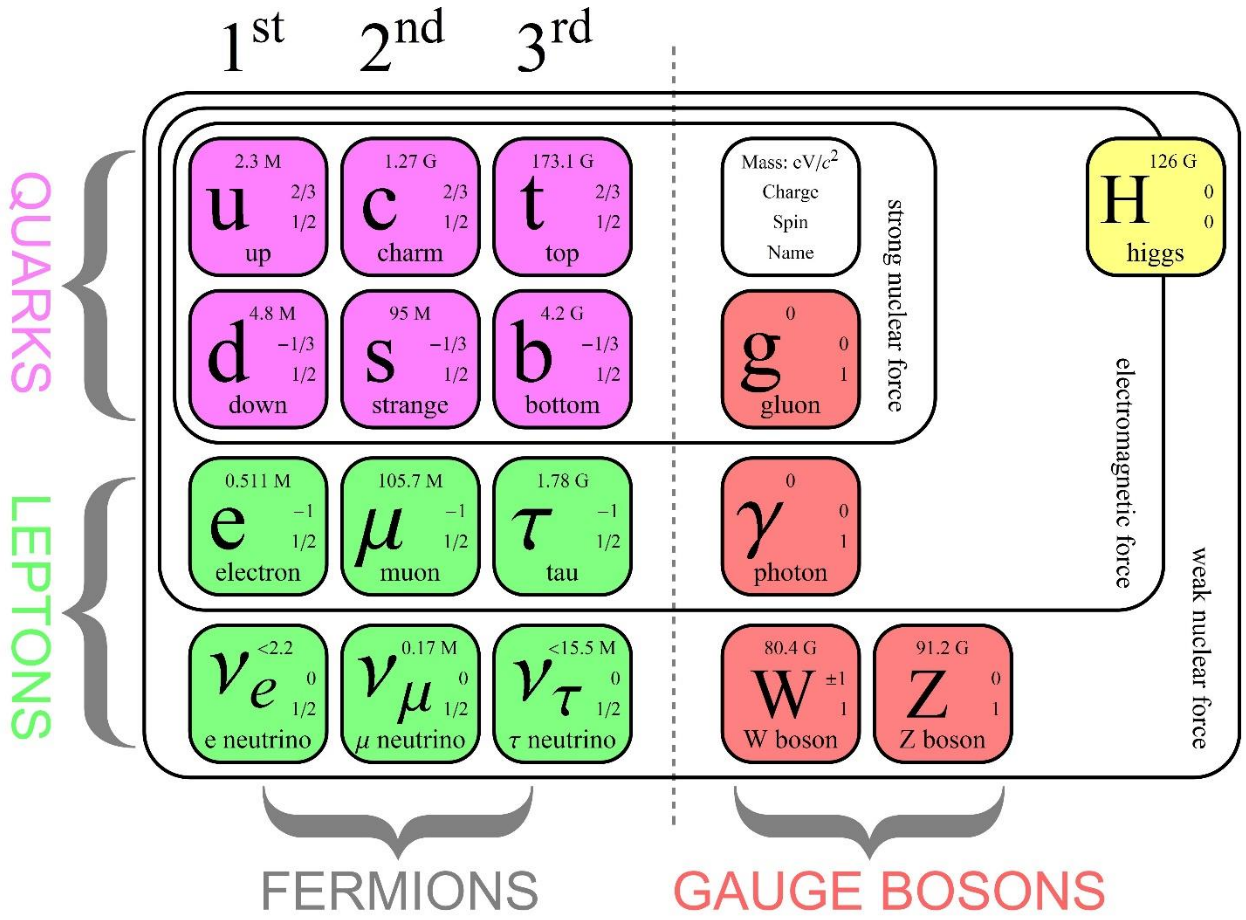
NOvA long-baseline neutrino experiment: recent results

Kirk Bays

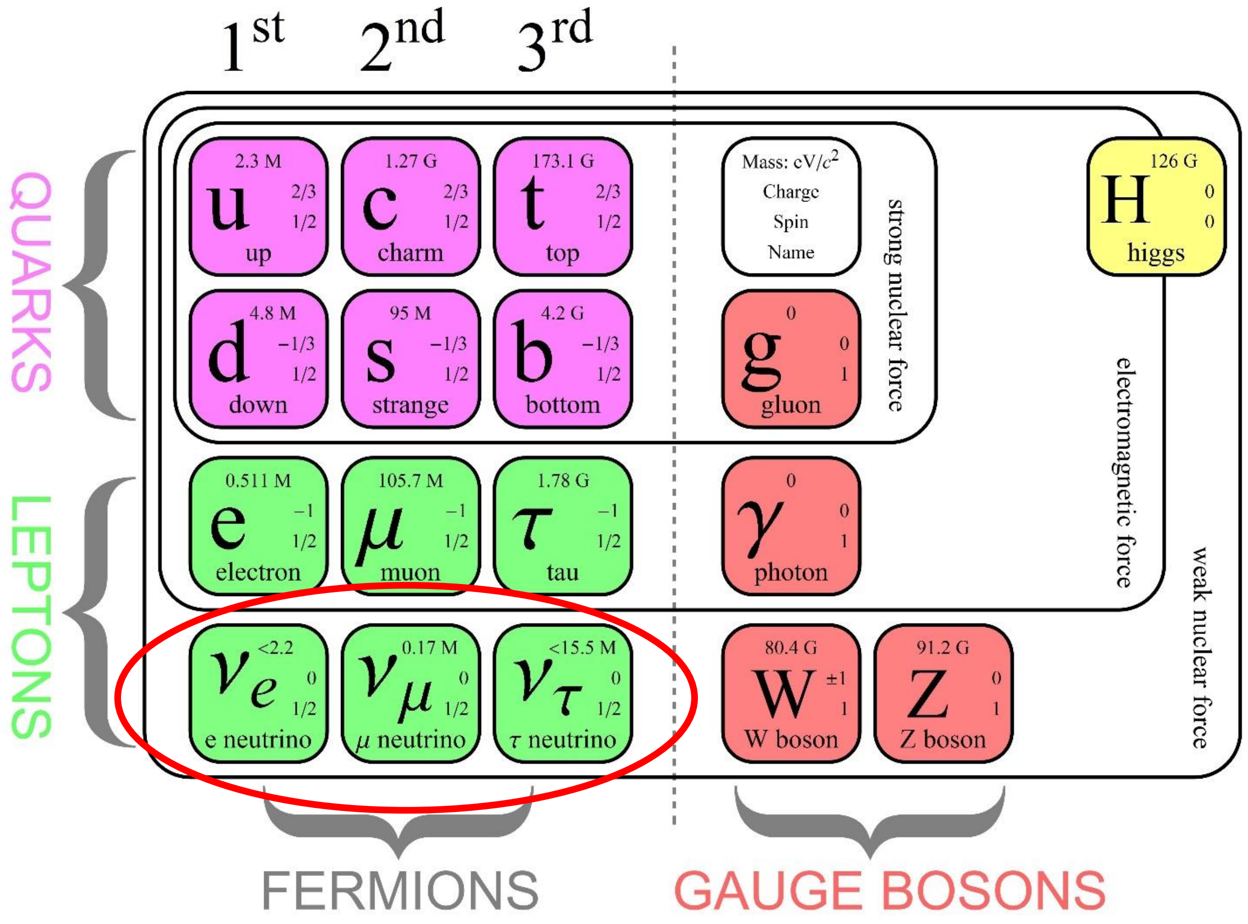
California Institute of Technology

April 3, 2018



Standard model of physics:

12 fundamental particles
3 forces / 4 gauge bosons
Higgs

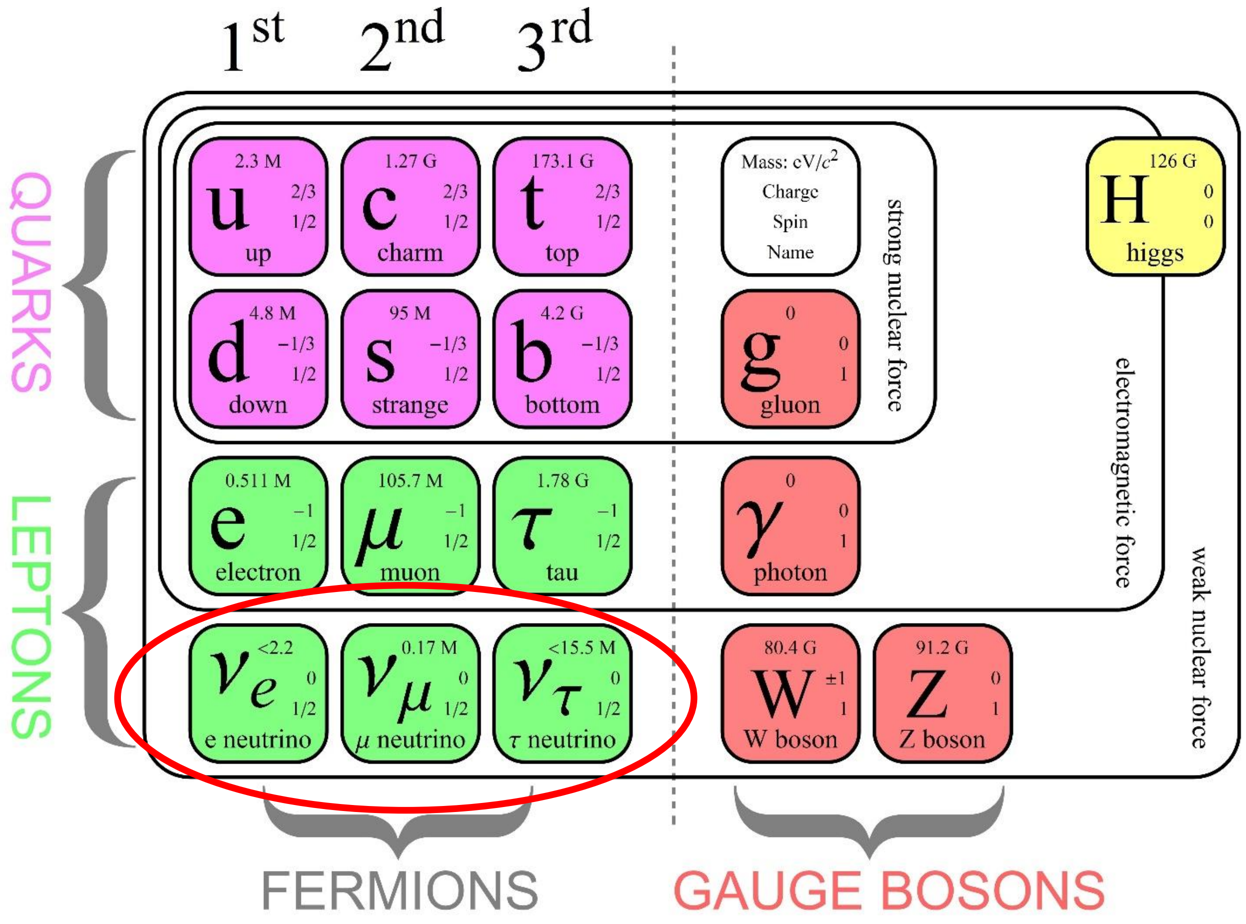


Standard model of physics:

12 fundamental particles
3 forces / 4 gauge bosons
Higgs

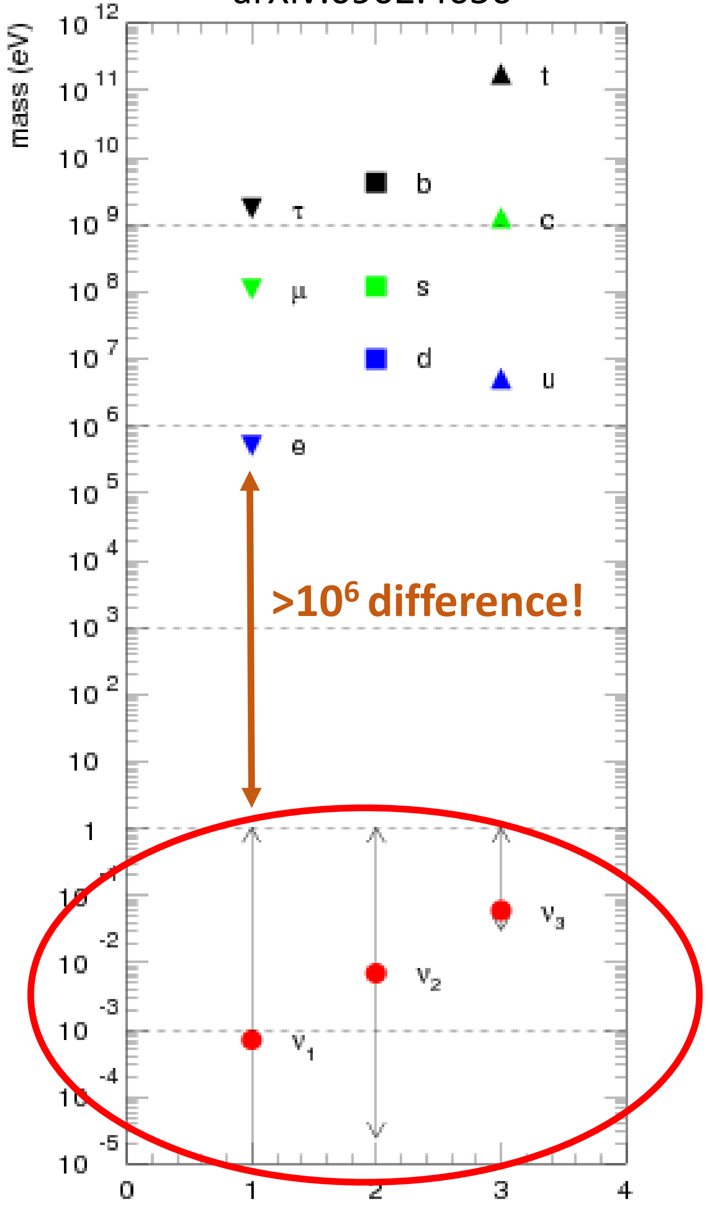
3 are neutrinos
Neutrinos are interesting! Why?

original theory: neutrino mass = 0
but we know this is wrong!



Neutrino masses are very small

arXiv:0902.4656



Neutrinos oscillate - their flavor states (e, μ, τ) are different than their mass states (1, 2, 3)

Connected by mixing matrix: $$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U^* \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

Mixing matrix → mixing angles – 2 flavor case: $$\begin{pmatrix}\nu_e\\ \nu_\mu\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\end{pmatrix}$$

3 flavor case:

Reactors; very recent!

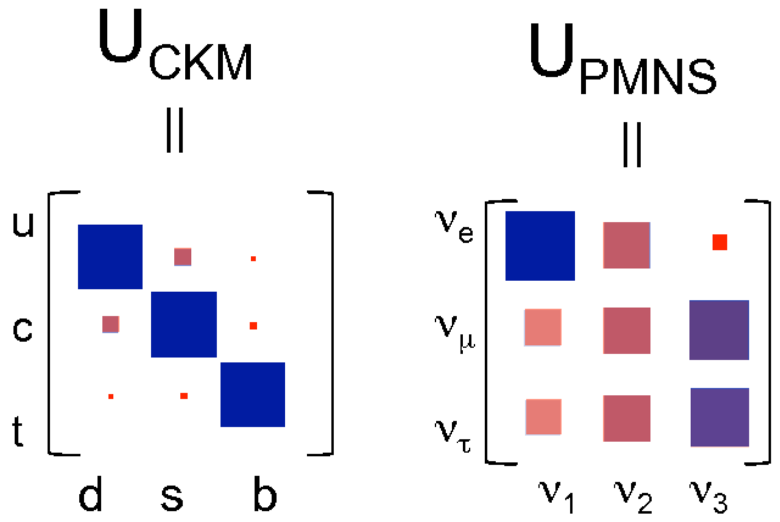
$$U = \begin{bmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu1} & U_{\mu2} & U_{\mu3}\\ U_{\tau1} & U_{\tau2} & U_{\tau3}\end{bmatrix} = \overbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}^{\text{Atmospheric}} \overbrace{\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{-i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}}^{\text{Reactors; very recent!}} \overbrace{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}^{\text{Solar}}$$

3 angles and a CP-violation term determine the matrix: $\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP}$

How well are angles measured so far? (PDG)

$\sin^2(\theta_{12})$ = 0.307 +- 0.013
$\sin^2(\theta_{23})$ = 0.51 +- 0.04 ('maximal'? or which octant?)
$\sin^2(\theta_{13})$ = 0.021 +- .0011

Neutrino mixing (U_{PMNS}) analogous to quark mixing (U_{CKM}) but much less diagonal



arXiv:1611.07770

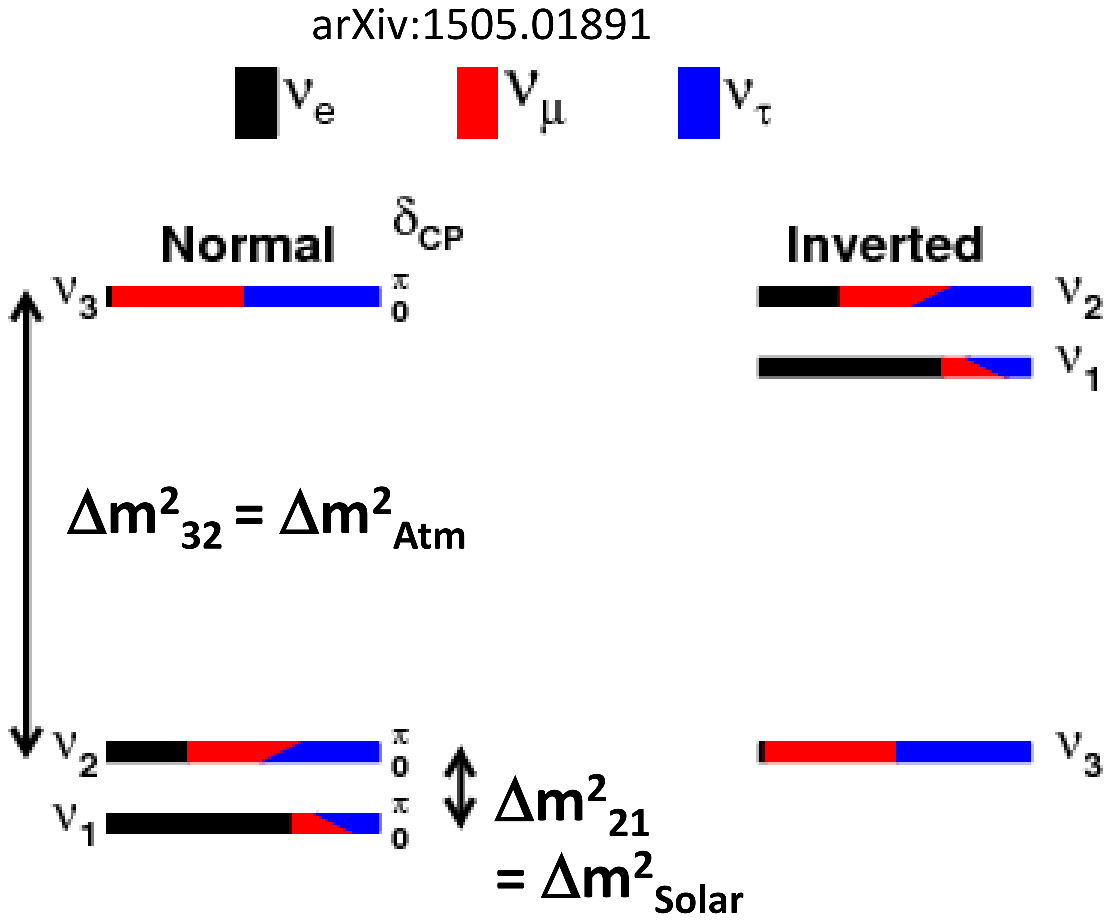
$$P_{\alpha\to\beta} = |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U_{\alpha i}^* U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

L = baseline
E of neutrino
} **experiment setup**

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

→

$\Delta m^2_{32} = m_3^2 - m_2^2$ **(to be measured)**
also Δm^2_{21}

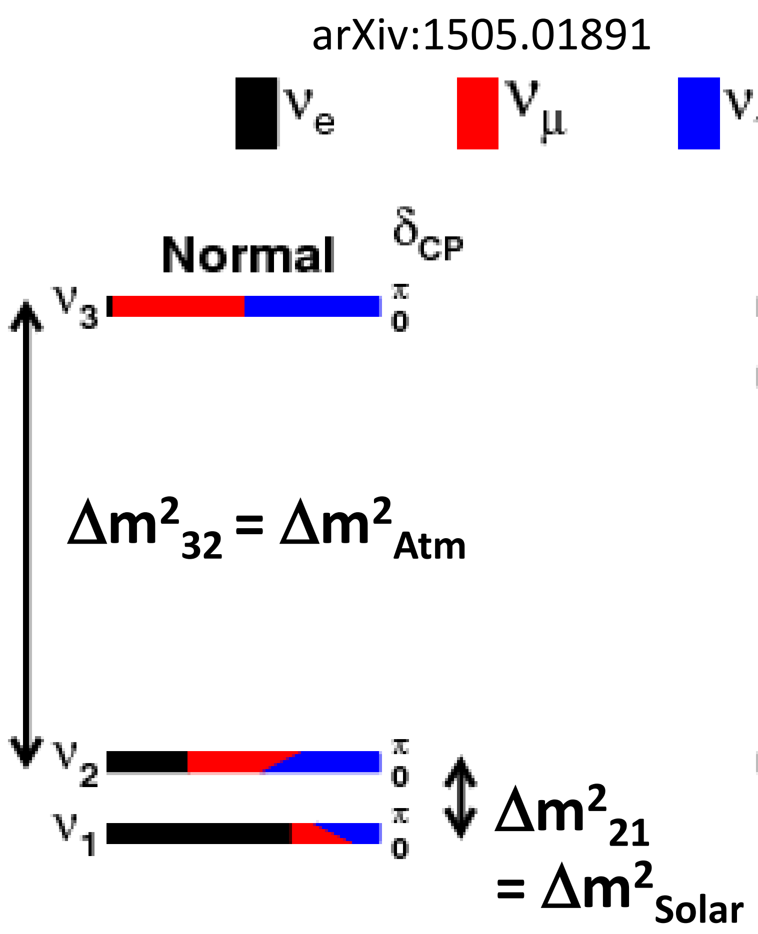


Δm^2_{21} = (7.53 +- 0.18) x 10^{-5} eV^2
Δm^2_{32} = (2.45 +- 0.05) x 10^{-3} eV^2

Two possible mass orderings (‘hierarchies’): ‘Normal’ and ‘Inverted’. Can’t tell which yet!

