NOvA long-baseline neutrino experiment: recent results

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

Connected by mixing matrix:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U^* \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

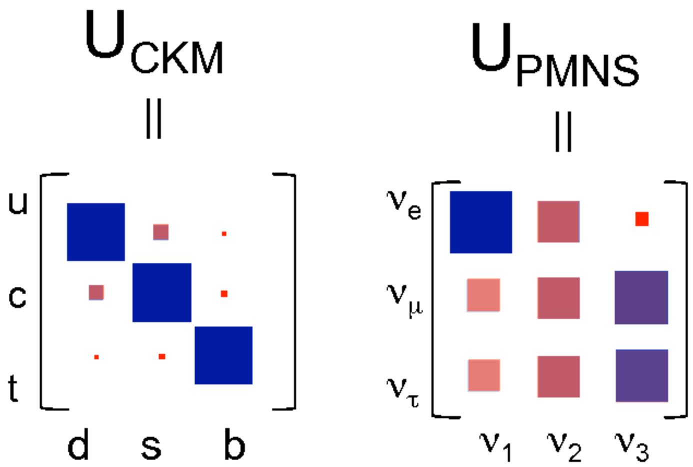
Mixing matrix → mixing angles – 2 flavor case:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix}$$

3 flavor case:

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

3 angles and a CP-violation term determine the matrix: θ_{12}, θ_{13}, θ_{23}, δ_{CP}



arXiv:1611.07770

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

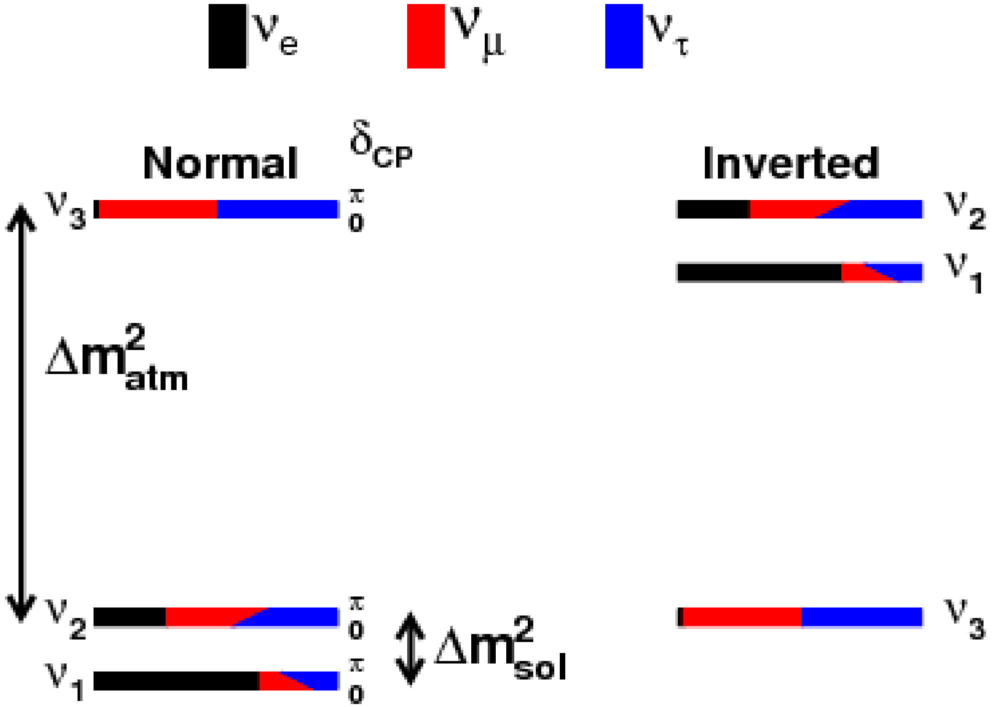
$$P_{\alpha\to\beta} = |\langle \nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

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

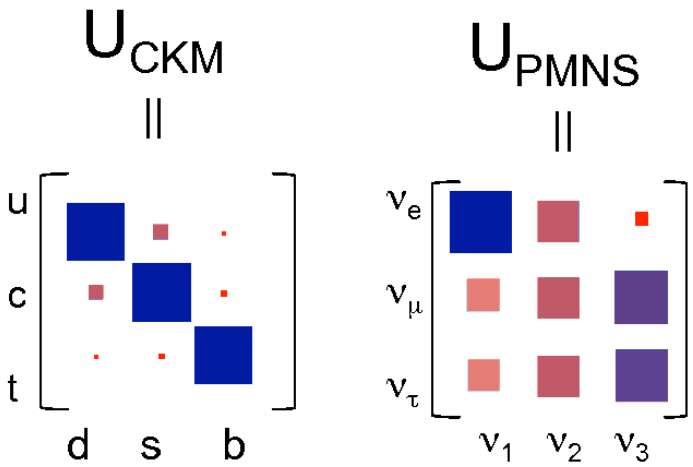
L = baseline
E of neutrino

experiment setup

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



arXiv:1505.01891



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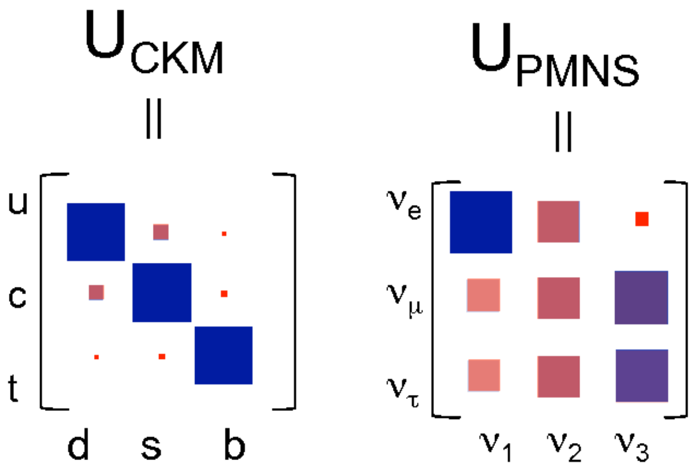
L = baseline
E of neutrino
} **experiment setup**

$\Delta m^2_{32} = m_3^2 - m_2^2$
also Δm^2_{21}

(to be measured)

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?)



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

$\Delta m^2_{32} = m_3^2 - m_2^2$
also Δm^2_{21}

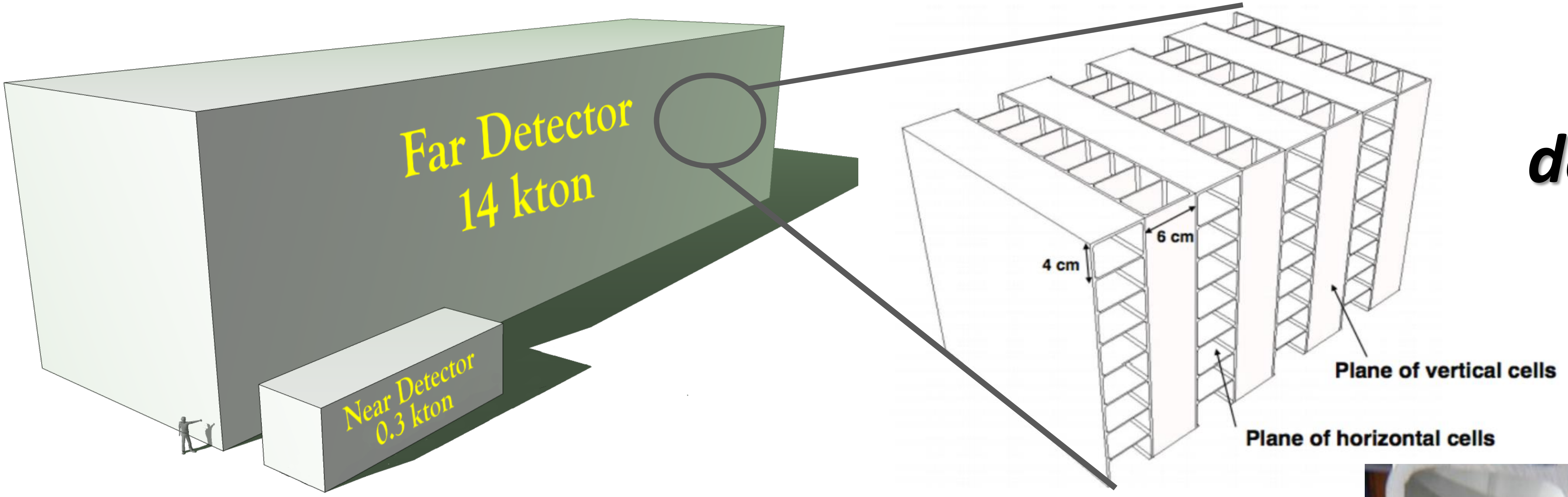
(to be measured)

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?)

arXiv:1505.01891

NOvA detectors

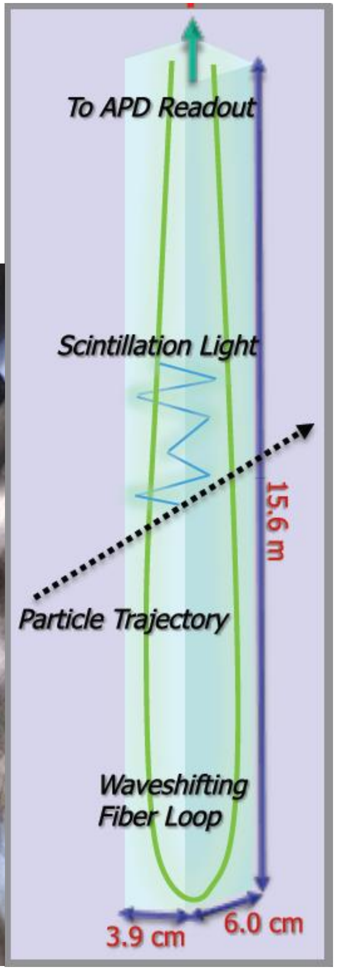


FD (at Ash River, MN, 810 km baseline):

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):

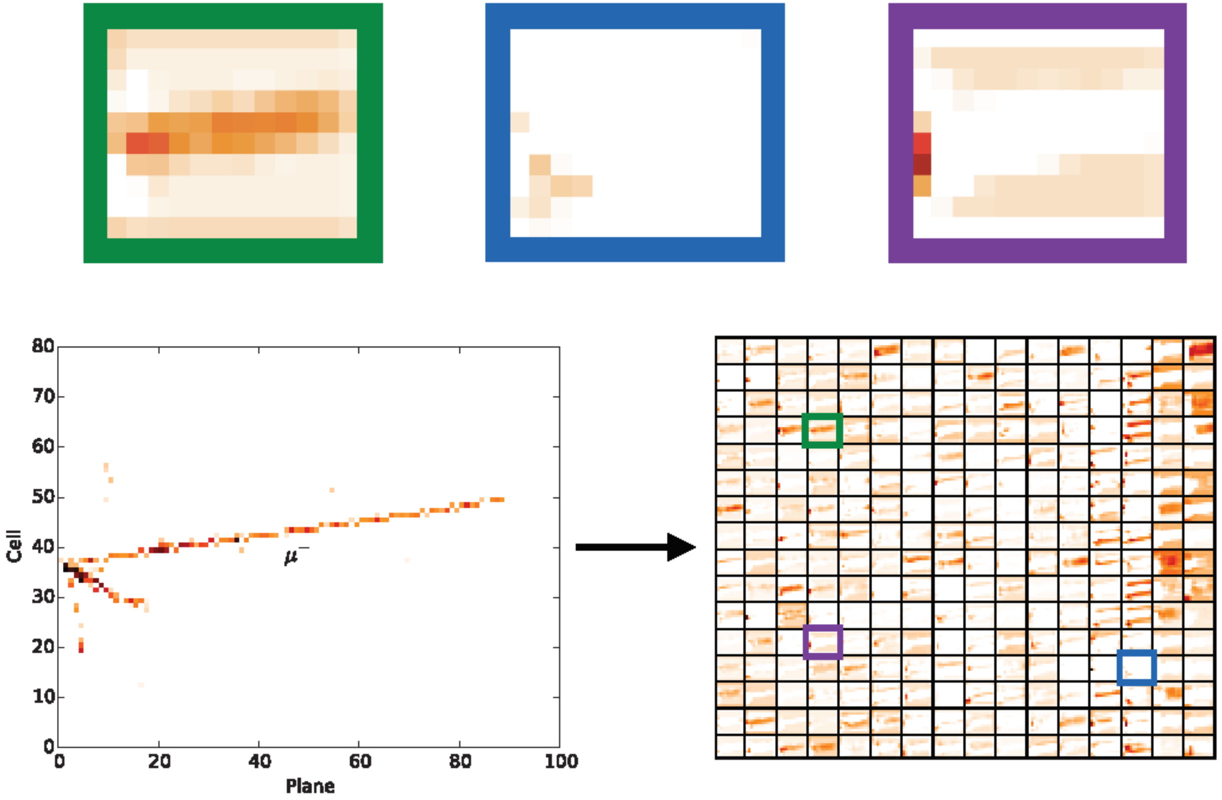
4m x 4m x 16m, 0.3kton, underground
~20,000 cells, design similar to FD



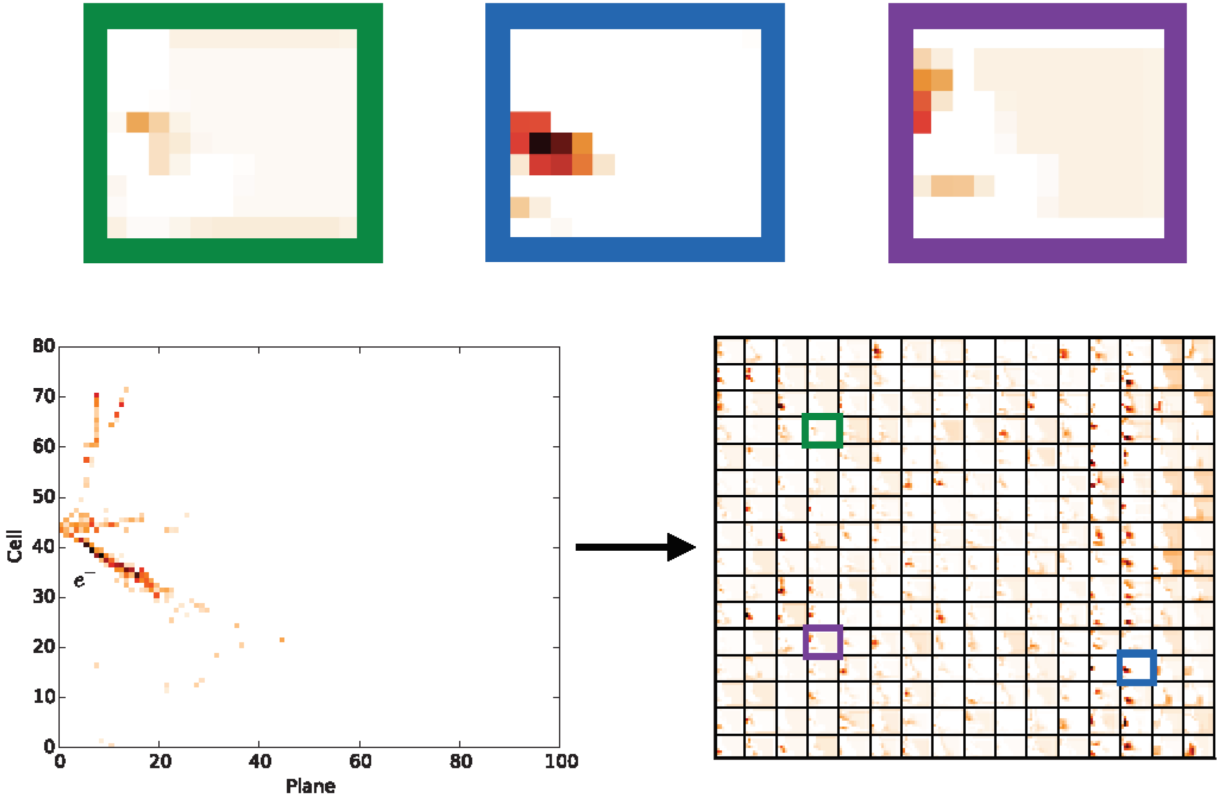
New from previous analysis:

- Better deep learning algorithms
- Improved simulation (addition of Cherenkov light)
- New cross-section tuning
  - custom 2p2h tuning
- More statistics (up to ~8.85e20 pot)
- More sophisticated analyses

CVN - disappearance

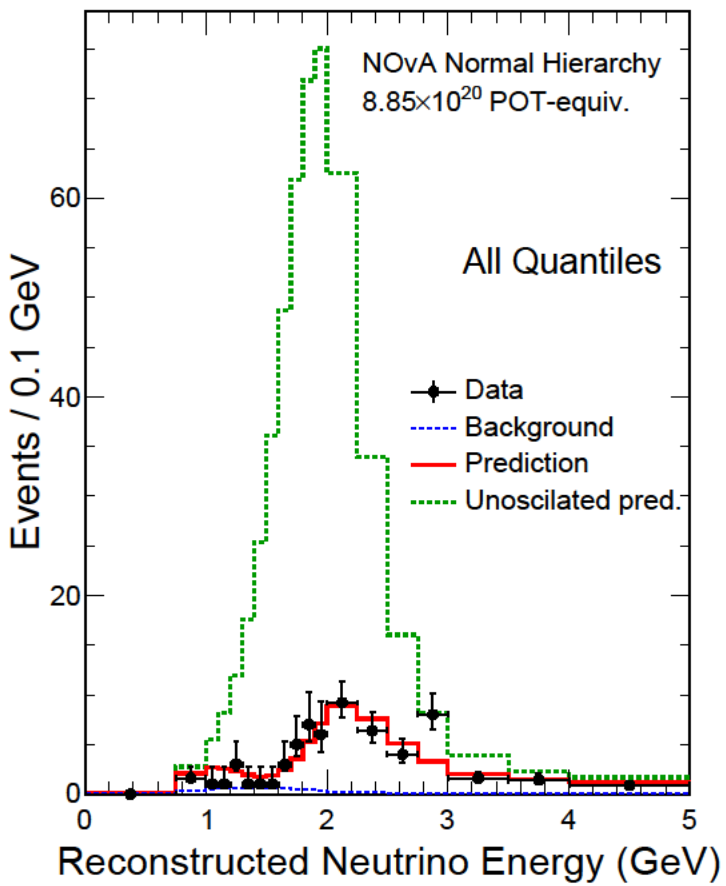


CVN - appearance

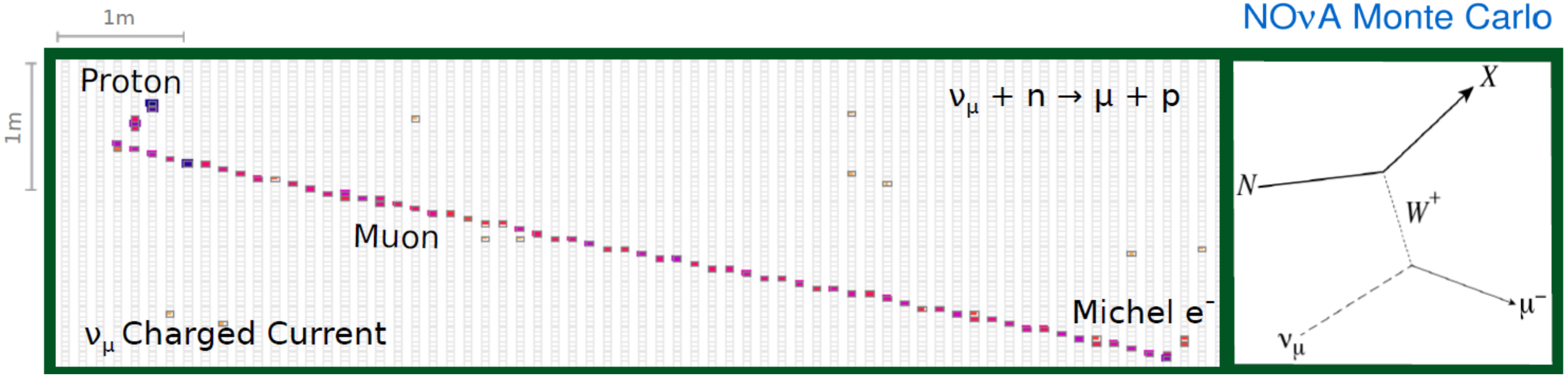


ν_μ disappearance

NOvA Preliminary



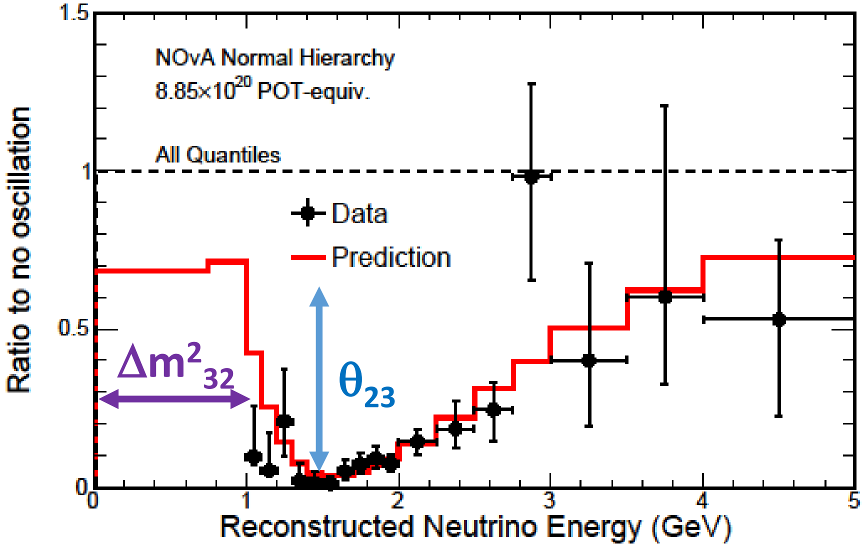
NOvA Monte Carlo



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

directly measure θ_{23} and Δm^2_{32}

NOvA Preliminary



signature: muon

backgrounds:

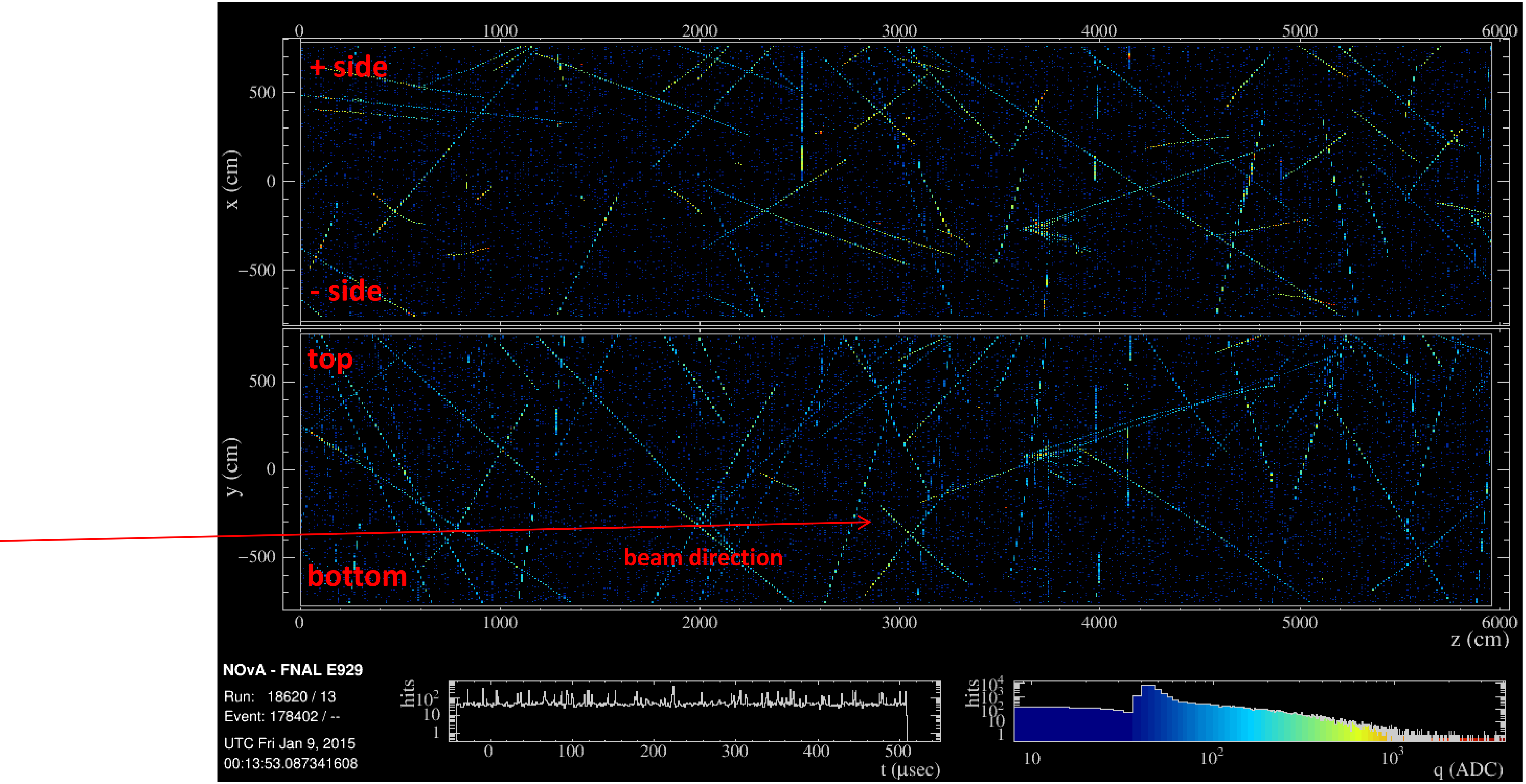
neutral current

- π, p can look like muons

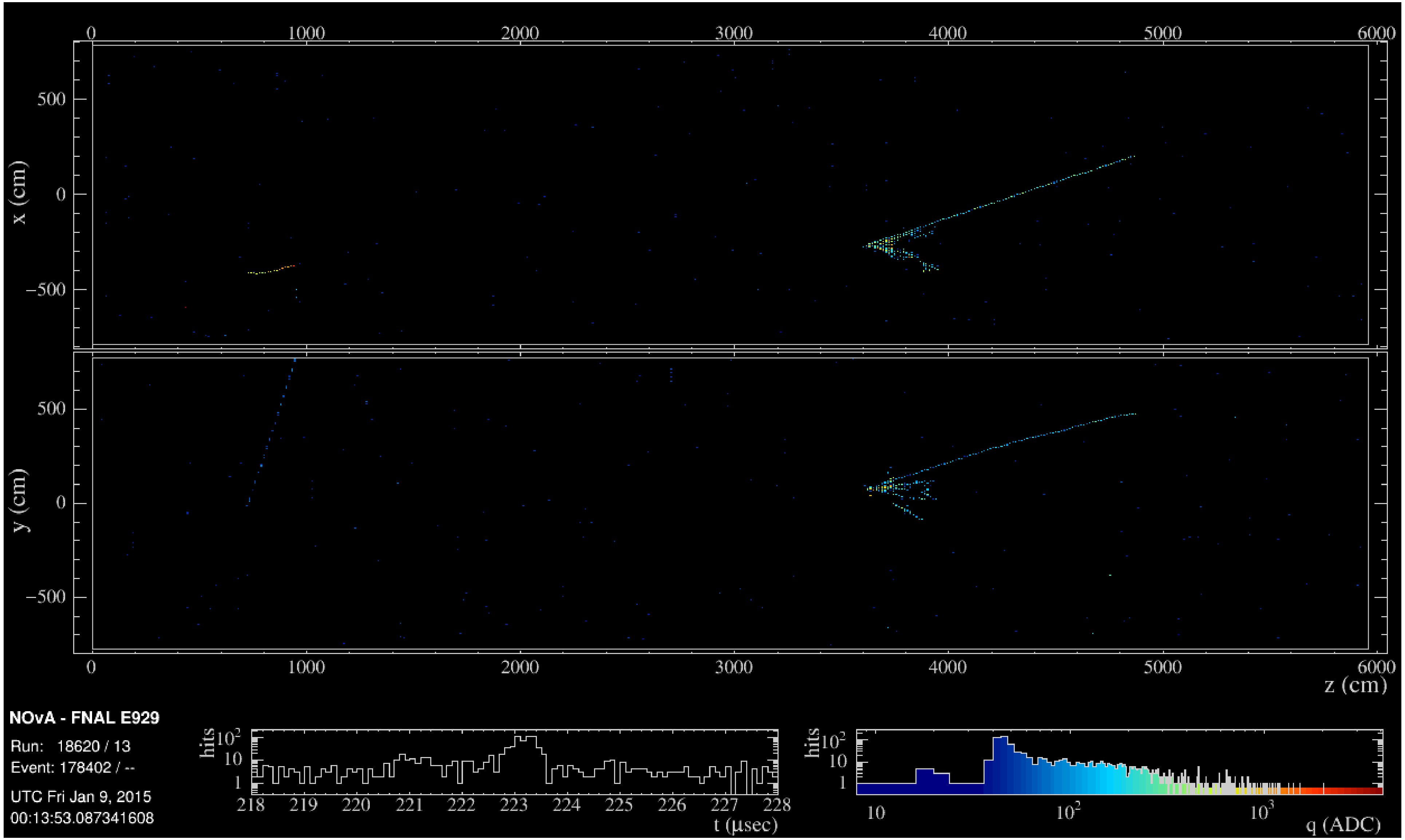
cosmic rays

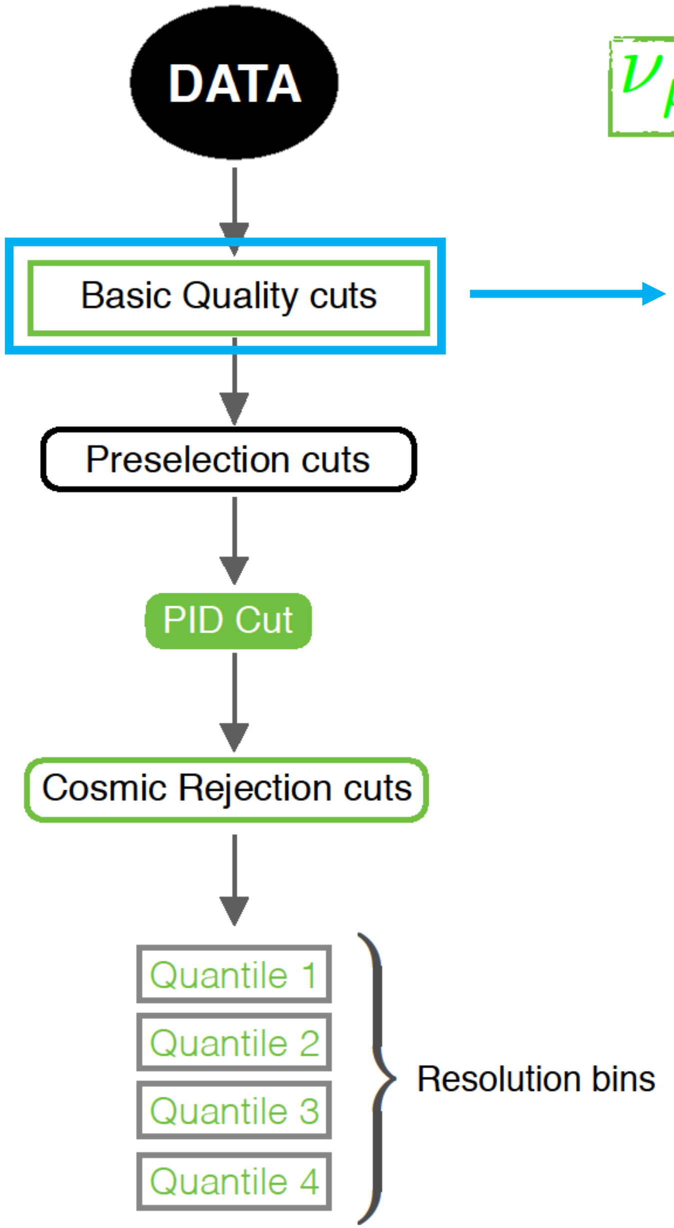
- surface detector, real muons

550 μs exposure of the Far Detector



Time-zoom on 10 μs interval during NuMI beam pulse

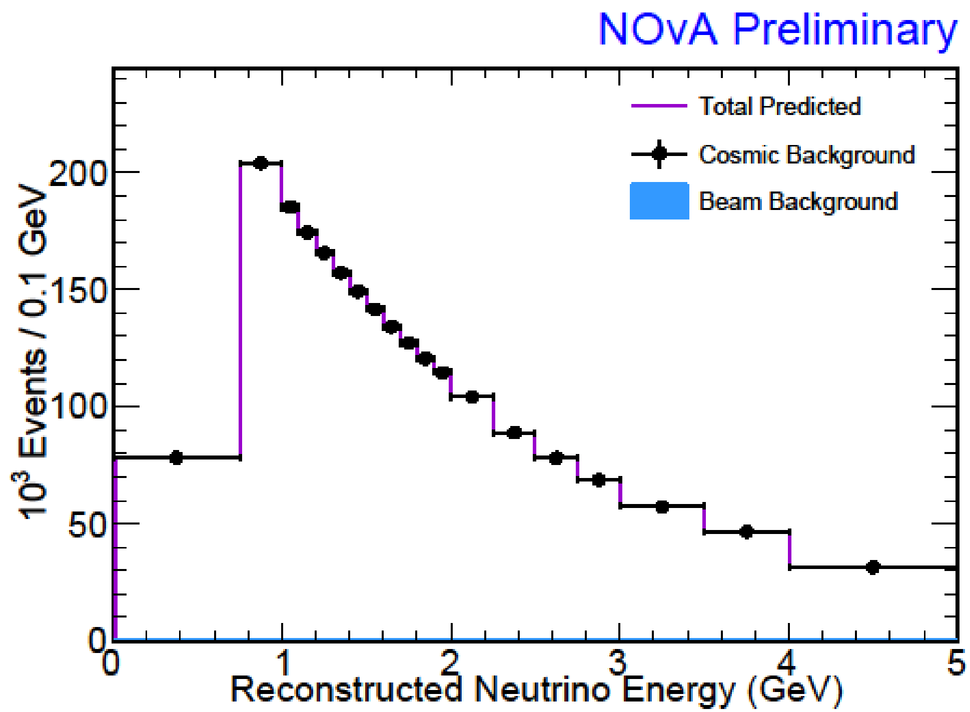


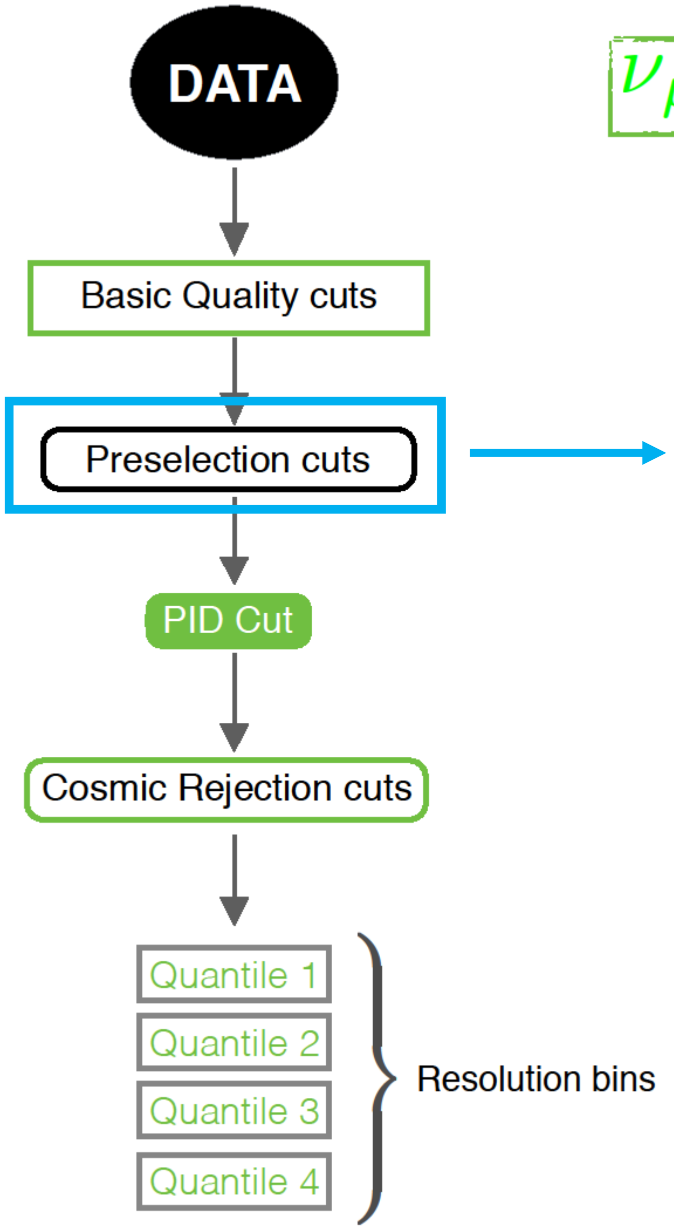


ν_μ selection

can reconstruct the event (ND + FD)

FD: ~10^6 events

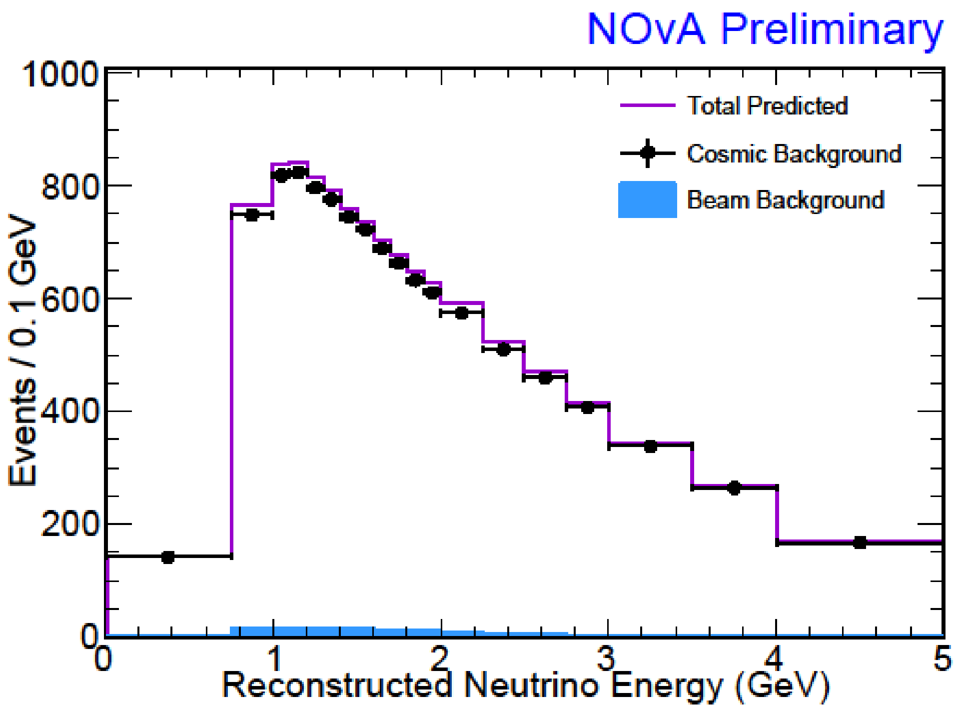




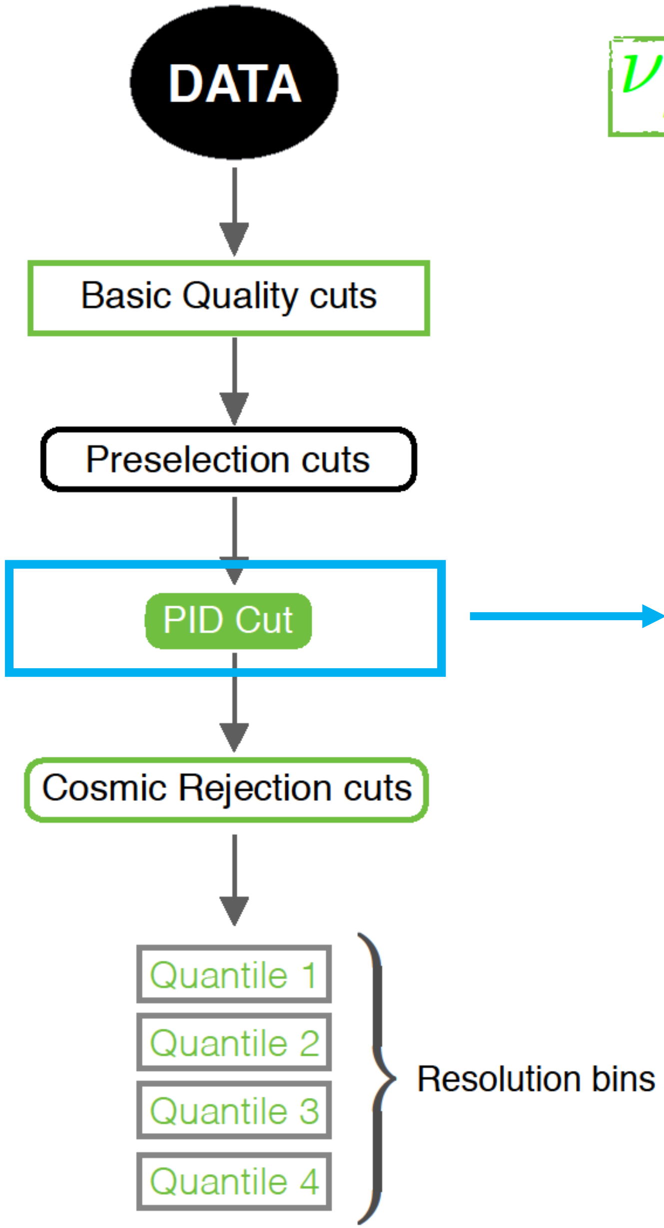
ν_μ selection

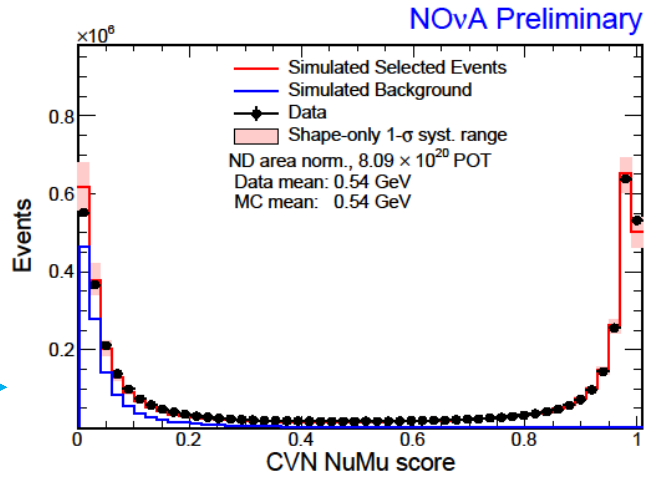
containment
(ND + FD)

FD: ~10^3 events



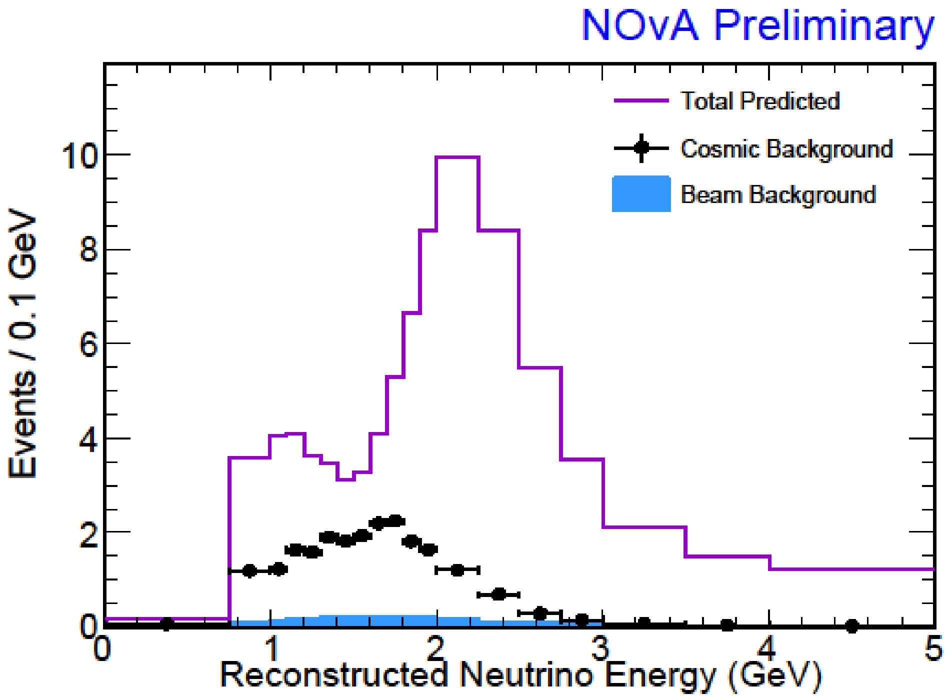
ν_μ selection

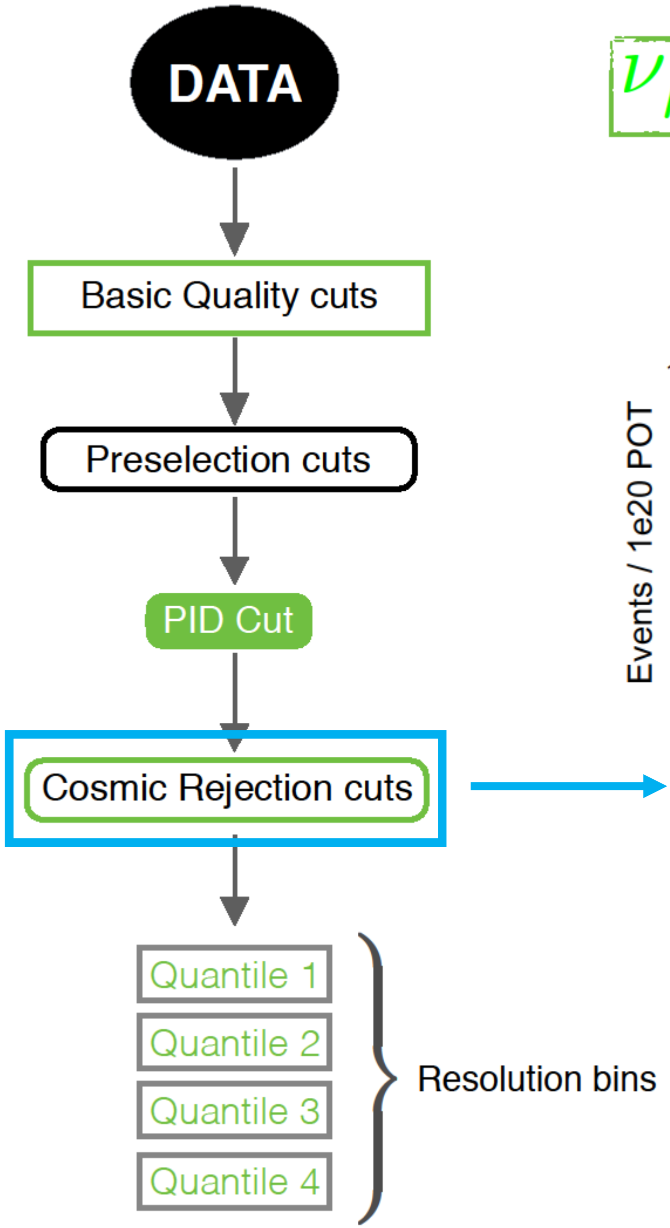




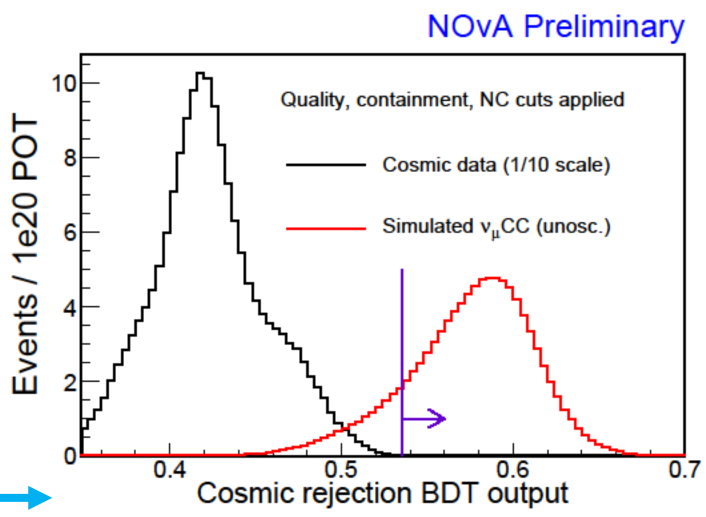
is it a ν_μ CC?
deep learning: CVN
removes NC, cosmics
(ND + FD)

