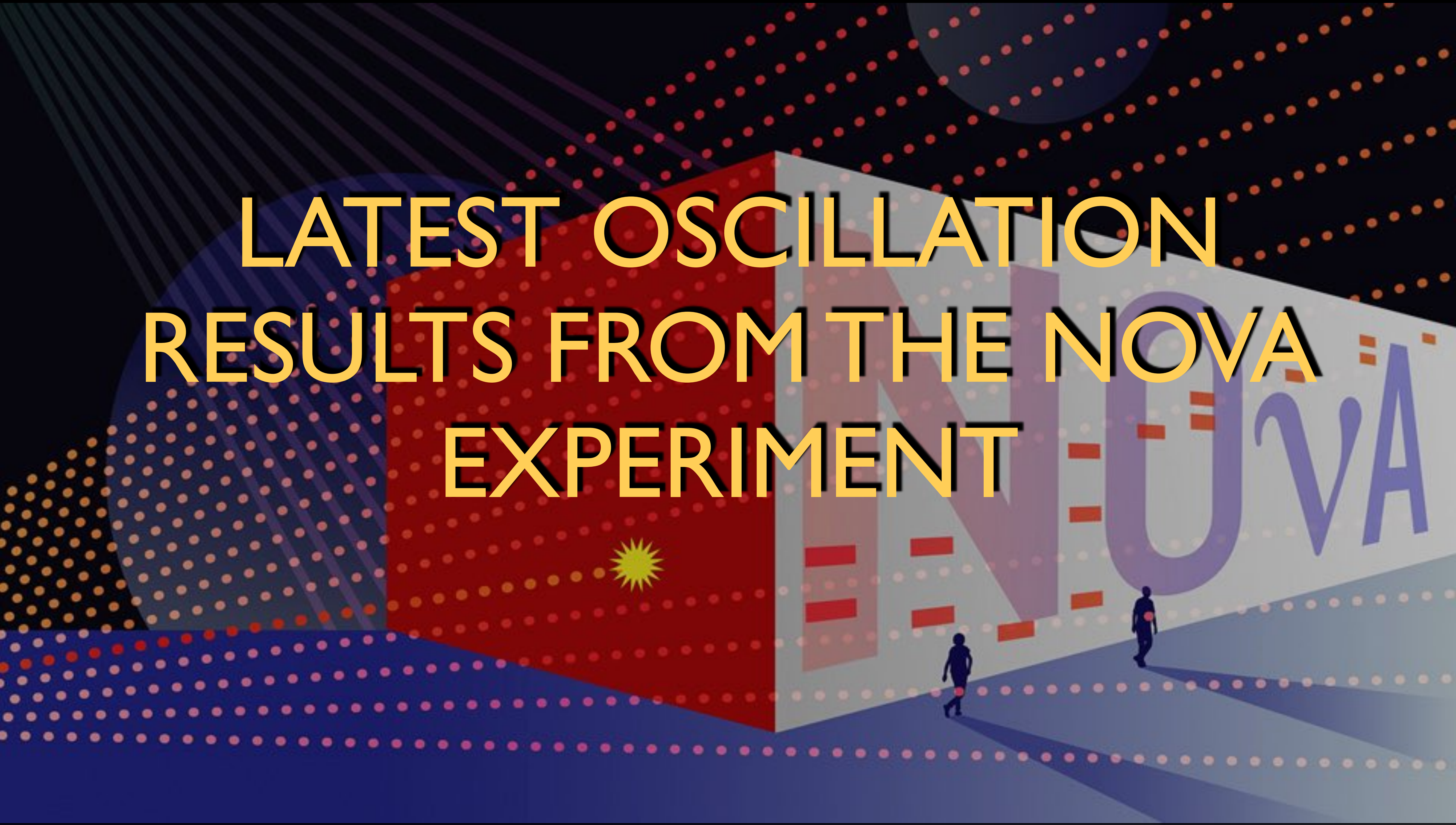
LATEST OSCILLATION RESULTS FROM THE NOVA EXPERIMENT



Bruno Zamorano

Granada - 23rd October 2018

Neutrino oscillations overview

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\mu e} = \sum_{j,k} U_{ej}^* U_{\mu j} U_{\mu k}^* U_{ek} \exp\left(-i\frac{\Delta m_{jk}^2 L}{2E}\right)$$

Oscillations

Neutrino oscillations overview

PMNS matrix

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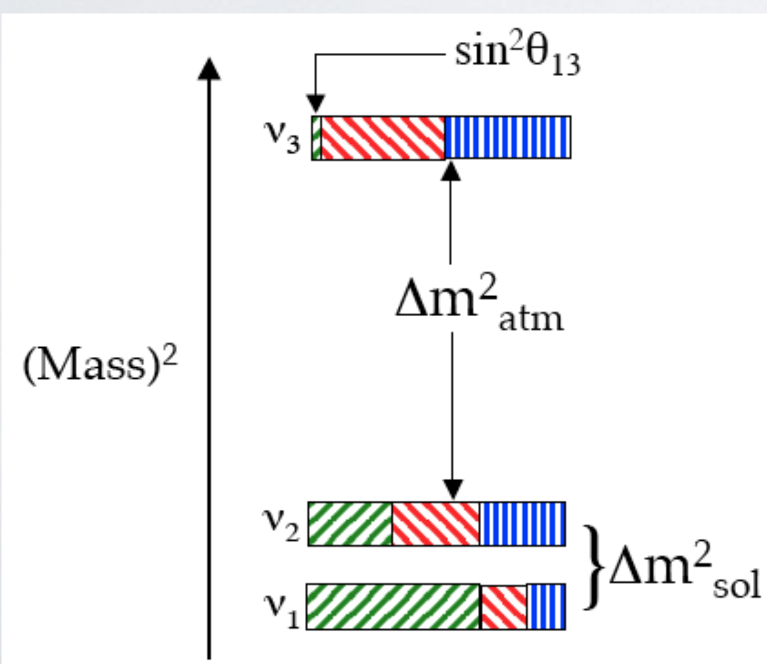
Oscillations

Atmospheric — Reactor — Solar

$$\begin{pmatrix}U_{e1} & U_{e2} & U_{e3}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3}\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \times \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta}\\ 0 & 1 & 0\\ -s_{13}e^{-i\delta} & 0 & c_{13}\end{pmatrix} \times \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}$$

Accelerators



$$\Delta m^2_{32} \simeq \Delta m^2_{31} \xrightarrow{Osc.max} L/E \approx 500\text{km/GeV}$$

$$\Delta m^2_{21} = m^2_2 - m^2_1 \xrightarrow{Osc.max} L/E \approx 15000\text{ km/GeV}$$

How well measured?

Solar	→ δm^2	2.8%
Atmosp.	→ Δm^2	1.3%
Solar	→ $\sin^2\theta_{12}$	4.2%
Reactor	→ $\sin^2\theta_{13}$	3.4%
Atmosp.	→ $\sin^2\theta_{23}$	~9%

NuFit 3.2 (2018), www.nu-fit.org

Most angles and masses have been measured using more than one experimental technique, including **accelerator-based**

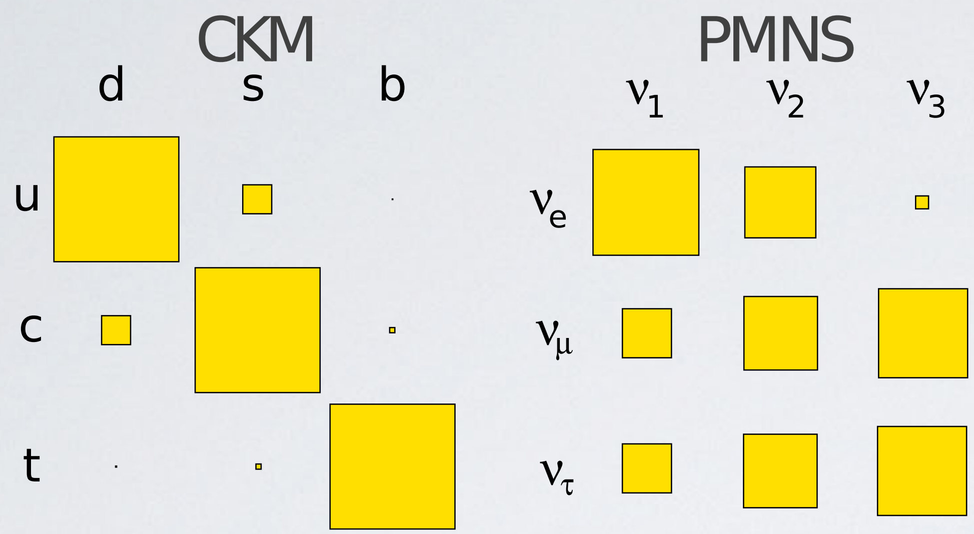
Measurable with accelerator experiments

- Is $\sin^2\theta_{23}$ maximal? ($\theta_{23} = \pi/2$?)
- Is there CP violation in the lepton sector?
- What's the mass-hierarchy? (is $m_3 > m_2$ or vice versa?)
- Are there more than 3 neutrino flavours? Is there a sterile neutrino?

Not directly measurable with accelerators

- Are neutrinos Dirac or Majorana?
- What's the mass scale?

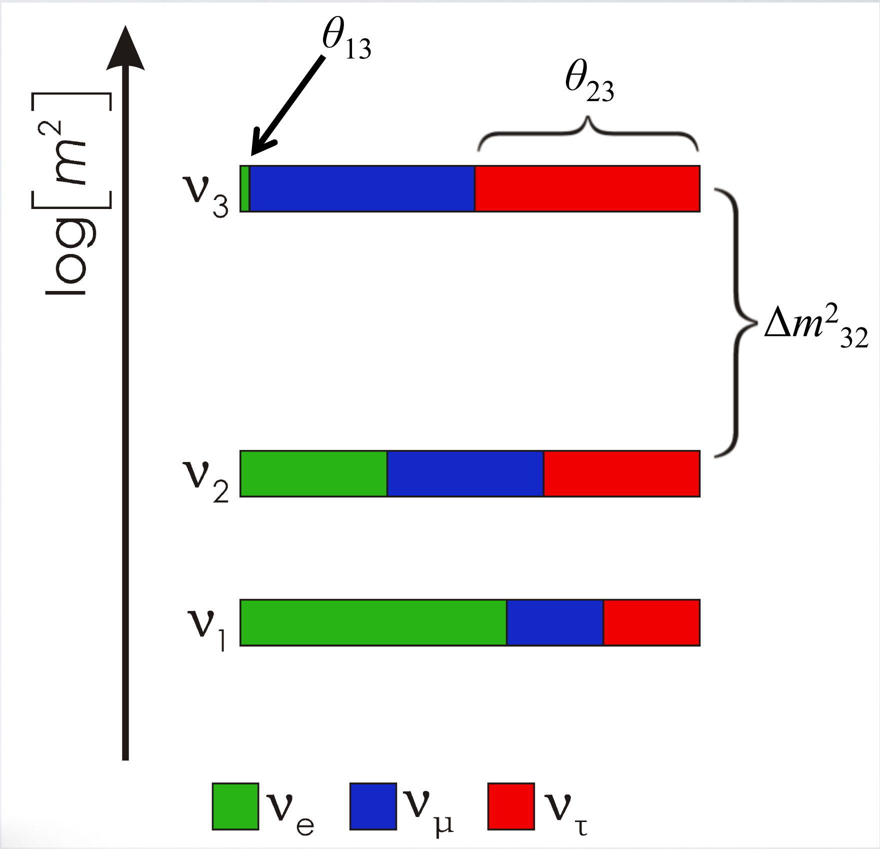
Models for neutrino mass



PMNS matrix is analogous to CKM in the quark sector

But, unlike quarks, mixings in the PMNS are large! Is there a pattern?

Normal hierarchy



- Only a small fraction of ν_e in $|\nu_3\rangle$: $\sin^2(2\theta_{13})$
- The remainder is split ~ 50/50 between ν_μ and ν_τ
- Accident or underlying symmetry? Is it really 45° or…
  - < 45°: $|\nu_3\rangle$ more ν_τ, like the quarks
  - > 45°: $|\nu_3\rangle$ more ν_μ, unlike quarks

Importance of reactor result

$$\times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times$$

$$CP \text{ violation} \Longleftrightarrow \theta_{13} \neq 0$$

Daya-Bay 2012

$\theta_{13} \sim 8.5°$

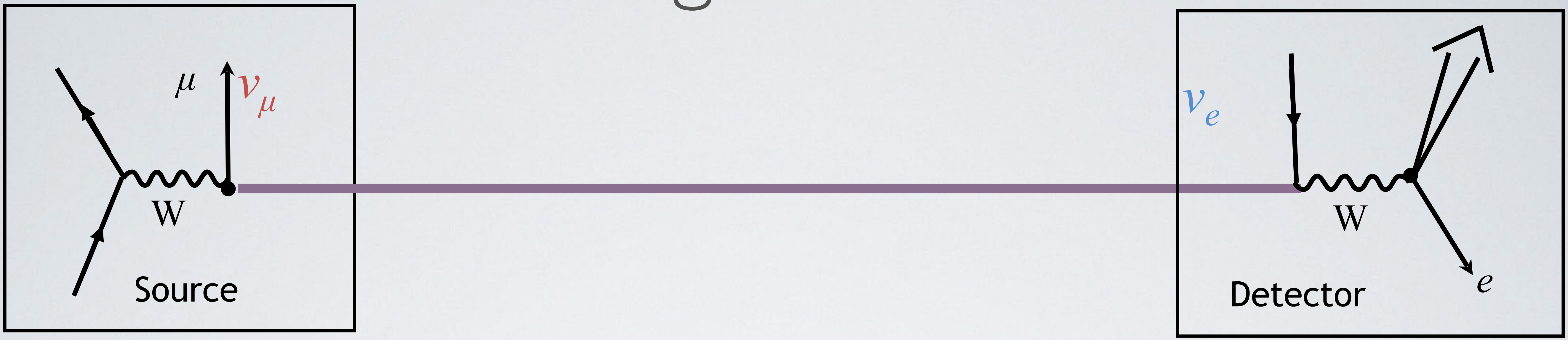
A new door to probing CP violation, the mass ordering and the octant of θ_{23}

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$+2\alpha \sin\theta_{13}\cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$-2\alpha \sin\theta_{13}\sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta + O(\alpha^2)$$

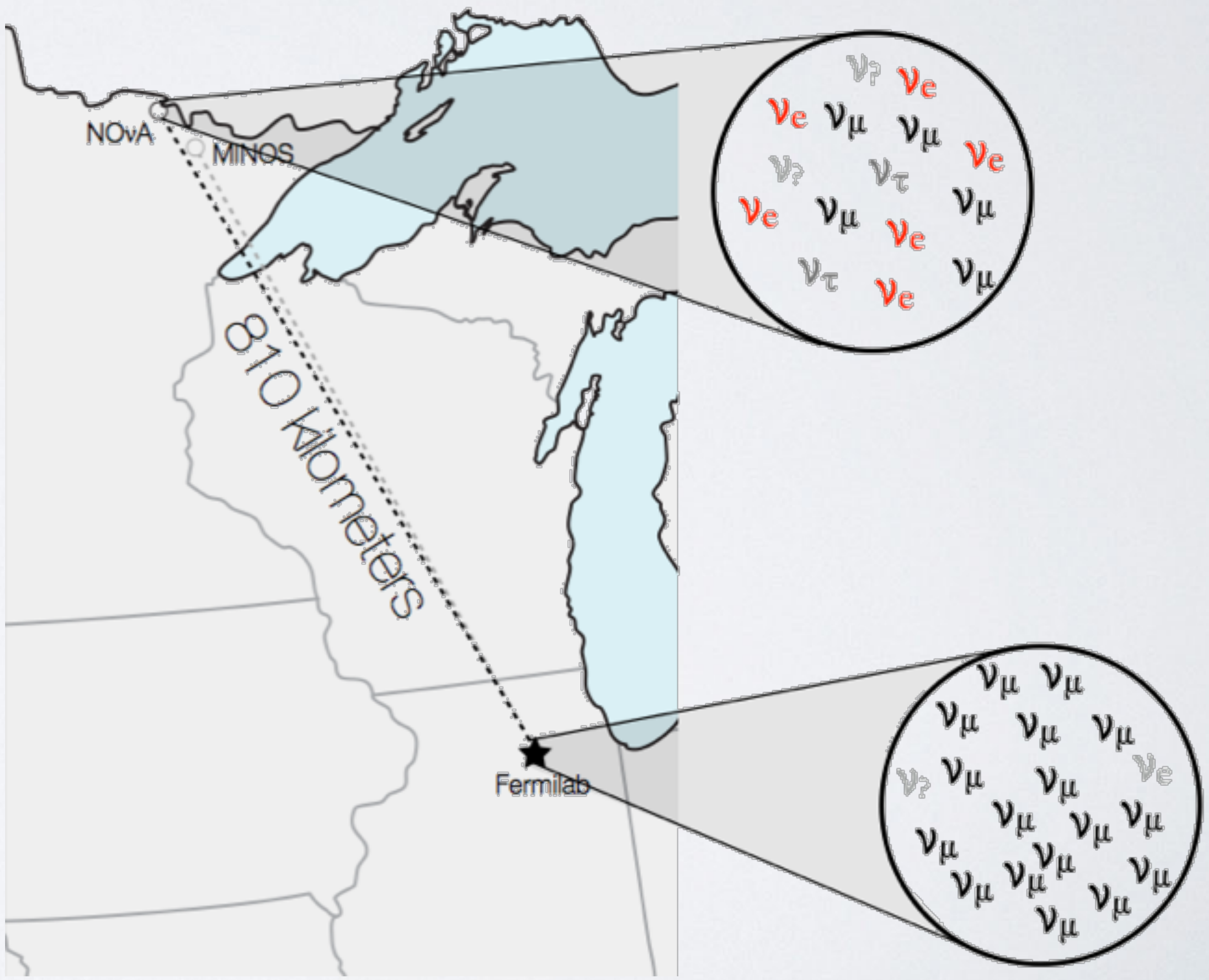
$\alpha = \Delta m^2_{12}/\Delta m^2_{31}$; $\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$

- Depends on **every** oscillation parameter!
- Benefit: can answer more questions. Drawback: degeneracies complicate things

Long-baseline



- Highly pure ν_μ beam
- Two detectors
  - ✓ Near detector:
    - Measure beam composition
    - Determine energy spectrum
  - ✓ Far detector:
    - Measure oscillations
    - Search for new Physics



NOvA

238 collaborators at 49 institutions across 7 countries

- **6 Publications + 2 in preparation**

  Phys.Rev.D98 (2018) no. 3 032012 (12 cites)

  Phys.Rev.D96 (2017) no. 7, 072006 (25 cites)

  Phys.Rev.Lett. 118 (2017) no. 23, 231801 (101 cites)

  Phys.Rev Lett. 118 (2017) no. 15, 151802 (93 cites)

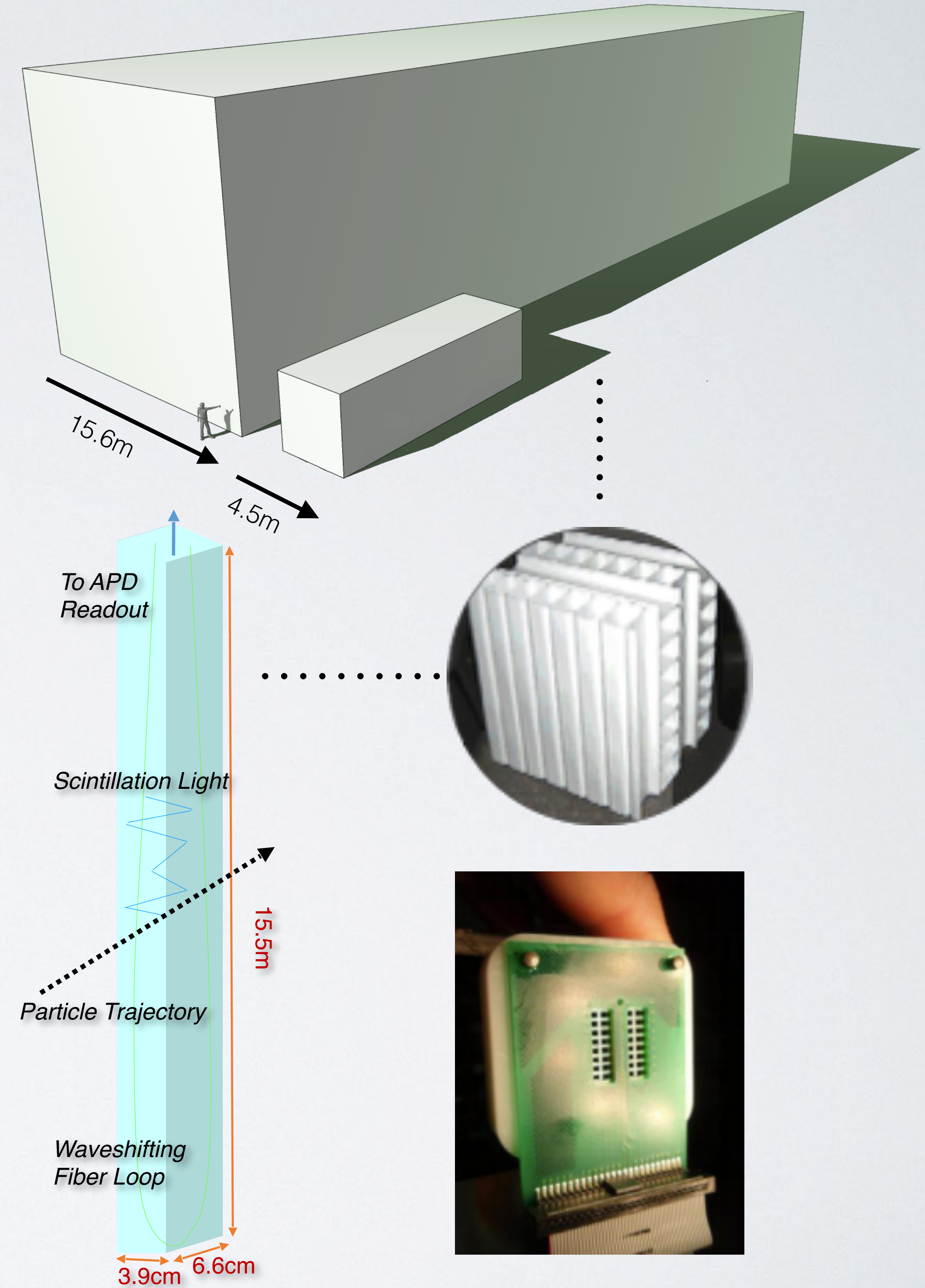
  Phys.Rev.D93 (2016) no. 5, 051104 (108 cites)

  Phys.Rev. Lett.116 (2016) no. 15, 151806 (172 cites)

- **24 PhDs, 11 since last summer**

NOvA

- NuMI Off-Axis ν_e Appearance
- Two highly active scintillator detectors:
  - Far Detector: 14 kT, on surface
  - Near Detector: 300 T, 105 m underground
- 14 mrad off-axis narrowly peaked muon neutrino flux at 2 GeV, L/E ~ 405 km/GeV
- ν_μ disappearance channel: θ_{23}, Δm^2_{32}
- ν_e appearance channel: mass hierarchy, δ_{CP}, θ_{13}, θ_{23} and octant degeneracy



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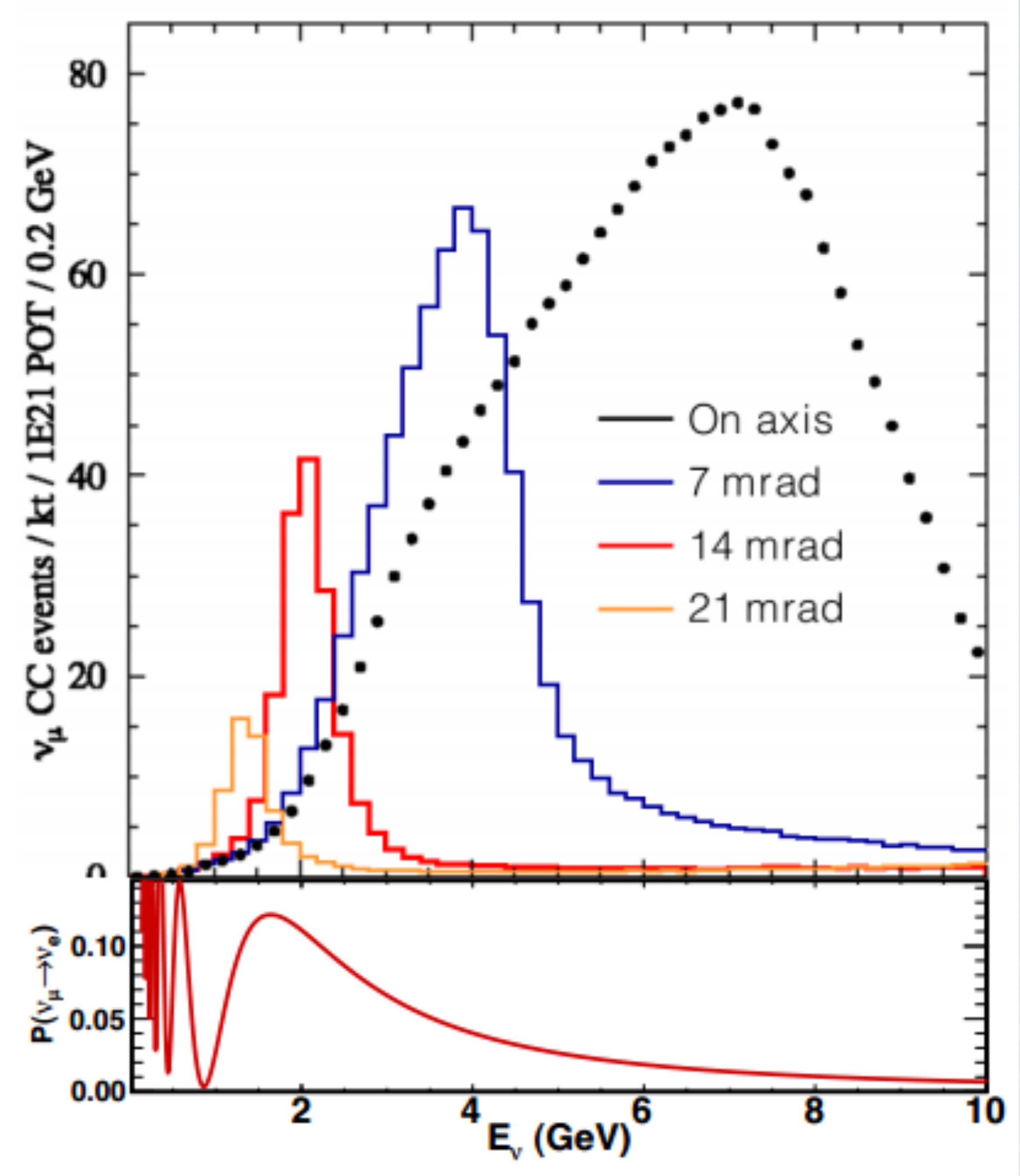
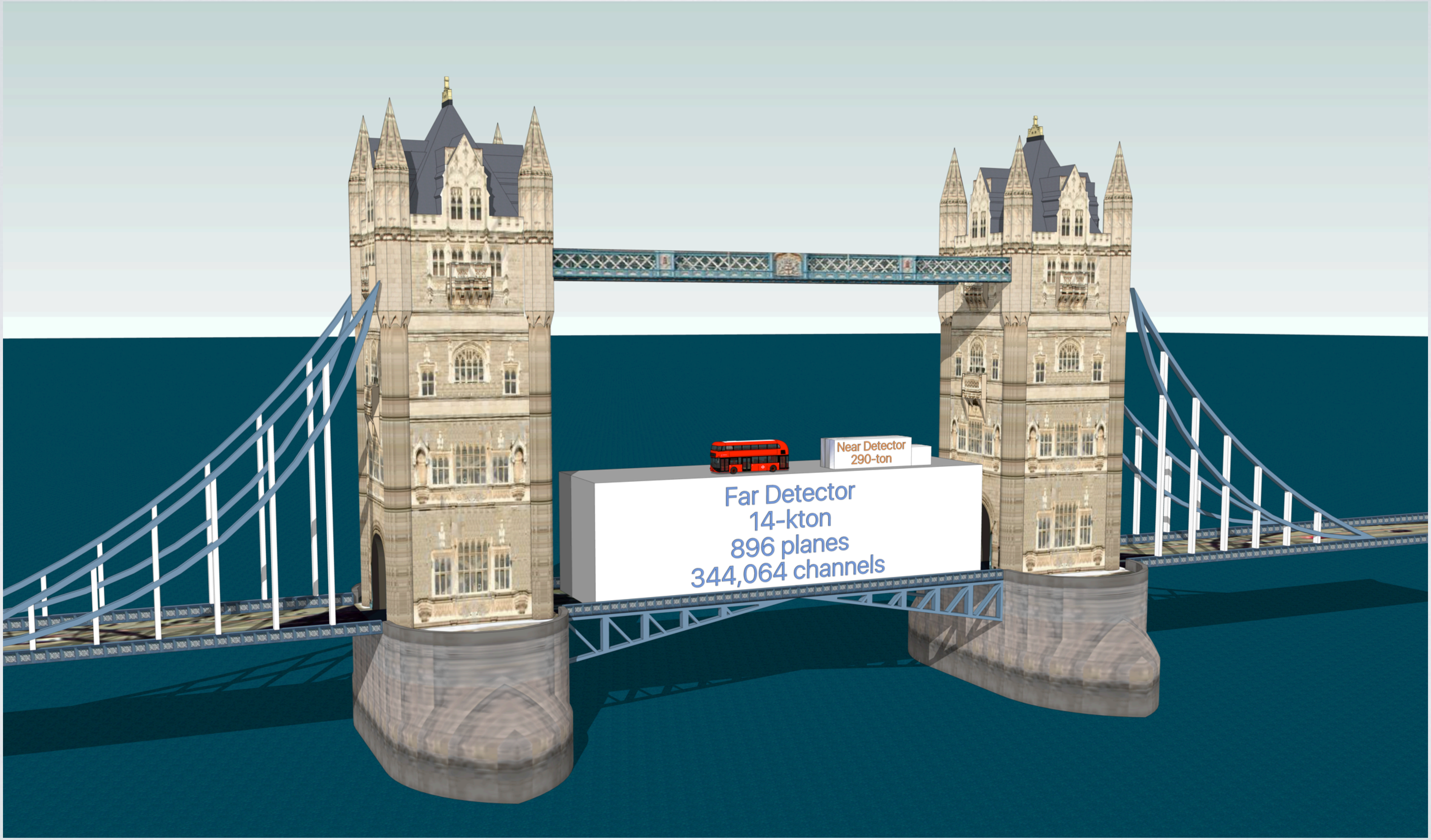


Also: neutrino cross sections at the ND, sterile neutrinos, supernovae…

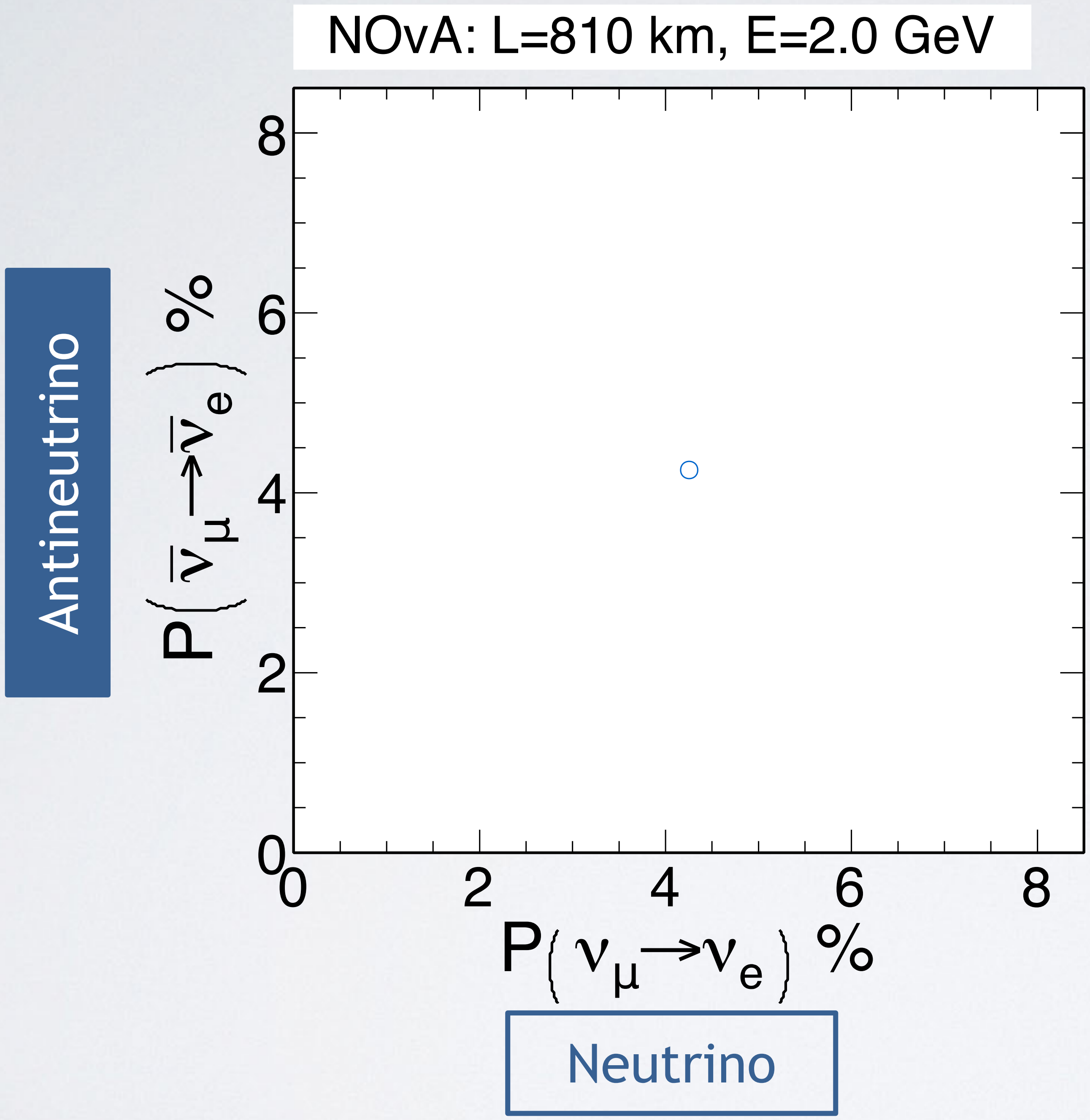
NOvA


Near Detector
290-ton
Far Detector
14-kton
896 planes
344,064 channels

NOvA

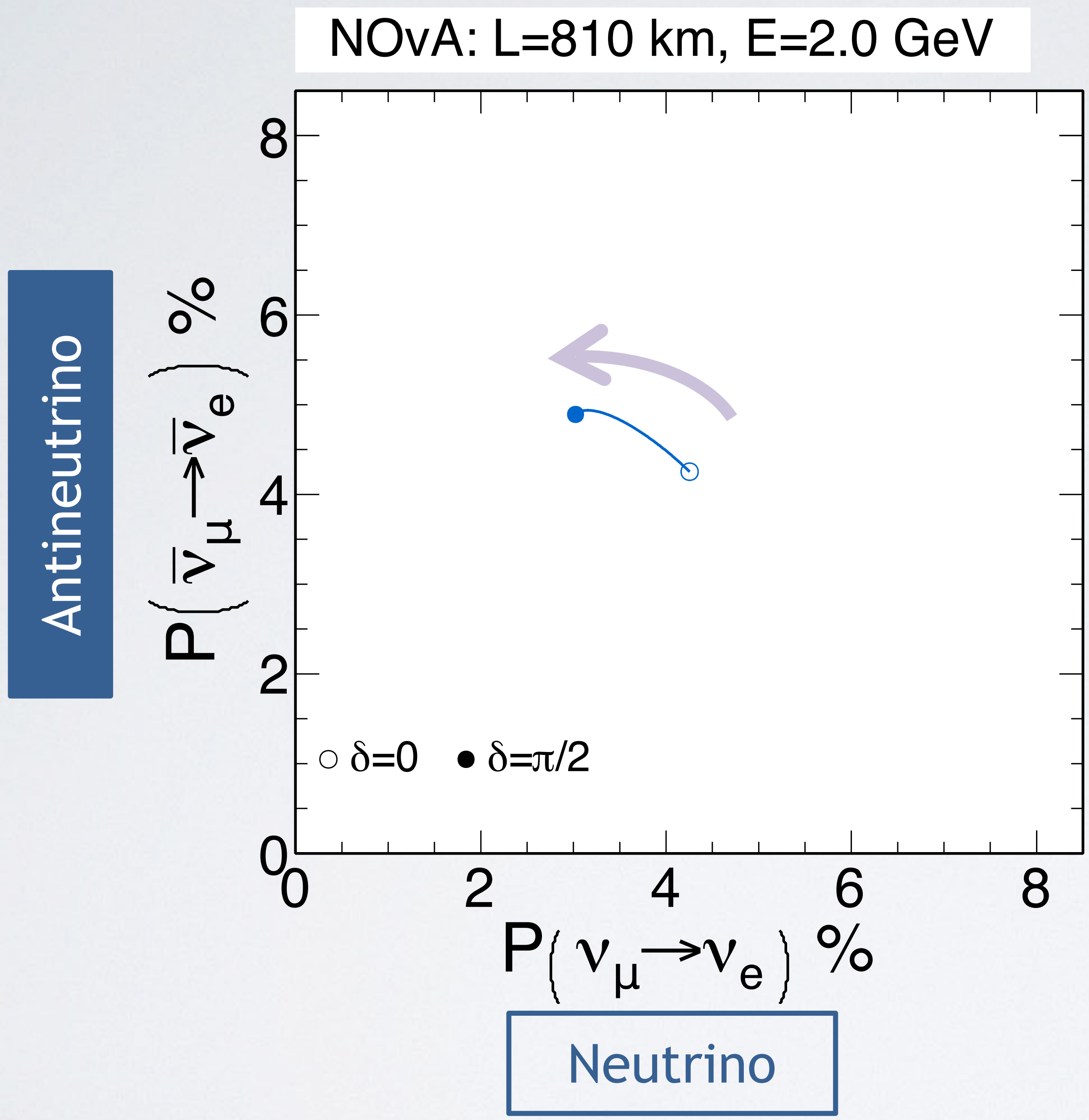
¡Foh!
ROBER
Near Detector
290-ton
Far Detector
14-kton
896 planes
344,064 channels

Neutrinos and antineutrinos



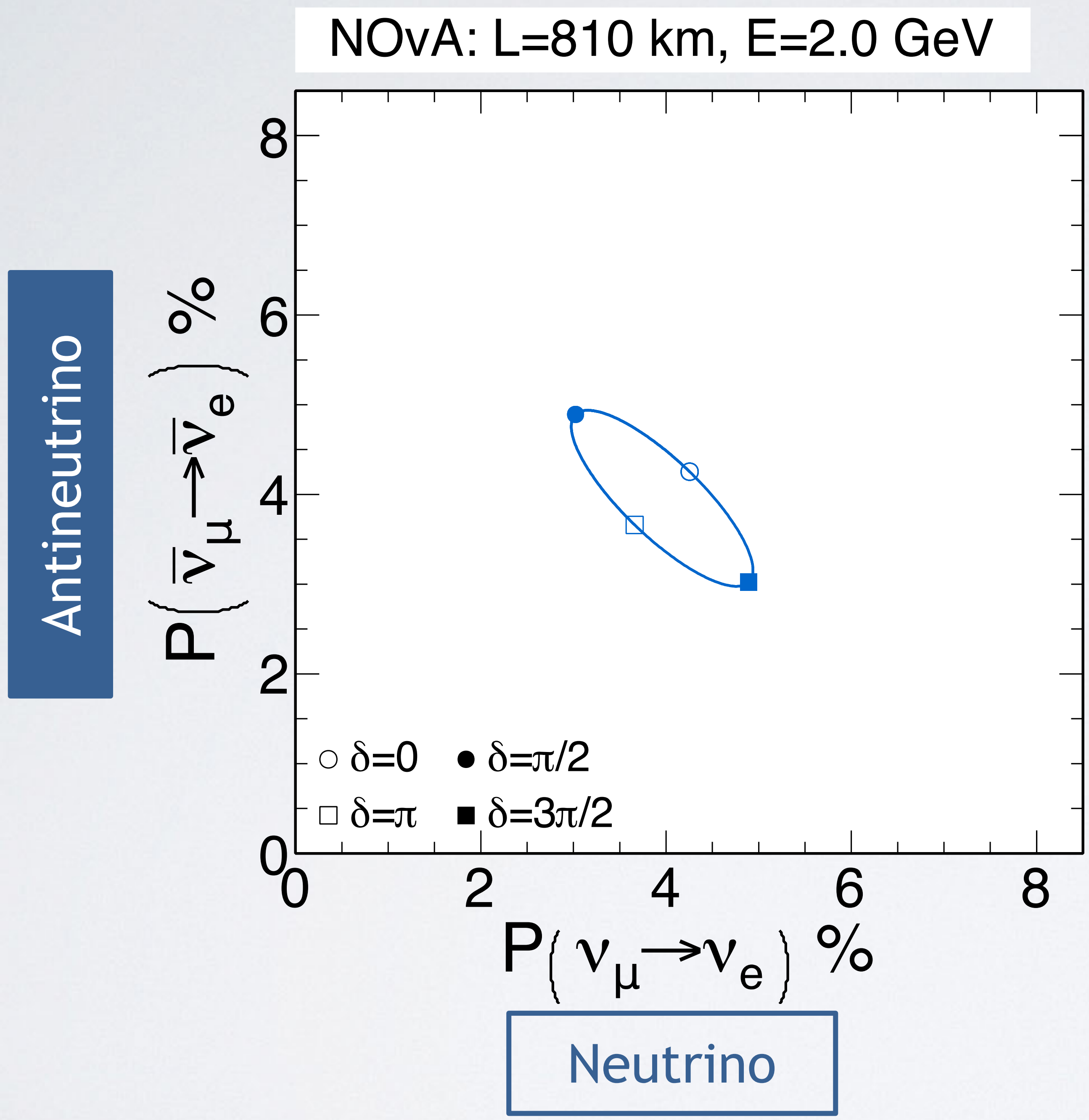
Vacuum and no CP violation: neutrinos and antineutrinos are the same