When travelling through matter, there are additional oscillation effects as ν_e feels extra ‘drag’

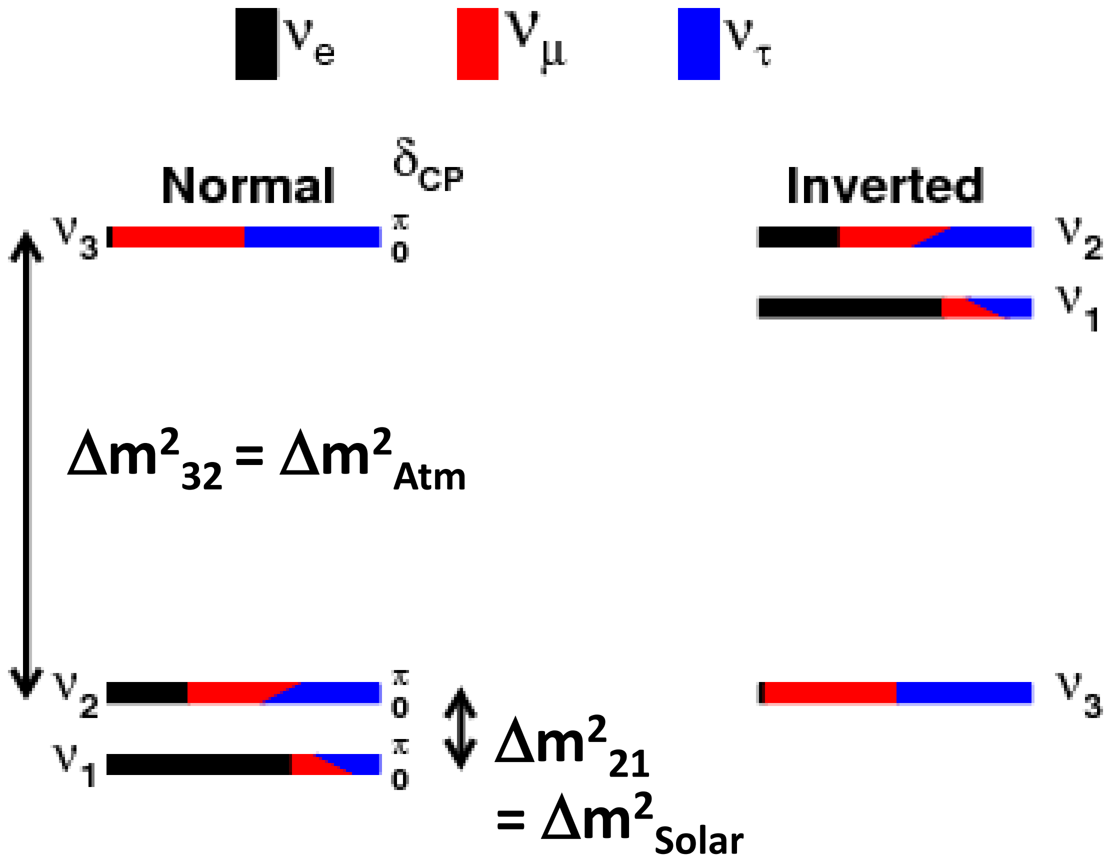
The farther the path through matter the better we measure the hierarchy



Things to be measured with neutrino oscillation experiments:

θ_{12}, θ_{13}, θ_{23}
Δm^2_{32}, Δm^2_{21}, mass hierarchy
δ_{CP} (is CP violated by neutrinos?)

arXiv:1505.01891



Long-baseline ν oscillation experiments can measure these especially well

θ_{12}, θ_{13}, θ_{23}

Δm^2_{32}, Δm^2_{21}, mass hierarchy

δ_{CP} (is CP violated by neutrinos?)

Why does it matter?

- Fundamental properties of neutrinos affect lots of other things:
  - Cosmology, astrophysics

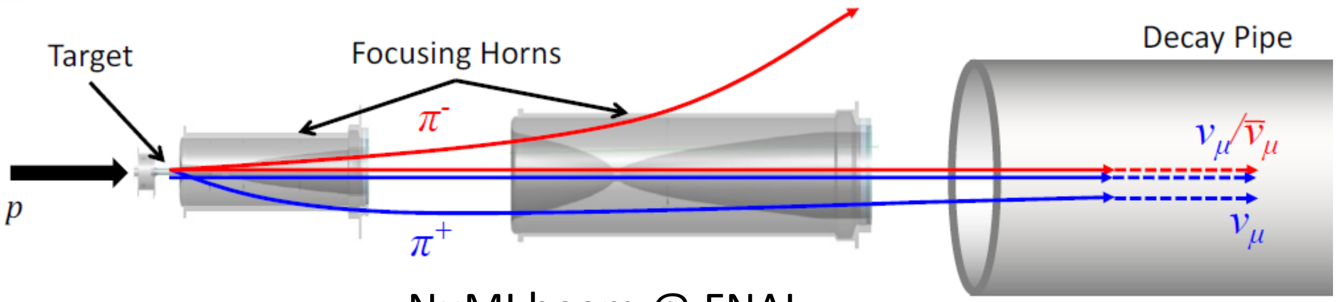
    Why is universe matter and not anti-matter? $\sin(\delta_{CP}) \neq 0 \rightarrow$ leptogenesis?
  - Phenomenology, GUTs

    Are neutrinos their own anti-particle (Majorana)? $0\nu\beta\beta$, see-saw mechanism
- Can also measure neutrinos to learn about interesting sources
  - supernova neutrinos
  - sterile neutrinos
  - solar, cosmic ray neutrinos

→ Detectors used in long-baseline experiments can do this too

A long-baseline experiment: NOvA

First, make a neutrino beam:
(almost pure ν_μ)

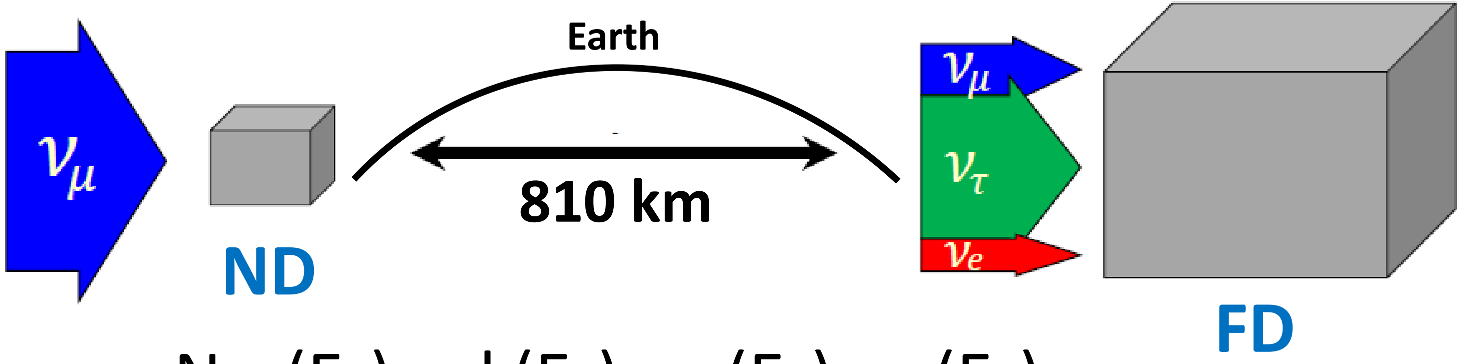


NuMI beam @ FNAL

Then shoot it at your detectors:

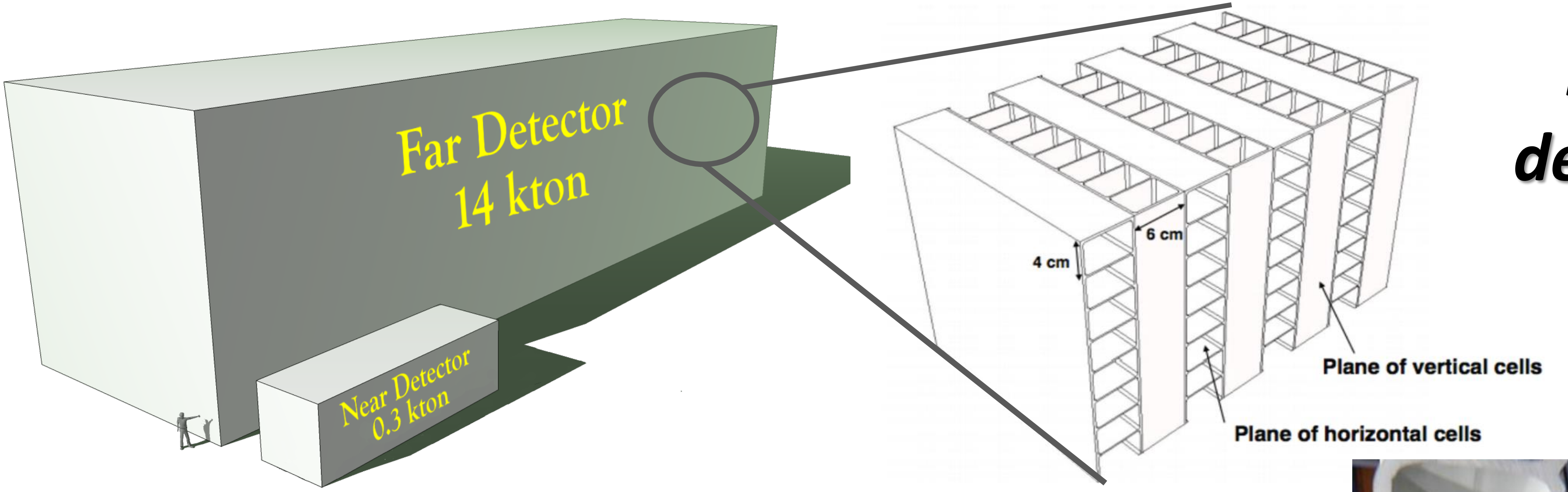
A Near Detector (ND) near the beam, before oscillations

And a Far Detector (FD) far away



$$N_{ND}(E_\nu) = \phi(E_\nu) \times \sigma(E_\nu) \times \varepsilon(E_\nu)$$
$$N_{FD}(E_\nu) = \phi(E_\nu) \times \sigma(E_\nu) \times \varepsilon(E_\nu) \times P(E_\nu) \ldots$$

ND helps constrain FD uncertainties



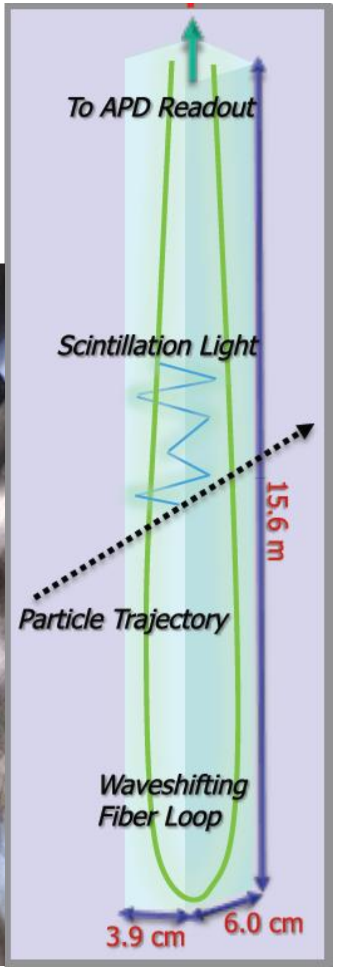
NOvA detectors

FD (at Ash River, MN, 810 km baseline):

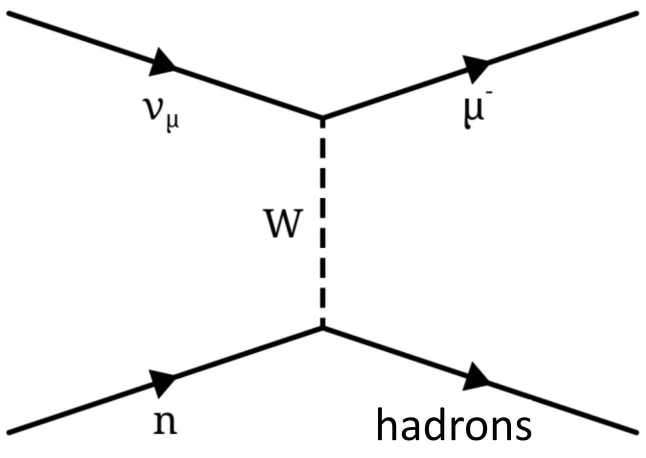
16m x 16m x 60m, 14kton, on surface (some barite overburden)
~2/3 liquid scintillator by mass, ~344,000 cells, 896 planes
low-Z, finely-segmented, 62% active
1 radiation length ~ 6-10 cells

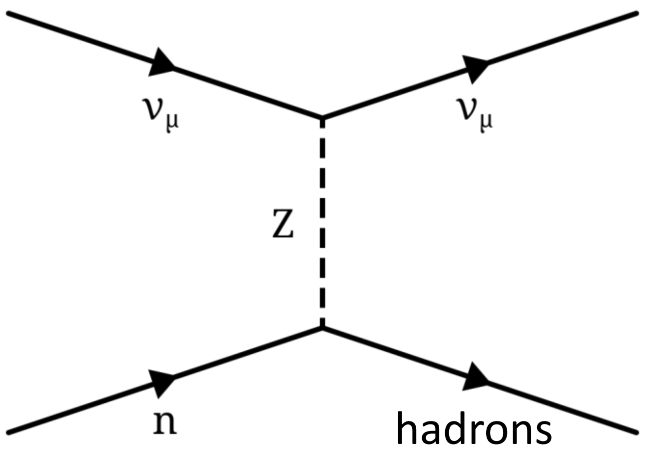
ND (@ FNAL, 1km from NuMI target):

4m x 4m x 16m, 0.3kton, underground
~20,000 cells, design similar to FD



Neutrino interactions

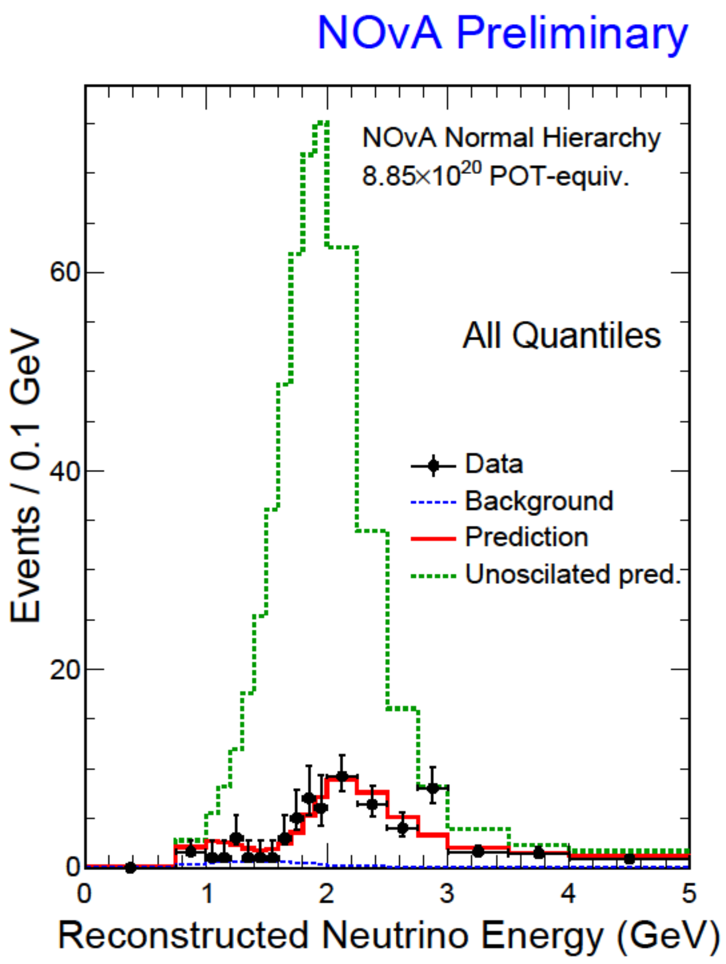


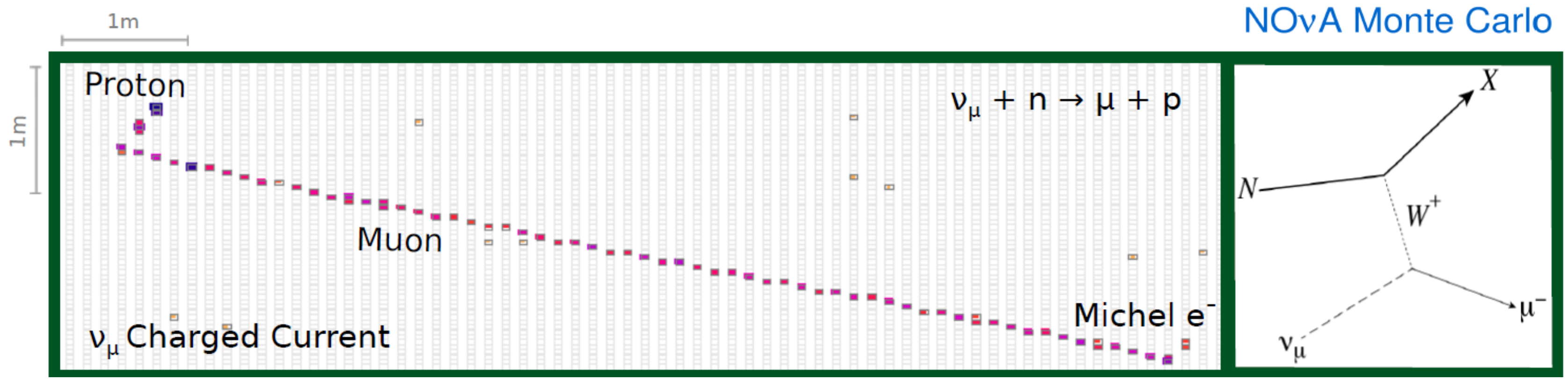


Charged current:
ν_x + nucleon → x + hadrons
x = e, μ, τ
hadrons: can be single p (QE)
can be shower (p, π, …)

Neutral current:
ν + nucleon → ν + hadrons
flavor blind
no lepton

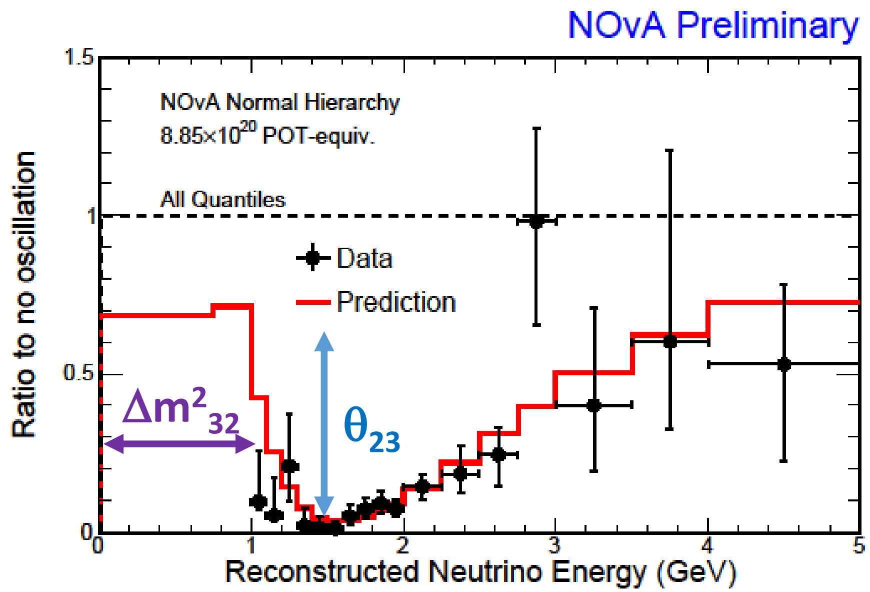
ν_μ disappearance





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

directly measure θ_{23} and Δm^2_{32}



signature: muon

backgrounds:

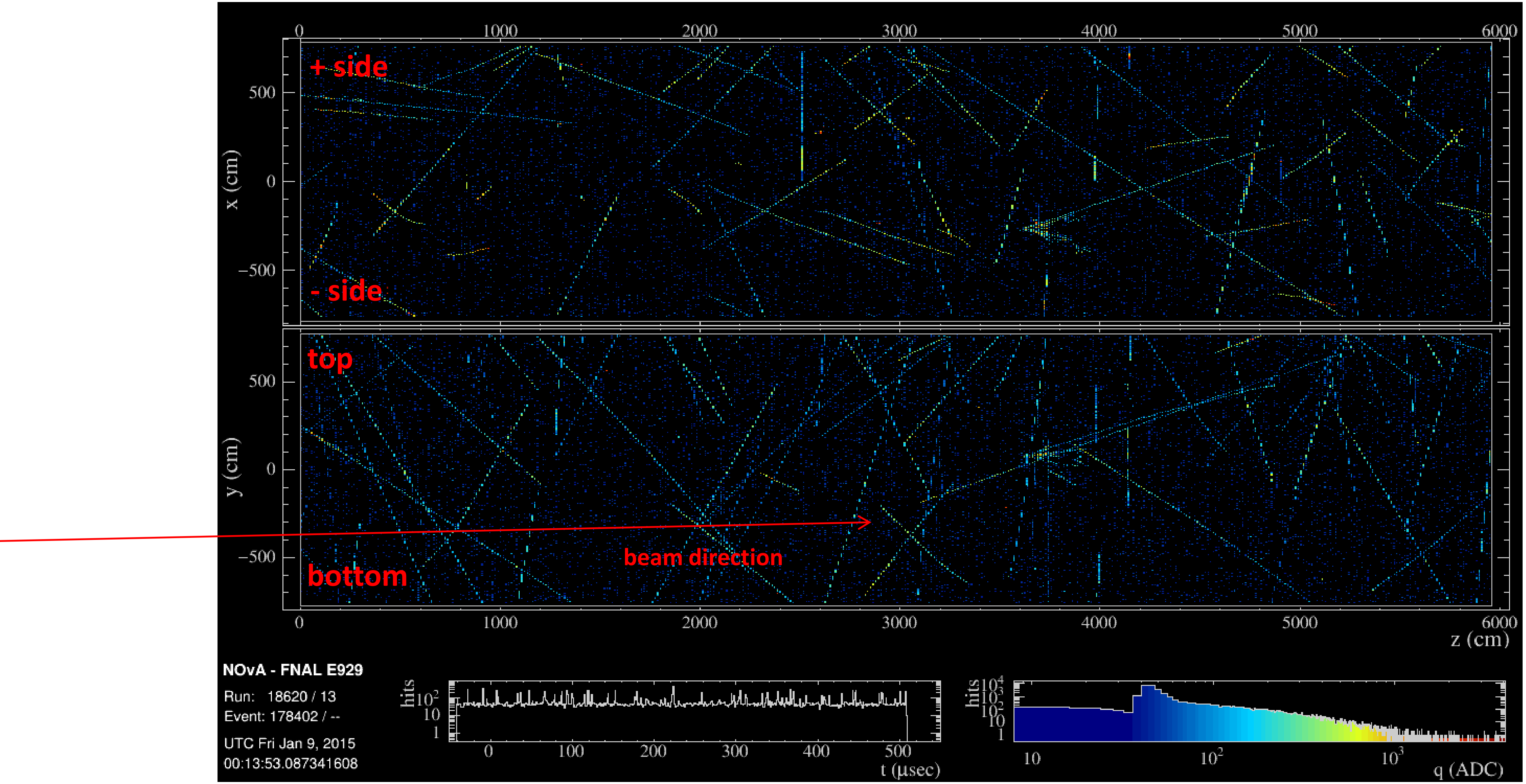
neutral current

- π, p can look like muons

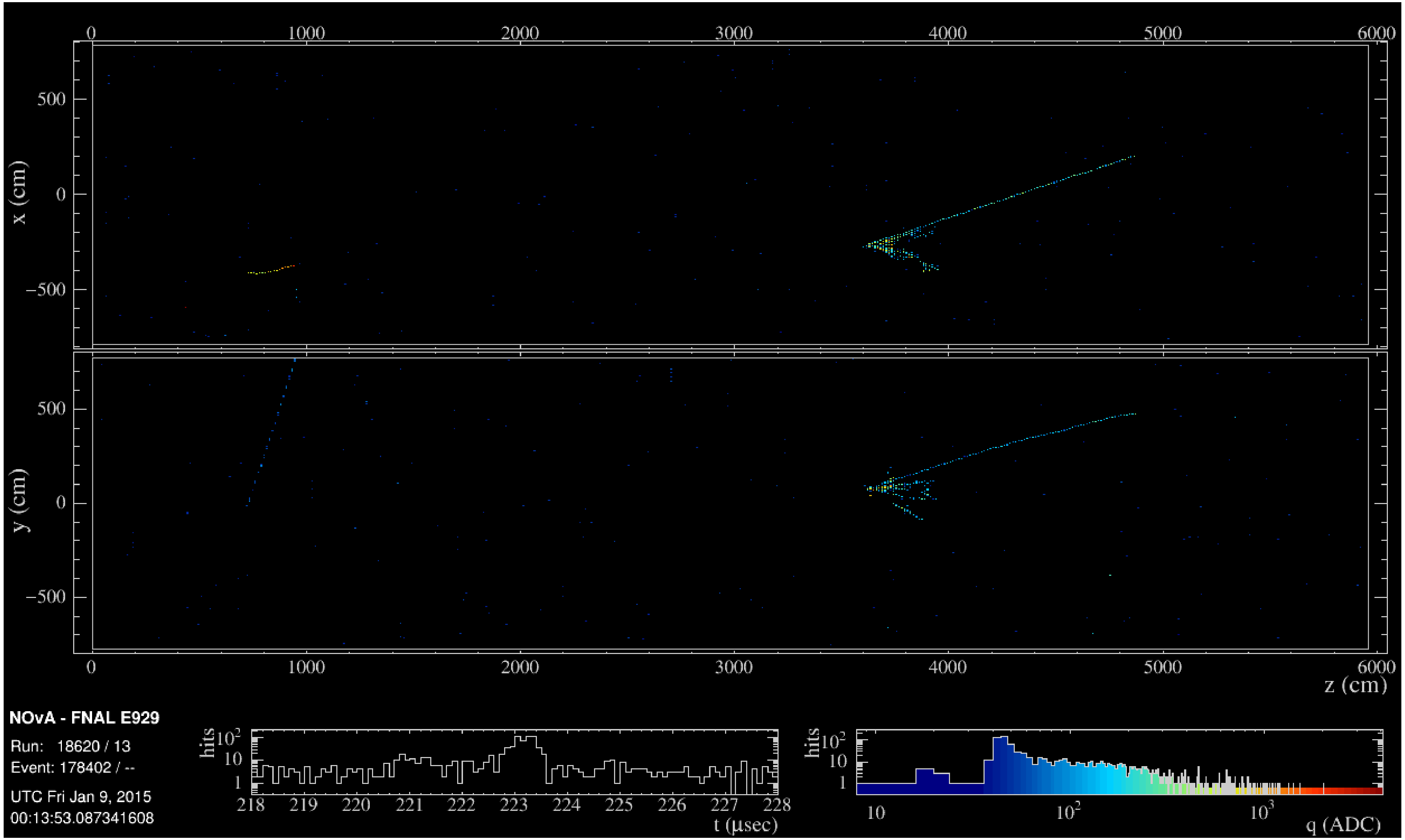
cosmic rays

- surface detector, real muons

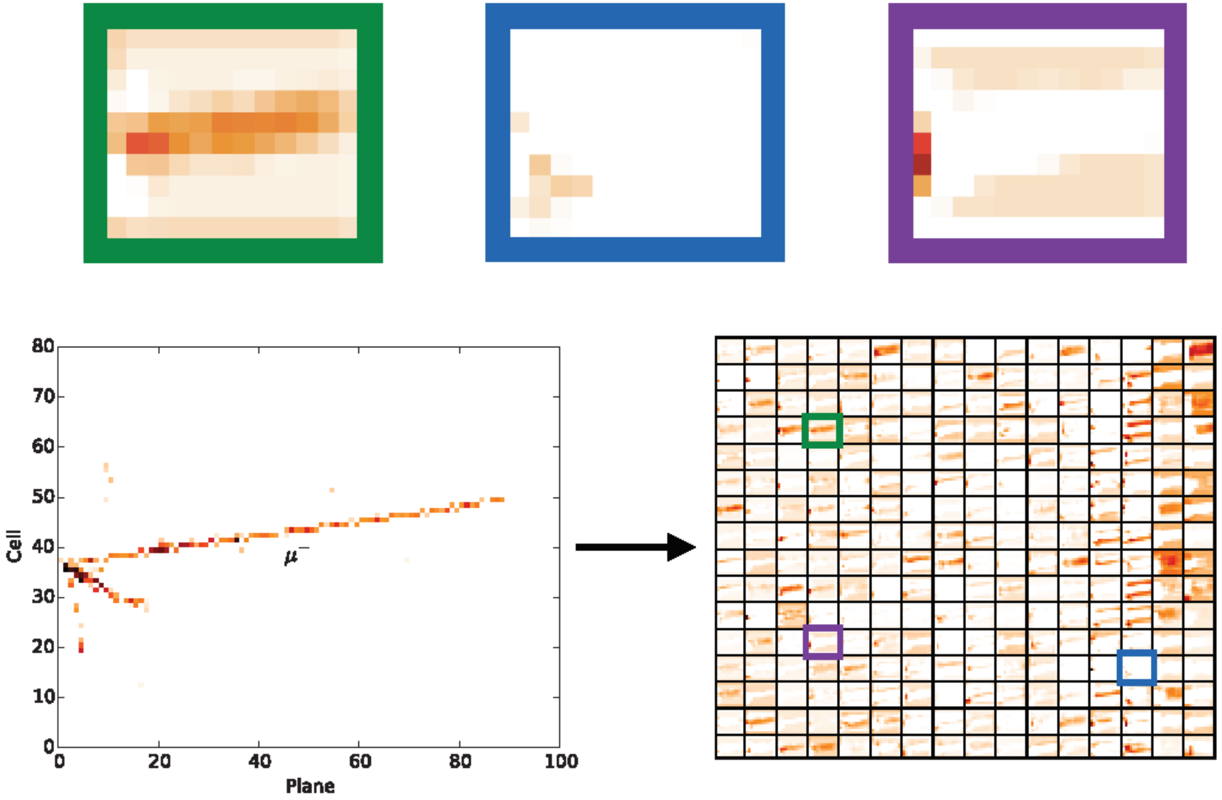
550 μs exposure of the Far Detector



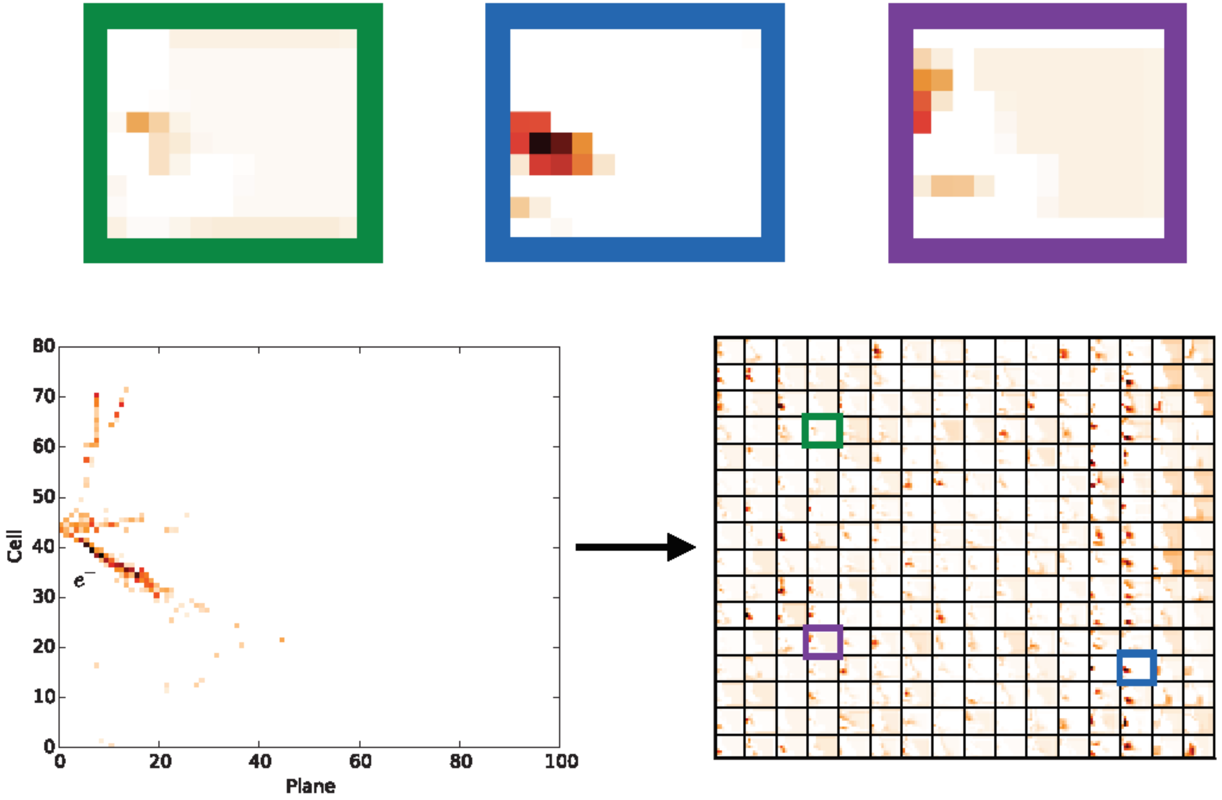
Time-zoom on 10 μs interval during NuMI beam pulse



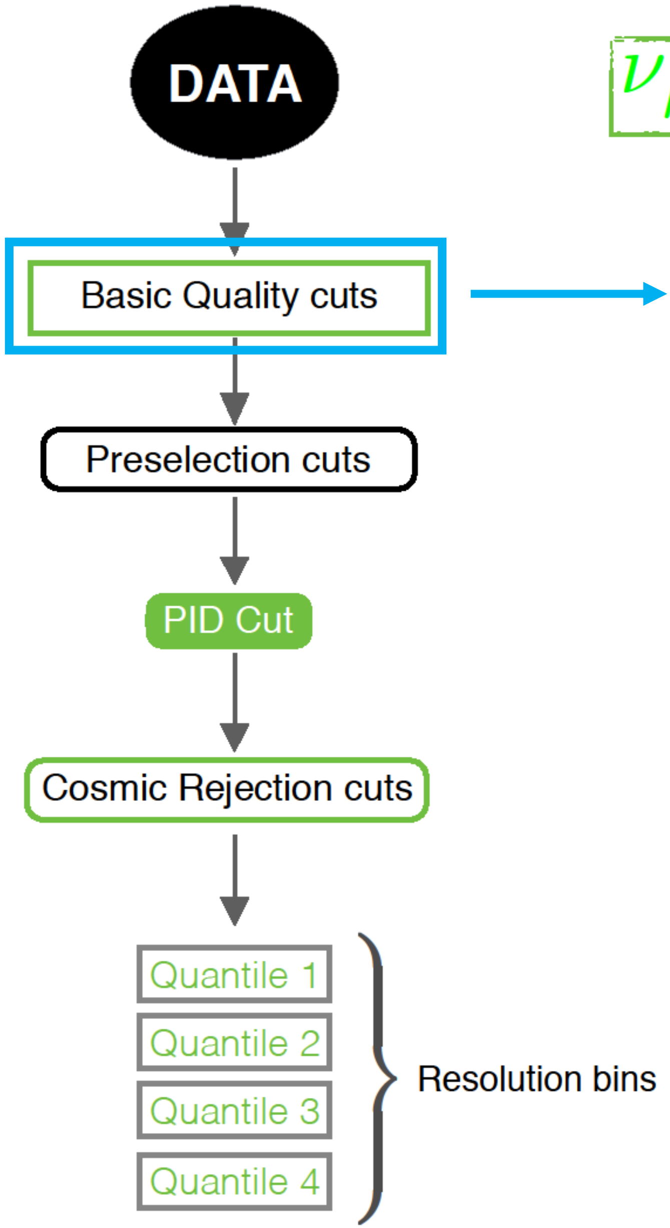
CVN - disappearance



CVN - appearance

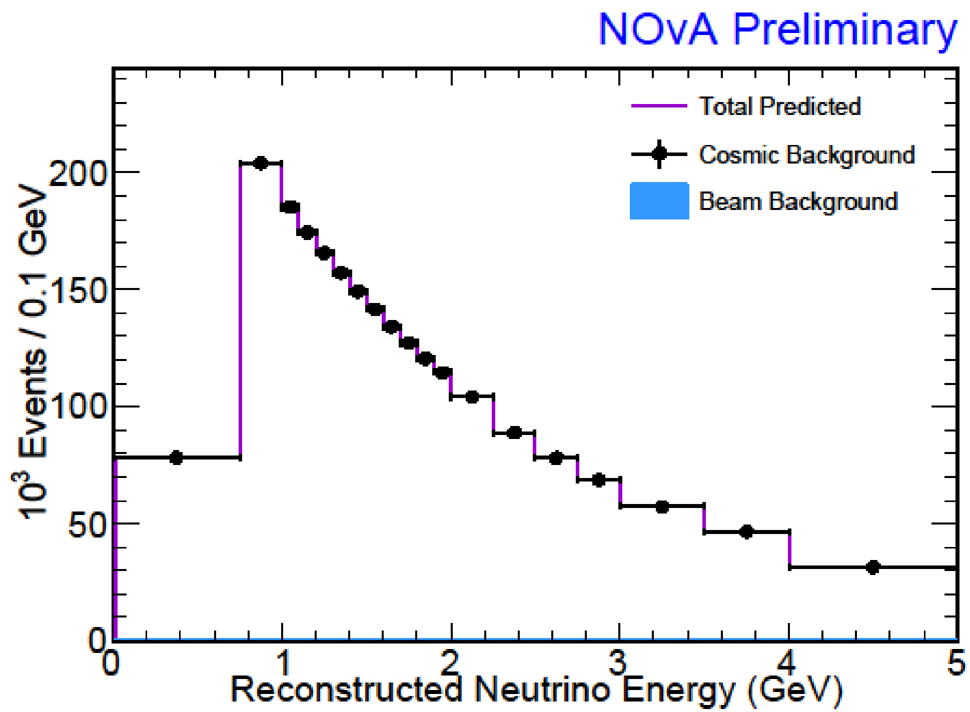


ν_μ selection

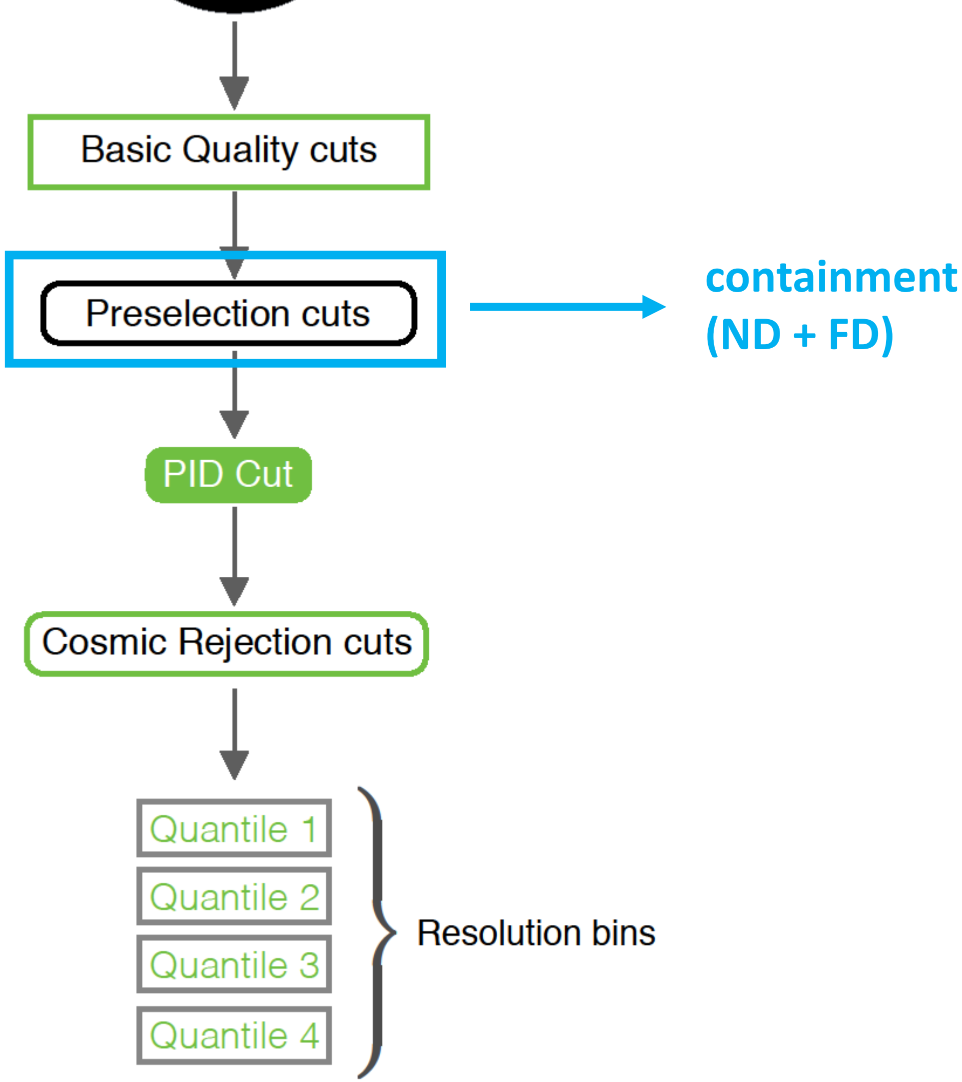


can reconstruct the event (ND + FD)

