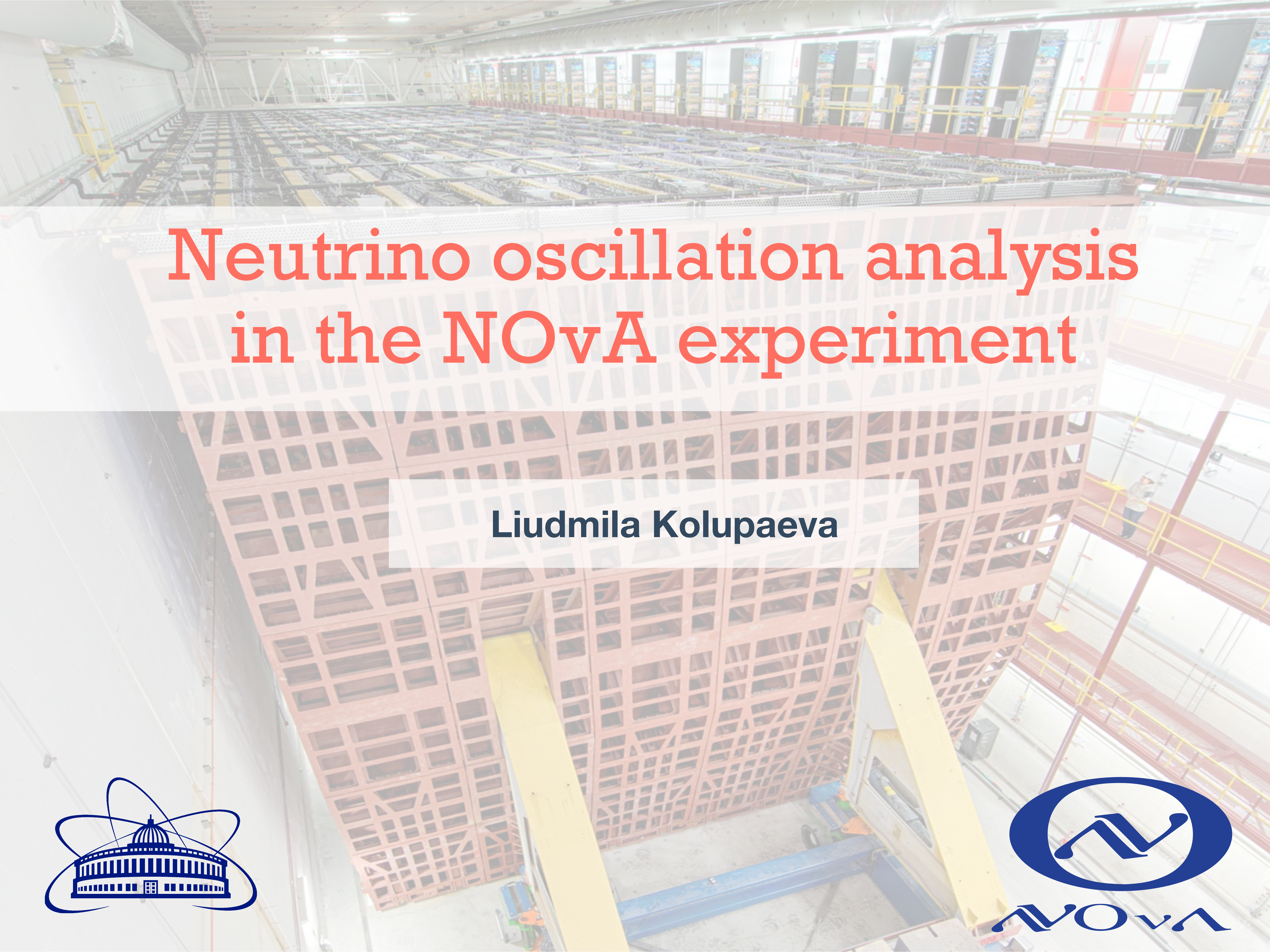


Neutrino oscillation analysis in the NOvA experiment

Liudmila Kolupaeva

Motivations to study neutrino oscillations

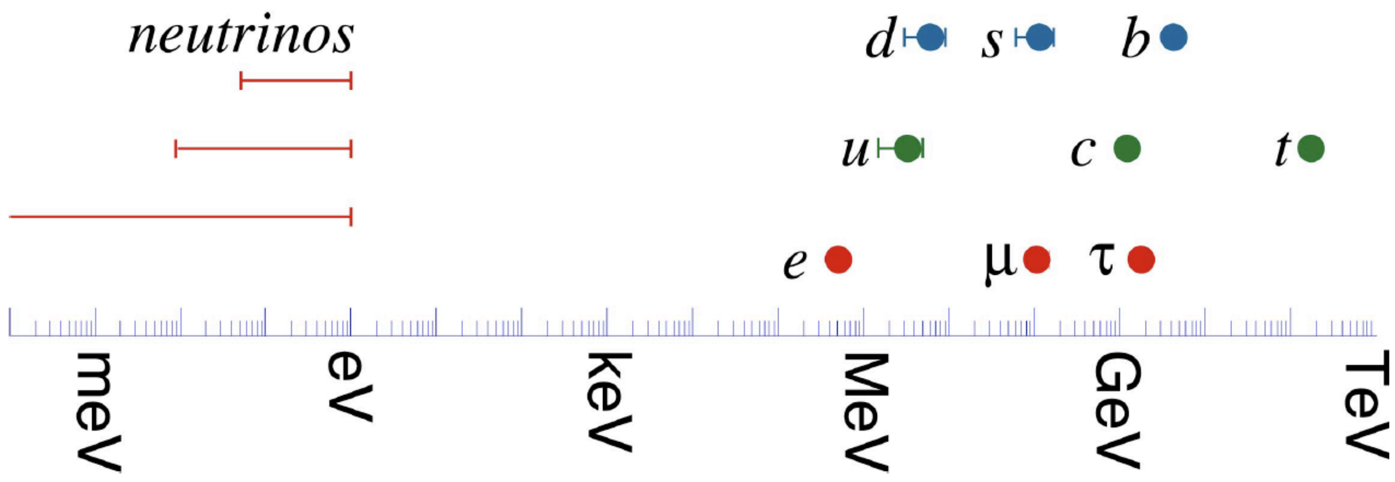
