NOνA Disappearance Analysis

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APS DPF, Ann Arbor

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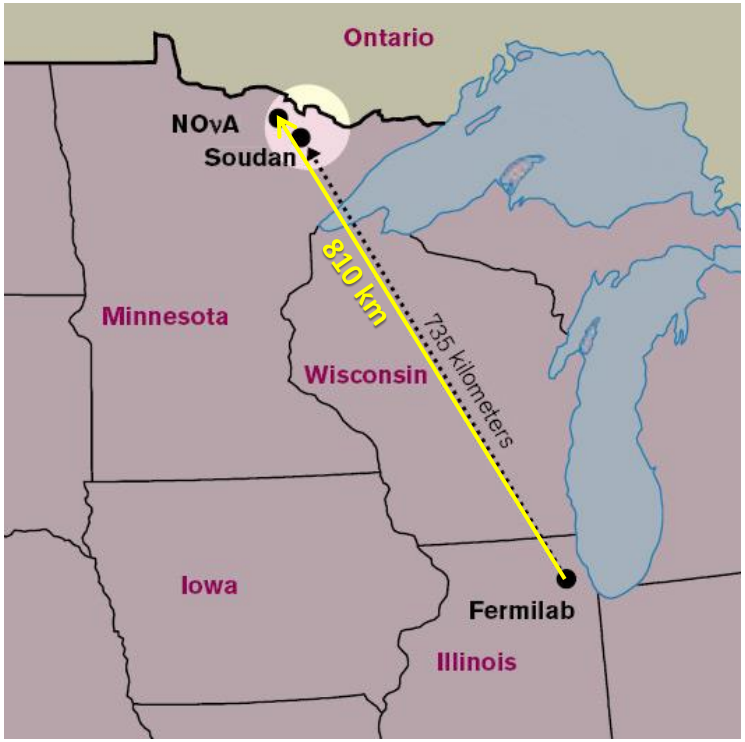
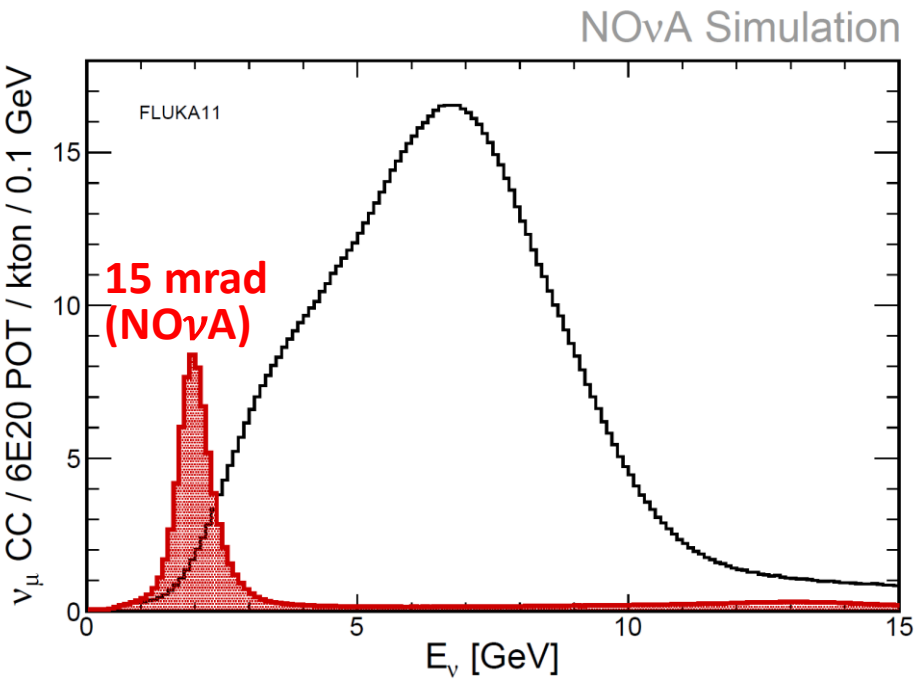
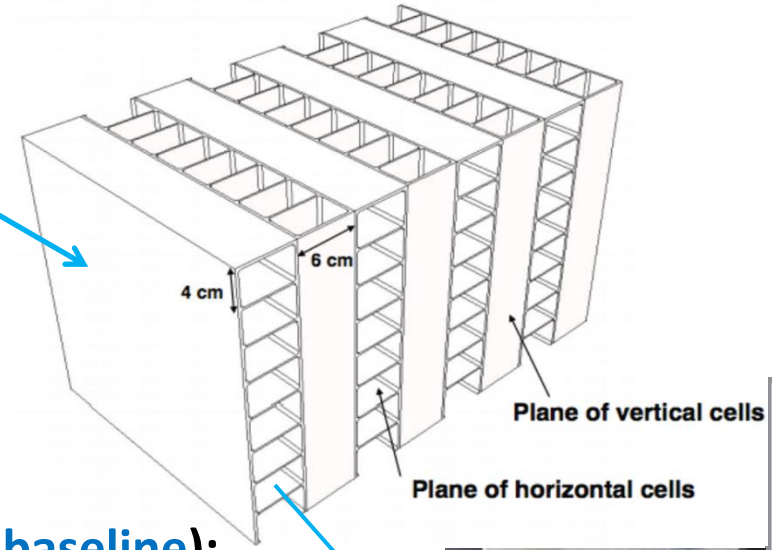
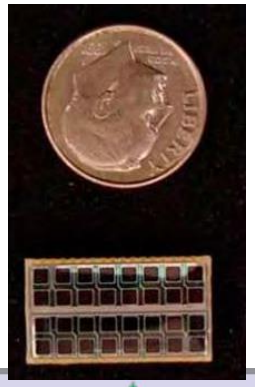
NOνA Overview

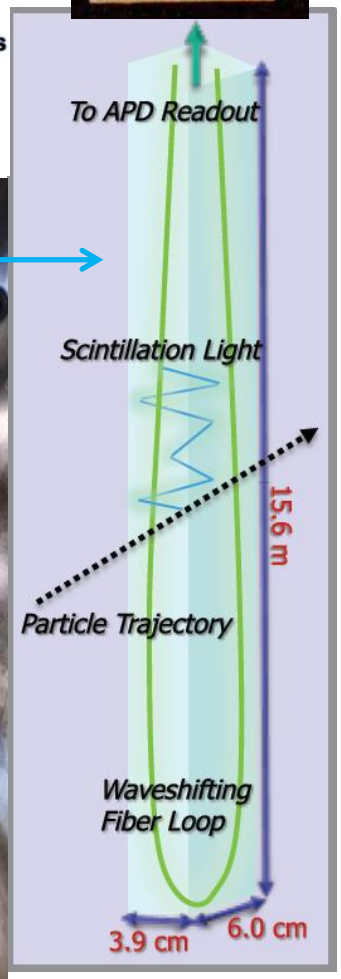
- Source: NuMI ν_μ beam (FNAL)
- Far Det (FD) (810 km @ Ash River, MN)
- Near Detector (ND) (1km @ FNAL)
- 15 mrad off axis (tight energy peak @2 GeV)
- Appearance and disappearance oscillation physics (parallel analyses)
- Beam upgrading to 700 kW (currently 500)
- Beam pulse: 10 μs every 1.33 s





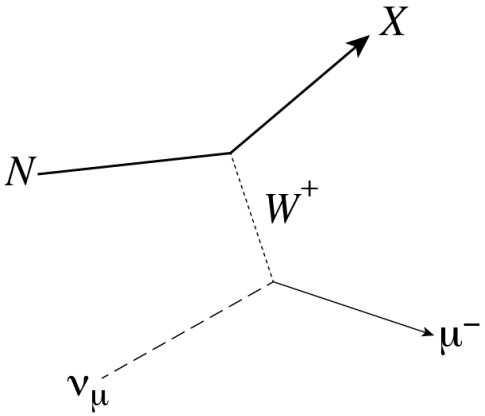




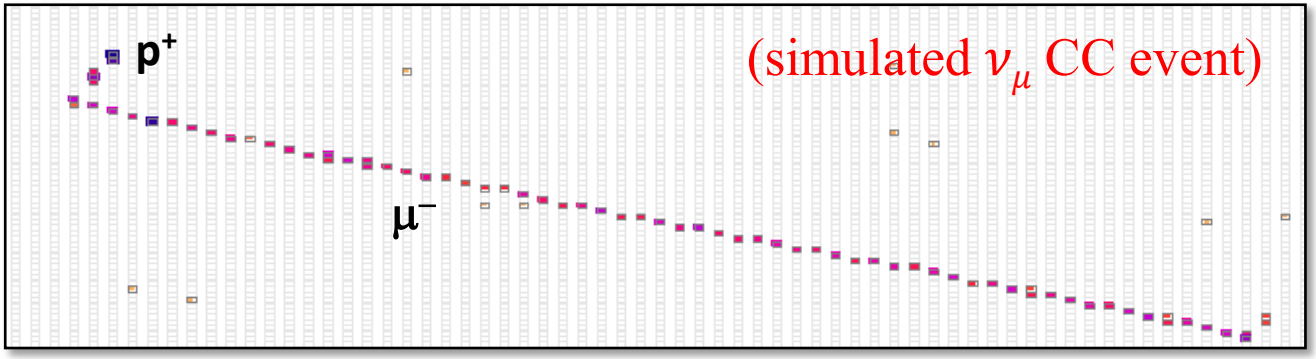


- **FD (at Ash River, MN, 810 km baseline):**
  - **16m x 16m x 60m, 14kton, on surface**
  - **~2/3 LS by mass, ~344,000 cells, 28x32 planes**
  - **99.5% of channels operational**
- **ND (@ FNAL, 1km from NuMI target):**
  - **4m x 4m x 16m, 0.3kton, underground**
  - **~20,000 cells, design similar to FD**
  - **main differences: size and ND muon catcher**
- **High resolution tracking calorimeters**
- **Radiation length = 38 cm = 6-10 cells**
- **Cells filled with liquid scintillator, wavelength shifting optical fiber**
- **Fiber traps light, channels it to an Avalanche Photo Diode (APD)**

