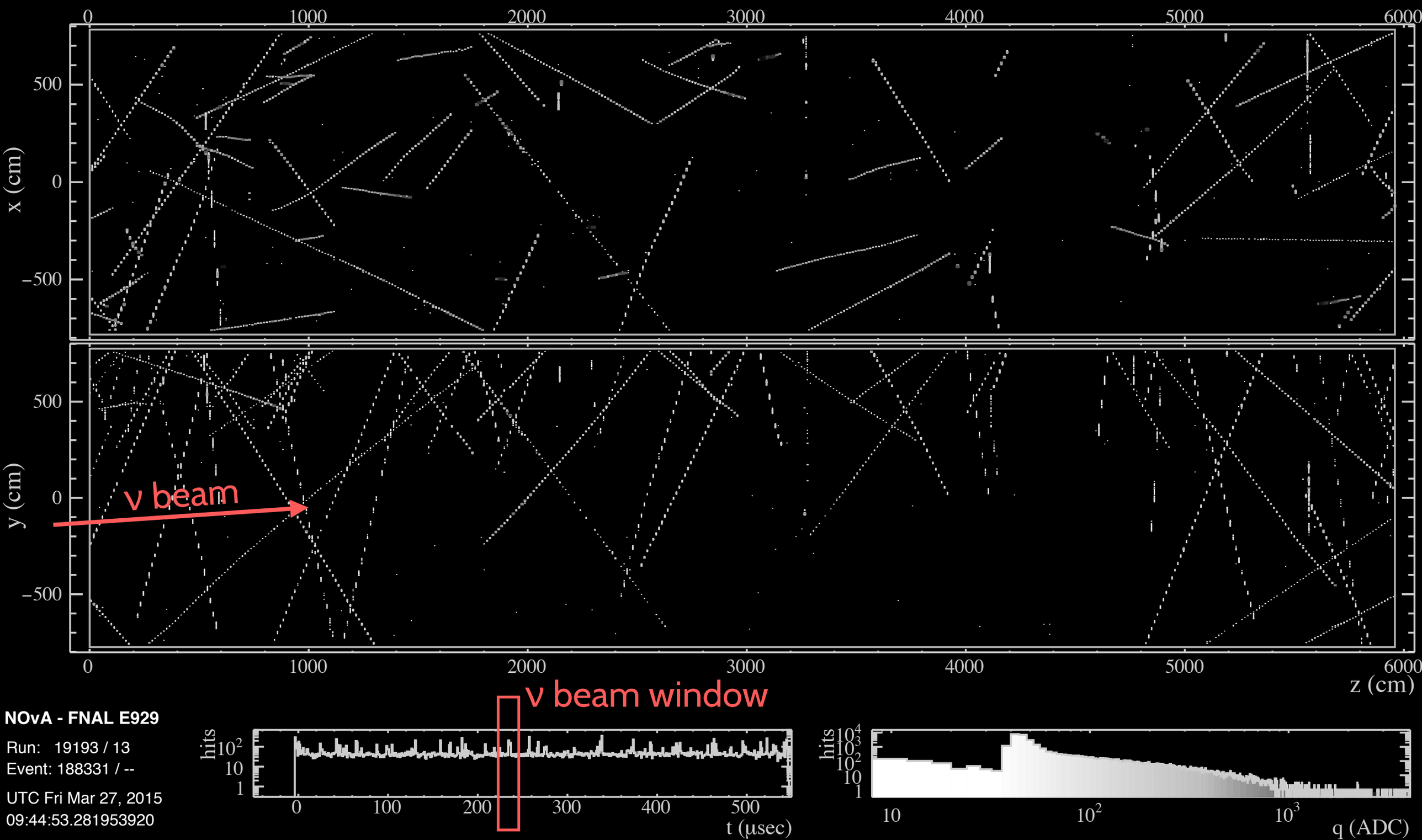
Charged particles are detected though the scintillation light produced in each cell.



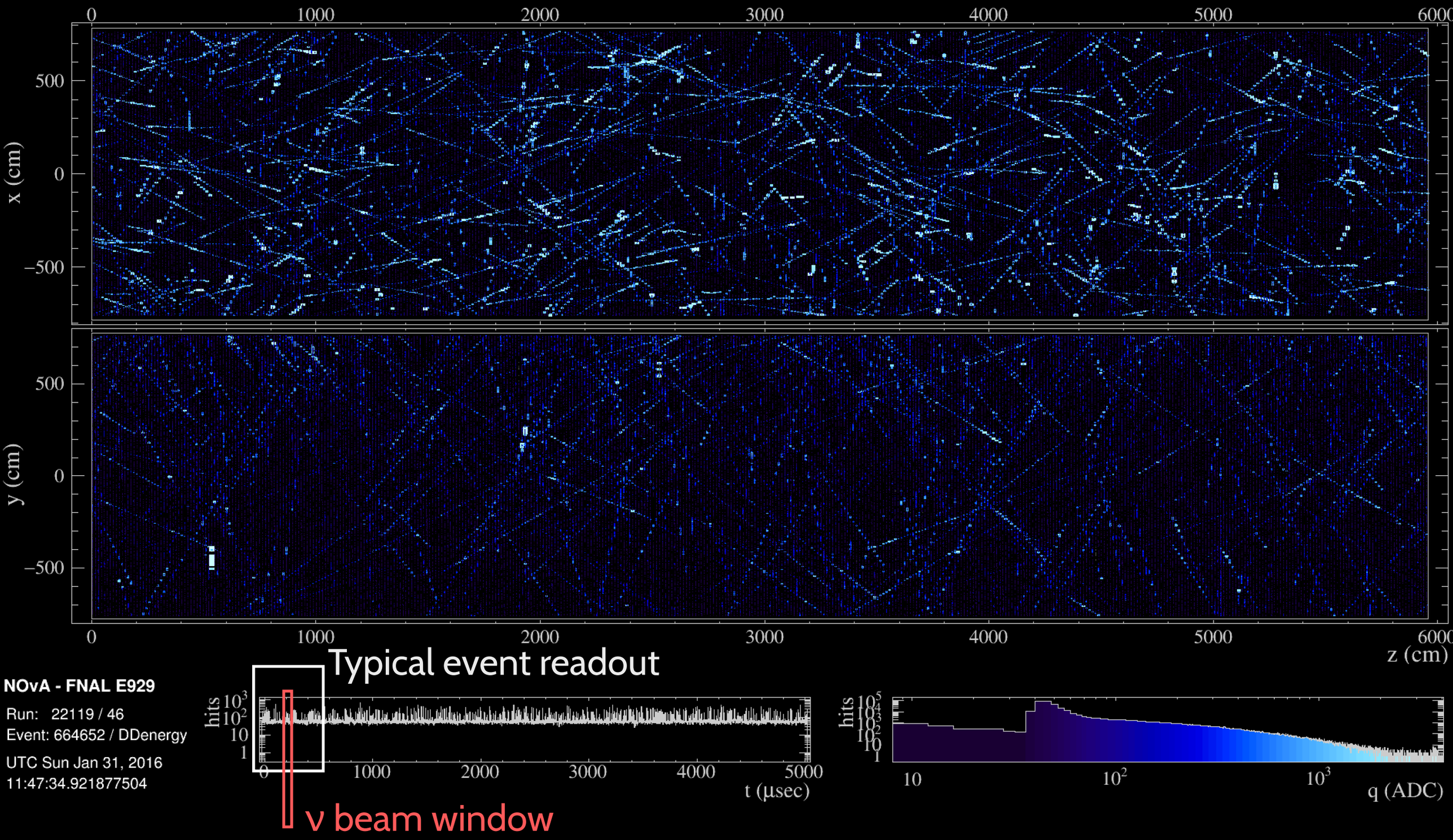


NOvA Readout and Neutrino Interactions

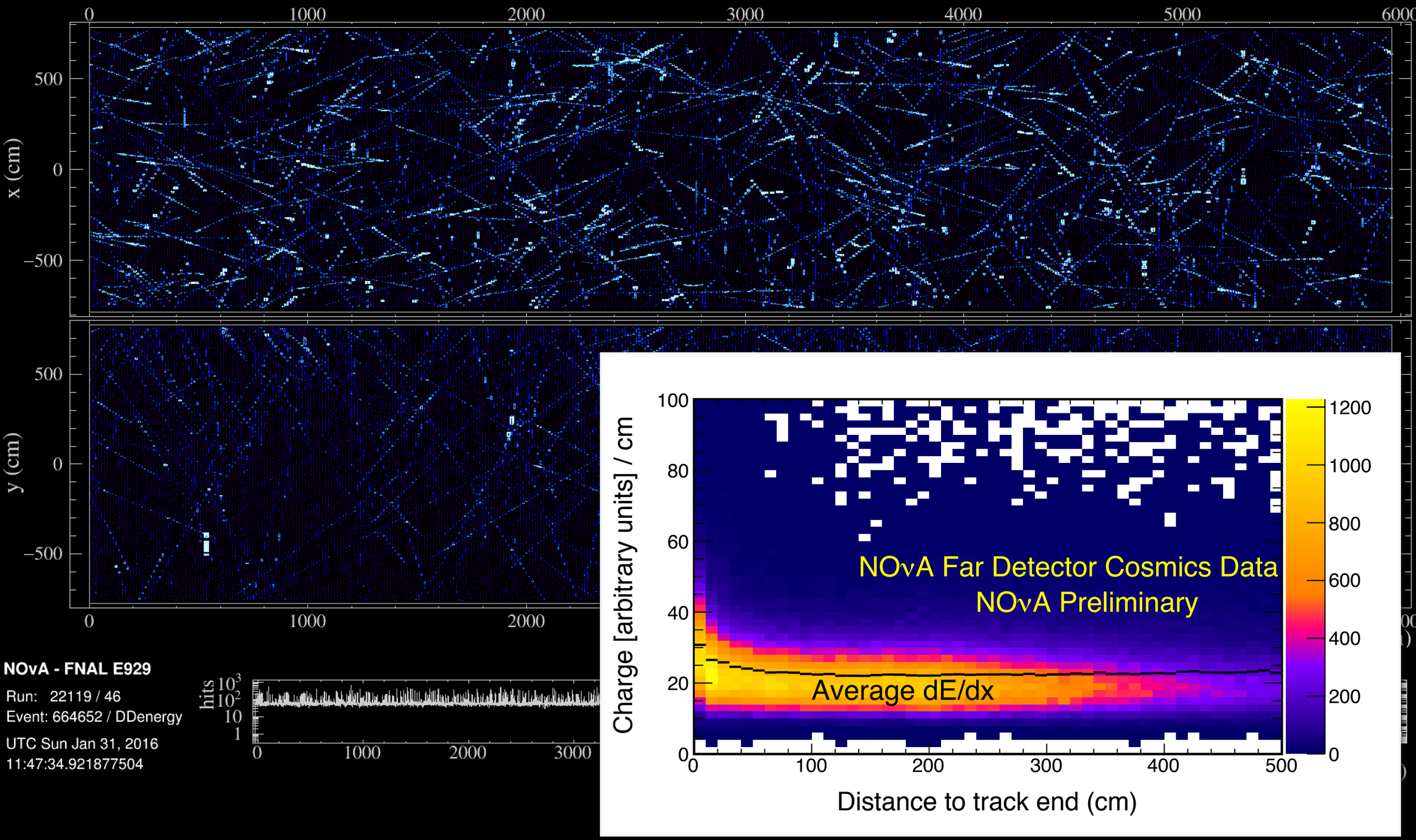
Events are 550 μs readouts around the neutrino beam spill.



Data handles on energy response



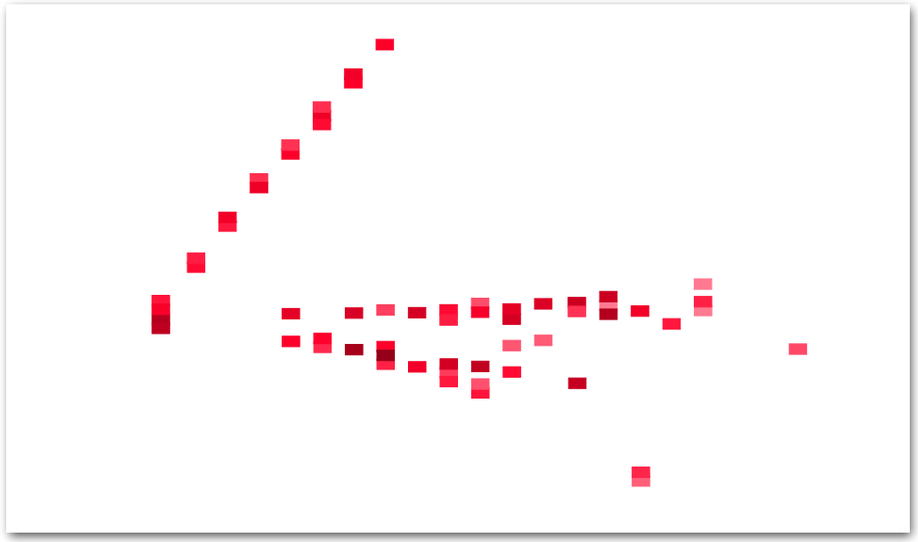
Data handles on energy response

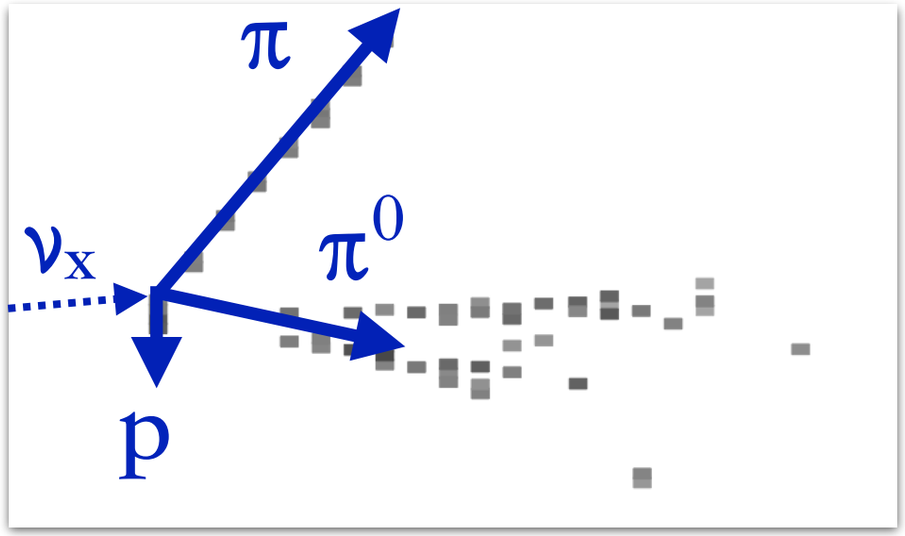


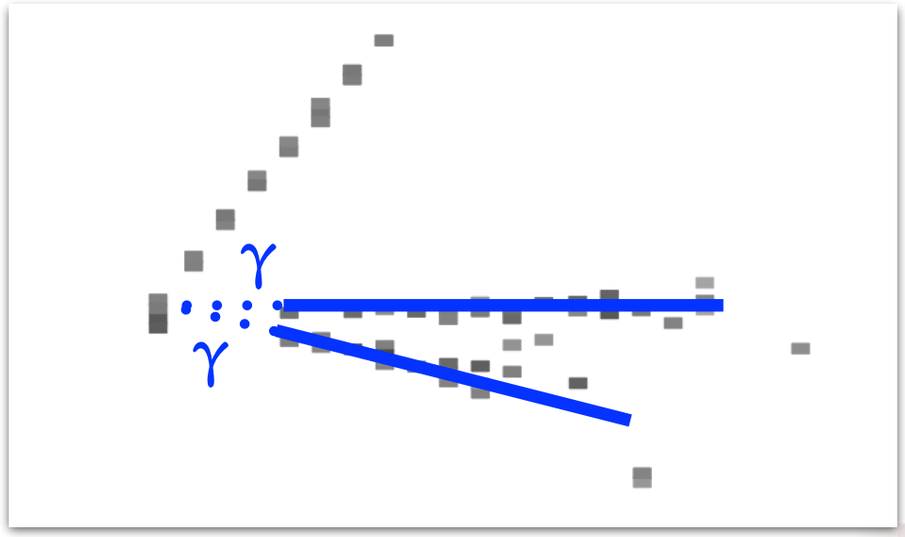
Data handles on energy response

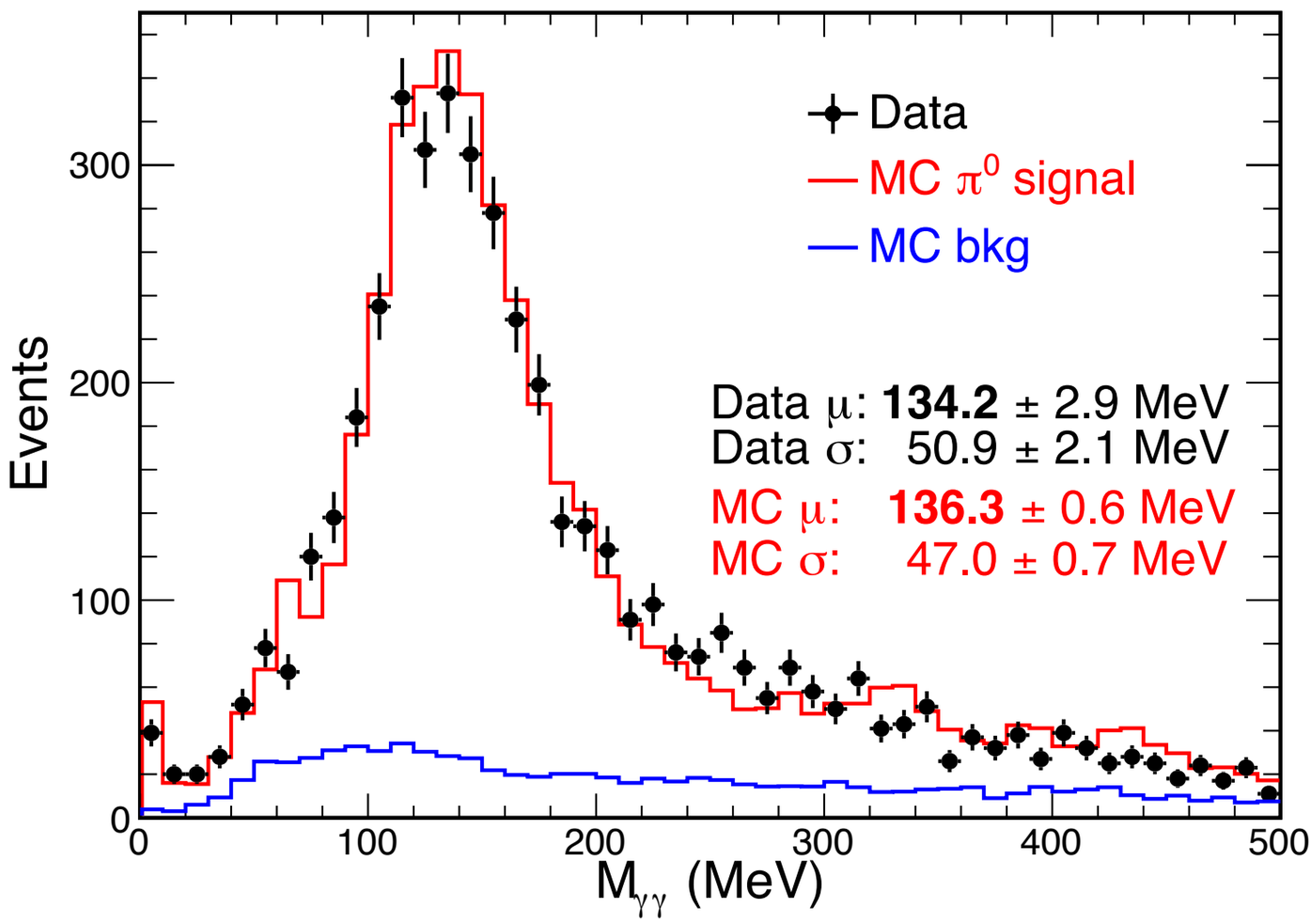
Reconstruct the well known π^0 mass from well identified pairs of photons.

This is a handle on the dead material correction for electromagnetic deposits.









