Recent results and outlook for the NOvA experiment

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November 4, 2016

NOvA

Oxscillation channels:

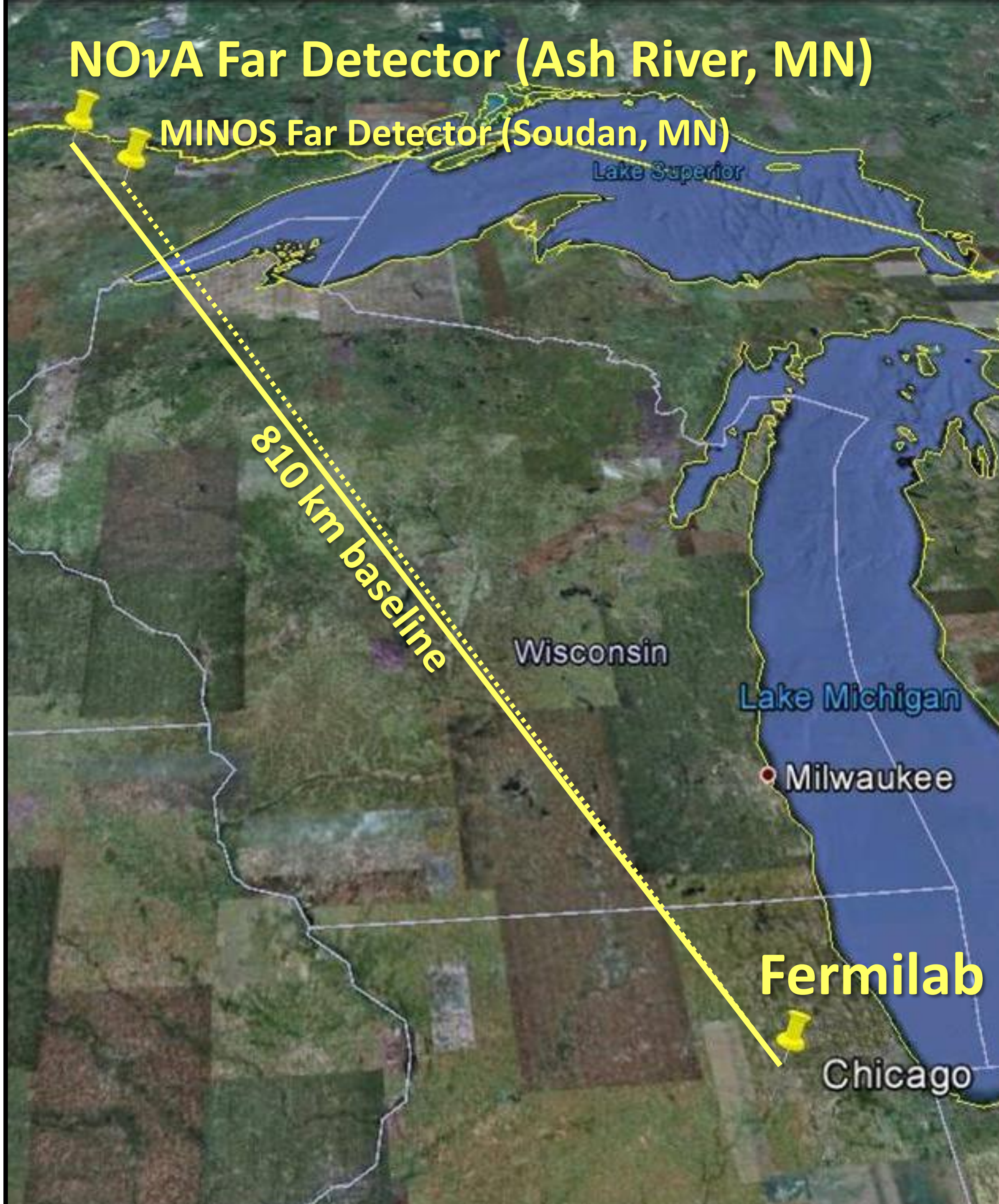
$\nu_\mu \to \nu_e$ $\bar{\nu}_\mu \to \bar{\nu}_e$

$\nu_\mu \to \nu_\mu$ $\bar{\nu}_\mu \to \bar{\nu}_\mu$

- **ν mass hierarchy ?**
- **θ_{23} octant ?** (ν_3 flavor mix)
- Allowed range of **δ_{CP} ?**
- Precision measurements of **$\sin^2\theta_{23}$** and **Δm^2_{32}** .
- **Over-constrain** the system (*Deviations from νSM ?*)

Also ...

- Sterile neutrinos, *CPT*v, NSI, and other exotica
- Supernova neutrinos
- Neutrino-nucleus scattering at Near Detector



Fermilab Neutrino Complex

Long shutdown in 2012–2013

Repurpose Recycler Ring
for injection, reduced cycle time

2016 shutdown ending now

→ *700 kW operation*

4.7×10^{20} p.o.t. delivered in FY16

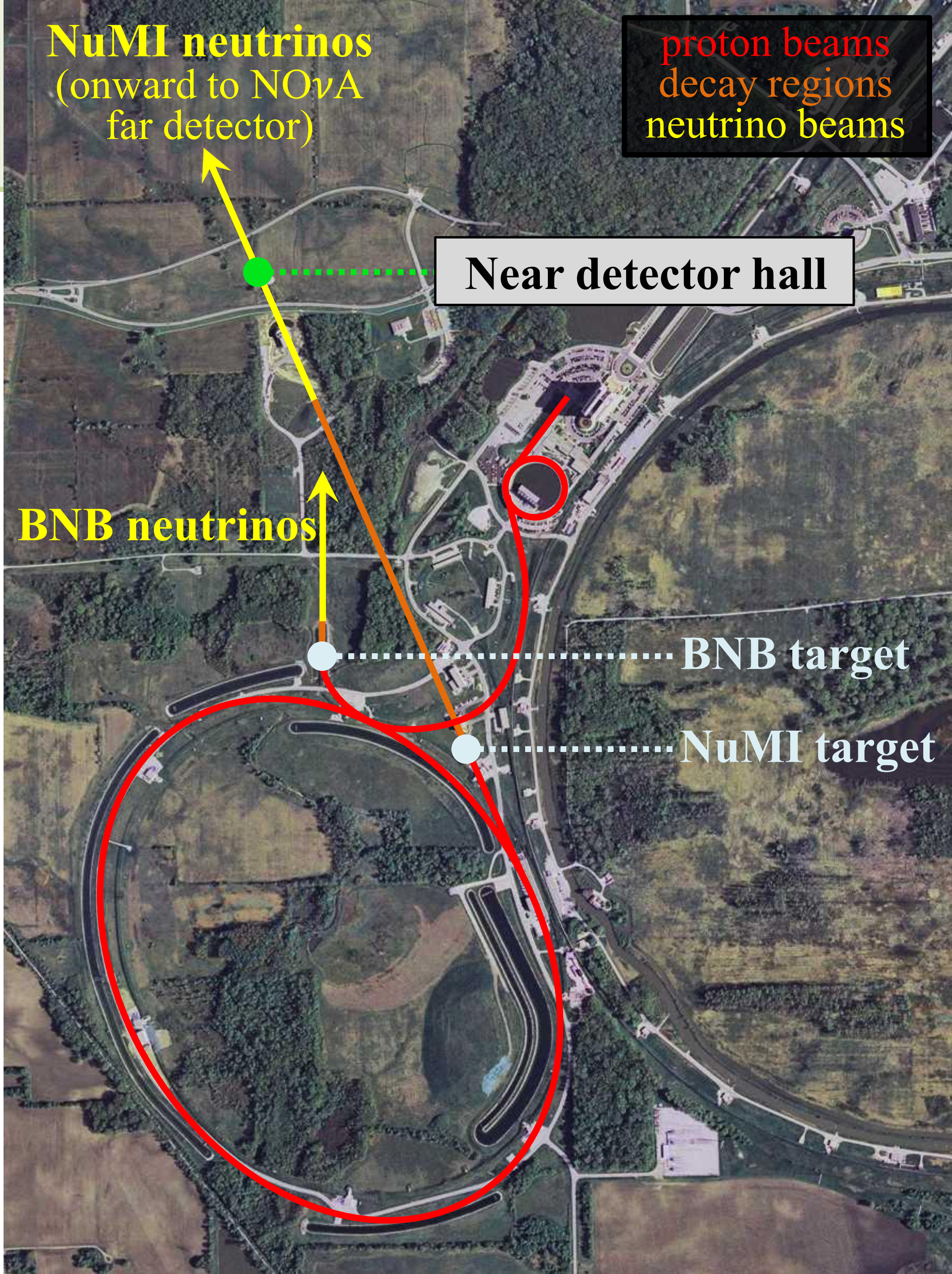
→ *a NuMI record*

Data shown today represents:

6.05×10^{20} protons-on-target*

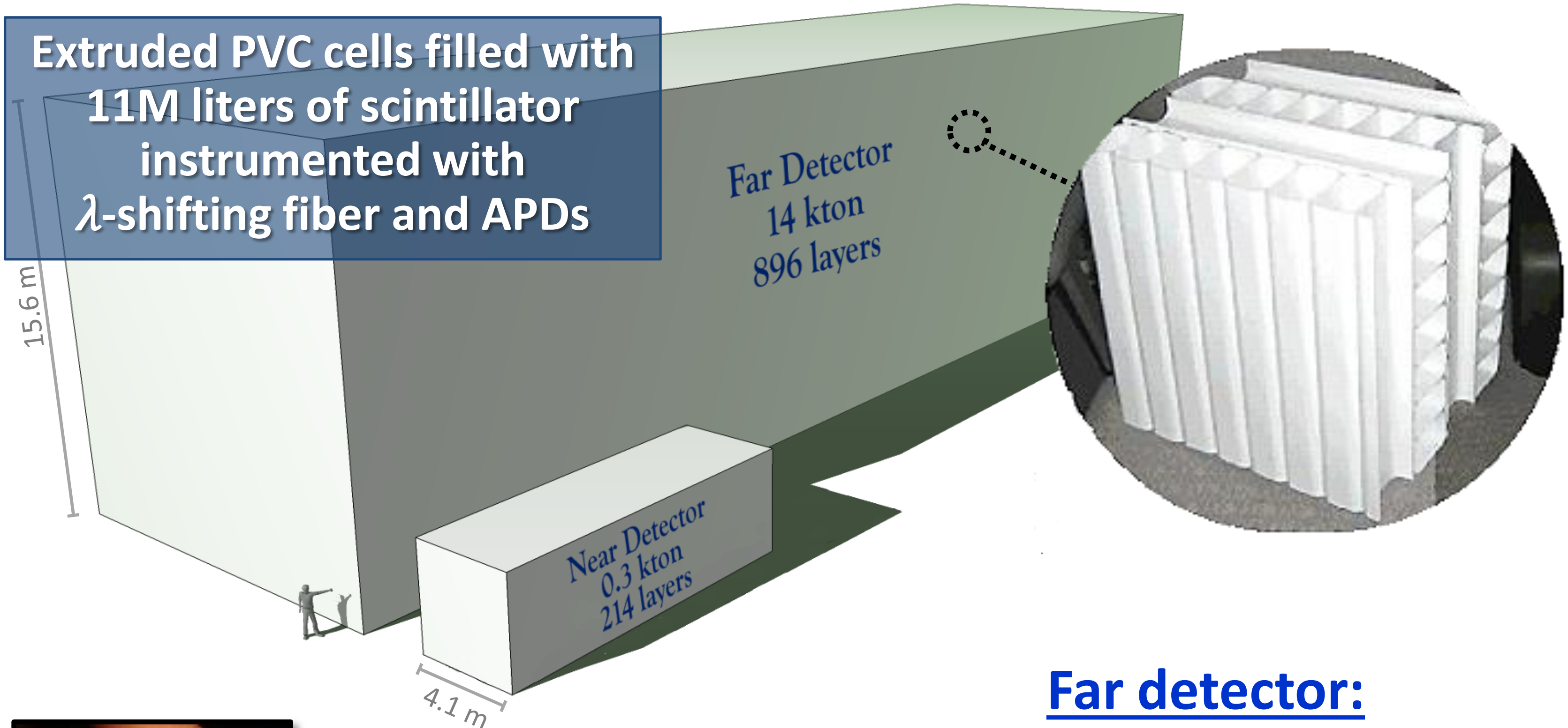
→ 17% of currently approved exposure

* As normalized to full-sized Far Detector. Actual FD size varied during commissioning and early running.

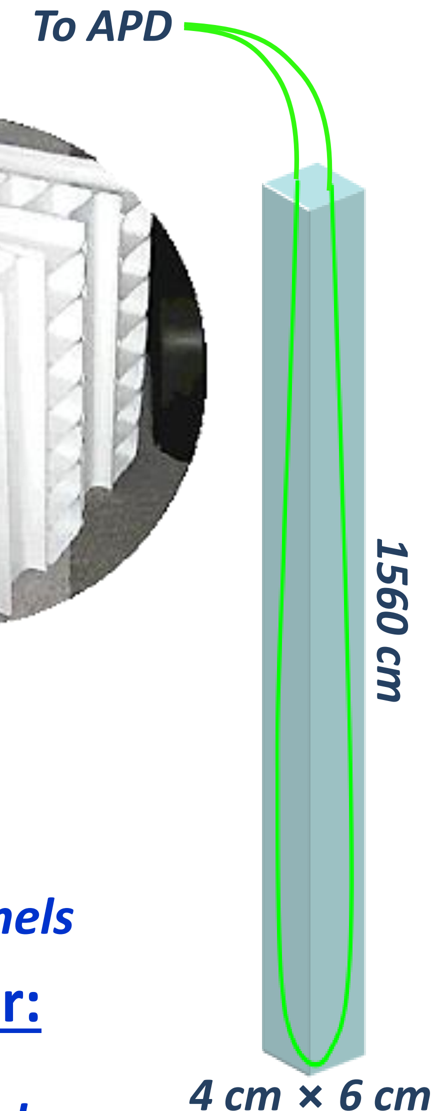


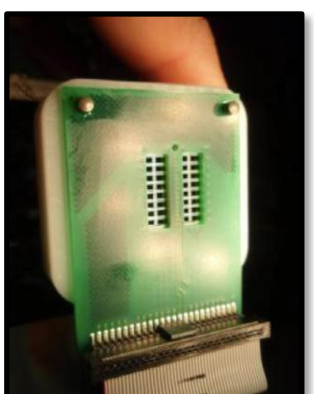
NOνA detectors

Extruded PVC cells filled with 11M liters of scintillator instrumented with λ-shifting fiber and APDs



A NOνA cell





32-pixel APD ←

Fiber pairs from 32 cells →

Far detector:

14-kton

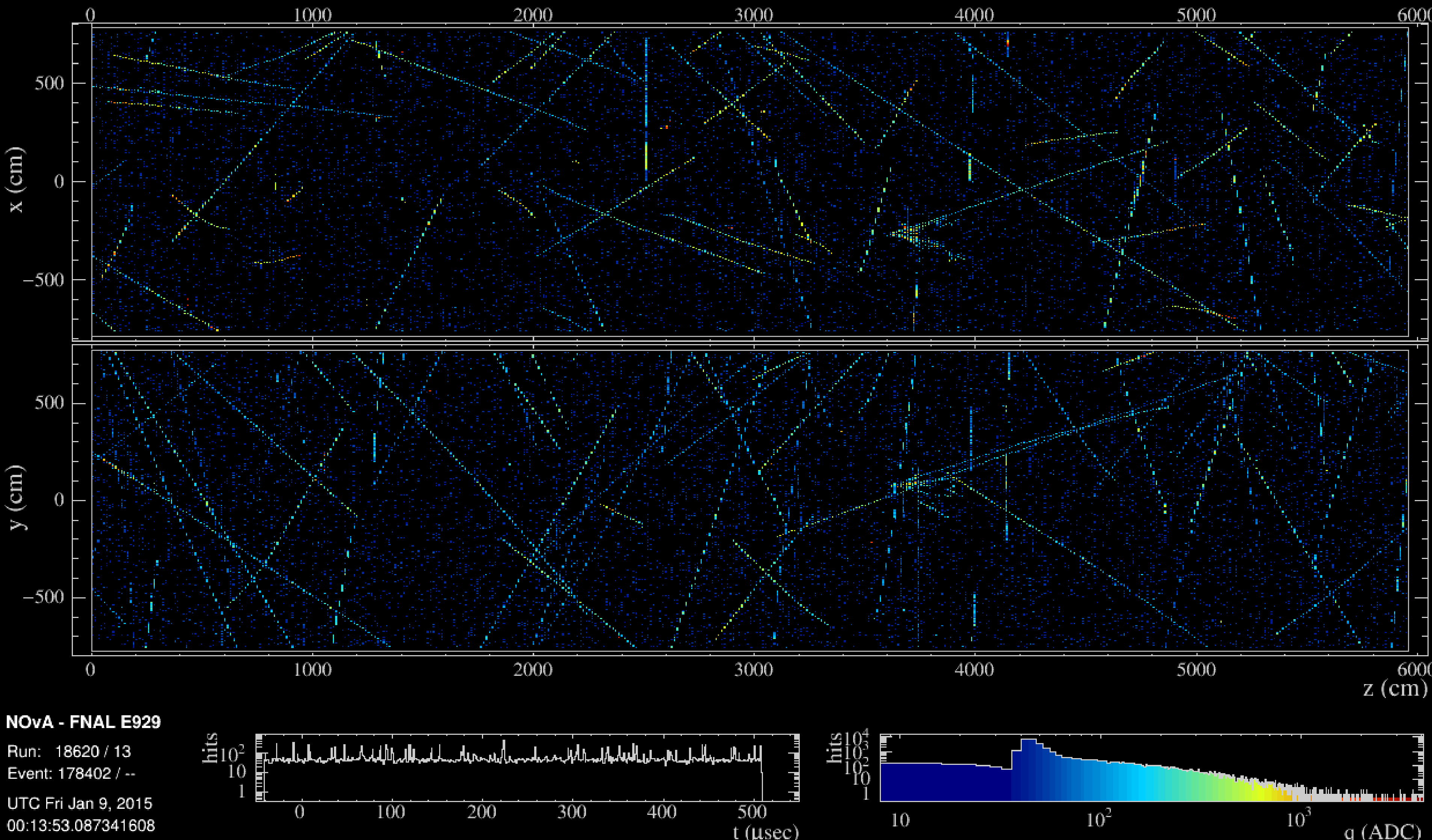
344,000 channels

Near detector:

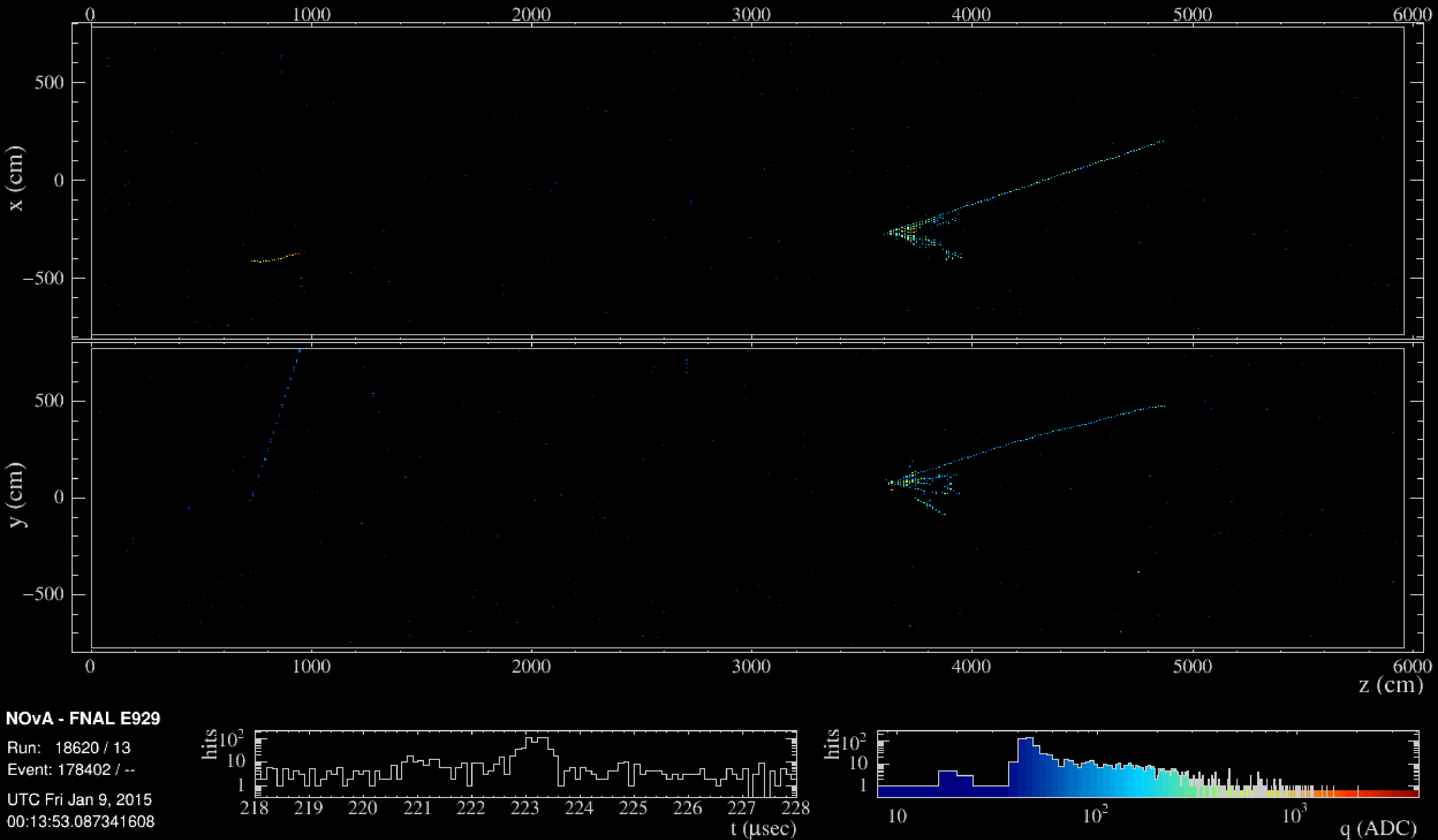
0.3-kton

20,000 channels

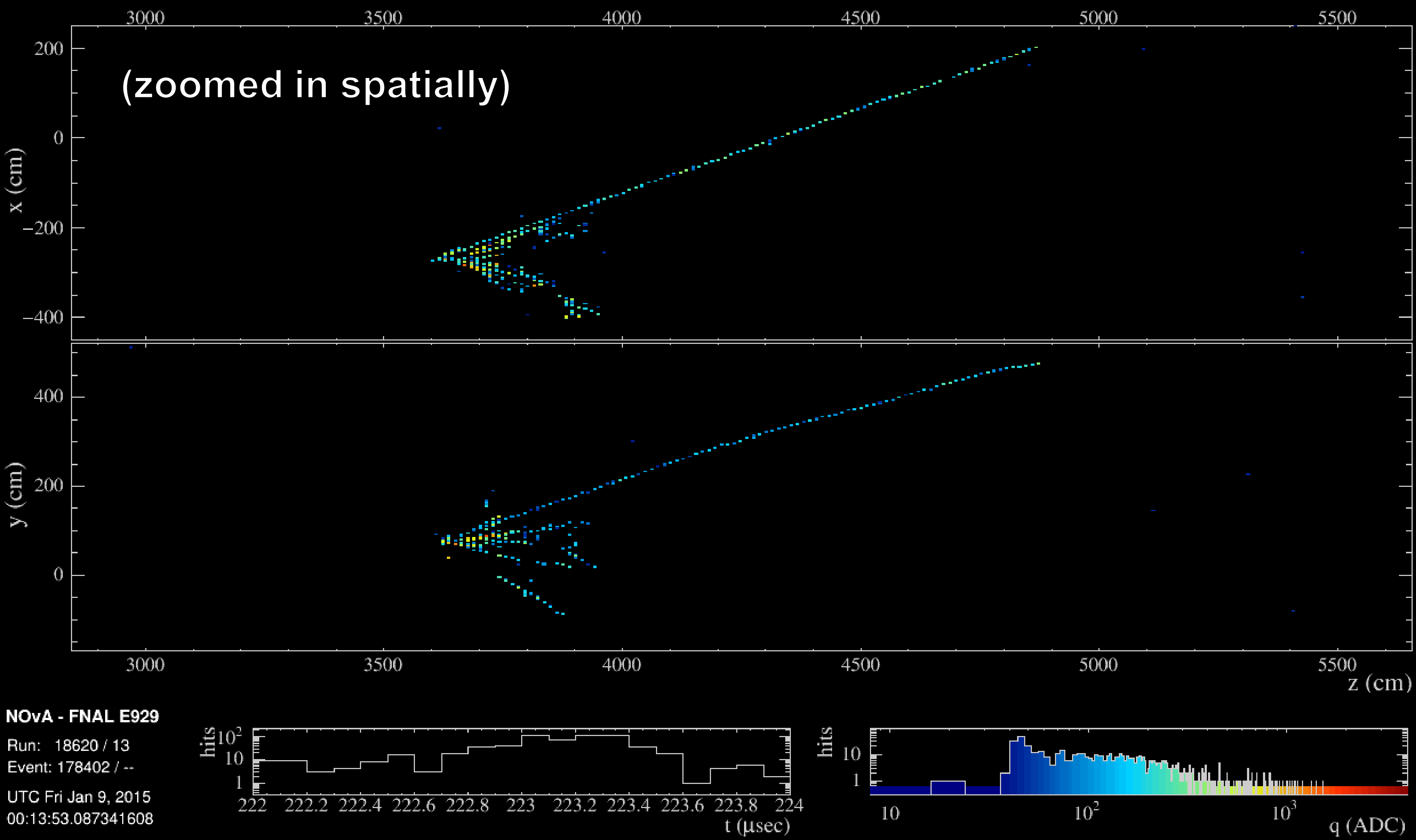
550 μs exposure of the Far Detector



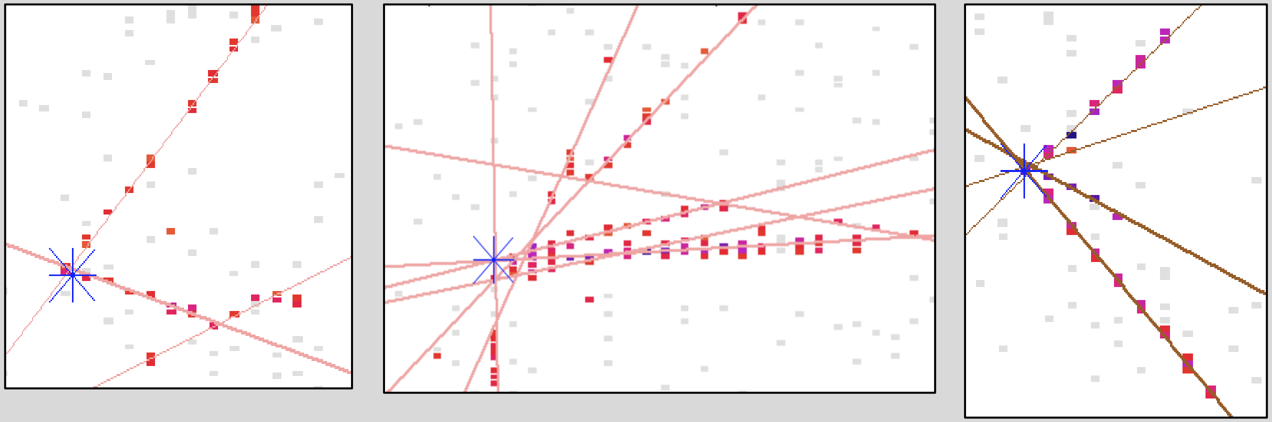
Time-zoom on 10 μs interval during NuMI beam pulse



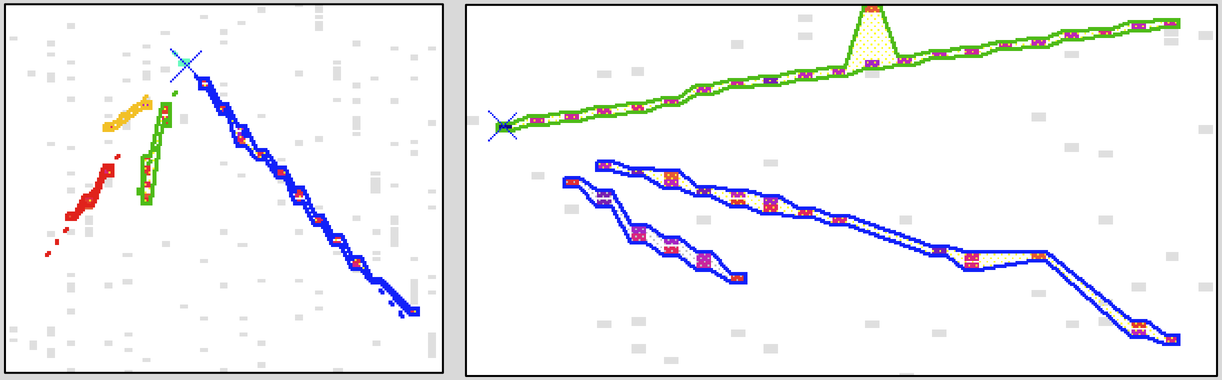
Close-up of neutrino interaction in the Far Detector



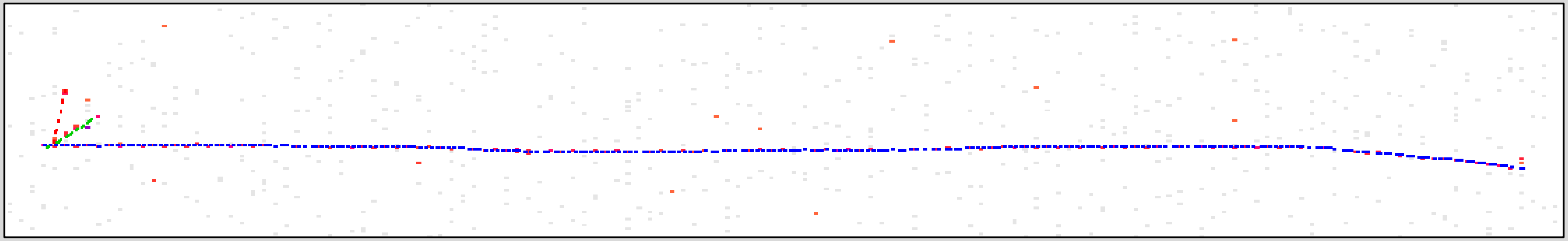
Vertexing:



Clustering:

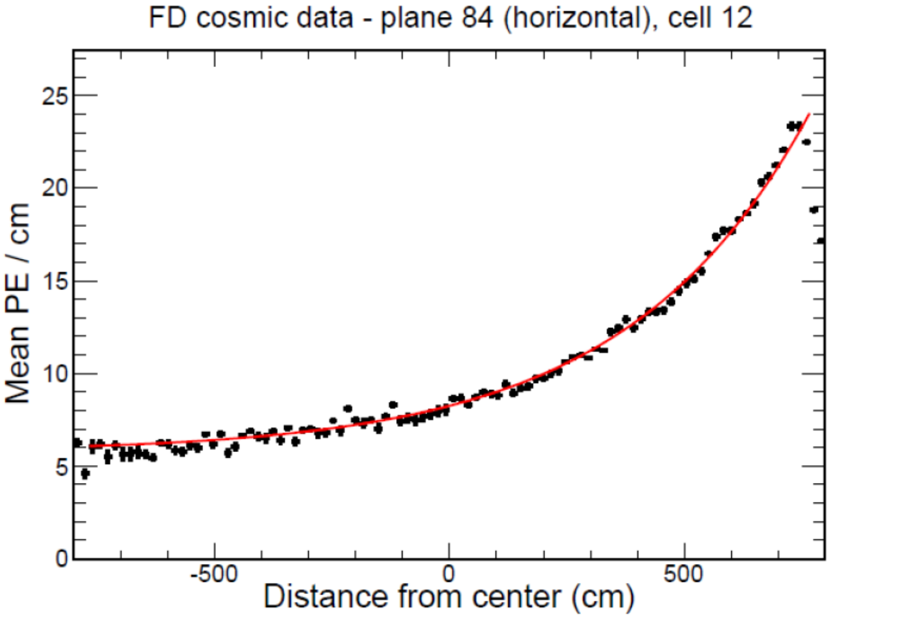


Tracking:

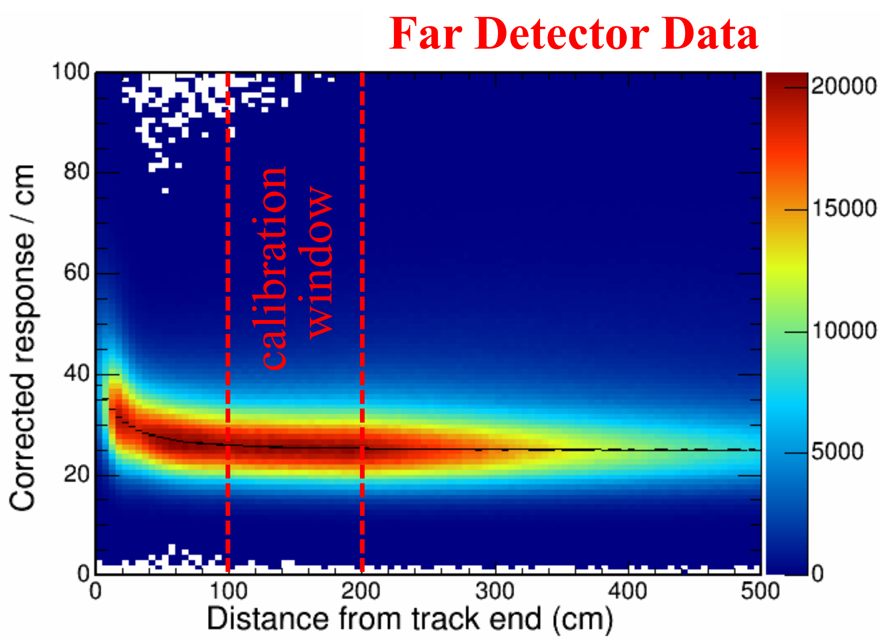


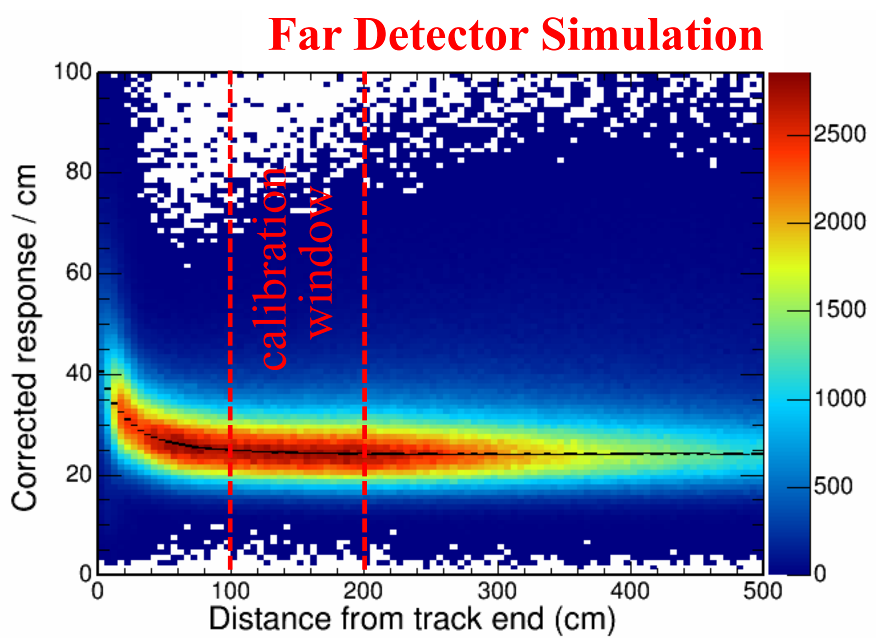
Calibration

Attenuation in the WLS fiber ⟶



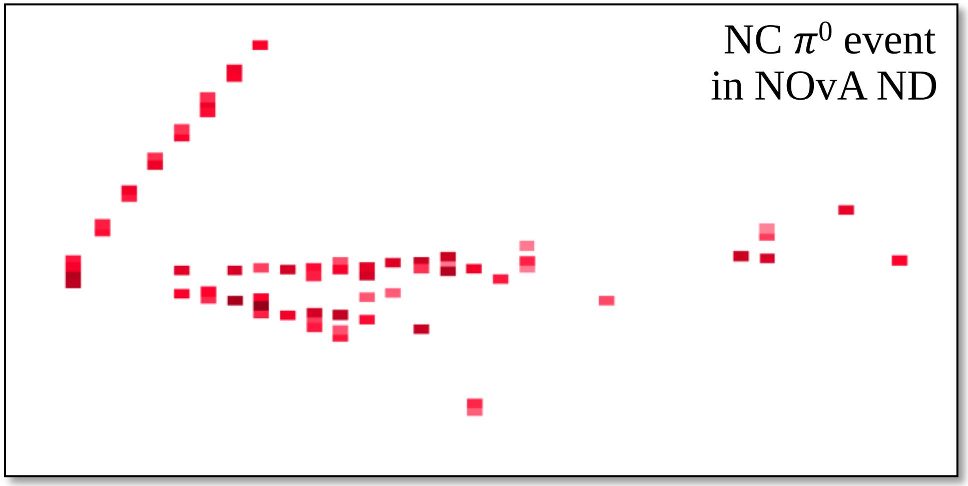
Stopping muons provide absolute energy scale *(below)*

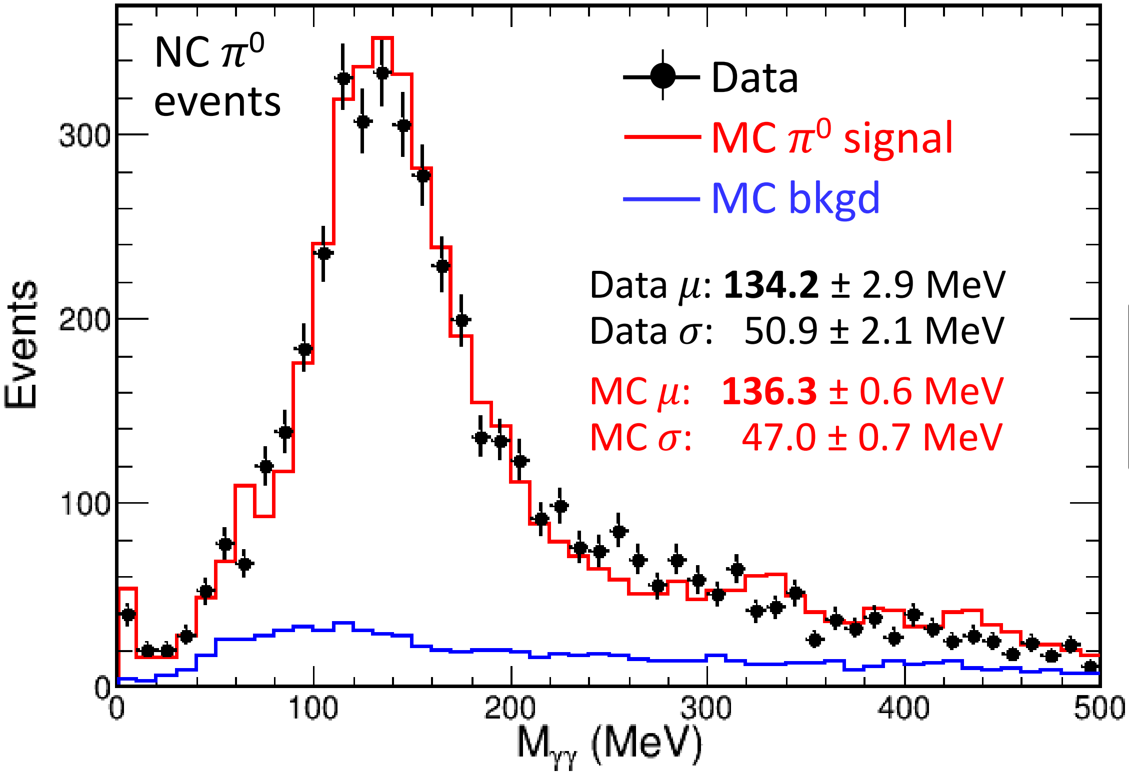




Checking energy scale

- ***μ dE/dx***, various positions/angles
- **Michel electron energy** (μ decay)
- **bremsstrahlung energy**
- **hadronic shower hits**



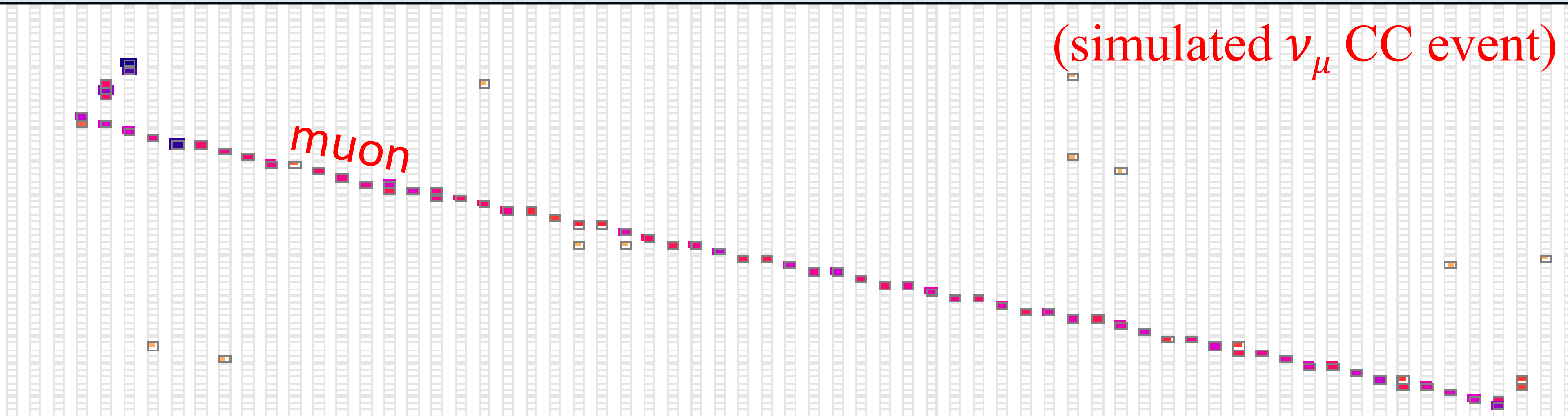


π^0 invariant mass

All agree within ±5%

ν_μ disappearance

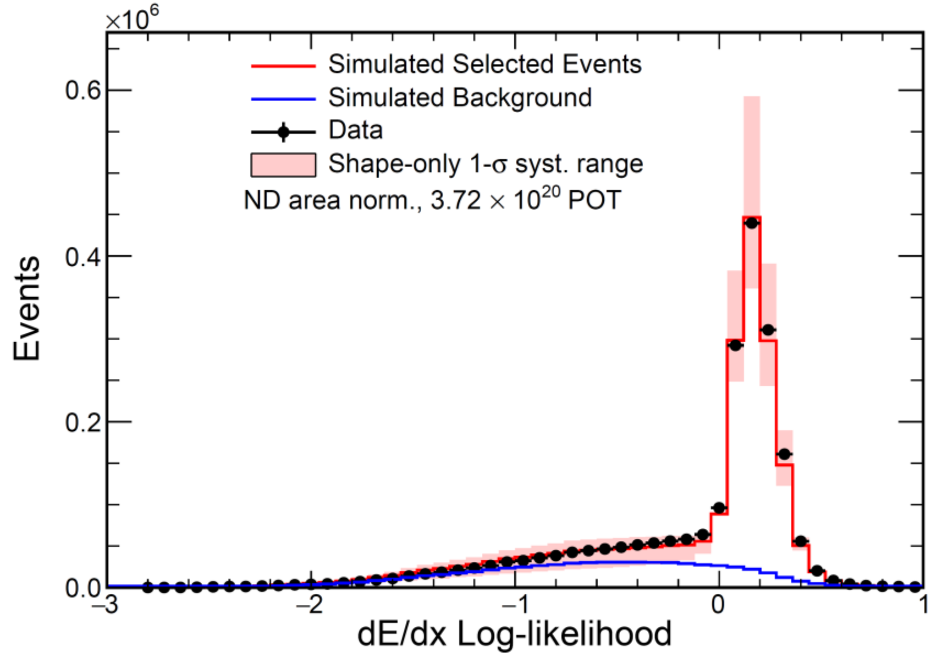
- Identify **contained ν_μ CC events** in each detector
- Measure their **energies**
- Extract oscillation information from differences between the **Far and Near energy spectra**

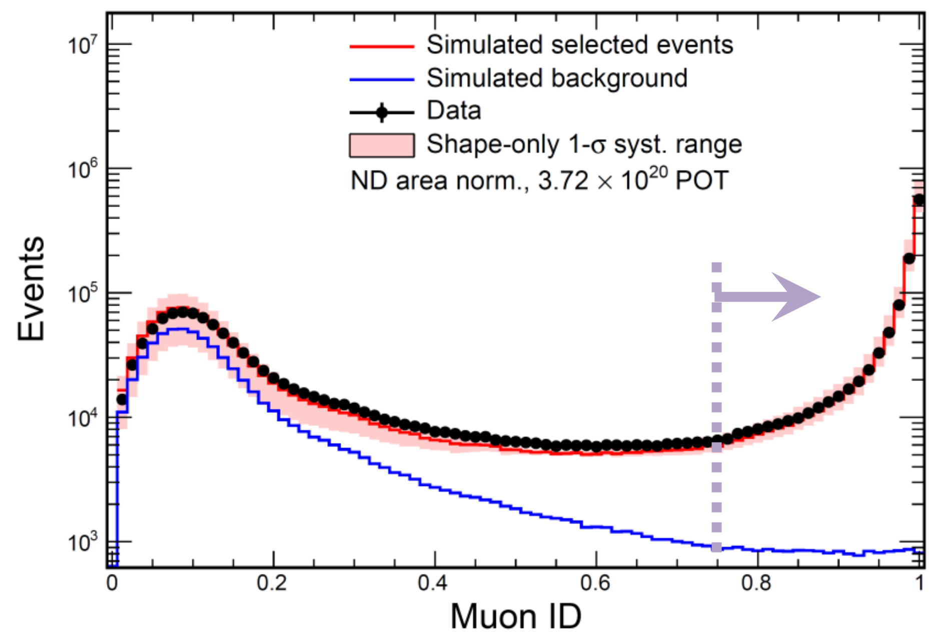


Look for muons:

- long tracks
- appropriate *dE/dx* profiles
- appropriate scattering

Resulting classifier





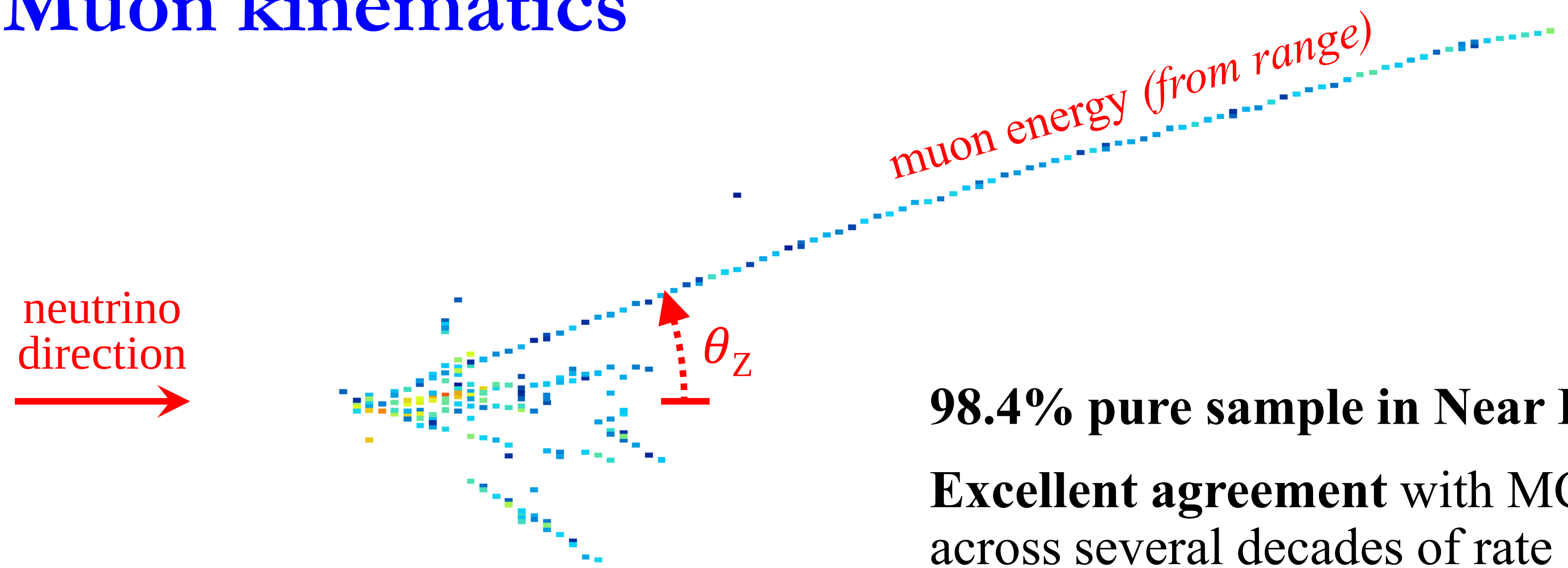
In Far Detector, must
also reject cosmic rays:

- beam timing ($\times 10^{-5}$)
- event location and shape ($\times 10^{-7}$)

Cosmic background rate **measured directly** with beam-off data.