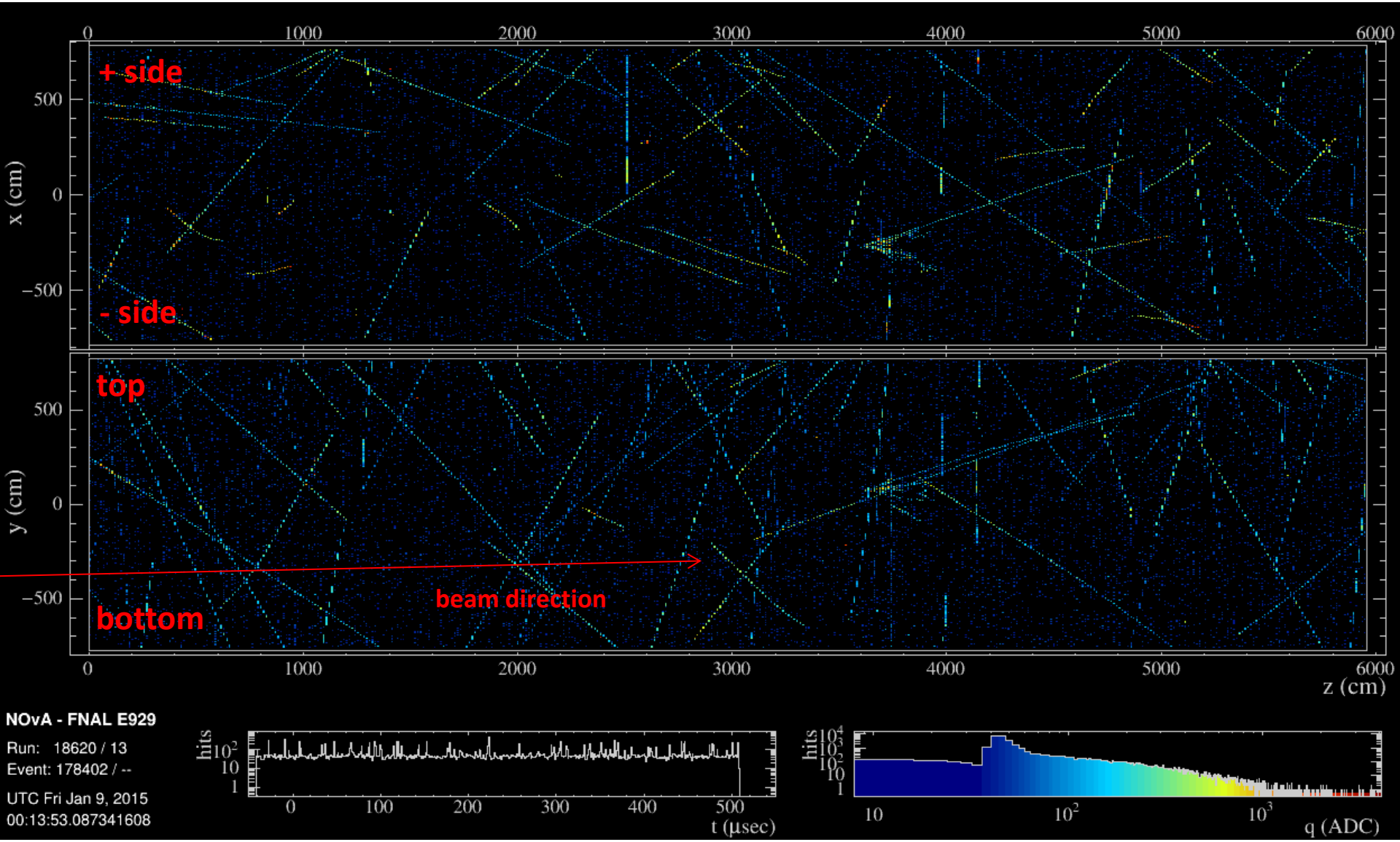
ν_μ Disappearance



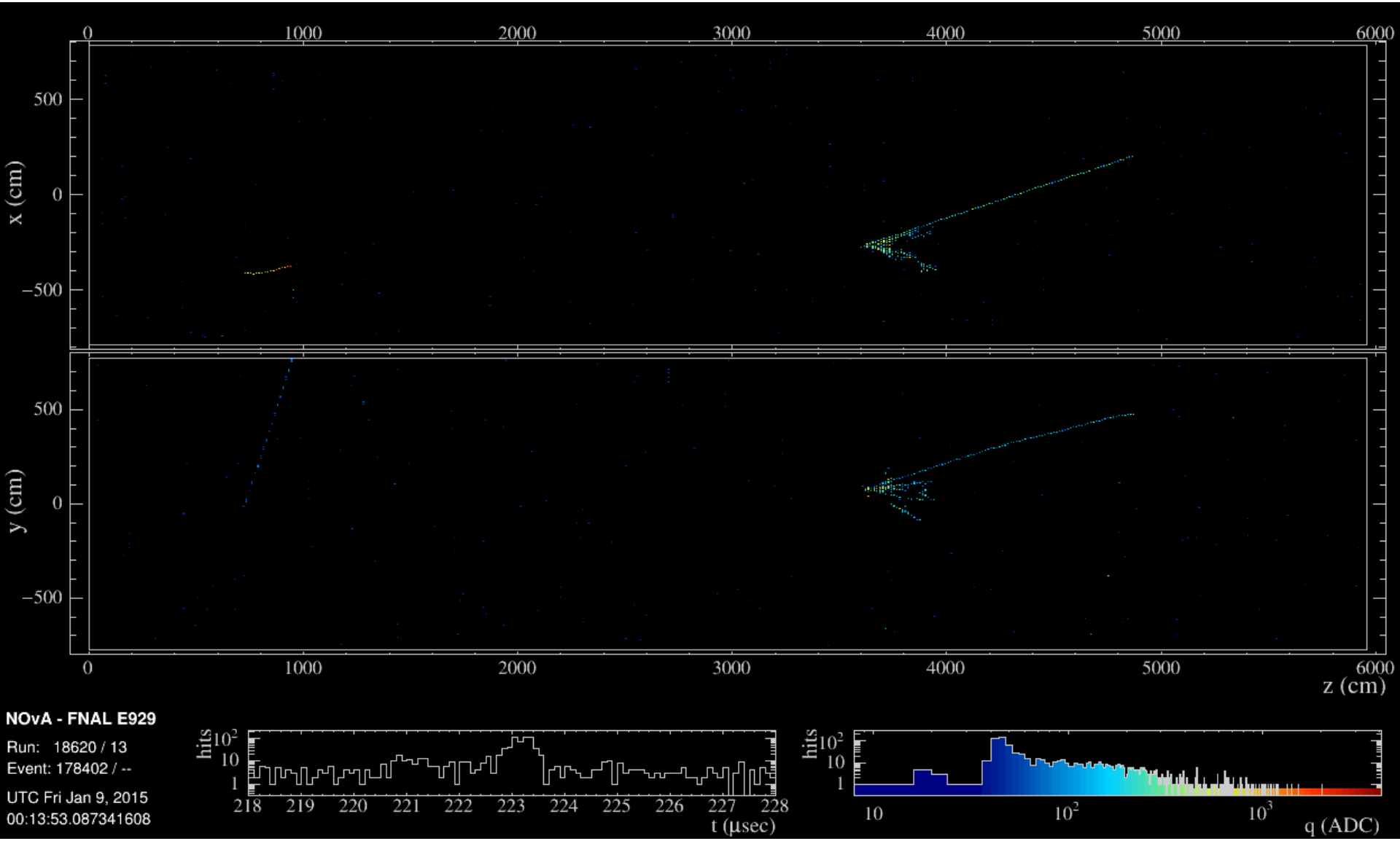
- **Start with a ν_μ beam (NUMI @ FNAL)**
- **ν_μ's oscillate to other flavors**
- **Survival probability:**
  - **$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}L/E)$**
- **Direct measurement of θ_{23} (maximal?), Δm^2_{23}**
- **Backgrounds for disappearance:**
  - **NC neutrino events**
  - **Cosmic ray background**
- **Signature is high E muon, possible vertex hadronic activity**



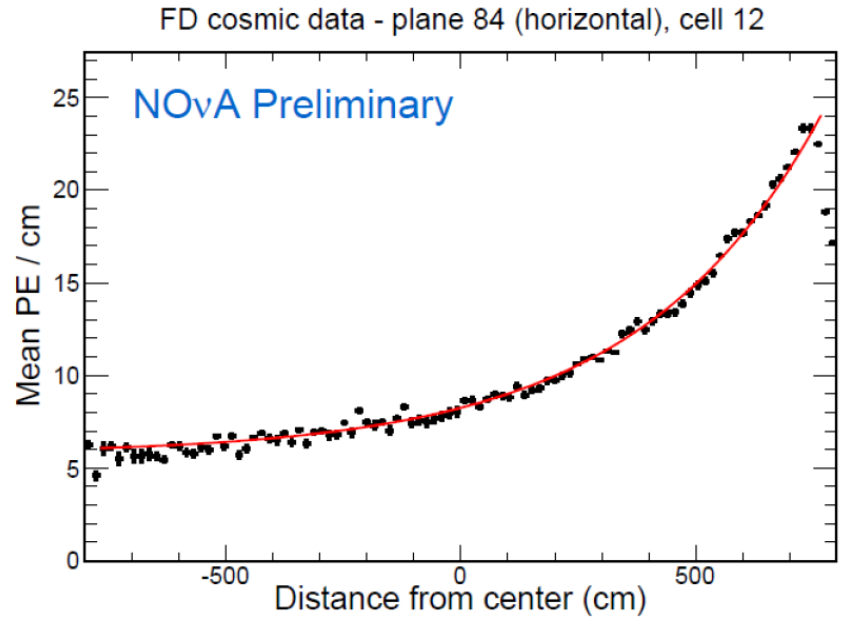
550 μs exposure of the Far Detector



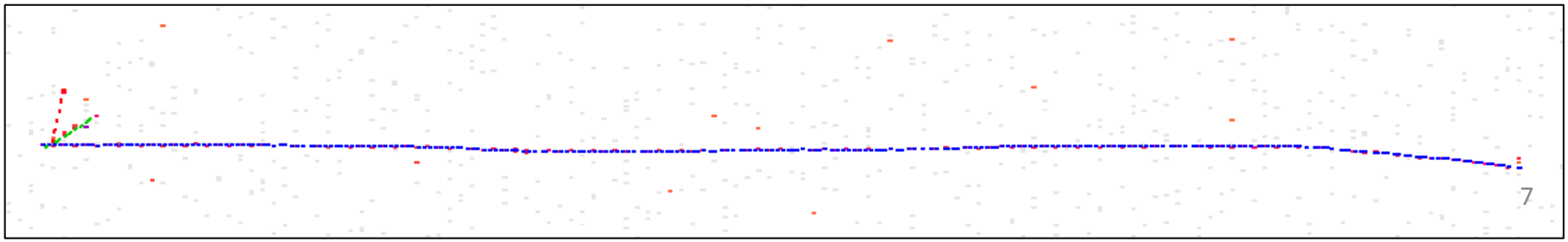
Time-zoom on 10 μs interval during NuMI beam pulse



Lots of pieces I don't have time to go into detail on!

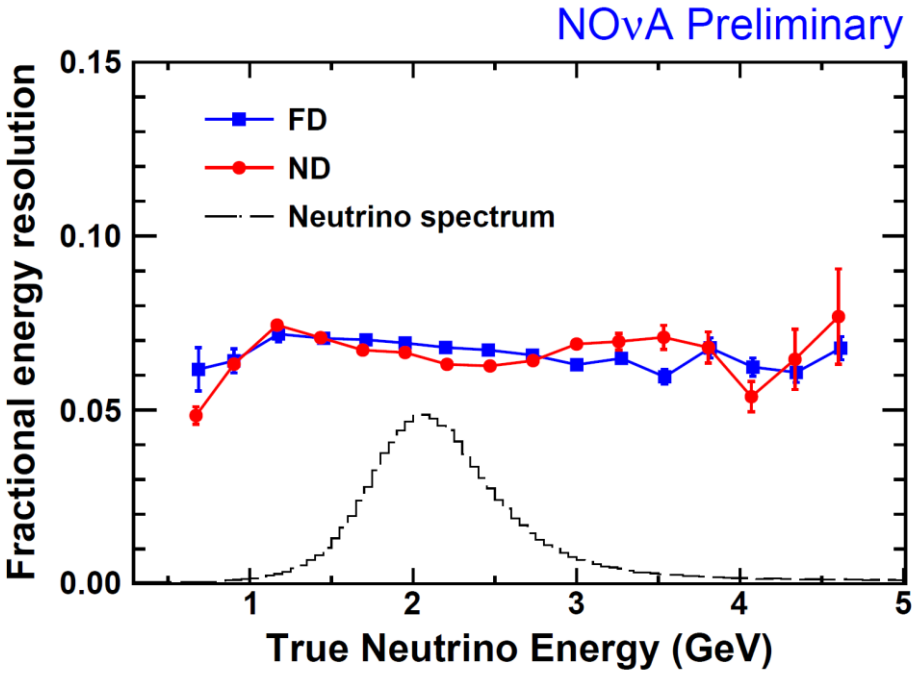


- **Calibration:**
  - Stopping μs → Absolute E scale
  - π^0, Michels, μ dE/dx …
  - WLS fiber attenuation corrections
- **Simulation:**
  - FLUKA/FLUGG: Beam hadron neutrino flux
  - GENIE: Neutrino interactions and FSI
  - GEANT4: Detector simulation
- **Reconstruction:**
  - Cluster in space and time (event)
  - Kalman filter based tracking



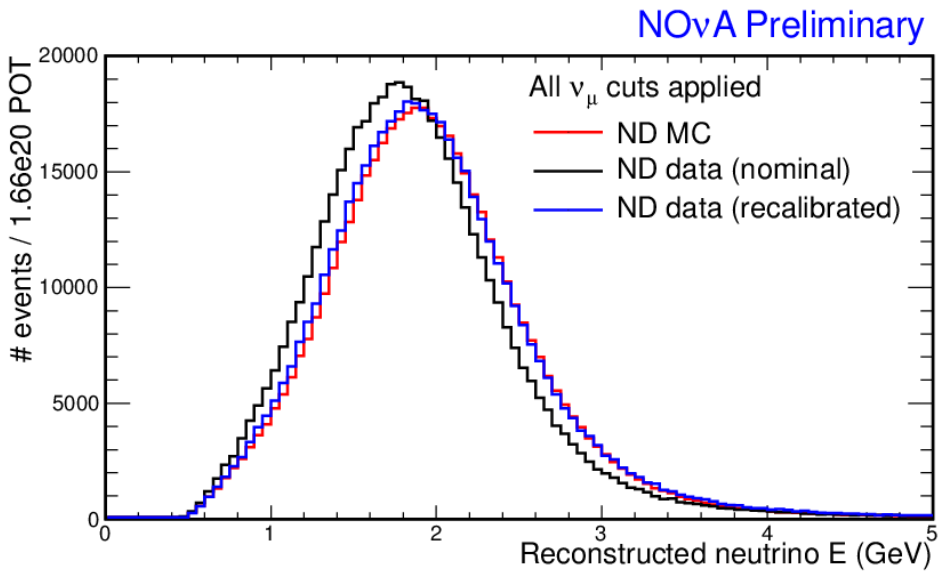
Energy Reconstruction:

- 2-part energy estimation:
  - 1) muon E from track length
  - 2) hadronic E from non-muon hit calorimetry
  - $E_\nu = E_\mu + E_{HAD}$
- ~ 7% FD energy resolution
- Estimators trained on MC



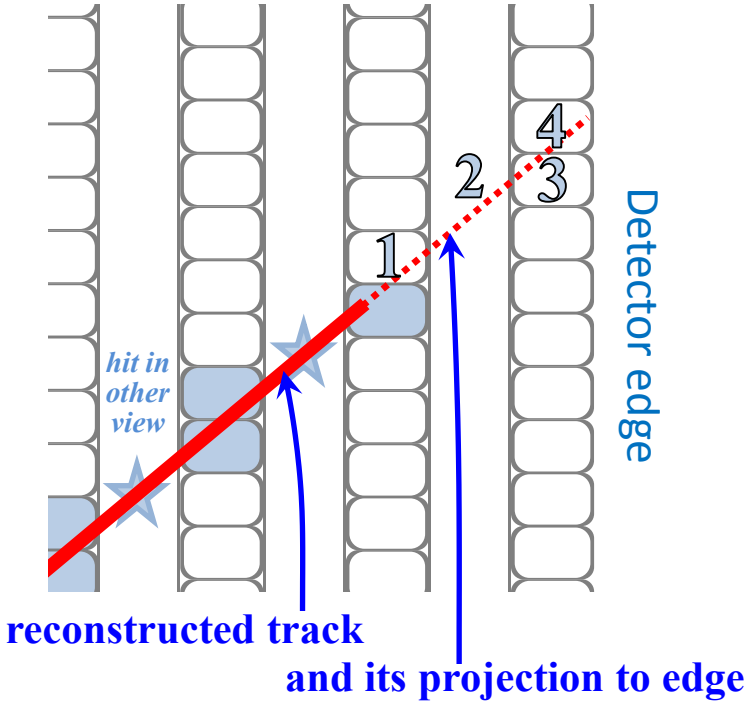
Hadronic E modeling:

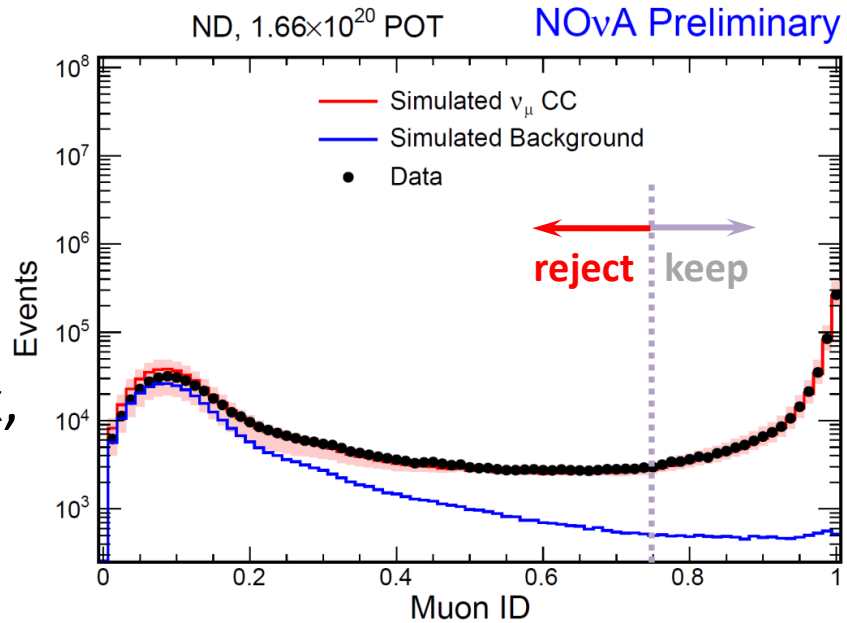
- Simulation (GENIE) hadronics inaccurate
- Not unexpected; limited data in this regime, no GENIE 2p2h
- Too many hadronic hits in MC, and thus too large of a reconstructed neutrino E
- To fix this we apply a 21% correction to hadronic E (6% E_ν)
- This fixes the neutrino E distribution, studies ongoing for deeper understanding
- This 21% is a recalibration applied to data to account for MC being off



Event Selection

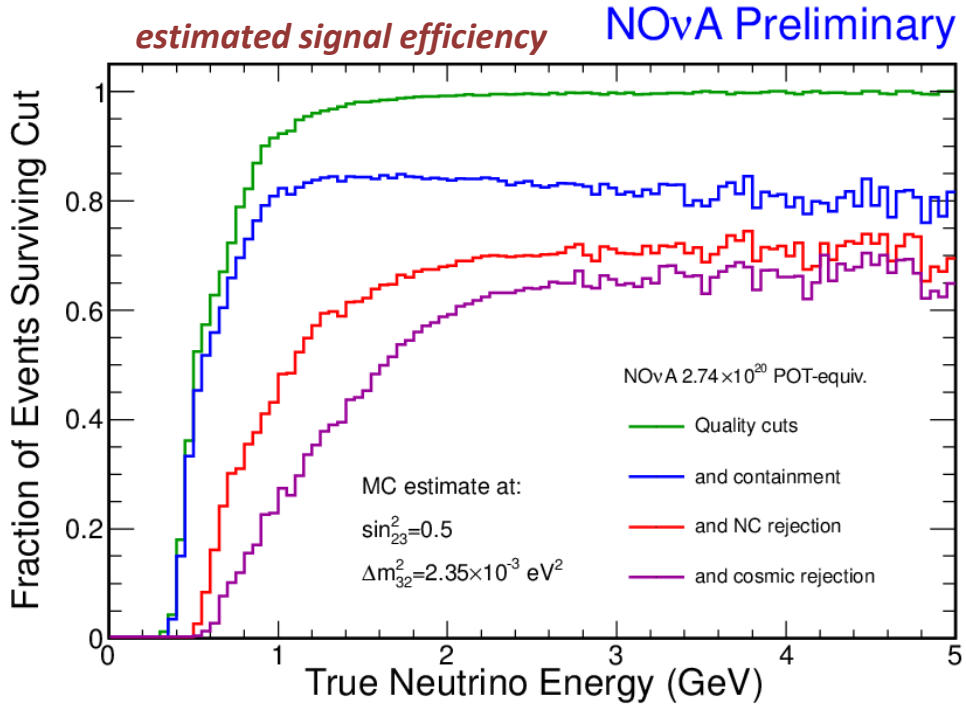
- Step 1: basic quality
  - remove unusable data
  - require good tracks
- Step 2: containment
  - veto events with activity in outer 2 cells
  - look at track projections to wall, veto if too few unhit cells to wall (<= 10 in FD)
- Step 3: select muons
  - use 4 parameter kNN
  - includes track length, dE/dx, scattering information
  - primary NC rejection

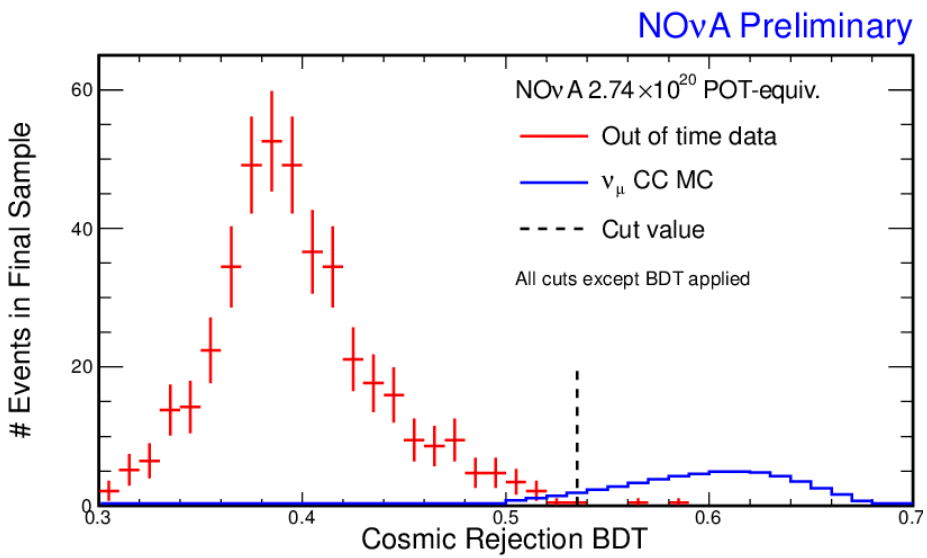


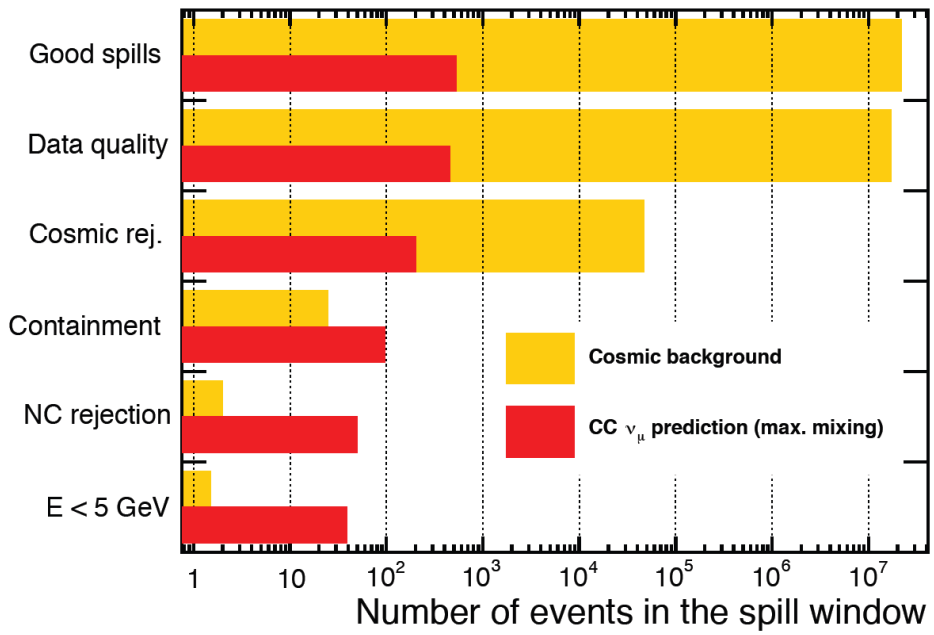


Event Selection

- Step 4: cosmic rejection
  - FD only (ND underground)
  - need ~10^7 cosmic reduction!
  - 11 variable BDT
  - main handles:
    - track directions
    - hadronic activity
    - nearness to detector top
  - BDT combined with hard cuts