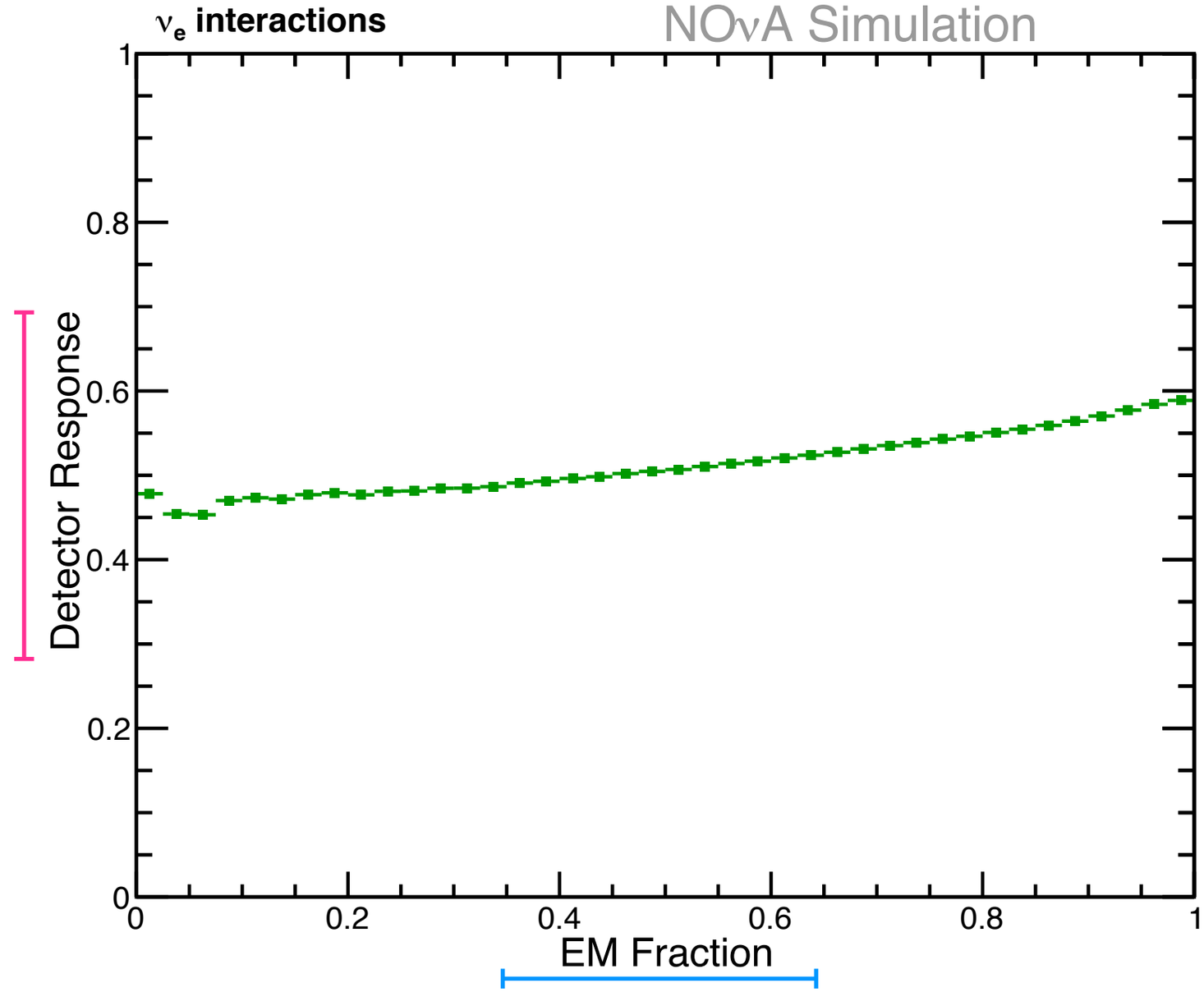
NOνA detectors' e/h response

Response:

Total Energy in Hits / Visible ν energy

$$e/h = \frac{\text{Response to EM}}{\text{Response to Hadronic}}$$

$$e/h \simeq 1.26 \pm 0.02$$

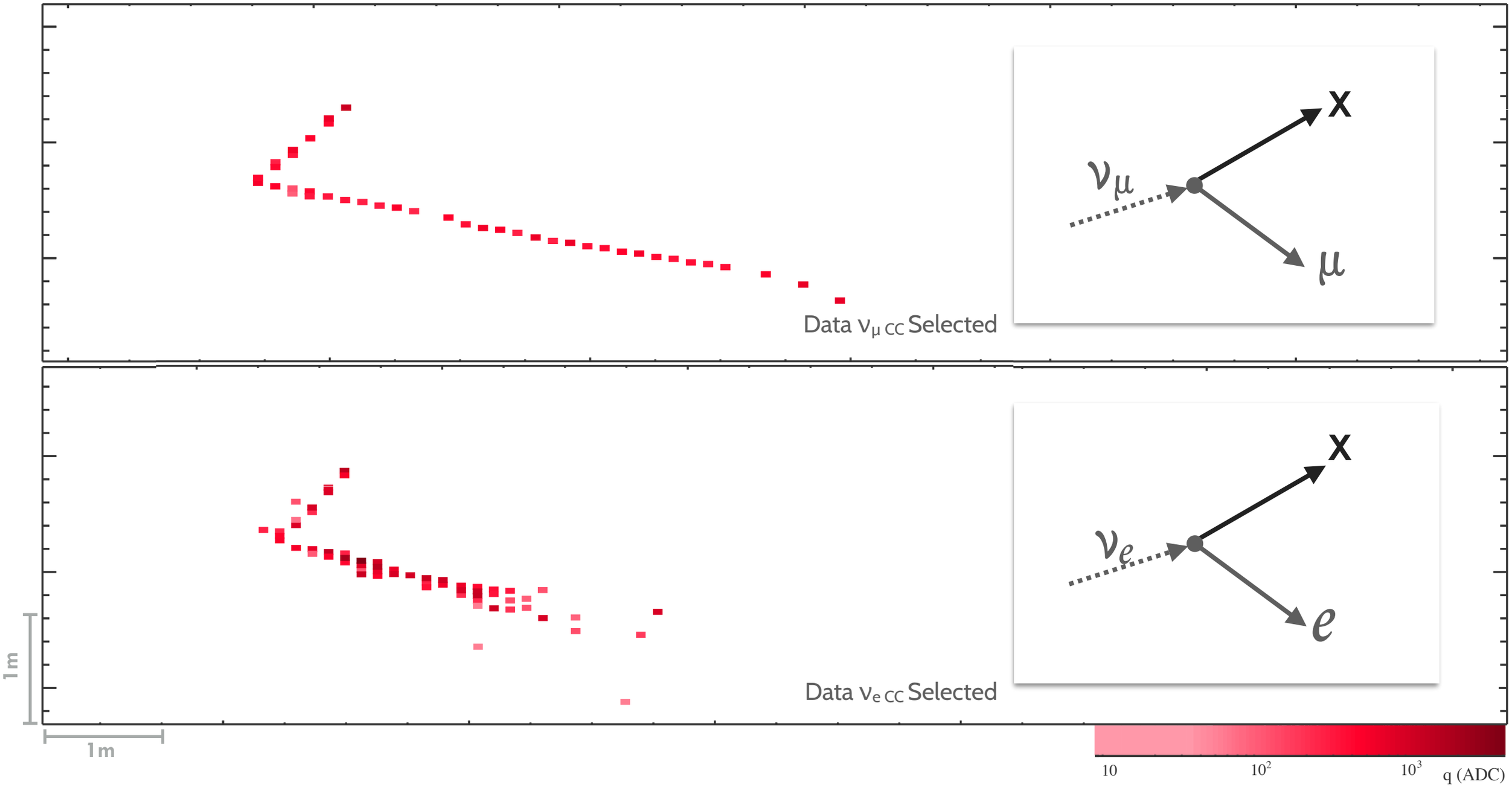


EM Fraction:

EM Energy in hits / Total Energy in Hits

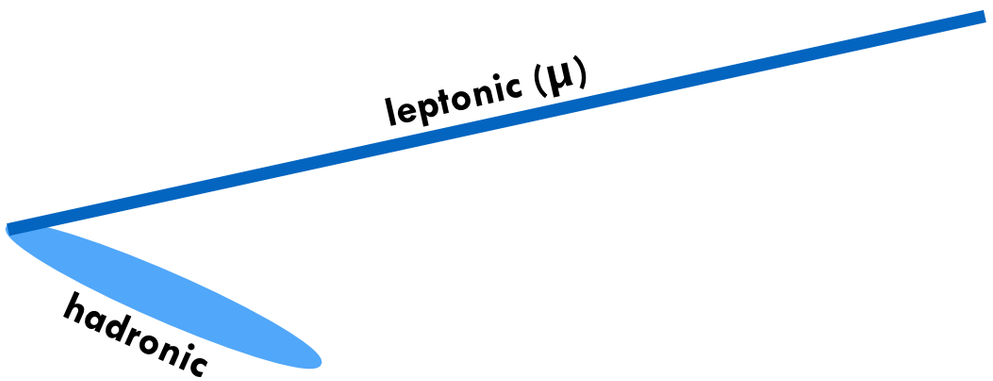
EM and Hadronic components need to be calibrated independently.

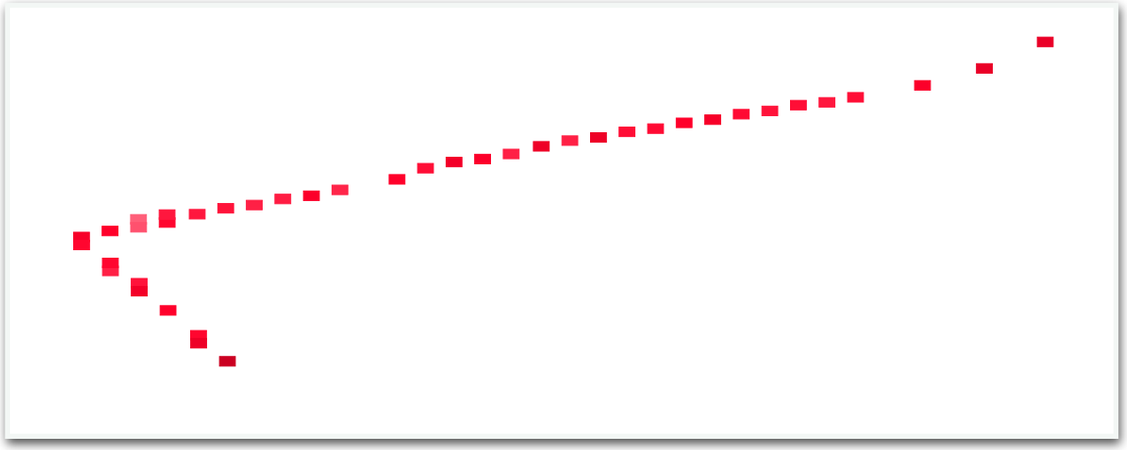
Signature Signal Events



Numu Energy Reconstruction

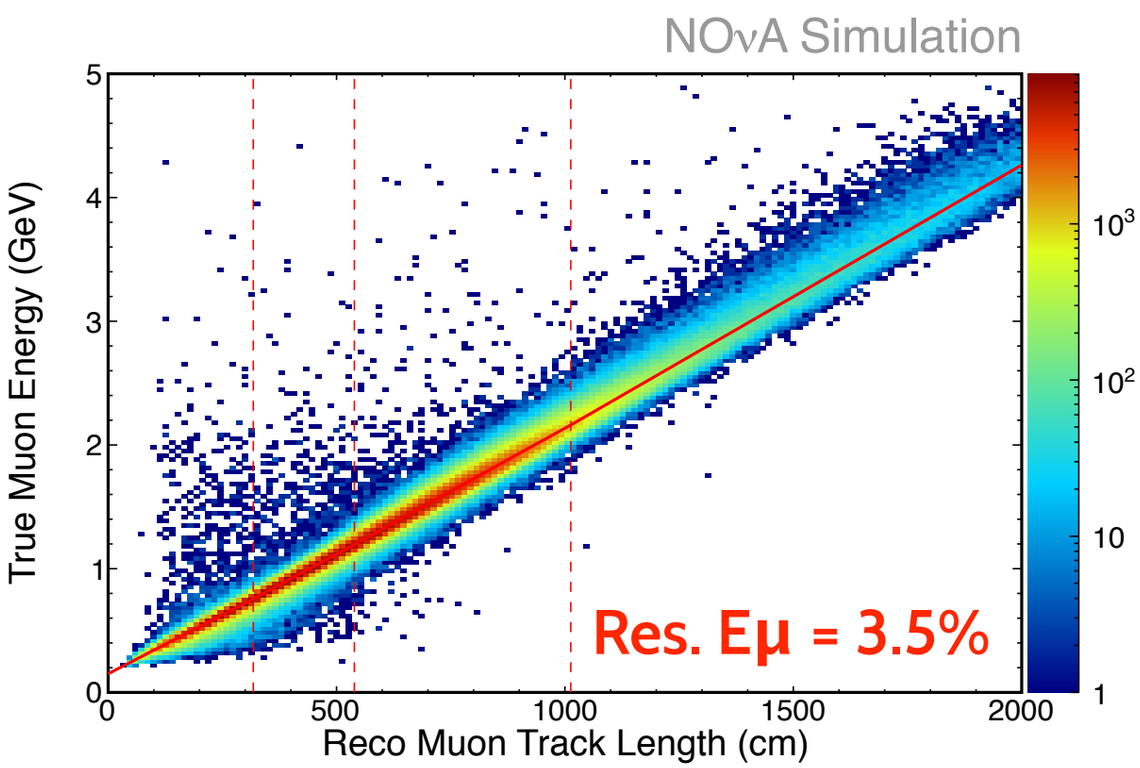
$E_\nu = E_\mu + E_{had}$

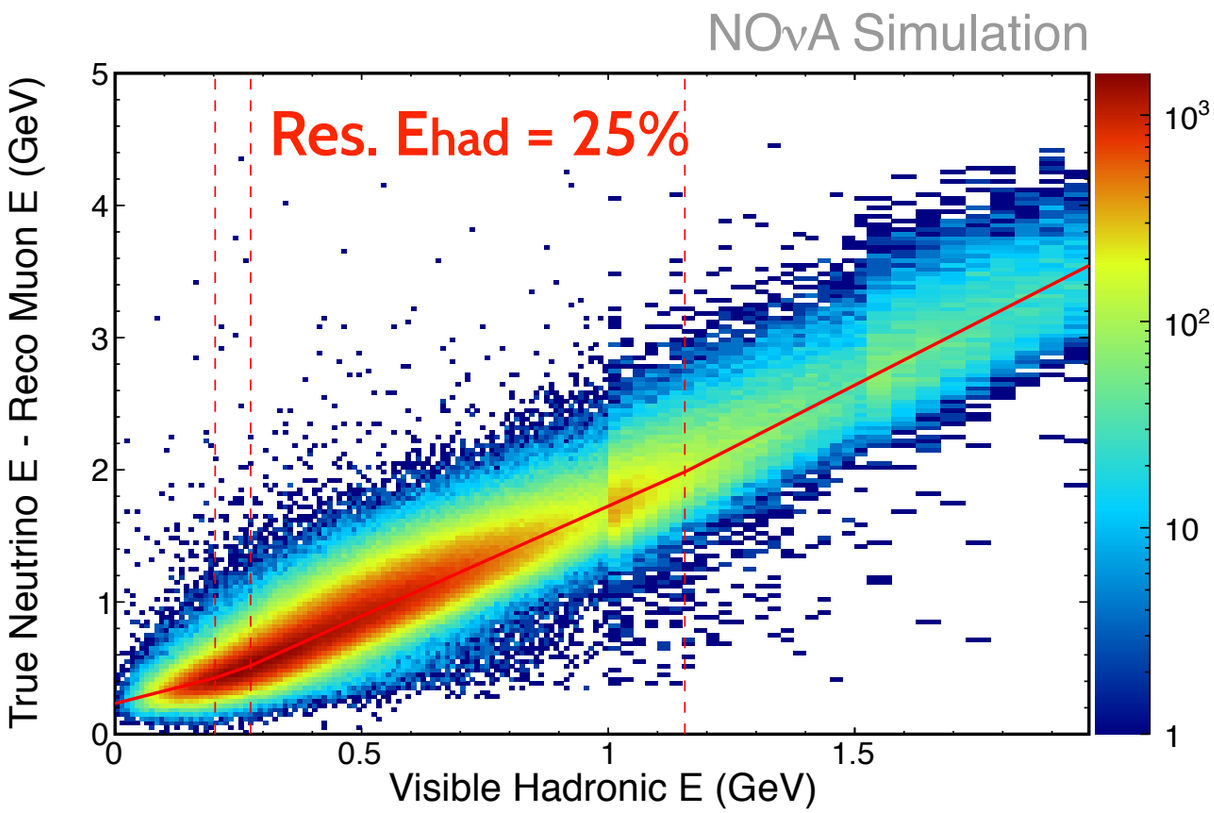




Use fits of true energy vs muon track length and visible hadronic energy respectively.

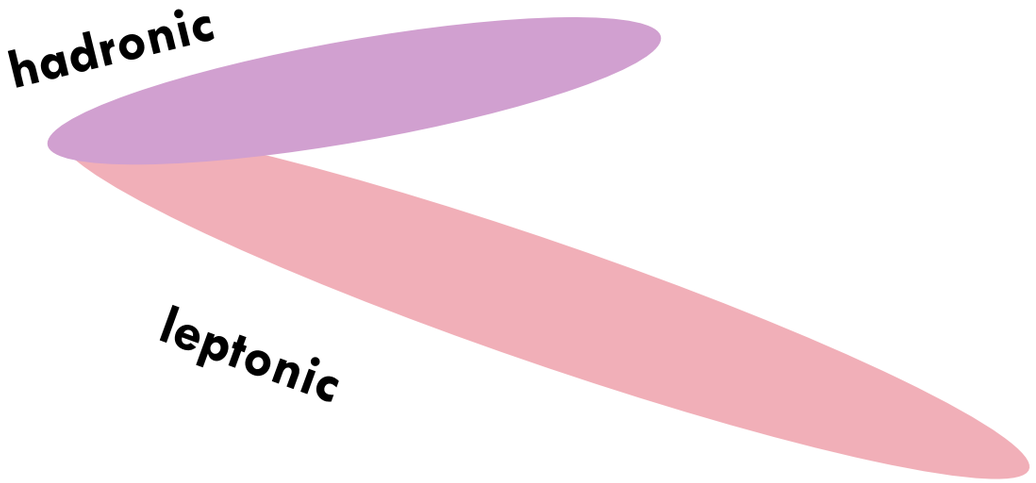
The resolution for Eν with this method is 7%