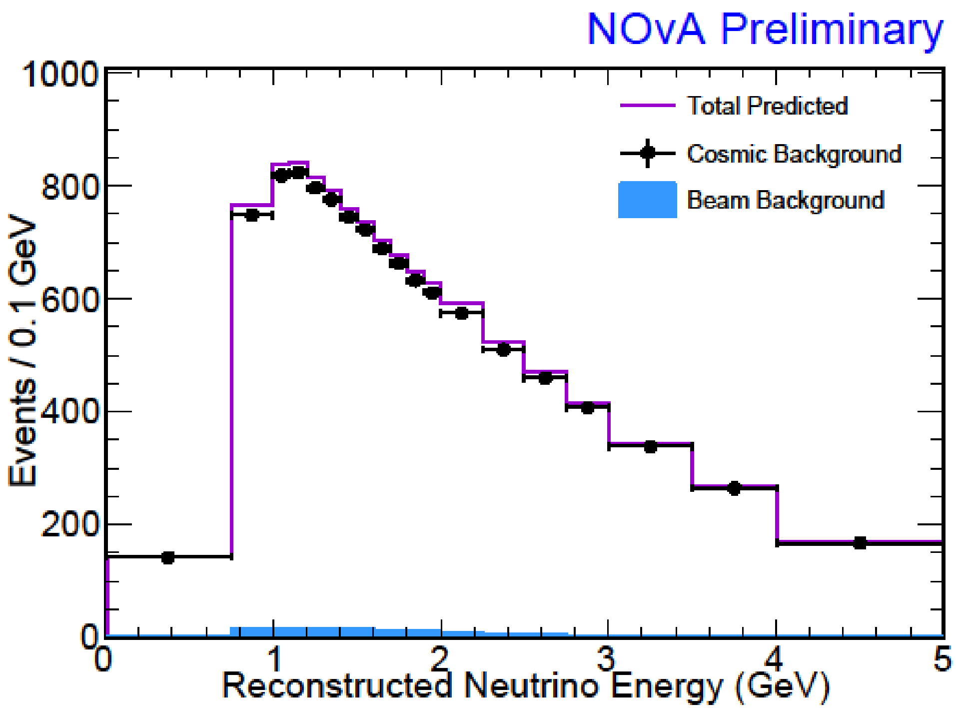
FD: ~10^6 events

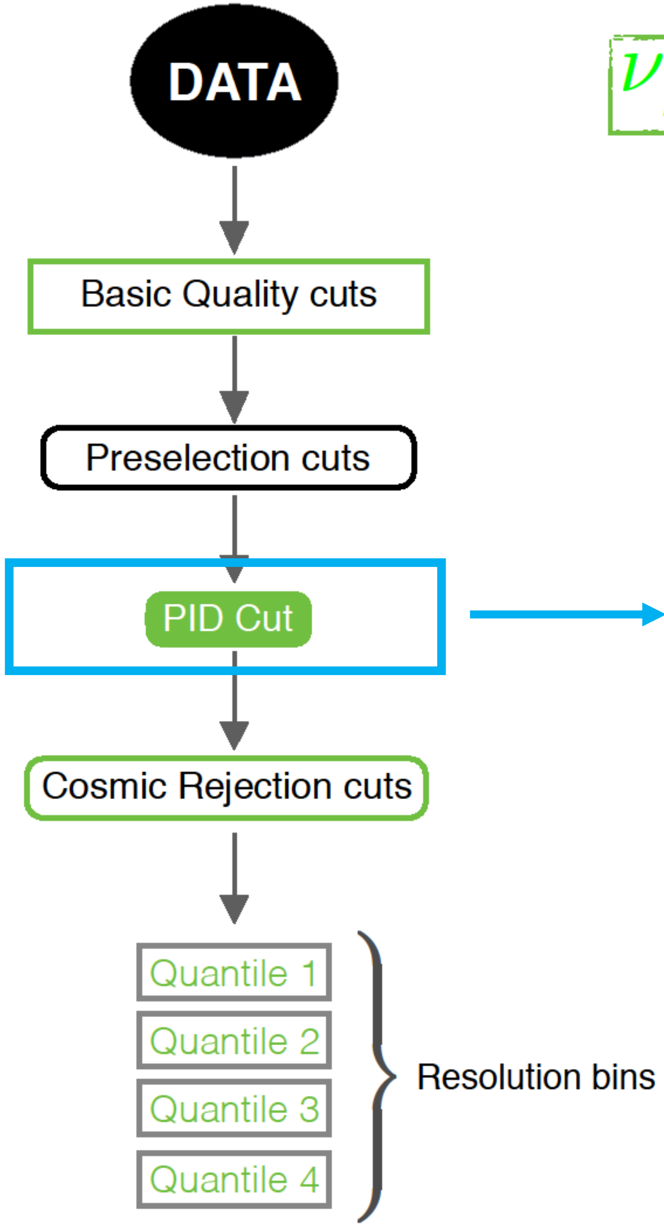


ν_μ selection

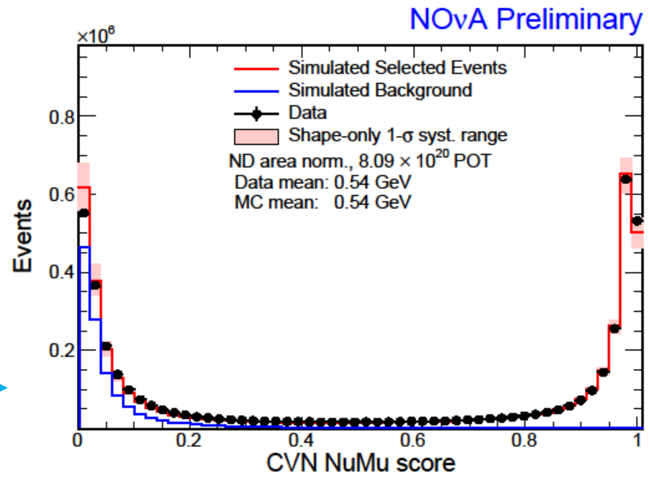


FD: ~10^3 events



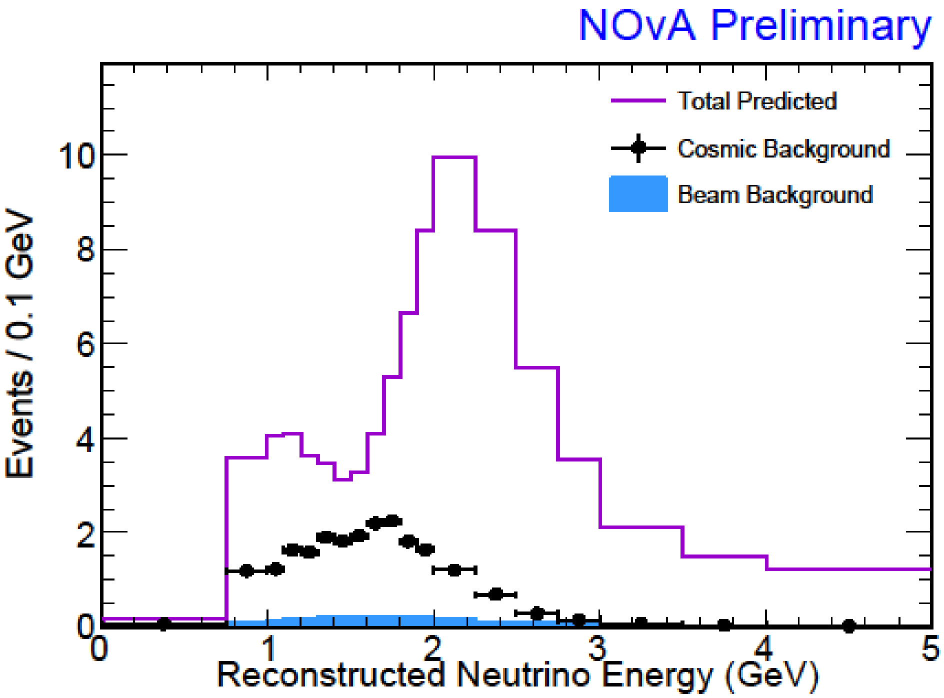


ν_μ selection

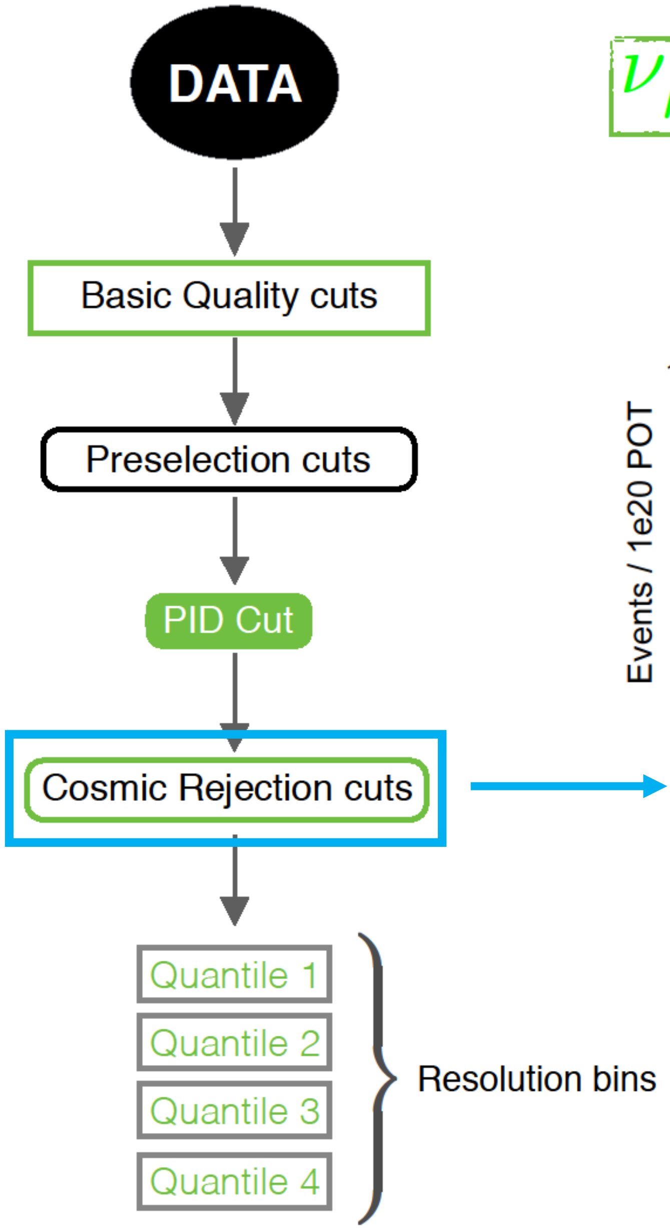


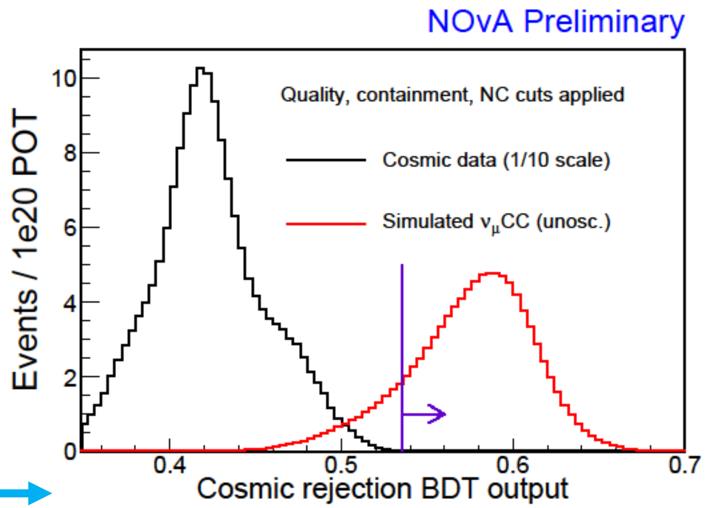
is it a ν_μ CC?
deep learning: CVN
removes NC, cosmics
(ND + FD)

FD: ~100 events



ν_μ selection

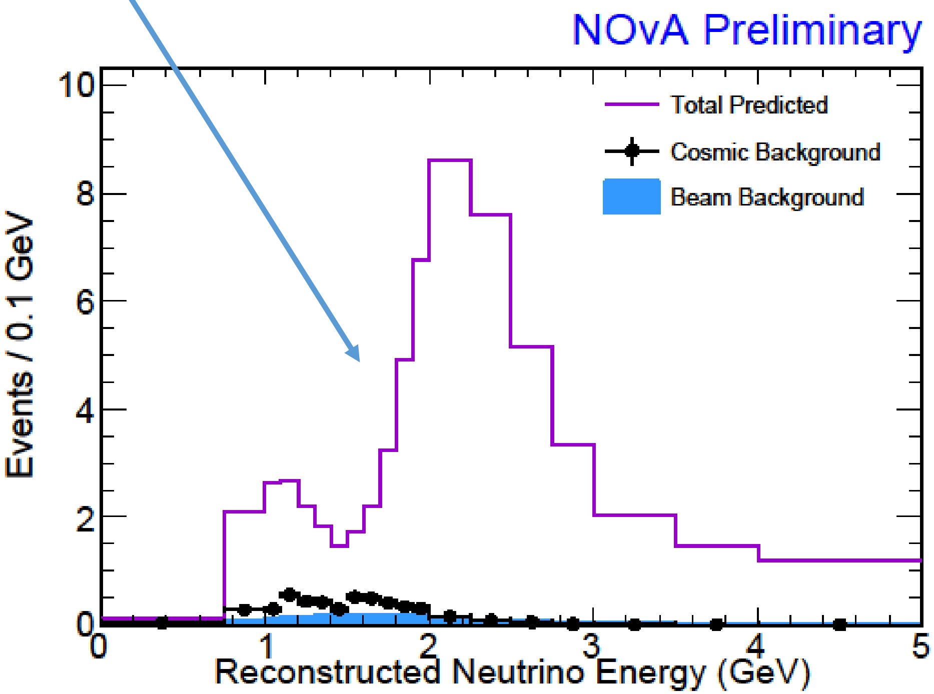




BDT to remove remaining cosmics (FD only)

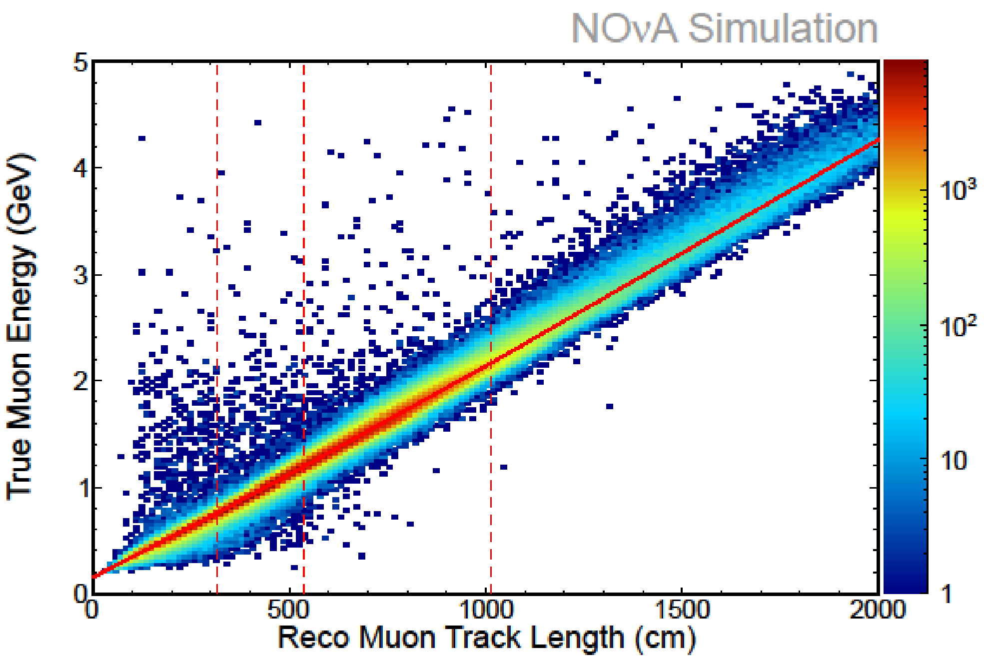
shape depends on oscillation parameters θ_{23} and Δm^2_{32}

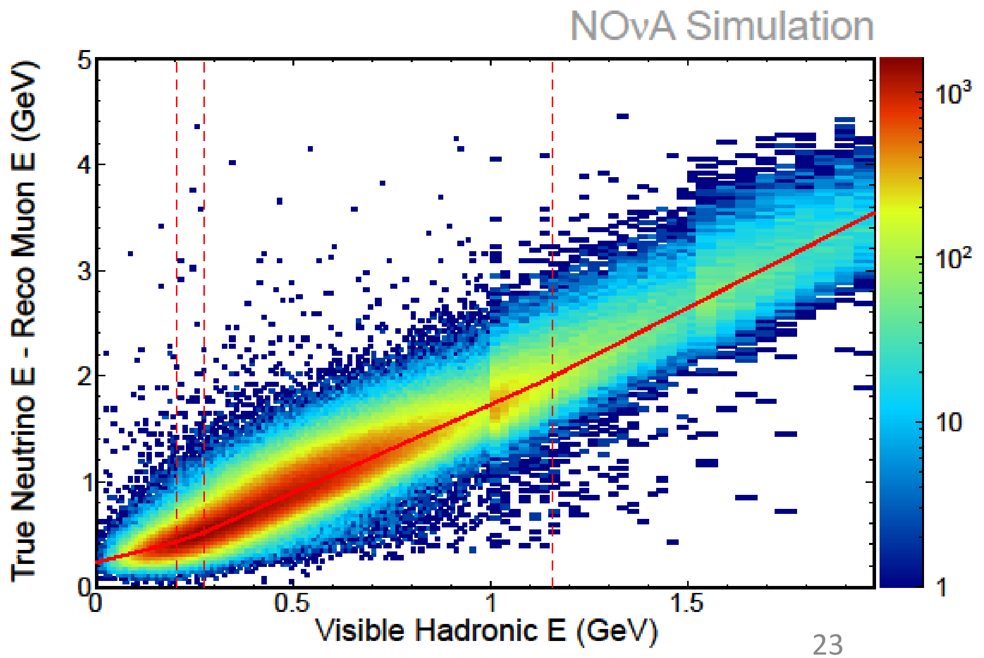
FD: ~100 events



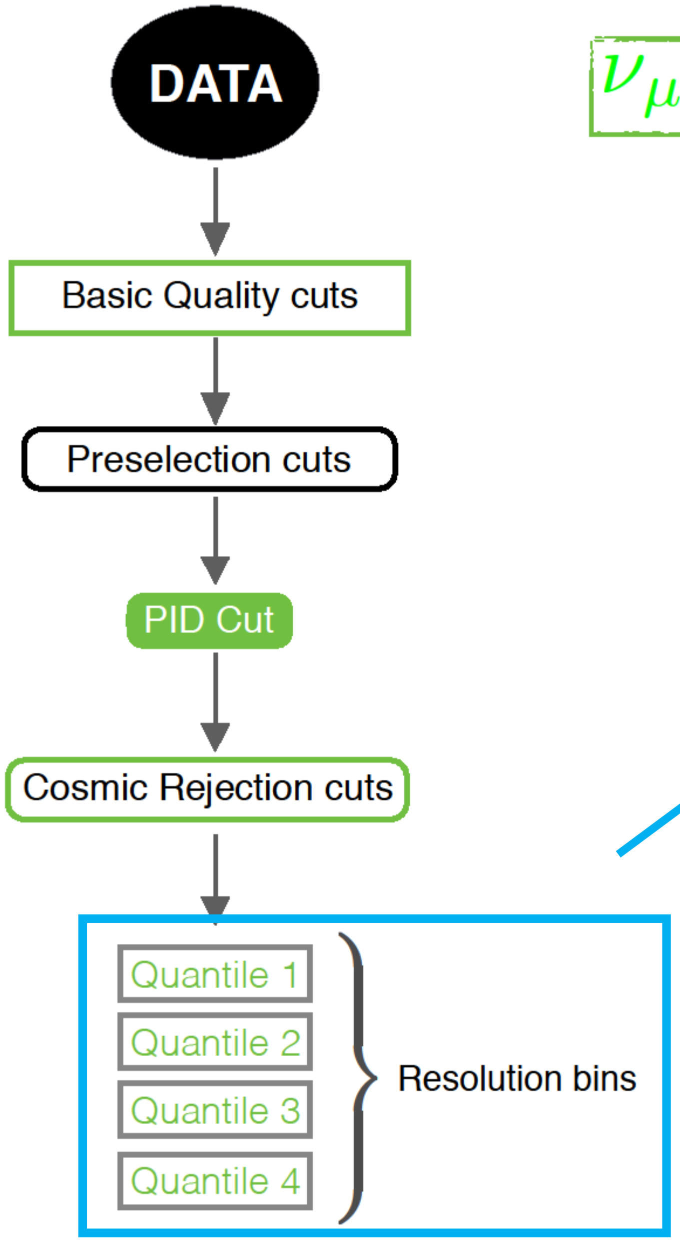
ν_μ energy reconstruction

Reconstructed neutrino E:
based on simulation
lepton part (E^{res}_{lep} = 3%)
hadronic part (E^{res}_{had} = 30%)
$E_\nu = E_{lep} + E_{had}$ (E^{res}_{ν} = 9%)

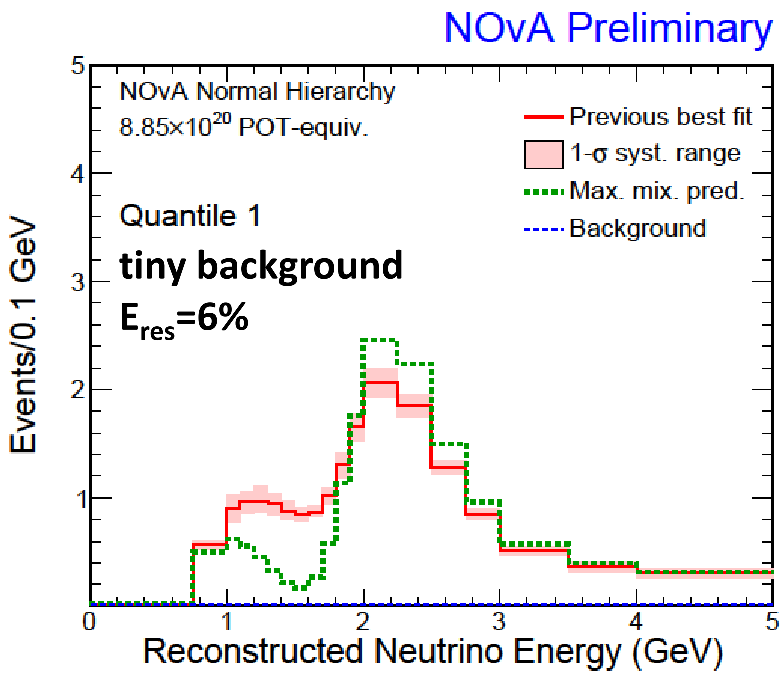


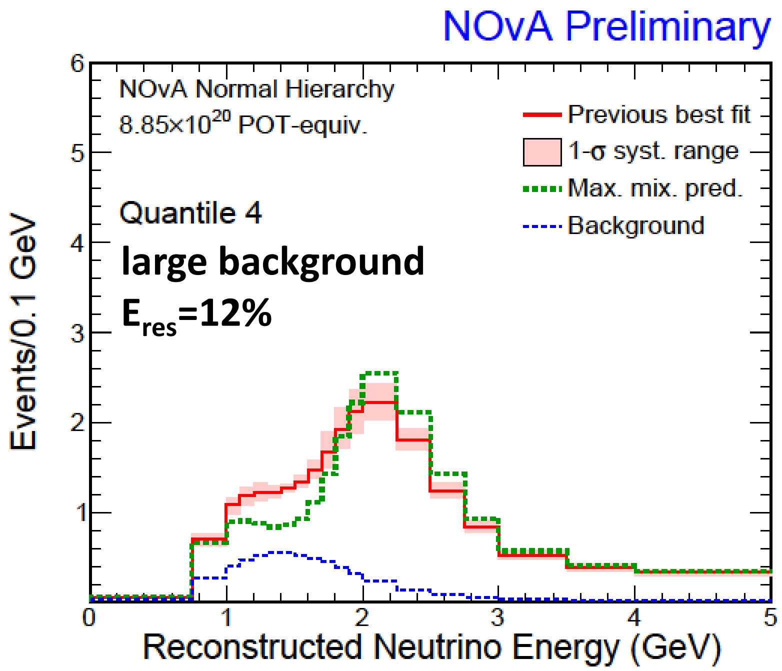


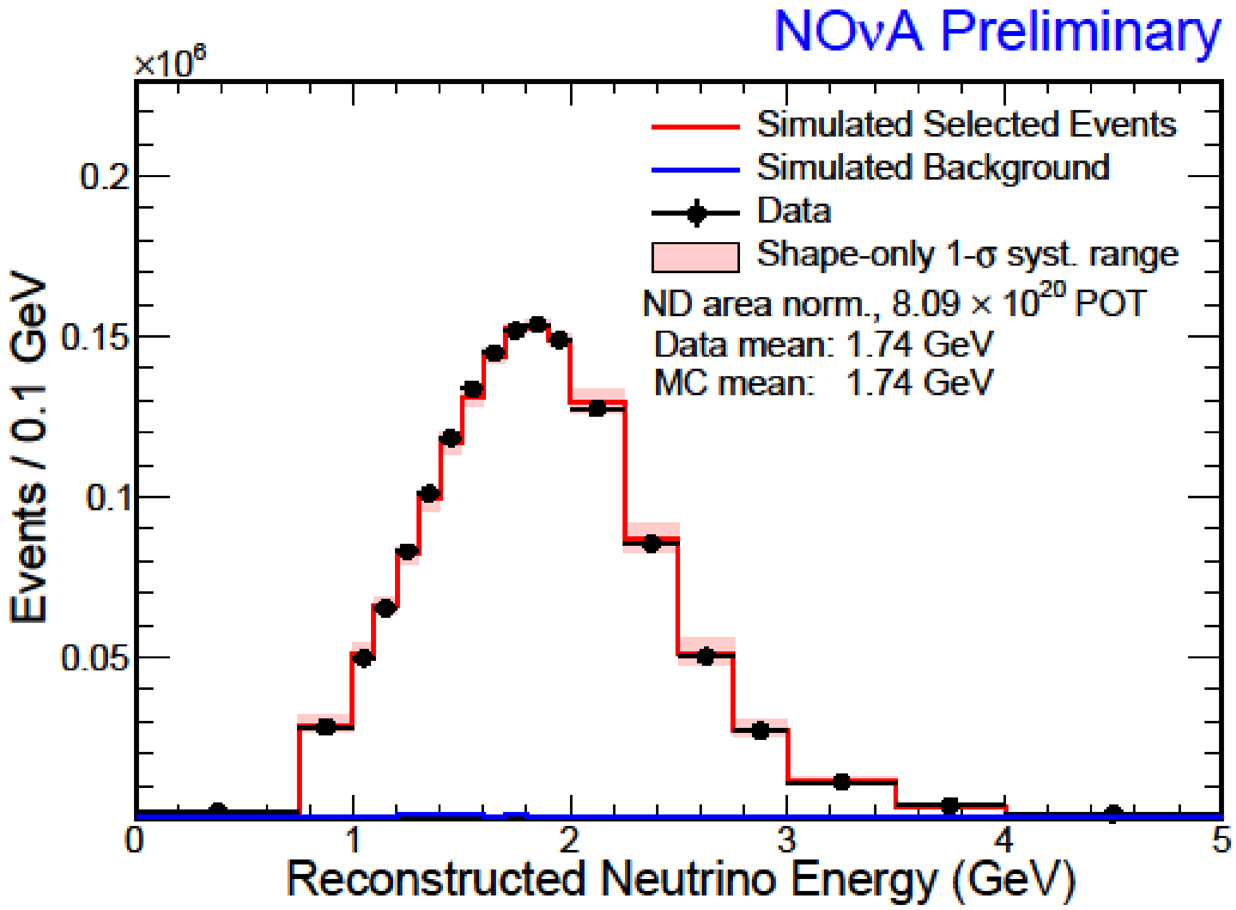
ν_μ selection



the less hadronic E the better the E resolution
divide into 4 E_{had}/E_ν quantiles