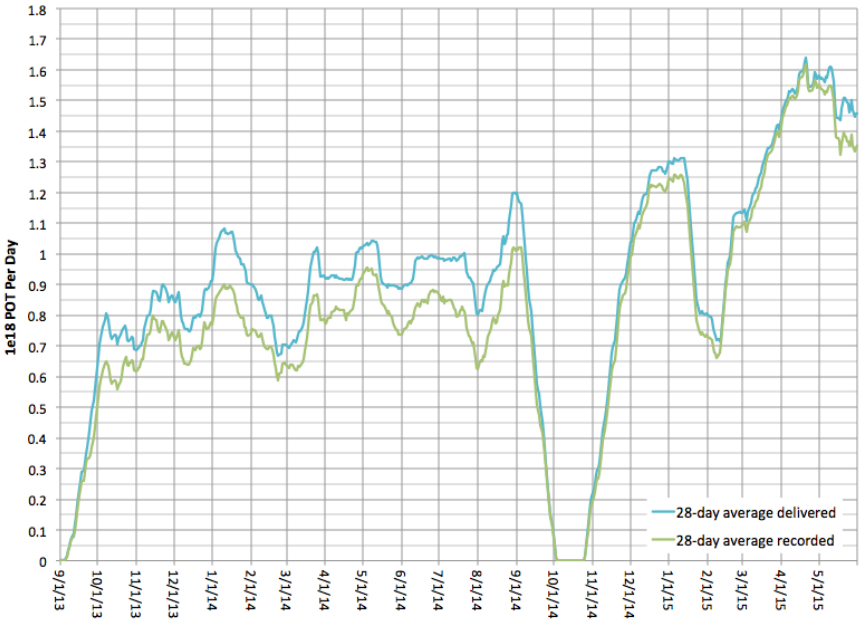


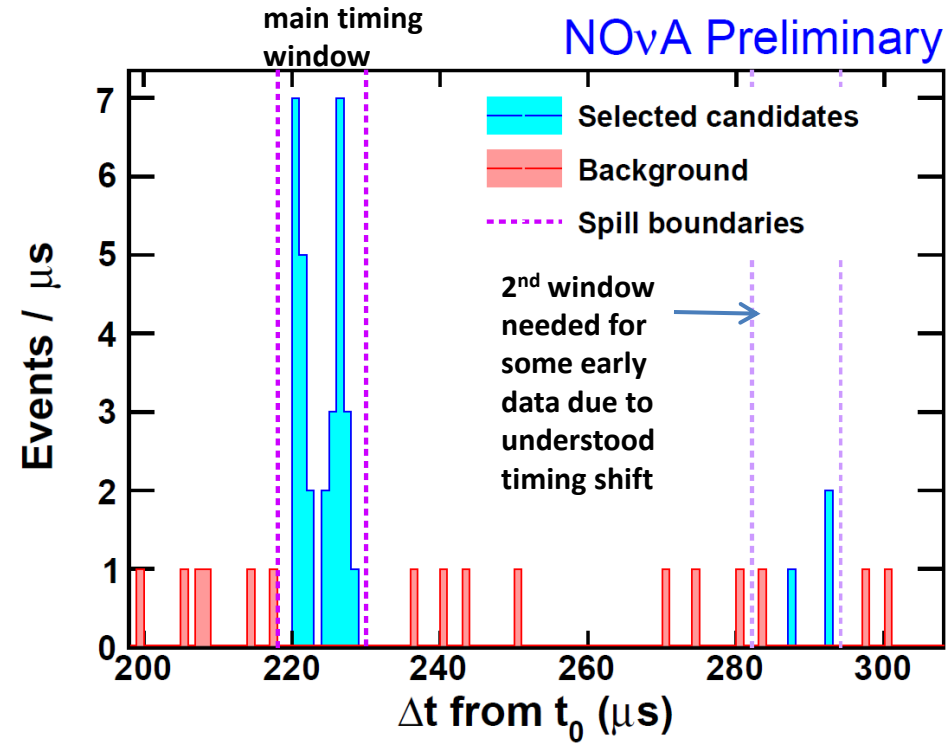
Extrapolation and Systematics

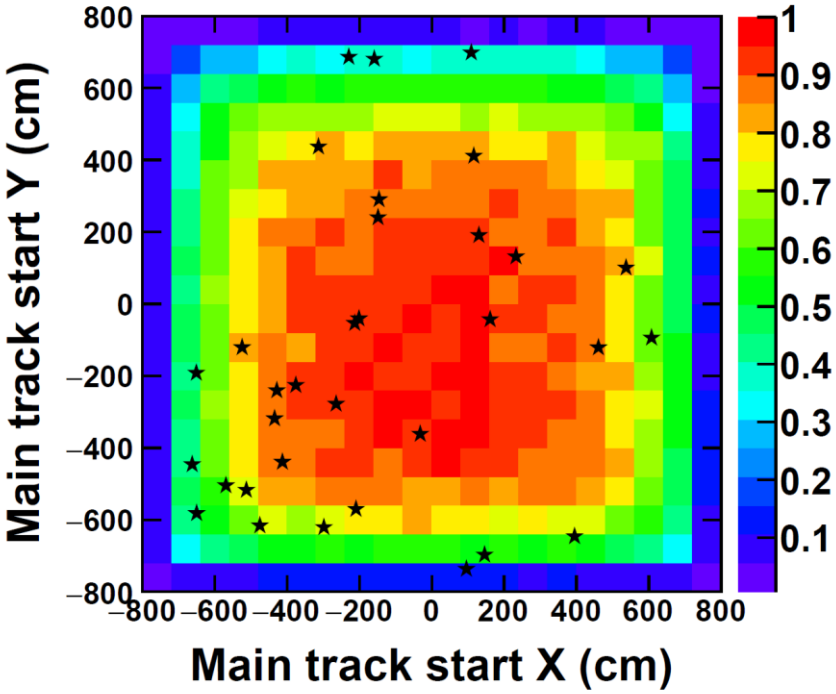
- The next talk is just about this! ***(L. Suter, Extrapolation Techniques…)***
- Basically a far/near extrapolation
- 16 systematics, 4 oscillation parameters marginalized over in fit
- Dominant systematic is 100% on E_{HAD} correction
- full 3 –flavor fit

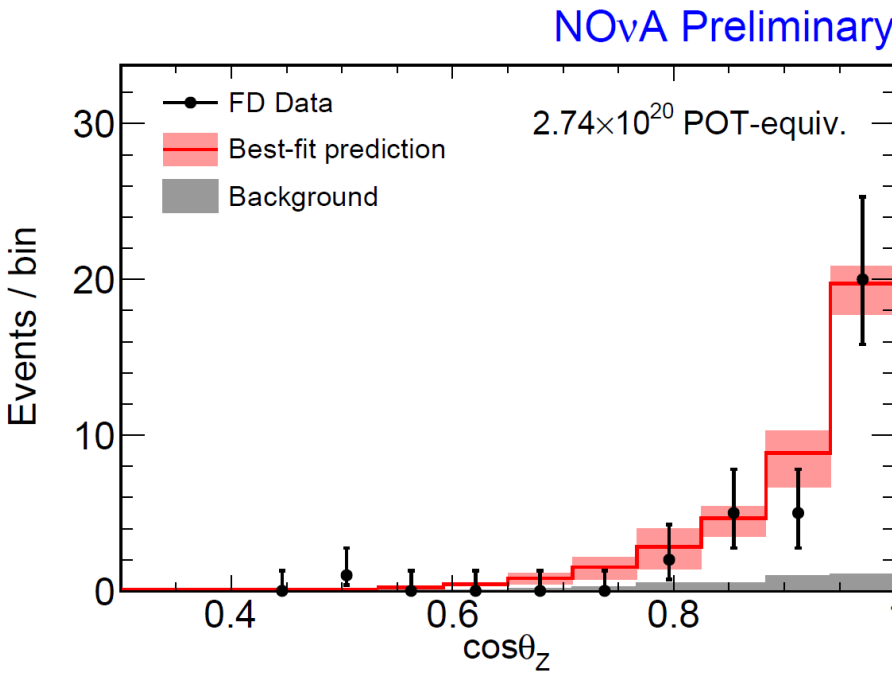
Data set

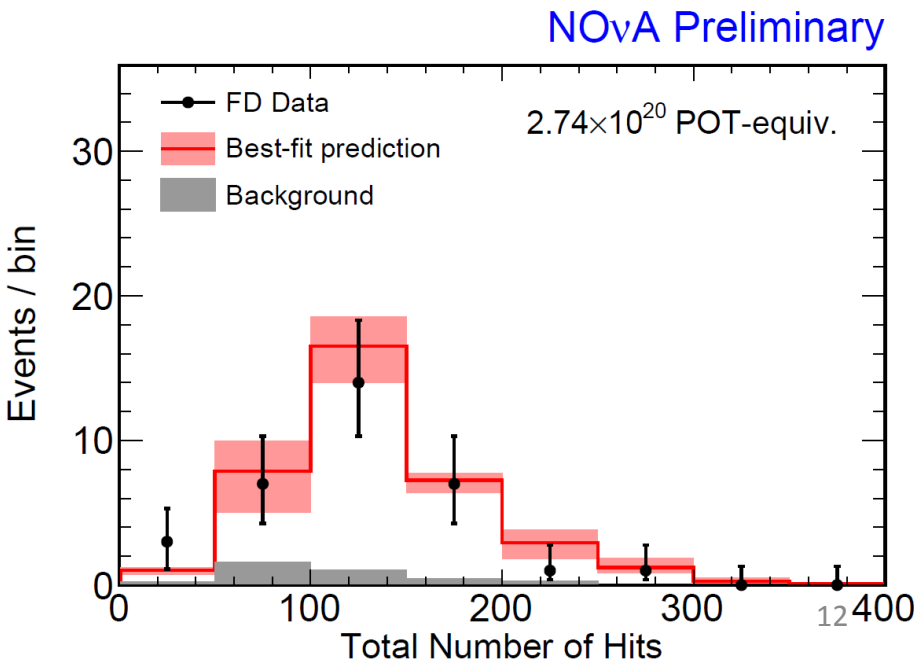
- Data taken as detector built; thus multiple FD detector configurations
- Simulations mirror this accurately
- FD: 3.466 x 10^{20} POT
- ND: 1.66 x 10^{20} POT
- Quote POT as 14 kton equiv. POT
- Allows easy comparison as we accumulate more data
- **First results public as of yesterday!**



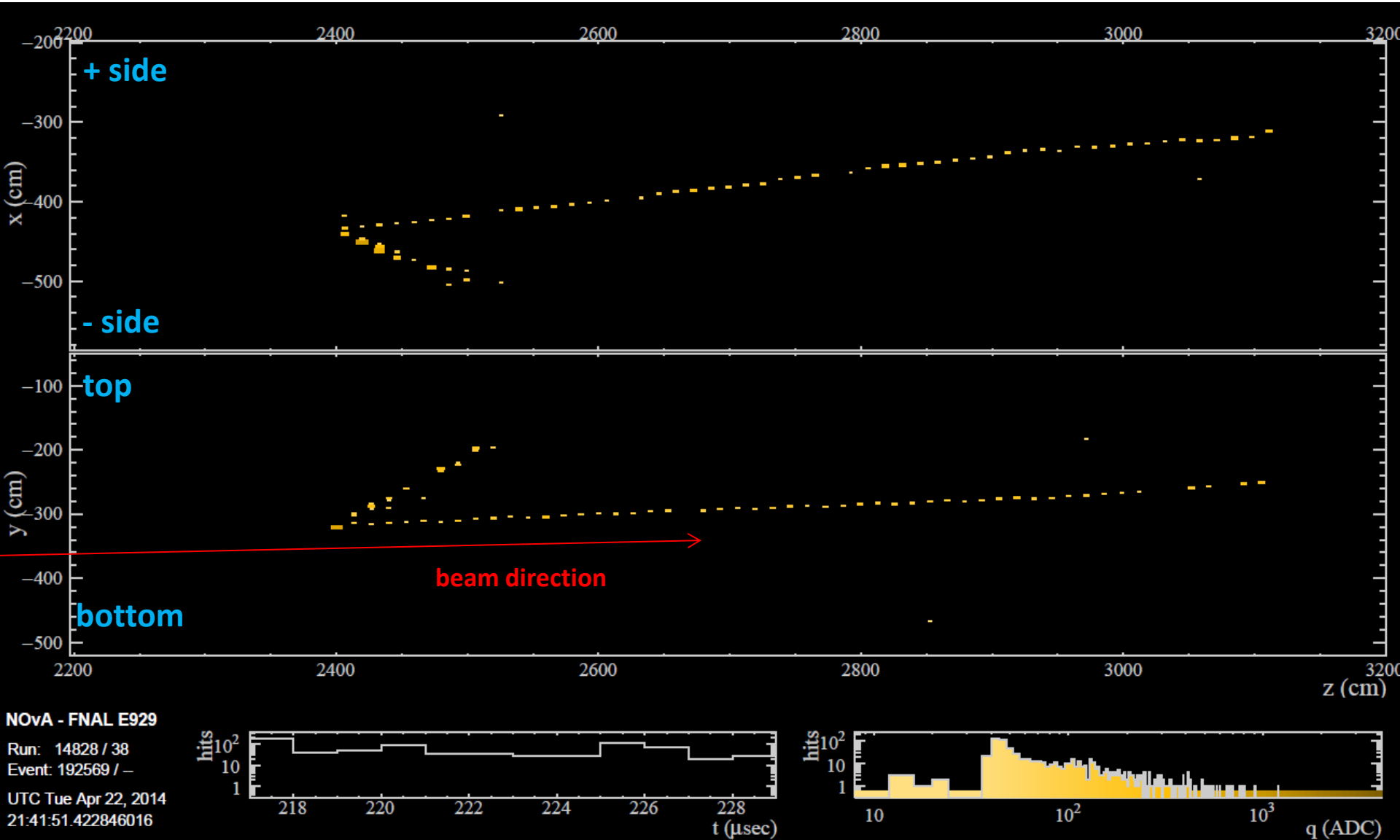

main timing window
NOνA Preliminary
Selected candidates
Background
Spill boundaries
2nd window needed for some early data due to understood timing shift
Events / μs
Δt from t0 (μs)


Main track start Y (cm)
Main track start X (cm)

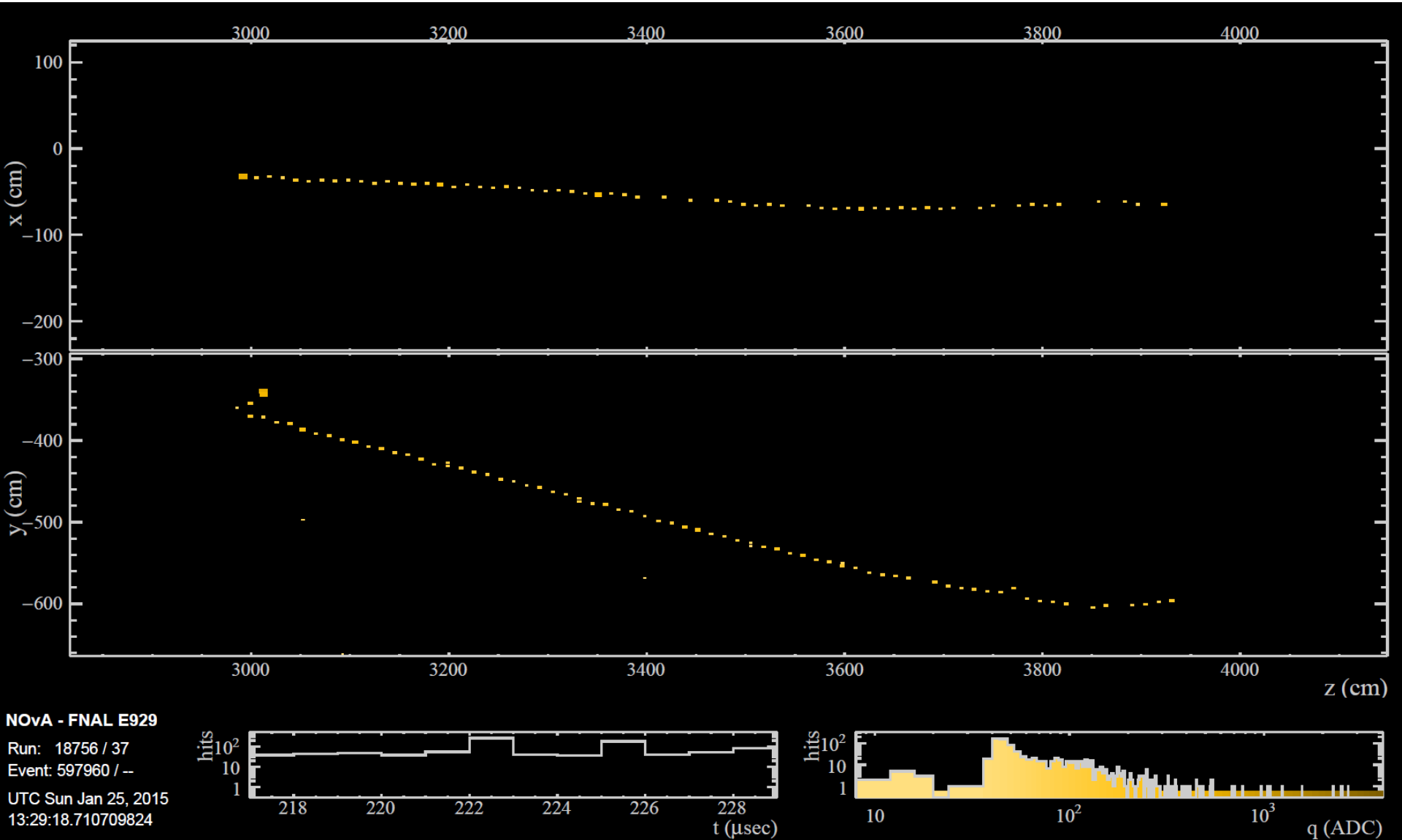

NOνA Preliminary
FD Data
Best-fit prediction
Background
2.74×10^20 POT-equiv.
Events / bin
cosθZ