Why study neutrino oscillations?

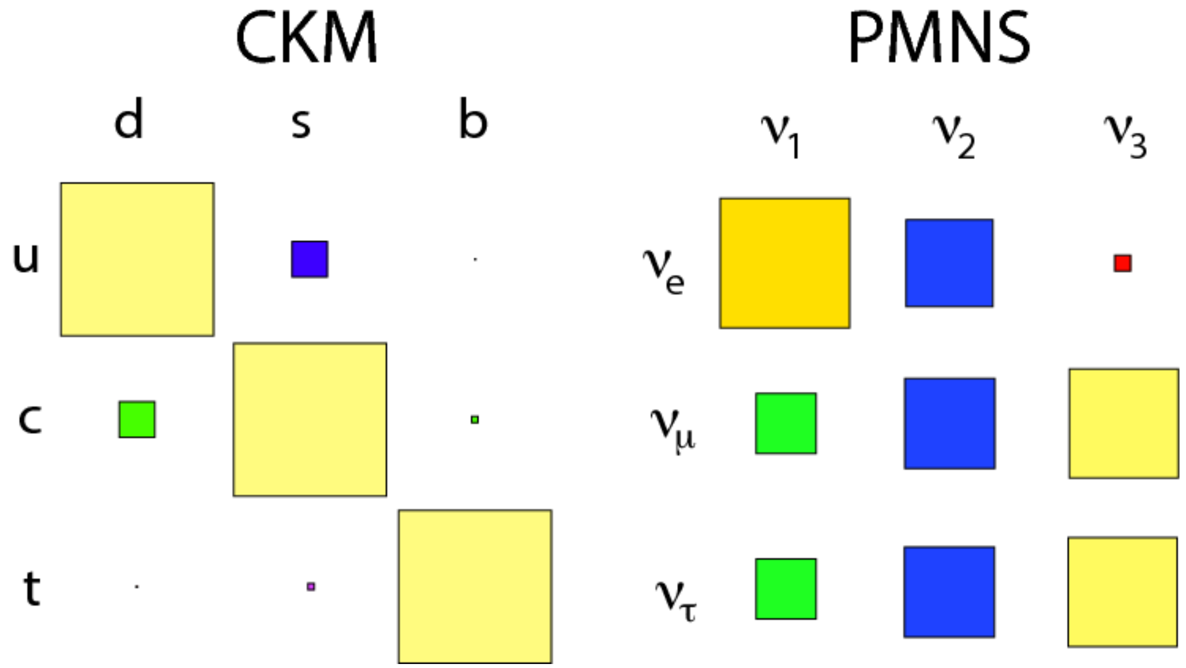
- Neutrinos are ”weird”:
  - neutrino masses are really small compared to the rest of the SM;
  - neutrino mixing looks very different from CKM.

