Neutrino Physics With NOvA

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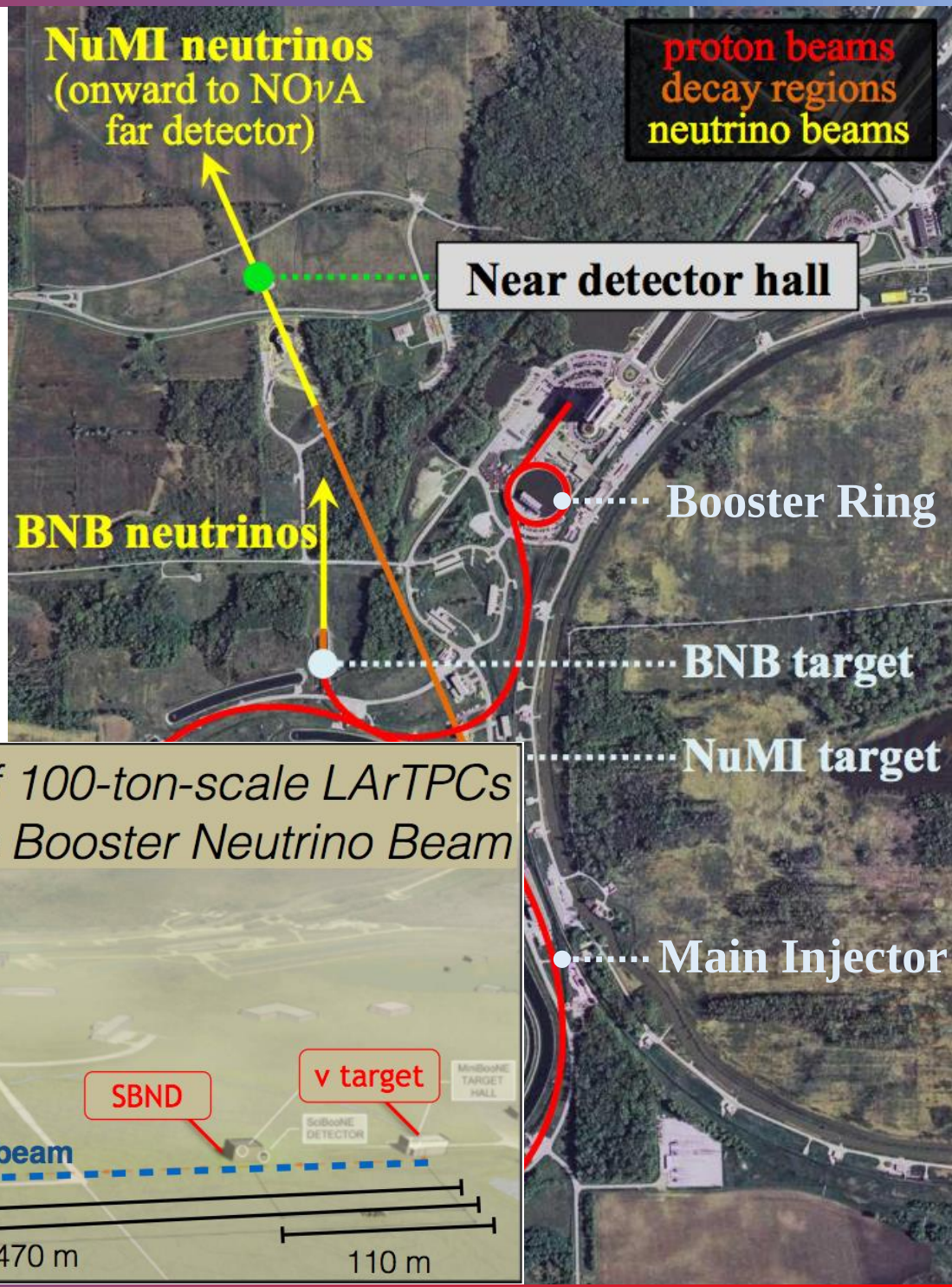
For the NOvA Collaboration

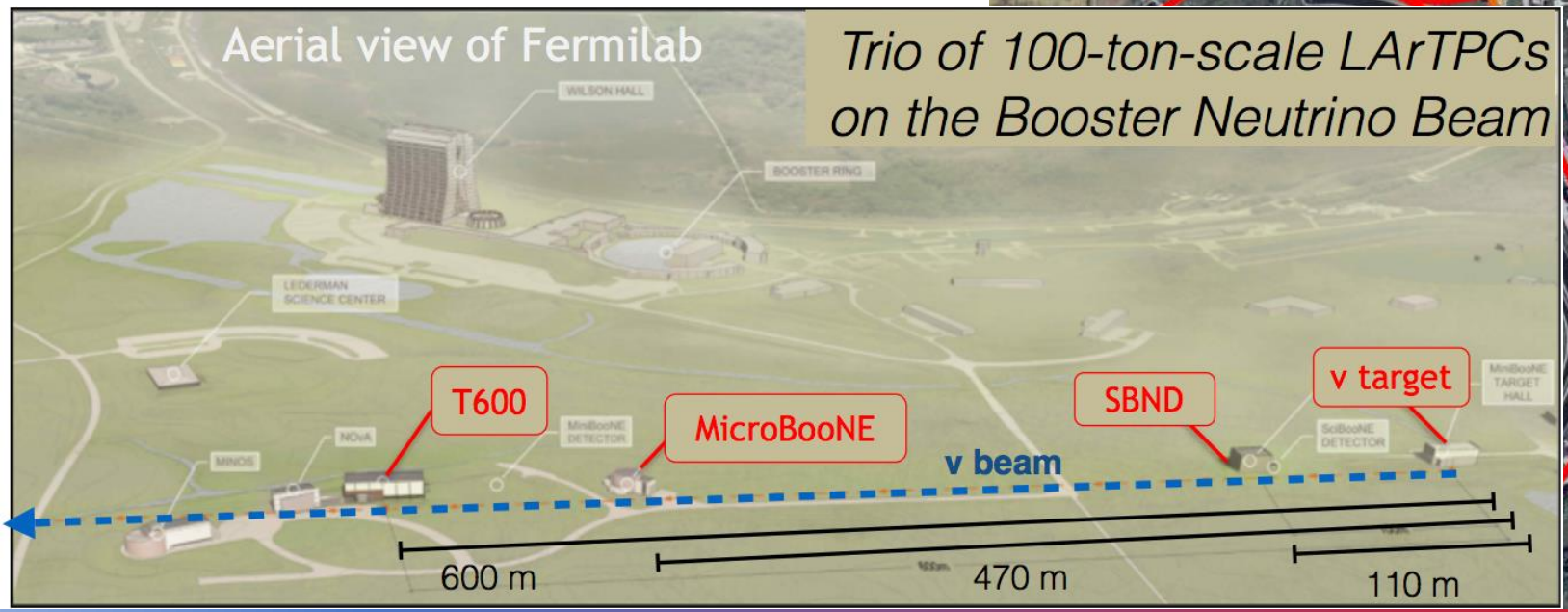
COMHEP, Medellín – Nov. 29th 2016

By: JEN

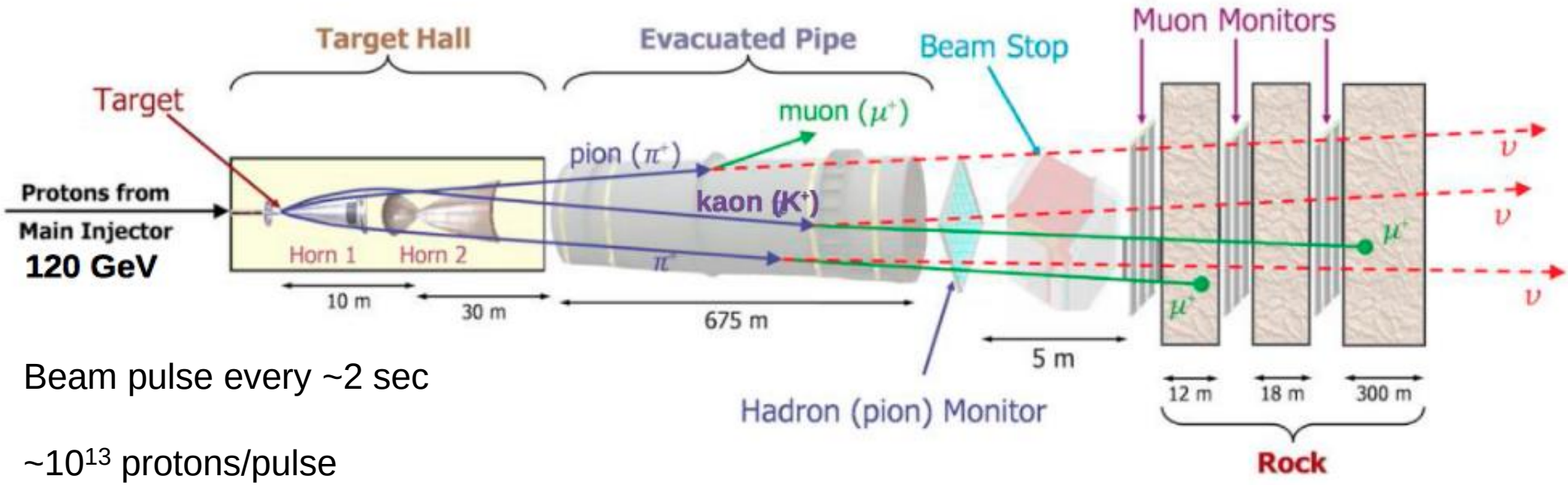
- Introduction to neutrino physics at Fermilab
- Frontiers in particle physics
- Intensity frontier & neutrino experiments at Fermilab
- Neutrino physics with NOvA
- NOvA overview
  - Physics program
  - Detectors
  - Capabilities
- NOvA results

- Neutrino research requires a neutrino source, a beam
- Fermilab accelerates protons up to 8 GeV with the Booster Ring
- There is a Booster Neutrino Beam (BNB)



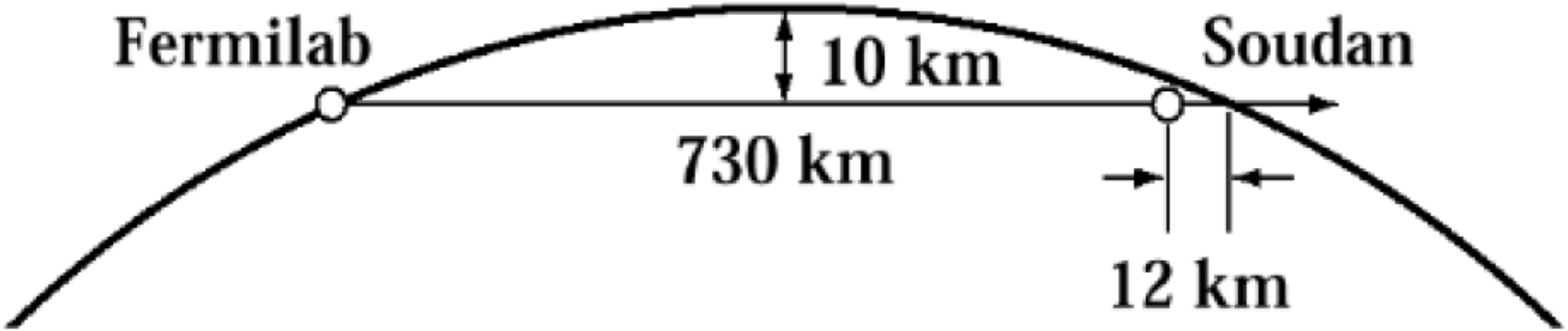


NuMI Beam

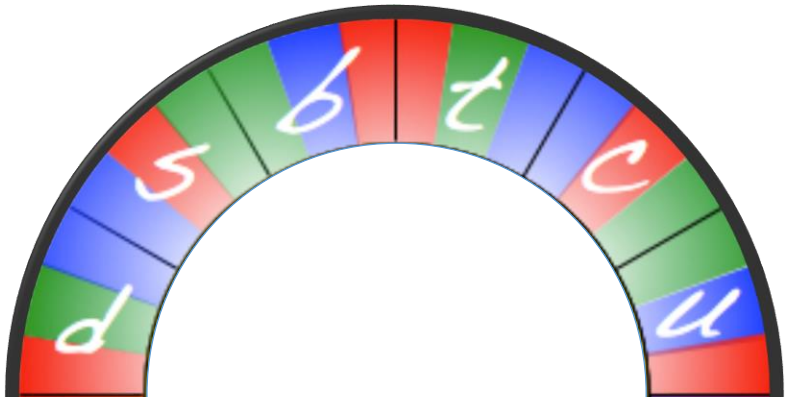


Beam pulse every ~2 sec

~10^{13} protons/pulse



Bosons



Quarks: -1/3

Quarks: +2/3

Leptons: -1

Neutrinos: 0

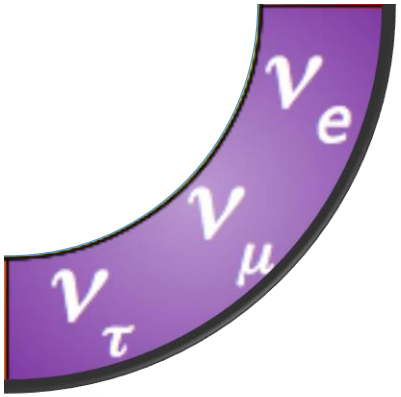
All have non-zero masses

Massless

- There are two bases to describe neutrino eigen states

- Mass eigen states:
  - ν_1, ν_2, ν_3

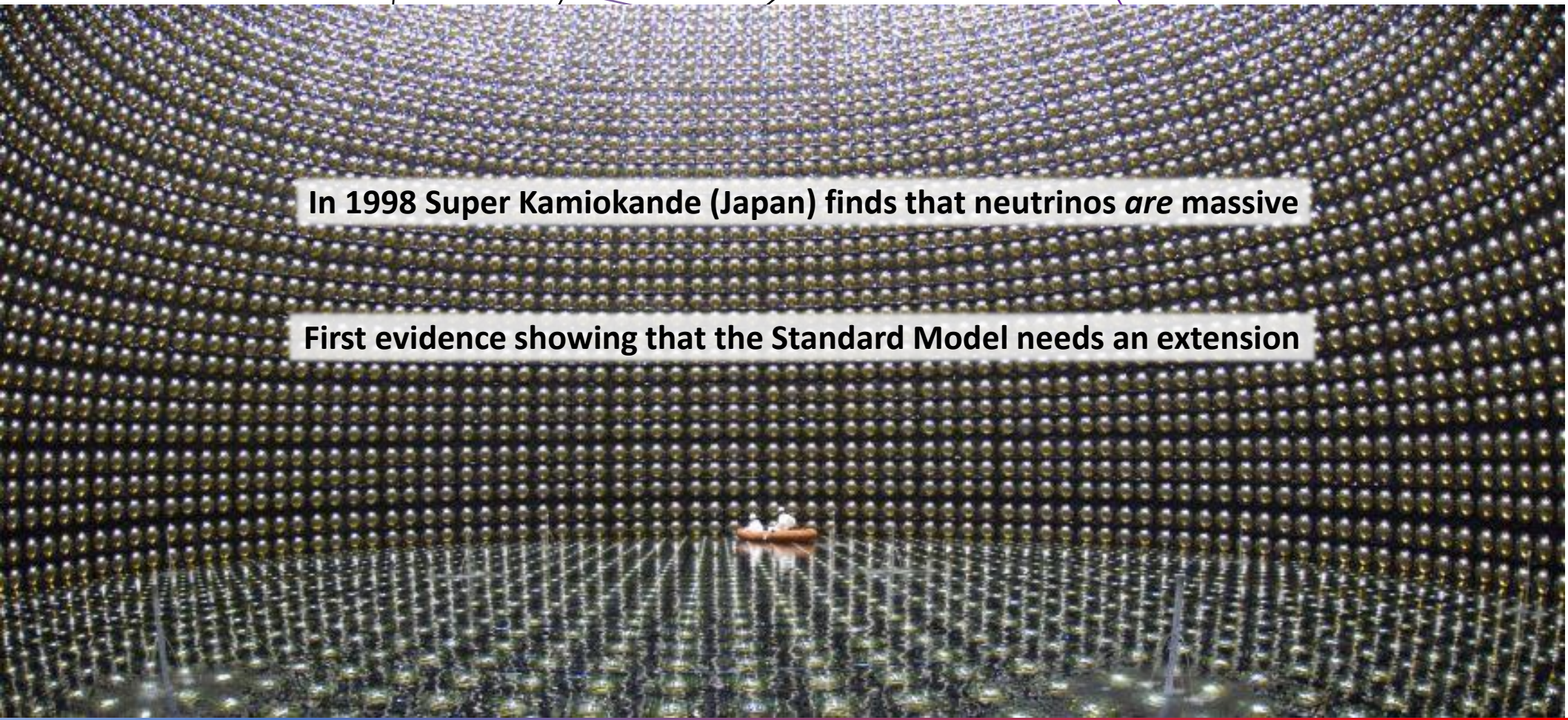
How do flavor eigen states evolve with time?



Flavor eigen states

$$|\nu^{\alpha}\rangle_t = e^{-\imath \mathbf{p} t} U \begin{pmatrix} 1-\imath\frac{m_1^2 t}{2E}+\cdots & & \\ & 1-\imath\frac{m_2^2 t}{2E}+\cdots & \\ & & 1-\imath\frac{m_3^2 t}{2E}+\cdots \end{pmatrix}$$

If the masses are different from zero: oscillations



In 1998 Super Kamiokande (Japan) finds that neutrinos *are* massive

First evidence showing that the Standard Model needs an extension

$$|\nu^{\alpha}\rangle_t = e^{-\imath \mathbf{p} t} U \begin{pmatrix} 1-\imath\frac{m_1^2 t}{2E}+\cdots & & \\ & 1-\imath\frac{m_2^2 t}{2E}+\cdots & \\ & & 1-\imath\frac{m_3^2 t}{2E}+\cdots \end{pmatrix} U^{\dagger}|\nu^{\beta}\rangle$$

- *i*: mass eigen values
- *α, β*: flavor eigen values

$$\langle\nu^{\beta}|\nu^{\alpha}\rangle_t = \sum U_{\alpha i} U^{\dagger}_{i\beta} e^{-\imath E_i t}$$

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-\imath\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{\imath\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{\imath\frac{\varphi_1}{2}} & 0 & 0 \\ 0 & e^{\imath\frac{\varphi_2}{2}} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13}e^{\imath\frac{\varphi_1}{2}} & s_{12}c_{13}e^{\imath\frac{\varphi_2}{2}} & s_{13}e^{-\imath\delta} \\ (-s_{12}c_{23}-c_{12}s_{23}s_{13}e^{\imath\delta})e^{\imath\frac{\varphi_1}{2}} & (c_{12}c_{23}-s_{12}s_{23}s_{13}e^{\imath\delta})e^{\imath\frac{\varphi_2}{2}} & s_{23}c_{13} \\ (s_{12}s_{23}-c_{12}c_{23}s_{13}e^{\imath\delta})e^{\imath\frac{\varphi_1}{2}} & (-c_{12}s_{23}-s_{12}c_{23}s_{13}e^{\imath\delta})e^{\imath\frac{\varphi_2}{2}} & c_{23}c_{13} \end{pmatrix}.$$

What happens if a neutrino type β propagates? When observed… Would it be: α = β?

Each matrix represents oscillation amongst two states

s_{ij} ➔ sen θ_{ij}
c_{ij} ➔ cos θ_{ij}
φ, δ: phases

Easiest case: oscillation amongst two states (good approximation)

$$\boxed{\Delta m^2 = m_2^2 - m_1^2}$$

$$U = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \qquad |\nu^\alpha\rangle(t) = \begin{pmatrix} \cos\frac{\Delta m^2}{4E}t - \imath \sin\frac{\Delta m^2}{4E}t\cos 2\theta & -\imath\sin\frac{\Delta m^2}{4E}t\sin 2\theta \\ -\imath\sin\frac{\Delta m^2}{4E}t\sin 2\theta & \cos\frac{\Delta m^2}{4E}t + \imath\sin\frac{\Delta m^2}{4E}t\cos 2\theta \end{pmatrix} |\nu^\beta\rangle$$

Oscillation amongst ν_μ & ν_e:

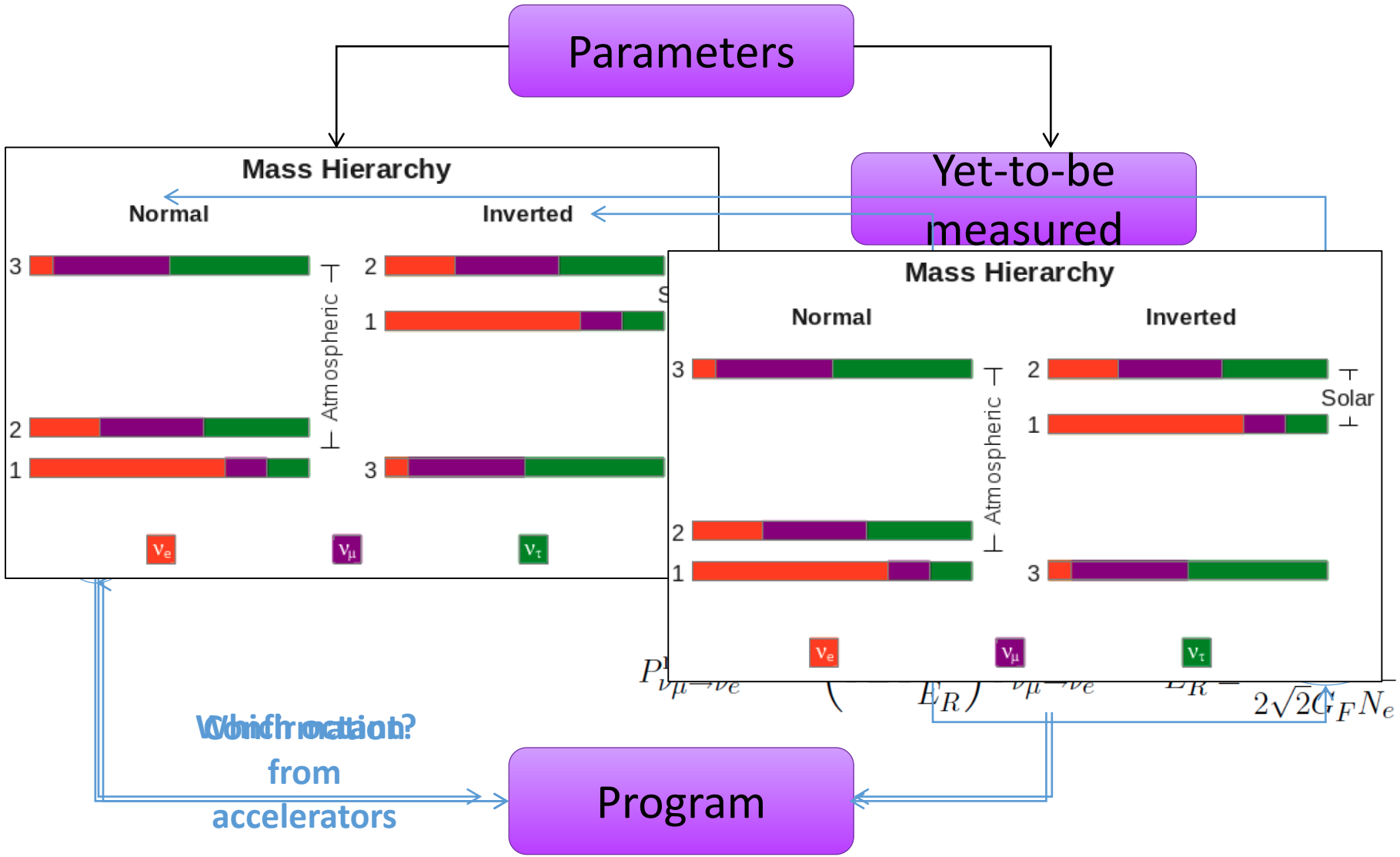
$$\langle\nu^\mu|\nu^e\rangle(t) = -\imath\sin\frac{\Delta m^2}{4E}t\sin 2\theta$$

$$P_{\nu_\mu\to\nu_e} = |\langle\nu^\mu|\nu^e\rangle(t)|^2 = \sin^2\frac{\Delta m^2}{4E}t\sin^2 2\theta$$ Probability

$$\boxed{t \approx L/c}$$

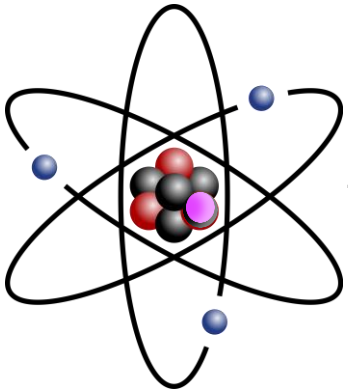
$$\boxed{\pi = \frac{\Delta m^2 L}{2E}}$$