NOνA Preliminary
FD Data
Best-fit prediction
Background
2.74×10^20 POT-equiv.
Events / bin
Total Number of Hits

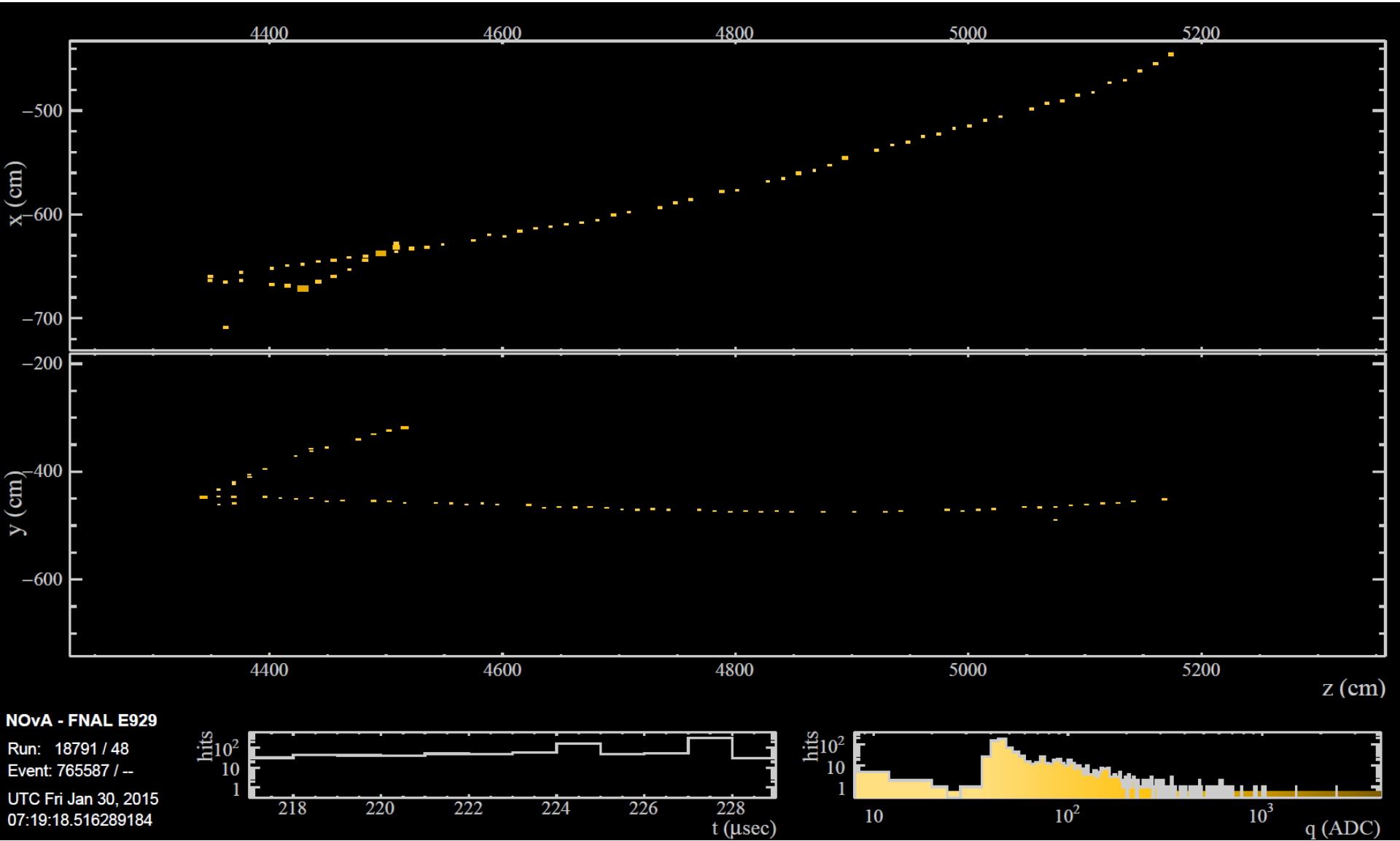
Example final sample event

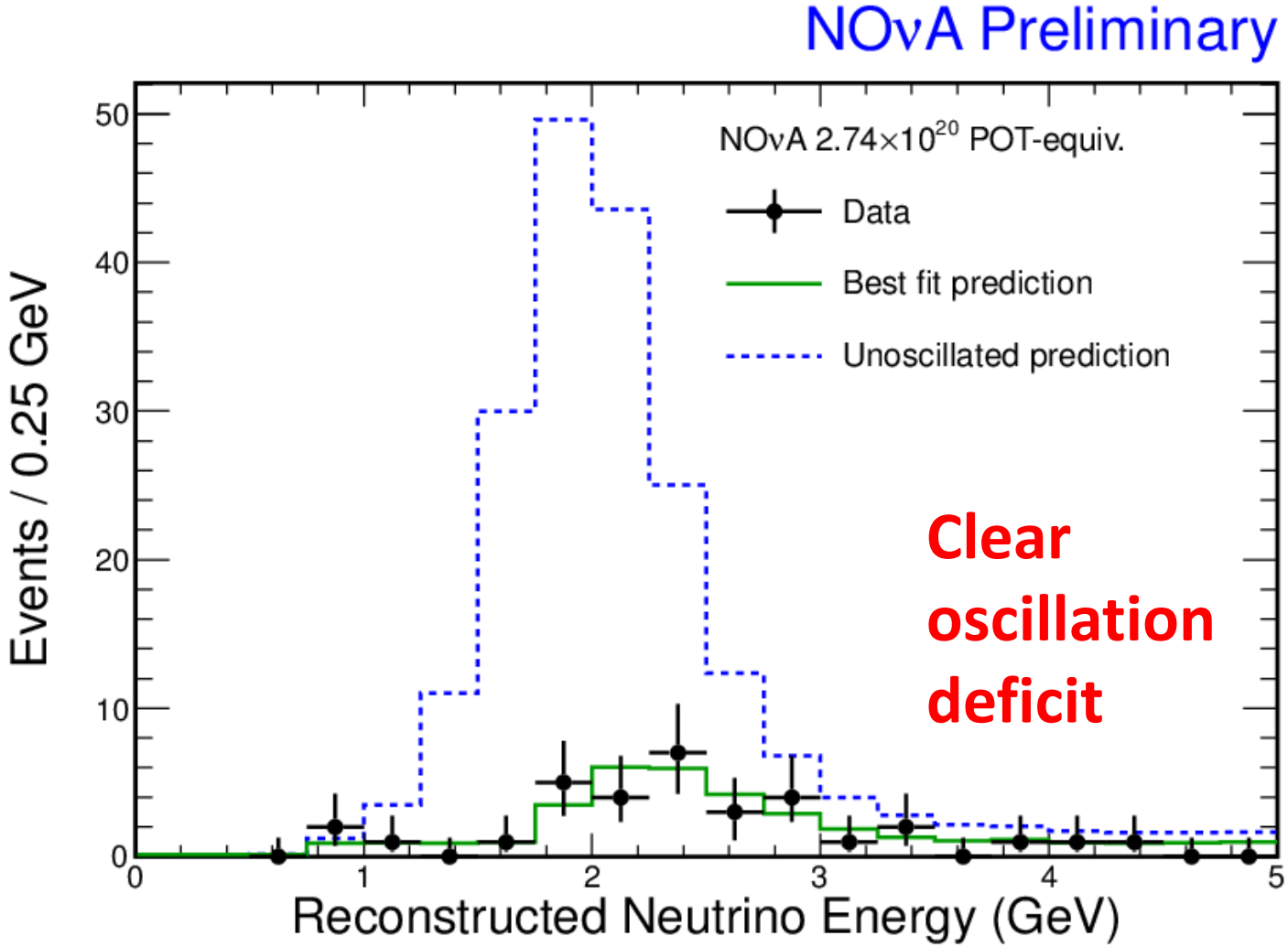


Example final sample event



Example final sample event





Real data: 33 events (0-5 GeV)

Unoscillated prediction: 201 events

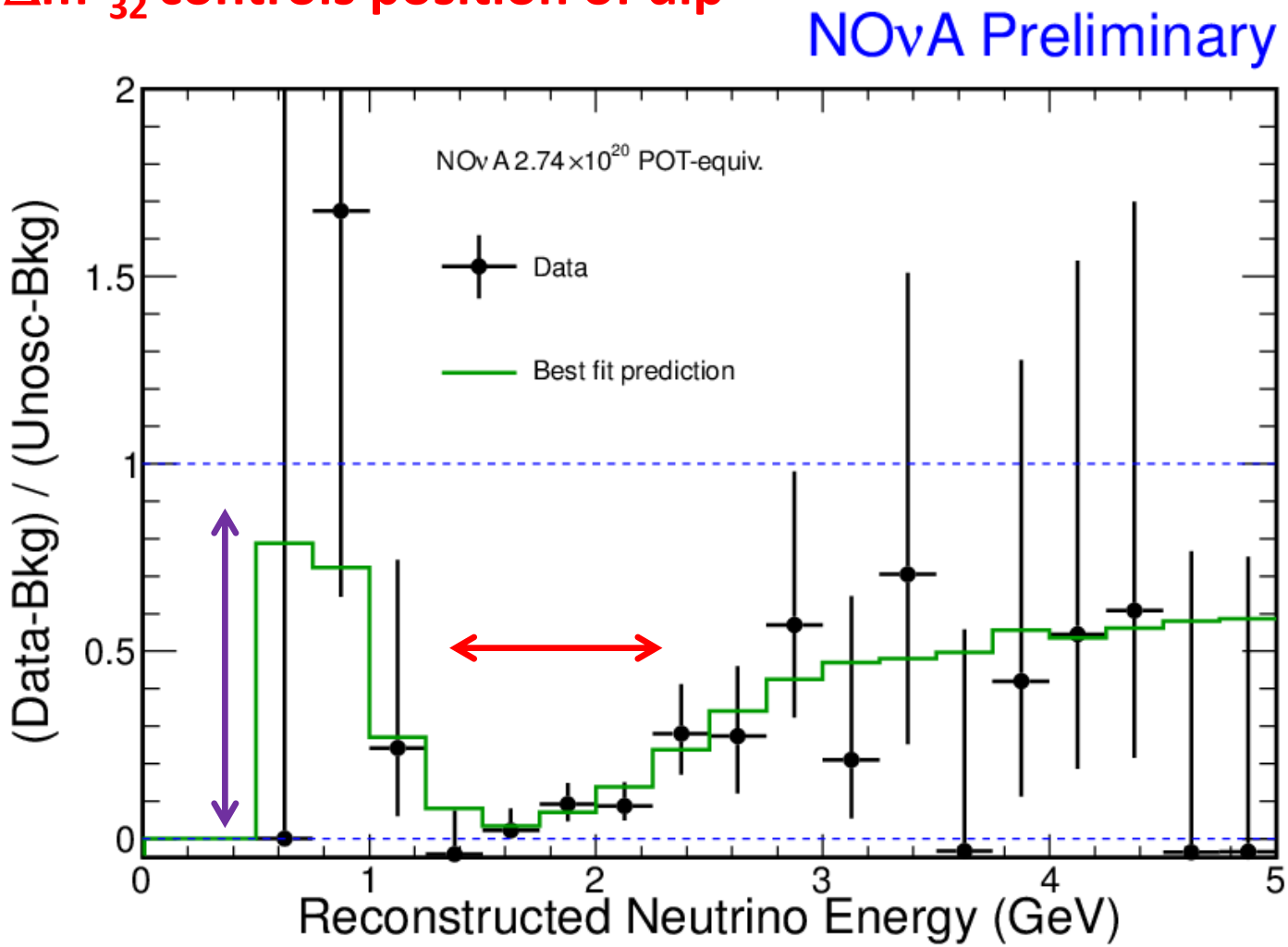
1.4 ± 0.2 of which are cosmics (cosmic estimation: out of time data)