FD: ~100 events





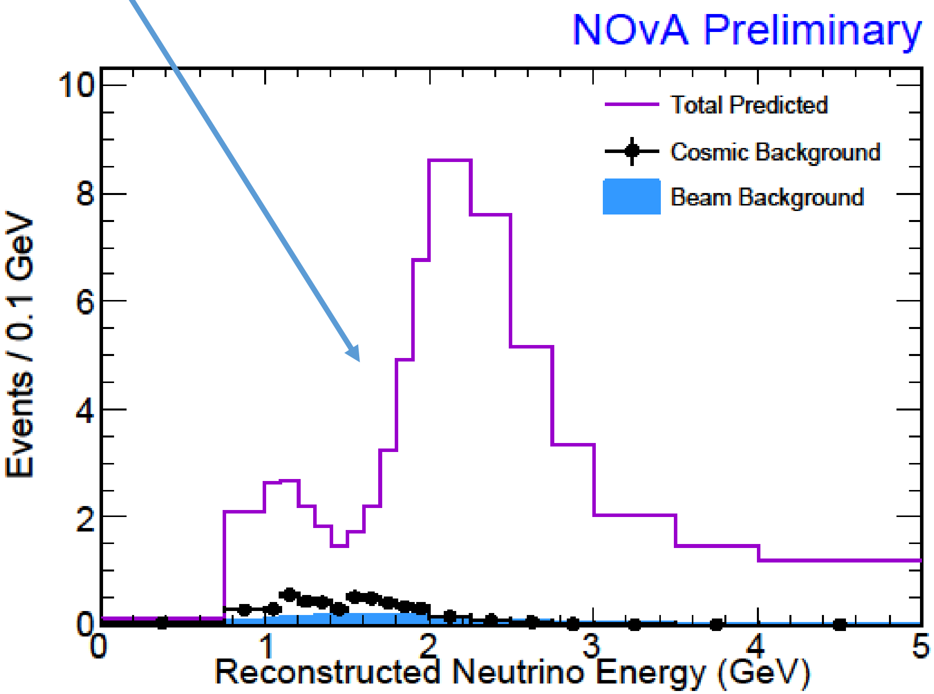
ν_μ selection



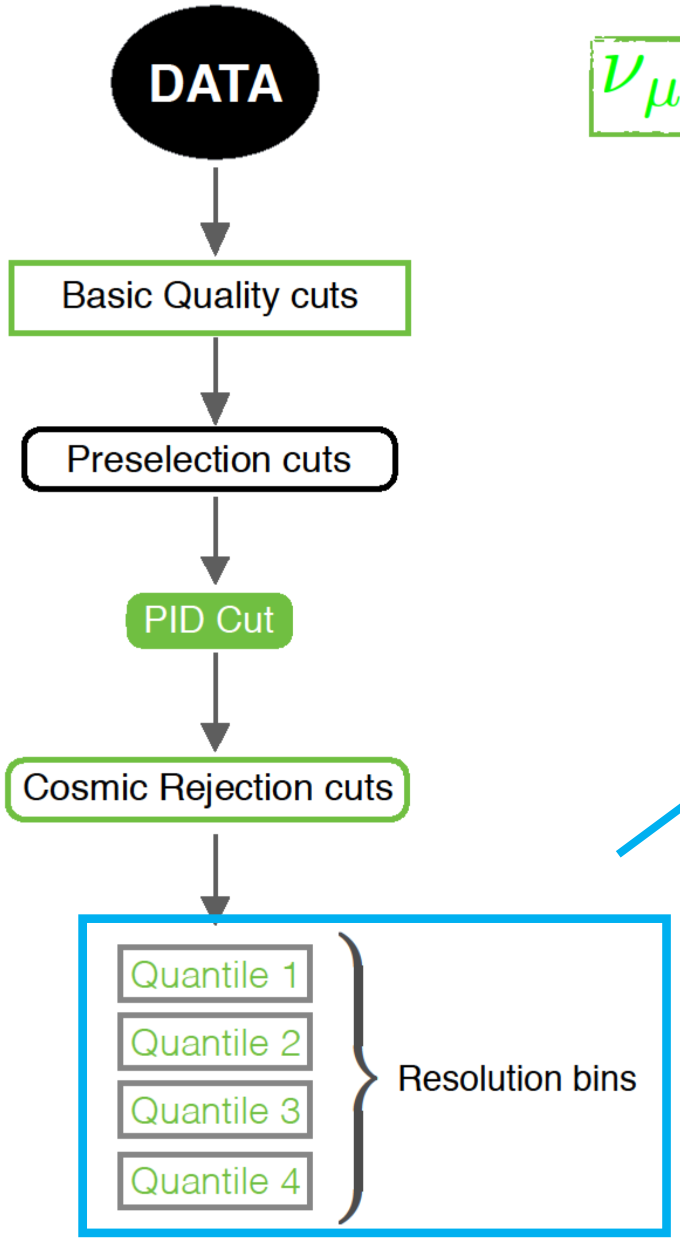
BDT to remove remaining cosmics (FD only)

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

FD: ~100 events

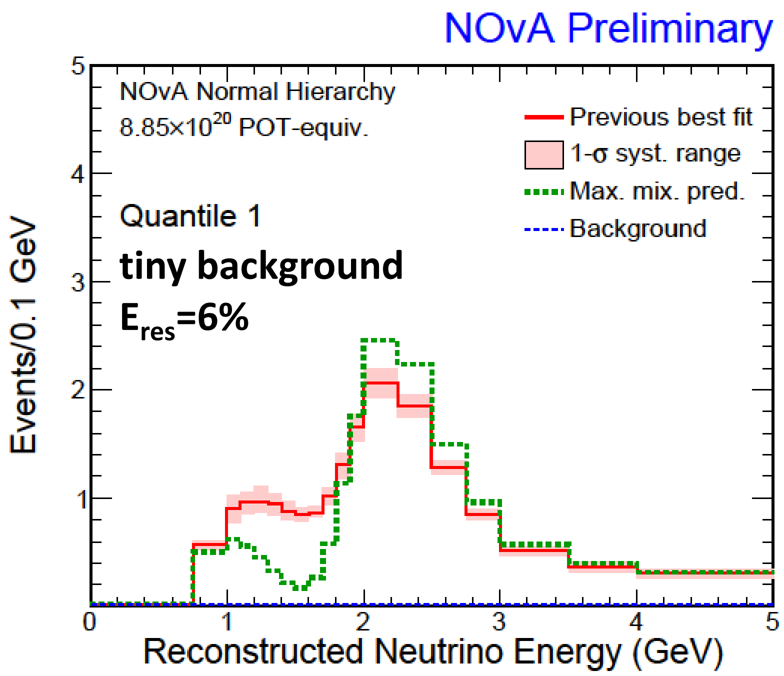


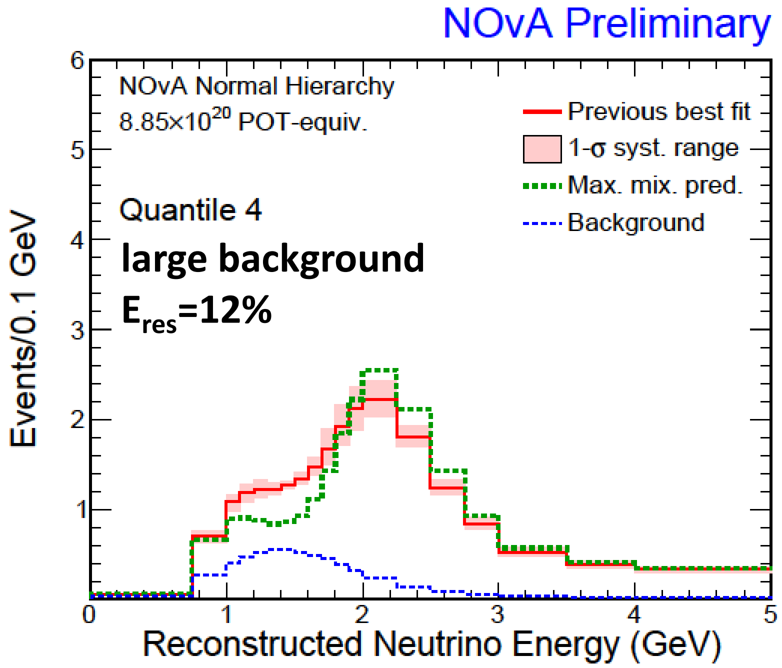
ν_μ selection

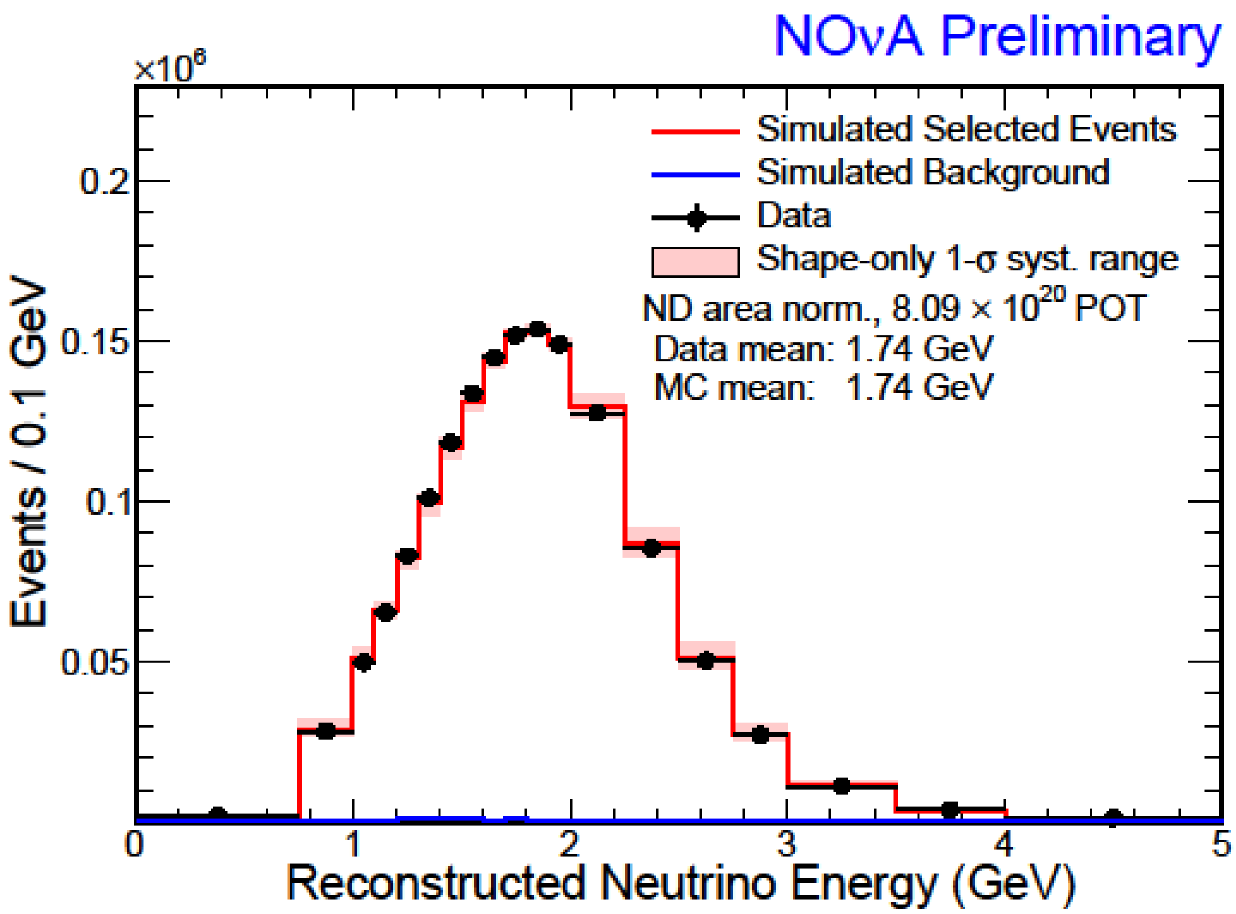


the less hadronic E the better the E resolution

divide into 4 E_{had}/E_ν quantiles

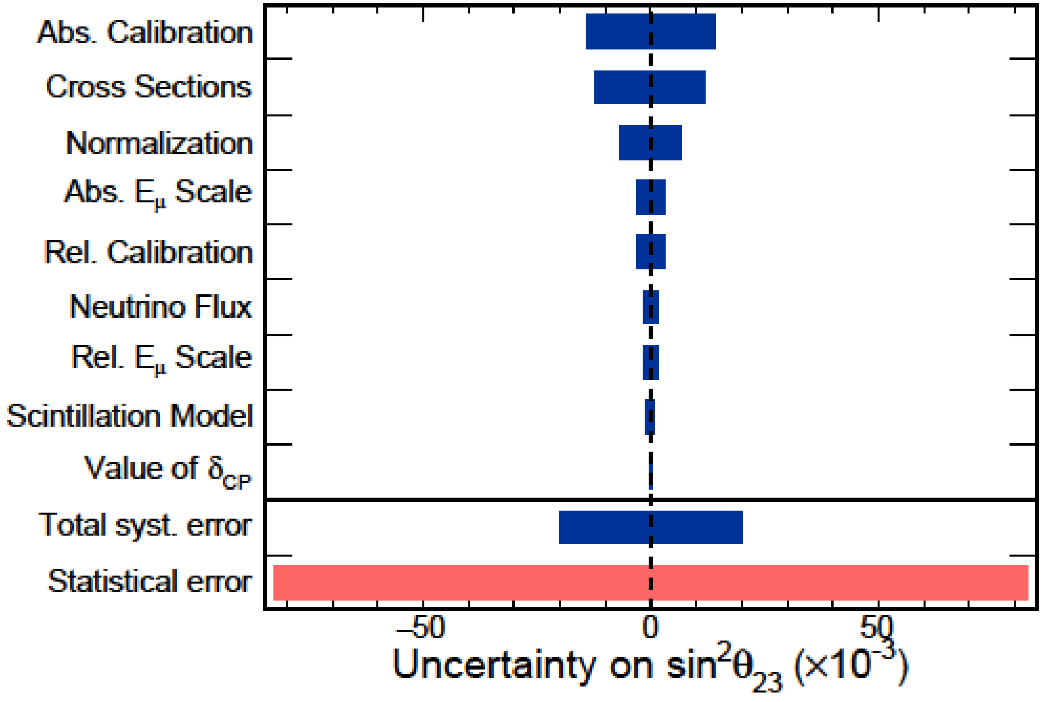




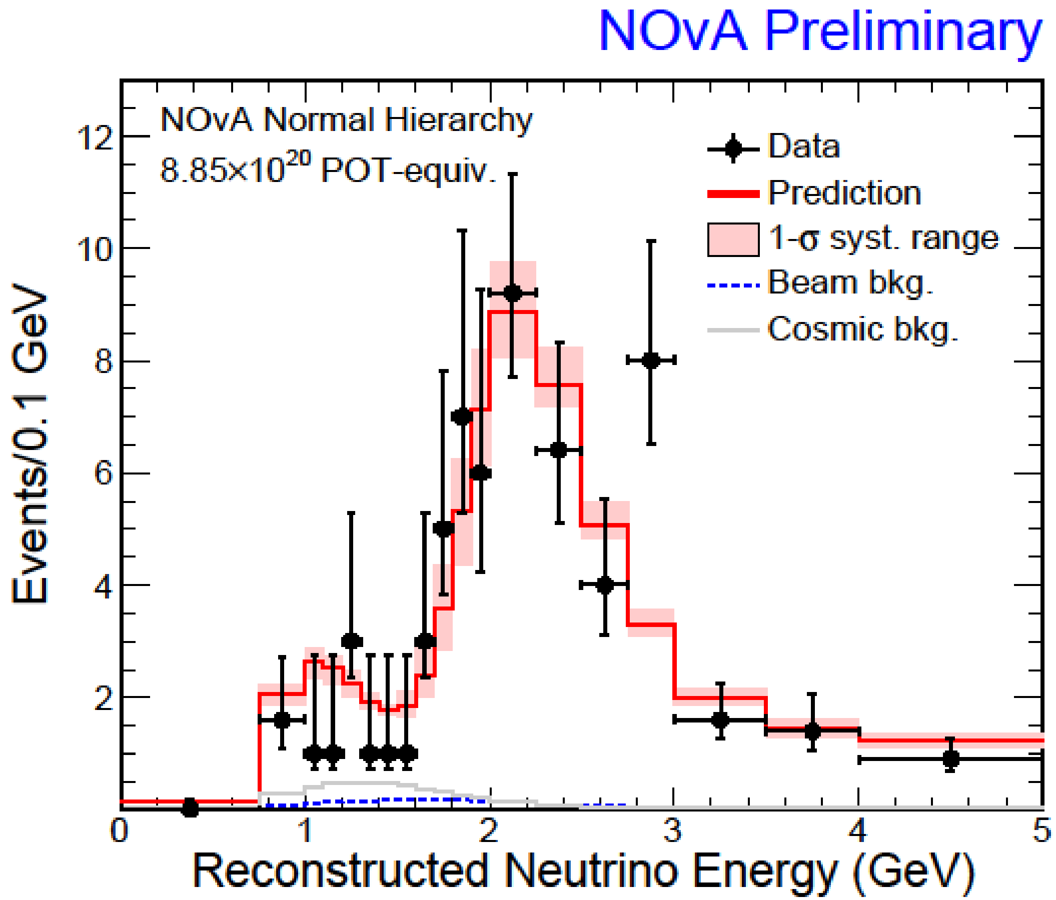


select ν_μ events in ND
data/MC agreement good
tells us simulation not too wrong

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



if no oscillations, predict 763 events observe 126 events

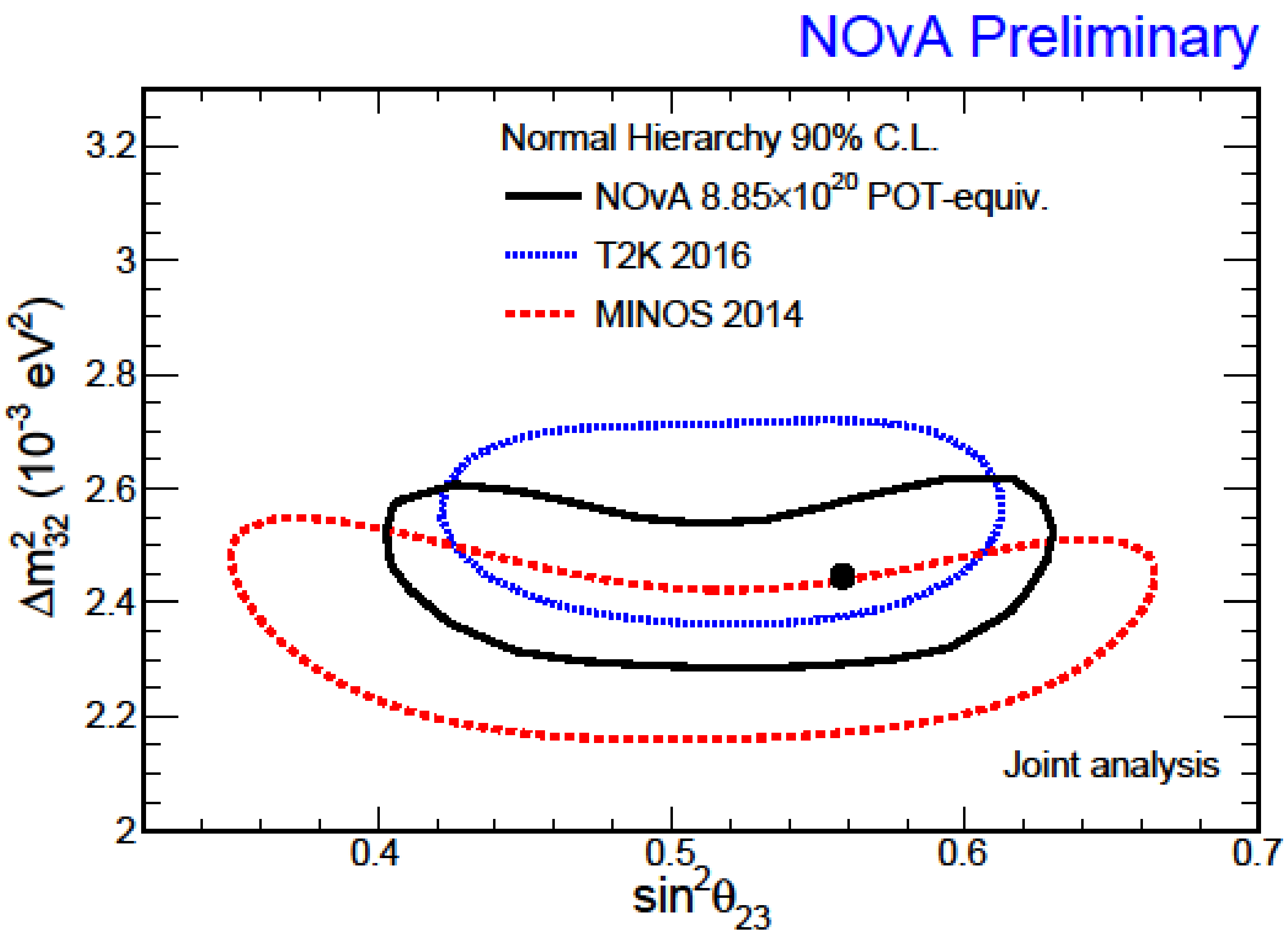


Can plot as 90% confidence contour in θ_{23}, Δm^2_{32} space

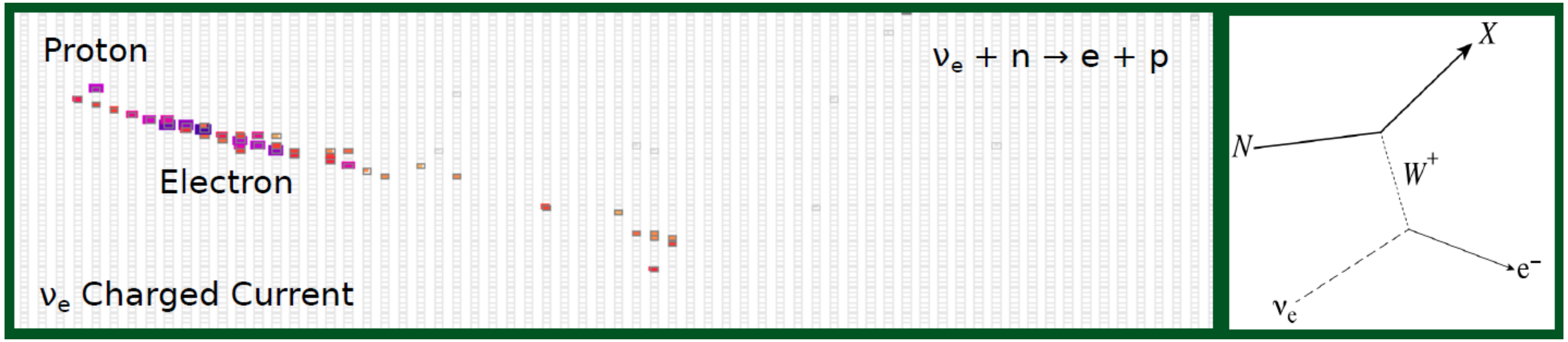
best fits:

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

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



ν_e Appearance



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

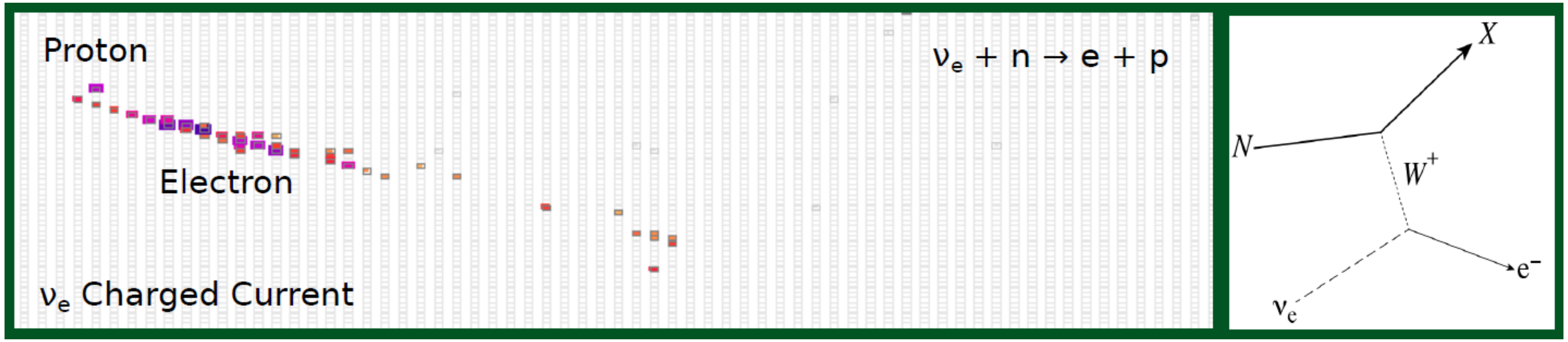
$$\overset{(+)}{-} 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{A-1} \sin\Delta$$

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

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

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

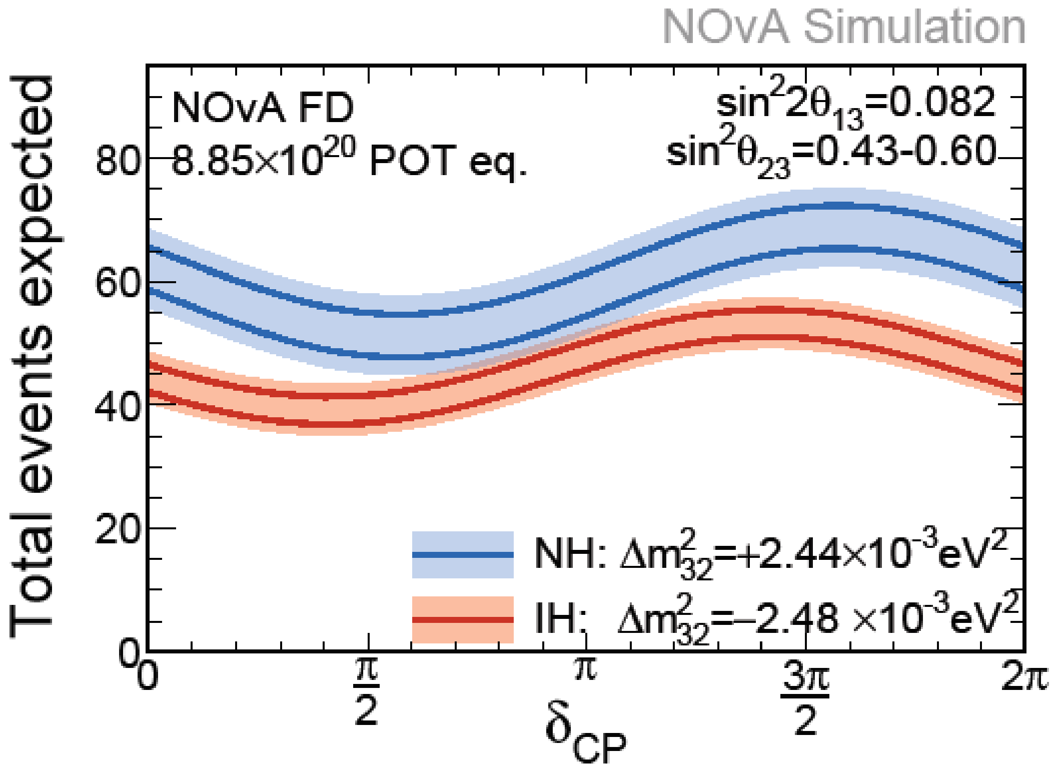
ν_e Appearance



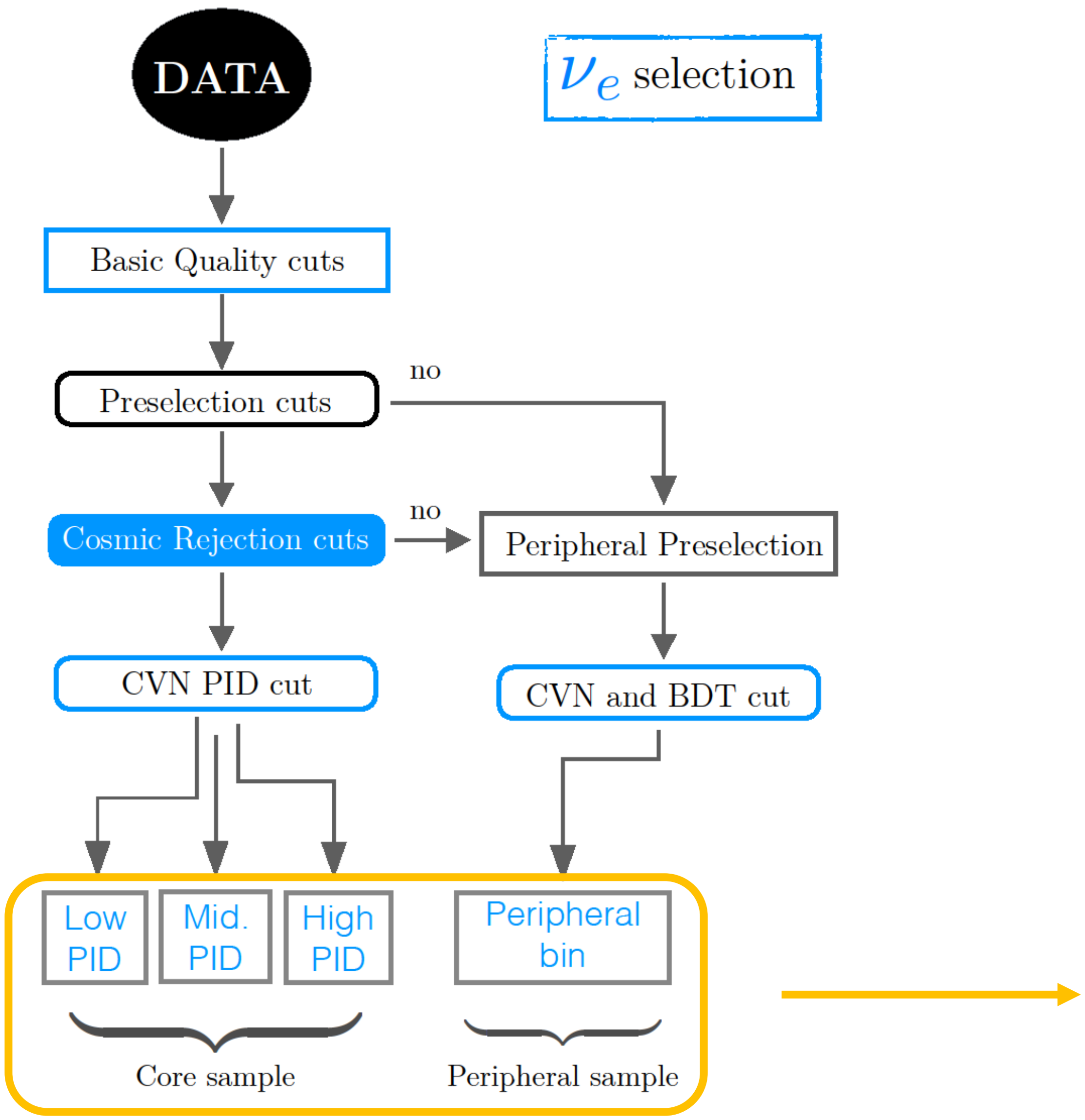
Signature is an electron shower

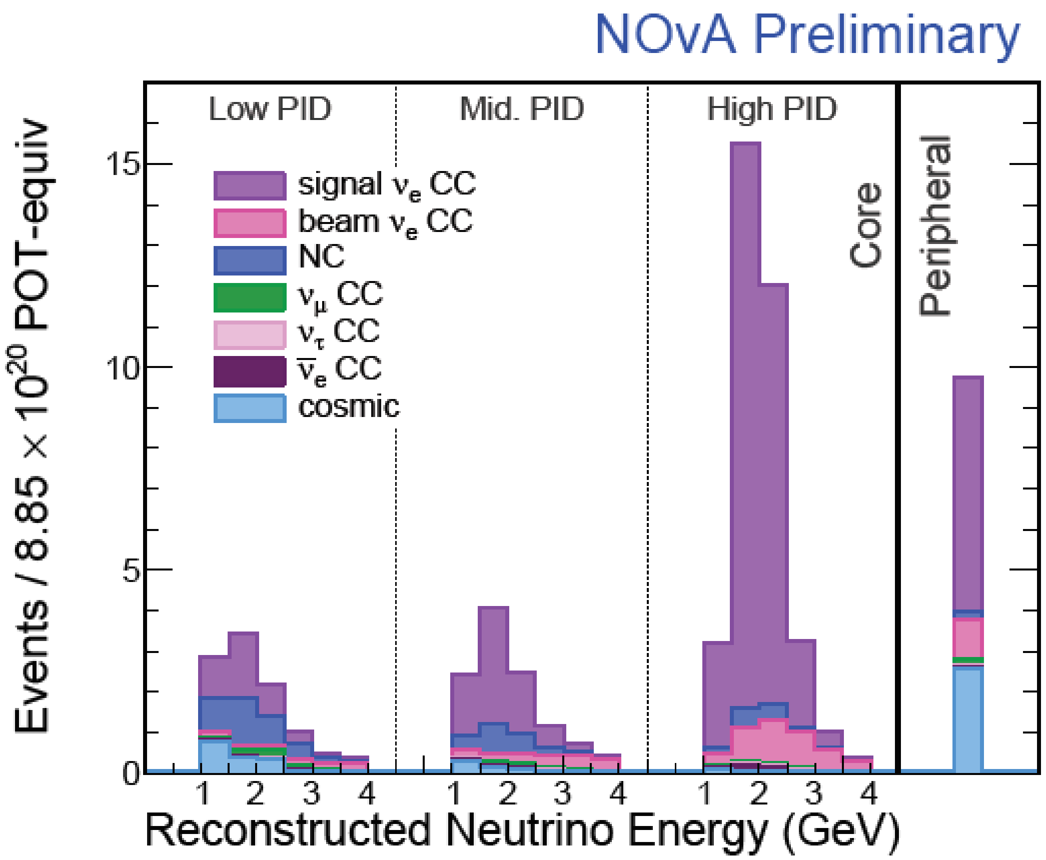
Backgrounds:
- **cosmics**
- **neutral current**
- **intrinsic beam ν_e**

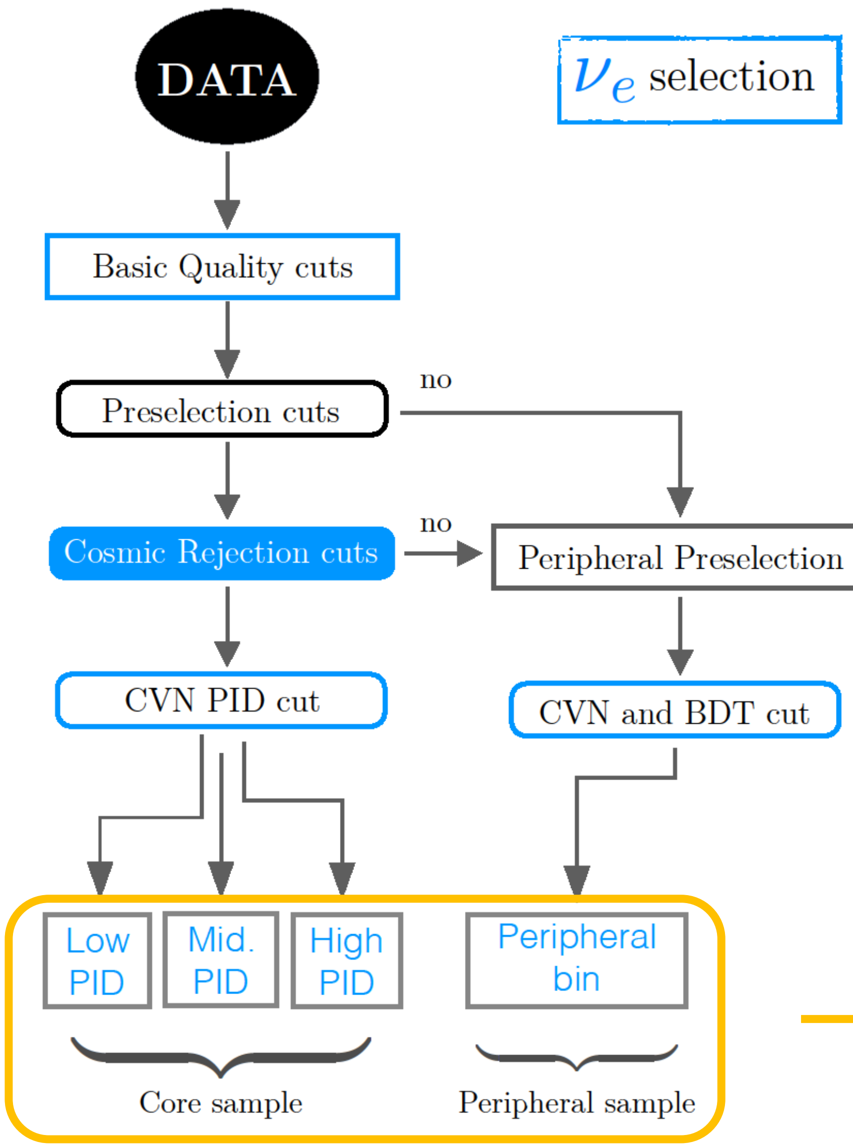
Use ND to measure intrinsic ν_e and neutral current background, extrapolate to FD



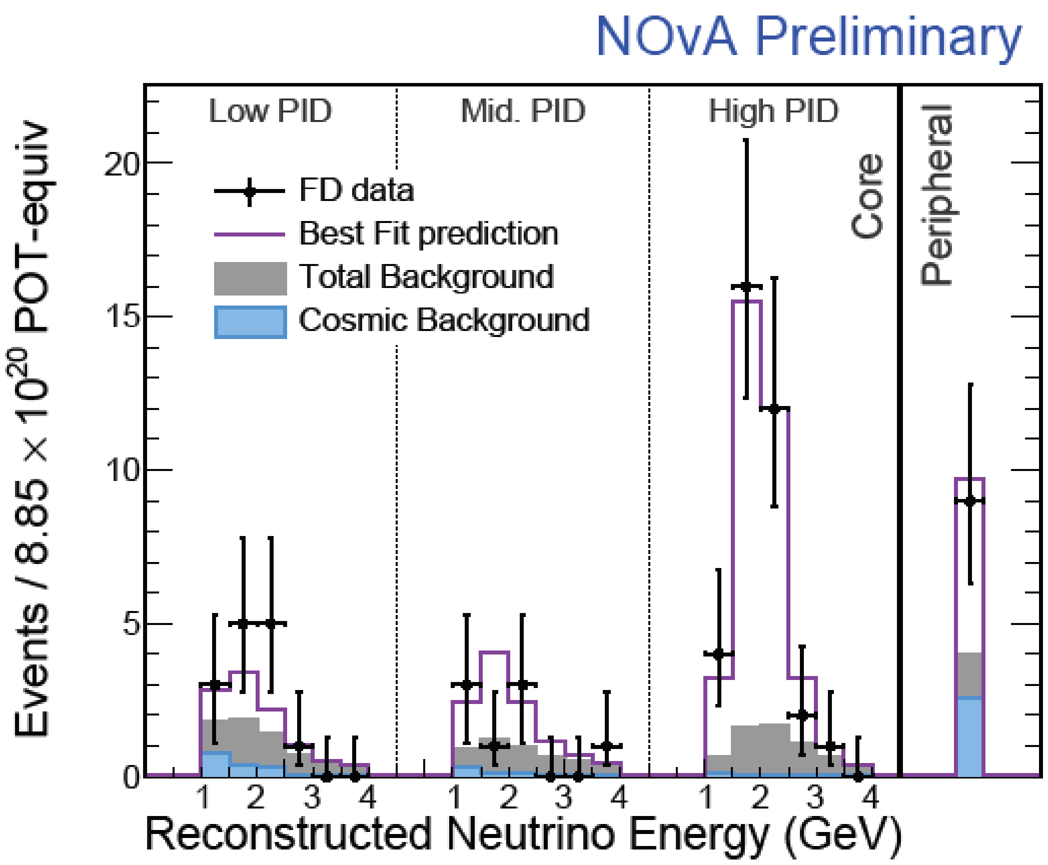
bin in energy for three PID bins + sideband

