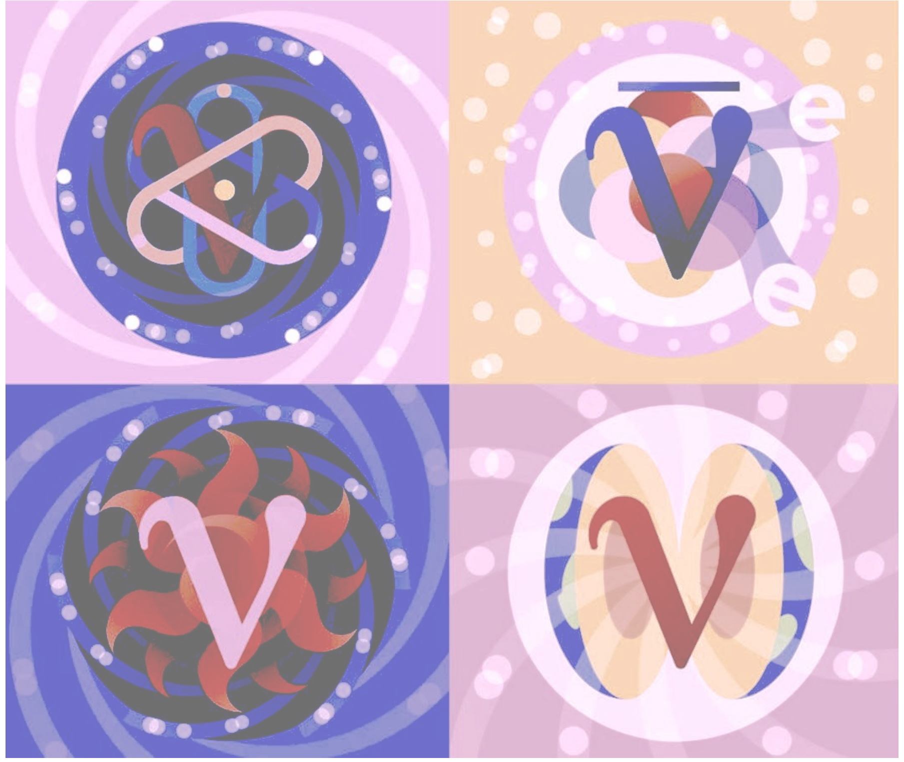
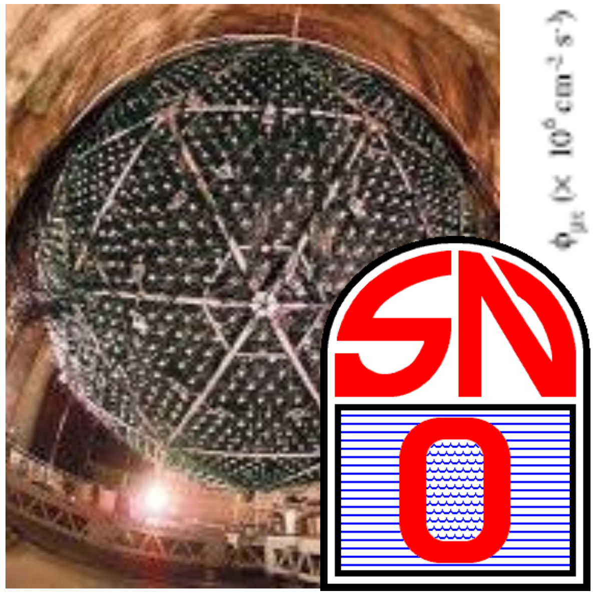
LBL NEUTRINO EXPERIMENTS AT FERMILAB

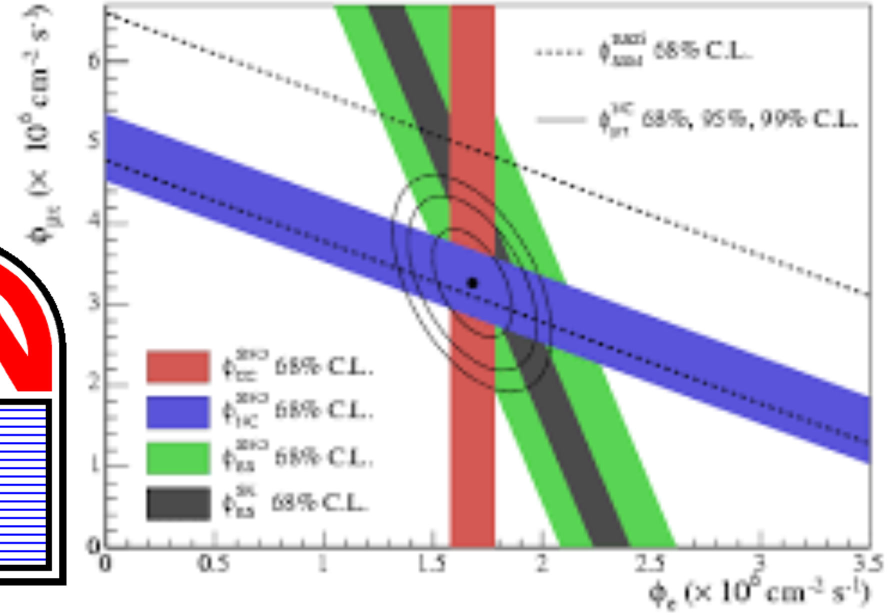
status and reach of long baseline neutrino oscillation experiments: **NOνA, MINOS+** and **DUNE**

Fernanda Psihas
Indiana University



The Elusive Neutrino

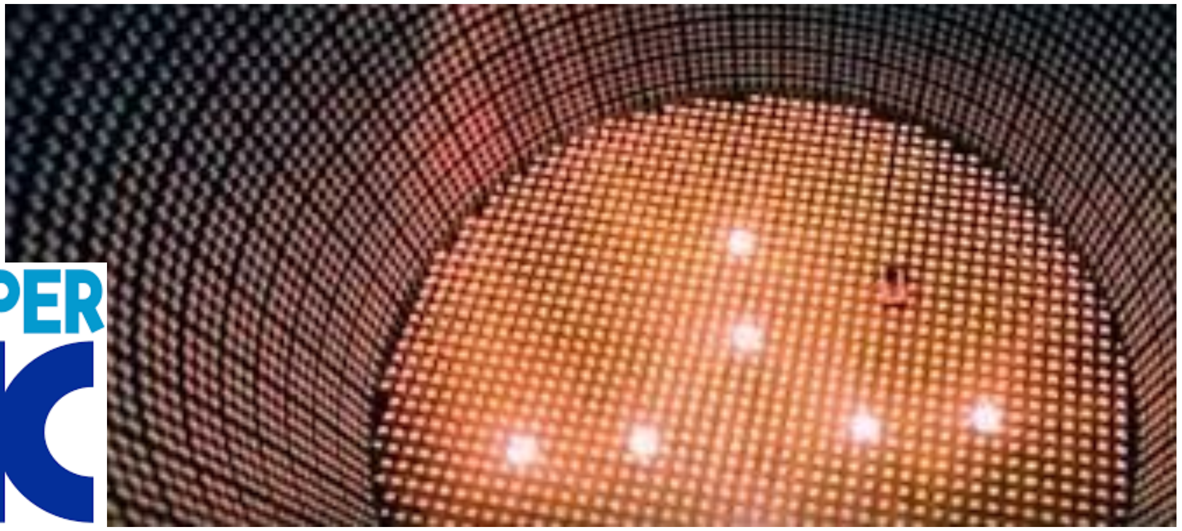


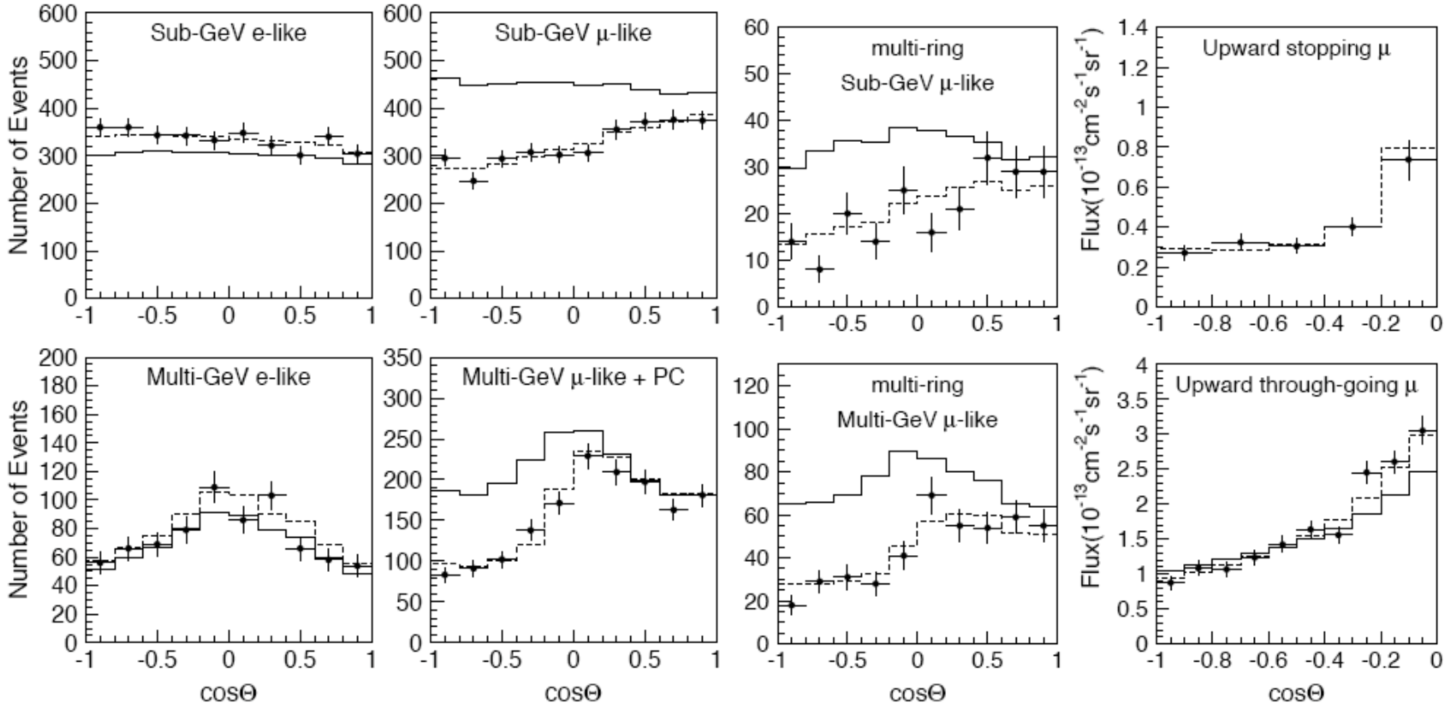


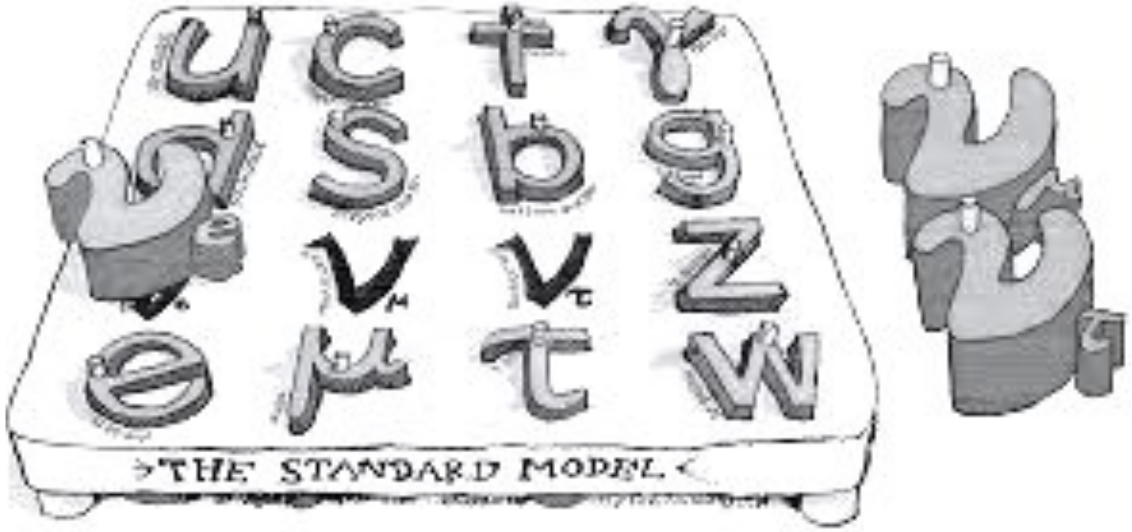
Neutrino mass eigenstates are superposition of flavor eigenstates

Nobel Price 2015 for first observations of ν oscillations

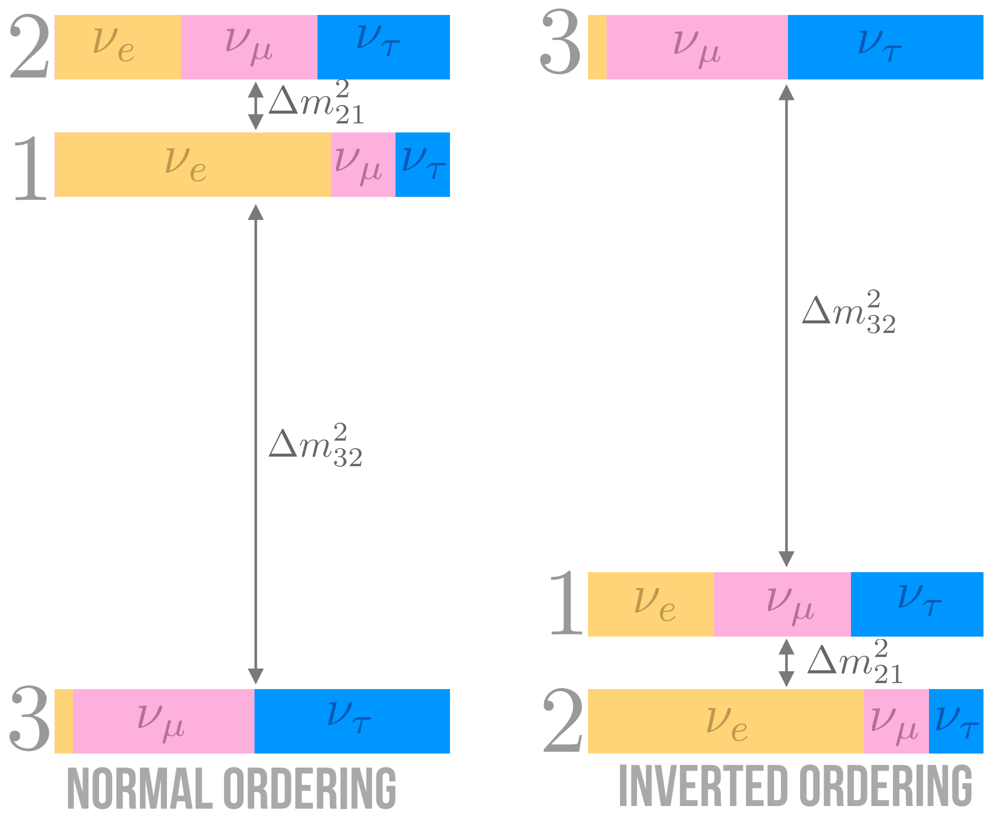
Oscillations require nonzero ν masses





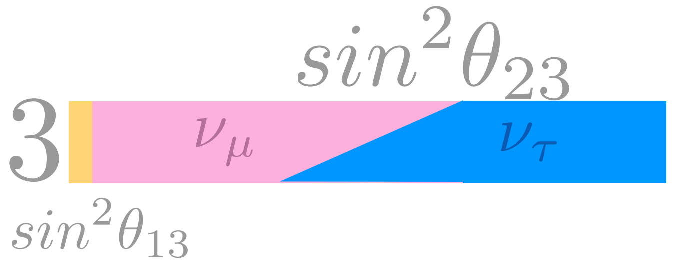


Questions in Neutrino Physics



There are probes on neutrino masses from cosmology and $0\nu\beta\beta$

The mass hierarchy may constrain the absolute mass scale and has implications to the Majorana nature of neutrinos

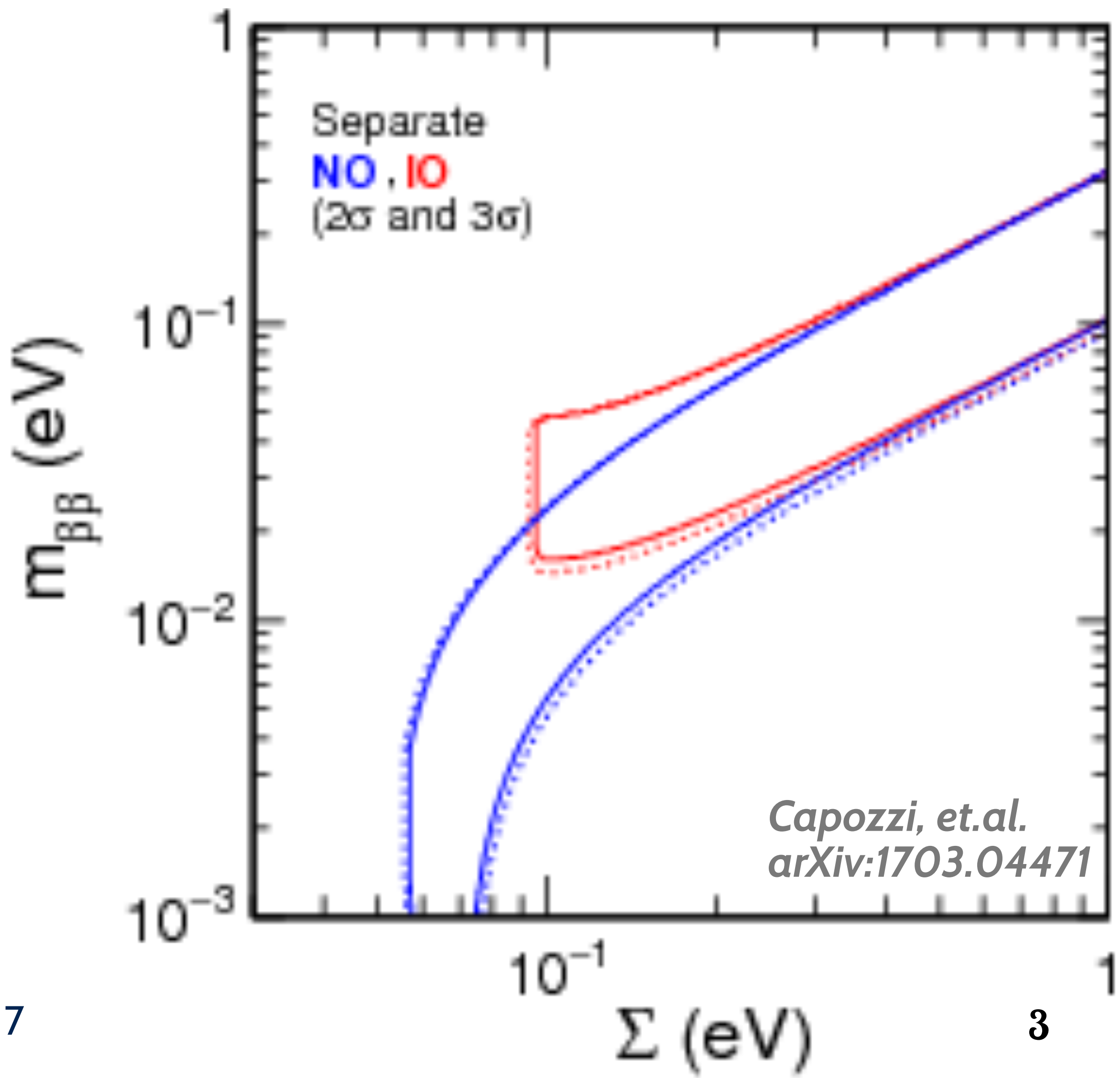


$P(\nu_\mu \rightarrow \nu_\mu)$

Precision measurements of θ_{23}.
The octant of θ_{23} has large impact on model building and other parameters.

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

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



Capozzi, et.al. arXiv:1703.04471

Neutrino Oscillations

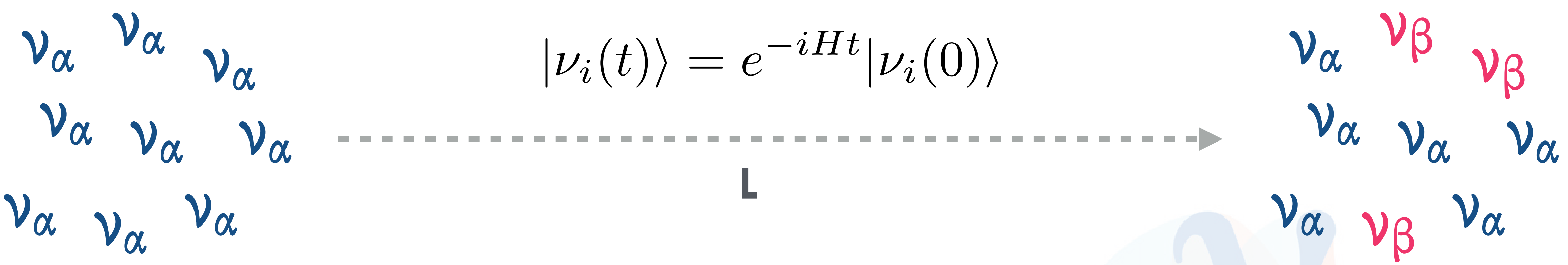
Are flavor eigenstate oscillations described by the PMNS matrix.

PMNS MATRIX

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{matrix}\right\rangle = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \left|\begin{matrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{matrix}\right\rangle$$

FLAVOR EIGENSTATES

MASS EIGENSTATES



$$|\nu_i(t)\rangle = e^{-iHt}|\nu_i(0)\rangle$$

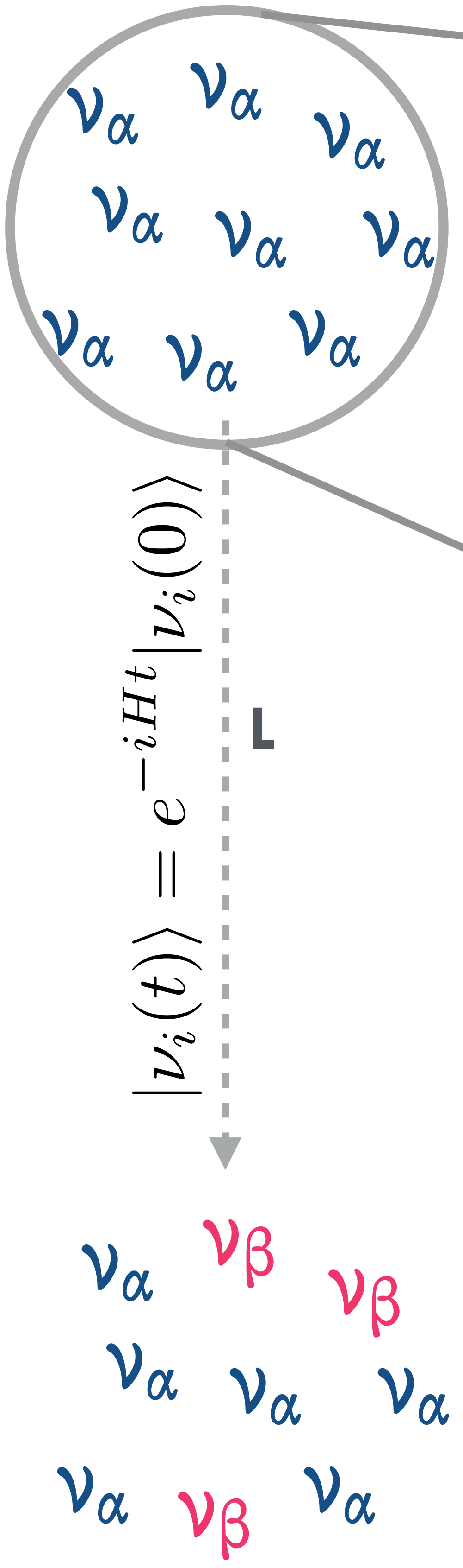
$$P(\nu_\alpha \rightarrow \nu_\beta) = \left| \sum_i \underline{U_{\beta i} U^*_{\alpha i}} e^{-i m_i^2 L/2E} \right|^2$$

OSCILLATION PARAMETERS

Goal: determine the PMNS parameters via oscillation probabilities.

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

Neutrino Oscillation Analyses



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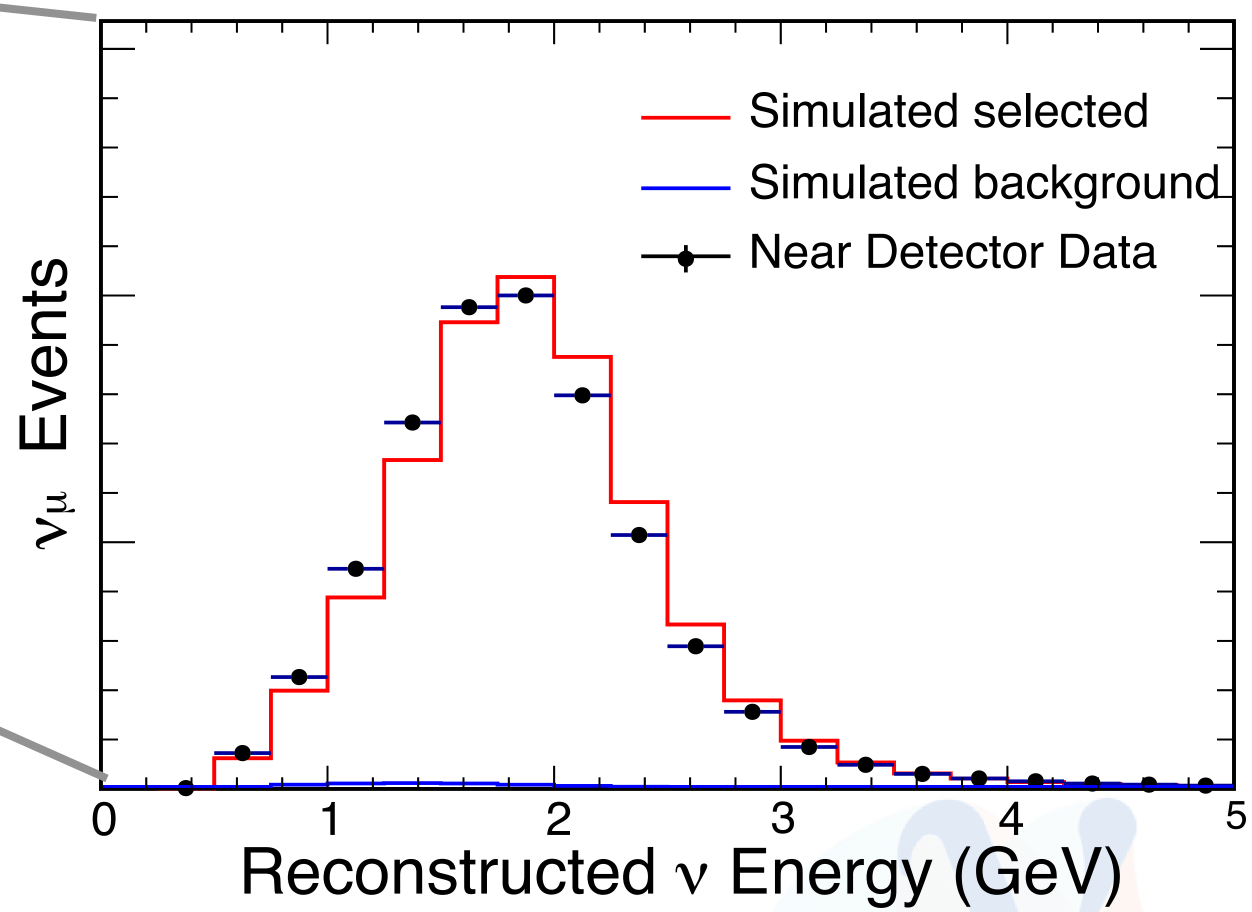
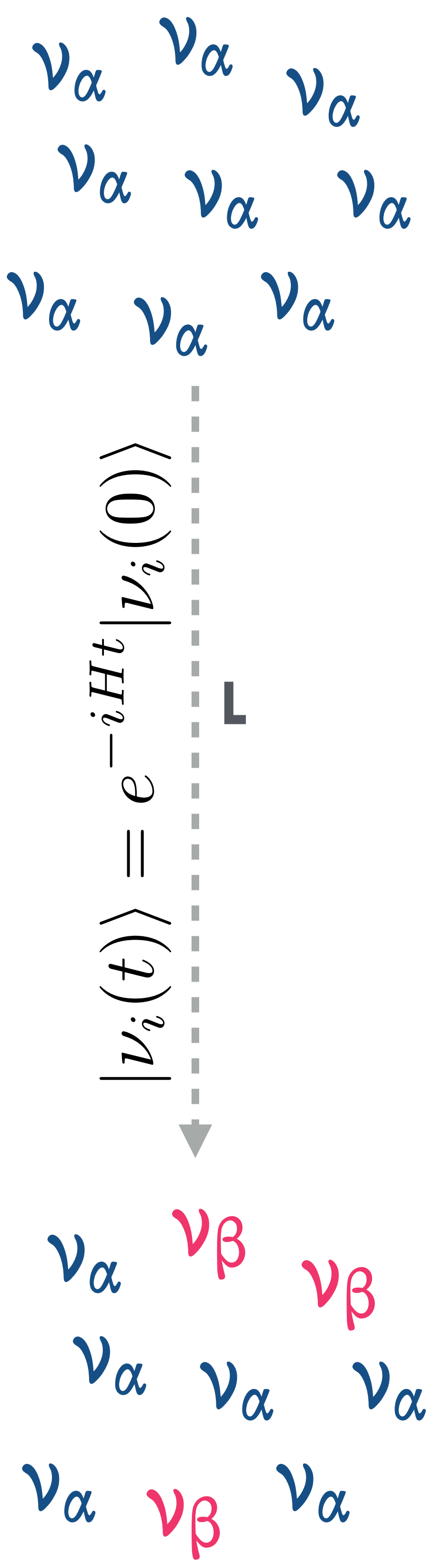
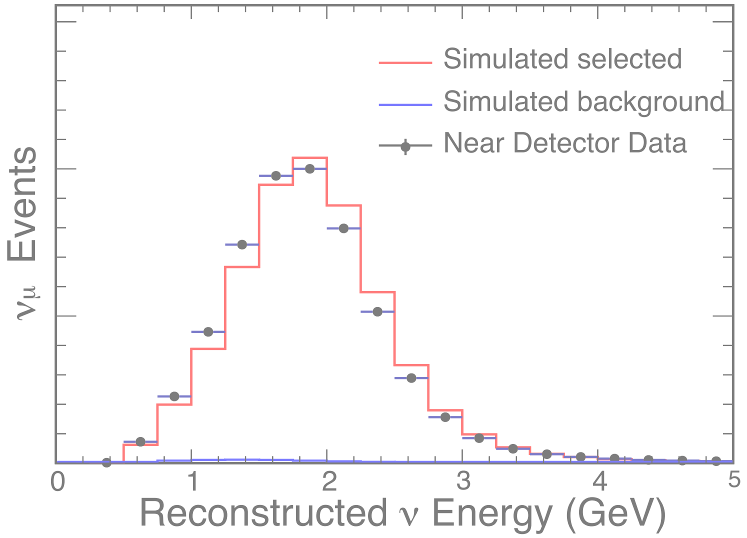


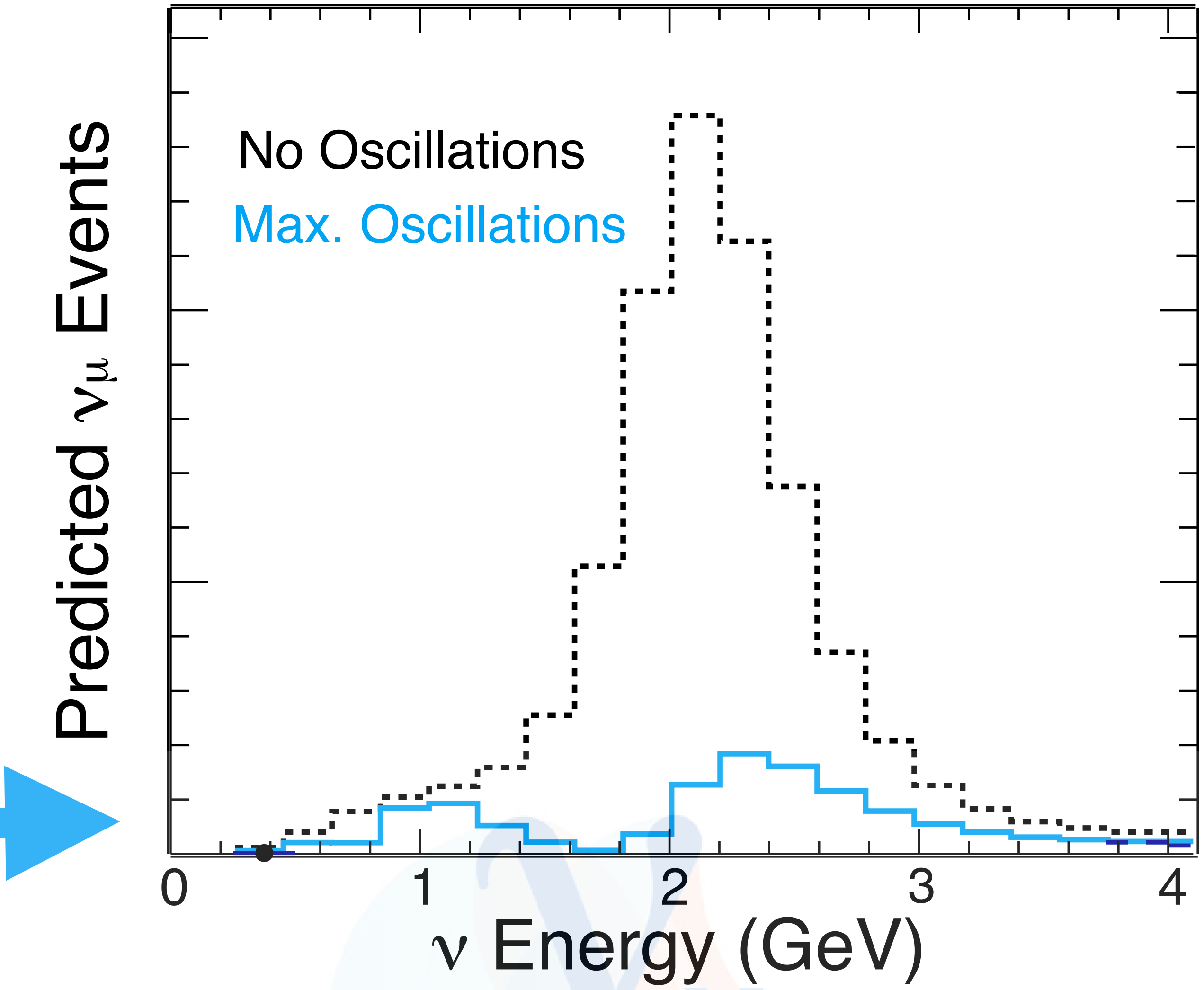
MEASURE FLUX AT NEAR DETECTOR

Neutrino Oscillation Analyses



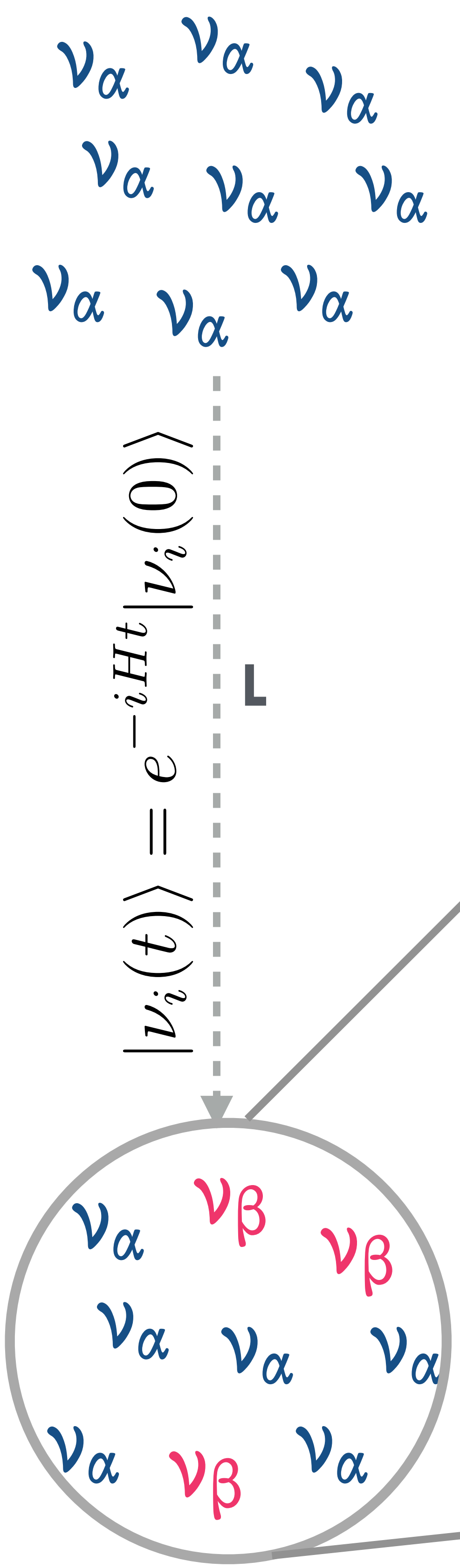
$$|\nu_i(t)\rangle = e^{-iHt}|\nu_i(0)\rangle$$

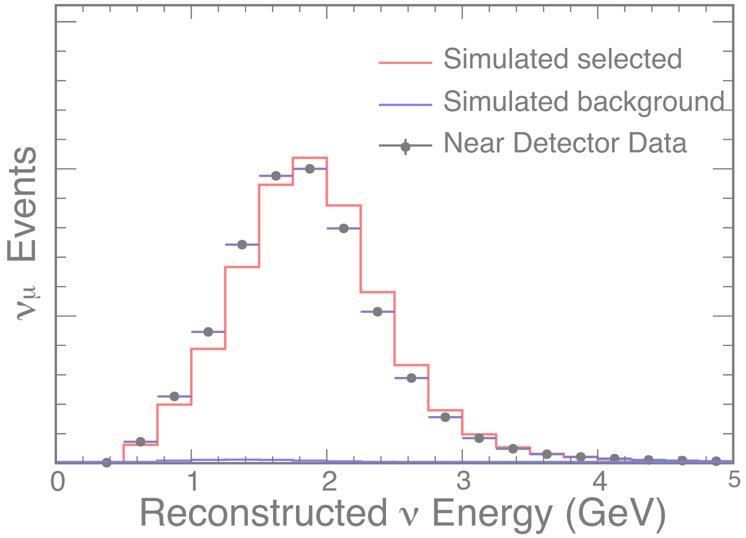


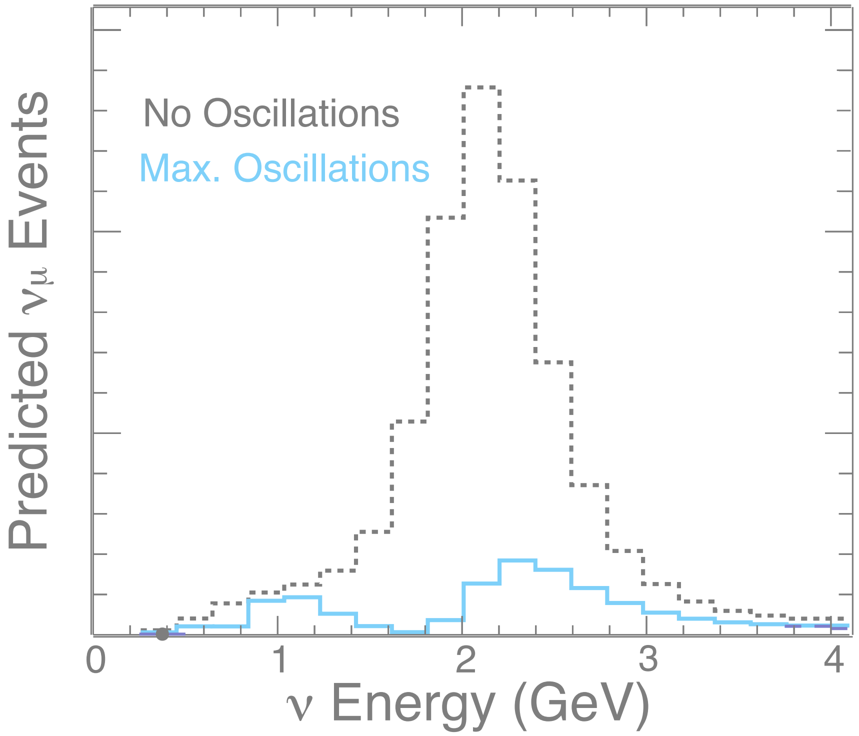


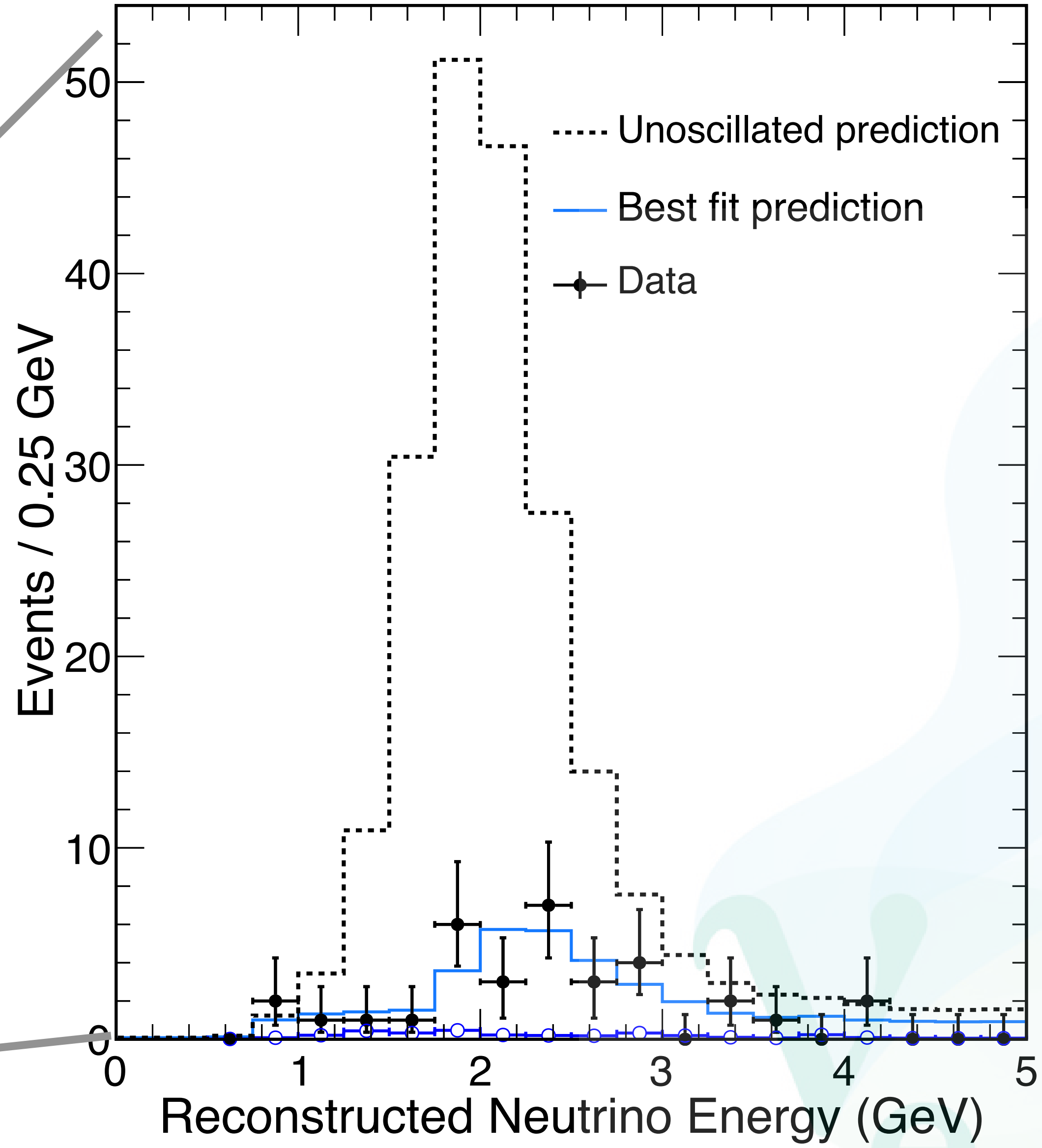
EXTRAPOLATE TO PREDICT SPECTRUM AT THE FAR DETECTOR

Neutrino Oscillation Analyses





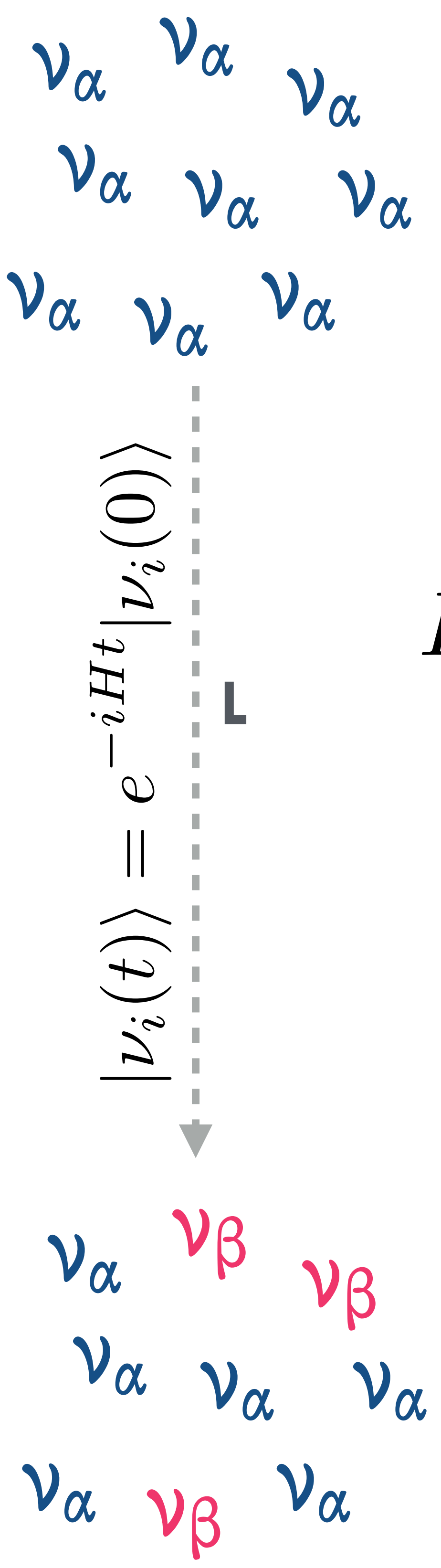




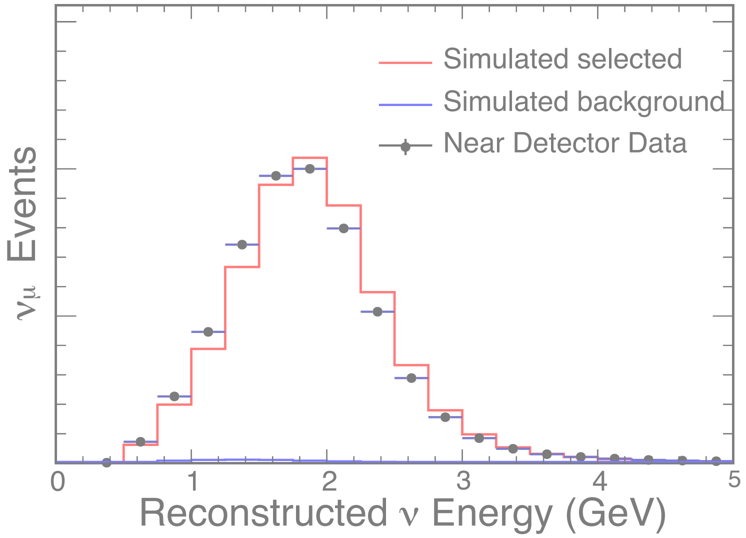
MEASURE SPECTRUM AT FAR DETECTOR

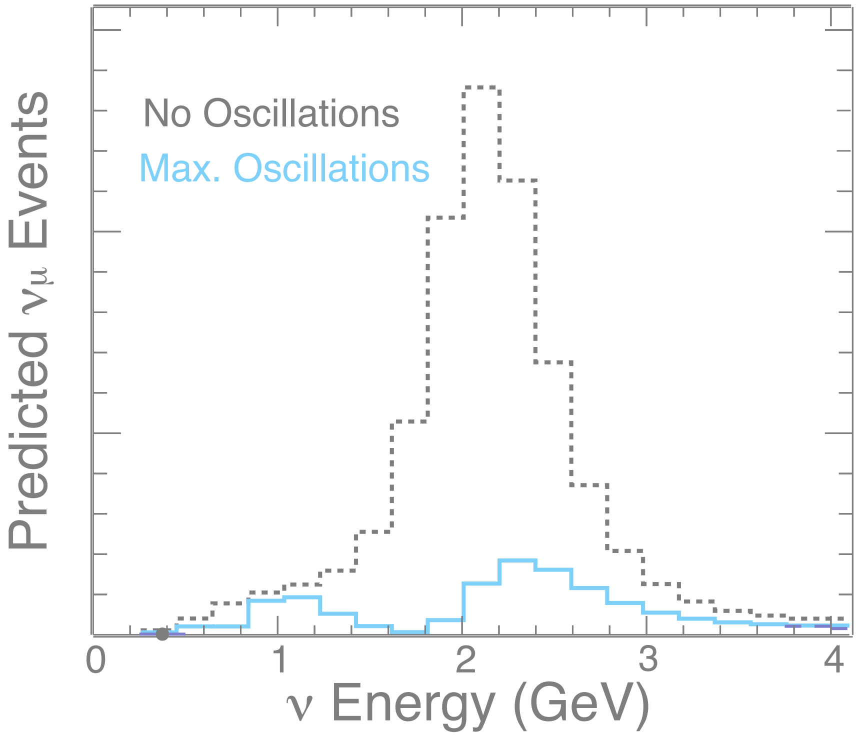
AND FIT

Neutrino Oscillation Analyses



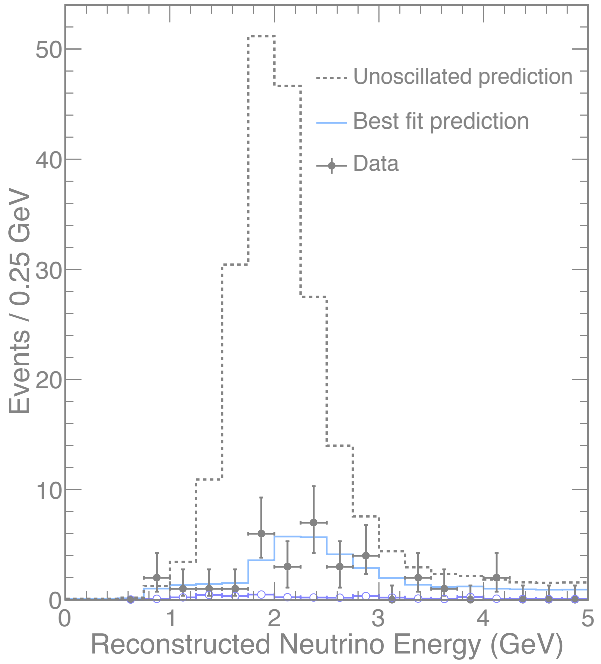
$$|\nu_i(t)\rangle = e^{-iHt}|\nu_i(0)\rangle$$