Neutrinos and antineutrinos



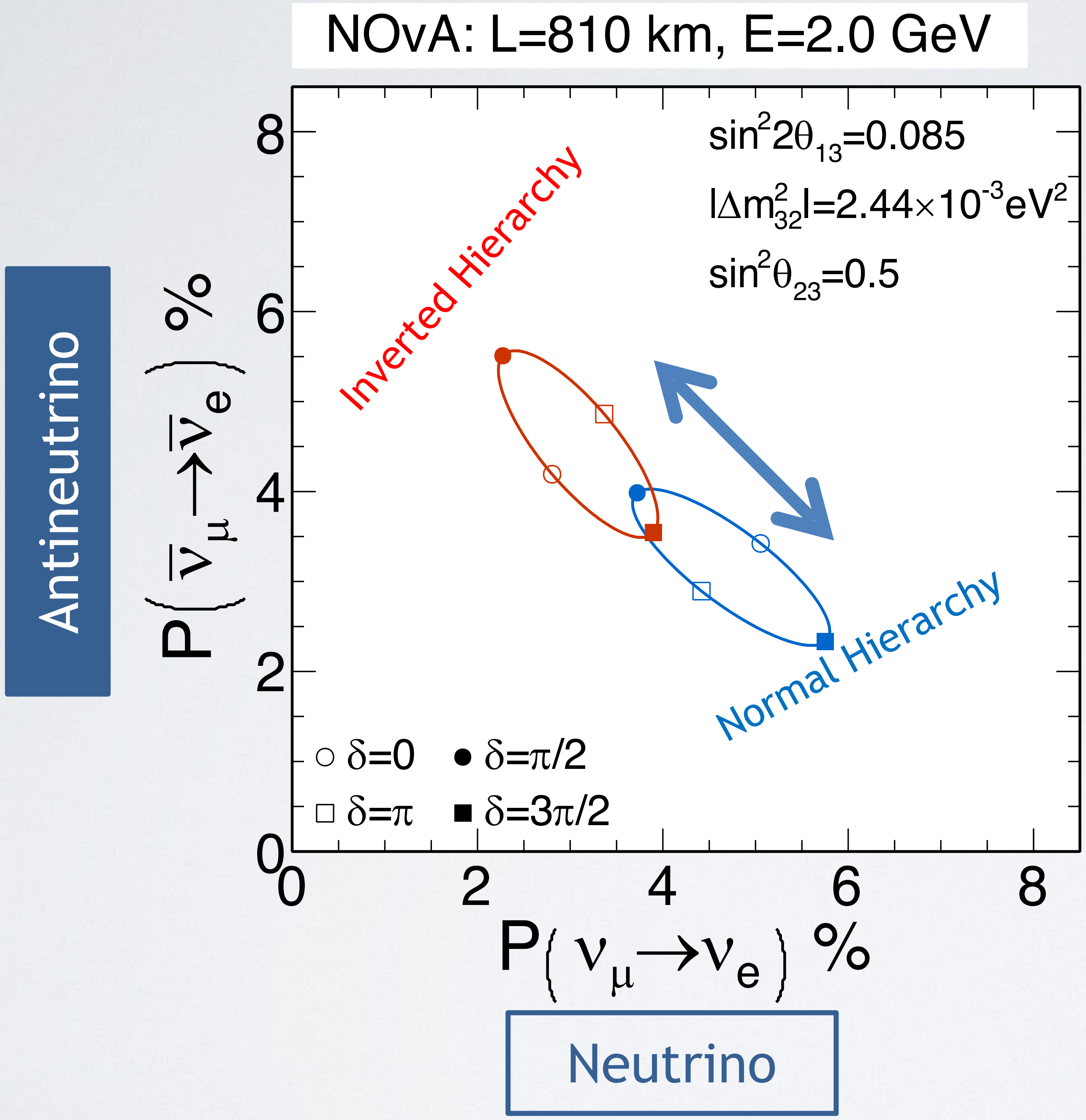
CP-violation through δ creates opposite effects in neutrinos and antineutrinos

Neutrinos and antineutrinos



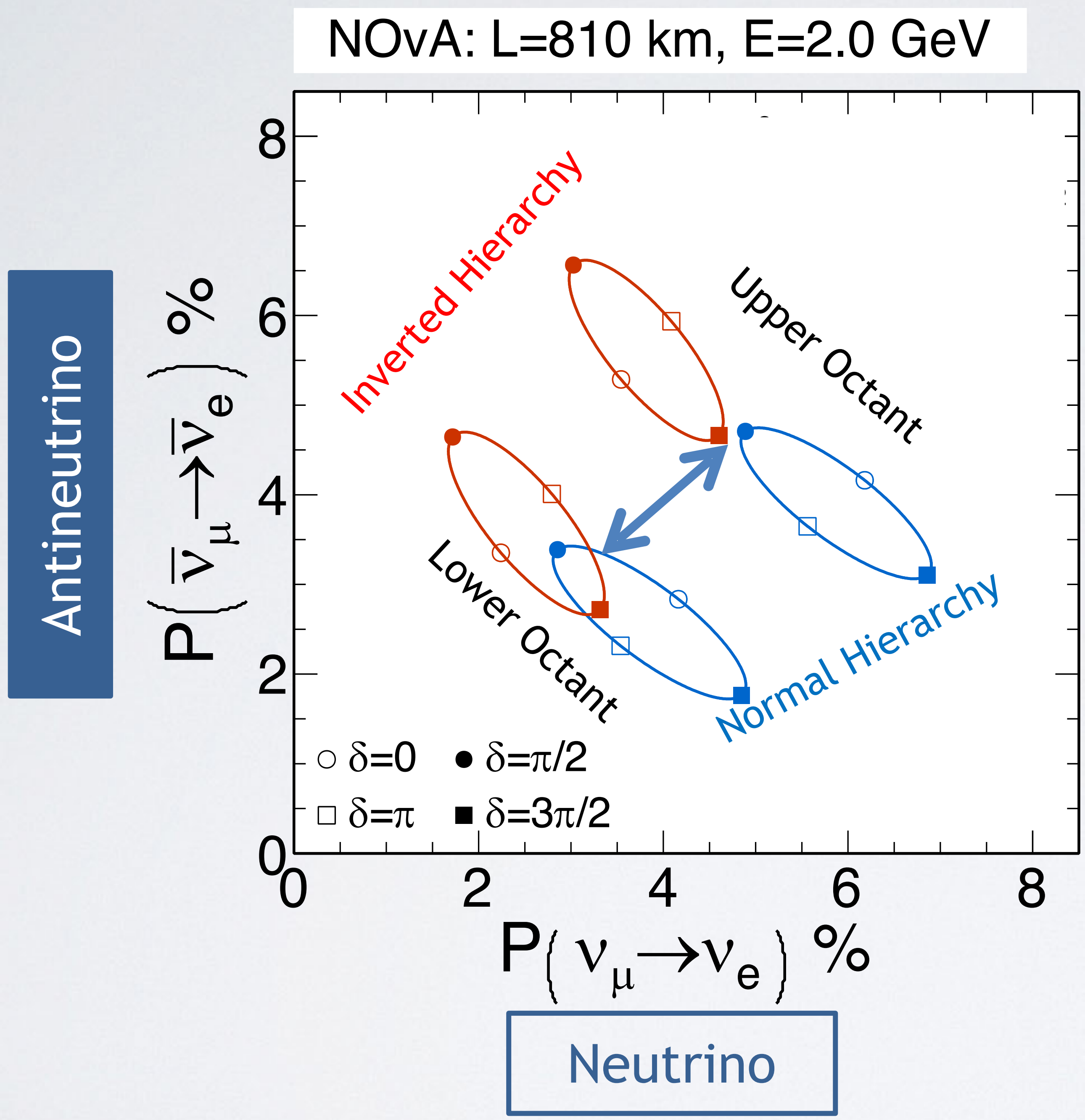
CP-violation through δ creates opposite effects in neutrinos and antineutrinos

Neutrinos and antineutrinos



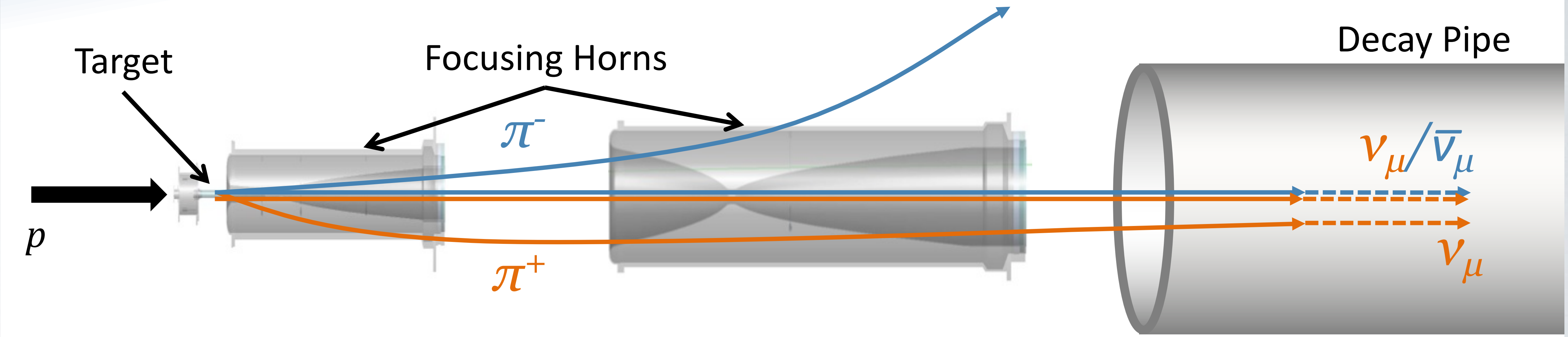
Matter effects also introduce opposite neutrino-antineutrino effects.

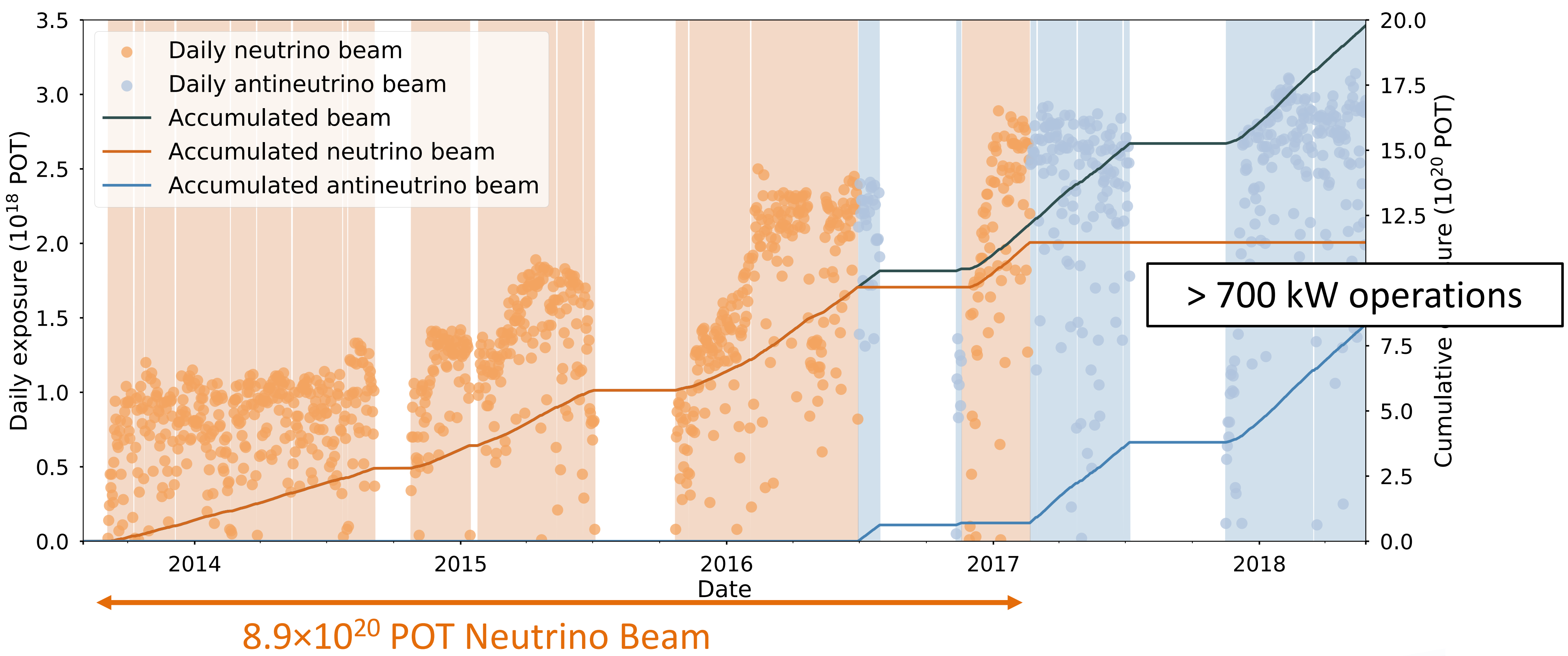
Neutrinos and antineutrinos



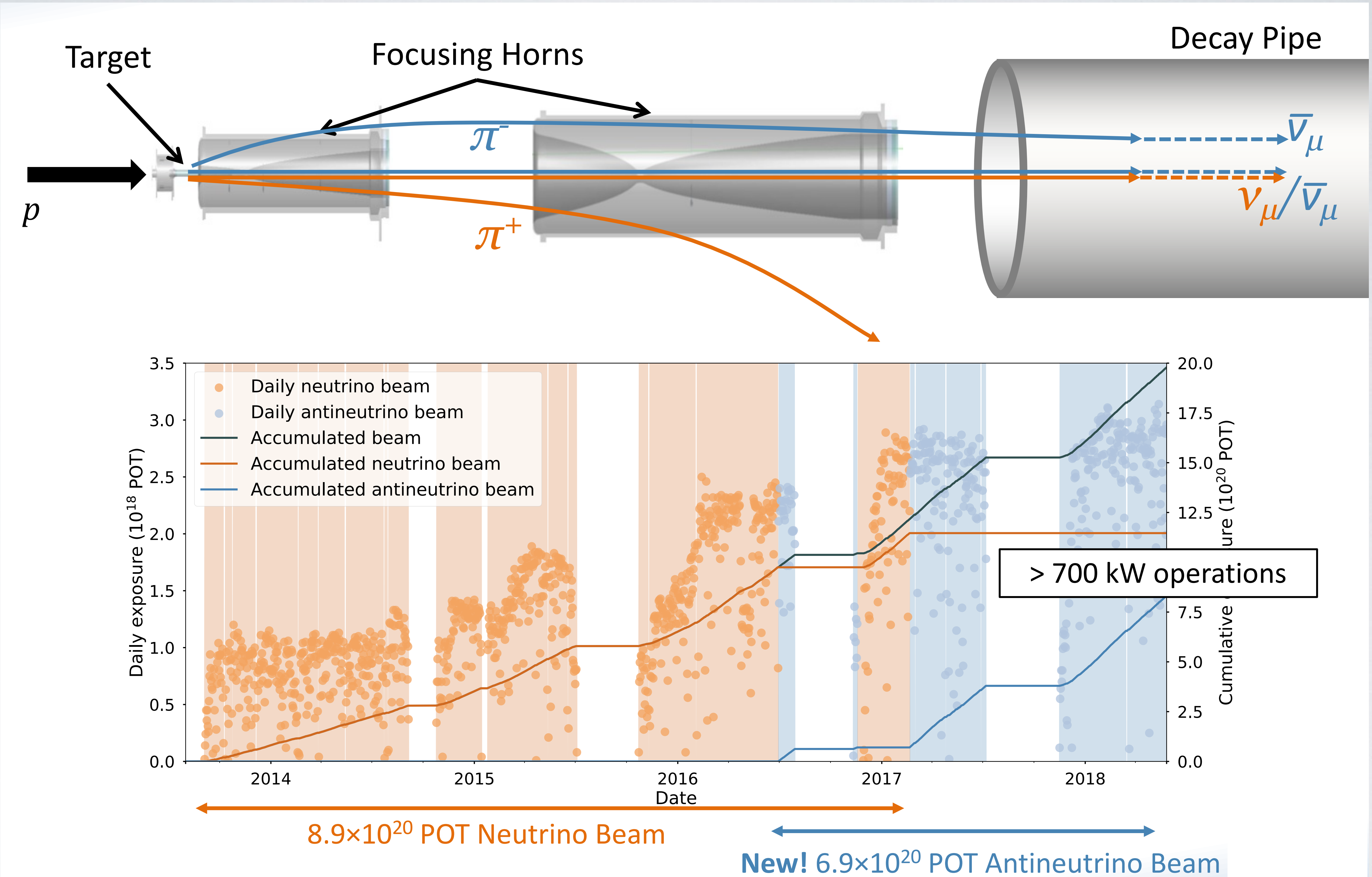
The octant creates the *same* effect in neutrinos and antineutrinos.

Neutrinos and antineutrinos

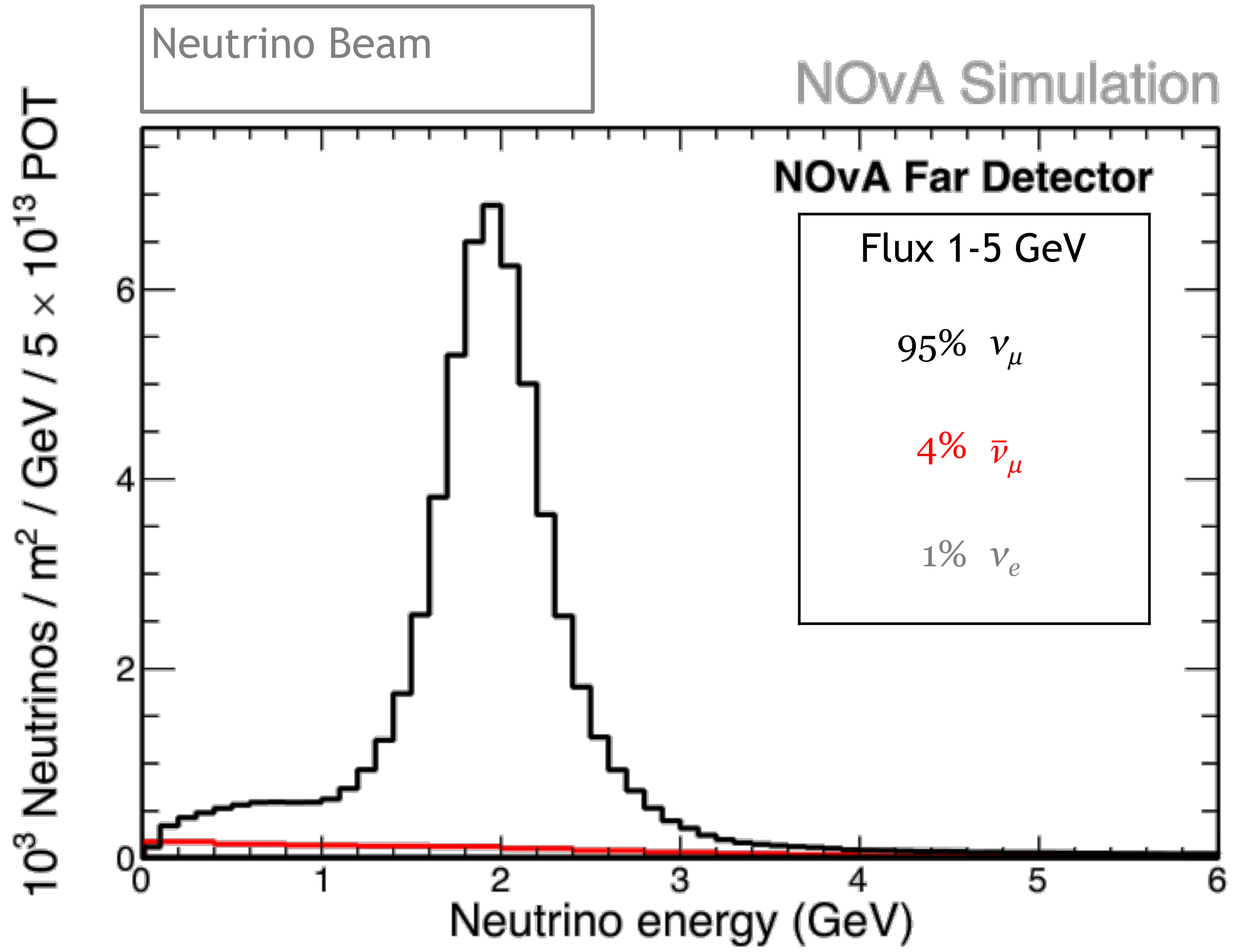


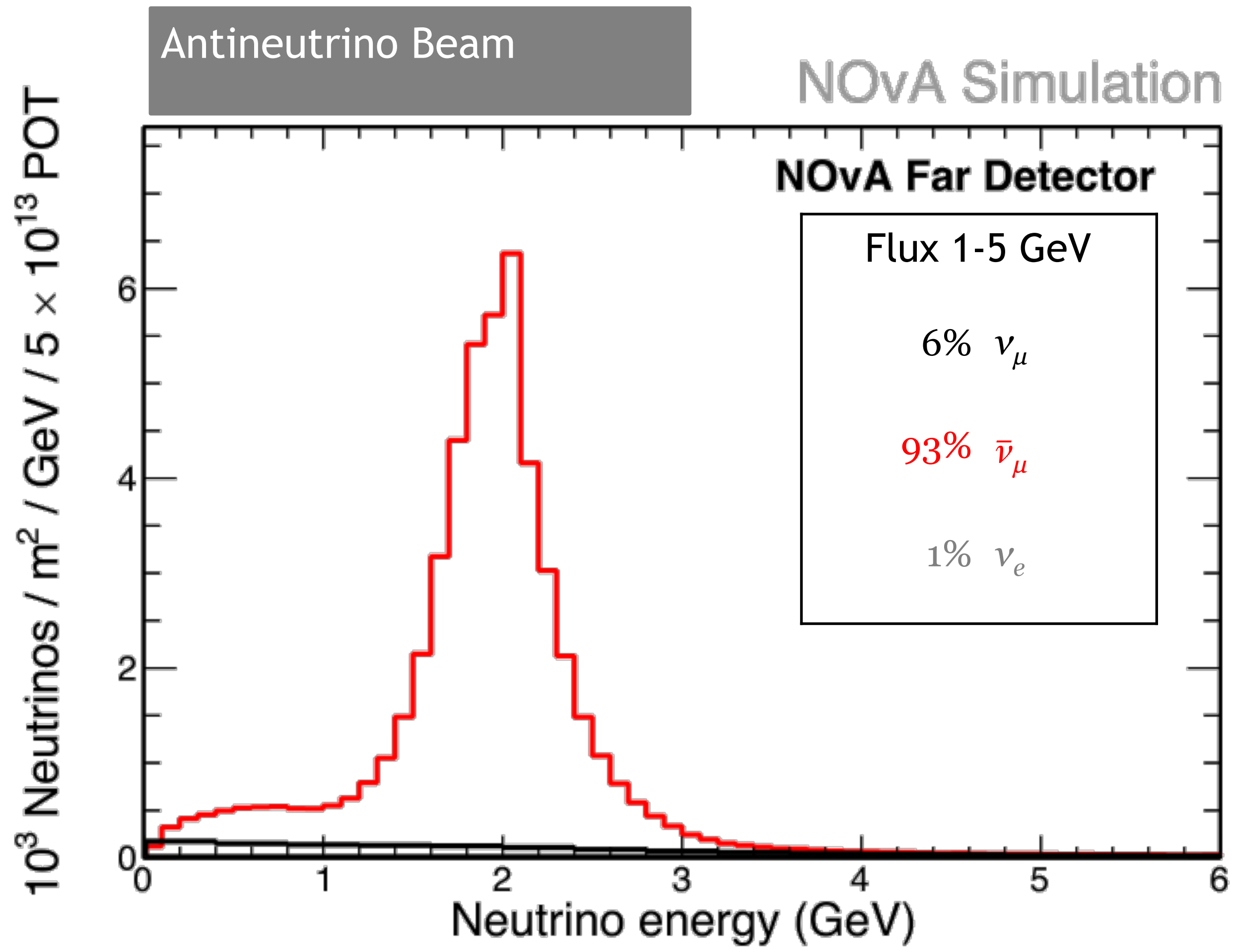


Neutrinos and antineutrinos



Neutrinos and antineutrinos

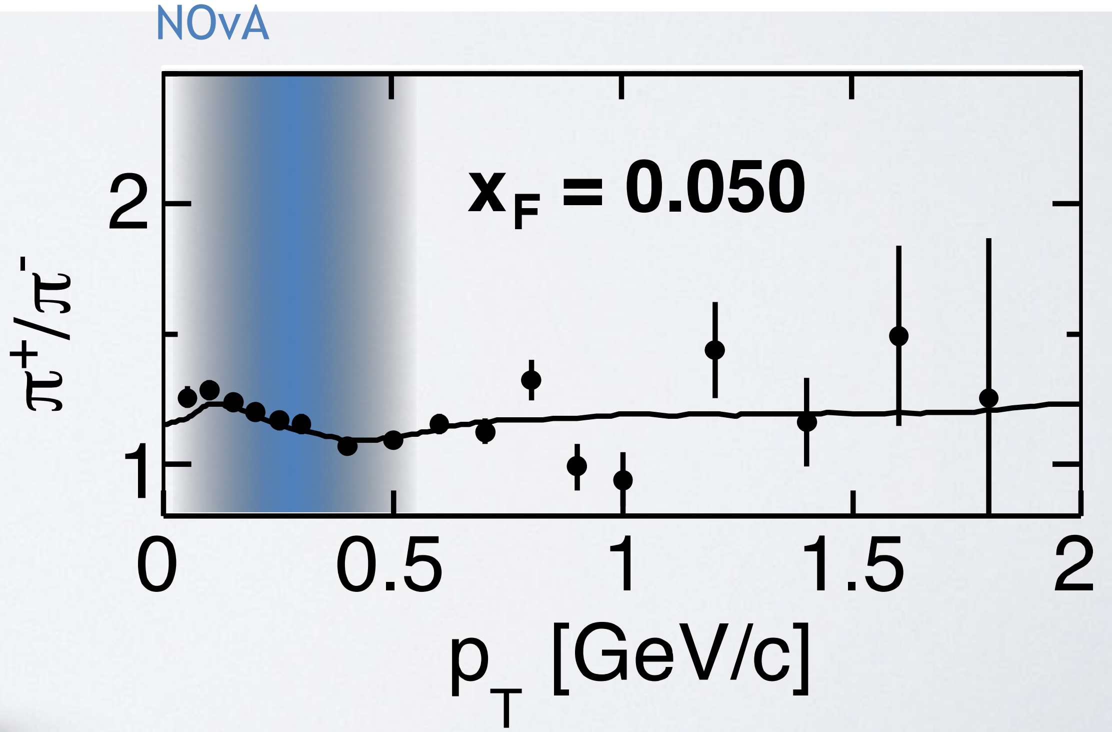




- Production cross section is a little higher for $\pi^+ \rightarrow \nu_\mu$ than for $\pi^- \rightarrow \bar{\nu}_\mu$

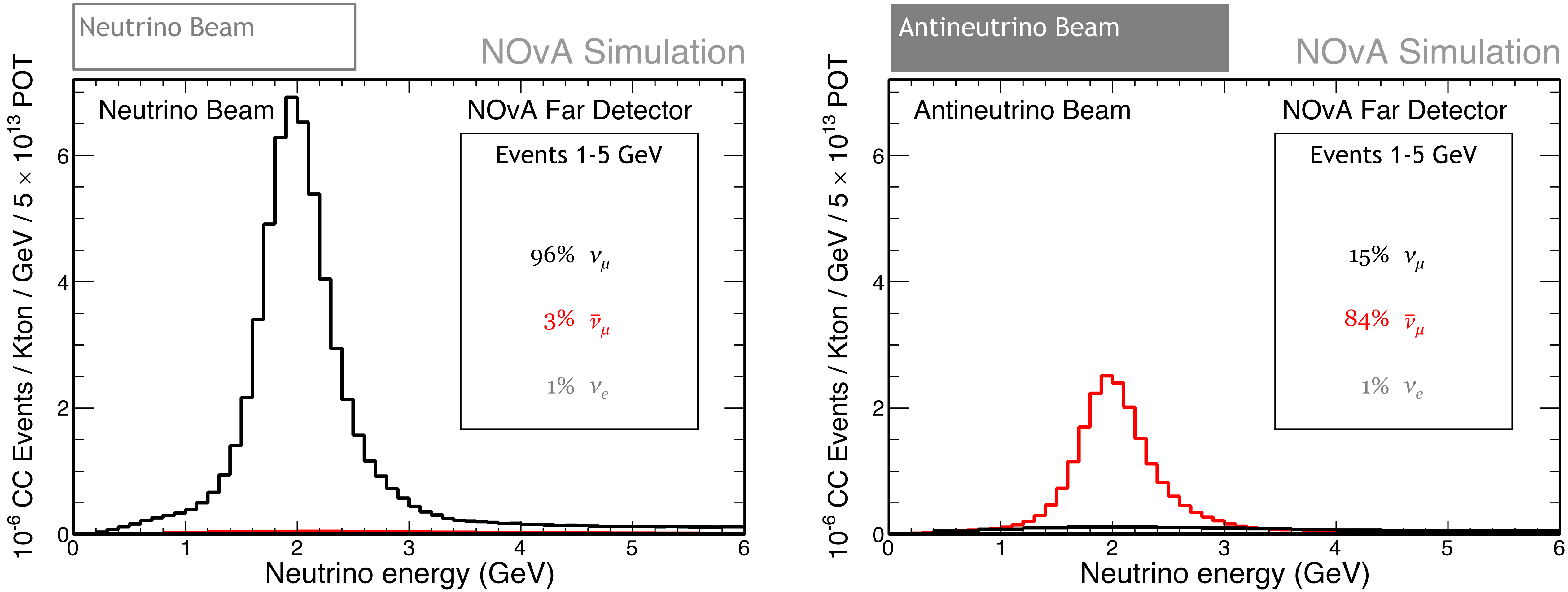
  p^+ colliding with p^+ and n^0 in the target
- Wrong-sign: ν in the $\bar{\nu}$ beam (or vice versa).
- Off-axis beam reduces the wrong-sign.

  WS primarily would primarily come from the unfocused high-energy tail.

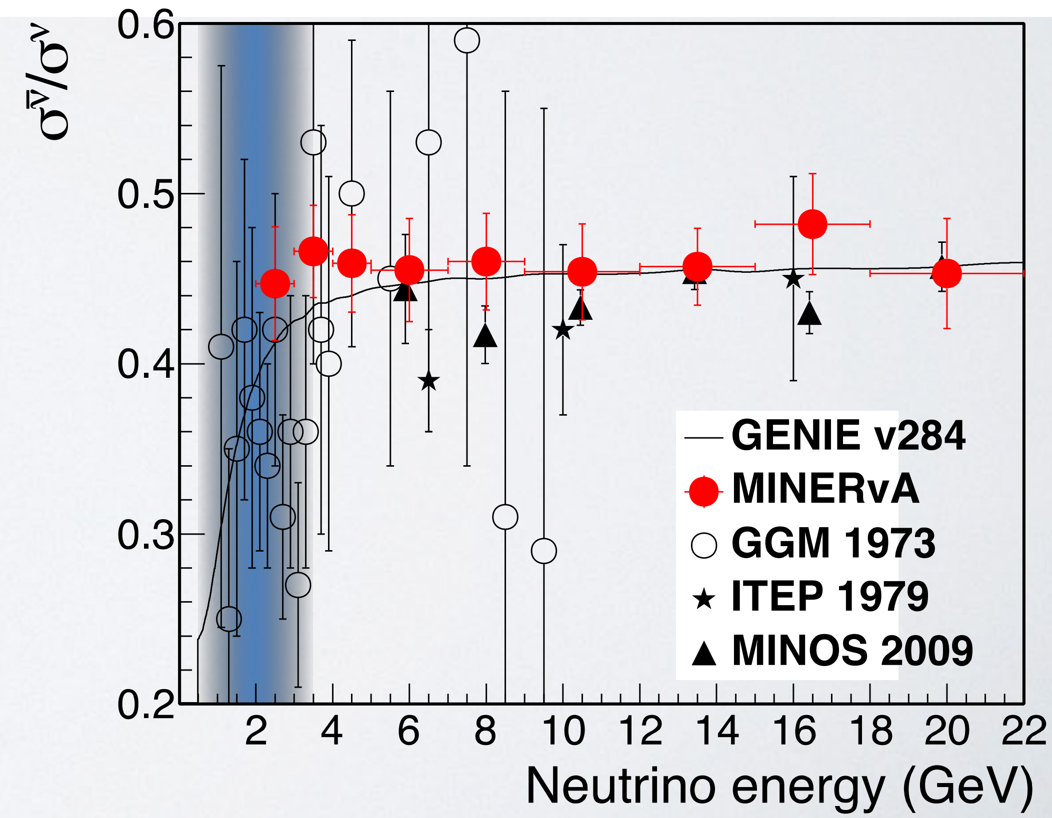


NA49, Eur. Phys. J. C 49 897 (2007)

Neutrinos and antineutrinos



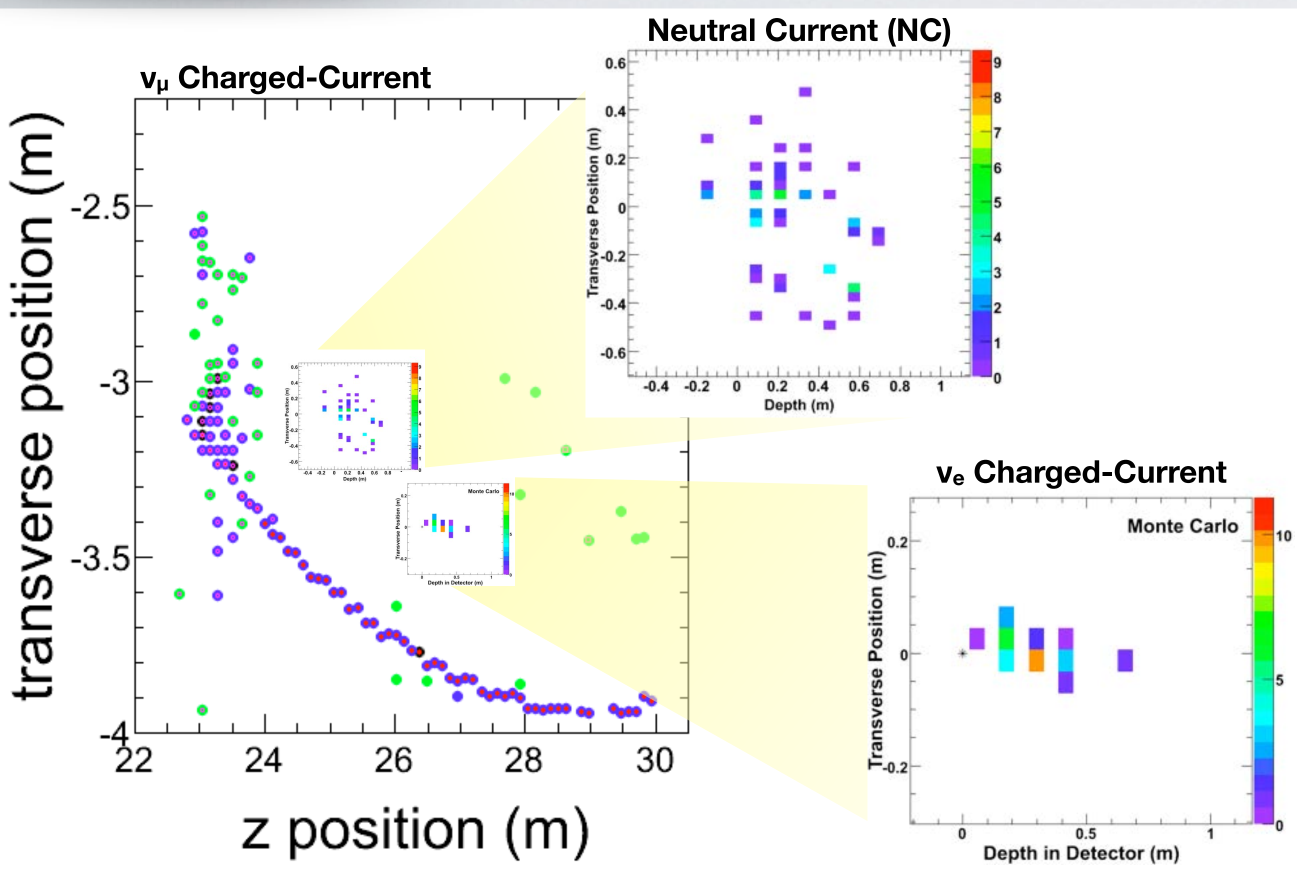
- The big difference is in the interaction: the cross section for antineutrinos is ~2.8 times lower than for neutrinos
- Antineutrinos also tend to have more lepton energy and less hadronic energy
  - Lower kinematic *y*
  - More forward-going



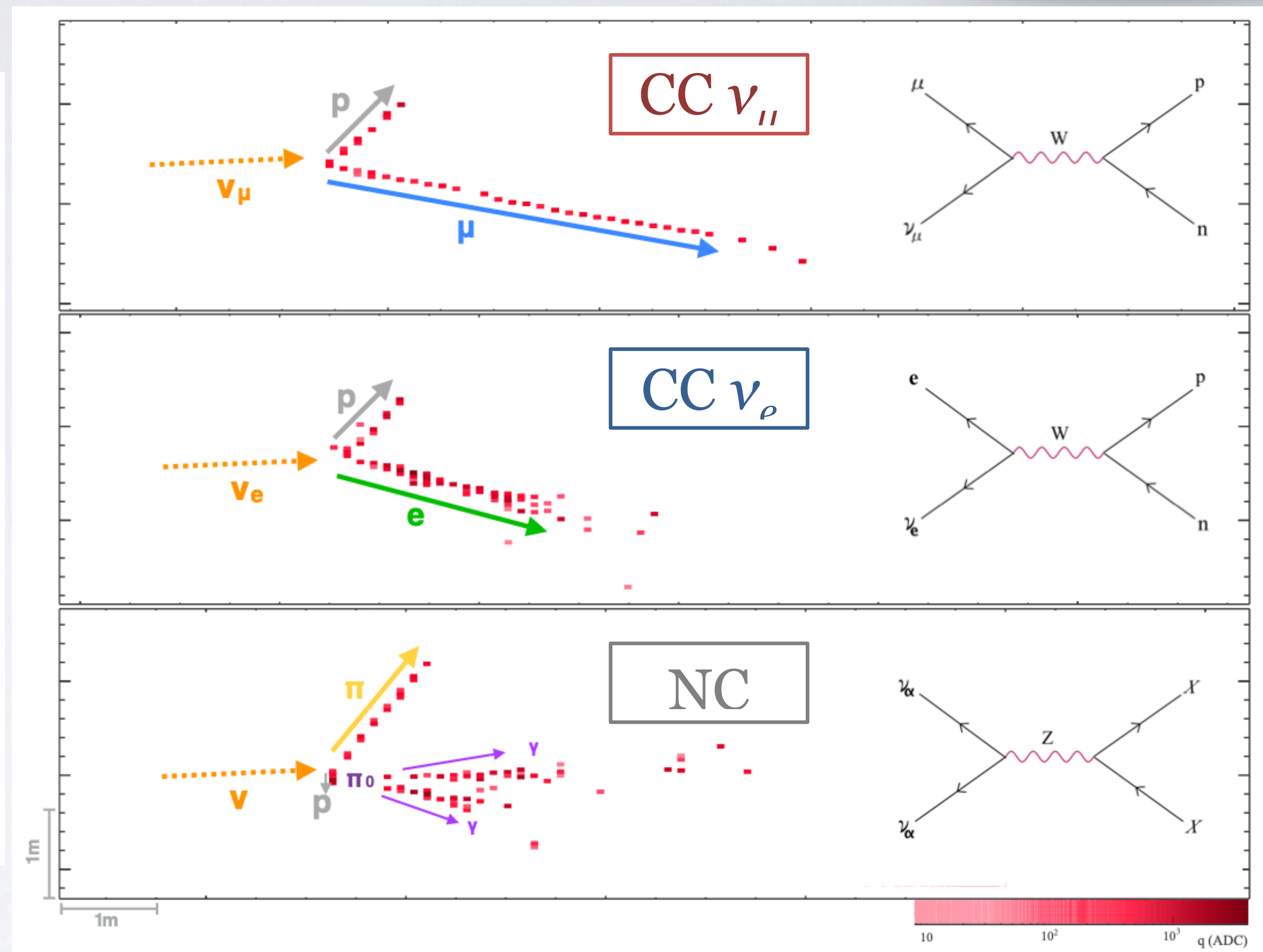
MINERvA, Phys.Rev. D95 (2017) no.7, 072009

