Exploring the ν_μ charged-current uncontained sample at the NOvA Far Detector

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New Perspectives 2017
Fermilab | June 5-6

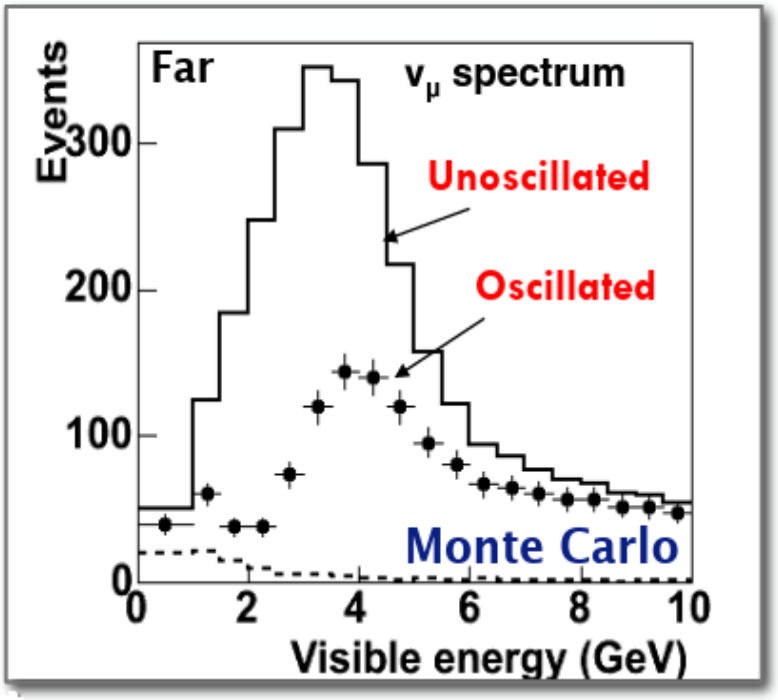
Analysis basics

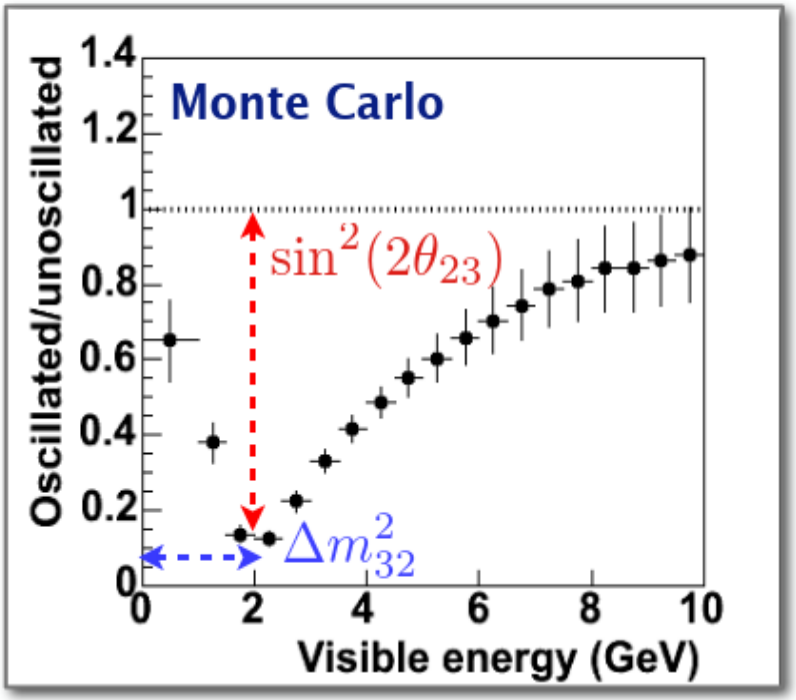
ν_μ disappearance

...to leading order

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

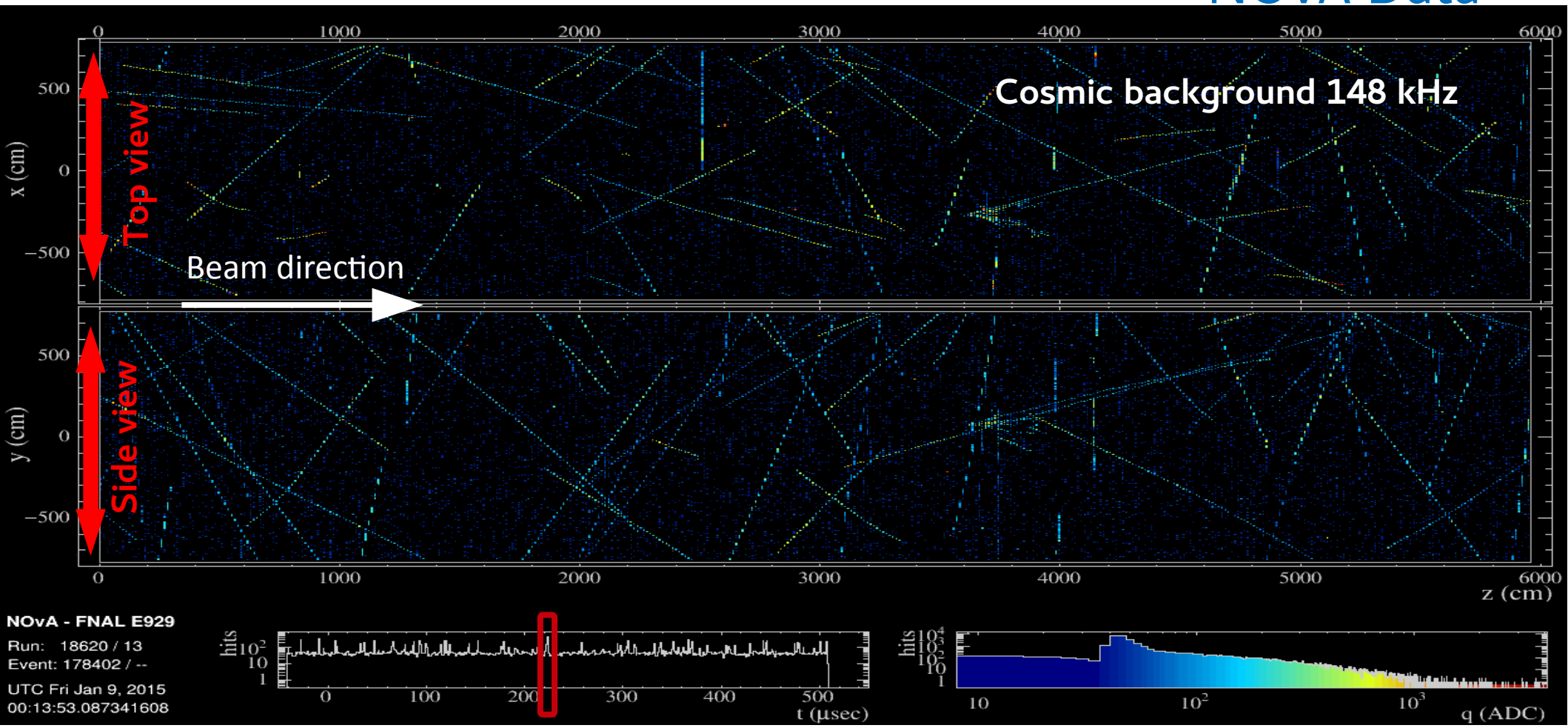
Input: $\sin^2(2\theta) = 1.0$, $\Delta m^2 = 3.35 \times 10^{-3}$ eV^2





NuMI neutrino events in Far detector

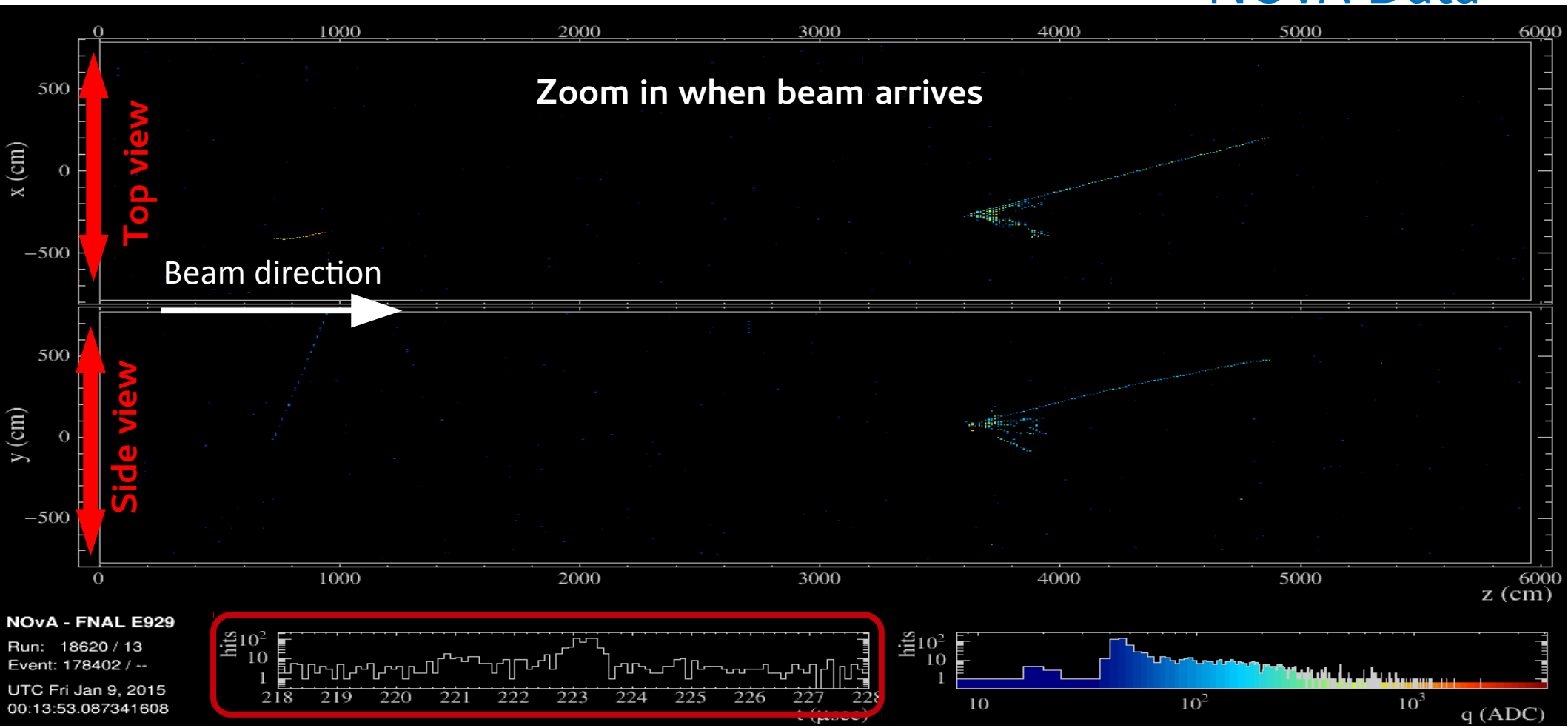
NOvA Data



Neutrinos at the Main Injector (NuMI) event with **full 550 µs trigger** window. Beam is coming from the left. Upper image represents top (XZ)- view. Lower image represents side (YZ)-view. The color of each hit represents its charge