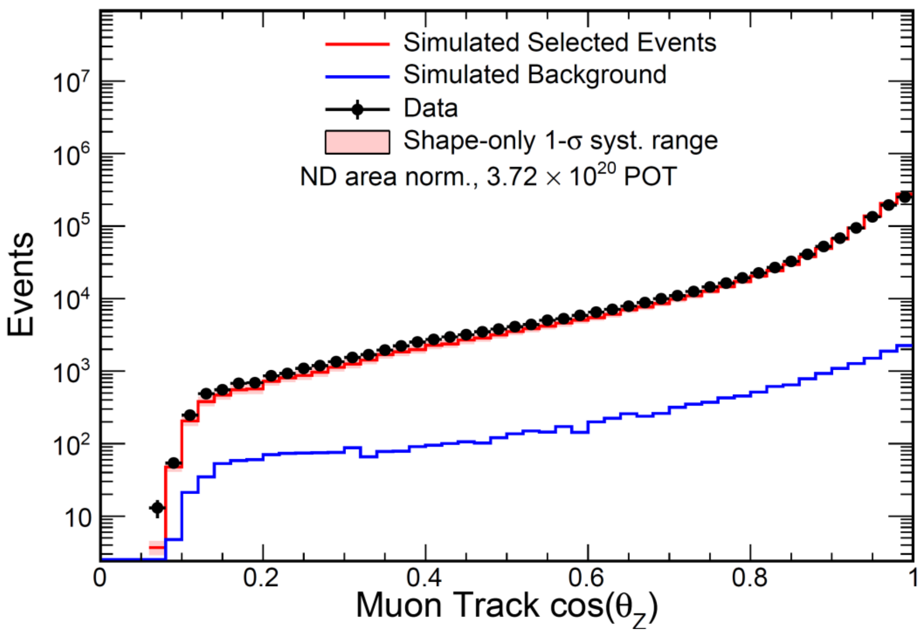
⇒ 3.5% of ν_μ CC candidates in FD are actually mis-ID'd cosmics

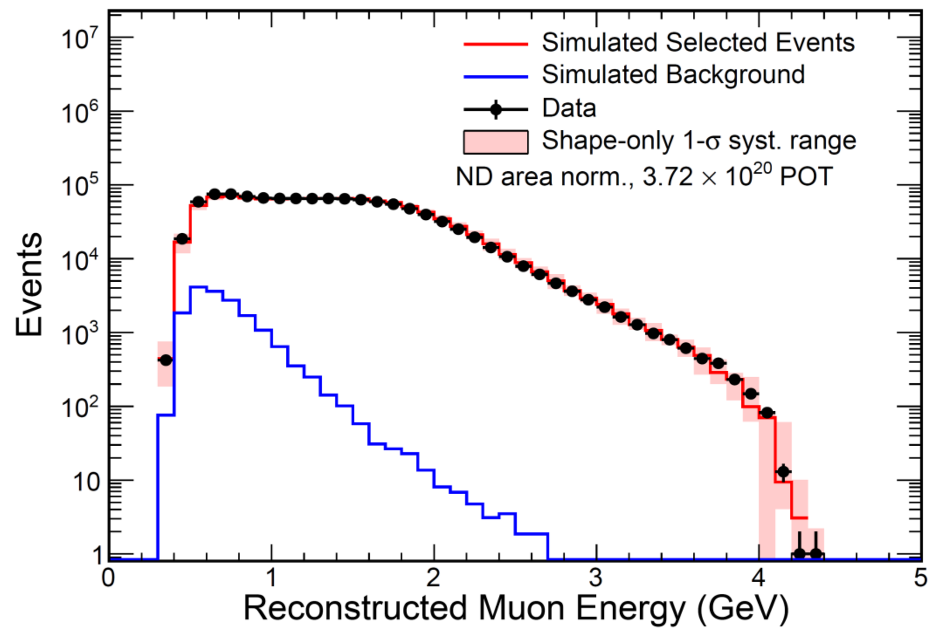
Muon kinematics



98.4% pure sample in Near Detector

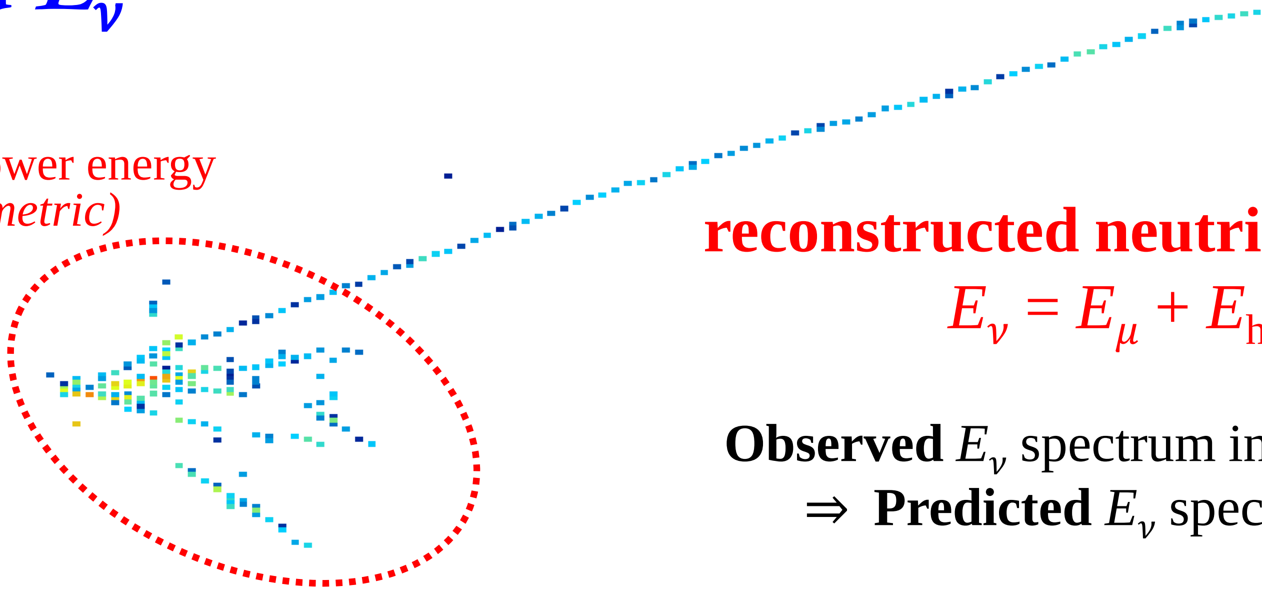
Excellent agreement with MC simulation across several decades of rate





E_{had} and E_ν

hadronic shower energy
(calorimetric)



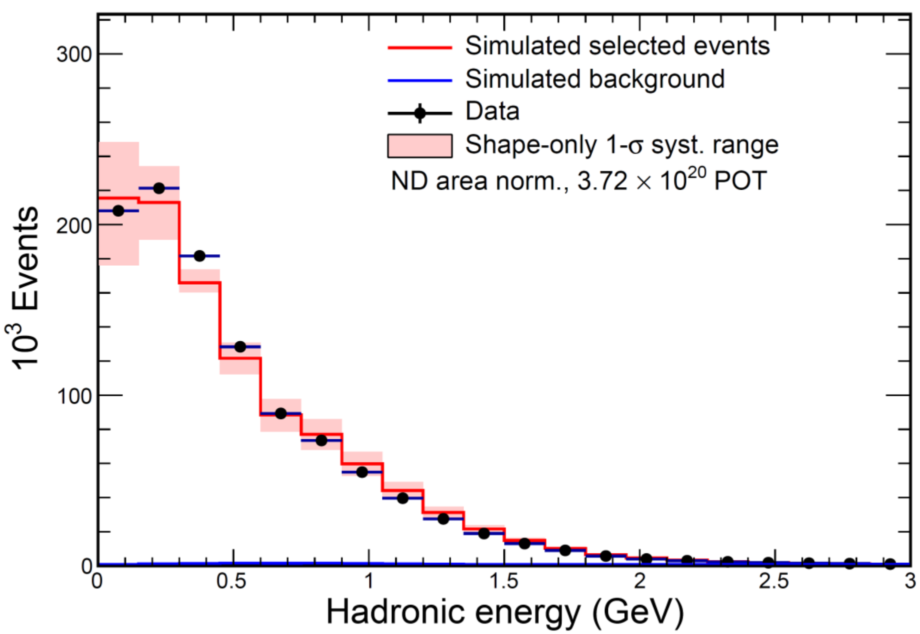
reconstructed neutrino energy:

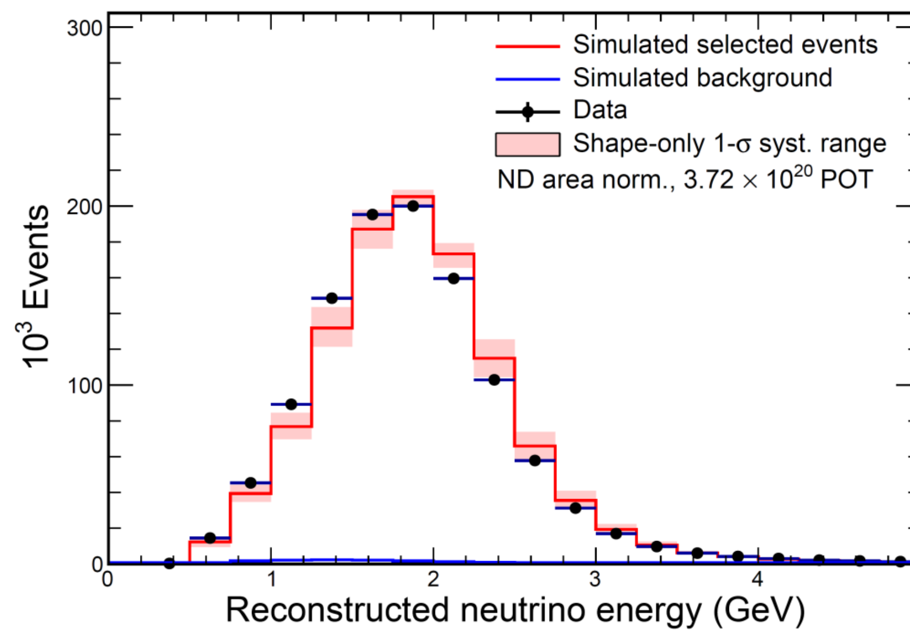
$$E_\nu = E_\mu + E_{\text{had}}$$

Observed E_ν spectrum in the ND

$\Rightarrow$ **Predicted** E_ν spectrum in the FD

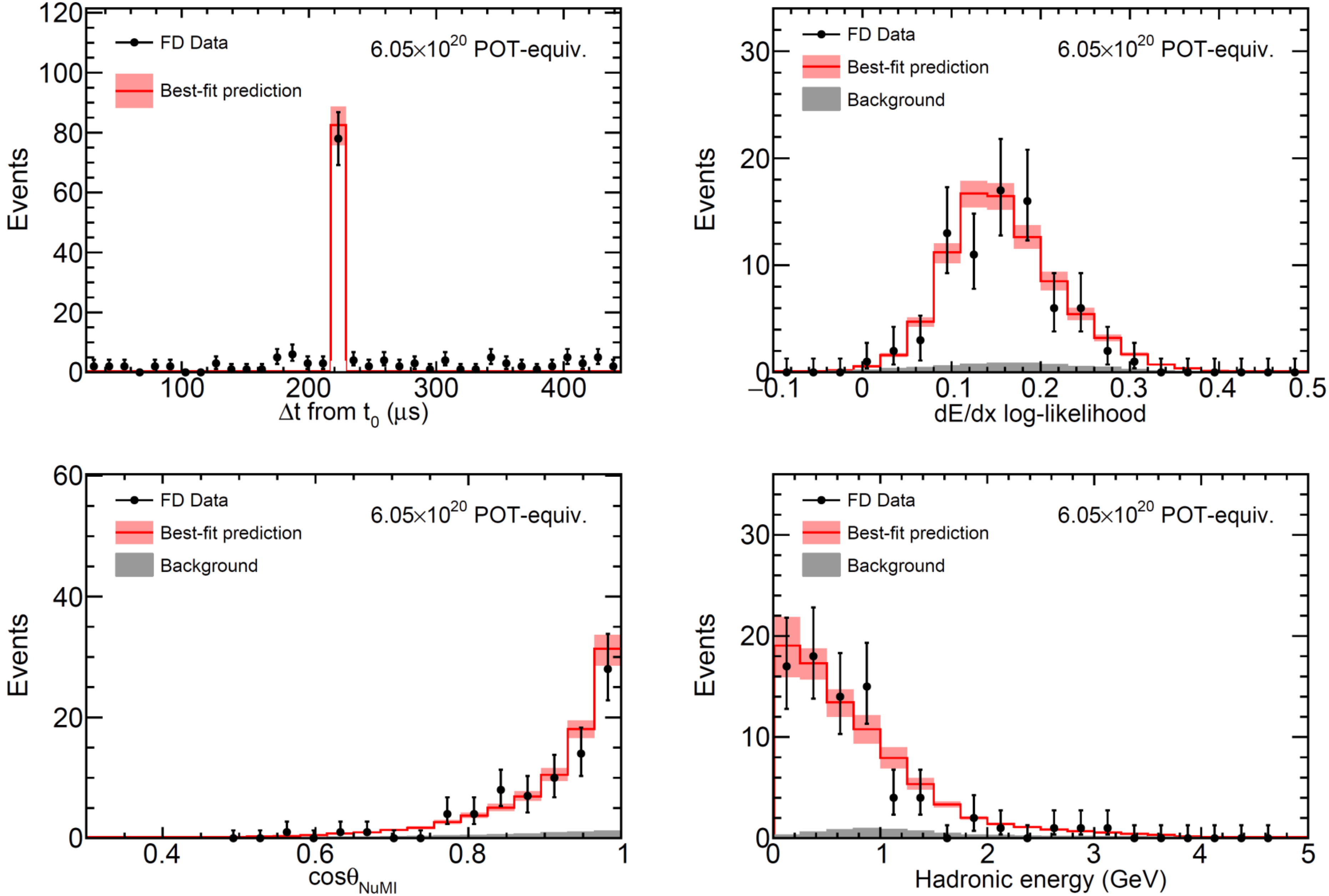
NOvA Preliminary





FD ν_μ CC candidates: example event distributions

All NOvA Preliminary

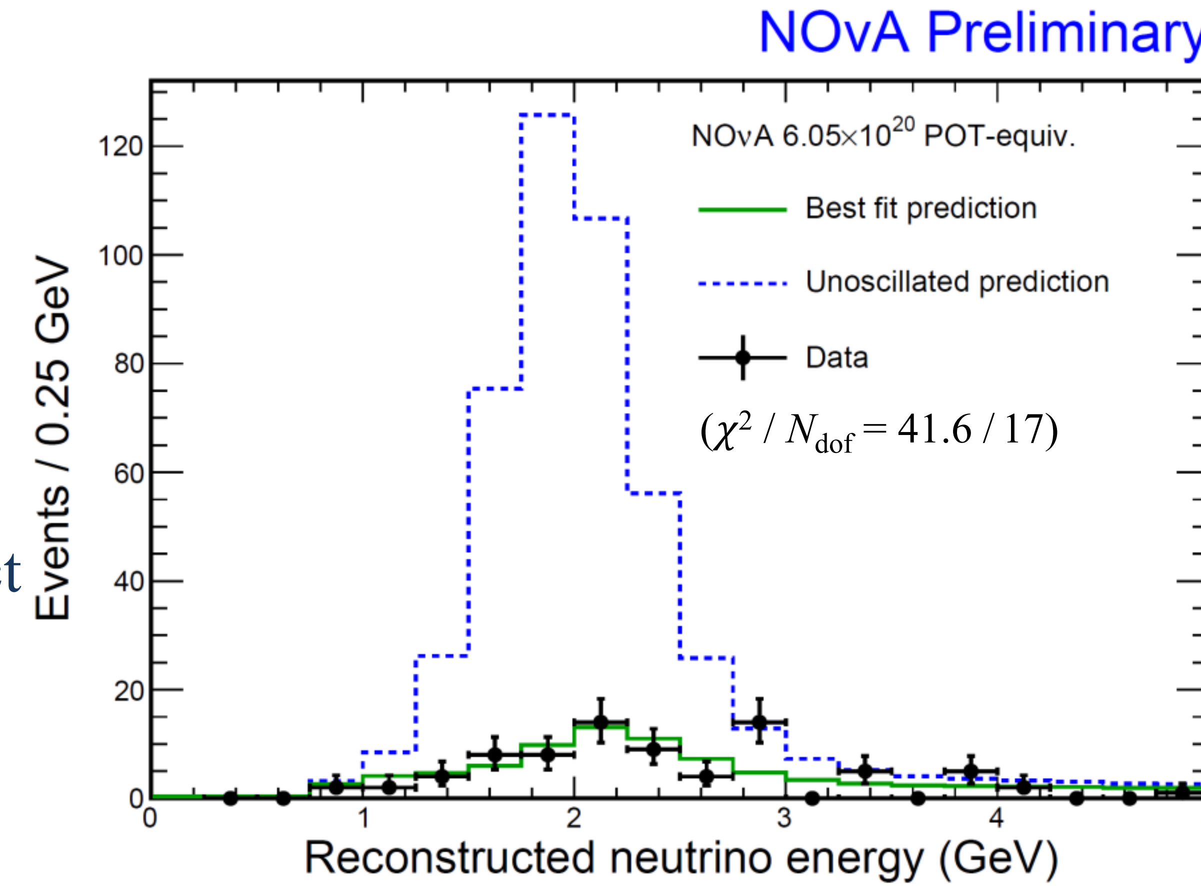


FD energy spectrum

78 events selected in Far Detector
(0 – 5 GeV)

In the absence of oscillations, would expect
473 ± 30 events

(including 3.7 beam bkgnd and 2.9 cosmic bkgnd)

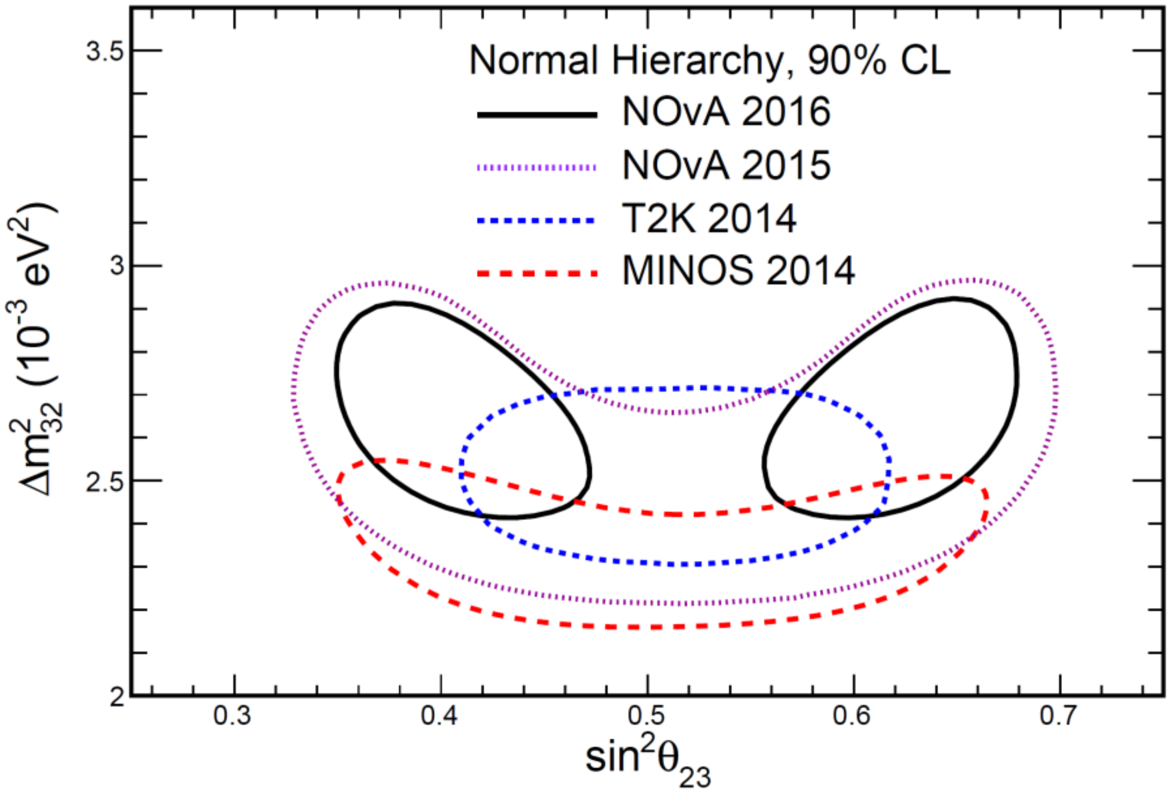


Clear observation of ν_μ disappearance

Oscillation fit for Δm^2_{32} and θ_{23}
(syst. uncertainties included in fit via nuisance parameters)

Allowed regions compatible with MINOS, T2K, and 2015 NOvA

(shown at right)



Non-maximal mixing favored at 2.5σ C.L.

[NH case]

$$\Delta m^2_{32} = (2.67 \pm 0.12) \times 10^{-3}\ \text{eV}^2$$

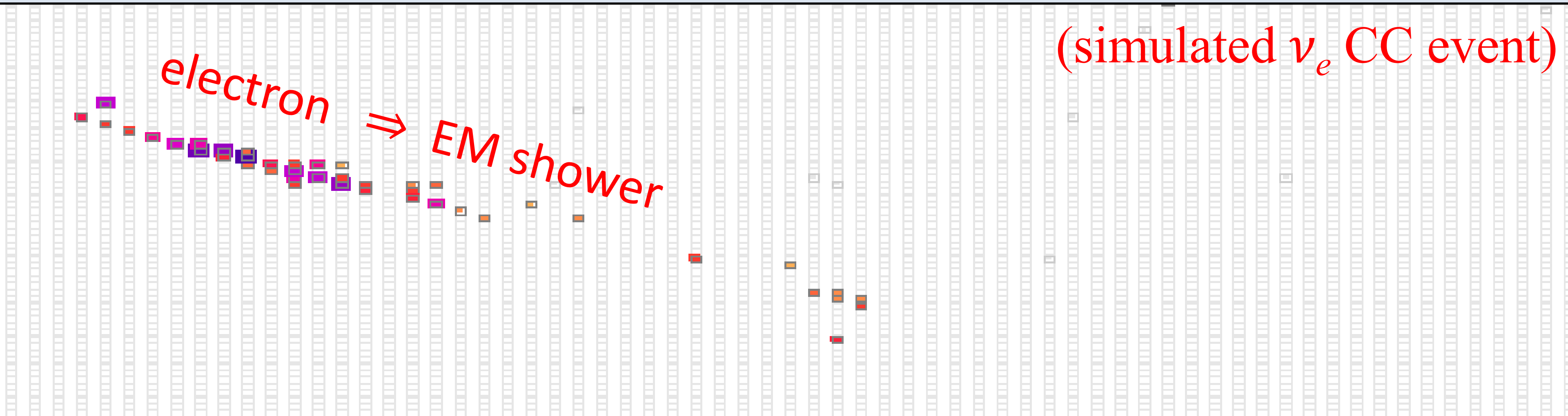
already 4.5% uncertainty
(MINOS closed at 3.8%)

$$\sin^2(\theta_{23}) = 0.40^{+0.03}_{-0.02} \quad (0.63^{+0.02}_{-0.03})$$

Systematic uncertainties still subordinate. Top systs. are those related to **energy calib**.
Previously on top: **hadronic modeling**. *(Continued reductions anticipated…)*
Many **analysis upgrades** under development: *improved selections, energy resolution binning*

ν_e appearance

- Identify **contained ν_e CC candidates** in each detector
- Use Near Det. candidates to **predict beam backgrounds** in the Far Detector
- Interpret any **Far Det. excess** over predicted backgrounds as ν_e appearance



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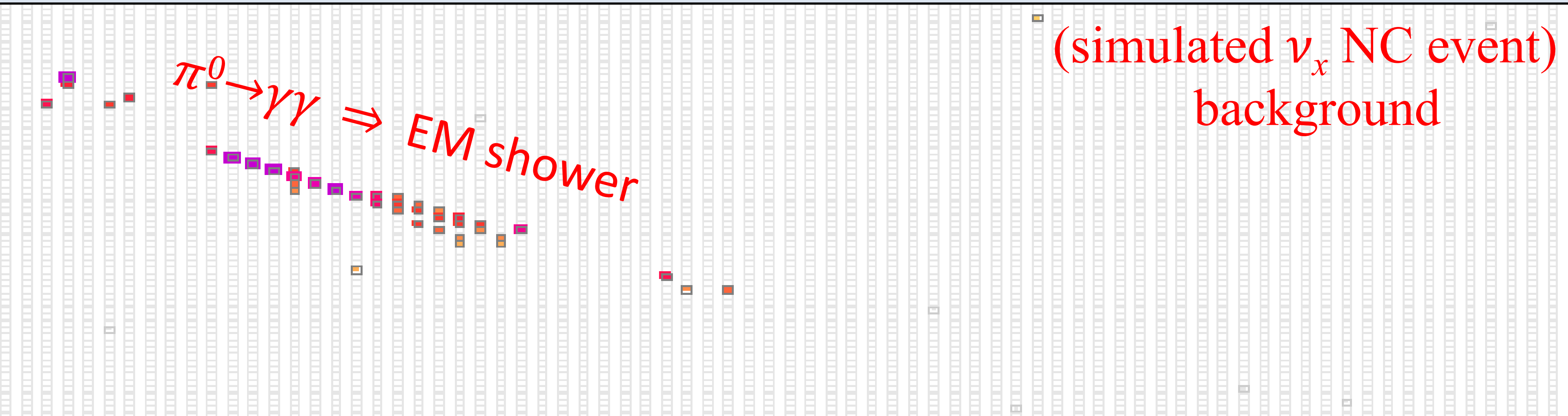
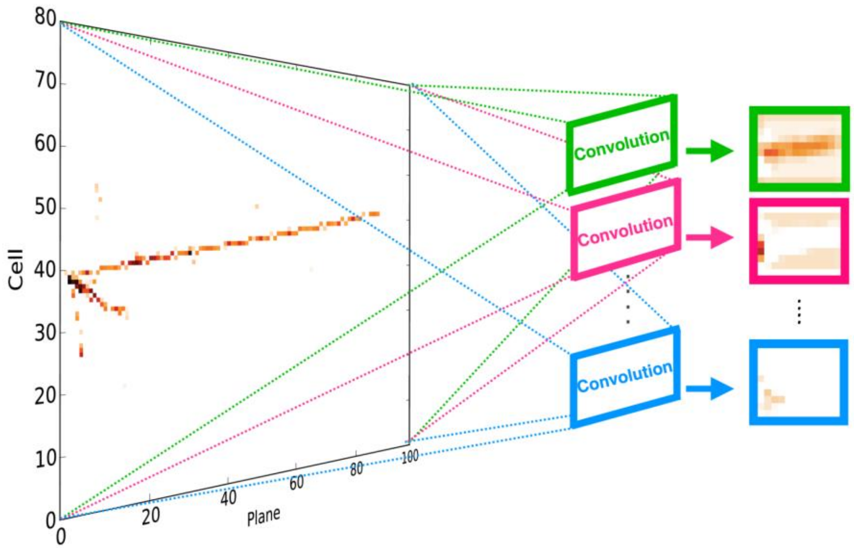


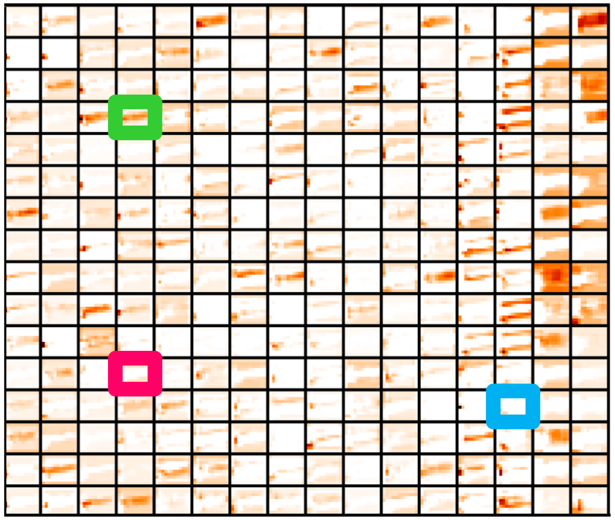
Identifying ν_e CC events

Three sophisticated **event ID algorithms** developed on NOvA[1,2,3]

Primary algorithm[1] for latest results based on **recent advancements** in the fields of **computer vision** and **deep learning**

→ *convolutional neural networks*





FEATURE MAPS

Highly optimized training for convolution kernels and connections in deep network

→ *Inception/GoogLeNet* and *Caffe* frameworks[4]