Event topologies

MINOS



NOvA

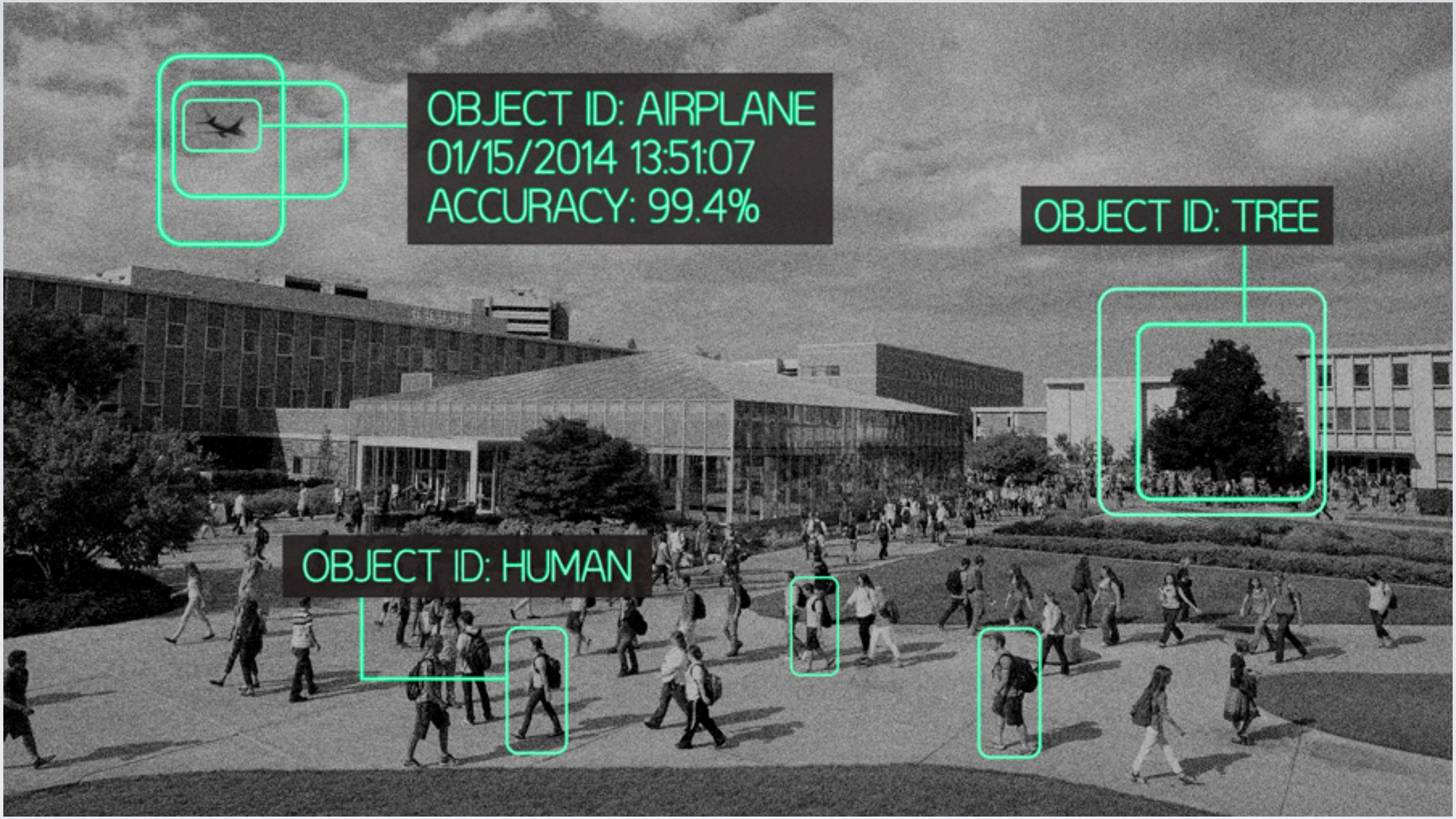


- Superb granularity for a detector this scale
- Outstanding event identification capability

1 radiation length = 38 cm

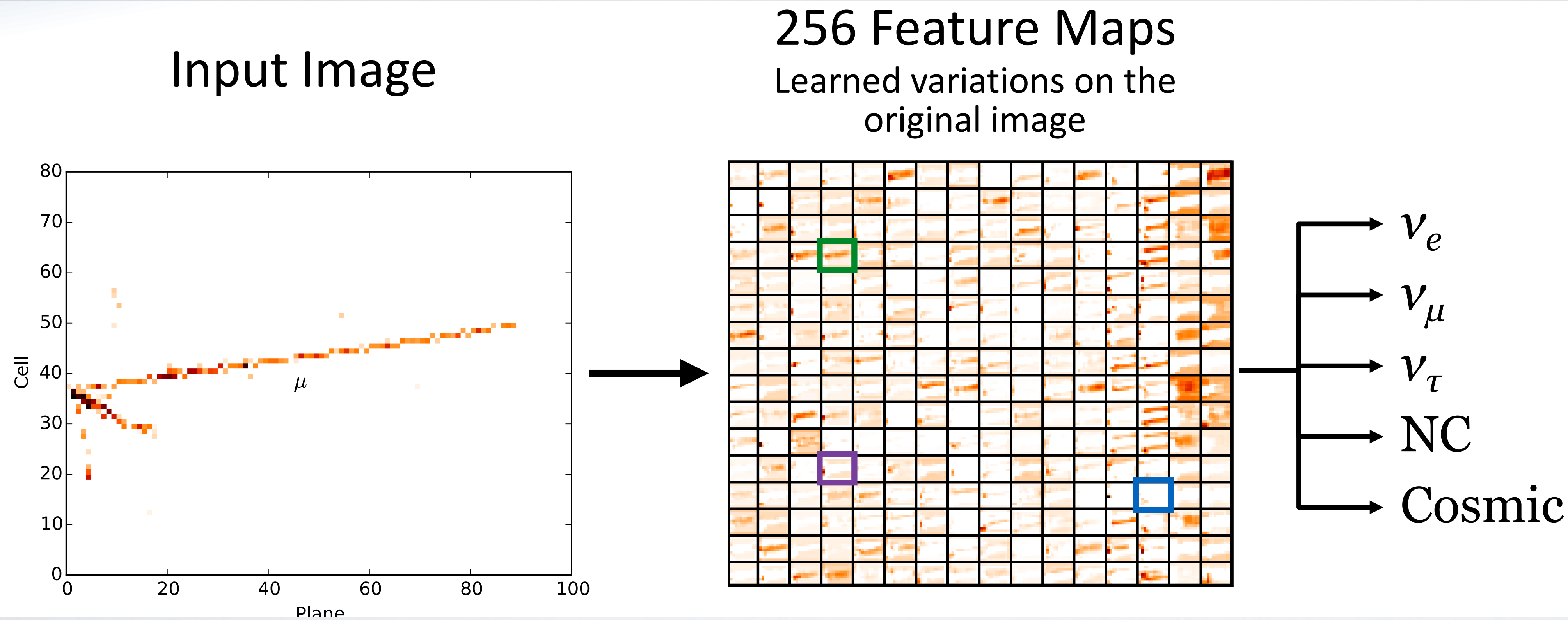
(6 cell depths, 10 cell widths)

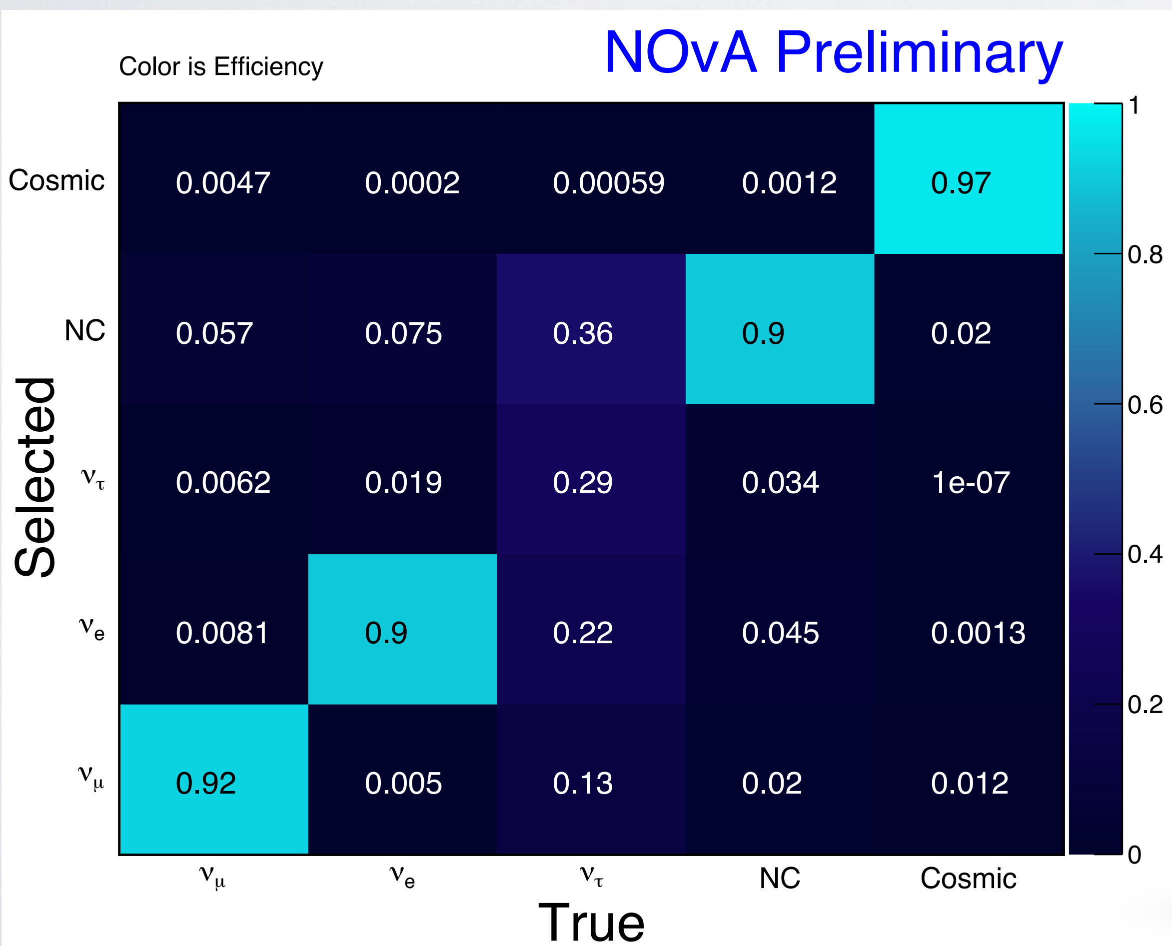
Identifying neutrinos in the NOvA detector



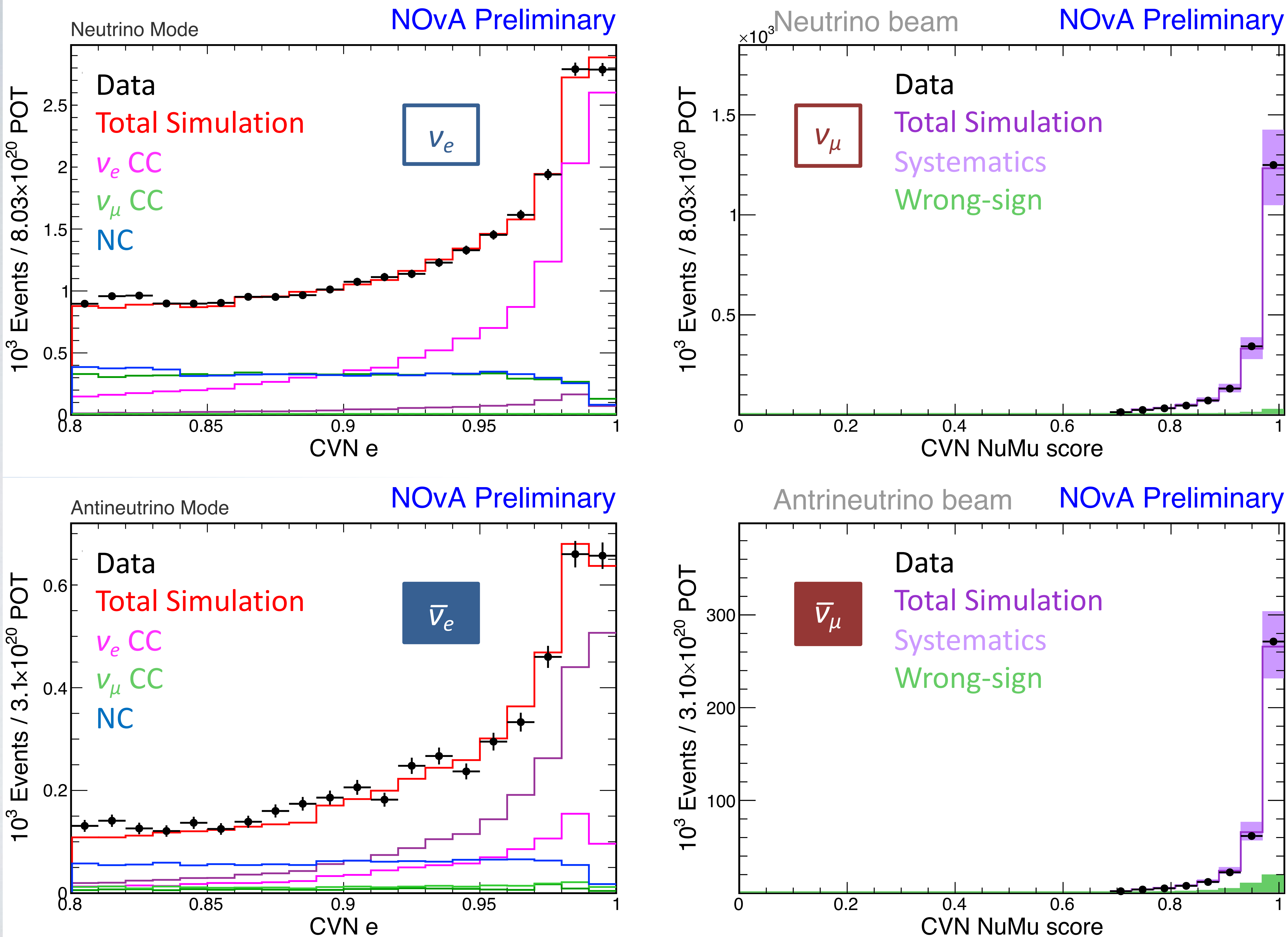
- First usage of image-recognition in particle physics!

Identifying neutrinos in the NOvA detector





- Efficiency above 90% for all except tau neutrinos
  - Exceptionally rare in NOvA due to narrow energy distribution

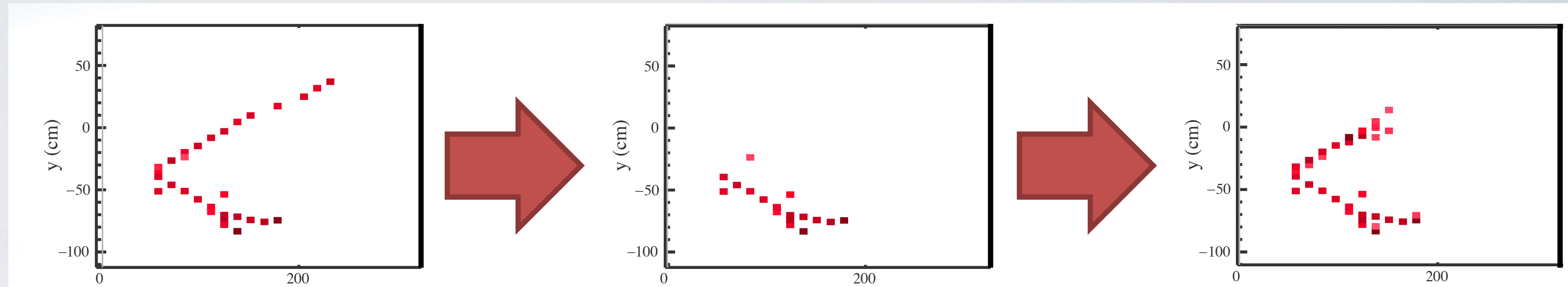


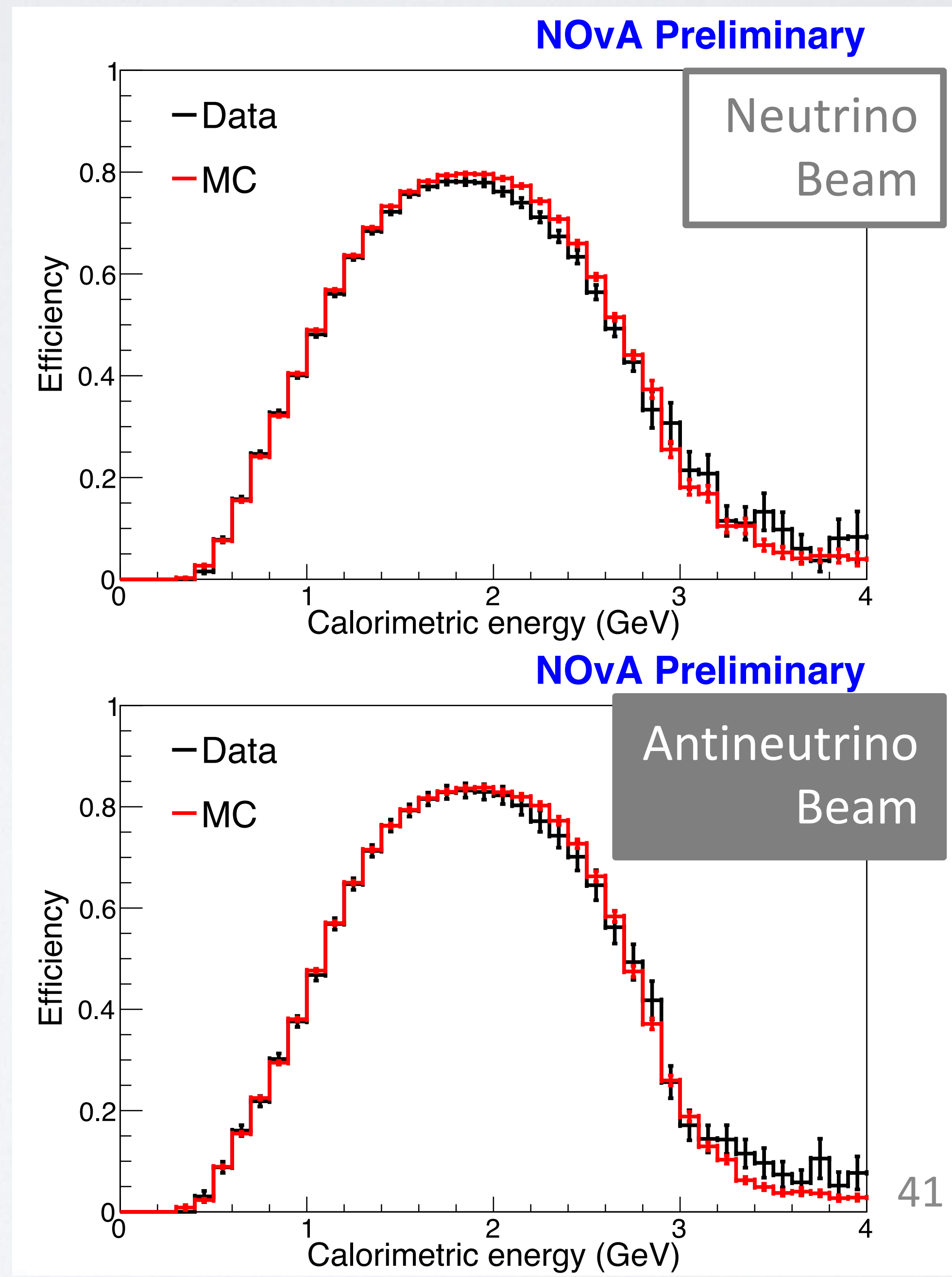
Neutrino Mode
NOvA Preliminary
Data
Total Simulation
ν_e CC
ν_μ CC
NC
ν_e
10^3 Events / 8.03×10^{20} POT
CVN e
Neutrino beam
NOvA Preliminary
Data
Total Simulation
Systematics
Wrong-sign
ν_μ
10^3 Events / 8.03×10^{20} POT
CVN NuMu score
Antineutrino Mode
NOvA Preliminary
Data
Total Simulation
ν_e CC
ν_μ CC
NC
$\bar{\nu}_e$
10^3 Events / 3.1×10^{20} POT
CVN e
Antrineutrino beam
NOvA Preliminary
Data
Total Simulation
Systematics
Wrong-sign
$\bar{\nu}_\mu$
10^3 Events / 3.10×10^{20} POT
CVN NuMu score

Data-driven crosschecks

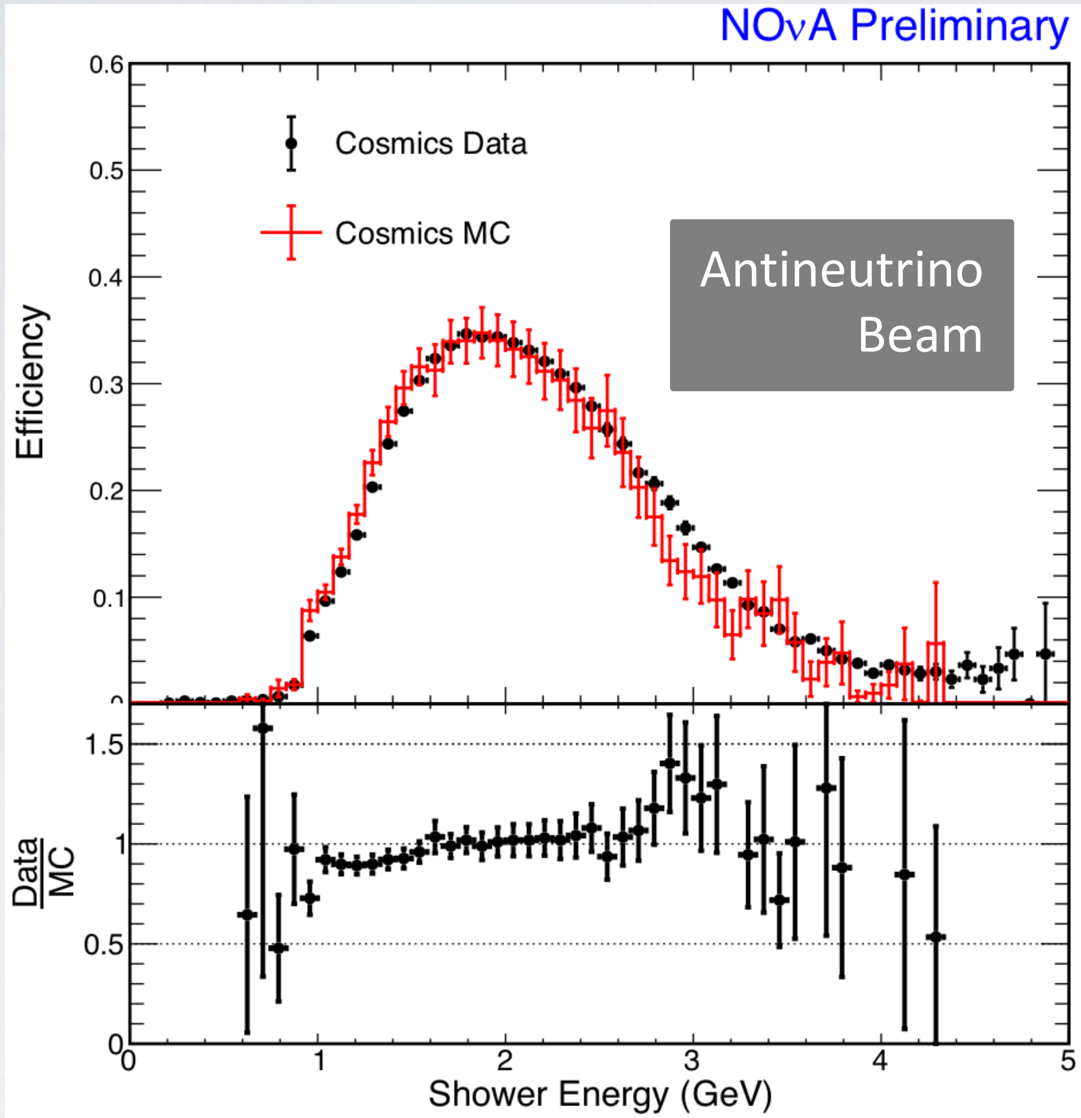
MRE

- Take a muon-neutrino event and remove the muon
- Replace by a simulated electron
- Compare efficiency between MRE events, real and simulated data
- Agreement within 2% for both neutrinos and antineutrinos

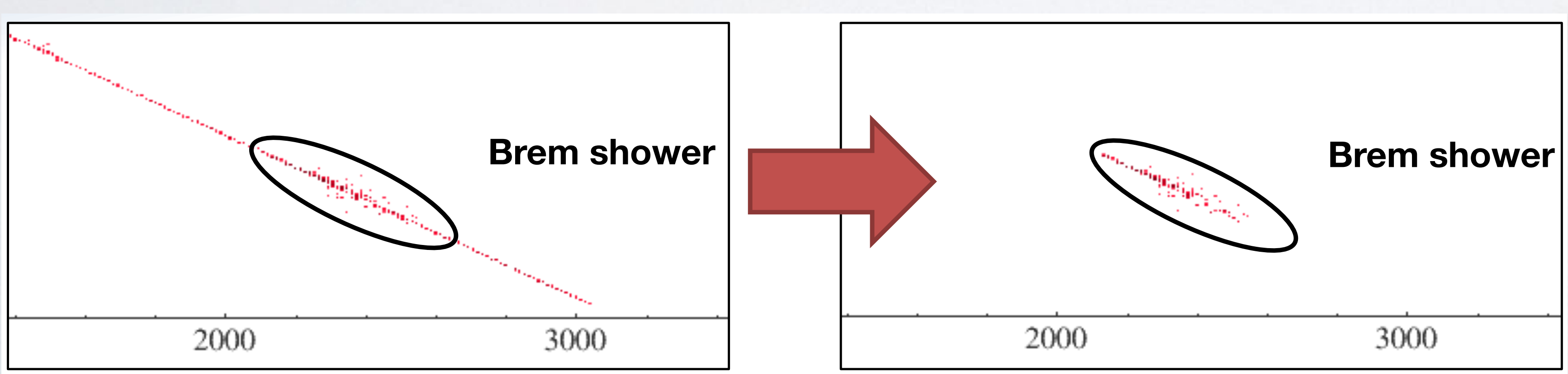




Data-driven crosschecks



- Similar idea using bremsstrahlung from cosmic muons
- Remove the muon and estimate efficiency in selecting electron showers
- Agreement within uncertainties

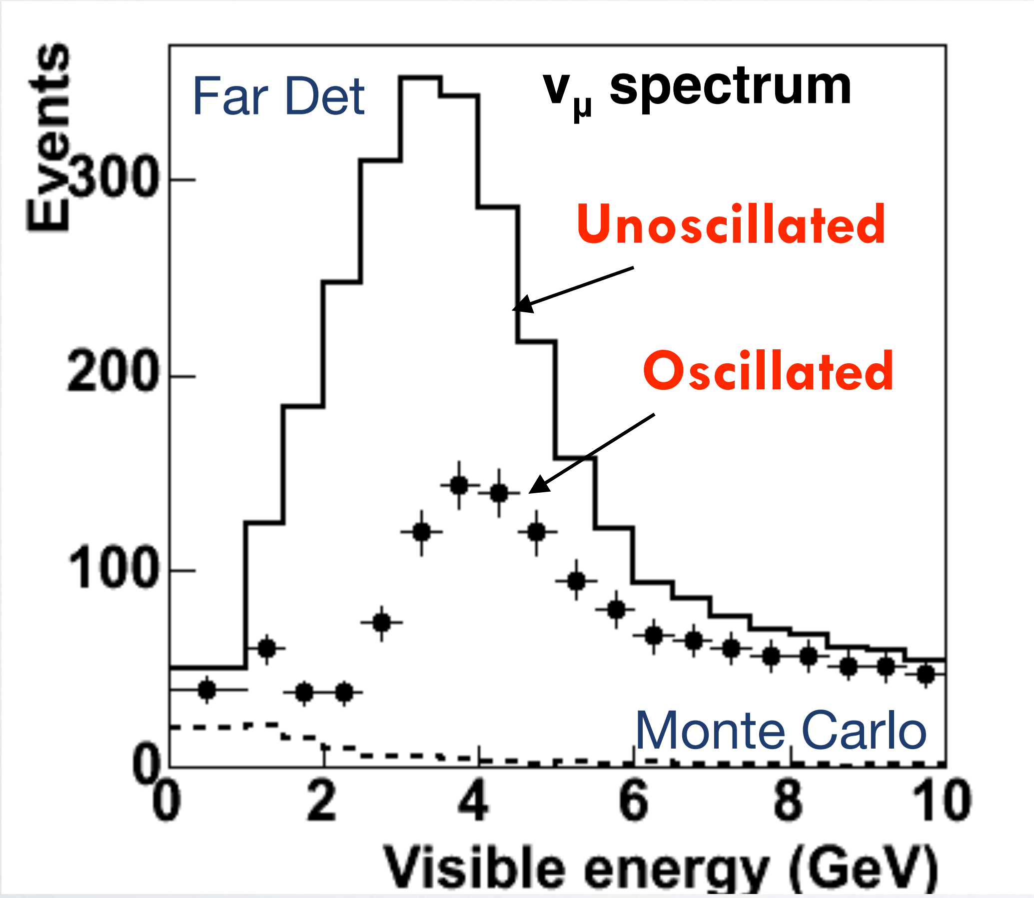


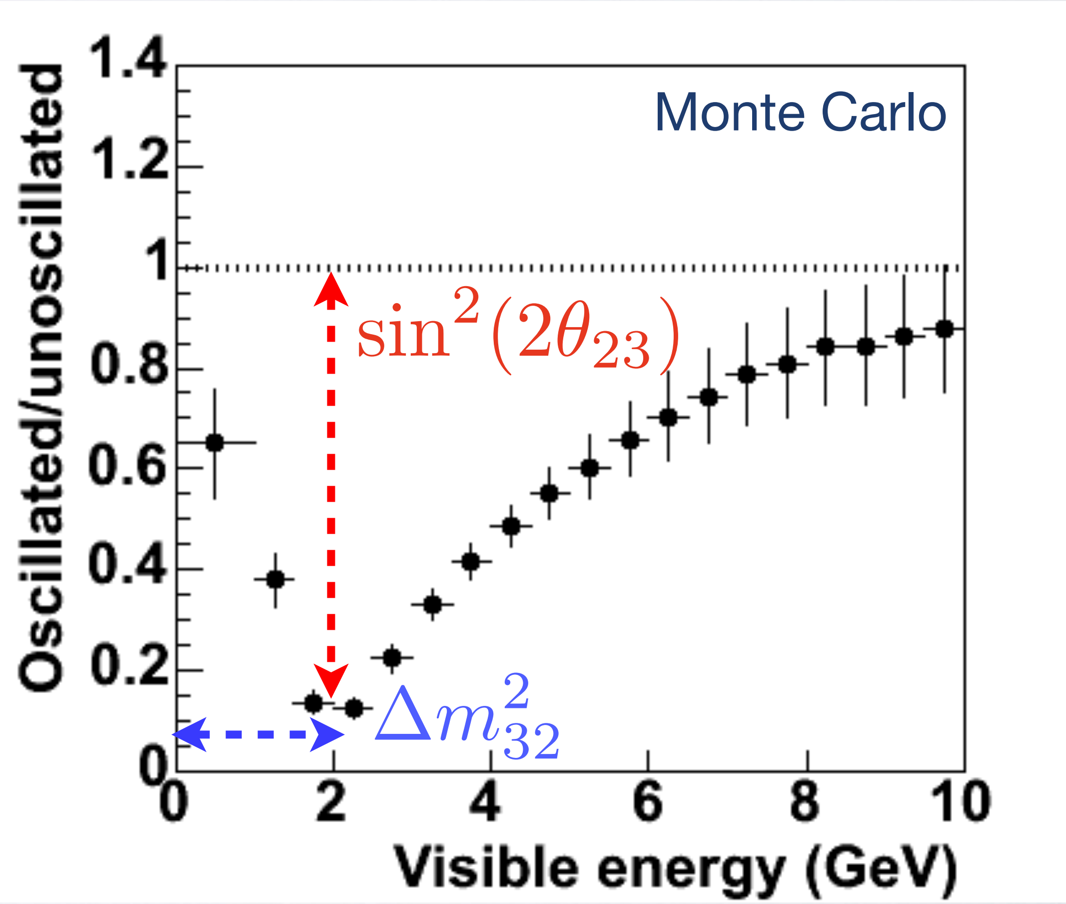
MRB

Muon neutrino disappearance analysis in a nutshell

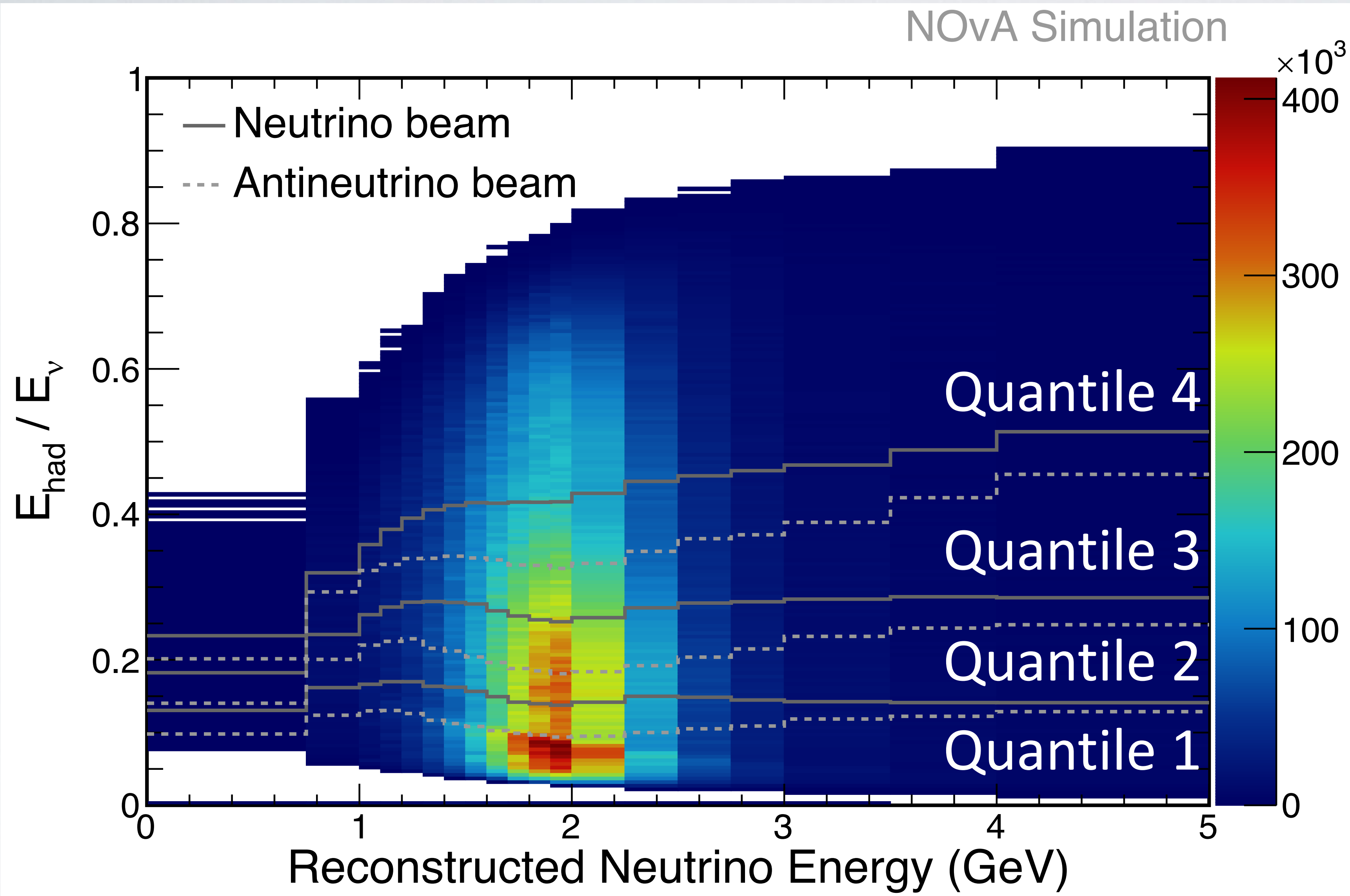
Identify contained ν_μ CC events in both detectors → Measure both energy spectra → Measure oscillation from comparison between near and far energy spectra

$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$



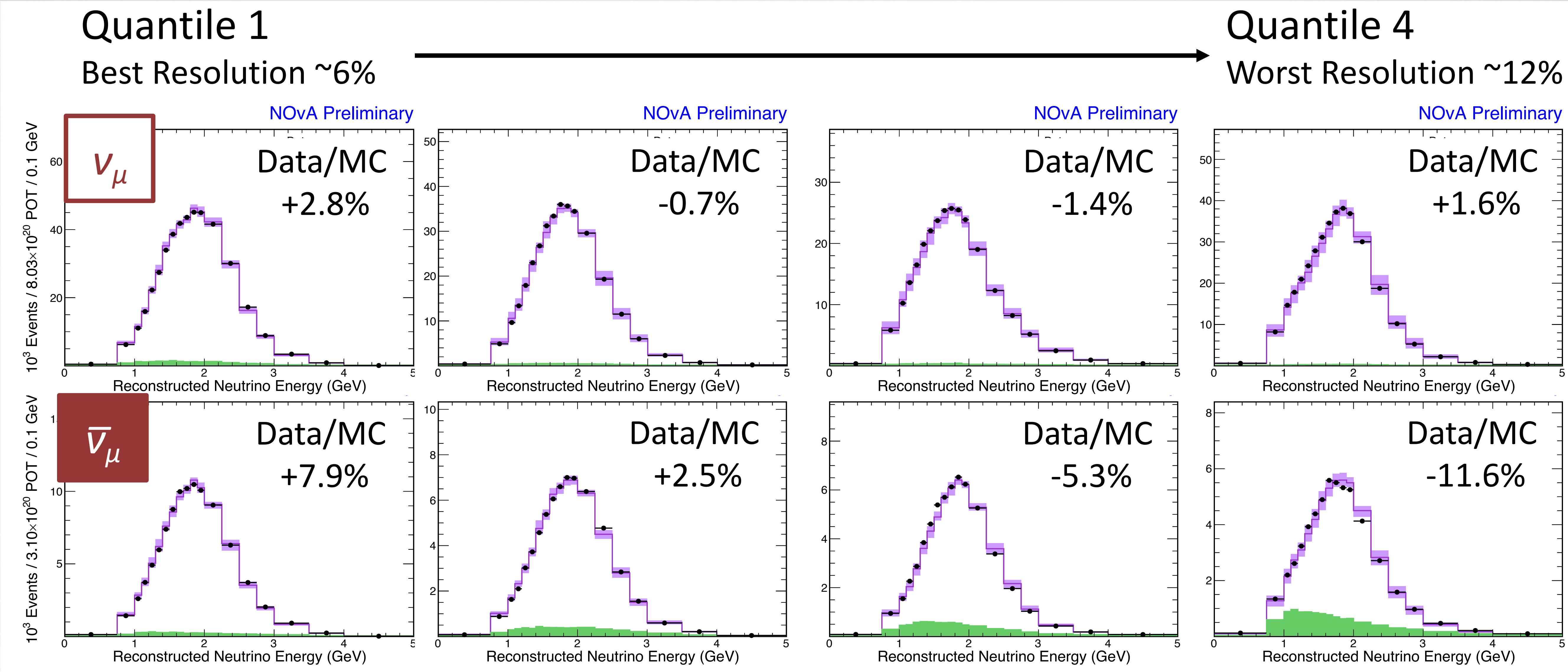


Energy resolution quartiles



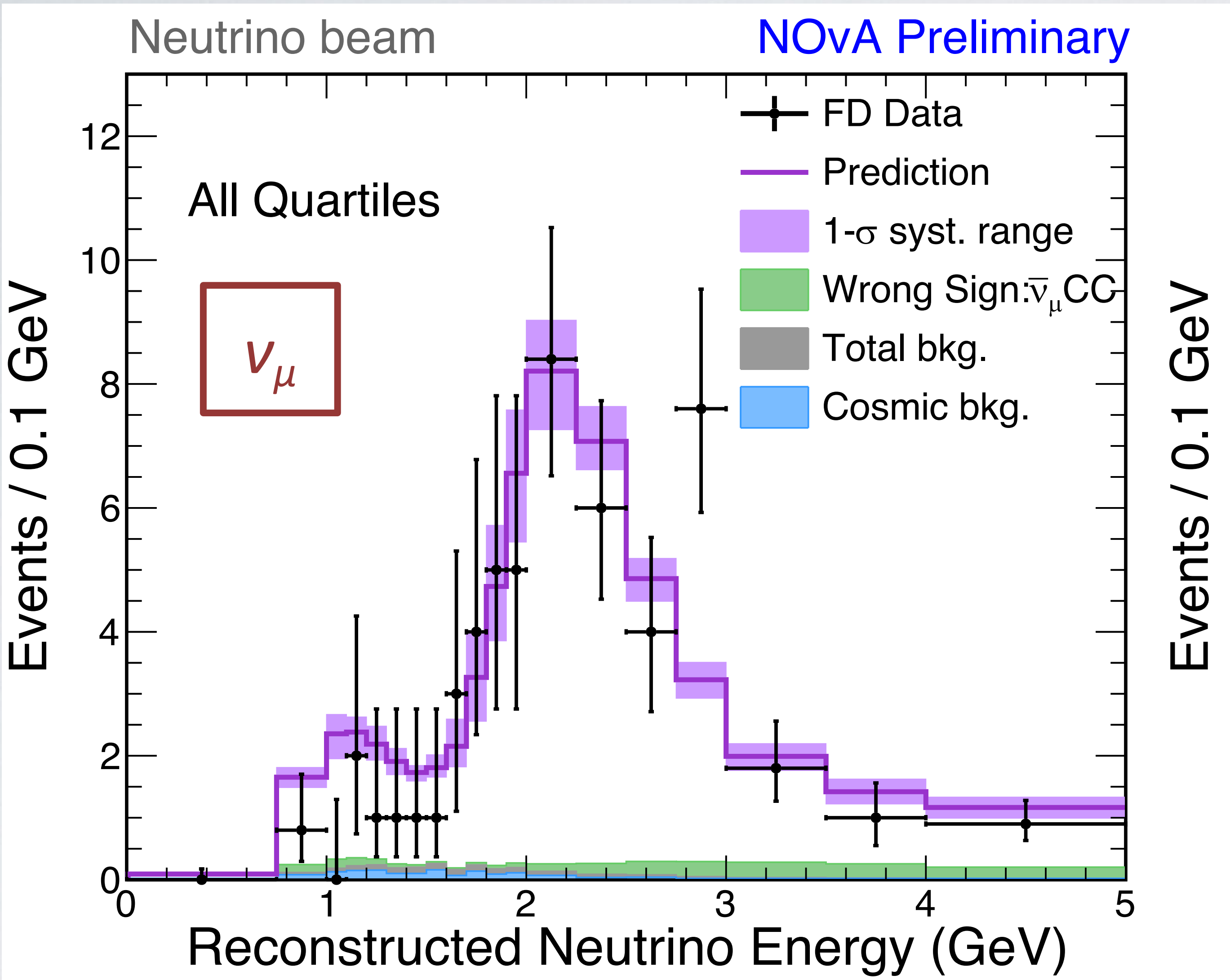
- Muons have a much better energy resolution (3%) than hadrons (30%)
- Hadronic energy fraction is a proxy for energy resolution
- Improve sensitivity by separating high-resolution and low-resolution events