Maximum of Probability


Parameters
Mass Hierarchy
Normal
Inverted
3
2
1
Atmospheric
ν_e
ν_μ
ν_τ
Yet-to-be measured
Mass Hierarchy
Normal
Inverted
Solar
Atmospheric
Program
from
accelerators

- Cross sections are a measure of how frequent an interaction is
  - Some precision measurements are currently doable
  - Oscillation experiments require these measurements for low uncertainty results

Neutrino



Target

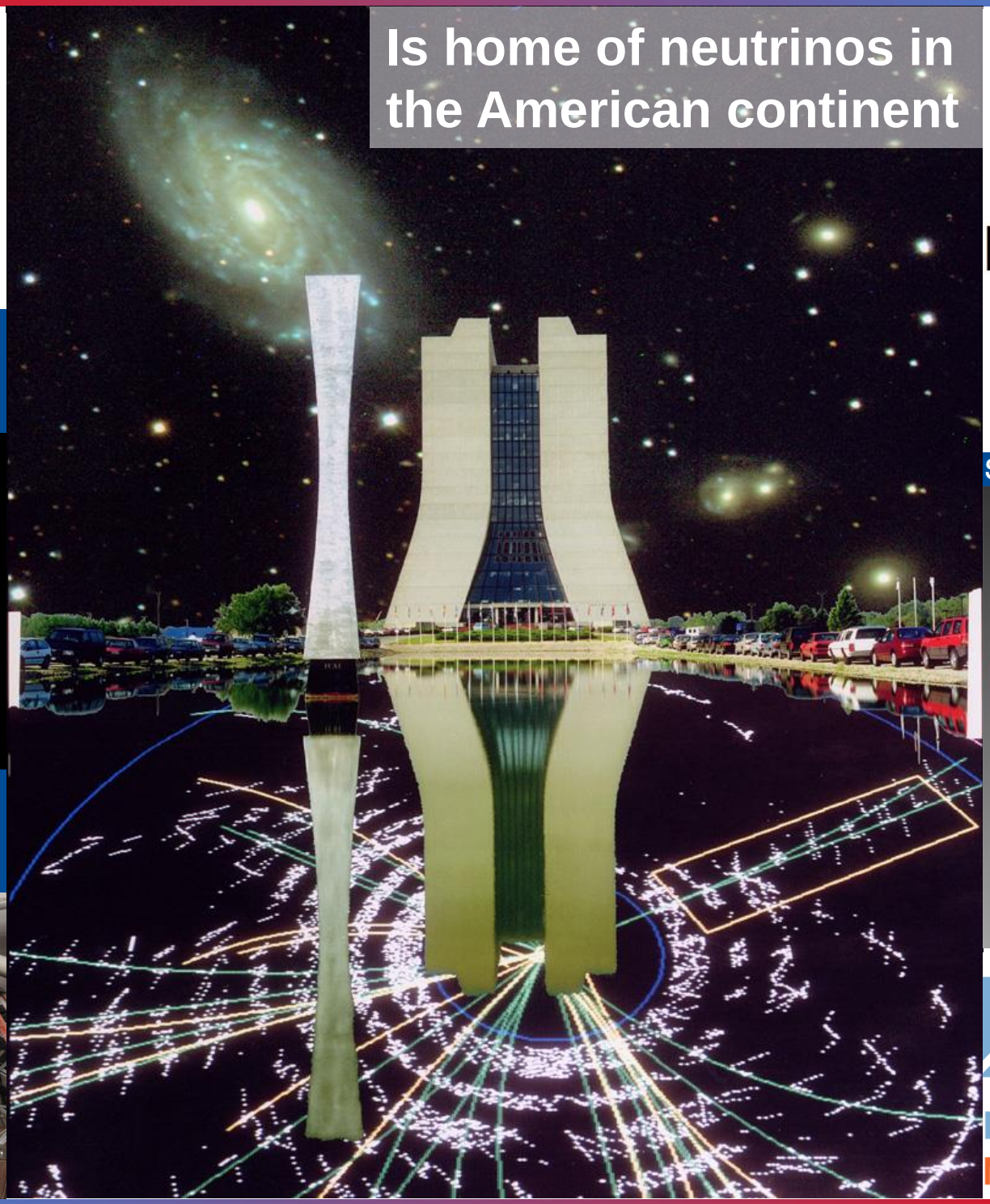
lepton

NOvA

MINERvA

LArIAT

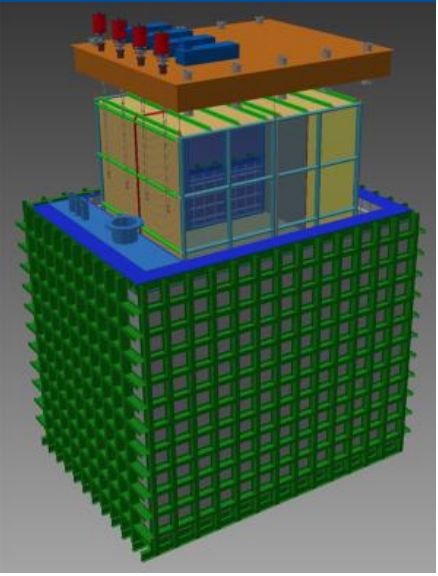
Is home of neutrinos in the American continent



MINOS+

µBooNE

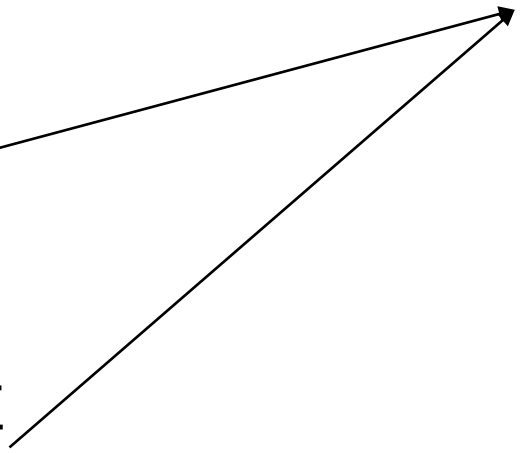
Short-Baseline Near Detector



DUNE

DEEP UNDERGROUND NEUTRINO EXPERIMENT

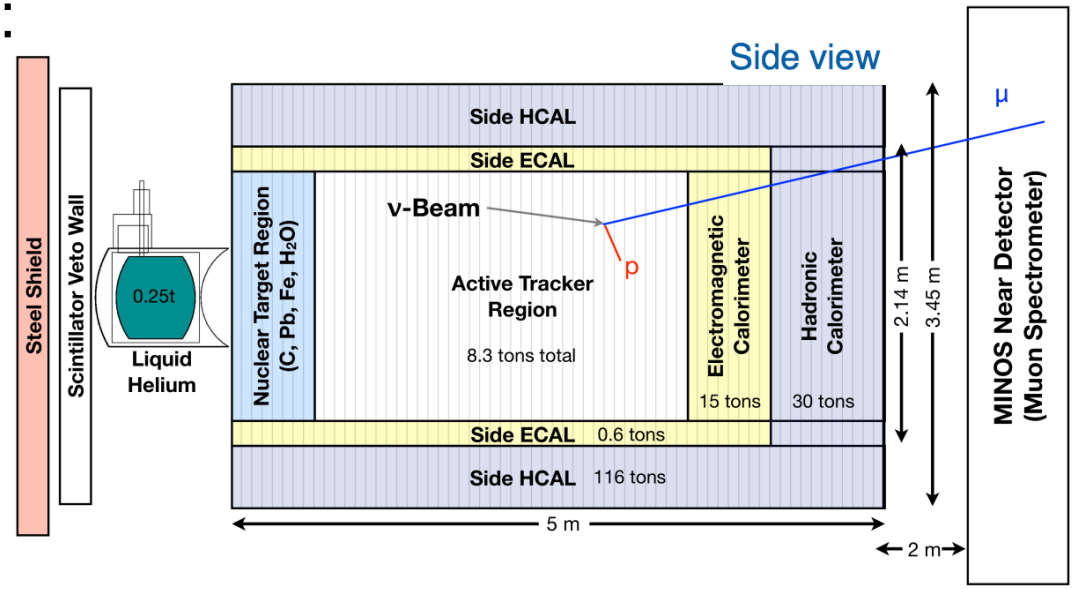
- Cross Section measurements:
  - MINERvA
  - NOvA (Near detector)
  - MicroBooNE
- Oscillations
  - Long base-line
    - NOvA
    - MINOS+
    - DUNE
  - Short base-line
    - MicroBooNE
    - SBND



LArIAT:
Liquid Argon time projection chamber In A Testbeam

- Cross Section measurements:
  - MINERvA
  - NOvA (Nea
  - MicroBooN
  - Oscillations
  - Long base-line
  - NOvA

Main Injector Neutrino Experiment for ν-A



"Measurement of **K⁺ production in charged-current** ν_μ interactions", Accepted by Phys. Rev. D.

"Measurement of Neutrino Flux using **Neutrino-Electron Elastic Scattering**", Phys. Rev. D 93, 112007 (2016)

"Measurement of Partonic Nuclear Effects in **Deep-Inelastic Neutrino Scattering** using MINERvA", Phys. Rev. D 93, 071101 (2016).

"Identification of nuclear effects in neutrino-carbon interactions at **low three-momentum transfer**", Phys. Rev. Lett. 116, 071802 (2016).

"Measurement of **electron neutrino quasielastic**

"**Single neutral pion production** by charged-current anti-$\nu\mu$ interactions on hydrocarbon at average E_ν of 3.6 GeV", Phys.Lett. B749 130-136 (2015).

"Measurement of **muon plus proton final states** in $\nu\mu$ Interactions on Hydrocarbon at average E_ν of 4.2 GeV" Phys. Rev. D91, 071301 (2015).

"Measurement of **Coherent Production of $\pi^\pm$** in Neutrino and Anti-Neutrino Beams on Carbon from ν_μ of 1.5 to 20 GeV", Phys. Rev.Lett. 113, 261802 (2014).

"**Charged Pion Production** in ν_μ Interactions on Hydrocarbon at average E_ν of 4.0 GeV" , Phys.Rev. D92, 092008 (2015).

"Measurement of ratios of ν_μ charged-current **cross sections on C, Fe, and Pb** to CH at neutrino energies 2–20 GeV", Phys. Rev. Lett. 112, 231801 (2014).

"Measurement of **Muon Neutrino Quasi-Elastic Scattering** on a Hydrocarbon Target at E_ν ~3.5 GeV", Phys. Rev. Lett. 111, 022502 (2013).

"Measurement of **Muon Antineutrino Quasi-Elastic Scattering** on a Hydrocarbon Target at E_ν ~3.5 GeV", Phys. Rev. Lett. 111, 022501 (2013).

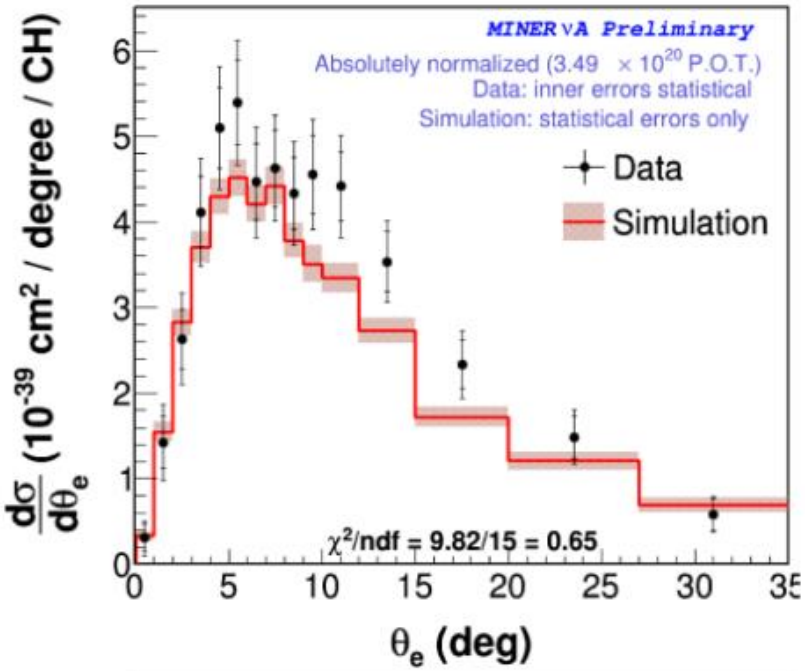
Evidence for **neutral-current diffractive neutral pion production** from hydrogen in neutrino interactions on hydrocarbon

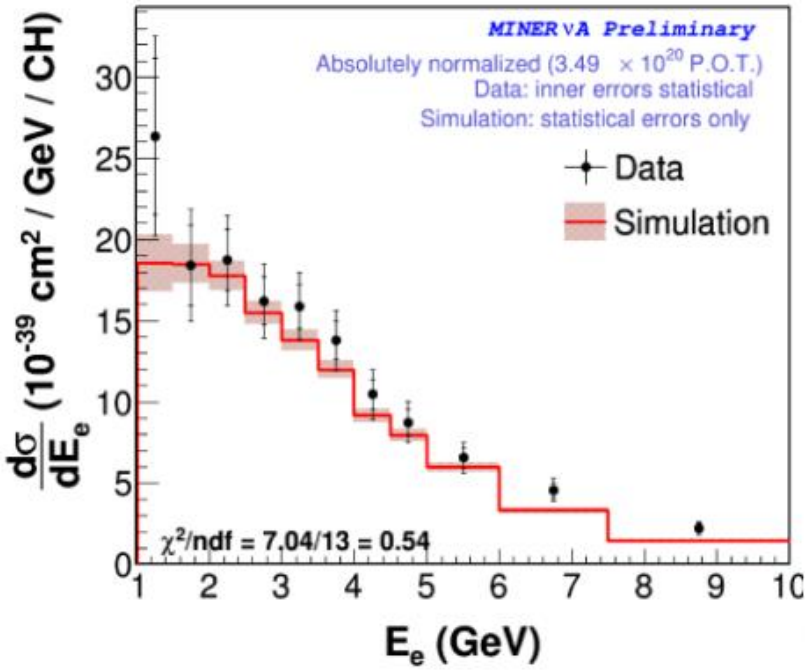
Cross sections for **neutrino and antineutrino induced pion production** on hydrocarbon in the few-GeV region using MINERvA

First evidence of **coherent K+ meson production** in neutrino-nucleus scattering

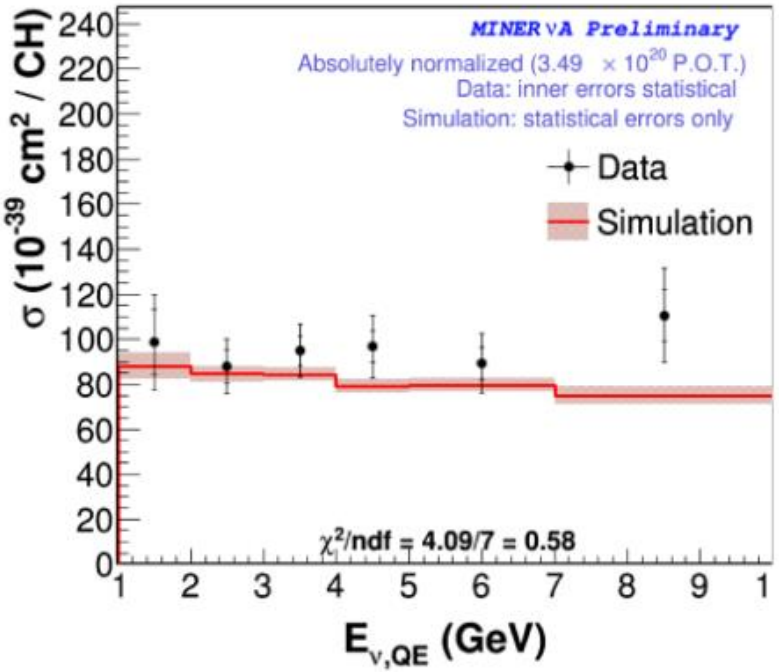
Thanks to Laura Fields

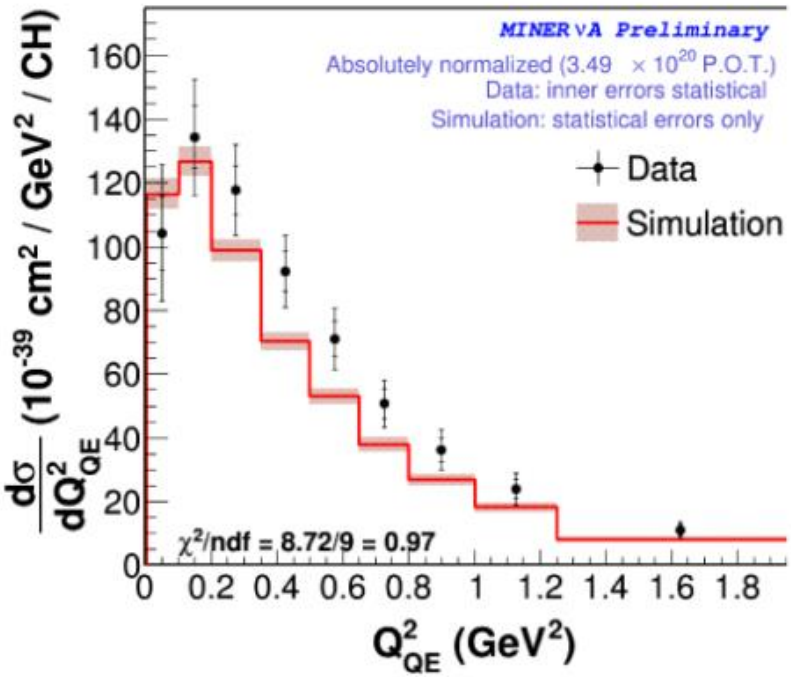
Phys. Rev. Lett. 116, 081802 (2016)





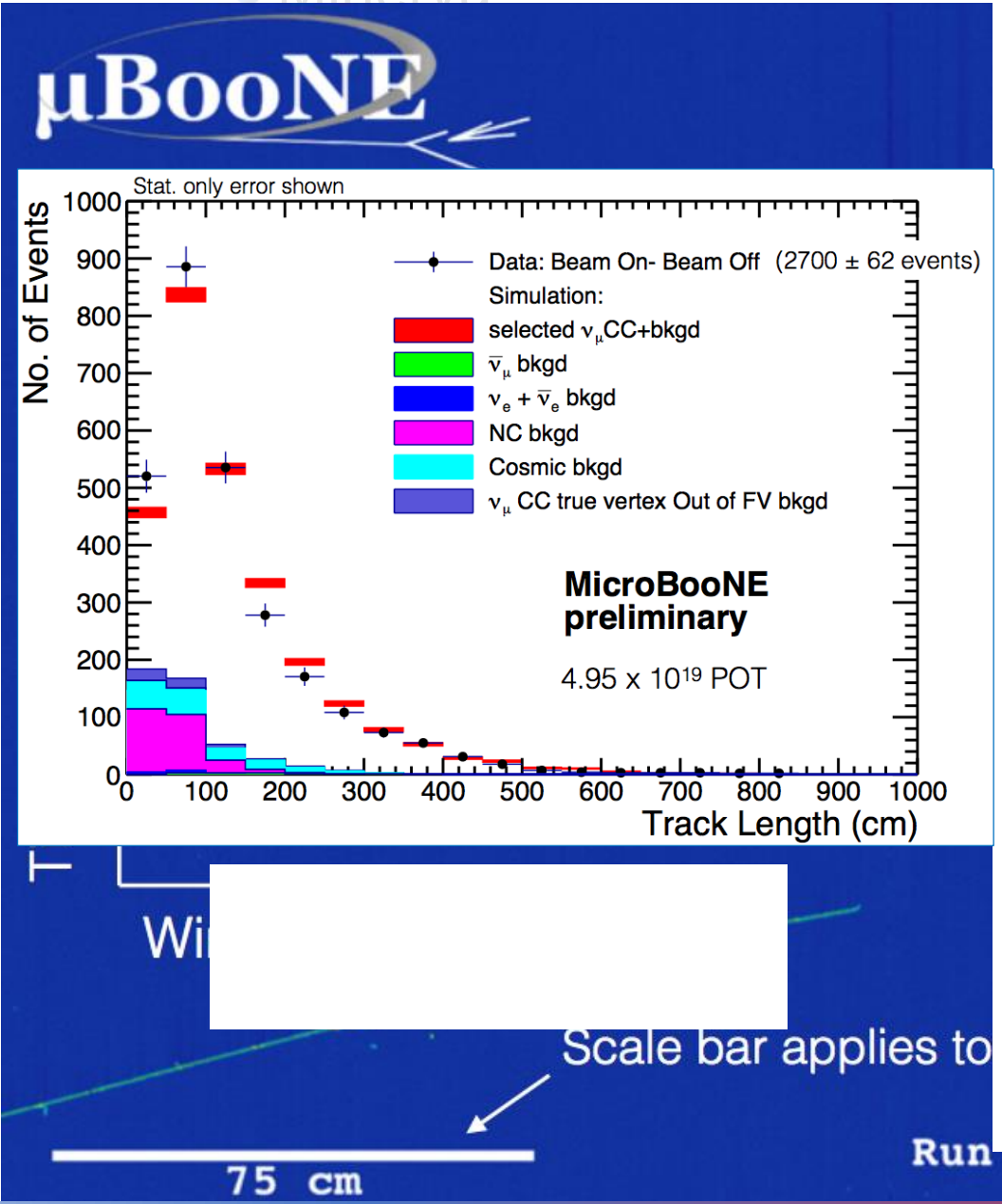
Measured cross-sections are consistent with the prediction from GENIE 2.6.2