- Potentially CP-violating:
  - might be a window into matter-antimatter asymmetry.

- Physics beyond the SM:
  - give access to high-scale physics.

- Open questions remain in the oscillation model.





Neutrino Oscillations

ATMOSPHERIC
ACCELERATOR

SHORT BASELINE REACTOR
ACCELERATOR

SOLAR
LONG BASELINE REACTOR

$$\left|\begin{matrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{matrix}\right\rangle = \begin{pmatrix}1&&\\&c_{23}&s_{23}\\&-s_{23}&c_{23}\end{pmatrix}\begin{pmatrix}c_{13}&&s_{13}e^{-i\delta}\\&1&\\-s_{13}e^{i\delta}&&c_{13}\end{pmatrix}\begin{pmatrix}c_{12}&s_{12}&\\-s_{12}&c_{12}&\\&&1\end{pmatrix}\left|\begin{matrix}\nu_1\\ \nu_2\\ \nu_3\end{matrix}\right\rangle$$

OSCILLATION PARAMETERS AND HOW PRECISELY DO WE KNOW THEM:

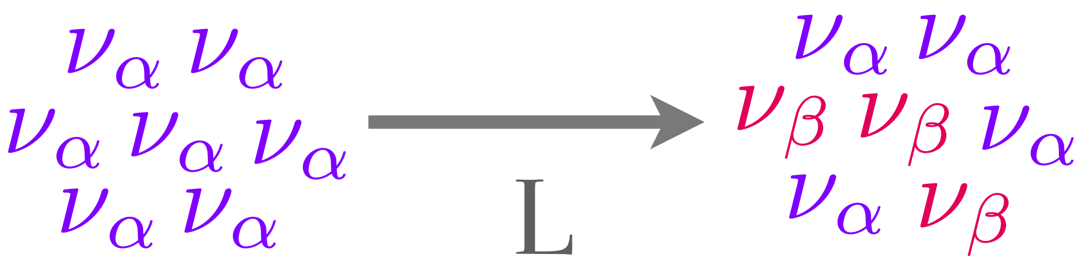
$\theta_{12} \approx 34^\circ$ (4.4%)

$\theta_{23} \approx 49^\circ$ (5.2%)

$\theta_{13} \approx 9^\circ$ (3.8%)

$\Delta m^2_{21} \approx 7.4 \times 10^{-5}\ \mathrm{eV}^2$ (2.2%)

$\Delta m^2_{32} \approx +2.5 \times 10^{-3}\ \mathrm{eV}^2$ (1.4%)