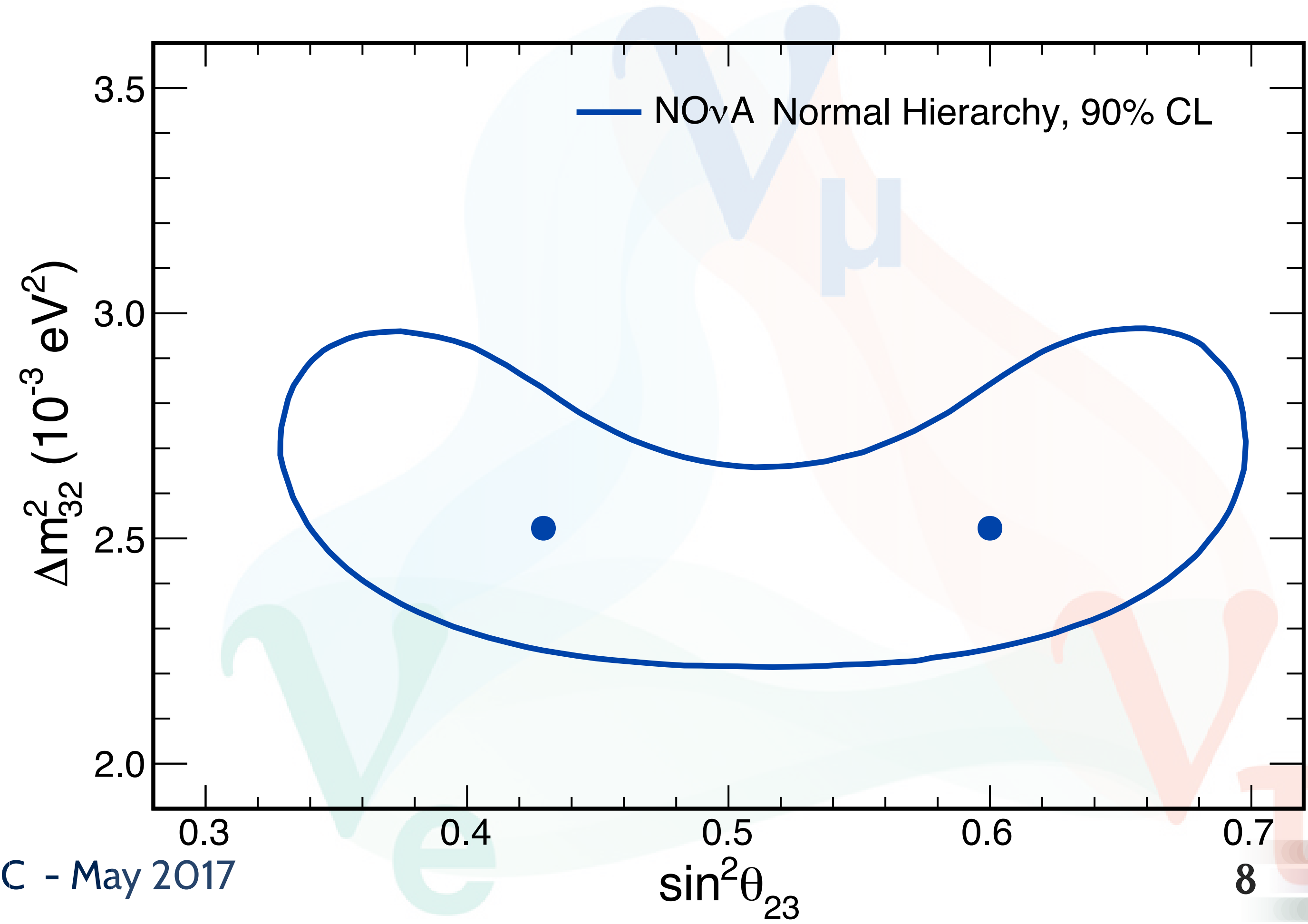




$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\ \ \sin^2(1.27\Delta m^2{}_{32}L/E)$$

RESULT





Neutrino Oscillations

$$P(\nu_\alpha \to \nu_\beta) = \left| \sum_i \underbrace{U_{\beta i} U^*_{\alpha i}}_{\text{OSCILLATION PARAMETERS}} e^{-i m_i^2 L/2E} \right|^2$$

The choice of L/E (Baseline in km/E_ν in GeV) determines which sector of parameters can be measured with higher precision.

$$U = \begin{pmatrix} 1 & & \\ & cos\theta_{23} & sin\theta_{23} \\ & -sin\theta_{23} & cos\theta_{23} \end{pmatrix} \begin{pmatrix} cos\theta_{13} & & sin\theta_{13} e^{-i\delta} \\ & 1 & \\ -sin\theta_{13} e^{i\delta} & & cos\theta_{13} \end{pmatrix} \begin{pmatrix} cos\theta_{12} & sin\theta_{12} & \\ -sin\theta_{12} & cos\theta_{12} & \\ & & 1 \end{pmatrix}$$

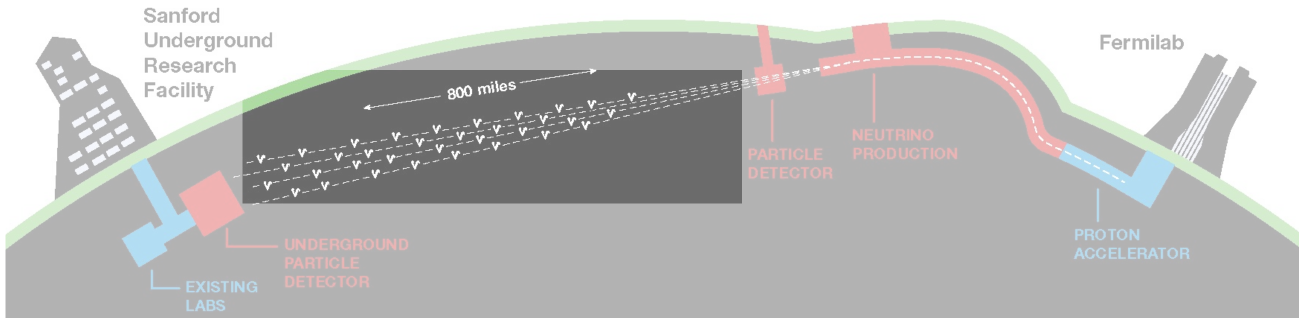
$\nu_\mu \to \nu_\tau$
Atmospheric

$\nu_\mu \to \nu_e$
Reactor & Accelerator

$\nu_e \to \nu_\mu + \nu_\tau$
Solar

Physics at Long Baselines

Matter Effects become more important at longer baselines. Thus, this affects the normal and inverted hierarchy cases differently.



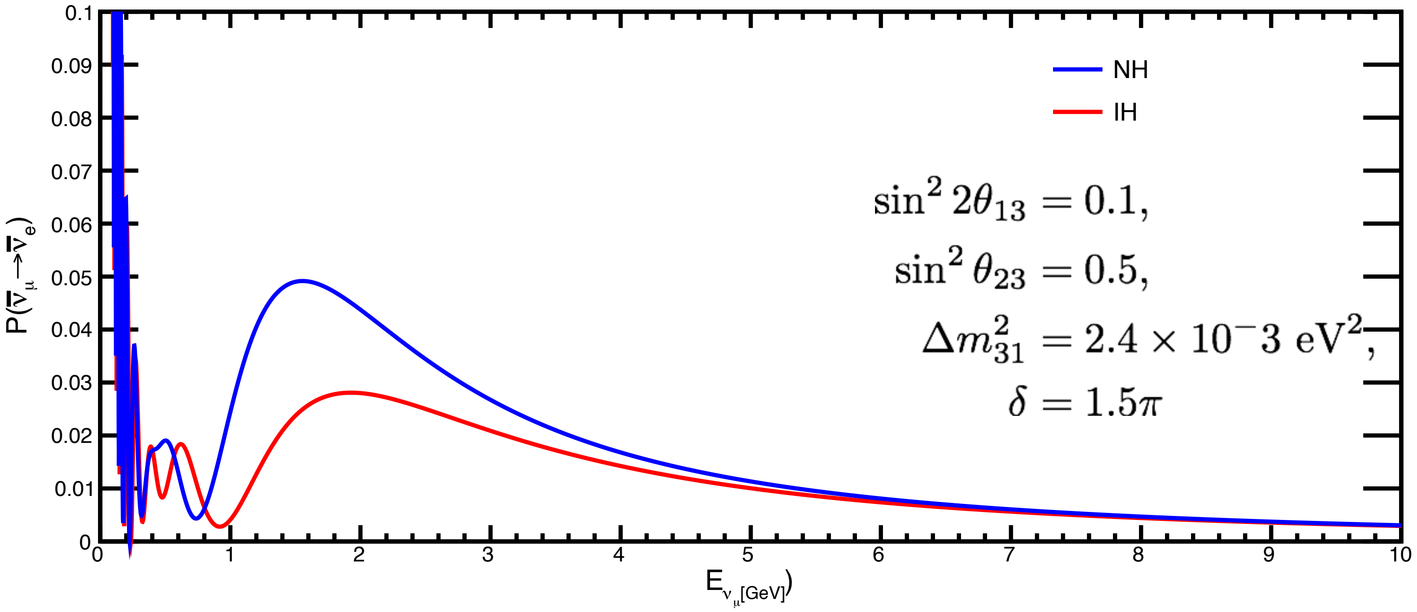
$$P_{\mu e} \simeq P_{e\mu} \simeq \sin^2\theta_{23}\sin^2 2\theta_{13}^{\rm eff}\sin^2\left(\frac{\Delta_{13}^{\rm eff}L}{2}\right),$$

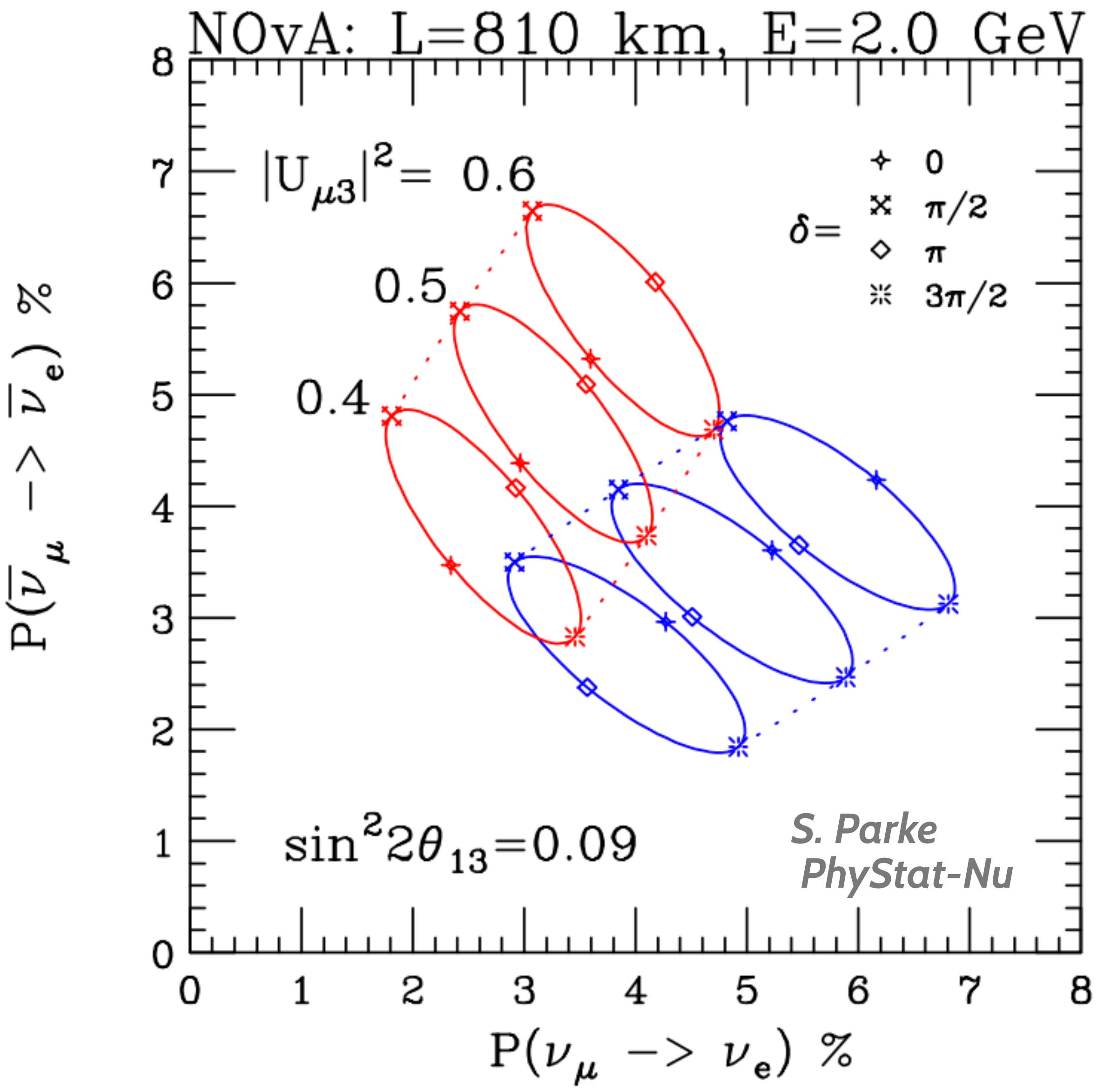
$$\sin^2 2\theta_{13}^{\rm eff} = \frac{\Delta_{13}^2\sin^2 2\theta_{13}}{(\Delta_{13}^{\rm eff})^2},$$

$$\Delta_{13}^{\rm eff} = \sqrt{(\Delta_{13}\cos 2\theta_{13} - A)^2 + \Delta_{13}^2\sin^2 2\theta_{13}},$$

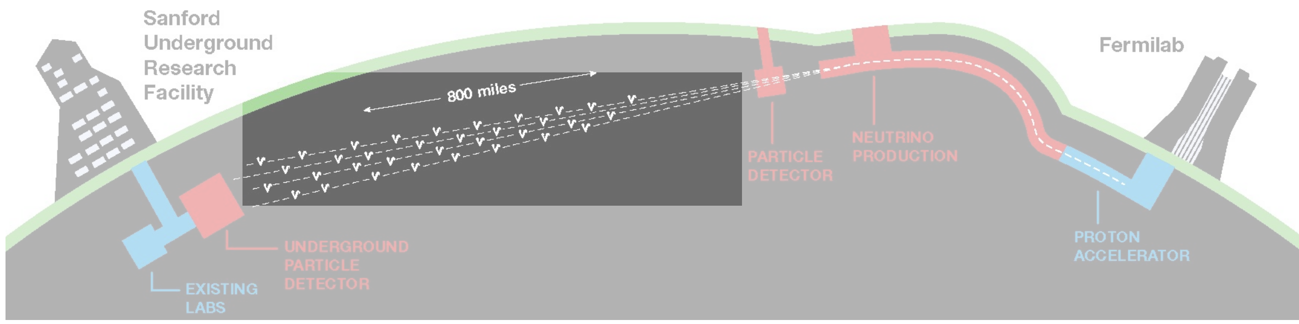
$$\Delta_{13} = \frac{\Delta m_{13}^2}{2E},$$

$$A \equiv \pm\sqrt{2}G_F N_e$$





Physics at Long Baselines



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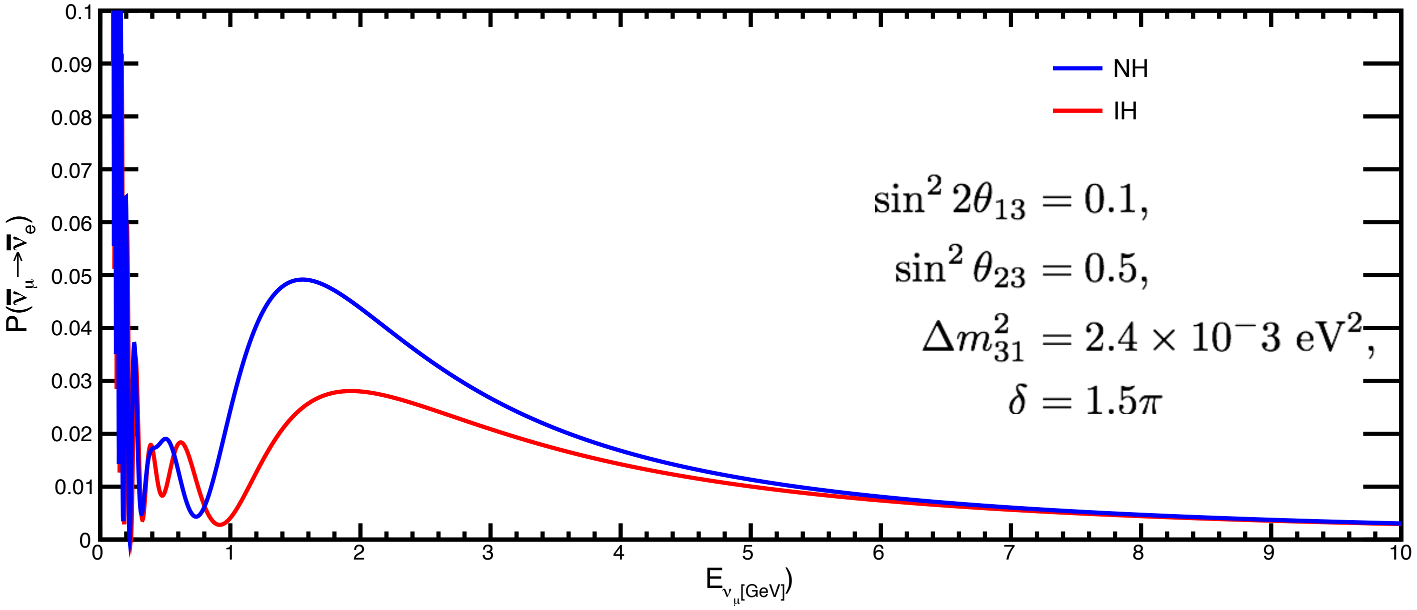
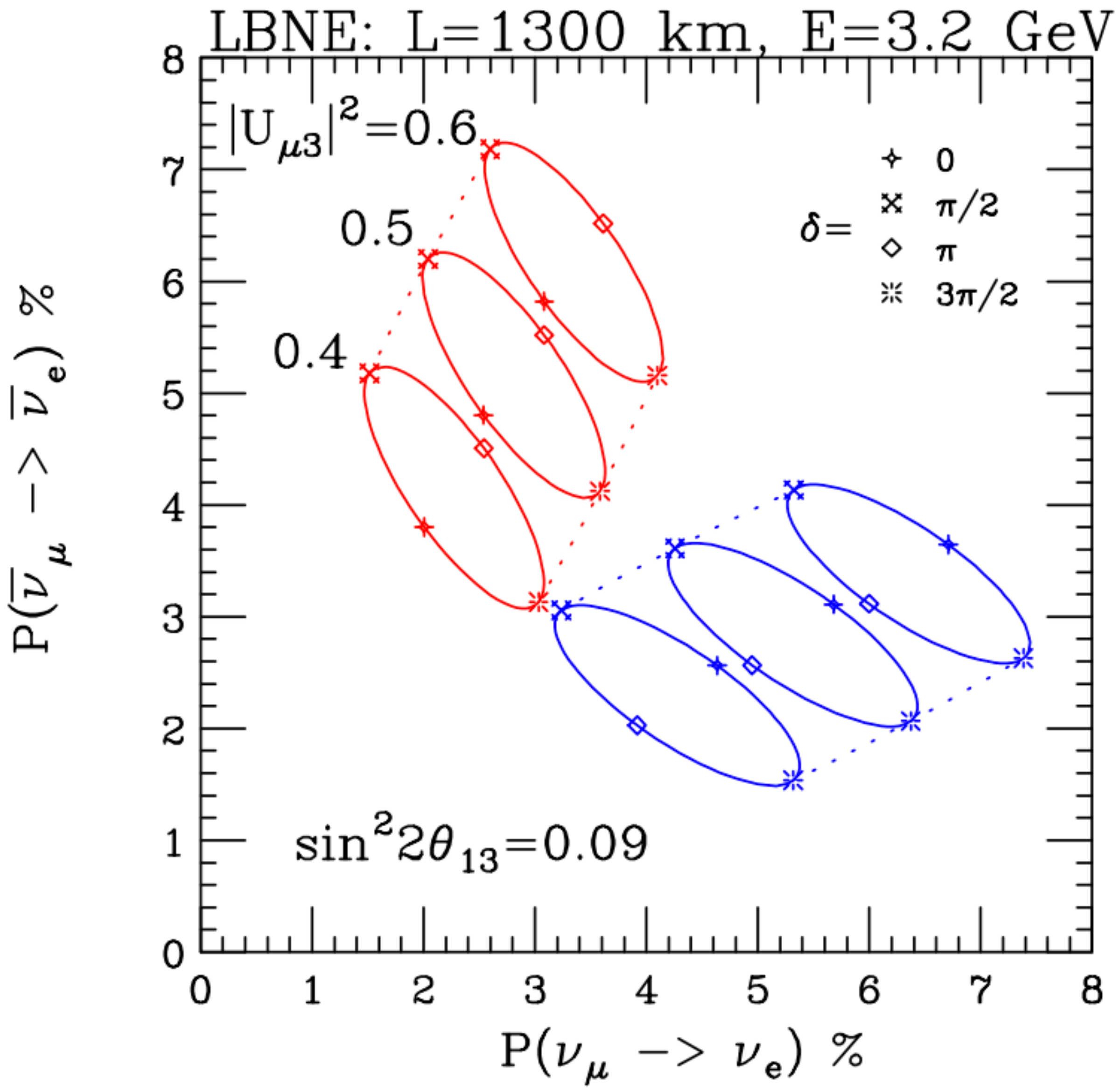
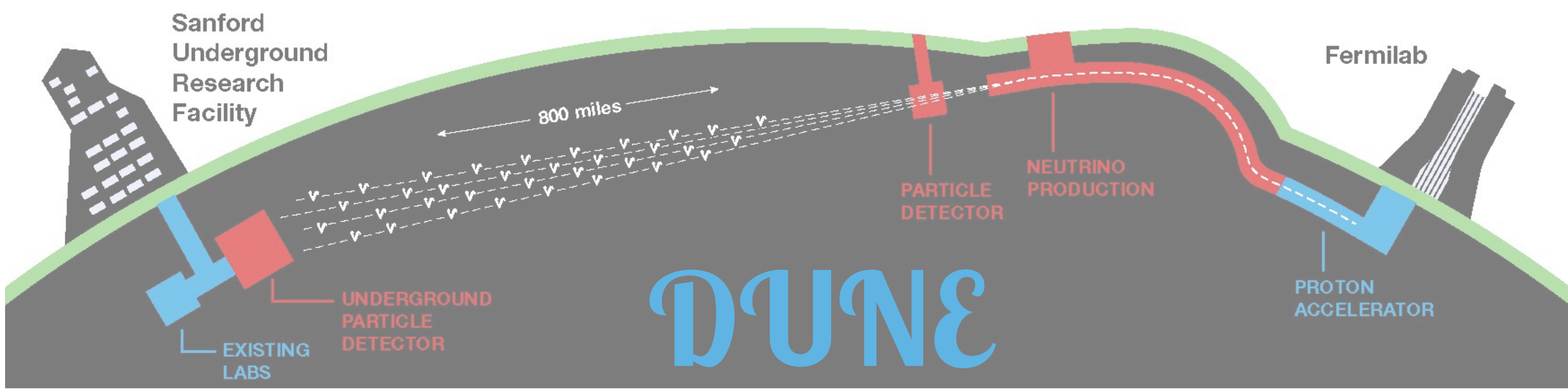
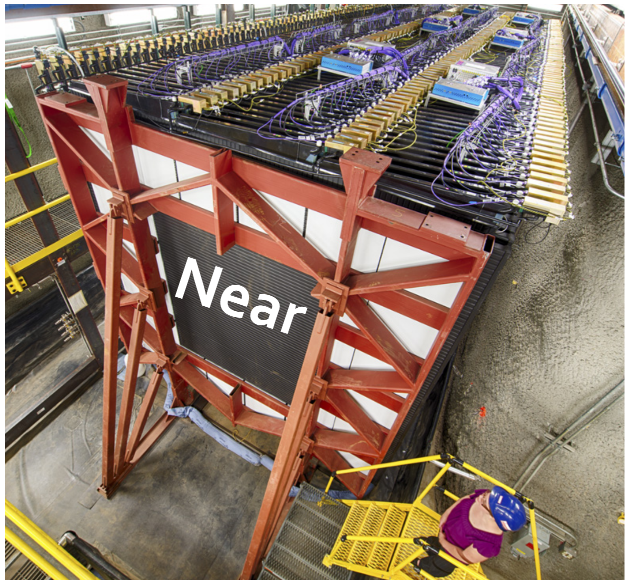


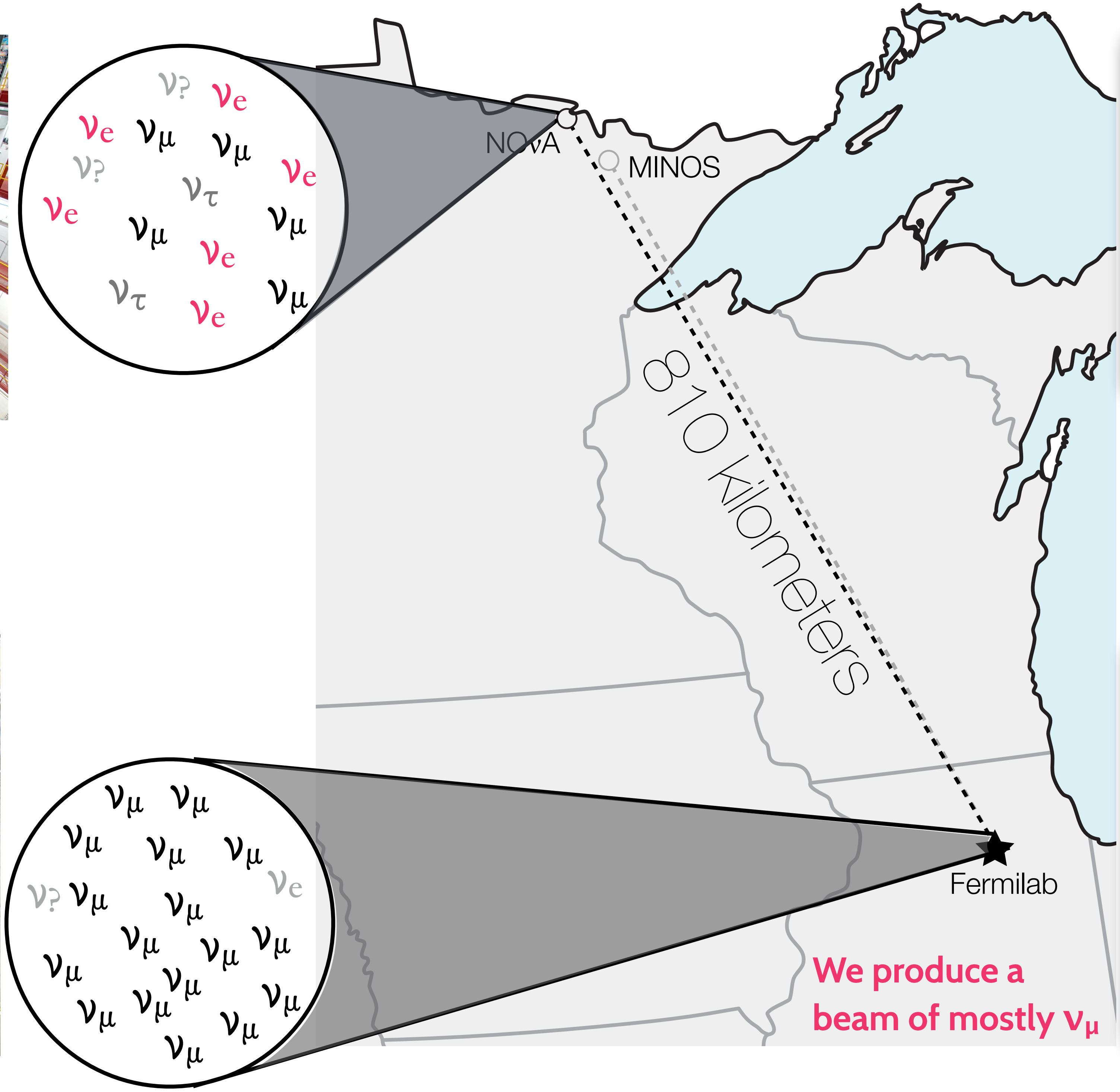


LONG BASELINE ν EXPERIMENTS

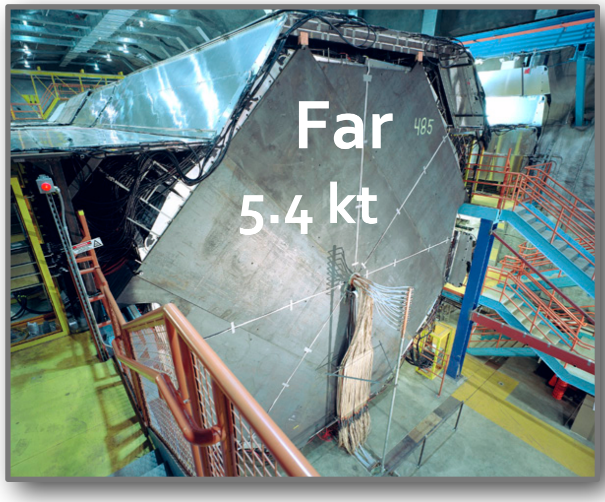


NOνA



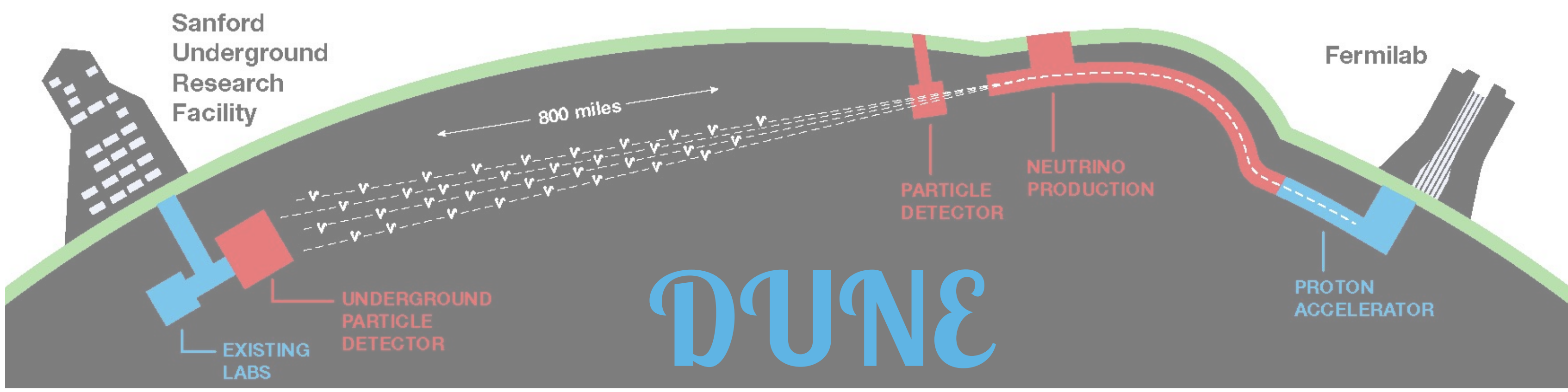


We produce a beam of mostly ν_μ

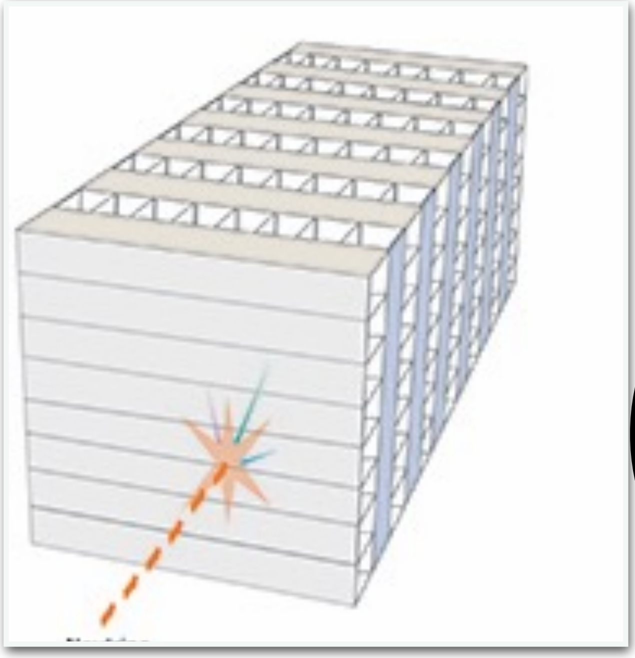


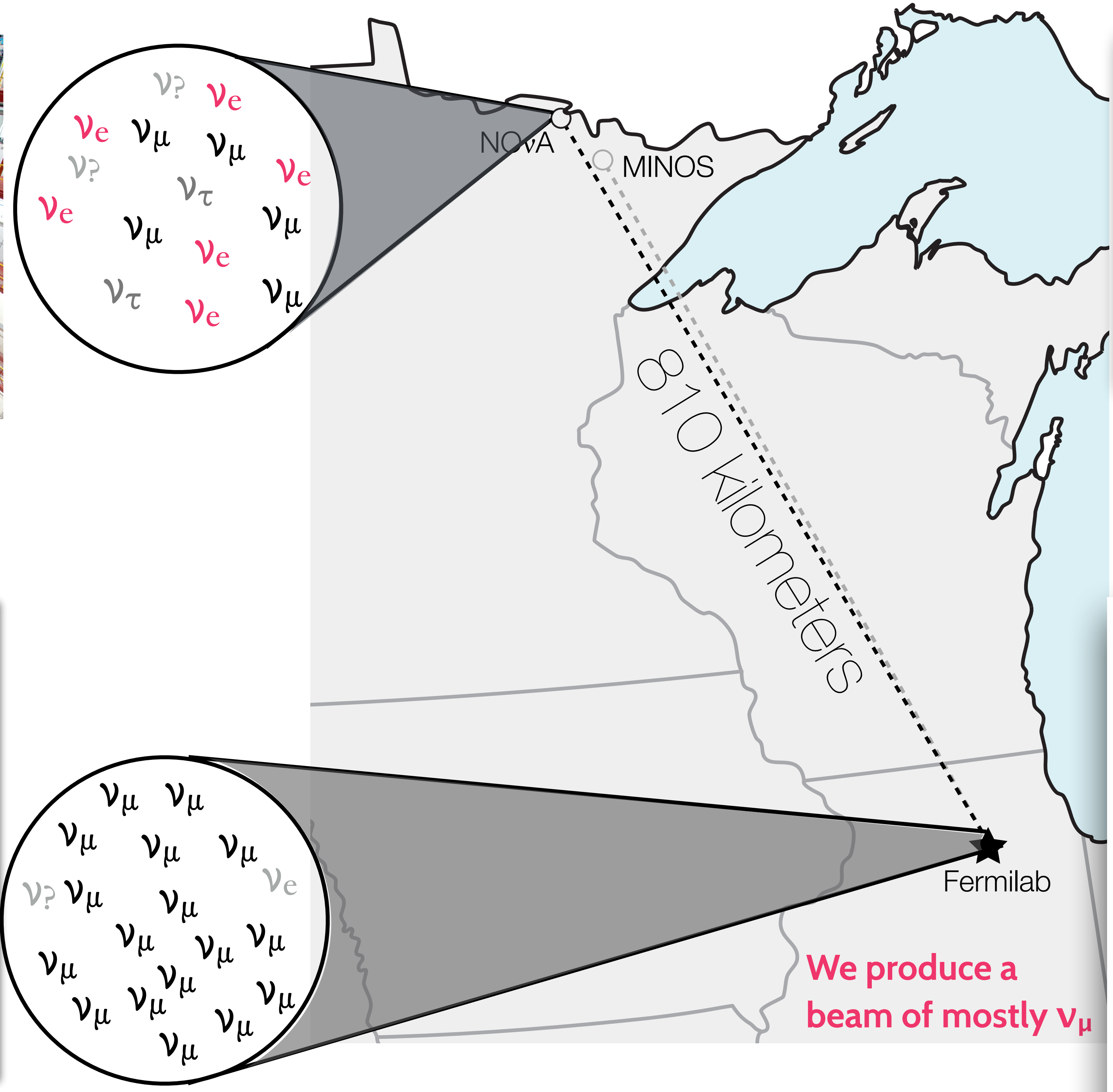
MINOS

LONG BASELINE ν EXPERIMENTS



NOνA





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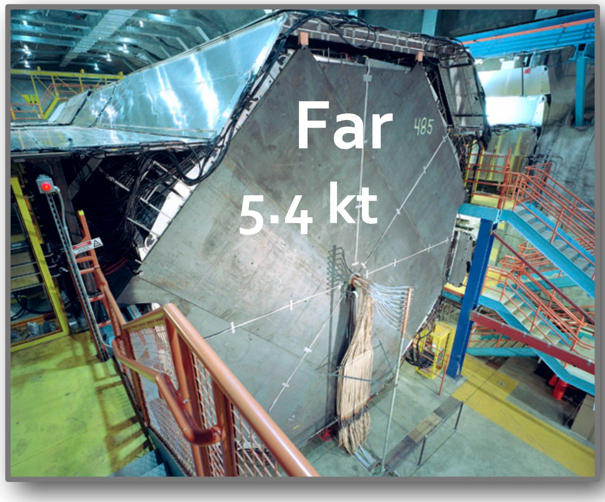
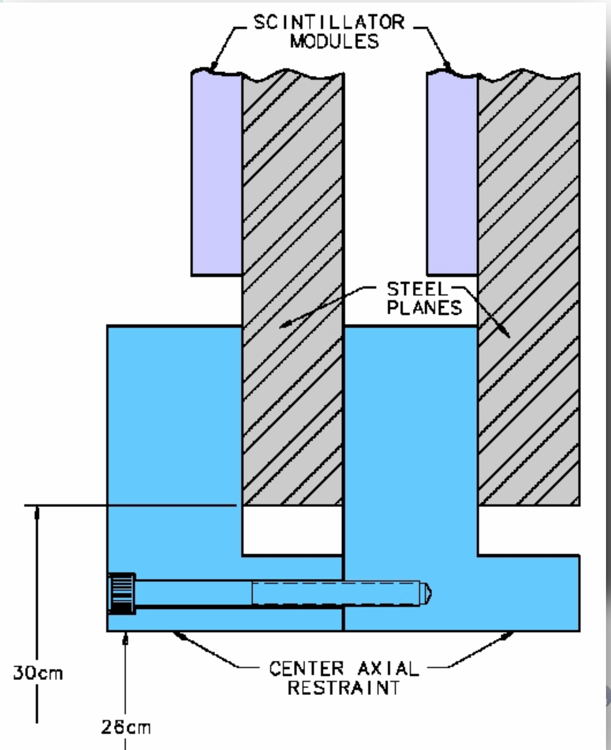


MINOS

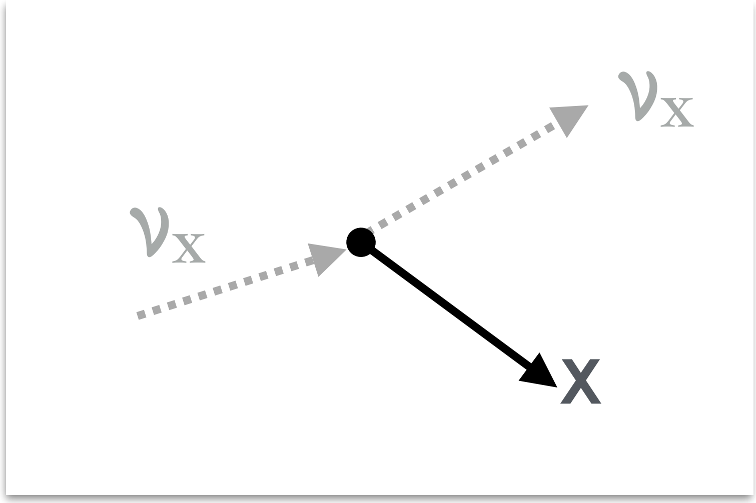


Fernanda Psihas

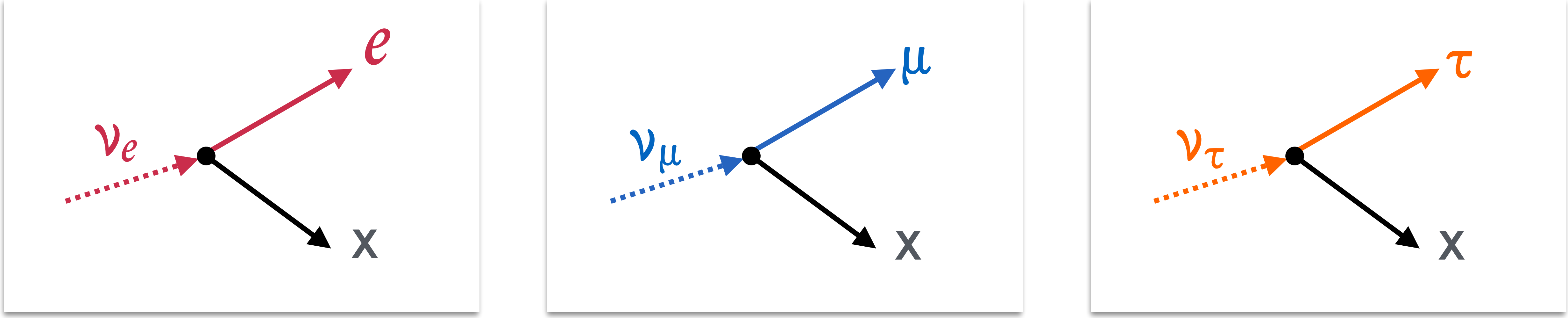
Flavor Identification

Neutrino interactions are flavor conserving, thus, they can be identified from the outgoing lepton.

Unless, of course, it is also a neutrino.