NuMI neutrino events in Far detector

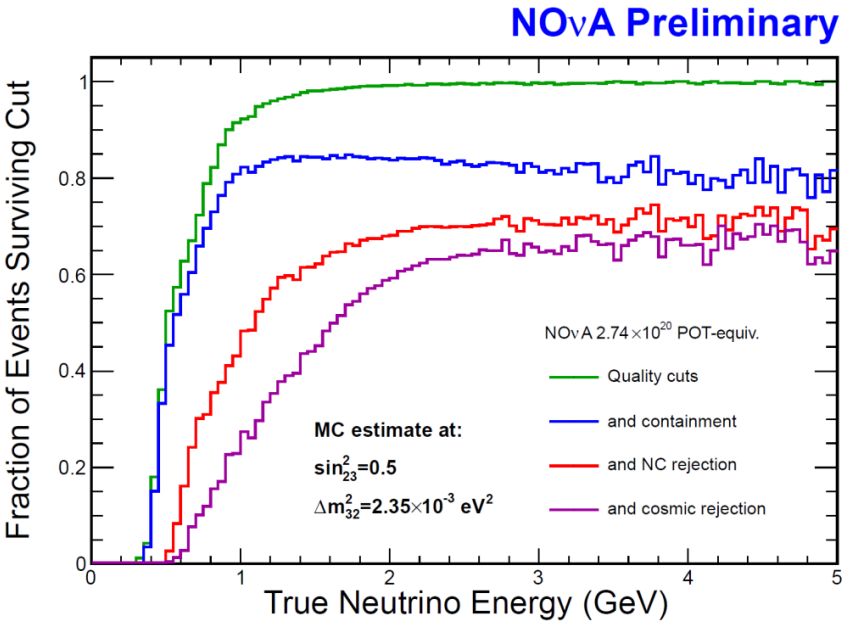
NOvA Data

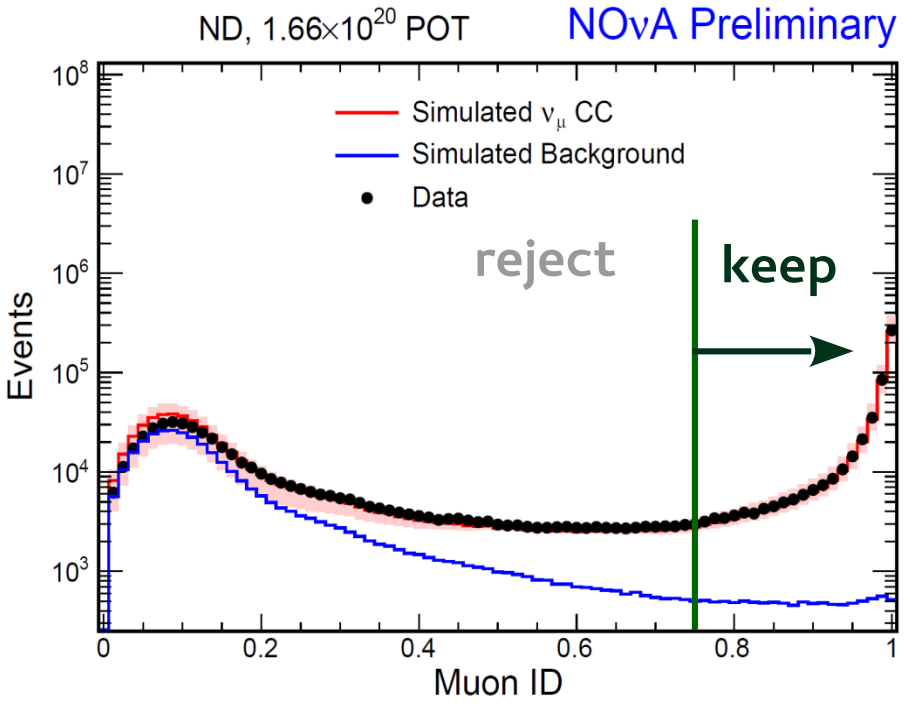


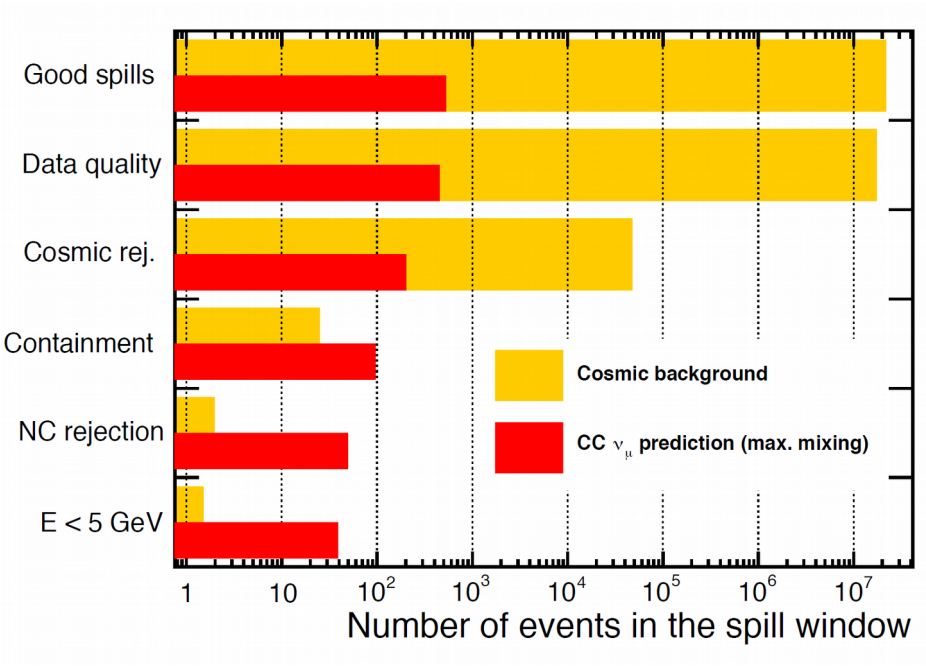
Neutrinos at the Main Injector (NuMI) event **within 10 μs beam** window. Beam is coming from the left. Upper image represents top (XZ)- view. Lower image represents side (YZ)-view. The color of each hit represents its charge

ν_μ CC selection

- **Step 1: Basic quality**
- **Step 2: Containment**
- **Step 3: Select muons**
- **Step 4: Cosmic Rejection**



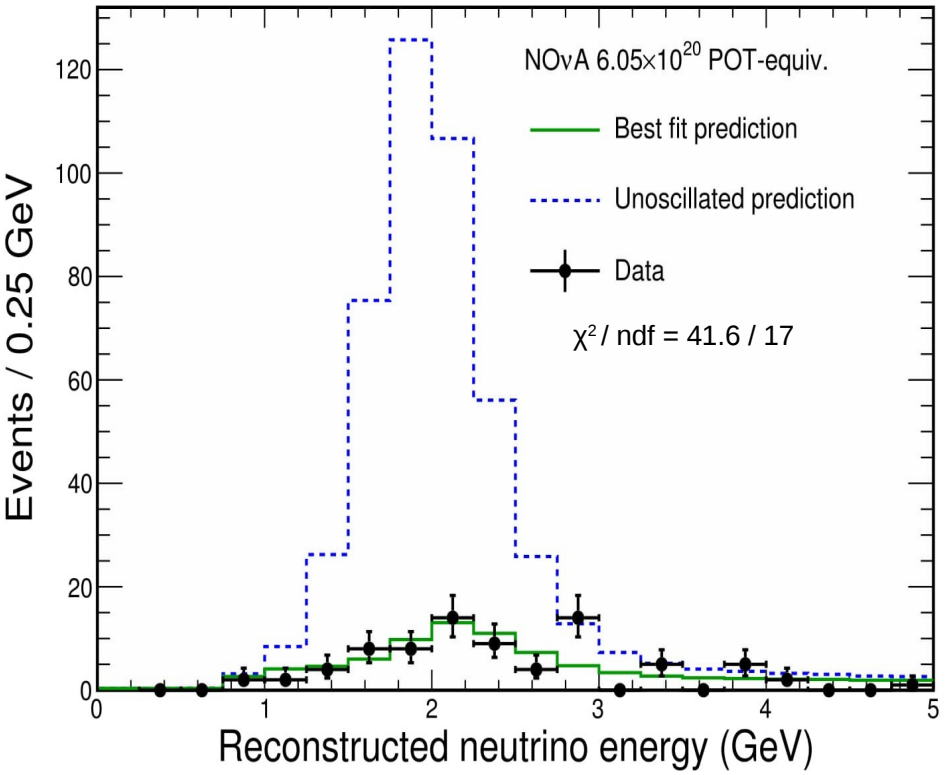




Latest analysis results

P. Adamson et al. (NOvA Collaboration)
Phys. Rev. Lett. 118, 151802

- There were **78 events observed** at the Far Detector:
  - **473 ± 30** with no oscillations
  - **82.4** at best oscillation fit
  - **3.9** beam + **2.7** cosmic backgrounds



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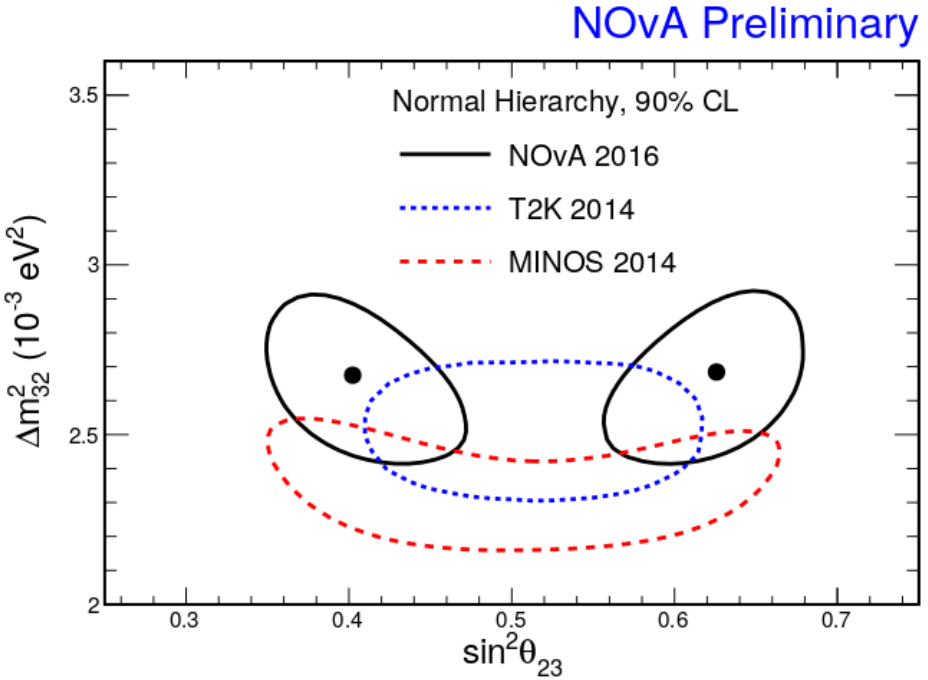
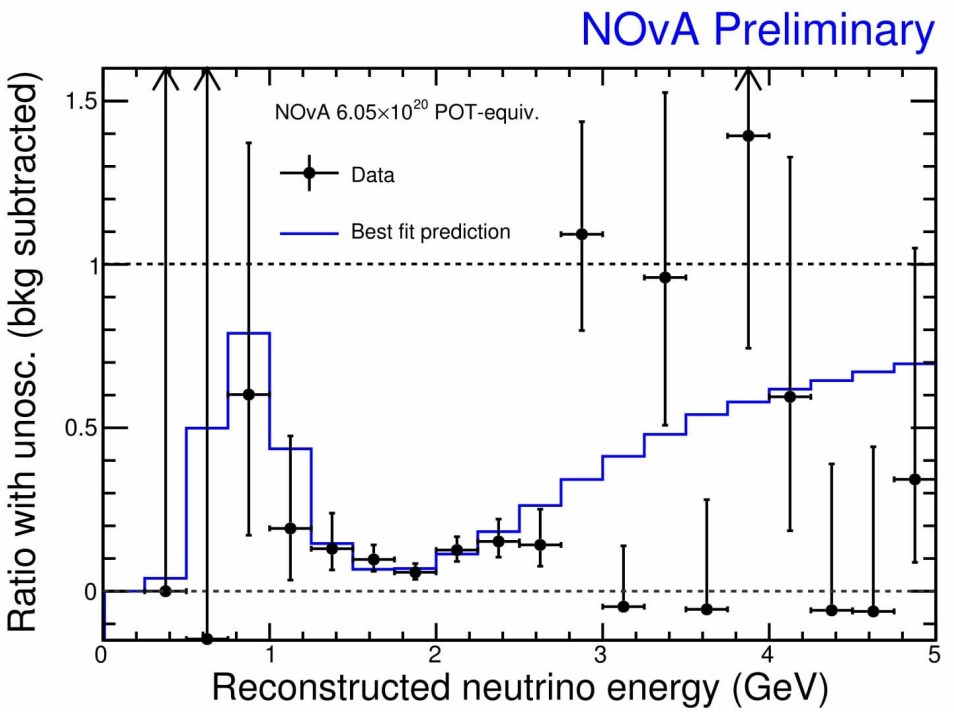