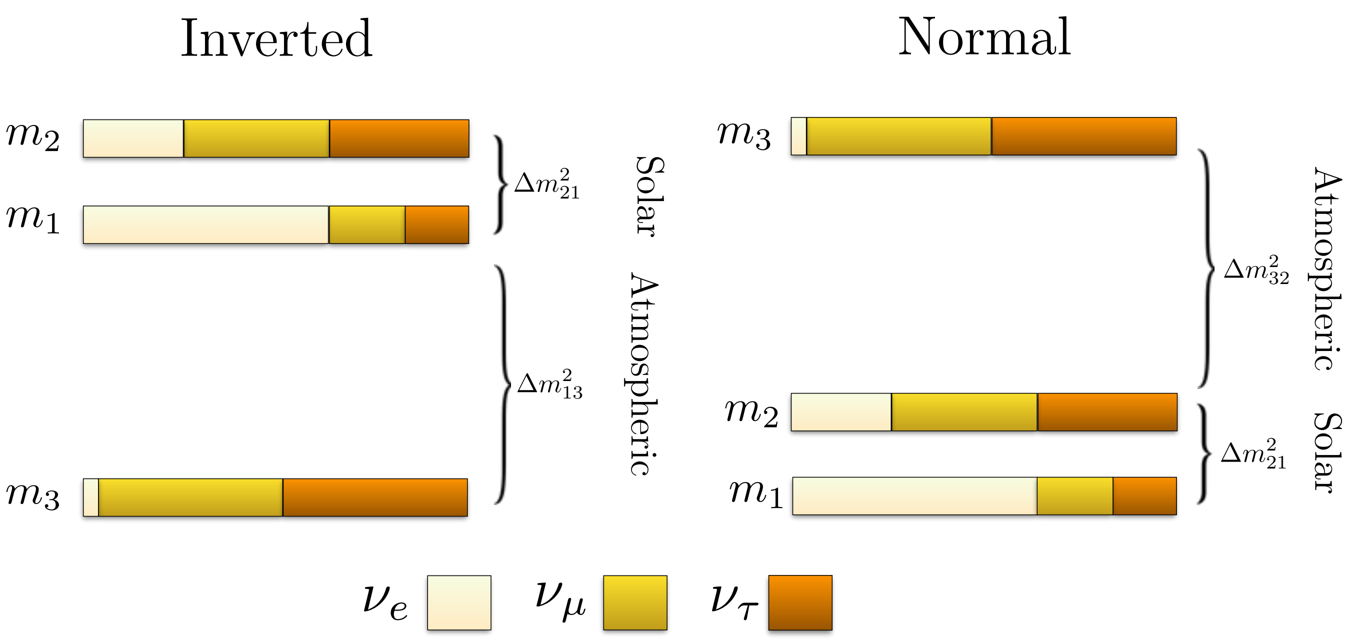


OPEN QUESTIONS:

Is θ_{23} 45°?

Is there CP violation in lepton sector?

Neutrino mass hierarchy is Normal or Inverted?

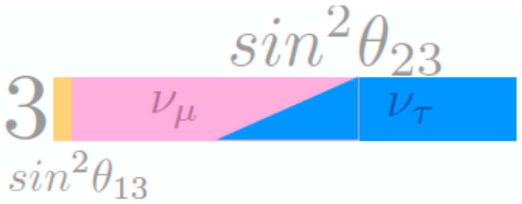


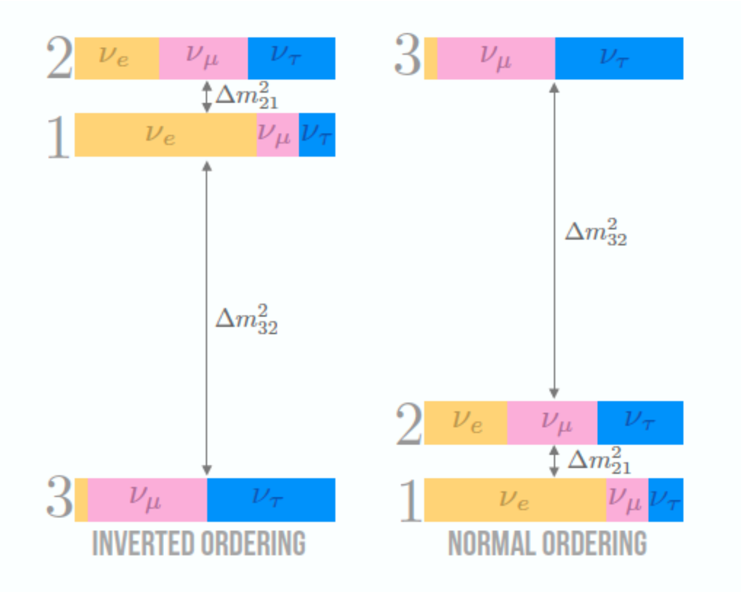
Neutrino Oscillation Probabilities

$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_e) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}(cos\Delta_{32}cos\delta_{CP} \overset{\nu \text{ vs } \bar{\nu}}{\mp} sin\Delta_{32}sin\boxed{\delta_{CP}})$$

$$\sqrt{P_{atm}} = sin(\boxed{\theta_{23}})sin(2\theta_{13})\frac{sin\boxed{(\Delta_{31} - aL)}}{\boxed{\Delta_{31} - aL}}\Delta_{31}$$