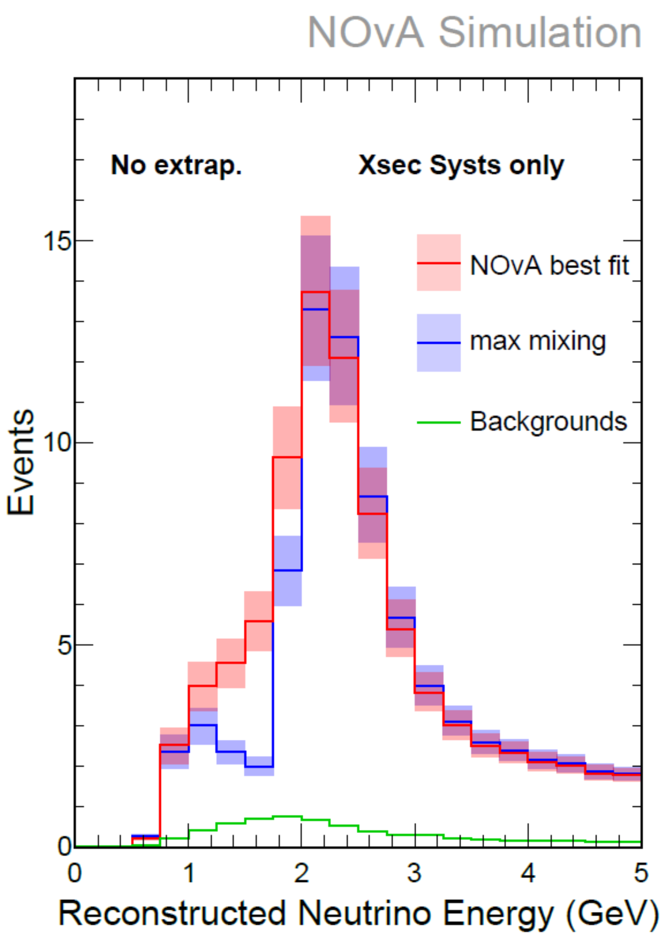


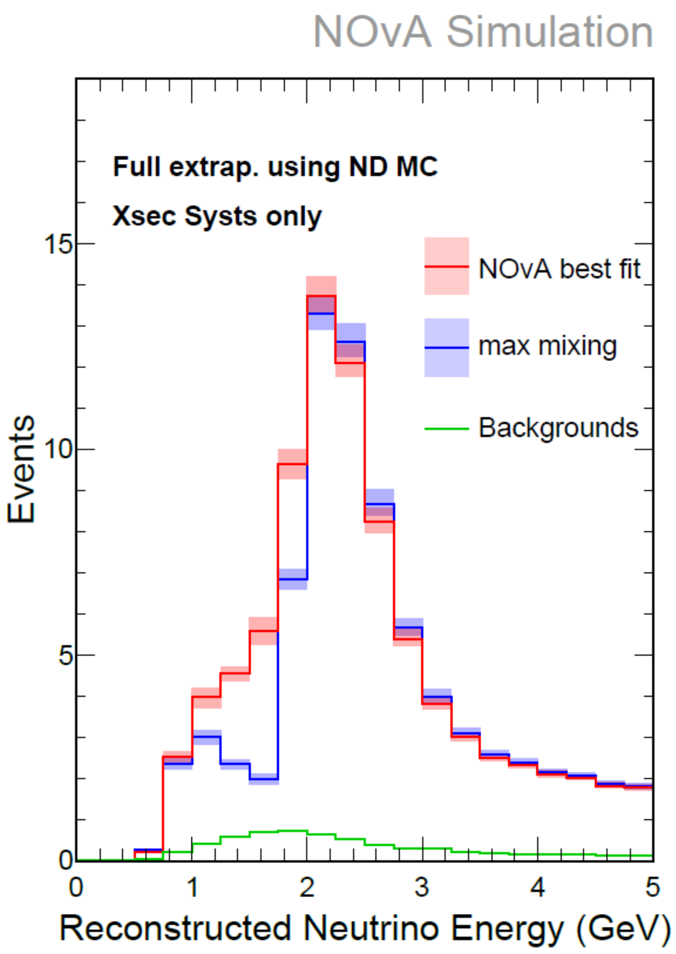


select ν_μ events in ND
data/MC agreement good
tells us simulation not too wrong

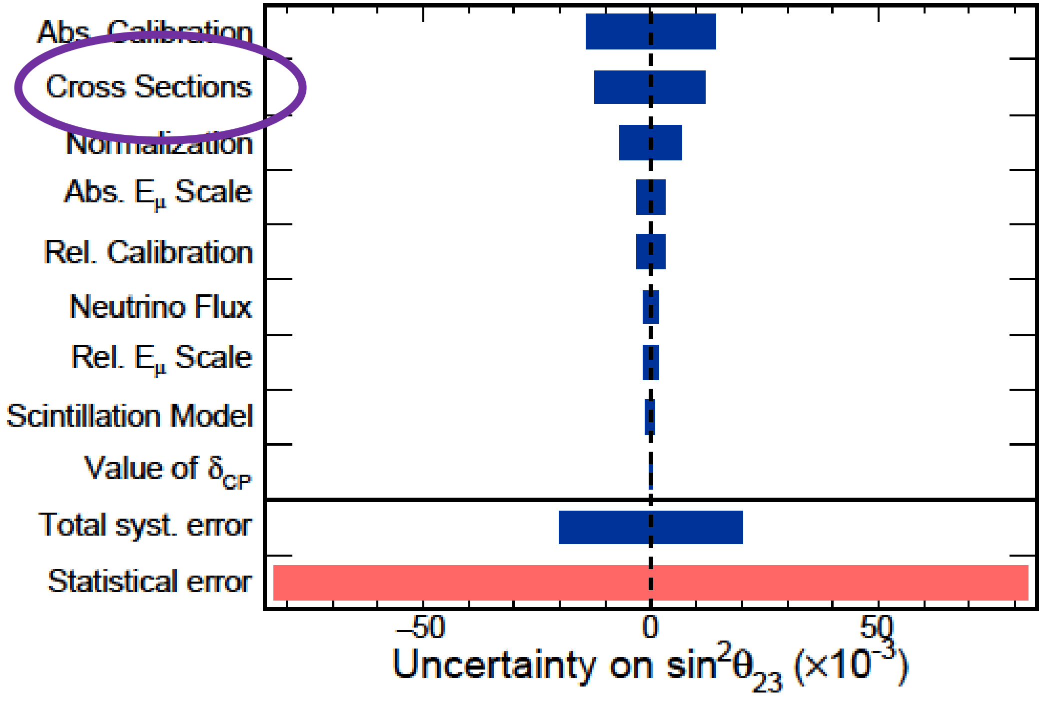
Use ND as a measurement to constrain uncertainties in the FD

Far/near extrapolation

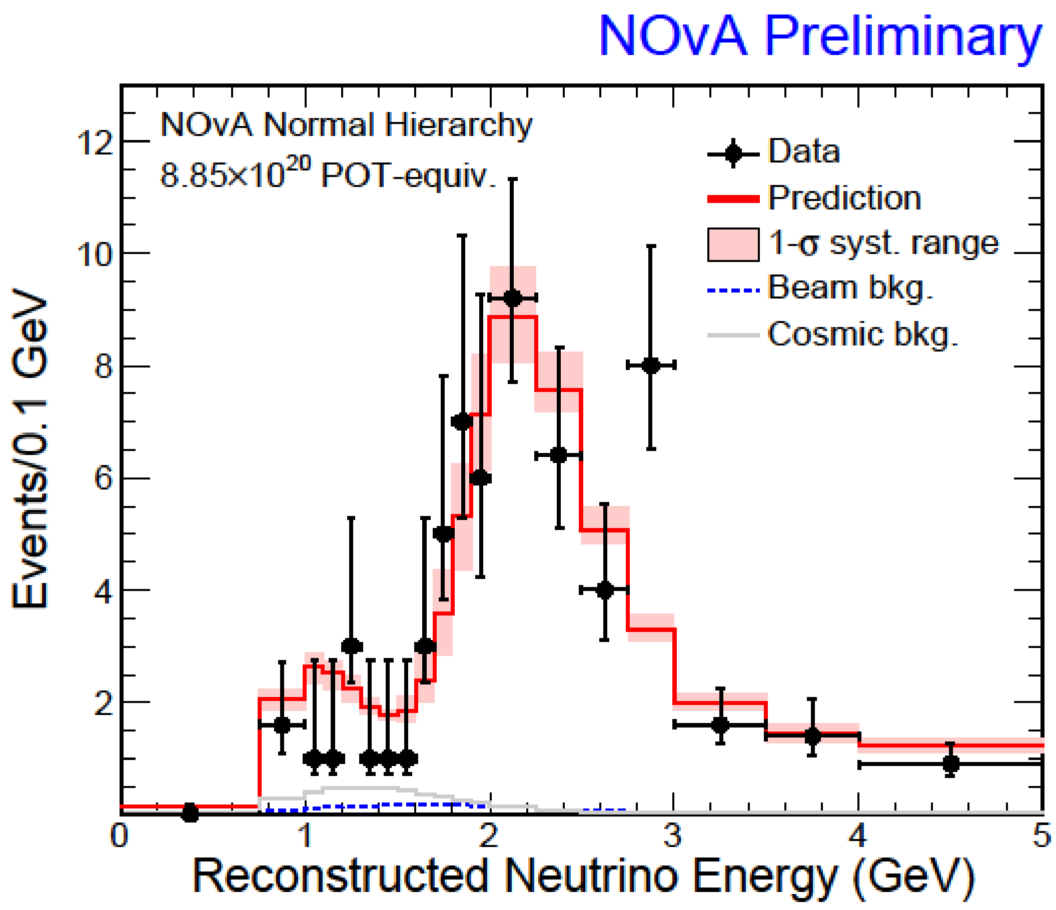




Each systematic is a penalty term in χ^2 fit to determine oscillation parameters



if no oscillations, predict 763 events observe 126 events

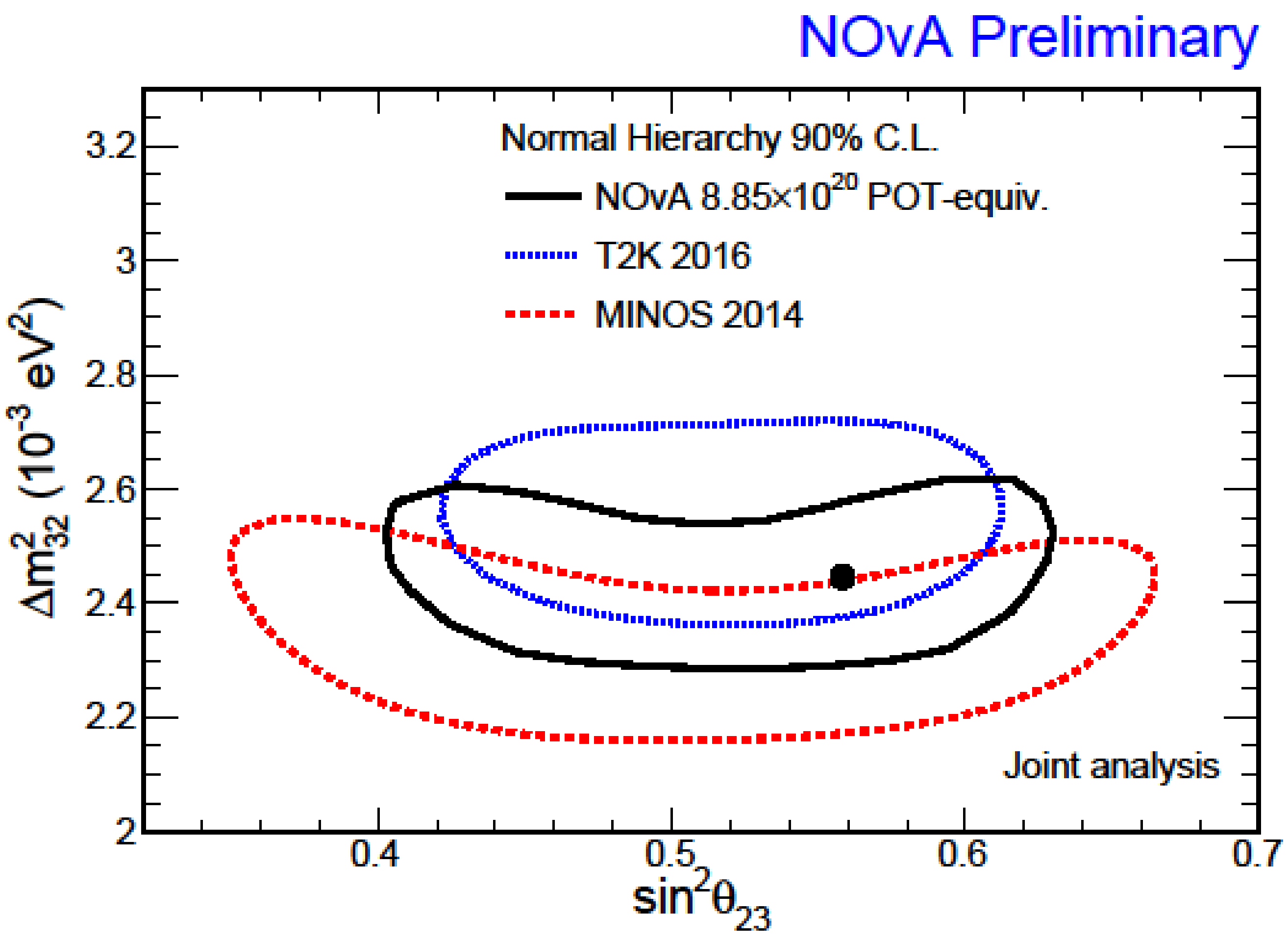


Can plot as 90% confidence contour in θ_{23}, Δm^2_{32} space

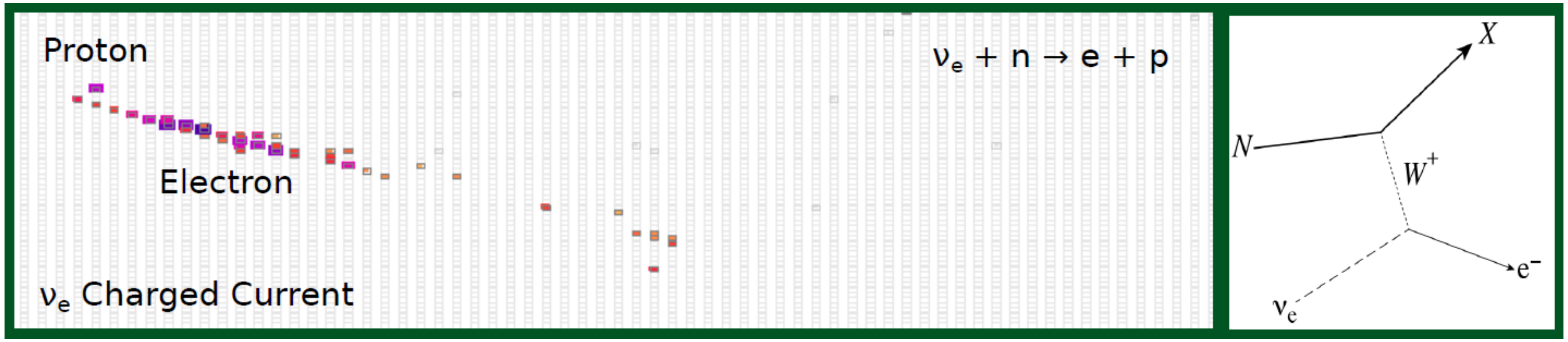
best fits:

$\sin^2\theta_{23} = 0.558^{+.041}_{-.033}$

$\Delta m^2_{32} = 2.444^{+.079}_{-0.077} \times 10^3 \text{ eV}^2$



ν_e Appearance



$$P(\overset{(-)}{\nu}_\mu \rightarrow \overset{(-)}{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1^2)}$$

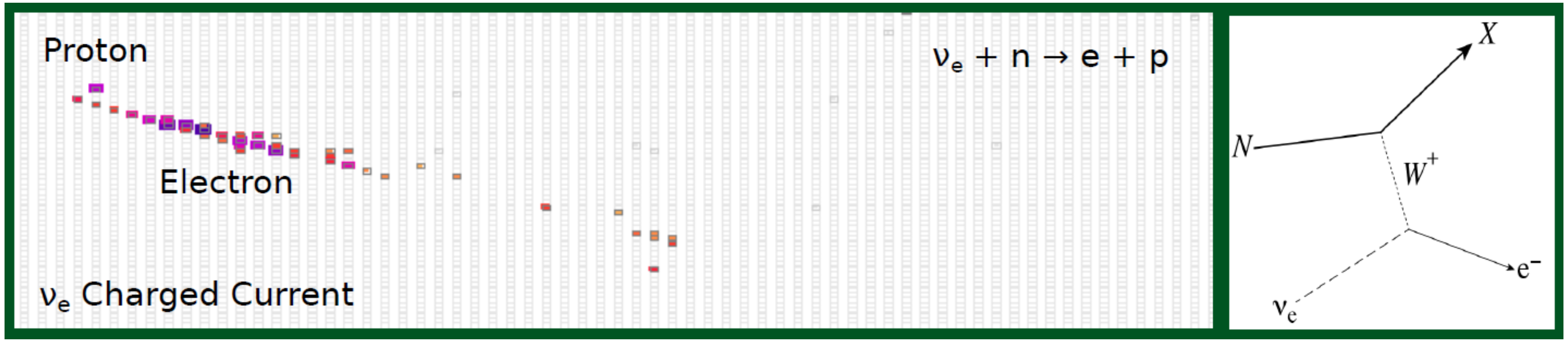
$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$

$$+ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \cos\Delta$$

$$\text{Where:} \quad \alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \quad \Delta = \Delta m^2_{31} \frac{L}{4E} \quad A = \overset{(-)}{+} G_f N_e \frac{L}{\sqrt{2}\Delta}$$

directly measure δ_{CP}, the mass hierarchy, additional information for θ_{23}

ν_e Appearance

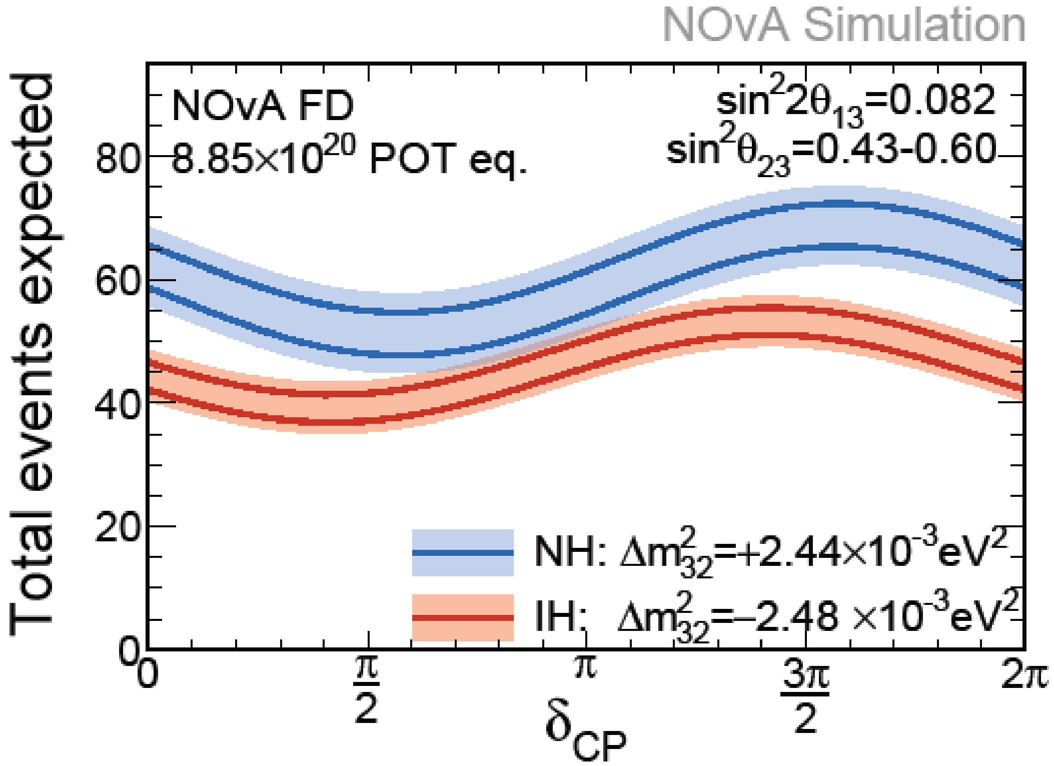


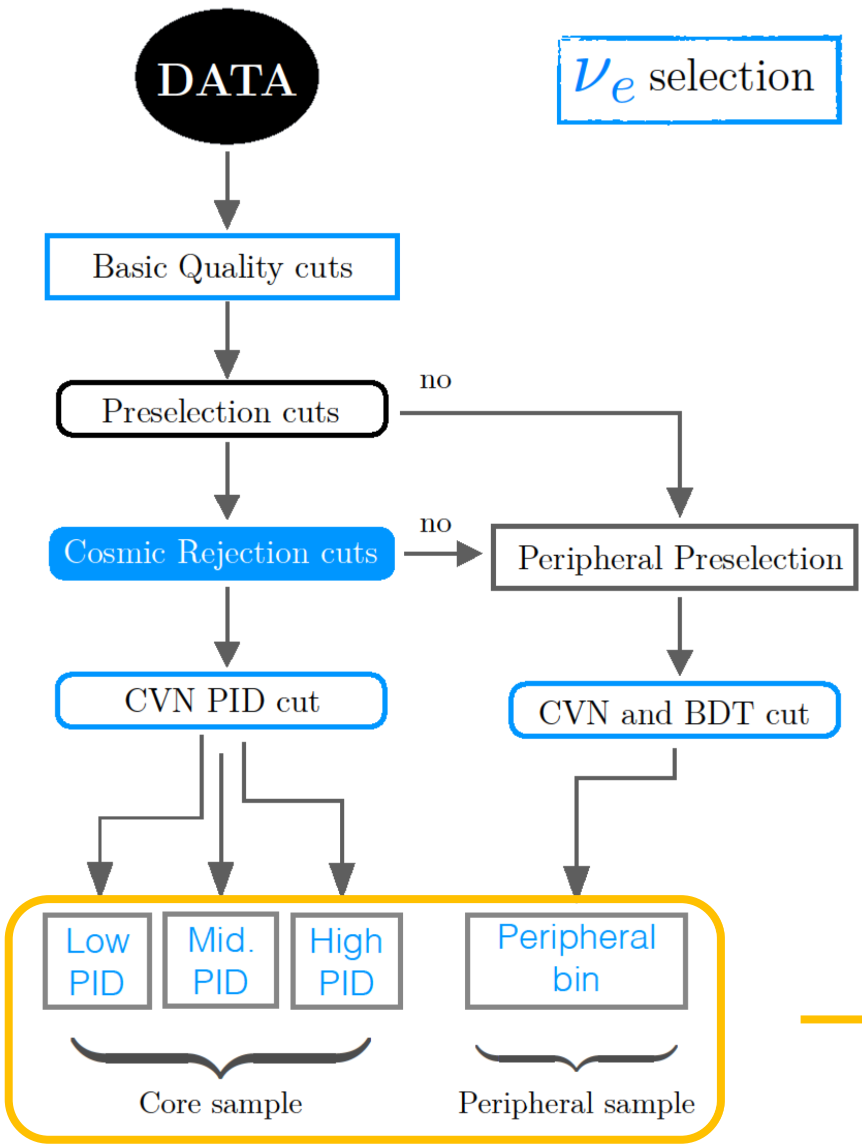
Signature is an electron shower

Backgrounds:

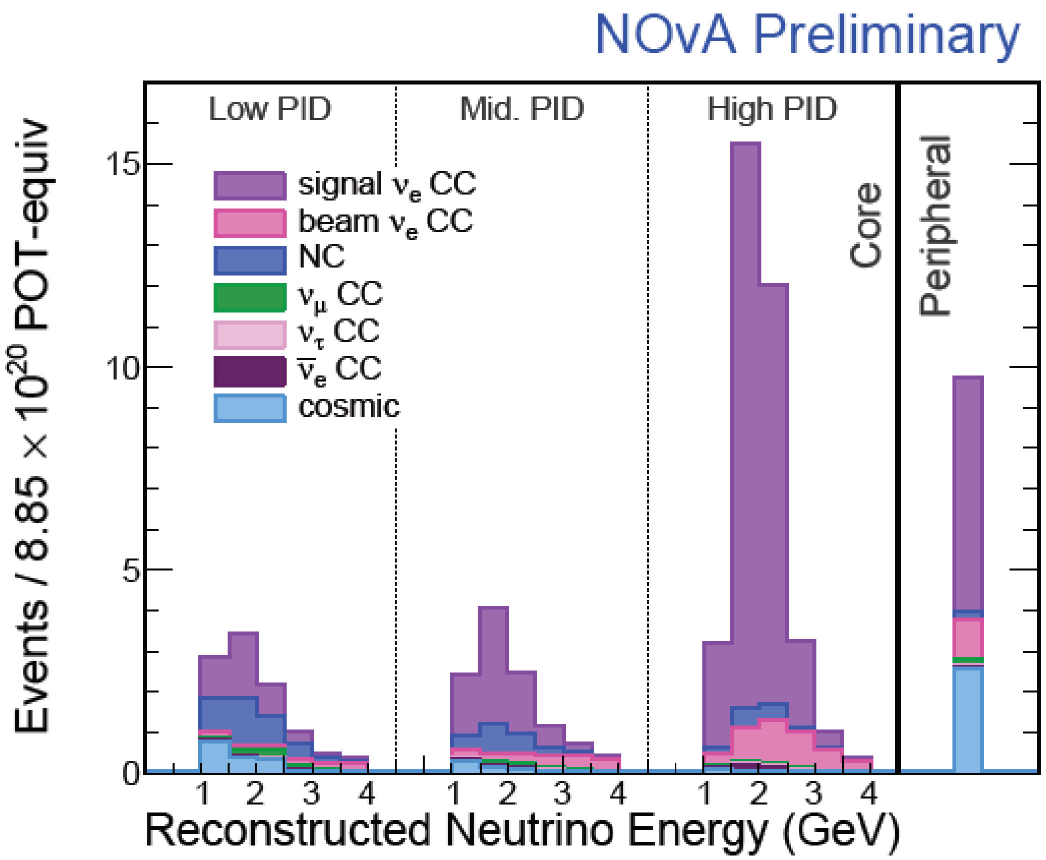
- **cosmics**
- **neutral current**
- **intrinsic beam ν_e**