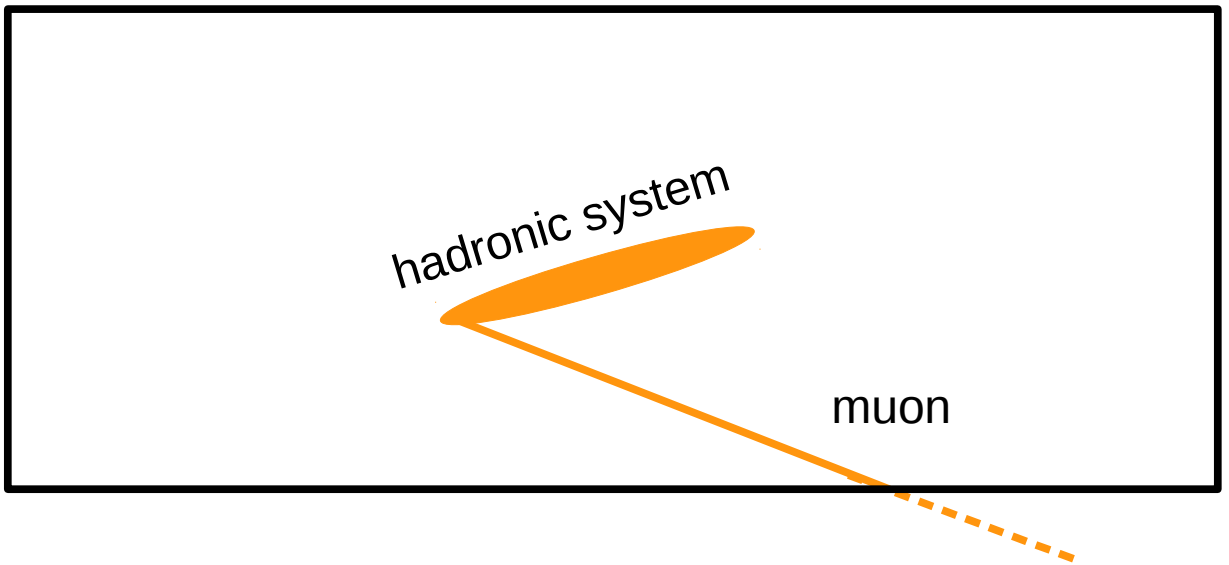
- Best fit (in Normal Hierarchy):

$$\Delta m^2_{32} = (+2.67 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.404\,^{+0.030}_{-0.022} \text{ and } 0.624\,^{+0.022}_{-0.030}$$

- **Maximal mixing excluded at 2.6σ**

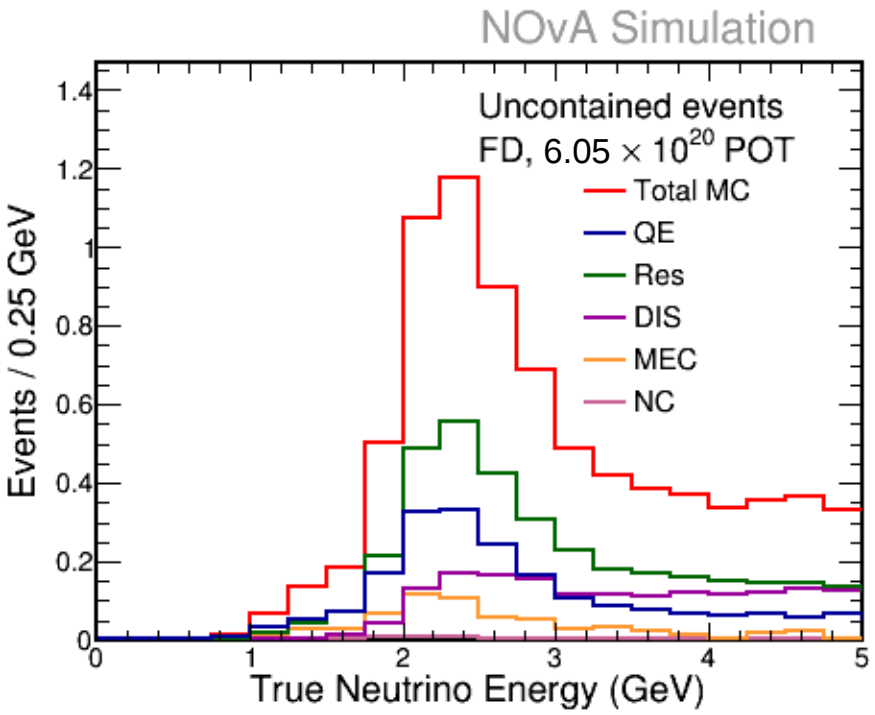
The plan ahead

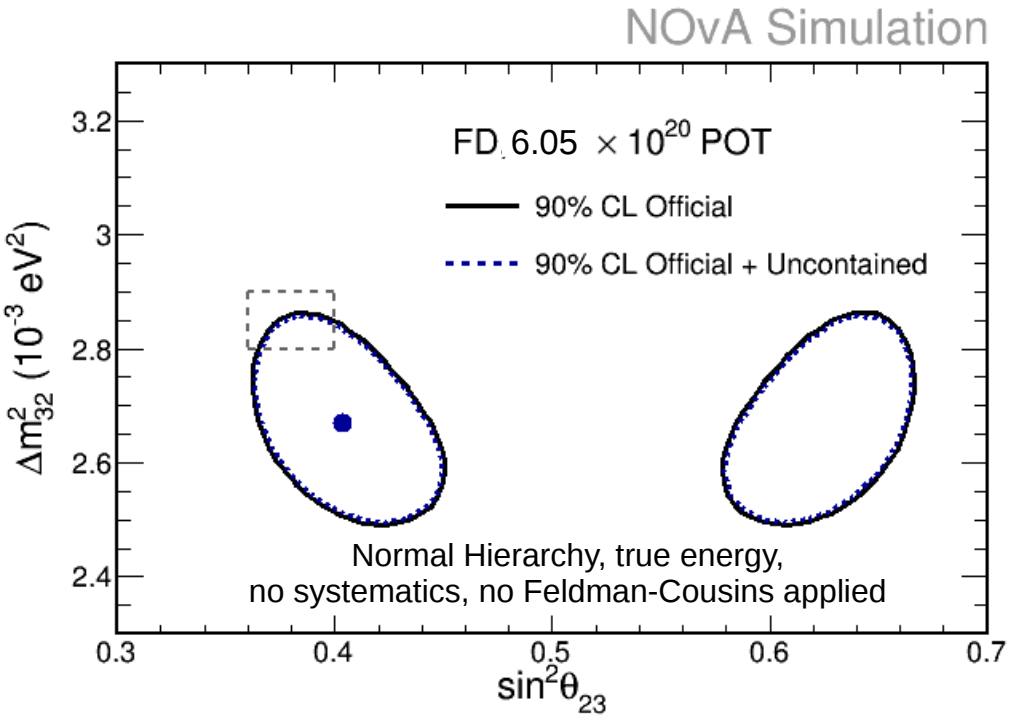
- In its first and second analysis, NOvA used **only** events with an interaction vertex and all secondary particles **fully contained** in the detectors
- Improving analysis by recovering uncontained (escaping) interactions (ν_μ-CC)



Improvements

- Using existing selection tools applied to our sample
- Combined sample with other instances of reconstruction
- Integral: **7.82 events** (around 10% improvement from total)





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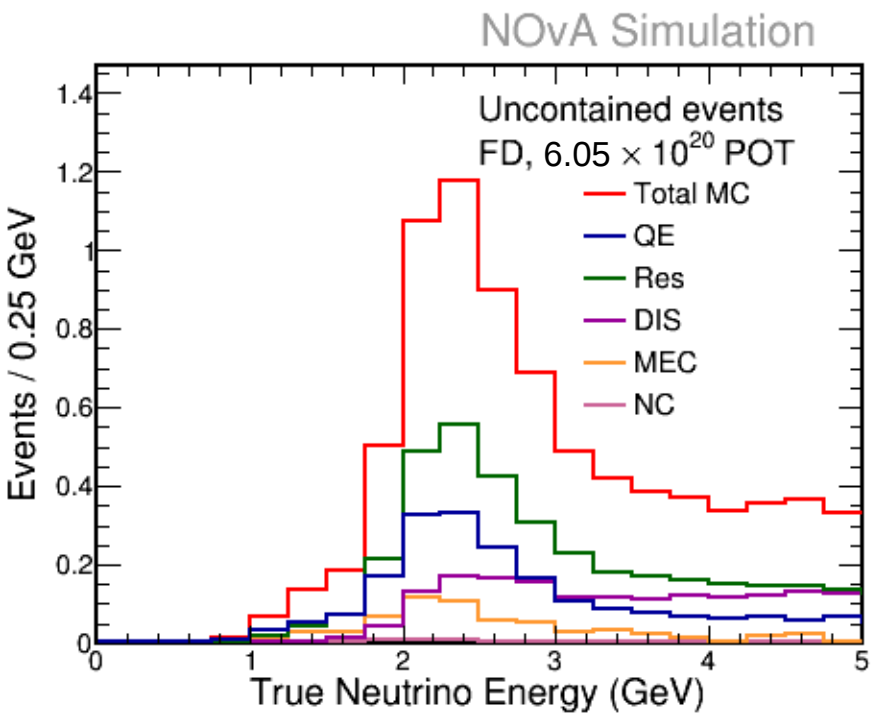
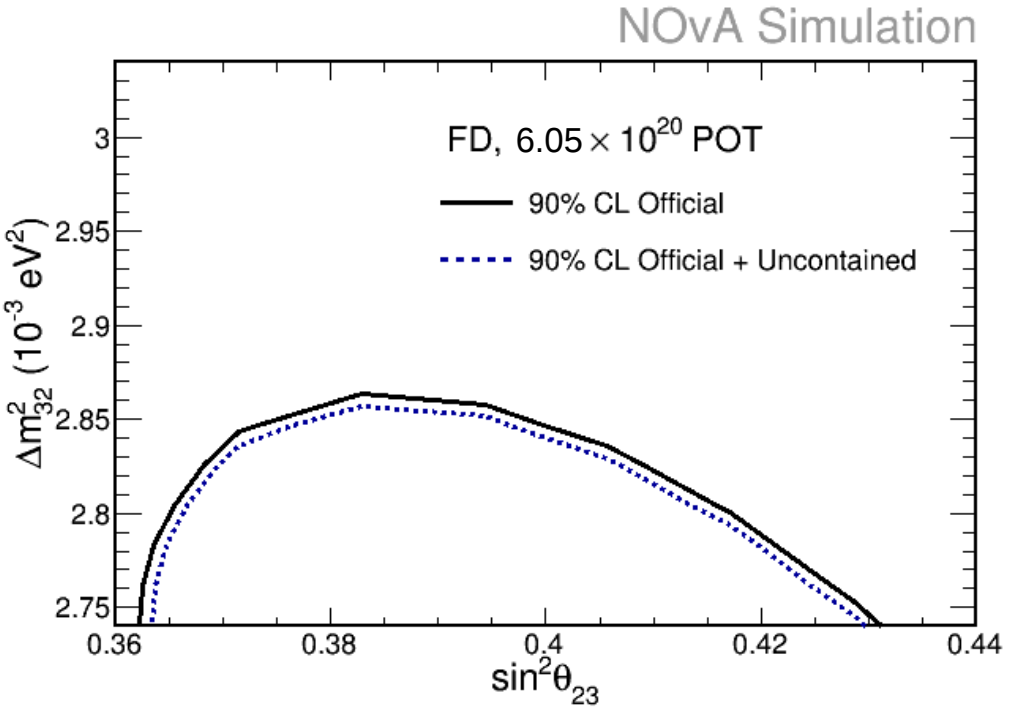
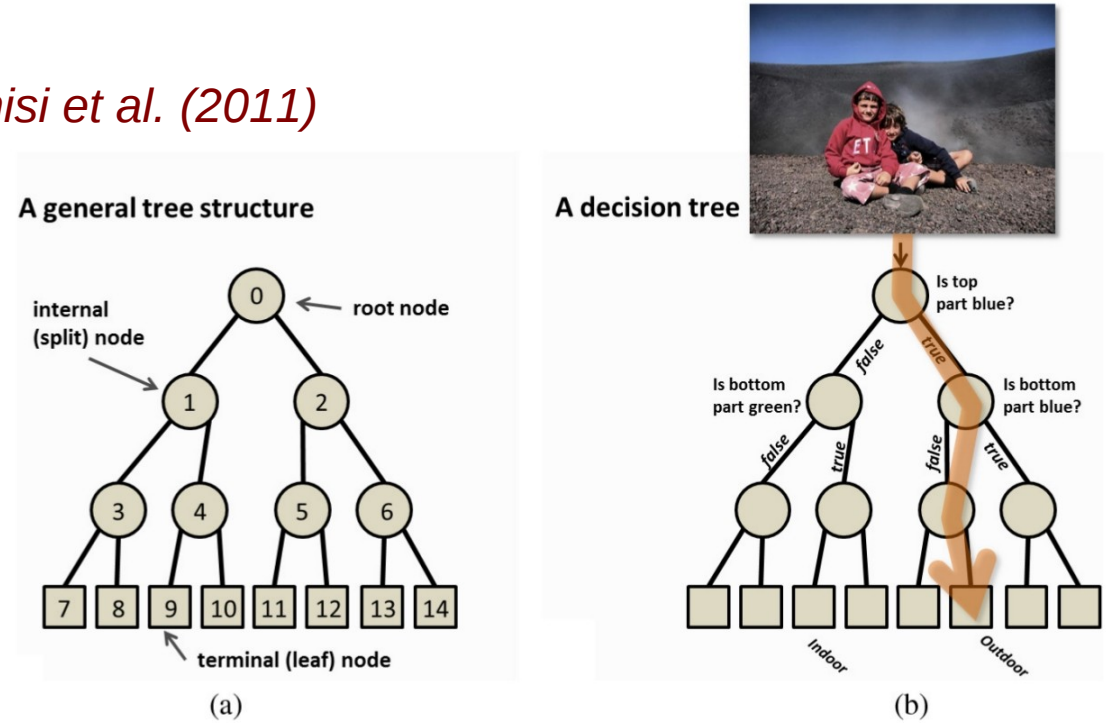