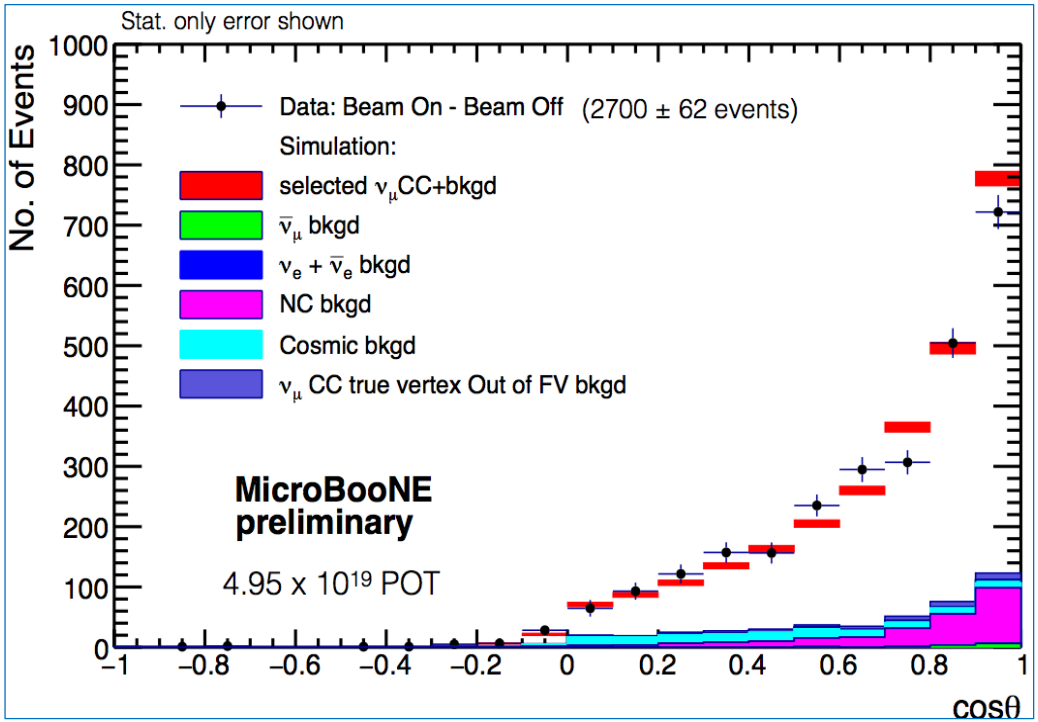




Thanks to Laura Fields

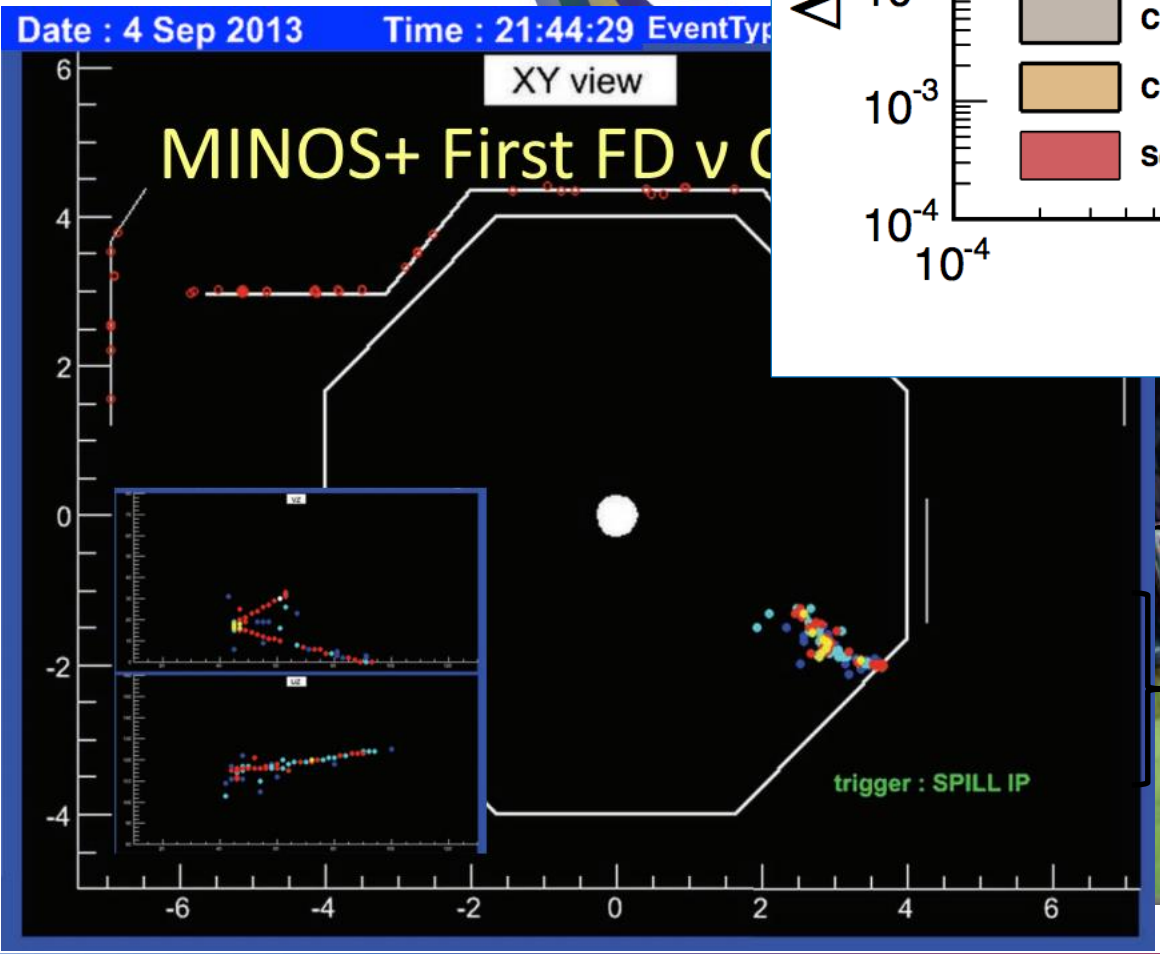
- Cross Section measurements:
  - Minerva

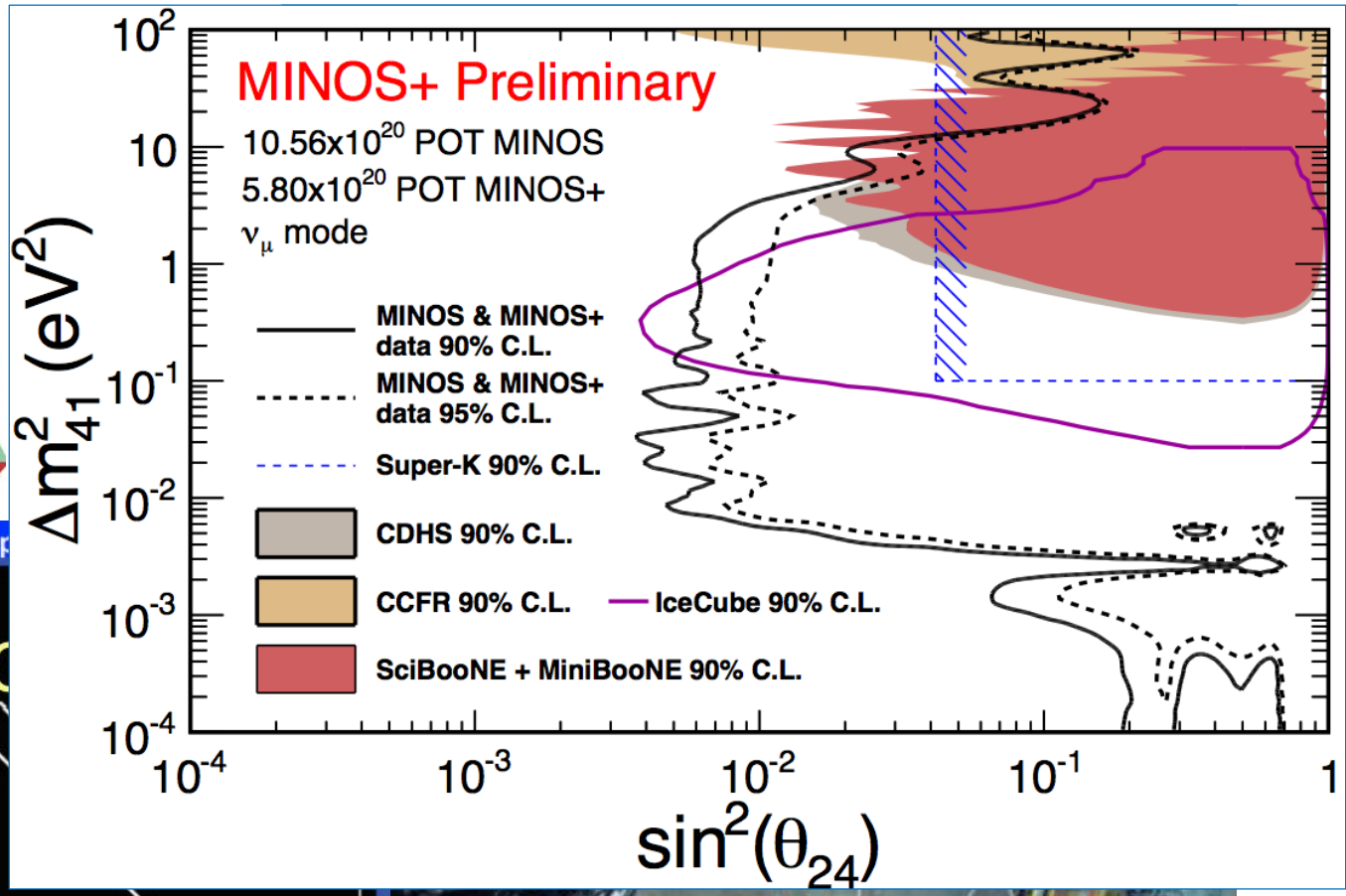




- Oscillations
  - Long base-line

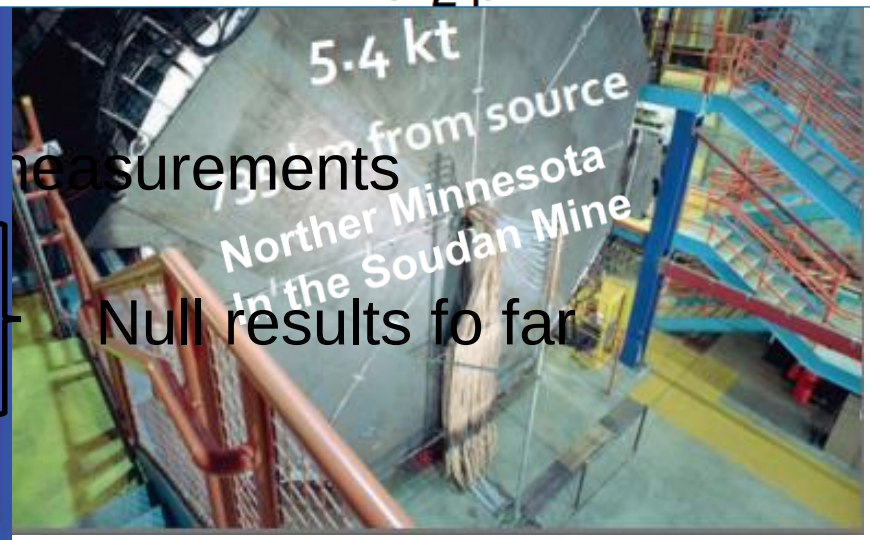
Main Injector Neutrino OScillations





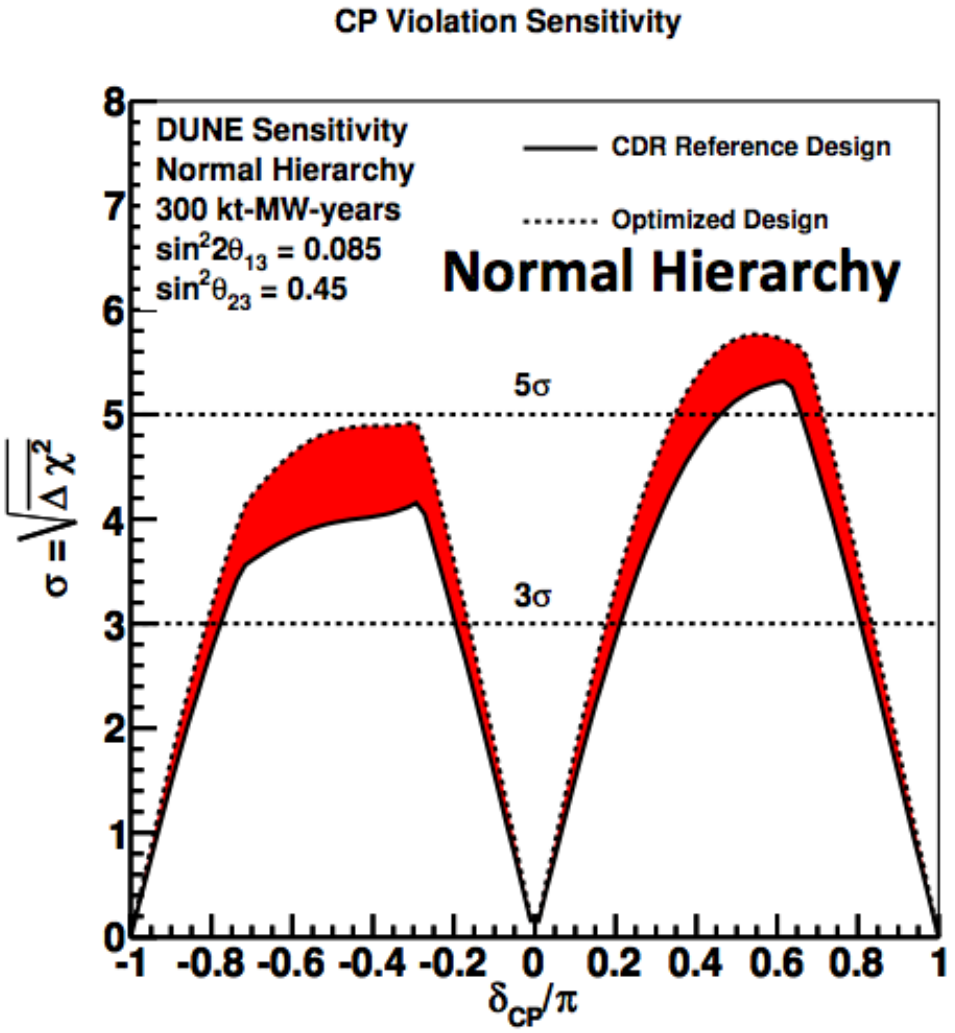
measurements

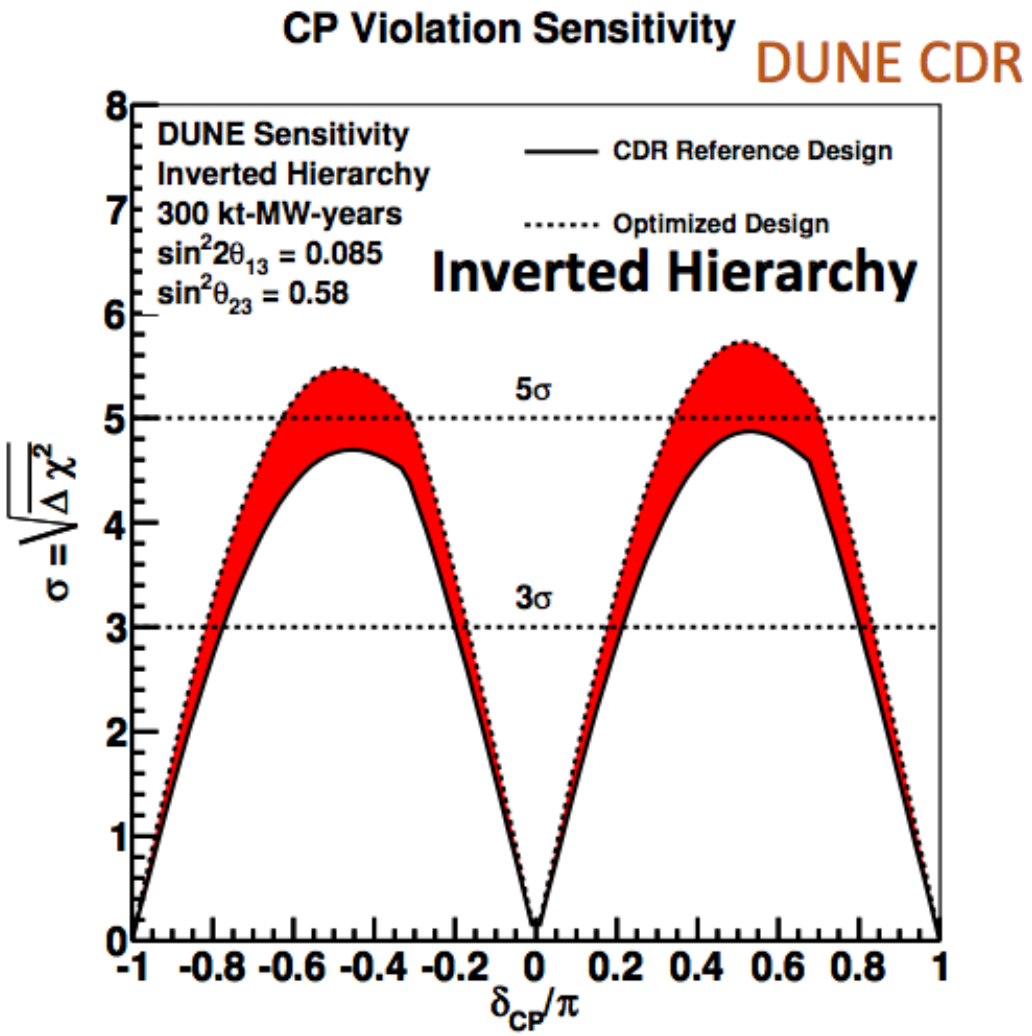
- Null results fo far



Thanks to Justin Evans & Alex Sousa

- Physics program:
  - Neutrinos Oscillations

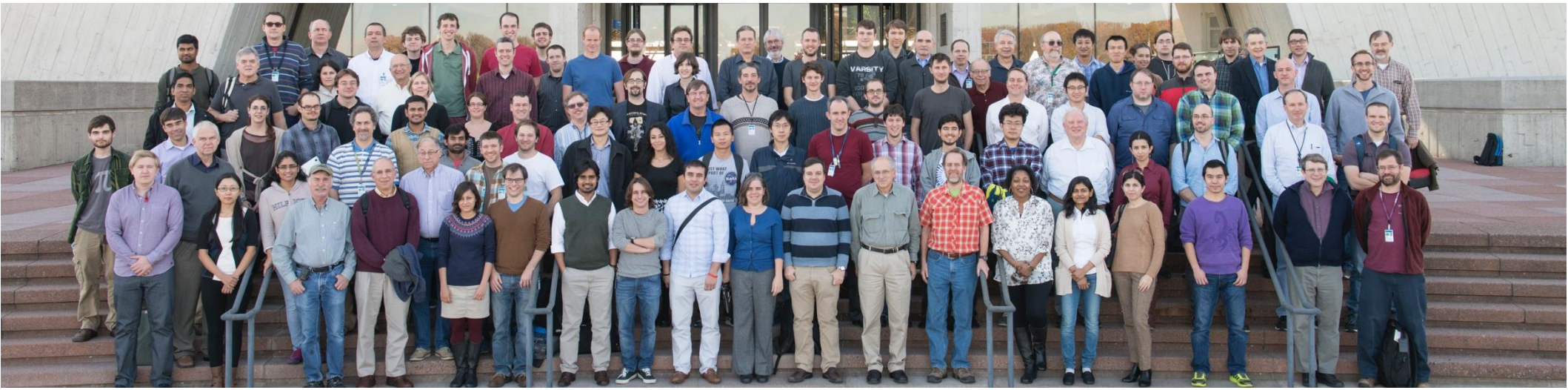




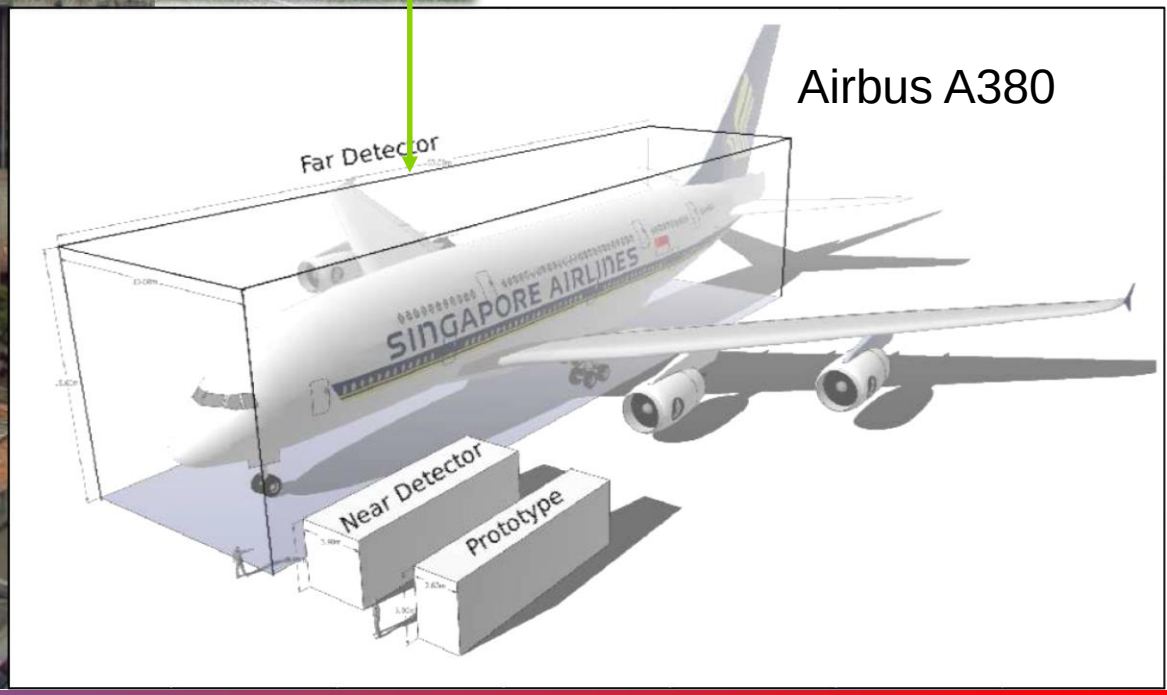
Thanks to Jon Urheim

- NuMI Off-axis ν_e Appearance, NOvA
- Headquarters @ Fermilab
- 220+ members
- 20+ Institutions from:

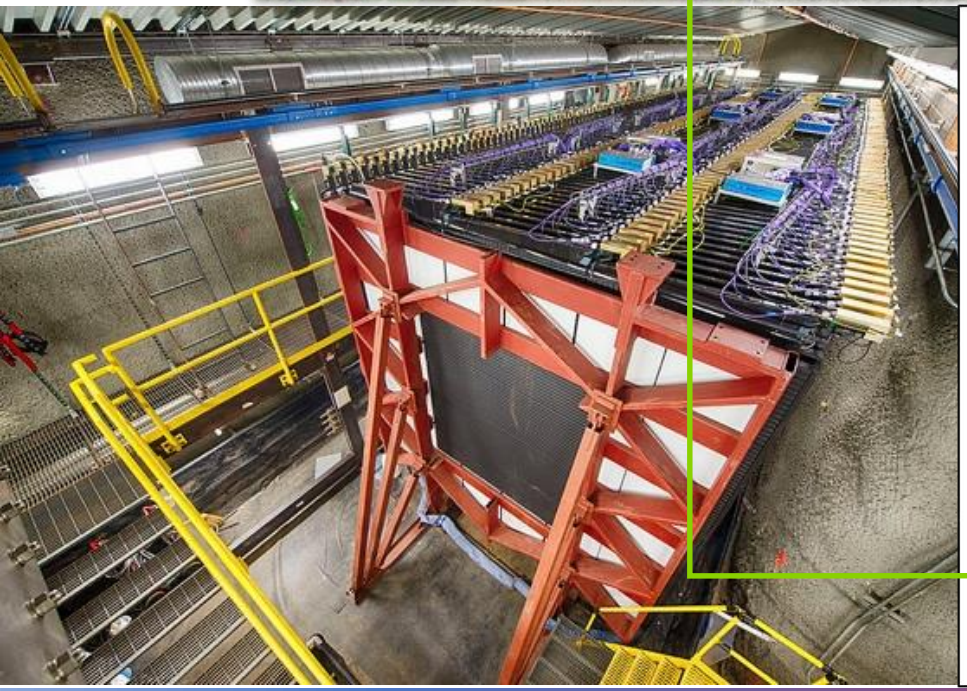
- NOvA has an extensive physics program
- Two main goals related to oscillations
  - Establish the neutrino mass hierarchy (3σ)
  - Measure the δ CP phase ($2,3\sigma$)
- Cross section program with near detector
- Sterile neutrinos
- Supernova neutrinos
- Exotics: Magnetic monopoles, neutrino magnetic moment, dark matter & more

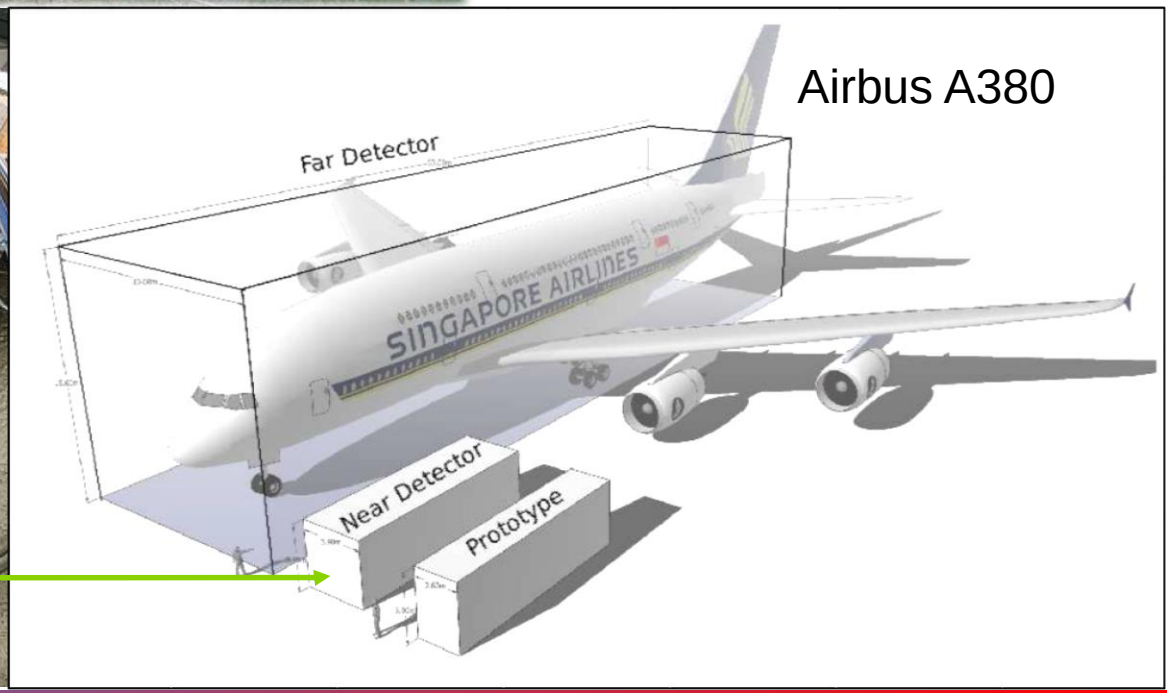


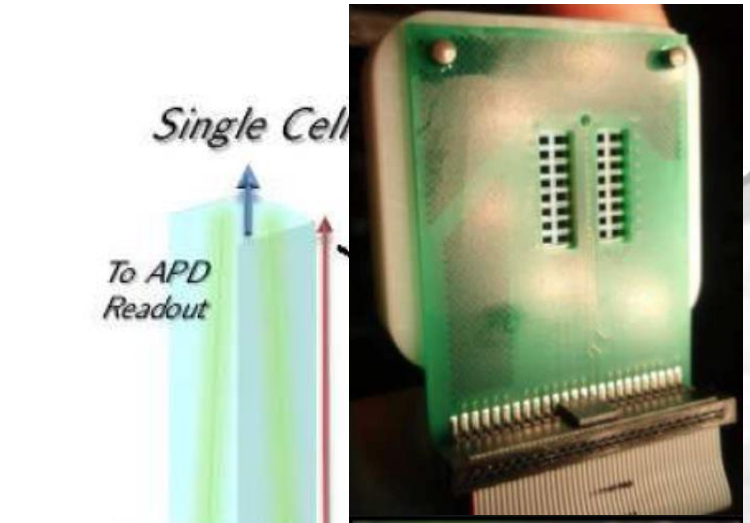
- Far detector:
  - $60 \times 15 \times 15\ m^3$
  - 14 kton
  - 344000 channels
  - Largest PVC free standing structure
  - ν_e appearance
  - ν_μ disappearance
  - Ash River, MN



- Near detector:
  - $14 \times 4 \times 4$ m^3
  - 300 ton
  - 20000 channels
  - 100 m below the surface
  - @ Fermilab
  - $\{_{e}$ background
  - $\{_{\mu}$ flux

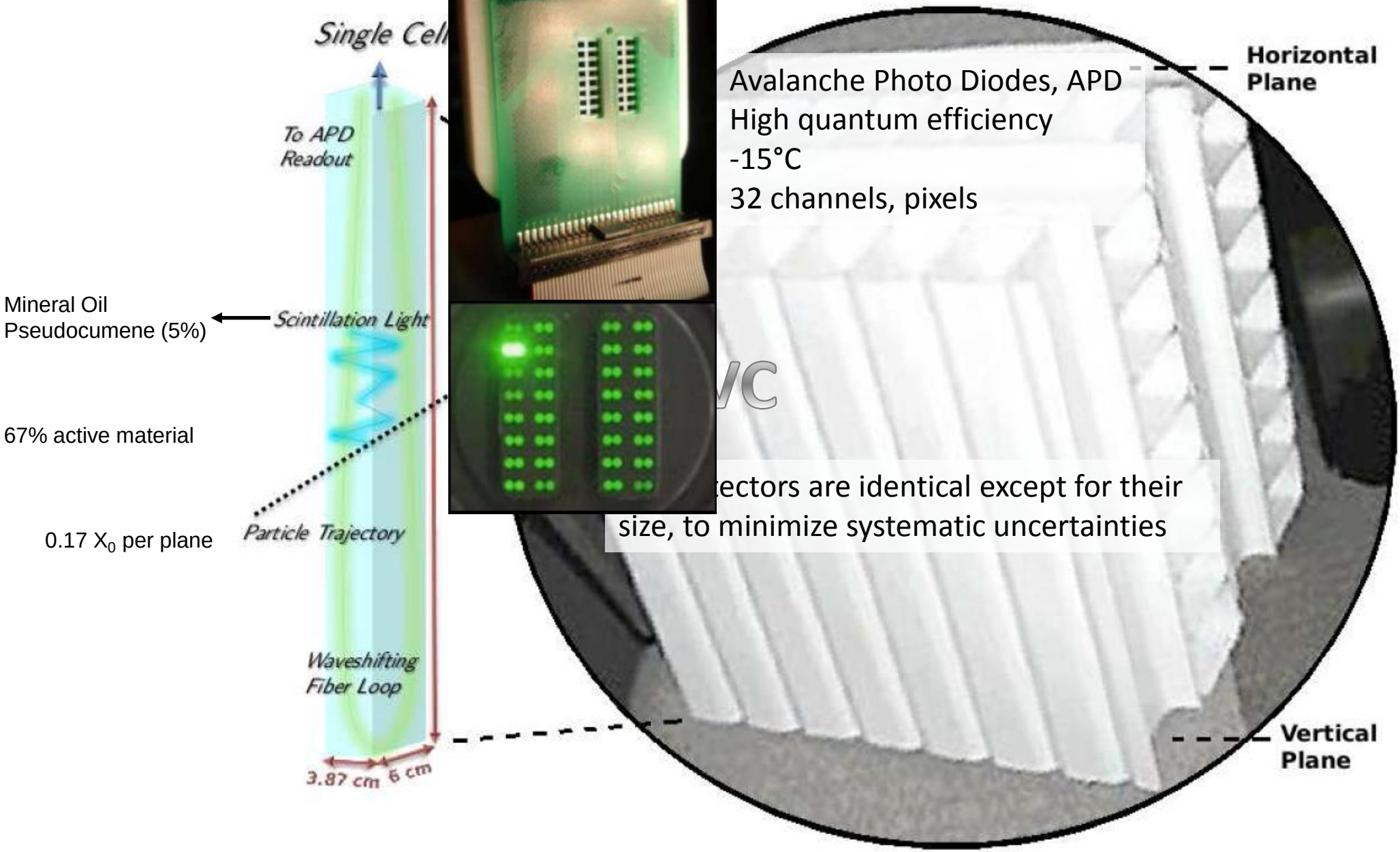


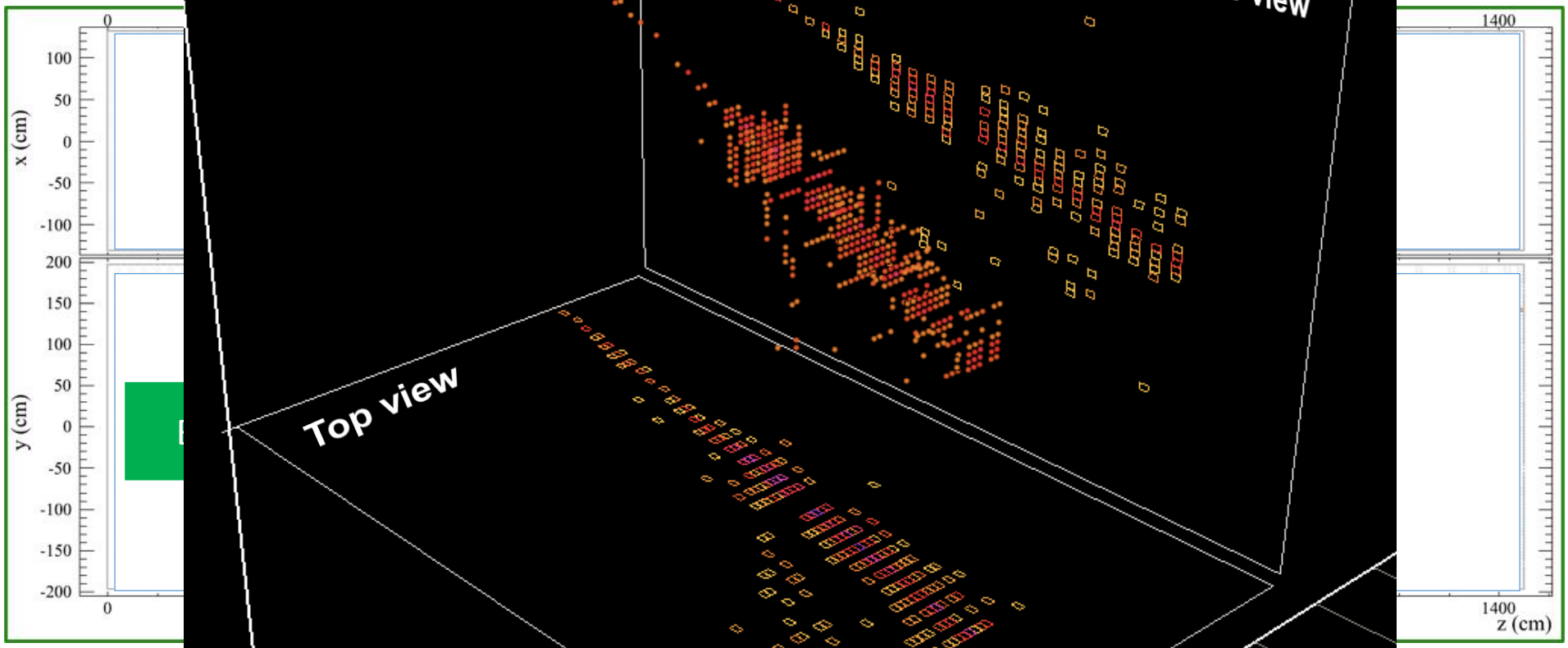




Avalanche Photo Diodes, APD
High quantum efficiency
-15°C
32 channels, pixels

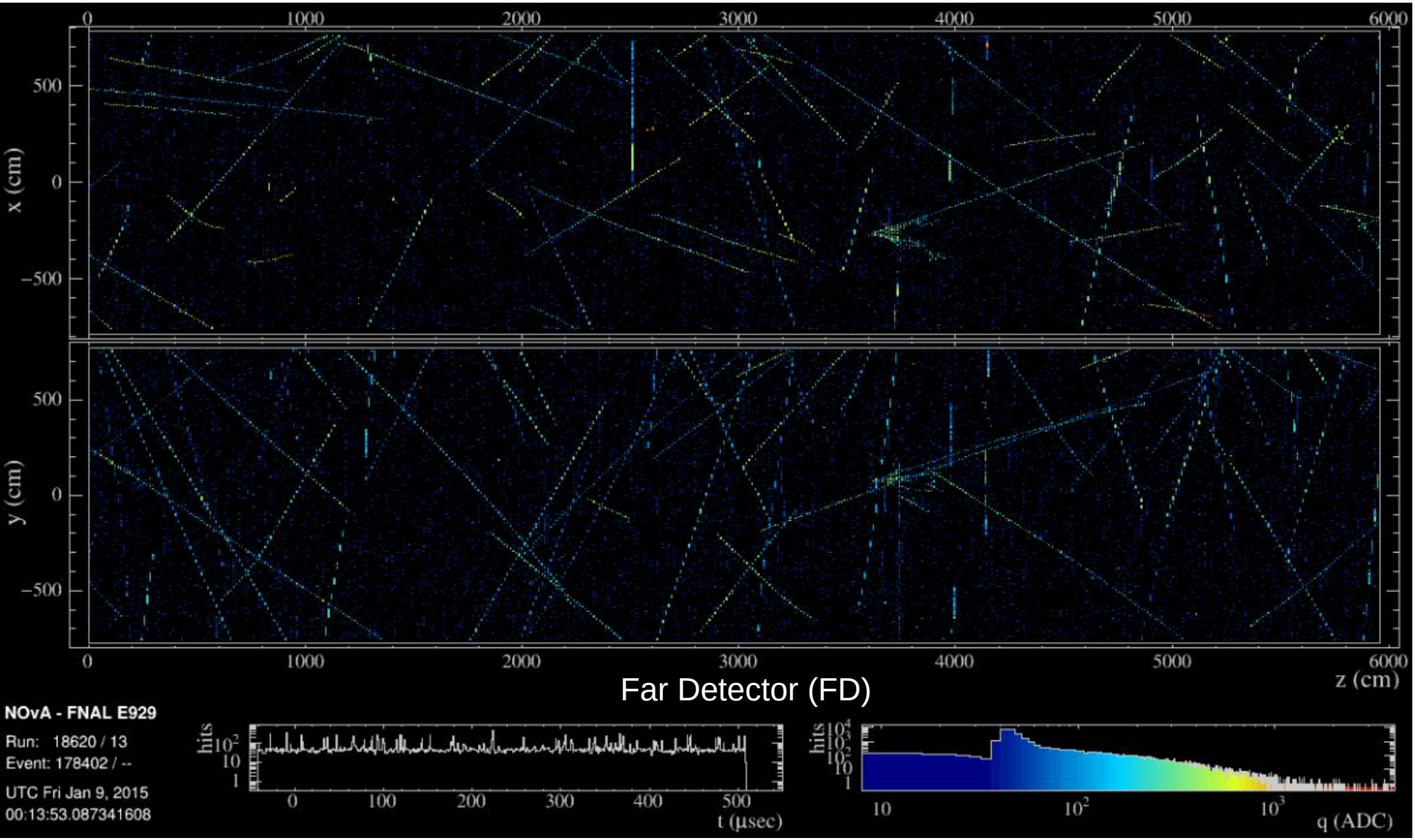
ectors are identical except for their size, to minimize systematic uncertainties





First 3D event
May 21st 2013

150 kHz of Cosmic rays

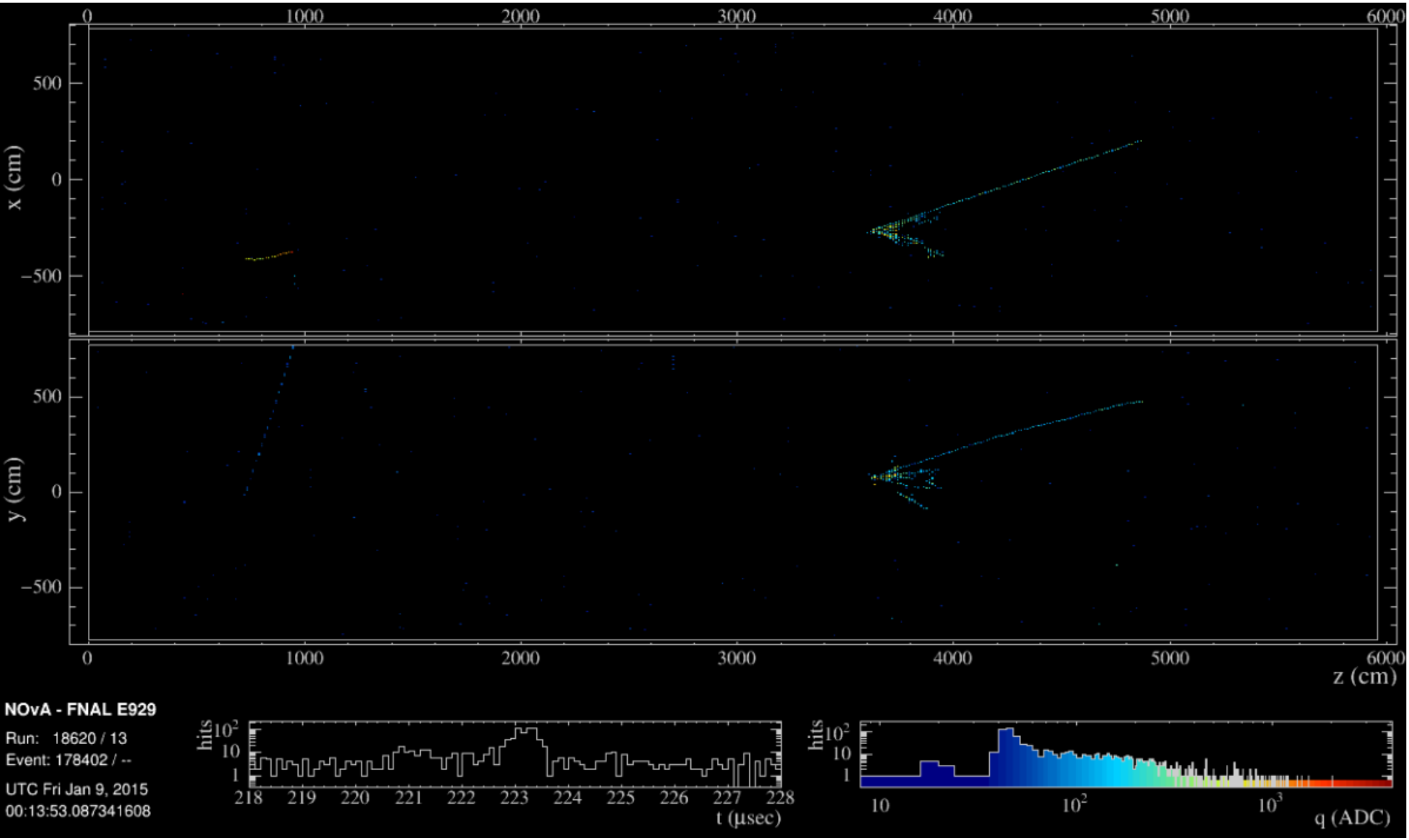


Far Detector (FD)