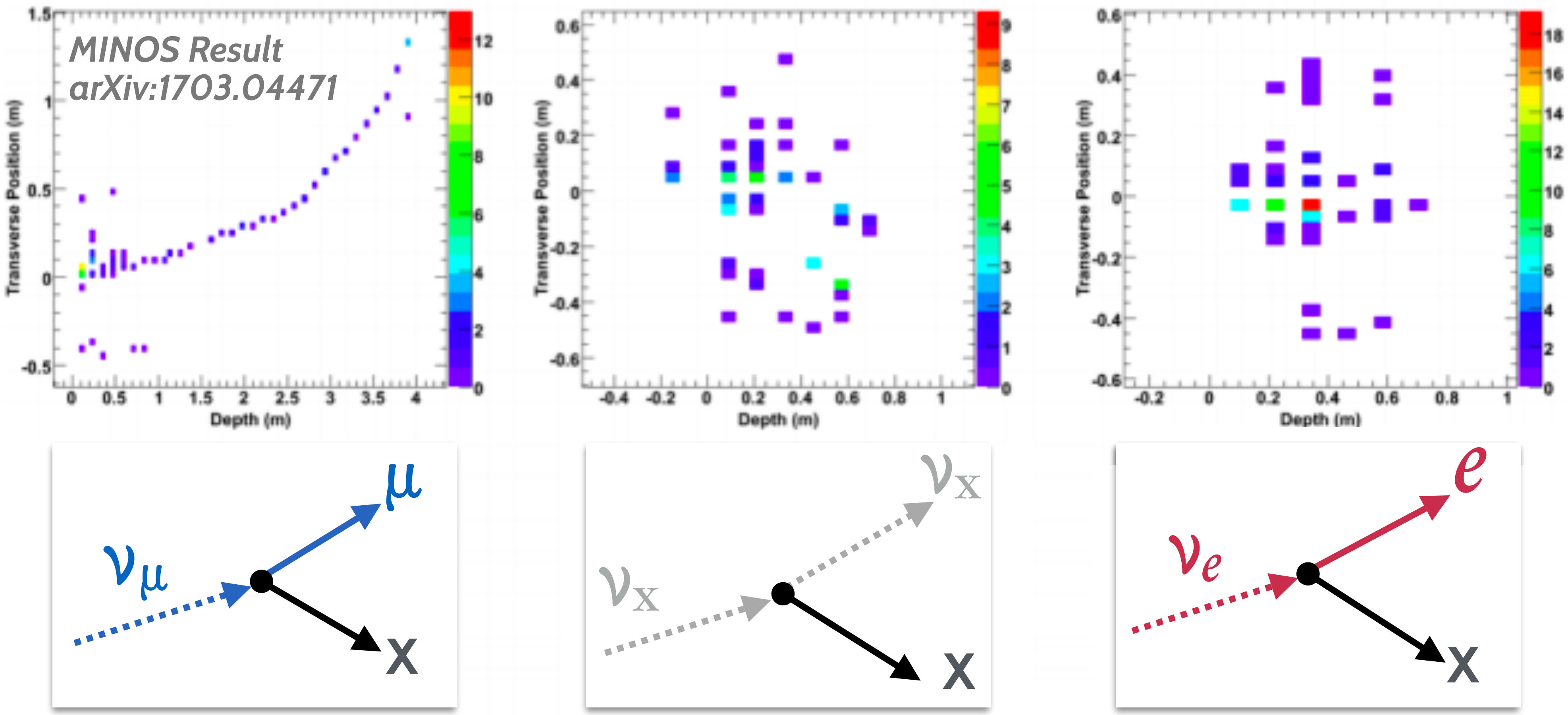


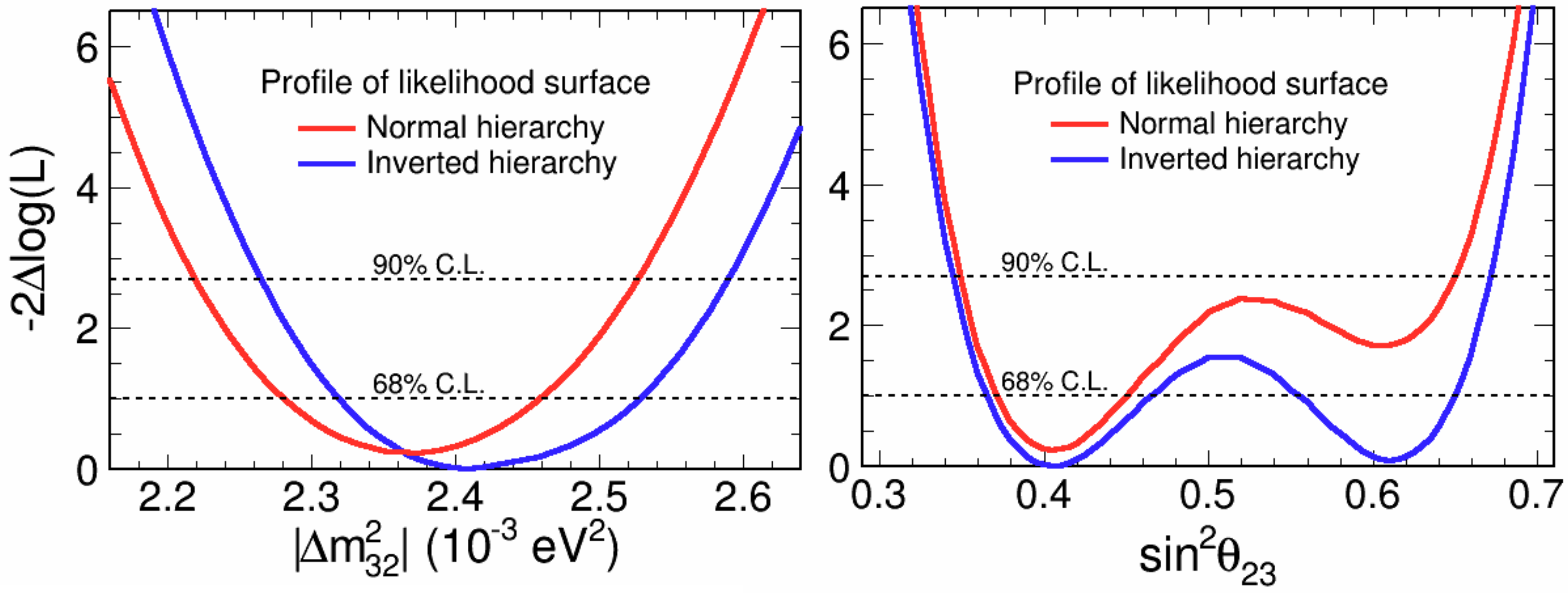
NEUTRAL CURRENT INTERACTIONS



CHARGED CURRENT INTERACTIONS

Main Injector Neutrino Oscillations Search


MINOS Result
arXiv:1703.04471

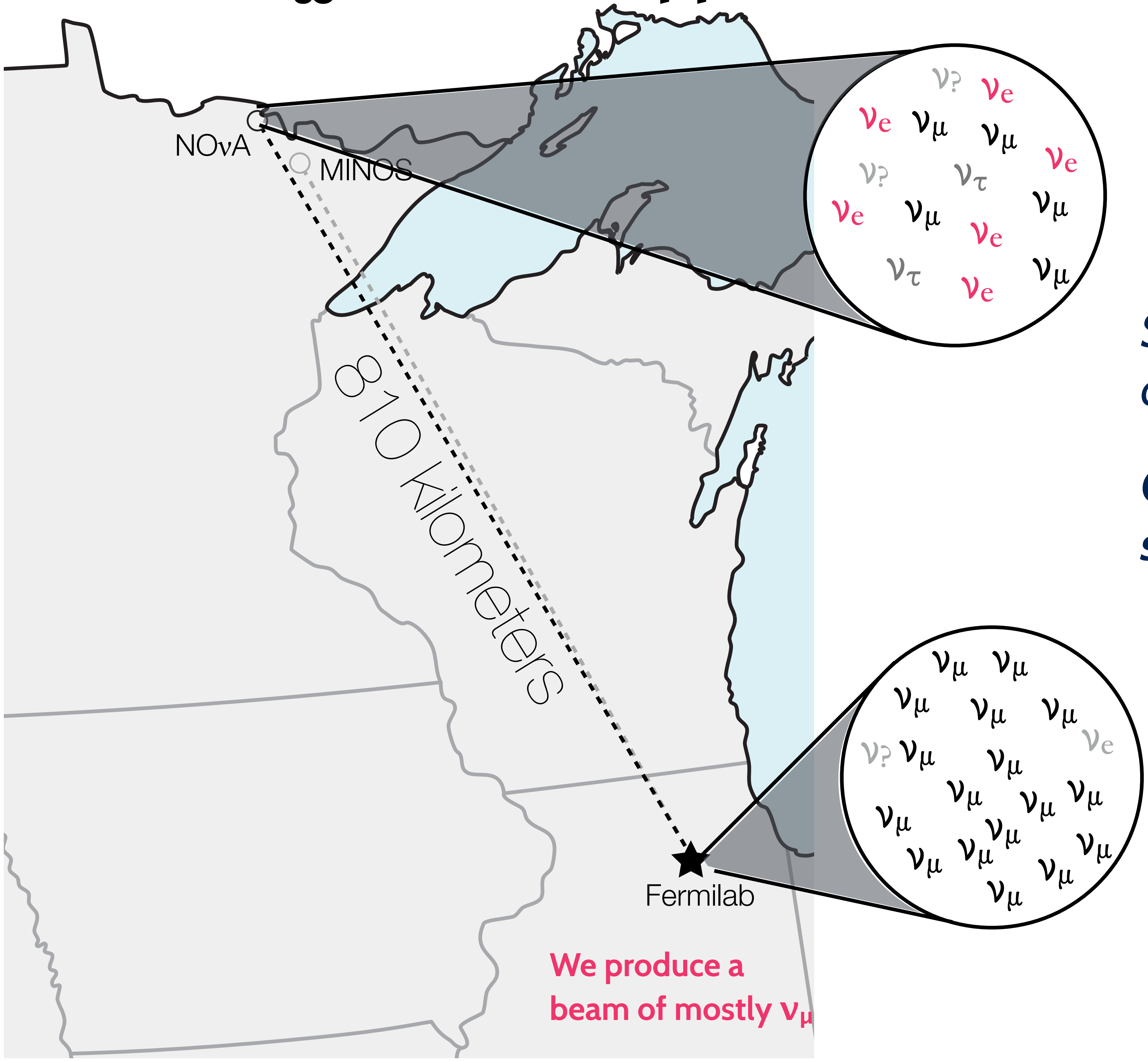


Ran from 2005-2012

~5% precision on the mass difference

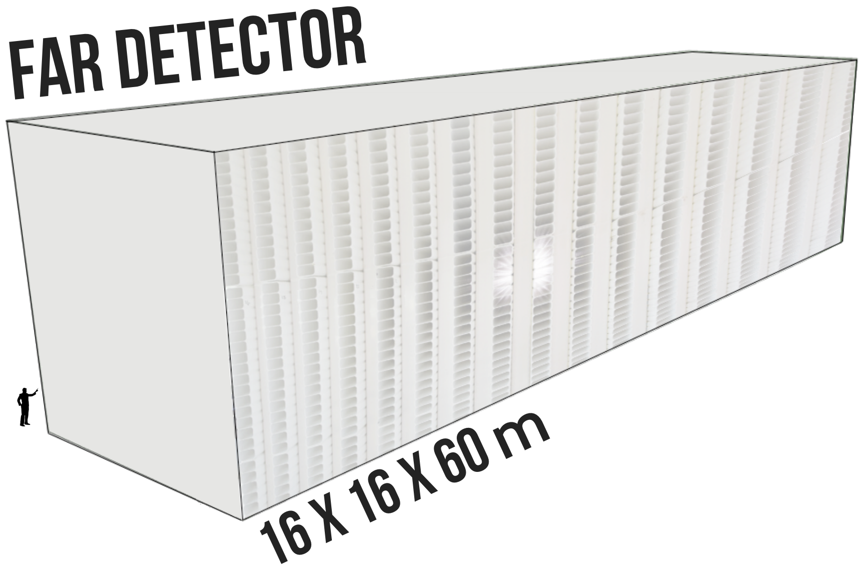
Soft indication of non-maximal mixing at ~1 σ

NuMI Off-axis ν_e Appearance



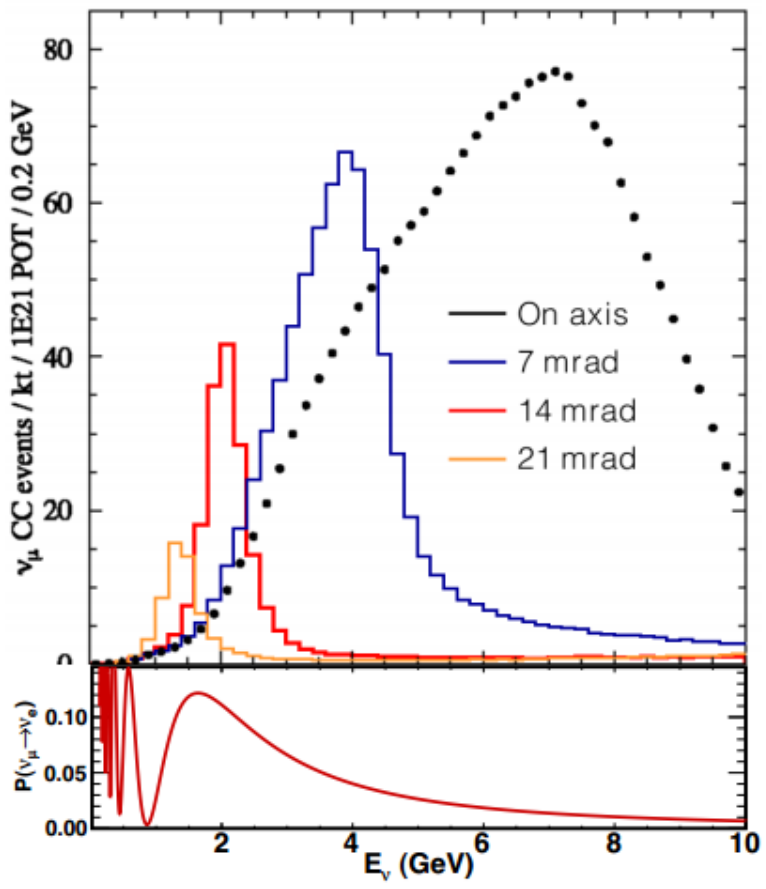
We produce a beam of mostly ν_μ

Technology optimized for electron identification at high spacial resolution

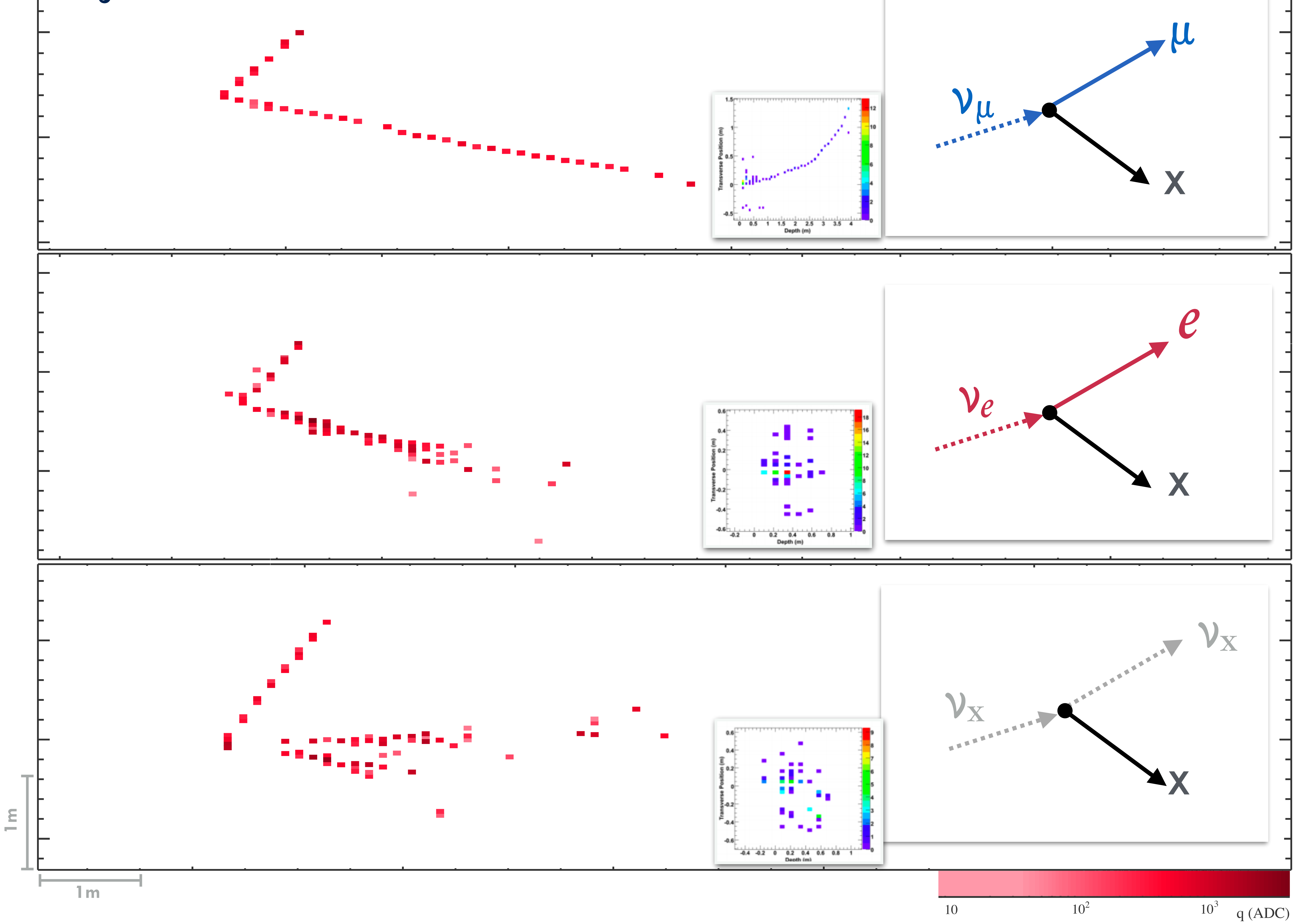


Study νe appearance and ν_μ disappearance in ν and $\bar{\nu}$ modes.

Off-Axis to constrain the energy spectrum

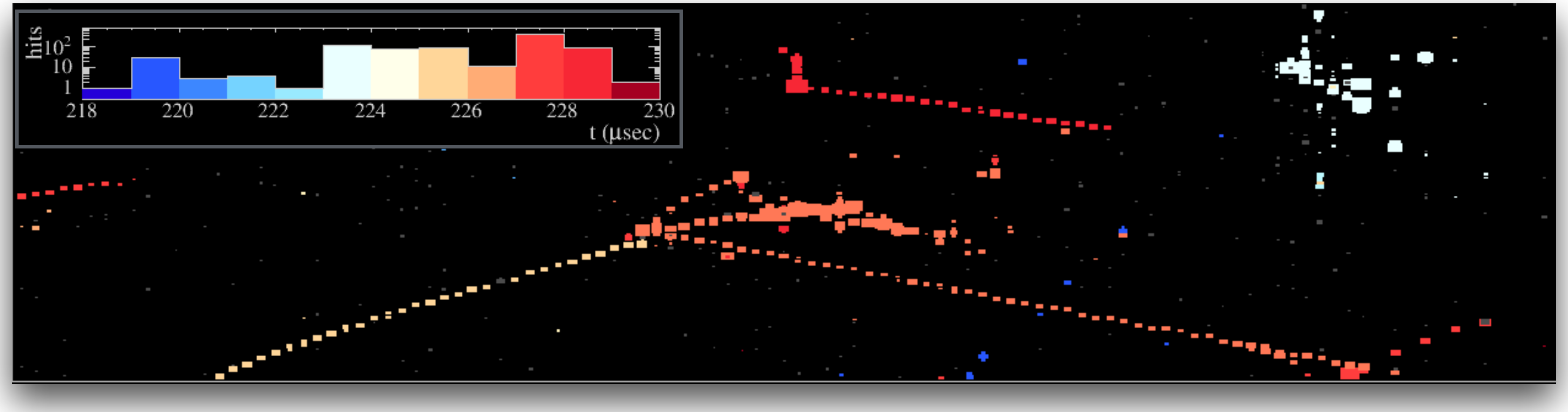


Signature Data Events

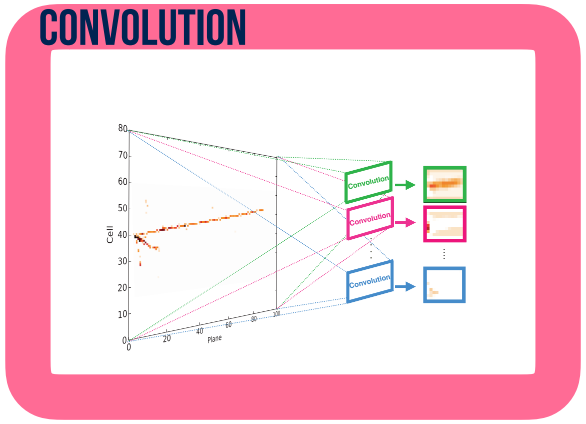


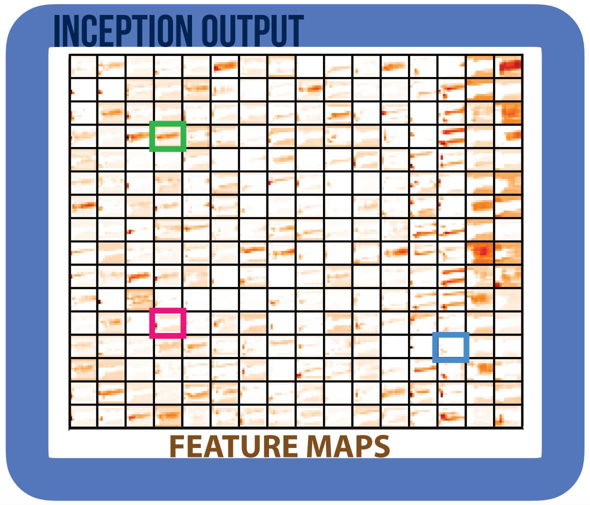
Event Selection & Reconstruction

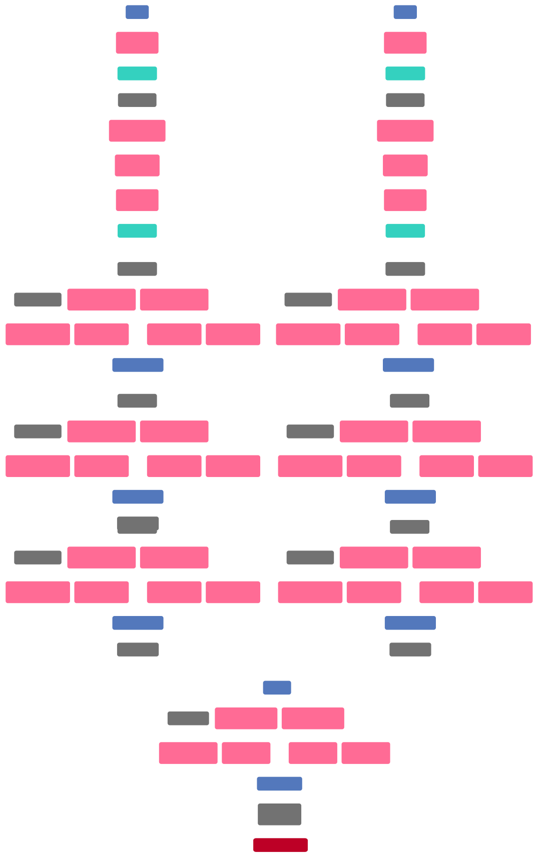
Using traditional reconstruction for ν_μ identification

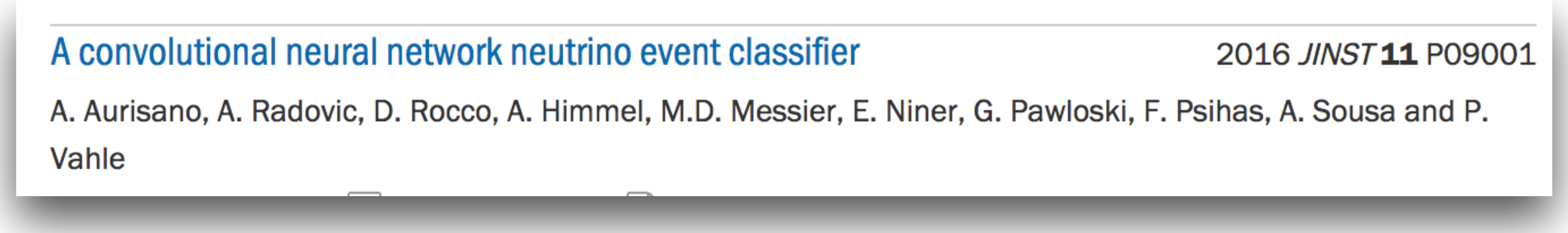


Using deep learning for ν_e *event* identification







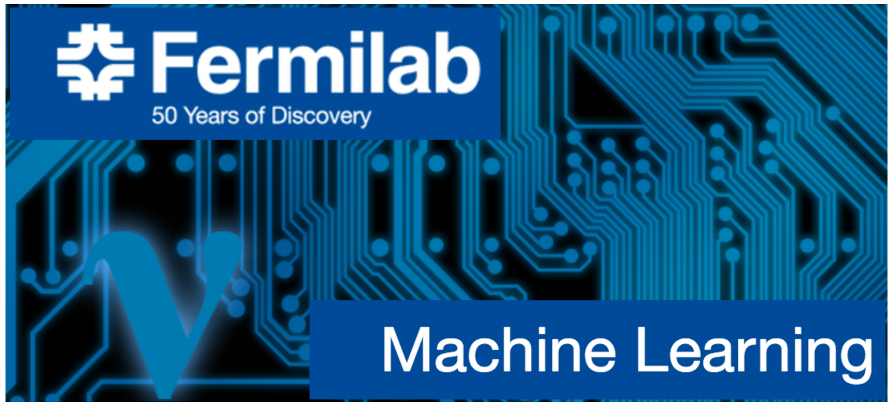


A convolutional neural network neutrino event classifier 2016 *JINST* **11** P09001

A. Aurisano, A. Radovic, D. Rocco, A. Himmel, M.D. Messier, E. Niner, G. Pawloski, F. Psihas, A. Sousa and P. Vahle

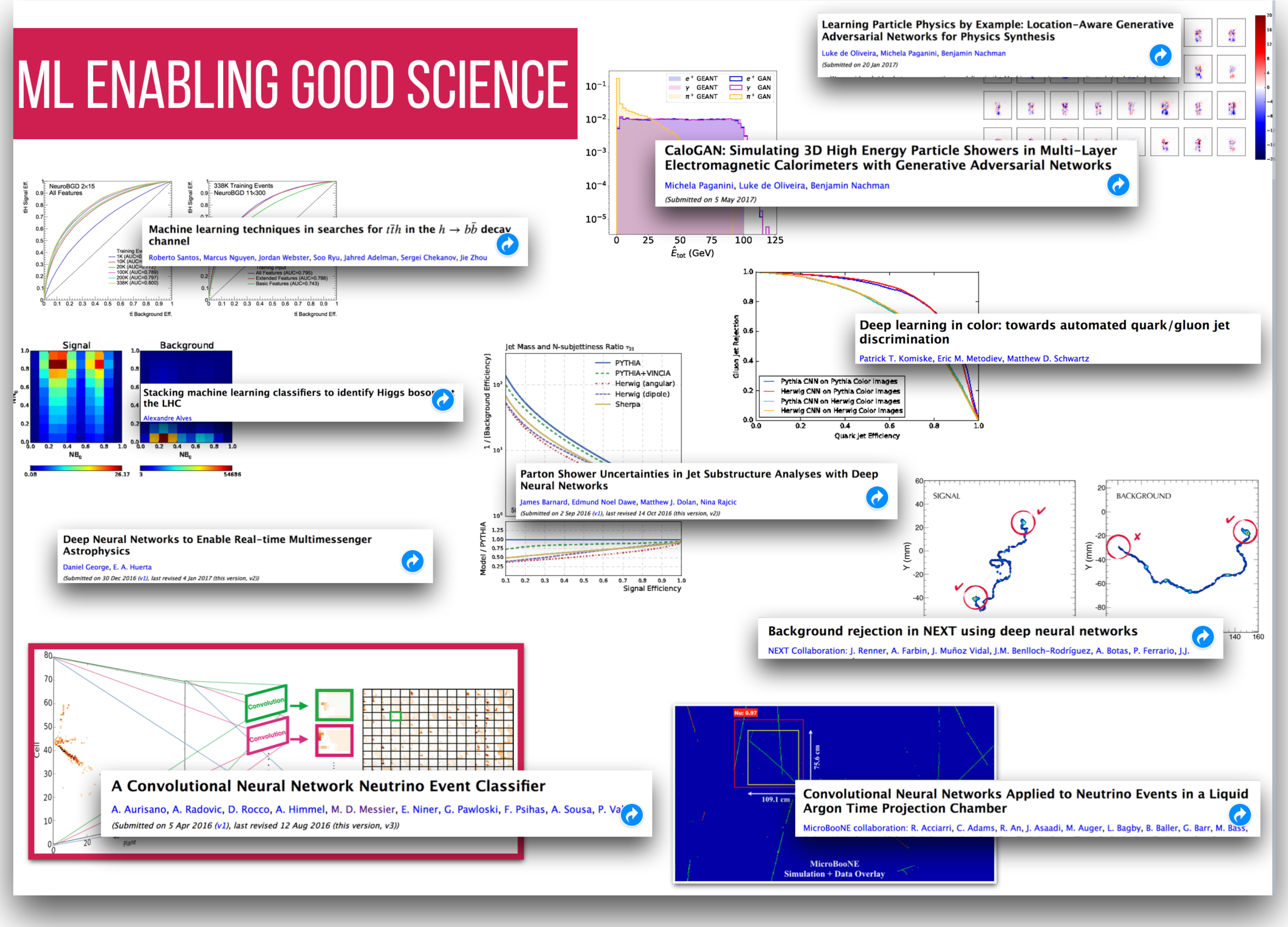
Machine Learning in HEP

Machine learning, especially deep learning applications are being explored in HEP experiments across the board.



http://machinelearning.fnal.gov/

New resources are available for the community to learn about machine learning, interface with industry and try new implementations.


ML ENABLING GOOD SCIENCE

Learning Particle Physics by Example: Location-Aware Generative Adversarial Networks for Physics Synthesis
Luke de Oliveira, Michela Paganini, Benjamin Nachman
(Submitted on 20 Jan 2017)

CaloGAN: Simulating 3D High Energy Particle Showers in Multi-Layer Electromagnetic Calorimeters with Generative Adversarial Networks
Michela Paganini, Luke de Oliveira, Benjamin Nachman
(Submitted on 5 May 2017)

Machine learning techniques in searches for $t\bar{t}h$ in the $h \rightarrow b\bar{b}$ decay channel
Roberto Santos, Marcus Nguyen, Jordan Webster, Soo Ryu, Jahred Adelman, Sergei Chekanov, Jie Zhou

Deep learning in color: towards automated quark/gluon jet discrimination
Patrick T. Komiske, Eric M. Metodiev, Matthew D. Schwartz

Stacking machine learning classifiers to identify Higgs bosons at the LHC
Alexandre Alves

Parton Shower Uncertainties in Jet Substructure Analyses with Deep Neural Networks
James Barnard, Edmund Noel Dawe, Matthew J. Dolan, Nina Rajcic
(Submitted on 2 Sep 2016 (v1), last revised 14 Oct 2016 (this version, v2))

Deep Neural Networks to Enable Real-time Multimessenger Astrophysics
Daniel George, E. A. Huerta
(Submitted on 30 Dec 2016 (v1), last revised 4 Jan 2017 (this version, v2))

Background rejection in NEXT using deep neural networks
NEXT Collaboration: J. Renner, A. Farbin, J. Muñoz Vidal, J.M. Benlloch-Rodríguez, A. Botas, P. Ferrario, J.J.

A Convolutional Neural Network Neutrino Event Classifier
A. Aurisano, A. Radovic, D. Rocco, A. Himmel, M. D. Messier, E. Niner, G. Pawloski, F. Psihas, A. Sousa, P. Va
(Submitted on 5 Apr 2016 (v1), last revised 12 Aug 2016 (this version, v3))

Convolutional Neural Networks Applied to Neutrino Events in a Liquid Argon Time Projection Chamber
MicroBooNE collaboration: R. Acciarri, C. Adams, R. An, J. Asaadi, M. Auger, L. Bagby, B. Baller, G. Barr, M. Bass,

Psihas, DS@HEP 2017


12/06/16

Deep learning takes on physics

Can the same type of technology Facebook uses to recognize faces also recognize particles?

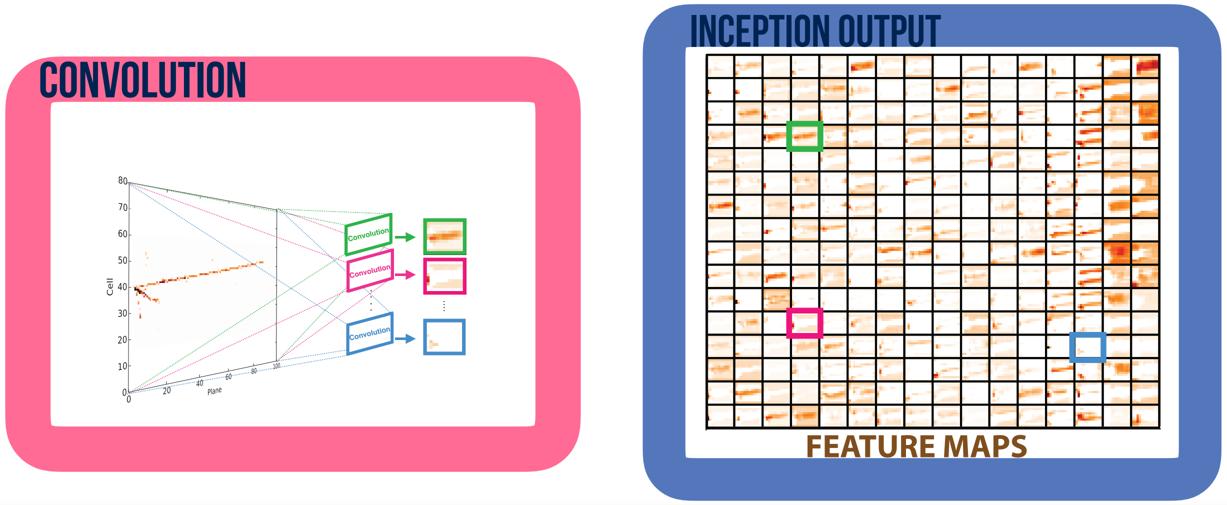
Symmetry December 2016

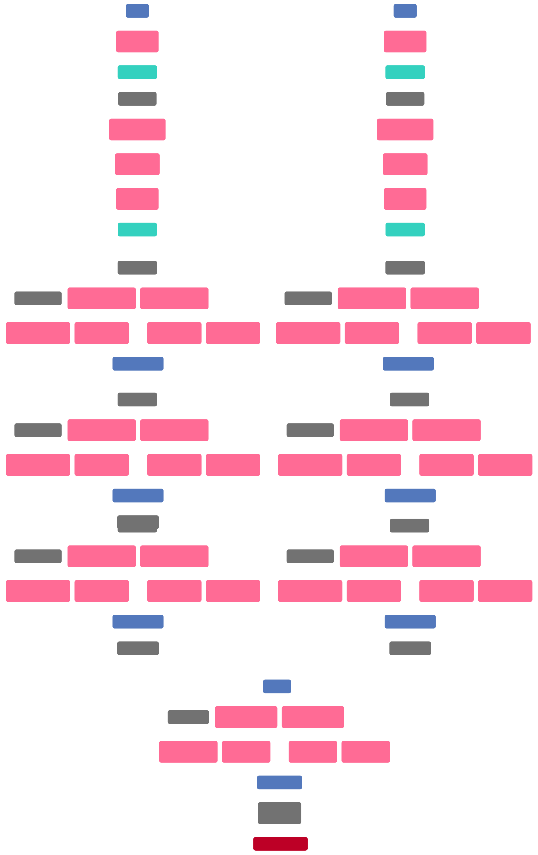
Event Selection & Reconstruction

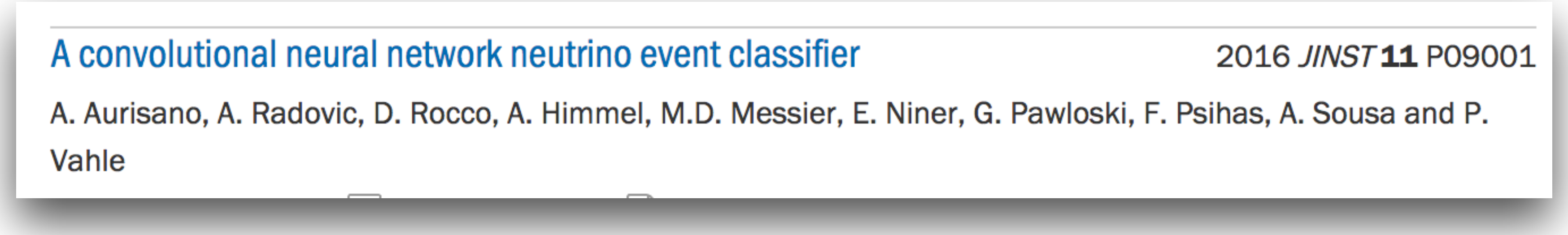
NOvA's implementation of Convolutional Neural Networks CNNs for Identification represented a 30% effective increase in exposure.

NOvA's 2016 νe appearance analysis was the first implementation of convolutional neural networks in a HEP result

Using deep learning for ν_e *event* identification







A convolutional neural network neutrino event classifier 2016 *JINST* **11** P09001

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NOvA Results

From Neutrino2016, now PRL

Measurement of the neutrino mixing angle θ23 in NOvA
PhysRevLett.118.151802
Constraints on oscillation parameters from νe appearance and νμ disappearance in NOvA arXiv:1703.03328

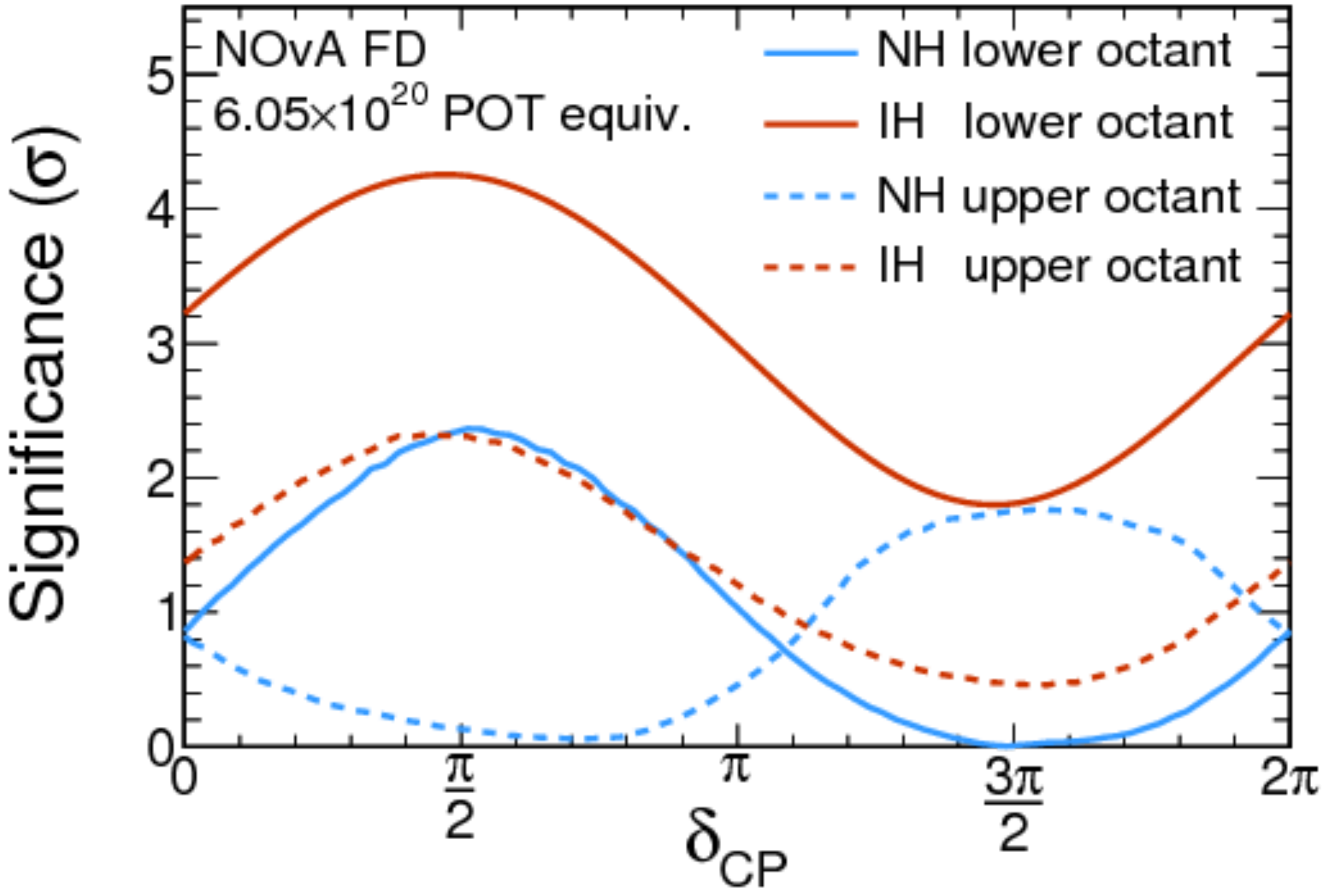
Best fit points:

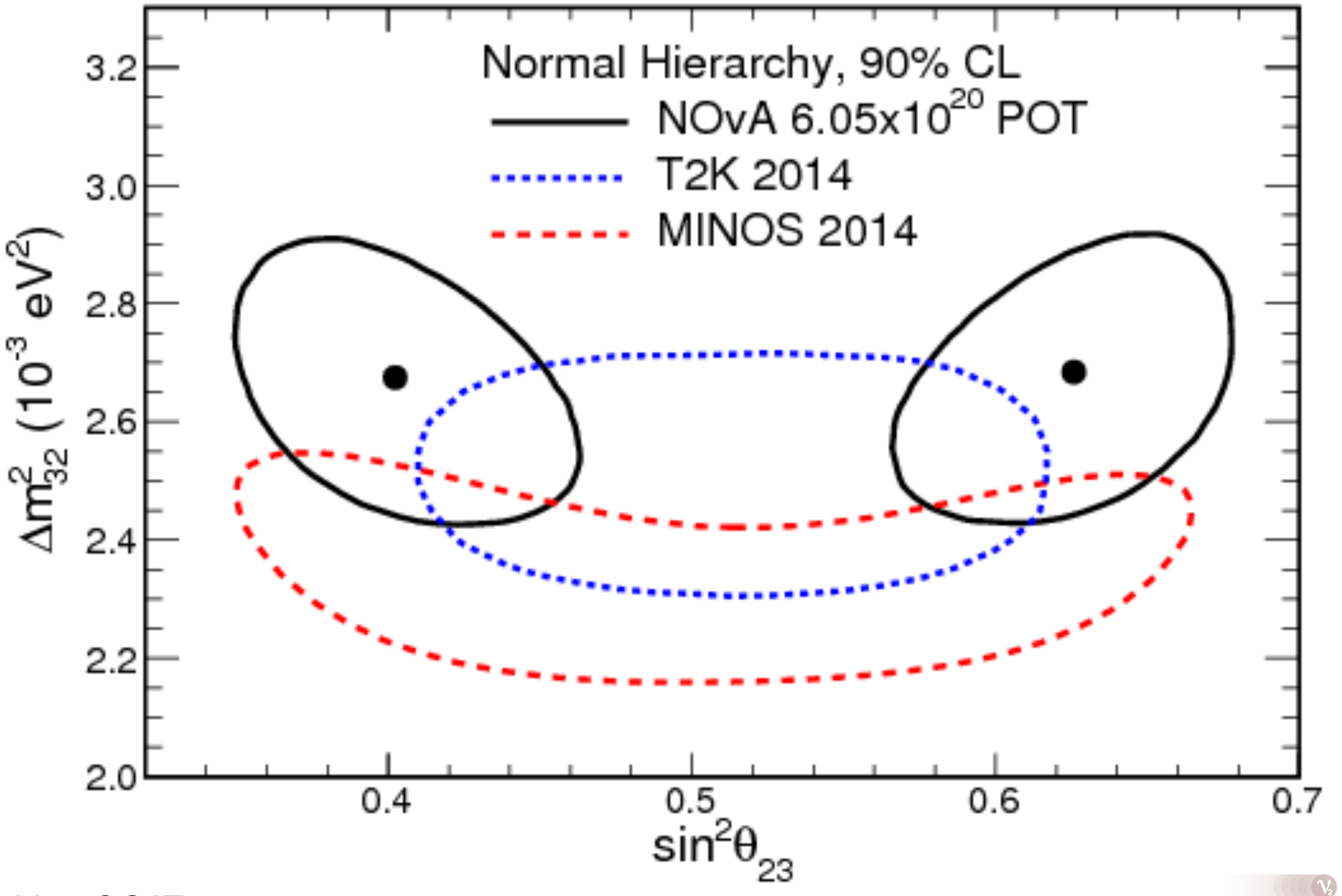
δcp = 1.48π Normal Hierarchy
δcp = 0.74π Inverted Hierarchy

Sin2θ23 = 0.404 Normal Hierarchy
Sin2θ23 = 0.623 Inverted Hierarchy

Inverted Hierarchy at lower octant is disfavored at ~2 σ

Maximal mixing excluded at 2.6 σ significance.