Decision trees

- A decision tree is a set of questions organized in hierarchical manner and represented graphically as a tree

Criminisi et al. (2011)

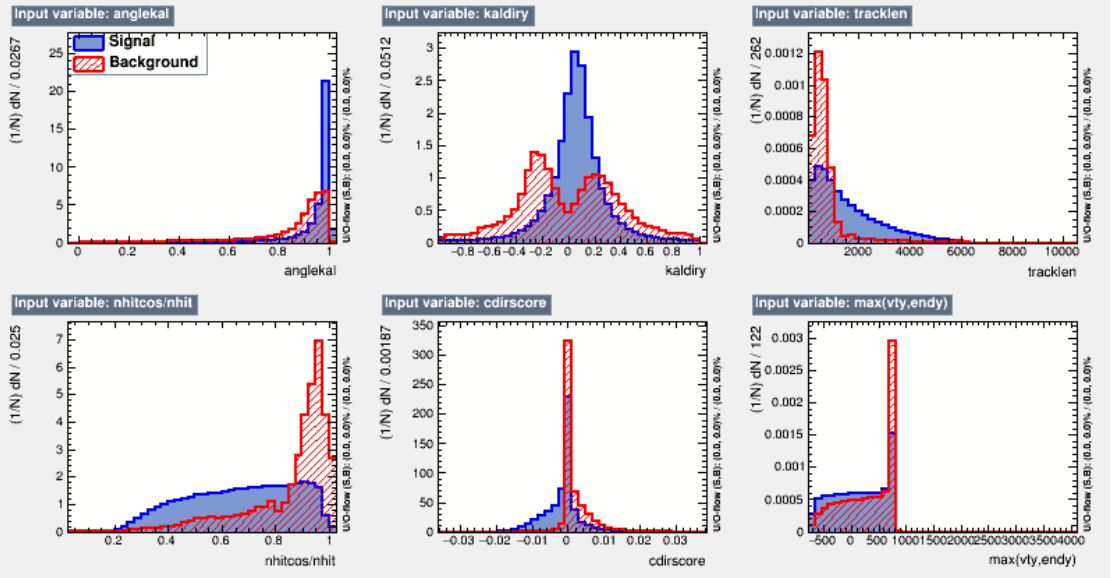


- Decision trees + ensemble methods = decision forests
- Two approaches to creating ensembles:
  - **Boosting:** if an event is (mis)classified, decrease(increase) its weight
  - Bagging: construct each tree on a different random subset of the data
- **Classification problem:** given an event, is it signal (neutrino) or background (cosmic)?

Cosmic rejection performance

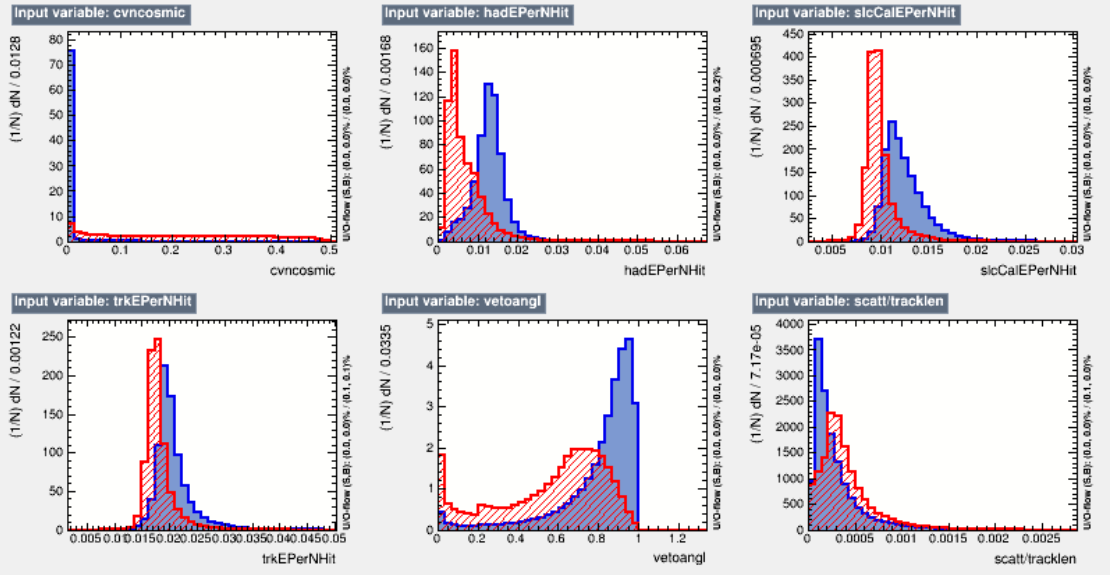
- Twelve input variables:

Angle



Track length

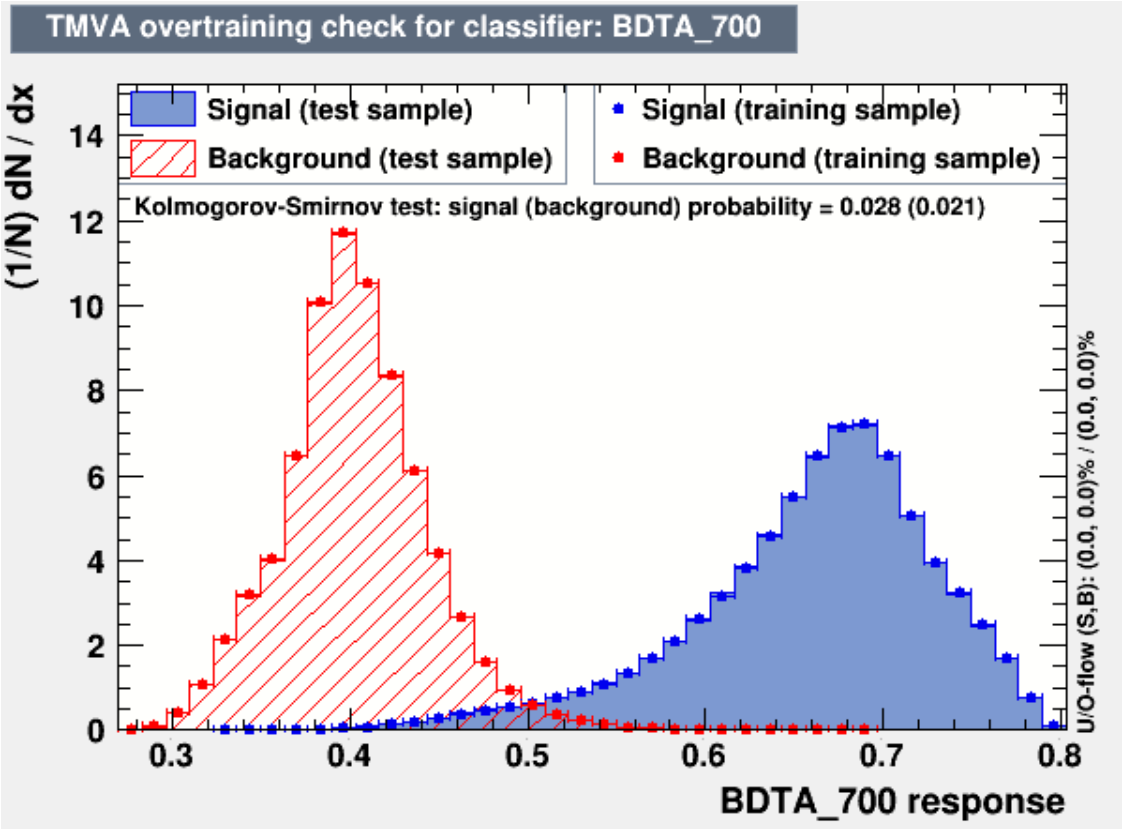
Cosmic-likeness



Energy per no. hit

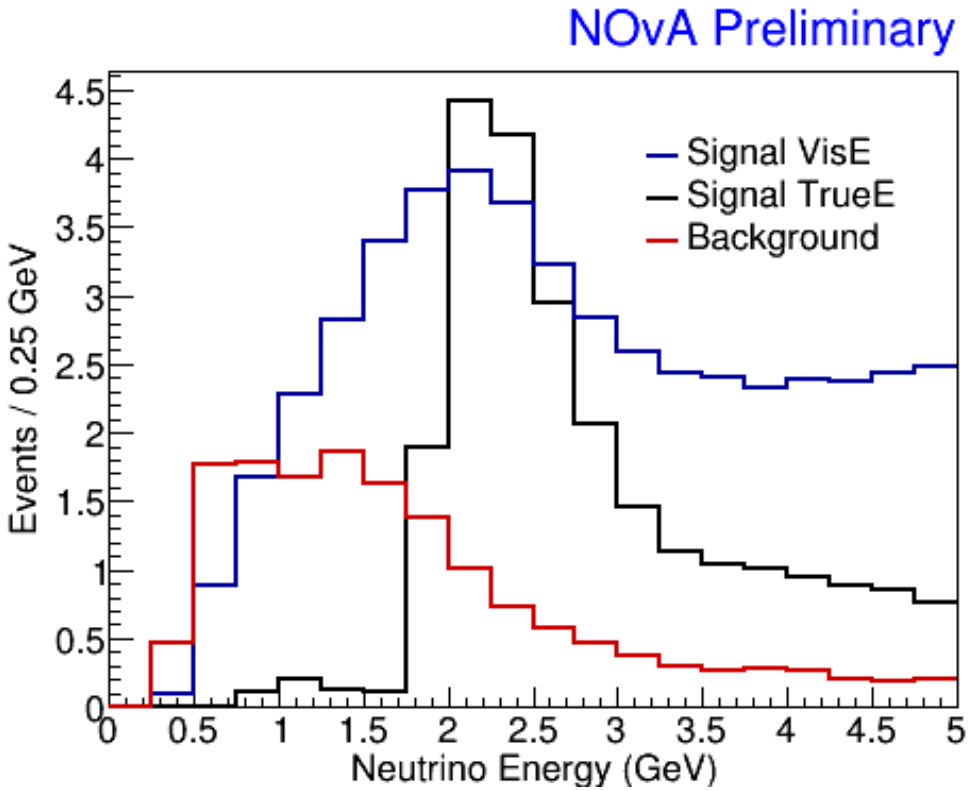
Cosmic rejection performance

- Twelve input variables:
  - Track length, angle w.r.t beam, vertical projection, etc
- Signal from simulation, background from cosmic data
- Efficiency: 94.6 %