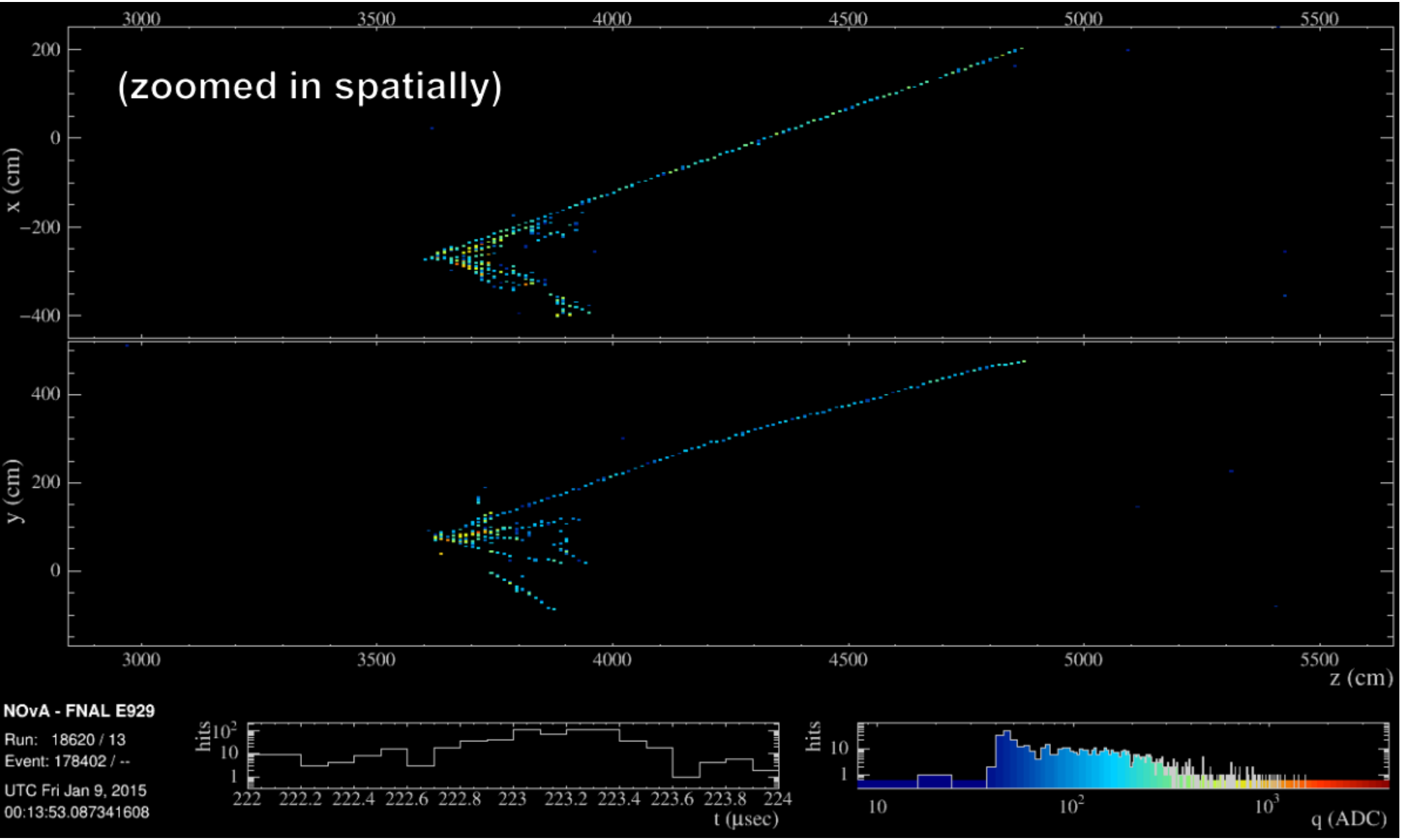
550 μsec exposure for FD

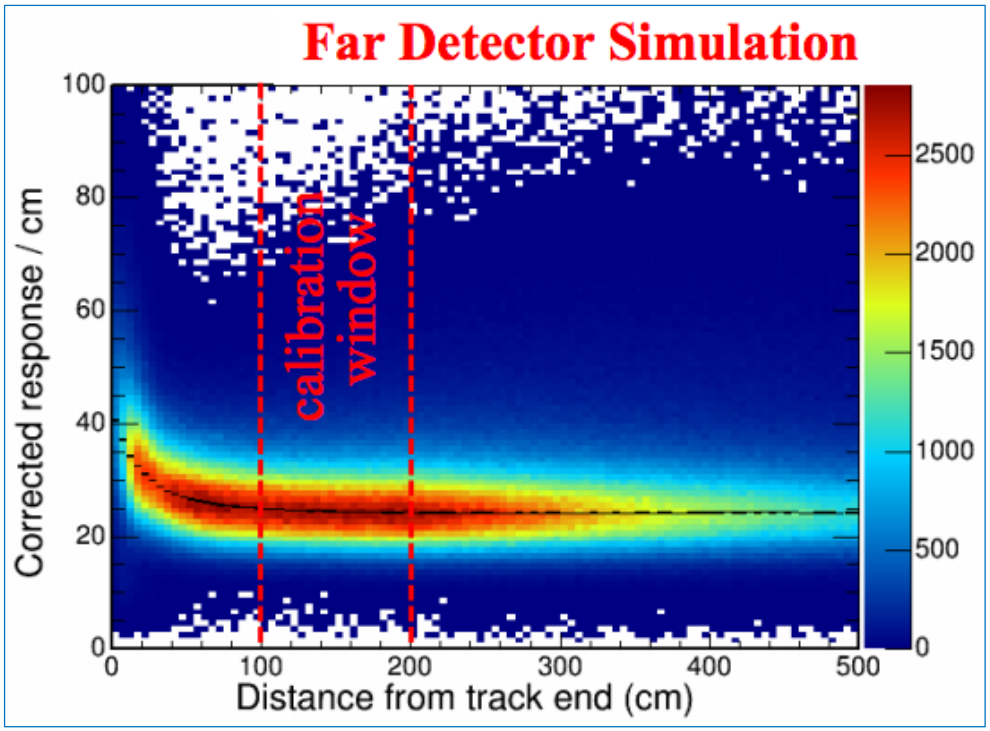
Charge (energy) deposition

Time-zoom on 10 μsec interval during NuMI beam pulse

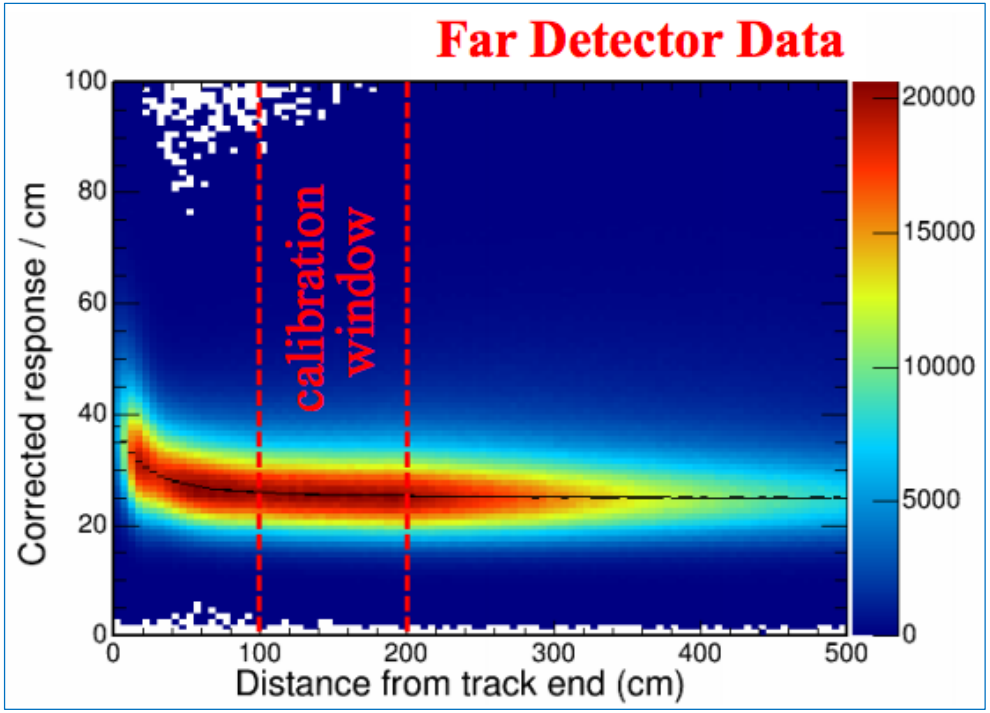


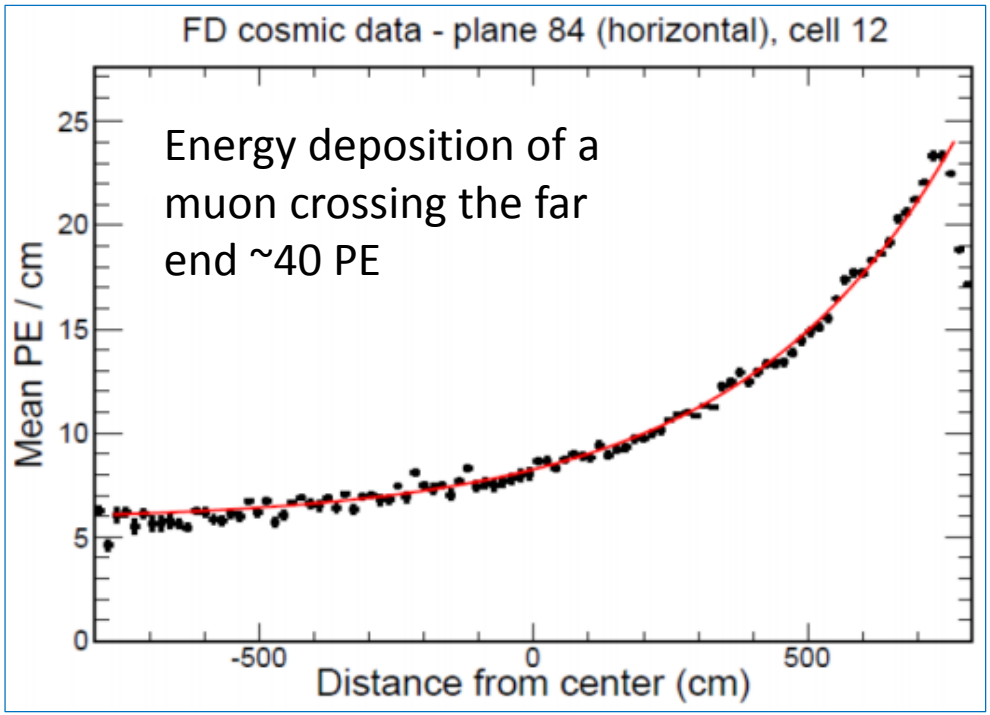
Close-up of neutrino interaction in the far detector



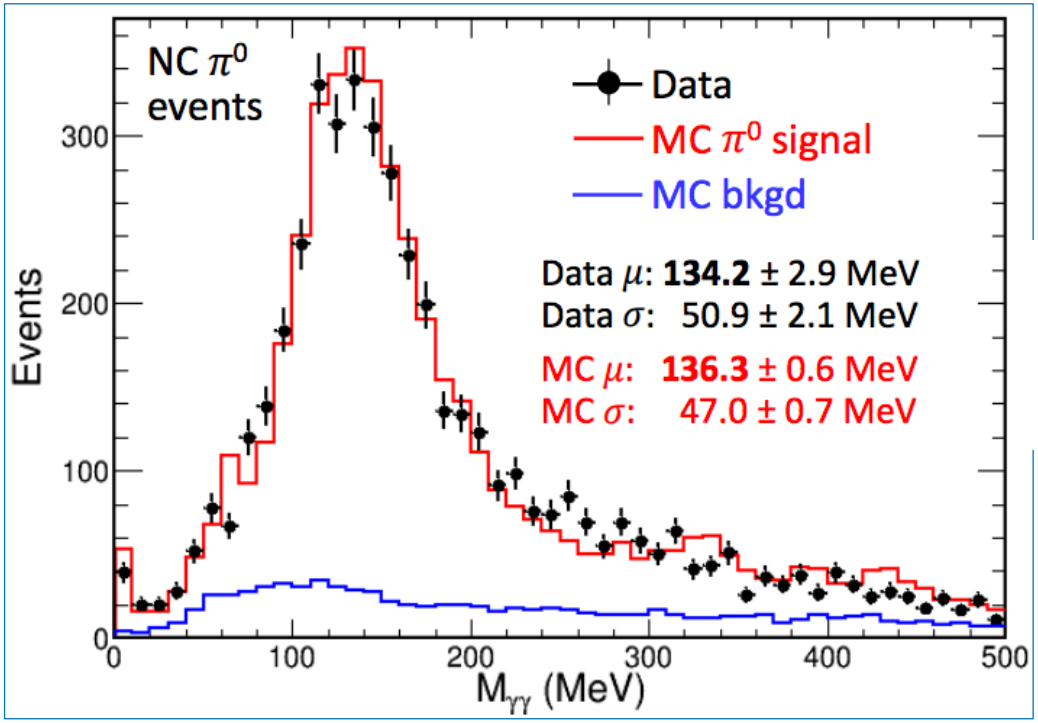


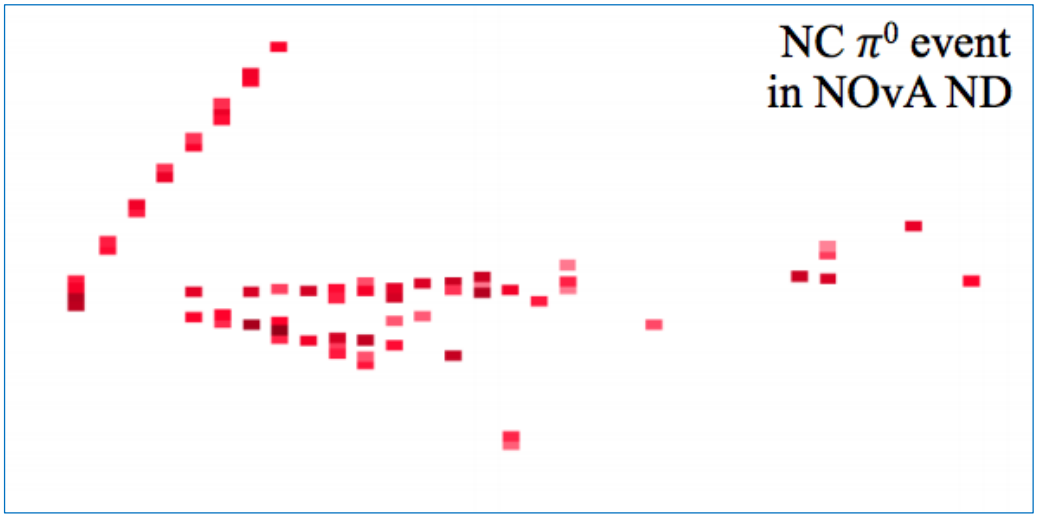
- Stopping muons provide absolute energy scale (dE/dX)
- Attenuation in the wavelength shifting fiber





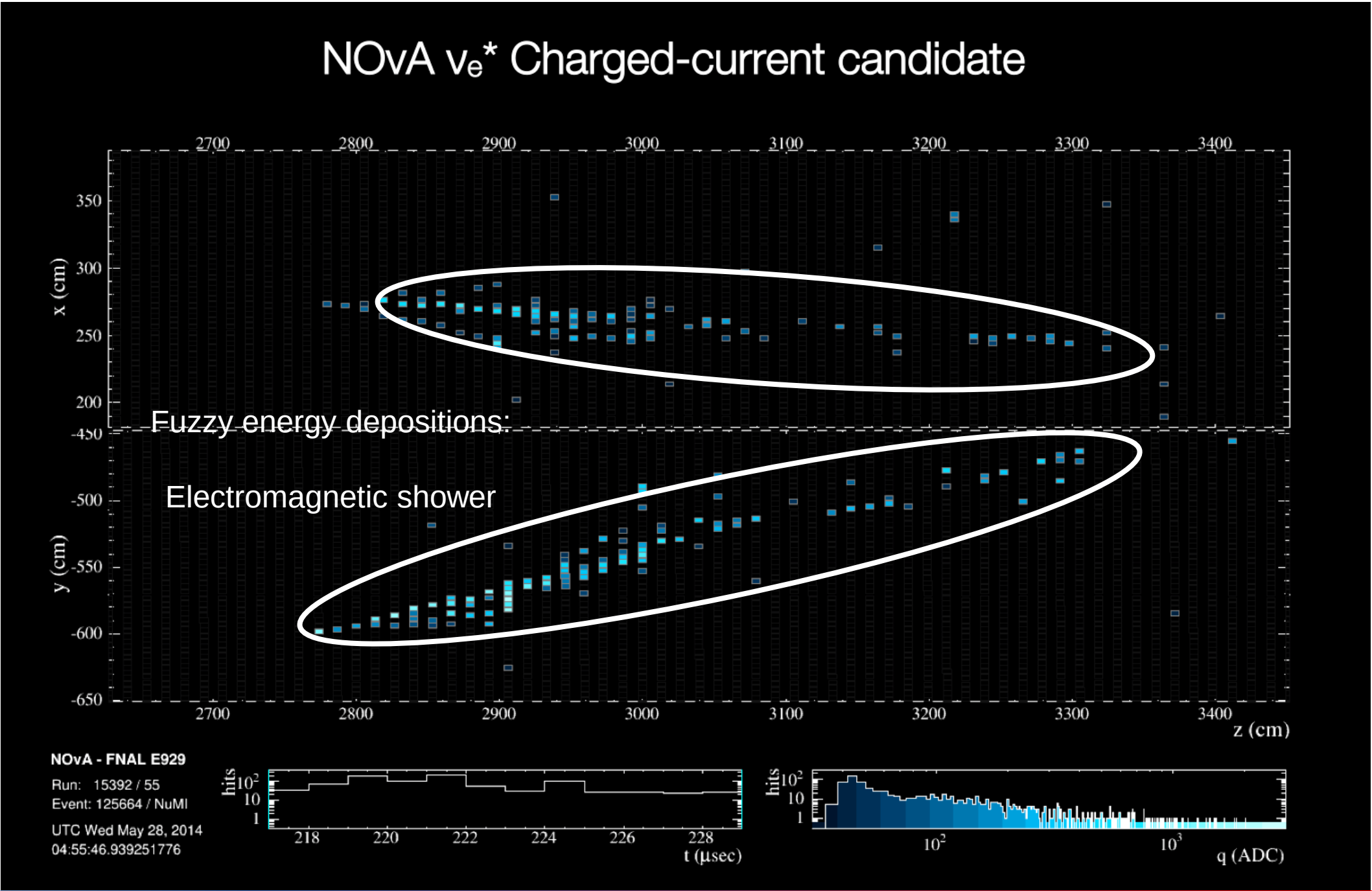
π^0 invariant mass



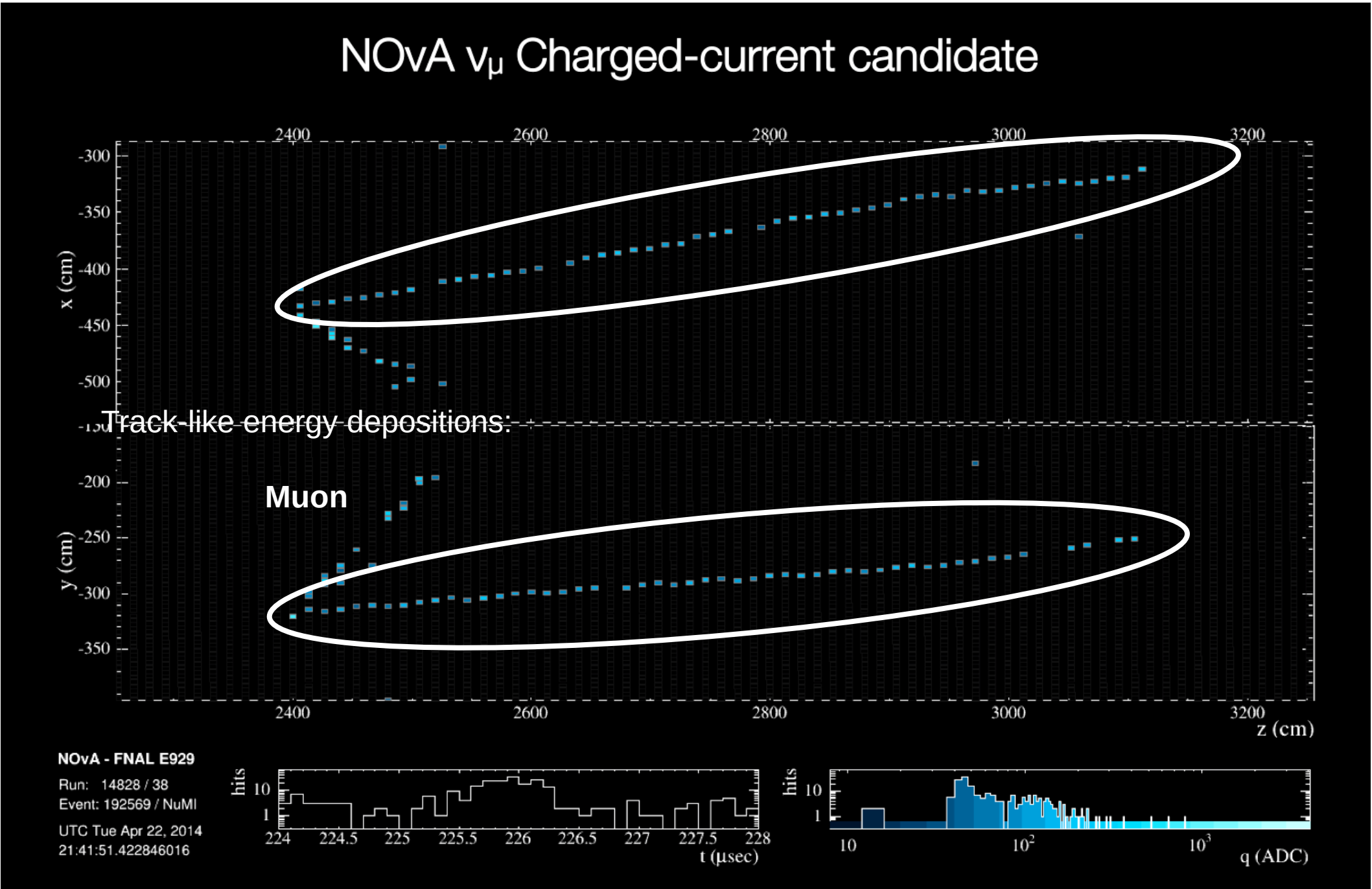


- Checks to energy scale:
  - Hadronic shower hits
  - Michael electron energy from muon decays
  - Bremsstrahlung energy
  - Muon dE/dX
- All within 5% agreement

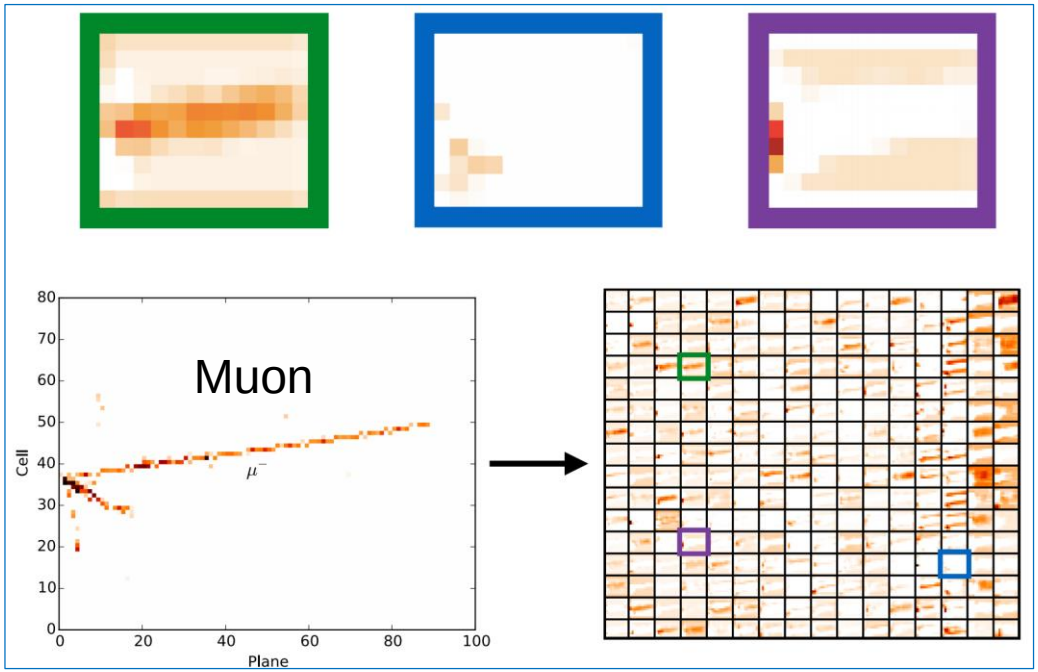
What are we looking for?