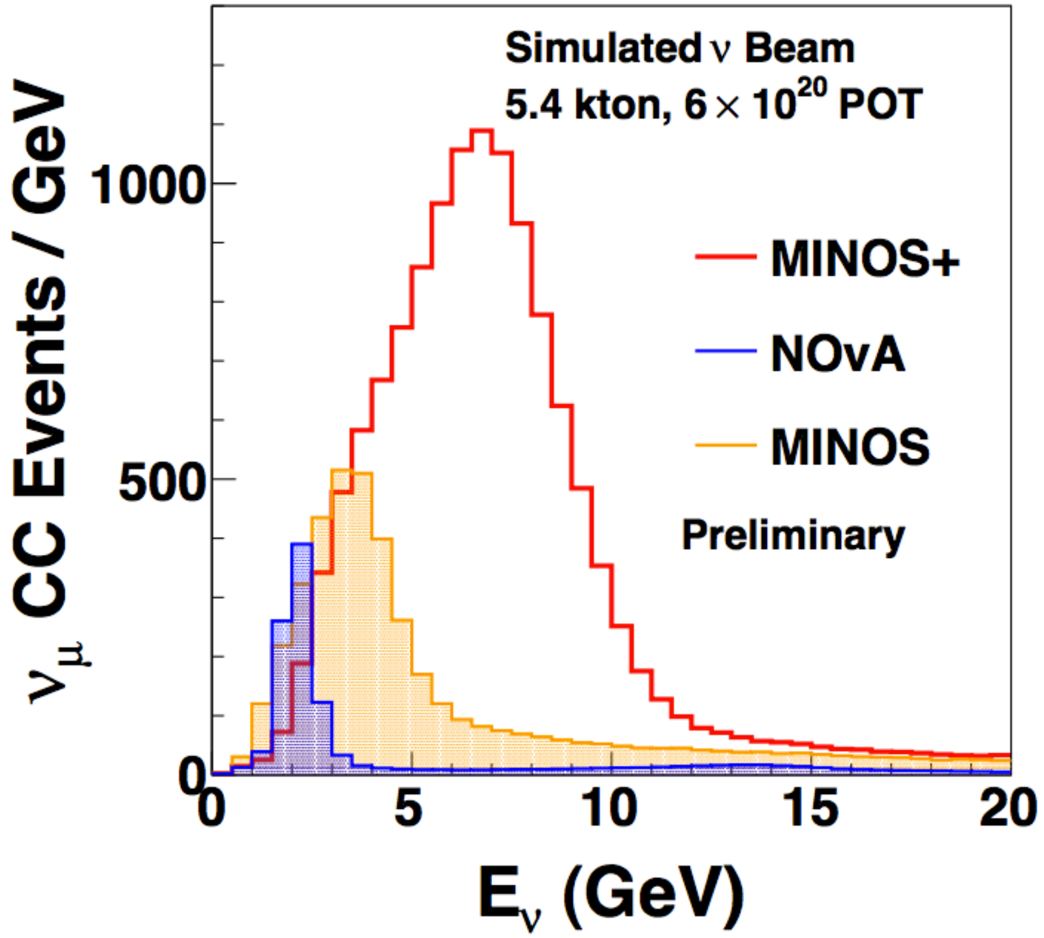




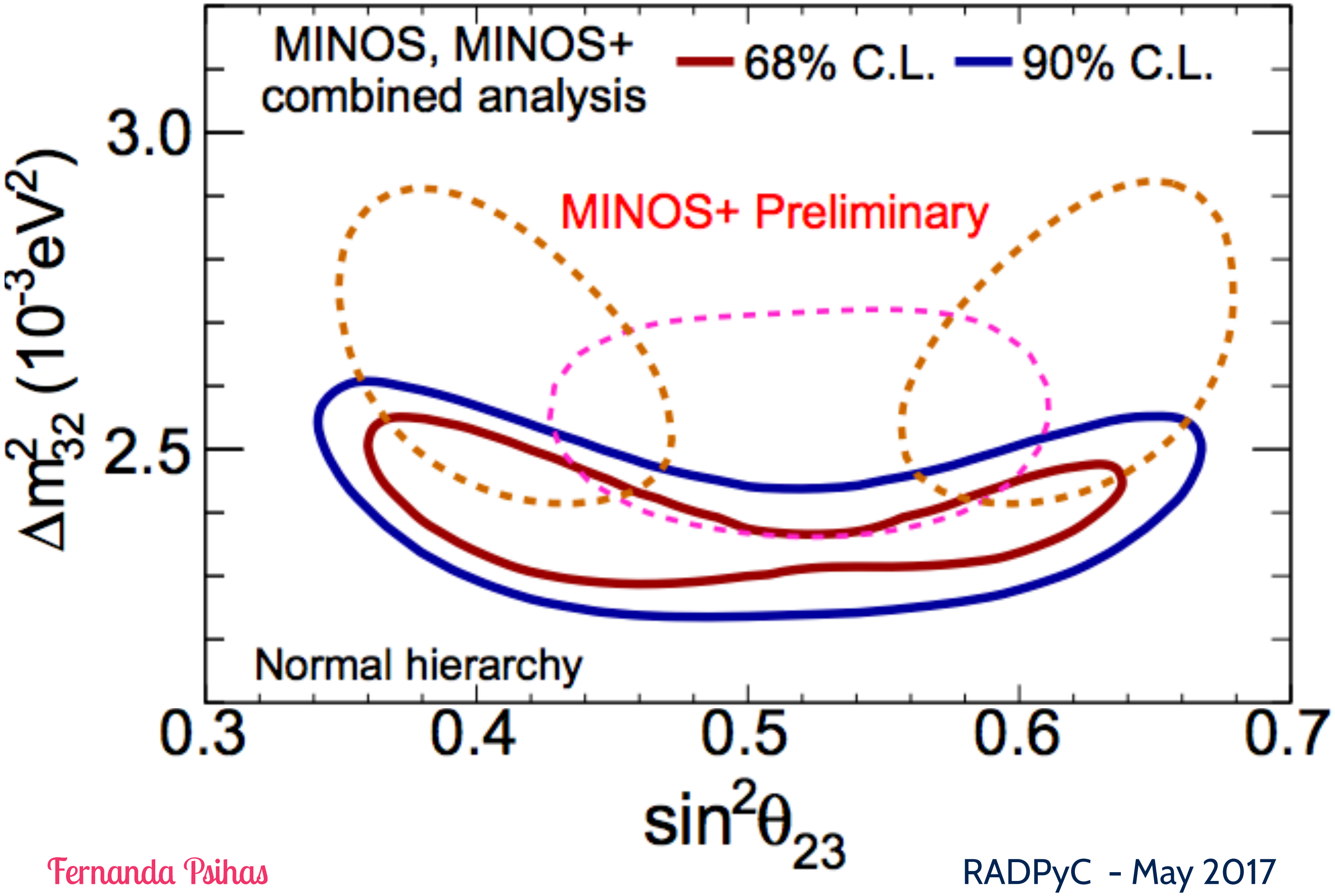
MINOS+

Looking for the same oscillations channels, now in the NOvA beam

Using the existing MINOS detectors



MINOS
arXiv:1703.04471



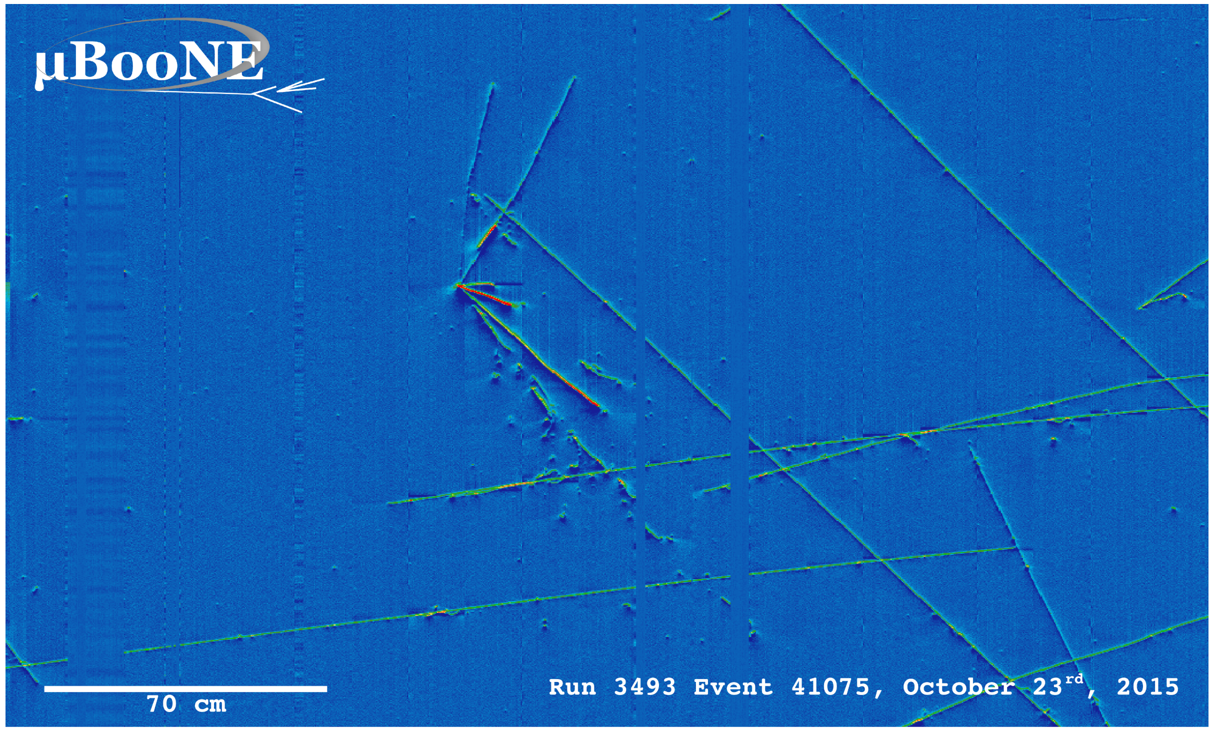
MINOS+ run ended in 2016 year

Improved results of oscillation analysis

Sterile searches

Deep Underground Neutrino Experiment

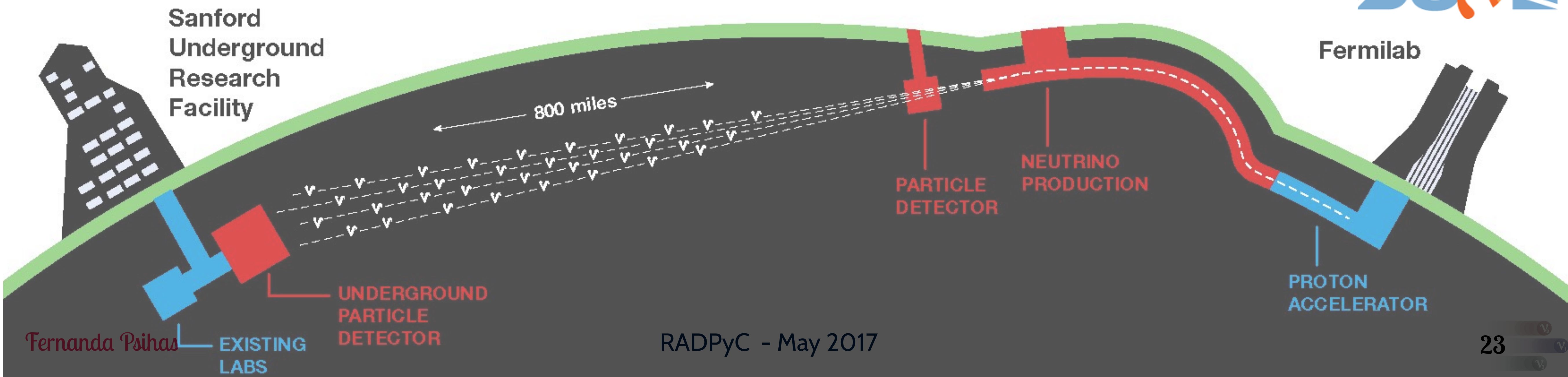
Optimized 1.2 MW beam at Fermilab upgradable to 2.4 MW



40 kT fiducial volume (Far Detector) underground at South Dakota

Large R&D program for LAr-TPC technology, linked to SBL at Fermilab

Construction planned for 2026 - Current R&D Effort in ProtoDUNE building now for test beam at CERN

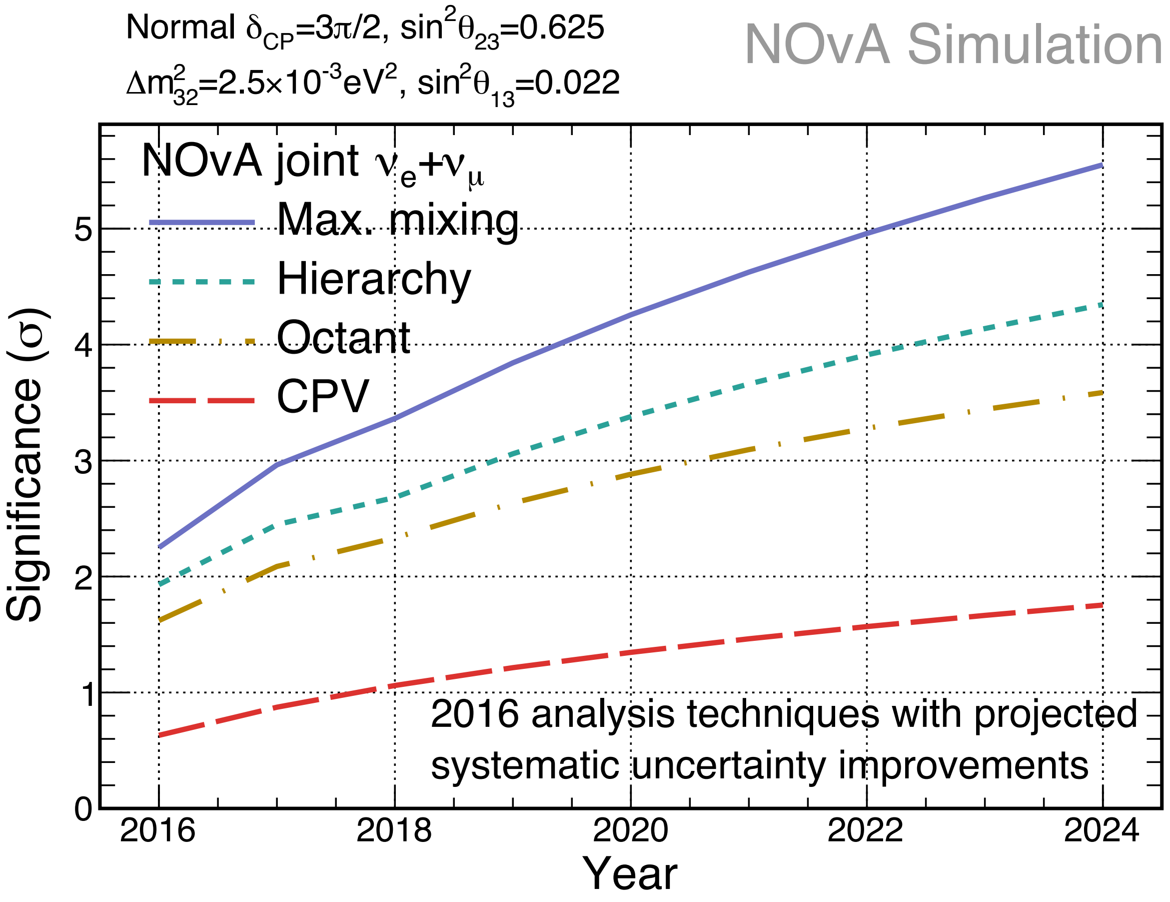


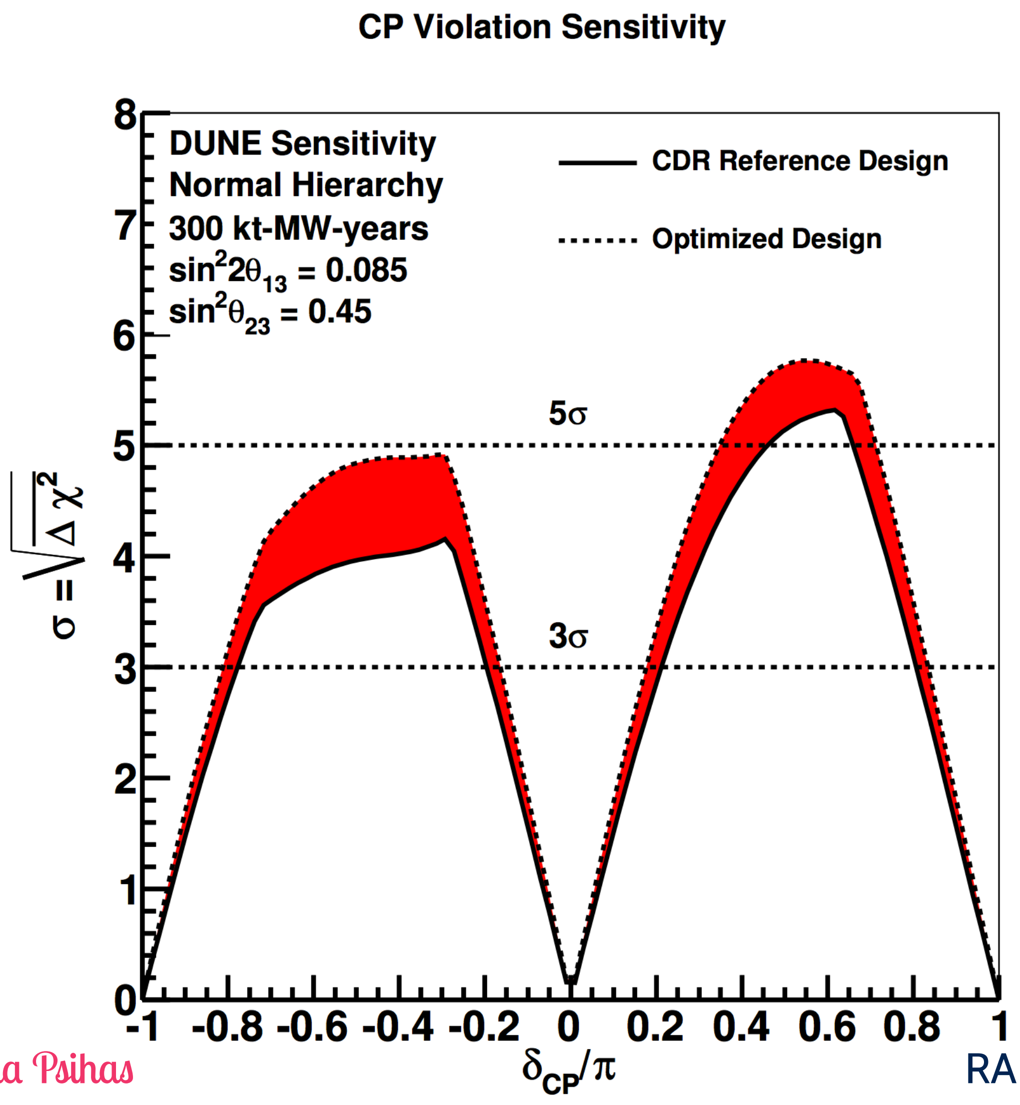
FUTURE SENSITIVITIES

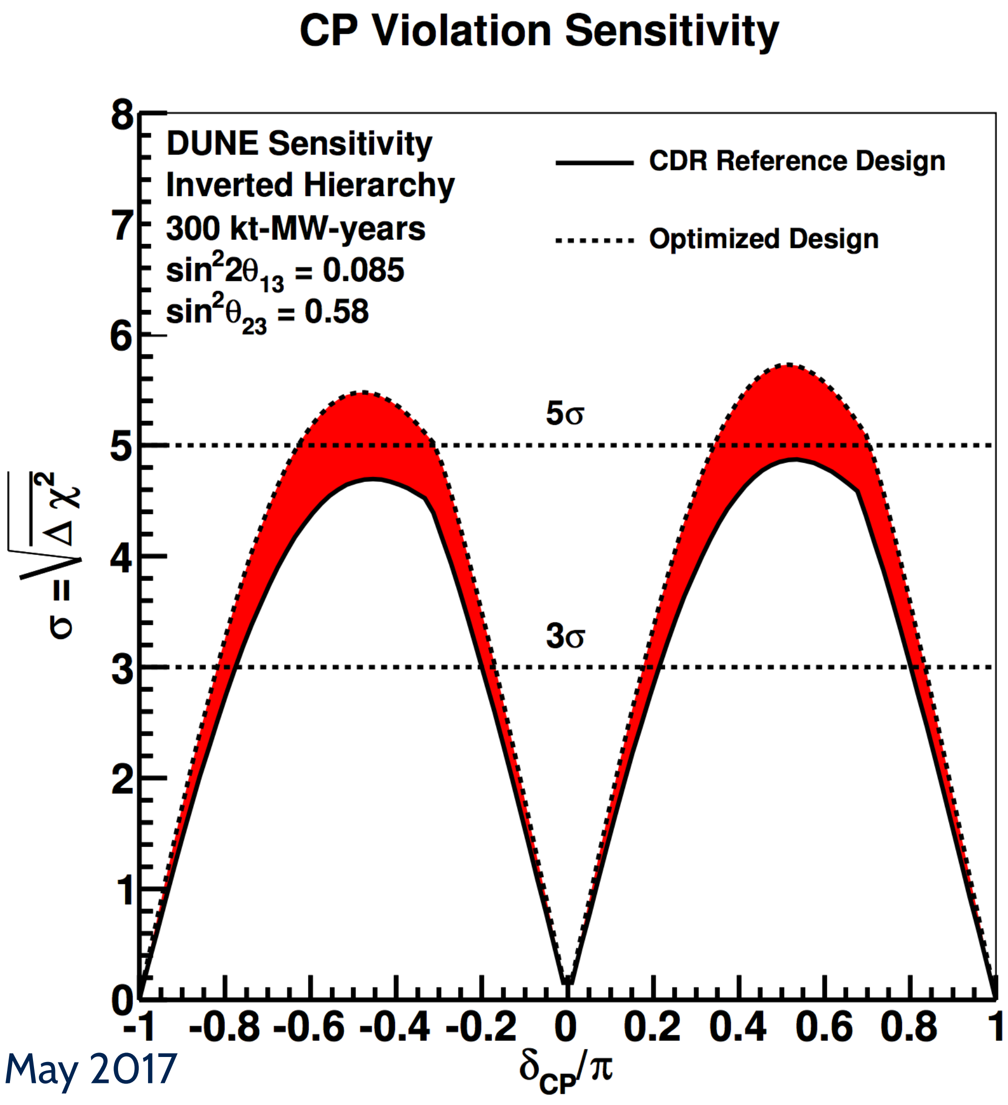
NOvA will add ~50% statistics to the 2016 analyses this year and will include antineutrino data for the 2018 analyses.

Under these assumptions, 5 σ is reachable for mass hierarchy determination by 2022

DUNE CDR shows 5 σ sensitivity for the CP phase at 300 kt-MW-year



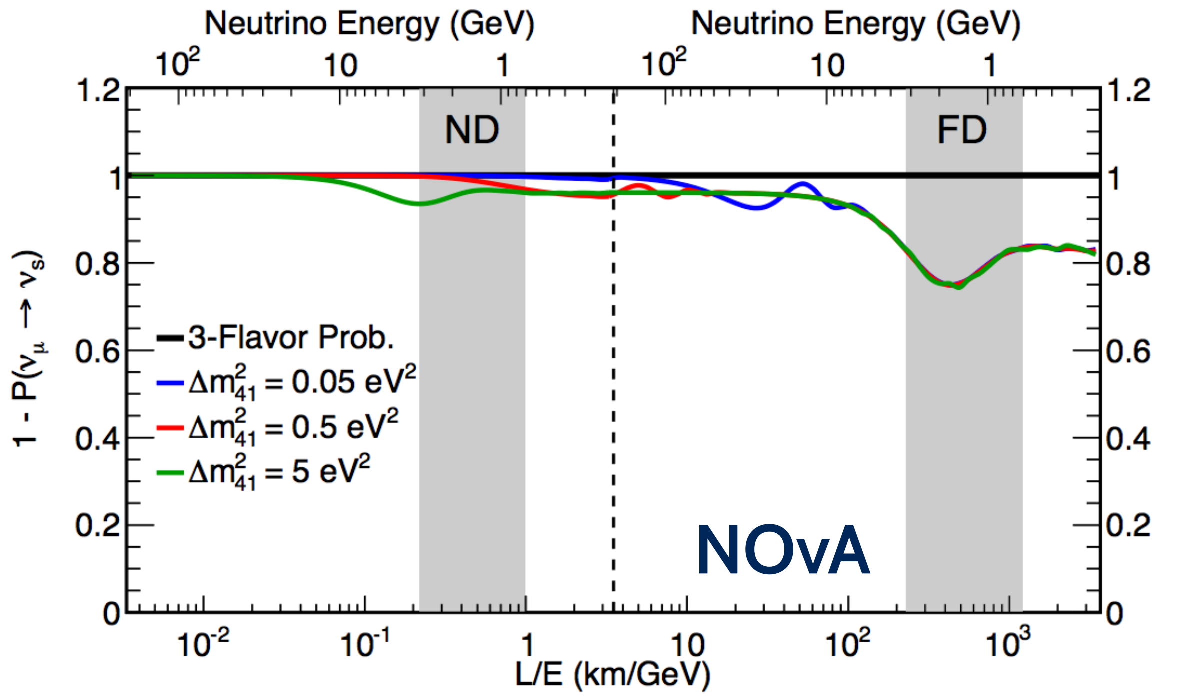




DUNE CDR arxiv:1512.06148

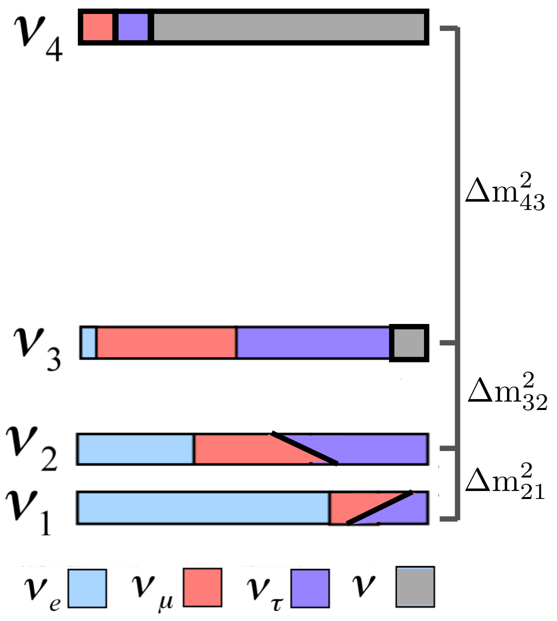
3+1 Neutrino Model

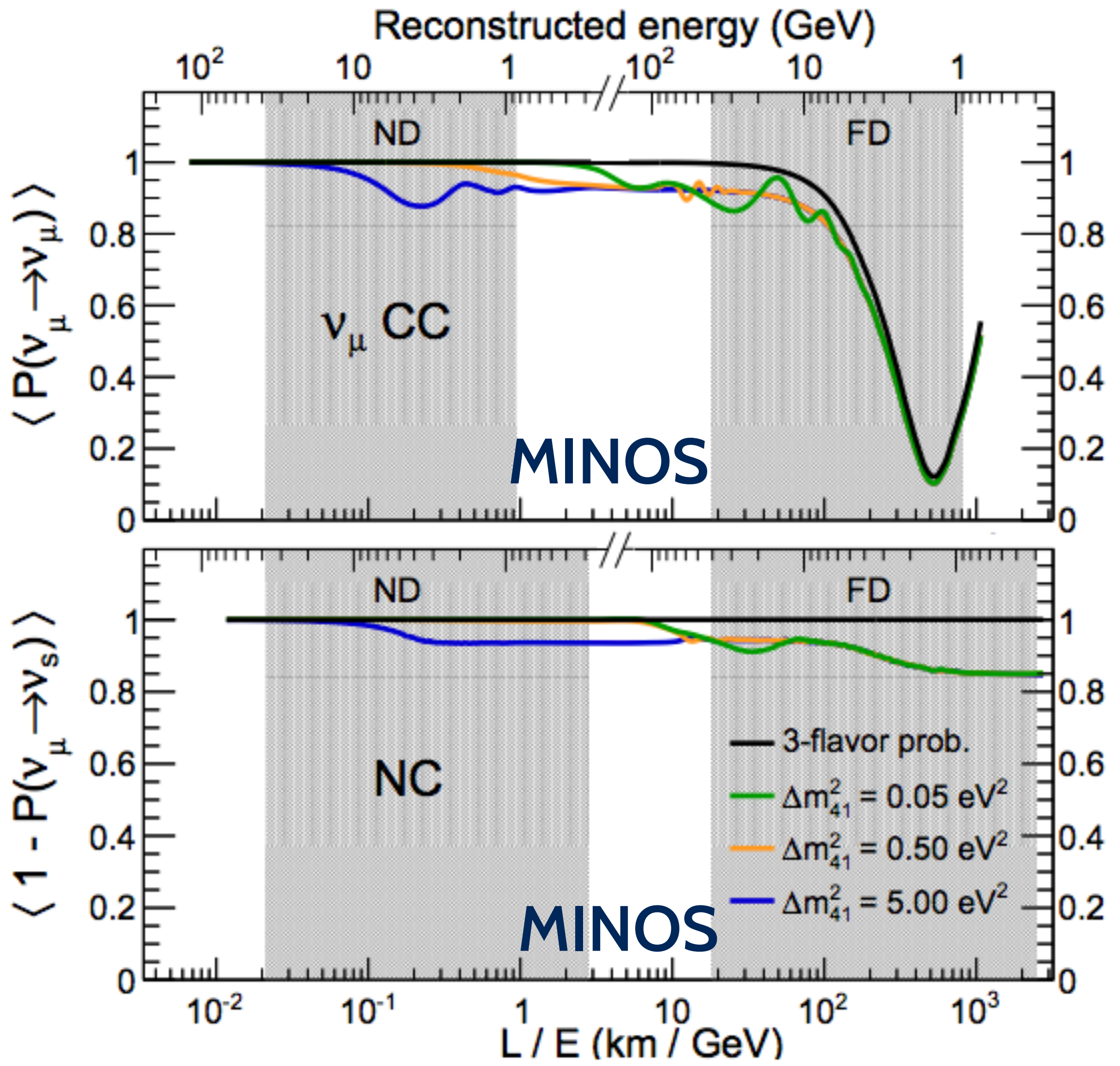
Low E excess from short baseline experiments (LSND an MiniBoone) can be accommodated by introducing oscillations into sterile neutrinos with a Δm2 ~1 eV2



$$U_{\mathrm{PMNS}}^{\mathrm{Extended}} = \begin{pmatrix} \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{U_{\mathrm{PMNS}}^{3\mathrm{x}3}} & \begin{matrix} \cdots & U_{en} \\ \cdots & U_{\mu n} \\ \cdots & U_{\tau n} \end{matrix} \\ \begin{matrix} \vdots & \vdots & \vdots \\ U_{s_n 1} & U_{s_n 2} & U_{s_n 3} \end{matrix} & \begin{matrix} \ddots & \vdots \\ \cdots & U_{s_n n} \end{matrix} \end{pmatrix}$$

The 3+1 model introduces new mixing angles, Δm terms and CP phases



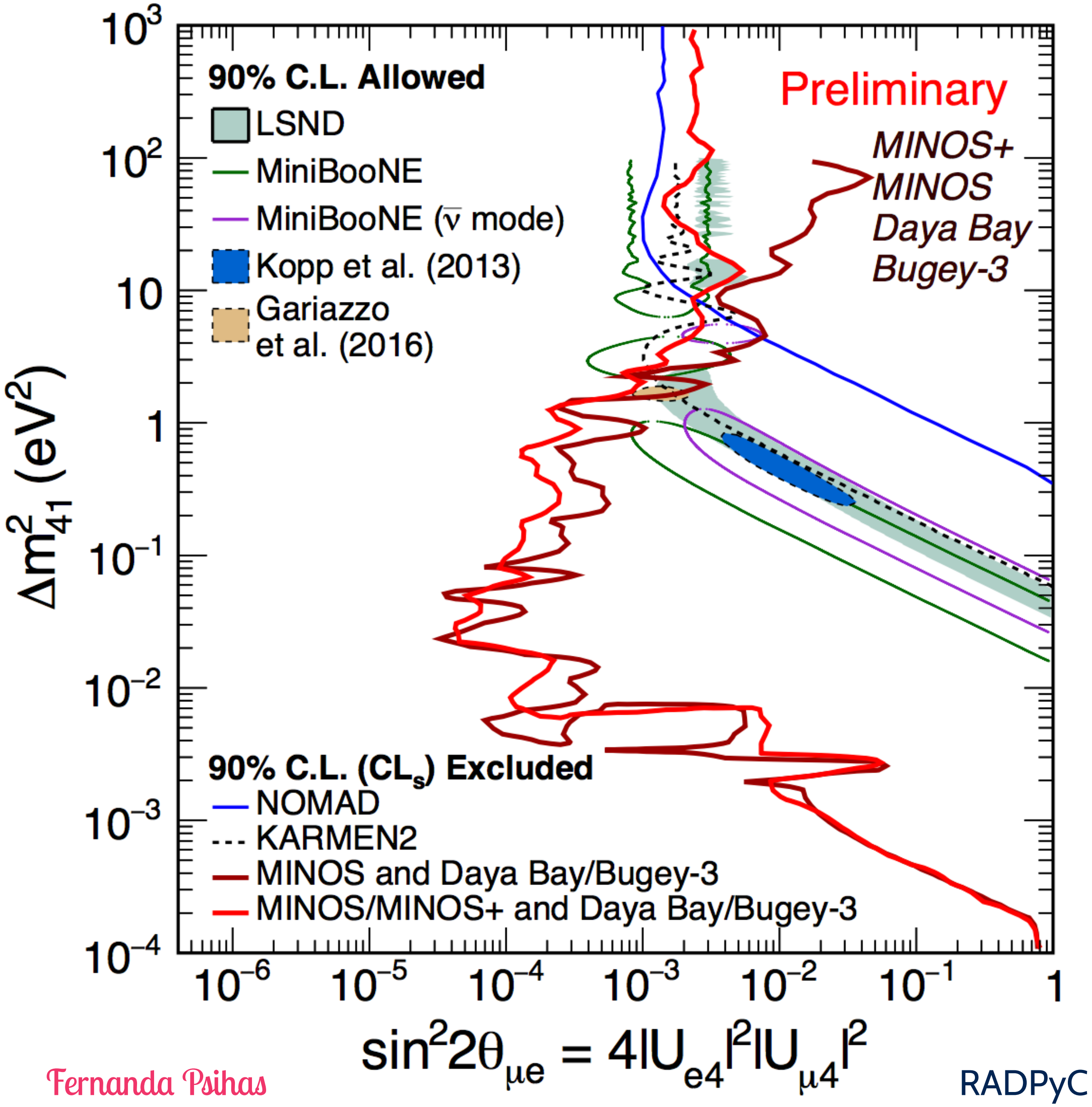


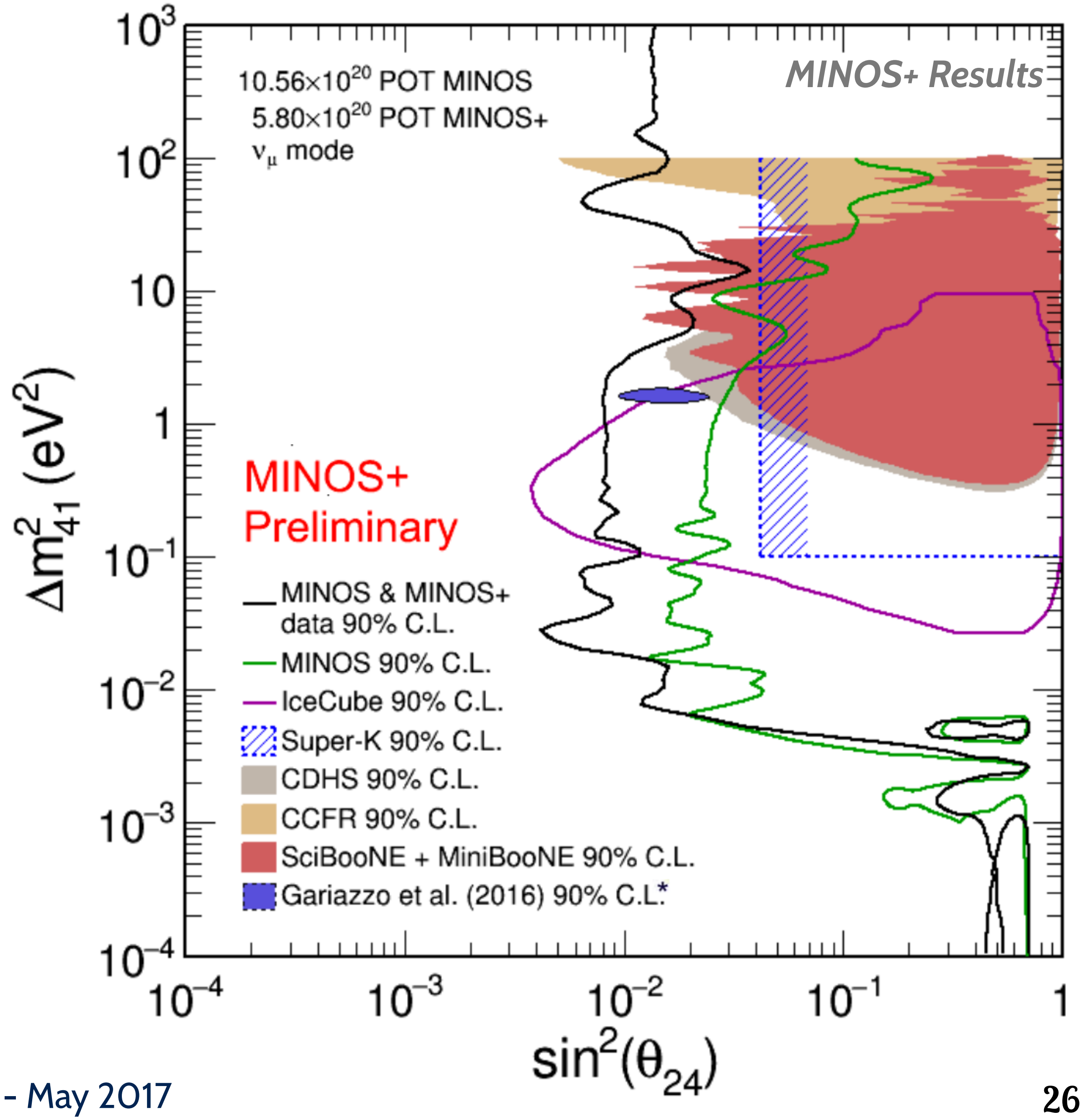
MINOS+

Ran from 2013 to 2016 on NOvA's NuMI beam.

Higher energy beam allows MINOS+ to probe oscillations to sterile neutrinos at higher sensitivity.

New results and combination with MINOS, Daya Bay and Bugey were shown at Fermilab just a few weeks ago.

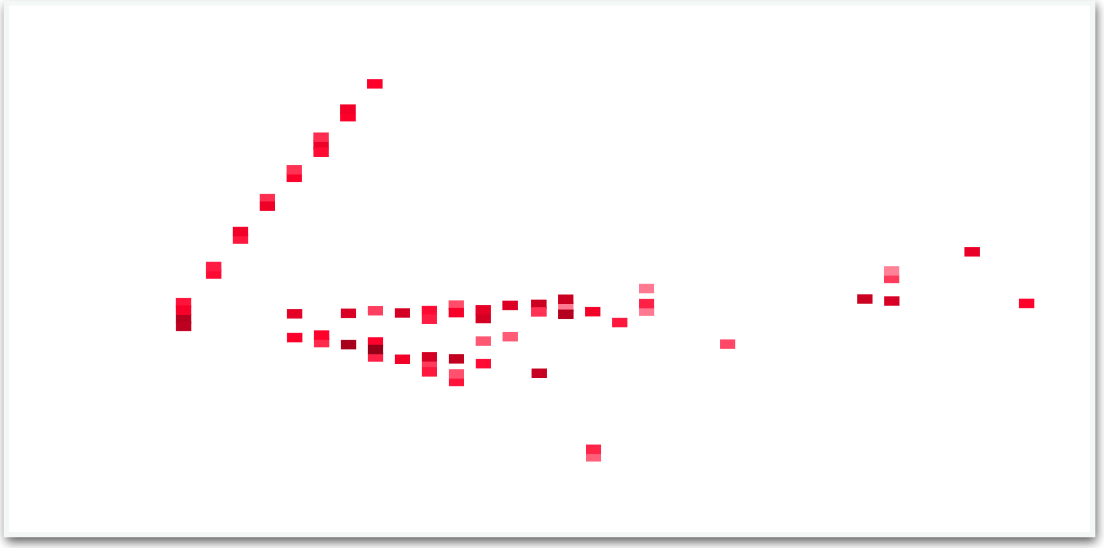




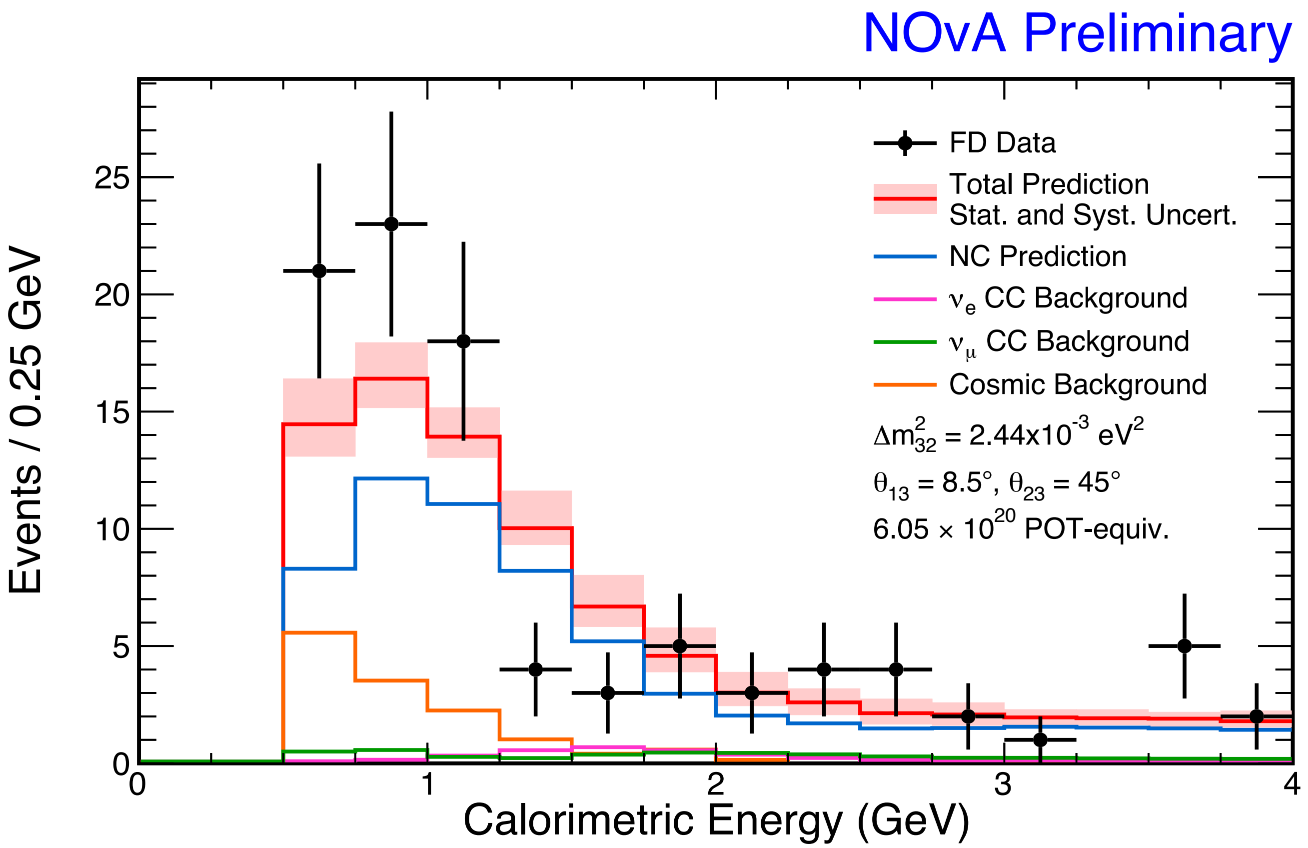
NOvA 3+1 NC

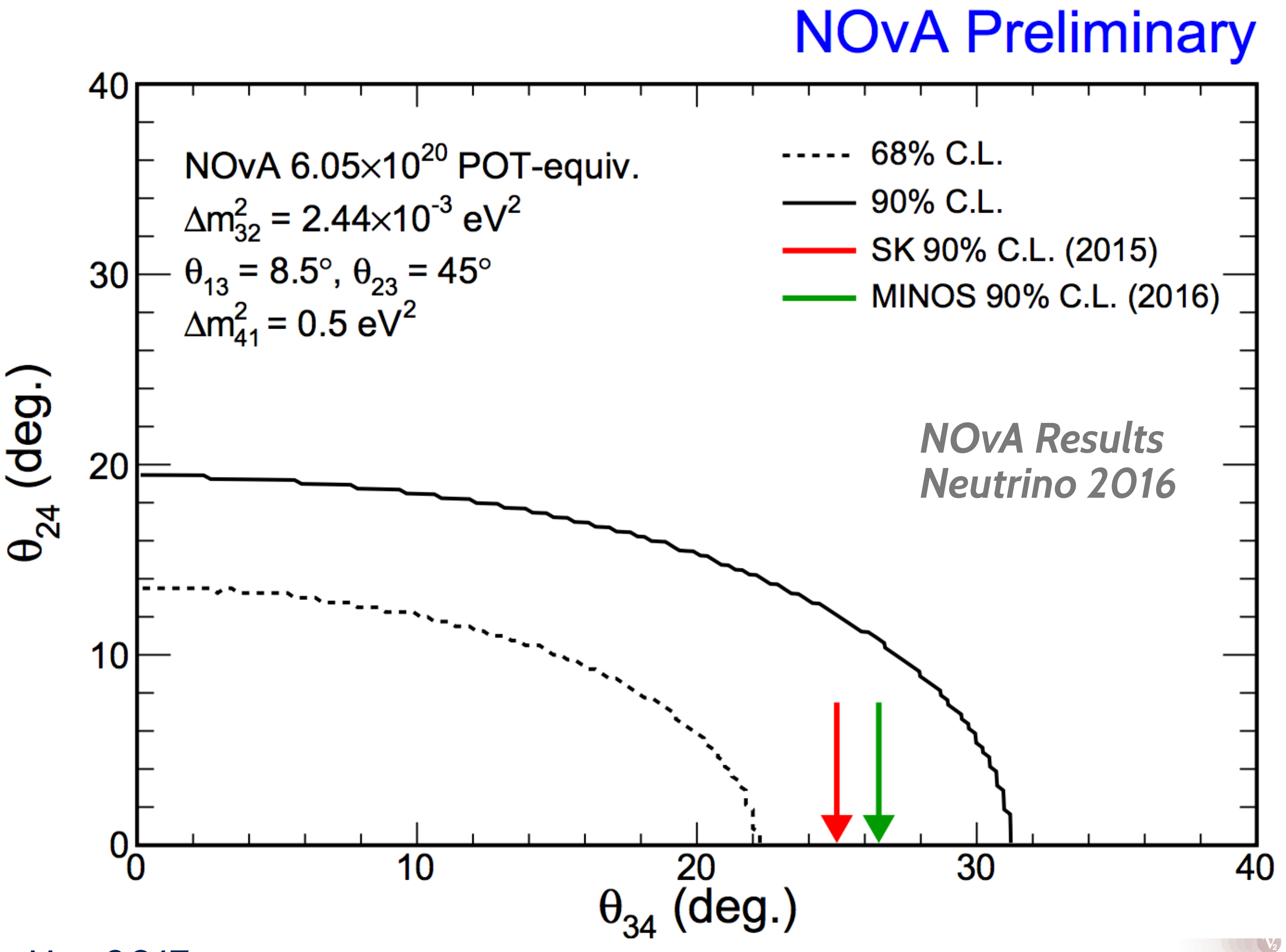
Oscillations from active to sterile neutrinos are measured in NC disappearance analysis.

First result is competitive with existing measurements. Improved analysis with 50% more statistics is in the workings.



$$1-P(\nu_\mu \rightarrow \nu_s) \;\approx\; 1-\frac{1}{2}\cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}$$
$$+A\sin^2\Delta_{31} - B\sin 2\Delta_{31},$$





NOvA Results Neutrino 2016

Upcoming NOvA Analyses

Beyond Oscillations

- ν Cross Sections
- Supernova trigger and SNEWS
- Magnetic monopole searches
- Studies of cosmic rays (day/night, seasonal effects, etc.)

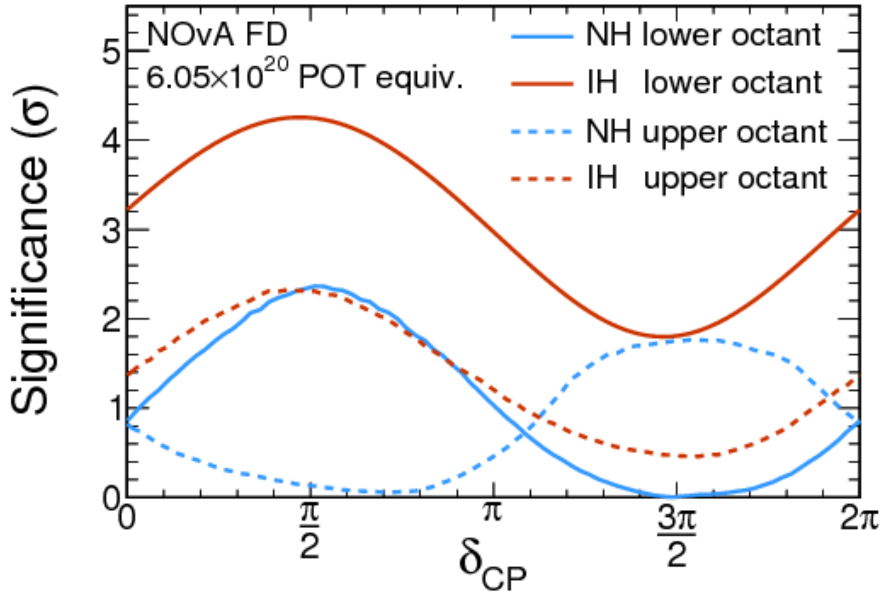
More on Sterile ν

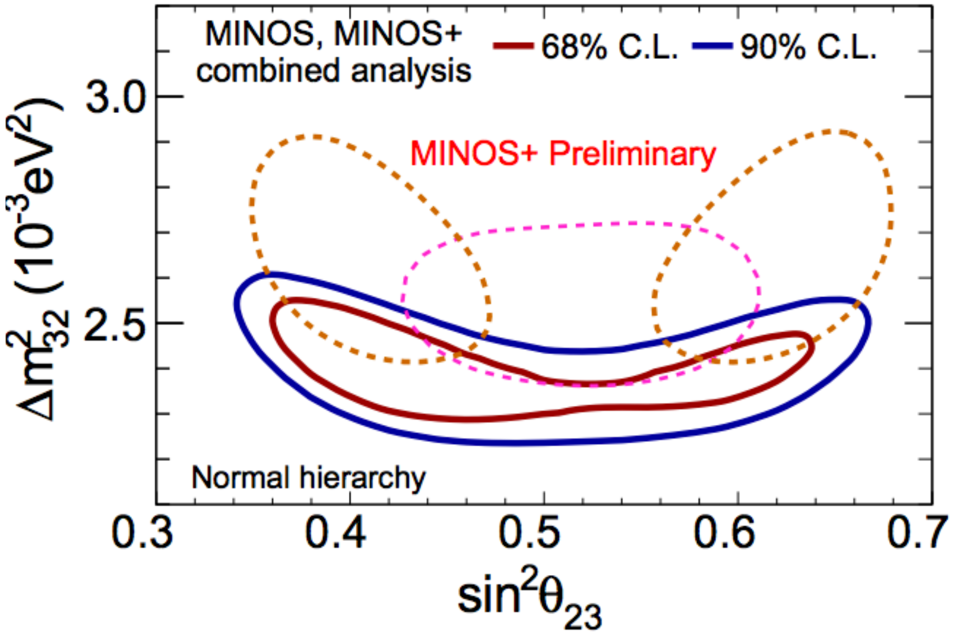
- ν_τ Appearance
- SBL Analyses
- ν_e Appearance
- ν_μ disappearance
- ν Non Standard Interactions

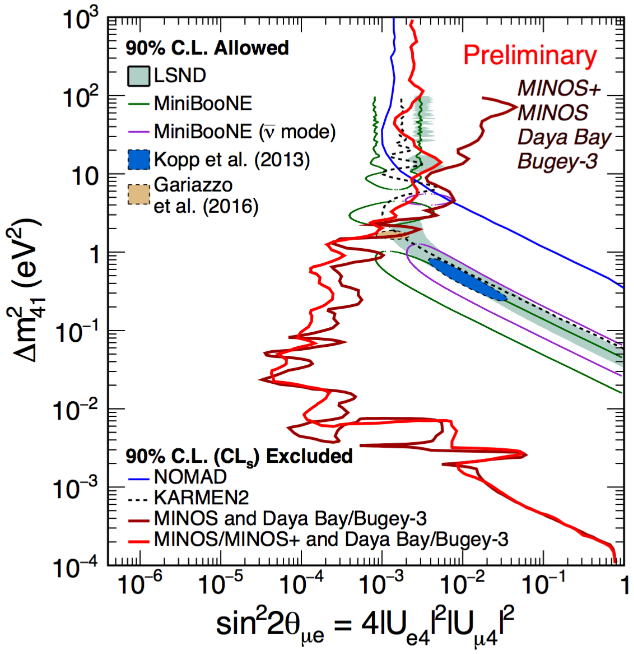
SUMMARY

LBL Experiments take advantage of matter effects + 2 detector array to maximize the reach of their neutrino oscillation analyses.