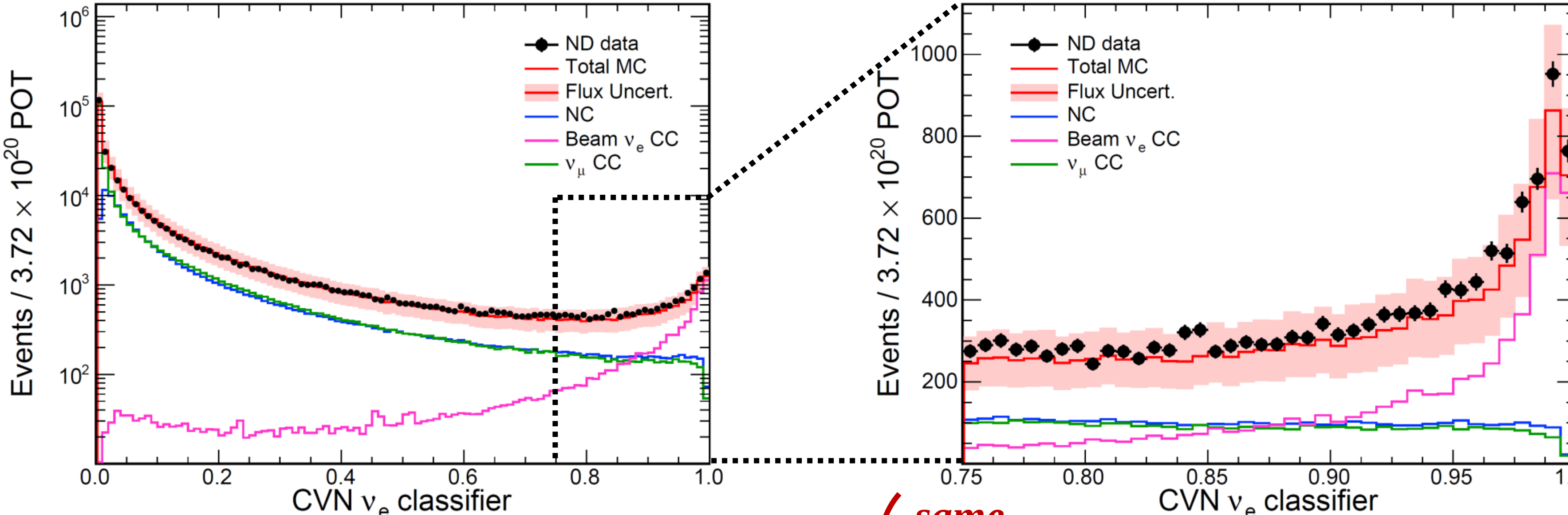
[1] A. Aurisano et al., JINST **11**, P09001 (2016)

[2] J. Bian, arXiv:1510.05708 (2015); E. Niner thesis, Indiana U (2015); K. Sachdev thesis, UMN (2015)

[3] C. Backhouse and R. B. Patterson, NIM A 778, 31 (2015)

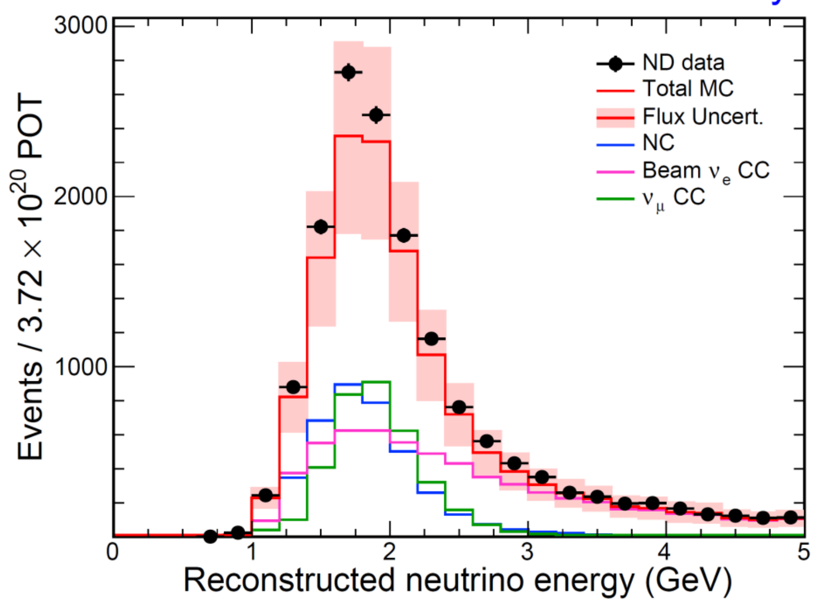
[4] C. Szegedy et al., arXiv:1409.4842 (2014); Y. Jia et al., arXiv:1408.5093 (2014)

In the Near Detector…



same events

NOvA Preliminary



Can pick apart ND sample:

→ Golden **ν_μ CC sample** constrains rate of intrinsic ν_e CC **(3% adjustment to sim.)**

→ Also constrains signal ν_e CC **(2%)**

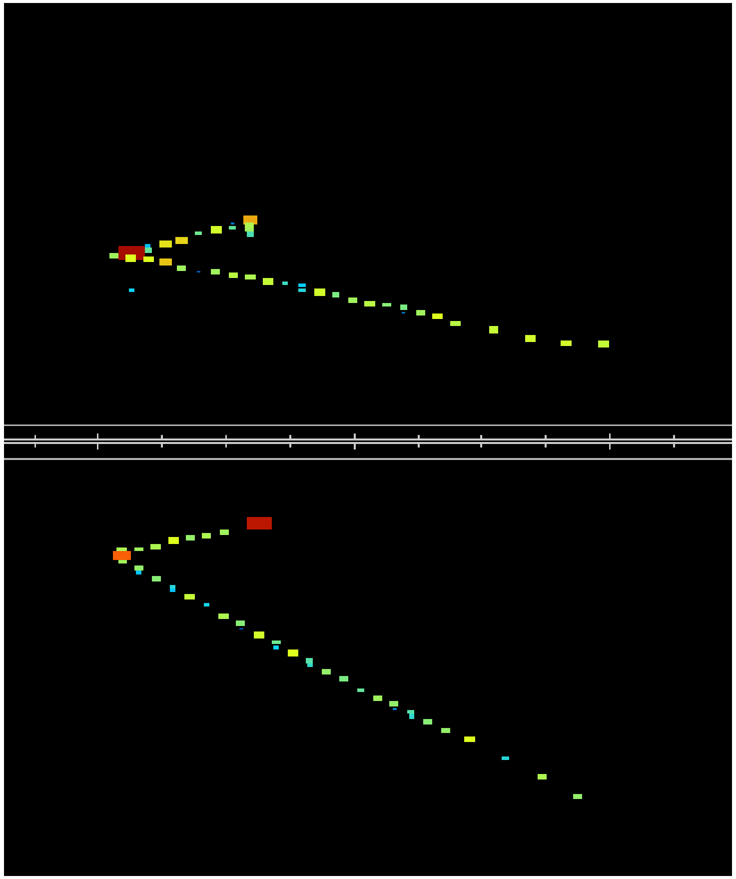
→ **Tagged μ decays** constrain relative mis-ID rates of ν_μ CC and NC **(10%, 17%)**

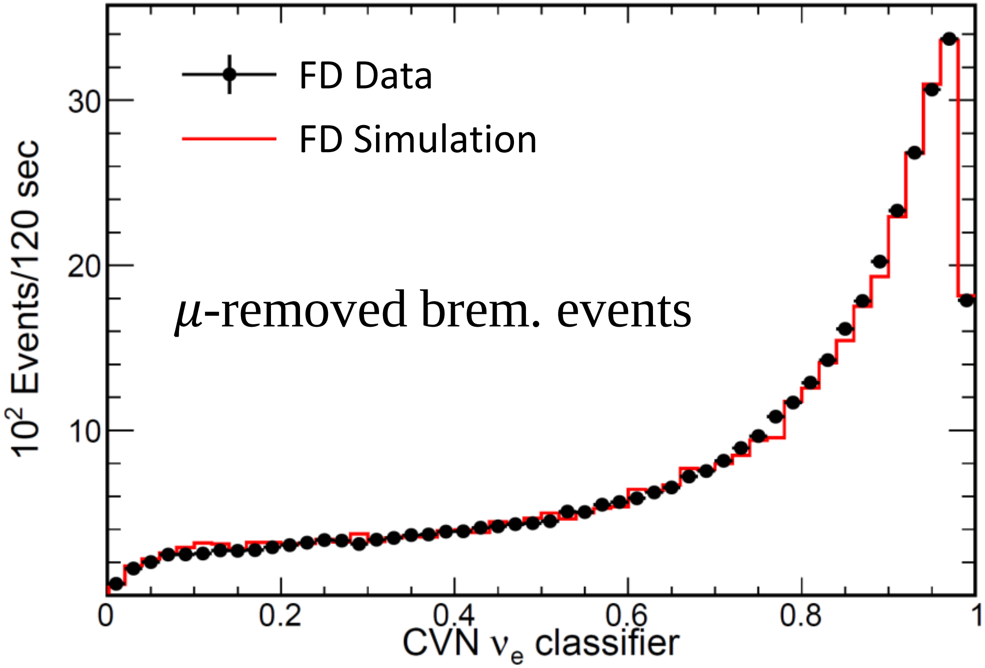
Checking signal efficiency

Effects from hadronic modeling?

→ Replace *muons* with simulated *electrons* in ν_μ CC events
(preserves hadronic piece of event)

→ **CVN efficiency agrees within 1%** between data and simulation





EM shower modeling?

Isolate bremsstrahlung showers in FD cosmic ray data

← CVN classifier **matches well** between data and simulation

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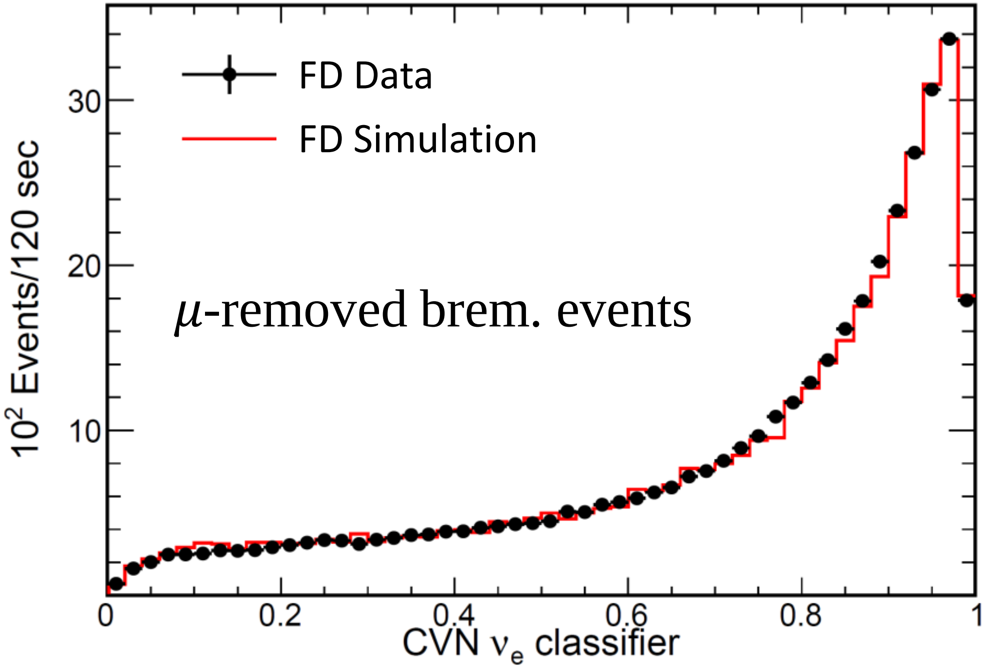

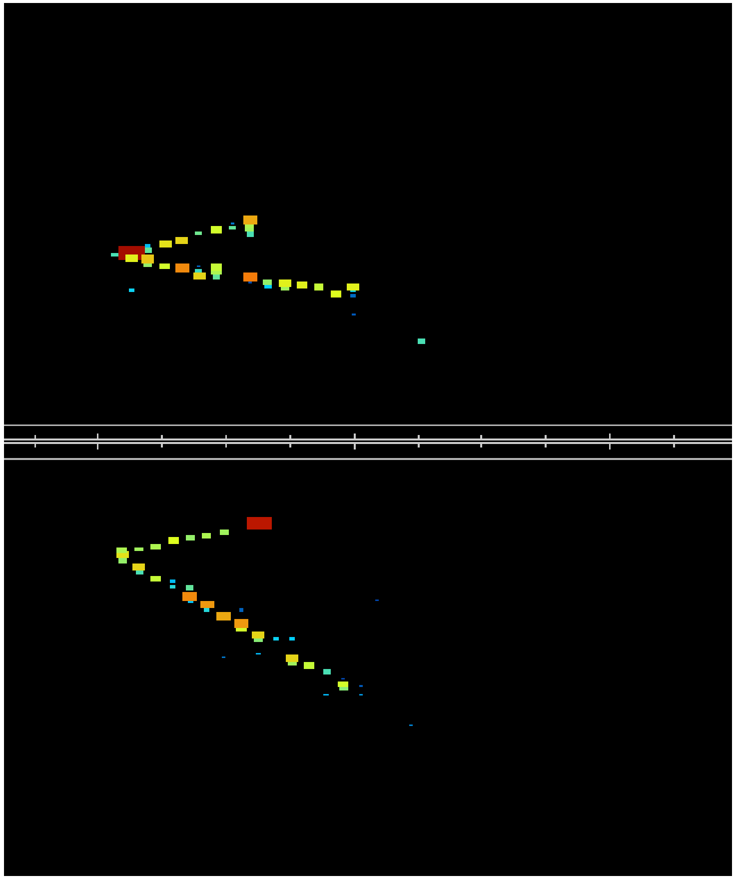

EM shower modeling?

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FD expectations…

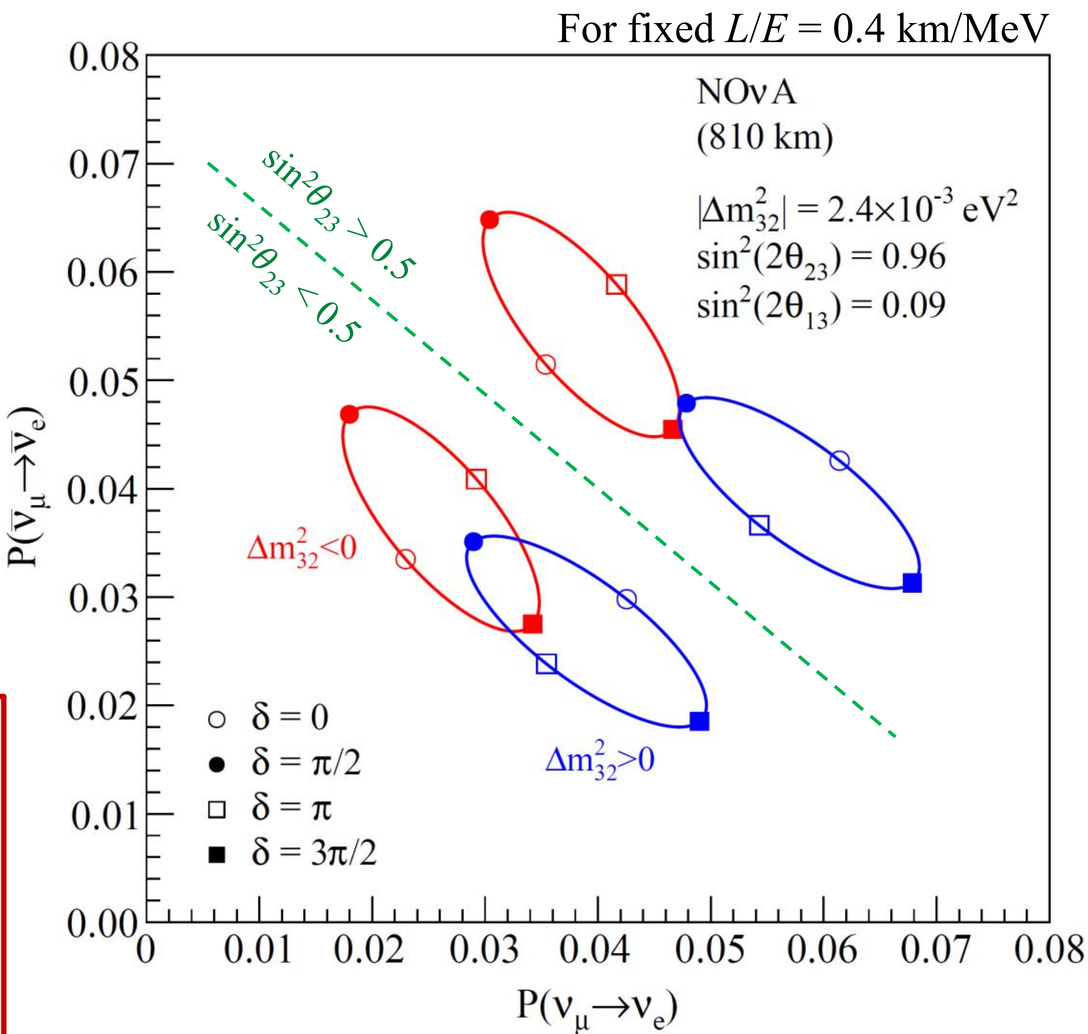
At right:

$P(\bar{\nu}_\mu \to \bar{\nu}_e)$ vs. $P(\nu_\mu \to \nu_e)$

plotted for a single neutrino energy and baseline

→ Strong dependence on δ and **ν mass hierarchy**

→ $P \propto \sin^2\theta_{23}$ *[approx.]*



Total prediction:

~17 to 42 ν_e candidates
(depending on osc. pars.)