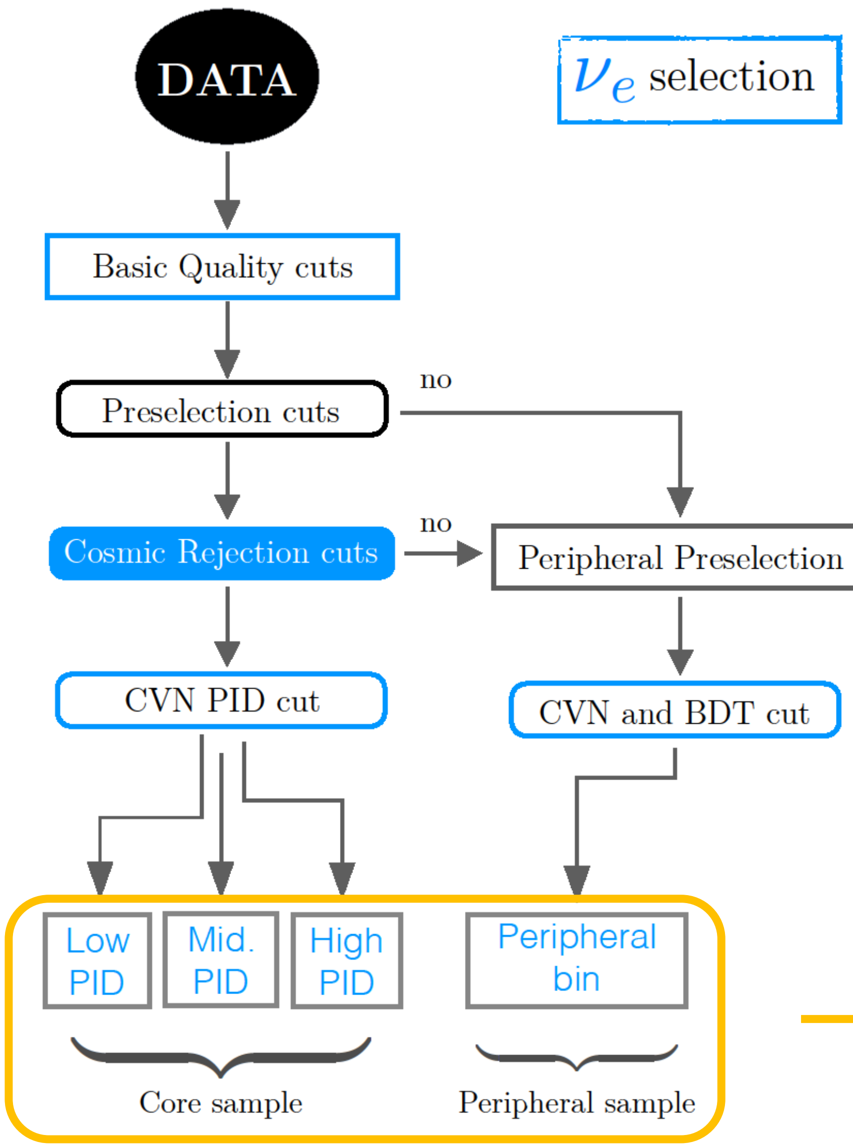
Use ND to measure intrinsic ν_e and neutral current background, extrapolate to FD



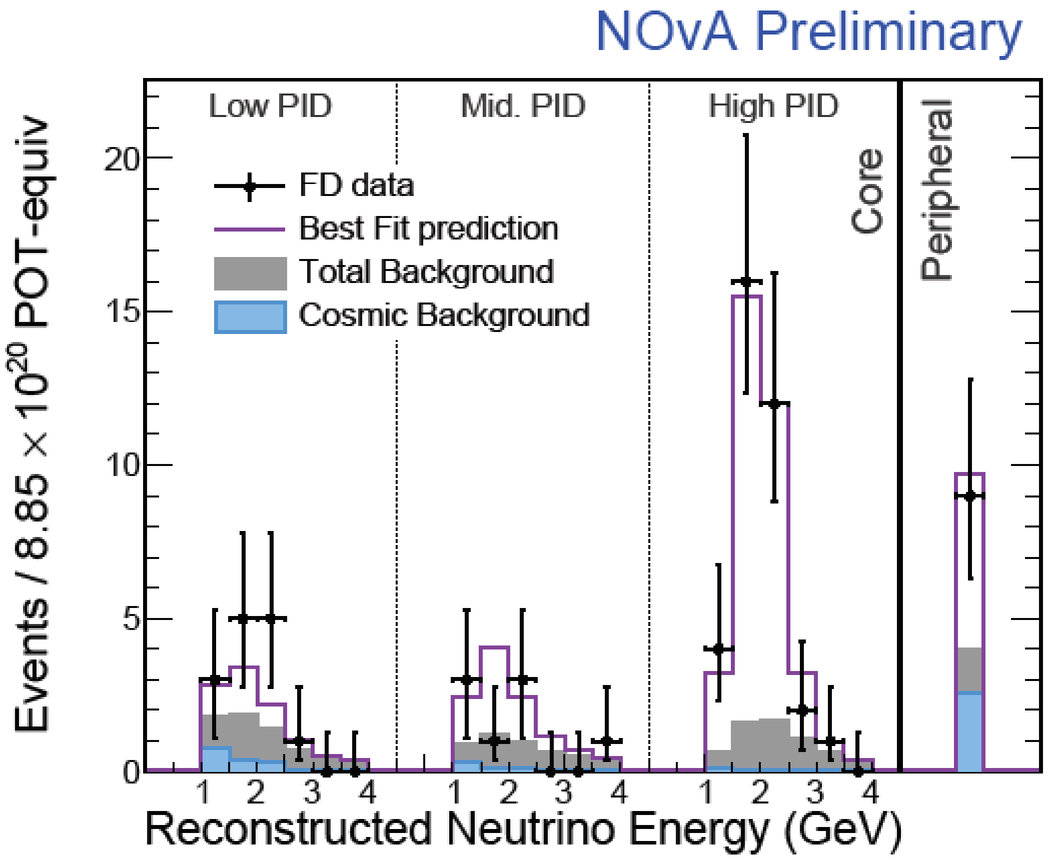


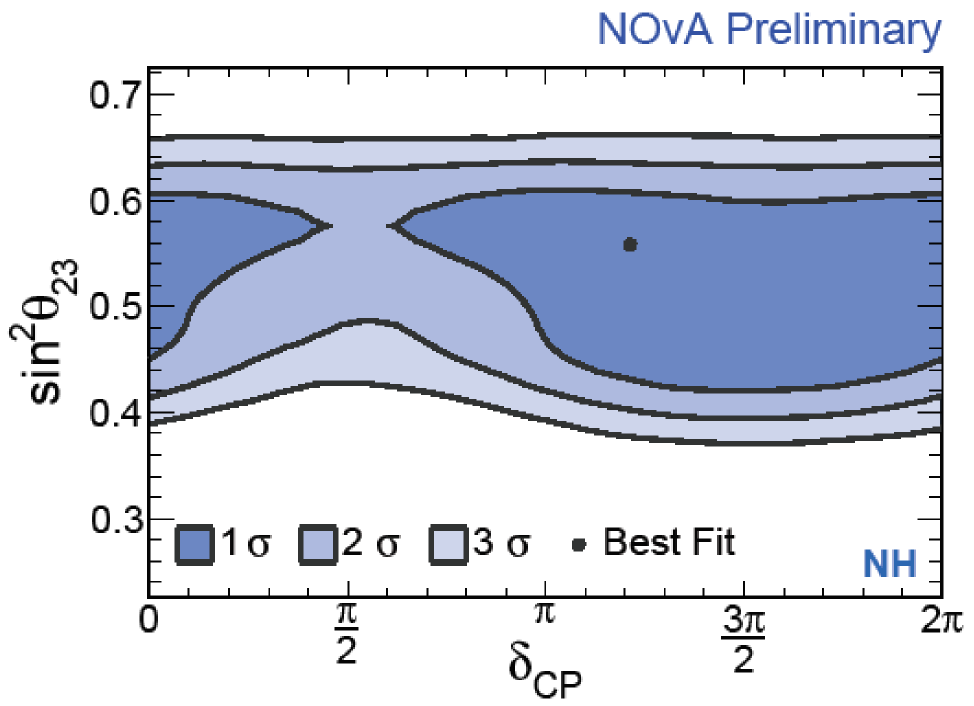
bin in energy for three PID bins + sideband