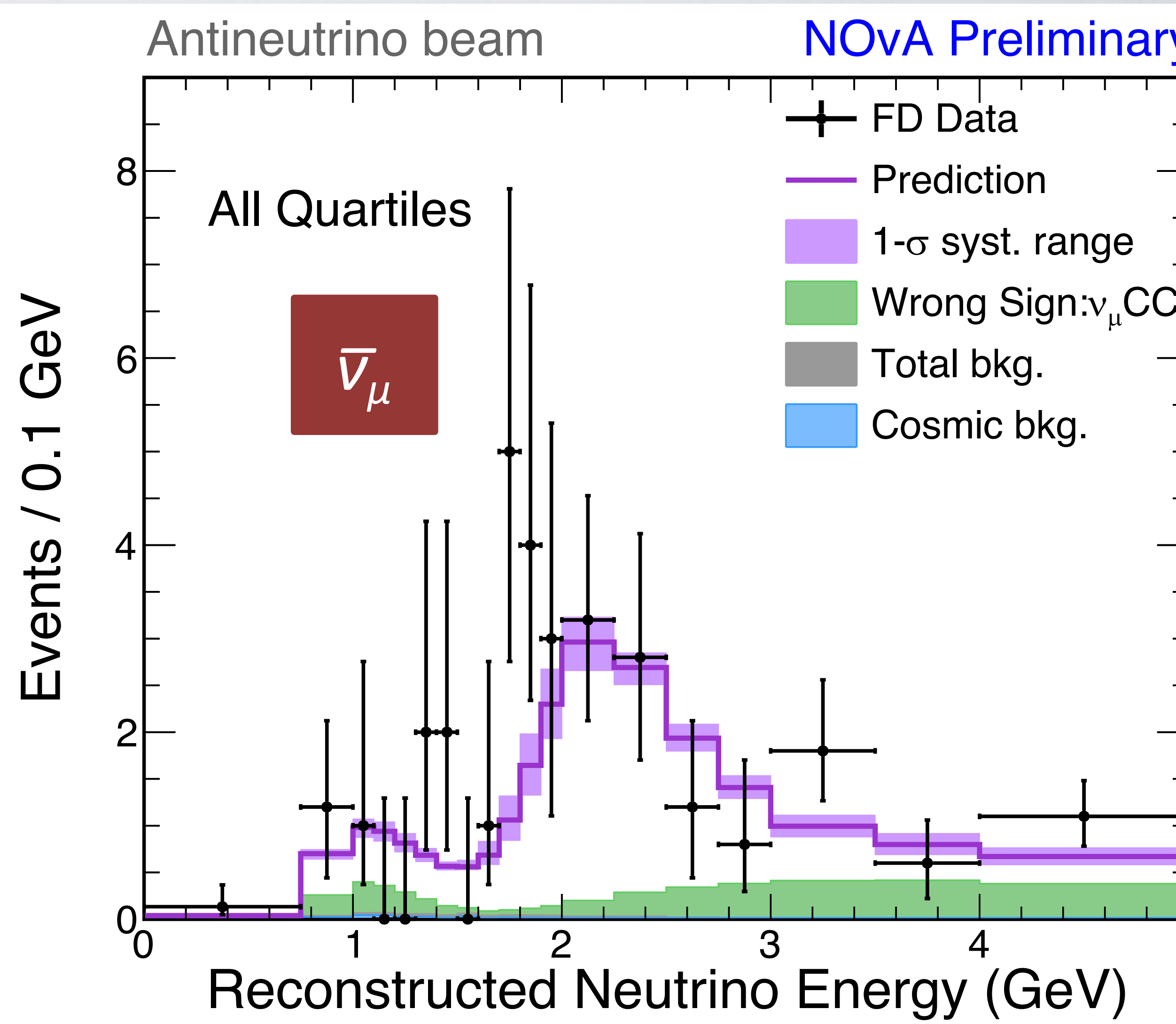
Energy resolution quartiles



- Good data/MC shape agreement across all quartiles
- By extrapolating each one separately, we are accounting for kinematic differences between data and simulation in the FD
  - This can be observed in the different normalisation for each quartile

Far detector data

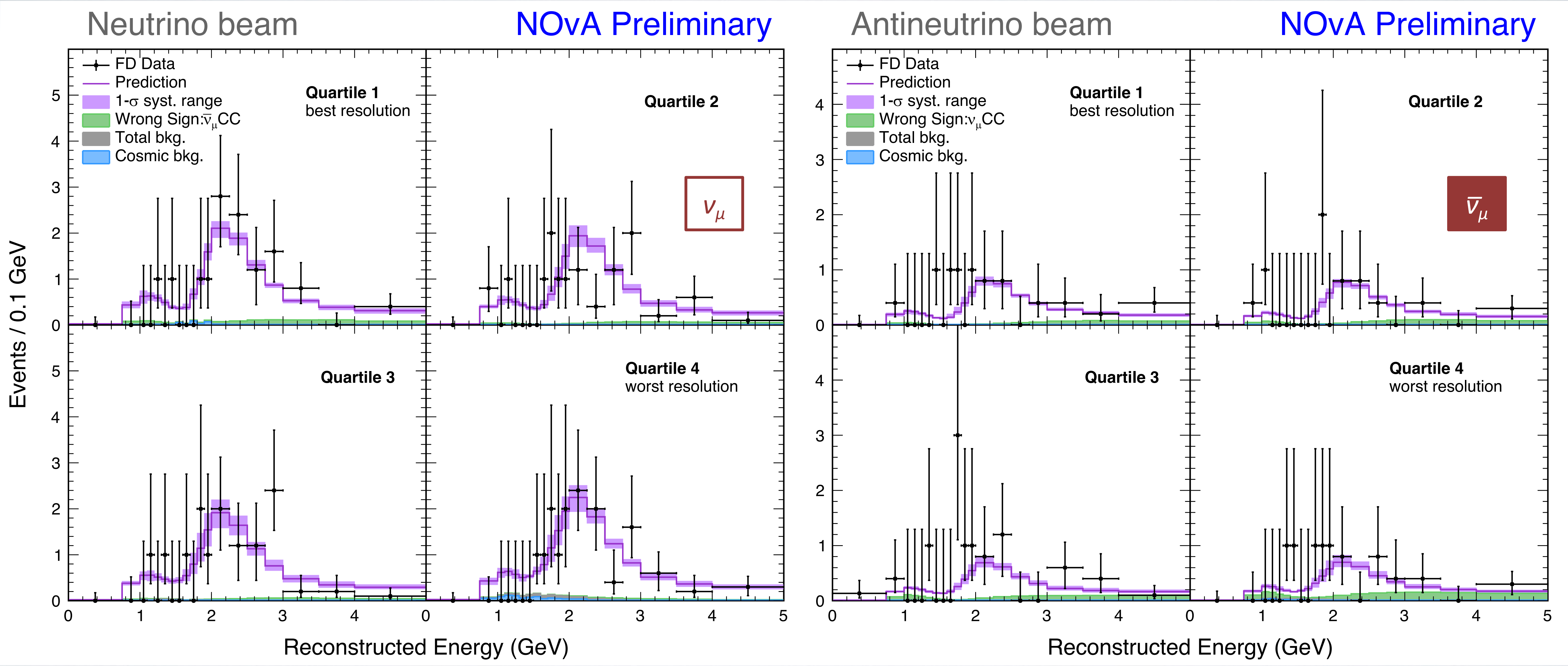




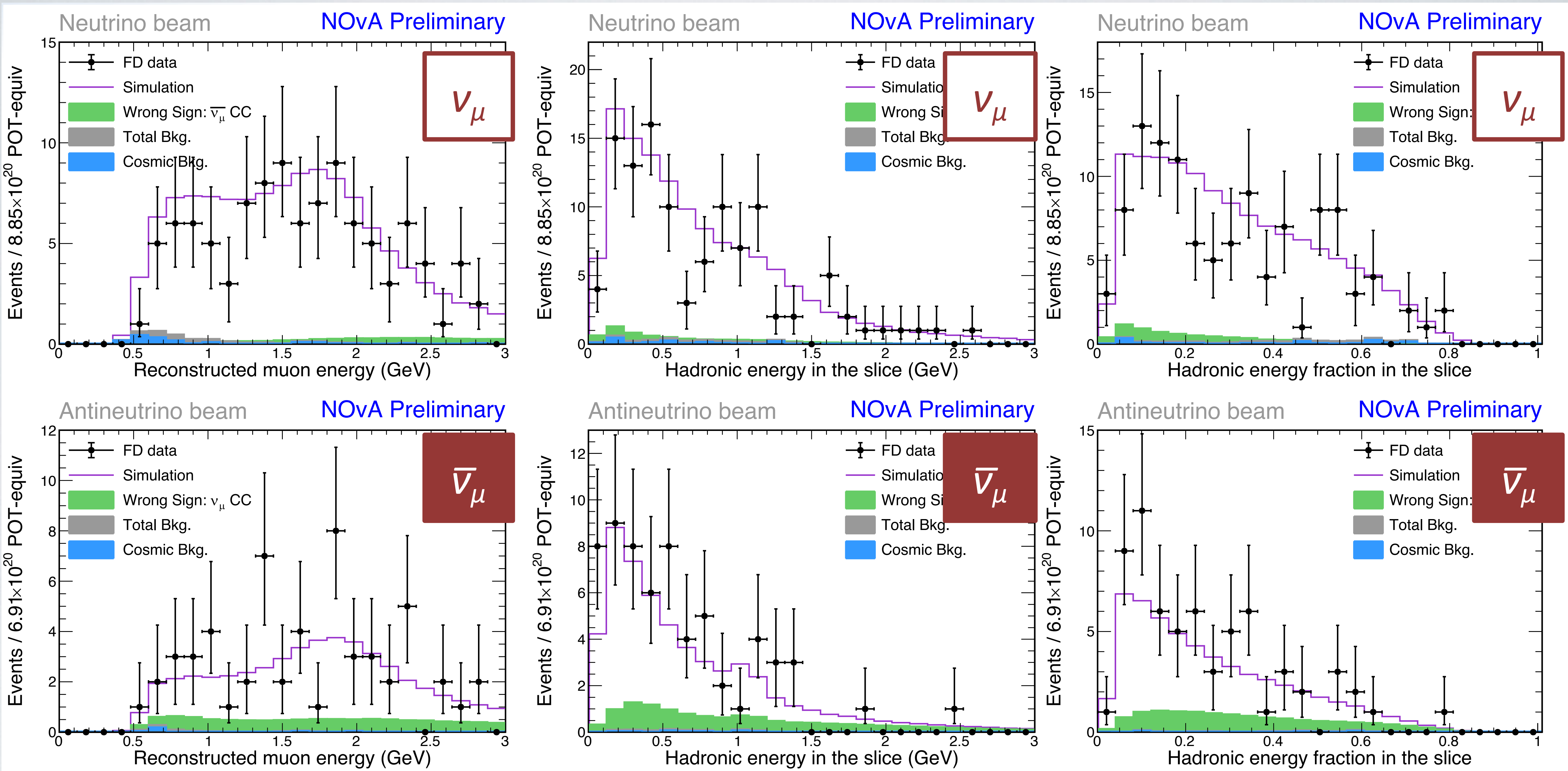
Total Observed	**113**
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

Total Observed	**65**
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266

Far detector data

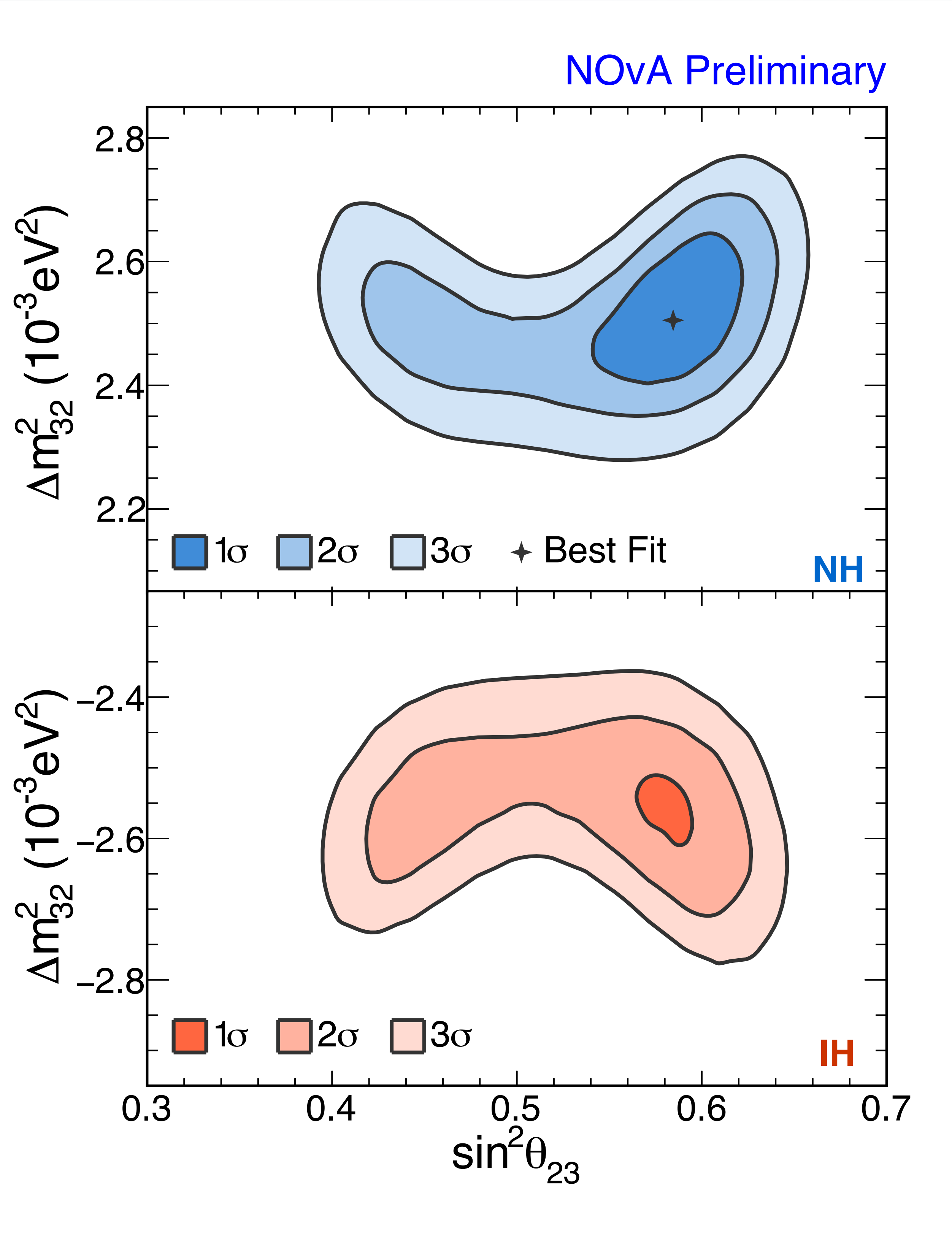


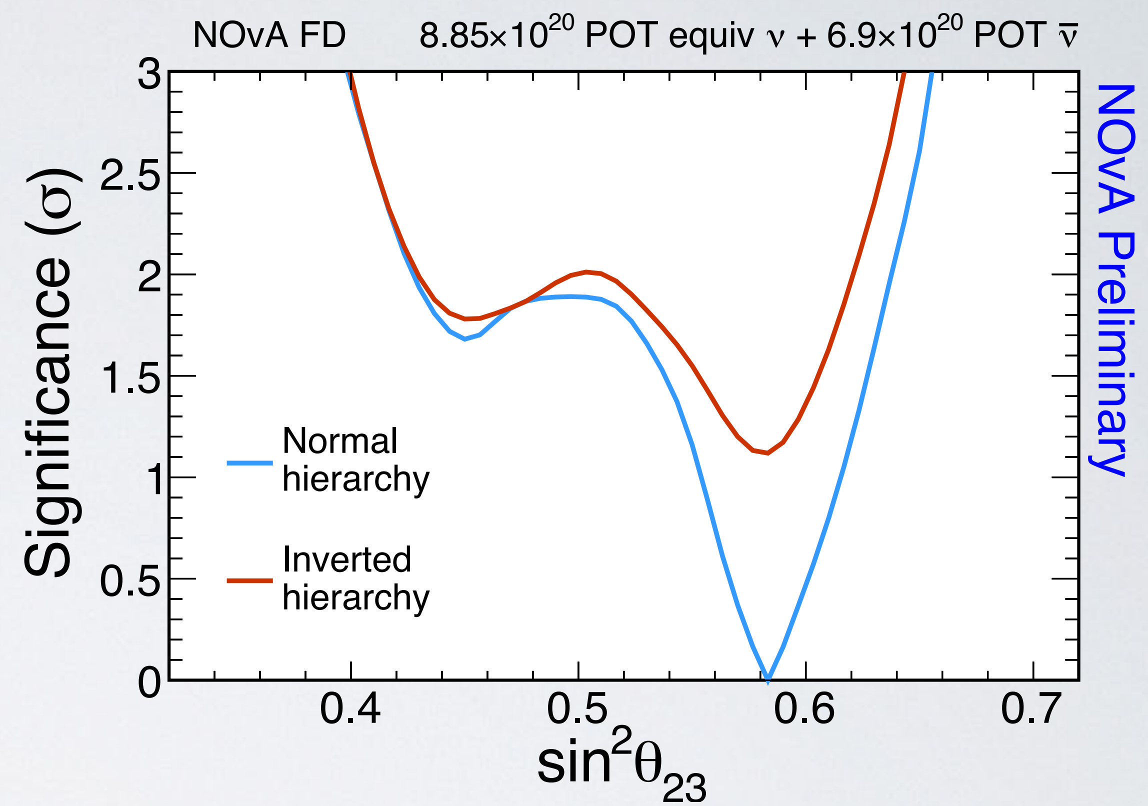
Far detector data



- Good agreement between data and MC for muon and hadronic energy, as well as inelasticity

Oscillation parameters



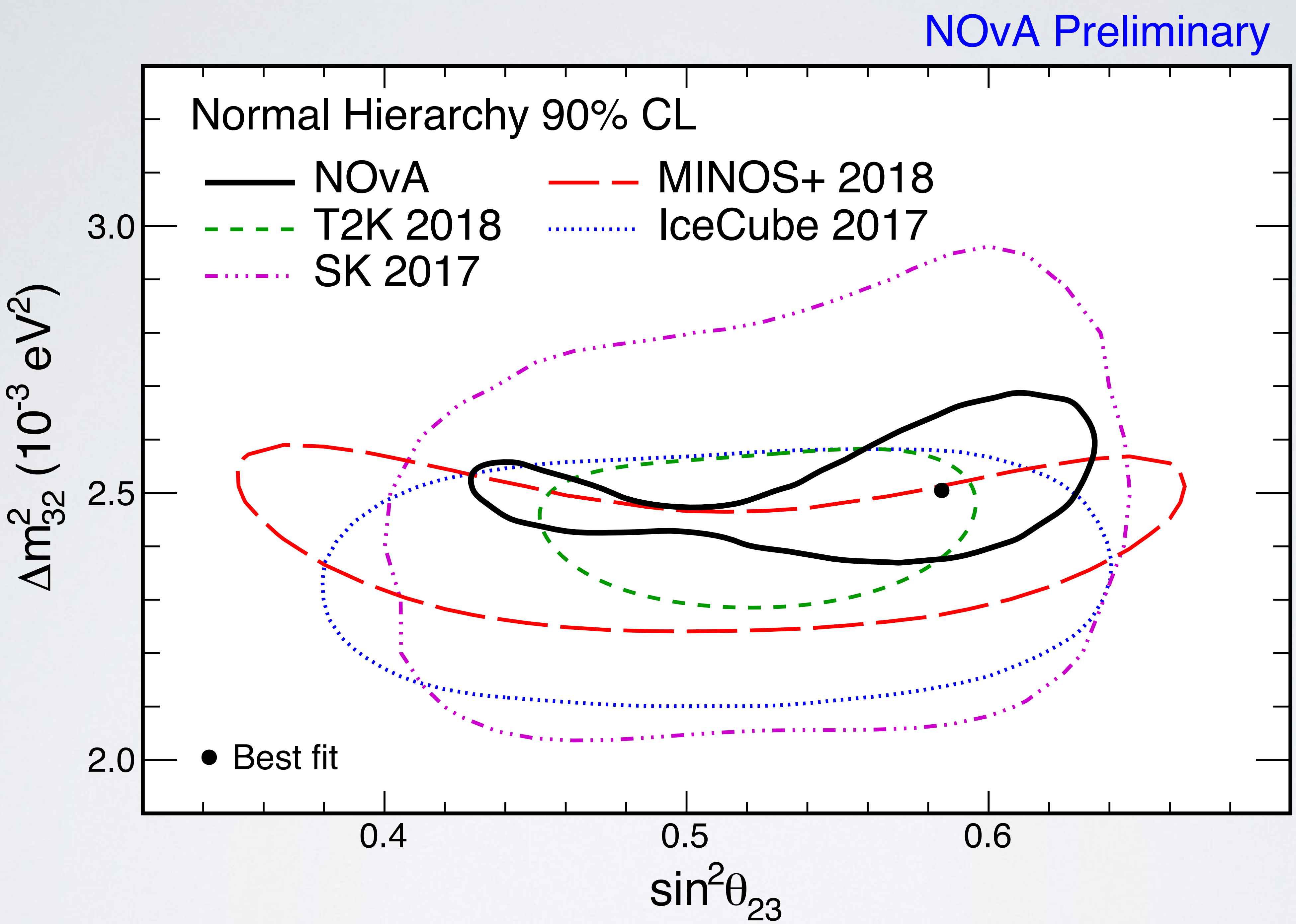


- Best fit:
  Normal Hierarchy
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ \mathrm{eV}^2$

Prefer non-maximal at 1.8σ

Exclude LO at similar level

Comparison with other experiments



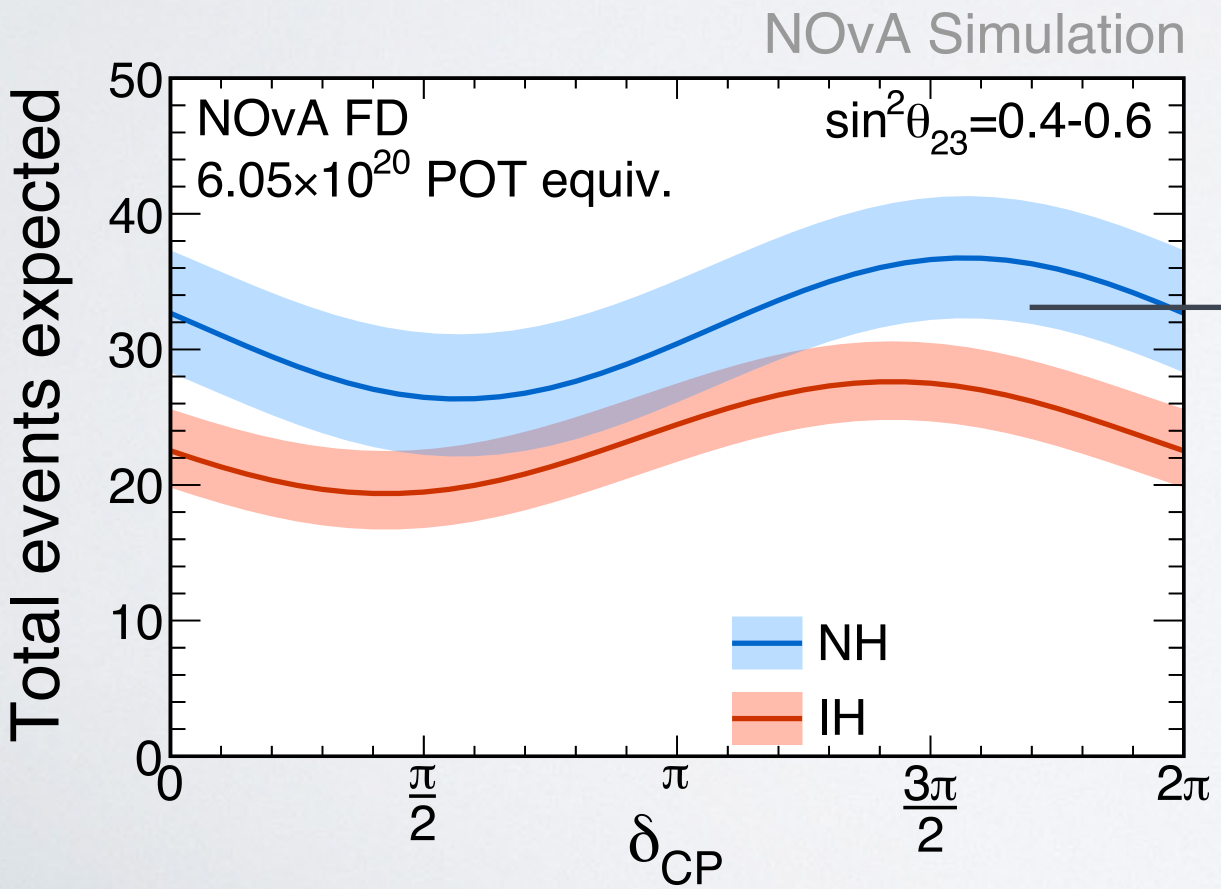
- 90% CL intervals are compatible across experiments

Electron neutrino appearance analysis in a nutshell

Identify ν_e CC events in both detectors

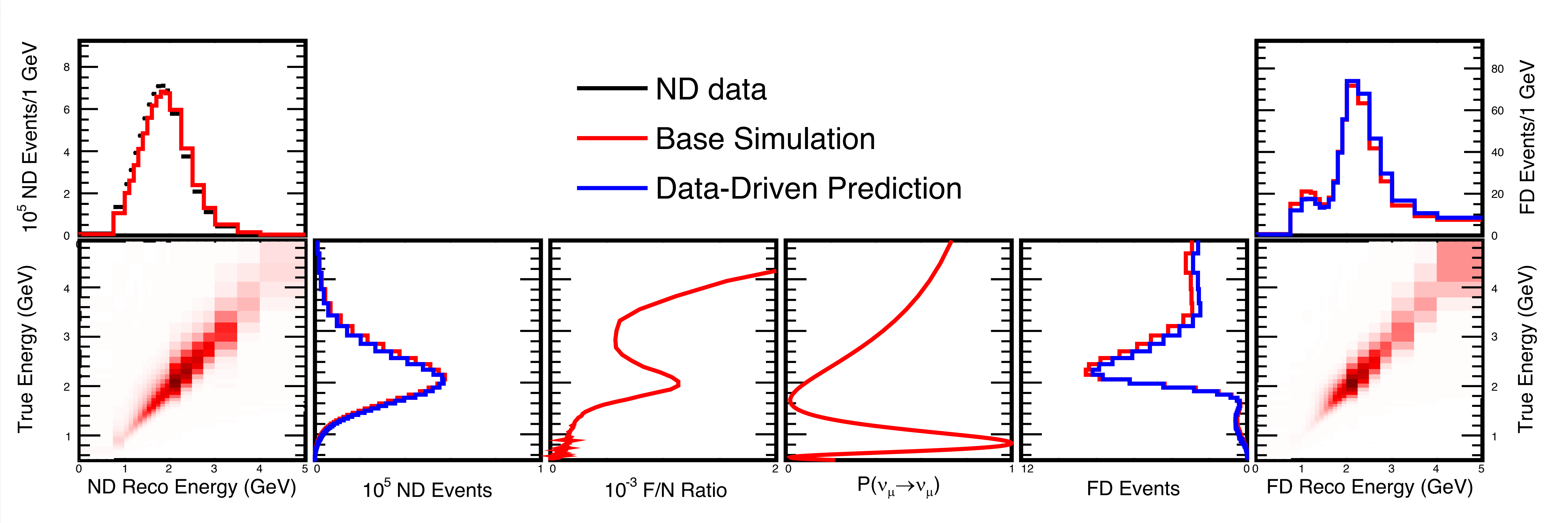
Use ND measurements to predict backgrounds in the FD

Interpret any FD excess over predicted backgrounds as ν_e appearance



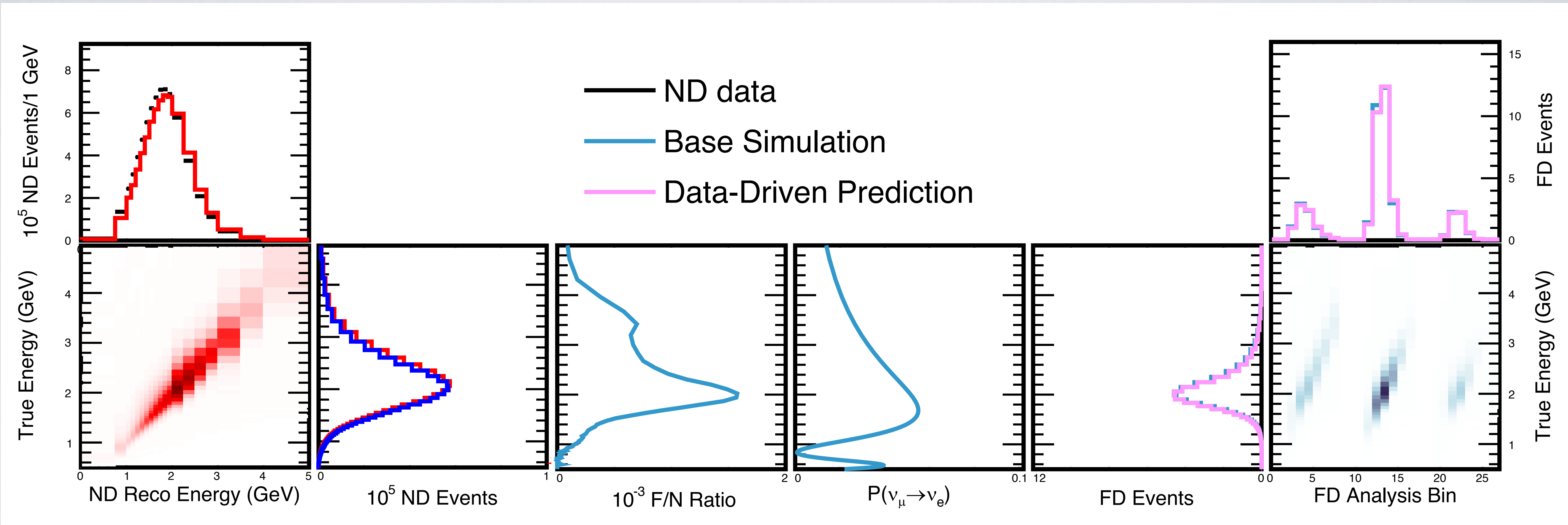
Number of observed events constraints δ_{CP} and mass hierarchy

Decomposition and extrapolation



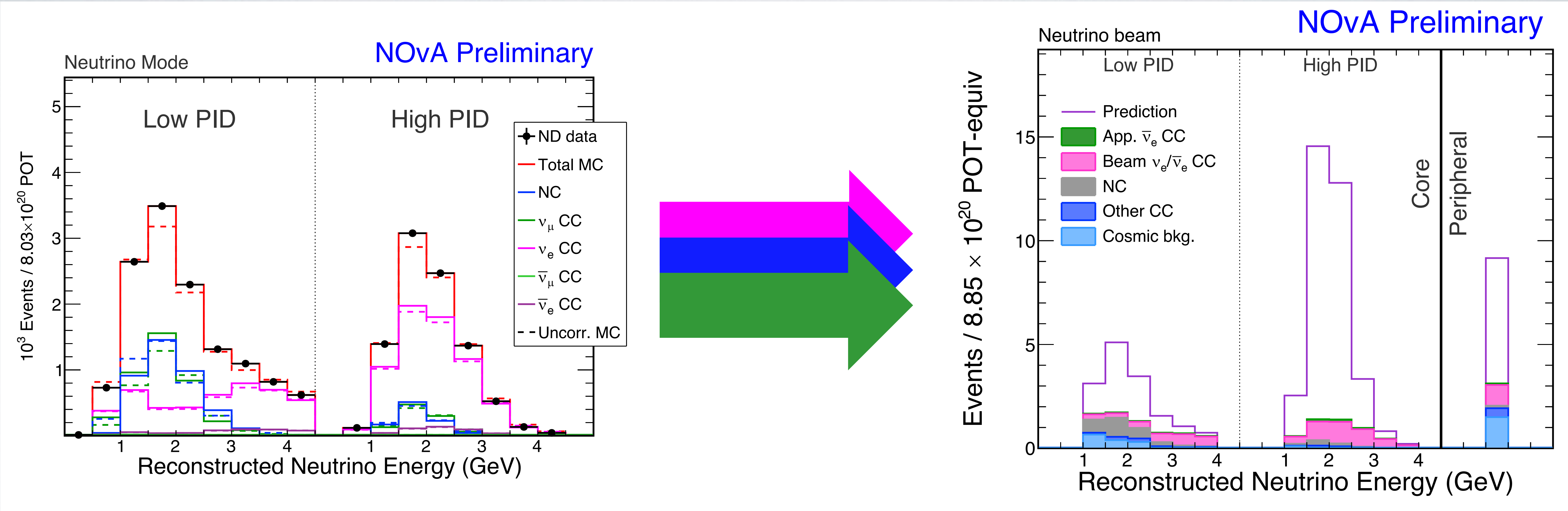
- Use the **ND ν_μ sample** to predict the **FD ν_μ sample**

Decomposition and extrapolation



- Use the **ND ν_μ sample** to predict the **FD ν_μ sample**
- Use the **ND ν_μ sample** to predict the **FD ν_e *signal***

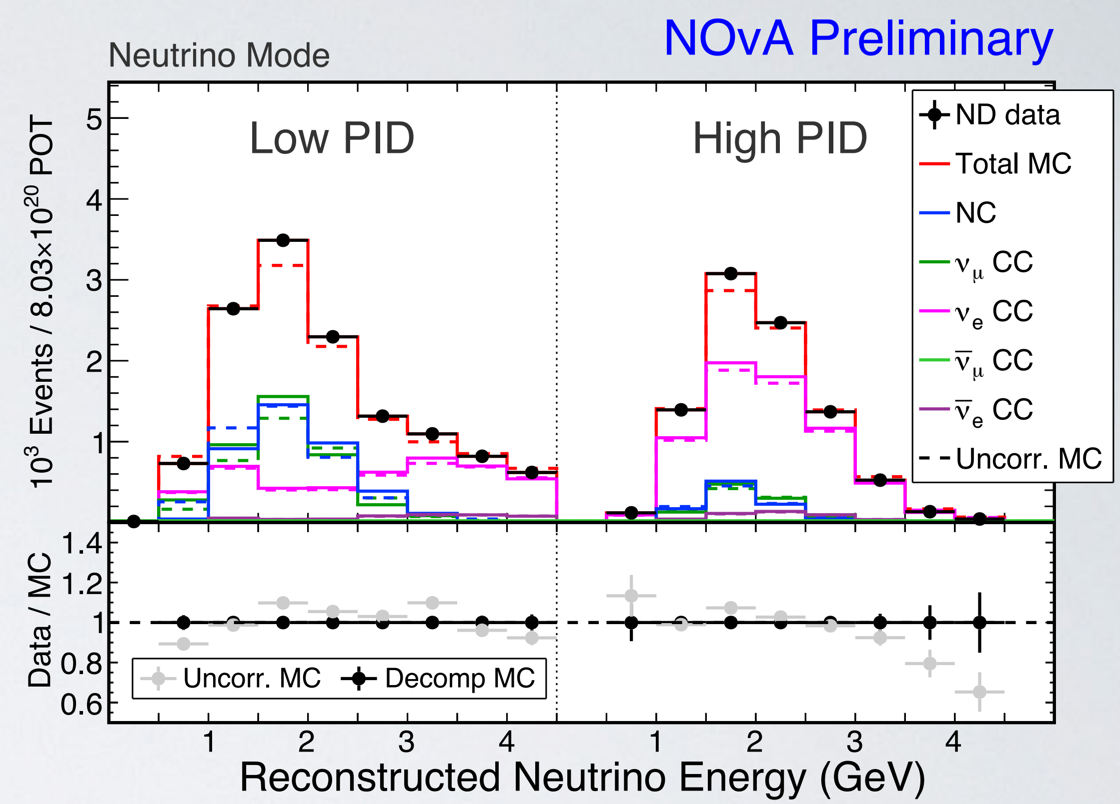
Decomposition and extrapolation

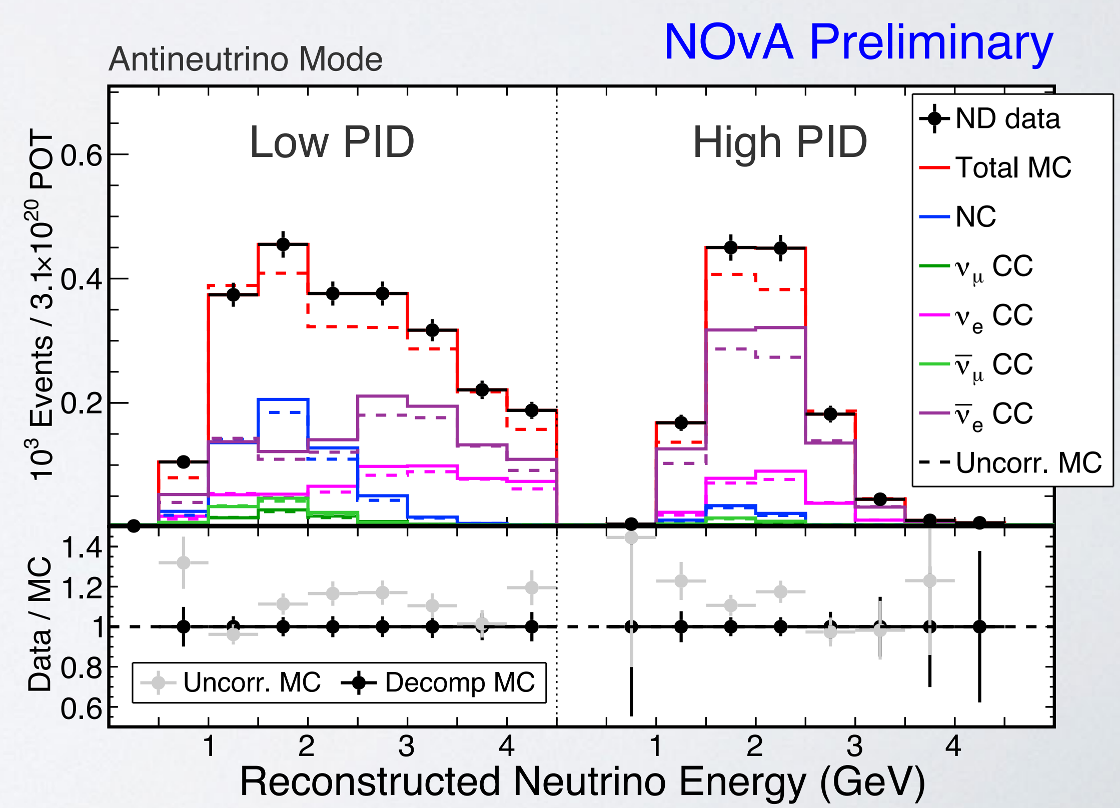


- Use the **ND ν_μ sample** to predict the **FD ν_μ sample**
- Use the **ND ν_μ sample** to predict the **FD ν_e *signal***
- Use the **ND ν_e-like sample** to predict the **FD ν_e *background***

Decomposition and extrapolation

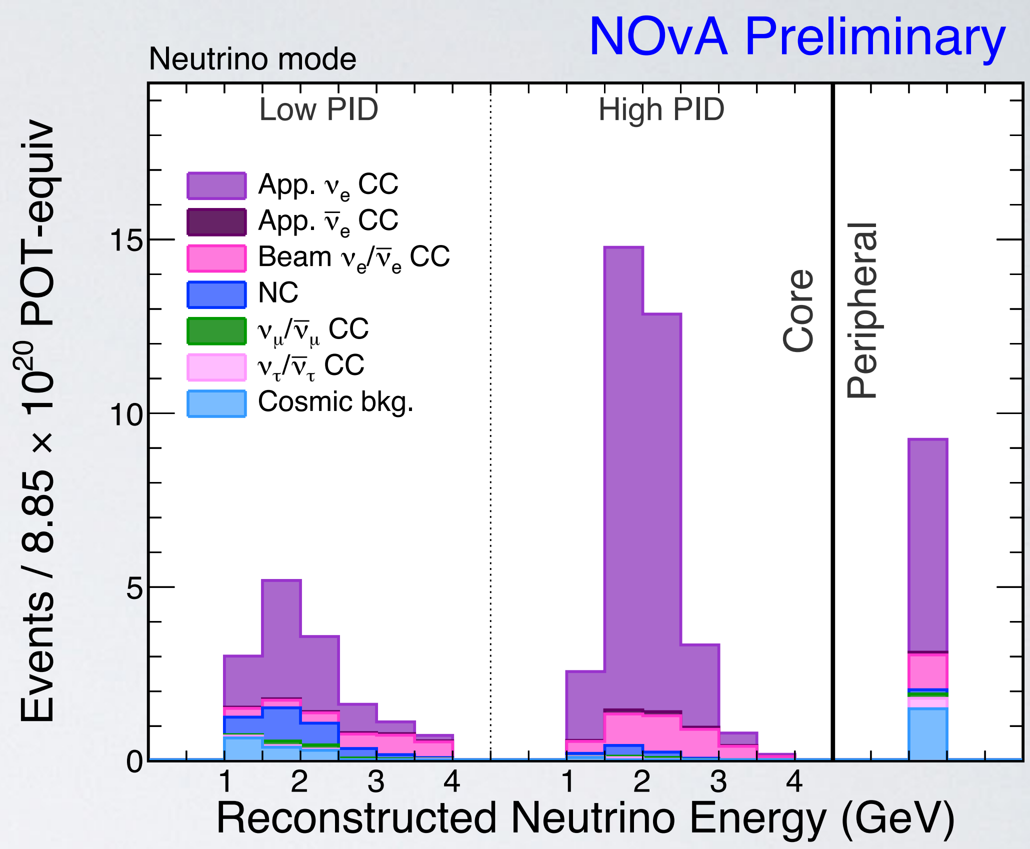
- Select **electron neutrino** events using particle ID in the ND for each beam mode
  - Separate into low and high particle ID (purity) range
- For the **neutrino** beam constrain:
  - The beam electron neutrinos using the muon neutrino spectrum, and
  - The muon neutrino background using Michel electrons
  - Remaining data/MC discrepancy is assigned to the NC component
- For the **antineutrino** beam, scale all components evenly to match the data