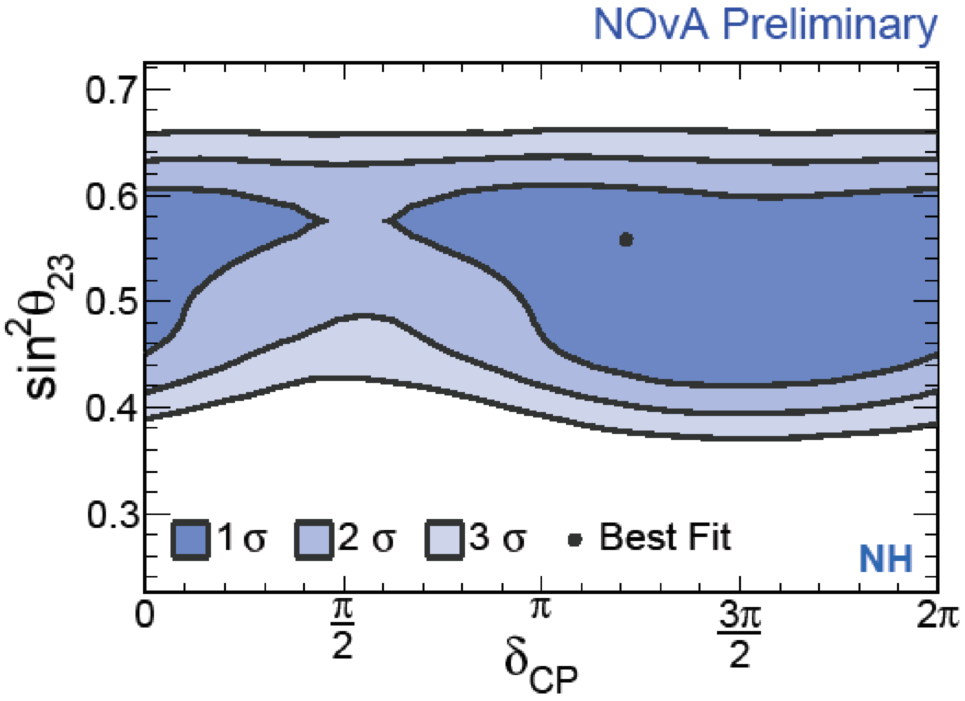




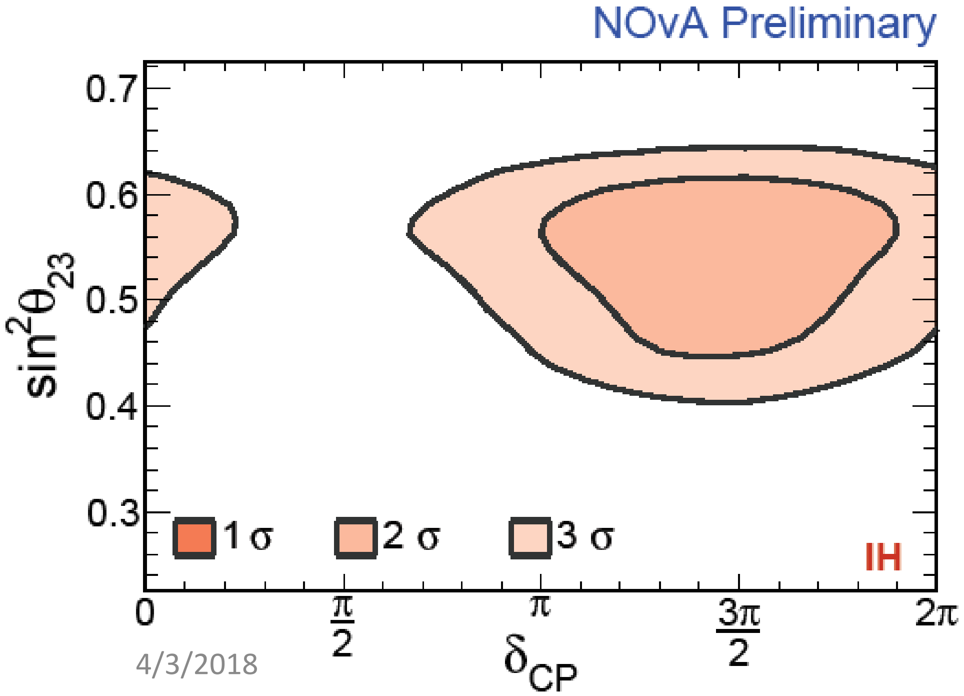


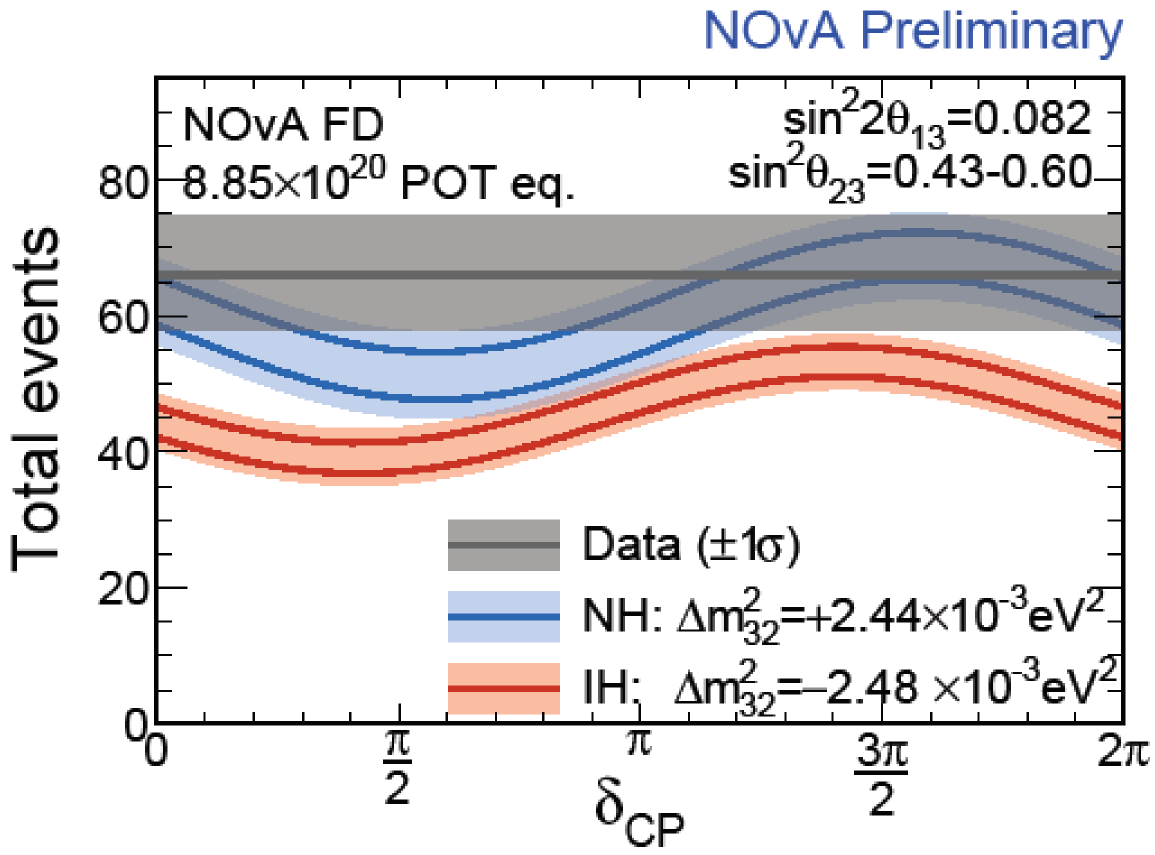
real data + best fit

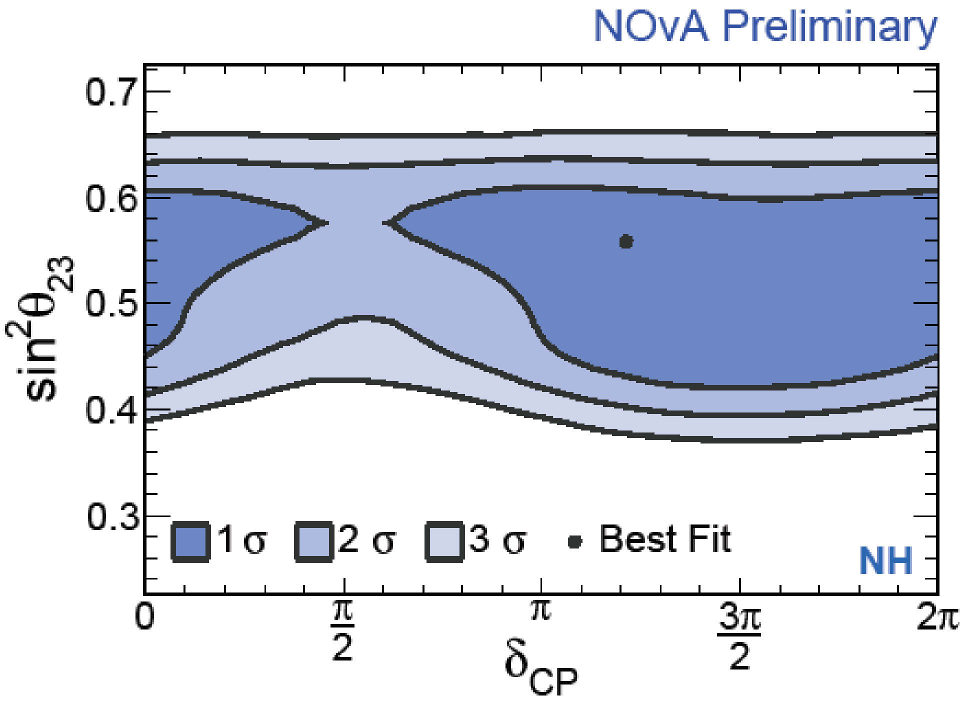


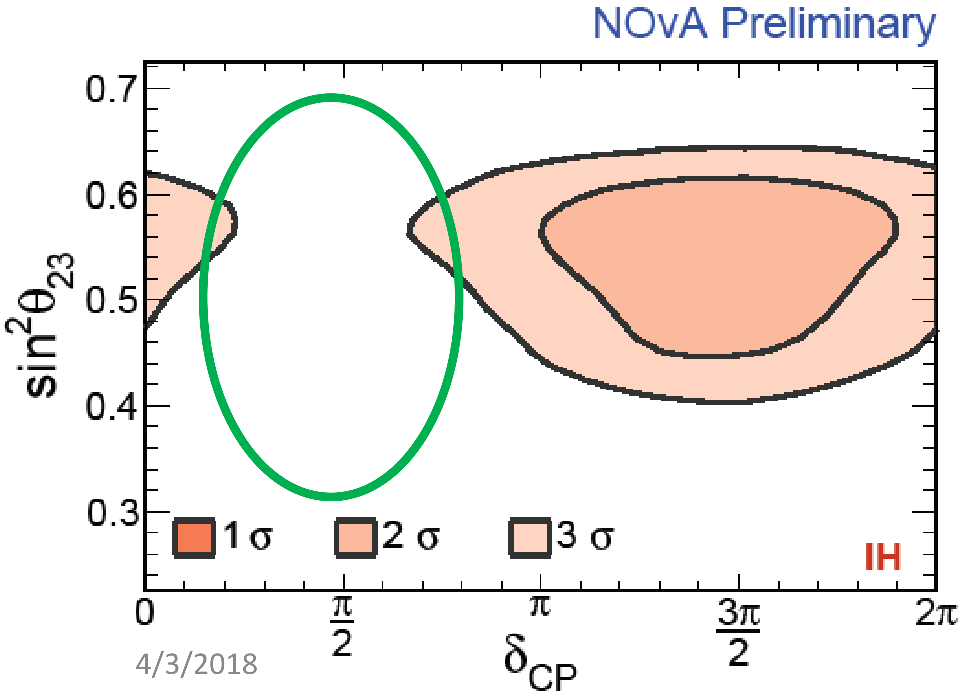


Contours in θ_{23}, δ_{CP} space
Depends a lot on mass hierarchy



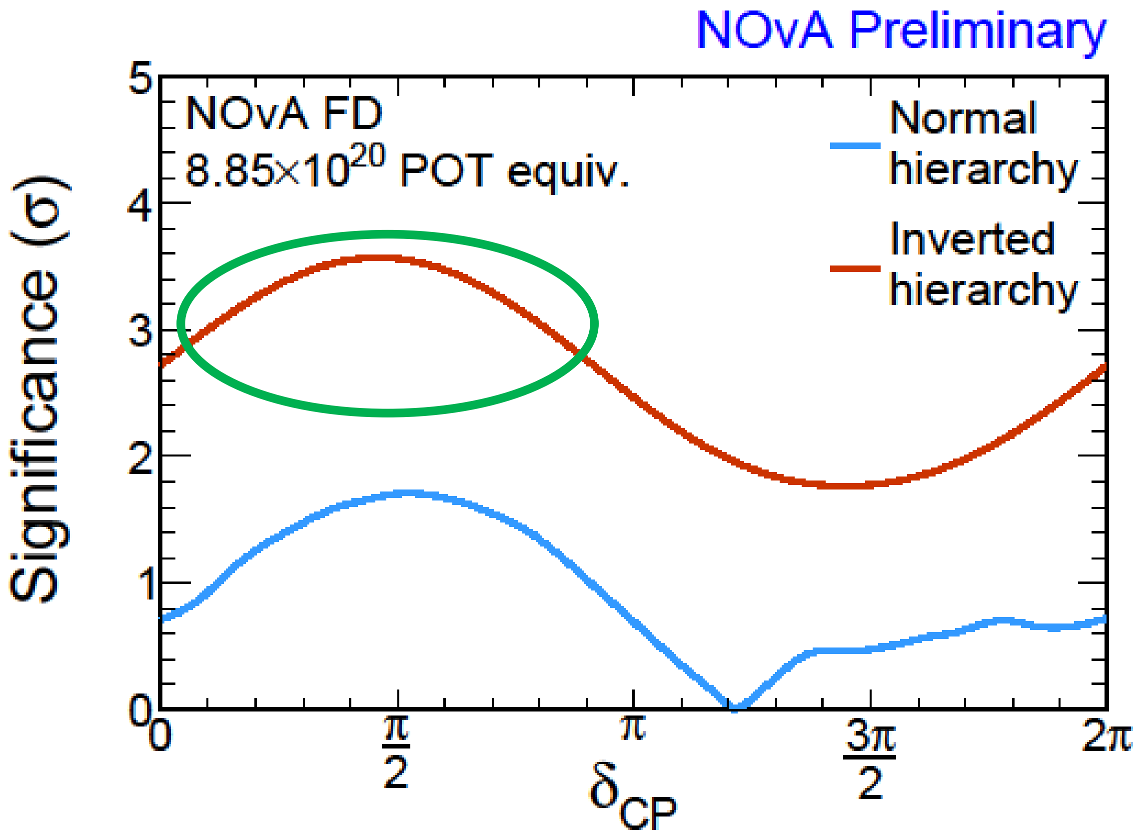






Contours in θ_{23}, δ_{CP} space
Depends a lot on mass hierarchy

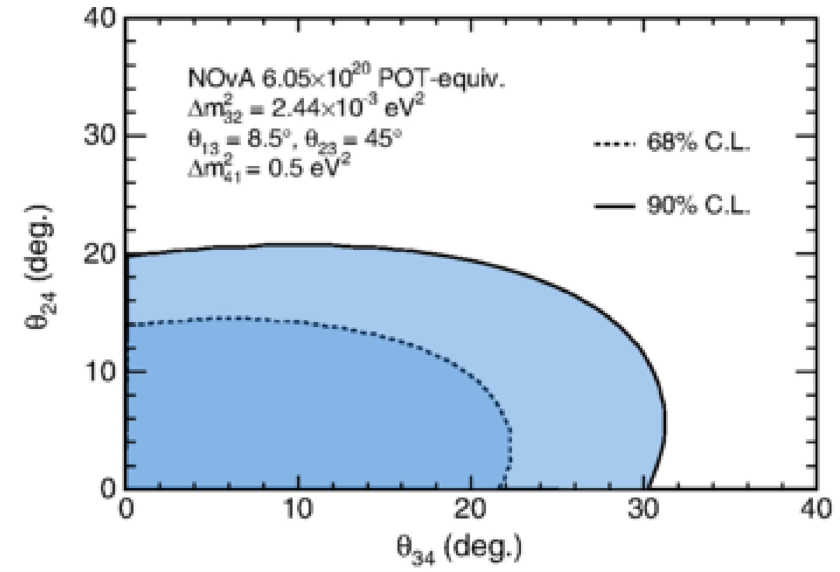
For IH, δ_{CP} 0-π is disfavored by > 3 σ!

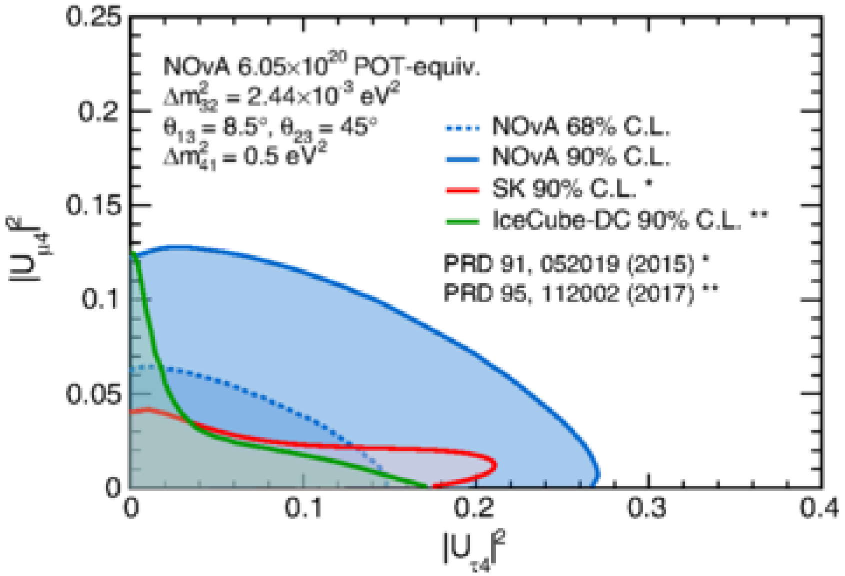


More from NOvA:

- 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 **NEW** oscillation analyses upcoming at NEUTRINO
  - existing neutrino-mode with new anti-neutrino mode data
  - even better cross-section tune

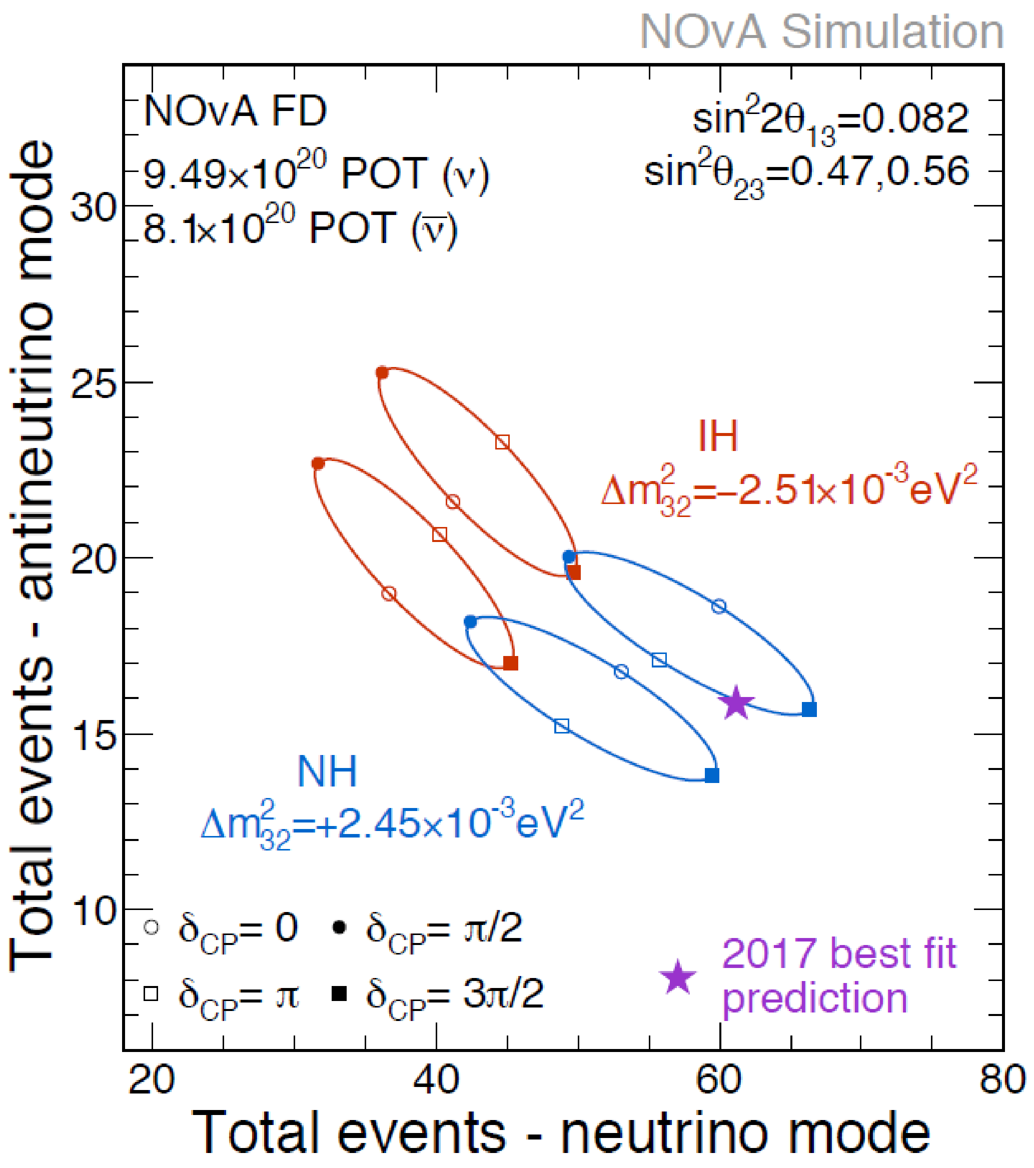
in paper draft

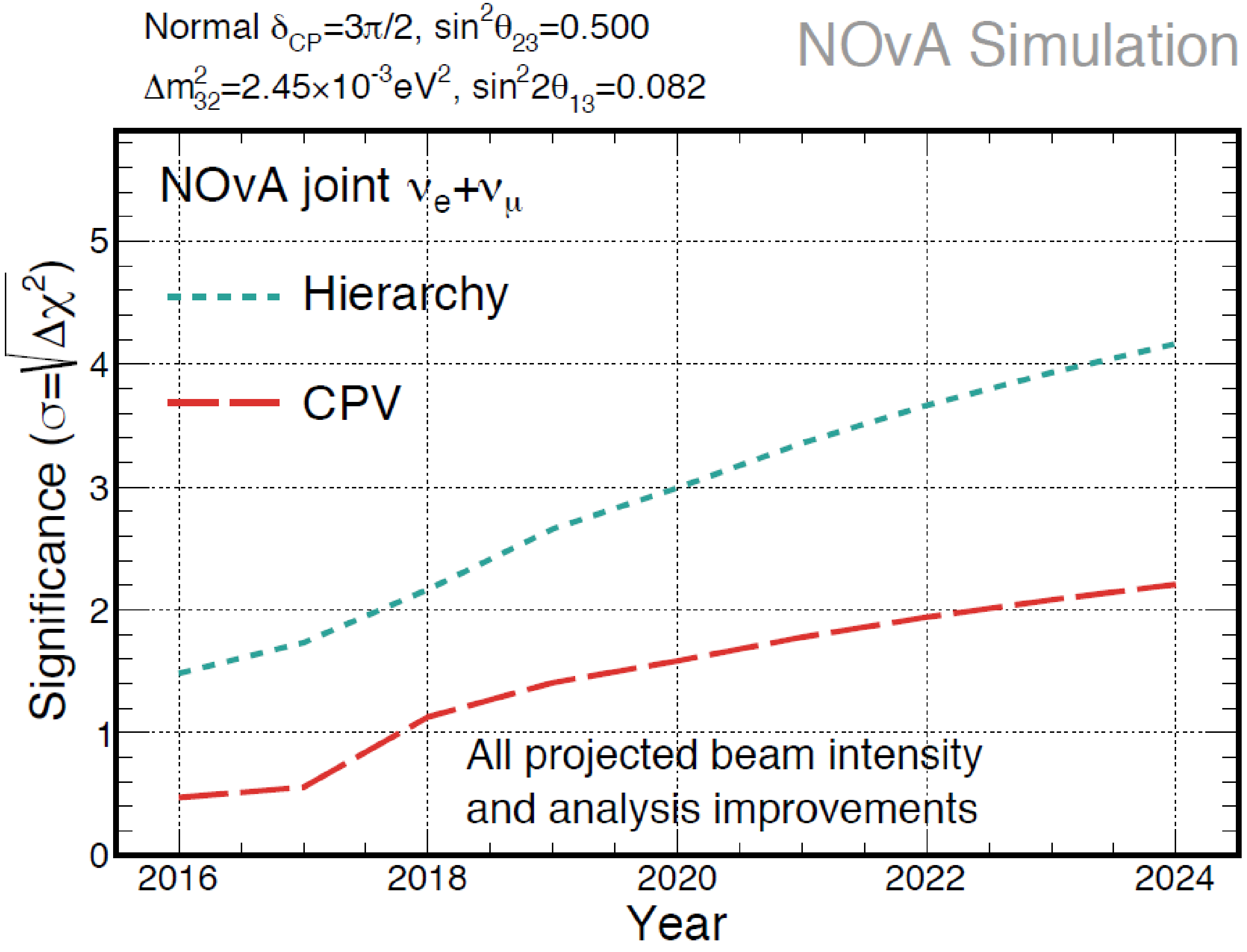




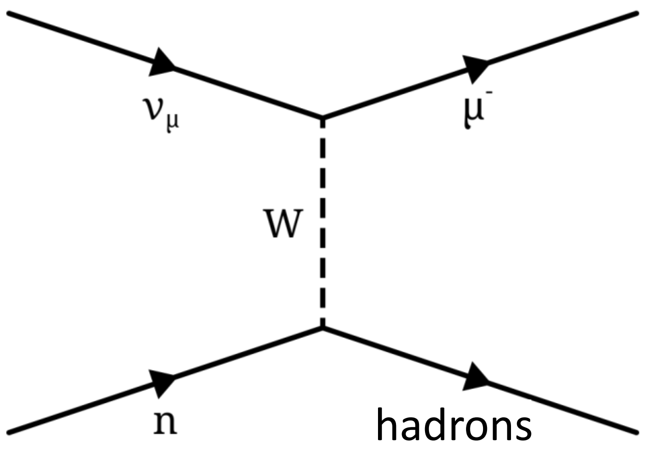

Thank you!
NOvA Collaboration
Fermilab
Fermilab
Fermilab
Fermilab
AISLE 1
AISLE 2
MAN F. RAMSEY
UDITORIUM