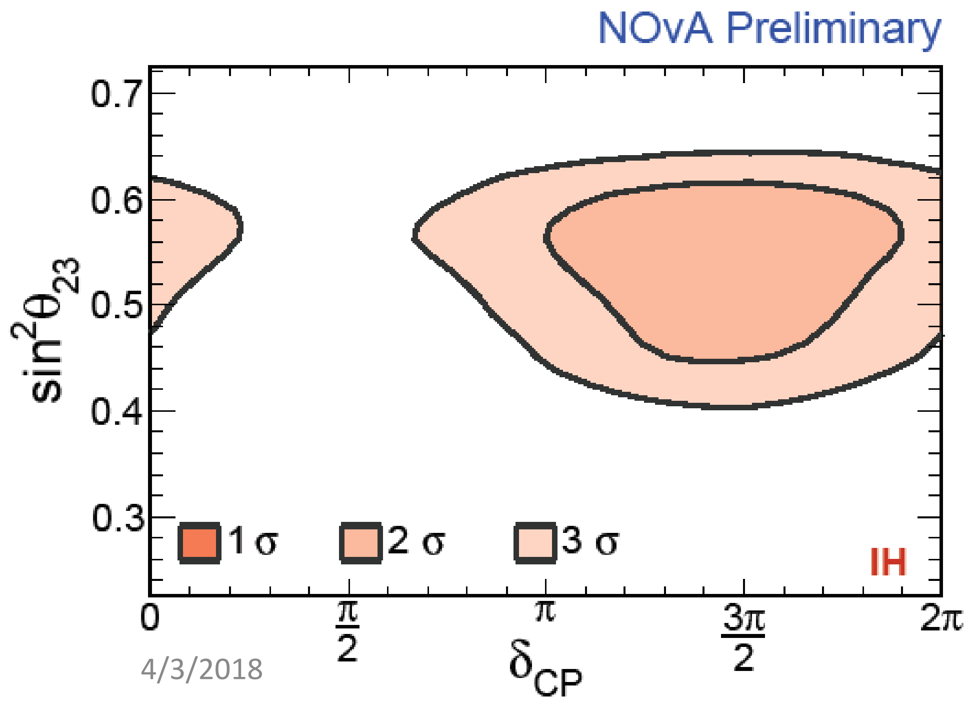




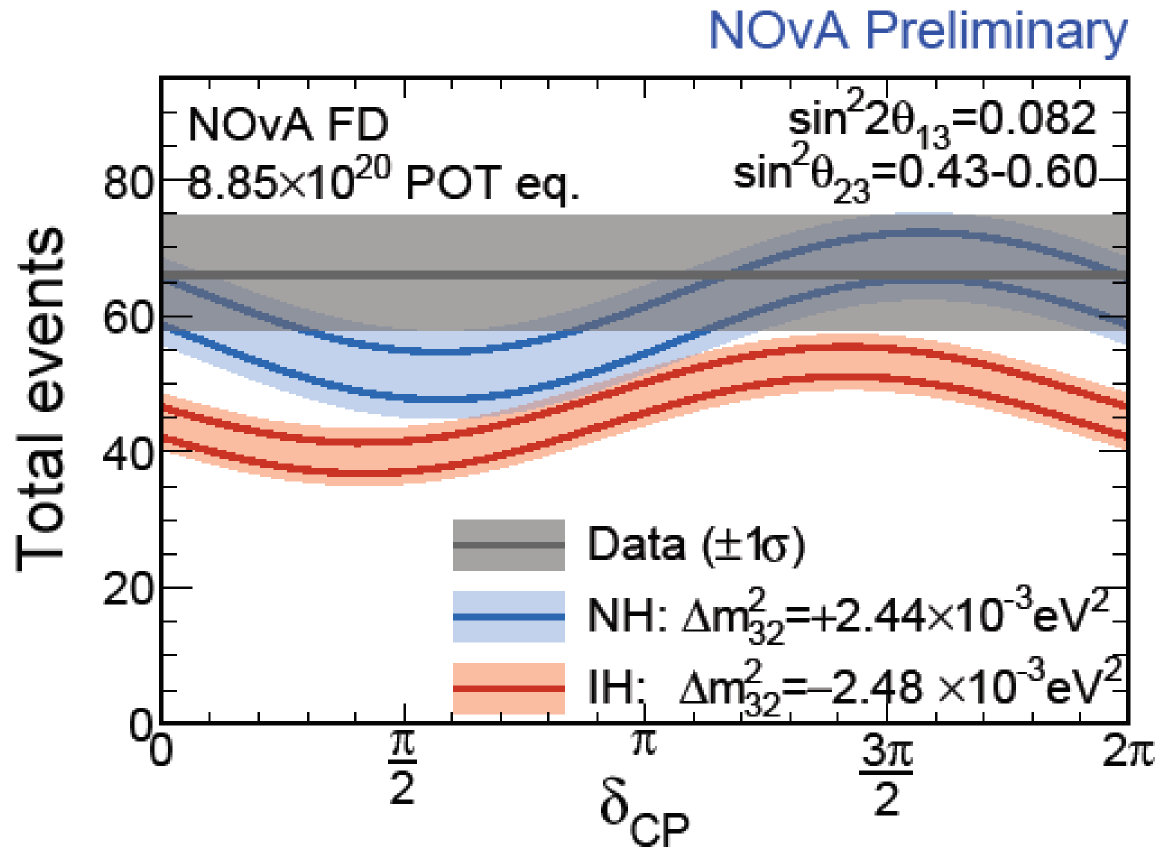
real data + best fit

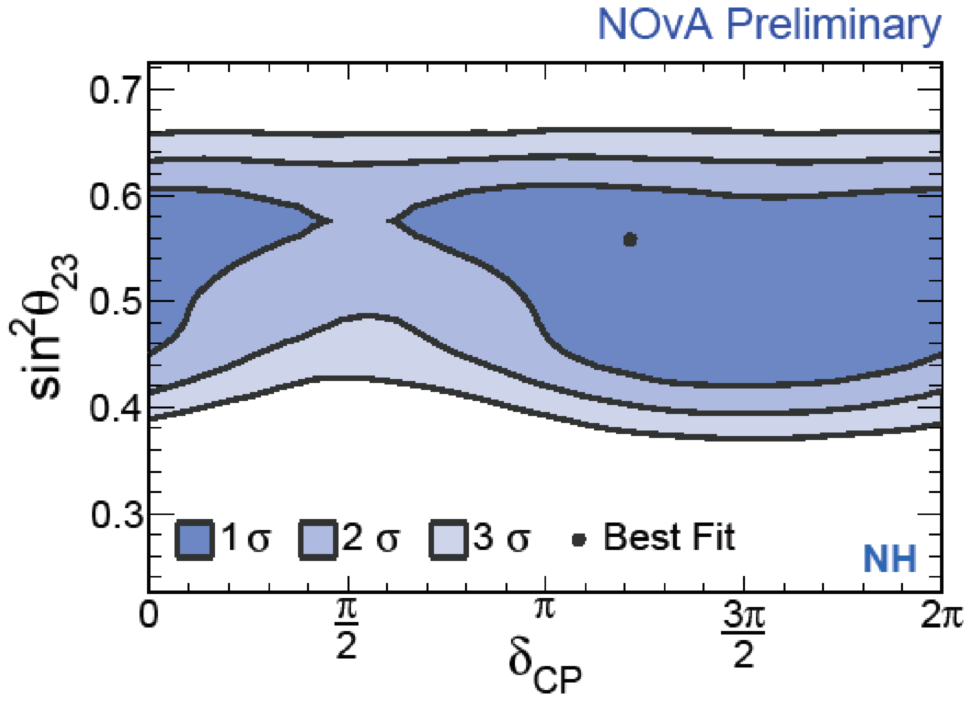


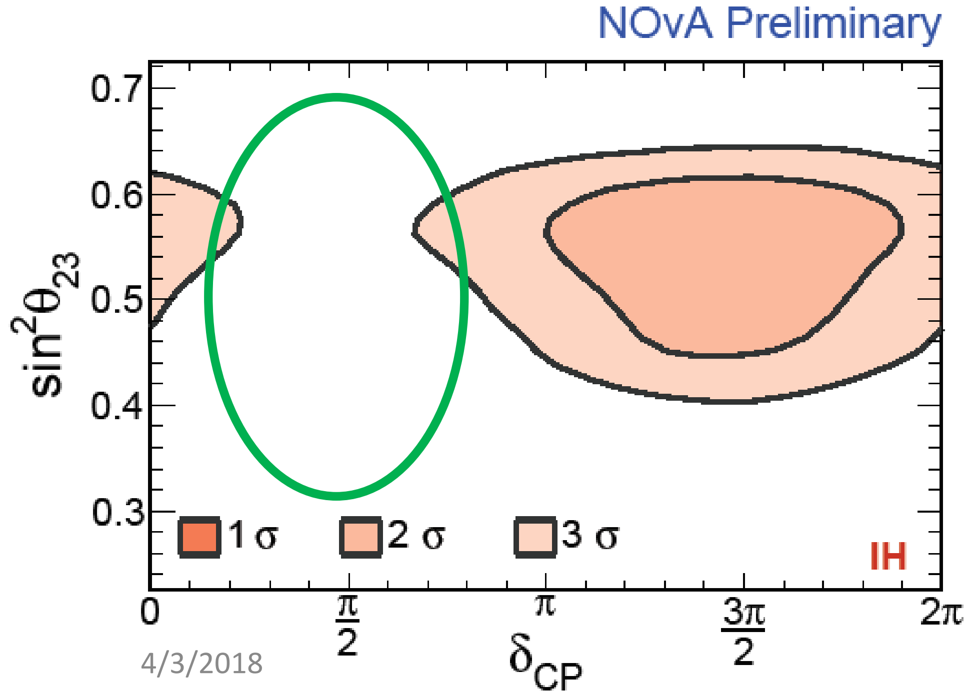




Contours in θ_{23}, δ_{CP} space
Depends a lot on mass hierarchy

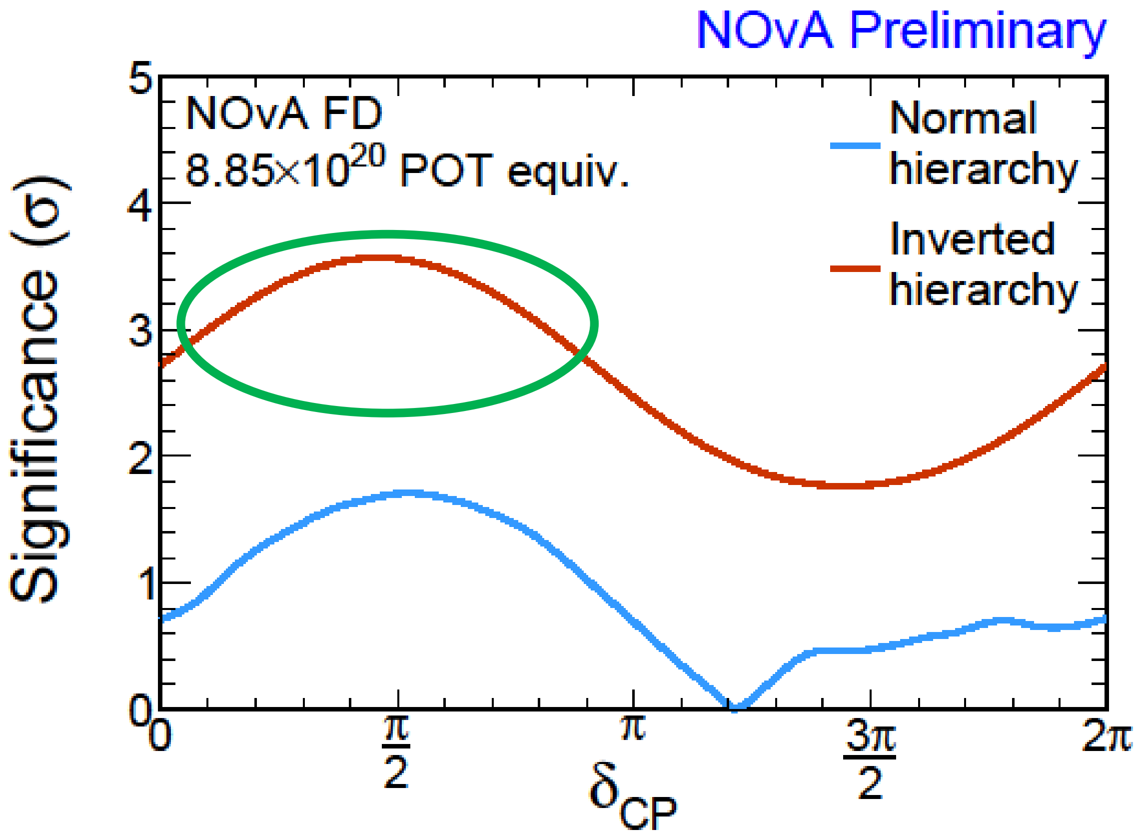


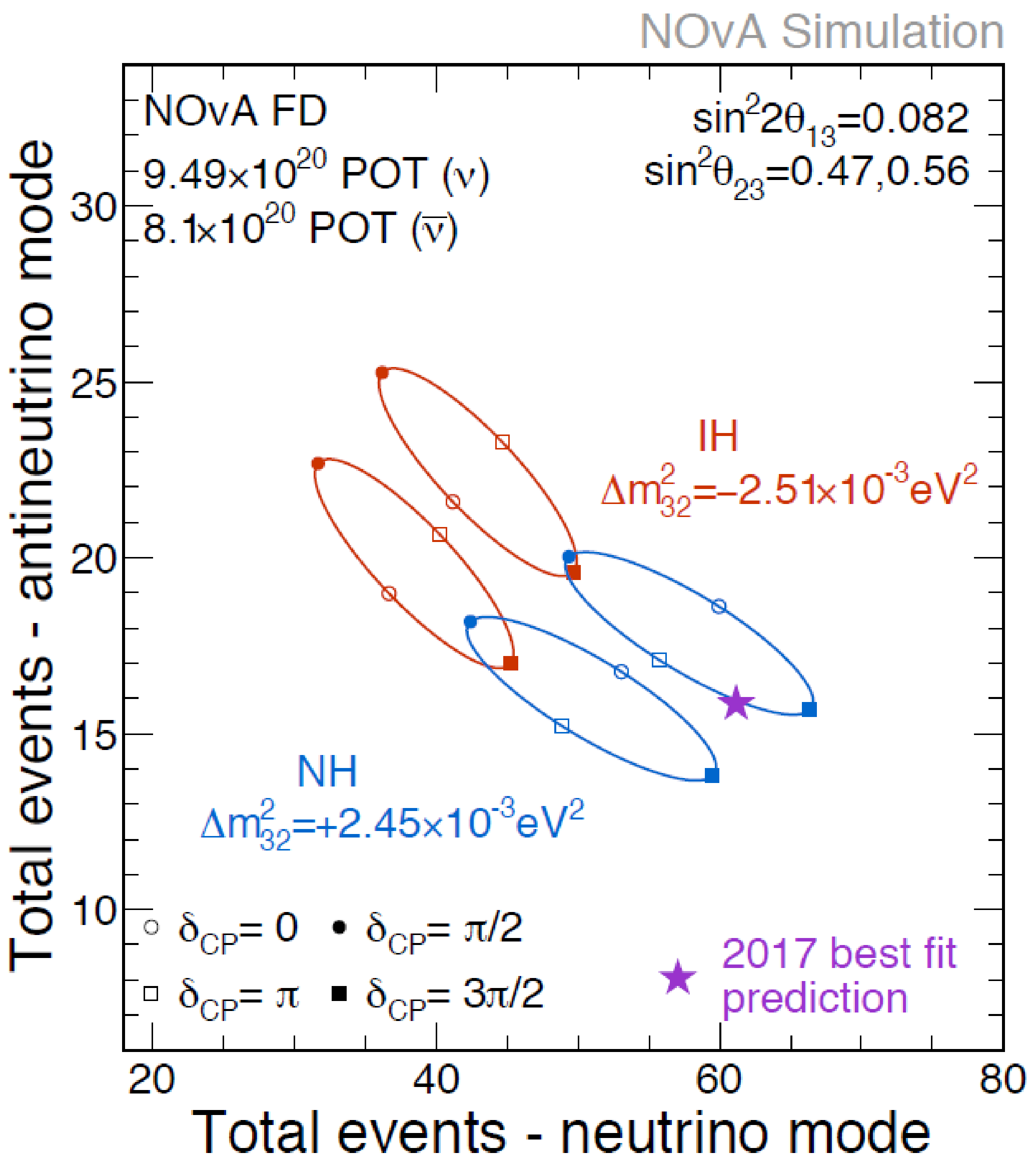




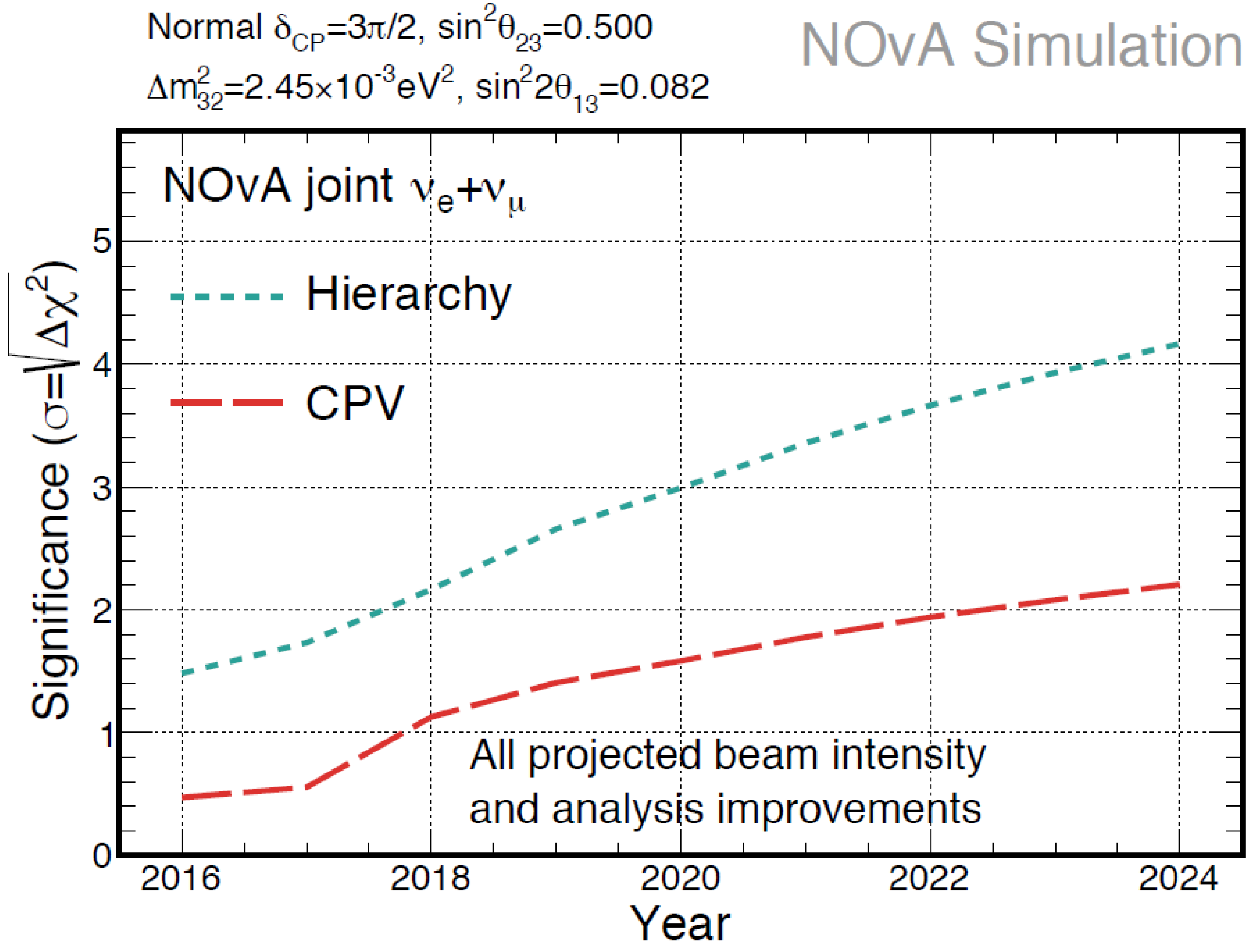
Contours in θ_{23}, δ_{CP} space
Depends a lot on mass hierarchy

For IH, δ_{CP} 0-π is disfavored by > 3 σ!



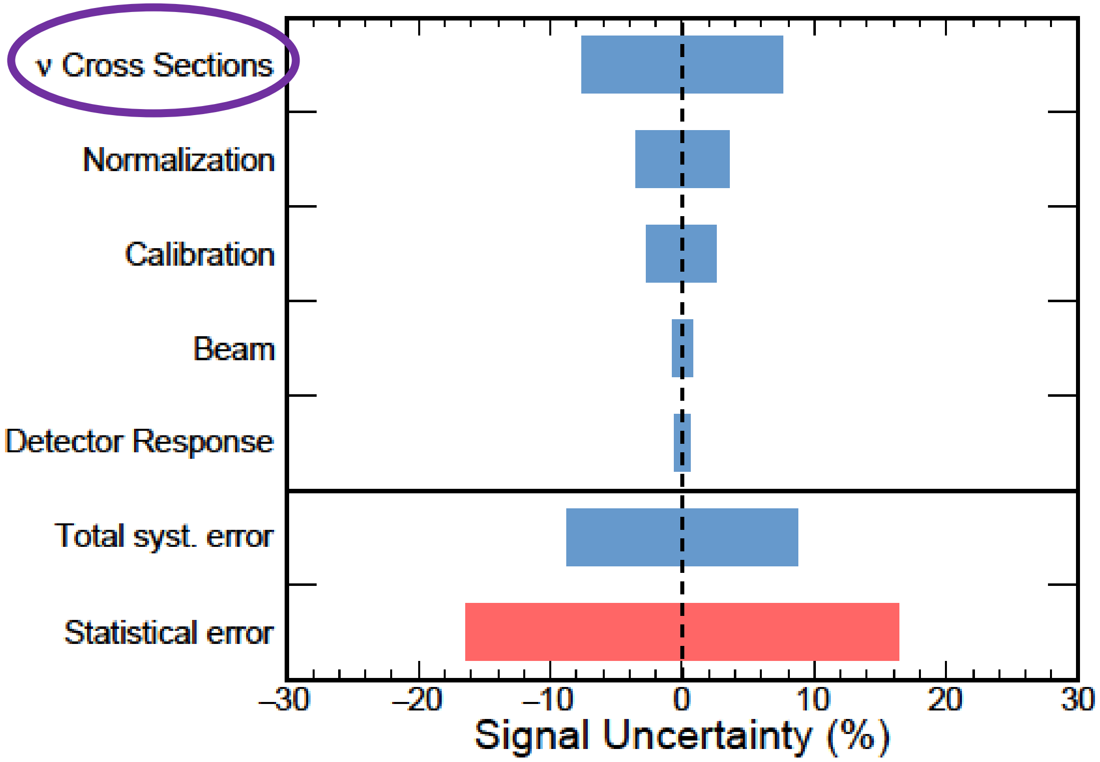


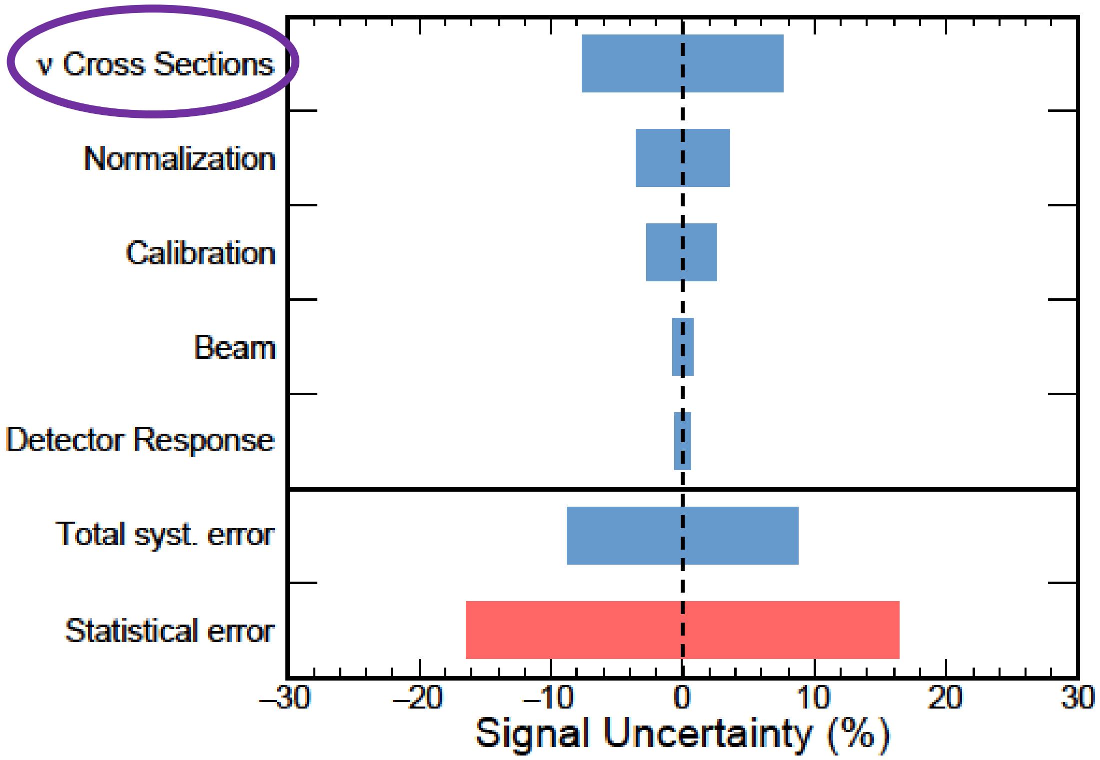
NOvA Simulation
NOvA FD
9.49×10^{20} POT (ν)
8.1×10^{20} POT ($\bar{\nu}$)
$\sin^2 2\theta_{13}$=0.082
$\sin^2\theta_{23}$=0.47,0.56
IH
$\Delta m^2_{32}=-2.51\times10^{-3}eV^2$
NH
$\Delta m^2_{32}=+2.45\times10^{-3}eV^2$
δ_{CP}= 0
δ_{CP}= $\pi/2$
δ_{CP}= π
δ_{CP}= $3\pi/2$
2017 best fit prediction
Total events - antineutrino mode
Total events - neutrino mode



Normal $\delta_{CP}=3\pi/2$, $\sin^2\theta_{23}$=0.500
$\Delta m^2_{32}=2.45\times10^{-3}eV^2$, $\sin^2 2\theta_{13}$=0.082
NOvA Simulation
NOvA joint $\nu_e+\nu_\mu$
Hierarchy
CPV
All projected beam intensity and analysis improvements
Significance ($\sigma=\sqrt{\Delta\chi^2}$)
Year

biggest uncertainty for appearance is cross-sections
still statistics limited but getting close
second biggest uncertainty for disappearance





cross-sections are hard! Lots of uncertainty

three standard interaction types:

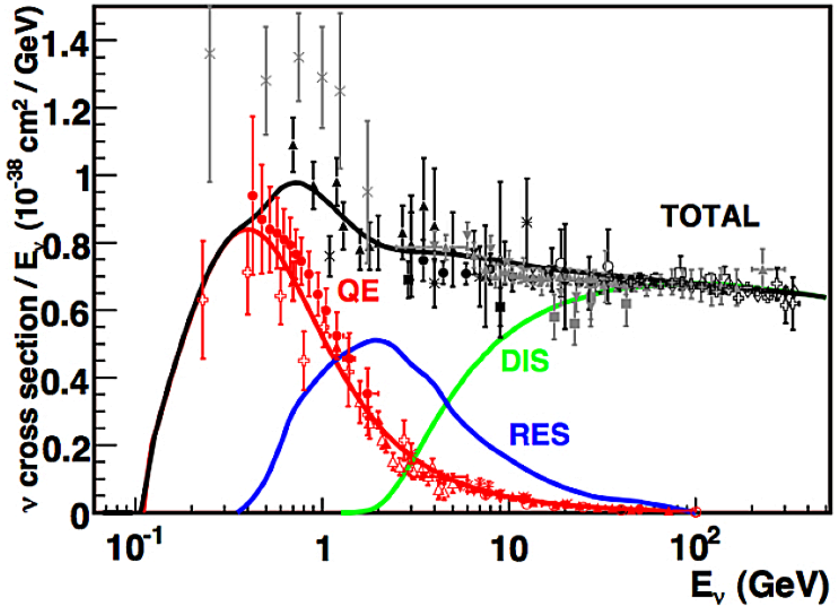
Quasi-Elastic: just lepton and proton

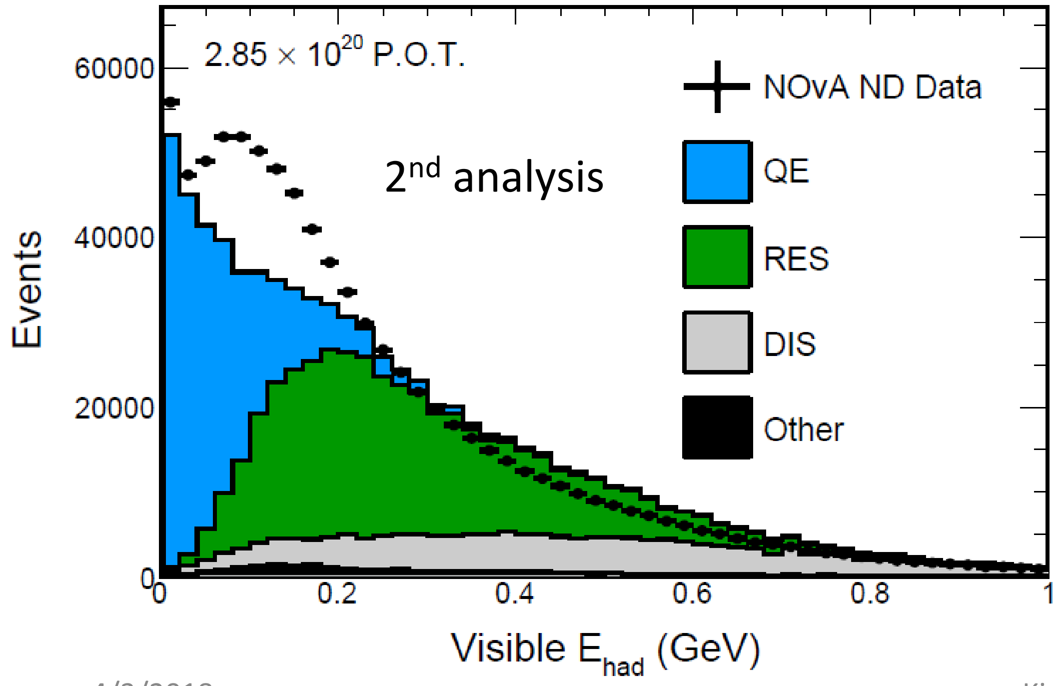
Resonance: hadronic system is resonance (ie delta) which decays

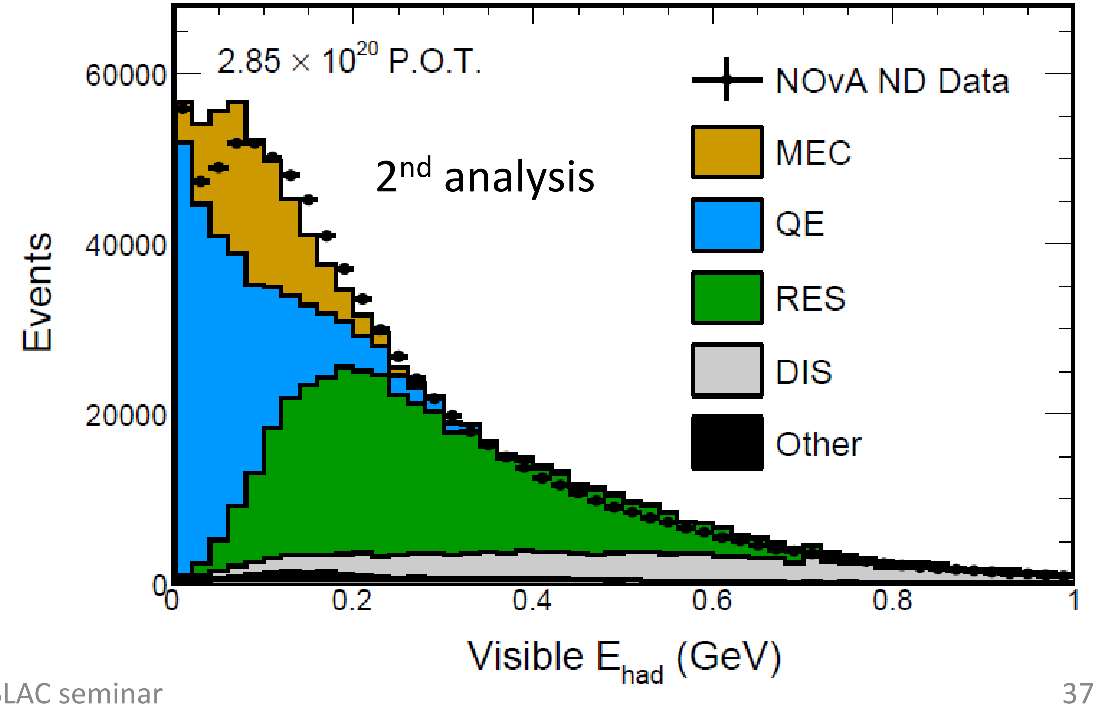
Deep Inelastic Scattering: neutrino hits quark directly

Meson Exchange Currents: only recently discovered

- still tons of uncertainty to rate and shape
- NOvA is measuring this! Important for not just NOvA!
- DUNE: current x-sec systs: ~10% needed: ~1%



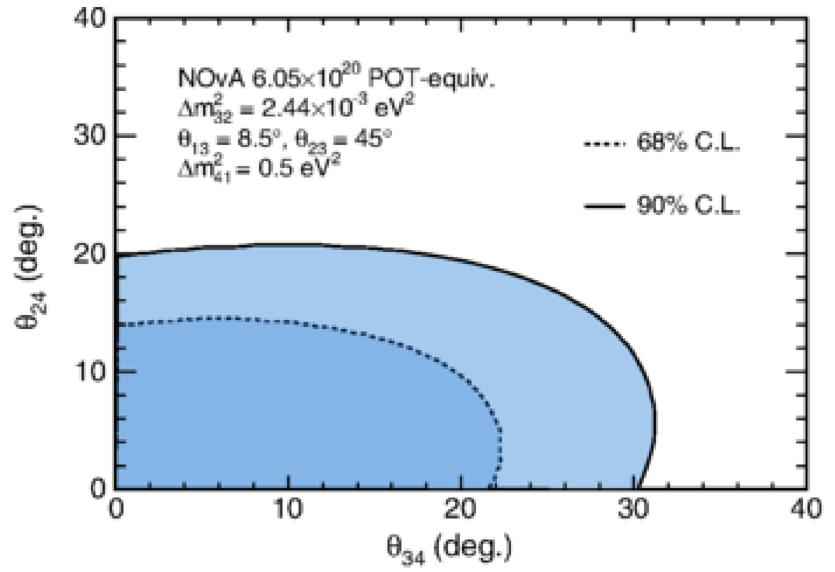


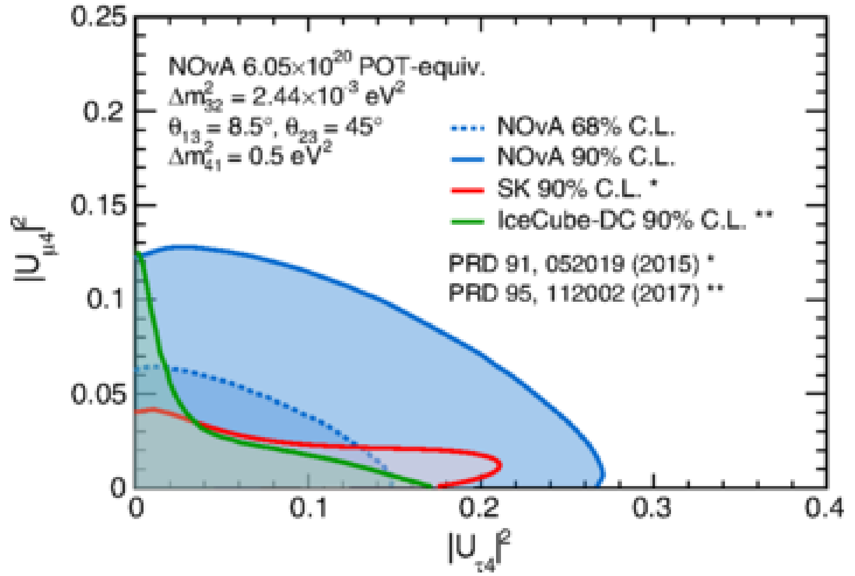


Other NOvA physics

- Sterile neutrinos: Phys. Rev. D **96**, 072006
- CVN classifier: JINST 11 (2016) no. 09, P09001
- Direct x-section measurements
  - NC coherent π^0
  - ν_μ CC π^0 inclusive
- Dark matter searches
- Magnetic monopoles
- Supernova physics
- … and much more

in paper draft



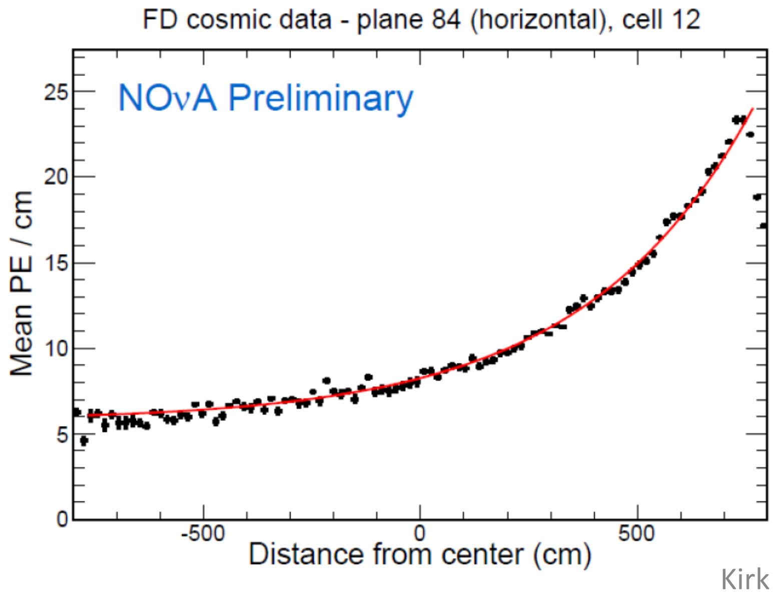


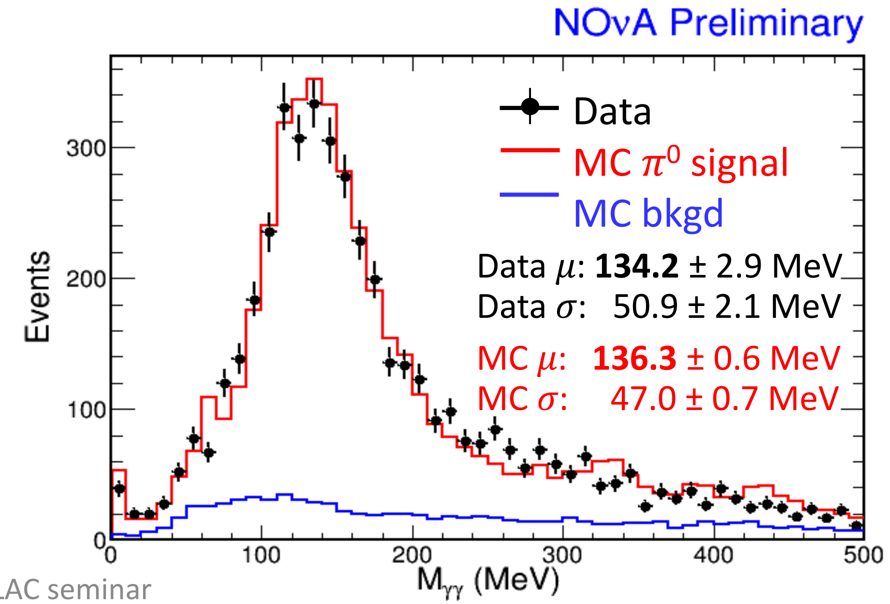

Thank you!
NOvA Collaboration
Fermilab
Fermilab
Fermilab
Fermilab
AISLE 1
AISLE 2
MAN F. RAMSEY
UDITORIUM