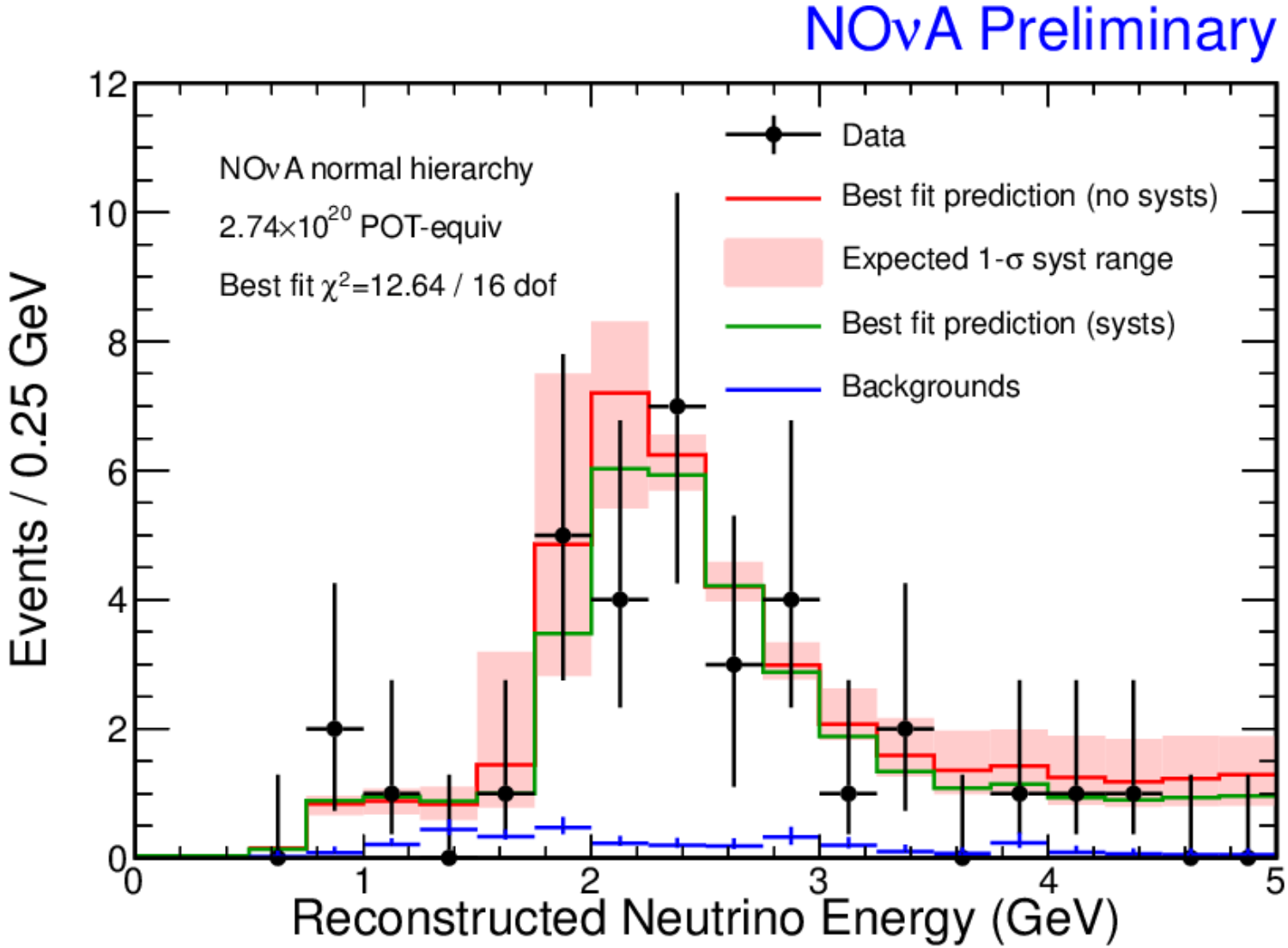
2.0 of which are other background (from simulation, mostly NC)

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

θ_{23} controls normalization

Δm^2_{32} controls position of dip





Best fit: 12.64 / 16 d.o.f.

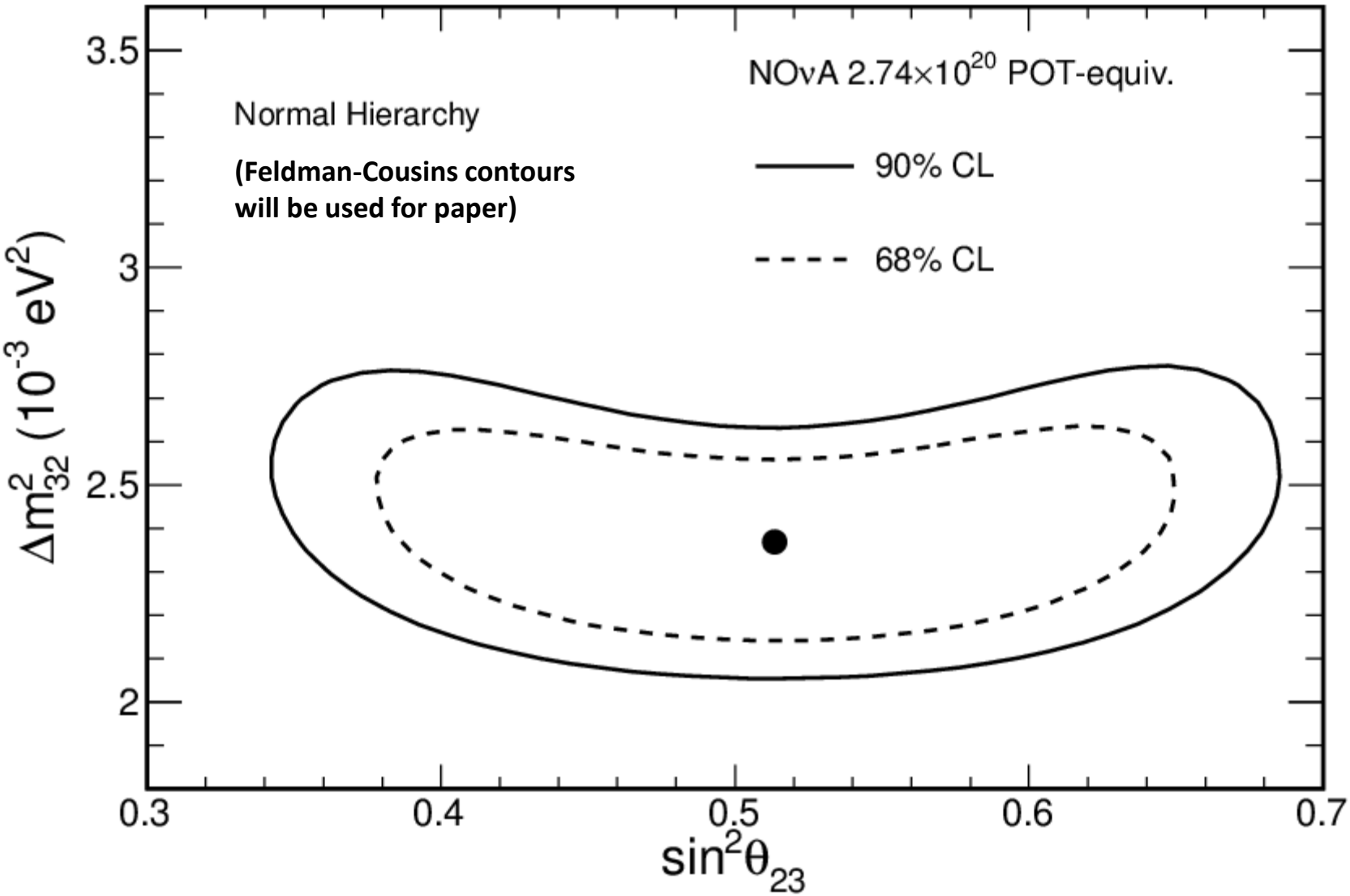
systematics pull fit due to deficit of data in high E tail

1-D 68% limits:

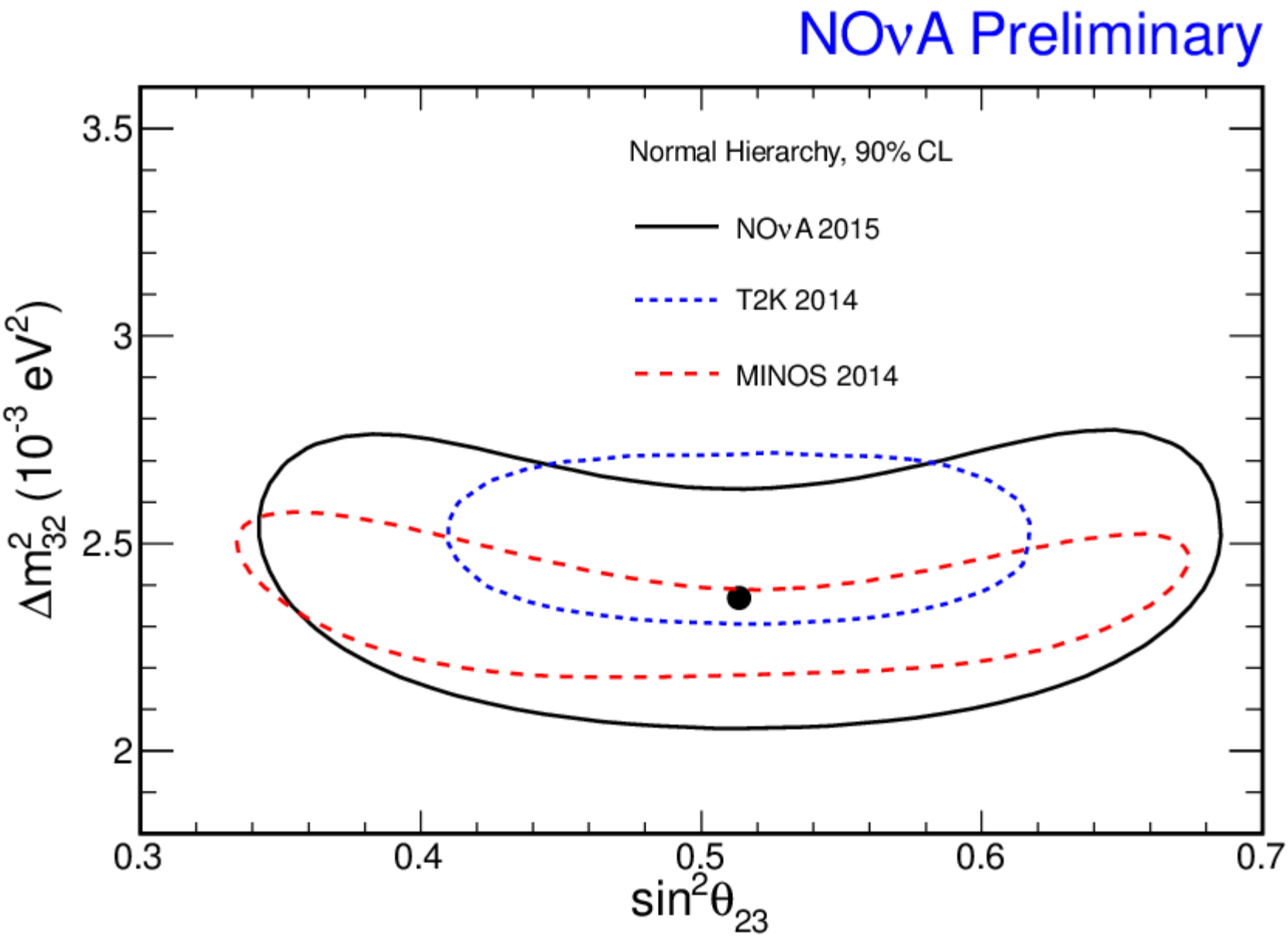
$$\Delta m^2_{32} = 2.37\ ^{+0.16}_{-0.15} \times 10^{-3}\ \mathrm{eV}^2$$