NOvA and MINOS+ results:







The DUNE program is underway on large R&D efforts.

The Long Baseline Neutrino program at Fermilab covers a wide range of physics beyond the main oscillations analyses…

Stay tuned for much more!

Backup

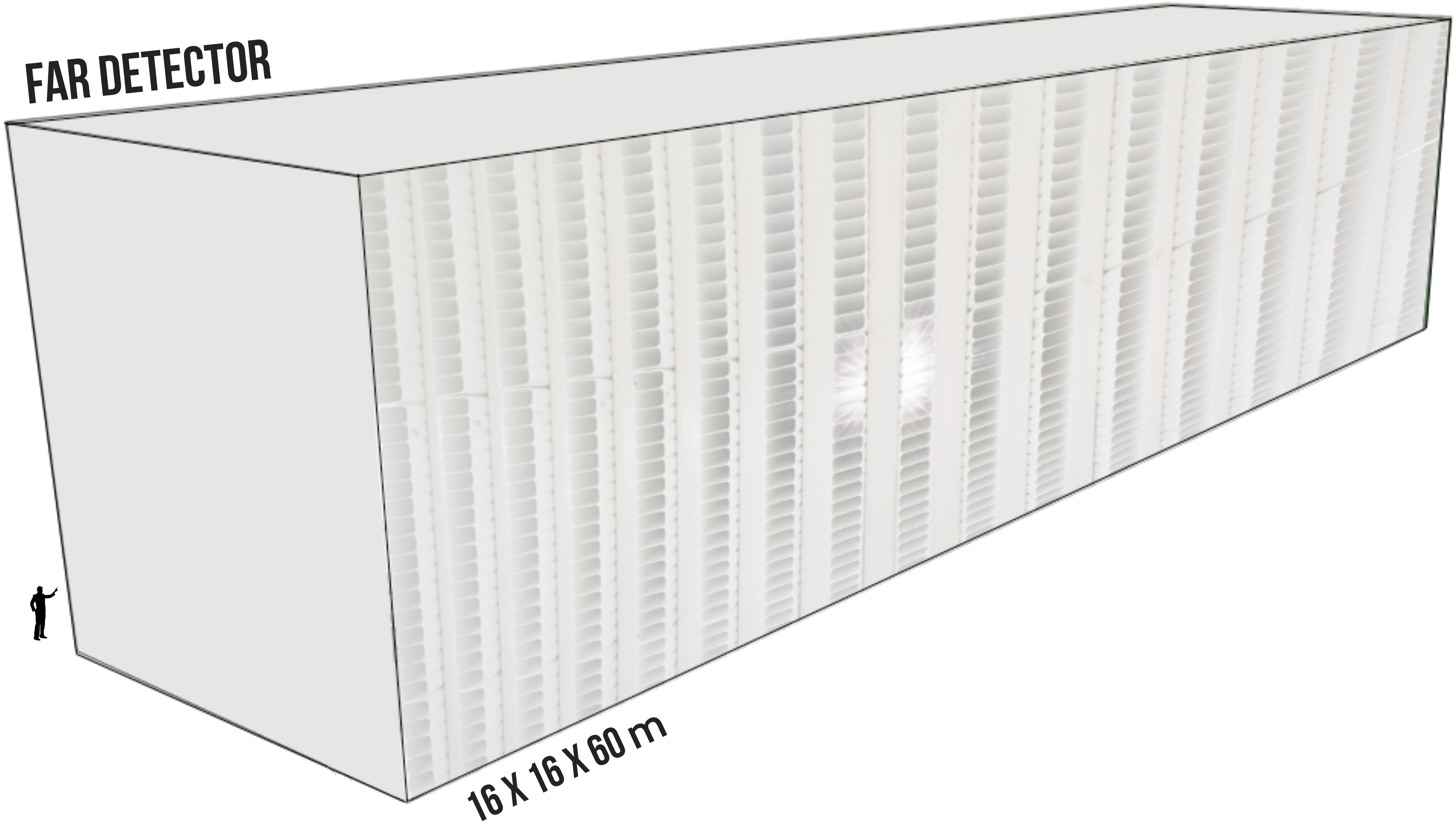
These are not the slides you're looking for

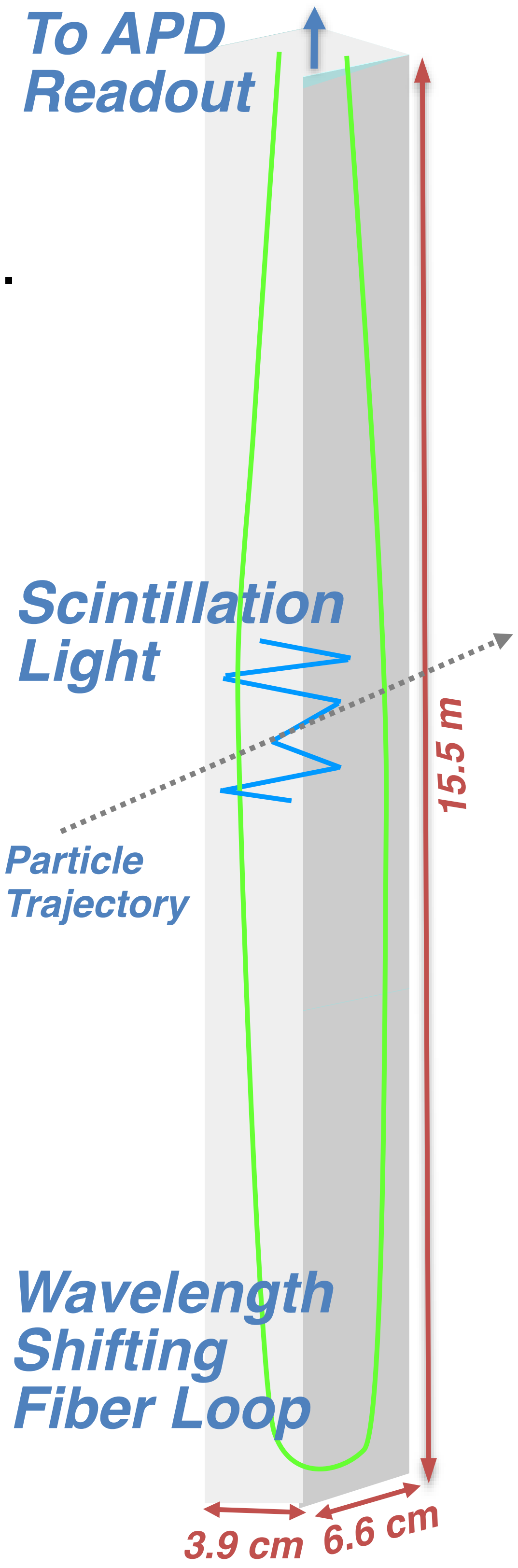
The NOνA Detectors

Sampling calorimeters optimized for electron identification.

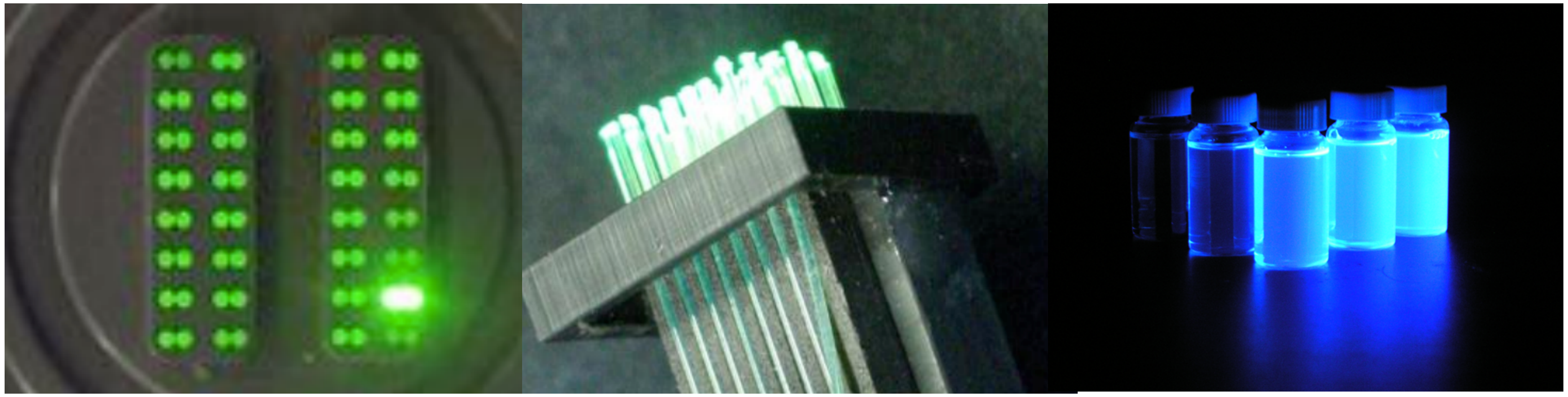
The detector building is on the surface.

Large volume at the Far detector to maximize signal statistics.

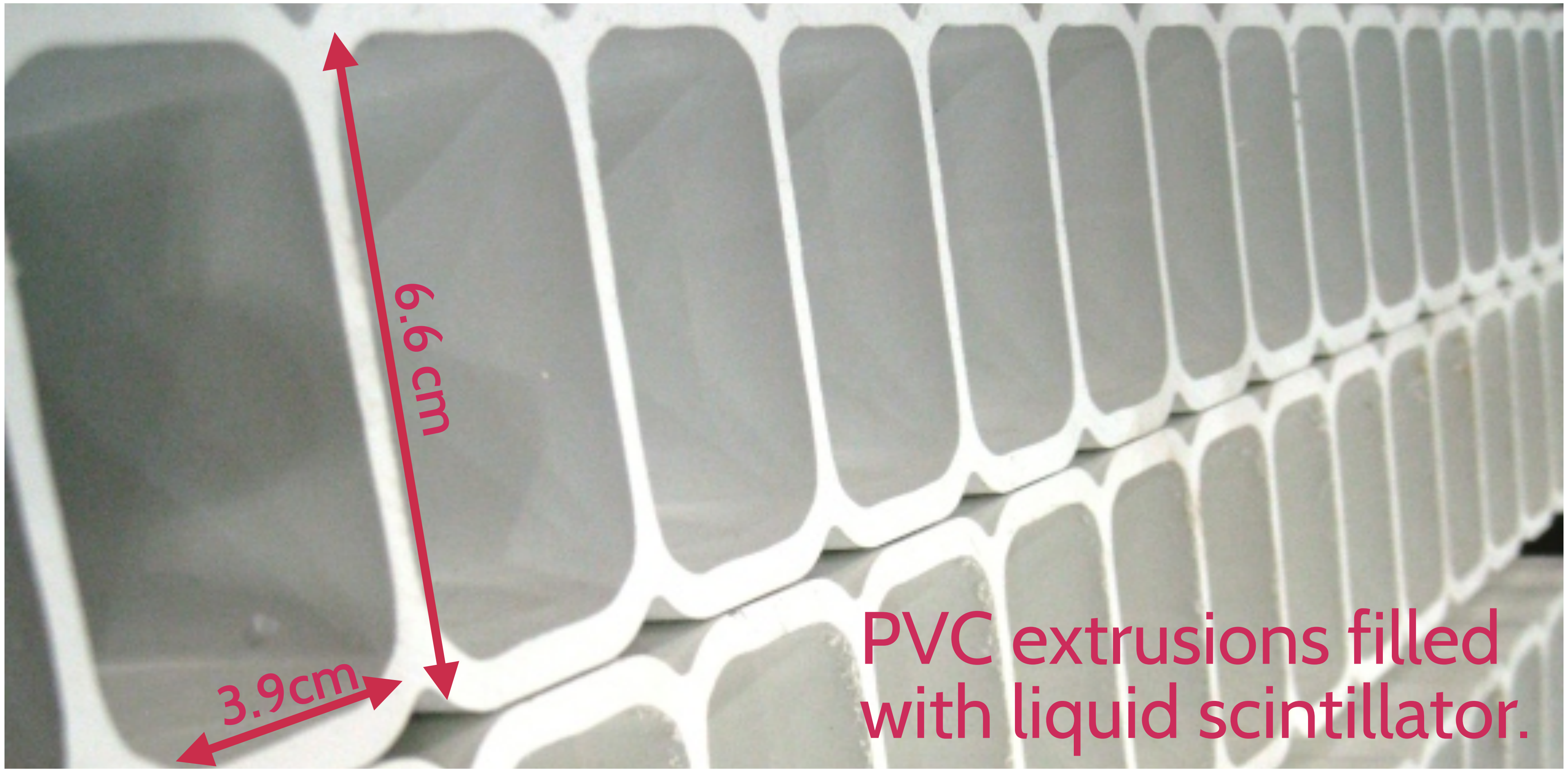




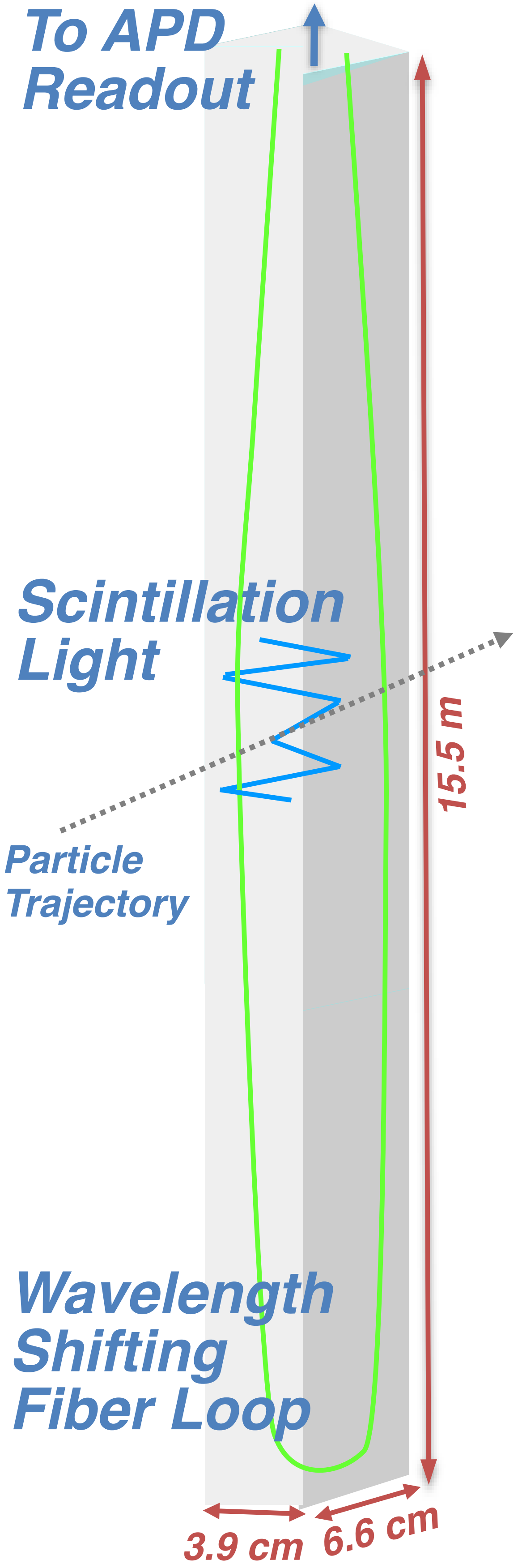
The NOvA Detectors



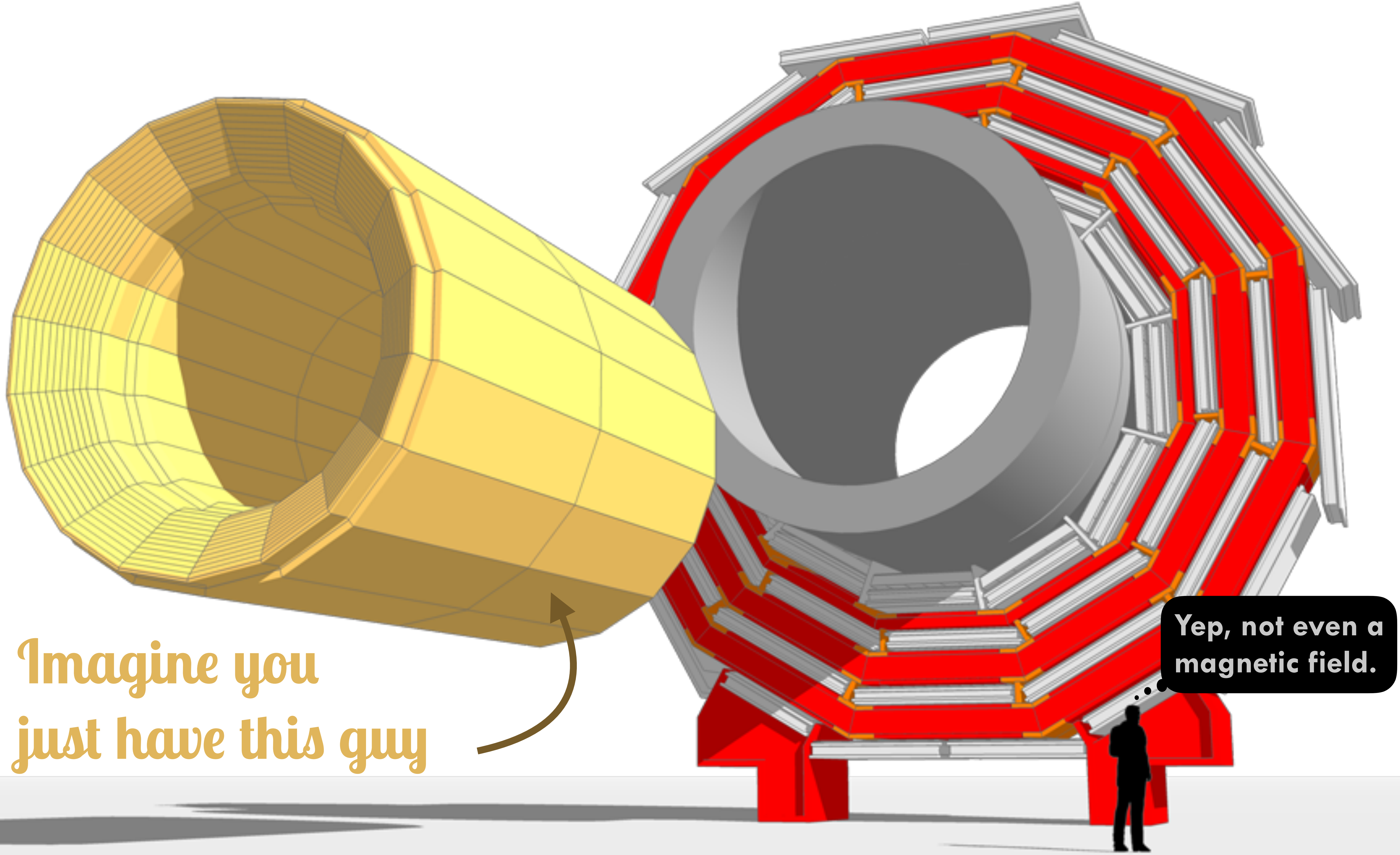
Charged particles are detected though the scintillation light produced in each cell.



PVC extrusions filled with liquid scintillator.

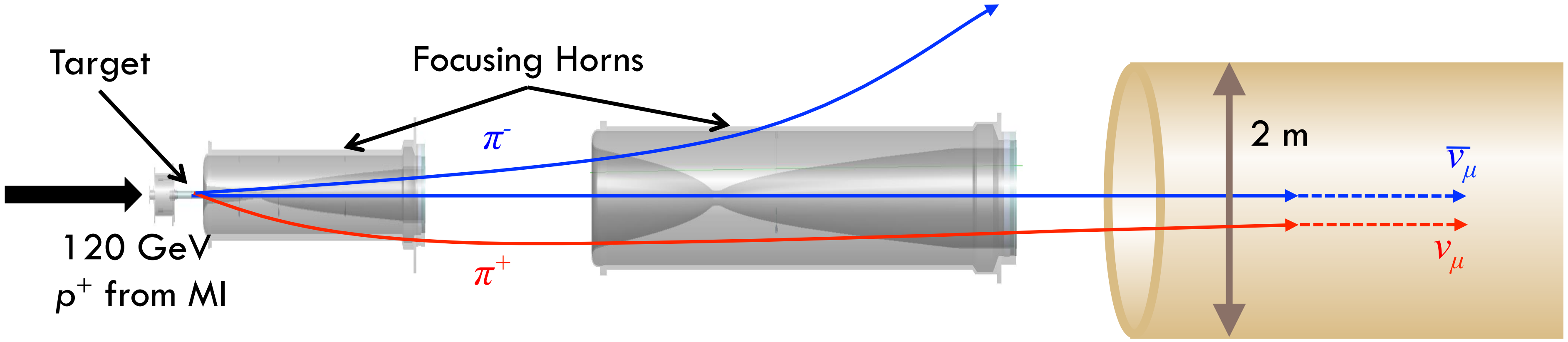


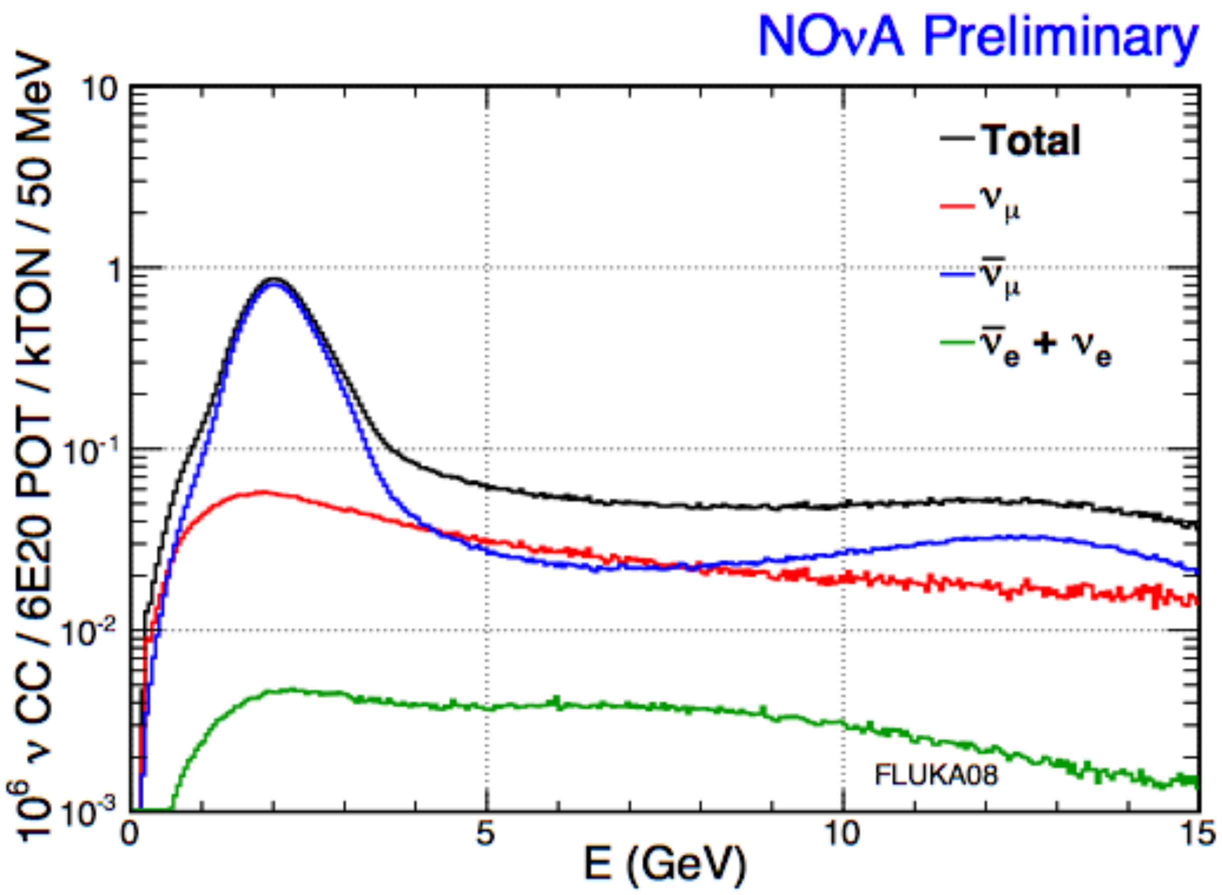
Some collider context

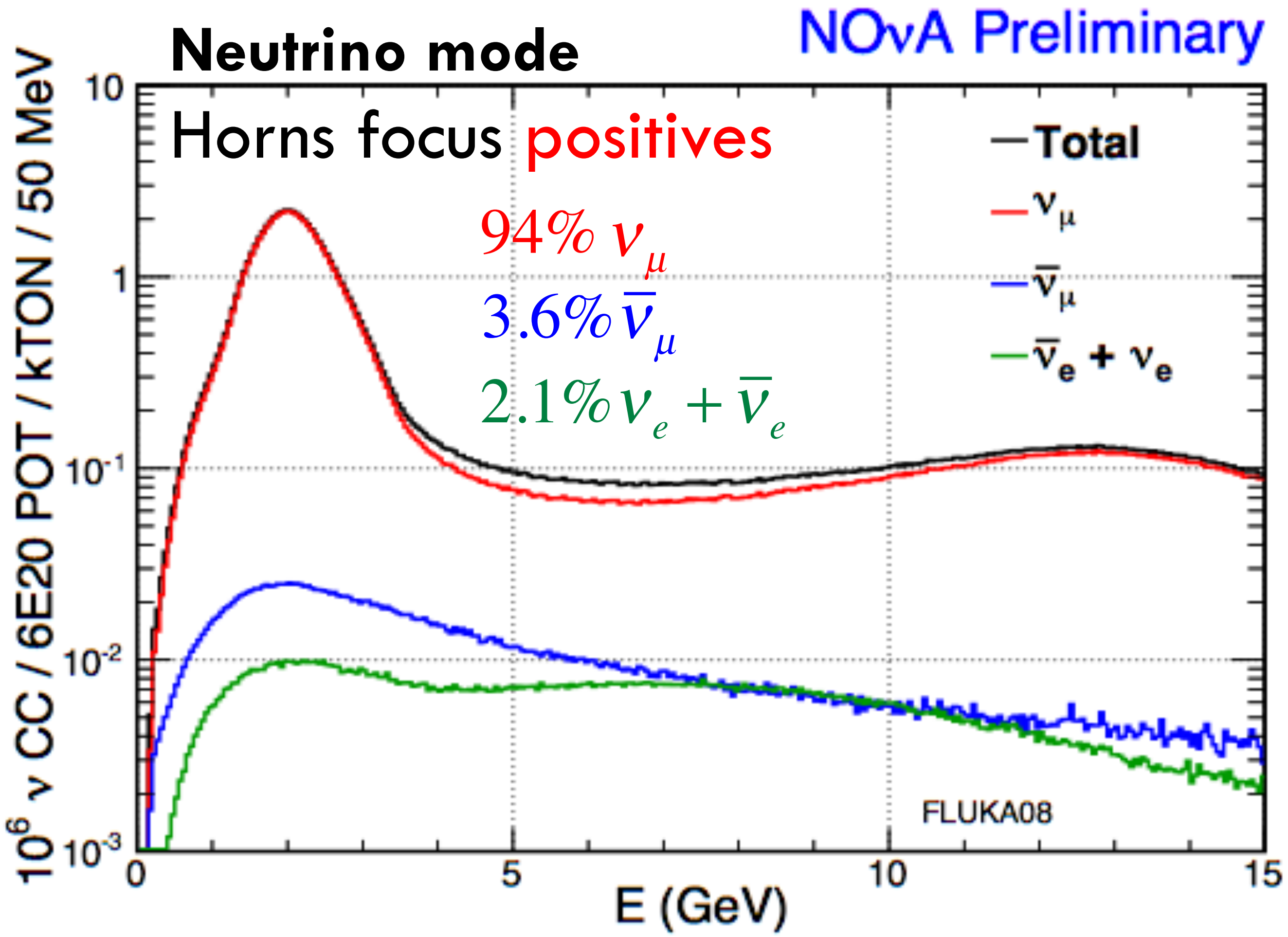


Imagine you just have this guy

https://twiki.cern.ch/twiki/bin/view/CMSPublic/SketchUpCMS







Neutrino mode

Horns focus positives

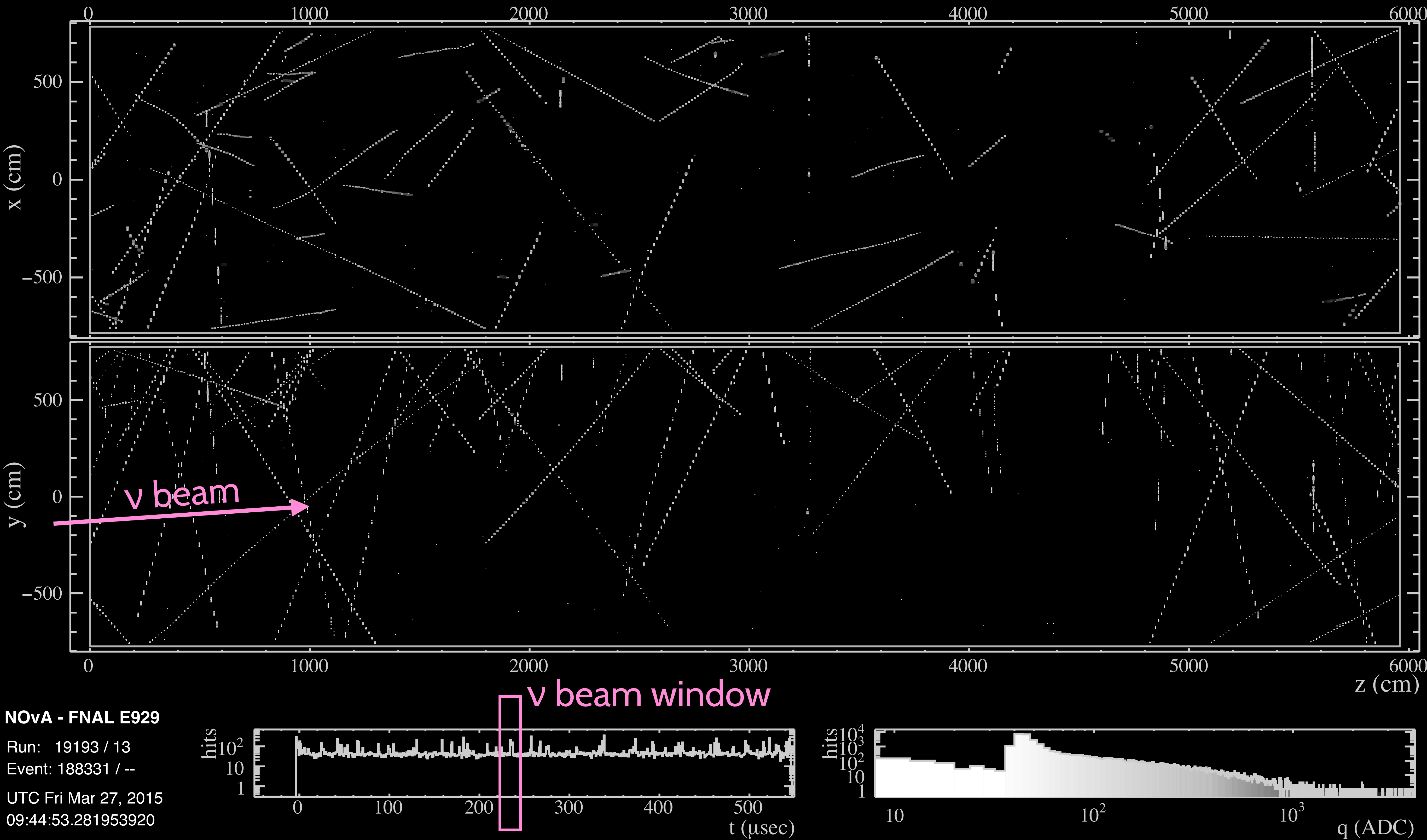
$94\%\ \nu_\mu$

$3.6\%\ \overline{\nu}_\mu$

$2.1\%\ \nu_e + \overline{\nu}_e$

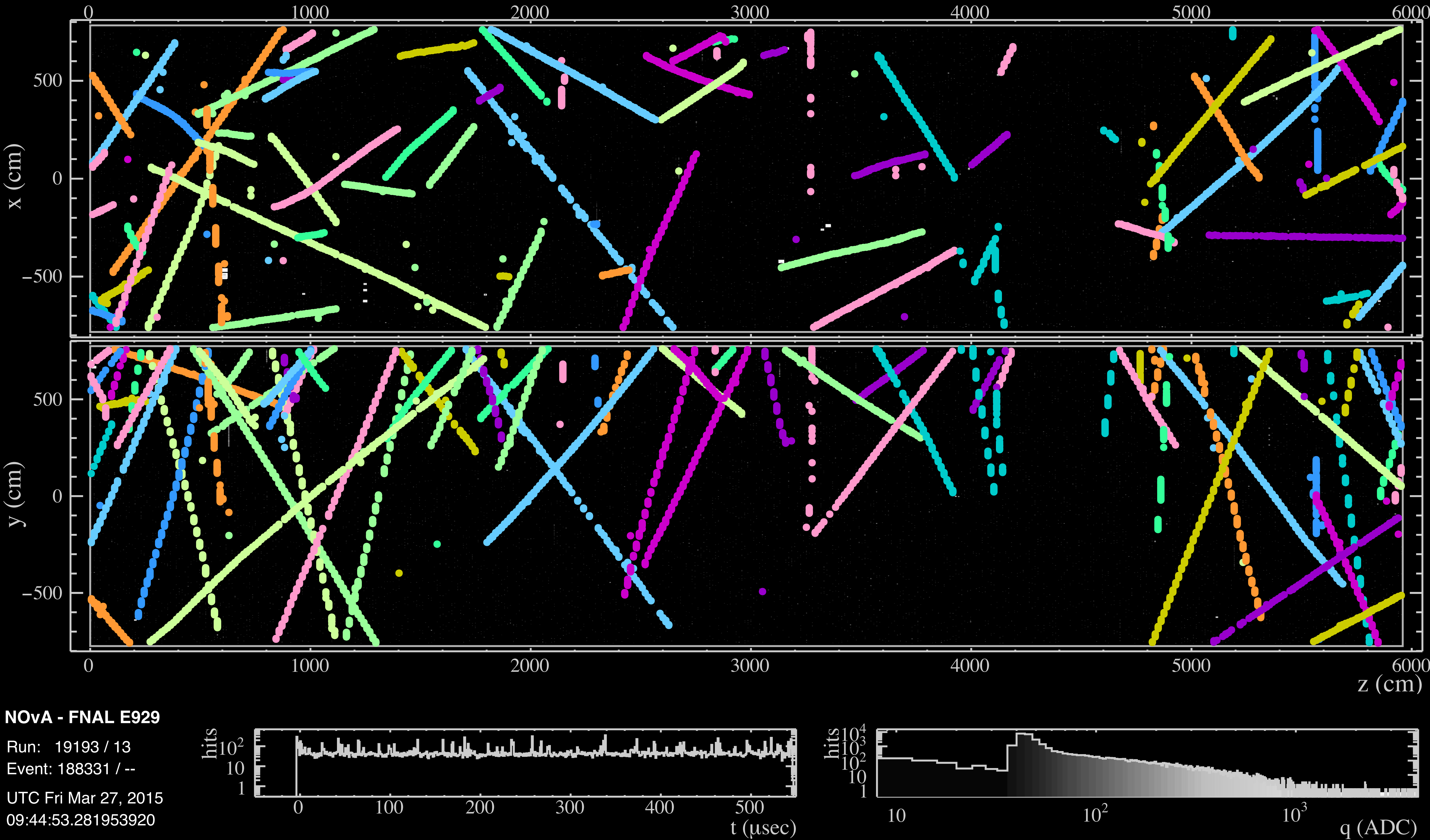
NOvA Readout and Neutrino Interactions

Events are 550 μs readouts around the neutrino beam spill.



Isolating neutrino interactions

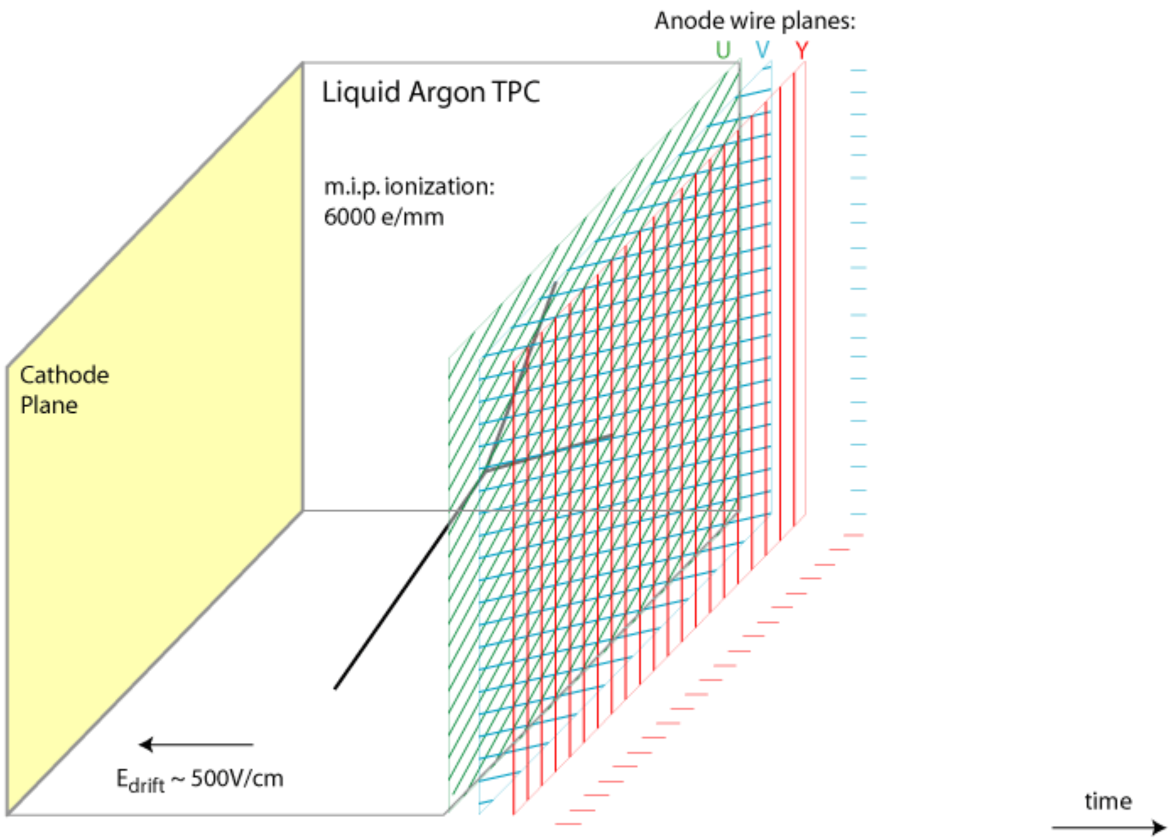
The first step in our reconstruction is dividing an **event** (550 µs of data) into slices (groups of hits with some time and space coincidence)

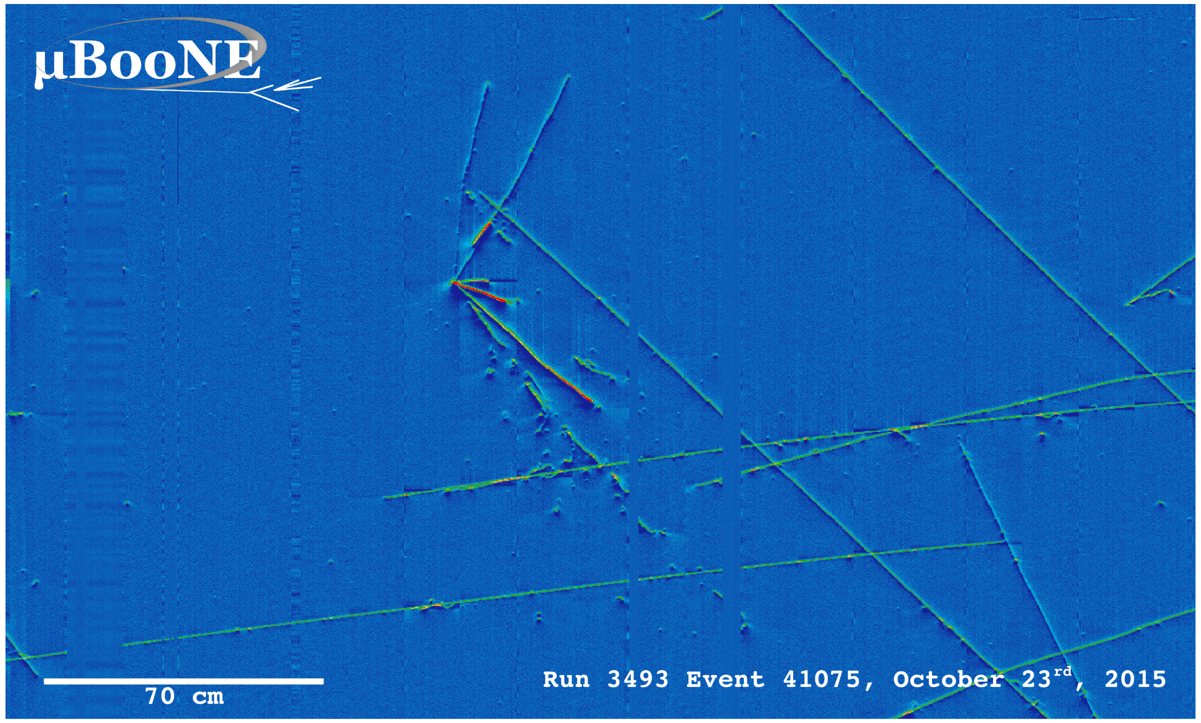


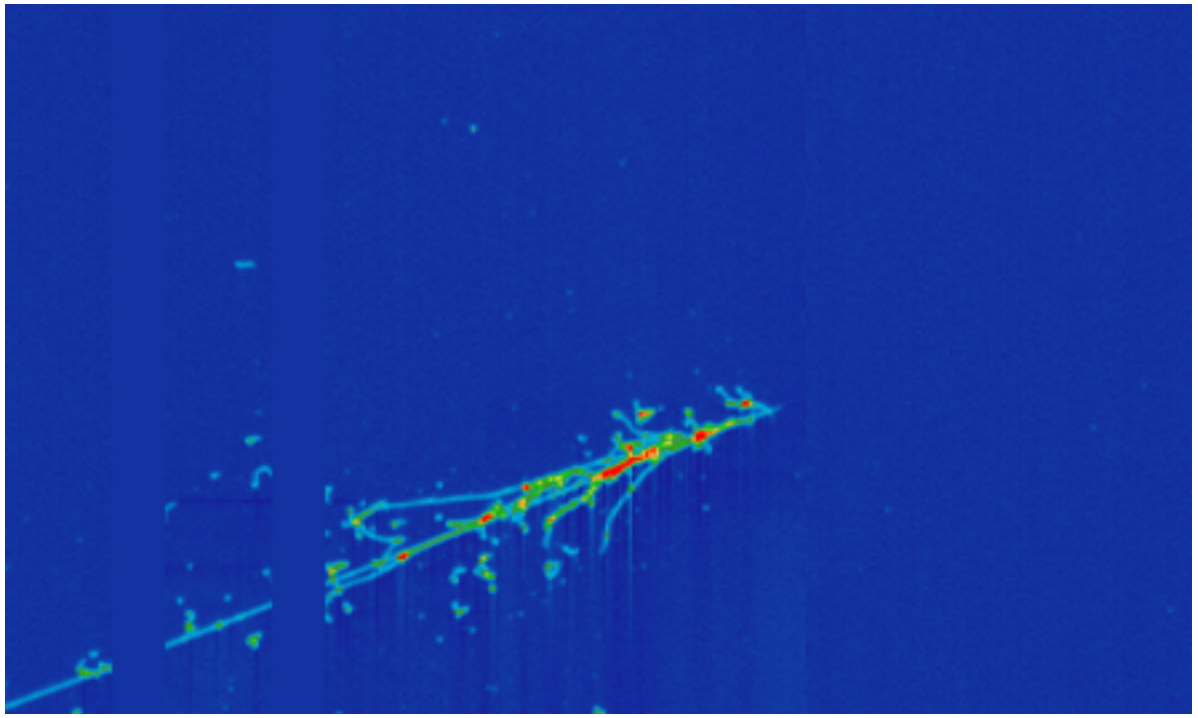
The DUNE Detectors

Liquid Argonne Time Projection Chambers

Detect ionization signal which has been drifted by an electric field.



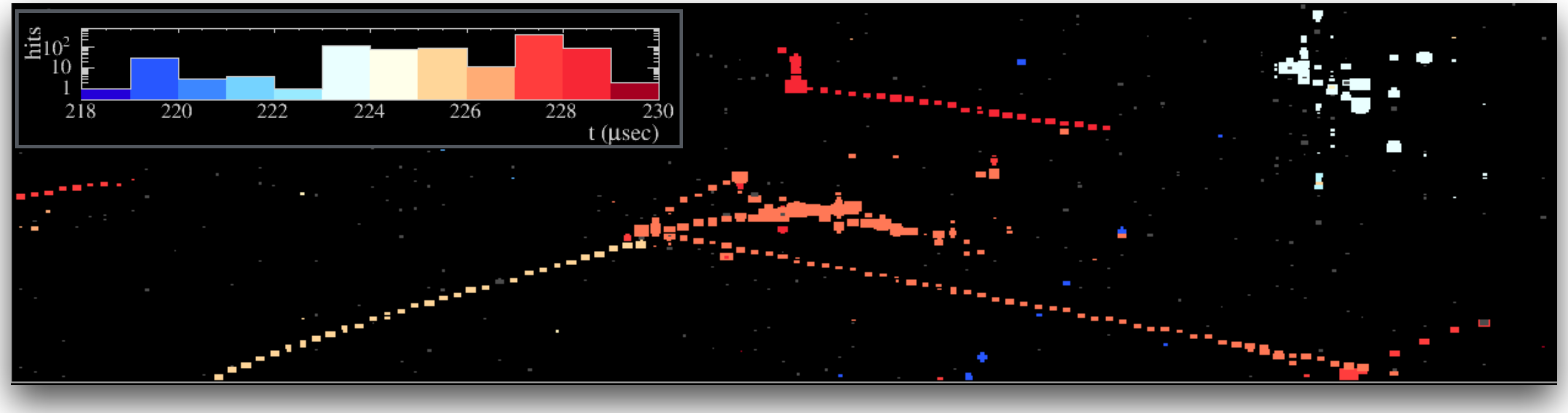




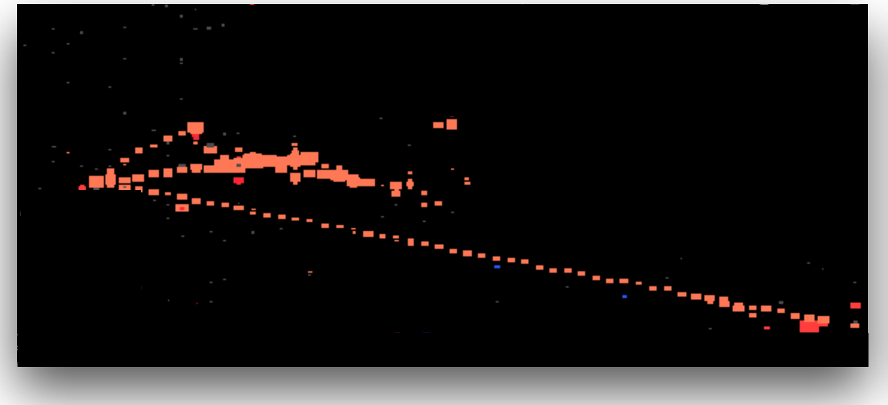
Traditional Reconstruction

Use the topology and magnitude of the energy depositions.