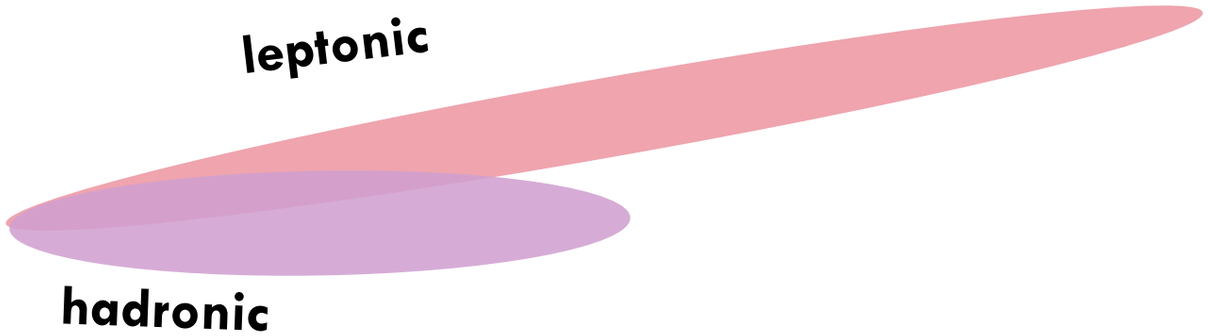




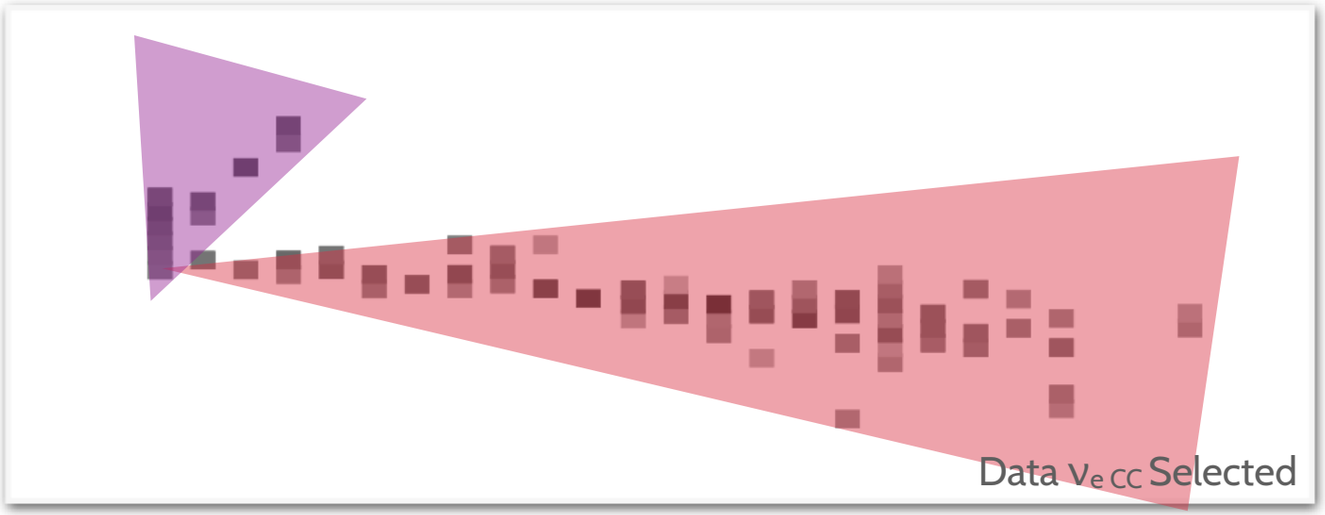
Nue Energy Reconstruction

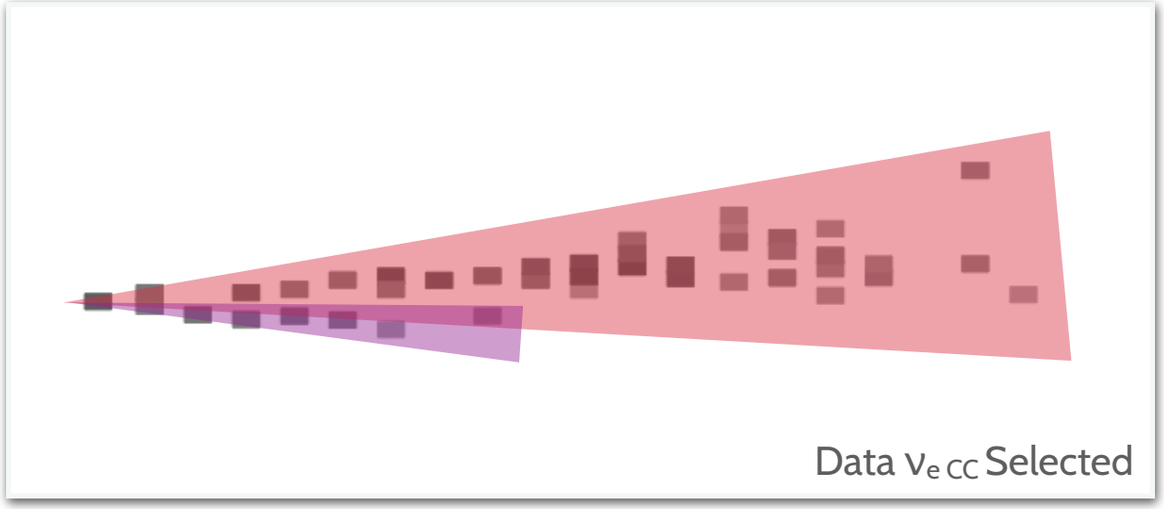
Nue Energy Reconstruction

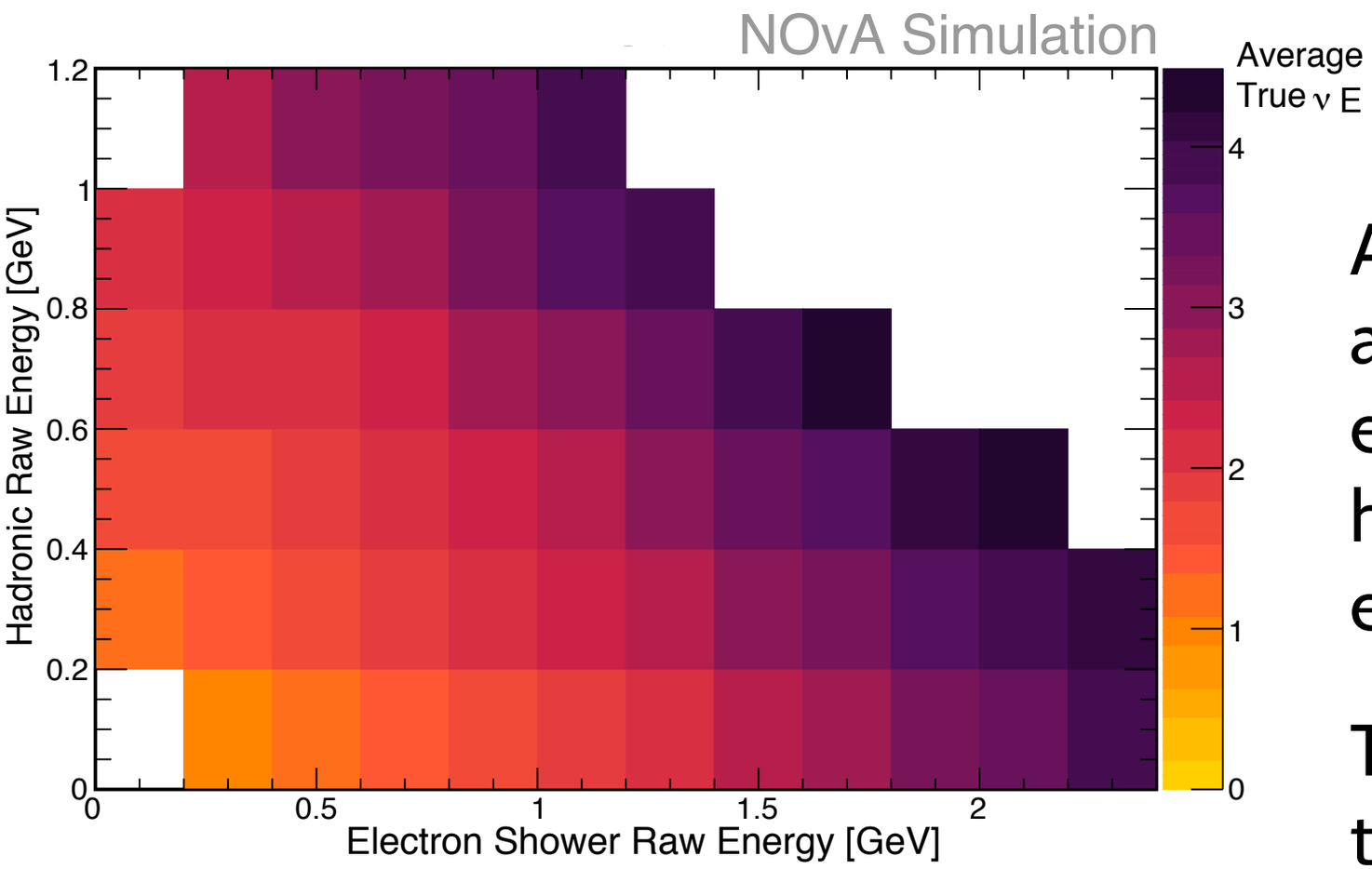




Nue Energy







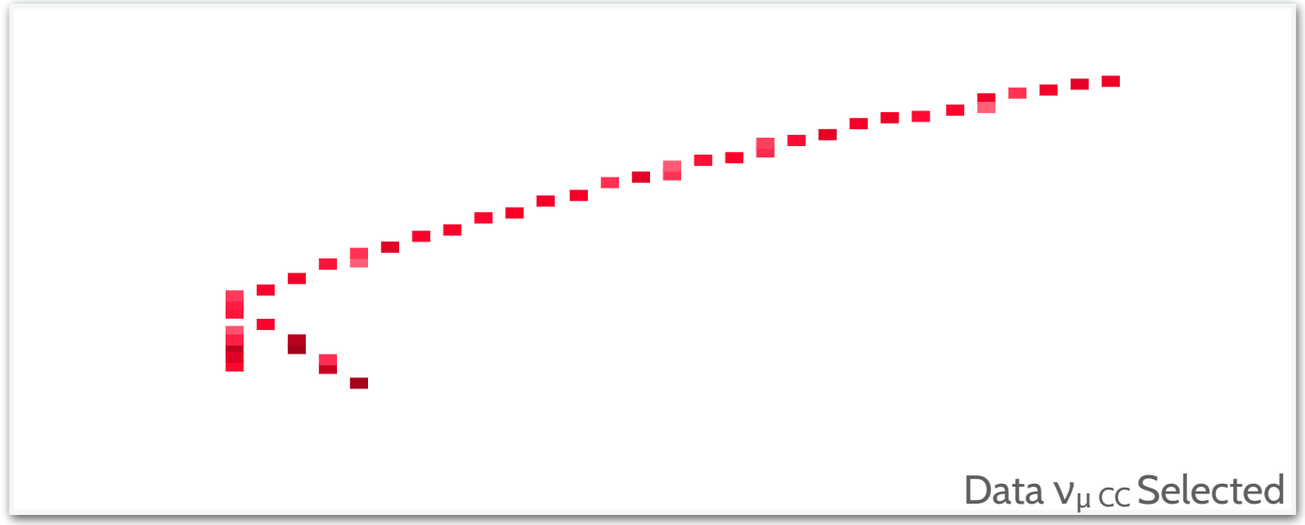
$$E_\nu = f\,(E_{EM}, E_{had})$$

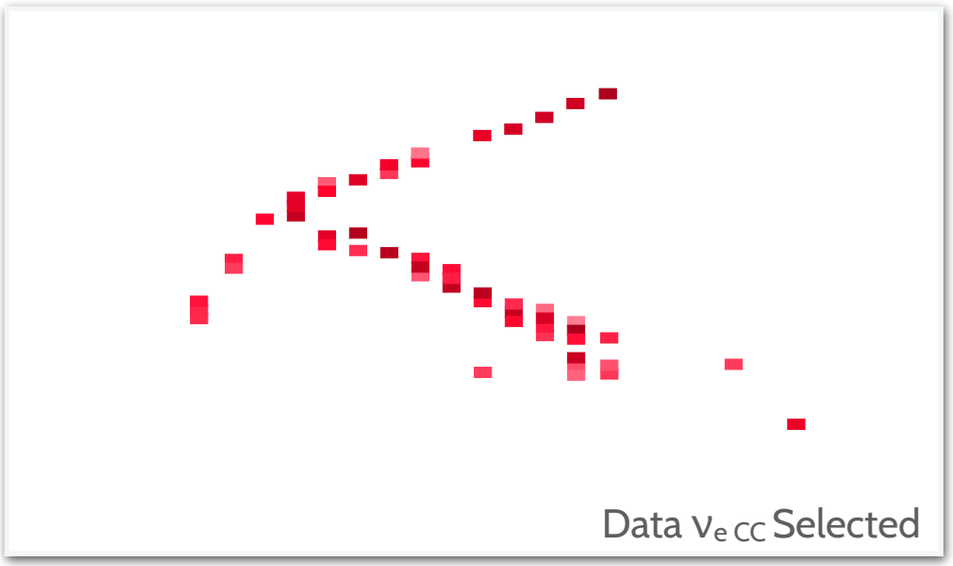
A quadratic fit to true energy as a function of electromagnetic energy and hadronic energy is used for estimation.

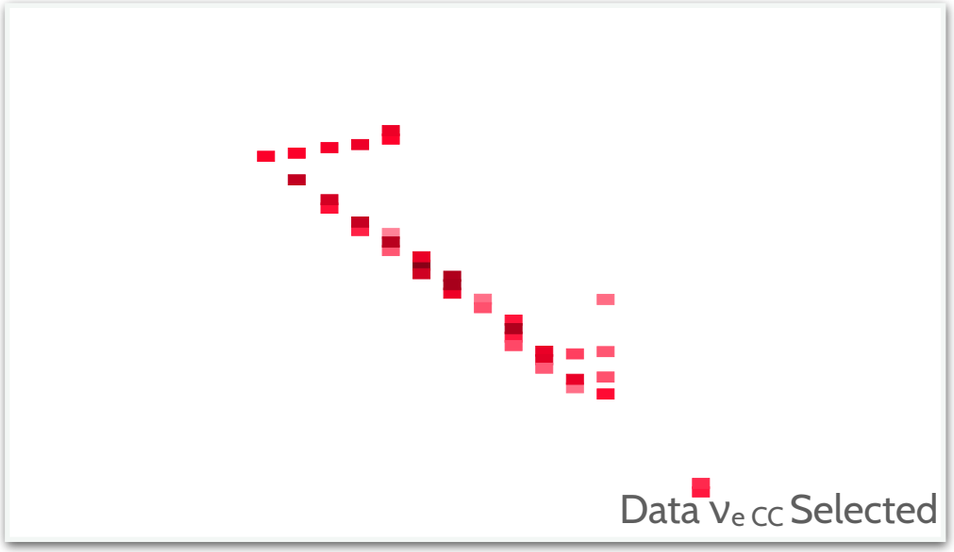
The energy resolution using this approach is 7%

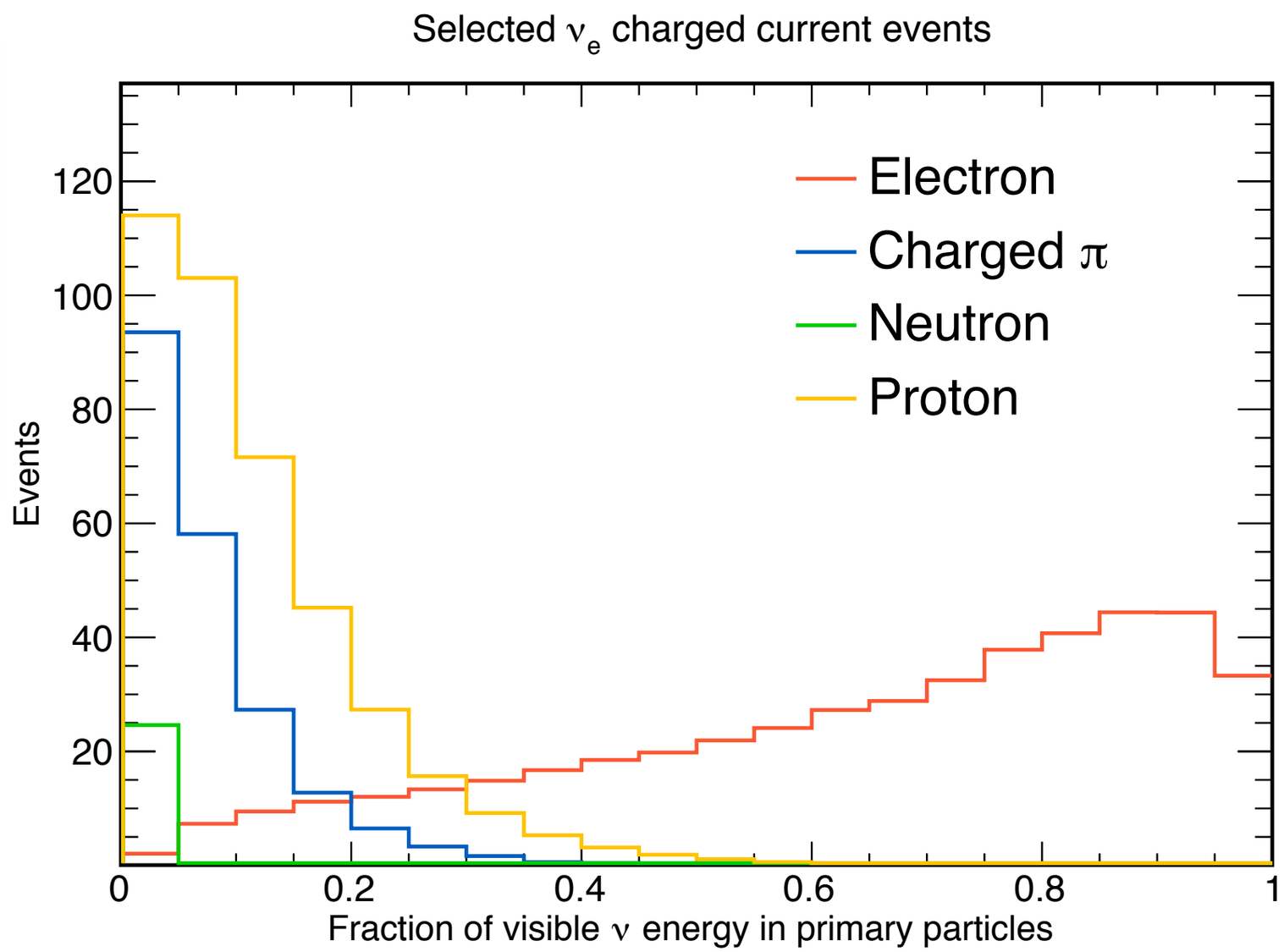
Improvements

We can take advantage of the detector's resolution to separate multiple components of the event.





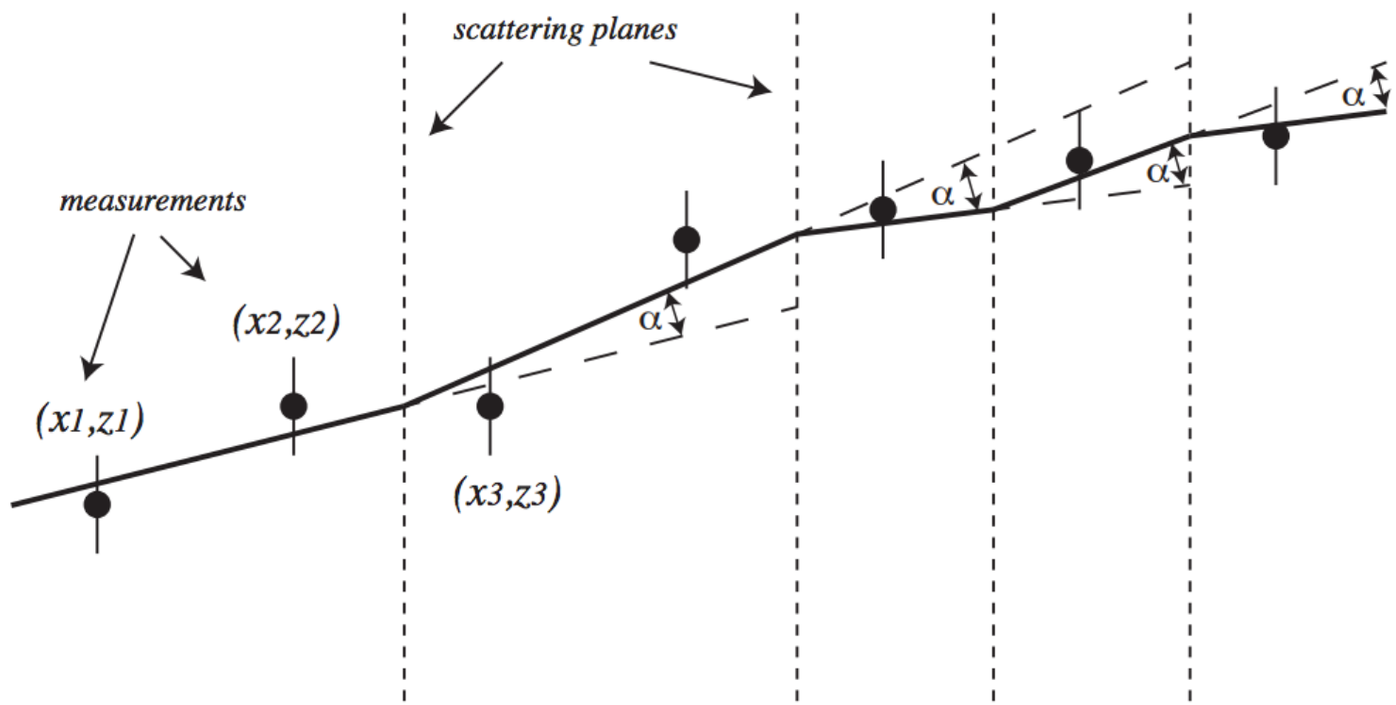




Improvements: Track and Energy Reconstruction

Fits each cluster under three different particle assumptions: muon, charged pion and proton.