Includes **8.2** background
(~independent of osc. pars.)

Syst. uncertainty:
±5% signal
±10% background

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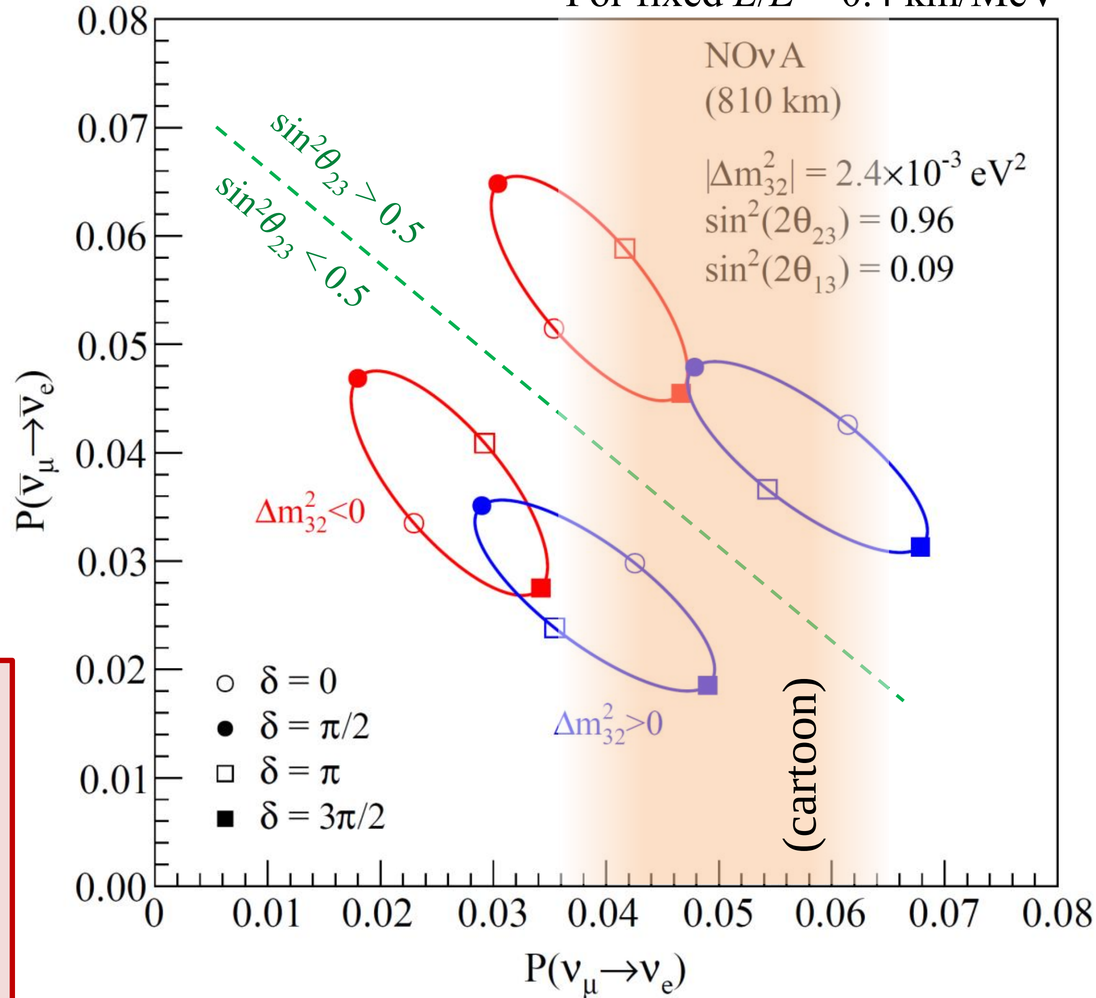
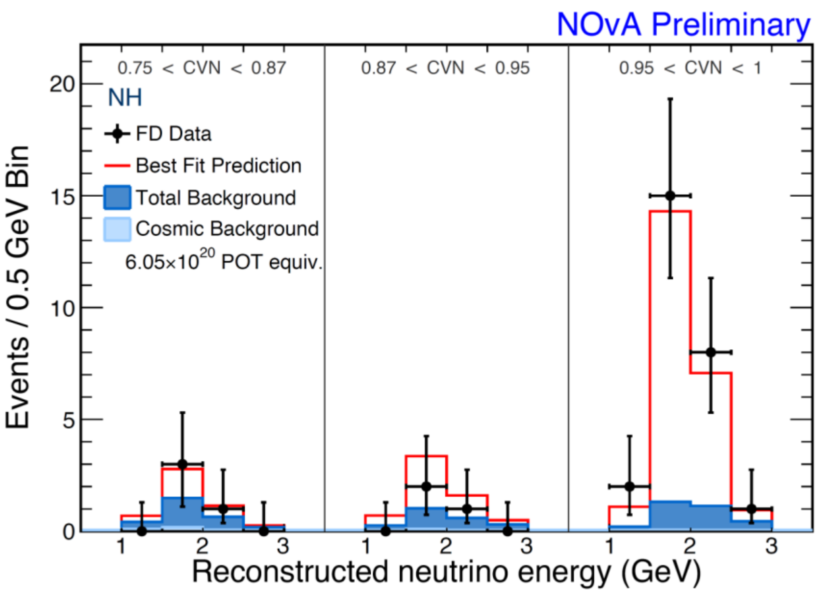
For fixed L/E = 0.4 km/MeV

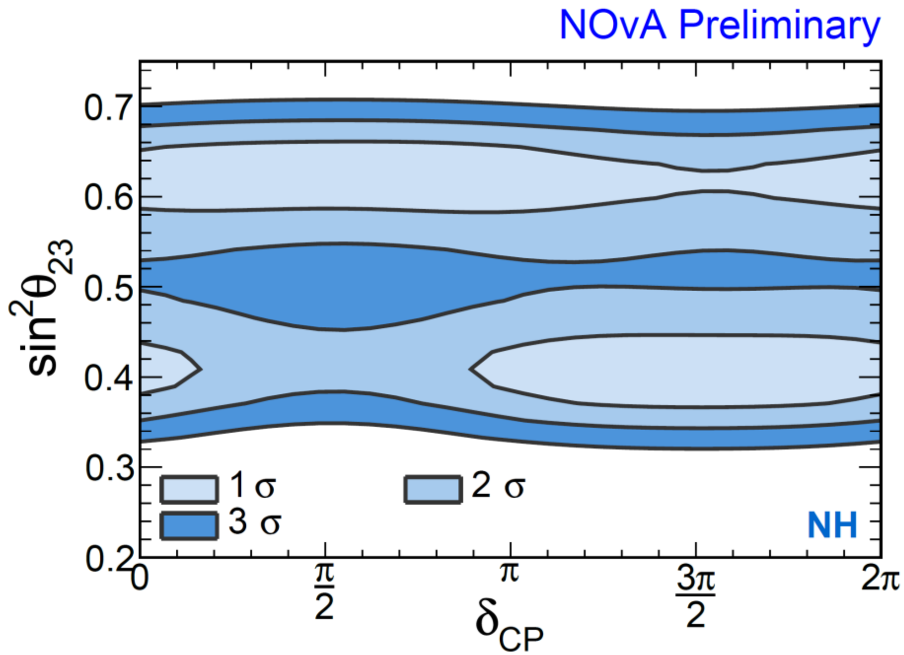


Observed in FD data:
33 ν_e candidates

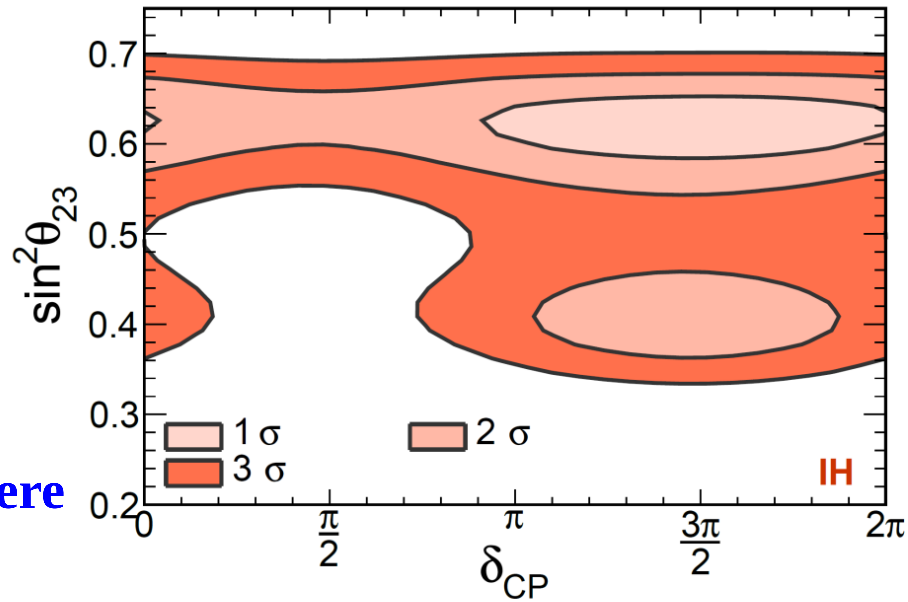
$>8\sigma$ observation of ν_e appearance

Measure signal in 2D bins of $E_\nu \times$ CVN





In terms of allowed physical parameters →



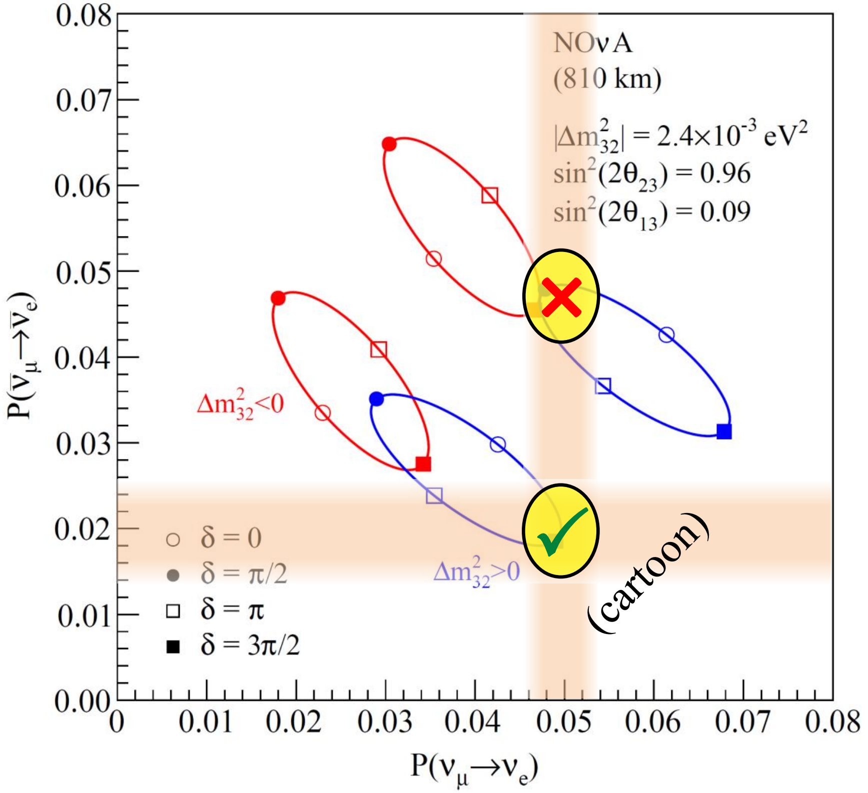
NH preference not signif.: $\Delta\chi^2$=0.46

>3σ exclusion of region in

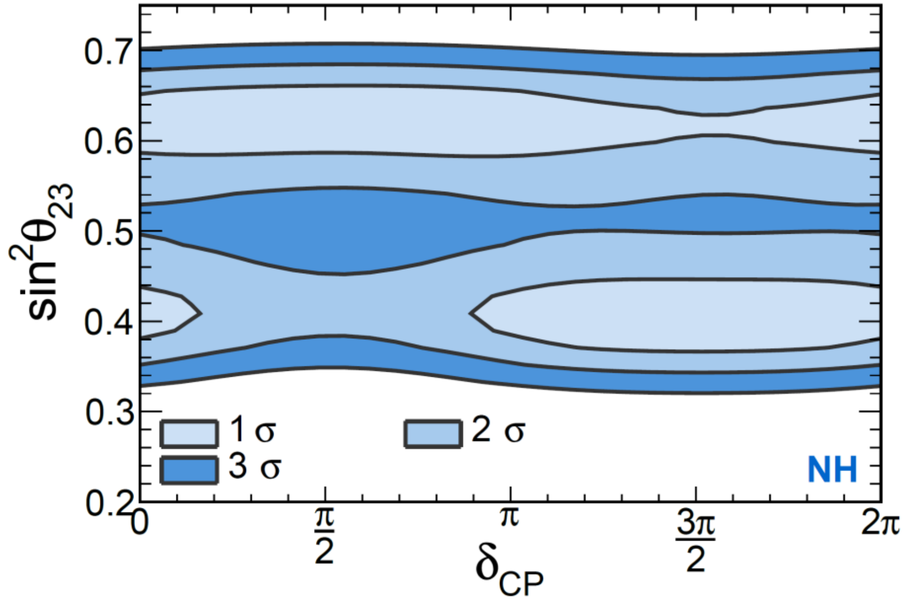
IH, lower octant, around δ=π/2

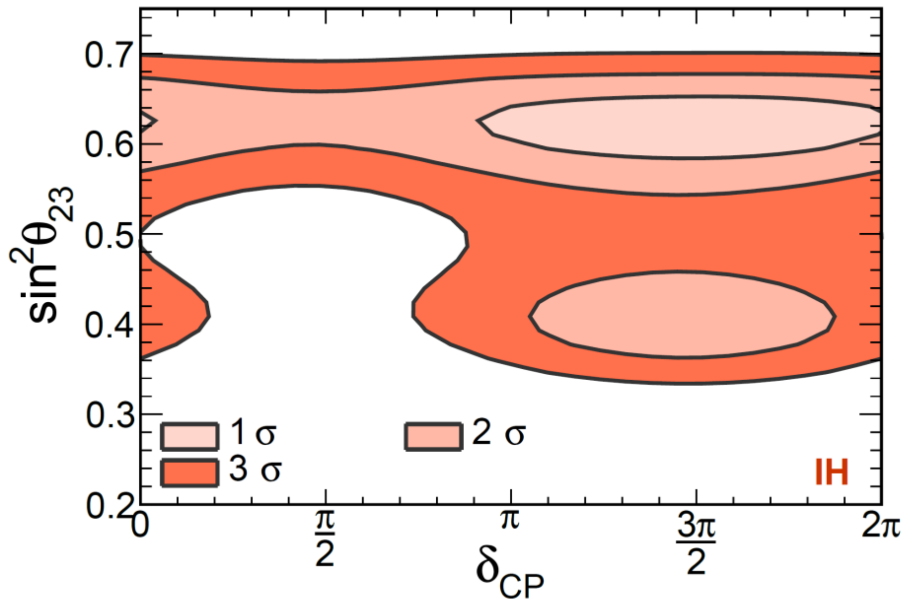
Feldman-Cousins corrections **not included here** (*will appear in forthcoming journal article*)