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

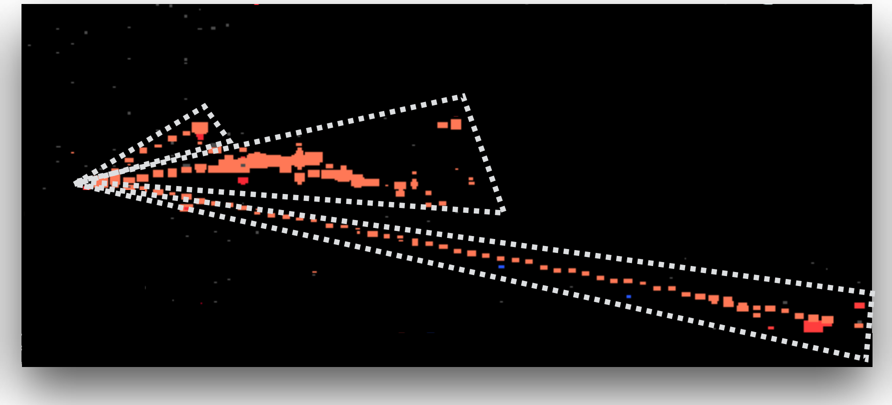


ISOLATE THE EVENT



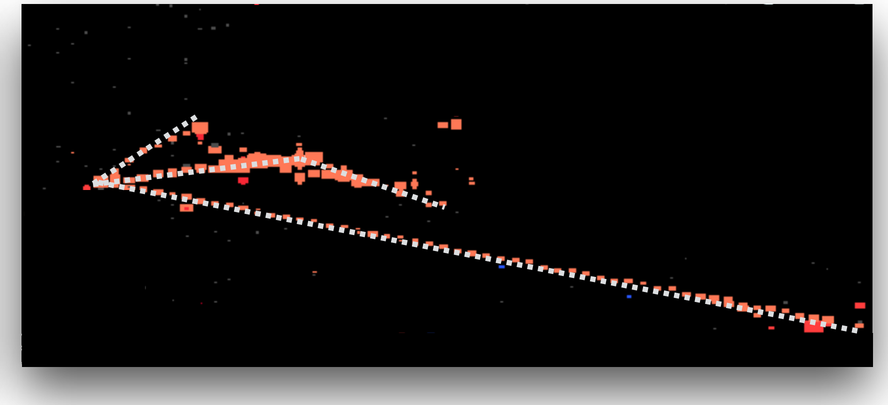
We isolate individual interactions using time and space correlation of the hits.

DEFINE CLUSTERS



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

FIT TRAJECTORY



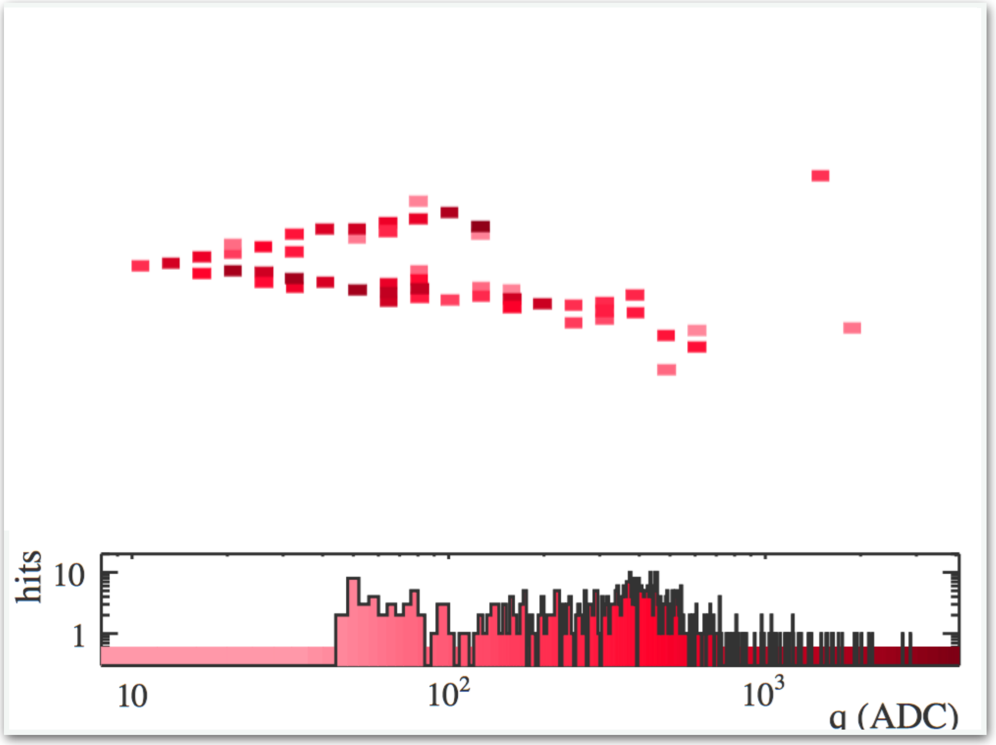
When necessary we can fit an assumed trajectory for each cluster of hits.

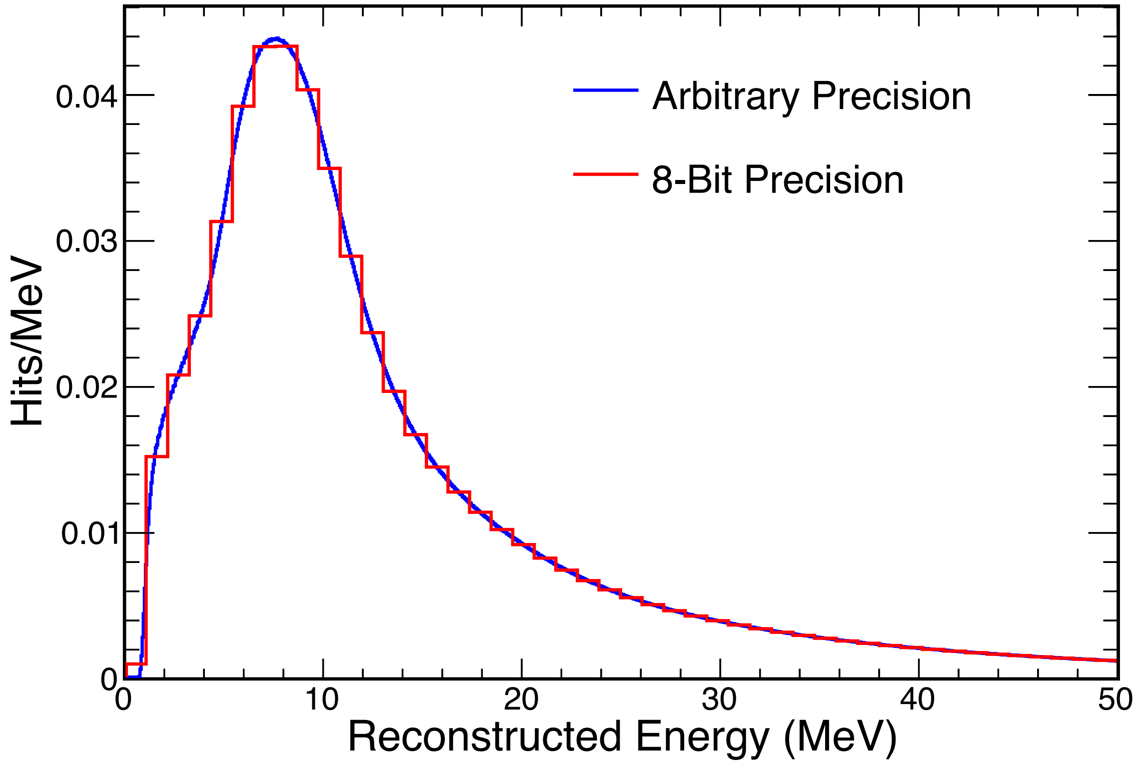
Event ID with Convolutional Neural Networks

Premise: Let a deep learning network extract features and draw correlations.

Disentangle the identification from reconstruction.

In practice: Use “images” of events to train a CNNs to identify neutrino flavor.

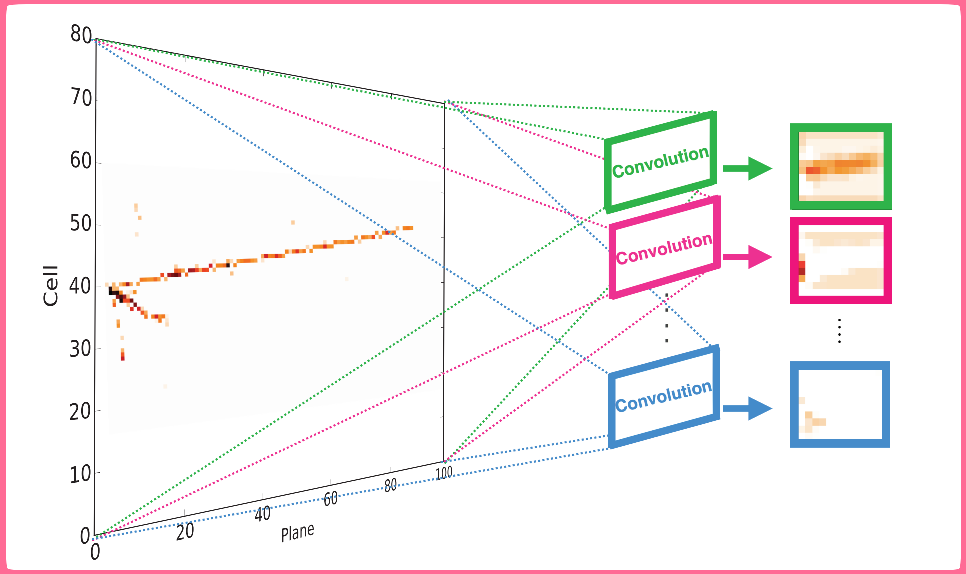




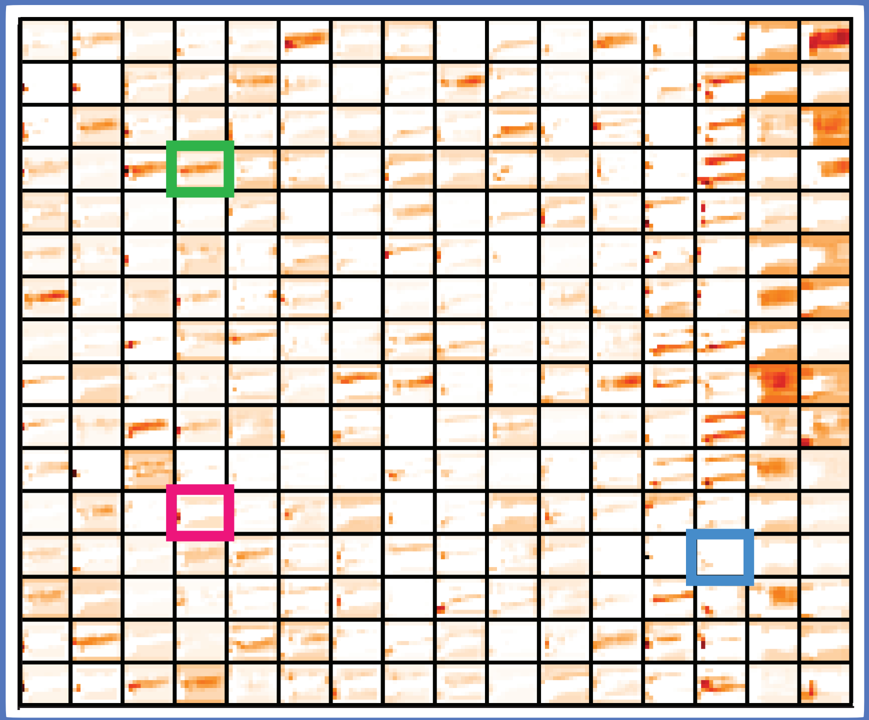
CVN Network Components

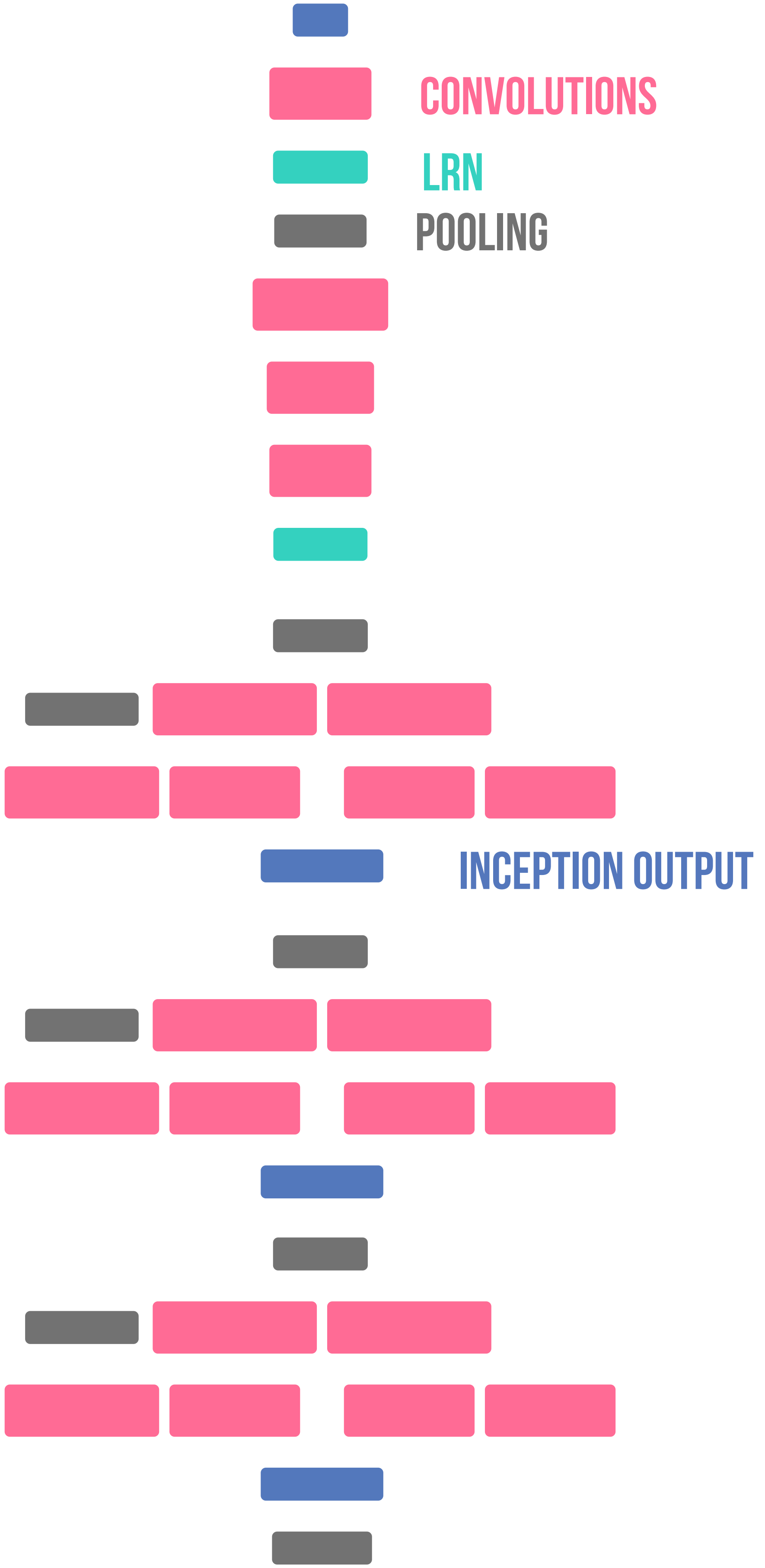
Convolutional Visual Network

CONVOLUTION



INCEPTION OUTPUT





CONVOLUTIONS

LRN

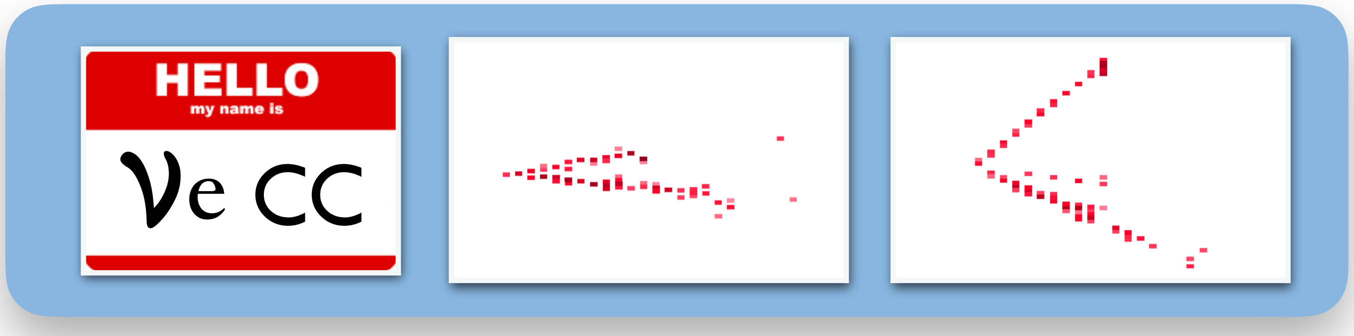
POOLING

INCEPTION OUTPUT

CVN for NOvA Events

Convolutional Visual Network

x4.7 million



Network Details:

Based on GoogLeNet.

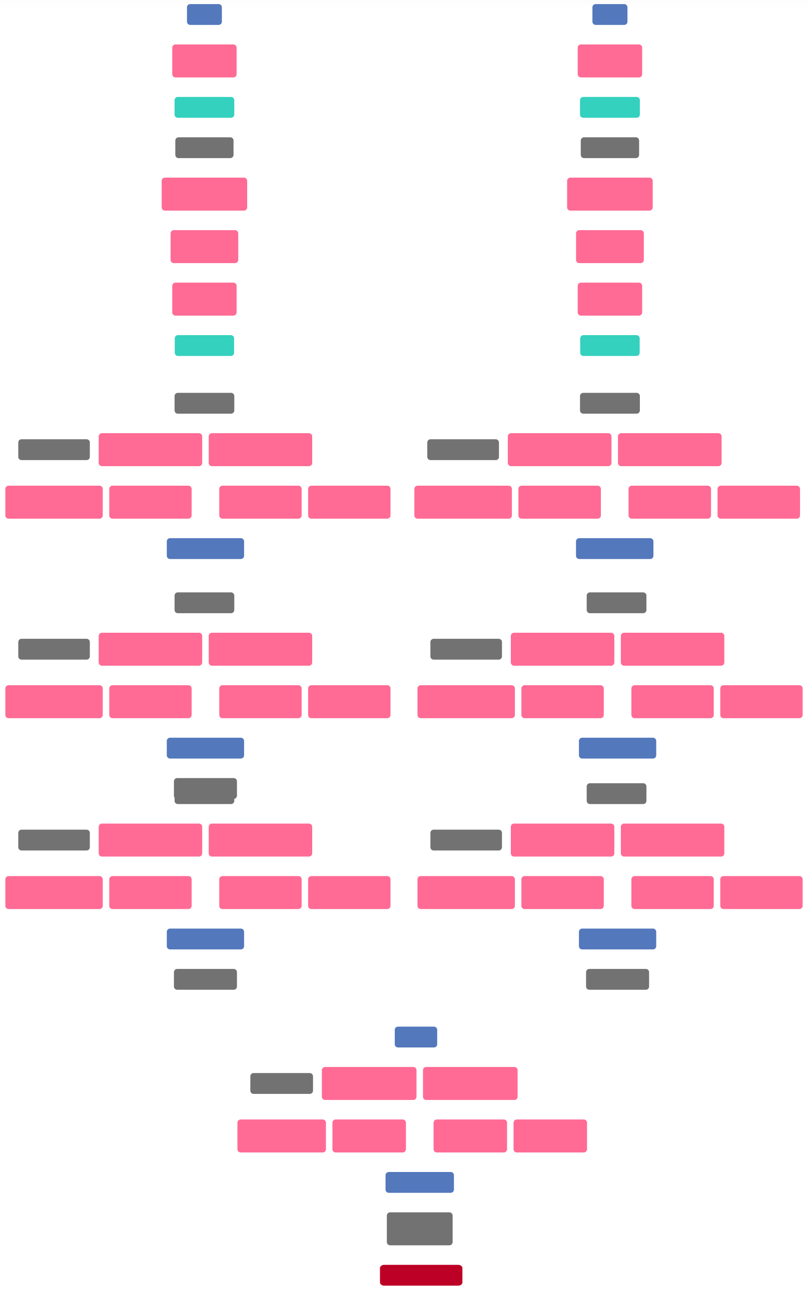
Two branch network (x and y views) . Takes 2 views separately, further down it merges the 2 views.

Optimized for overall accuracy and main analysis FOM.

Caffe

NVIDIA

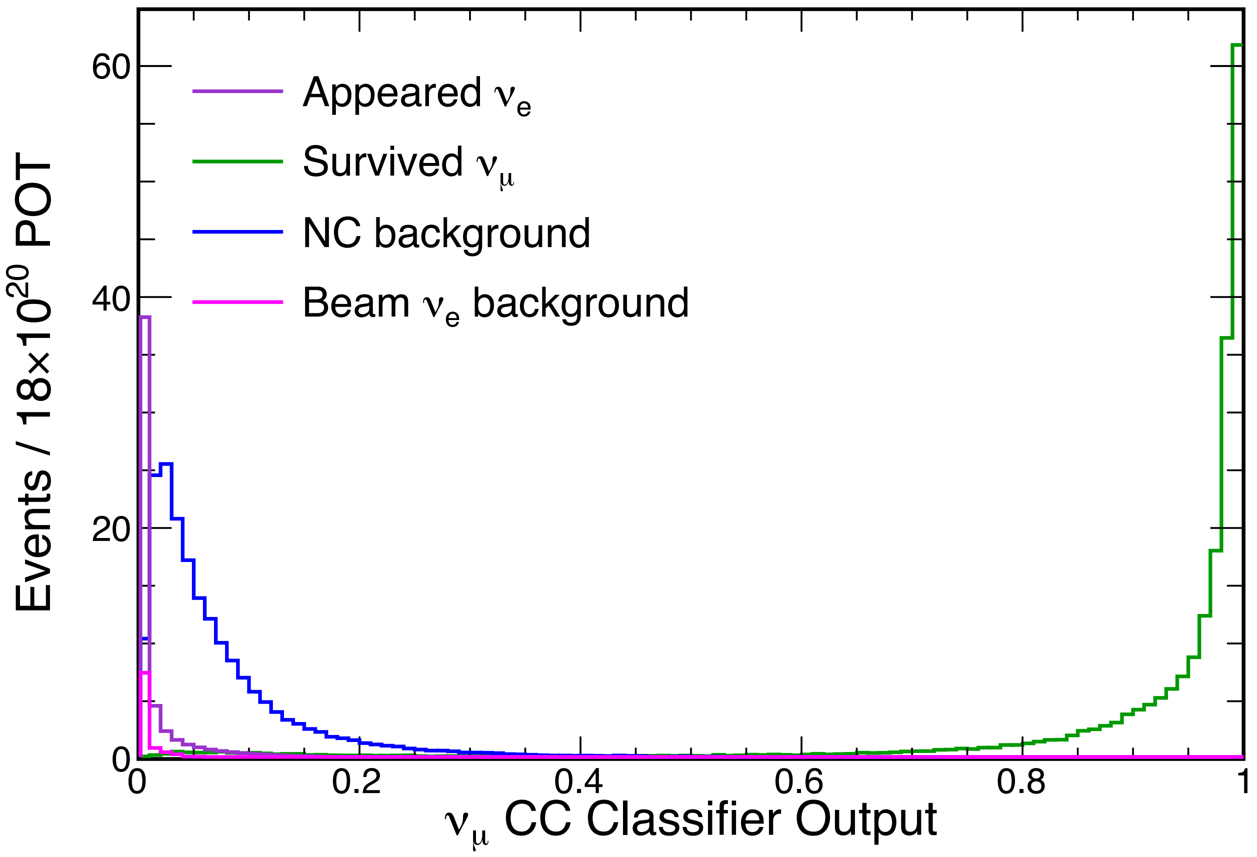
Trained on Fermilab's Wilson cluster, two NVIDIA K40 GPUs

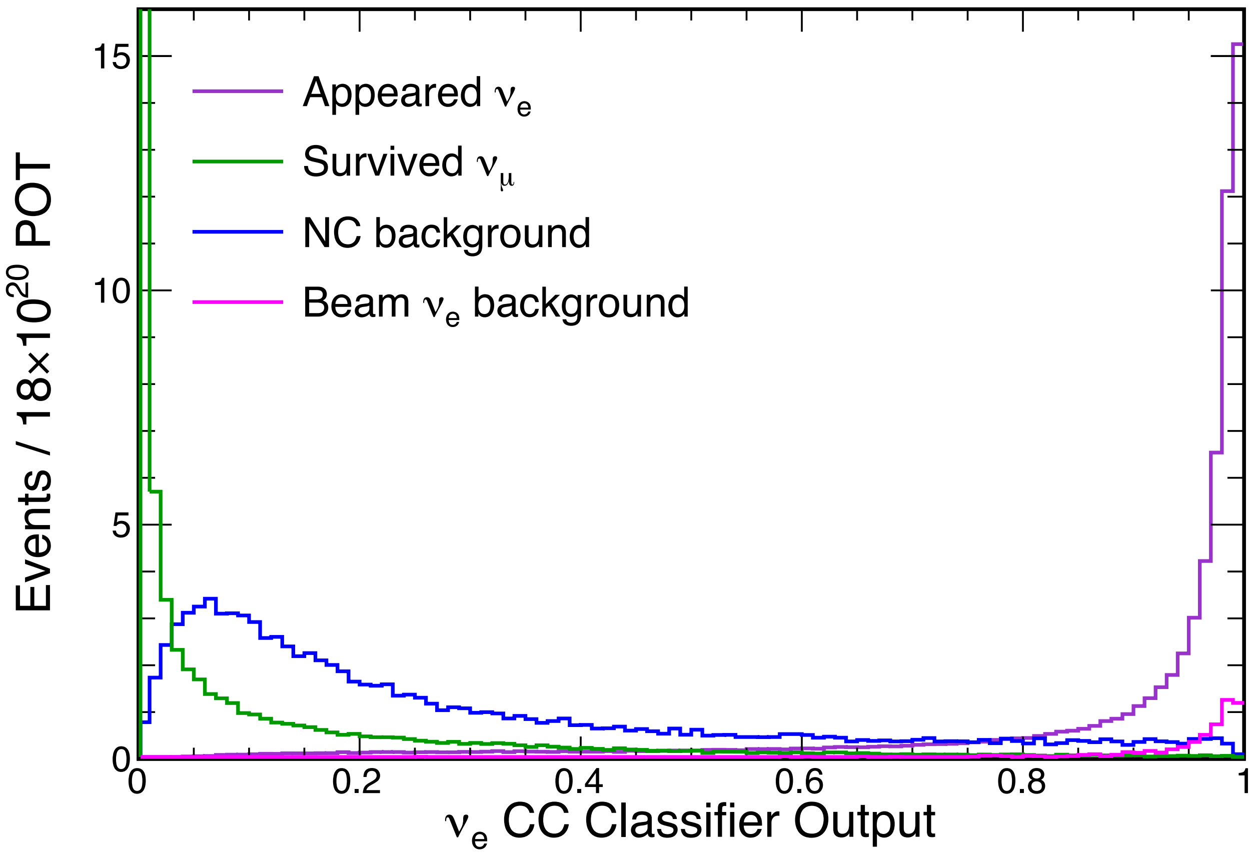


Classifier output

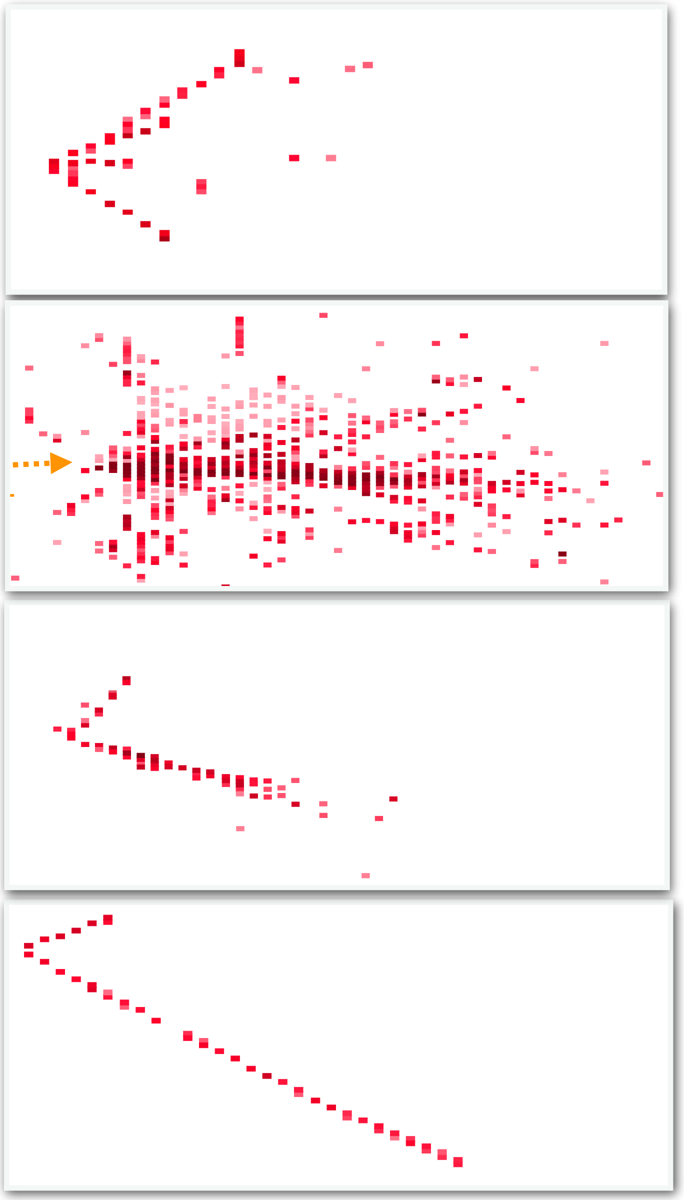
One PID value for each category, normalized to sum 1 over all possible labels.

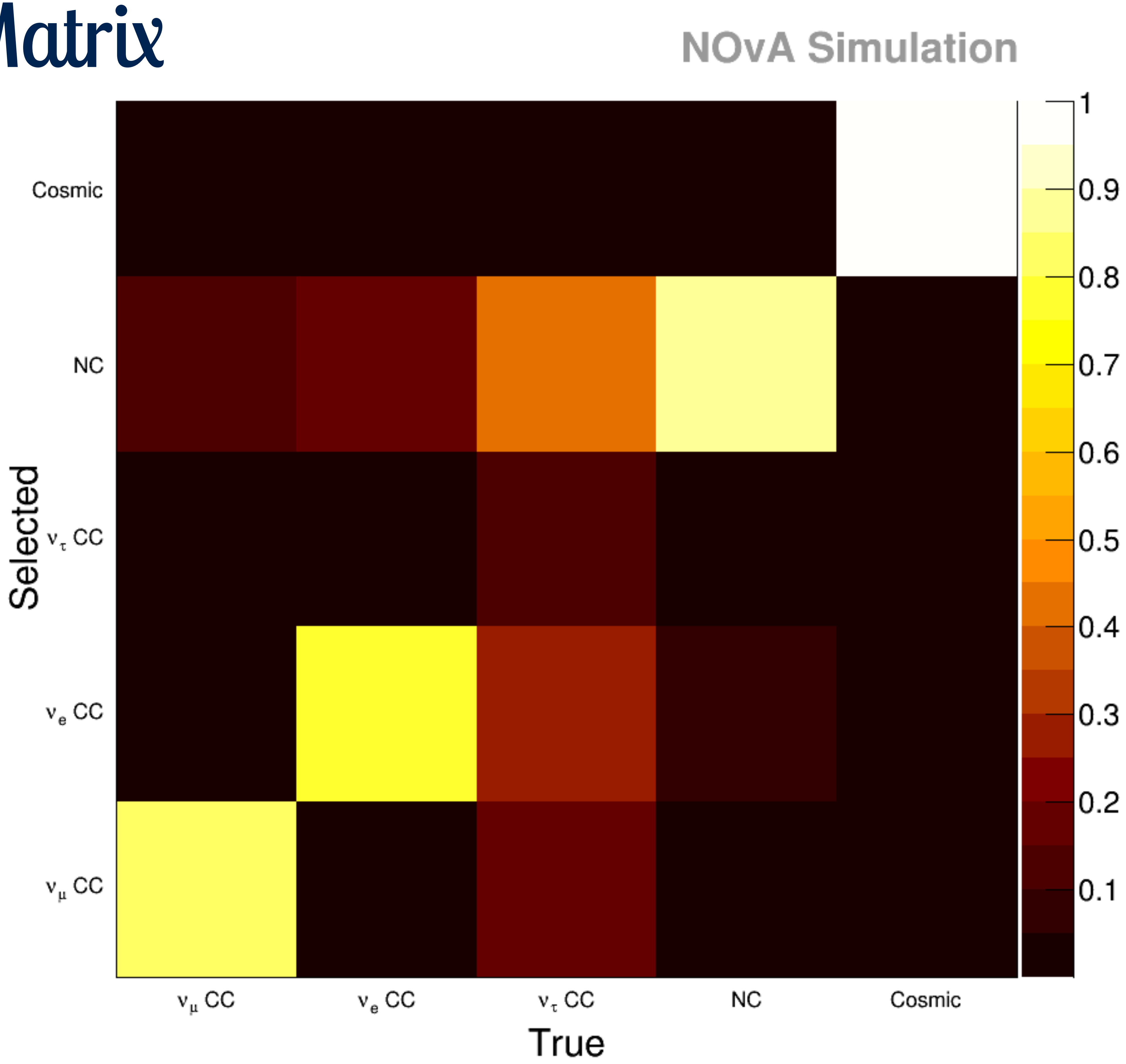
In principle, this means one can extract more information than a single PID value.



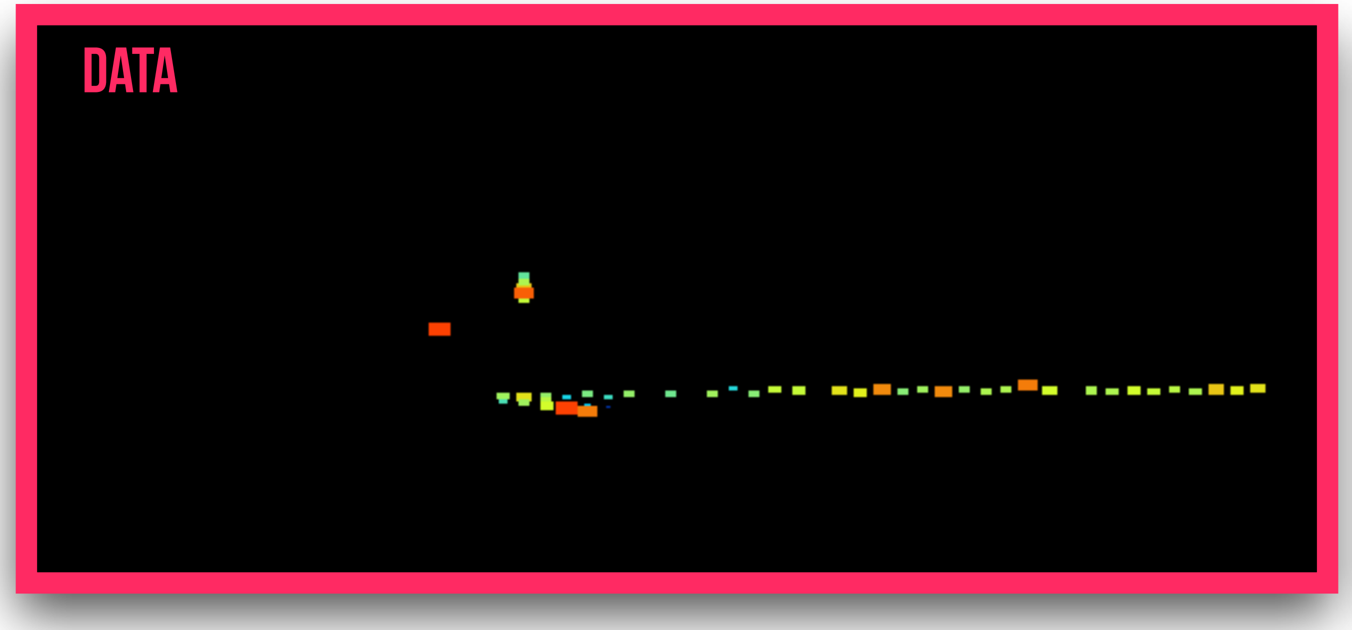


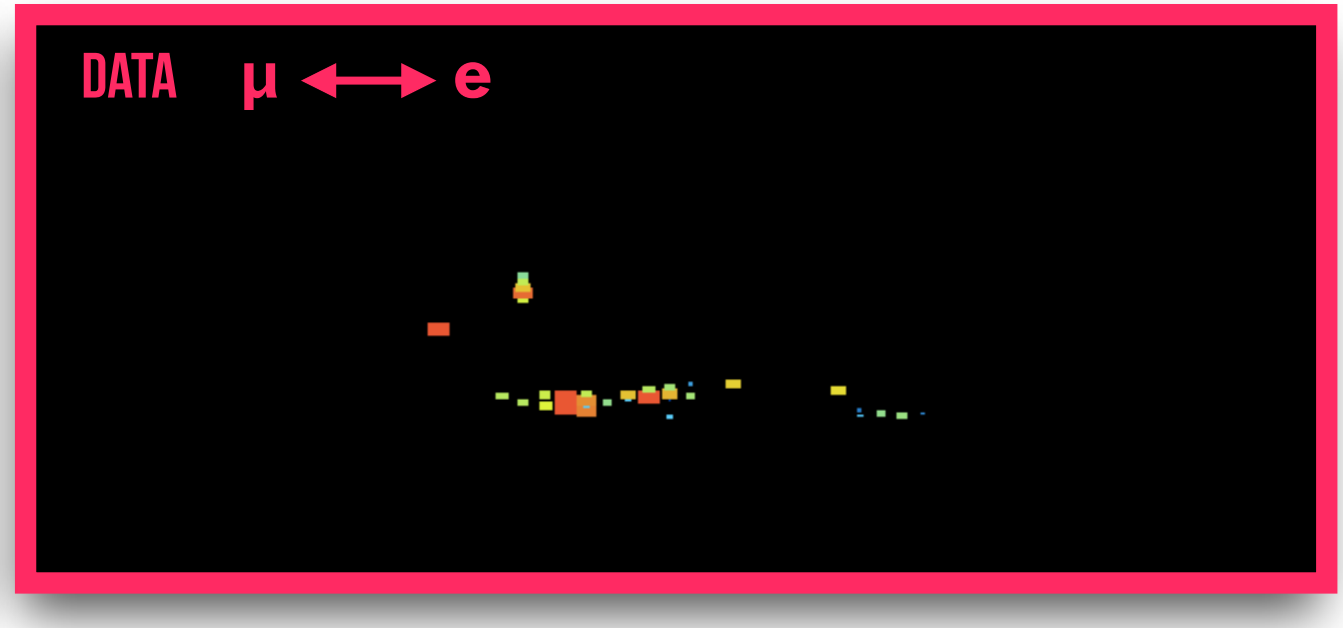
Correlation Matrix

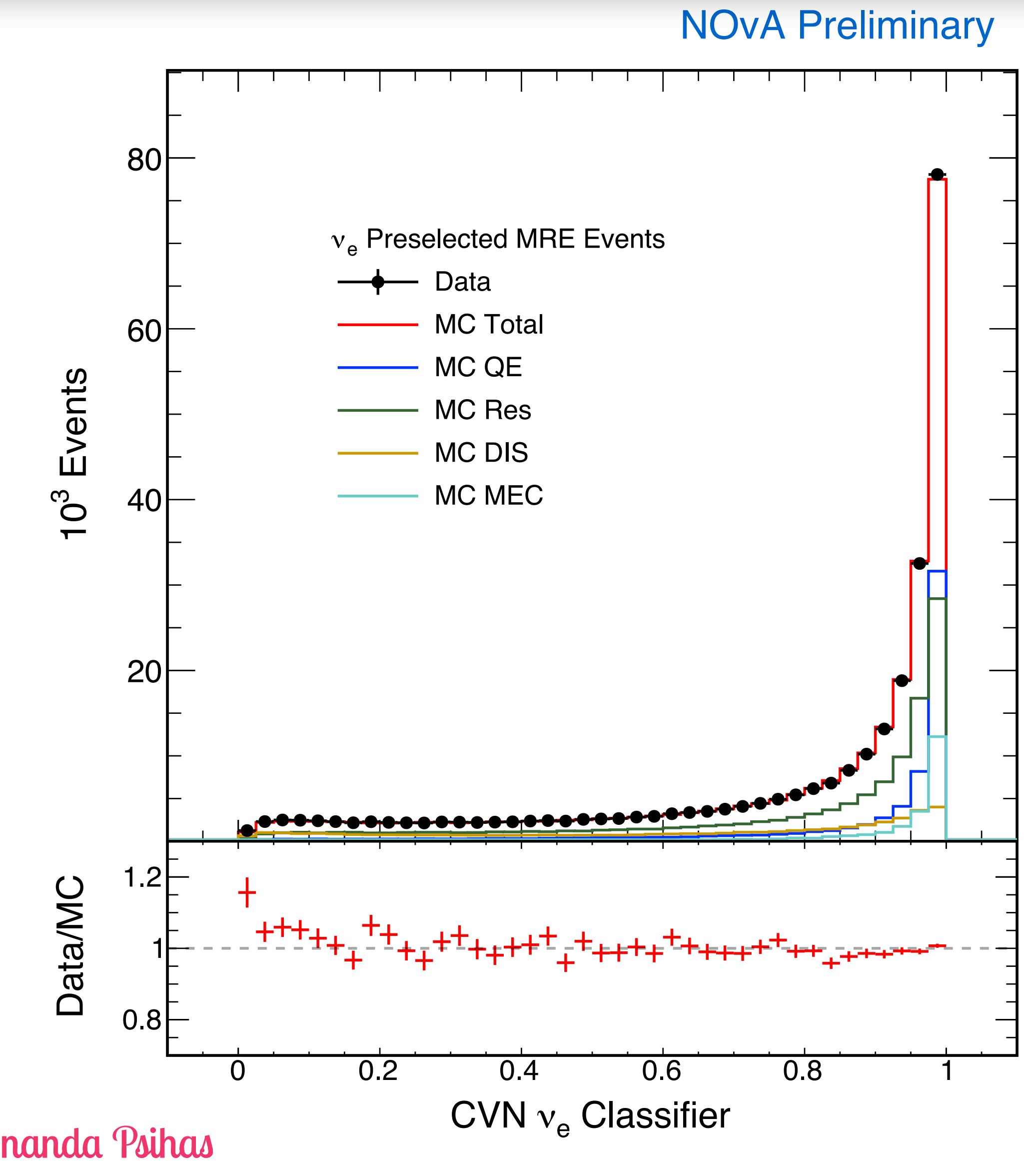




CVN Performance On Real Data







MRE (Muon Removed - Electron):

Select a muon neutrino interaction with traditional ID methods.

Remove the muon hits and replace them with a single simulated electron of matching momentum.

Data/MC comparisons show less than 1% difference in efficiency.