Tuning cosmic rejection: results

- Signal to background ratio: 3.11
- In addition, optimized vertex fiducial cut
- Signal events are in oscillation region (lower energy)



Sample	# Events (0-6 GeV)	# Events (1-3 GeV)
Signal VisE	48.02	25.92
Signal TrueE	24.17	15.96
Bkg VisE	15.44	9.34

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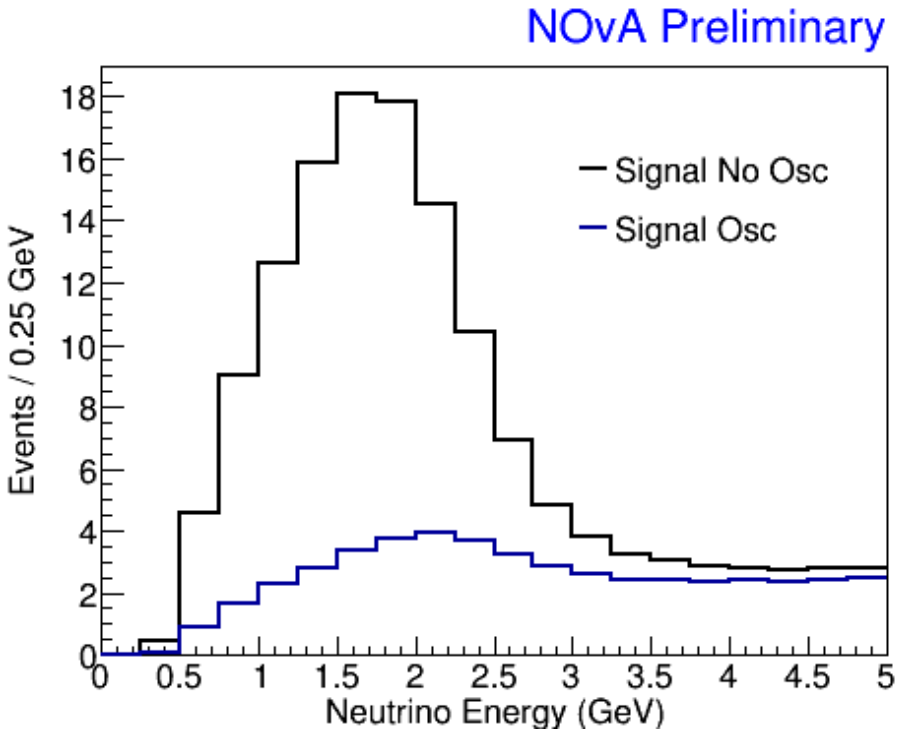
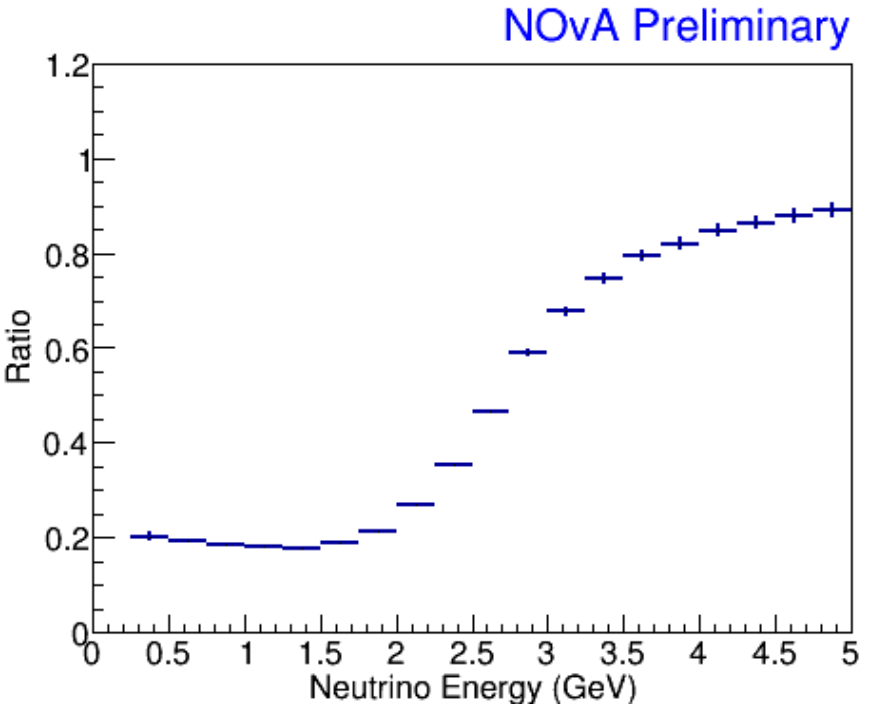




Conclusions

- With a total exposure of 6.05 x 10^{20} POT, the NOvA ν_μ-disappearance analysis group reports **78 events observed** at the Far Detector (out of 473 ± 30 with no oscillations)
- Maximal mixing is **excluded at 2.6σ**
- Uncontained events at the far detector are challenging: signal mimics background
- Tuned cosmic rejection and vertex fiducial selection: **signal/background is 3.11**
- Work in progress: energy estimator for uncontained events

NOvA at New Perspectives:

- Results from the joint fit to ν_e appearance and ν_μ disappearance in NOvA, S. Yu (after break)

-Sterile neutrino search in the NOvA Far Detector, S. Edayath (after previous)

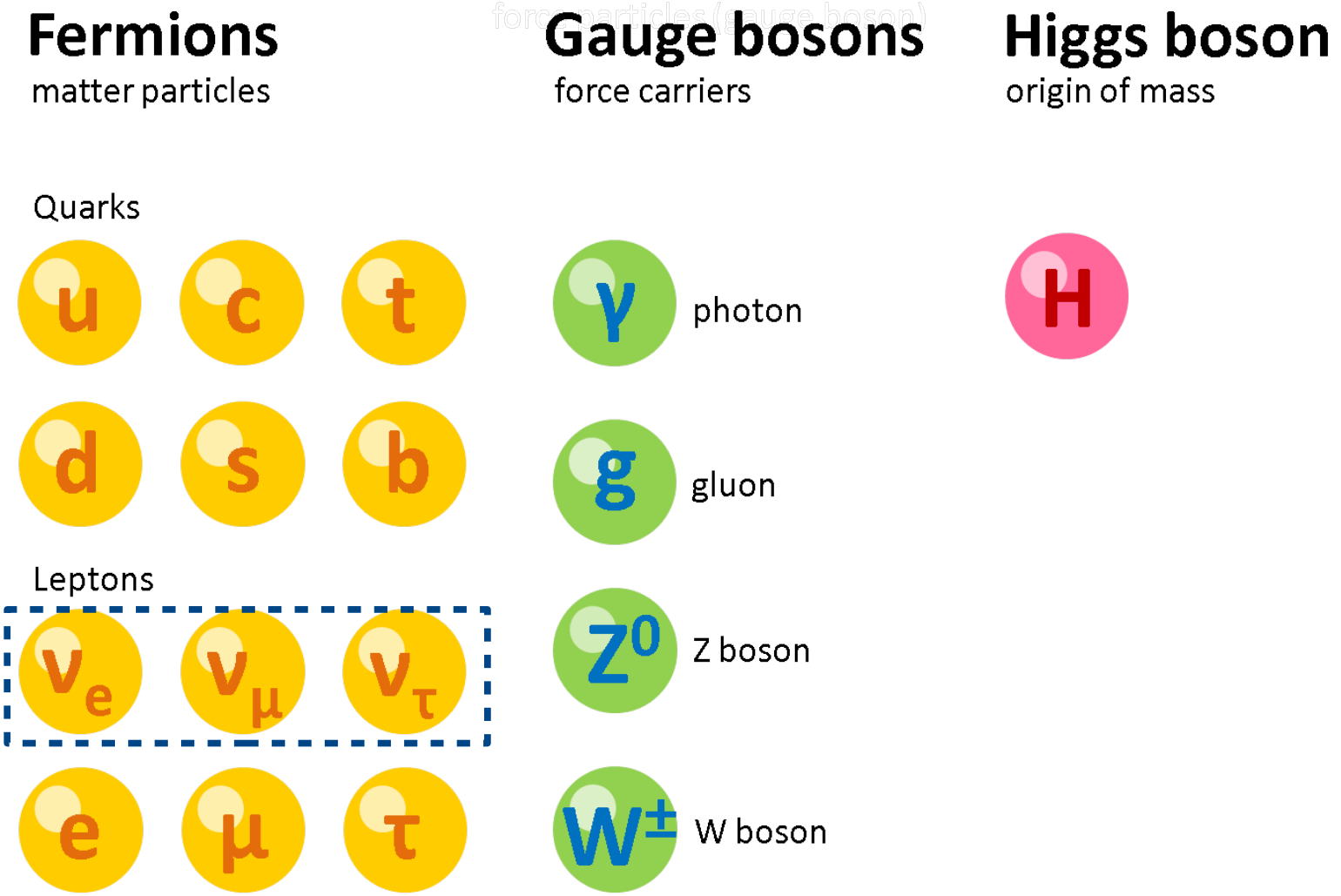
200+ scientists, engineers and students From 43+ institutions from 8 countries.

www-nova.fnal.gov


NOvA collaboration meeting @ANL
Summer 2016
Thank you!

Backup

Standard Model



NOvA Overview

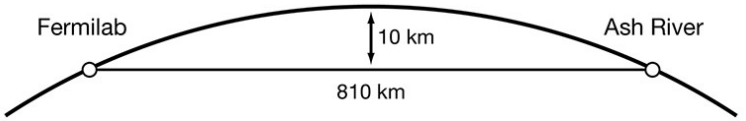
NuMI off-axis electron neutrino appearance experiment.

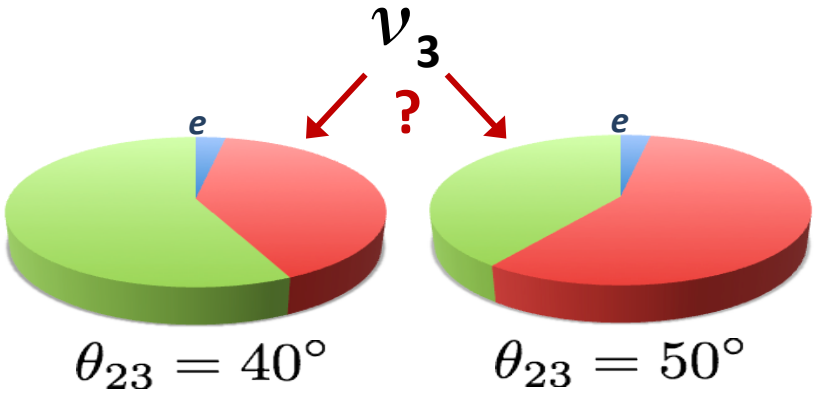
$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ (disappearance)

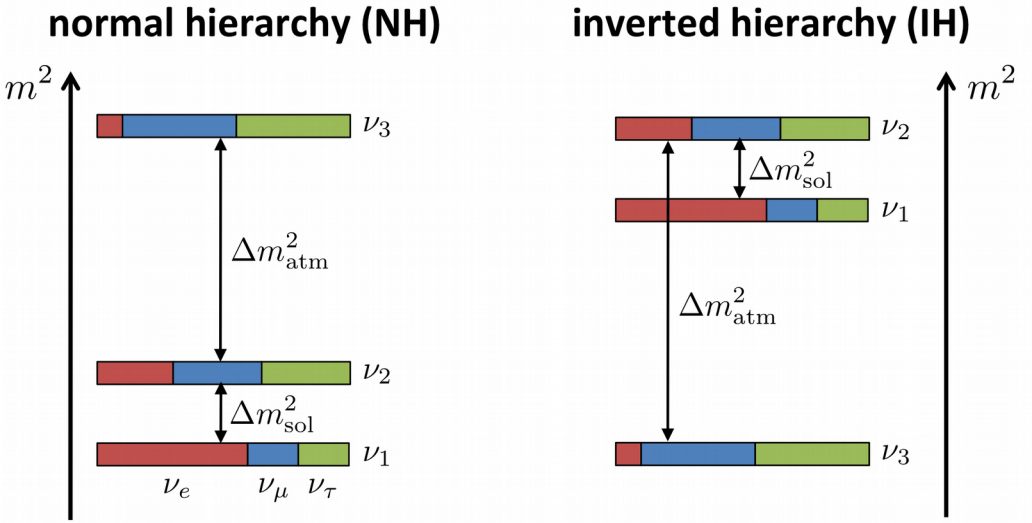
- Precision measurements of $\sin^2(2\theta_{23})$ and $\Delta m^2_{32.}$