$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

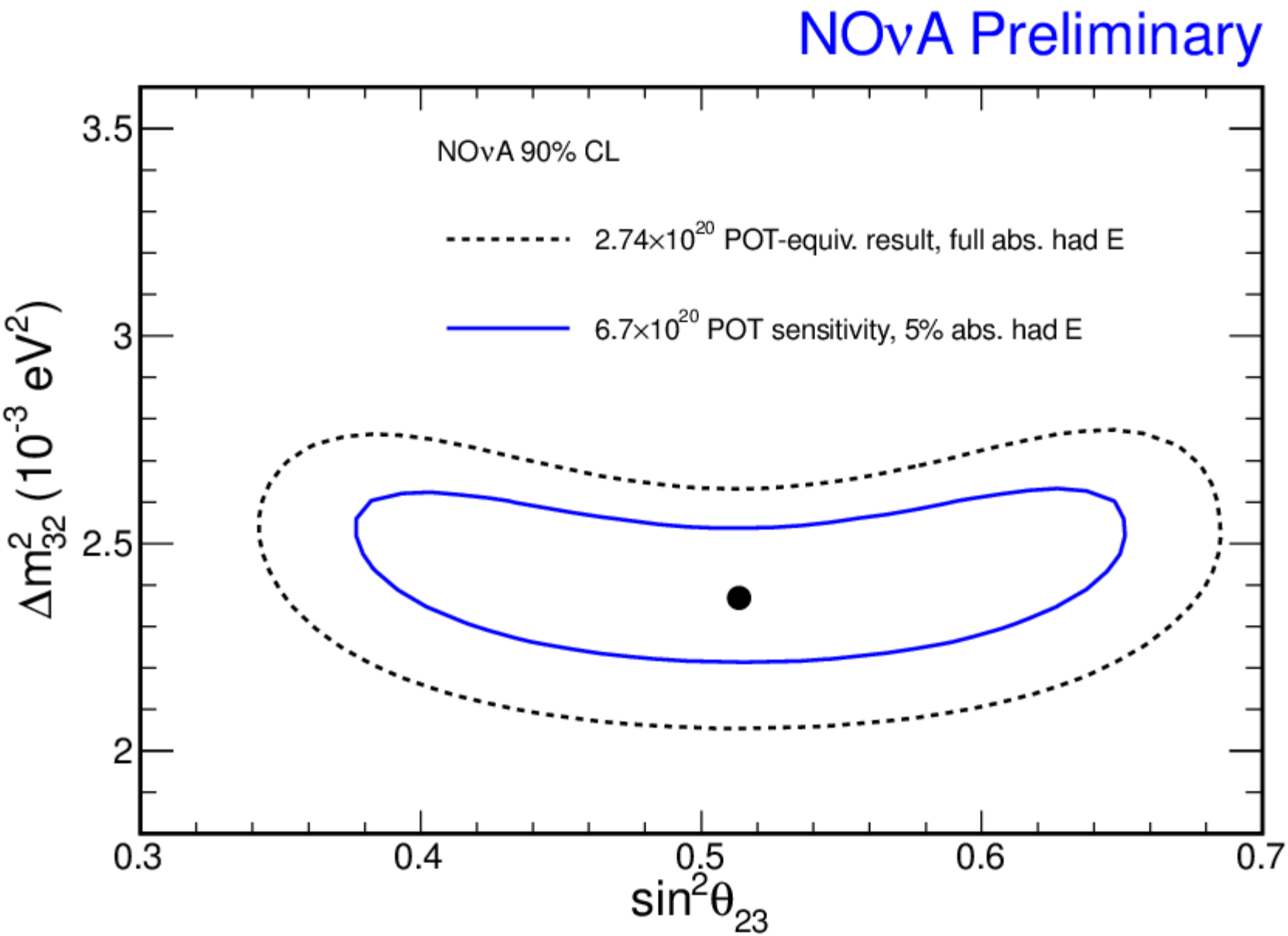
NOνA Preliminary



Agreement with T2K and MINOS
This is only 7.6% of NOνA total planned exposure!



with 1 more year data, and the hadronic E better understood



Conclusions

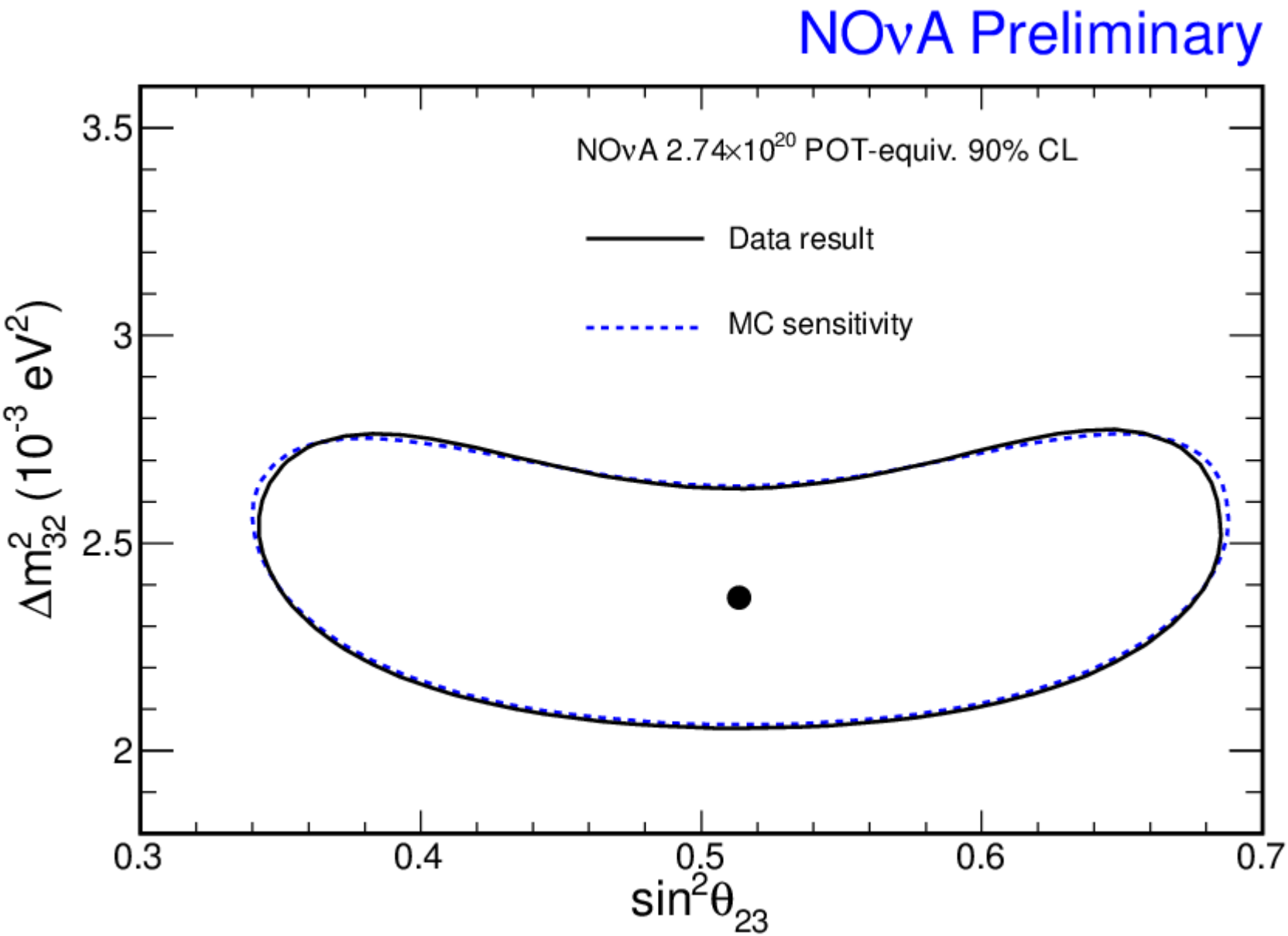
- NOνA detector complete, beam partially upgraded, more upgrades underway
- NOνA first results public (as of just yesterday!)
- Disappearance analysis sees clear oscillations
- Contours agree with T2K, MINOS
- Less than 8% of final exposure so far!
- Look for more soon!

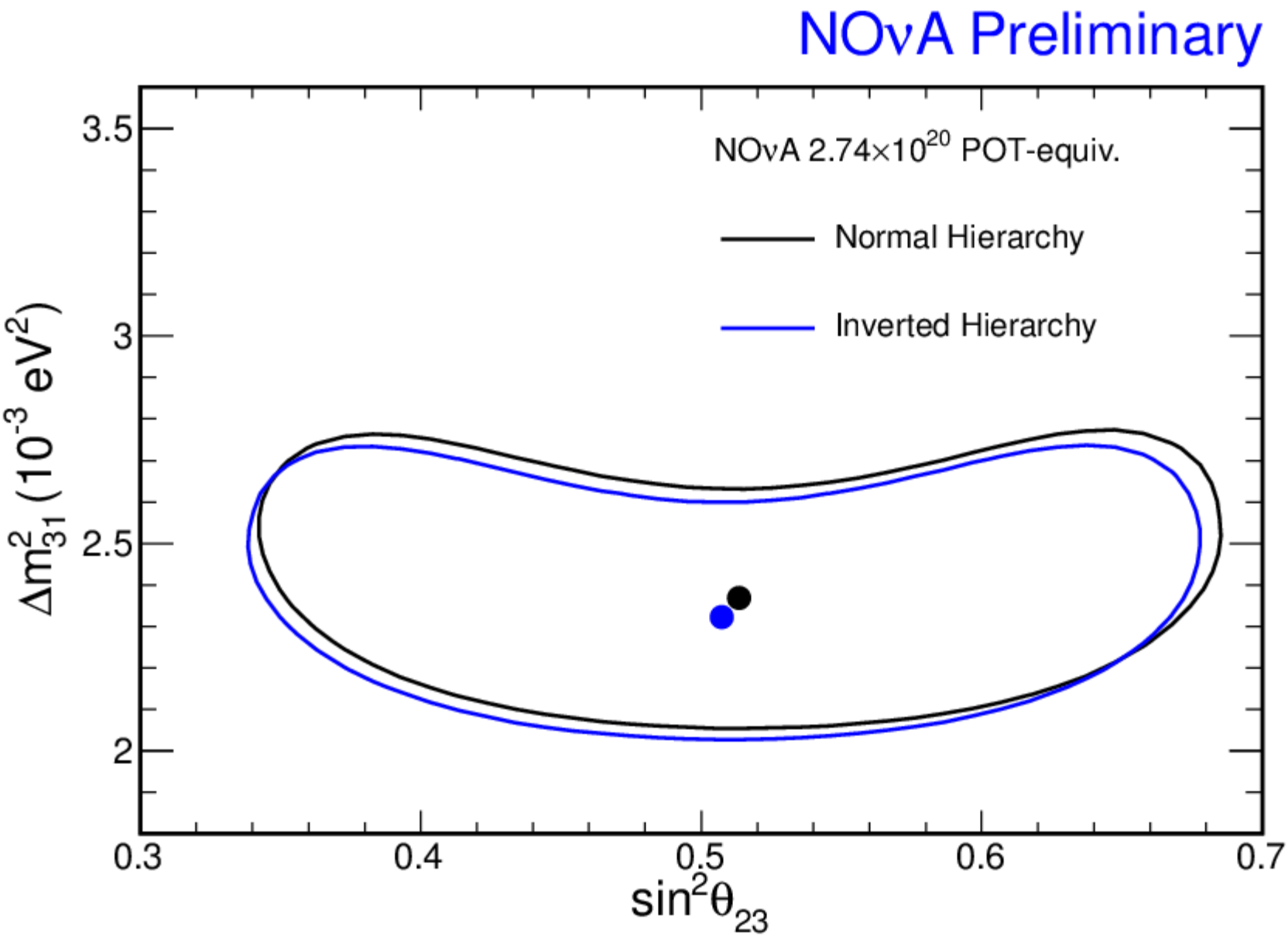
Thanks!

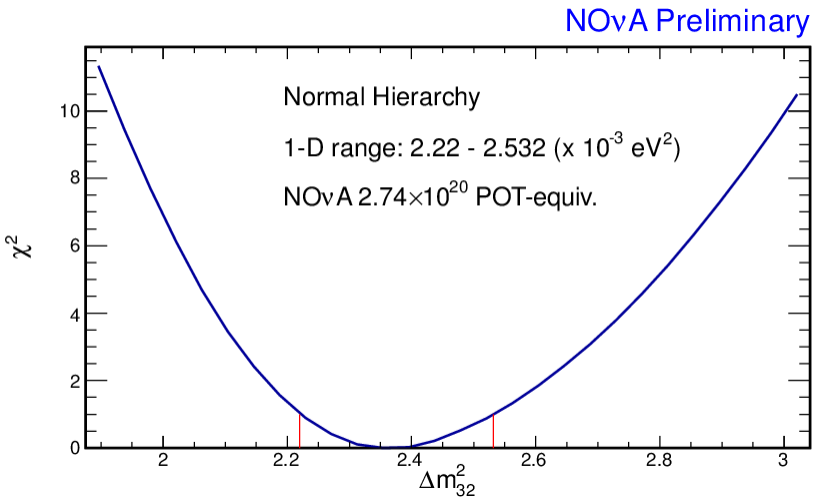
~40 Institutions, > 220 members, 6 countries

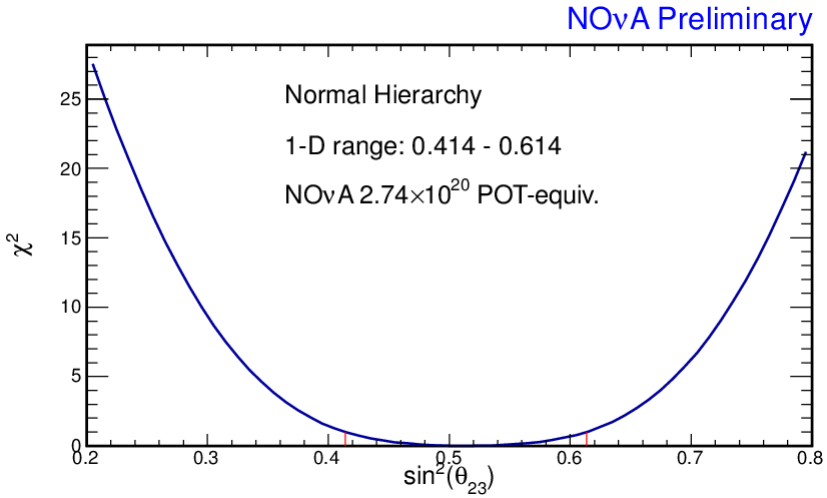
Backups

Very close agreement with MC estimated sensitivity!