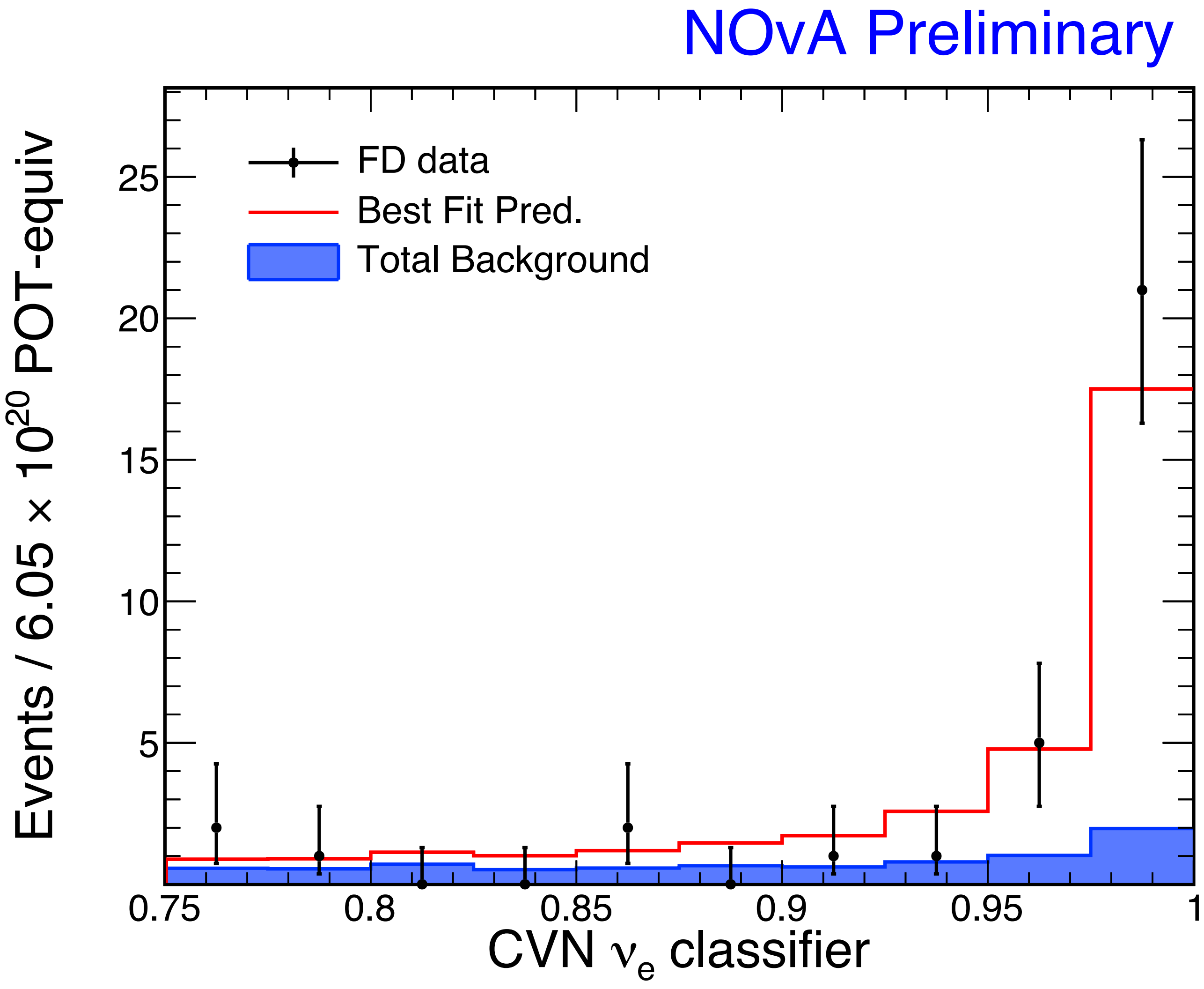
PID	Sample	Preselection	PID	Efficiency	Efficiency diff %
CVN	Data	262884	188809	0.718222	-0.36%
	MC	277320	199895	0.720809	

CVN Performance on ν_e

Implemented in NOvA's main analysis for the results shown this summer at Neutrino 2016 was the **first implementation of a CNN in a HEP result.**

Total bkg	NC	Beam ν_e	ν_μCC	ν_τCC	Cosmogenic
8.2	3.7	3.1	0.7	0.1	0.5

33 events selected with estimated background of ~8

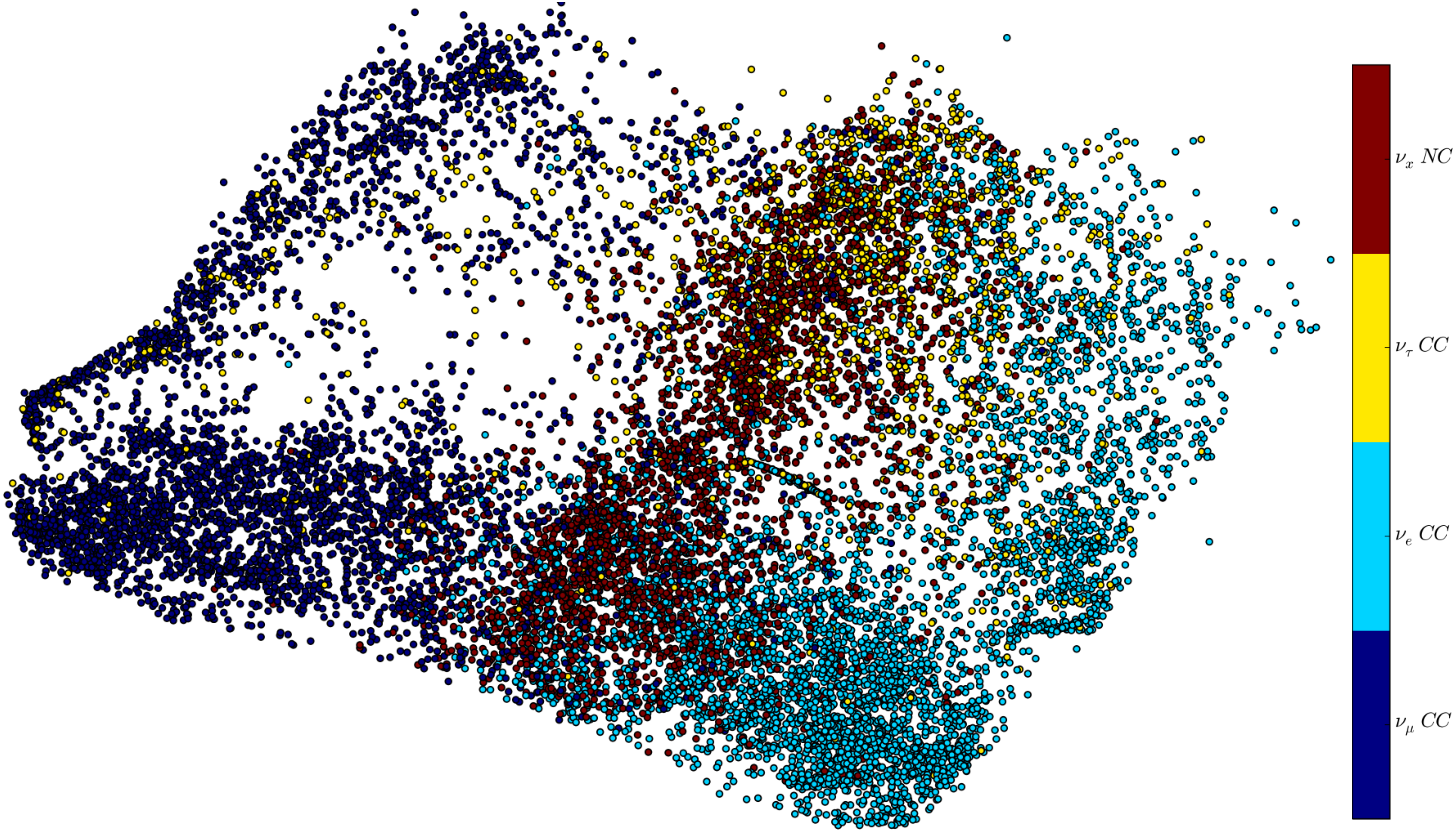


76% Purity

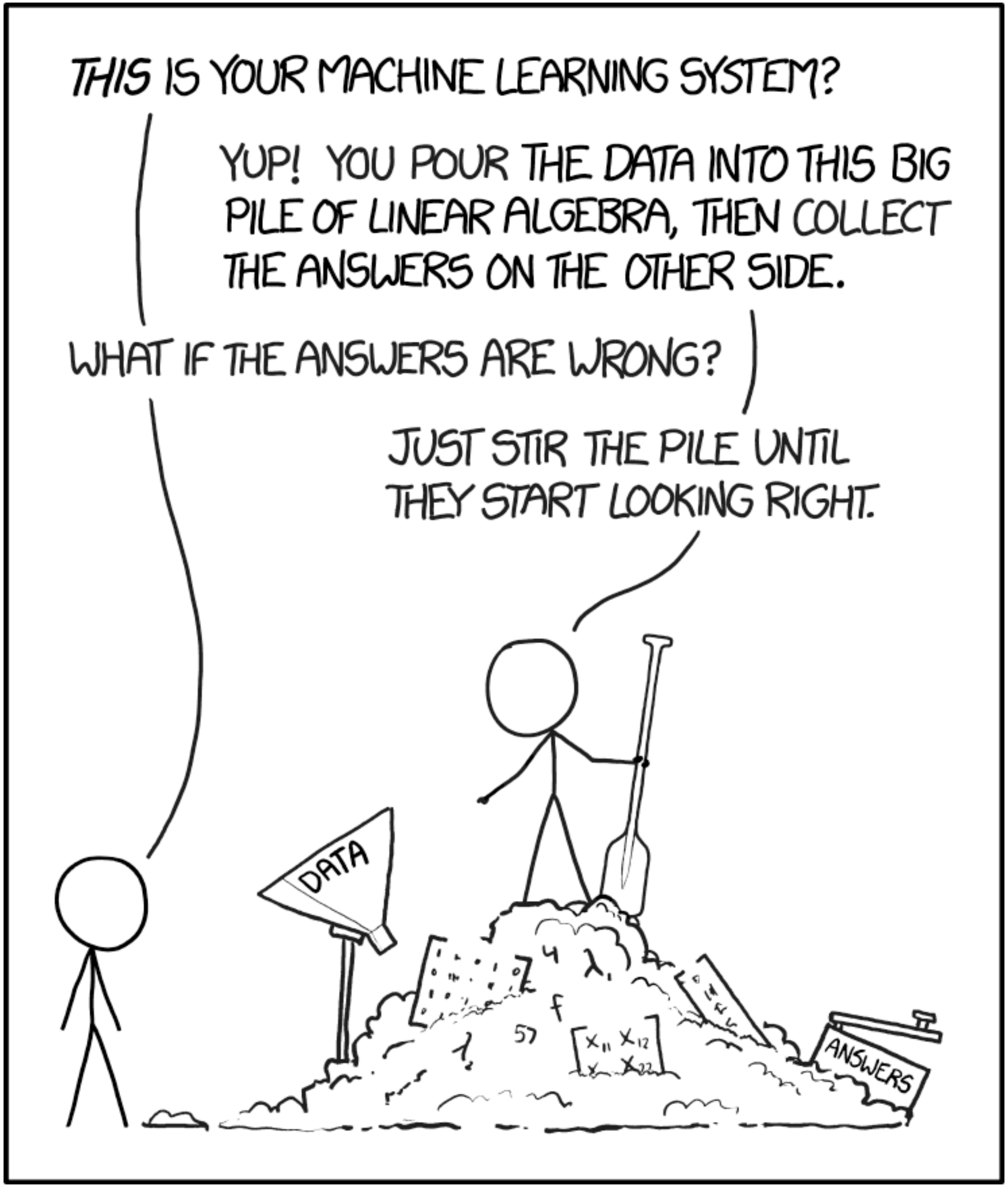
73% Efficiency

An equivalent increased exposure of 30%

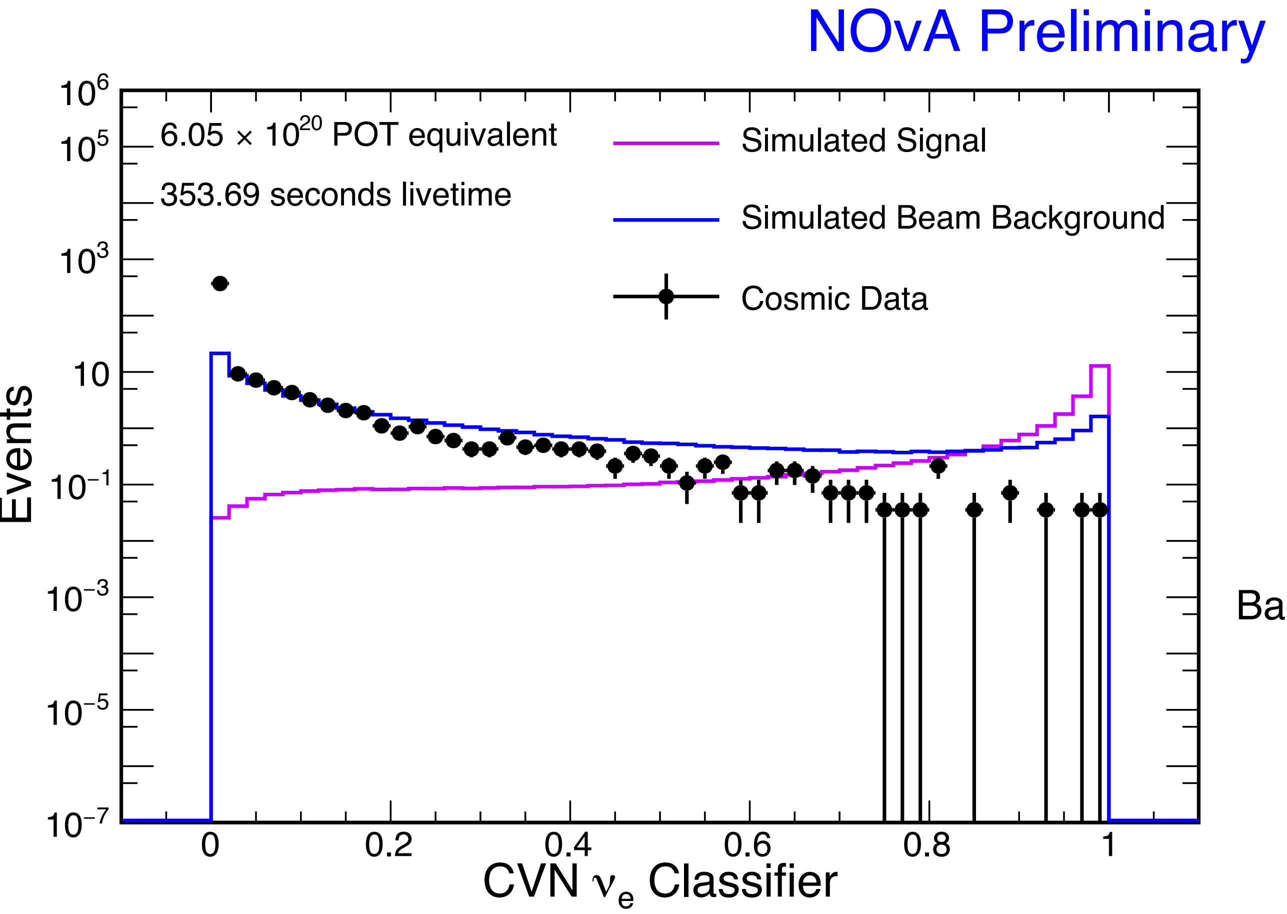
t-SNE

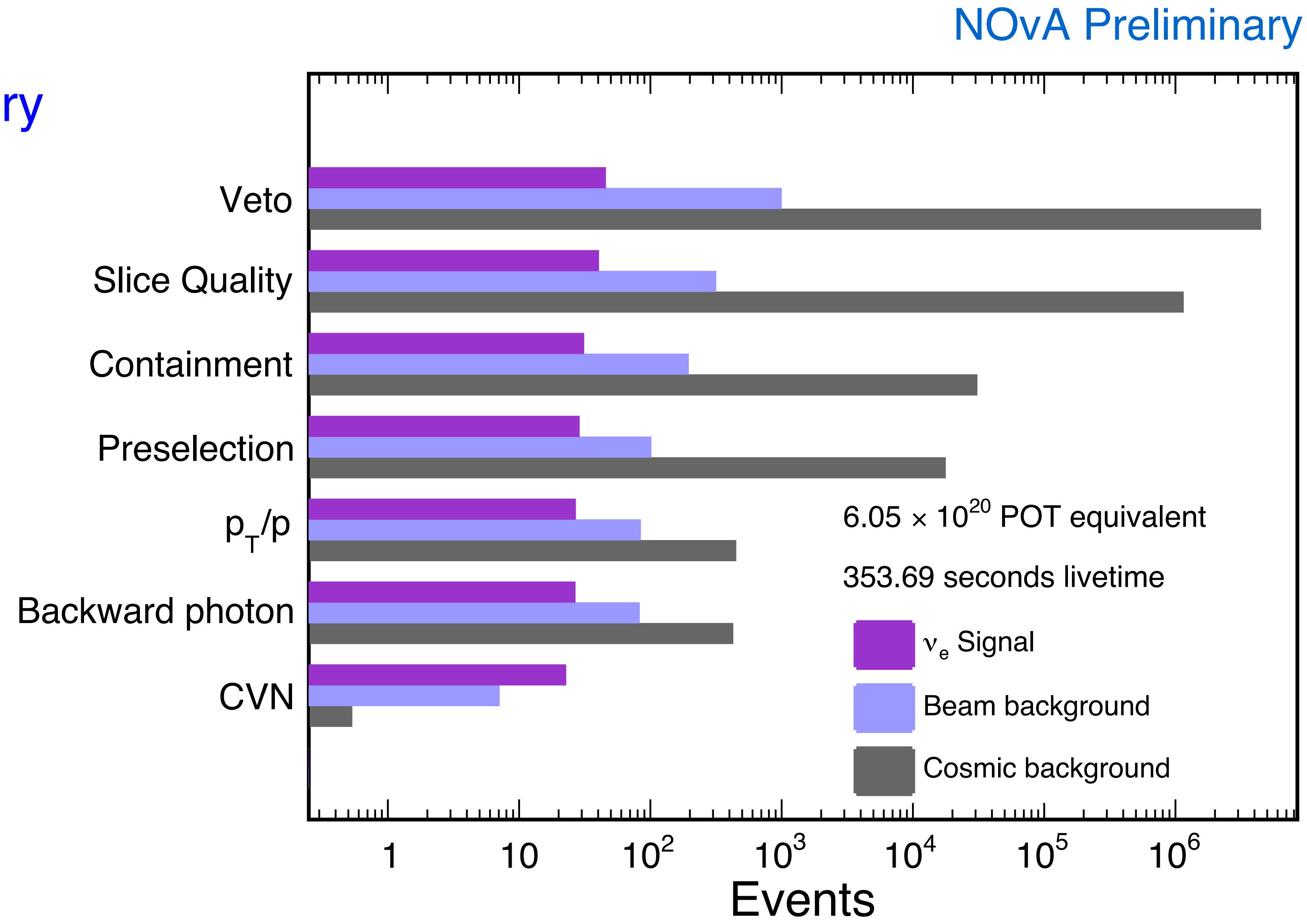


https://indico.io/blog/visualizing-with-t-sne/

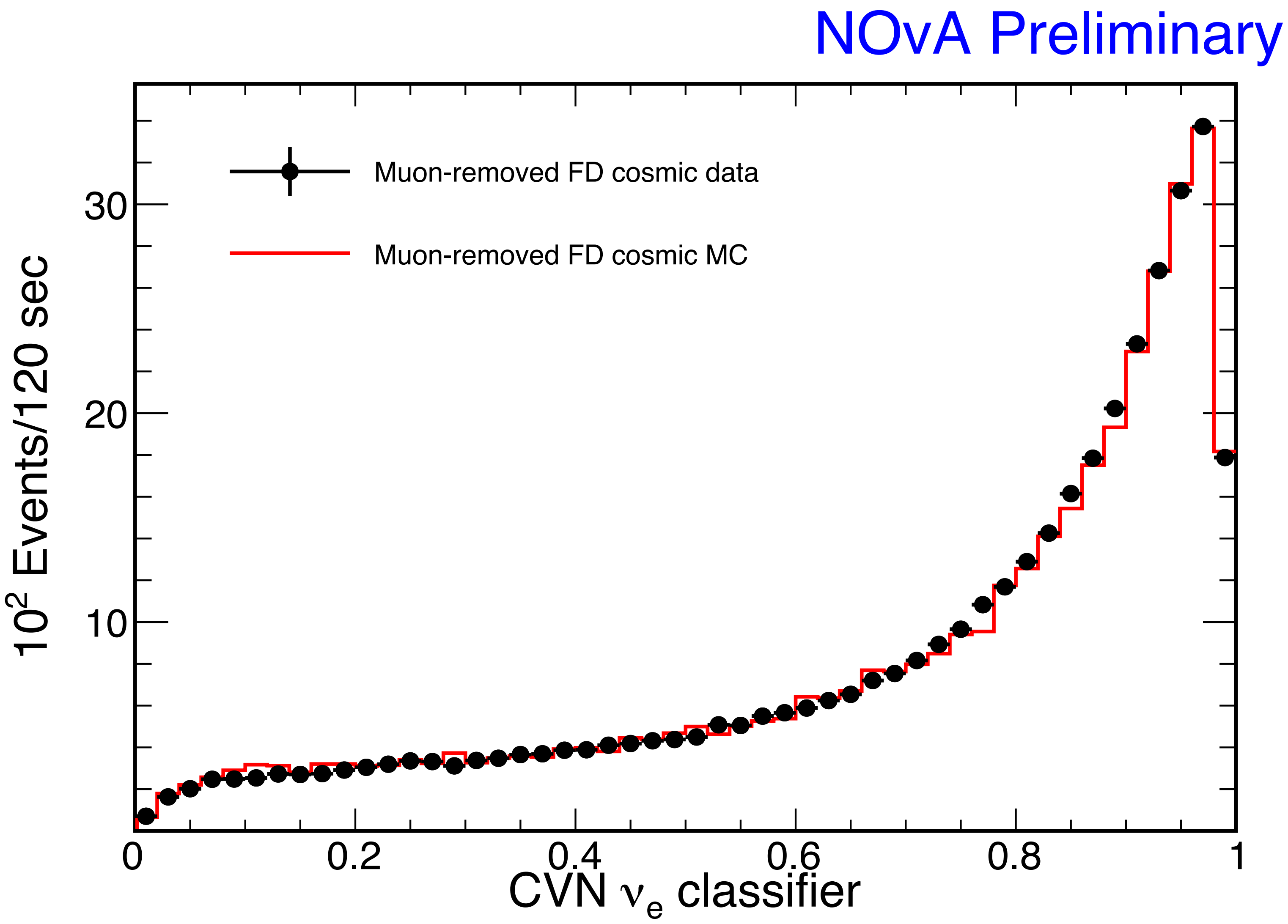

THIS IS YOUR MACHINE LEARNING SYSTEM?
YUP! YOU POUR THE DATA INTO THIS BIG PILE OF LINEAR ALGEBRA, THEN COLLECT THE ANSWERS ON THE OTHER SIDE.
WHAT IF THE ANSWERS ARE WRONG?
JUST STIR THE PILE UNTIL THEY START LOOKING RIGHT.
DATA
ANSWERS

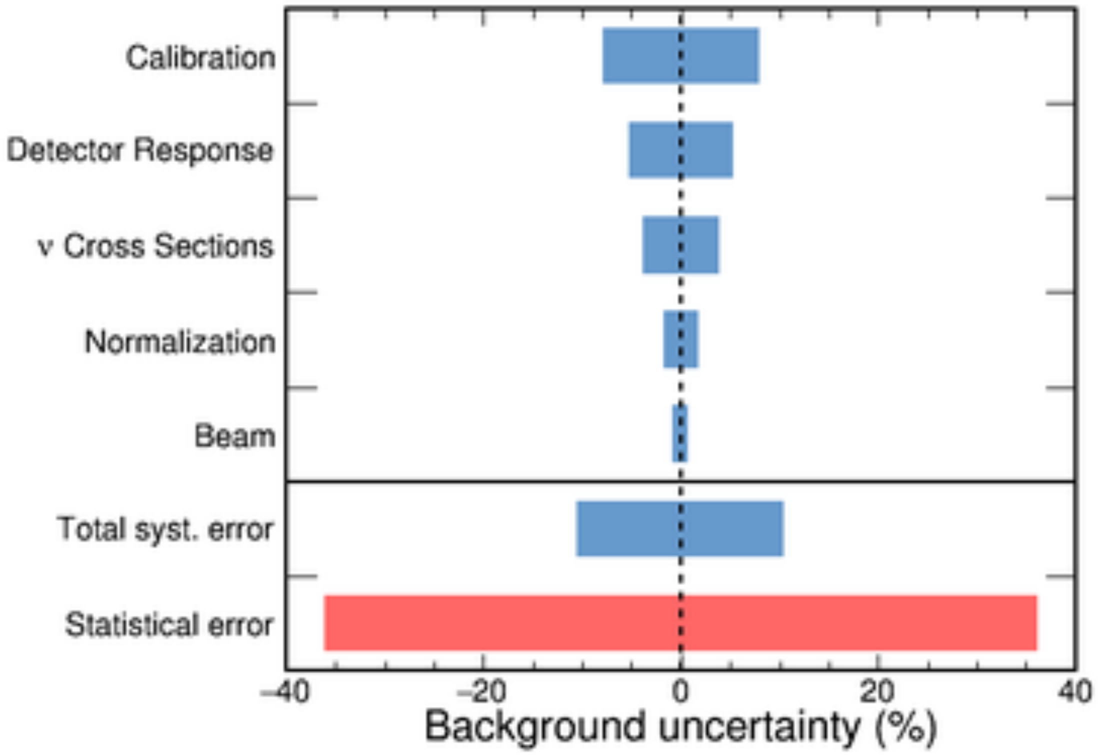
Performance on Cosmic Background



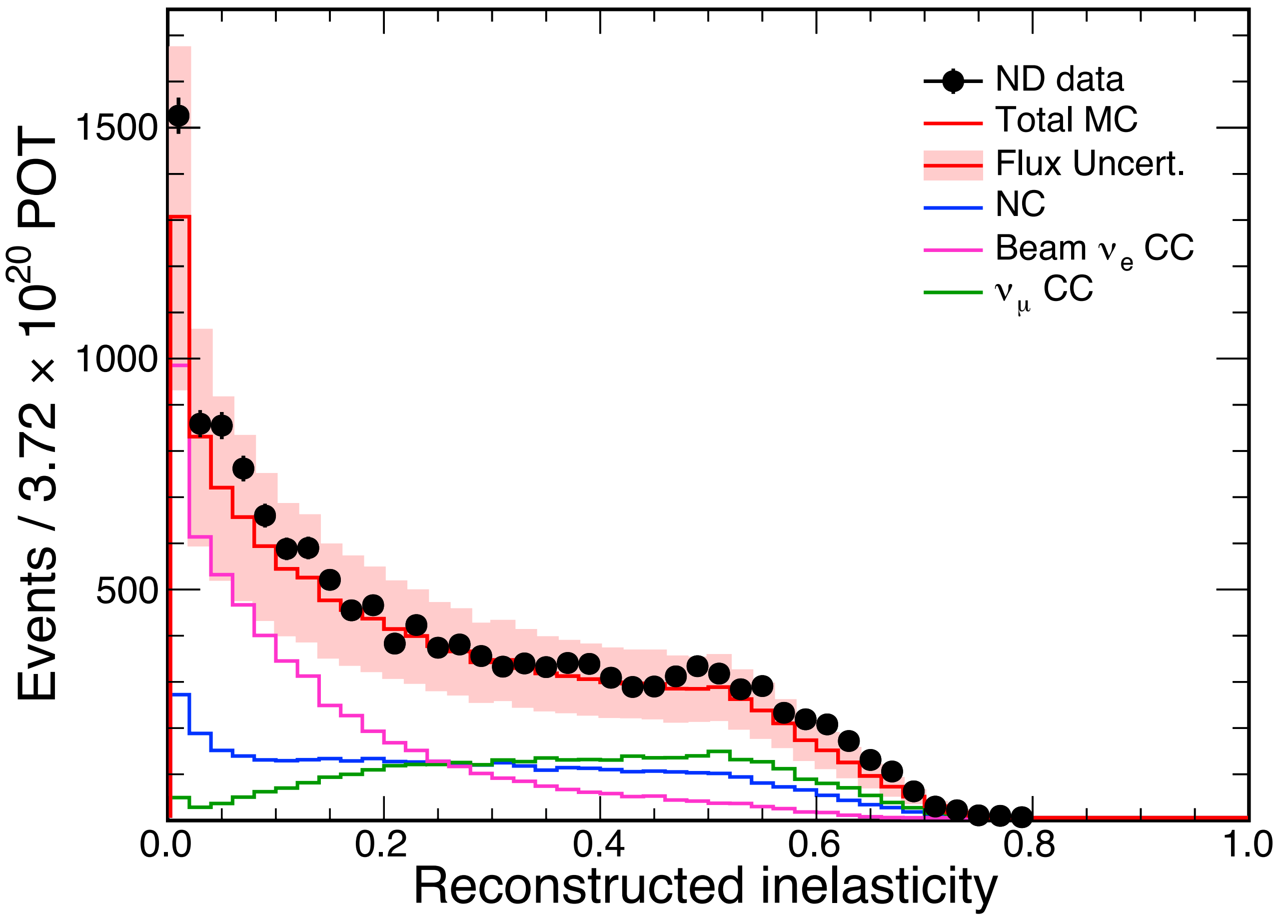


Data Driven Tests - MRBrem

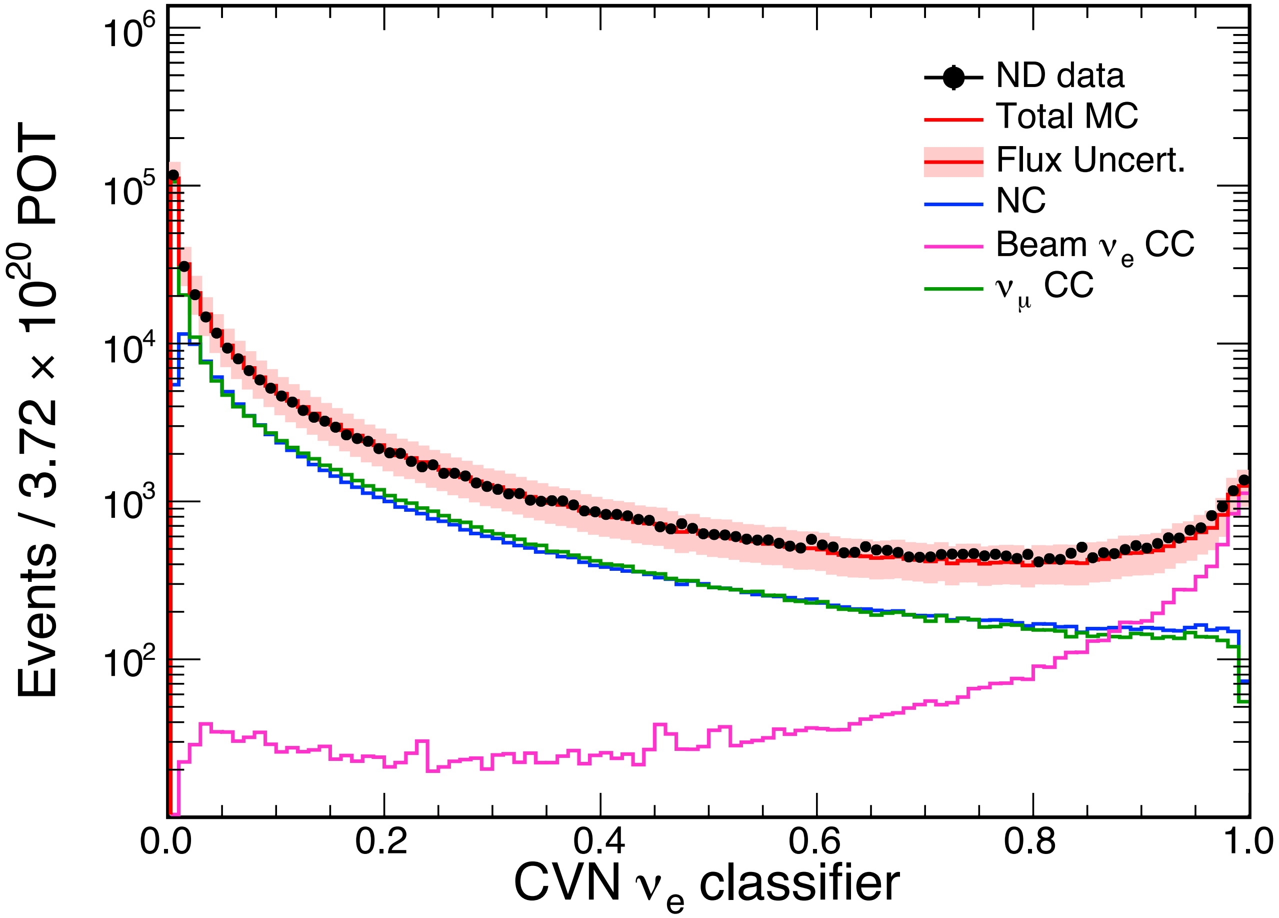


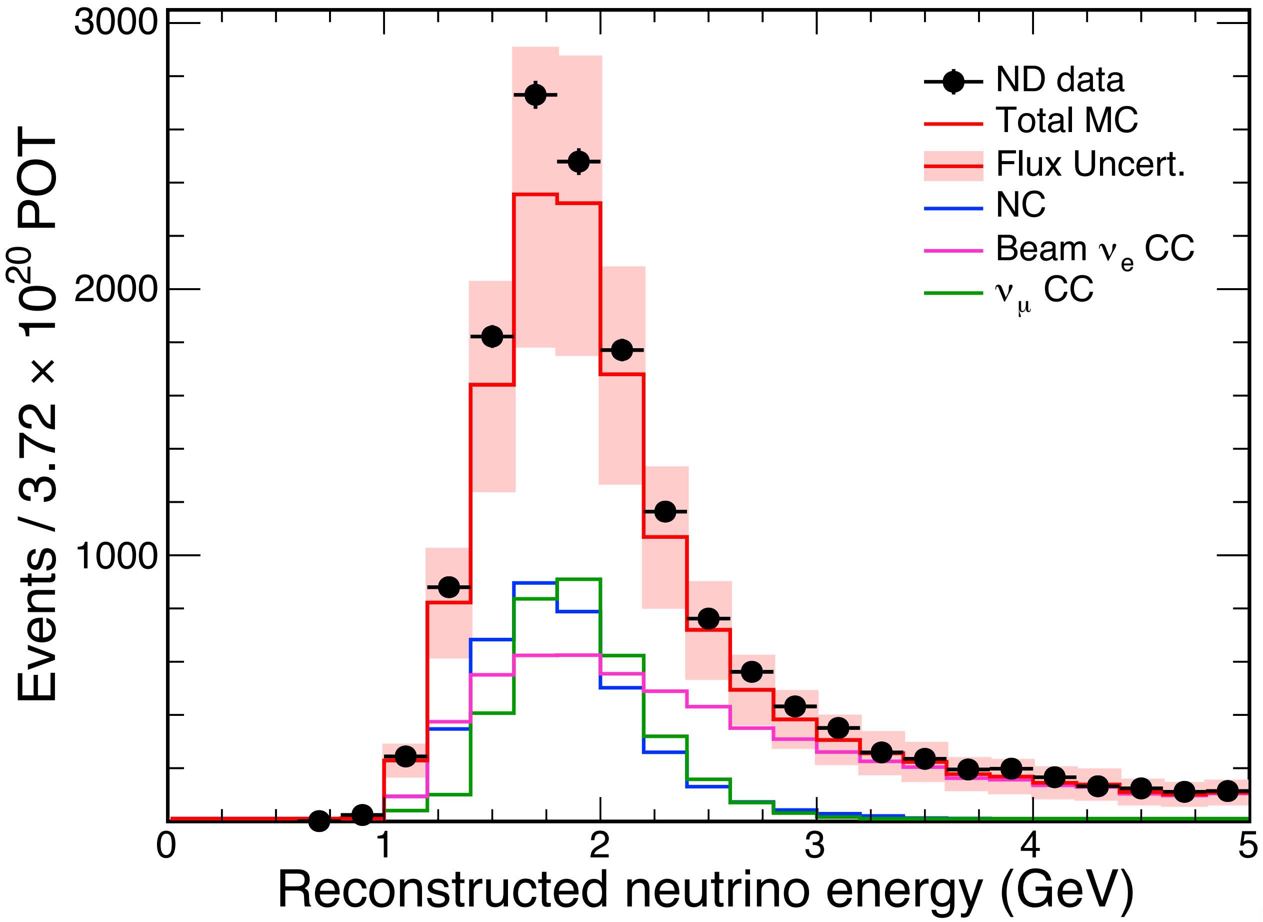


NOvA Preliminary

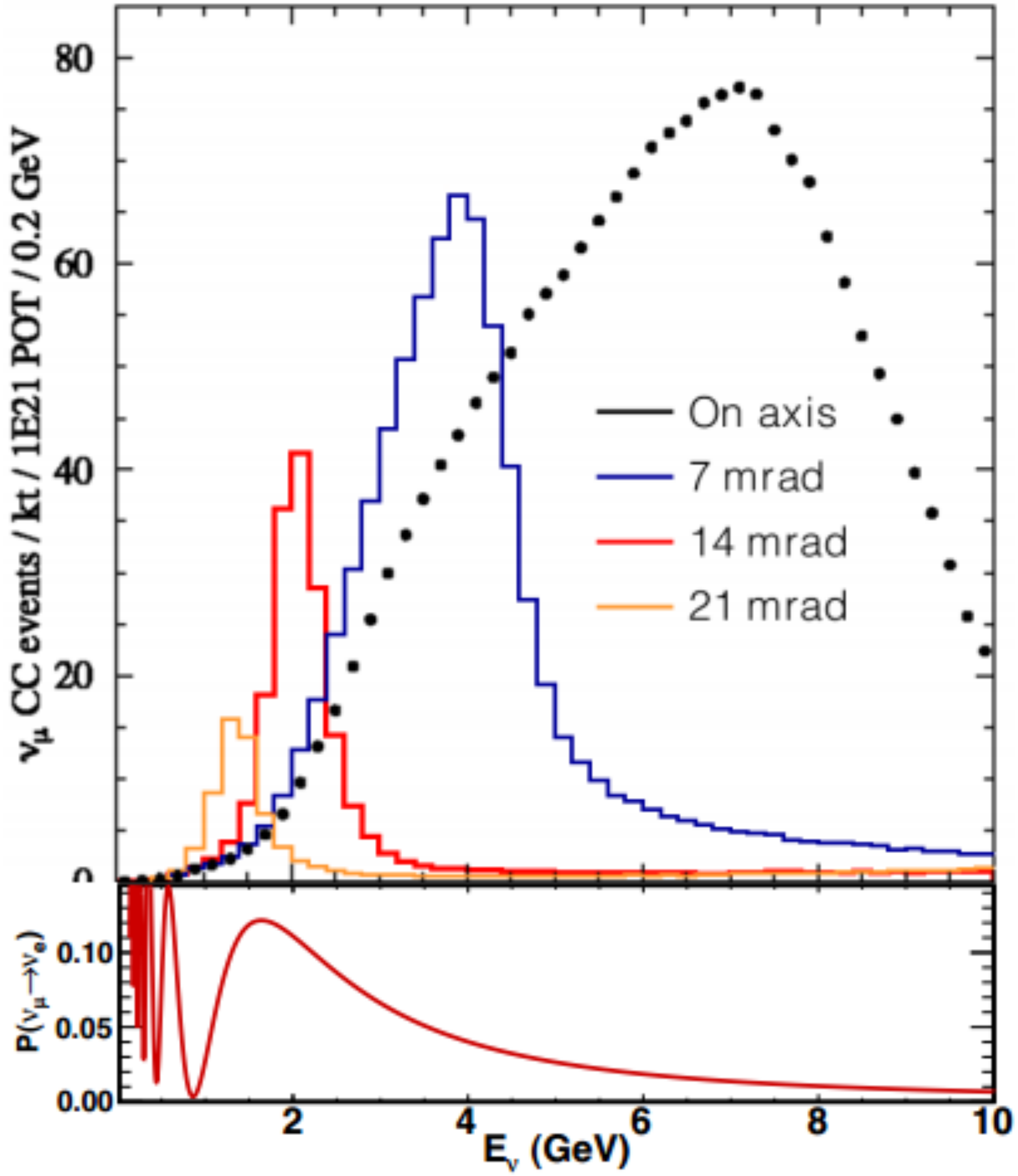


NOvA Preliminary

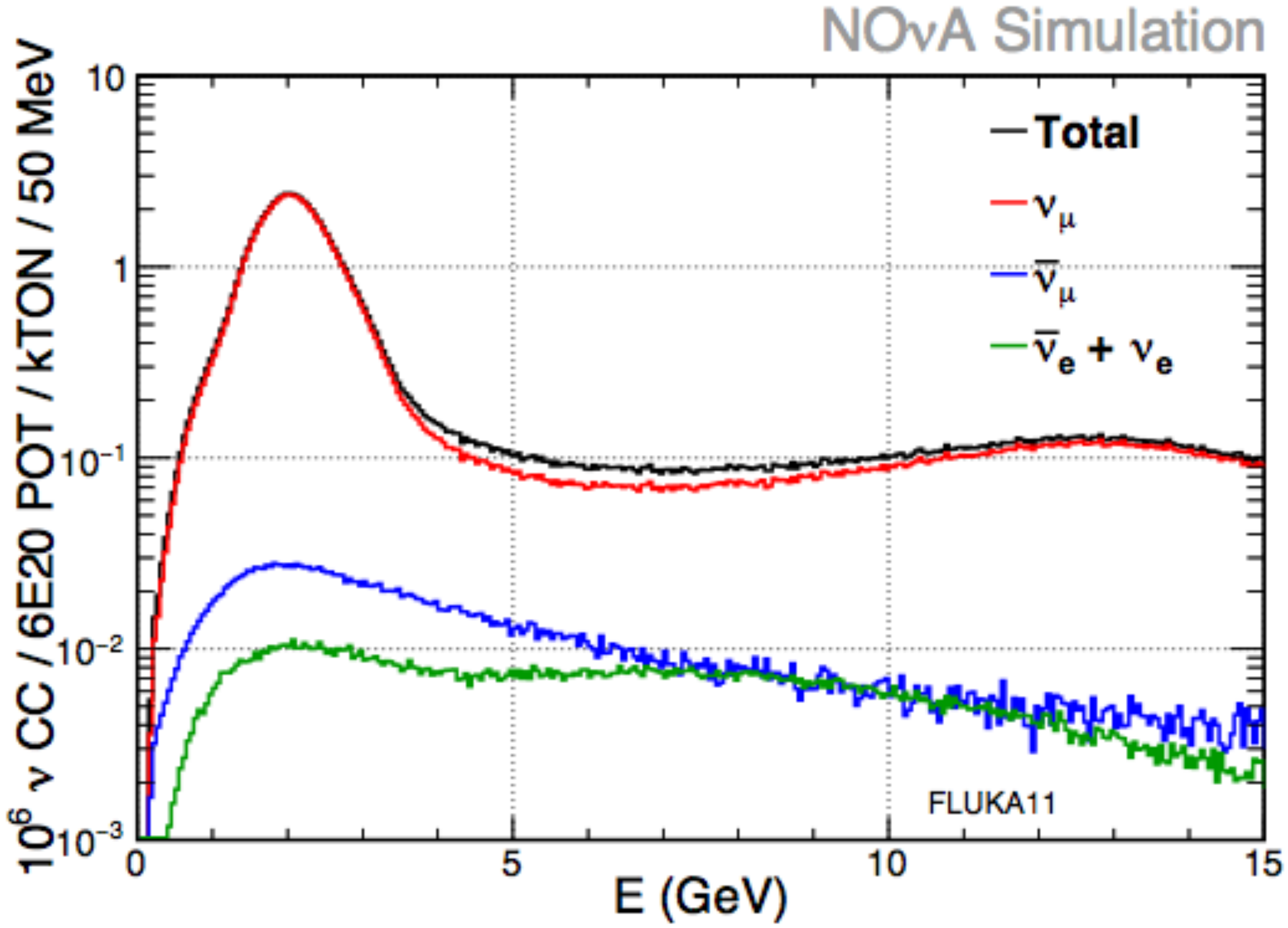




NuMI Beam



ν_μ CC events / kt / 1E21 POT / 0.2 GeV
80
60
40
20
0
On axis
7 mrad
14 mrad
21 mrad
$P(\nu_\mu \rightarrow \nu_e)$
0.10
0.05
0.00
2
4
6
8
10
E_ν (GeV)

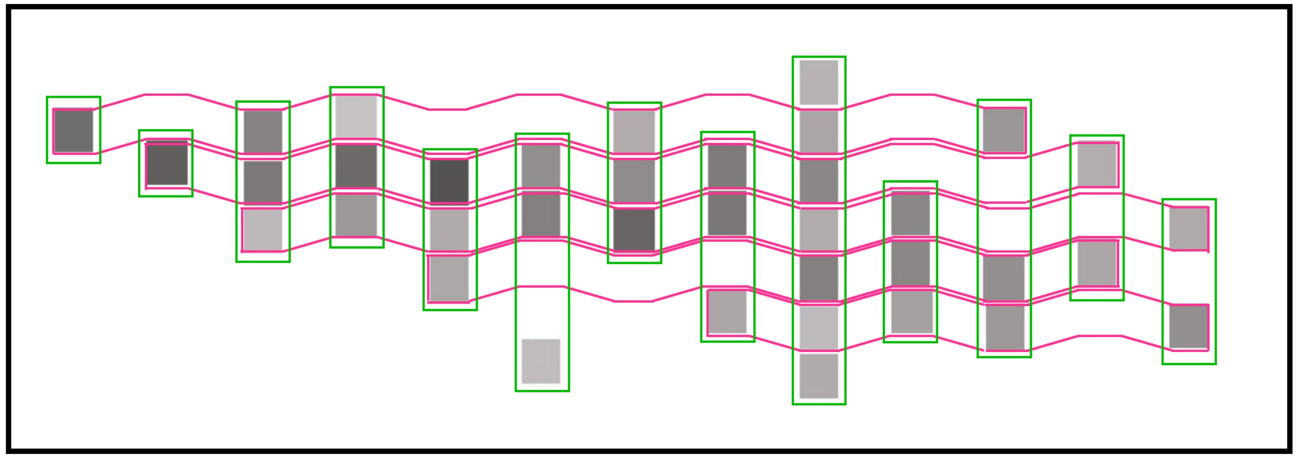


NOvA Simulation
10^6 ν CC / 6E20 POT / kTON / 50 MeV
10
1
10^{-1}
10^{-2}
10^{-3}
Total
ν_μ
$\bar{\nu}_\mu$
$\bar{\nu}_e + \nu_e$
FLUKA11
0
5
10
15
E (GeV)

Traditional ID Methods

Mostly focused on identifying the lepton in the event. Extracted features (i.e. track length and scattering for muons, topology of energy depositions for electromagnetic showers)

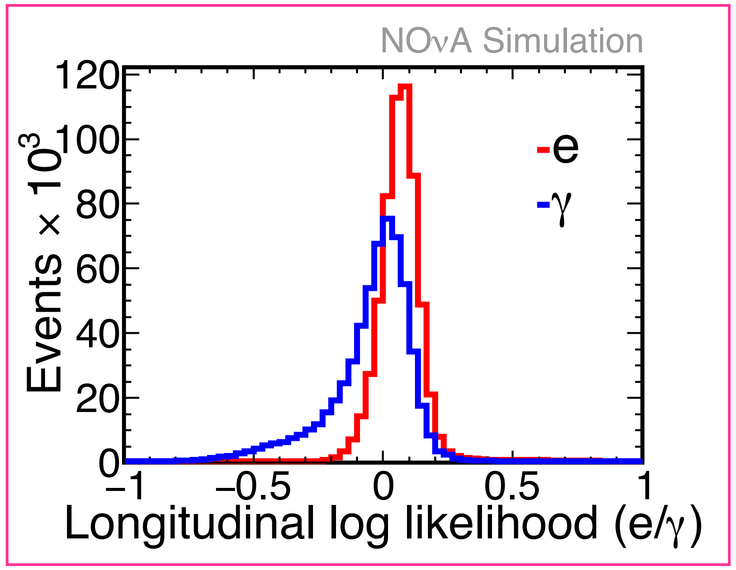
- ⋆ **Require Previous reconstruction.**
- ⋆ **Features are pre-defined, based on MC or test data.**

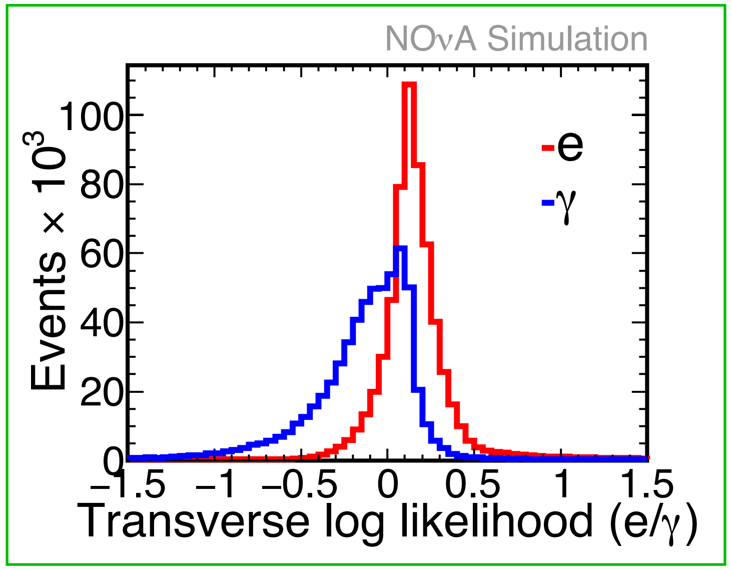


Example: The Likelihood ID method

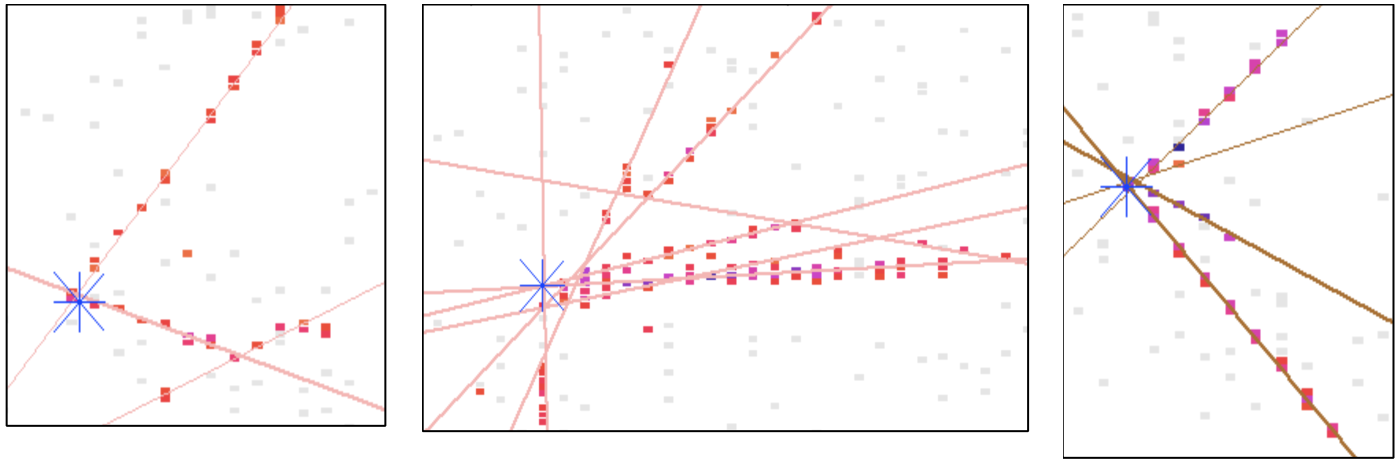
- ⋆ Reconstruct electron shower.
- ⋆ Find likelihoods from it’s dE/dx profiles compared to particle hypotheses.