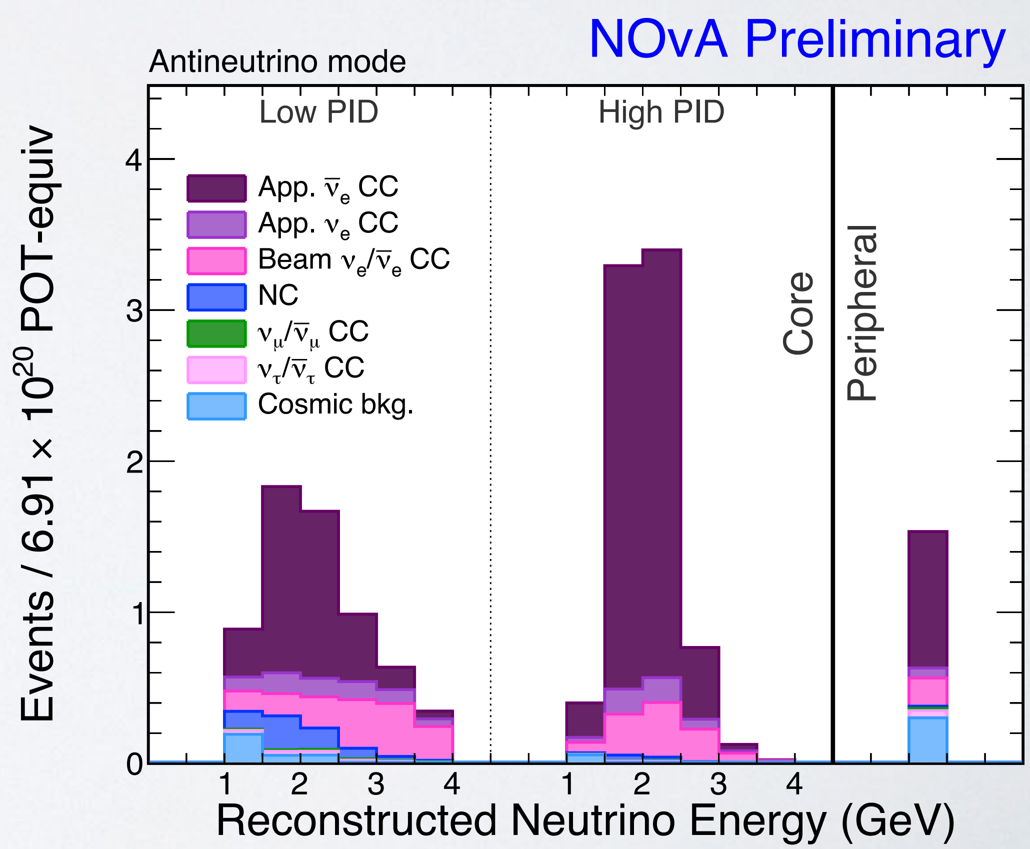




Decomposition and extrapolation

- We use the ND data to predict the background in the FD. Each component is propagated independently in bins of energy and particle ID bins
- Add a one-bin peripheral signal sample. This sample has a less stringent containment selection, but stronger ID requirements
- ND wrong sign component is 22% (32%) of the ν_e background for the high (low) PID bin
  - Data-based cross-checks using identified protons and event kinematics within systematic uncertainty





Joint fit

- In previous analyses, muon neutrino disappearance and electron neutrino appearance were fitted separately
- In this analysis we have moved to a joint-fit, which in practice involves fitting 14 experiments
- Although the data are independent across experiments, the systematics are correlated and have to be handled with care

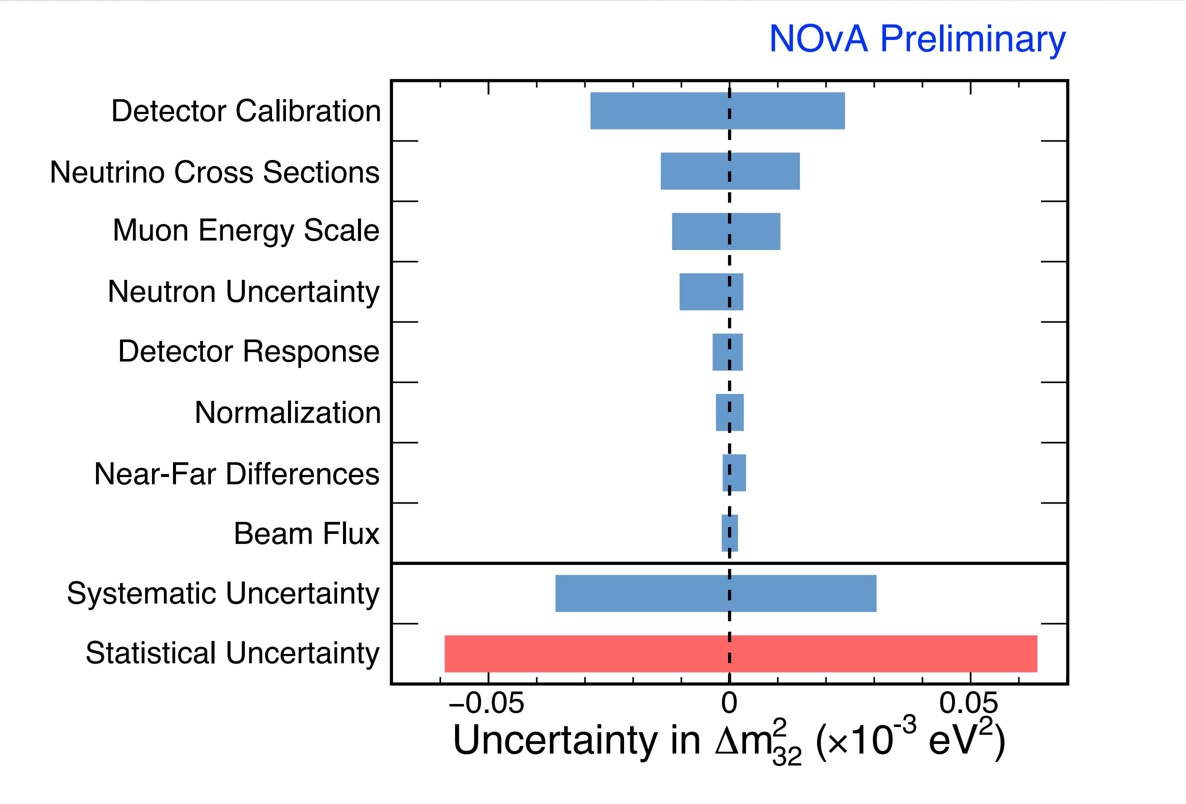
Neutrinos

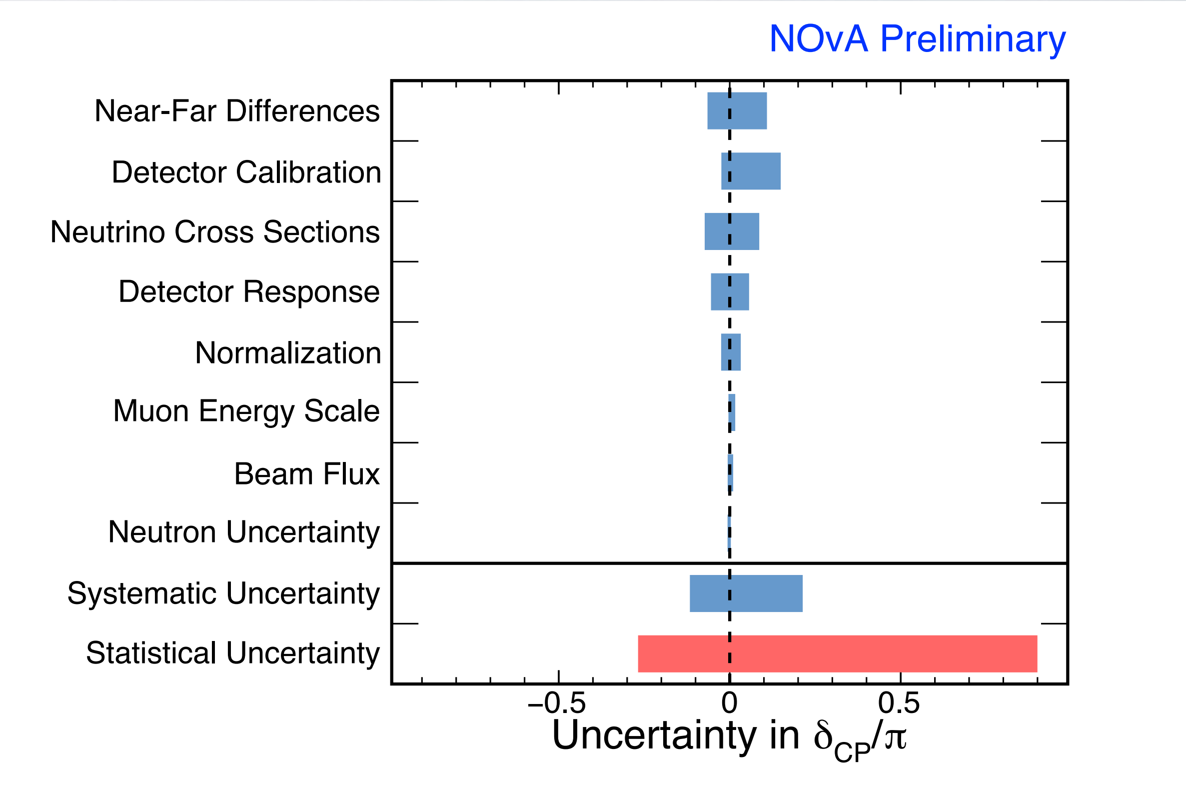
- Appearance: low / high CVN + peripheral
- Disappearance: Q1-Q4

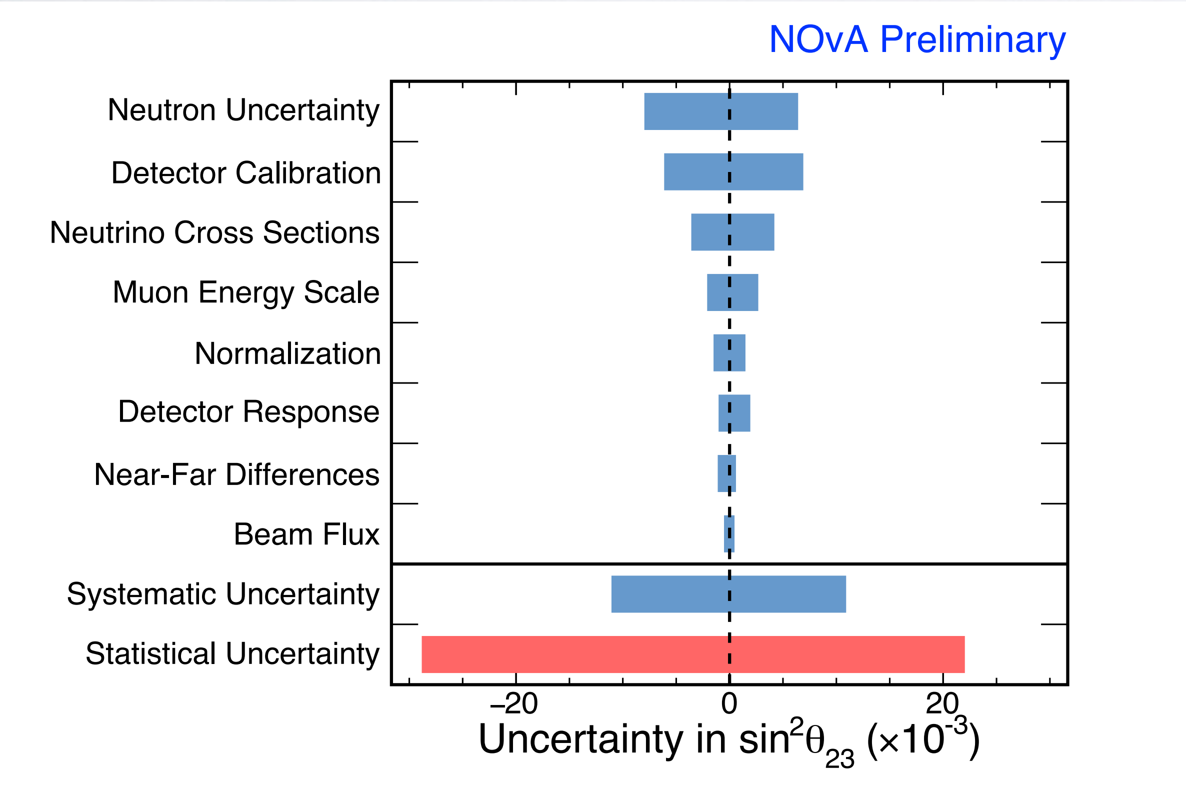
Antineutrinos

- Appearance: low / high CVN + peripheral
- Disappearance: Q1-Q4

Systematic uncertainties





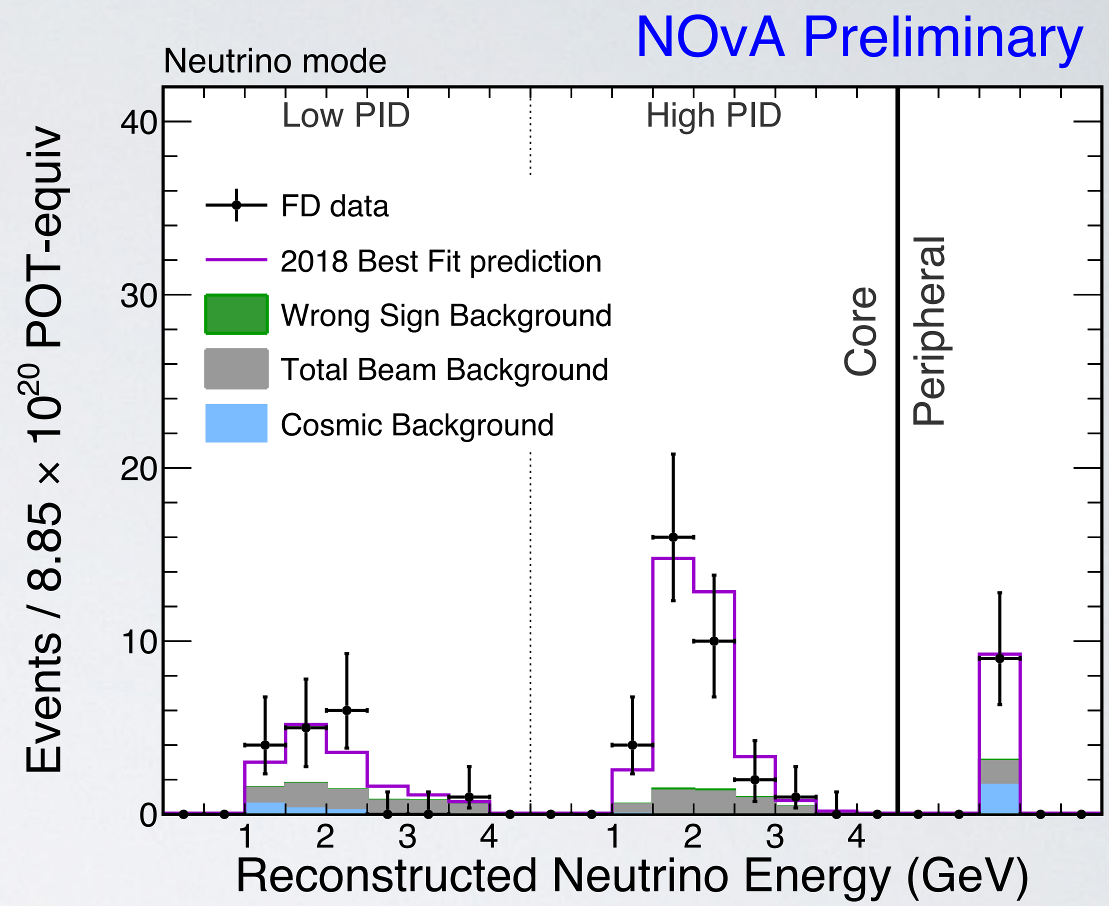


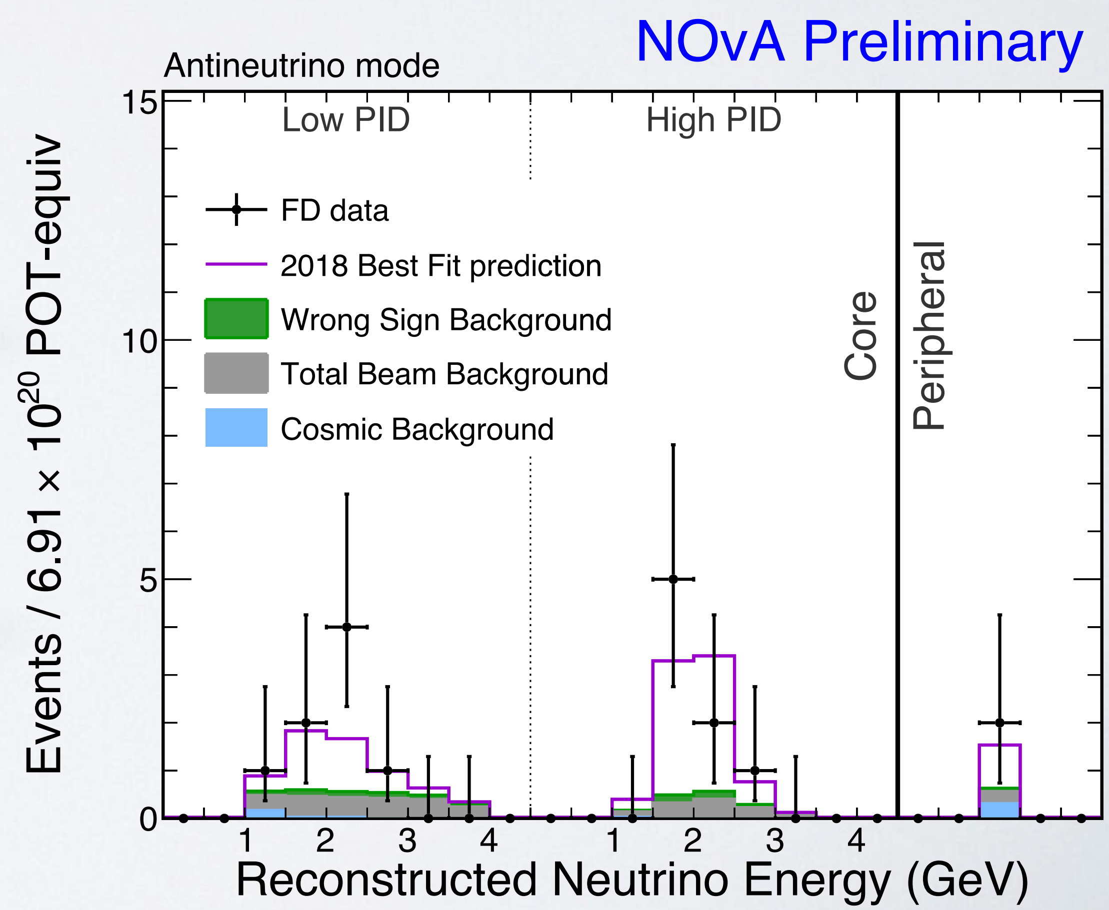
- Measurements are still statistics limited but calibration and cross sections are the largest uncertainties
- Upcoming test beam programme will address the calibration and detector response uncertainties

FD data

- On the **neutrino** beam we observe **58 events** and expect 15 background interactions
  - 11 beam, 3 cosmic background and < 1 wrong sign background
- On the **antineutrino** beam we observe **18 events** and expect 5 background interactions
  - 3.5 beam background, < 1 cosmic background and 1.1 wrong sign background

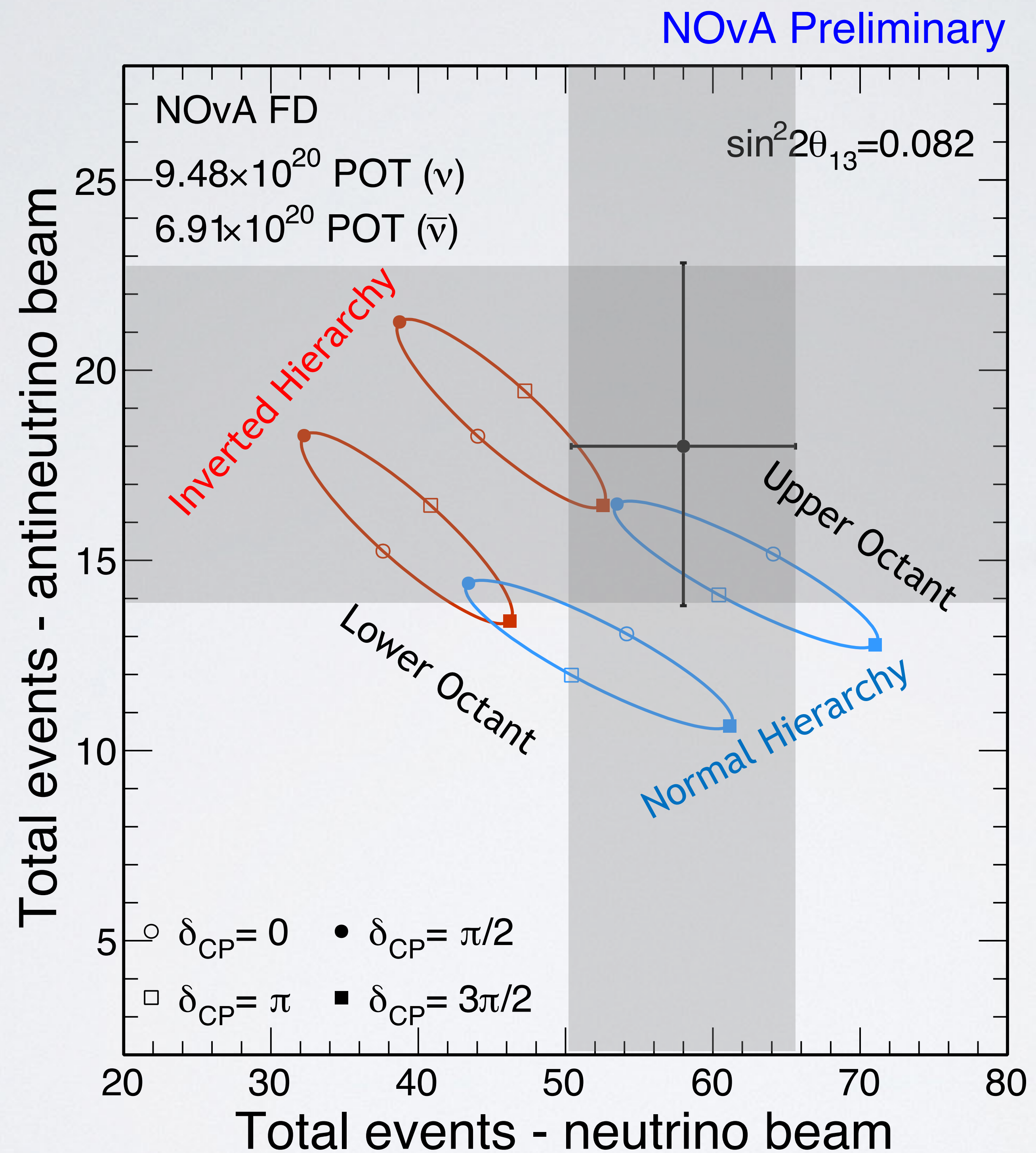
>4σ evidence of electron antineutrino appearance





Event count

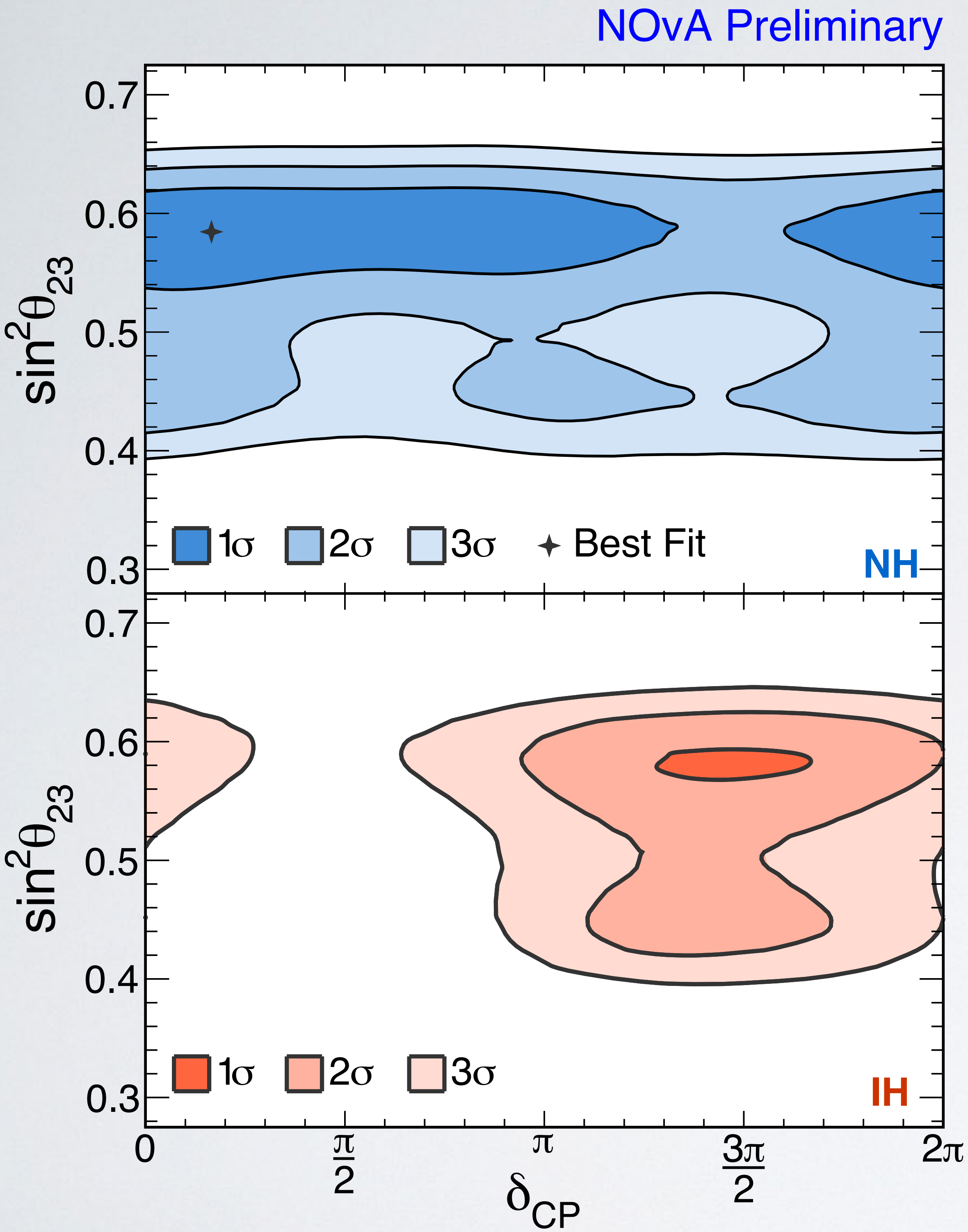
18 observed $\bar{\nu}_e$

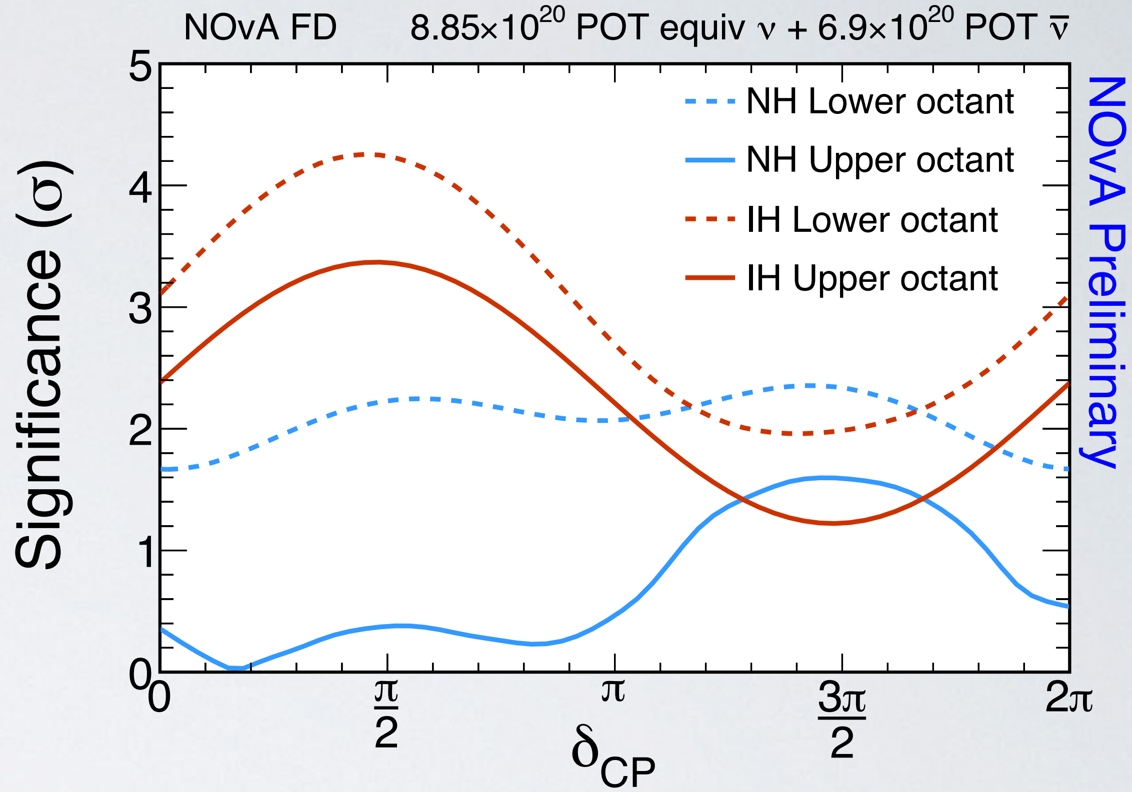


Not a golden region at this round

58 observed ν_e

Oscillation parameters

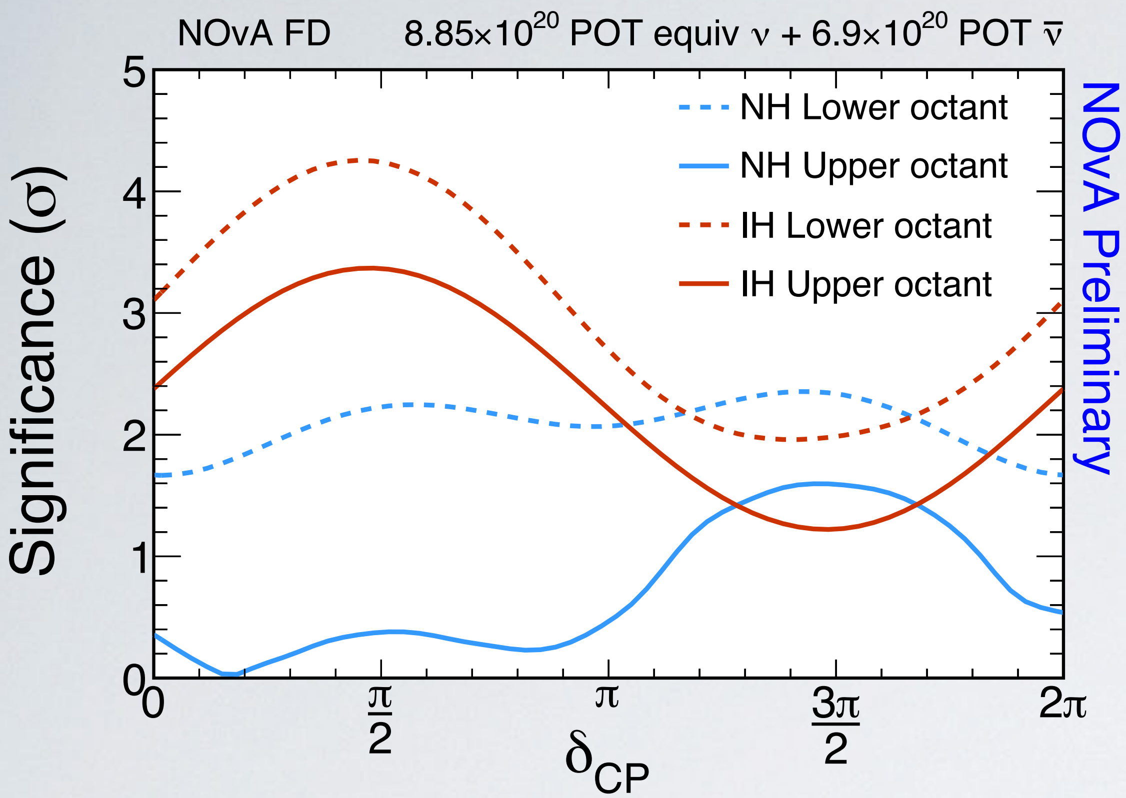




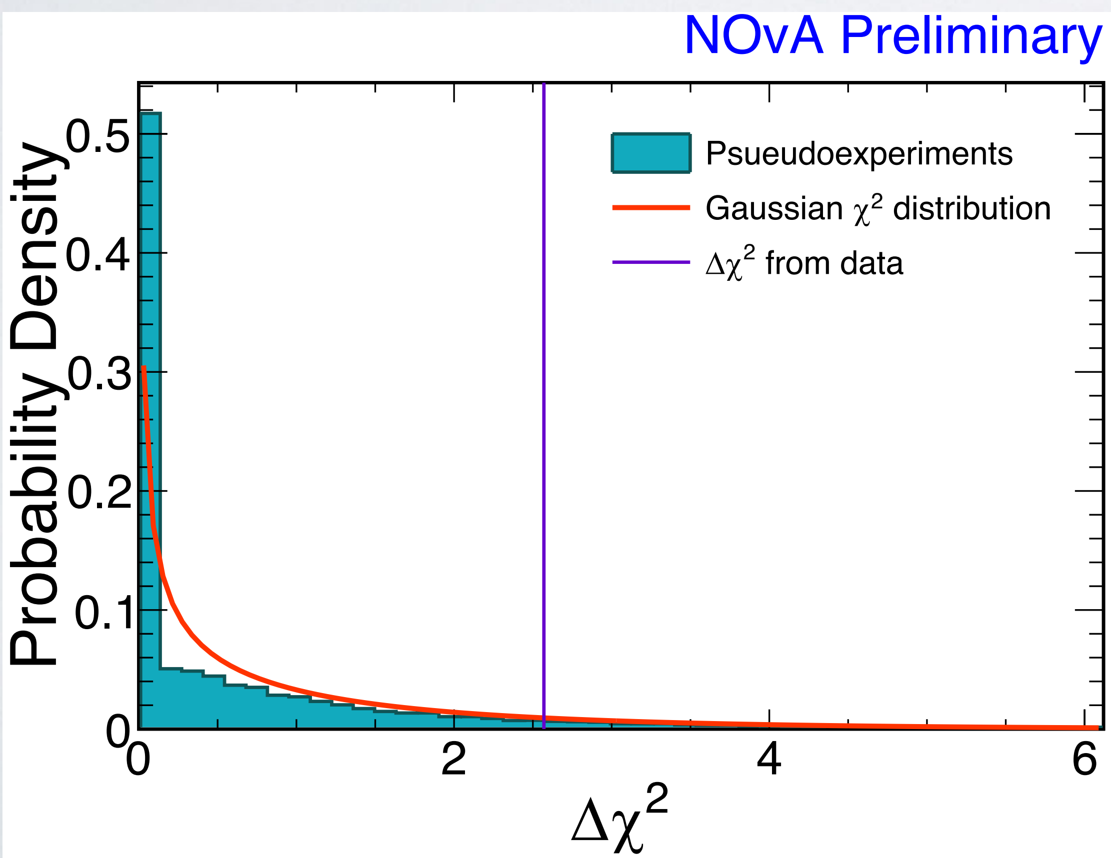
- Best fit: Normal Hierarchy
  $\delta_{CP} = 0.17\pi$
  $\sin^2\theta_{23} = 0.58 \pm 0.03$ (UO)
  $\Delta m^2_{32} = (2.51^{+0.12}_{-0.08}) \cdot 10^{-3}\ \mathrm{eV}^2$

Prefer NH by 1.8σ

Exclude $\delta = \pi/2$ in the IH at > 3σ



- One **cannot** read the rejection of IH from this plot
  - This is a FC-corrected plot of significance for rejecting particular sets of values (**δ**, octant, hierarchy)
  - Not a likelihood surface, so it can't be profiled nor marginalised
- Besides, the mass hierarchy is a highly non-Gaussian parameter (binary NH/IH), so we need to use a dedicate Feldman-Cousins analysis



$$\chi^2(\text{IH}) - \chi^2(\text{IH}) = 2.47$$

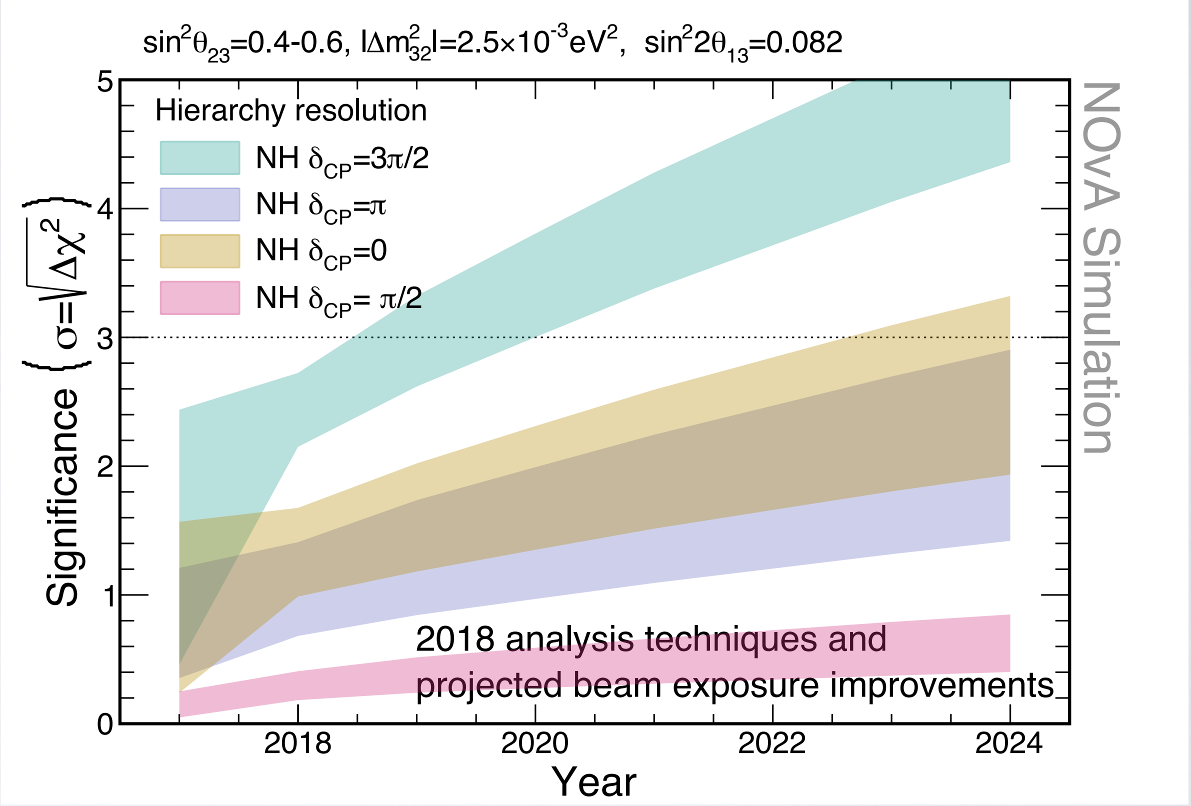
p-value of 0.076 from the FC empirical χ^2

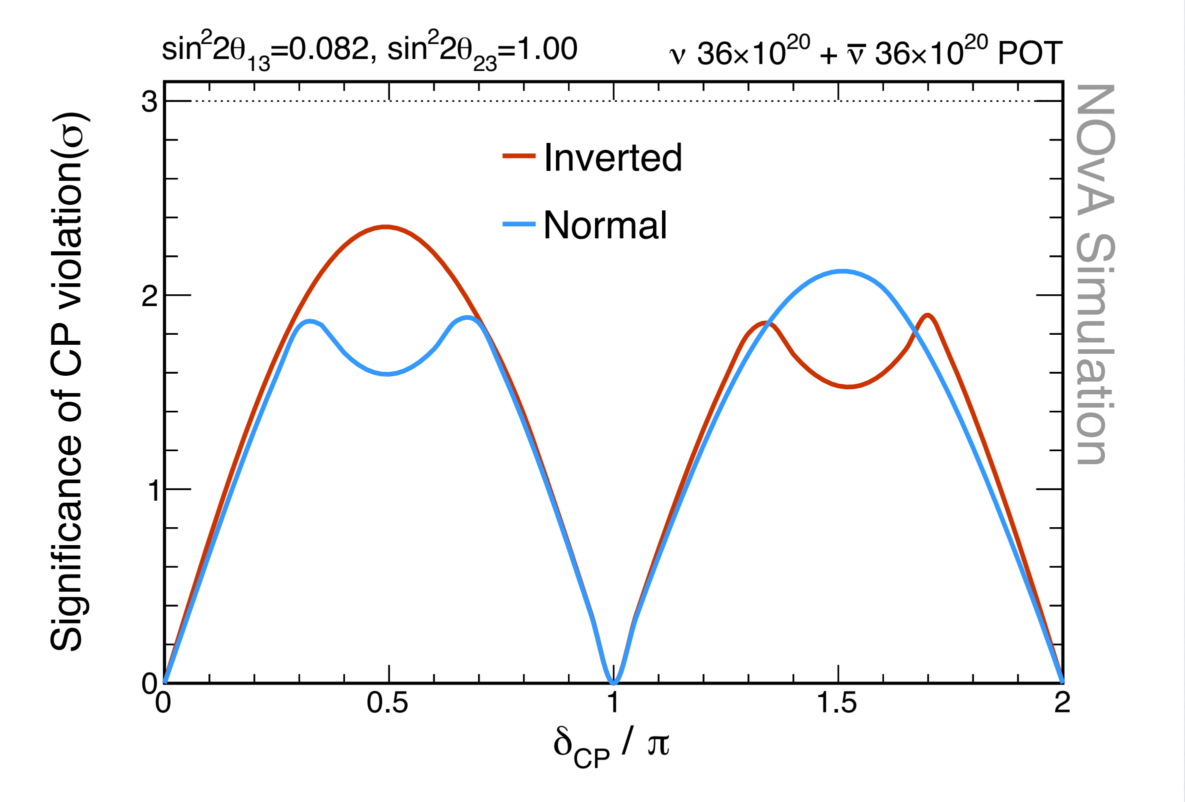
Or equivalently

1.8**σ** rejection of IH

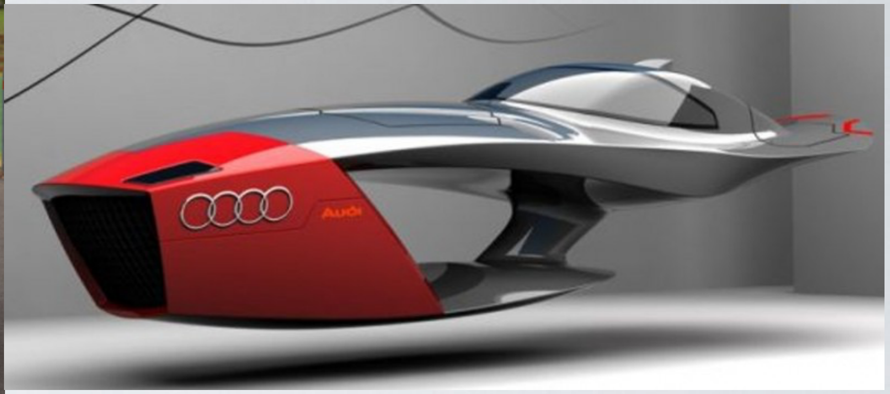
NOvA prospects

- Currently running anti-neutrino beam. Run 50% neutrino, 50% anti-neutrino after 2018.
- Extended running through 2024, proposed accelerator improvement projects and test beam program enhance NOvA's ultimate reach.
- 3σ sensitivity to hierarchy (if NH and $\delta_{CP}=3\pi/2$) for allowed range of θ_{23} by 2020. 3σ sensitivity for 30-50% (depending on octant) of δ_{CP} range by 2024.
- $>2\sigma$ sensitivity for CP violation in both hierarchies at $\delta_{CP}=3\pi/2$ or $\delta_{CP}=\pi/2$ (assuming unknown hierarchy) by 2024.