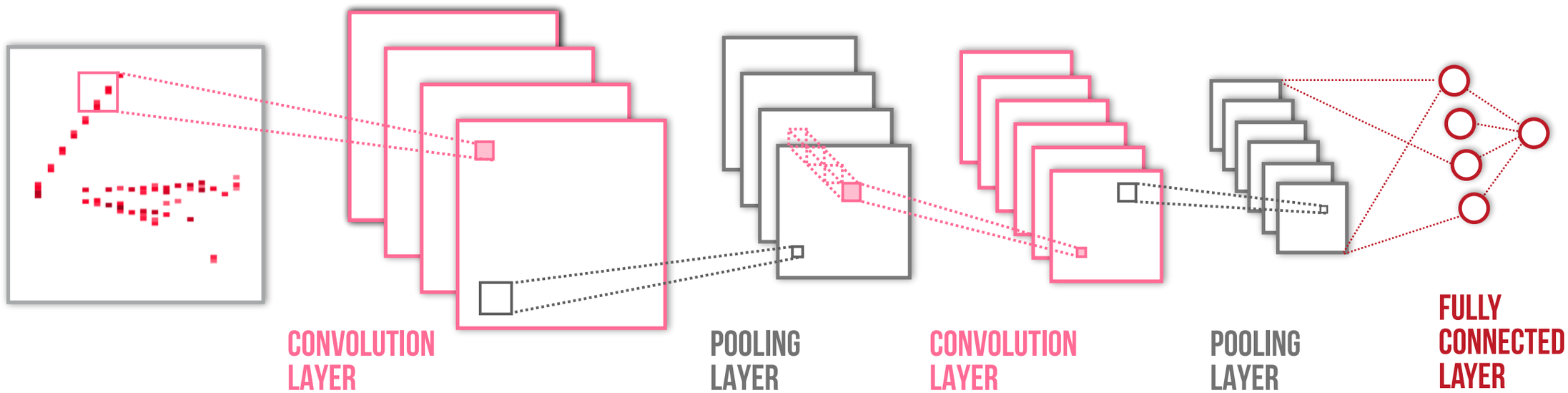
Also makes an initial momentum estimate for each assumption.

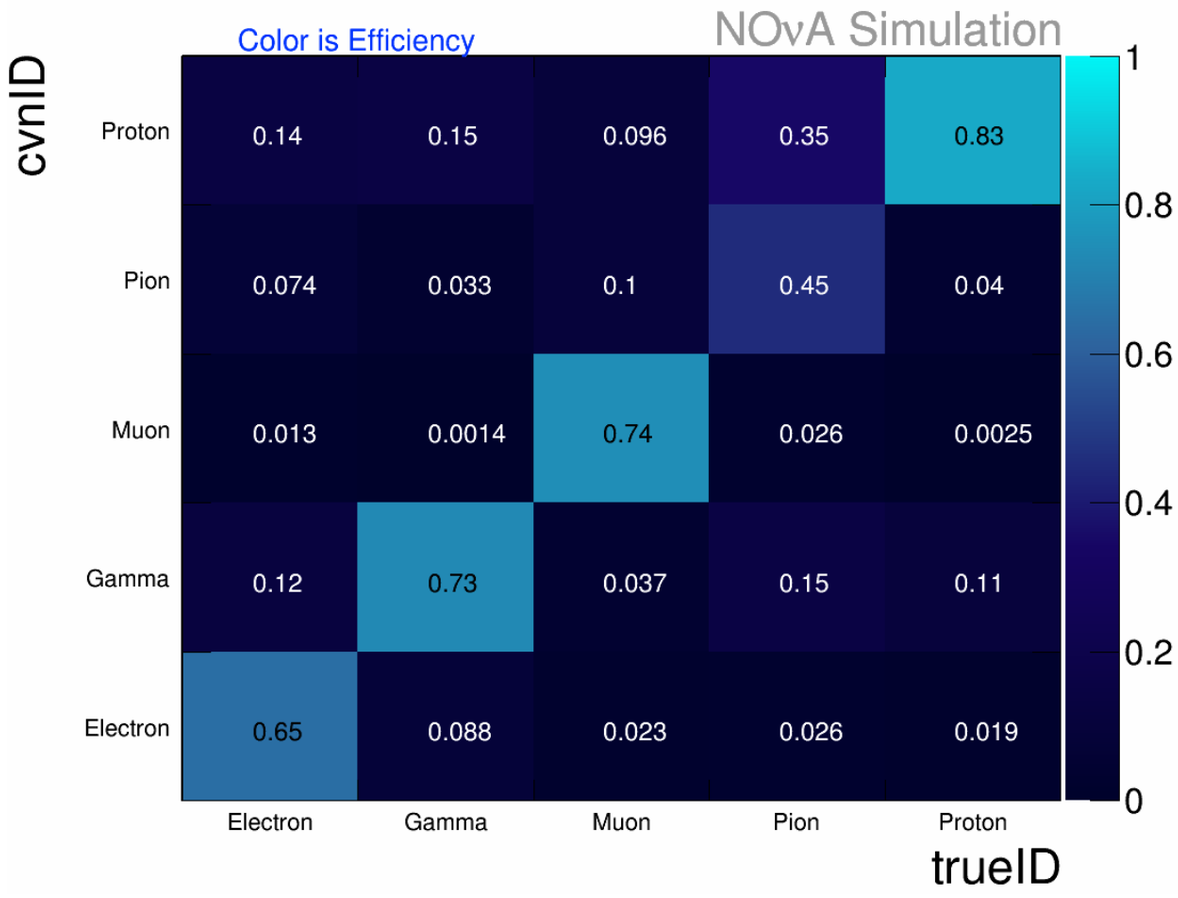


$$\chi^2 = \chi^2(a, b, \alpha_1, \ldots \alpha_N) = \sum_{i=1}^{n} \frac{(\xi_i - x_i)^2}{\sigma_{x_i}^2} + \sum_{J=1}^{N} \frac{(\beta_J - \alpha_J)^2}{\sigma_{S_J}^2}$$

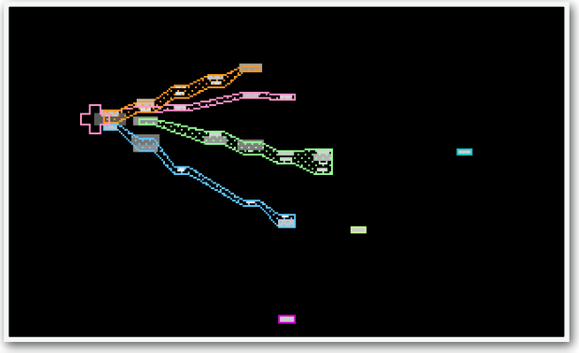
$$\theta_{rms} = \frac{13.6\text{MeV}}{\sqrt{3}\,\beta p} \sqrt{x}\,(1 + 0.038 \ln(x))$$

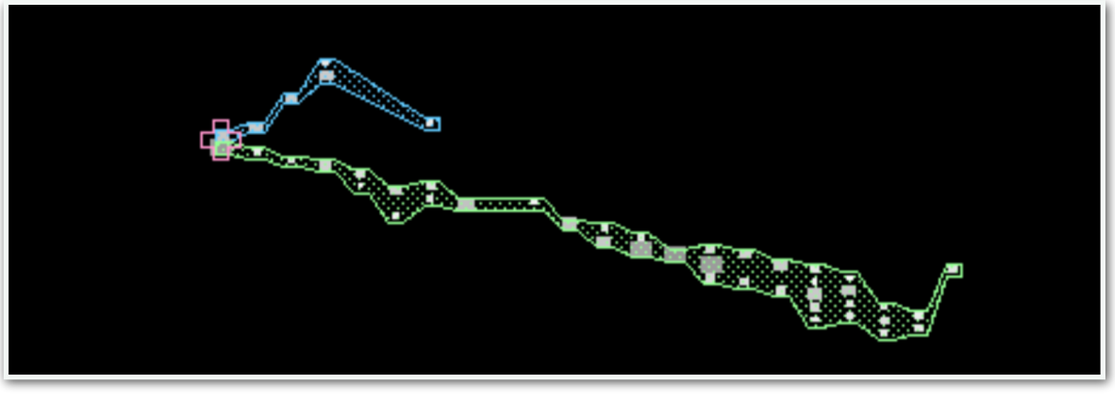
Improvements Particle Identification





We use our Deep CNN classifier to identify each cluster.



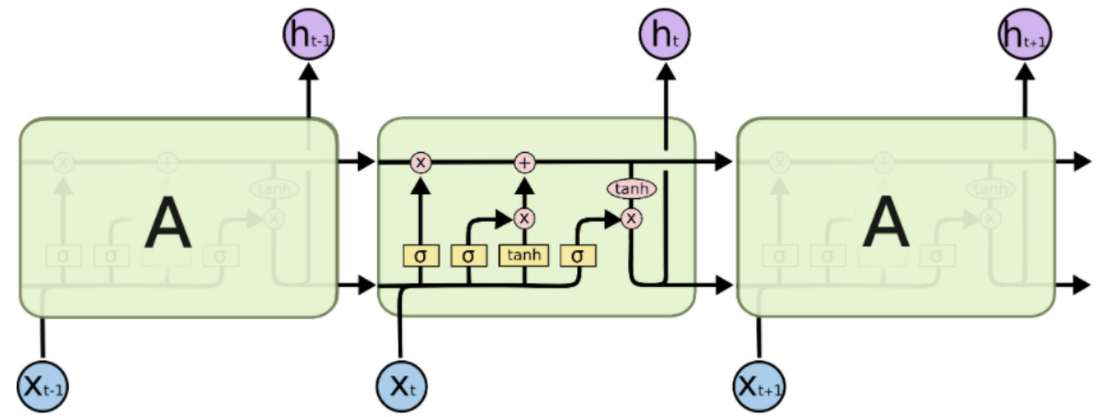


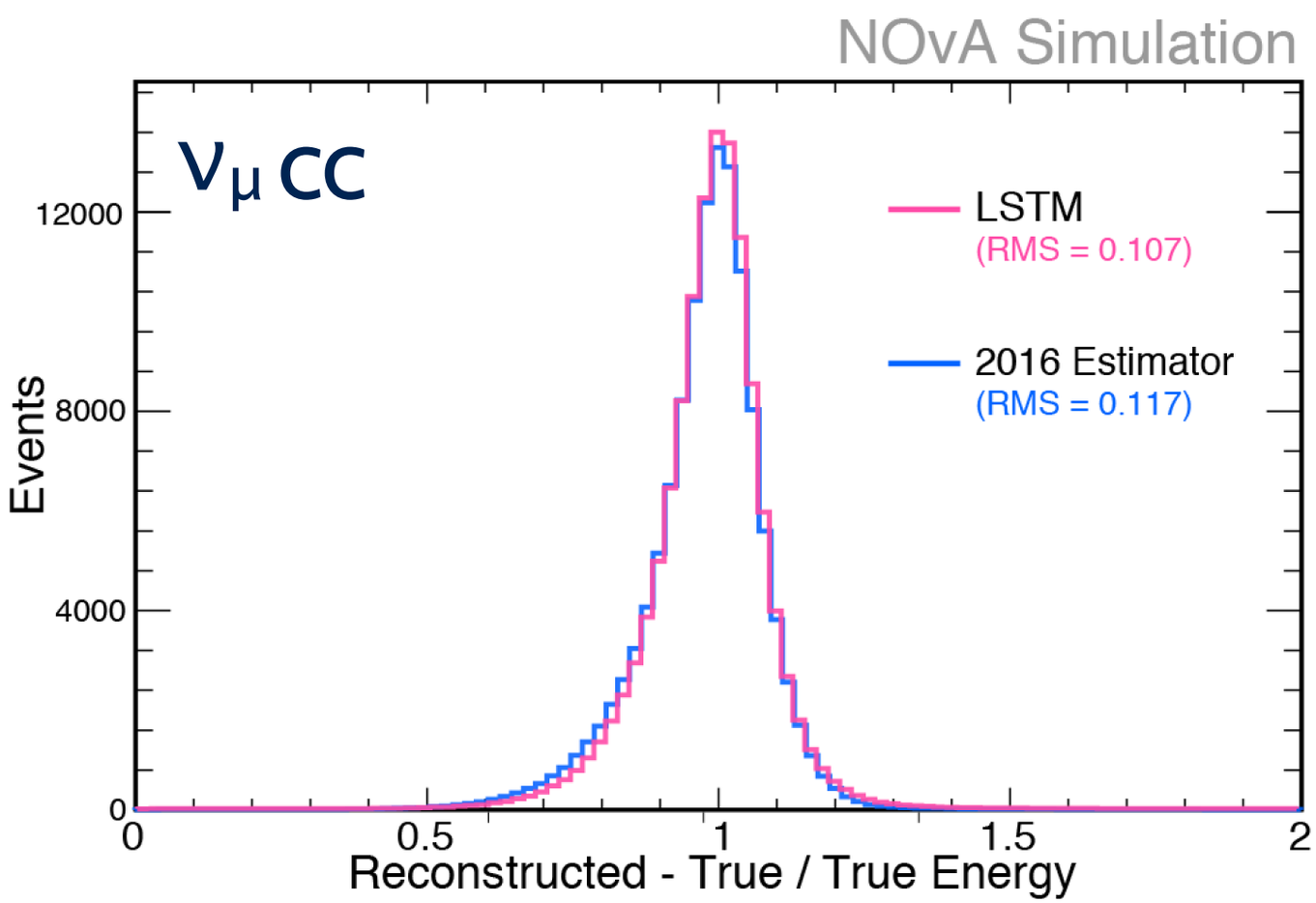
OnGoing: RNNs for Energy Estimation

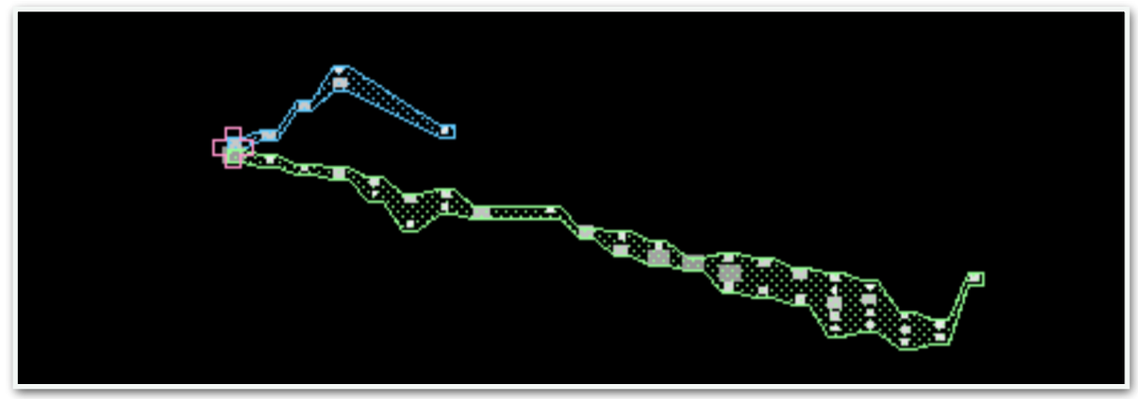
Recurrent Neural Networks:

Sequential network using the current state of the system + the output from last iteration.

LSTM: RNN + Long term memory cell



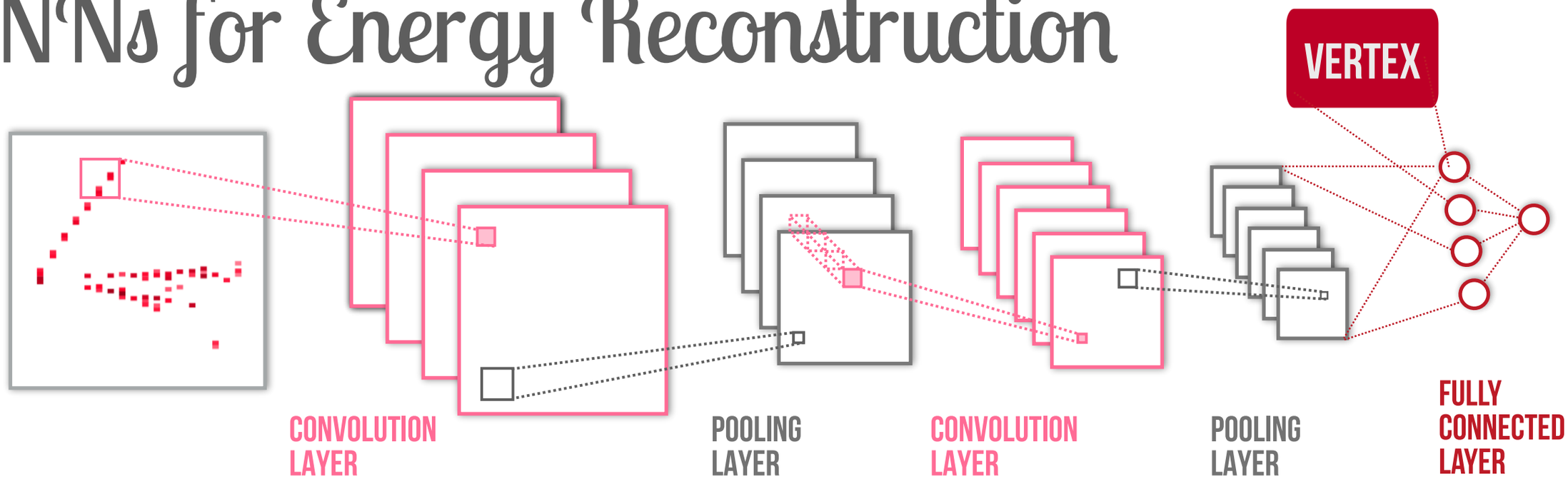




Input for each cluster:

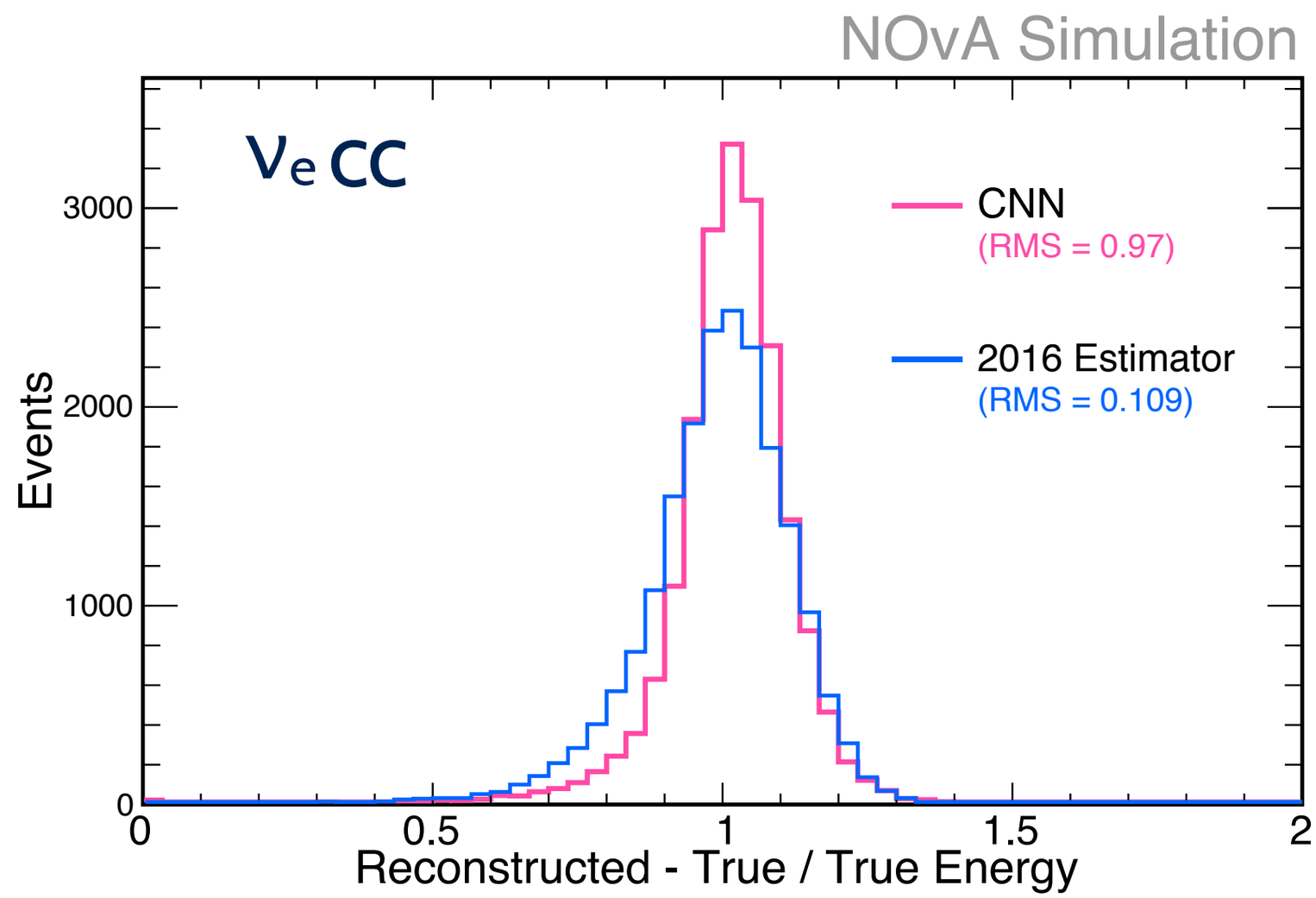
- Direction and length
- Cluster Particle ID
- Energy estimates
- Event calibrated energy