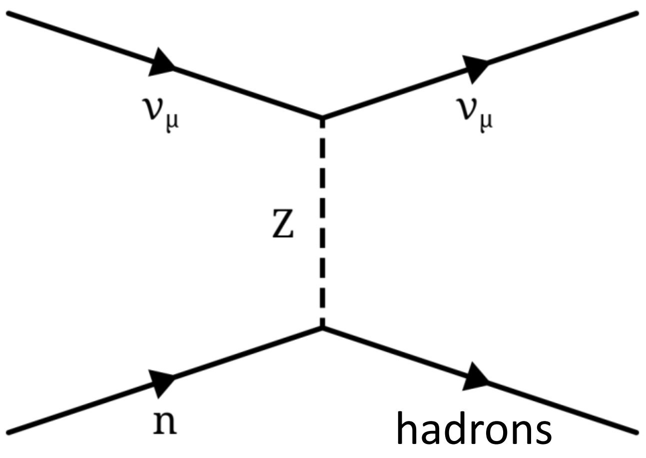
Backups


NOvA Simulation
NOvA FD
9.49×10^20 POT (ν)
8.1×10^20 POT (ν̄)
sin²2θ13=0.082
sin²θ23=0.47,0.56
IH
Δm²32=−2.51×10^-3 eV²
NH
Δm²32=+2.45×10^-3 eV²
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
2017 best fit prediction
Total events - antineutrino mode
Total events - neutrino mode
10
15
20
25
30
20
40
60
80


Normal δCP=3π/2, sin²θ23=0.500
Δm²32=2.45×10^-3 eV², sin²2θ13=0.082
NOvA Simulation
NOvA joint νe+νμ
Hierarchy
CPV
All projected beam intensity and analysis improvements
Significance (σ=√Δχ²)
Year
0
1
2
3
4
5
2016
2018
2020
2022
2024

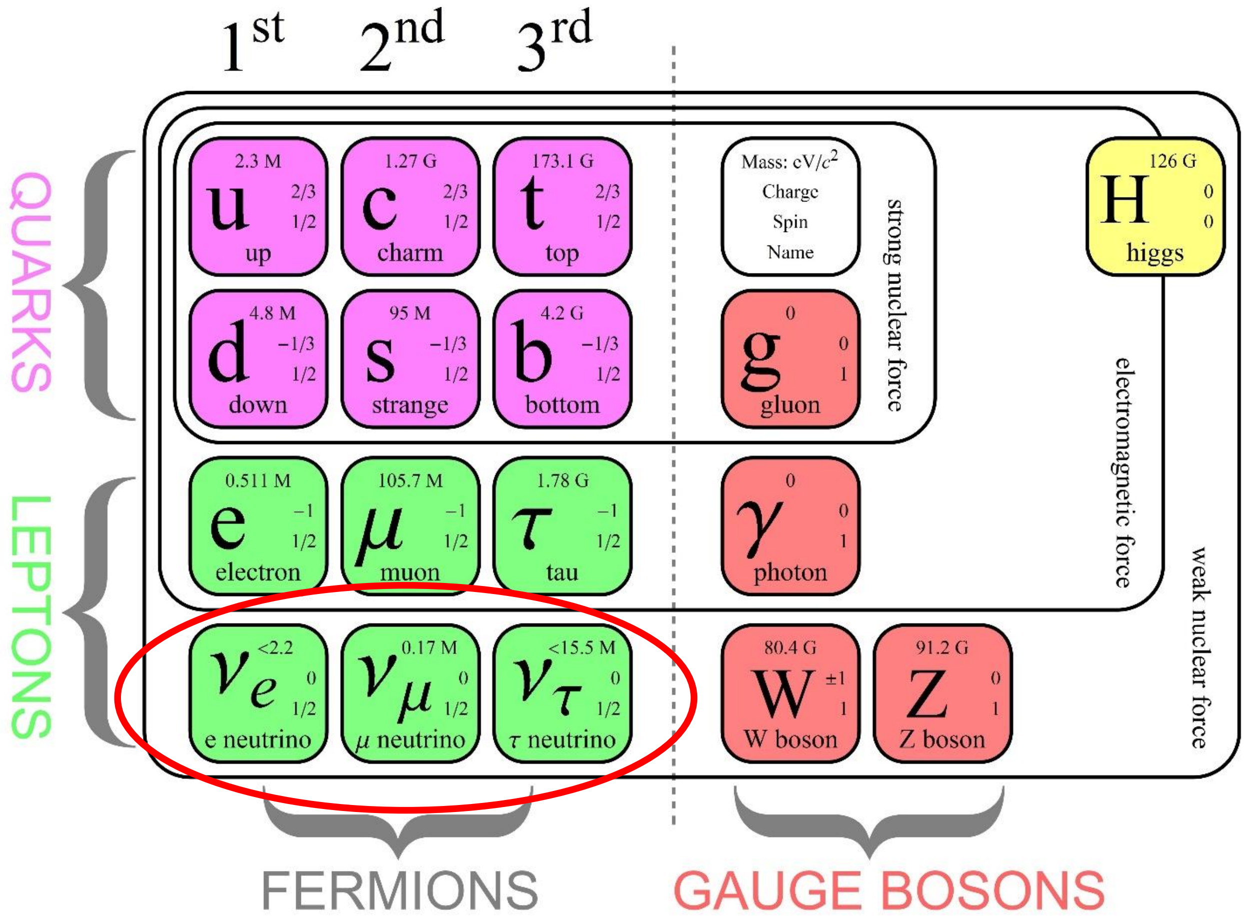
Neutrino interactions





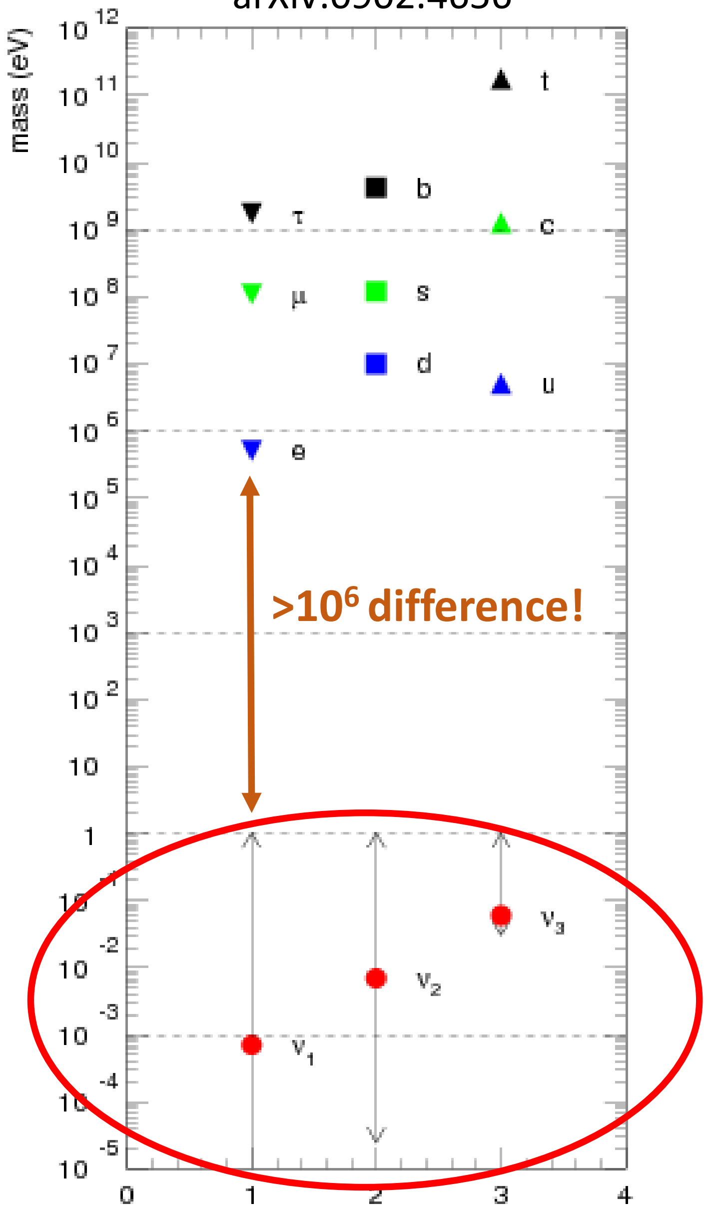
Charged current:
ν_x + nucleon → x + hadrons
x = e, μ, τ
hadrons: can be single p (QE)
can be shower (p, π, …)

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

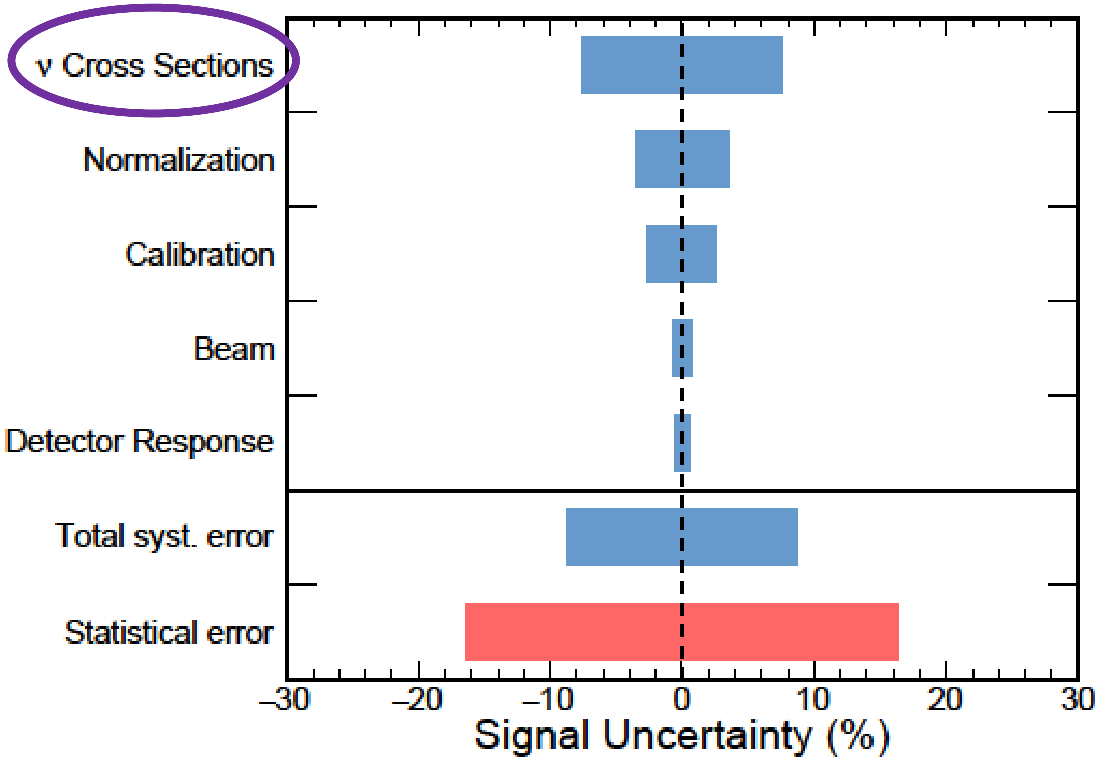


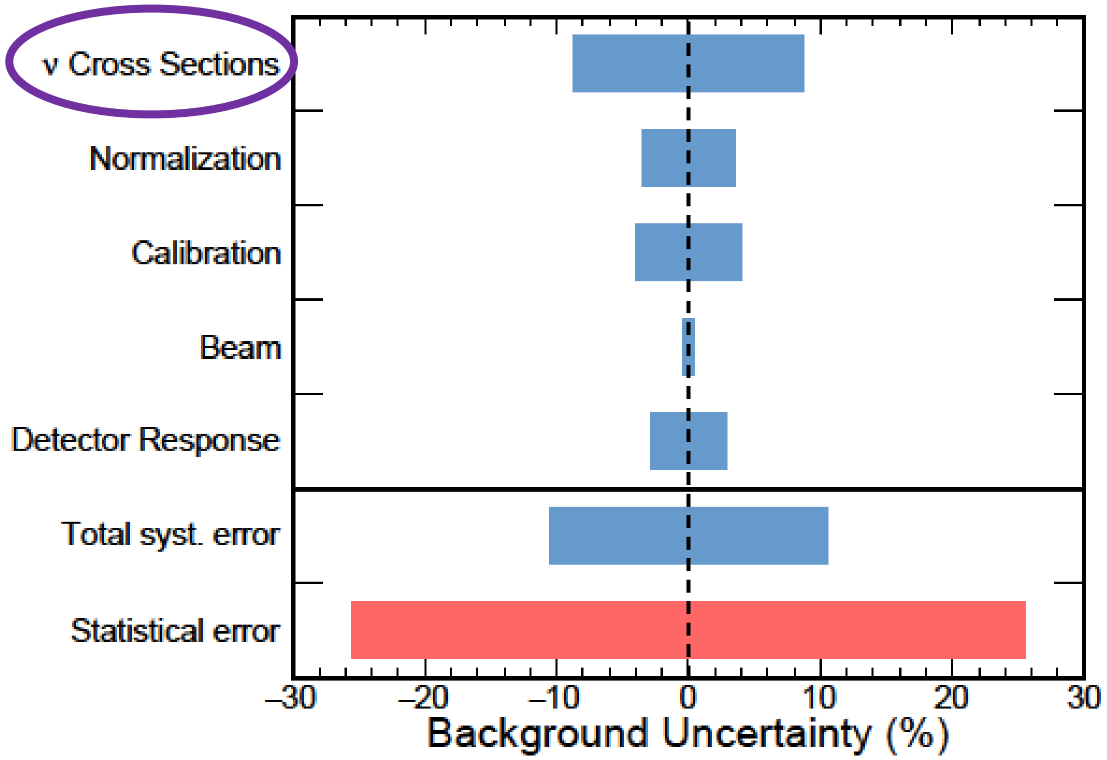
Neutrino masses are very small

arXiv:0902.4656



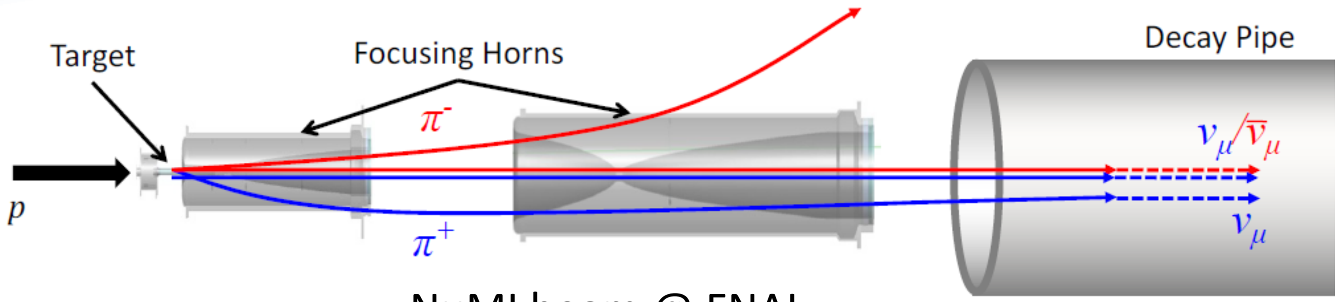
biggest uncertainty for appearance is cross-sections
still statistics limited but getting close
second biggest uncertainty for disappearance





A long-baseline experiment: NOvA

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

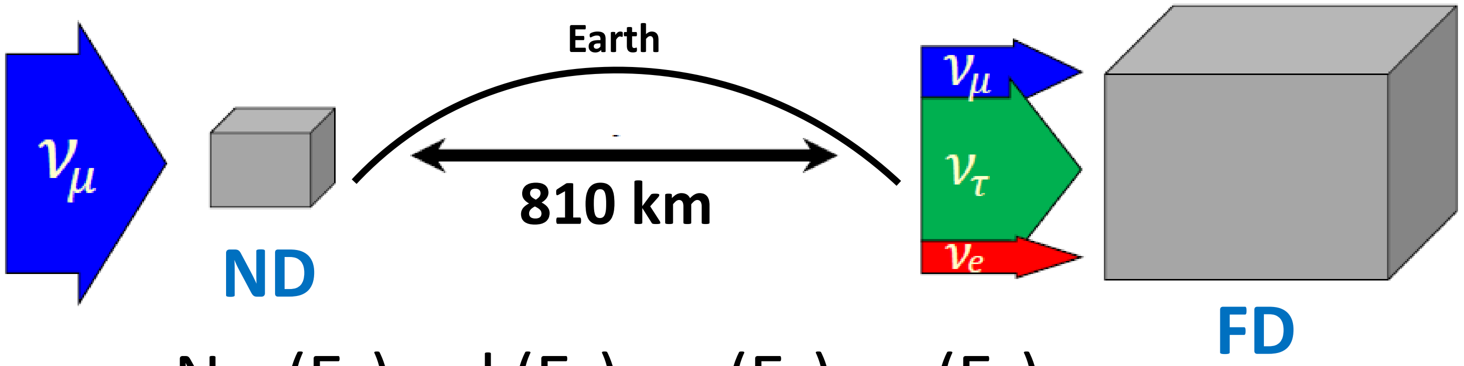


NuMI beam @ FNAL

Then shoot it at your detectors:

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

And a Far Detector (FD) far away

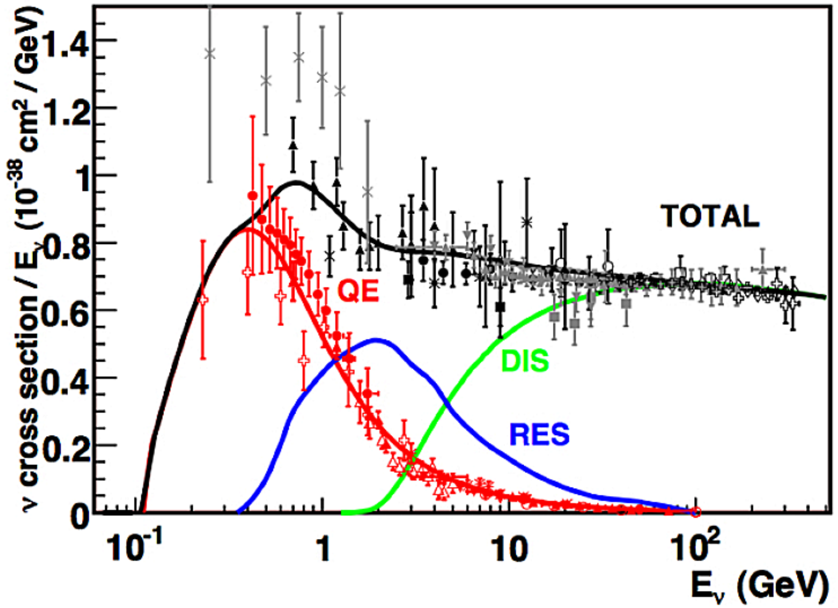


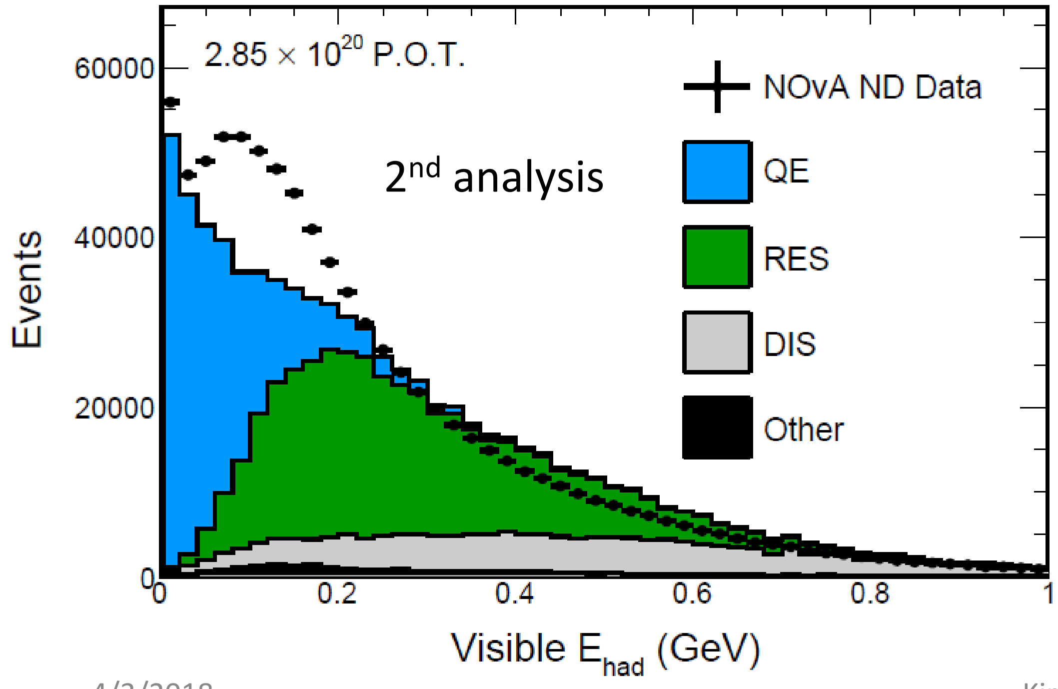
$N_{ND}(E_\nu) = \phi(E_\nu) \times \sigma(E_\nu) \times \varepsilon(E_\nu)$

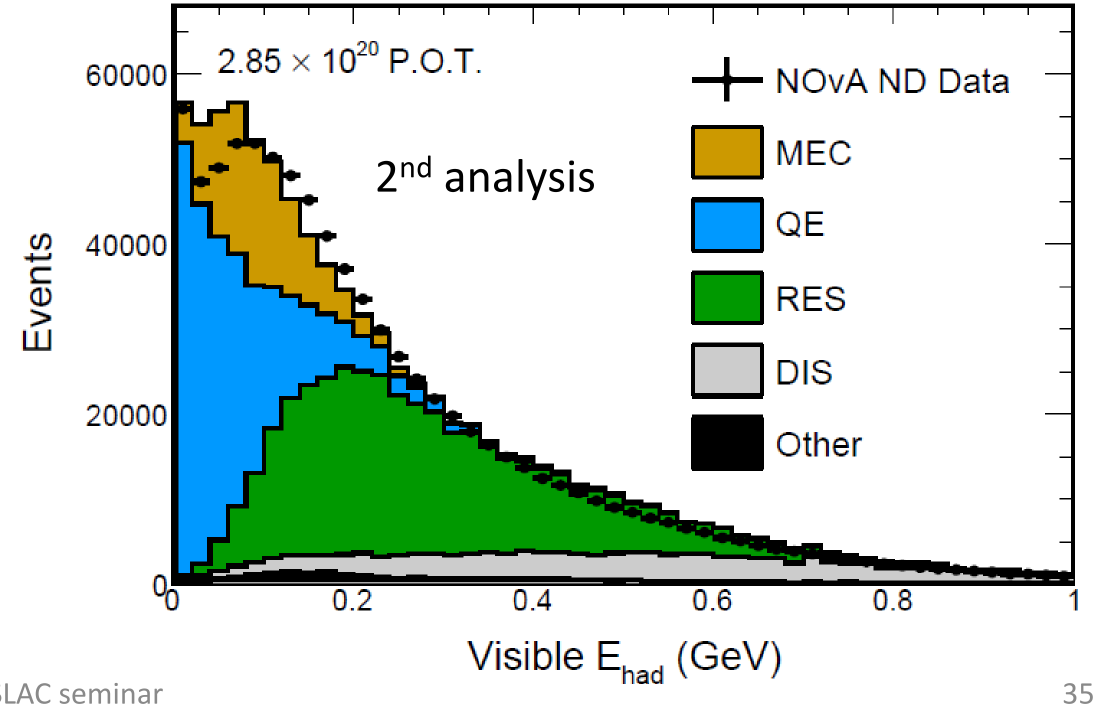
$N_{FD}(E_\nu) = \phi(E_\nu) \times \sigma(E_\nu) \times \varepsilon(E_\nu) \times P(E_\nu)$ ...