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (appearance)

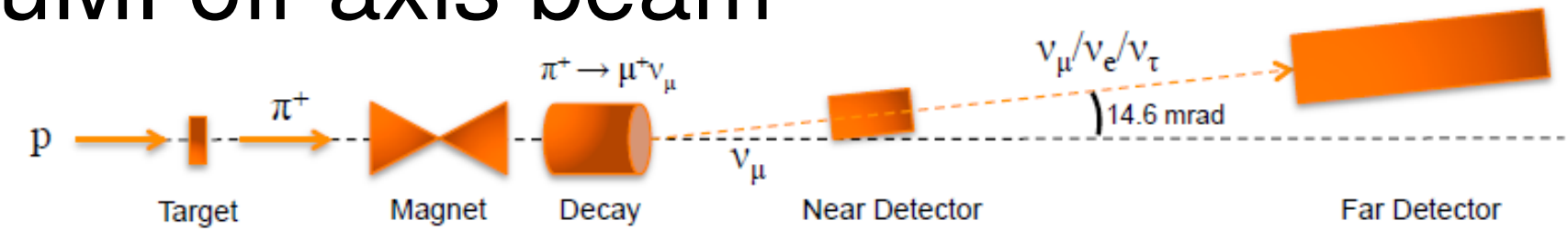
- Determine the ν mass ordering.
- Determine the θ_{23} octant.
- Constrain $\delta_{CP.}$



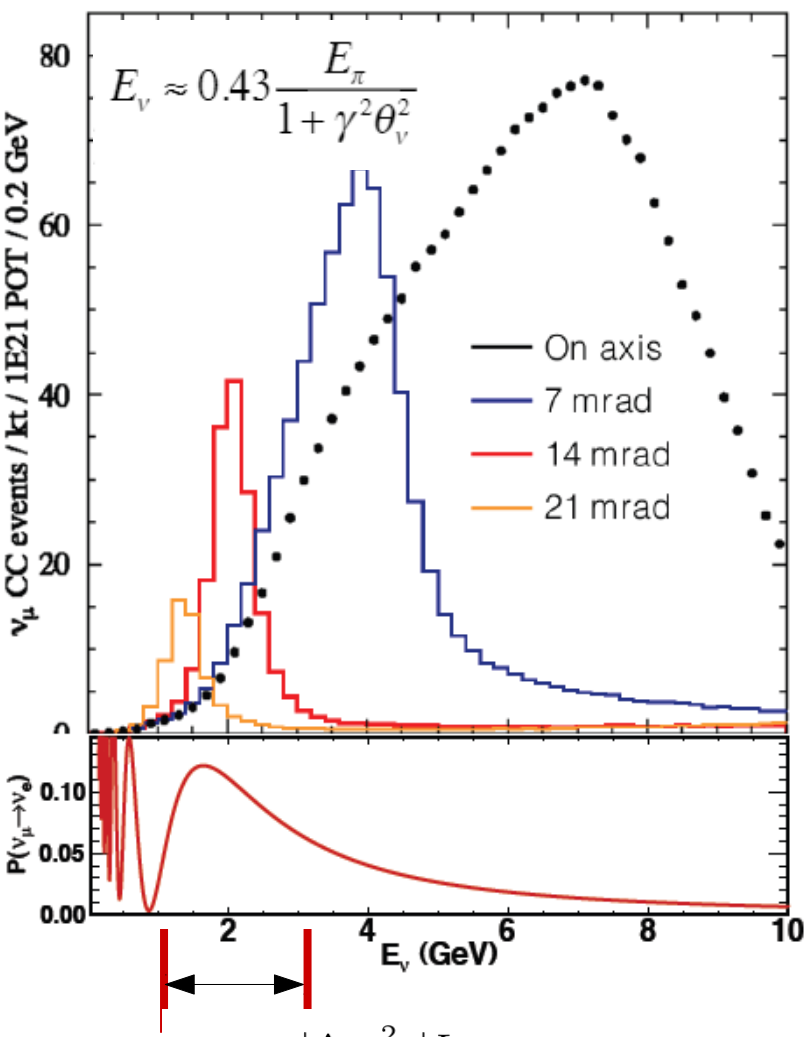




NuMI off-axis beam

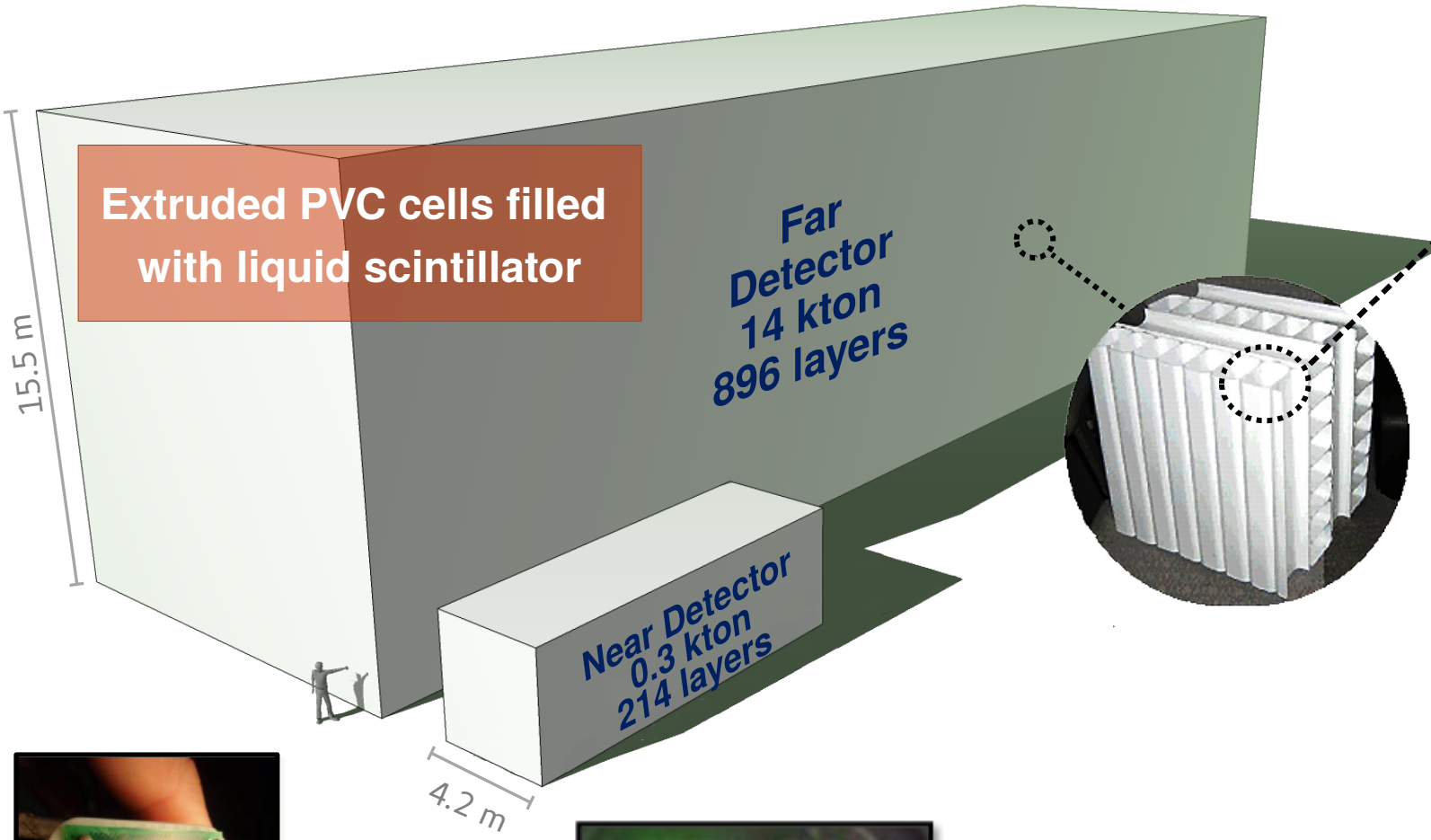


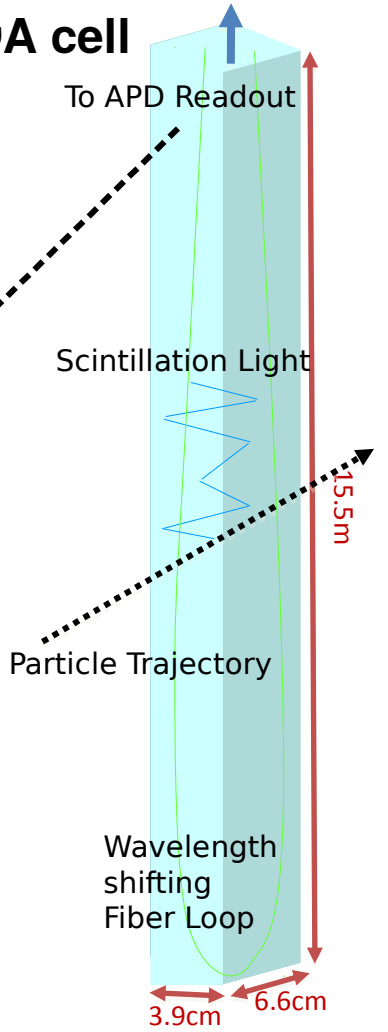
- NuMI = Neutrinos at the Main Injector.
- Plan to upgrade to 700kW power becoming most intense beam.
- Beam is produced in pulses of 10μs (a spill) every 1.33 sec producing 10^{18} protons-on-target (PoT) per day.
- Detectors are14 mrad off the NuMI beam axis.
- Narrow peak energy and reduces neutral current (NC) background.
- But integrated flux is reduced.

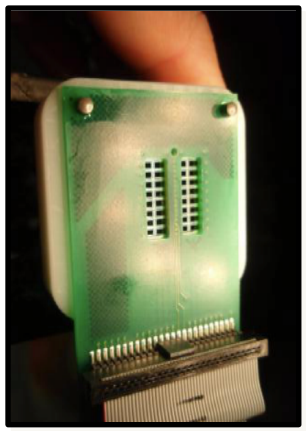


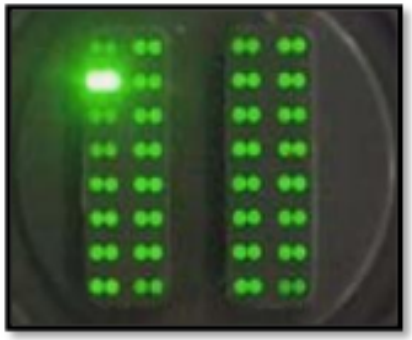
$$E_\nu = \frac{|\Delta m^2_{32}| L}{2\pi} \approx 2 \text{ GeV}$$