Next generation experiments



1st generation | 2nd generation | 3rd generation

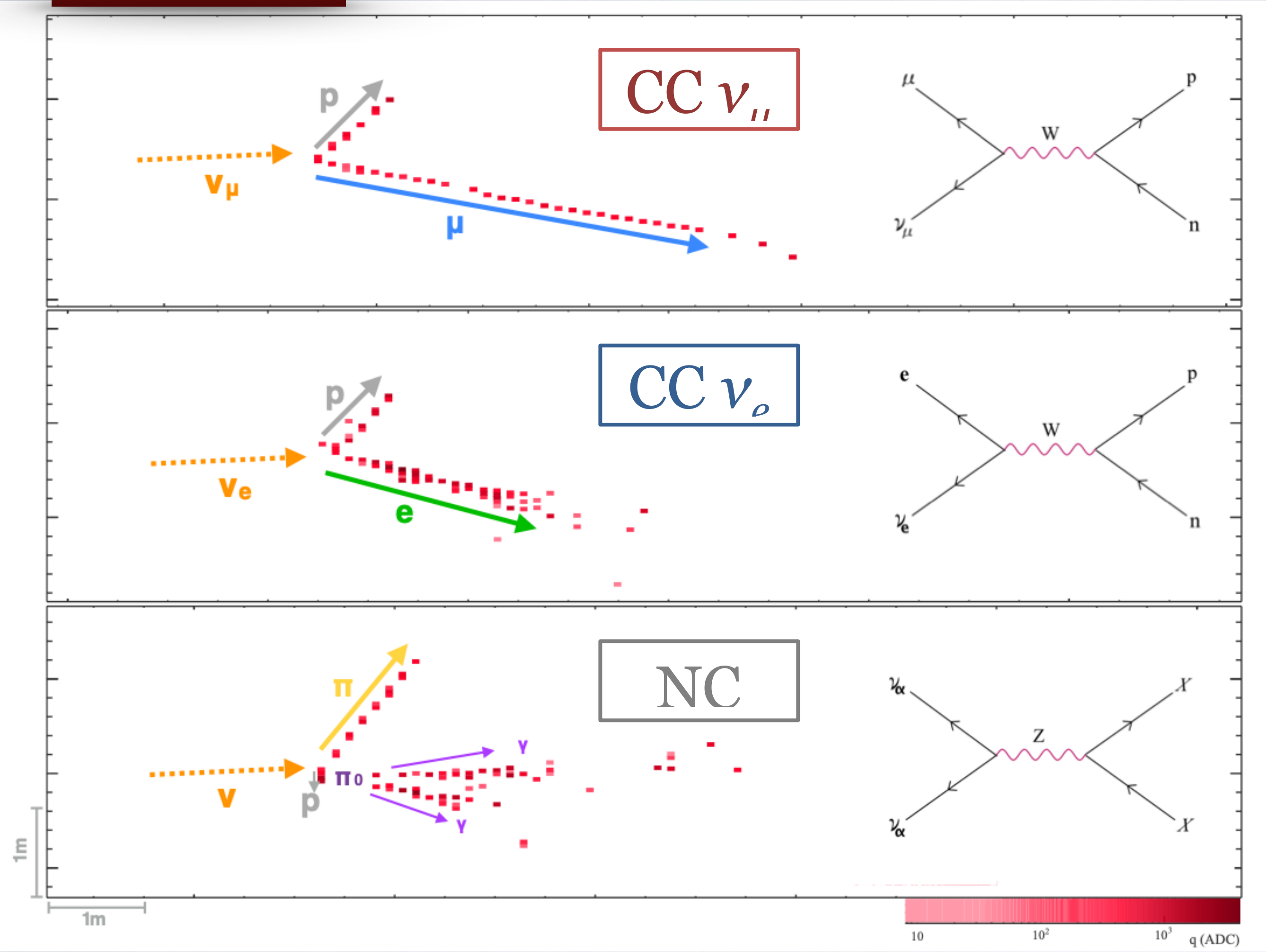
- Higher intensity beams can provide more neutrinos and allow for a longer baseline
- Similarly, larger mass can allow to collect more neutrinos
- Finally, higher detector resolution allows for better background rejection

In the US, DUNE is being planned with a baseline of 1300 km, a new 2.3 MW beam and high resolution liquid argon detectors

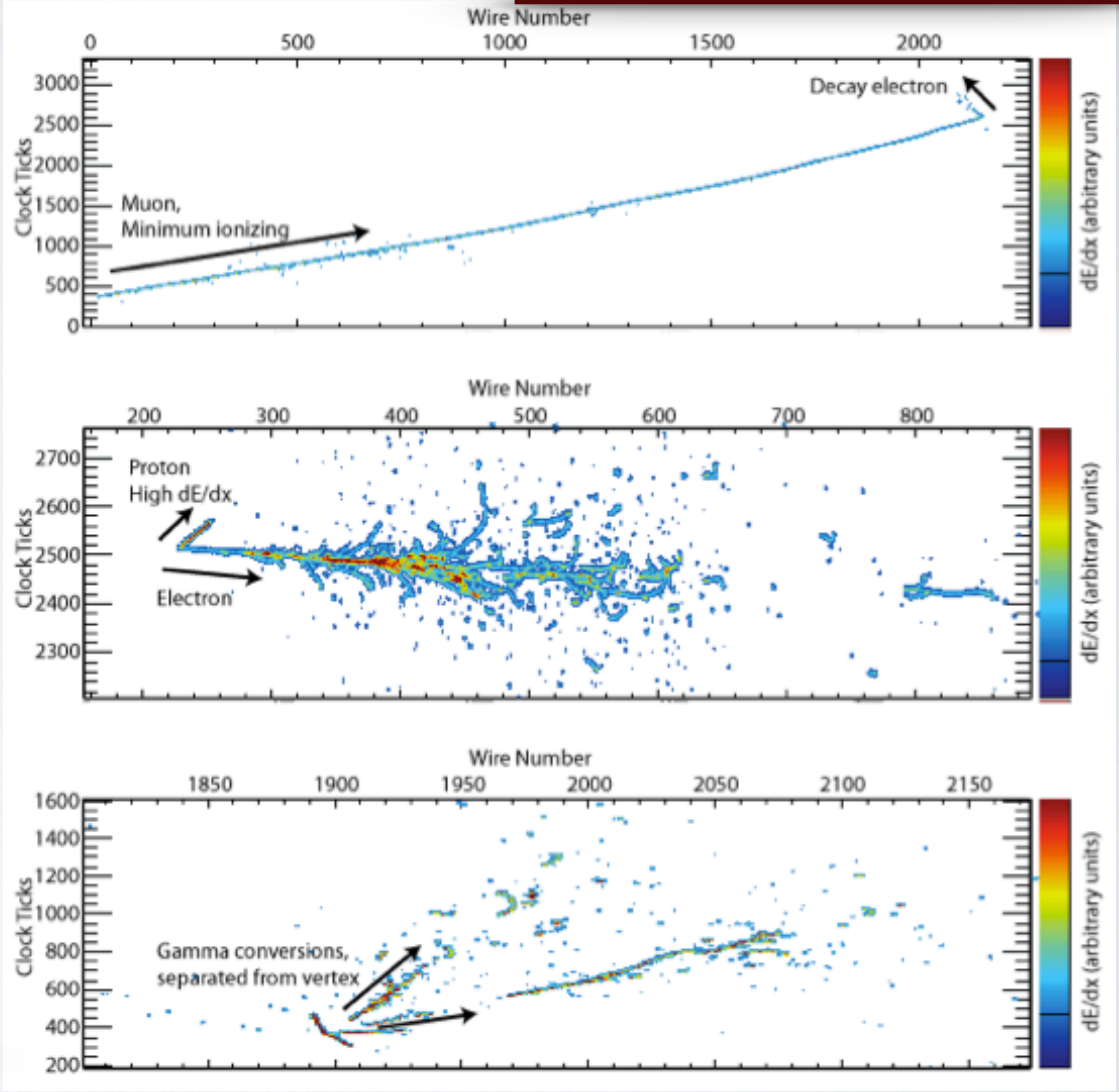
In Japan, HyperK is also being planned with an upgrade to 1.3 MW beam and 500 kton detector

Event topologies (II)

NOvA



DUNE simulation



Like going from VHS/analogue to DVD/DTV and now 8K!

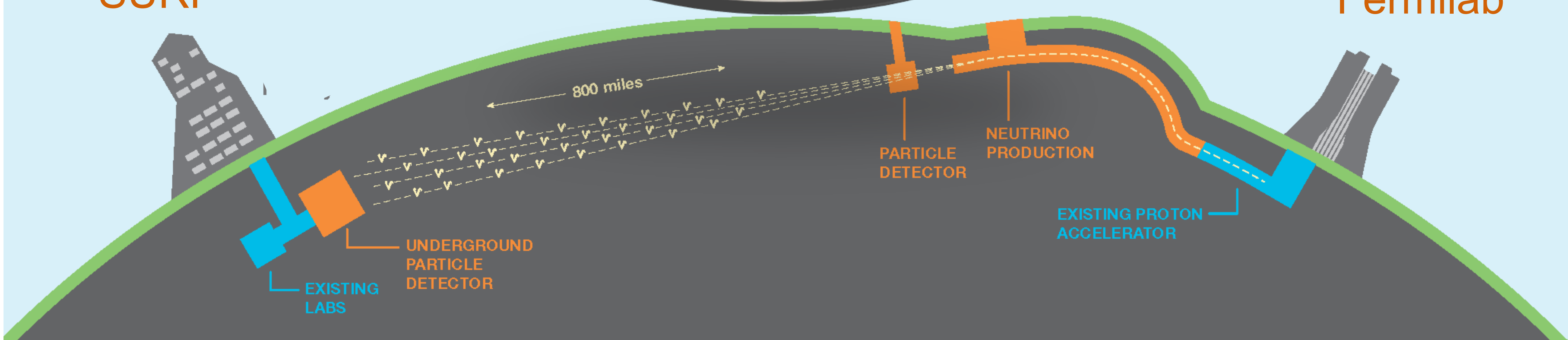
DUNE Experiment

Observe ν_e appearance and ν_μ disappearance at long baseline in wideband beam to measure MH, CPV, and neutrino mixing parameters in a single experiment. Deep underground location reduces cosmogenic background and enables sensitivity to low-energy physics.

SURF

>1000 collaborators & 32 countries

Fermilab



Timeline

2018: protoDUNEs at CERN

2019: Technical Design Report

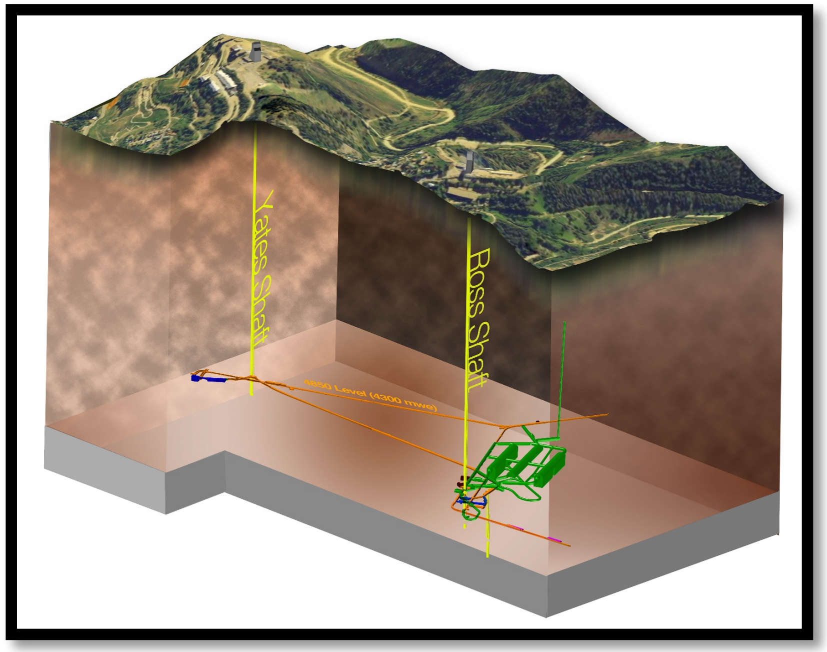
2019: Far Site Primary Excavation Begins

2022: First Module Installation Begins

2026: Neutrino Beam Available

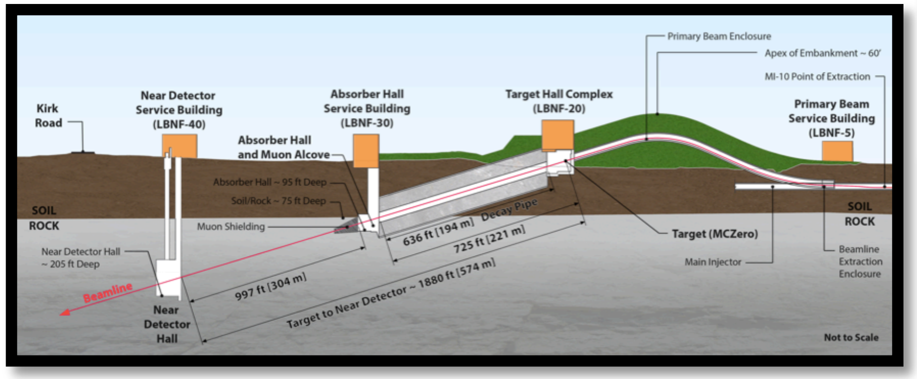
DUNE Far Detector Interim Design Report (2018)

Will be made public soon…



Physics data as soon as 1st module complete

- Atmospheric νs
- SNB and solar νs
- Baryon number violation
- Detector calibration



Conclusions

- Discovery of non-zero θ_{13} has opened the door to a 2nd golden age of neutrino oscillation physics
- New NOvA data disfavour maximal mixing at 1.8σ and the lower octant at a similar level
- Prefer normal hierarchy at 1.8σ. Also exclude $\delta_{CP} \sim \pi/2$ in the inverted hierarchy at 3σ
- More than 4σ significance electron antineutrino appearance
- Future NOvA running can reach 3σ sensitivity for the mass hierarchy by 2020 and cover significant CP range by 2024
  - Compelling discovery of CP-violation will require new experiments
- Highly precise 3rd generation will allow testing the 3 flavour neutrino oscillation framework

Extremely active and exciting field! Theoretical questions to answer, experiments currently taking data and new projects down the line. Stay tuned!

THANK YOU FOR YOUR ATTENTION

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New constraints on oscillation parameters from ν_e appearance and ν_μ disappearance in the NOvA experiment

M. A. Acero *et al.* (NOvA Collaboration)
Phys. Rev. D **98**, 032012 – Published 24 August 2018

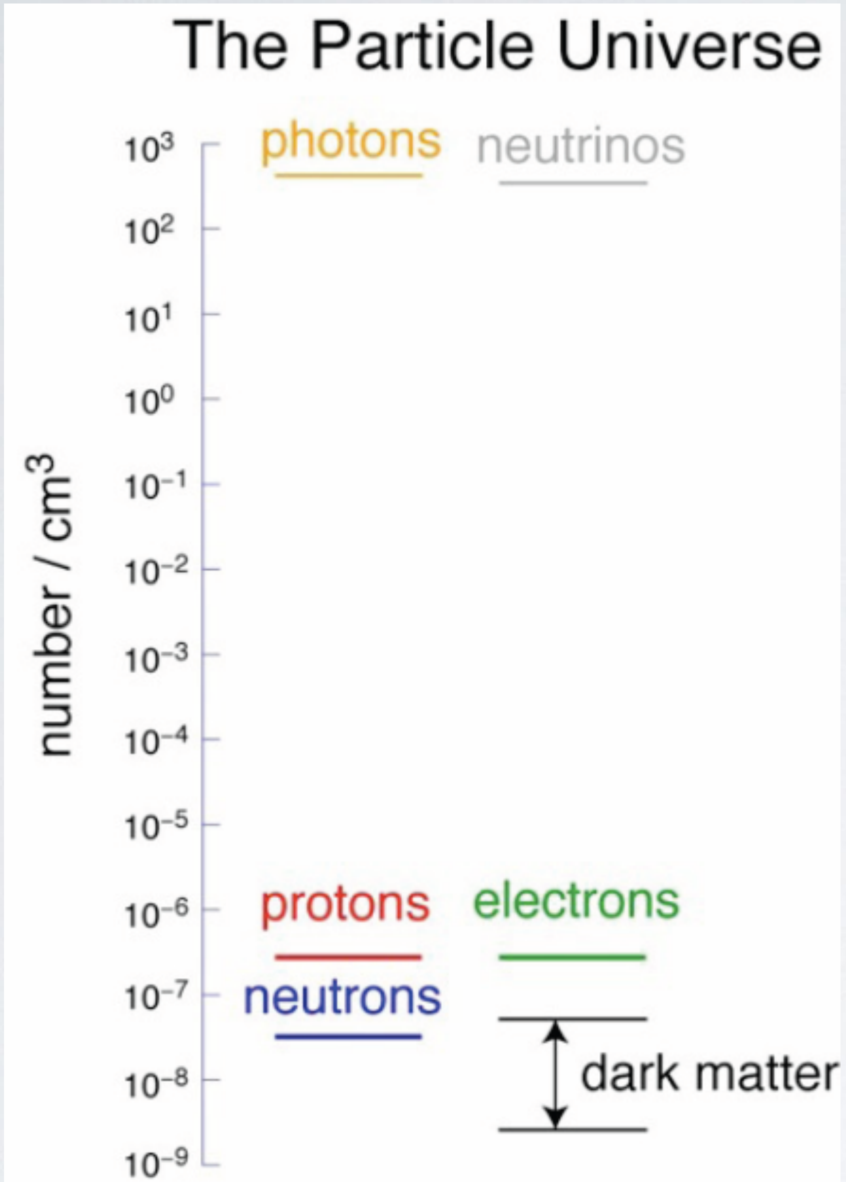
@Bruno_Zamorano

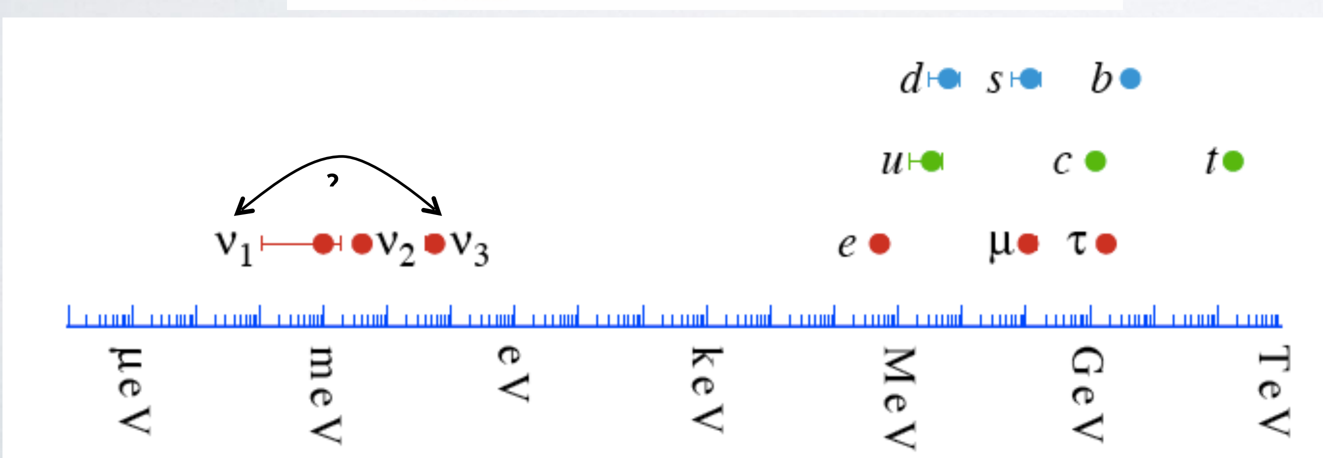
www-nova.fnal.gov

BACKUP SLIDES

These aren't the slides you're looking for

Why study neutrino oscillations?





- Second most abundant particle in the Universe and yet the worst understood
- Dark Matter aside, the only measured confirmation of Physics beyond the Standard Model
- ~25 000 neutrino papers since the discovery of neutrino oscillations
- Nobel prize 2015 and Breakthrough prize 2016
- Many open questions: CP violation (matter-antimatter asymmetry), mass ordering and mass scale, Dirac or Majorana, why are they so light…
- Oscillation parameters are, to our best knowledge, fundamental constants of Nature

Long-baseline neutrino oscillation experiments

1st generation (past)

- MINOS / MINOS+
- K2K

Firmly established 3-flavour scenario

Precise measurements of Δm^2_{32} and $\sin^2\theta_{23}$

2nd generation (present)

- NOvA
- T2K
- OPERA

Optimised for electron-neutrino appearance

Constraints on δ_{CP}, mass hierarchy and octant

3rd generation (future)

- DUNE
- Hyper-K

Precision measurement of δ_{CP} and the remaining unknowns

Key features of 2nd generation

- Narrow band (off-axis) beam
- Detectors optimised for:
  - ν_e flavour identification
  - ν_e appearance maximum (L/E)
- High-intensity neutrino beam
- Longer (or shorter) baseline to enhance (reduce) the matter effect: 10% in T2K, 30% in NOvA

NOvA

- Baseline: 810 km
- Segmented scintillation calorimeter
- 700 kW neutrino / antineutrino beam
- 14.3 mrad off-axis

T2K

- Baseline: 295 km
- Cherenkov detector (SuperK)
- 420 kW neutrino / antineutrino beam
- 2.5° off-axis

Very complementary projects!

Example of optimisation: MINOS to NOvA

How to enhance the appearance measurement?

Maximise signal	Reduce background	Detailed reconstruction
• Large and massive detector • Limited passive material (highly active) • High intensity beam	• Off-axis: smaller NC and ν_μ background • low Z: identify gaps and distinguish electrons from photons • Optimise L/E	• High granularity • Efficient signal collection: APDs

Pros and cons

DUNE

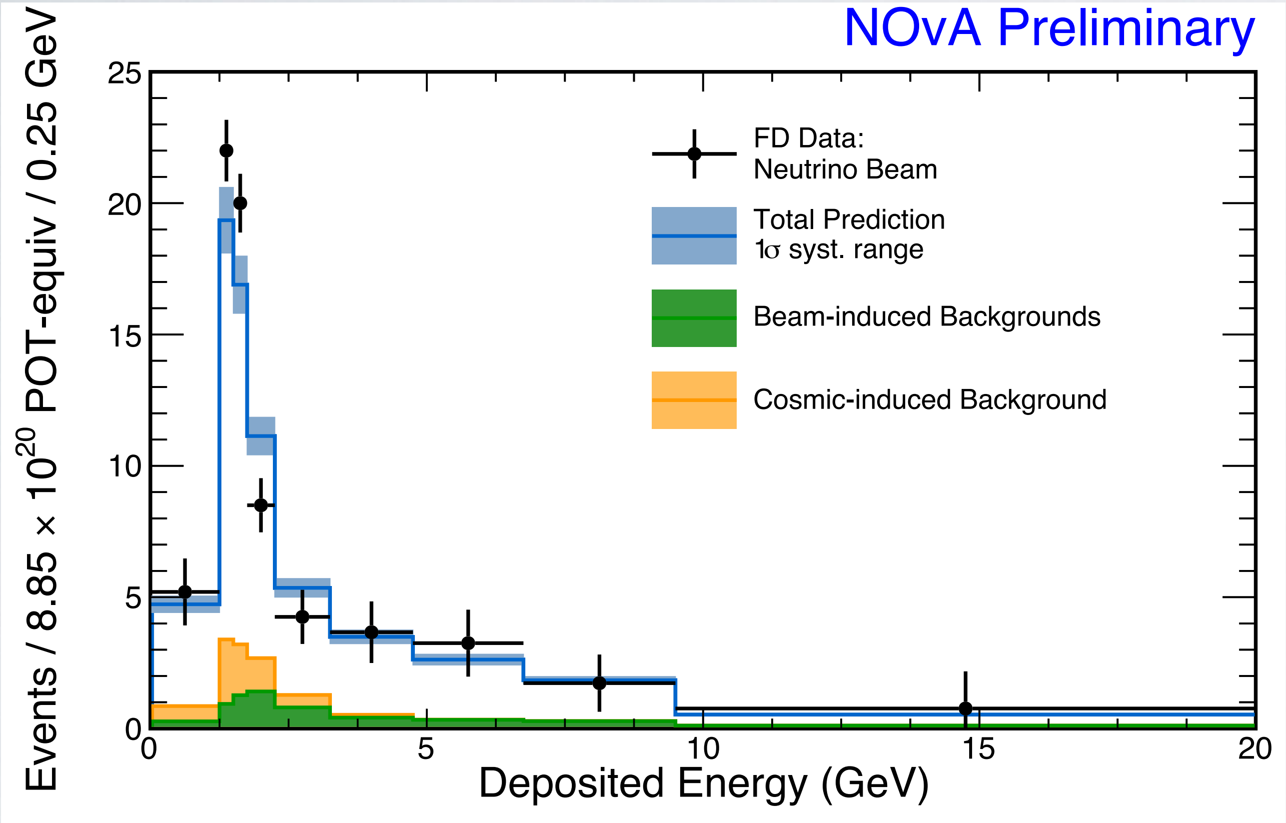
- Long 1300 km baseline
  - Excellent MH measurement
  - Access to 2nd oscillation maximum with greater CP asymmetry
- Wide band beam
  - See more effects of oscillation
  - Good sensitivity to non-standard effects (e.g., test 3-flavour model)
- Exquisite detector imaging
  - High efficiency and purity
  - Lower statistics

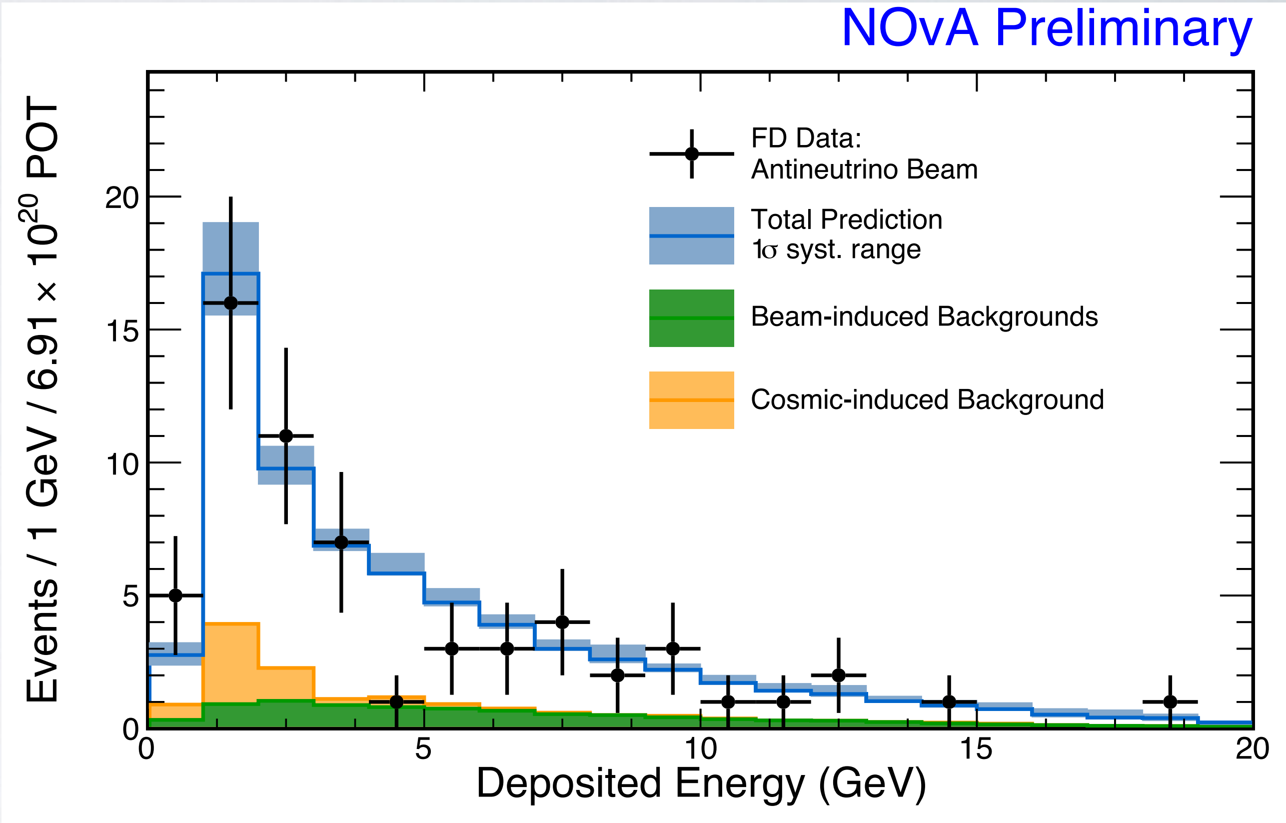
HyperK

- Really huge detector
  - High statistics
  - Excellent early CP-violation sensitivity
  - Limited information on hadronic recoil system
- Short baseline
  - Much smaller matter effects
  - Need to know mass hierarchy
- Narrow band beam
  - Less background to reject
  - Less energy information

Very complementary projects!

Observed neutral current spectra in the FD



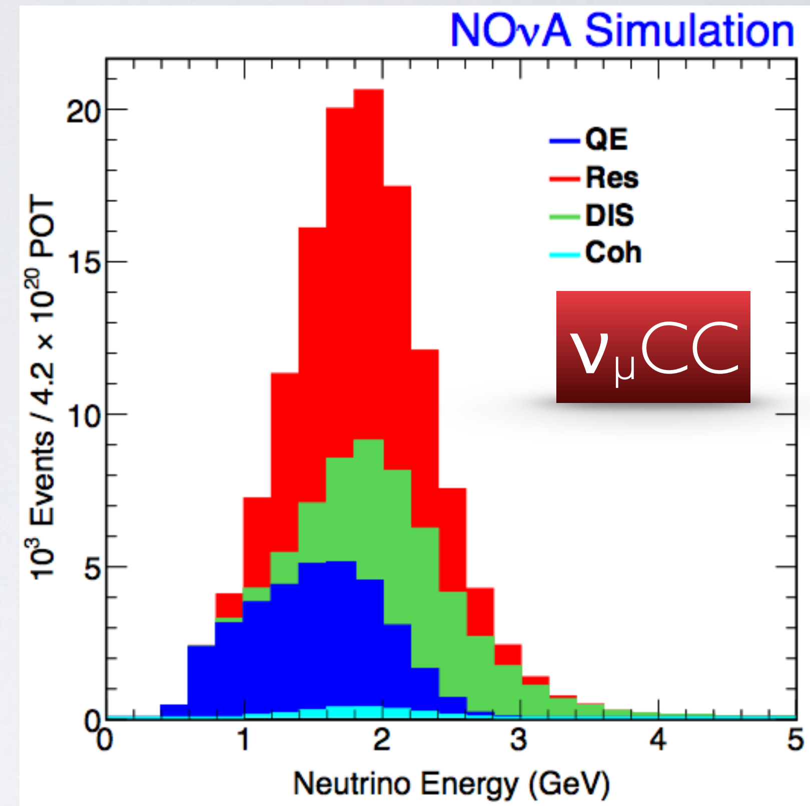


- For the neutrino beam sample we predict 188 ± 13 (syst.) interactions (38 bkg.) and observe 201.
- For the antineutrino beam sample we predict 69 ± 8 (syst.) interactions (16 bkg.) and observe 61.

No significant suppression of Neutral current interactions observed for neutrinos or antineutrinos

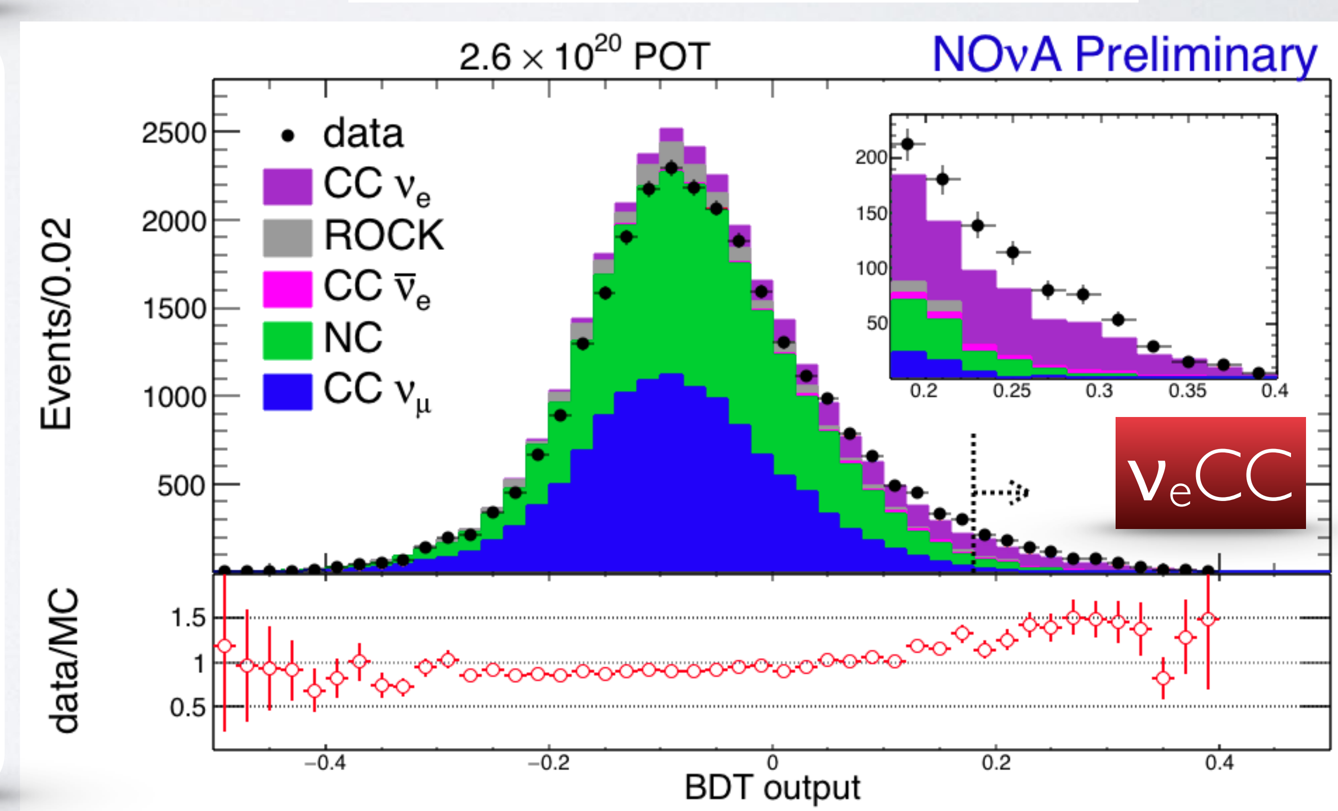
ND measurements

- Uniquely sensitive to QE, RES and DIS (almost equally across the three)
- Absolute cross section or yield measurements will be limited to ~10% due to flux uncertainties
- Ability to measure a huge number of FSI channels

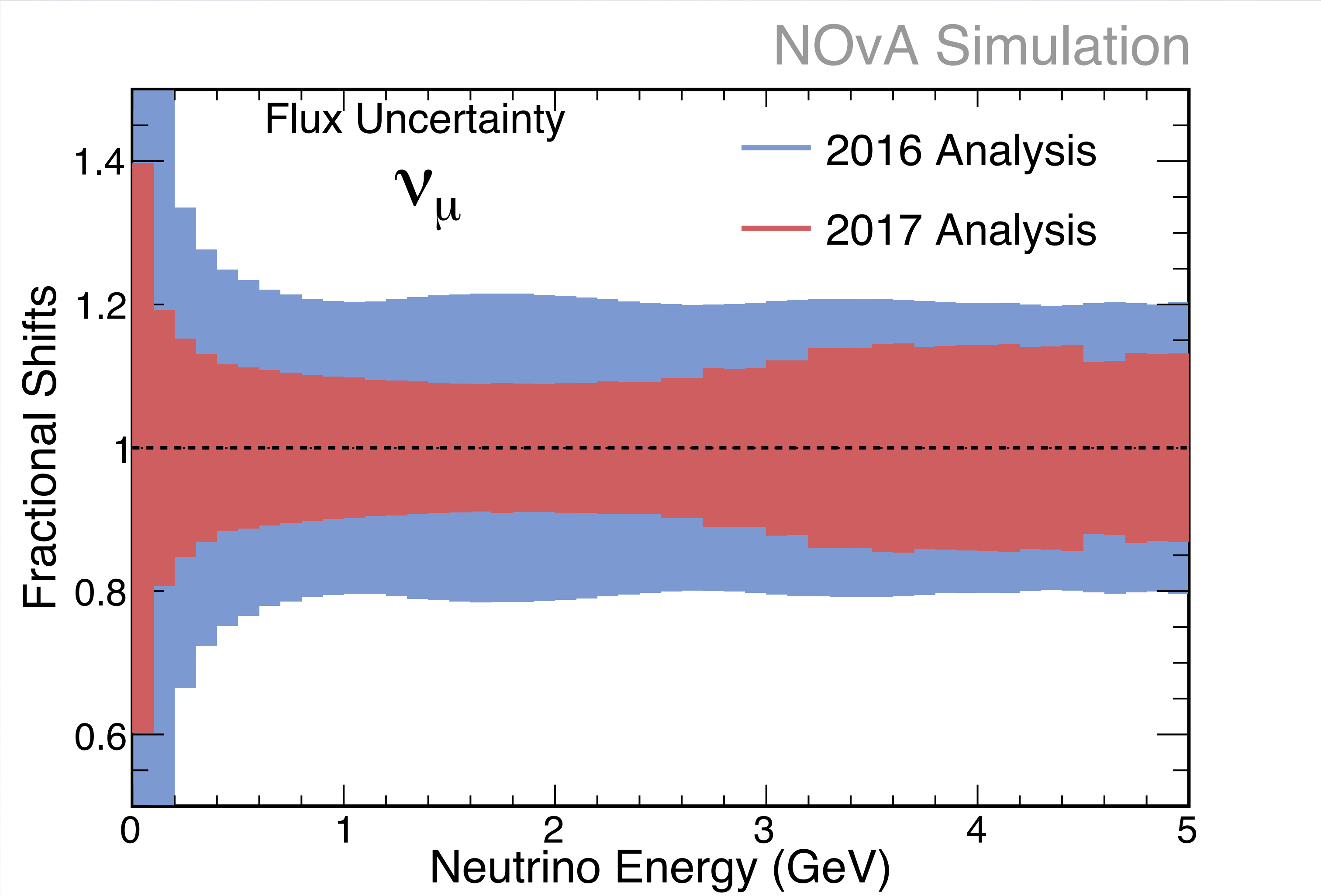


- ν_μCC inclusive and channels (0-π, 2p2h, Coh, π^0, …)
- ν_eCC inclusive and channels (0-π, π^0, …)
- NC inclusive and channels (π^0, 2p2h, …)
- ν_μ on ν_e scattering (flux constraint)