Backups

NOvA Calibration:

- Critical for any detector. Very briefly:
- Absolute energy scale is calibrated with stopping muons (dE/dx, Bethe-Bloch)
- Biggest cell by cell effect: attenuation in WLS fiber
- Check energy scales with cosmics, beam events, Michels, π^0 mass/hadronic showers in ND data (all agree to ~5%)

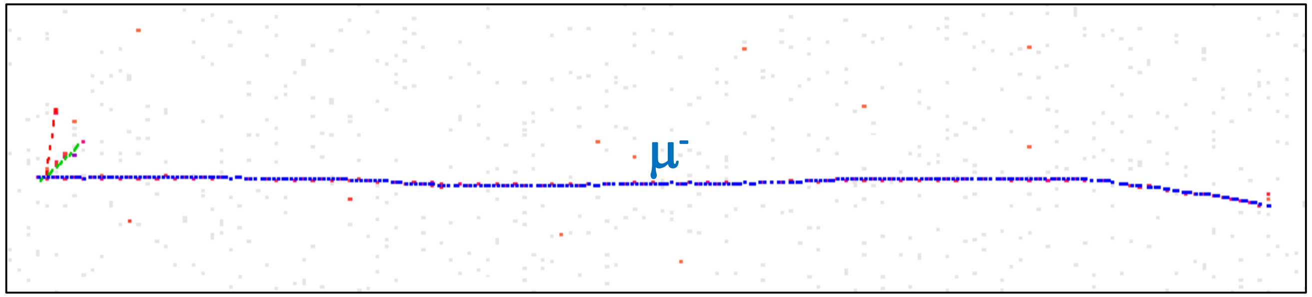




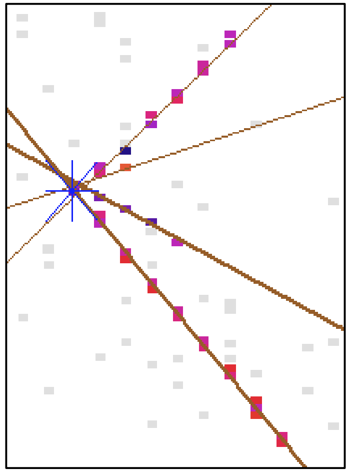
NOvA Reconstruction Basics:

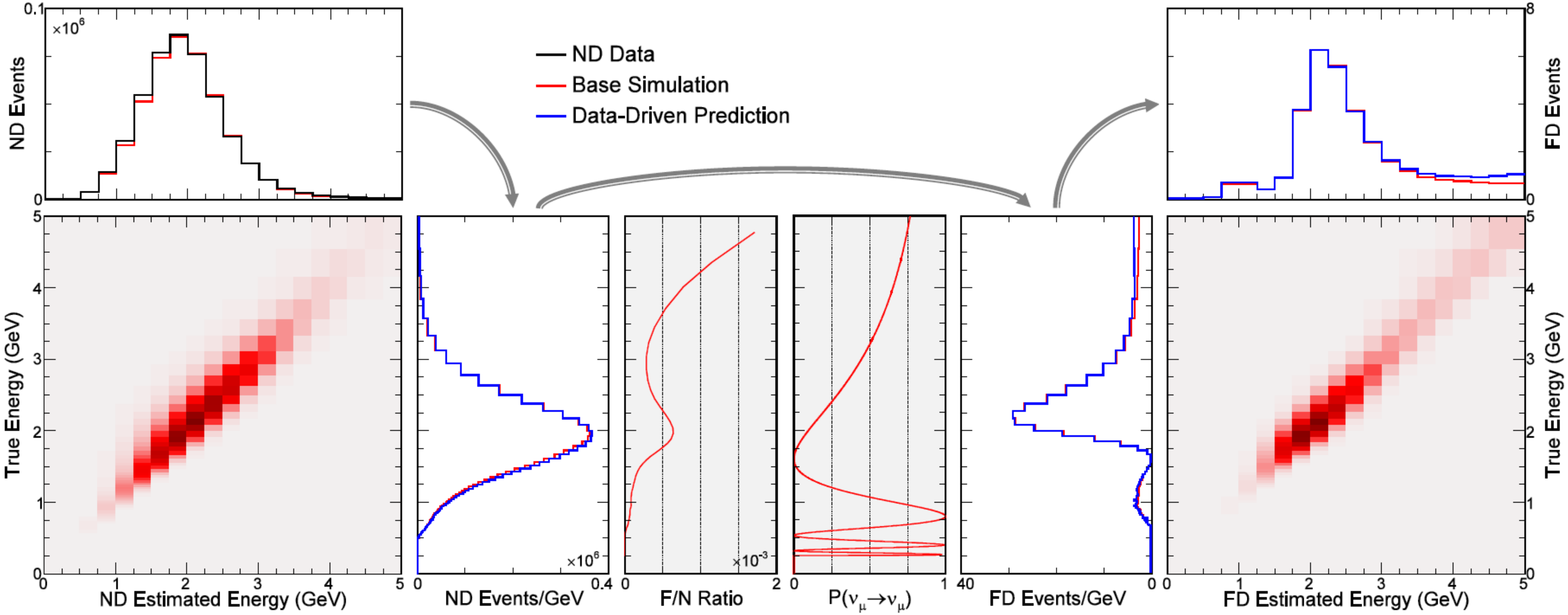
- **Slicing: cluster hits is space and time to isolate physics interactions; highly accurate, can distinguish between > 50 FD muons in the 550 μs spill window with almost no overlap**
  - **timing resolutions: FD ~ 150ns, ND ~ 50ns**
- **Tracking: for muons especially, also protons and pions (disappearance). Use a Kalman Filter inspired algorithm**
- **Vertexing: for showers, hadronics: track lines of energy deposition back to a single start point (appearance)**

tracking example

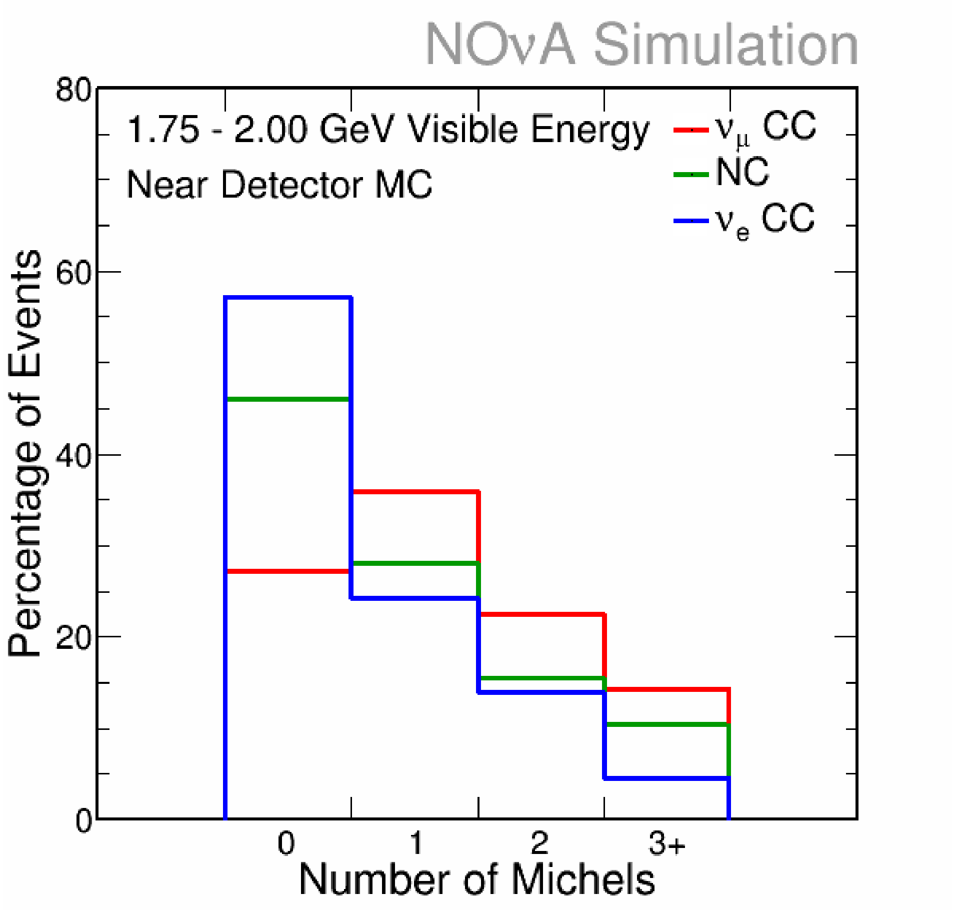


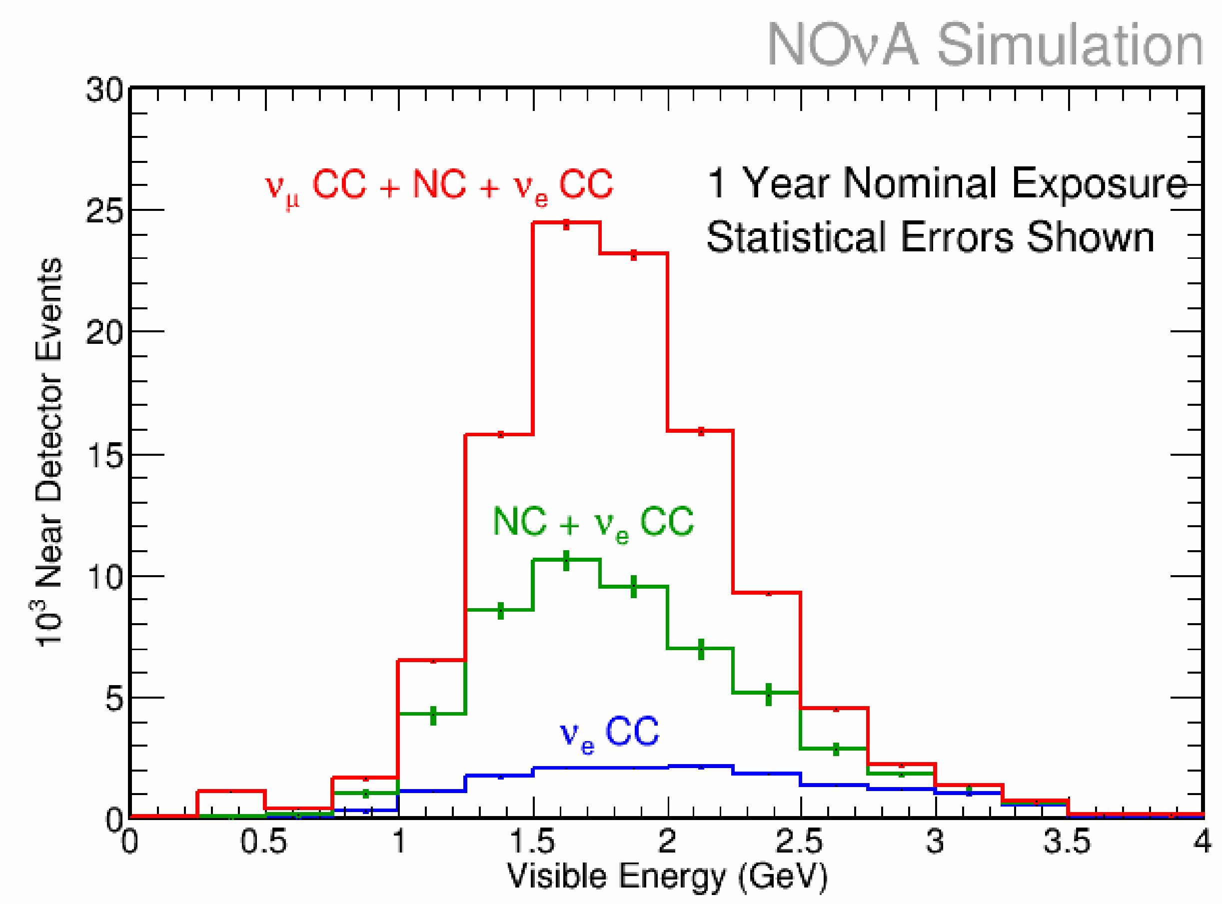
vertexing example





- This entire procedure is re-done beginning to end for each combination of oscillation parameters or systematics being tested
- The extrapolation provides a data-driven approach to help fix any simulation errors and constrain uncertainties
- It is not perfect though – it deals well with normalization effects, but poorly with large energy shifts
- Thus it is also important to make the simulation as accurate as possible


NOνA Simulation
1.75 - 2.00 GeV Visible Energy
Near Detector MC
ν_μ CC
NC
ν_e CC
Percentage of Events
Number of Michels
0
1
2
3+
0
20
40
60
80


NOνA Simulation
ν_μ CC + NC + ν_e CC
1 Year Nominal Exposure
Statistical Errors Shown
NC + ν_e CC
ν_e CC
10^3 Near Detector Events
Visible Energy (GeV)
0
0.5
1
1.5
2
2.5
3
3.5
4
5
10
15
20
25
30

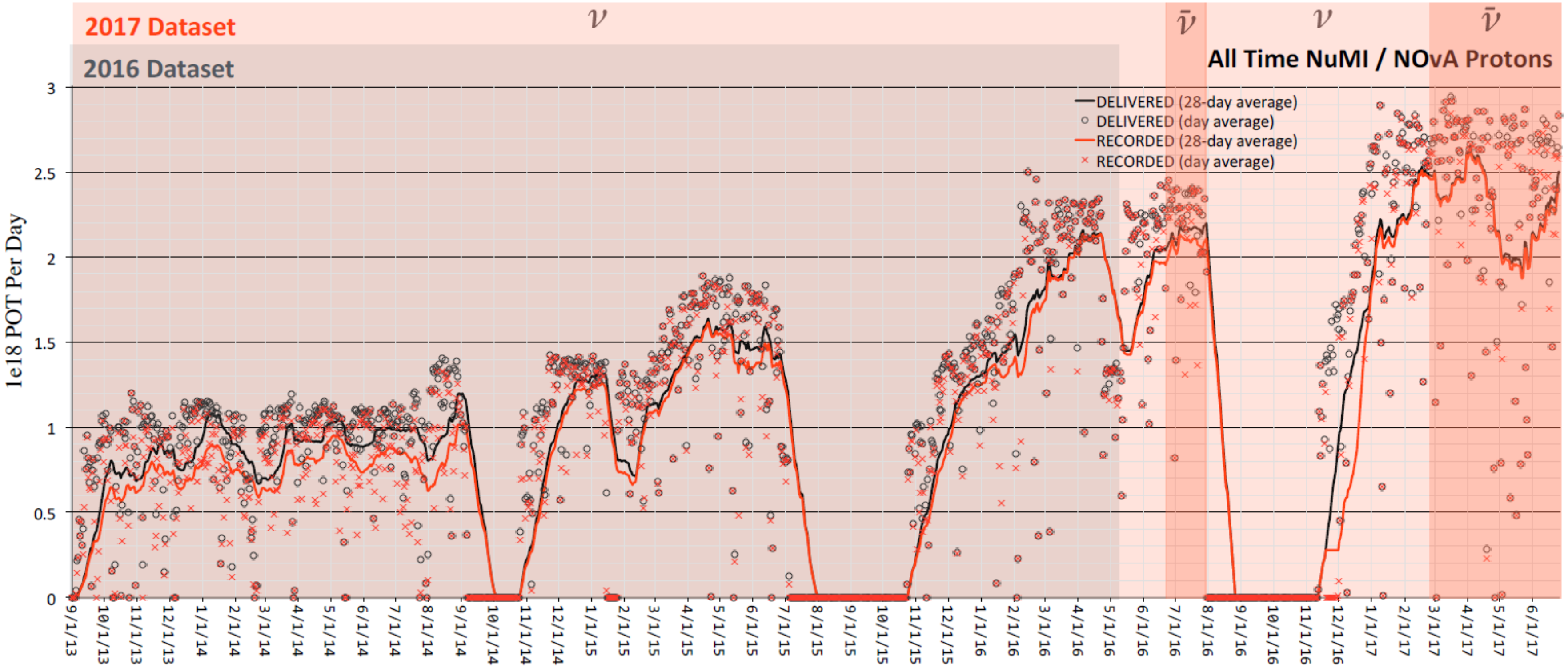
NuMI beam most powerful neutrino beam in the world

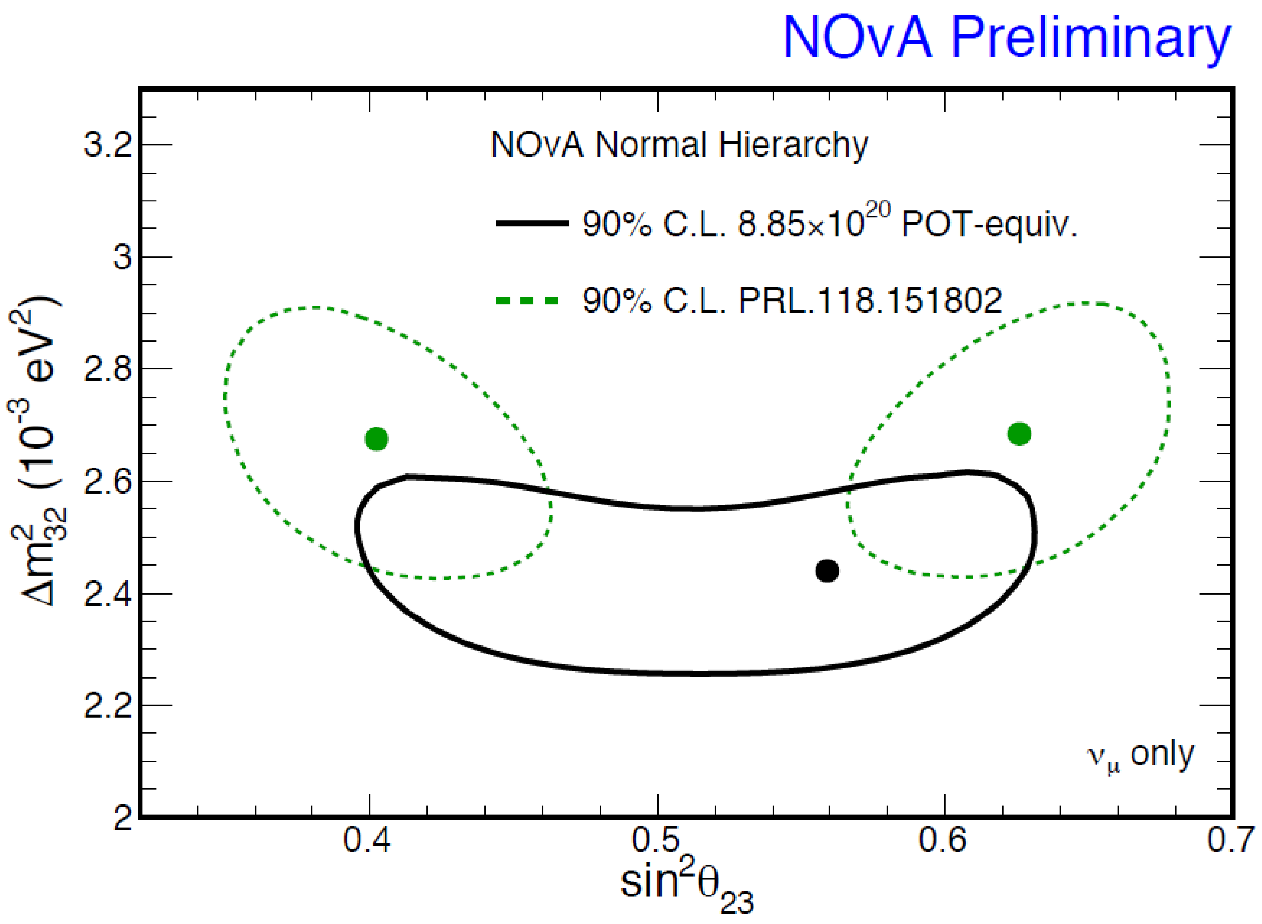
Recent upgrades, up to goal of 700 kW

NOvA recently released third set of oscillation results

- based on 8.85 x 10^{20} POT

All neutrino mode running, anti-neutrino data analyses ongoing





From 2.6 → 0.8 σ exclusion of max mixing

new light model (include Cherenkov light) this changes E resolution (7% → 9%) and shifts hadronic E (~70 MeV on average), which coincidentally pushes 3 events across bin boundaries (expected: 0.5)

New analysis techniques – energy resolution binning separates out poor resolution events that may be background; removes impact of possible background fluctuation