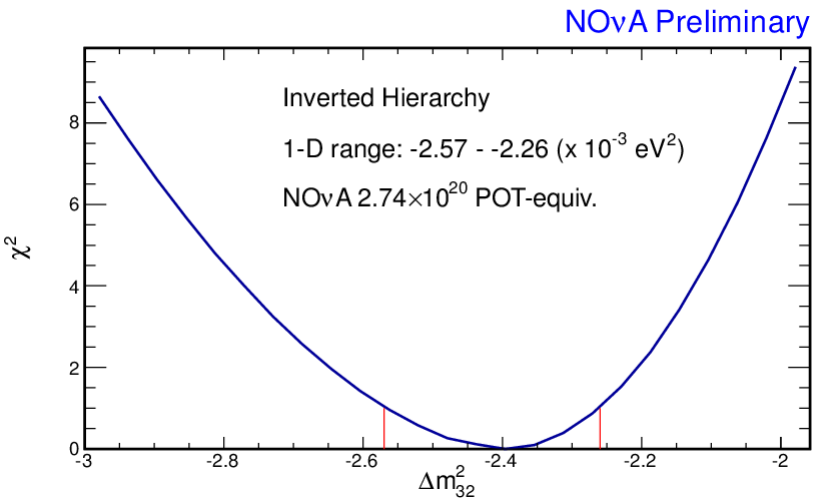


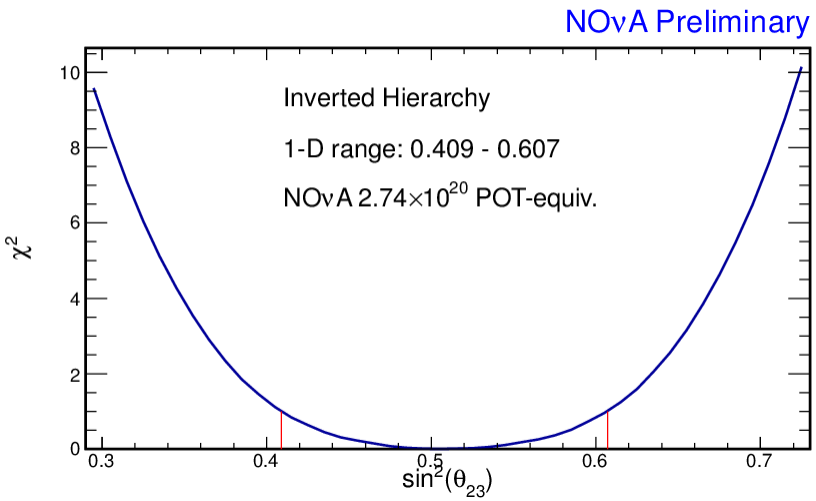

NOνA Preliminary
NOνA 2.74×10^20 POT-equiv.
Normal Hierarchy
Inverted Hierarchy
3.5
3
2.5
2
0.3
0.4
0.5
0.6
0.7
Δm²₃₁ (10⁻³ eV²)
sin²θ₂₃

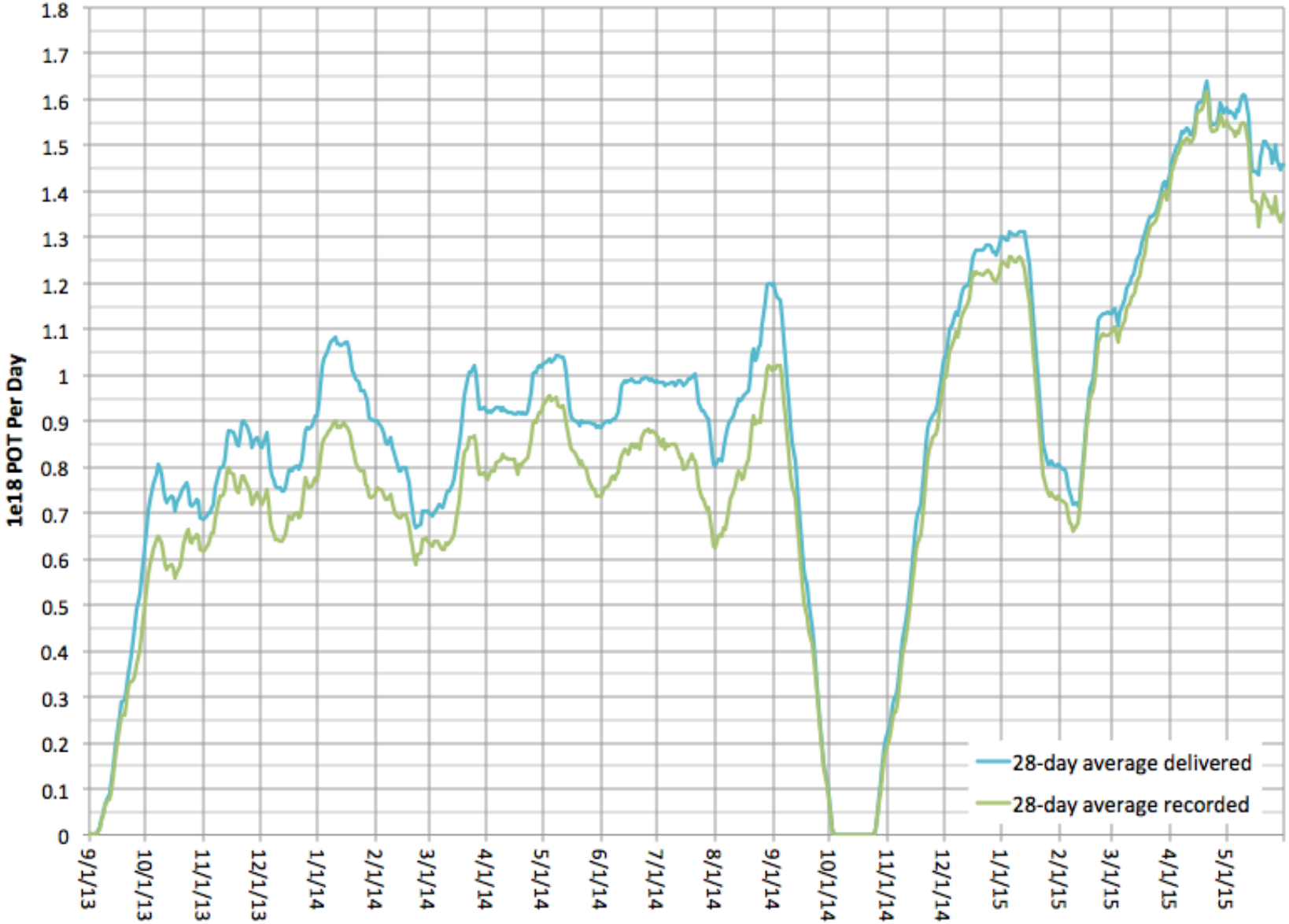


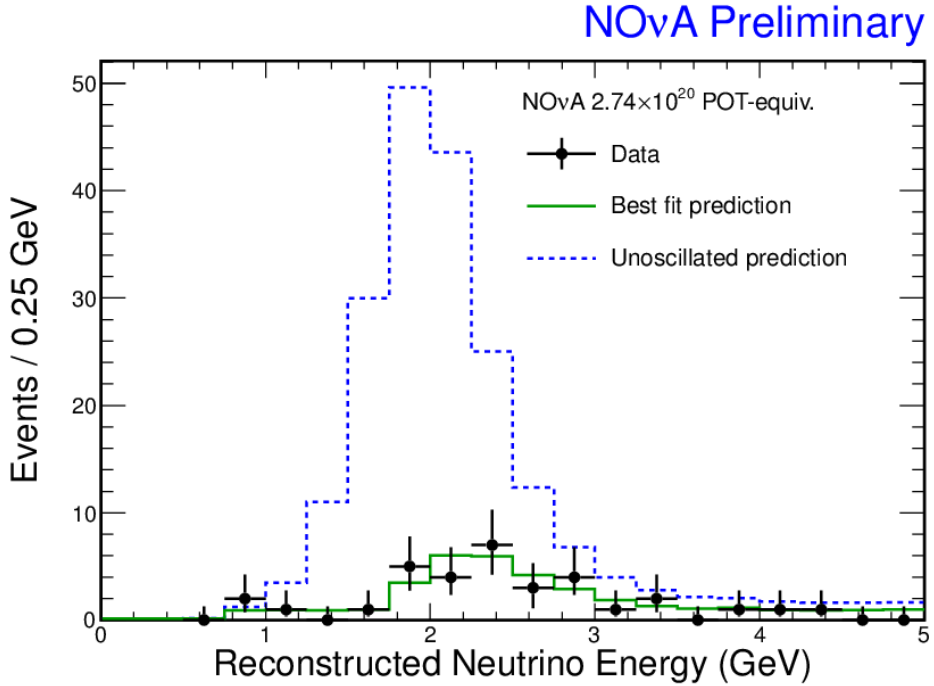


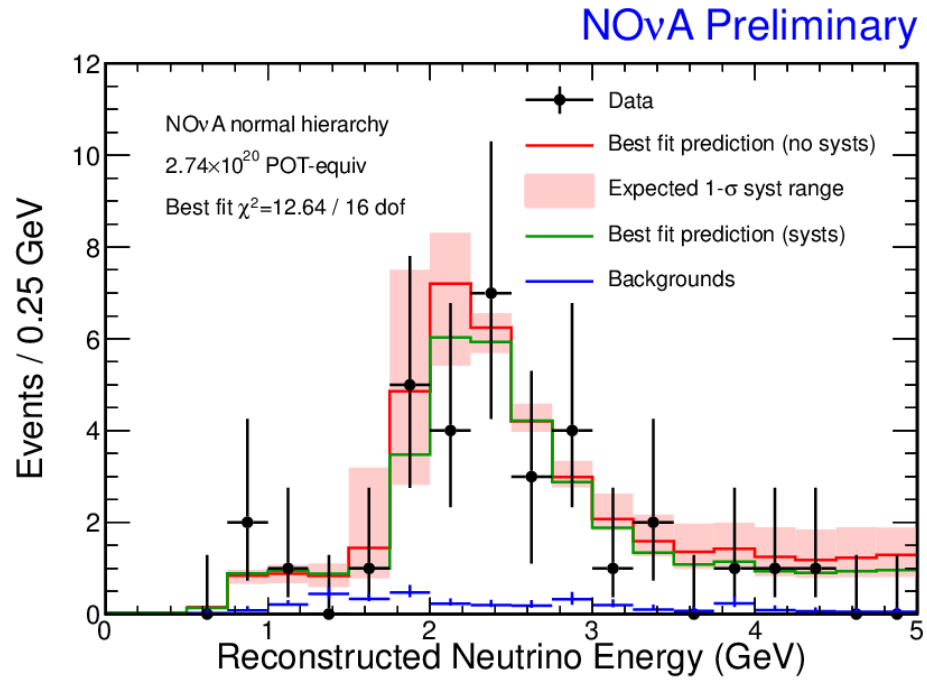
1-D χ^2 profiles

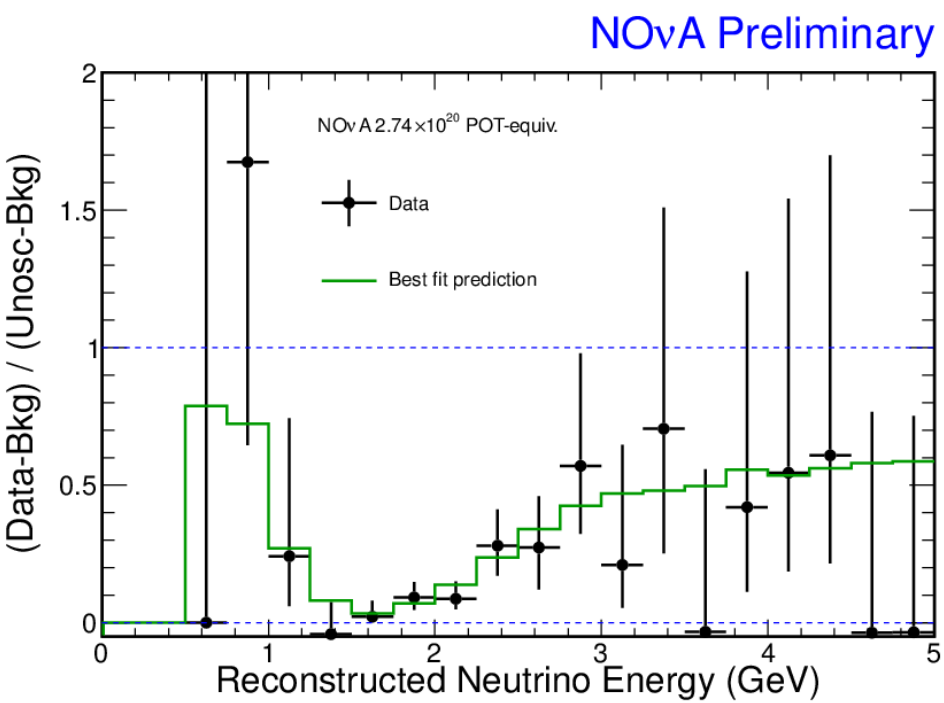





1e18 POT Per Day
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
9/1/13
10/1/13
11/1/13
12/1/13
1/1/14
2/1/14
3/1/14
4/1/14
5/1/14
6/1/14
7/1/14
8/1/14
9/1/14
10/1/14
11/1/14
12/1/14
1/1/15
2/1/15
3/1/15
4/1/15
5/1/15
28-day average delivered
28-day average recorded







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