And all of the above with antineutrinos

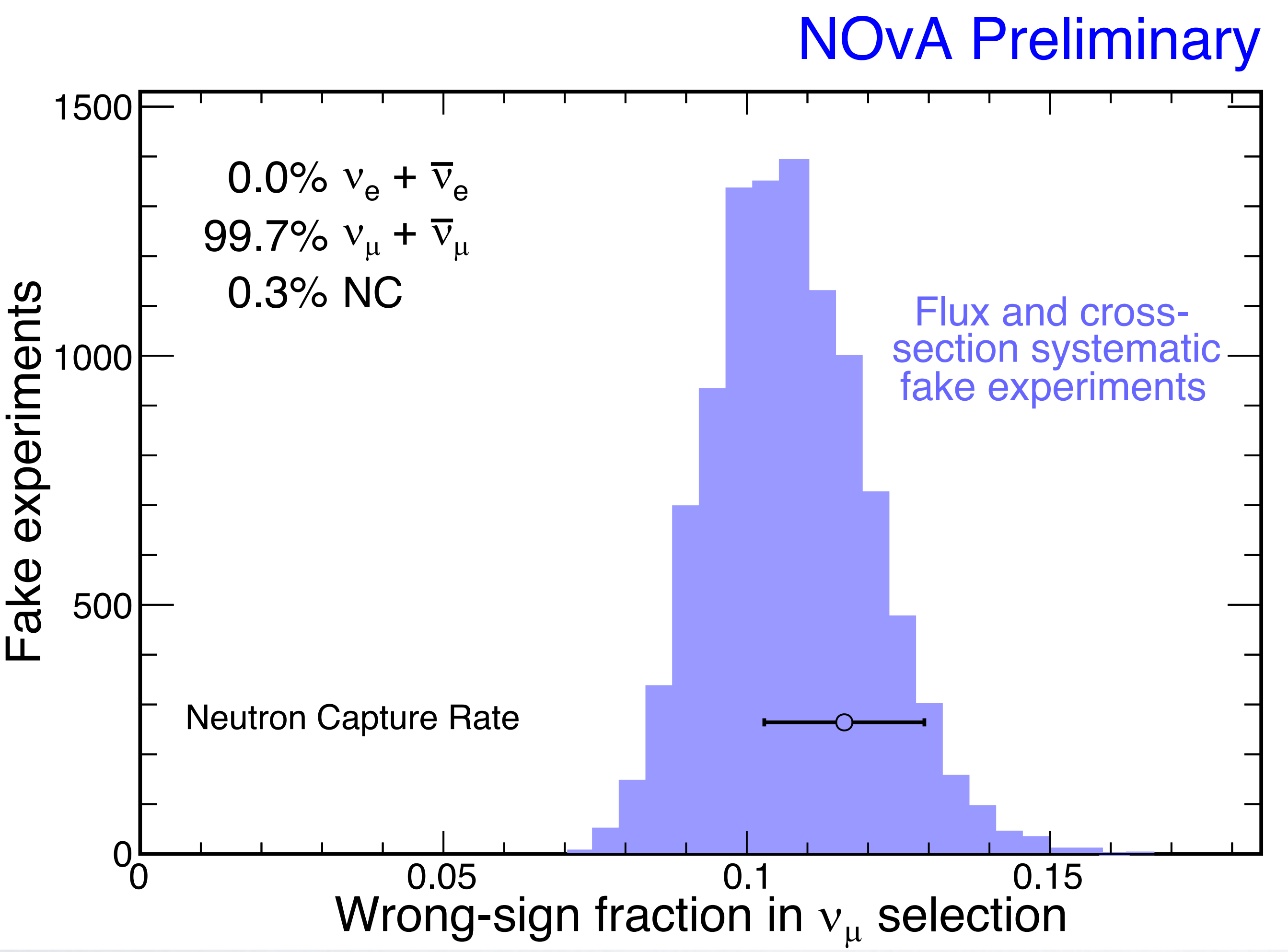


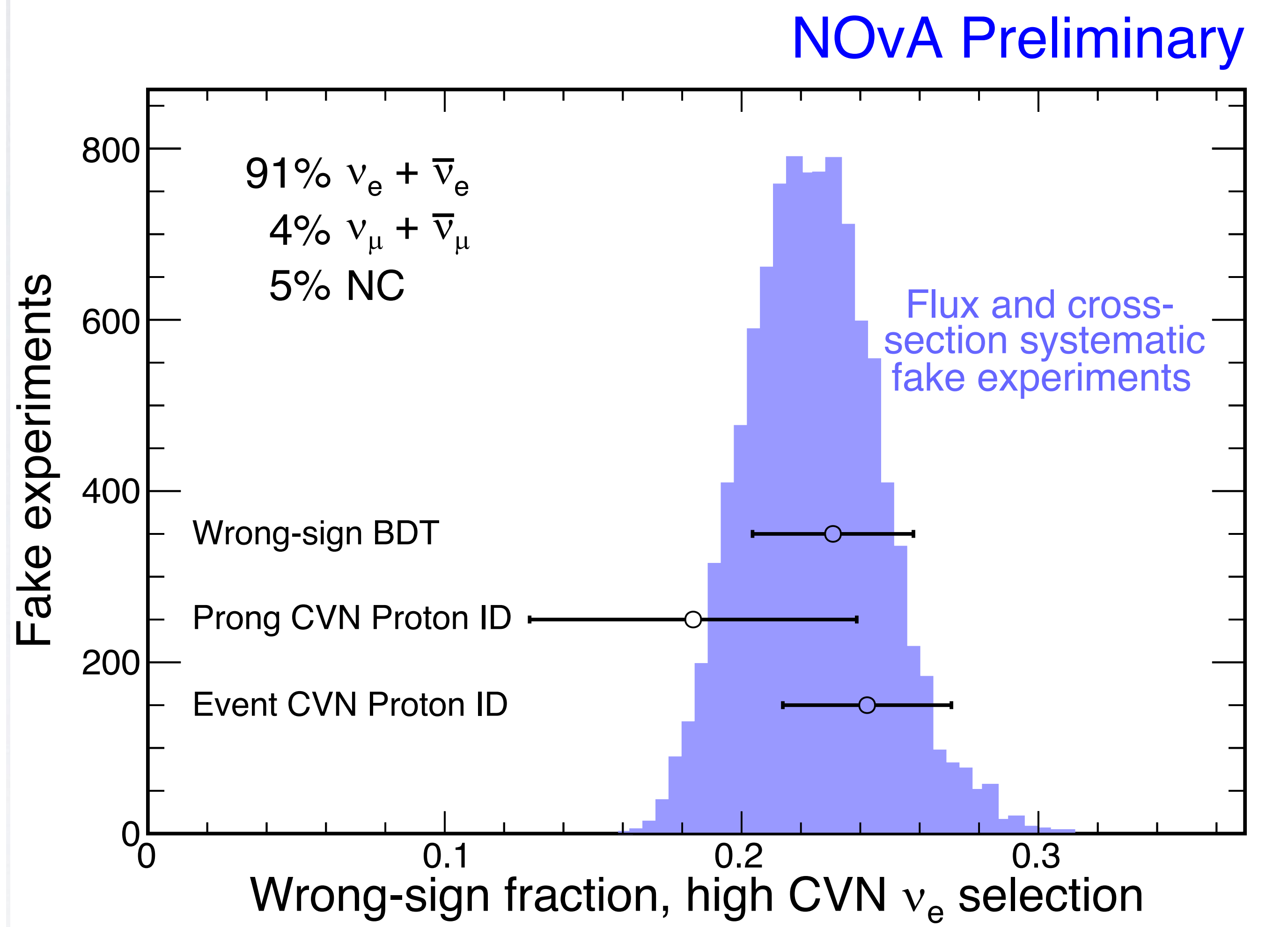
NuMI beam uncertainties



- The prediction of the NuMI beam at the NOvA detectors is made by constraining the hadron production model used in the beam simulation with external measurements on thin targets. We use the Package to Predict the FluX (PPFX) developed by MINERvA (Phys. Rev. D 94, 092005. 2016)
- The beam optics uncertainties are also incorporated by propagating the errors in the alignment of the beam-line elements such us the horn and NuMI target geometries, magnetic fields, etc

Wrong sign contamination





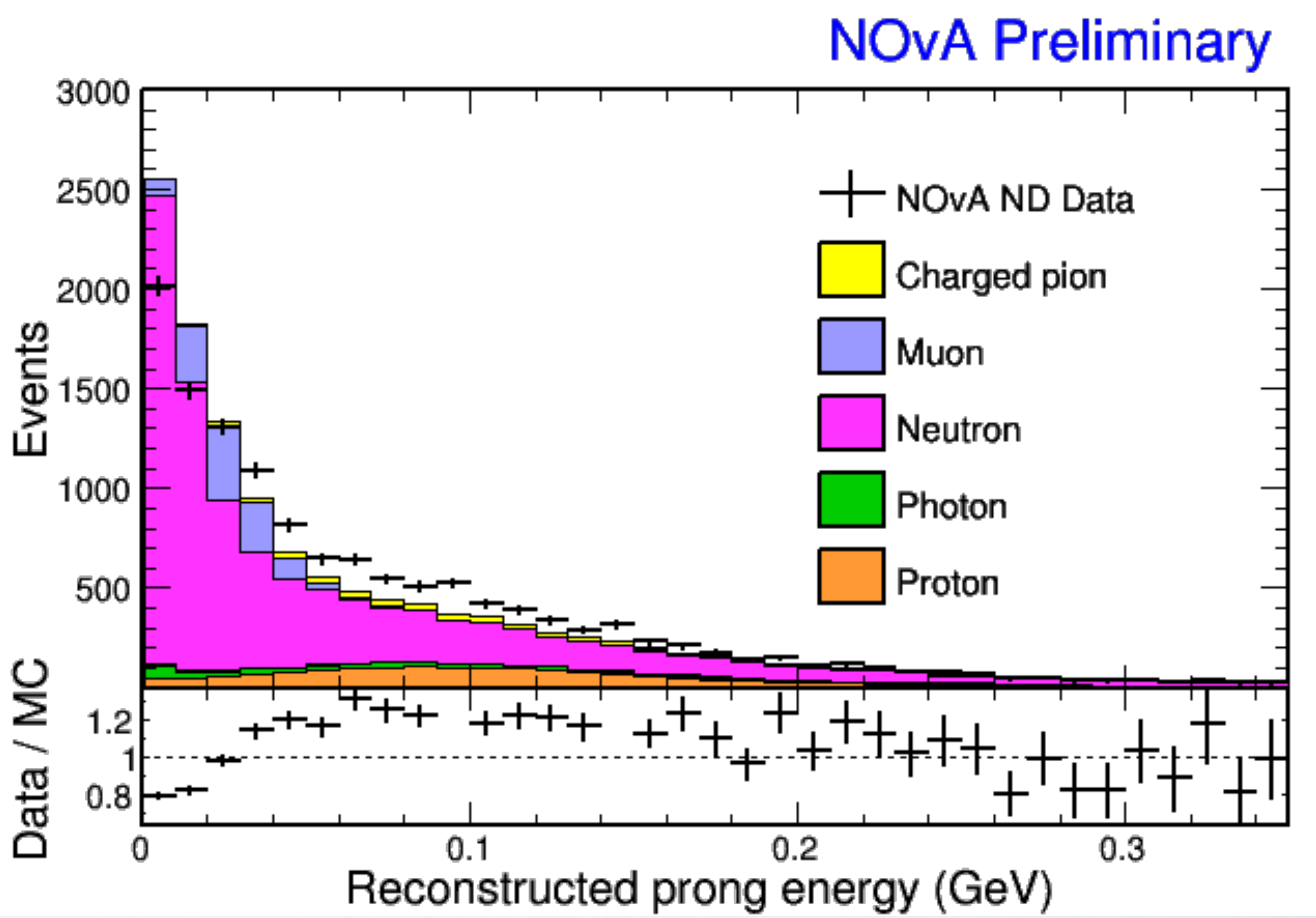
- 11% wrong-sign in the ν_μ ND sample background

  Consistent with data-based cross-check using neutron captures.
- 22% (32%) in the ν_e ND background in the high (low) PID bin

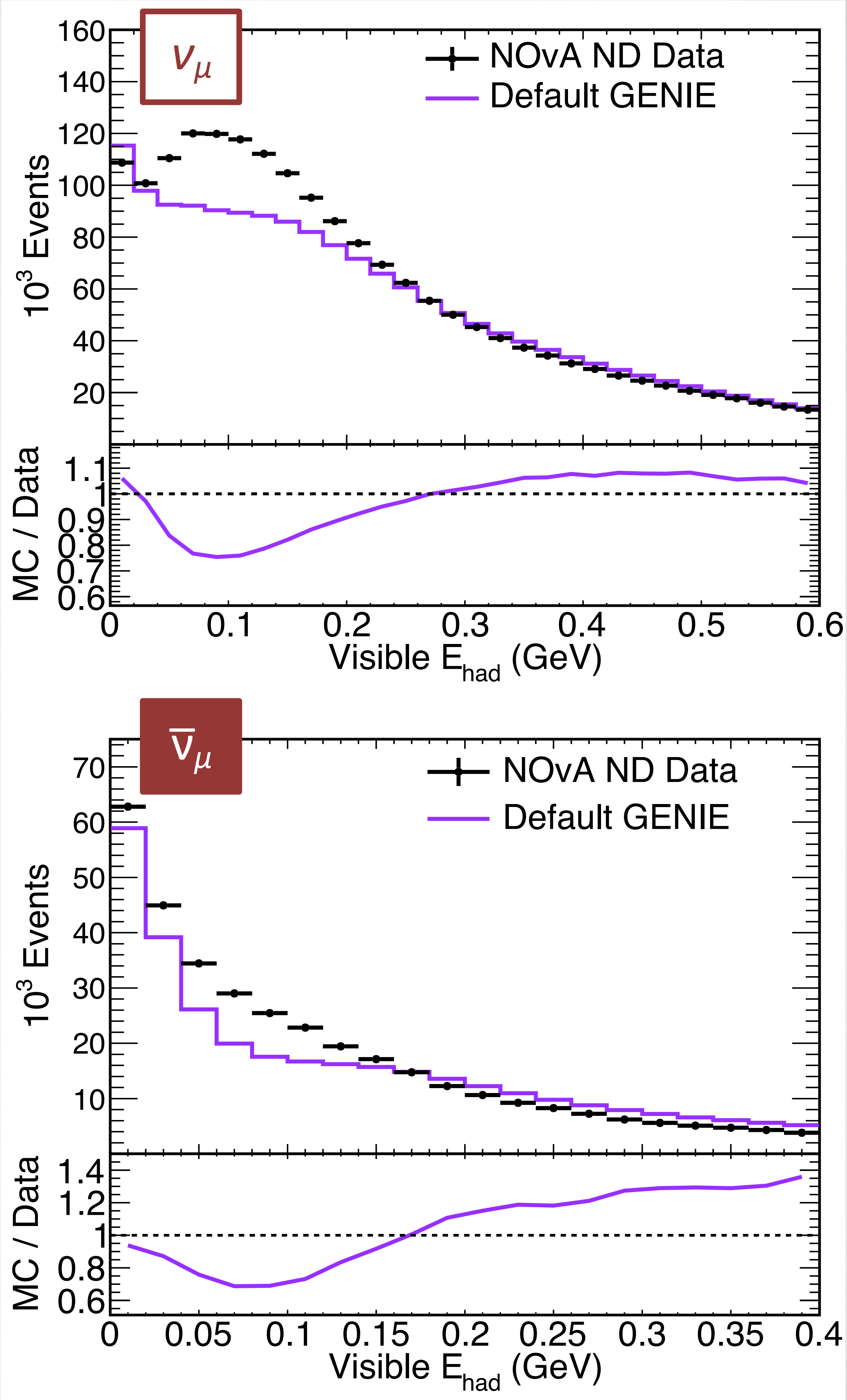
  Consistent with data-based cross-checks using identified protons and event kinematics.
- ~10% systematic uncertainty from flux and cross section
- Does not include uncertainties from detector effects.

Neutrons

- Anti-ν's produce neutrons where ν's produce protons
- Neutron energies are typically several hundred MeV
  - Modelling these fast neutrons is a challenge
- We identified an enriched sample of neutron-like prongs which shows some discrepancies
- We introduced a systematic which covers them
  - Scales the amount of deposited energy of some neutrons.

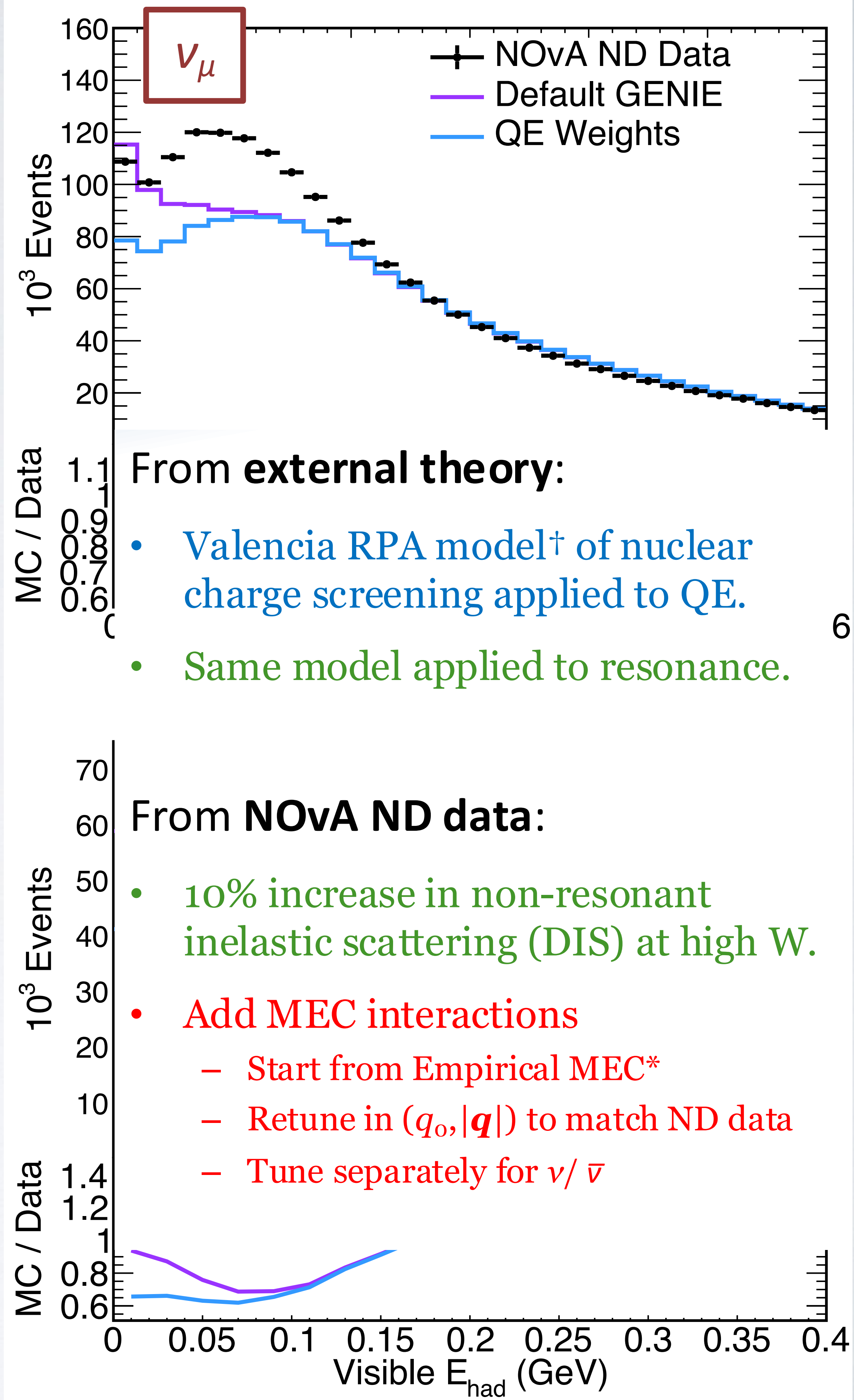


- We tune the cross-section model primarily to account for nuclear effects
  - Backstory: Disagreements observed in cross-sections as measured on single nucleon vs more complex nuclei
  - Nuclear effects likely the reason, but incomplete models
  - We tune using a combination of external theory and our own ND data

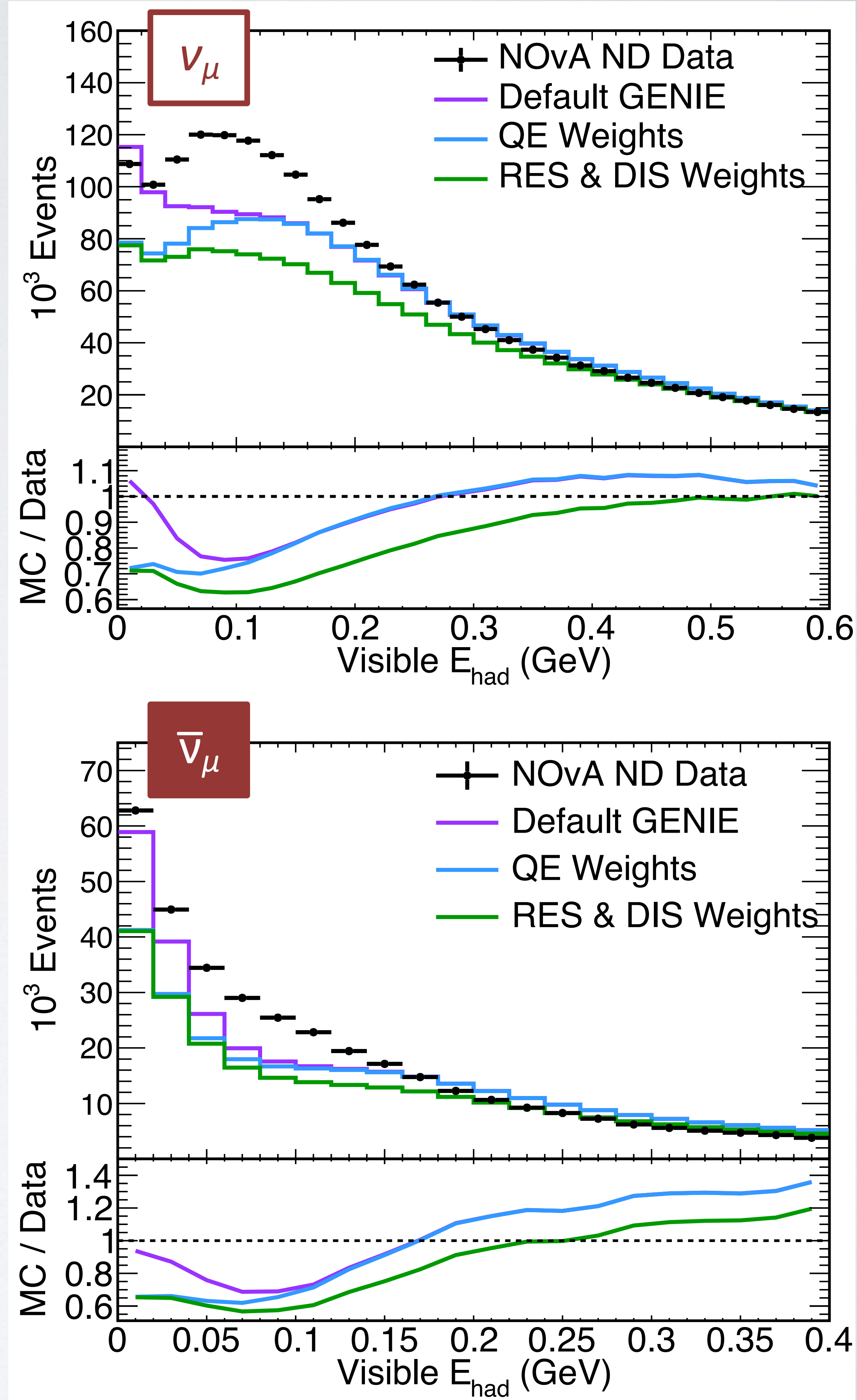


• From **external theory**:

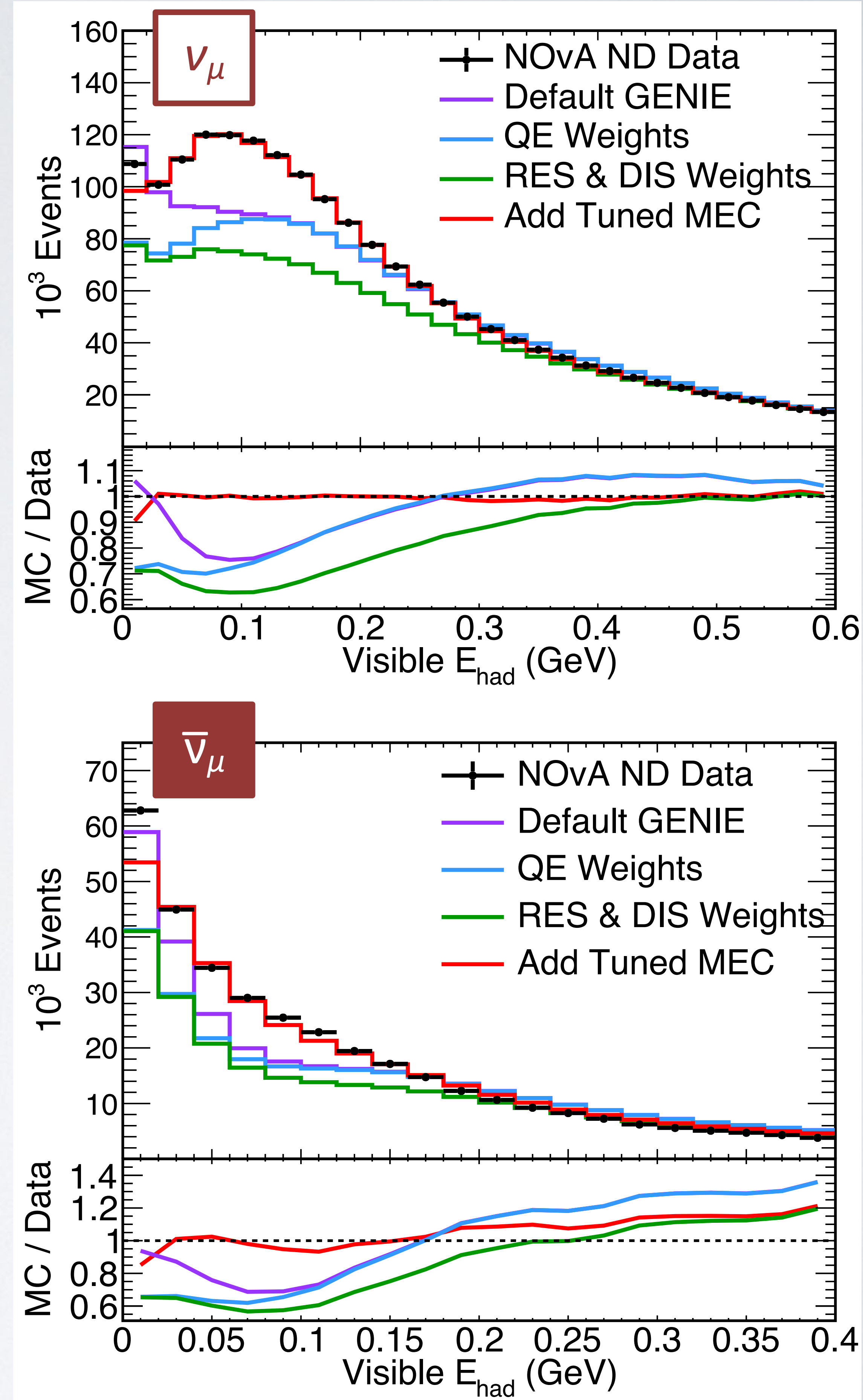
- València RPA model of nuclear charge screening applied to QE
- Same model applied to resonance



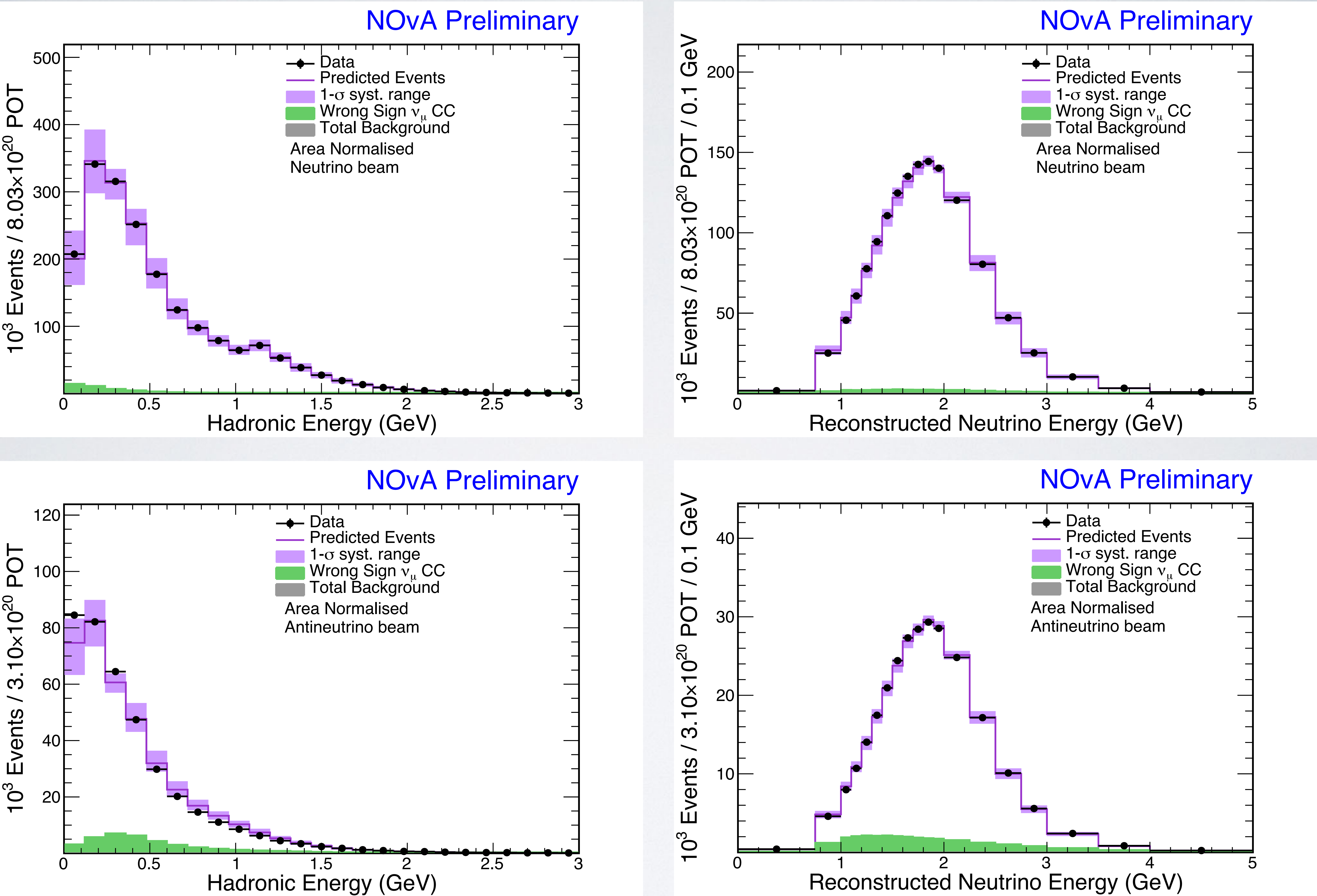
- From **external theory**:
  - València RPA model of nuclear charge screening applied to QE
  - Same model applied to resonance
- From **NOvA ND data**:
  - 10% increase in non-resonant inelastic scattering (DIS) at high W



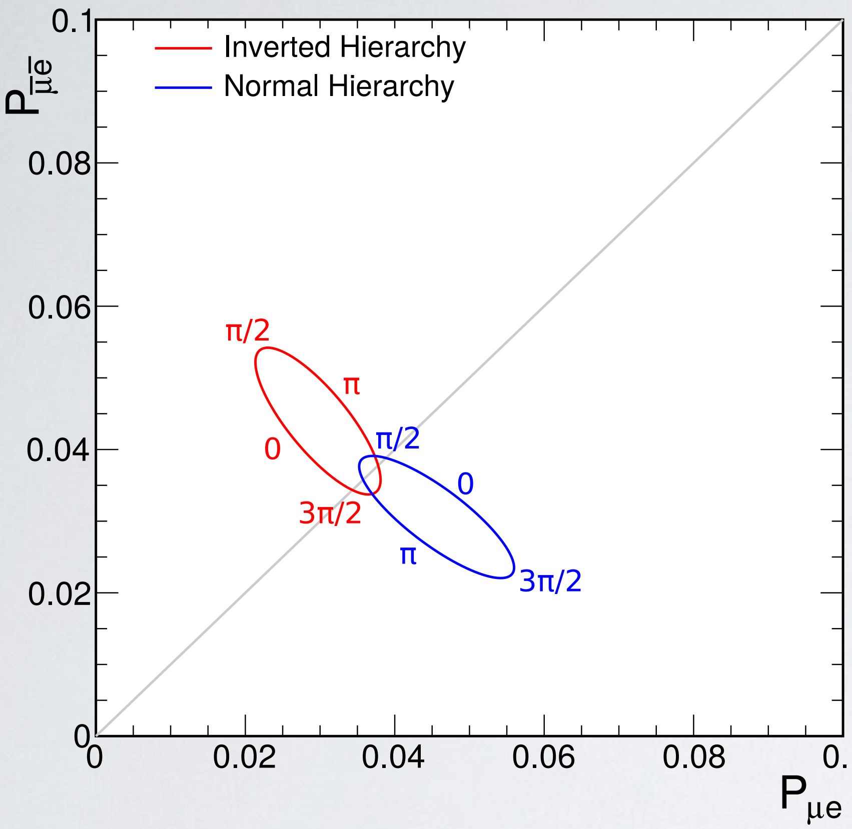
- From **external theory**:
  - València RPA model of nuclear charge screening applied to QE
  - Same model applied to resonance
- From **NOvA ND data**:
  - 10% increase in non-resonant inelastic scattering (DIS) at high W
  - Add MEC interactions
    - ➡Start from empirical MEC
    - ➡Retune in (q0, |q|) to match ND data
    - ➡Tune separately for neutrinos and antineutrinos
- MINERvA's independent tuning matches ours to 1 sigma, providing an additional handle for systematic uncertainty

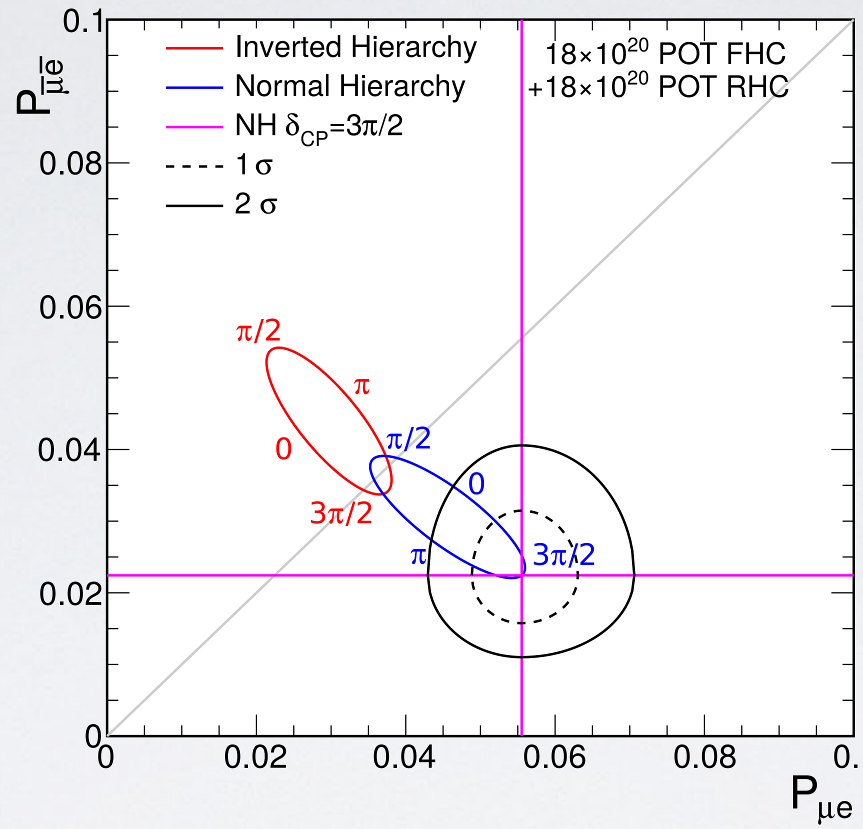


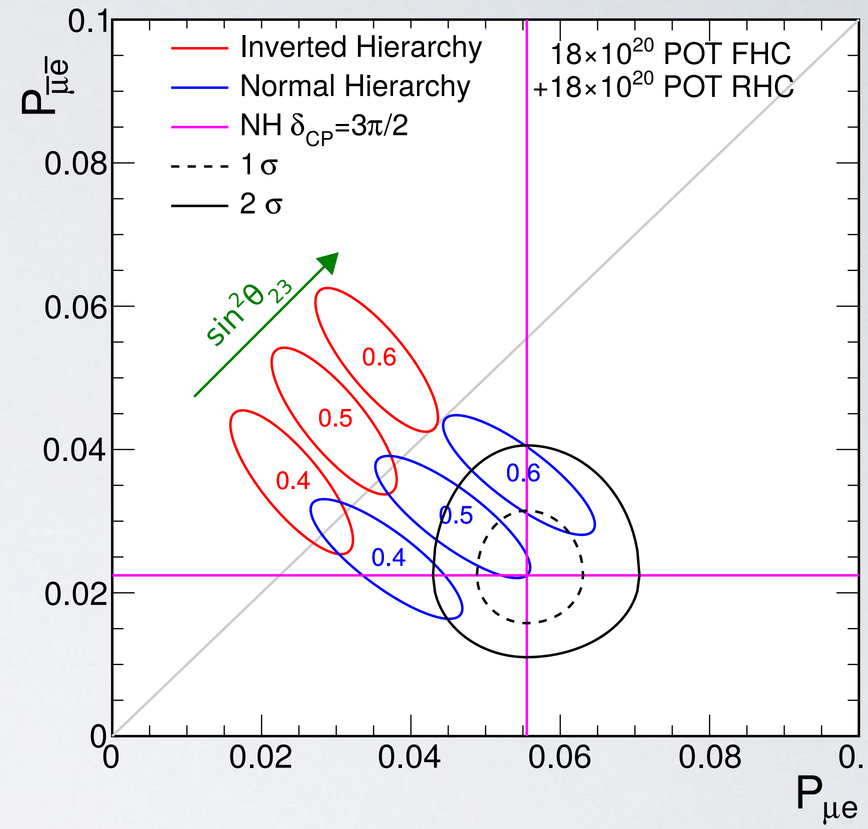
Final model performance



Bi-probabilities







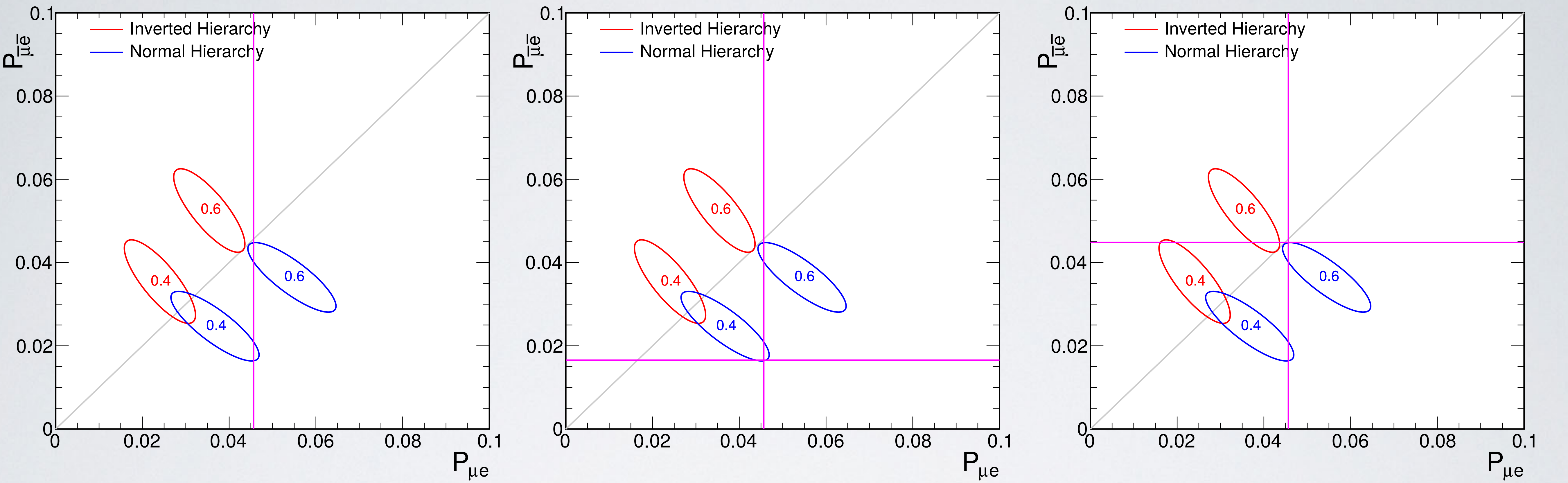
To first order, one measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

These depend on the MH and δ_{CP}

Measurements in neutrino and antineutrino mode provide a point with some uncertainty