The detectors



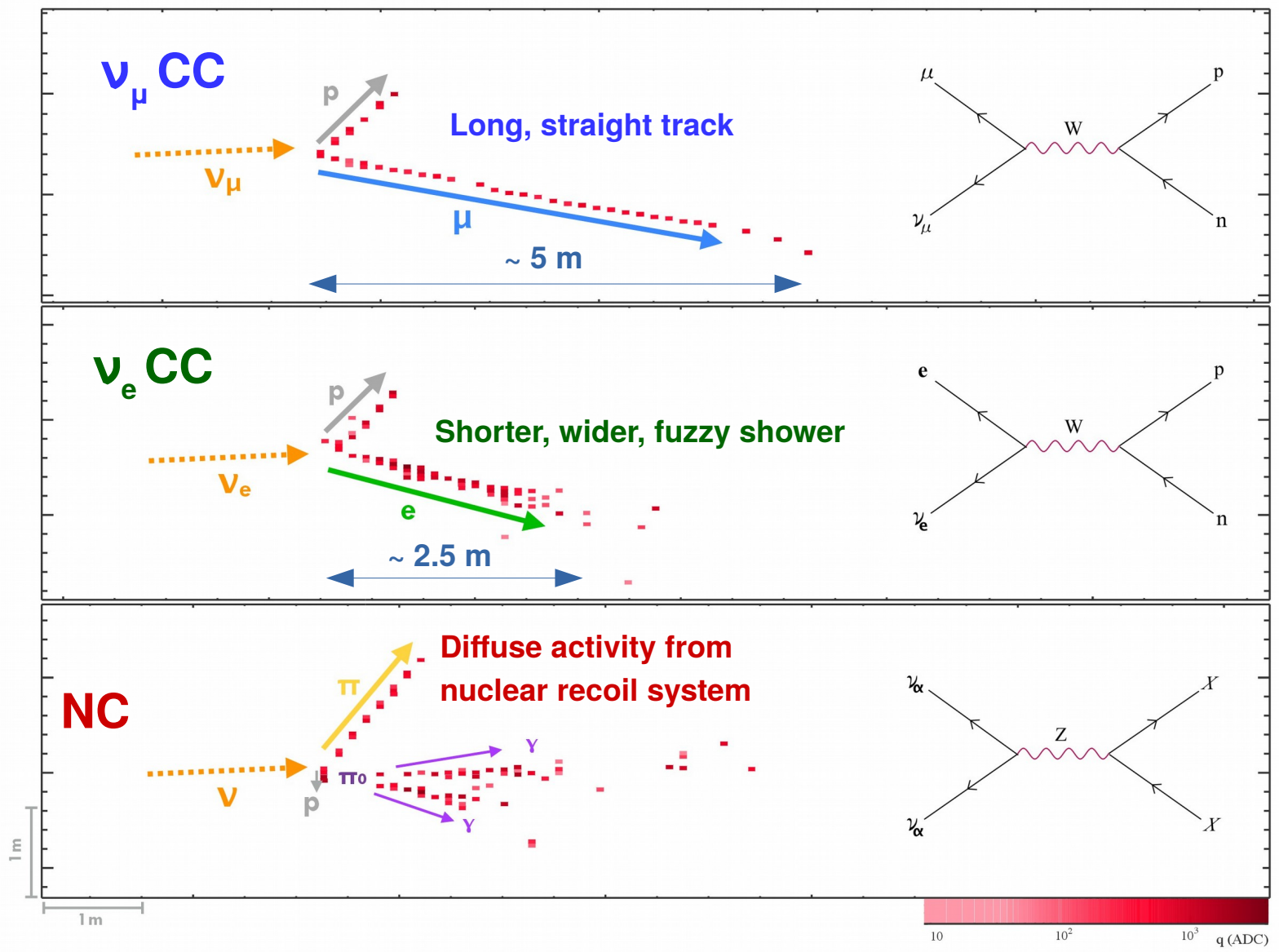






- **FarDet:** 14 kton, fine grained, low Z, highly active, tracking calorimeters (344 k channels)
- **NearDet:** 0.3 kton version of FarDet (20 k channels)

Final state classifications



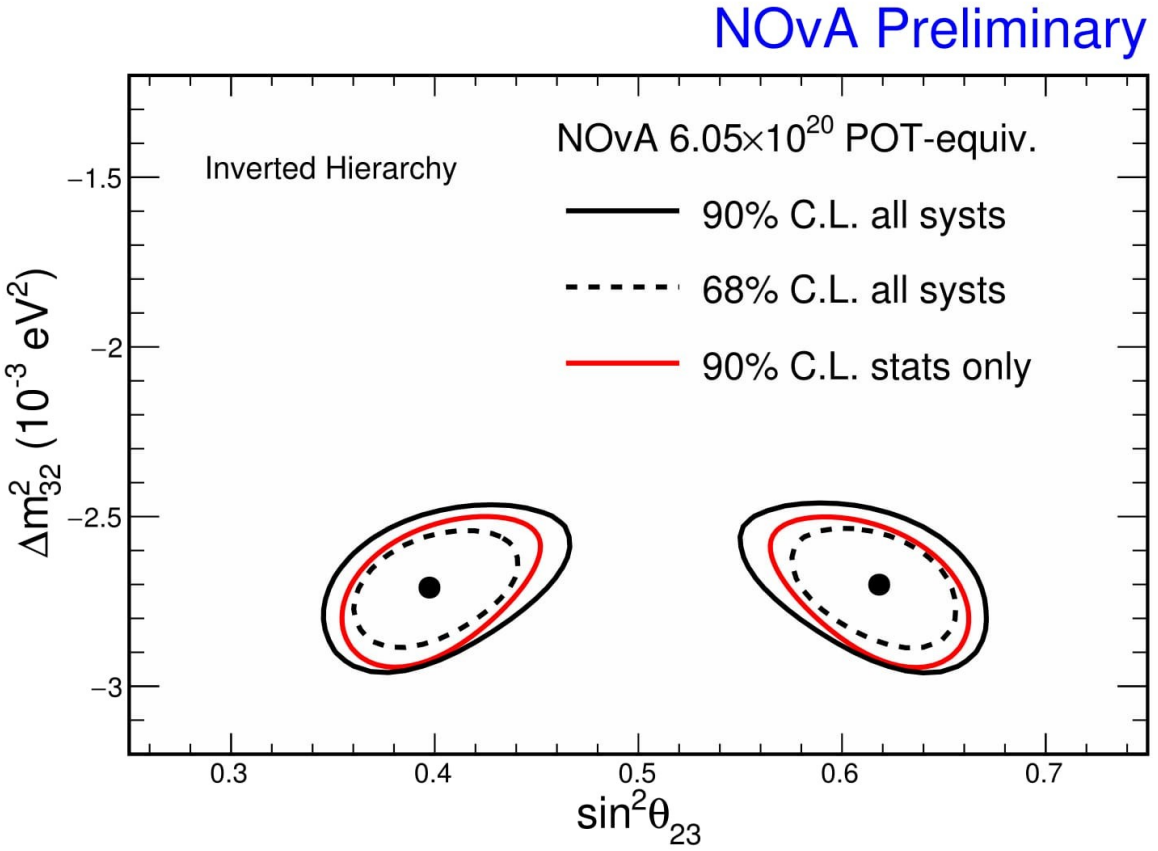
CC event

CC event

NC event

Inverted hierarchy

P. Adamson et al. (NOvA Collaboration)
Phys. Rev. Lett. 118, 151802

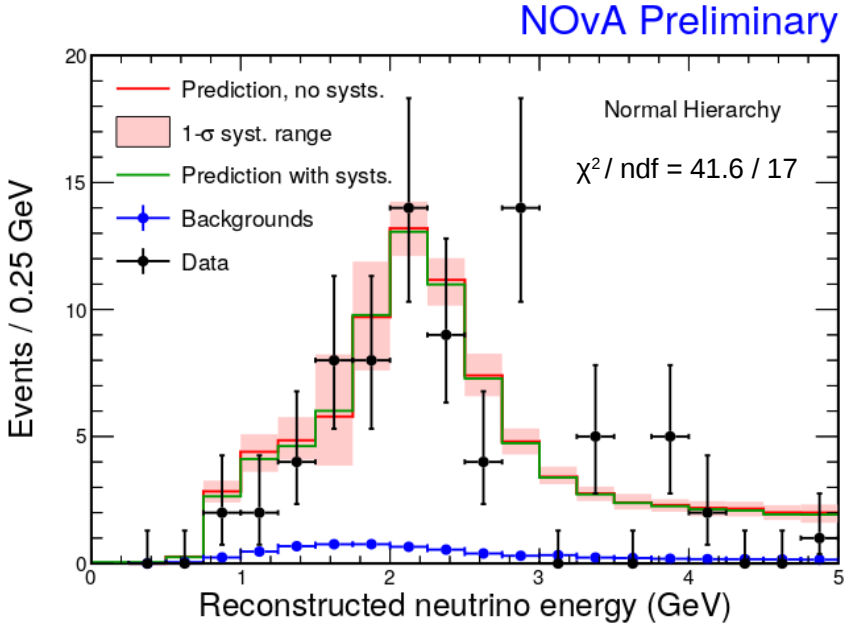


- Best fit (Inverted Hierarchy):

$$\Delta m^2_{32} = (-2.72 \pm 0.11) \times 10^{-3}\,\mathrm{eV}^2$$
$$\sin^2(\theta_{23}) = 0.398\,^{+0.030}_{-0.022} \text{ and } 0.618\,^{+0.022}_{-0.030}$$

Systematic uncertainties

P. Adamson et al. (NOvA Collaboration)
Phys. Rev. Lett. 118, 151802



Source of uncertainty	Uncertainty in $\sin^2\theta_{23}(\times 10^{-3})$	Uncertainty in Δm^2_{32} $(\times 10^{-6}$ eV$^2)$
Absolute muon energy scale [±2%]	+9 / -8	+3 / -10
Relative muon energy scale [±2%]	+9 / -9	+23 / -14
Absolute hadronic energy scale [±5%]	+5 / -5	+7 / -3
Relative hadronic energy scale [±5%]	+10 / -11	+29 / -19
Normalization [±5%]	+5 / -5	+4 / -8
Cross sections and final state interactions	+3 / -3	+12 / -15
Neutrino flux	+1 / -2	+4 / -7
Beam background normalization [±100%]	+3 / -6	+10 / -16
Scintillation model	+4 / -3	+2 / -5
δ_{CP} $[0-2\pi]$	+0.2 / -0.3	+10 / -9
Total systematic uncertainty	+17 / -19	+50 / -47
Statistical uncertainty	+21 / -23	+93 / -99

Discrete vs Real AdaBoost

- Discrete: the weak classifier $G_m(x)$ returns a discrete class label
- Real: base weak $G_m(x)$ returns a real value prediction (e.g., a probability mapped to the interval [-1,1])