CNNs for Energy Reconstruction

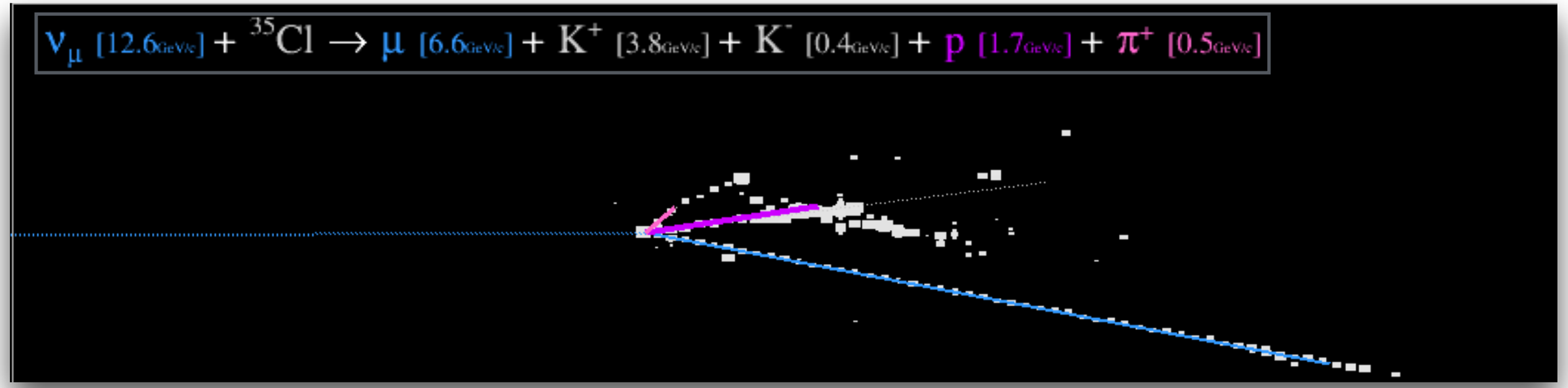


The target is Energy instead of PID values.

Incorporates information from the reconstruction at the fully connected stage.



Summary of Energy Reconstruction

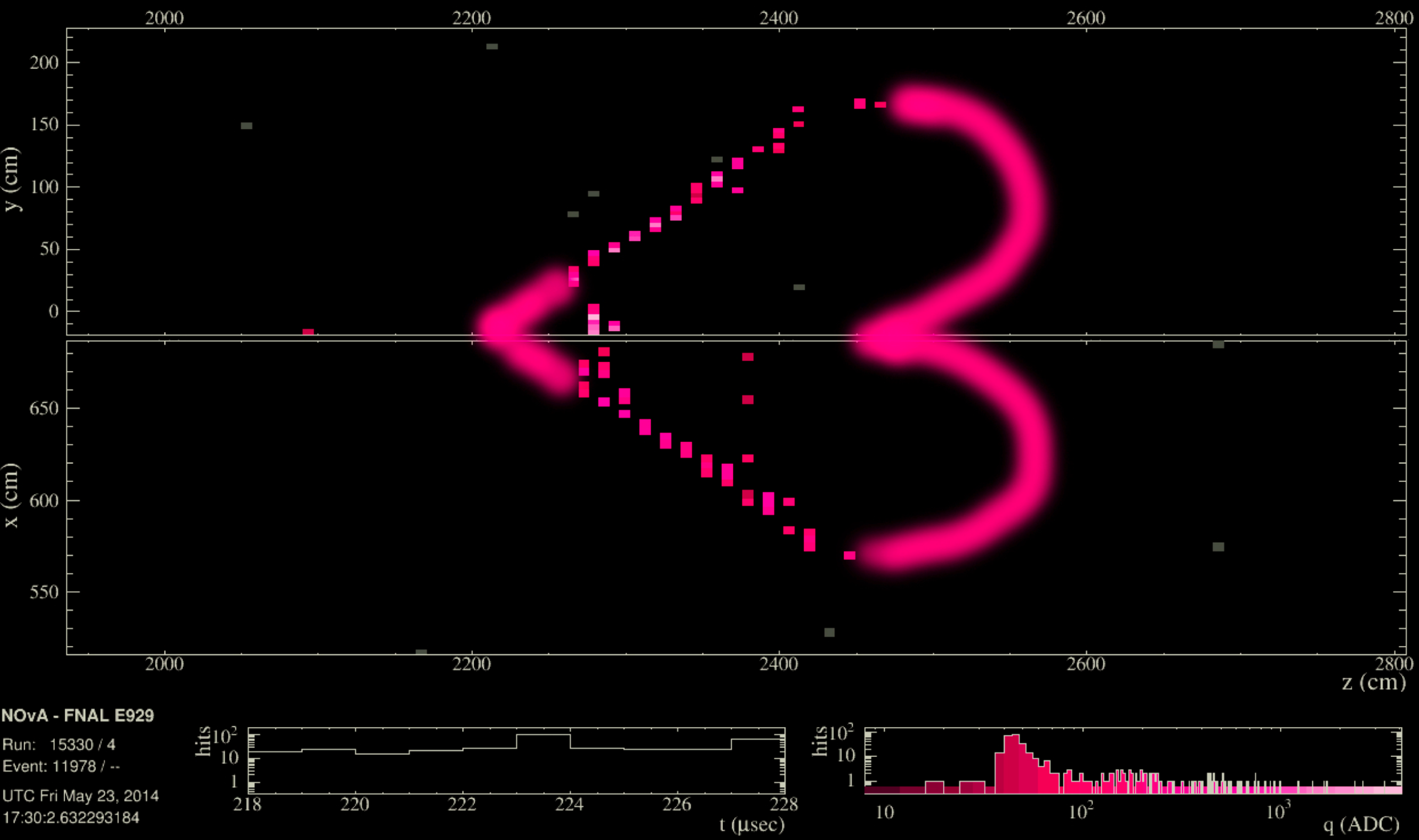


NOvA's energy already yields ~ 7% resolution for signal events.

Energy reconstruction is under development from multiple, competitive approaches.

More Implementations combining like deep learning and full traditional reconstruction approaches are being tested

Thank you


2000
2200
2400
2600
2800
200
150
100
50
0
y (cm)
650
600
550
x (cm)
z (cm)
NOvA - FNAL E929
Run: 15330 / 4
Event: 11978 / --
UTC Fri May 23, 2014
17:30:2.632293184
hits
10^2
10
1
218
220
222
224
226
228
t (μsec)
10
10^2
10^3
q (ADC)

Backup

Electromagnetic vs Hadronic Energy Losses

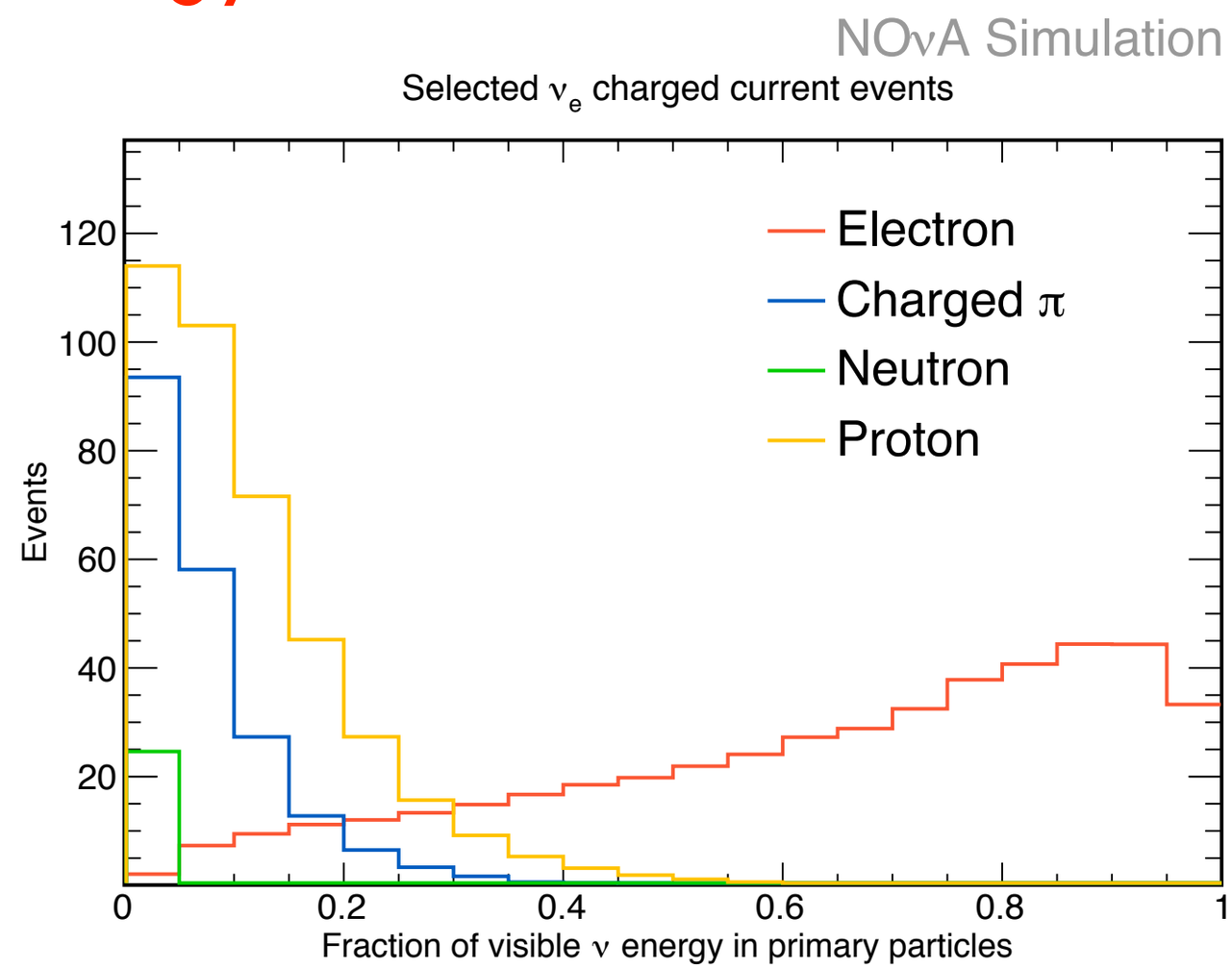
$$E_{neutrino} \approx \Sigma\, E_{deposited} \text{ in each cell}$$

Electromagnetic energy depositions: Mostly to Bremsstrahlung, electromagnetic showers.

$$E_{em} \approx \Sigma\, E_{deposited} \text{ in each cell}$$

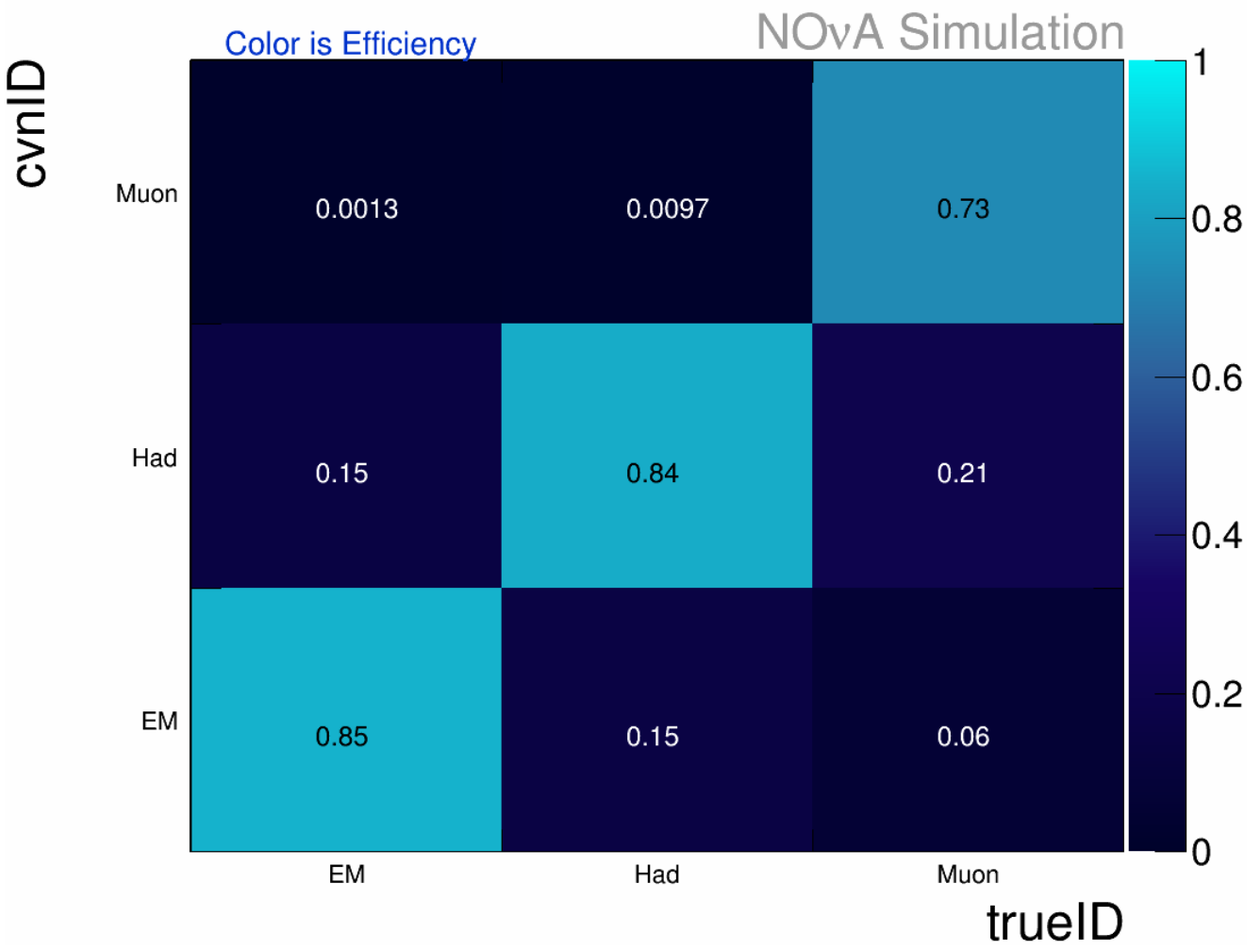
Hadronic energy depositions: Mostly through ionization and nuclear interactions. Large energy losses.

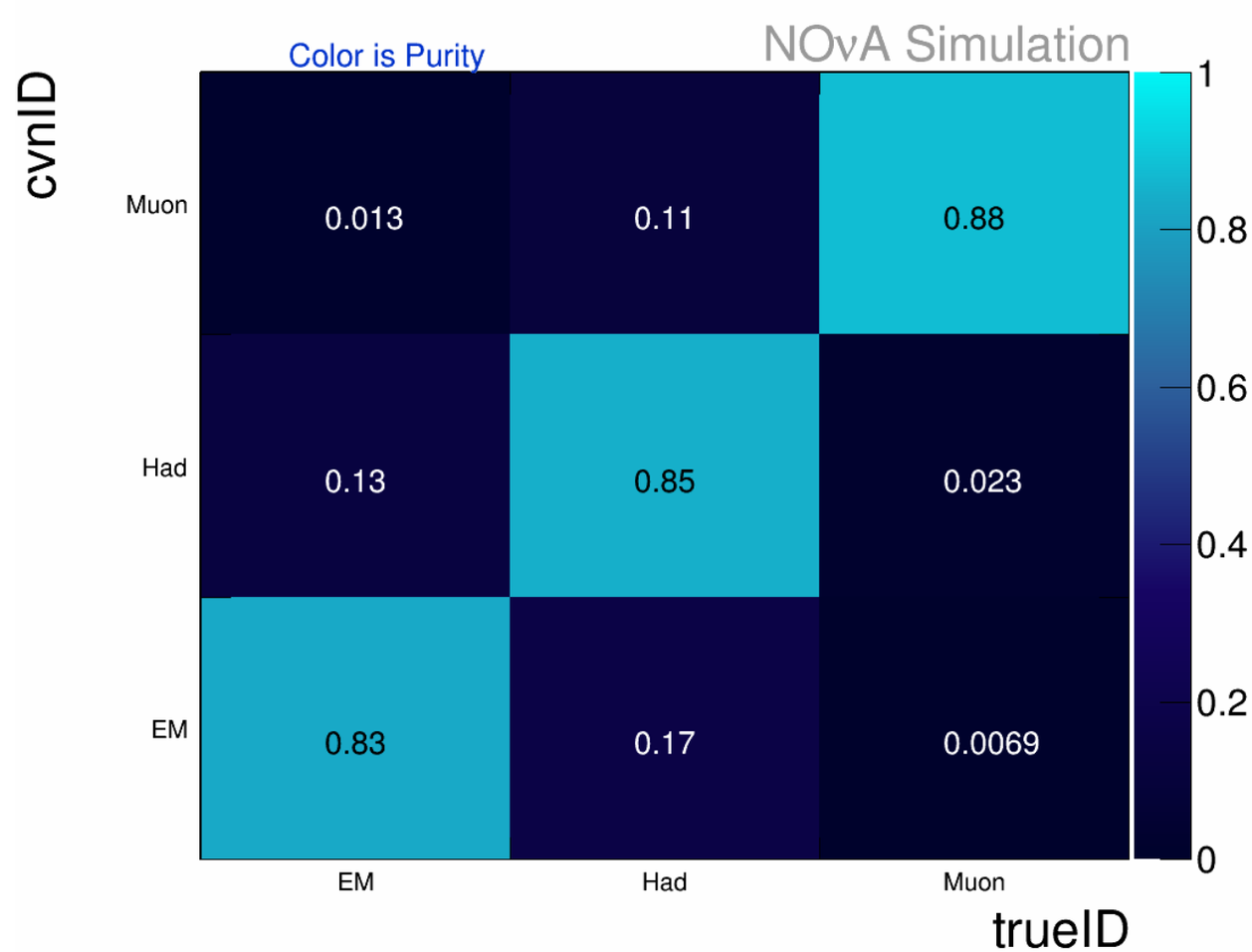
$$E_{had} \not\approx \Sigma\, E_{deposited} \text{ in each cell}$$