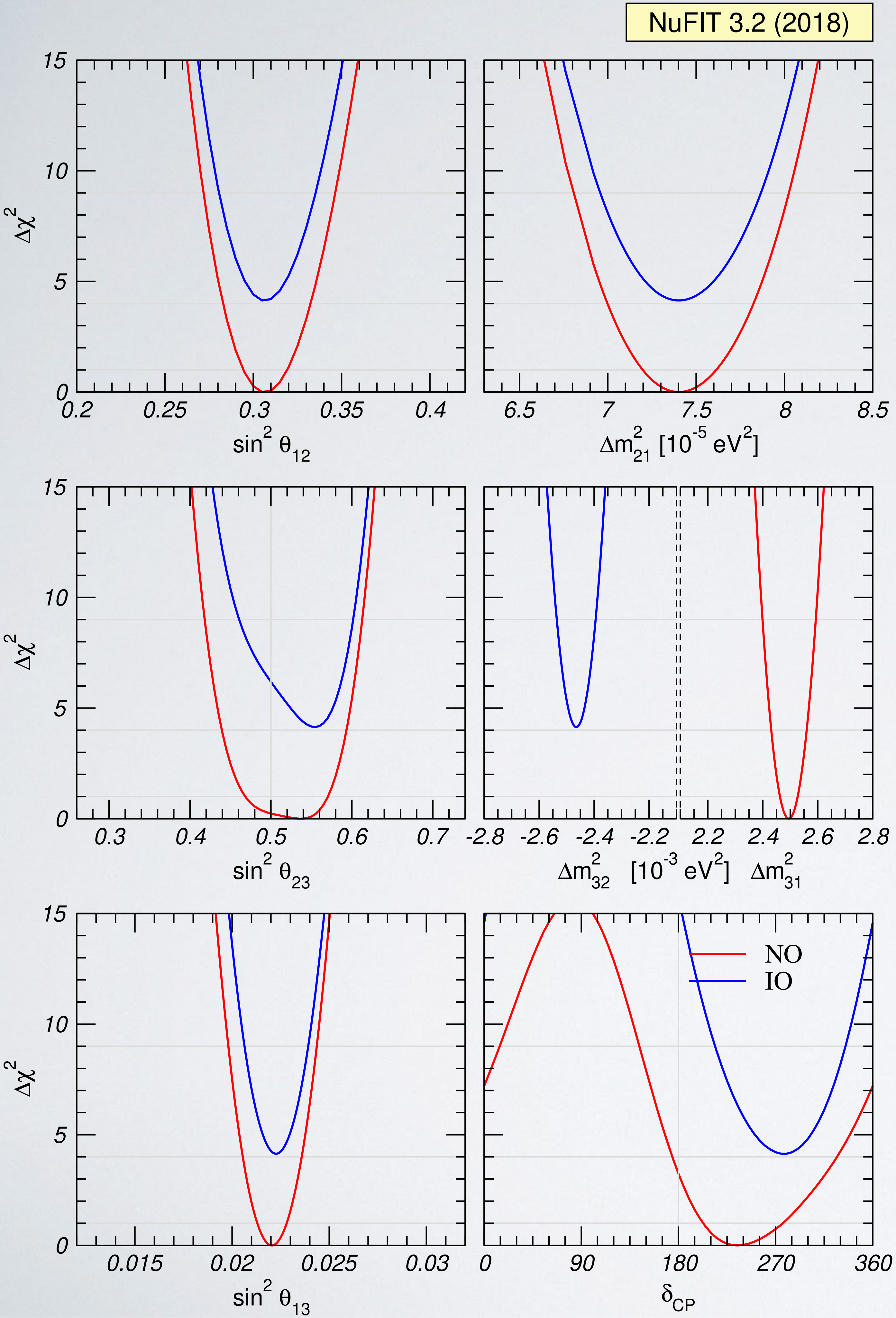
Given overall dependence to $\sin^2\theta_{23}$, sensitivity to the 3 observables

Bi-probabilities II

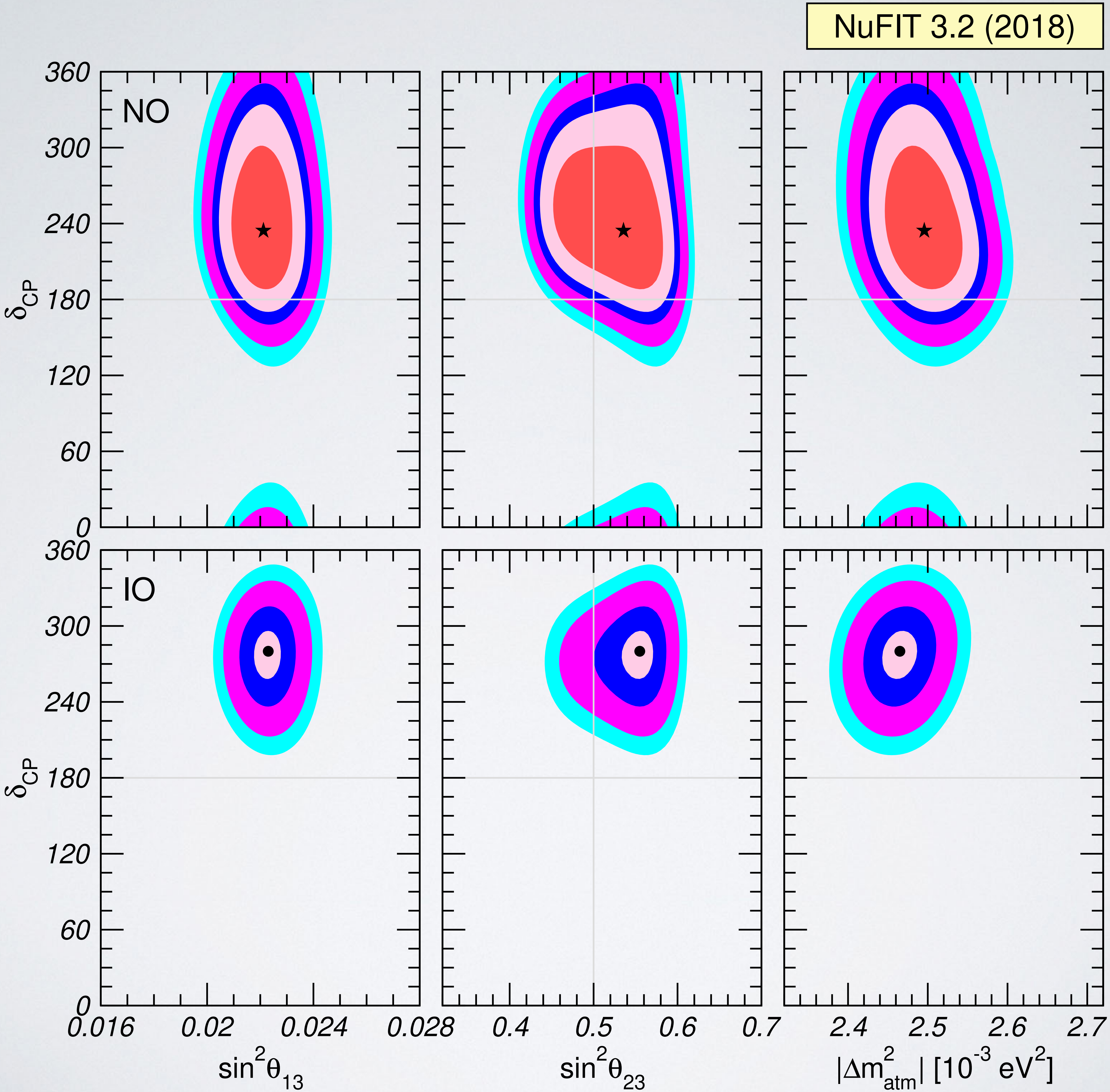


If the scenario is not so clear, antineutrino data help breaking the degeneracies

More than a factor 2 difference in the rate of antineutrinos between solutions

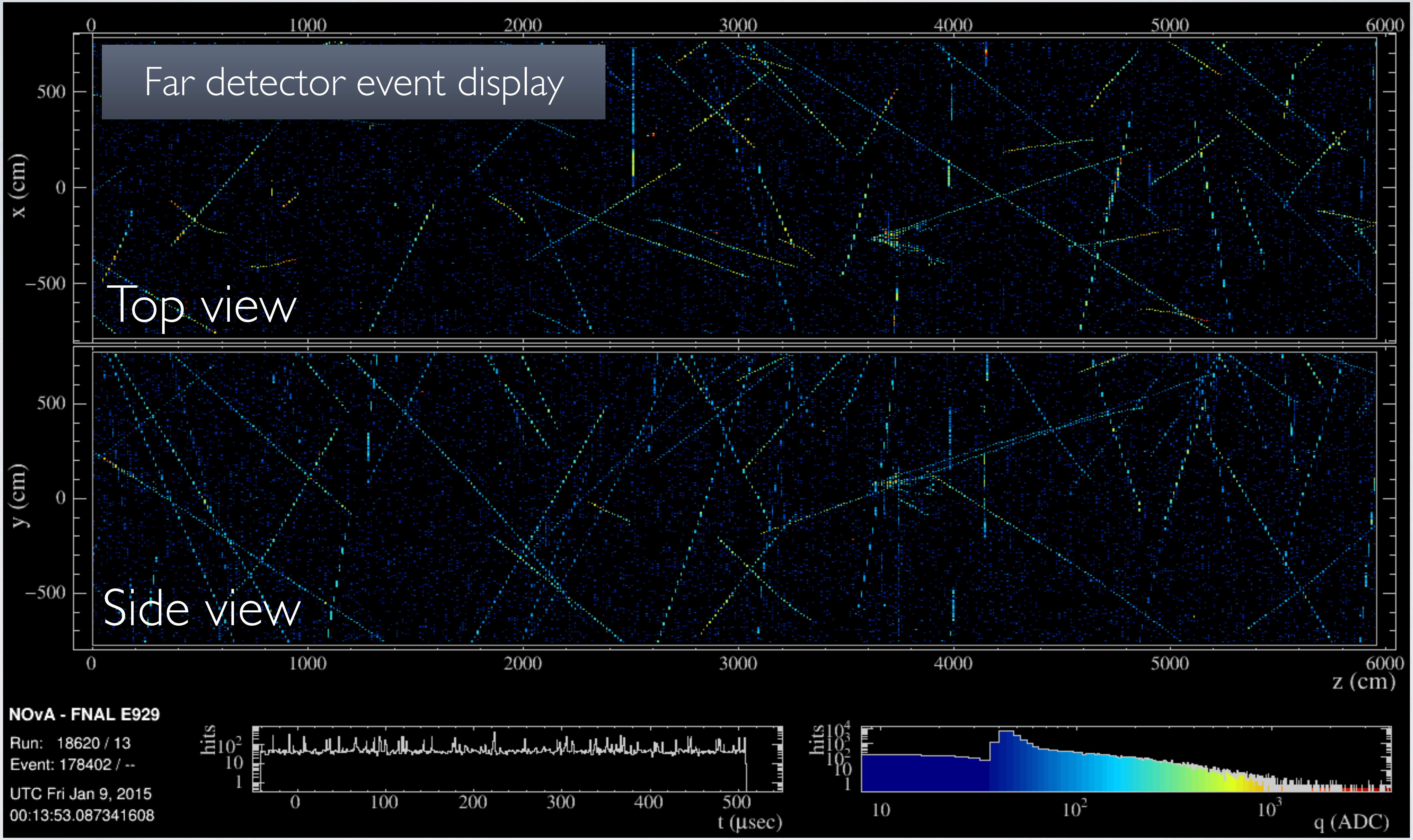


- Combining all the World data. Mass squared differences and mixing angles are well defined



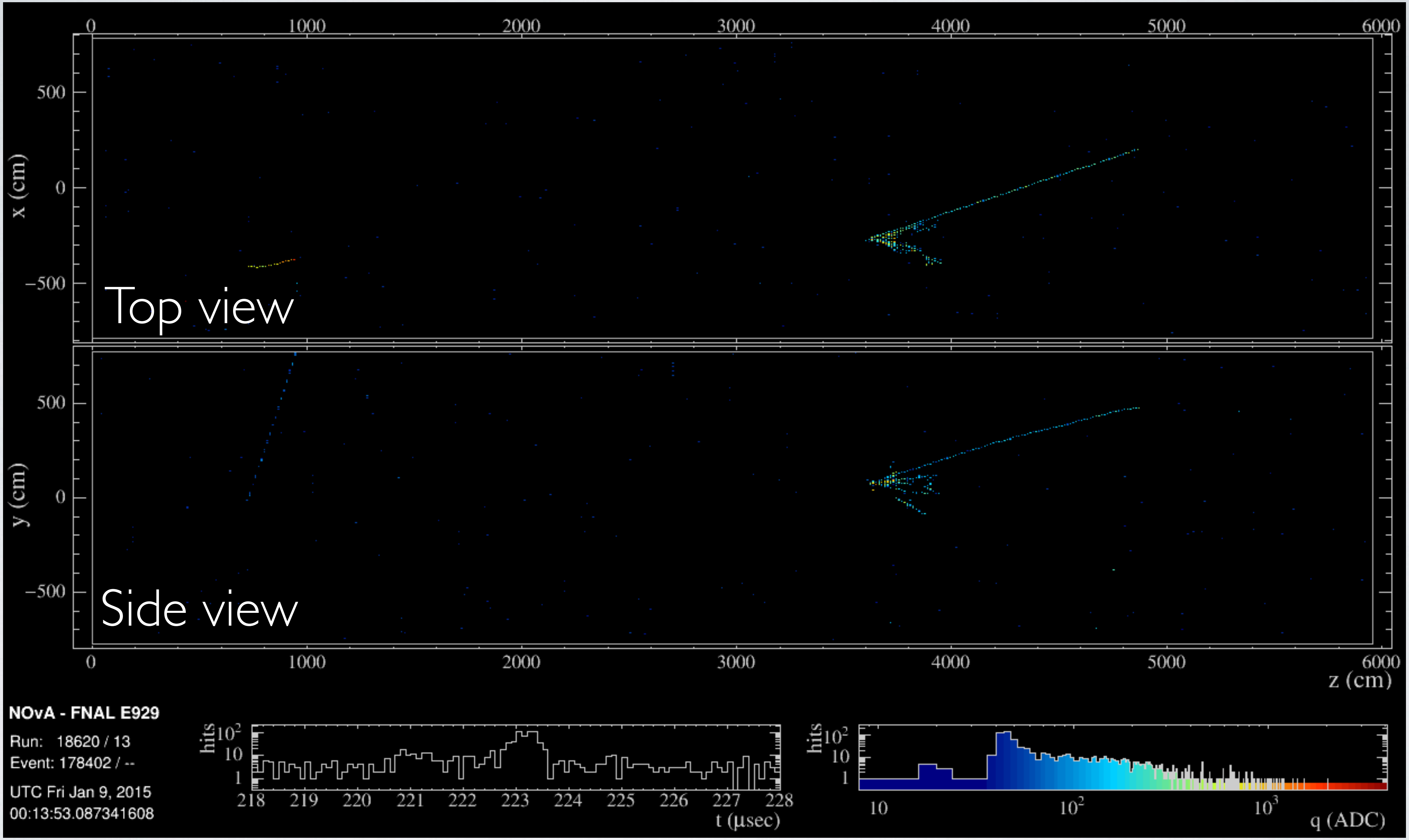
NuFIT 3.2 (2018)
NO
IO
δ_{CP}
0
60
120
180
240
300
360
0.016
0.02
0.024
0.028
0.4
0.5
0.6
0.7
2.4
2.5
2.6
2.7
$\sin^2\theta_{13}$
$\sin^2\theta_{23}$
$|\Delta m^2_{atm}|$ [10^{-3} eV^2]

Timing sync



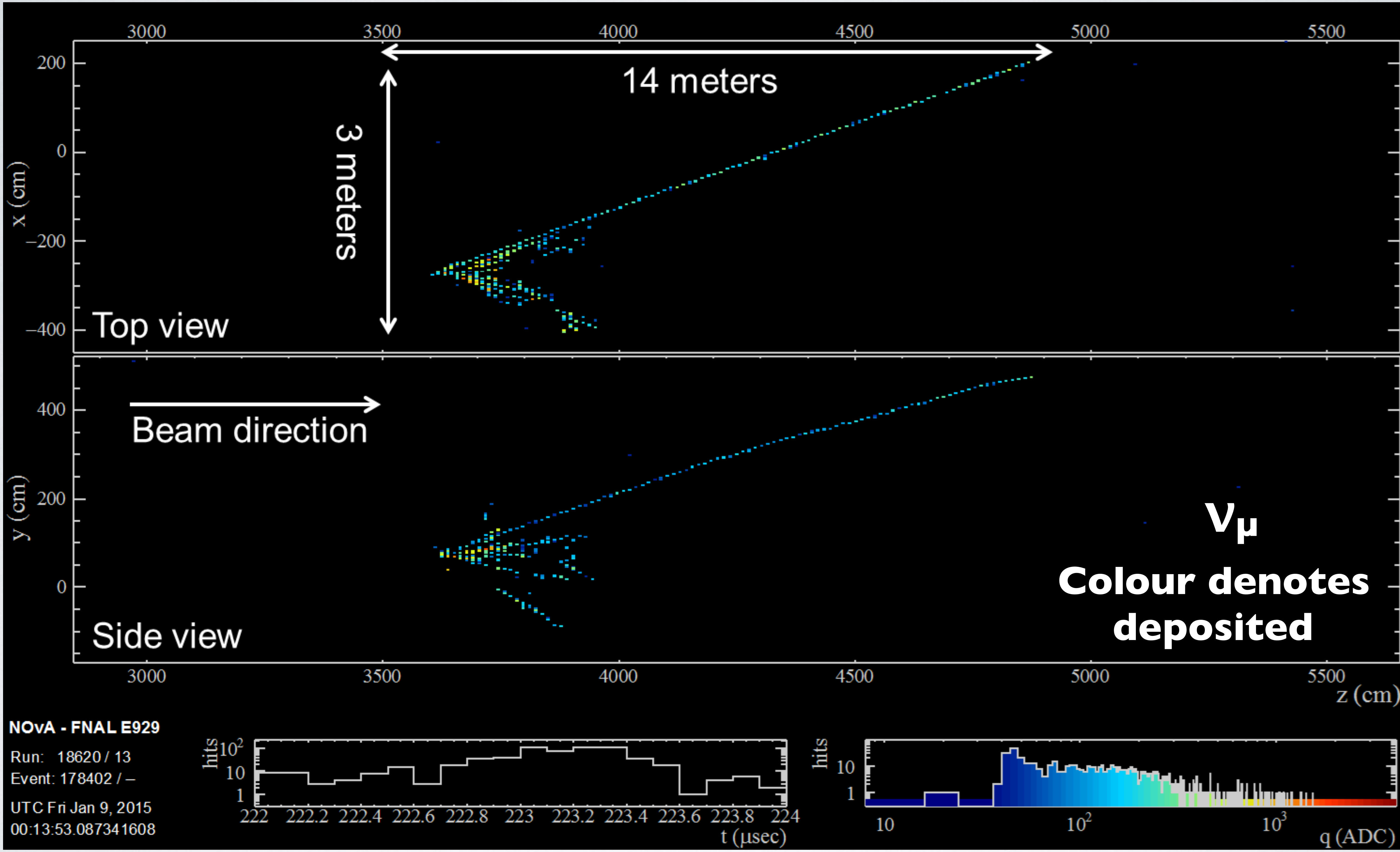
Full 550 μs readout (colours show charge)

Timing sync



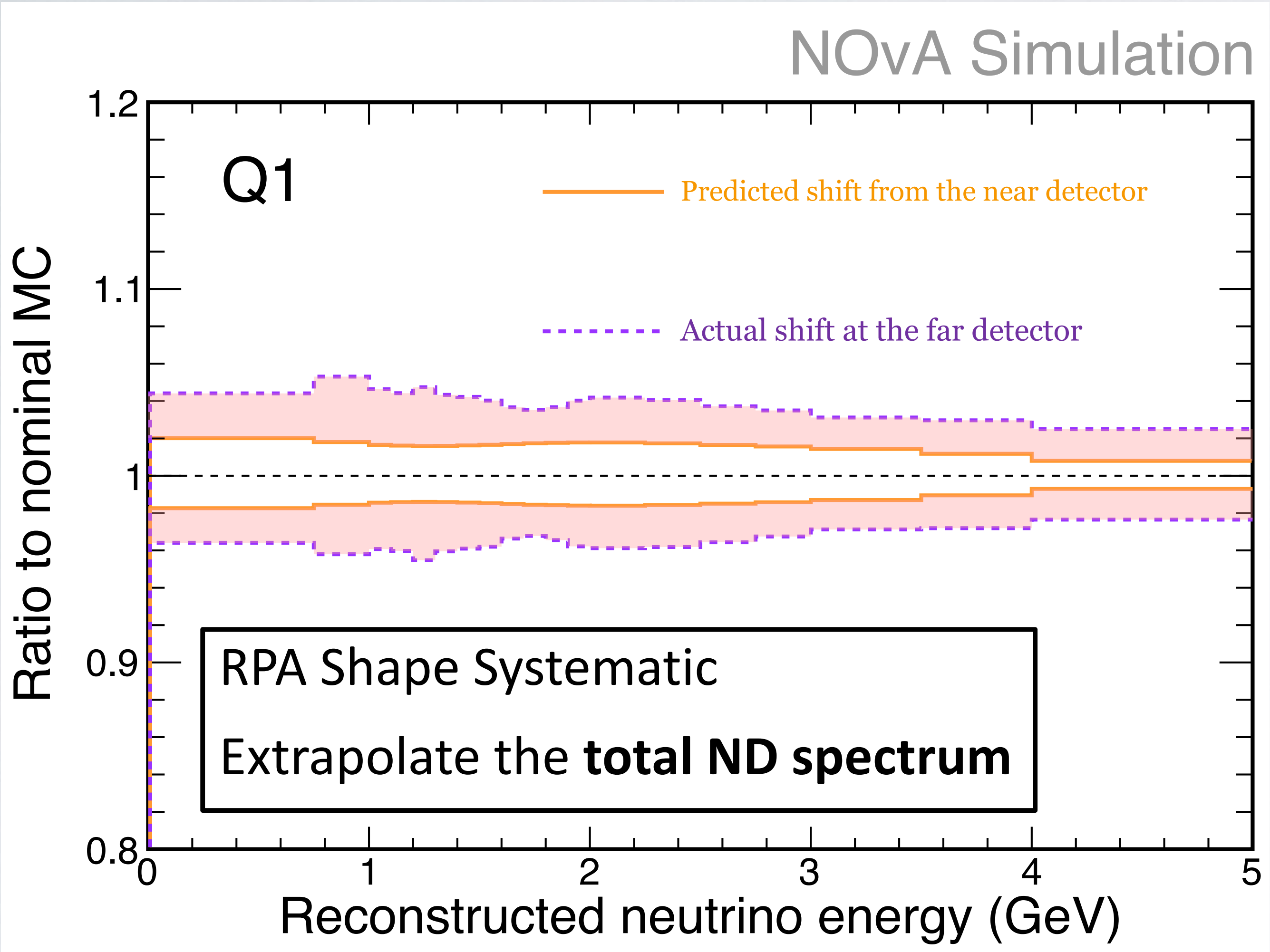
Zoomed on the 10 μs beam spill window

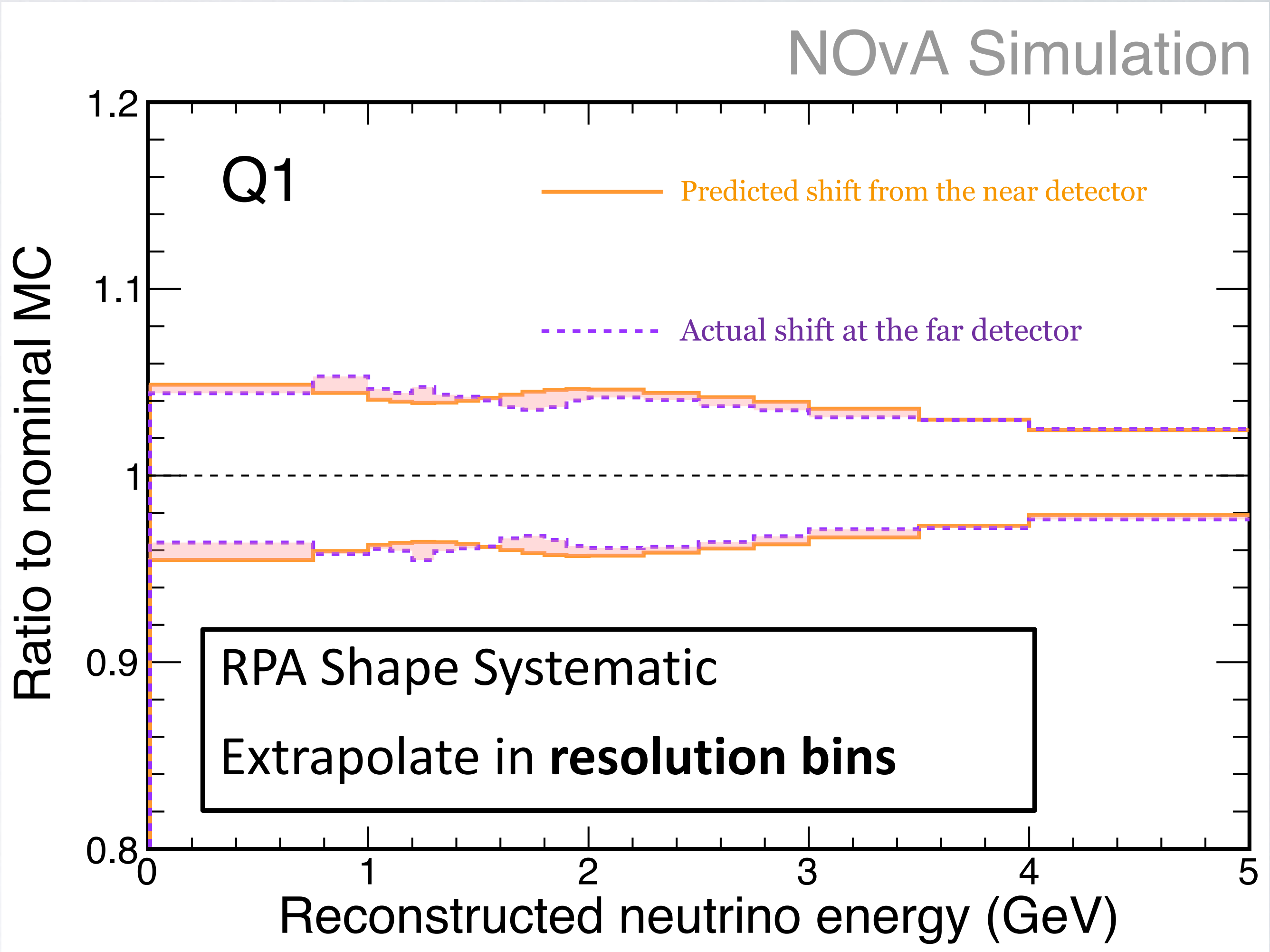
Timing sync



Zoomed on the time slice

Extrapolation in quartiles



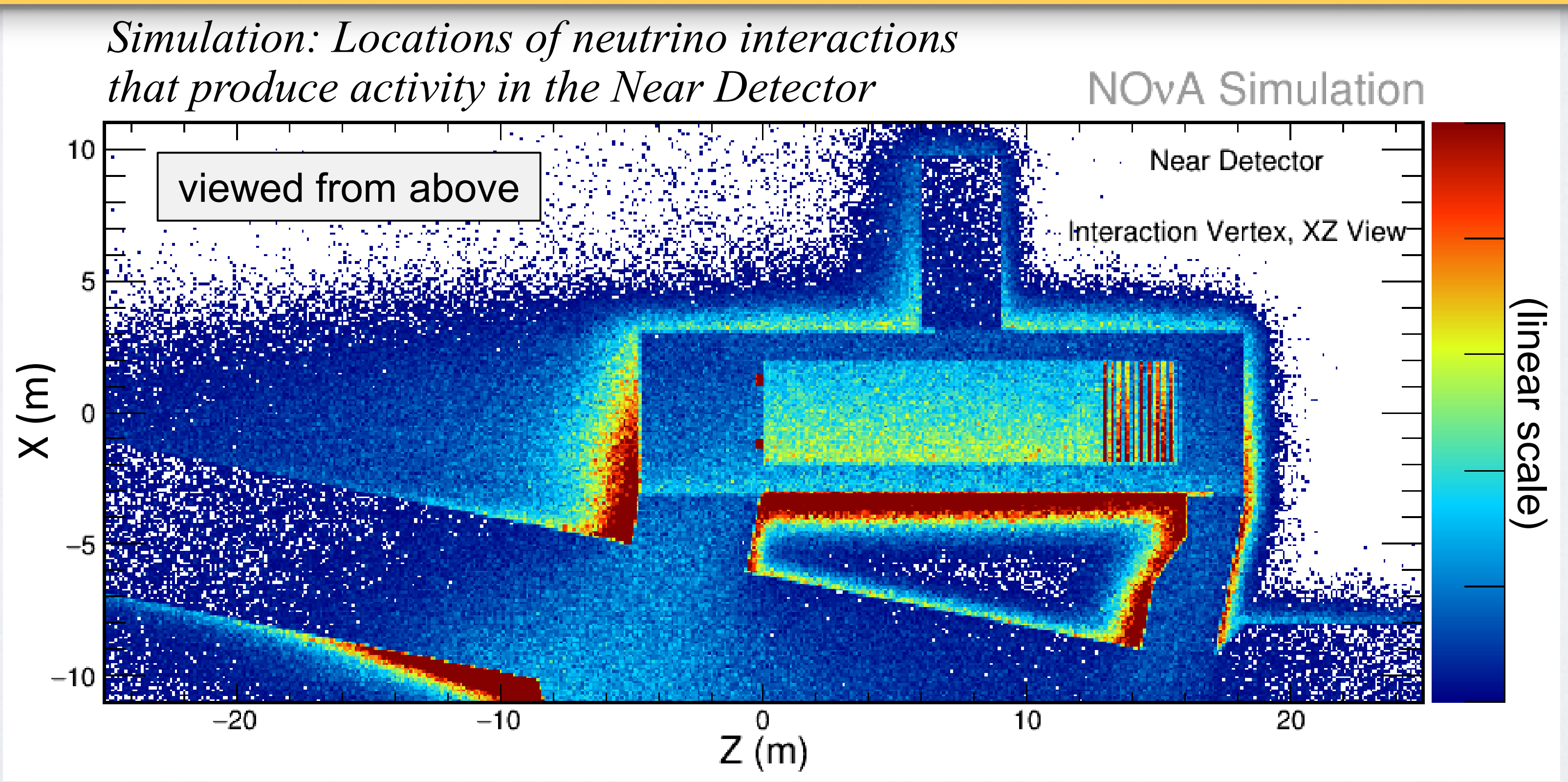


- By extrapolating each one separately, we are accounting for kinematic differences between data and simulation in the FD
  - Quartile extrapolation is more robust against shape systematics

Simulation in NOvA

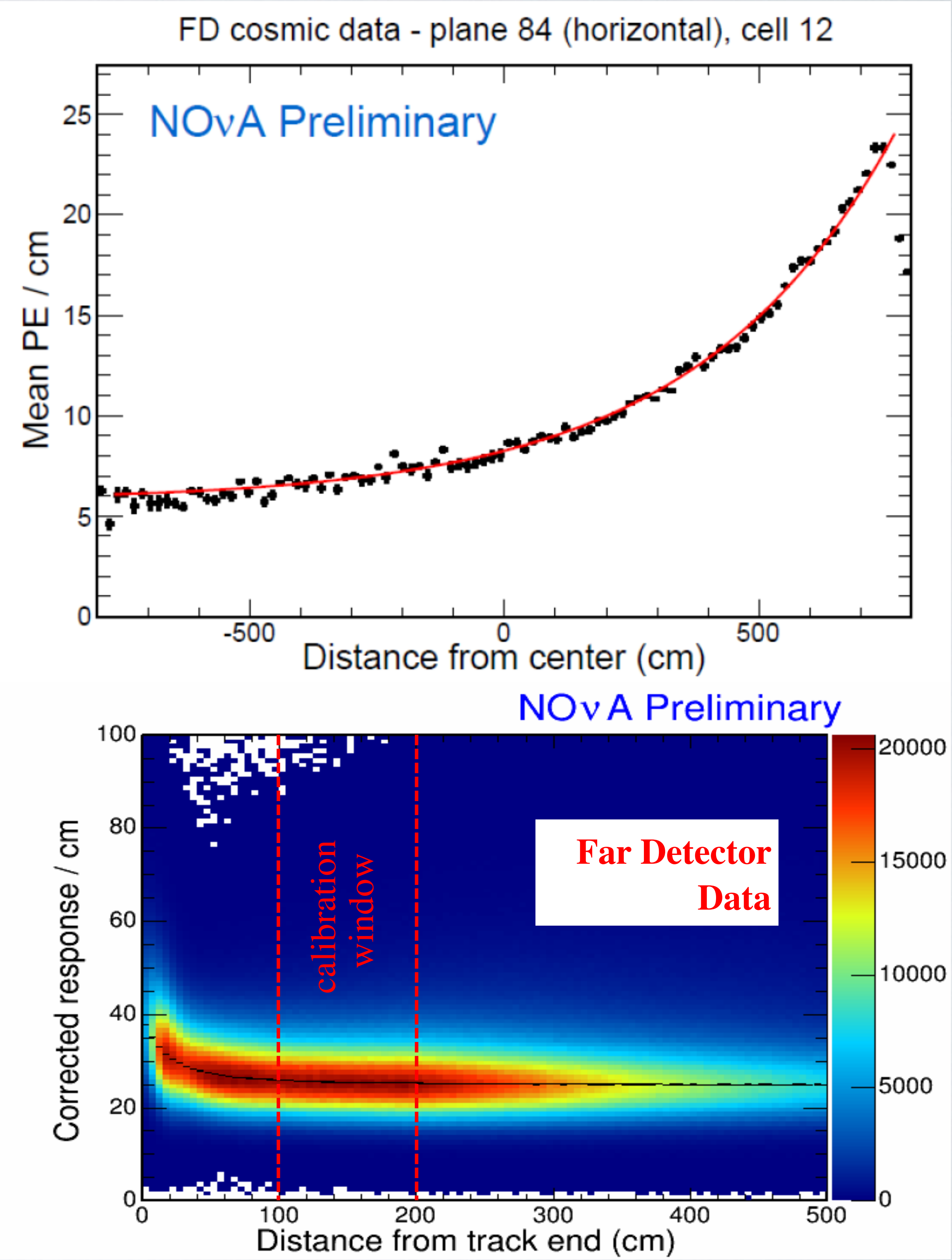
Highly detailed end to end simulation chain

- Beam hadron production, propagation, neutrino flux: **FLUKA/FLUGG**
- Cosmic ray flux: **CRY** (CORSIKA soon)
- Neutrino interactions and FSI modelling: **GENIE**
- Detector simulation: **GEANT4**
- Readout electronics and DAQ: **custom simulation routines**



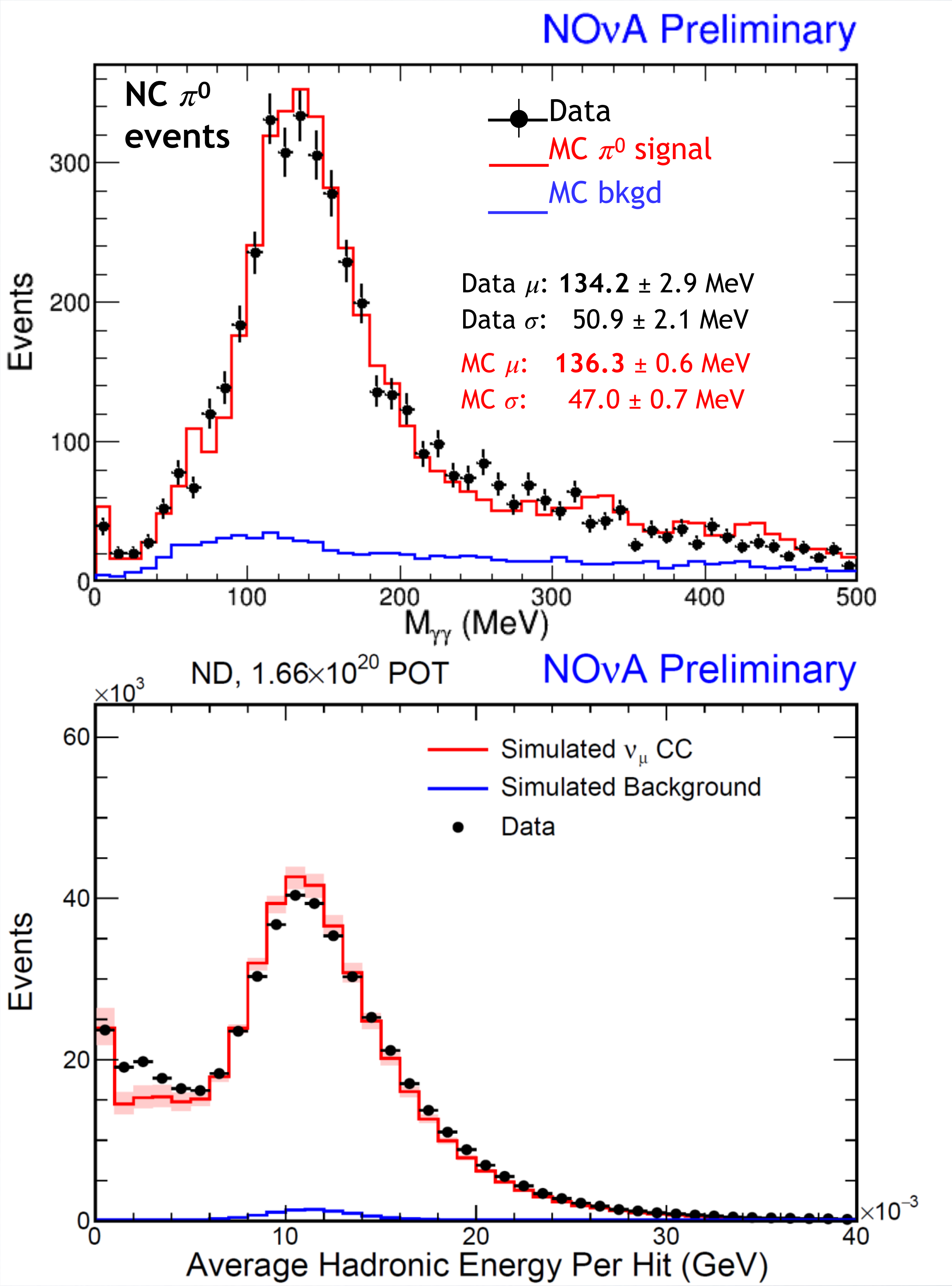
Calibration

- Calibration achieved using cosmic rays
- Light levels drop by a factor of 8 across a FD cell
- Stopping muons provide a standard candle

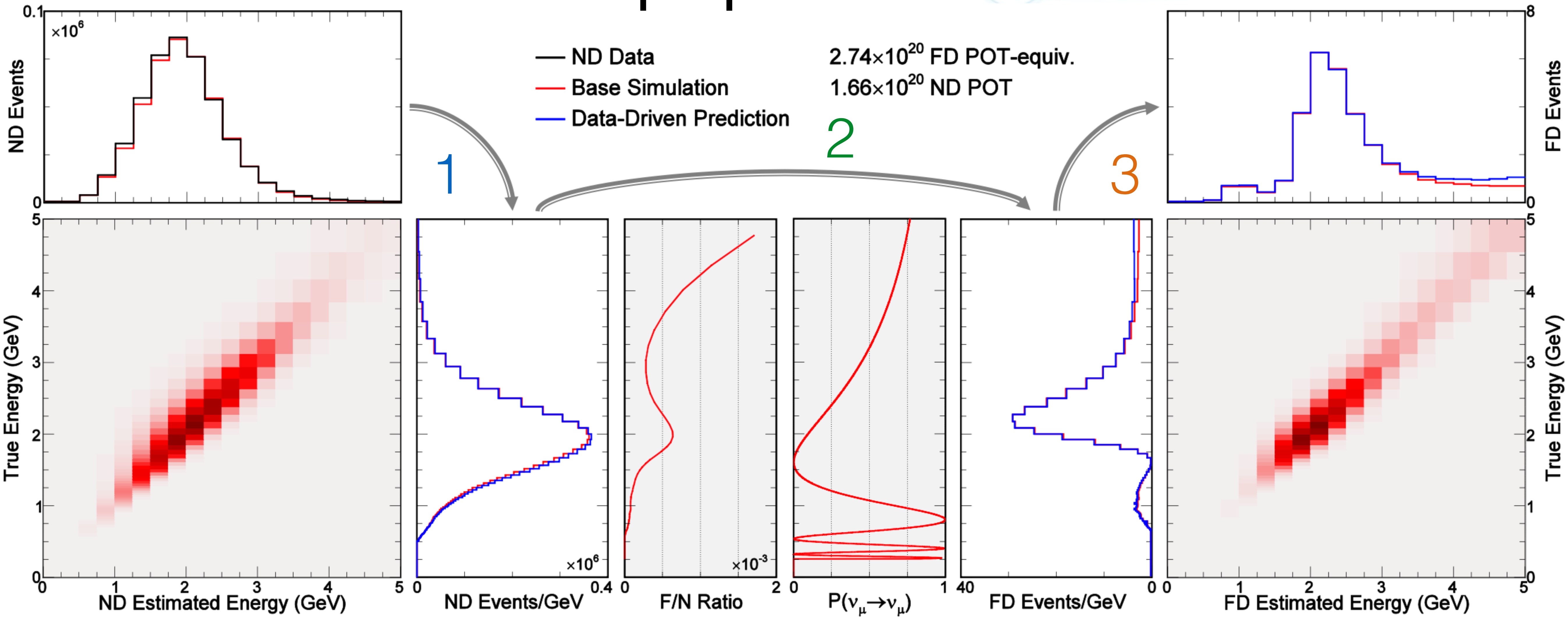


Energy Scale

- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e- spectrum
  - π^0 mass
  - hadronic shower E-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel e- spectrum
- All agree to 5%



ND to FD extrapolation is a three step process



1) Unfold ND reconstructed energy to true energy

2) Use Far/Near ratio to convert to FD true energy spectrum

3) Translate back to reconstructed energy

DUNE event counts

- Physics (MH, θ_{23}, θ_{13}, δ) extracted from combined analysis of 4 samples:

CDR estimates, assuming: CDR optimized beam, 56% LBNF uptime, FastMC detector response

Physics inputs: δ **= 0,** θ_{23} **= 45°**, others from NuFIT: Gonzalez-Garcia, Maltoni, Schwetz, JHEP 1411 (2014)

ν mode / 150 kt-MW-yr	ν_e appearance	ν_μ disappearance
Signal events (NH / IH)	**945 (521)**	**7929**
Wrong-sign signal (NH /IH)	13 (26)	511
Beam ν_e background	204	–
NC background	17	76
Other background	22	29

Anti-ν mode / 150 kt-MW-yr	$\overline{\nu}_e$ appearance	$\overline{\nu}_\mu$ disappearance
Signal events (NH / IH)	**168 (438)**	**2639**
Wrong-sign signal (NH /IH)	47 (28)	1525
Beam ν_e background	105	–
NC background	9	41
Other background	13	18