In **non-maximal mixing** scenario, **antineutrino data** critical to run plan

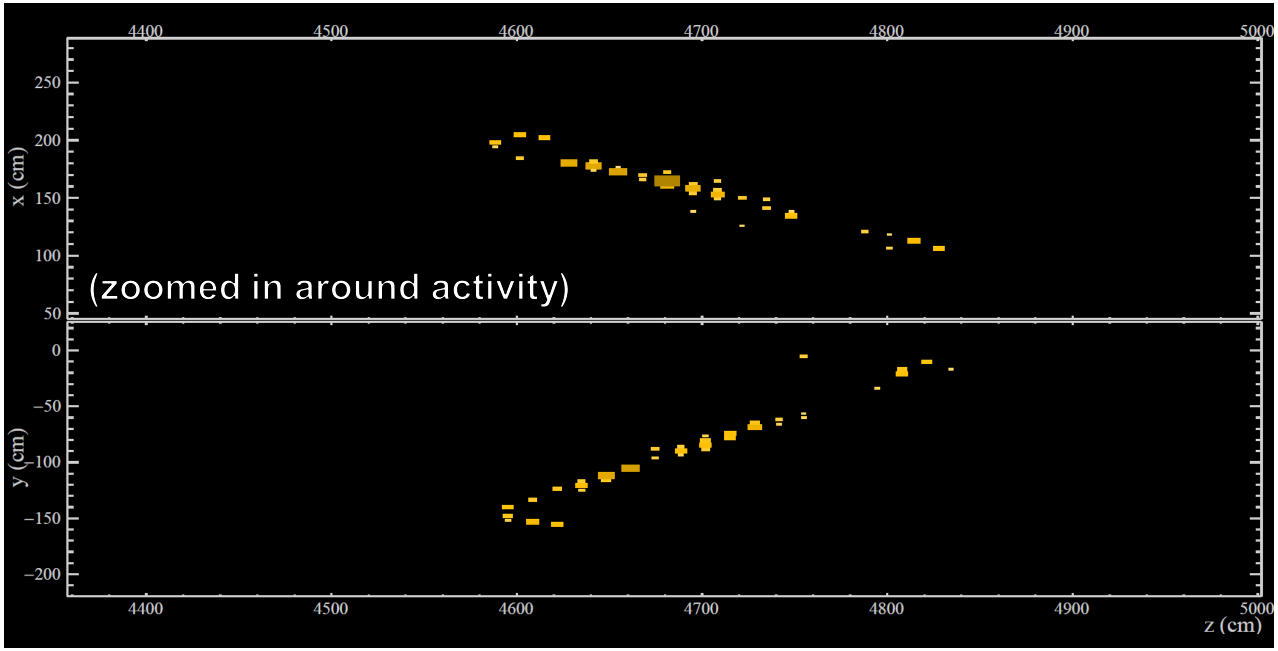


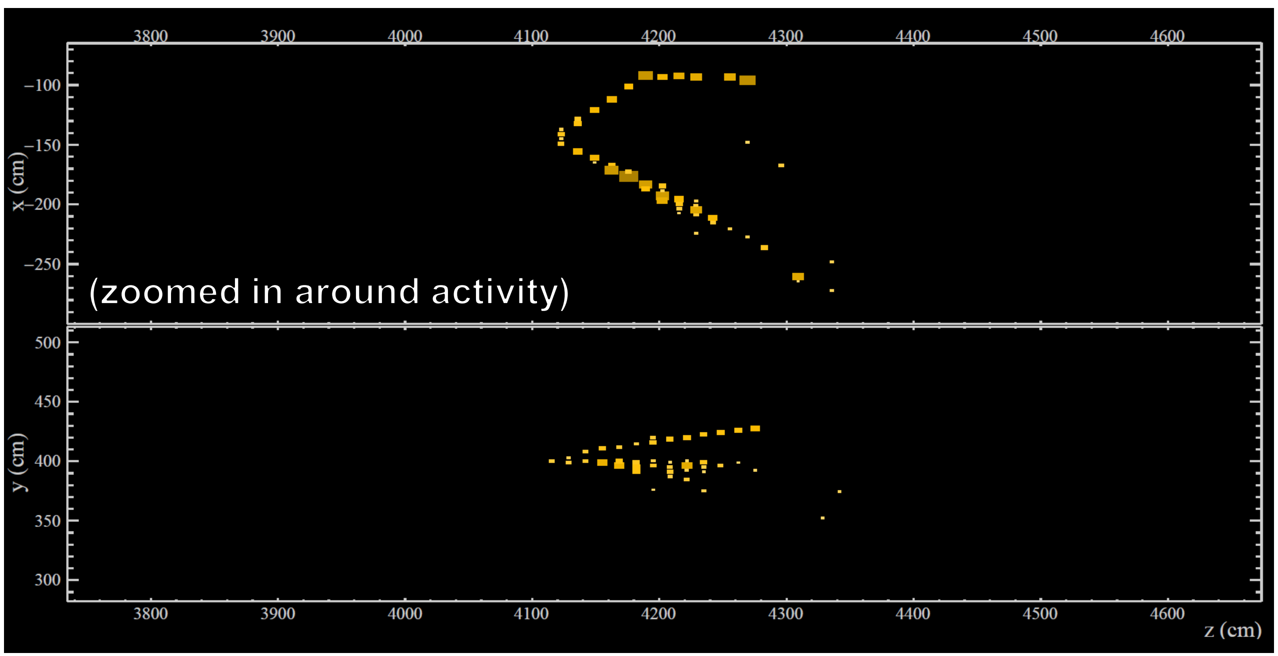
NOvA Preliminary

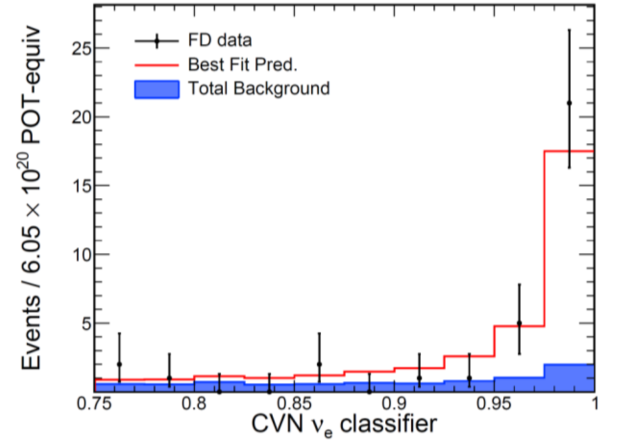


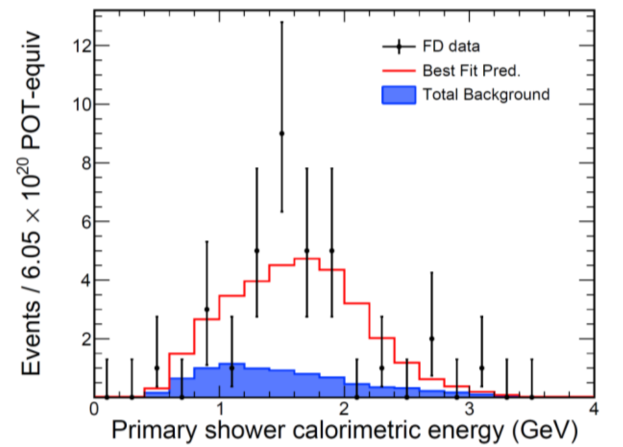


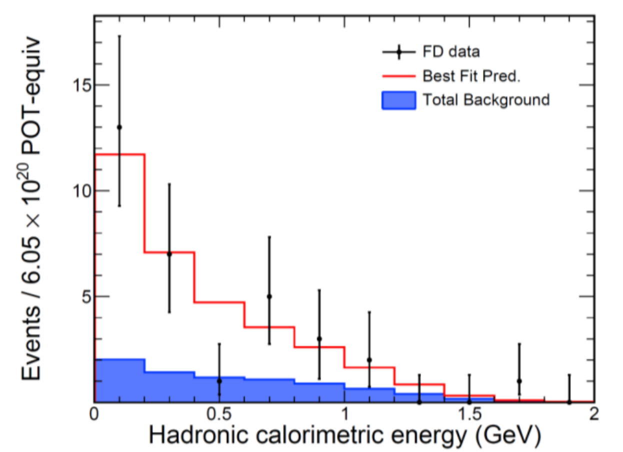
Brief look at FD ν_e sample



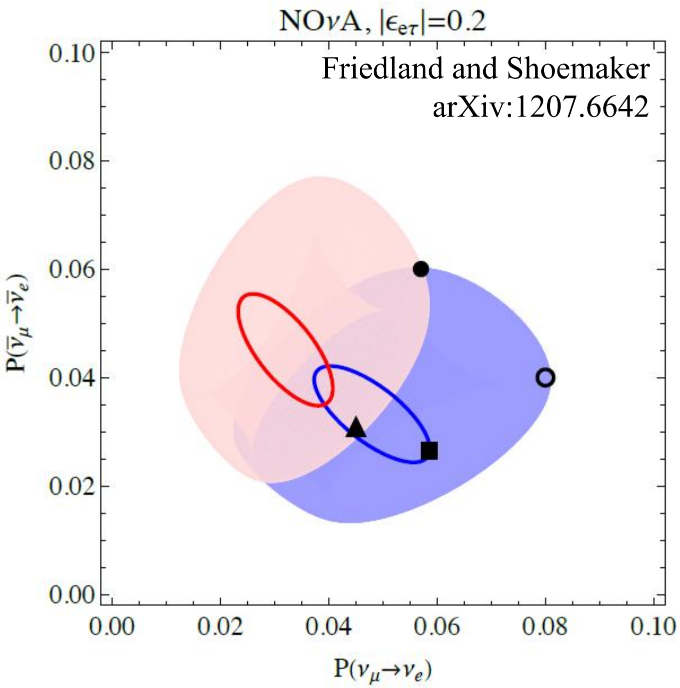




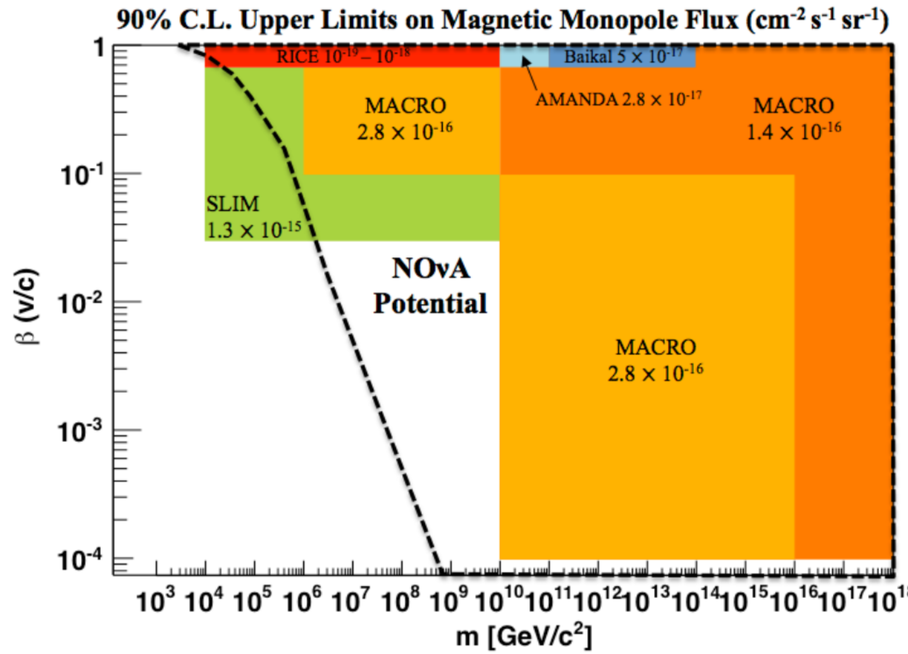




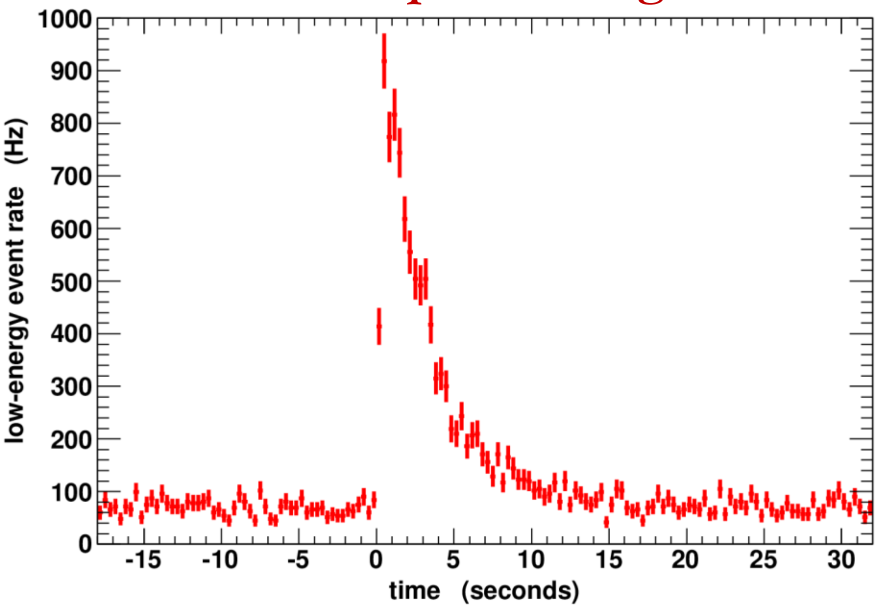
Non-standard interactions



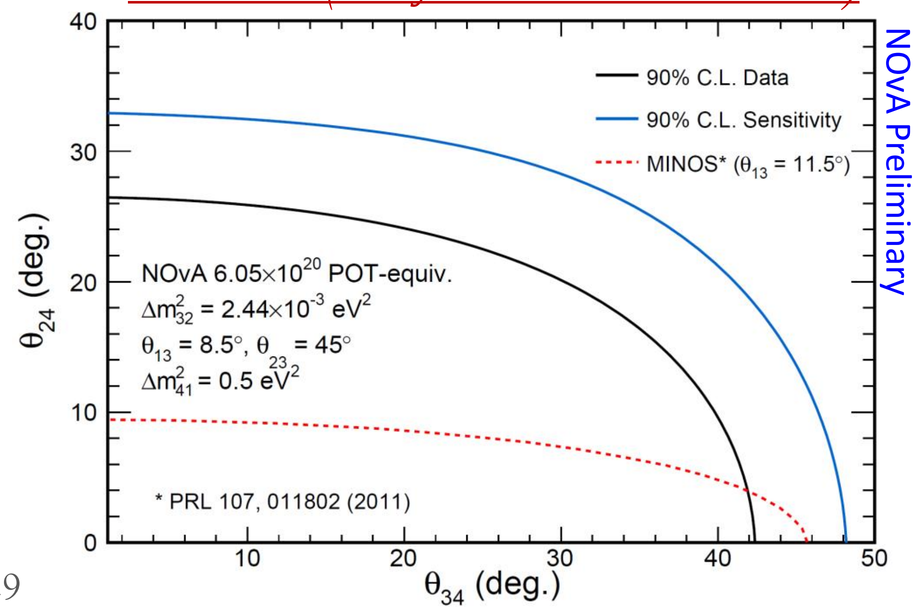
Monopole searches



Galactic supernova signal



Sterile ν *(early NOvA results below!)*



Outlook

- **NOvA operating beautifully**, returning from shutdown this month
  - Neutrino mode until ~spring, then antineutrino mode
- *Below:* **sensitivity vs. time** assuming…
  - currently favored osc. parameters *(lower/upper octant ↔ left/right panel)*
  - current analysis techniques *(several improvements in the works!)*
  - modestly improved systematic uncertainties
  - 6×10^{20} p.o.t./yr, with a balance of $\nu/\bar{\nu}$ in out-years
- **In the very near term** (*c.* 2018/2019) under above assumptions:
  - **wrong hierarchy rejection** at >95% C.L.
  - **wrong octant rejection** at >95% C.L.
  - **max-mix rejection** at $>3\sigma$