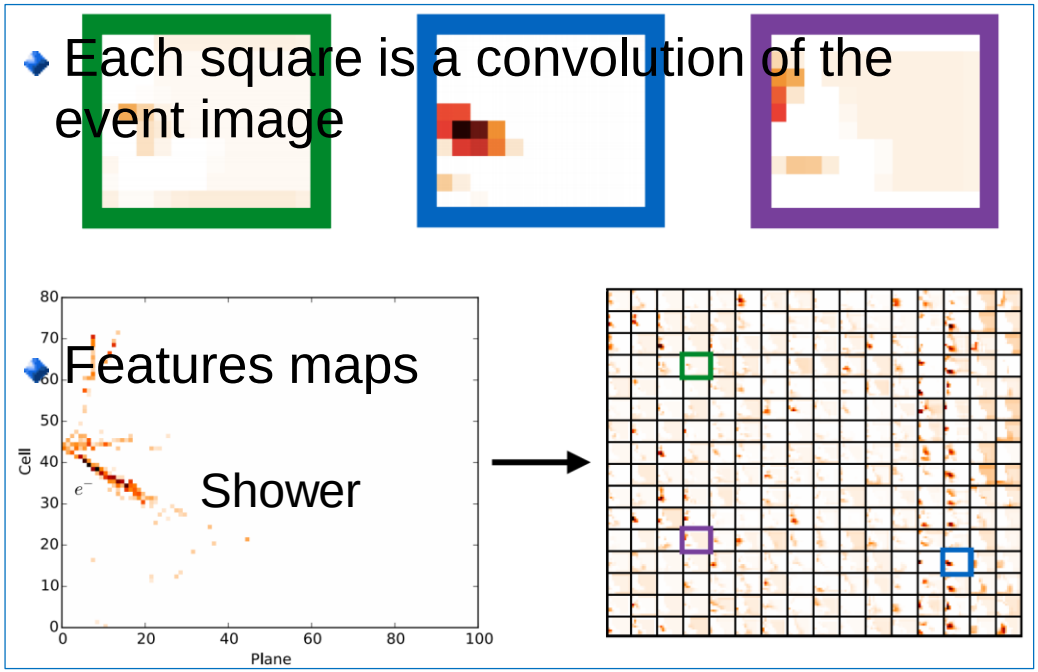


What are we looking for?



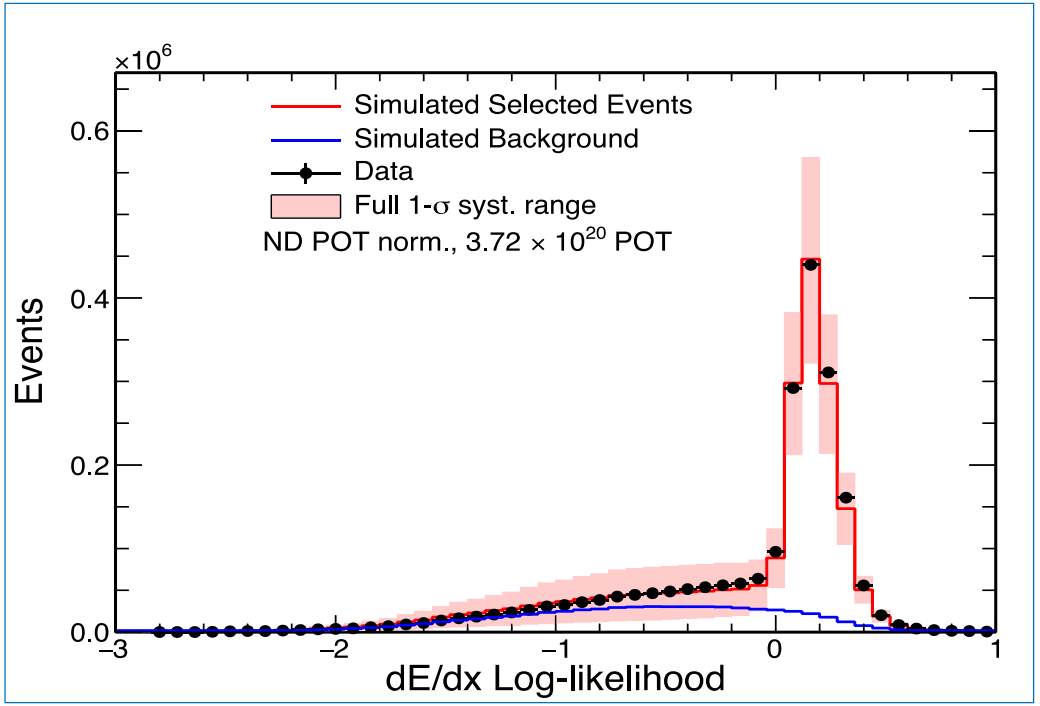
- Recent advancements in the fields of deep learning and computer vision allow for a new event selection technique
- A Convolutional Visual Network (CVN) uses as input calibrated hit maps
- Abstract features are extracted from transformations applied to series of processed images
- The CVN uses the abstract features to classify events

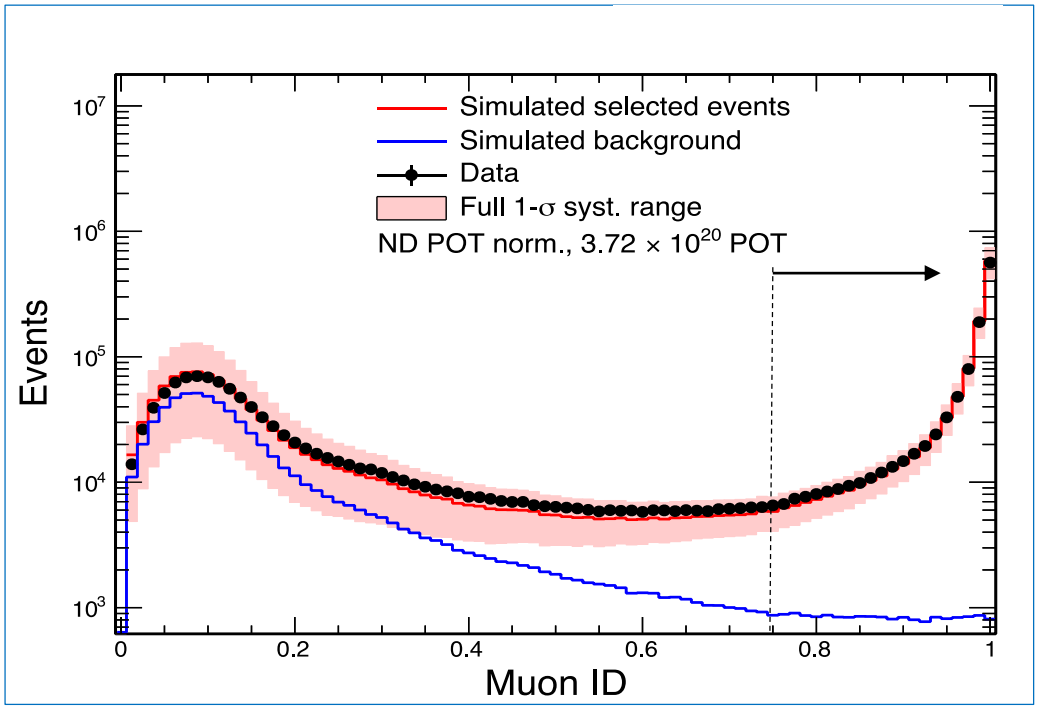




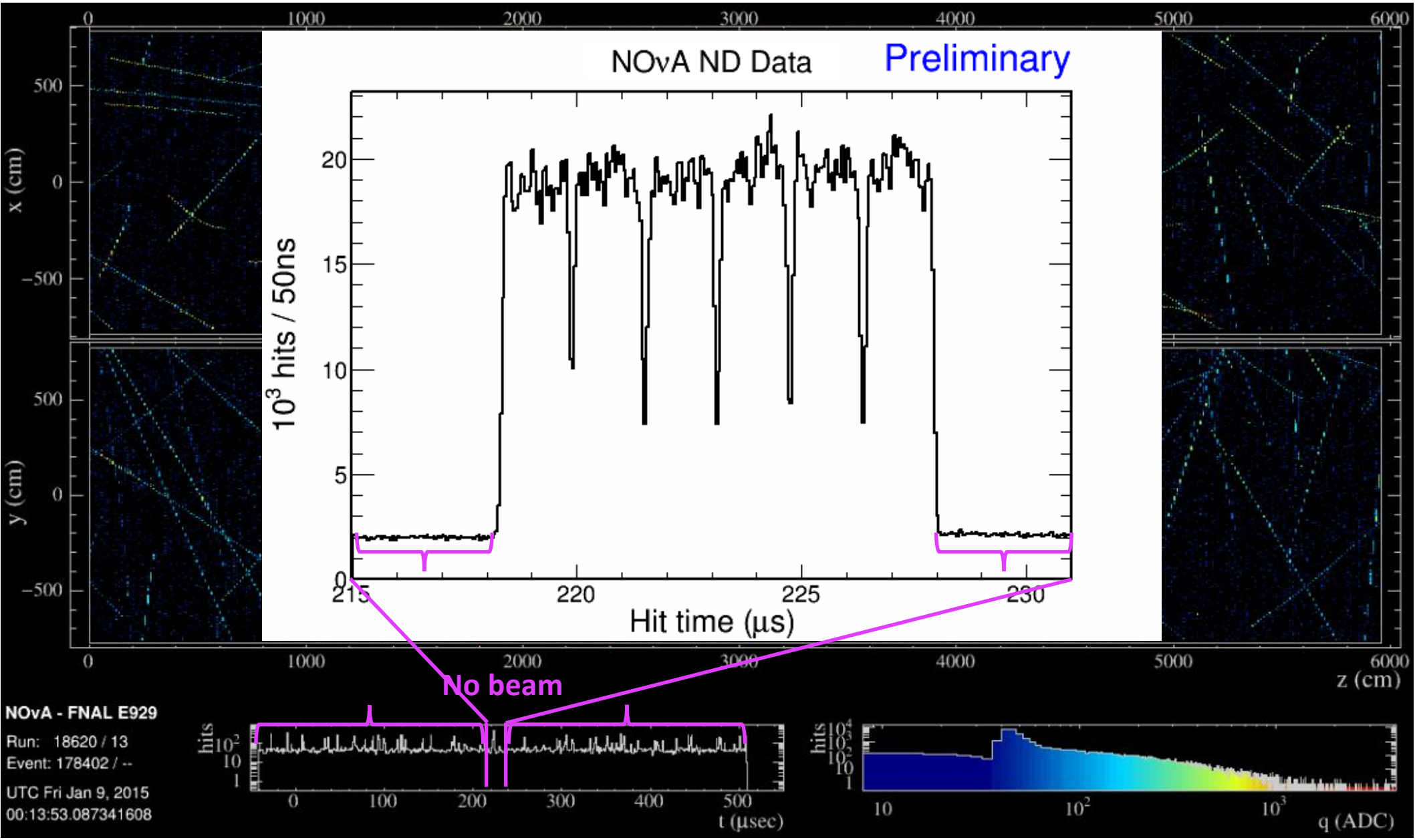
A. Aurisiano *et. al.*, JINST **11**, P09001 (2016)

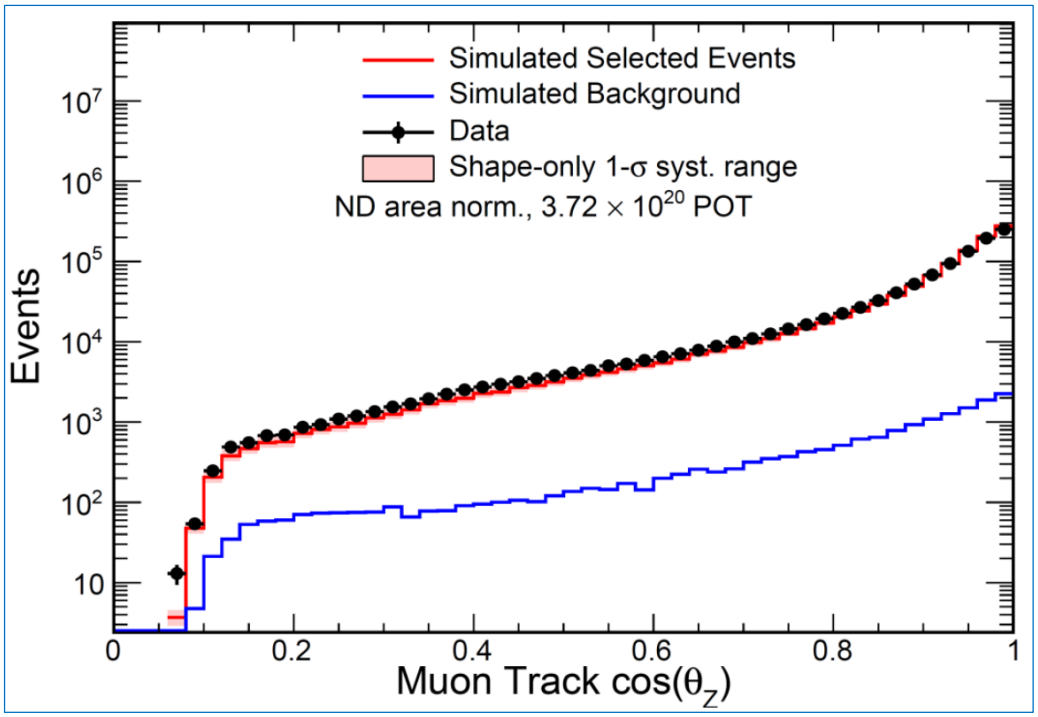
- For the muon neutrino disappearance analysis NOvA uses mainly the energy deposition profiles of muons to identify them

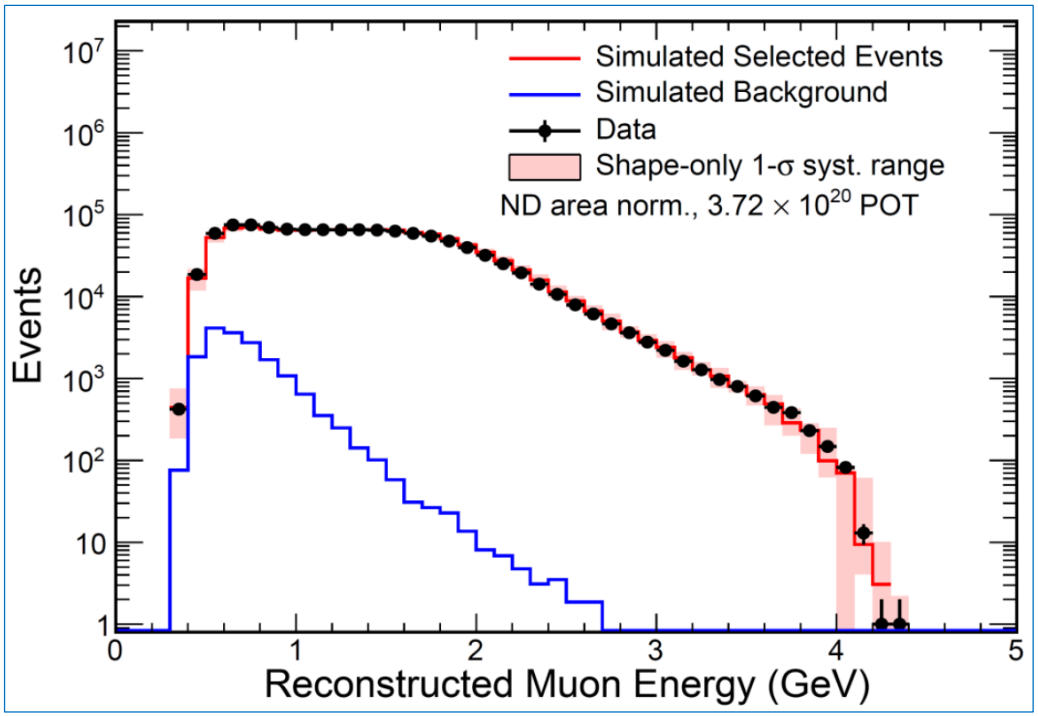




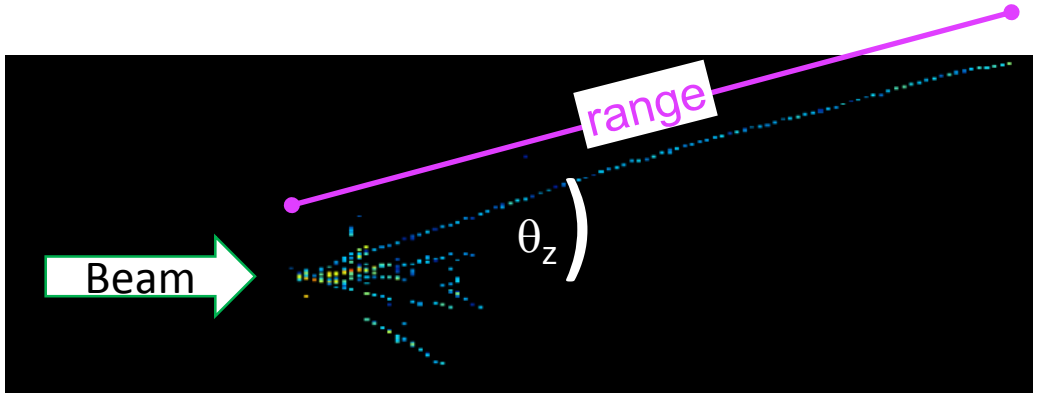
Cosmic background rejection



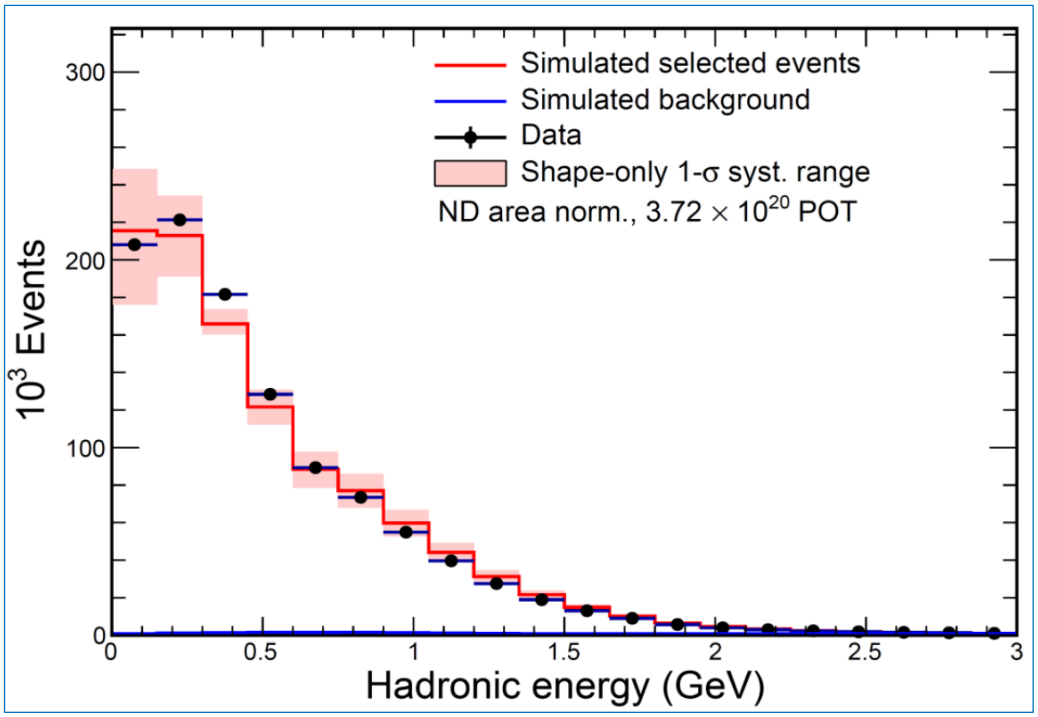




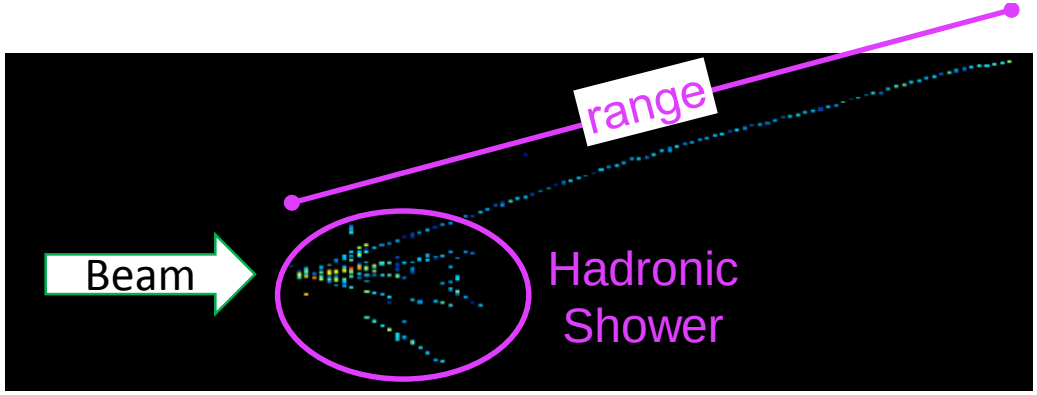
- ND 98.4% beam purity
- Excellent agreement between data & MC