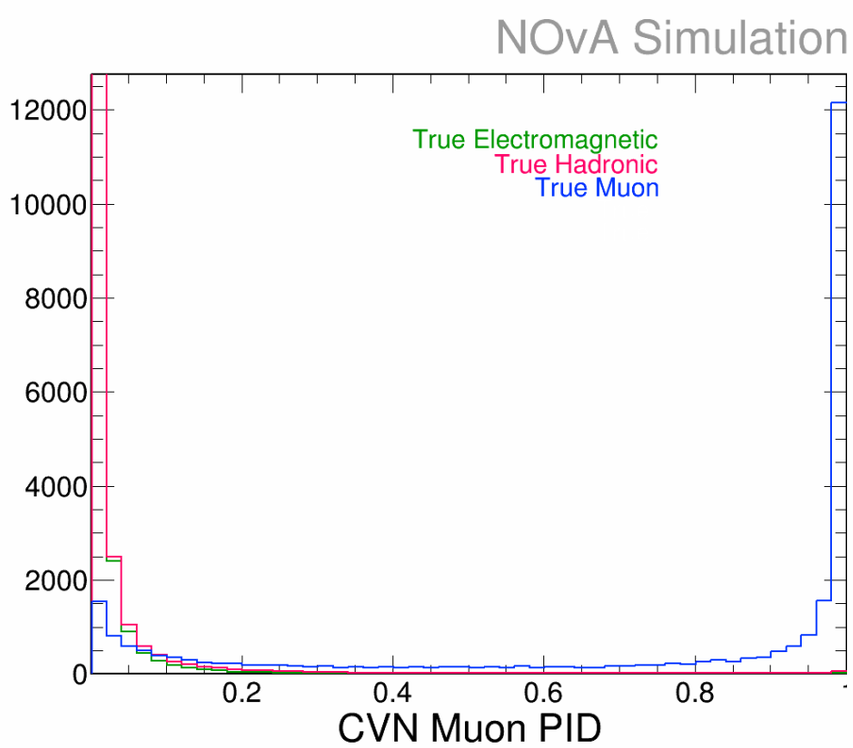


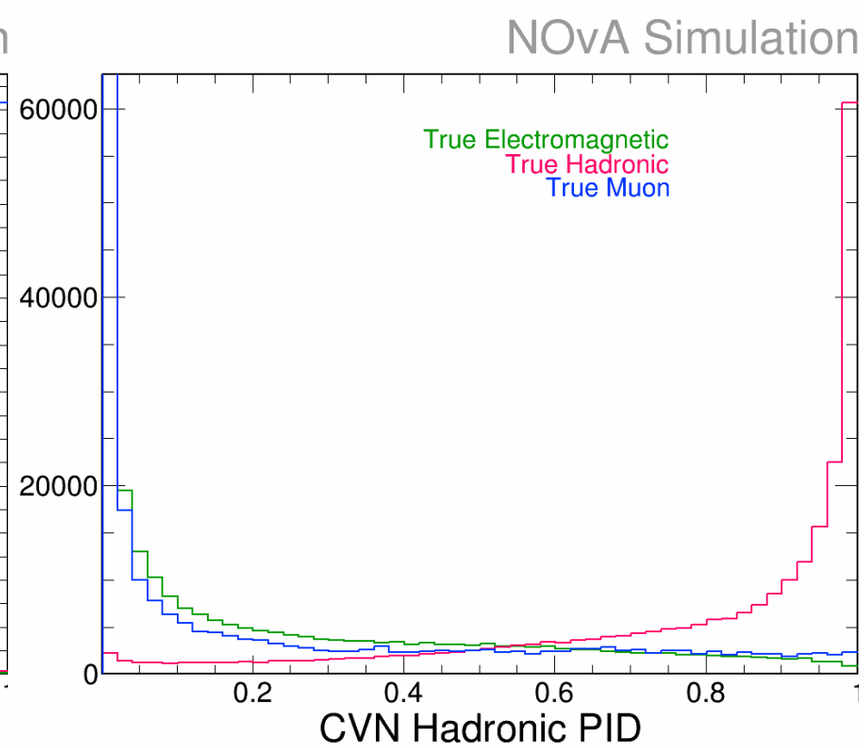
The relative response of the NOvA detectors to electromagnetic vs hadronic energy is $e/h \simeq 1.26 \pm 0.02$

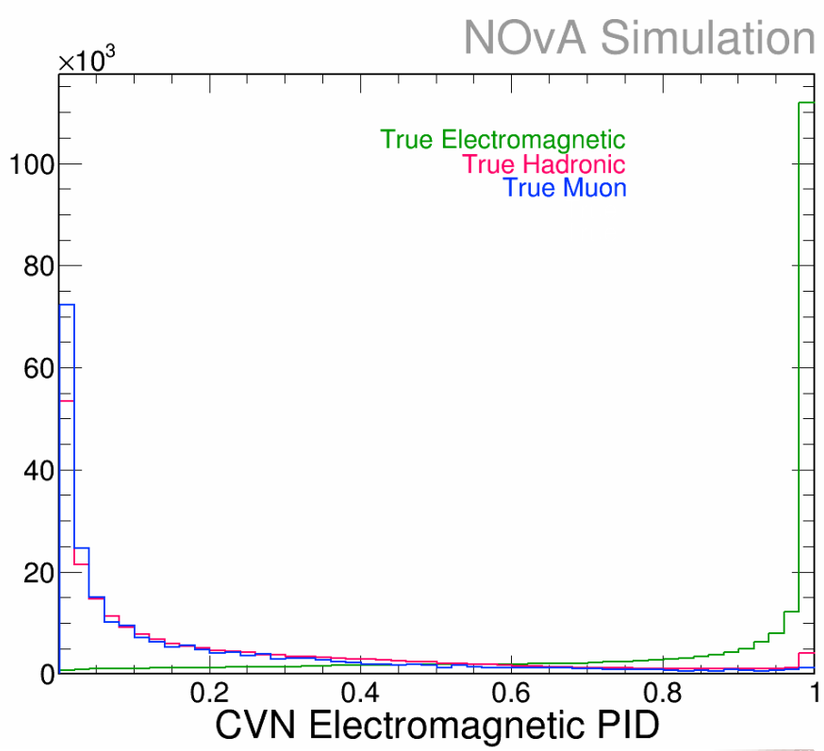
$$E_\nu = E_e + E_{had}$$


Color is Efficiency
NOvA Simulation
cvnID
Muon
Had
EM
0.0013
0.0097
0.73
0.15
0.84
0.21
0.85
0.15
0.06
EM
Had
Muon
trueID
1
0.8
0.6
0.4
0.2
0


Color is Purity
NOvA Simulation
cvnID
Muon
Had
EM
0.013
0.11
0.88
0.13
0.85
0.023
0.83
0.17
0.0069
EM
Had
Muon
trueID
1
0.8
0.6
0.4
0.2
0


NOvA Simulation
True Electromagnetic
True Hadronic
True Muon
12000
10000
8000
6000
4000
2000
0
0.2
0.4
0.6
0.8
CVN Muon PID


NOvA Simulation
True Electromagnetic
True Hadronic
True Muon
60000
40000
20000
0
0.2
0.4
0.6
0.8
CVN Hadronic PID


NOvA Simulation
×10^3
True Electromagnetic
True Hadronic
True Muon
100
80
60
40
20
0
0.2
0.4
0.6
0.8
1
CVN Electromagnetic PID

The NOvA Detectors are Sampling Calorimeters

$E_{neutrino} \approx \Sigma\ E_{deposited}$ in each cell

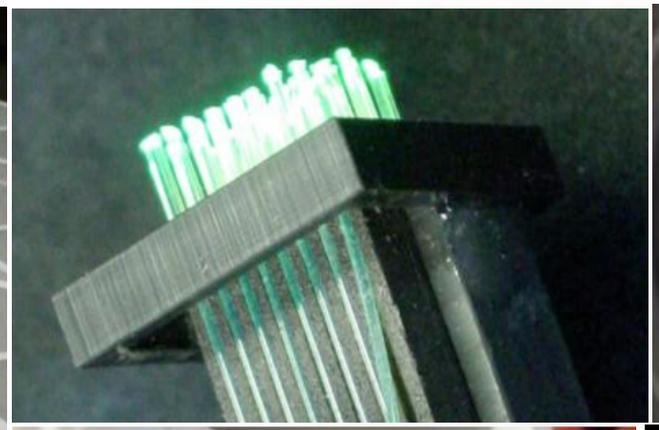
Optimized for electron identification.

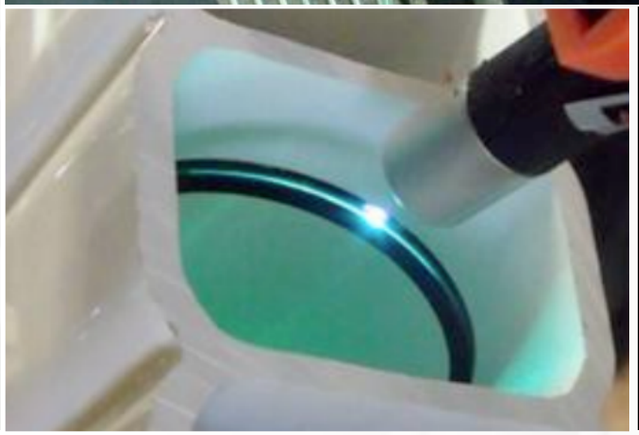
Low Z segmented detector.

PVC extrusions filled with liquid scintillator.

λ_{rad} ~ 40 cm
~ 6-10 cells

Molière radius ~13 cm
~2-3 cells

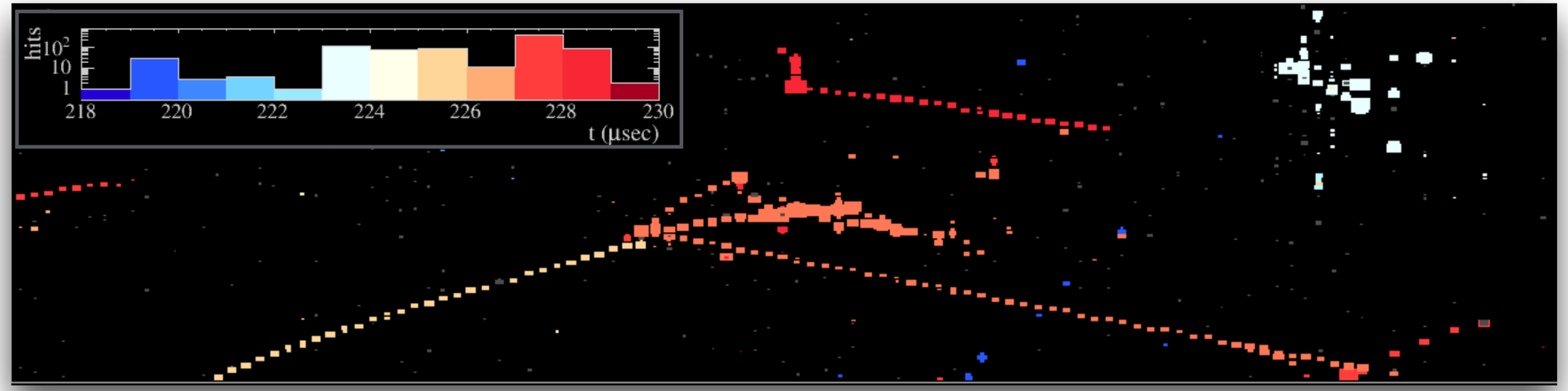




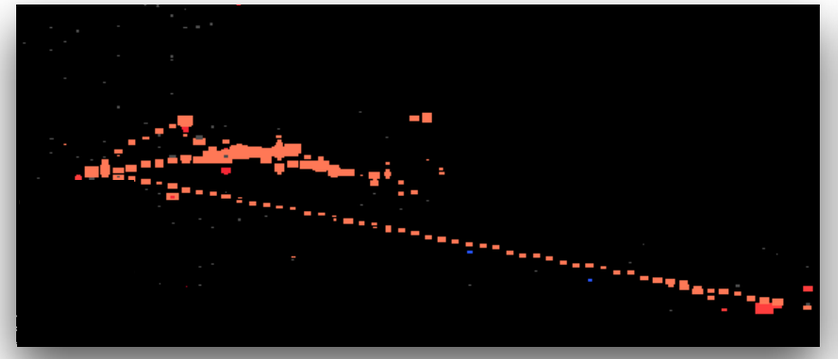
Traditional Reconstruction

Use the topology and magnitude of the energy depositions.

Takes advantage of the granularity and time resolution of our detectors.

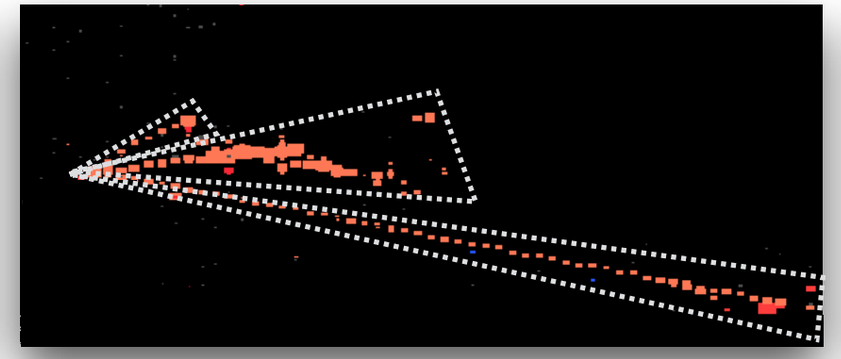


ISOLATE THE EVENT



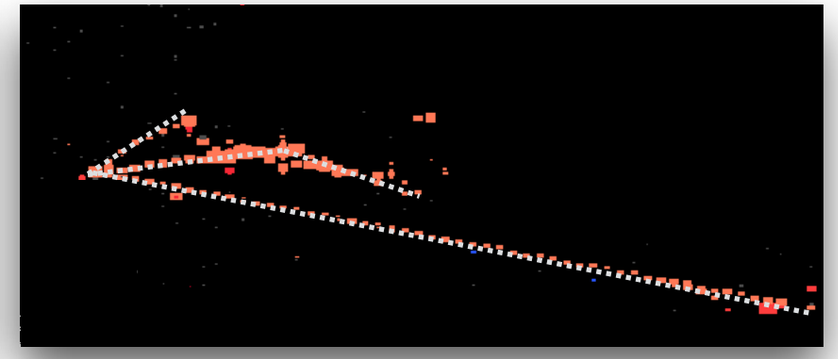
We isolate individual interactions using time and space correlation of the hits.

DEFINE CLUSTERS



Groups of hits can be clustered as following the path of same particle starting at the interaction point.

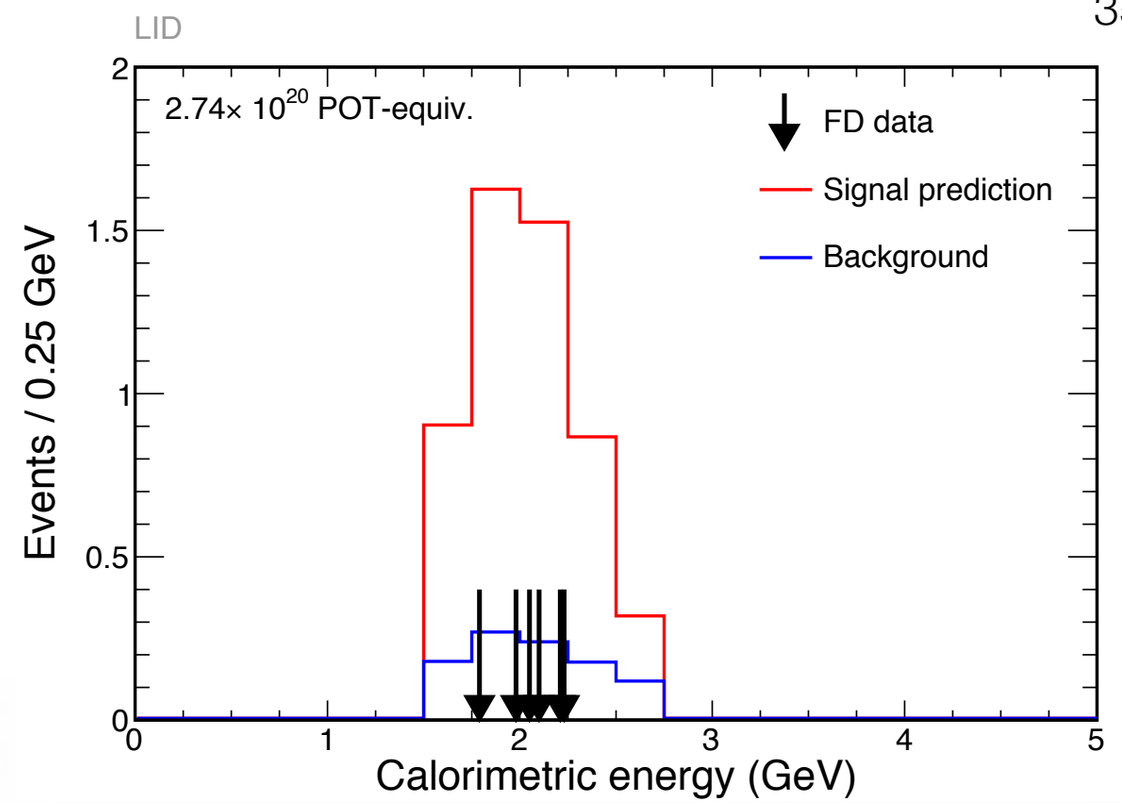
FIT TRAJECTORY



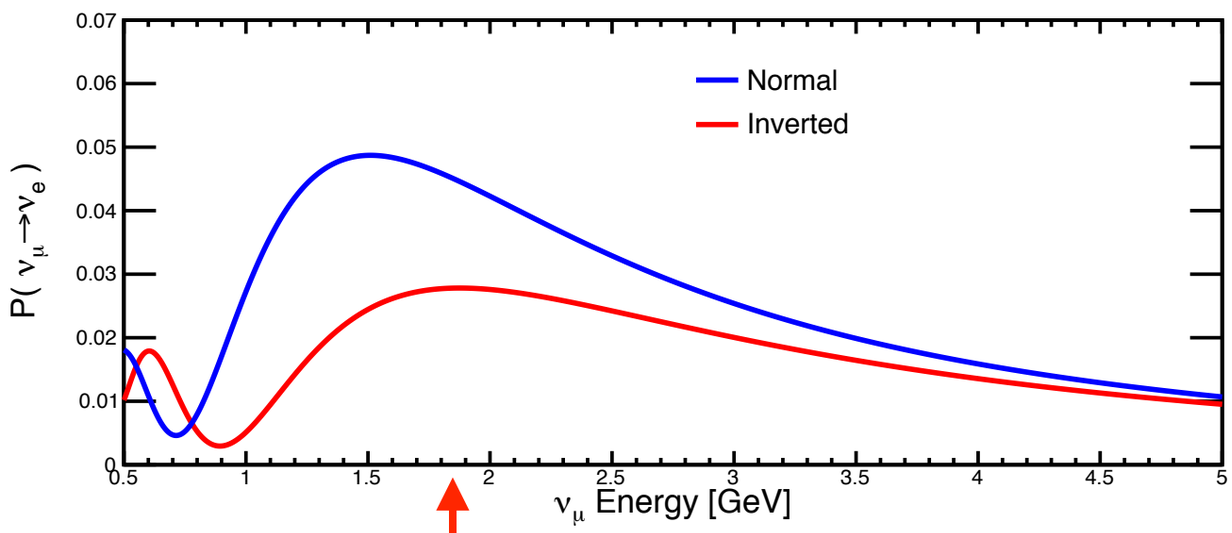
When necessary we can fit an assumed trajectory for each cluster of hits.

Why Improve Energy Resolution?

NOvA's first results were a cut & count analysis, observation of nue appearance.