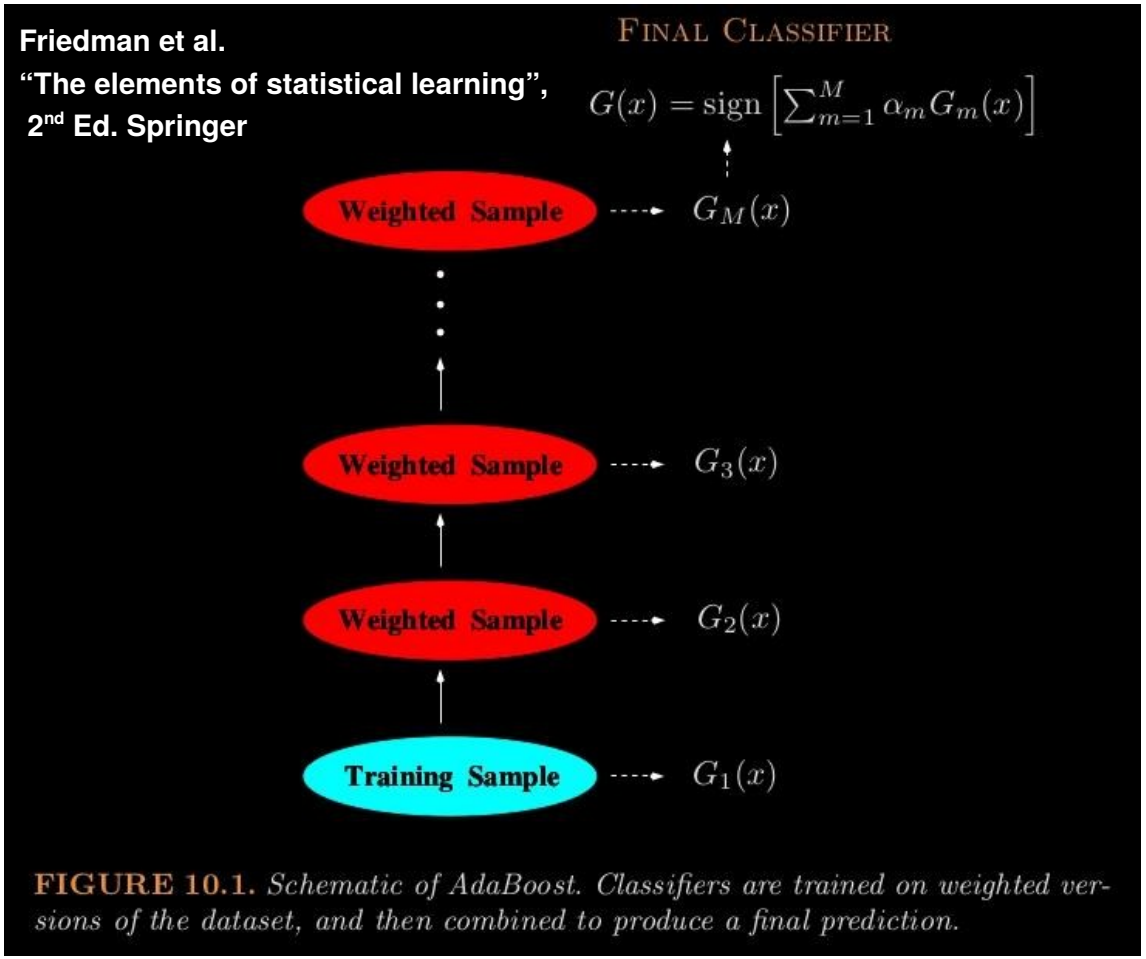
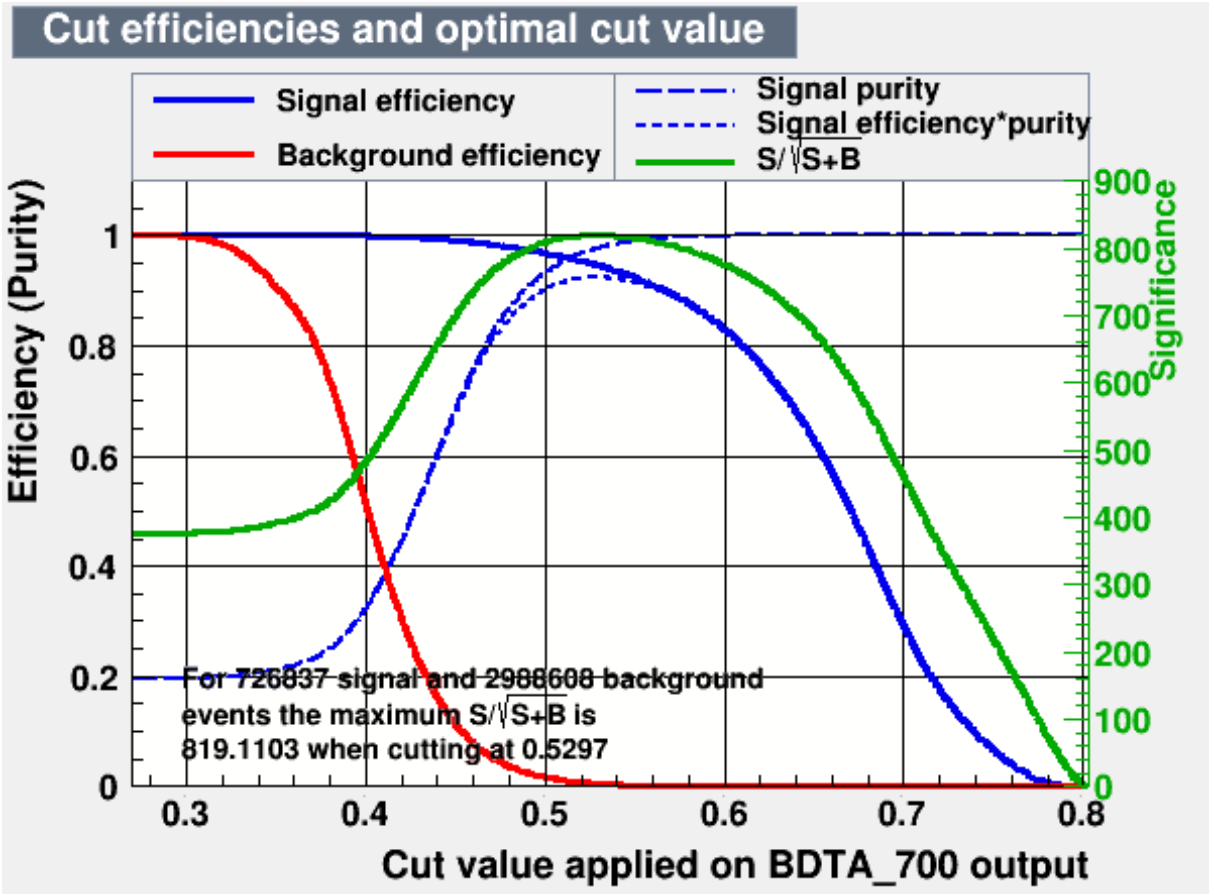


FIGURE 10.1. *Schematic of AdaBoost. Classifiers are trained on weighted versions of the dataset, and then combined to produce a final prediction.*

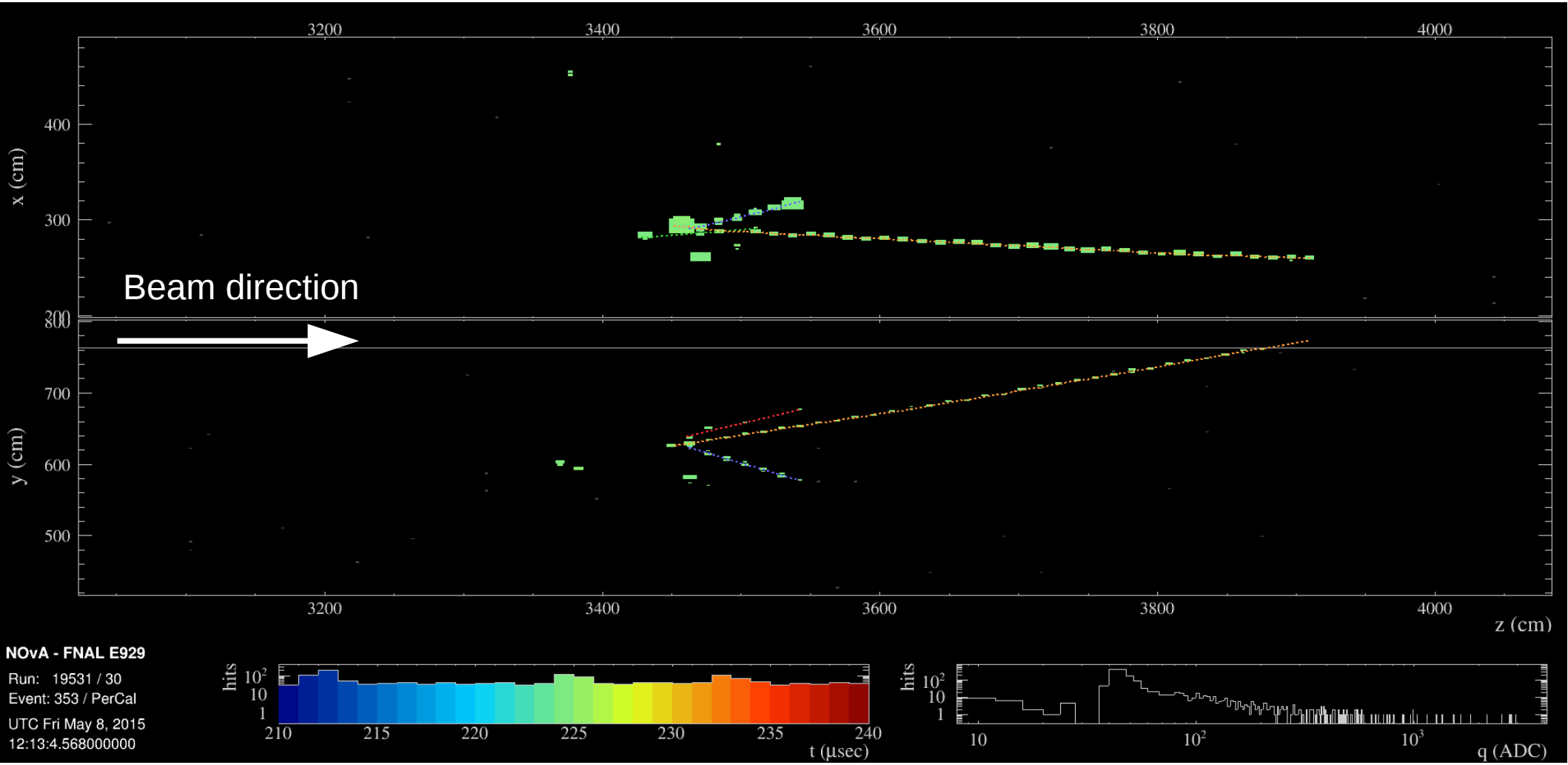
Decision trees

- Random forest of 700 trees, with Real AdaBoost
- Signal efficiency: 94.6 %



Signal event

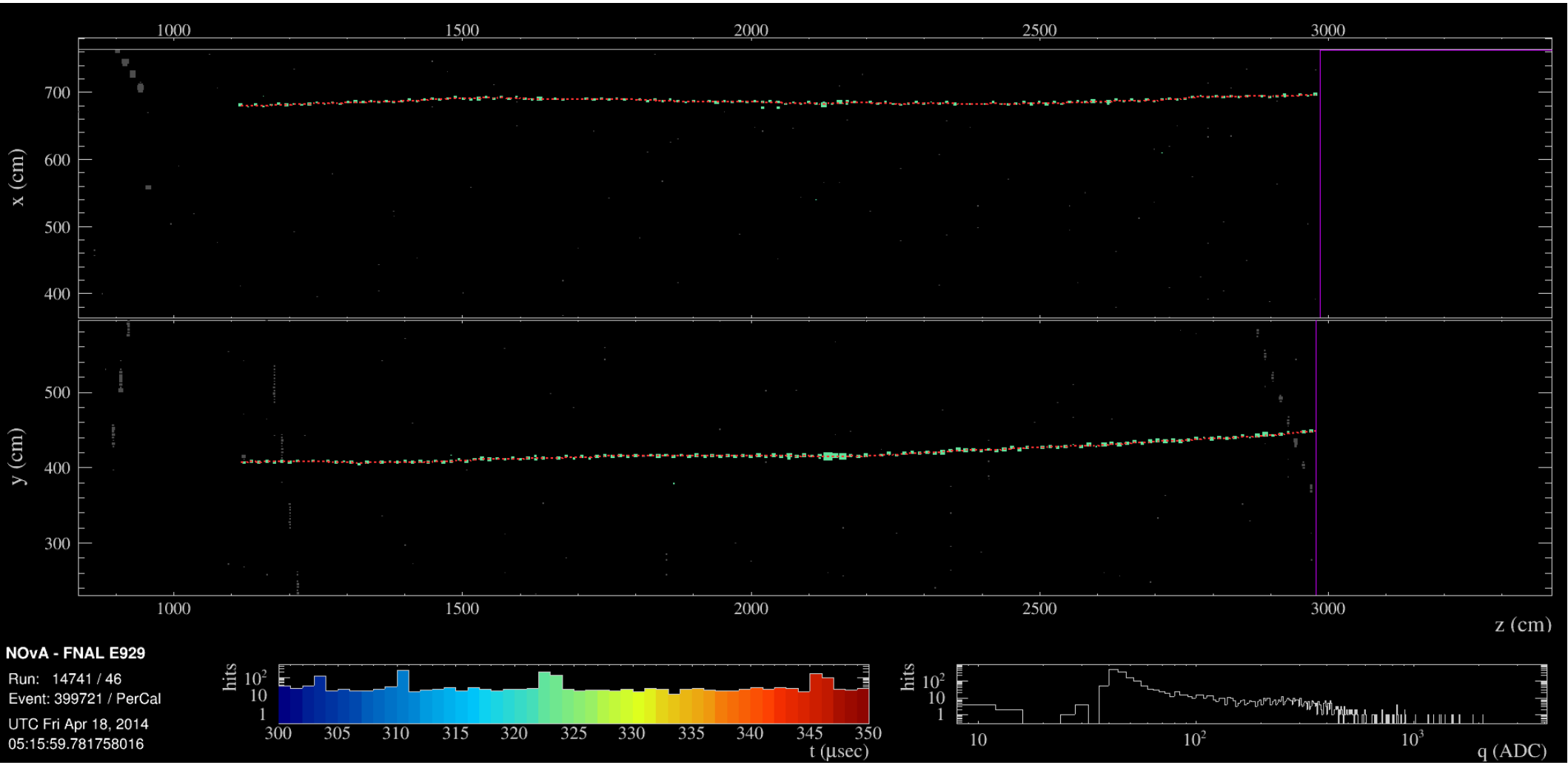
NOvA Simulation



Details: run 19531, subrun 30, event 353, subevent 32, TrueE 3.08 GeV

Background event

NOvA Data



Details: run 14741, subrun 46, event 399721, subevent 19, VisE 5.13 GeV