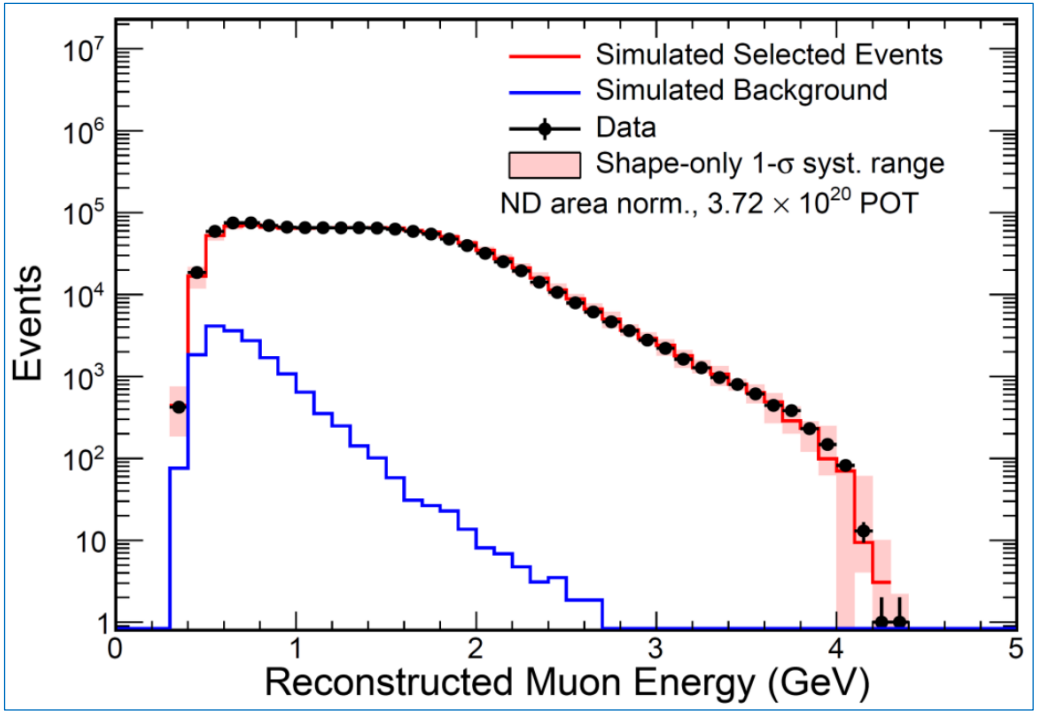


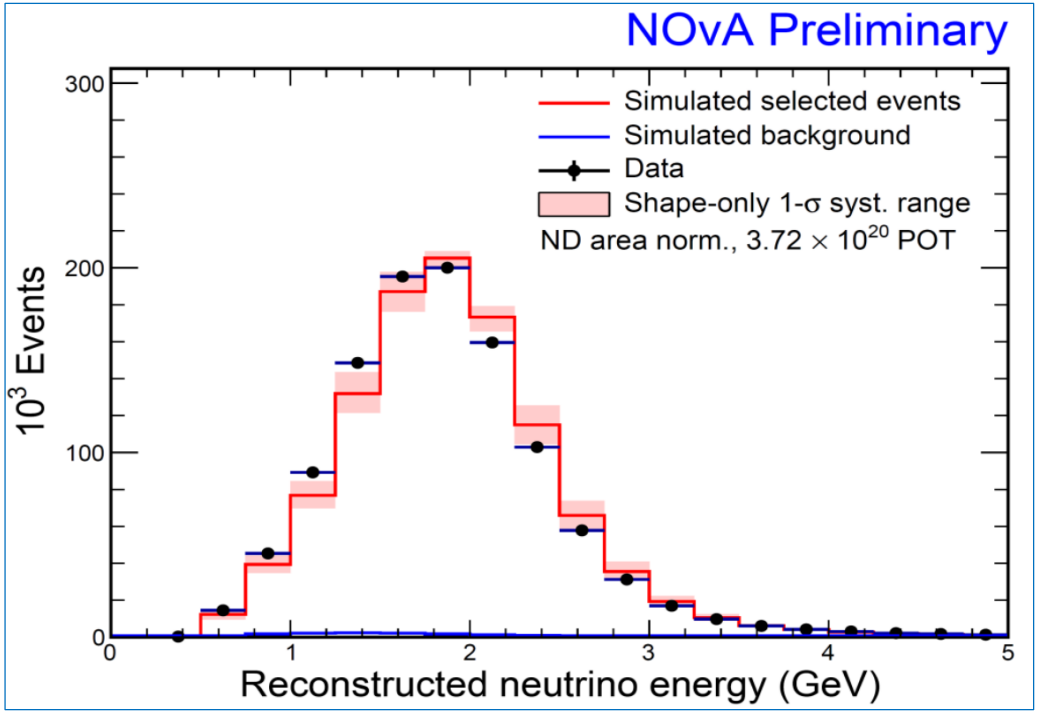
- Muon energy from range



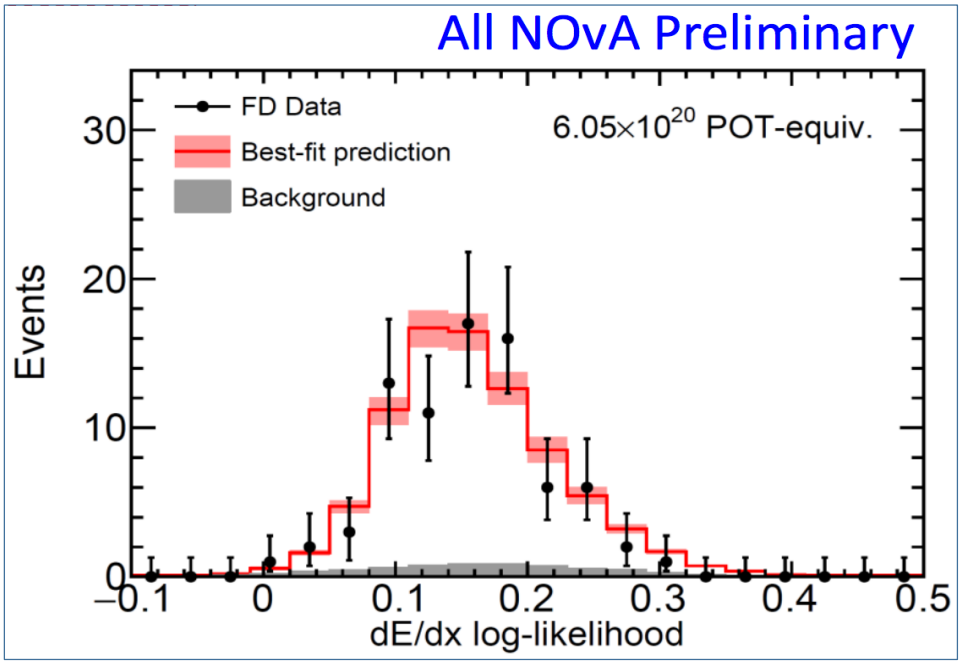
- Hadronic energy shower from calorimetry

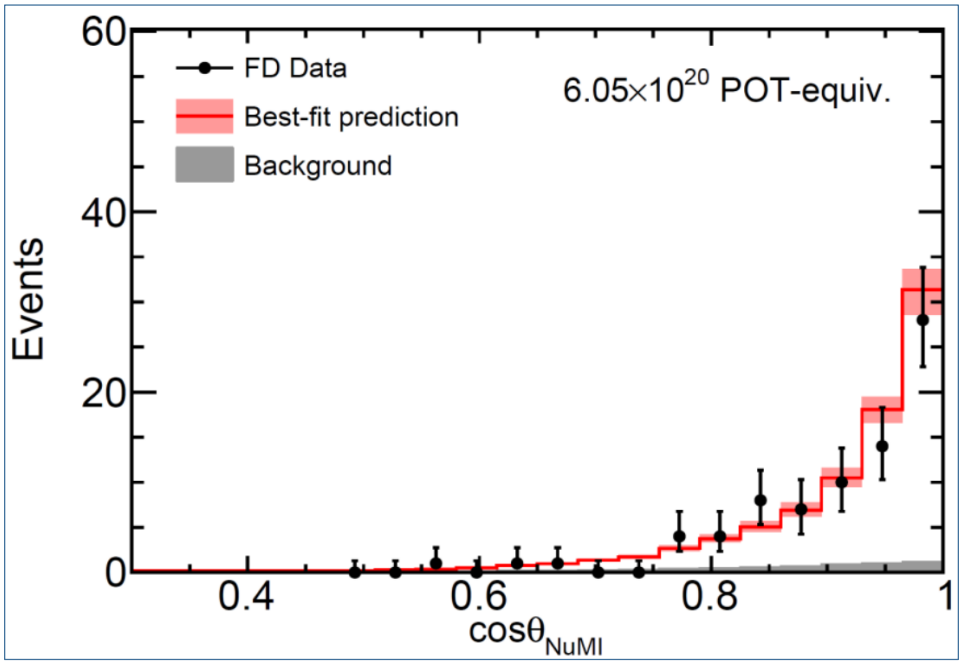


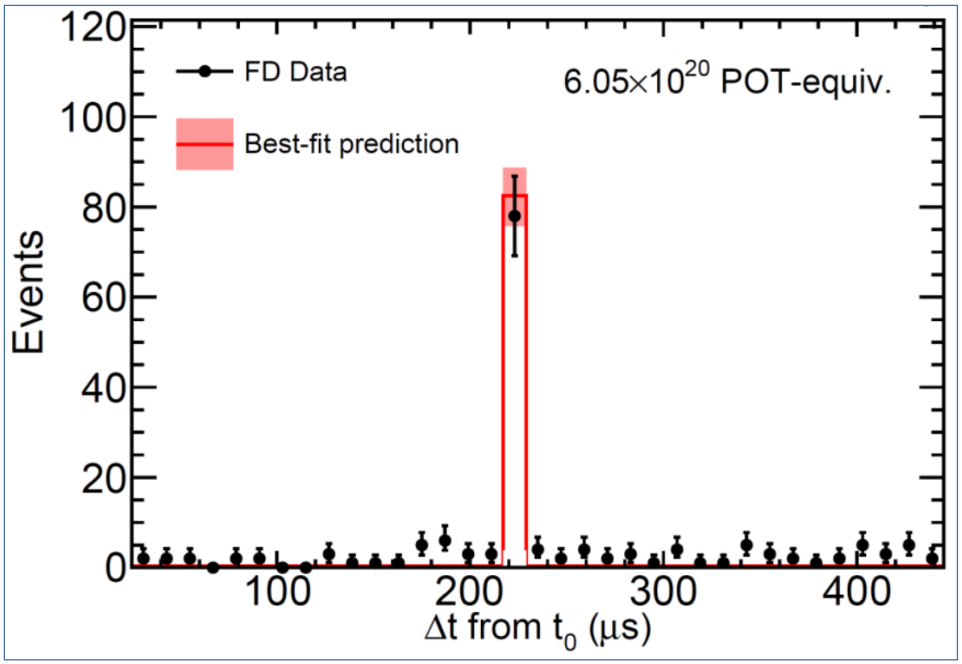


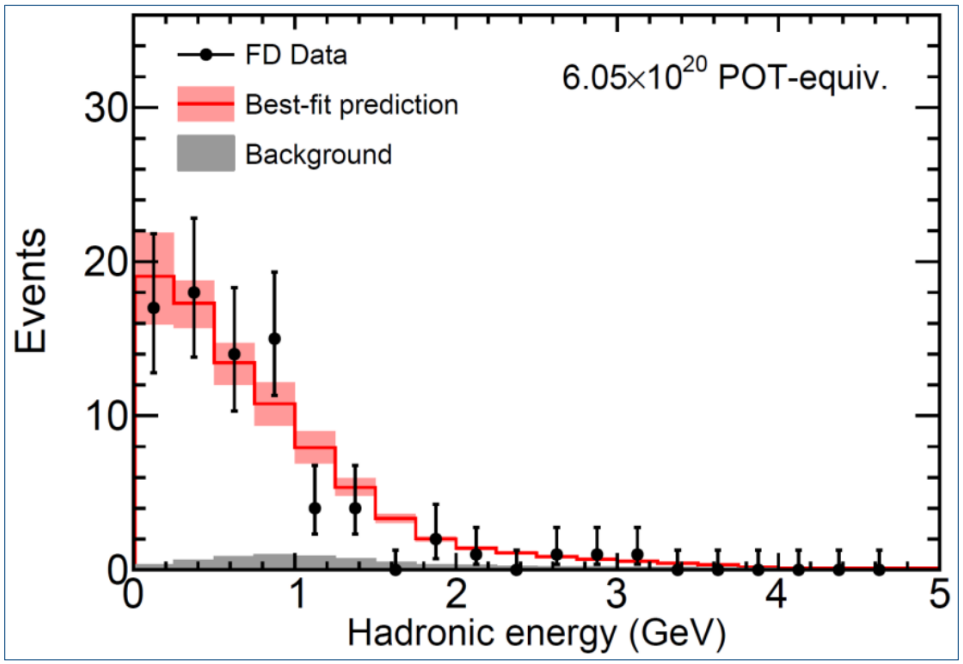


ν_μ CC FD candidate events distributions

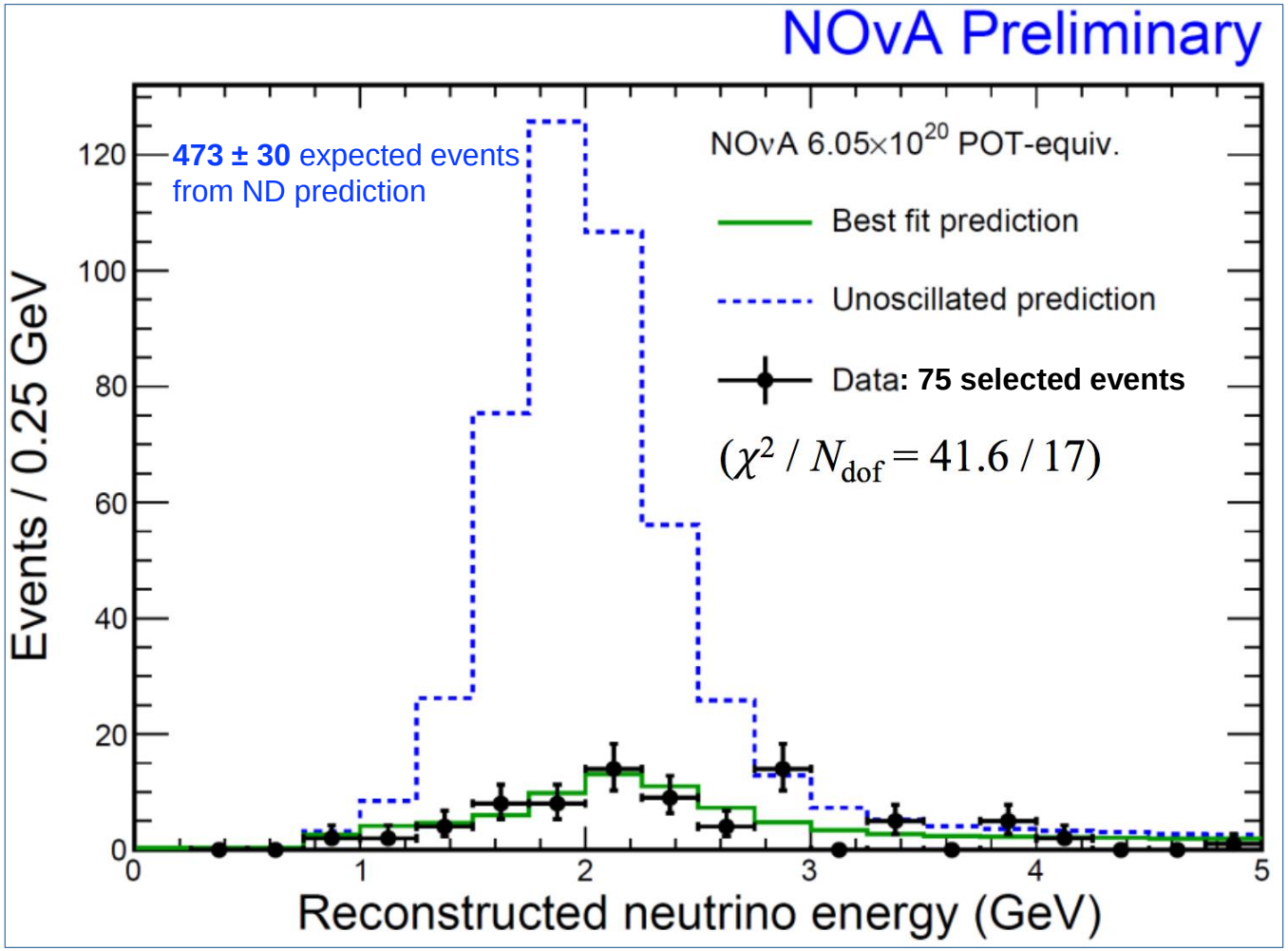








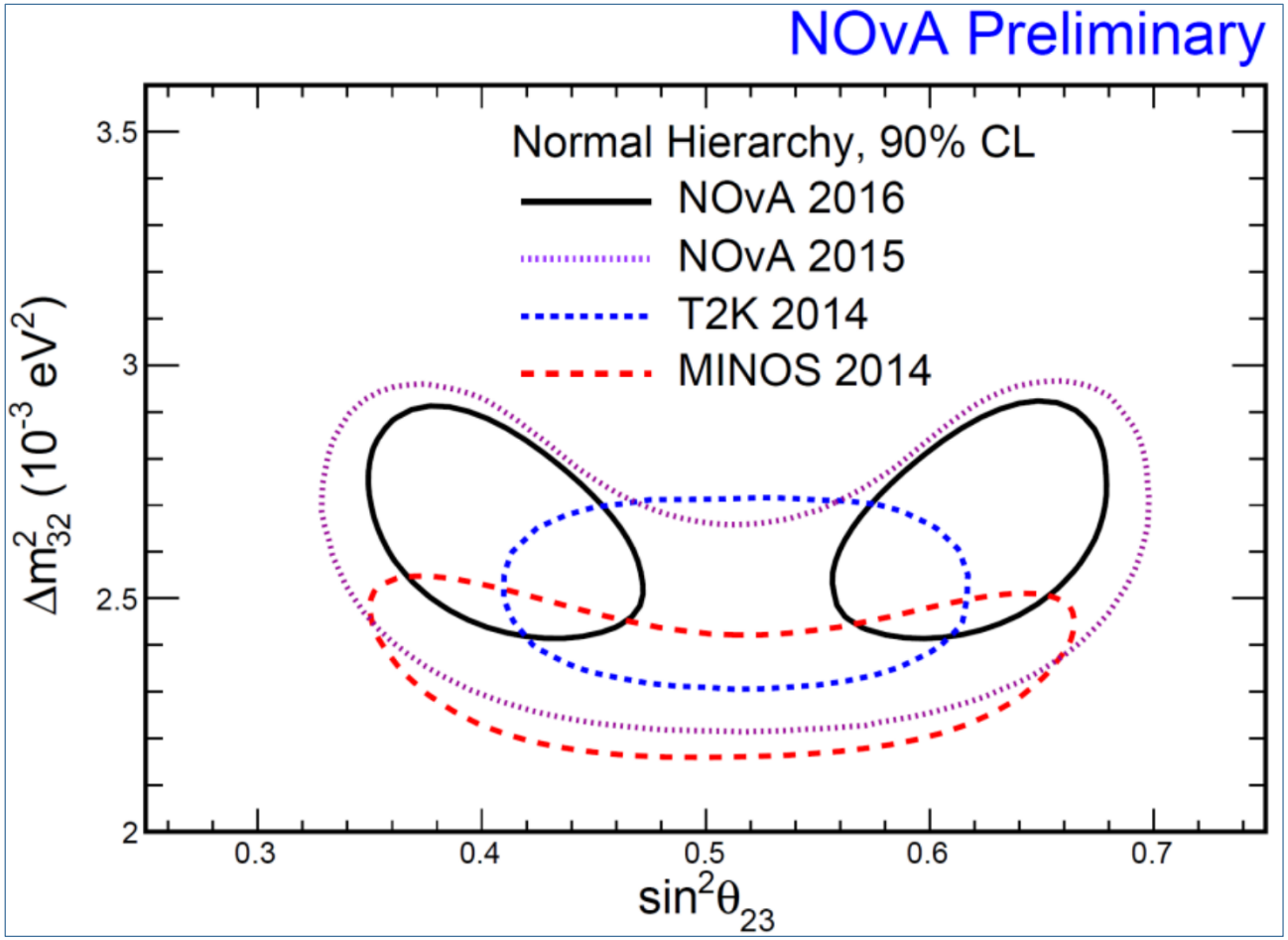
ν_μ CC FD energy spectrum



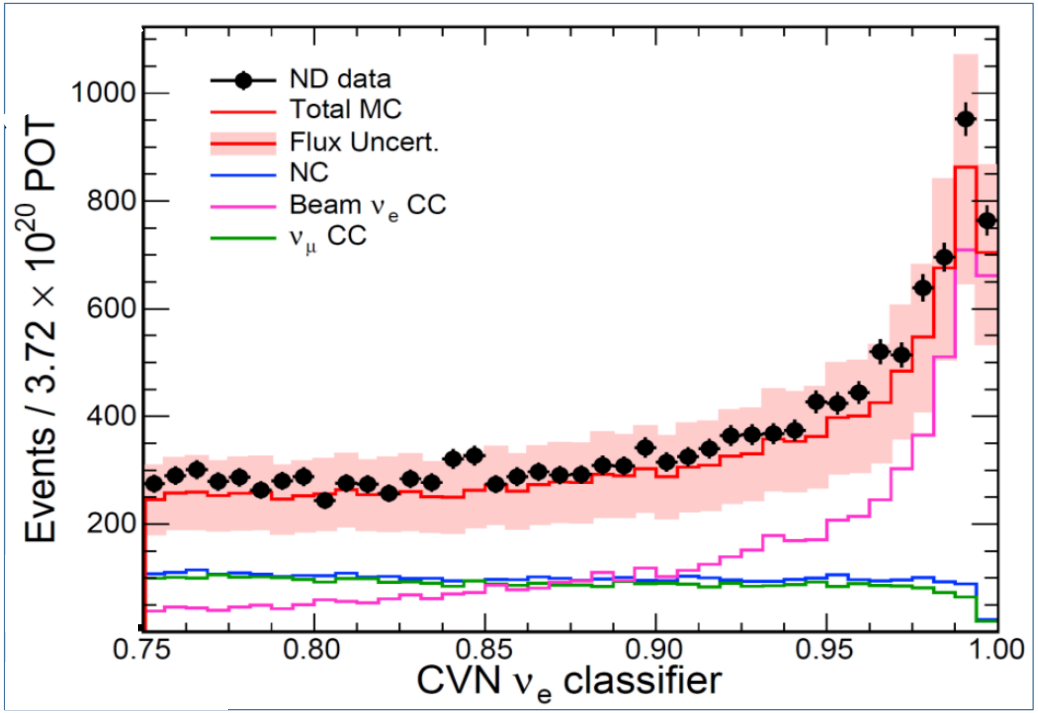
- Background candidates:
  - 3.7 from beam
  - 2.9 from cosmic rays

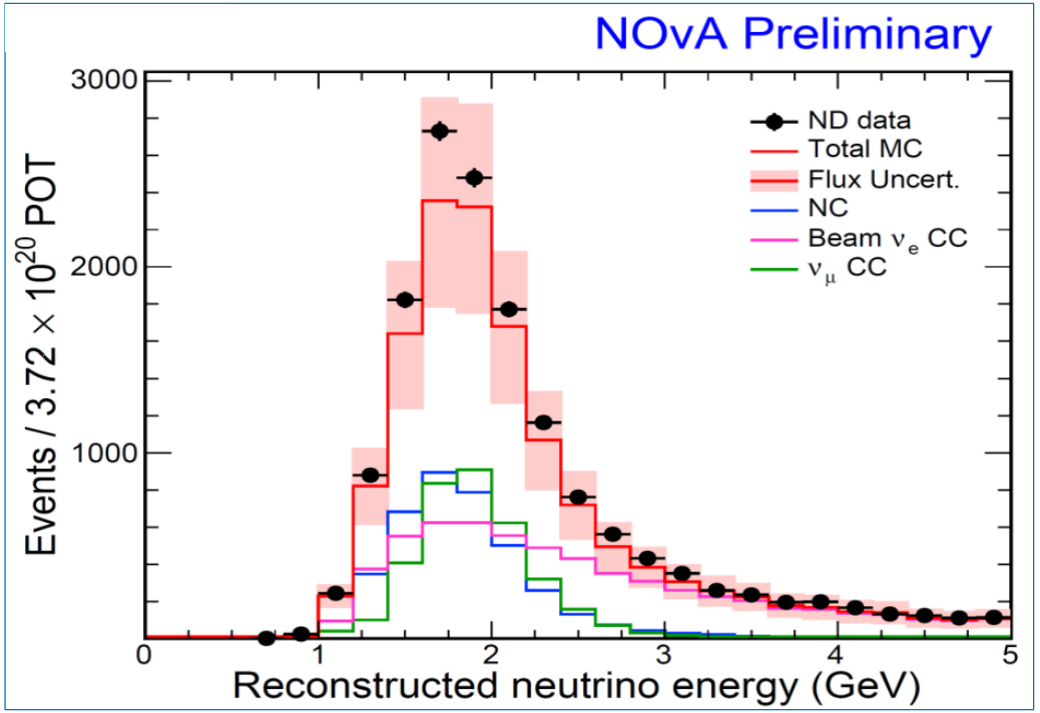
ν_μ Disappearance observation!