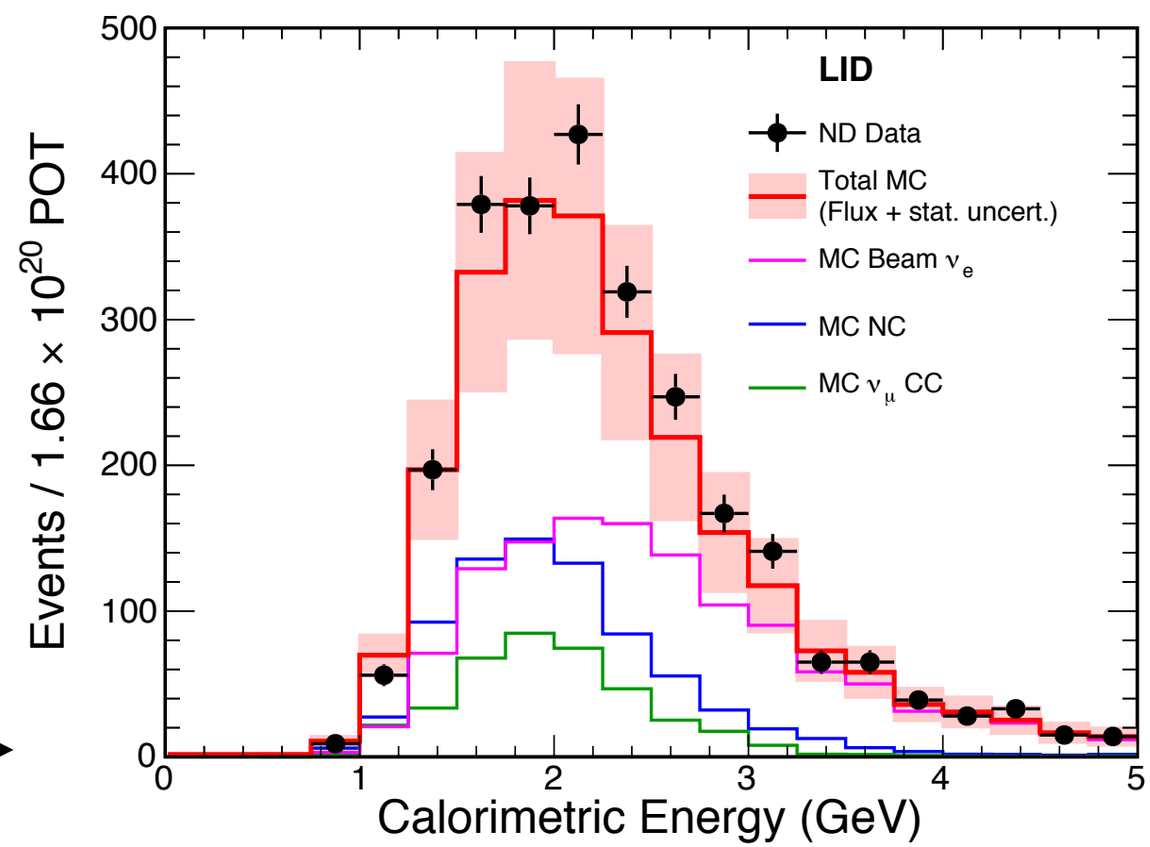


Improving energy resolution gives us access to more precise measurement of P(Eν), δcp and the mass hierarchy.

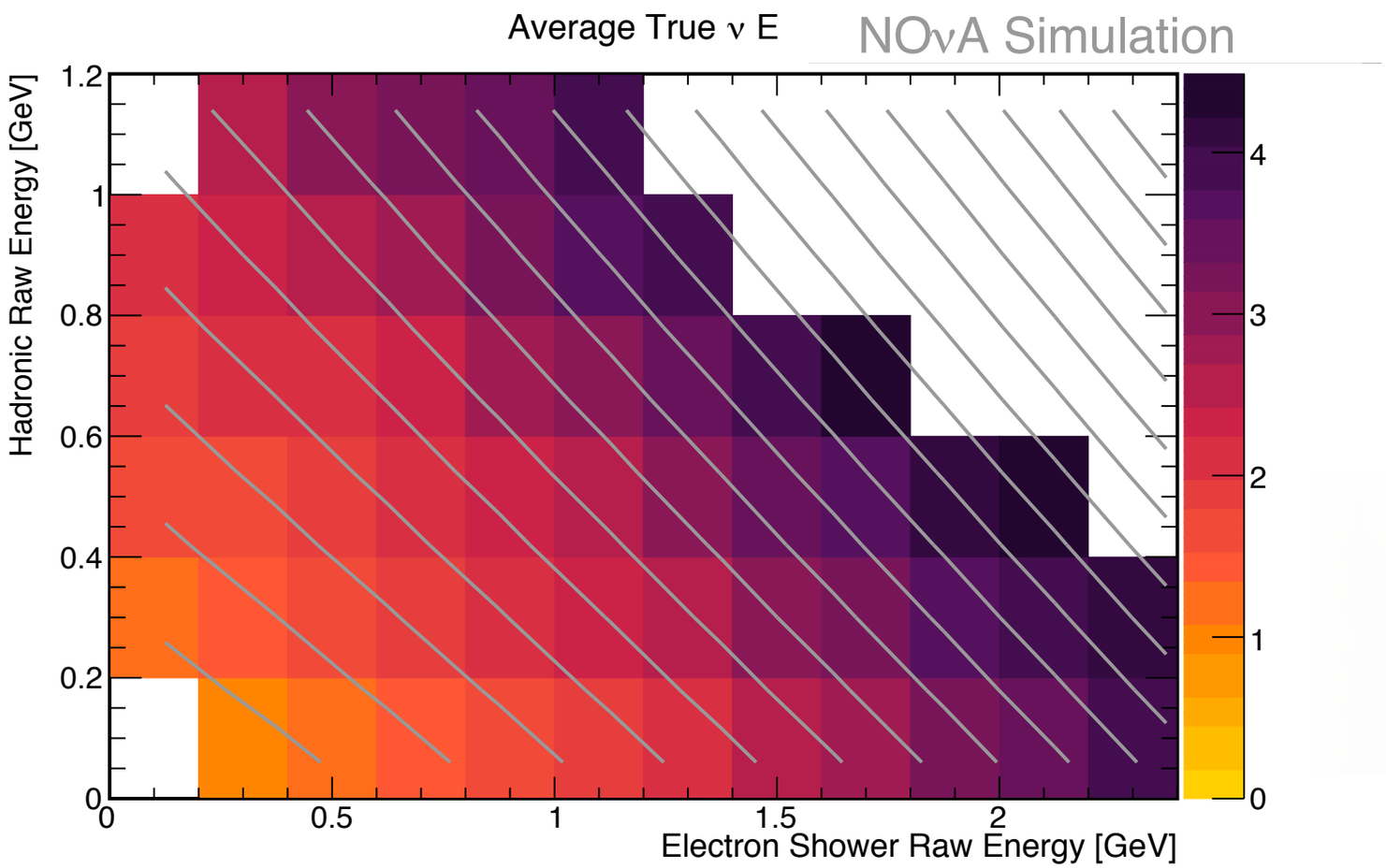


NOvA's Energy Peak

Good energy resolution can also improve background decomposition.

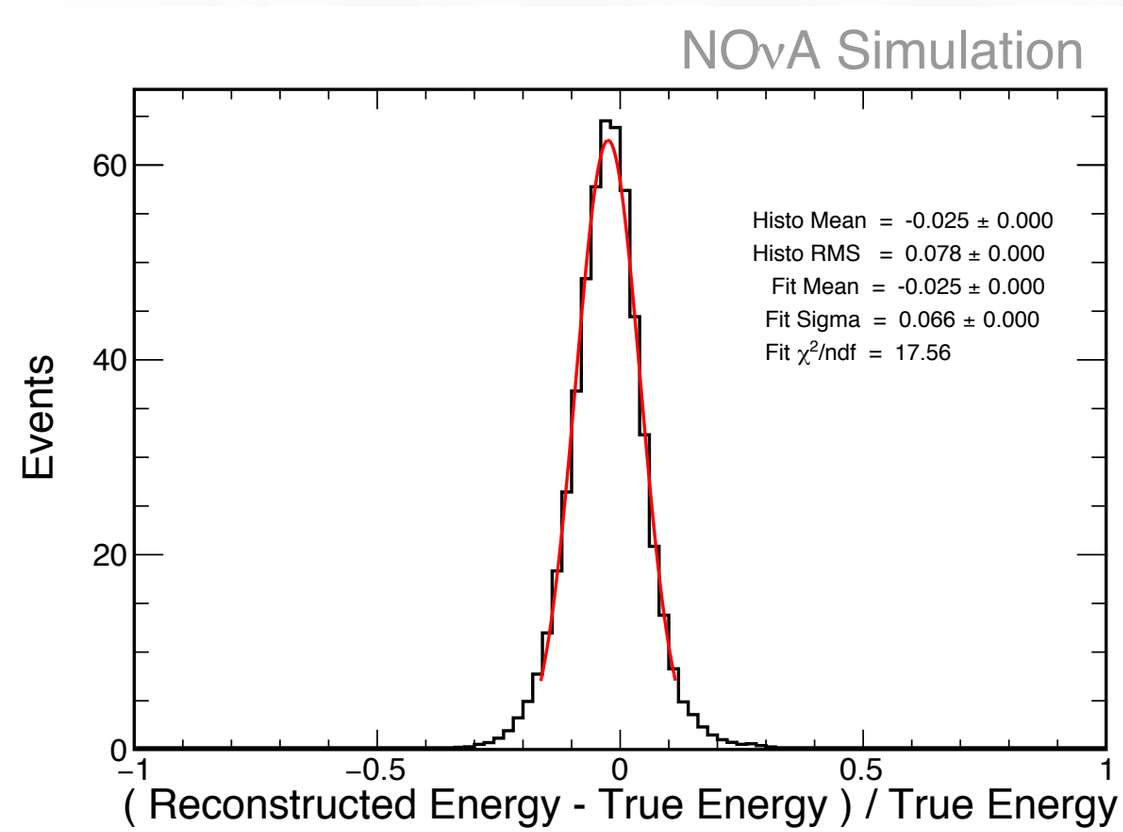


Estimating ν Energy



A quadratic fit to true energy as a function of em energy and had energy is used for estimation:

$$0.687 + 0.701\, E_{em} + 1.211\, E_{had} + 0.543\, E_{em} E_{had} + 0.248\, E^2_{em} + 0.139\, E^2_{had}$$



A fit to both components accounts for **overlapping** hadronic and electron showers.

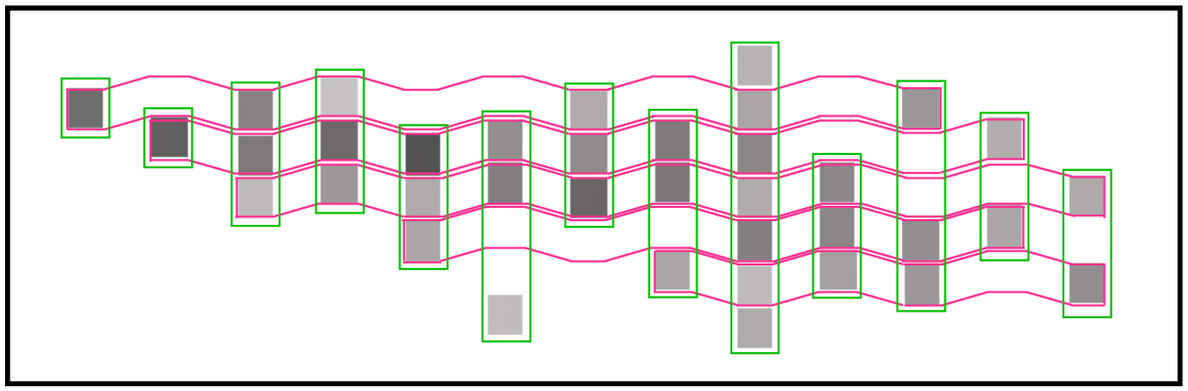
7% Energy resolution is a **22% improvement** from our first analysis approach

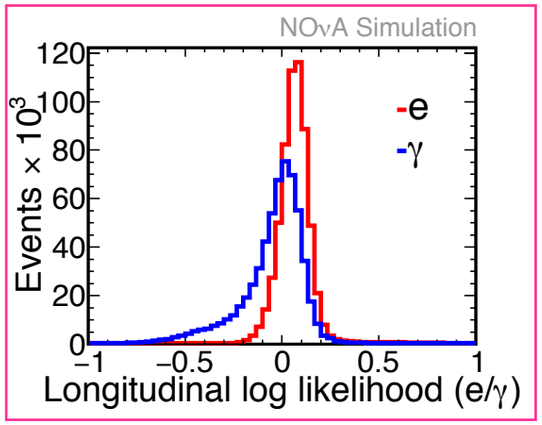
Neutrino Identification (First Analysis)

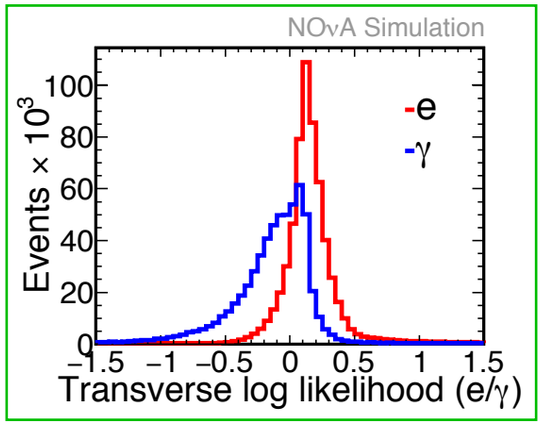
LID

Likelihood Identification

Premise: Electron showers have characteristic transverse and longitudinal energy deposition profiles.







In practice:

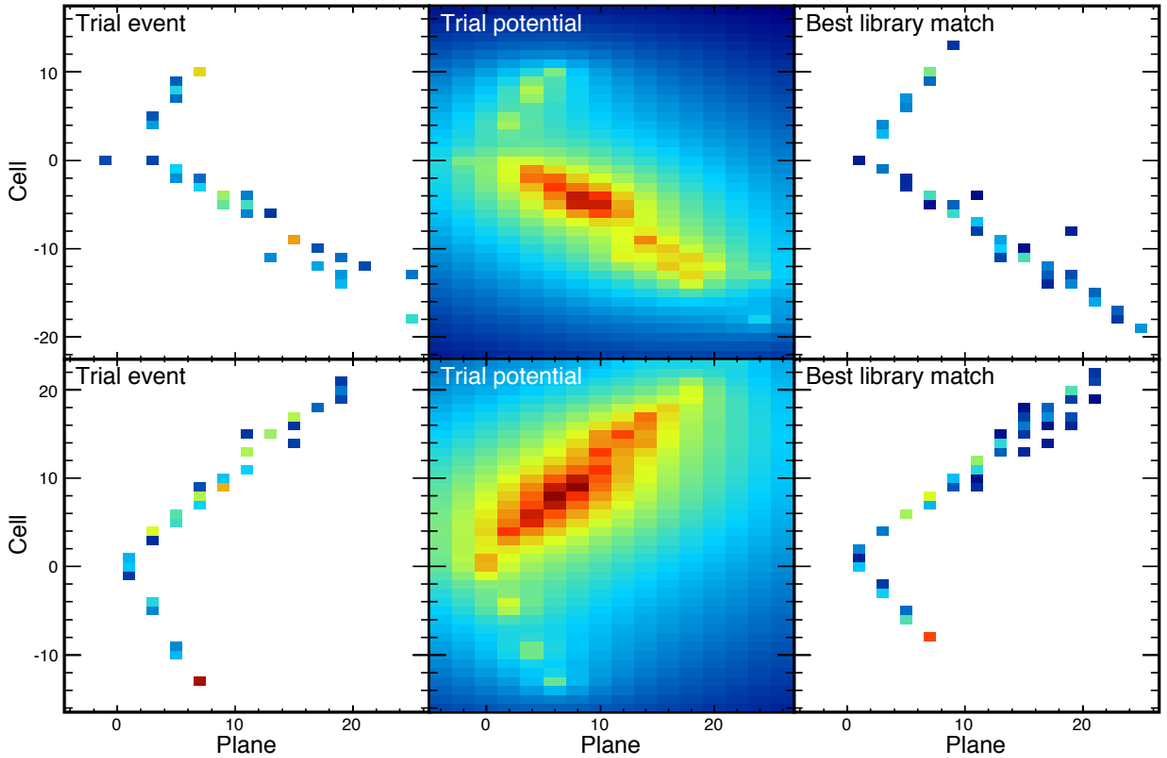
- ★ Reconstruct electron shower.
- ★ Find likelihoods from it's dE/dx profiles compared to particle hypotheses.

Likelihoods → *Neural Network*

LEM

Library Event Matching

Premise: We have a large library of simulated event templates, large enough that we can use it to compare pixel by pixel.

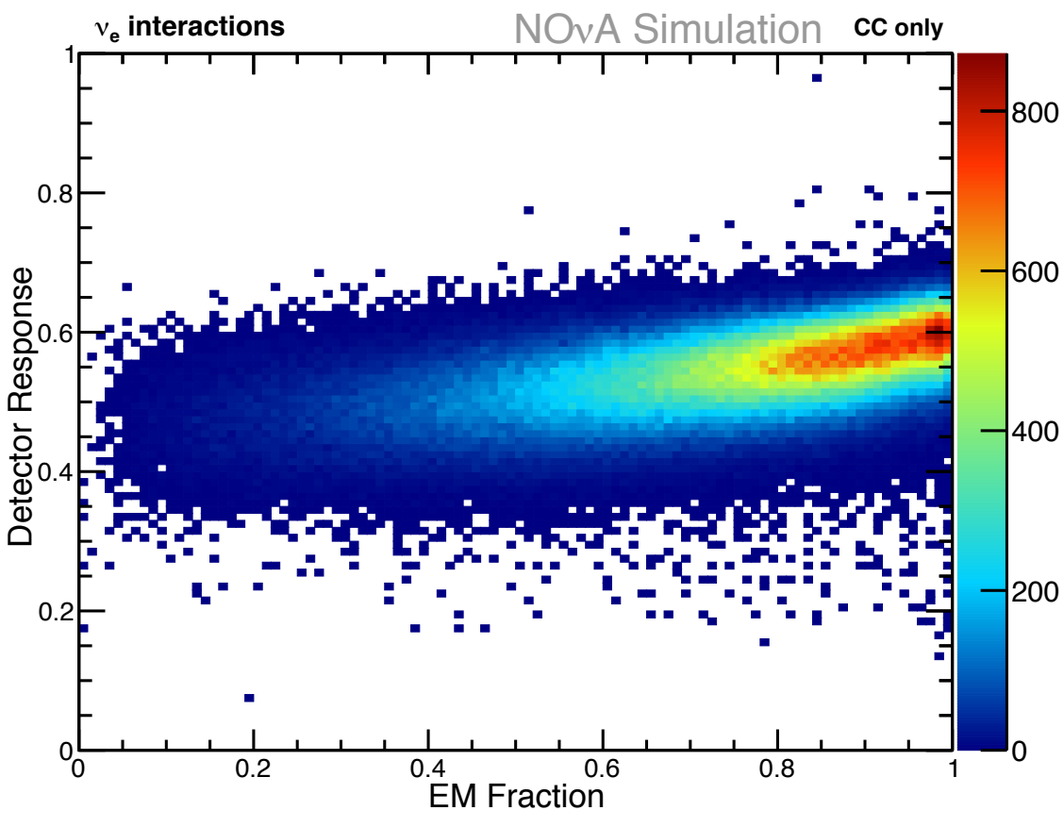


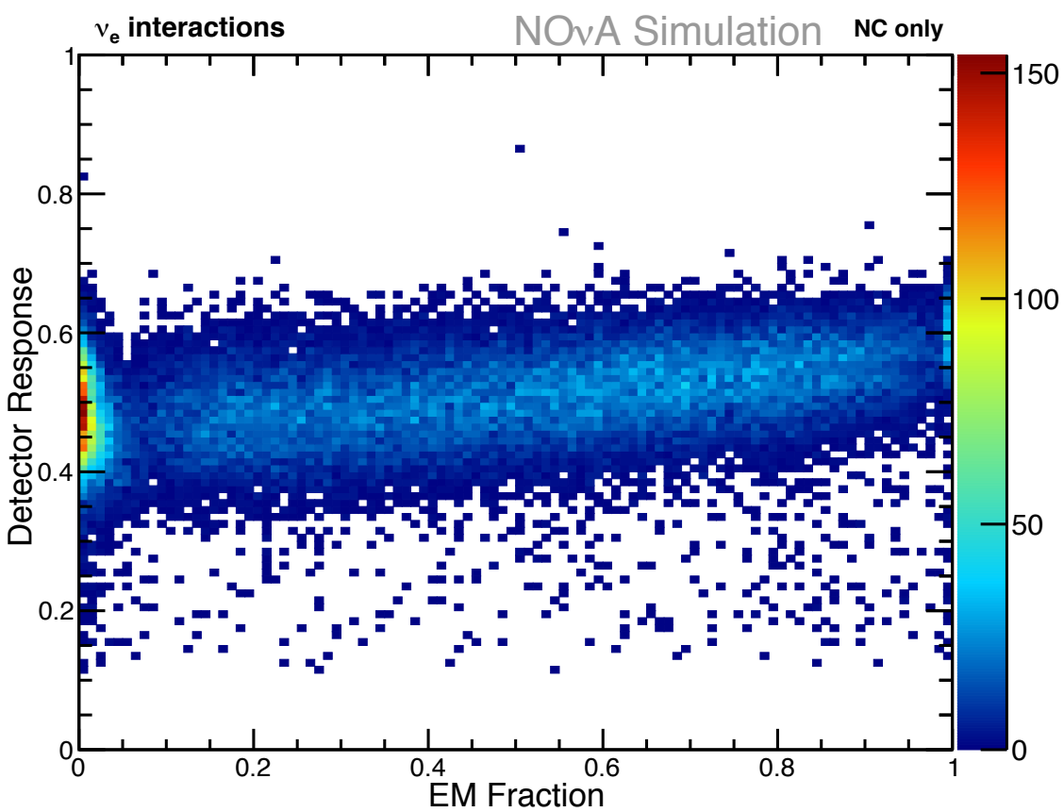
In practice:

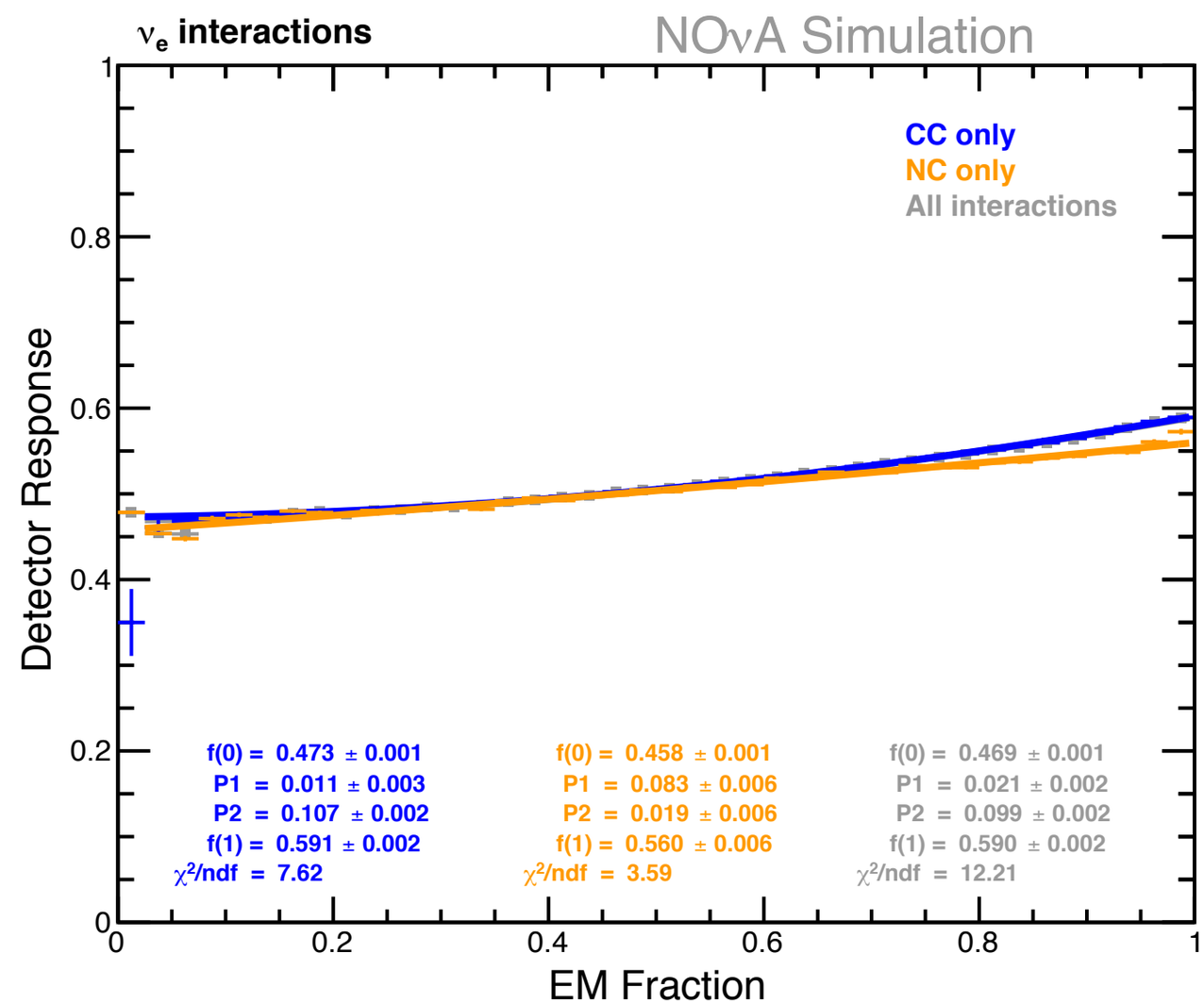
- ★ Find the best matches from the event library.
- ★ Extract features from best matches.

Features → *Decision Tree*

NOνA detectors' e/h

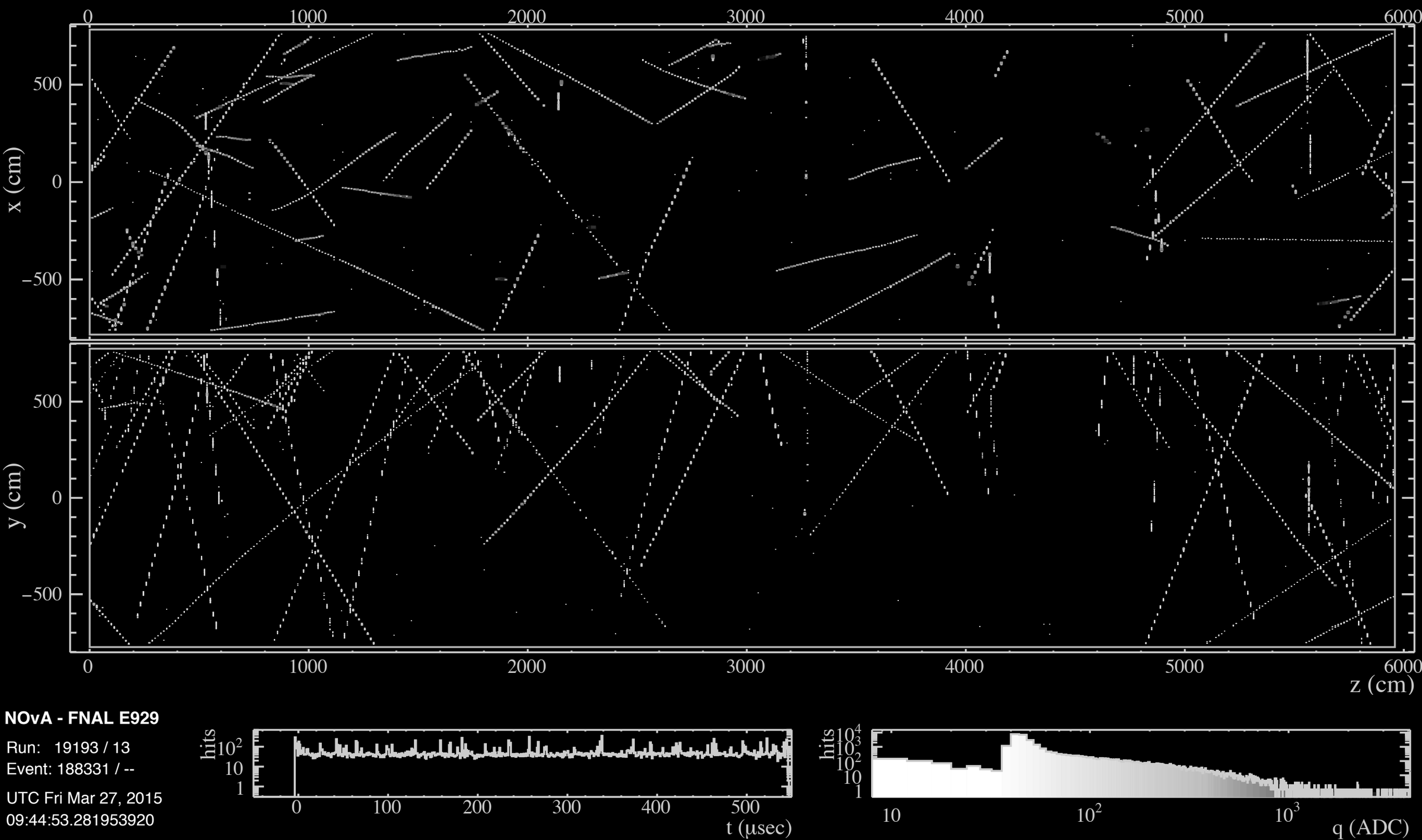






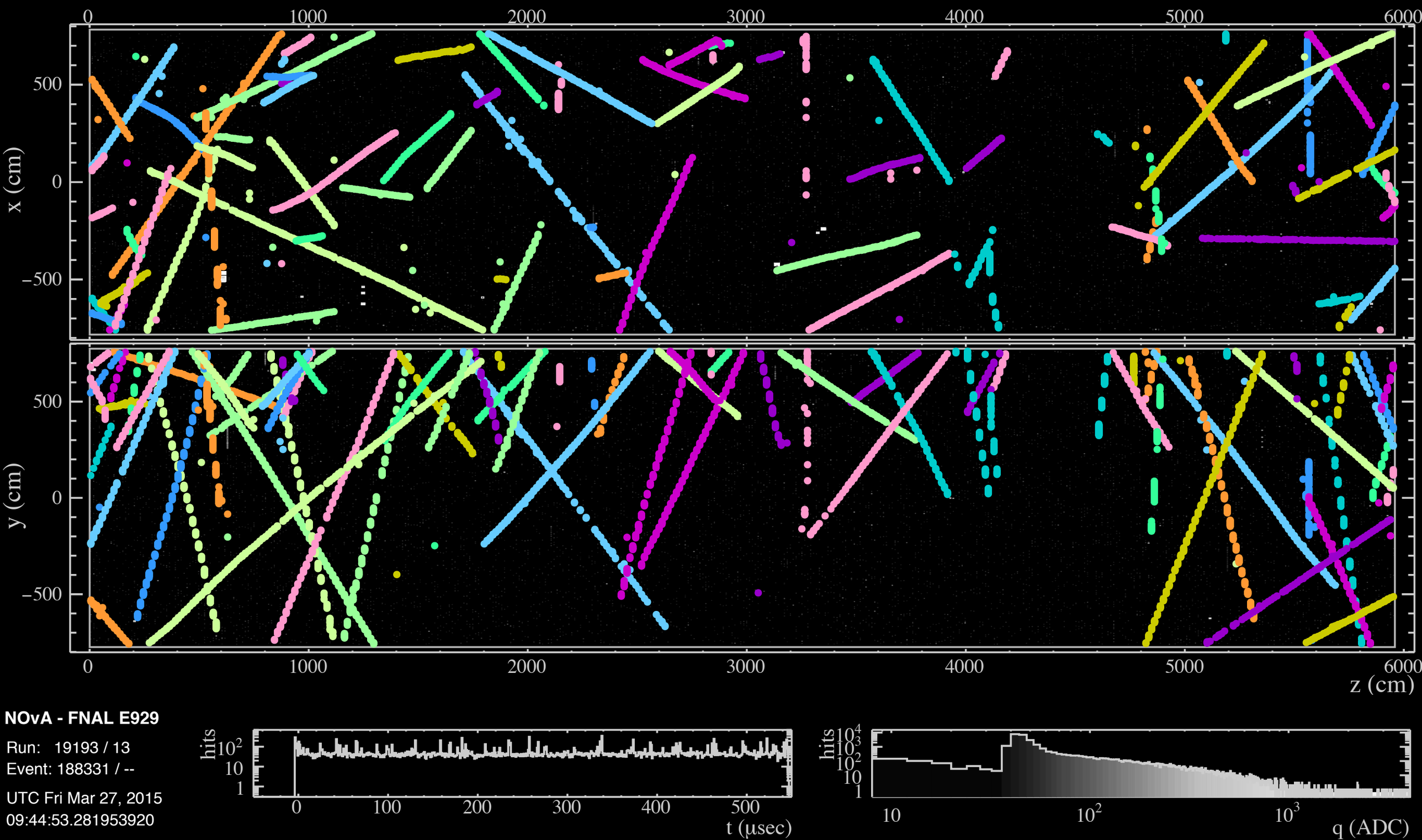
Isolating neutrino interactions

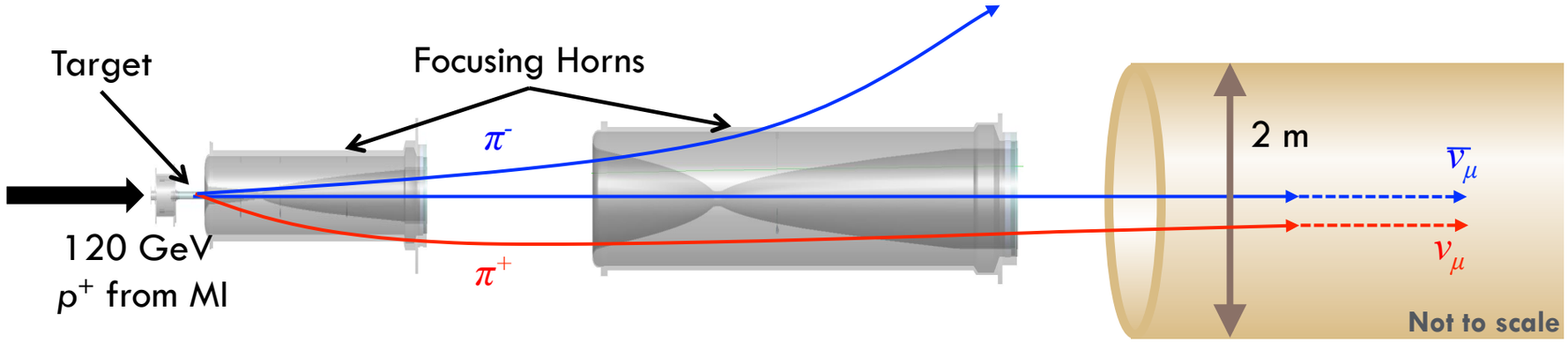
The first step in our reconstruction is dividing an **event** (550 μs of data)

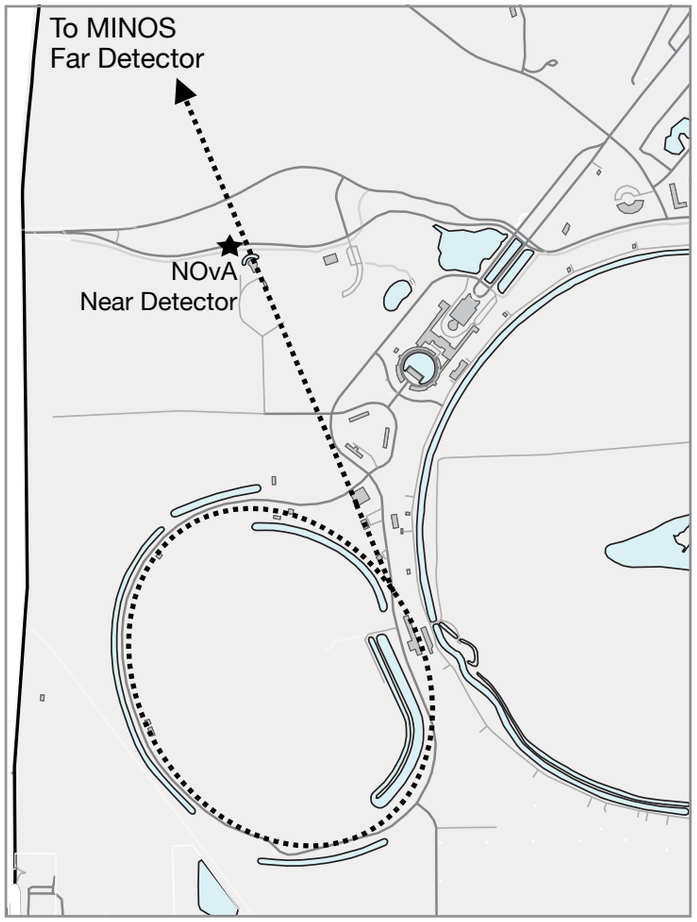


Isolating neutrino interactions

The first step in our reconstruction is dividing an **event** (550 μs of data) into slices (groups of hits with some time and space coincidence)



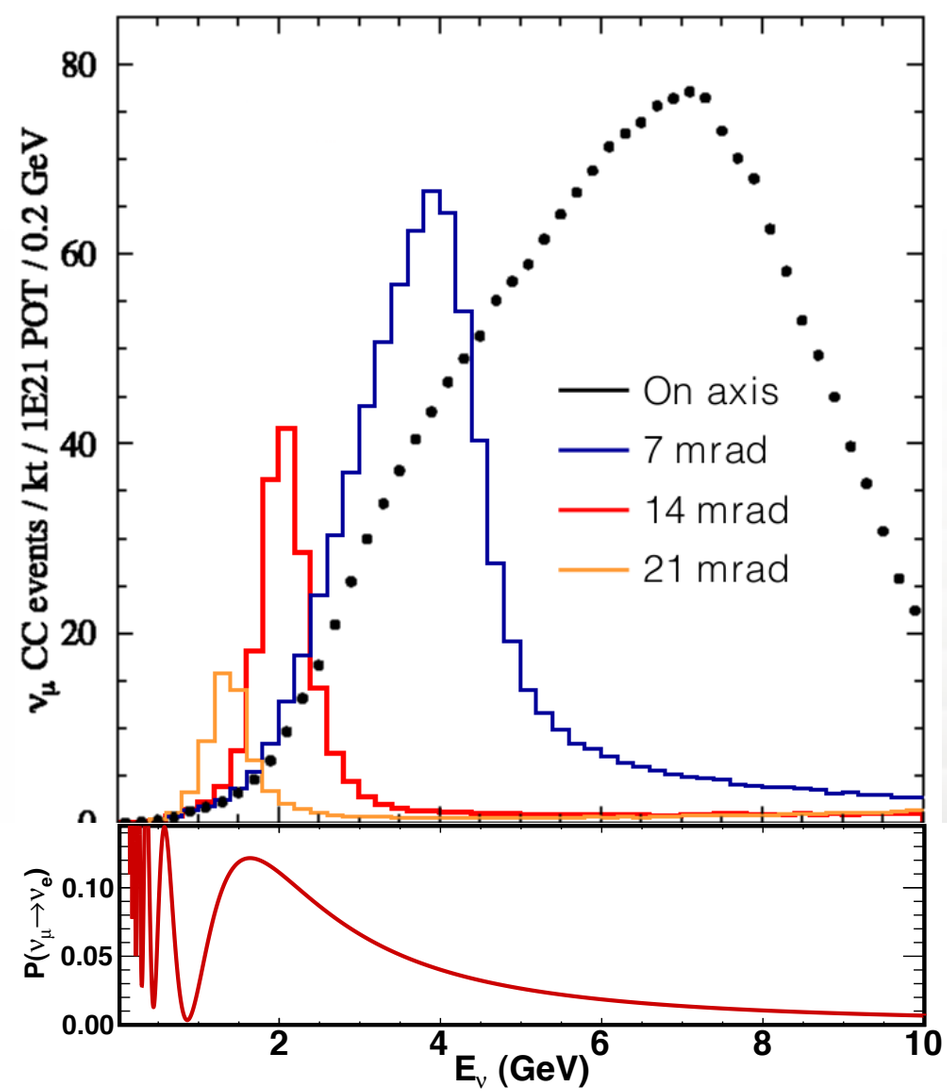




We use **neutrinos from the main injector,** made from π decays from p-target collisions. We expect 6×10^{20} POT protons on target per year of running.

This ν beam used originally by MINOS has been upgraded and will reach up to 700kW.

Angle with respect to beam direction defines the energy distribution of outgoing neutrinos.



Constraining the energy range also reduces beam backgrounds.