ND helps constrain FD uncertainties

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%

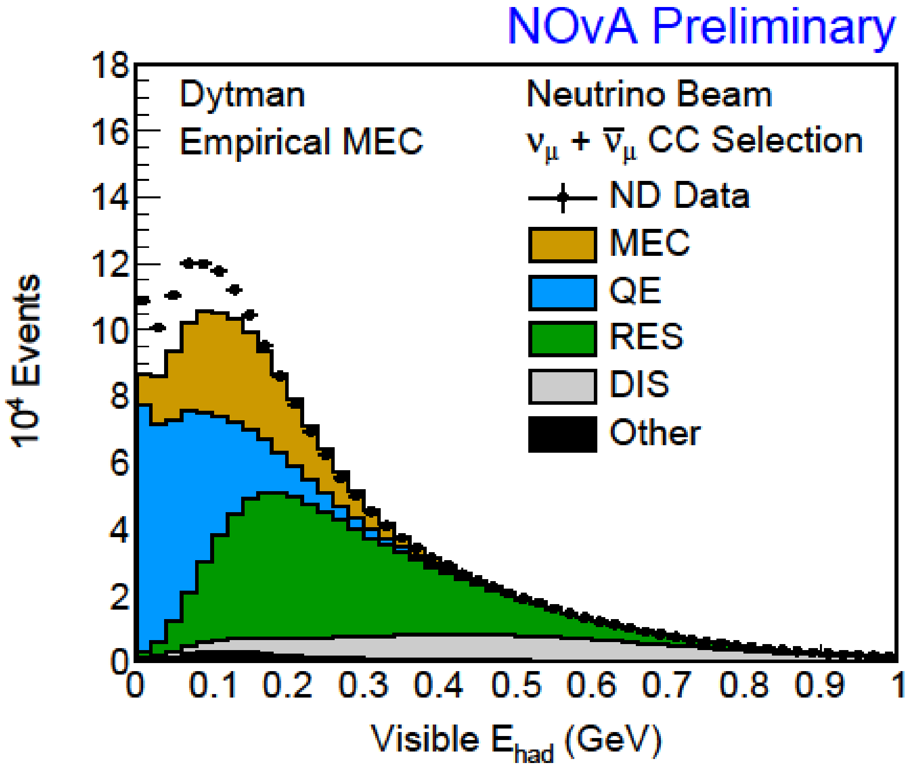




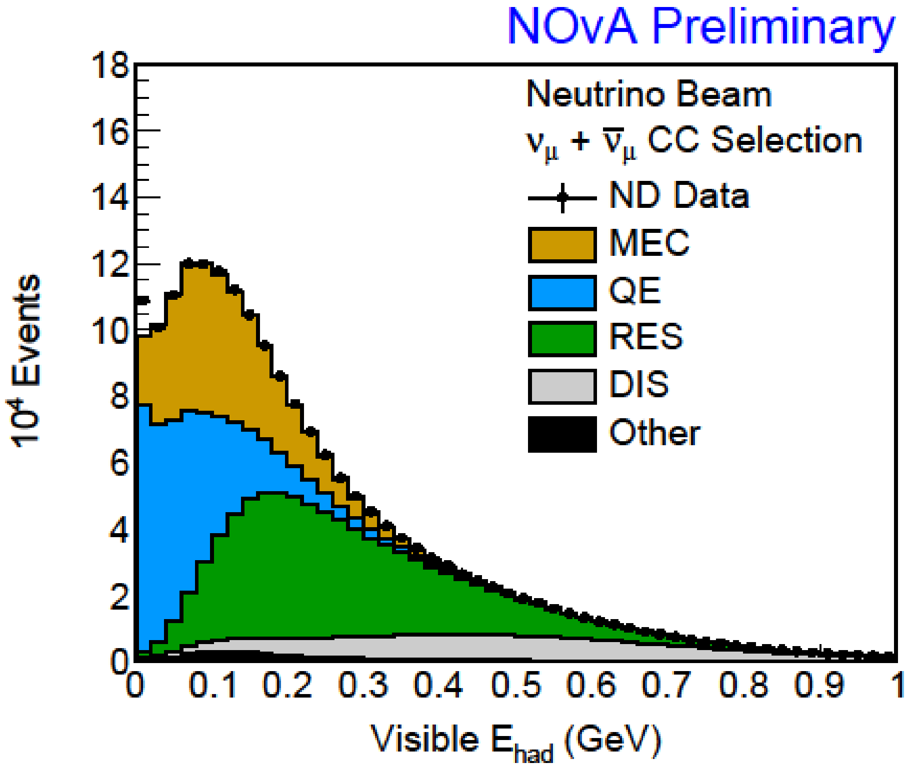


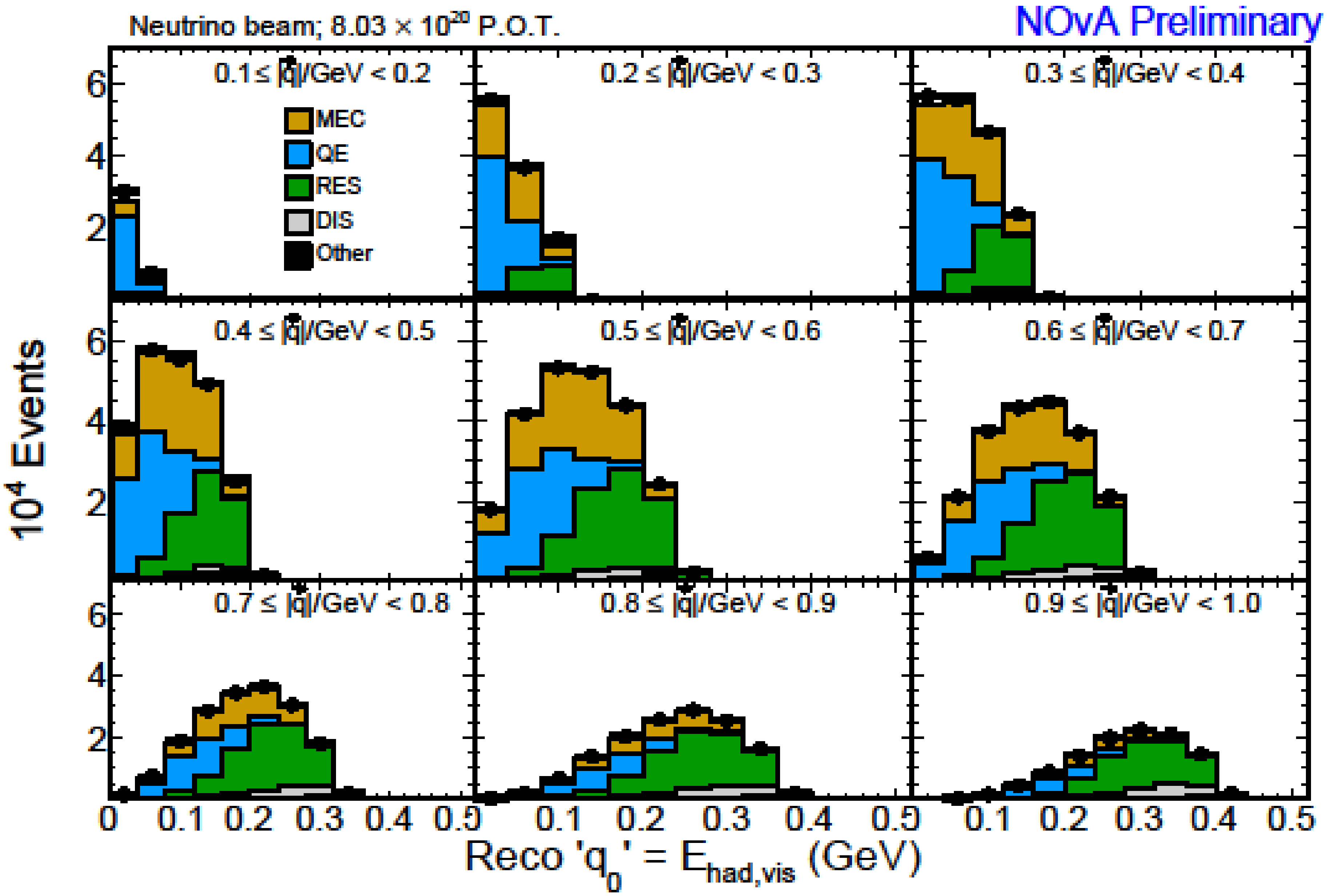
2018 cross-section tune

right out of GENIE MEC

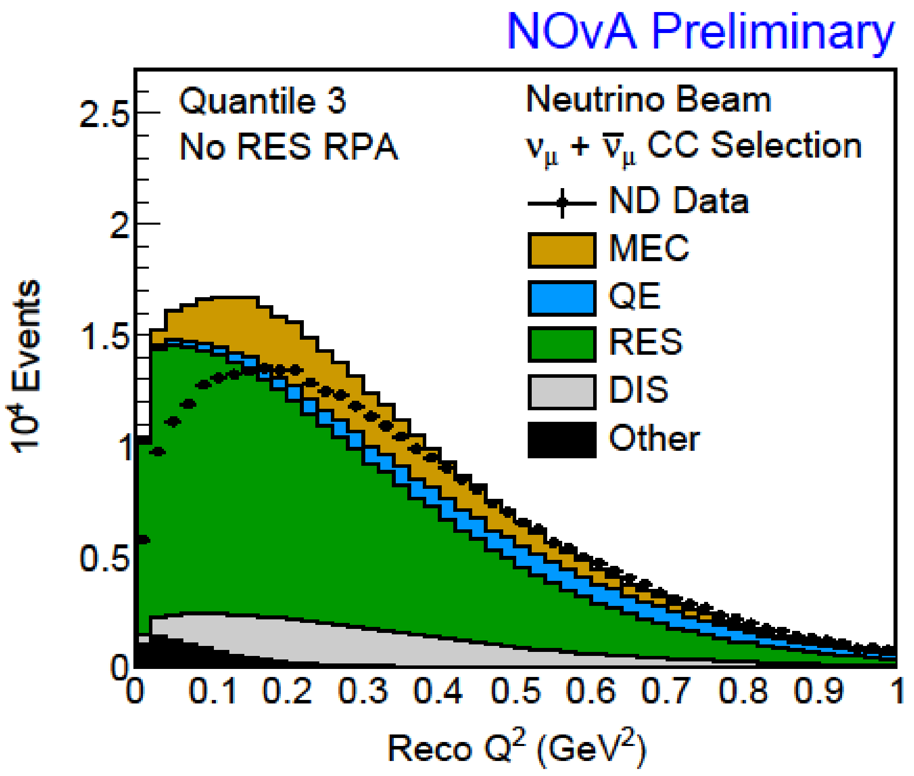


tuned MEC

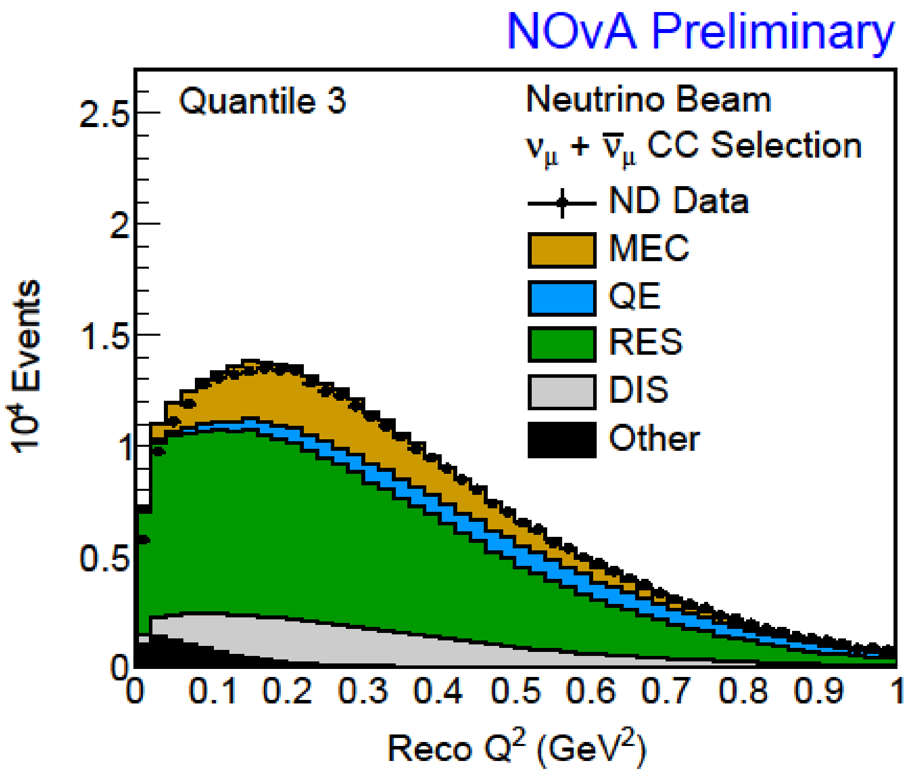



Neutrino beam; 8.03 × 10²⁰ P.O.T.
NOvA Preliminary
0.1 ≤ |q|/GeV < 0.2
0.2 ≤ |q|/GeV < 0.3
0.3 ≤ |q|/GeV < 0.4
0.4 ≤ |q|/GeV < 0.5
0.5 ≤ |q|/GeV < 0.6
0.6 ≤ |q|/GeV < 0.7
0.7 ≤ |q|/GeV < 0.8
0.8 ≤ |q|/GeV < 0.9
0.9 ≤ |q|/GeV < 1.0
MEC
QE
RES
DIS
Other
10⁴ Events
Reco 'q₀' = E_had,vis (GeV)

2018 cross-section tune, no RES RPA



2018 cross-section tune, with RES RPA



Why does it matter?

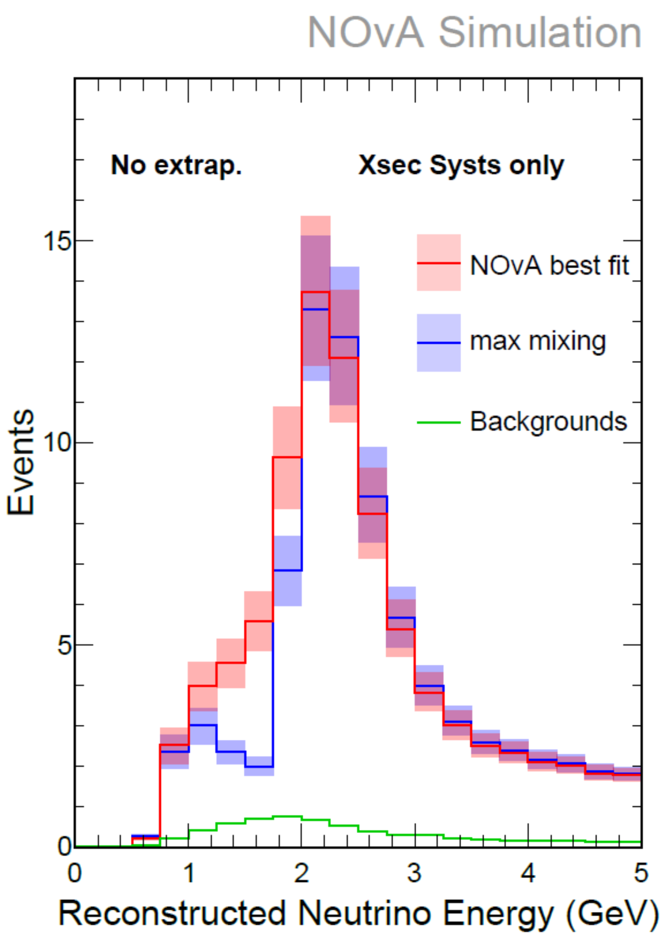
- Fundamental properties of neutrinos affect lots of other things:
  - Cosmology, astrophysics

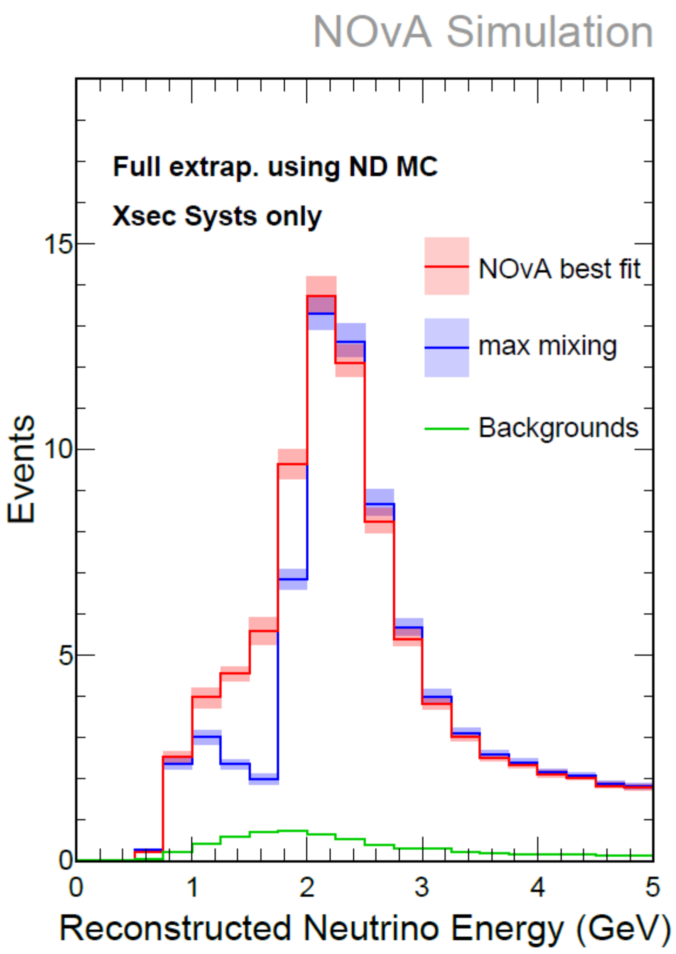
    Why is universe matter and not anti-matter? $\sin(\delta_{CP}) \neq 0$ → leptogenesis?
  - Phenomenology, GUTs

    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

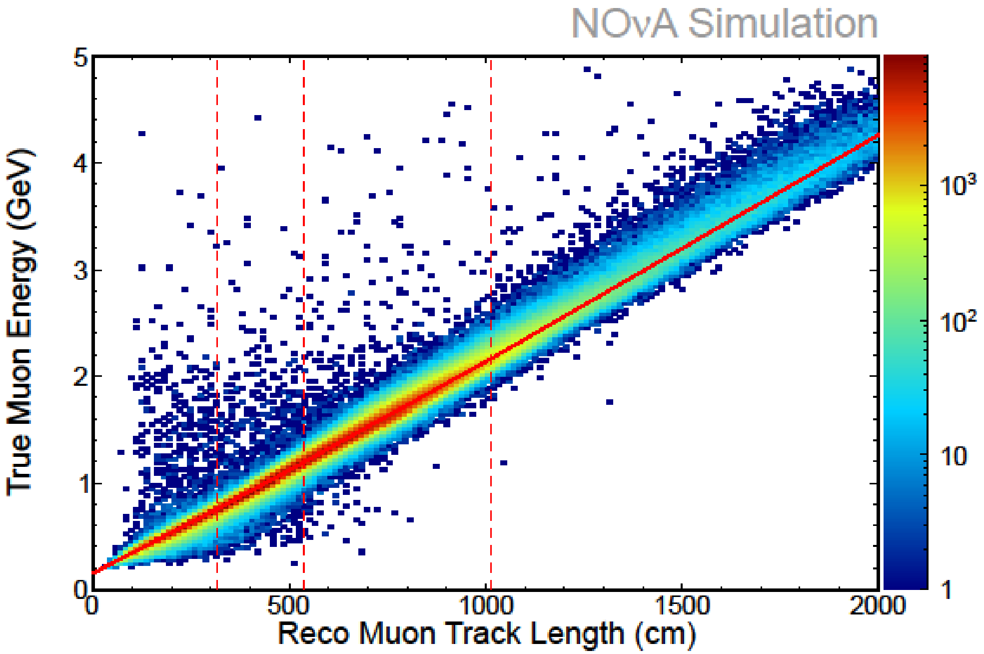
Use ND as a measurement to constrain uncertainties in the FD Far/near extrapolation