Likelihoods → *Traditional Neural Network*

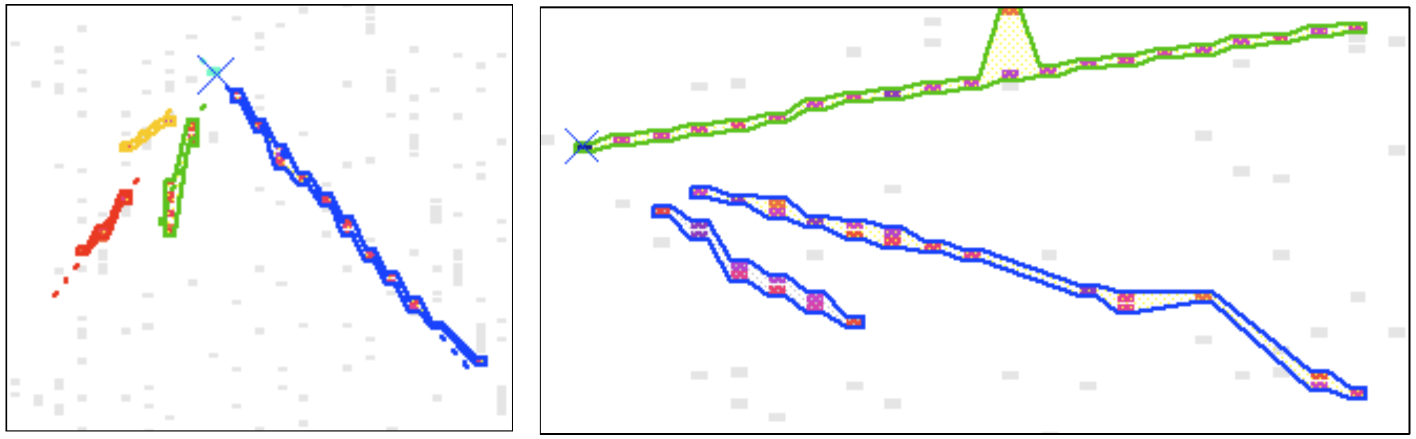




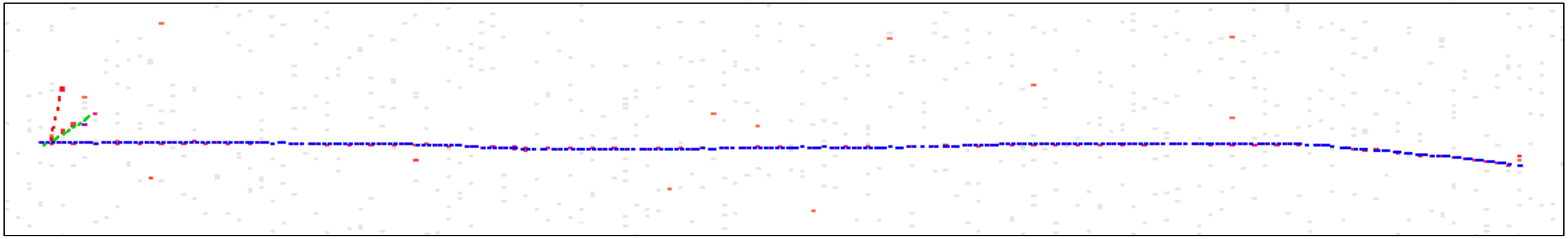
Vertexing: use lines of energy deposition formed with hough transforms to find intersections



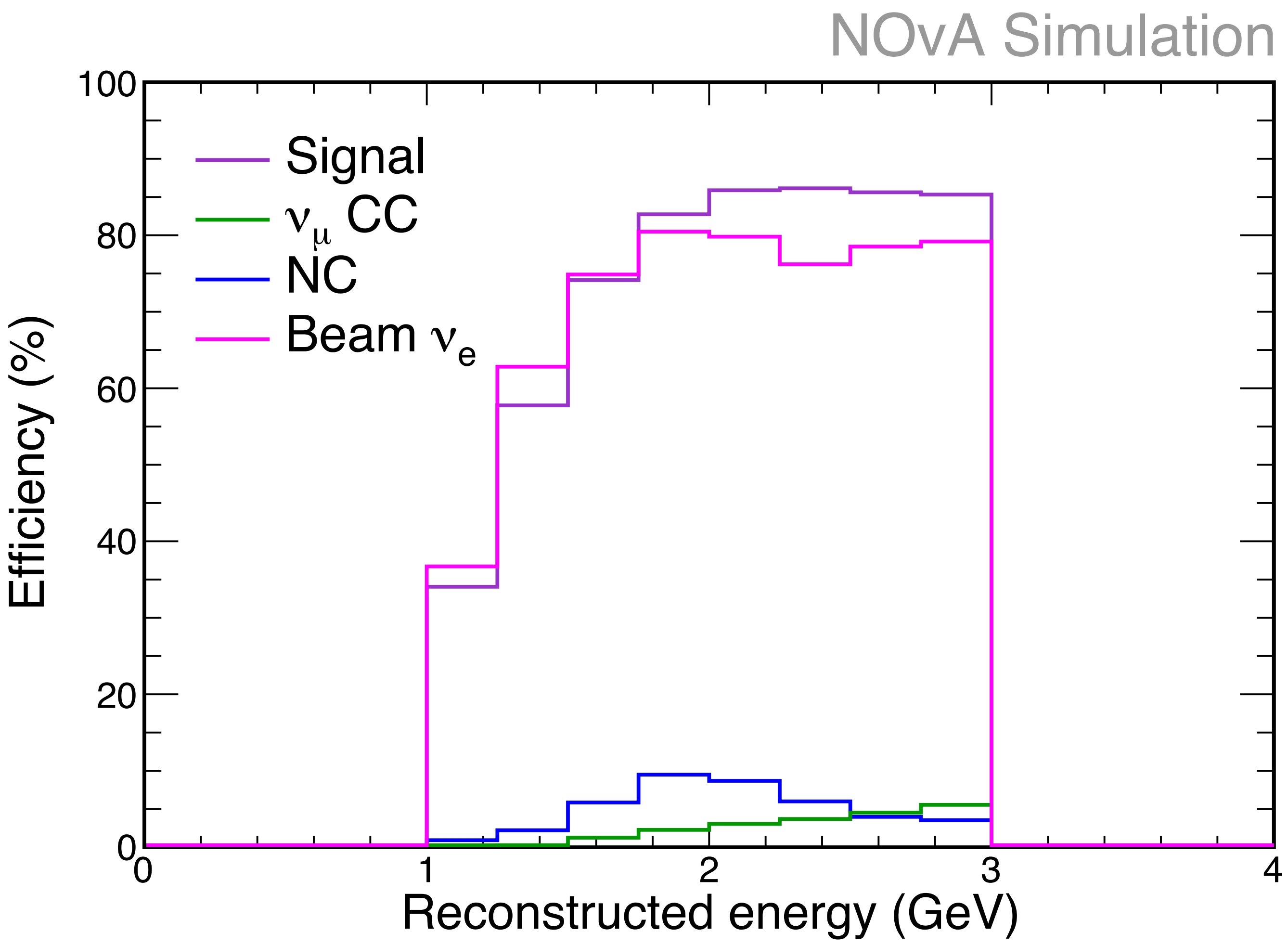
Clustering: find clusters in angular space around the vertex and merge views via topology and prong dE/dx

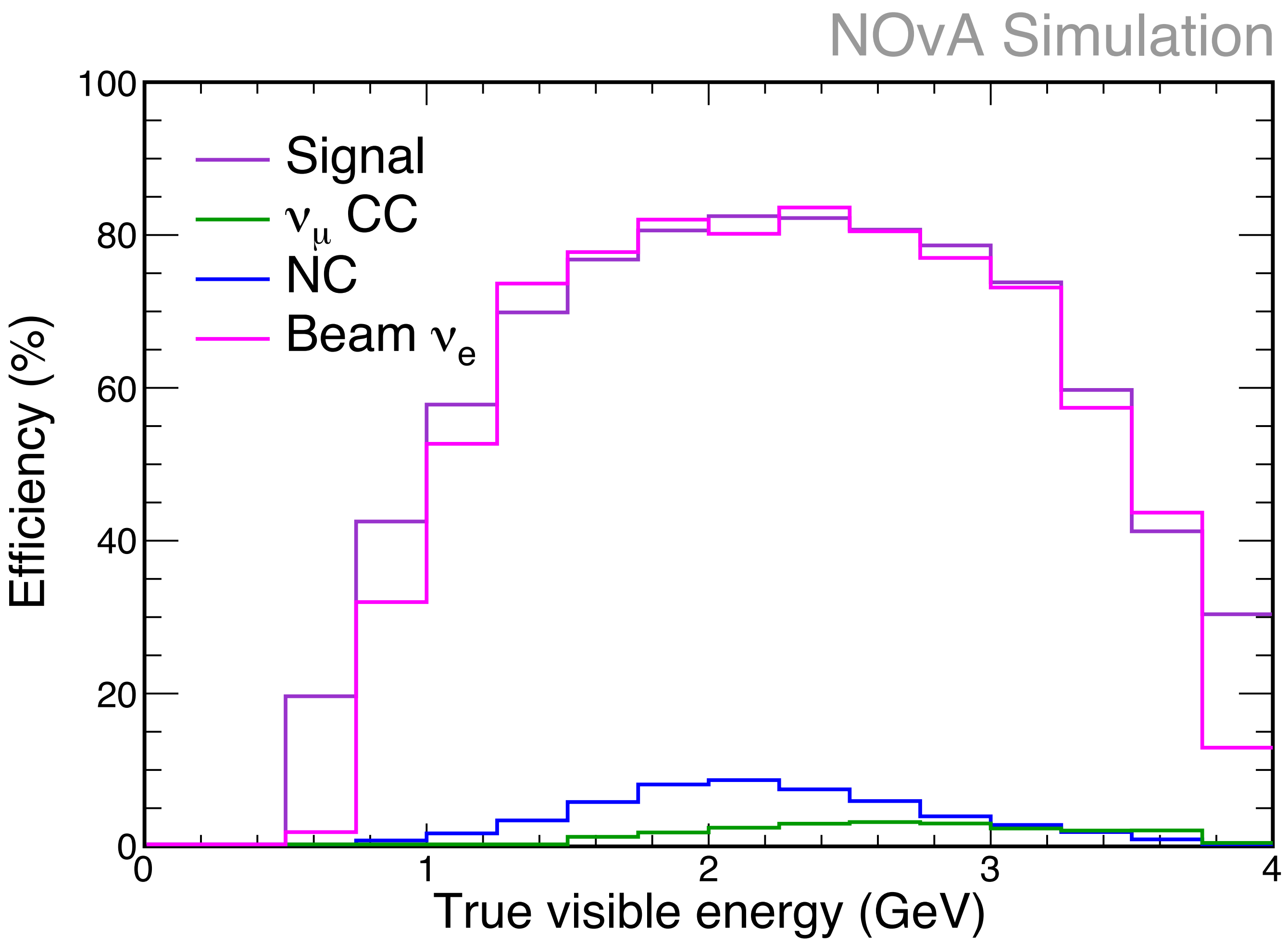


Tracking: Trace particle trajectories using a kalman filter, example below

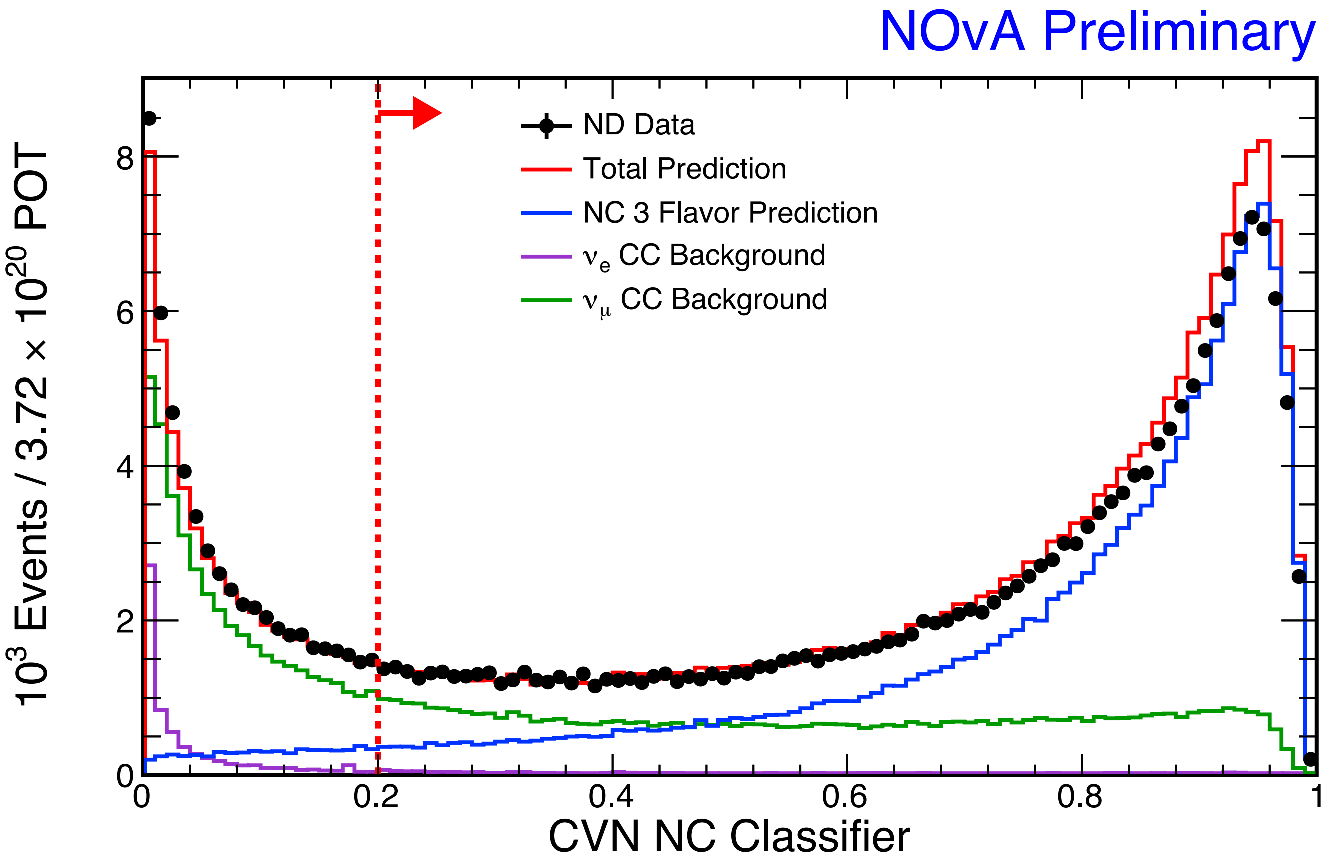


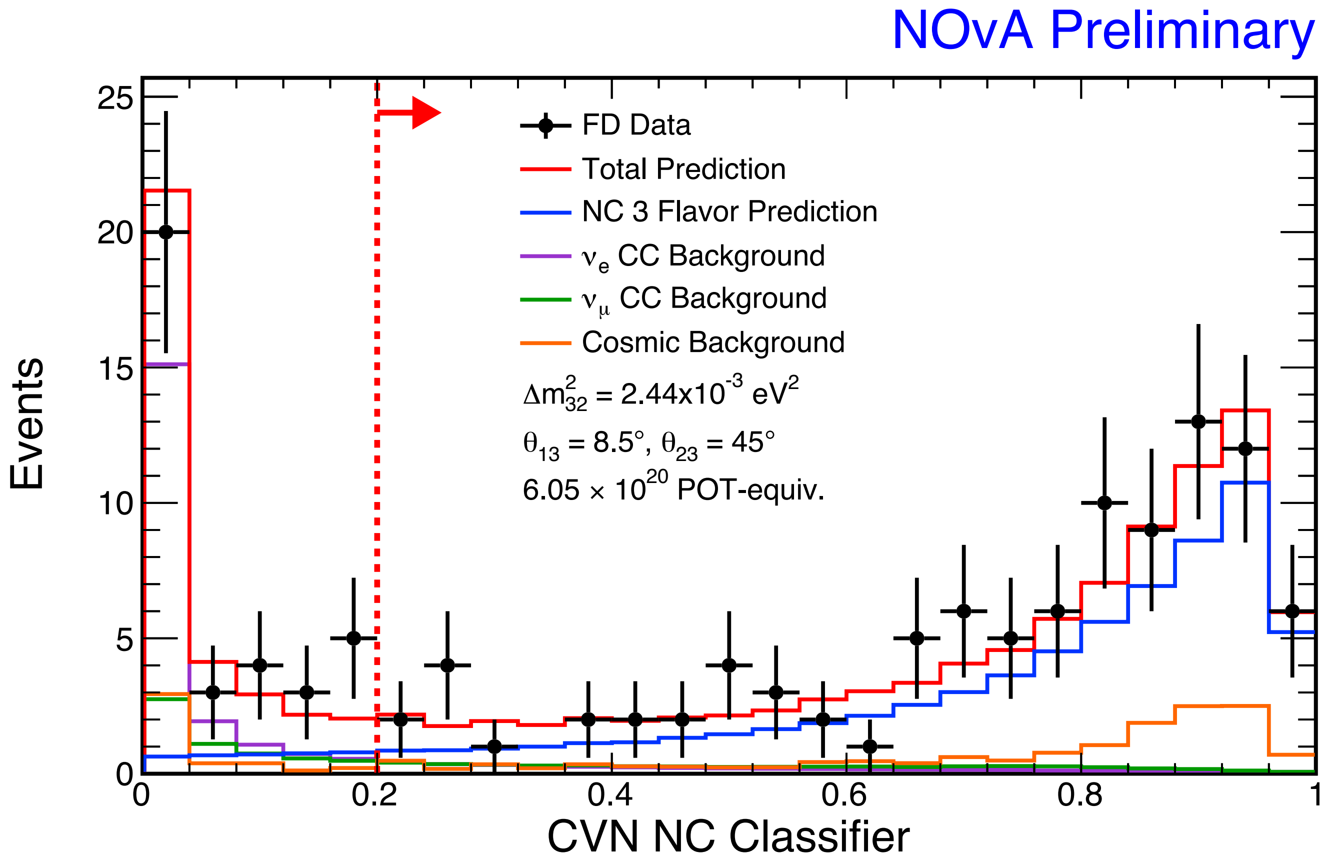
CVN MC Efficiency



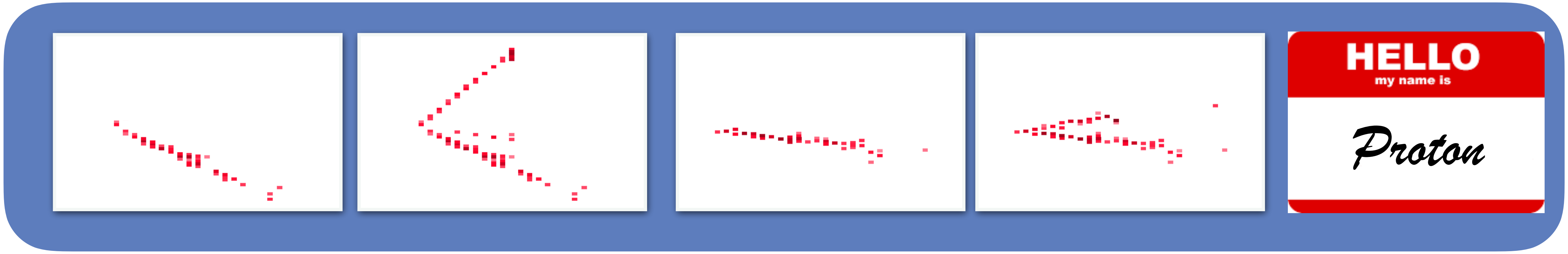


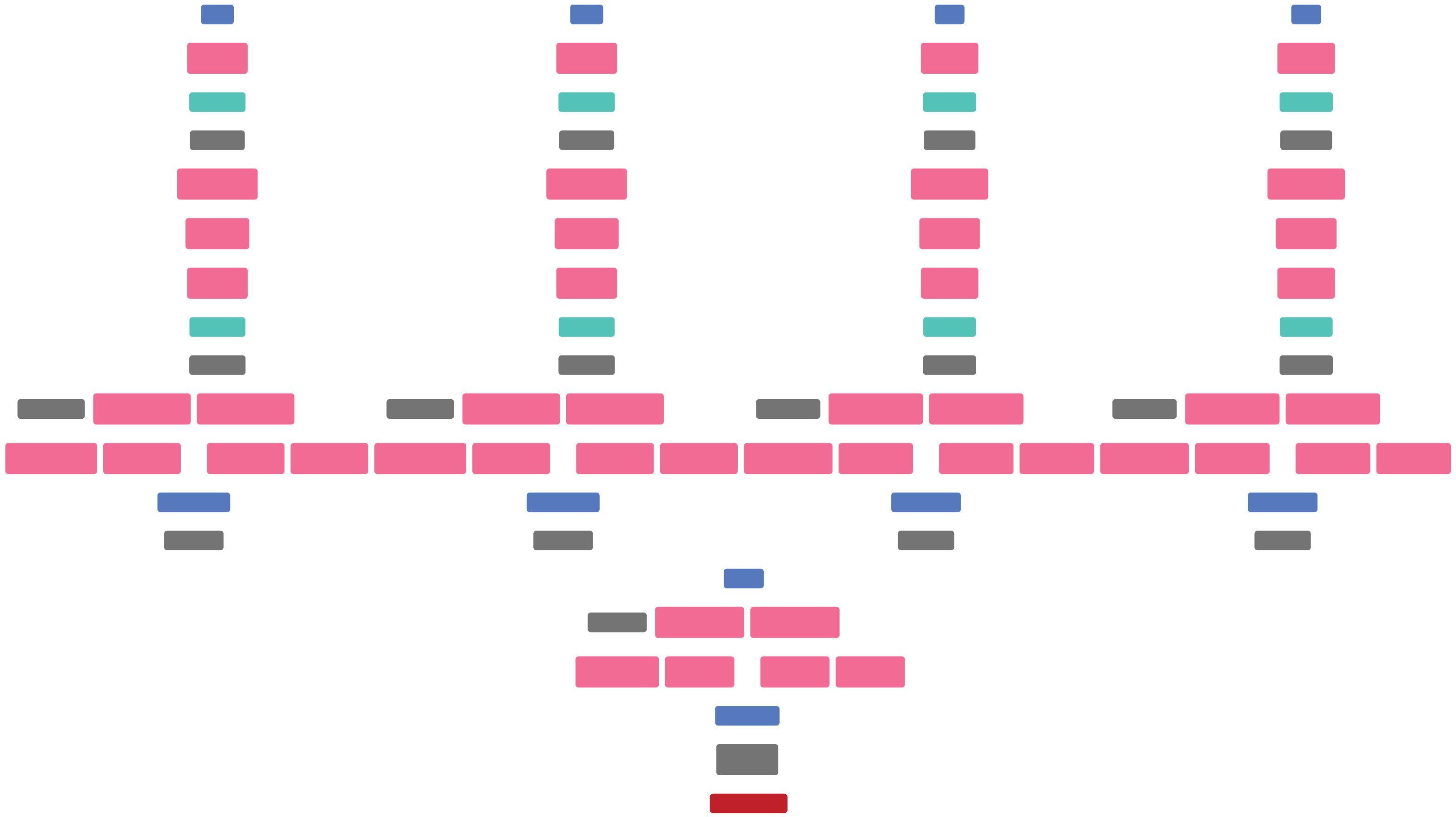
Neutral Current Neutrino Analysis





CVN Particle Tagging





Using the existing reconstruction.

Improved CVN network to optimize for running time

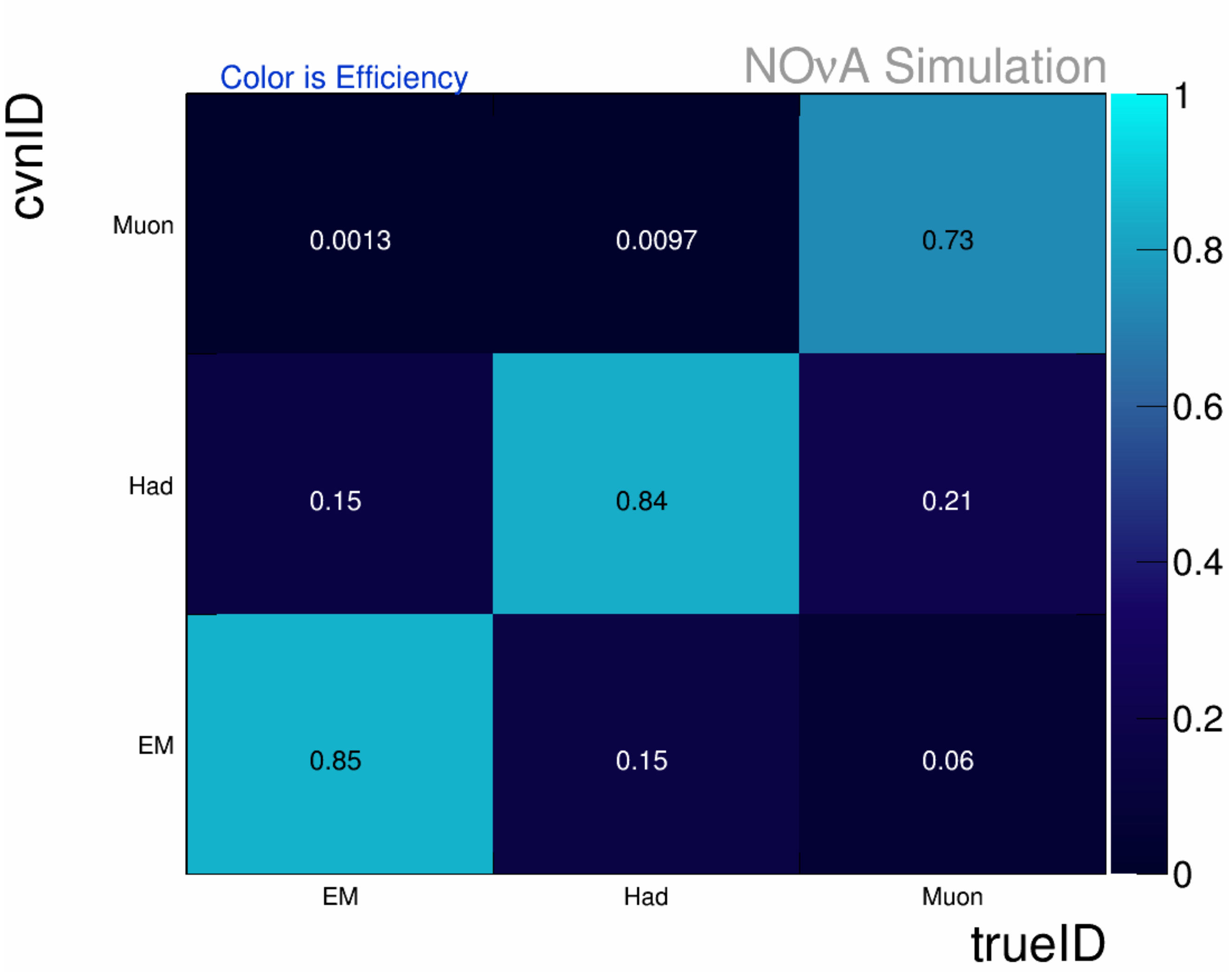
Modified to take 4 views (event + prong)

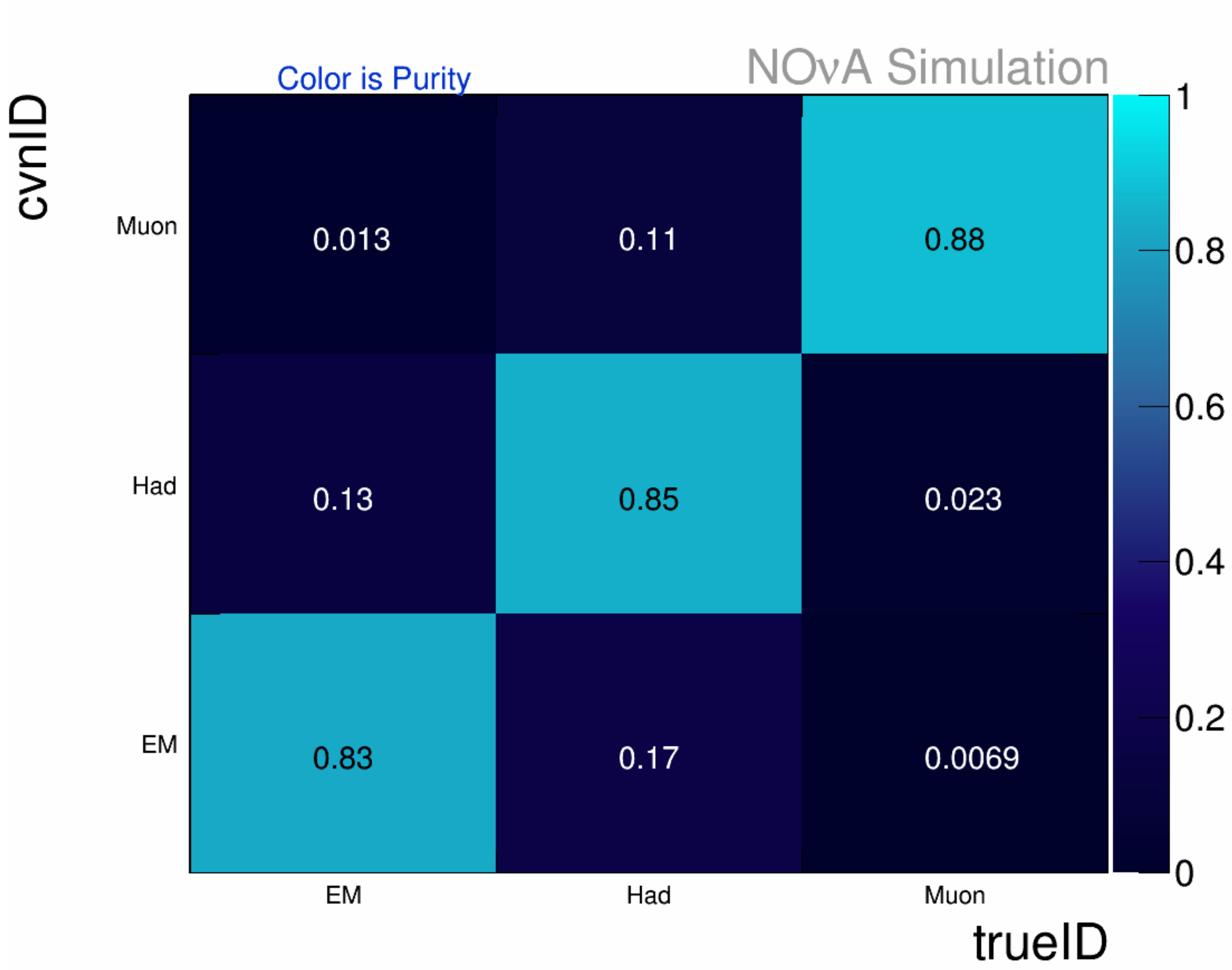
Trained on prongs from all events above some minimum purity

Caffe NVIDIA

CVN prong results

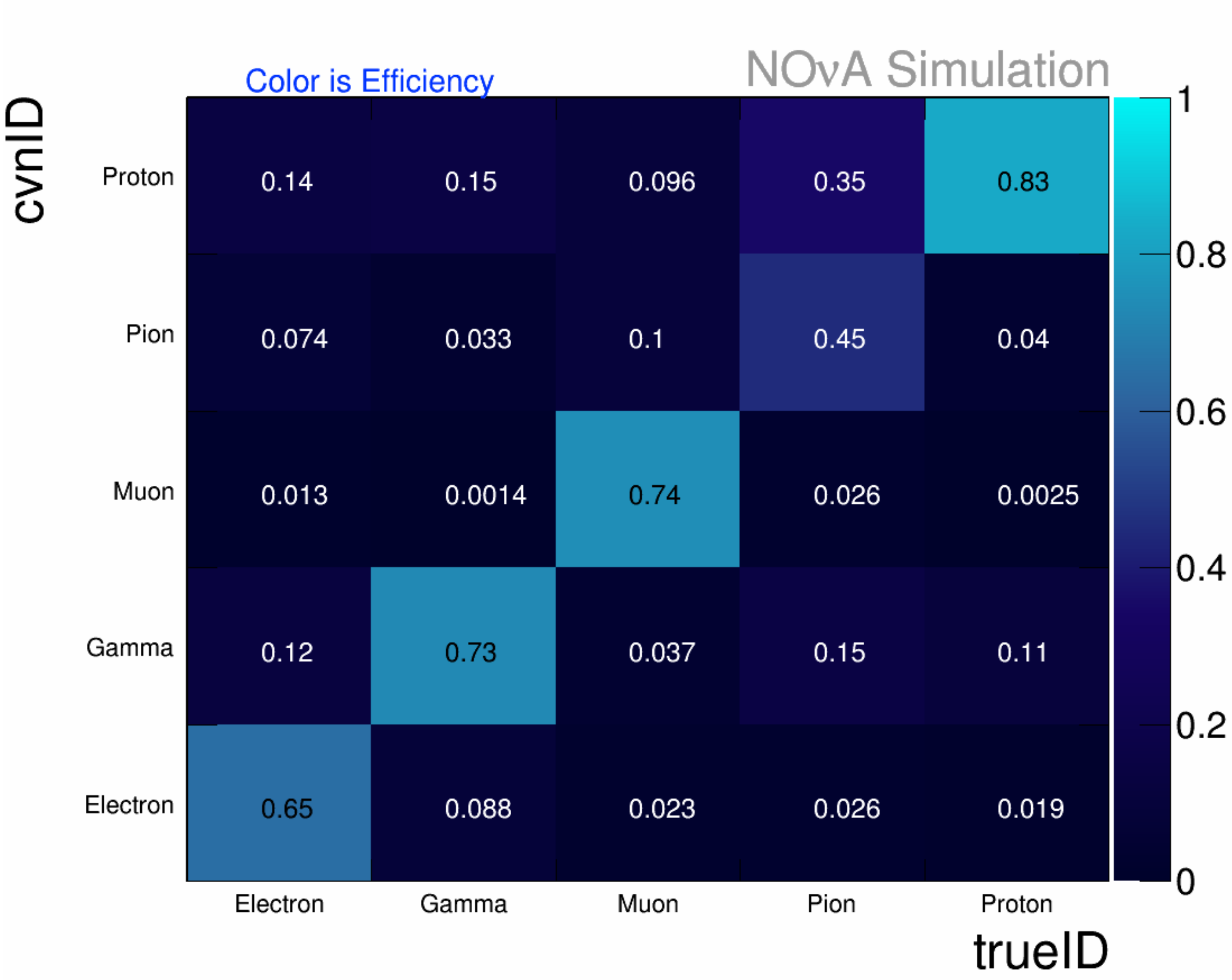
Broad categories separate electromagnetic and hadronic contributions as well as muons.



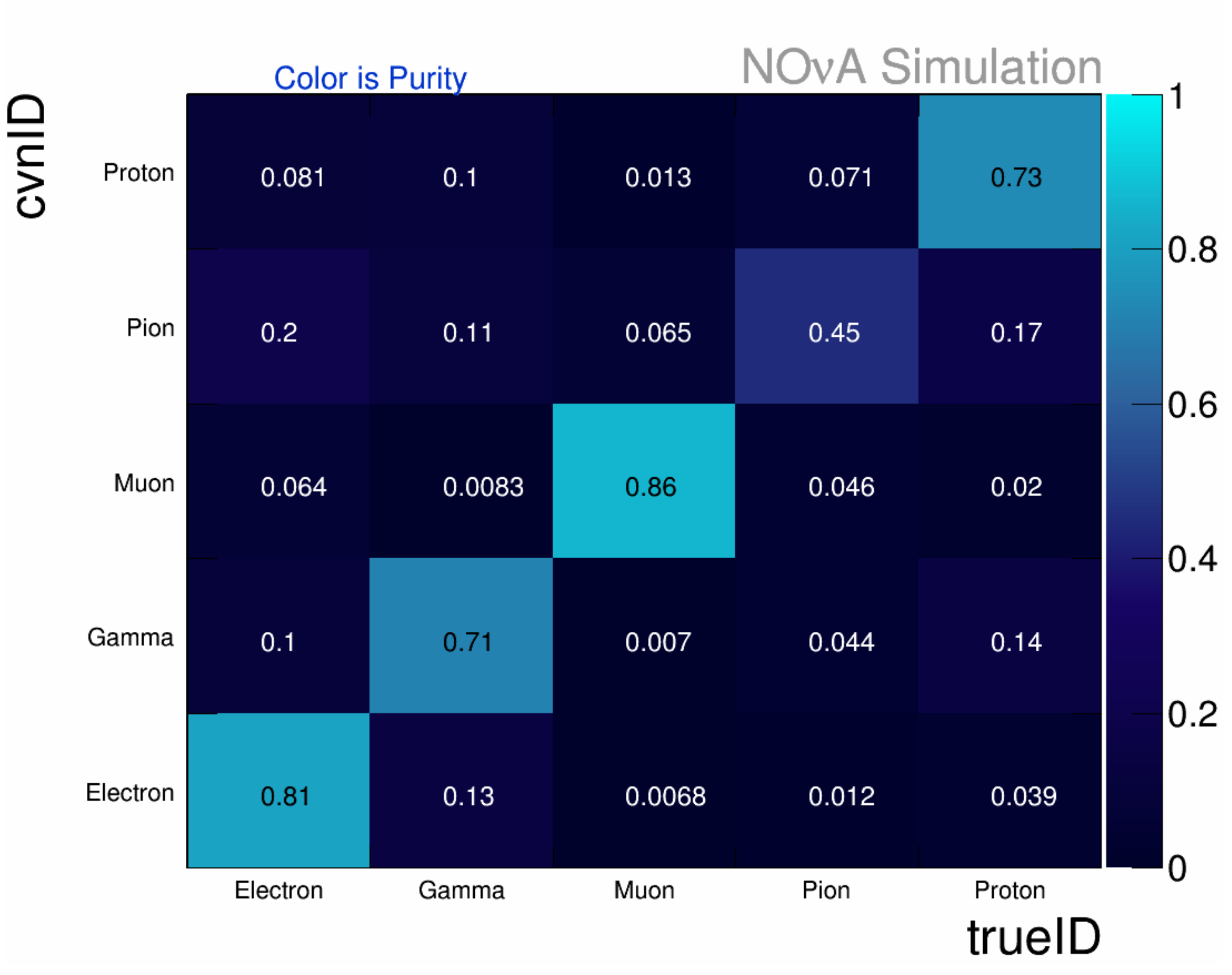


CVN prong results

Full set of training categories for single particle tagging.



cvnID \ trueID	Electron	Gamma	Muon	Pion	Proton
Proton	0.14	0.15	0.096	0.35	0.83
Pion	0.074	0.033	0.1	0.45	0.04
Muon	0.013	0.0014	0.74	0.026	0.0025
Gamma	0.12	0.73	0.037	0.15	0.11
Electron	0.65	0.088	0.023	0.026	0.019

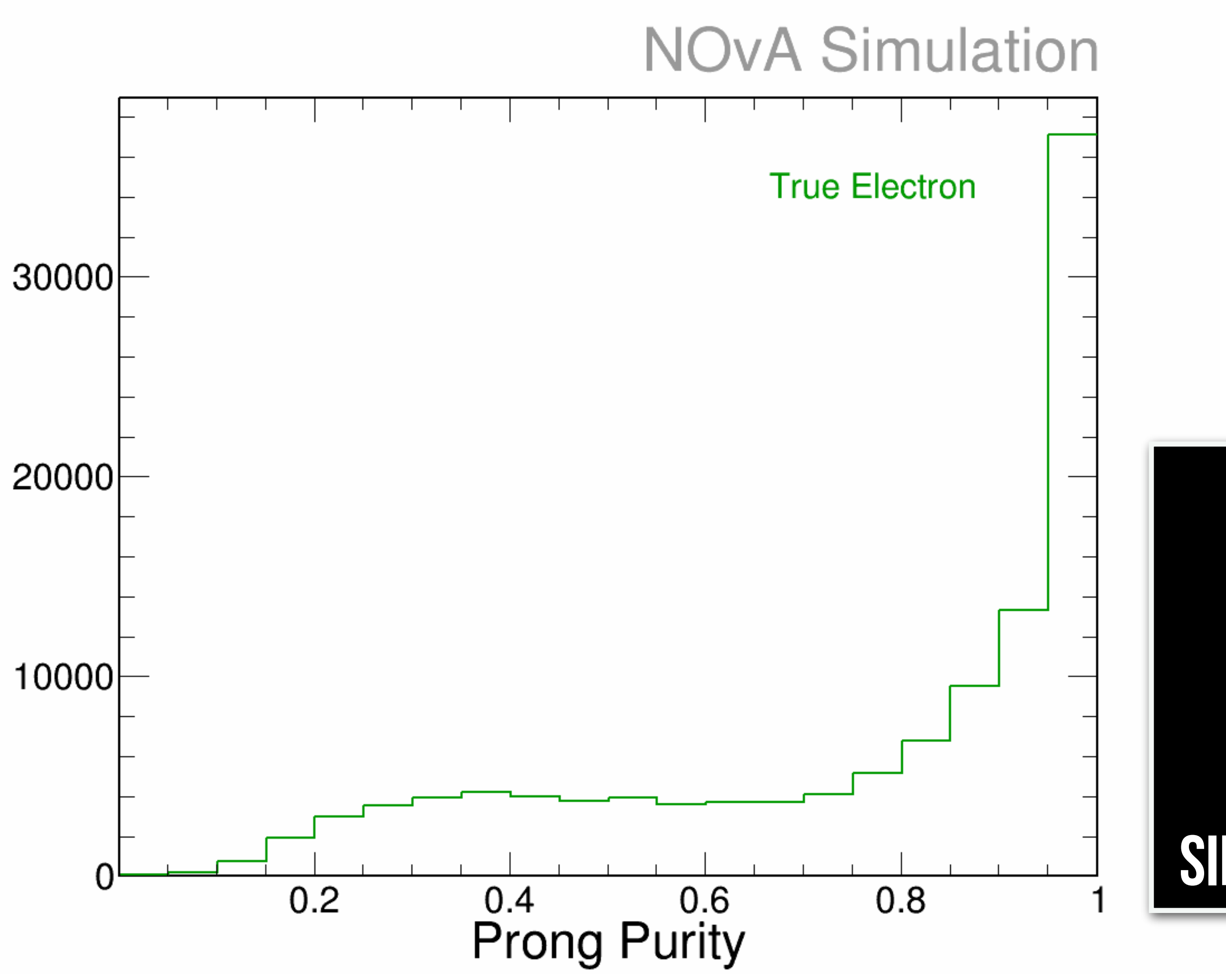


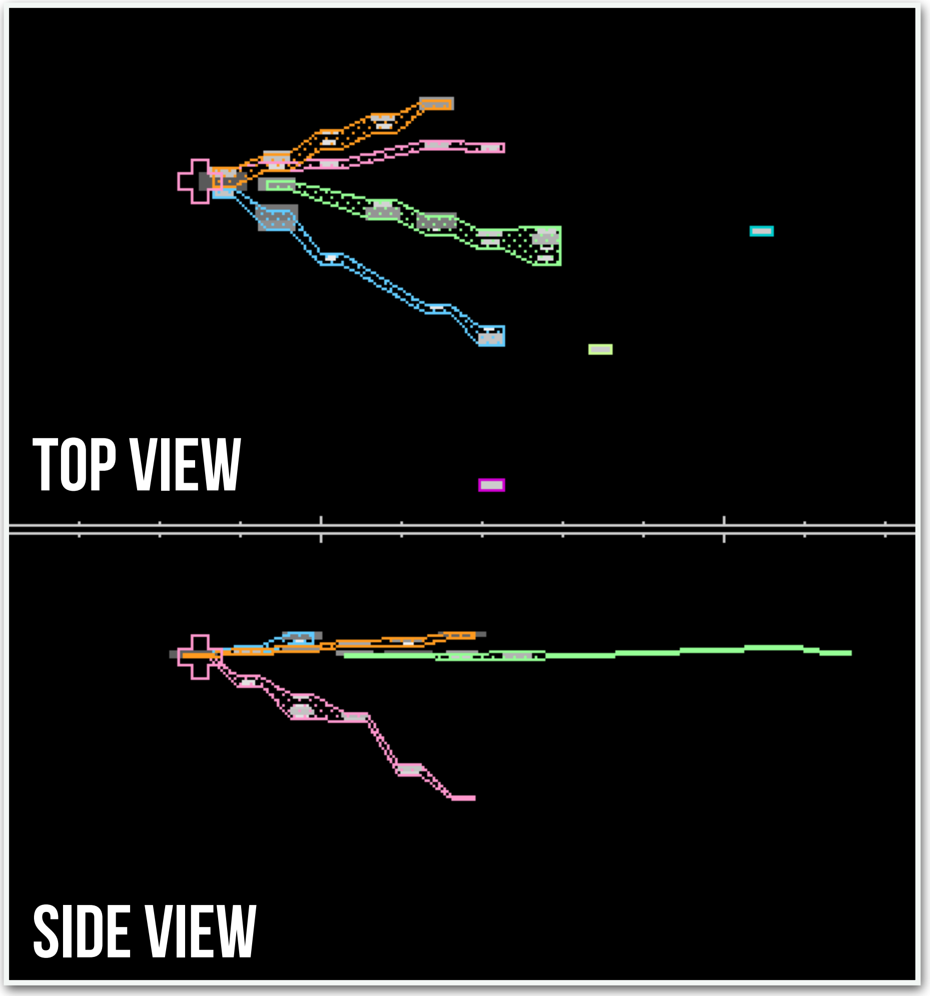
cvnID \ trueID	Electron	Gamma	Muon	Pion	Proton
Proton	0.081	0.1	0.013	0.071	0.73
Pion	0.2	0.11	0.065	0.45	0.17
Muon	0.064	0.0083	0.86	0.046	0.02
Gamma	0.1	0.71	0.007	0.044	0.14
Electron	0.81	0.13	0.0068	0.012	0.039

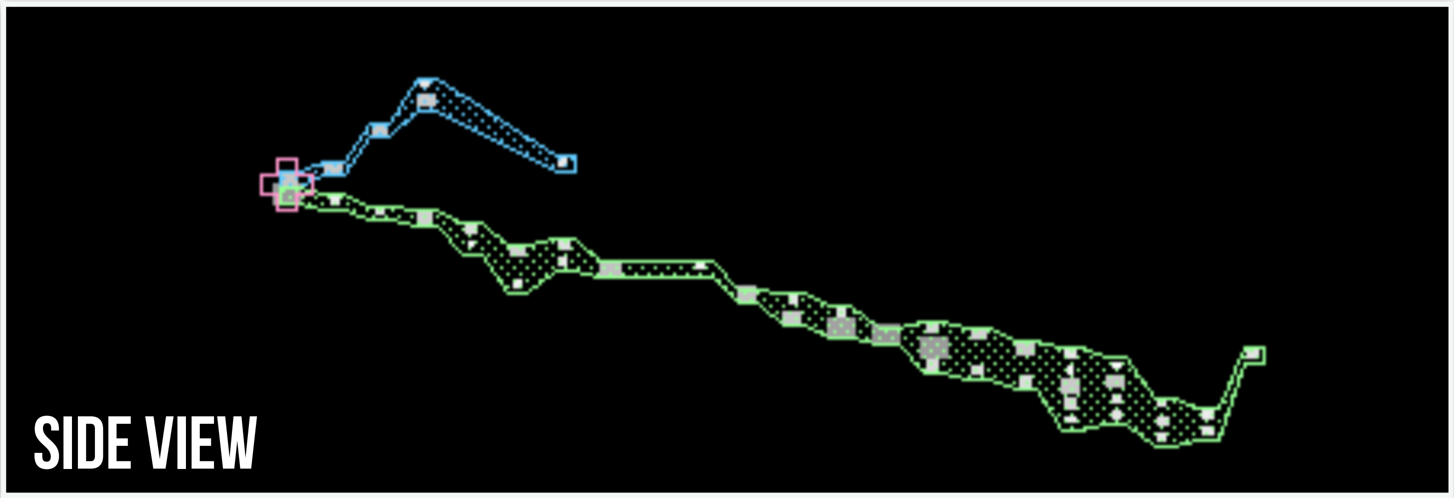
Caveats from the reconstruction

Prong quality depends on view matching and vertex reconstruction.

Purity impacts classifier performance.







Caveats from the reconstruction

Prong quality impacts the performance of our classifier