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



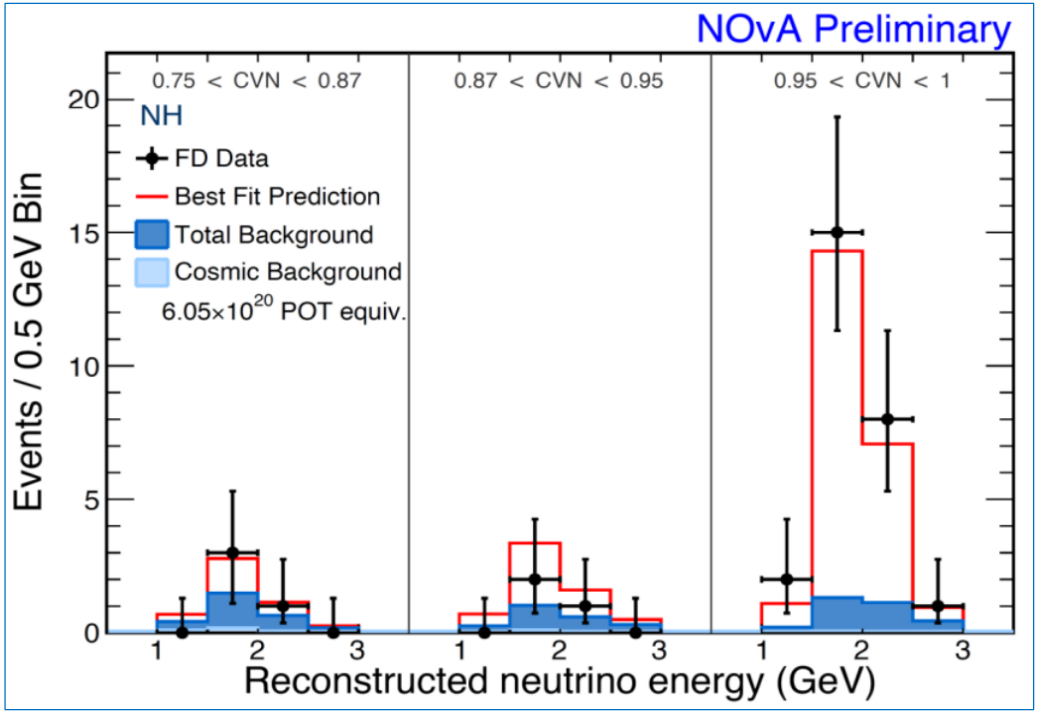
- Normal hierarchy case:
  - 4.5% uncertainty, MINOS 3.8%
  - $\Delta m^2_{32} = (2.67 \pm 0.12) \times 10^{-3}$ eV^2
  - $\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}$ $(0.63^{+0.02}_{-0.03})$



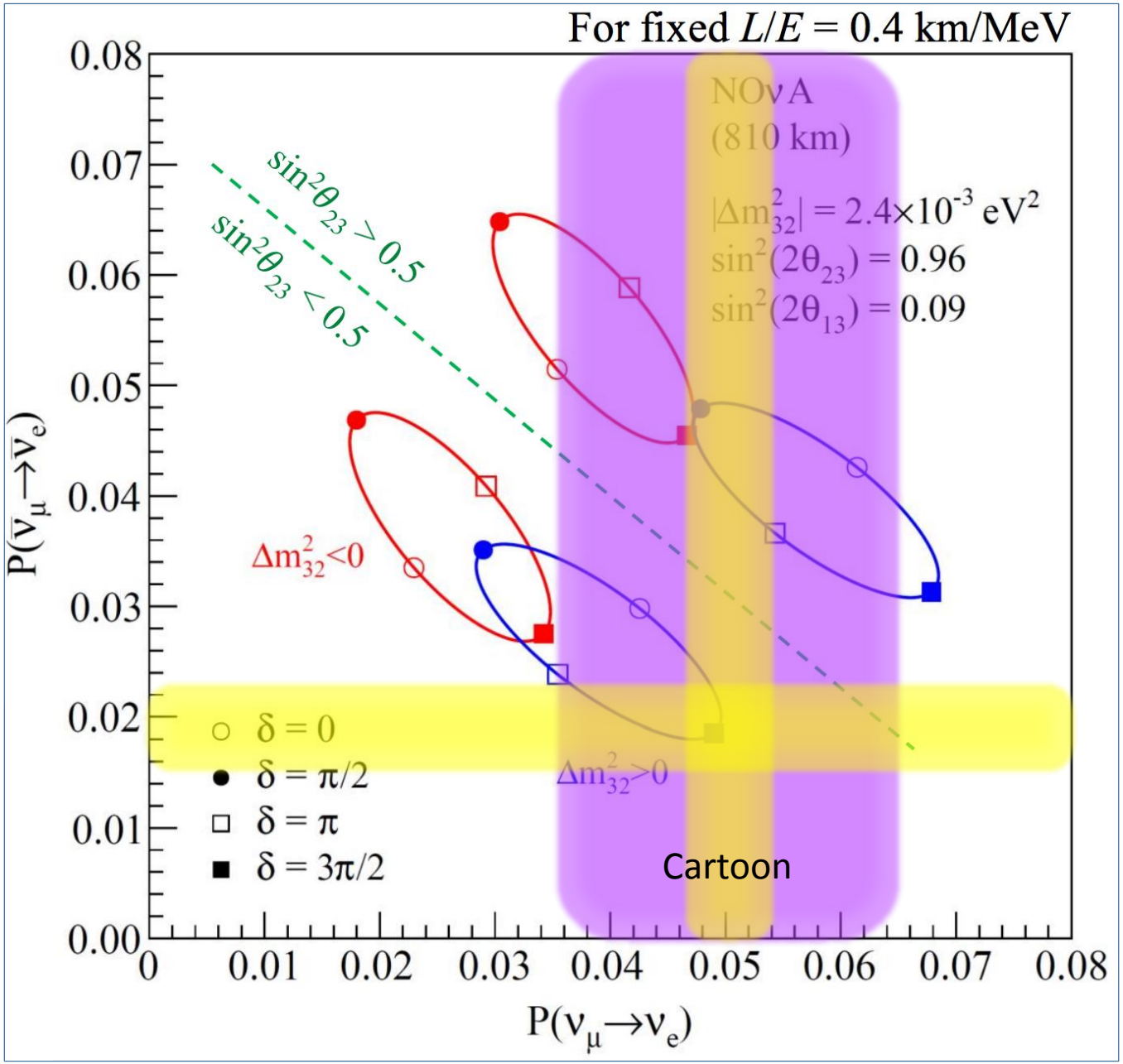


- ν_μ CC sample constrains:
  - The intrinsic ν_e CC (3% adjustment to simulation)
  - The ν_e CC signal (2%)

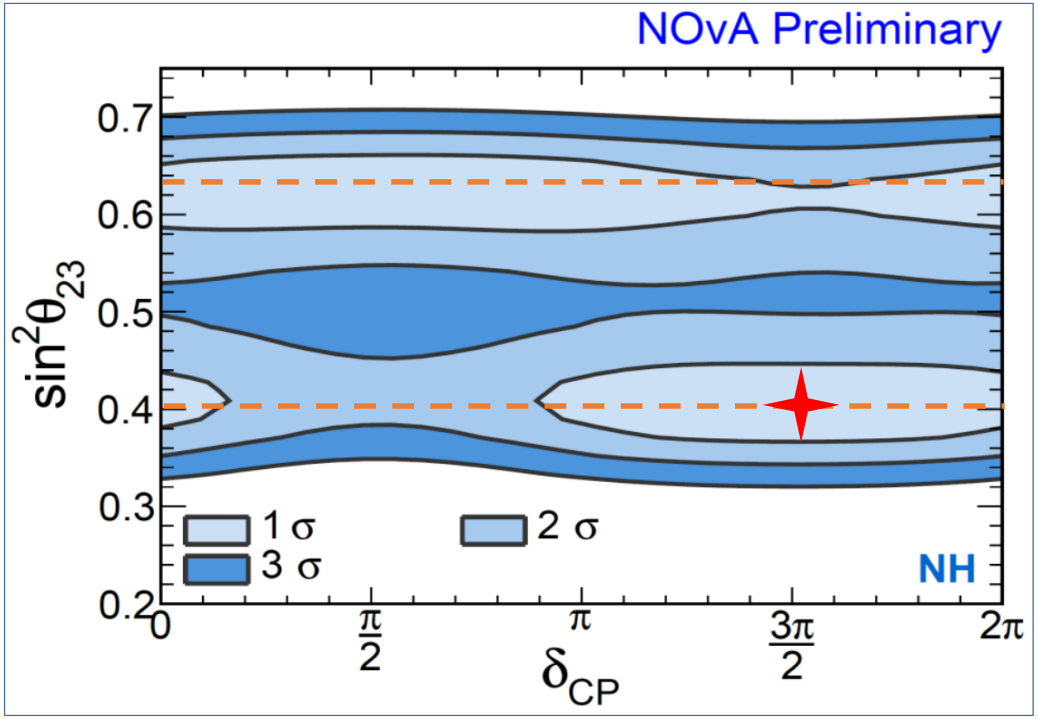
~17 to 42 predicted ν_e CC candidates (depending on oscillation parameters)

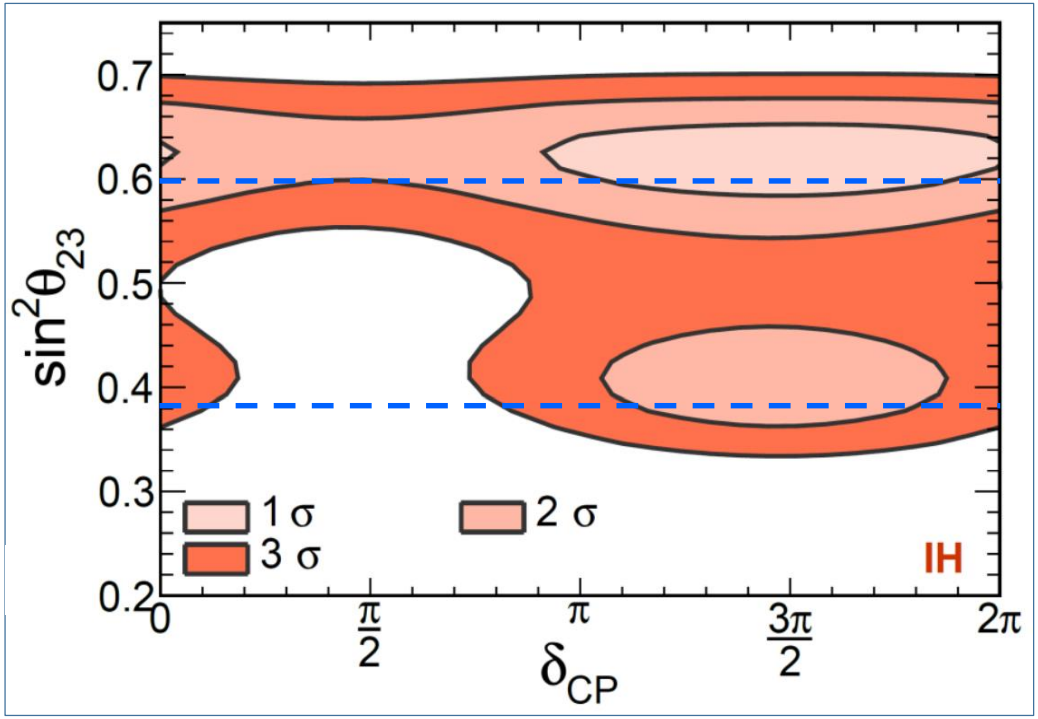


Single neutrino energy and baseline per ellipse



- Normal hierarchy (NH)
- Inverted hierarchy (IH)



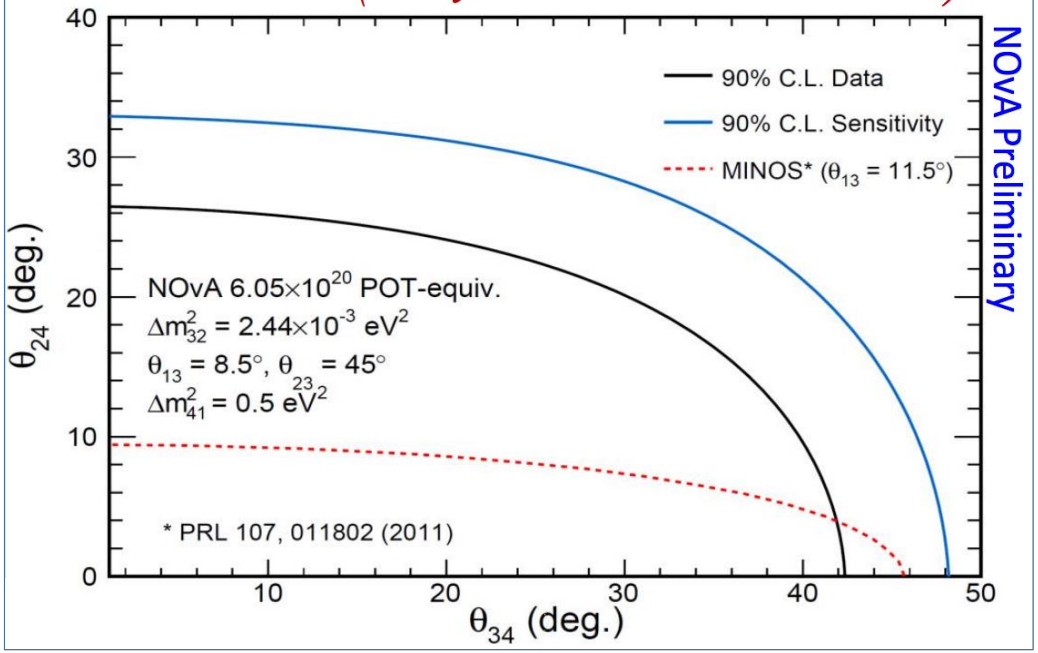


- NH/IH & $\sin^2\theta_{23} > 0.5$:

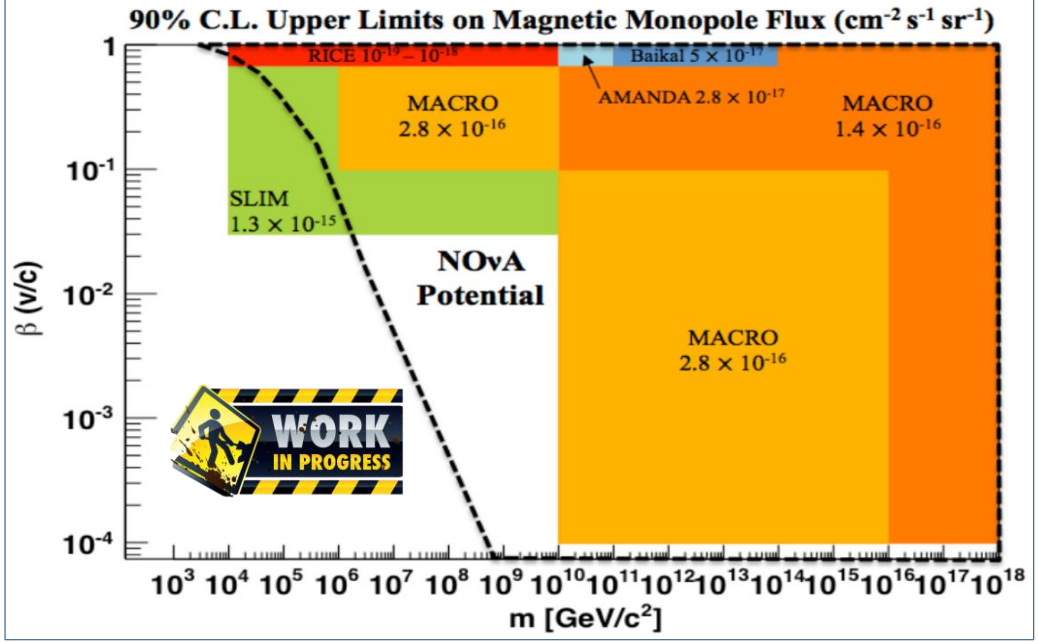
Best fit NH/IH: $\Delta\chi^2 = 0.47$

- Allowed at 1σ

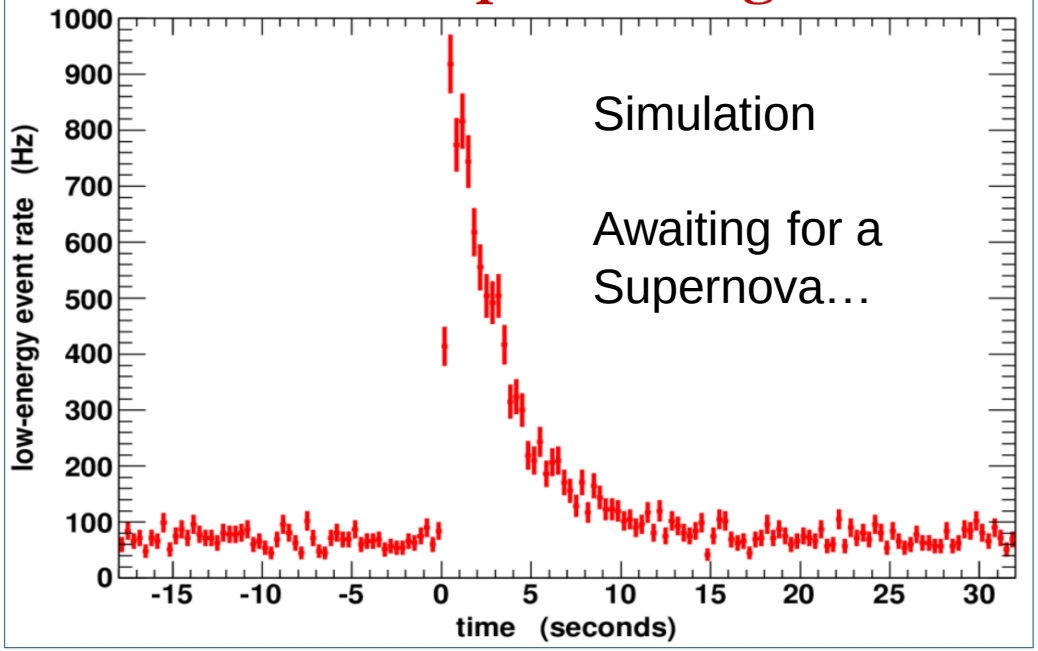
Sterile ν *(early NOvA results below!)*



Monopole searches



Galactic supernova signal



Cross Section Studies

ν_μ CC Inclusive	ν_μ CC $\pi_{+/-}$
anti-ν_μ CC Inclusive	ν_μ CC π_0 Inclusive
ν_e CC Inclusive 1	ν on e
ν_e CC Inclusive 2	NC Coh π_0
NC π_0 Inclusive	Booster ν
ν_μ CC 0π/QE	ν_μ CC COH Inc
ν_μ CC 2p2h	ν_μ CC Δ^+ Production

CONCLUSION

- The Intensity Frontier is a global effort to measure all terms of the oscillation matrix
- NOvA operates better that initially expected
- NOvA confirmed ν_e appearance (>8σ)
- NOvA favors Normal Hierarchy and maximal ($\delta_{cp} = 3\pi/2$) CP violation
- NOvA anti-neutrinos run next Spring will aid reducing uncertainty on oscillation parameters
- NOvA favors non-maximal value of $\sin^2 \theta_{23}$
- NOvA found no evidence of Sterile Neutrinos so far
- Much more to come, stay tuned!

THANK YOU!

earrietadiaz@smu.edu

www-nova.fnal.gov