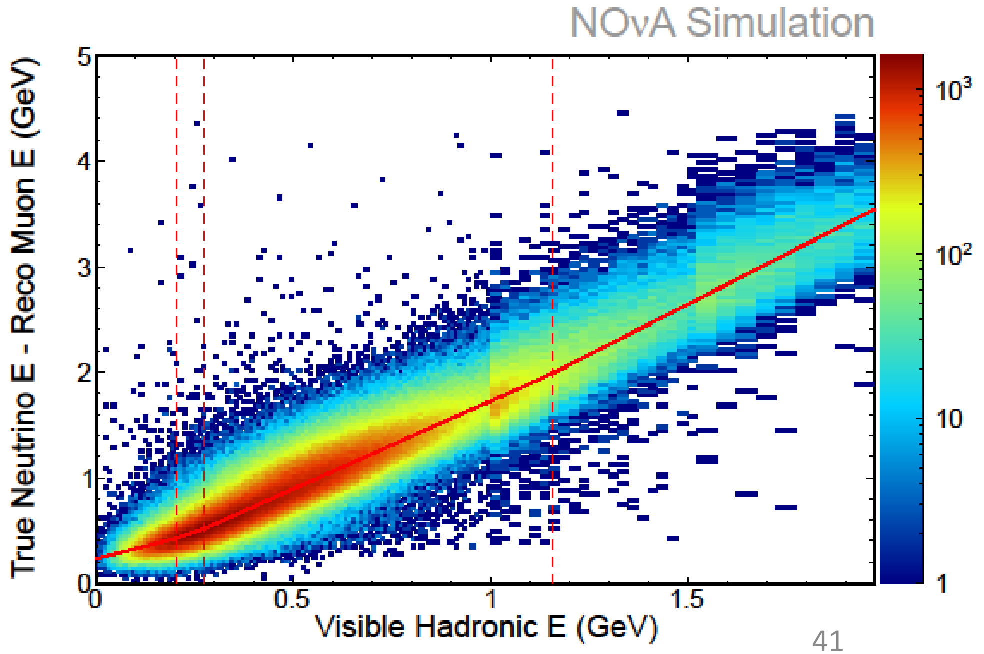




ν_μ energy reconstruction

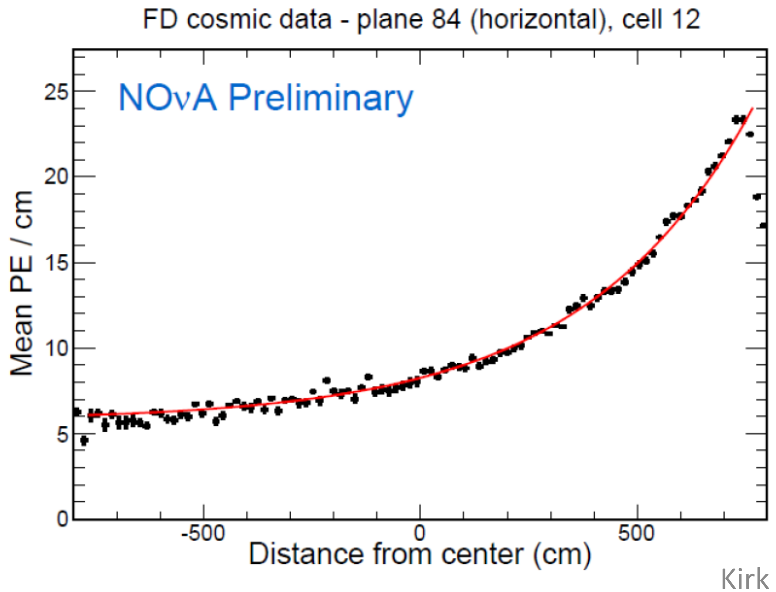
Reconstructed neutrino E:
based on simulation
lepton part (E_{lep}^{res} = 3%)
hadronic part (E_{had}^{res} = 30%)
$E_\nu = E_{lep} + E_{had}$ (E_ν^{res} = 9%)

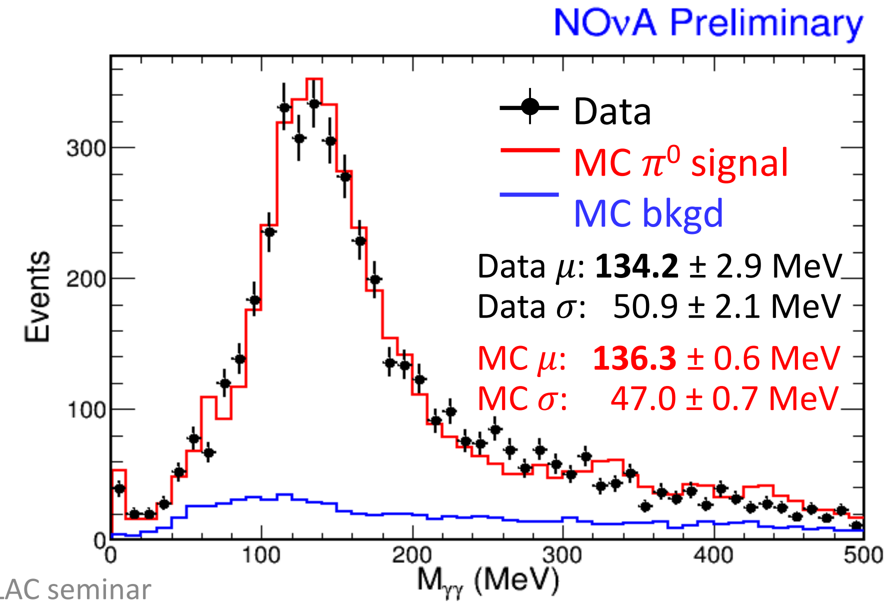




NOvA Calibration:

- 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%)

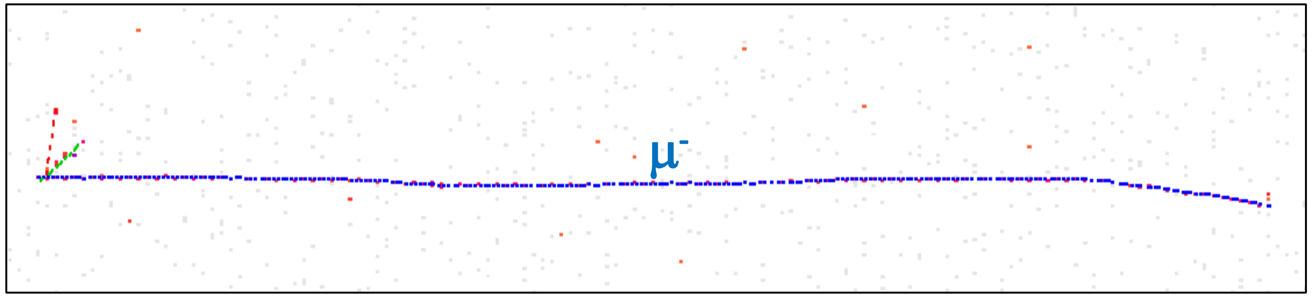




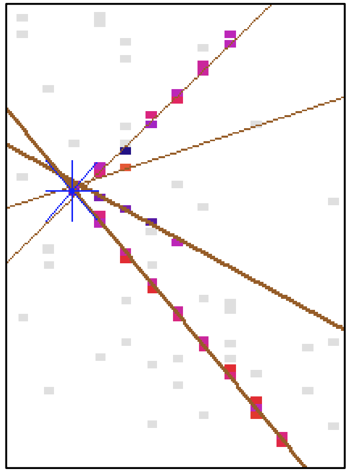
NOvA Reconstruction Basics:

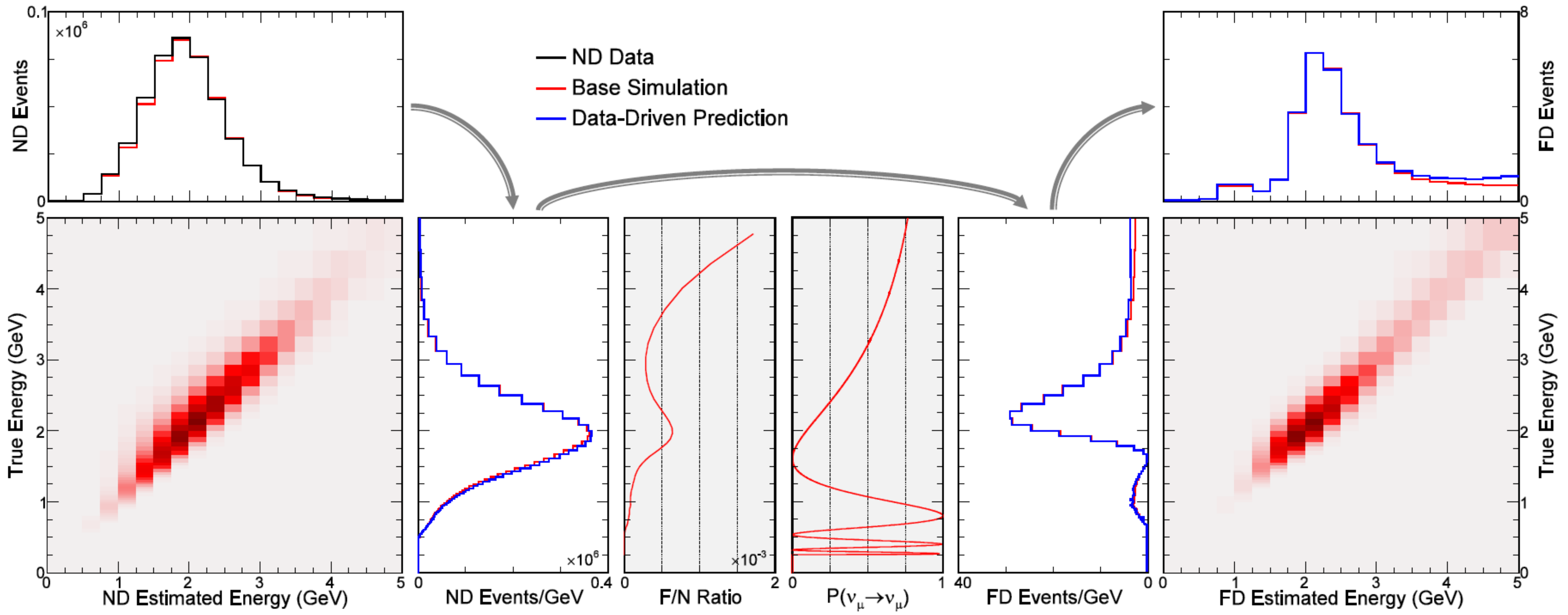
- **Slicing: cluster hits is space and time to isolate physics interactions; highly accurate, can distinguish between > 50 FD muons in the 550 μs spill window with almost no overlap**
  - **timing resolutions: FD ~ 150ns, ND ~ 50ns**
- **Tracking: for muons especially, also protons and pions (disappearance).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

tracking example

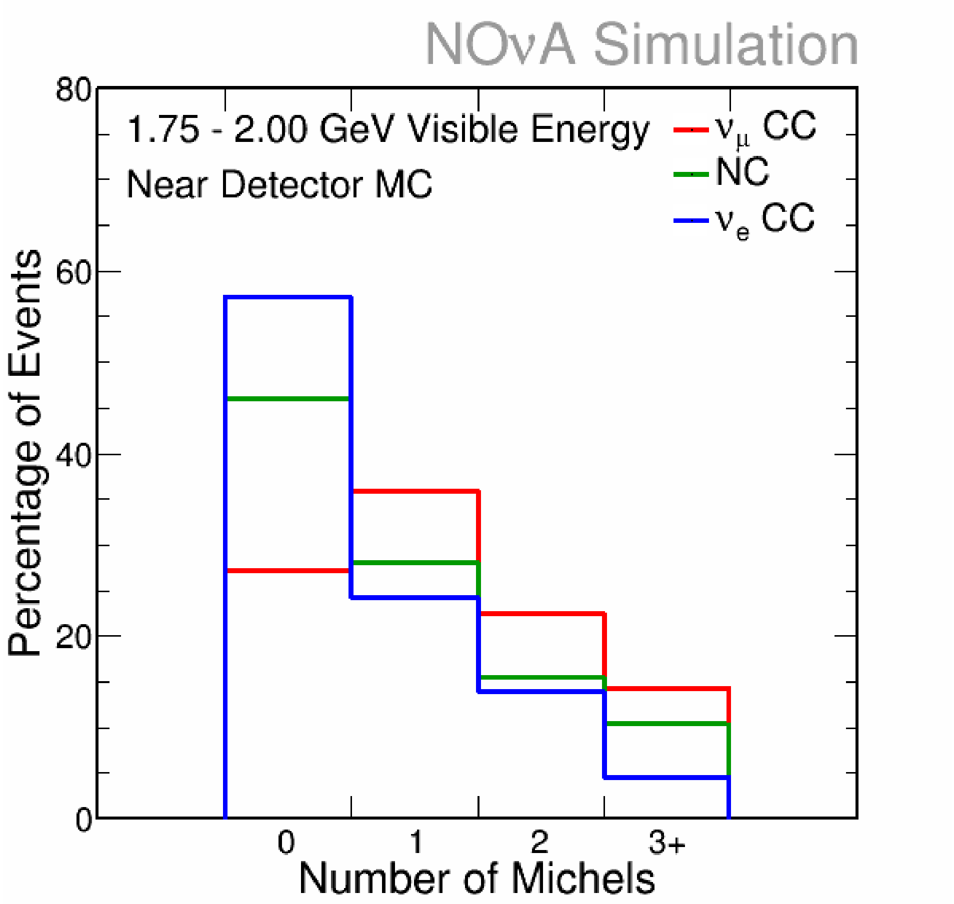


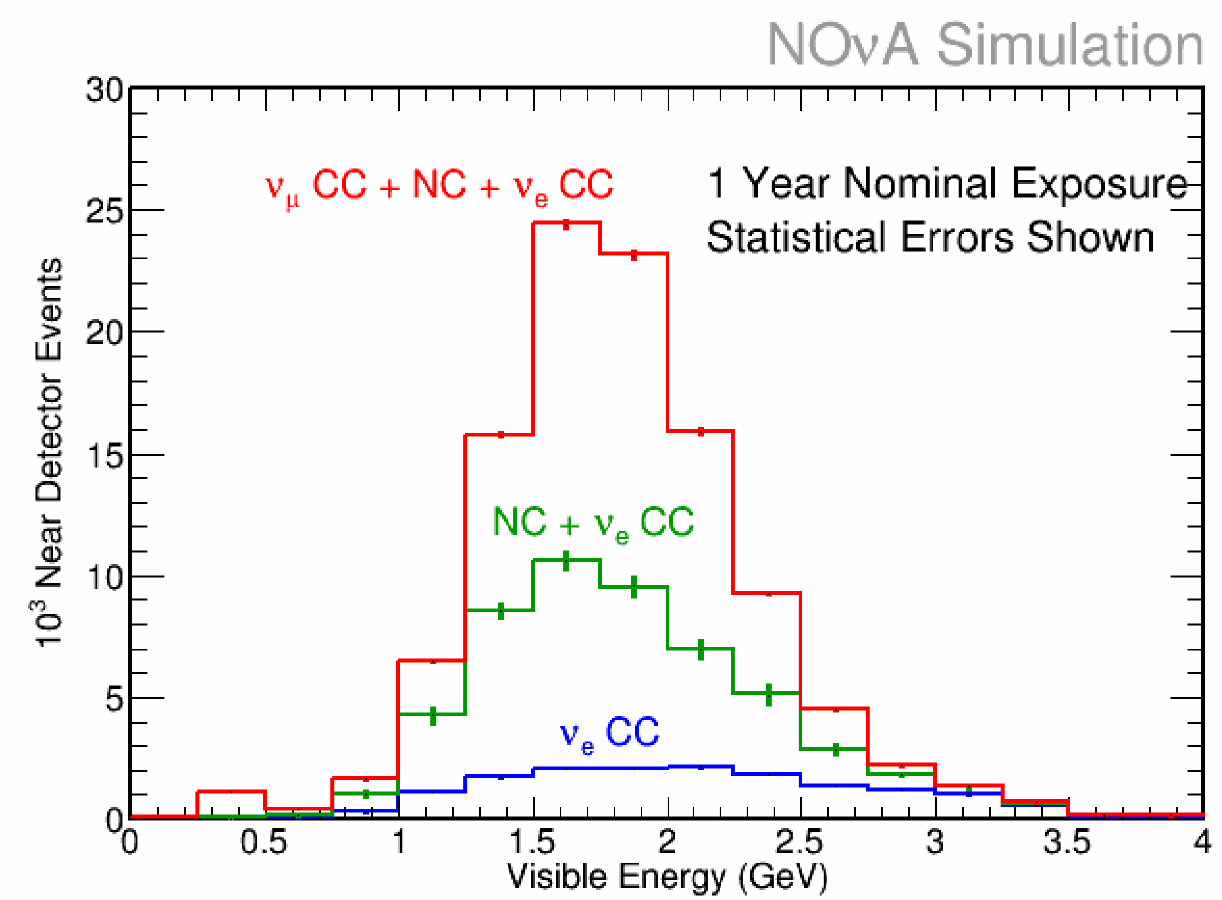
vertexing example





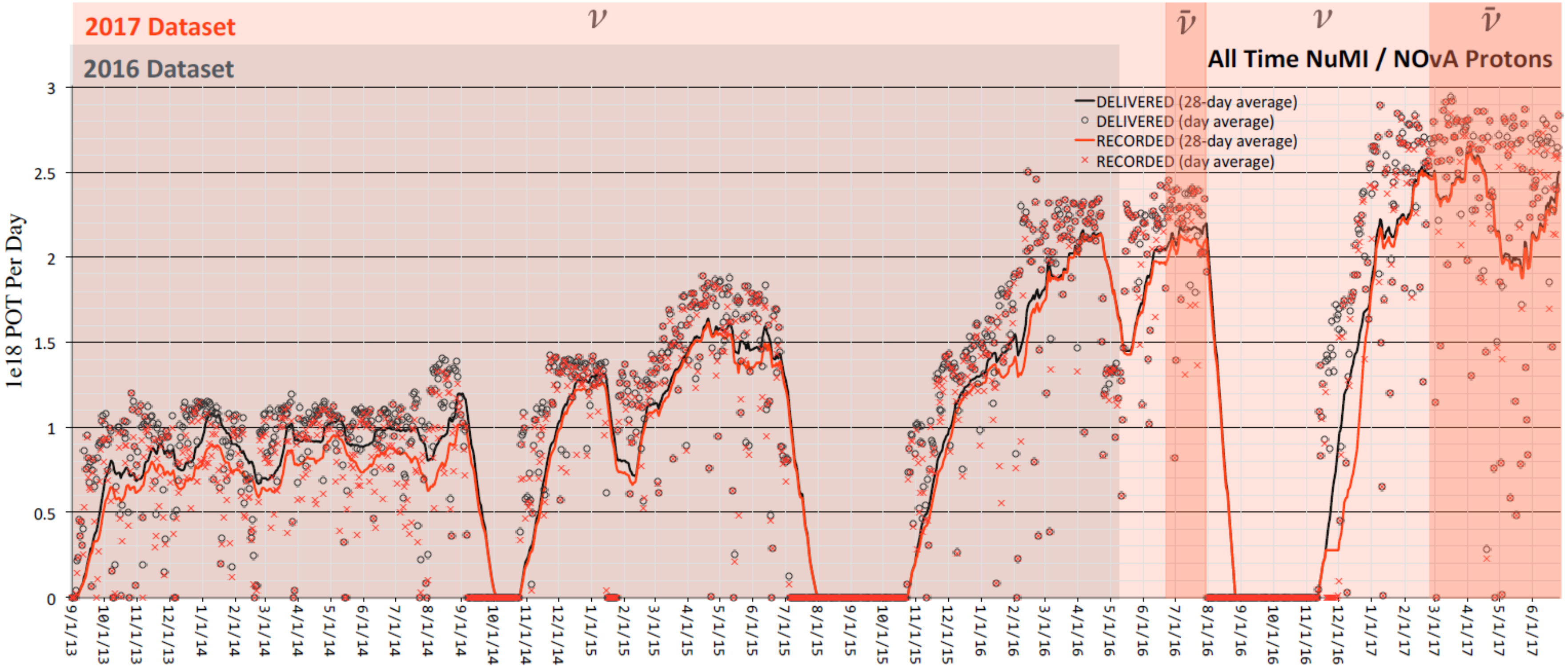
- This entire procedure is re-done beginning to end for each combination of oscillation parameters or systematics being tested
- The extrapolation provides a data-driven approach to help fix any simulation errors and constrain uncertainties
- It is not perfect though – it deals well with normalization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

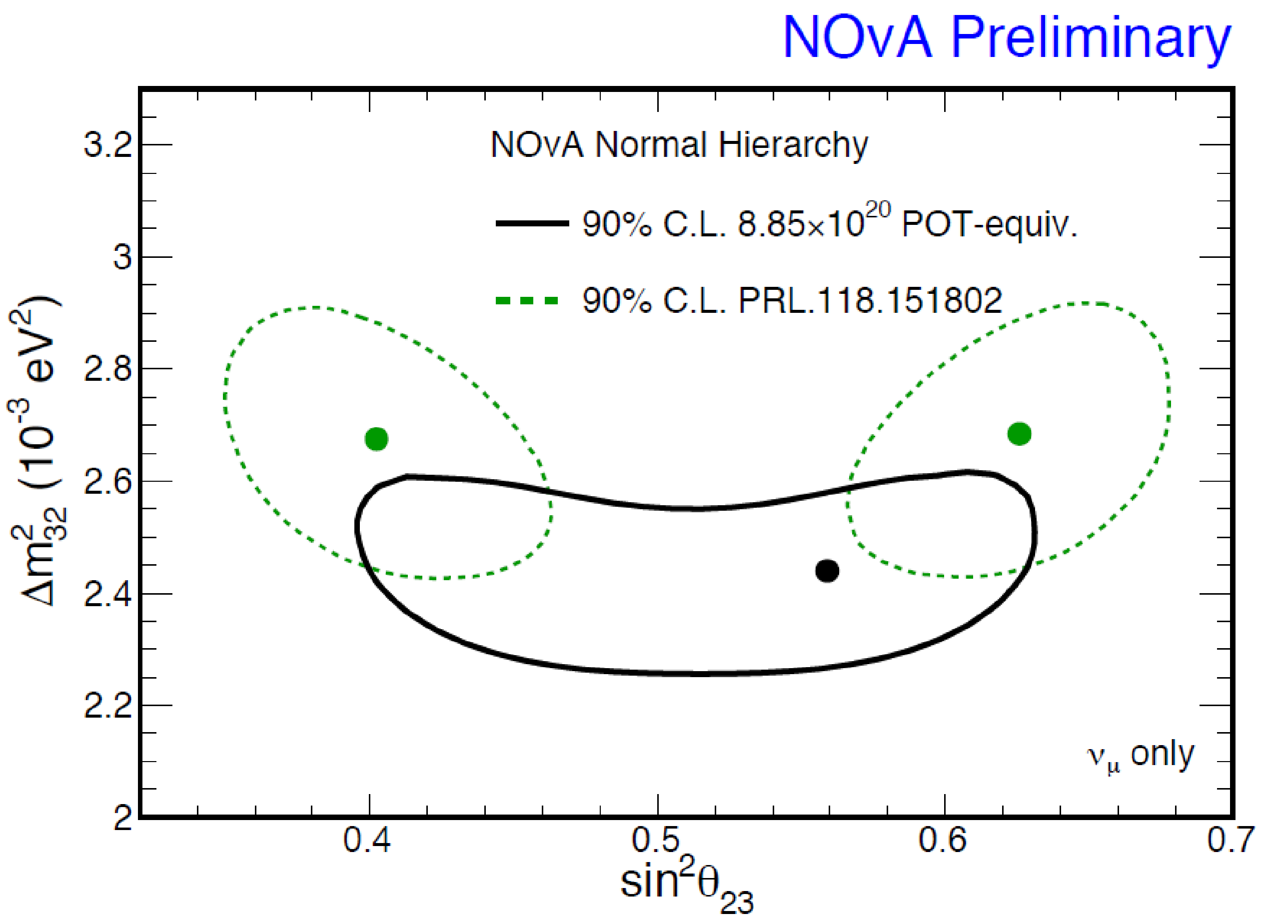

NOνA Simulation
1.75 - 2.00 GeV Visible Energy
Near Detector MC
νμ CC
NC
νe CC
Percentage of Events
0
20
40
60
80
0
1
2
3+
Number of Michels


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

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