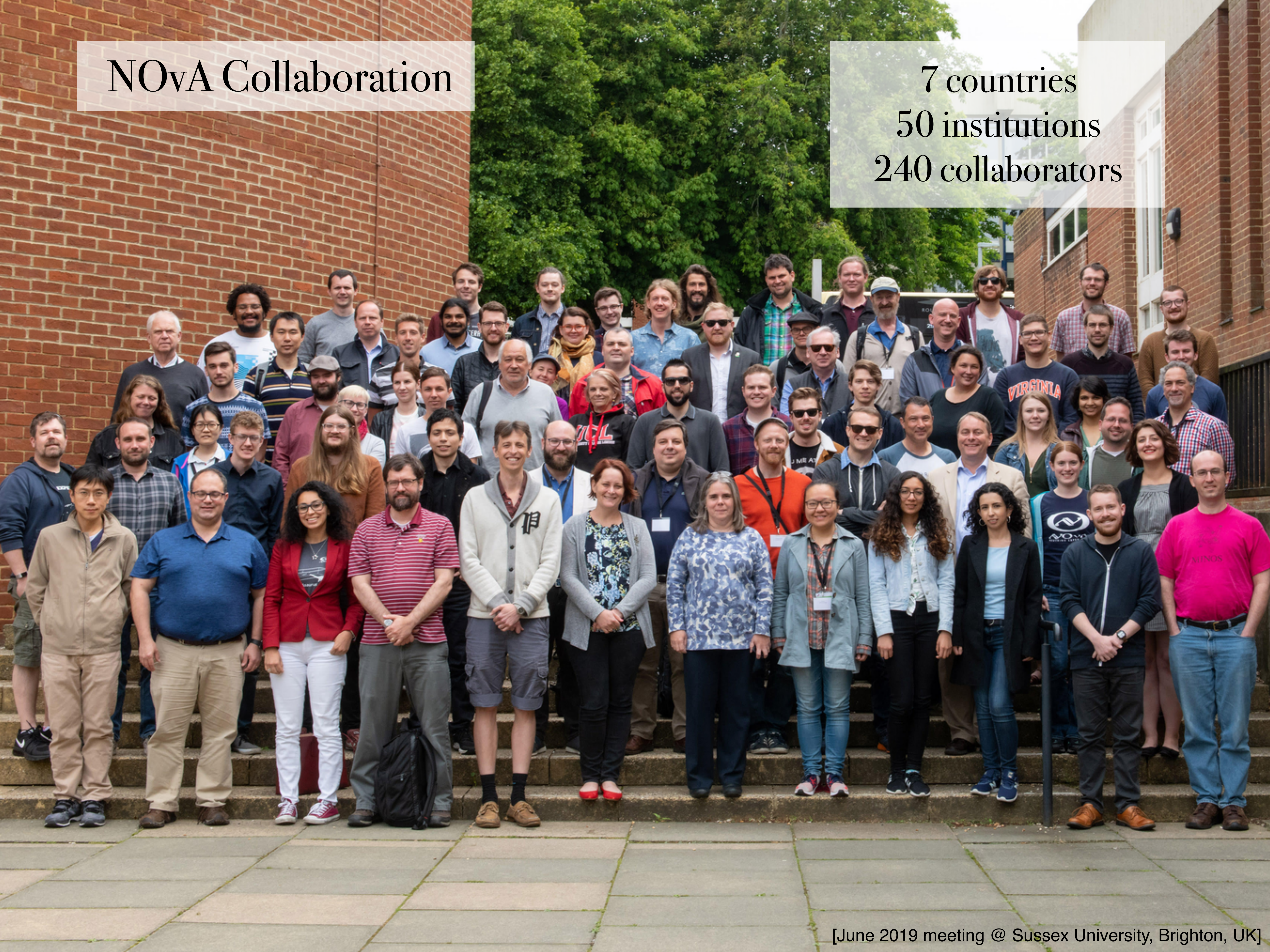
$$\Delta P_{\nu\bar{\nu}} \sim sin\ \delta_{CP}$$





$$P(\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu) \approx 1 - sin^2(2\boxed{\theta_{23}})sin^2\left(\frac{\Delta m^2_{32}L}{4E}\right)$$

NOvA Collaboration



7 countries
50 institutions
240 collaborators

[June 2019 meeting @ Sussex University, Brighton, UK]

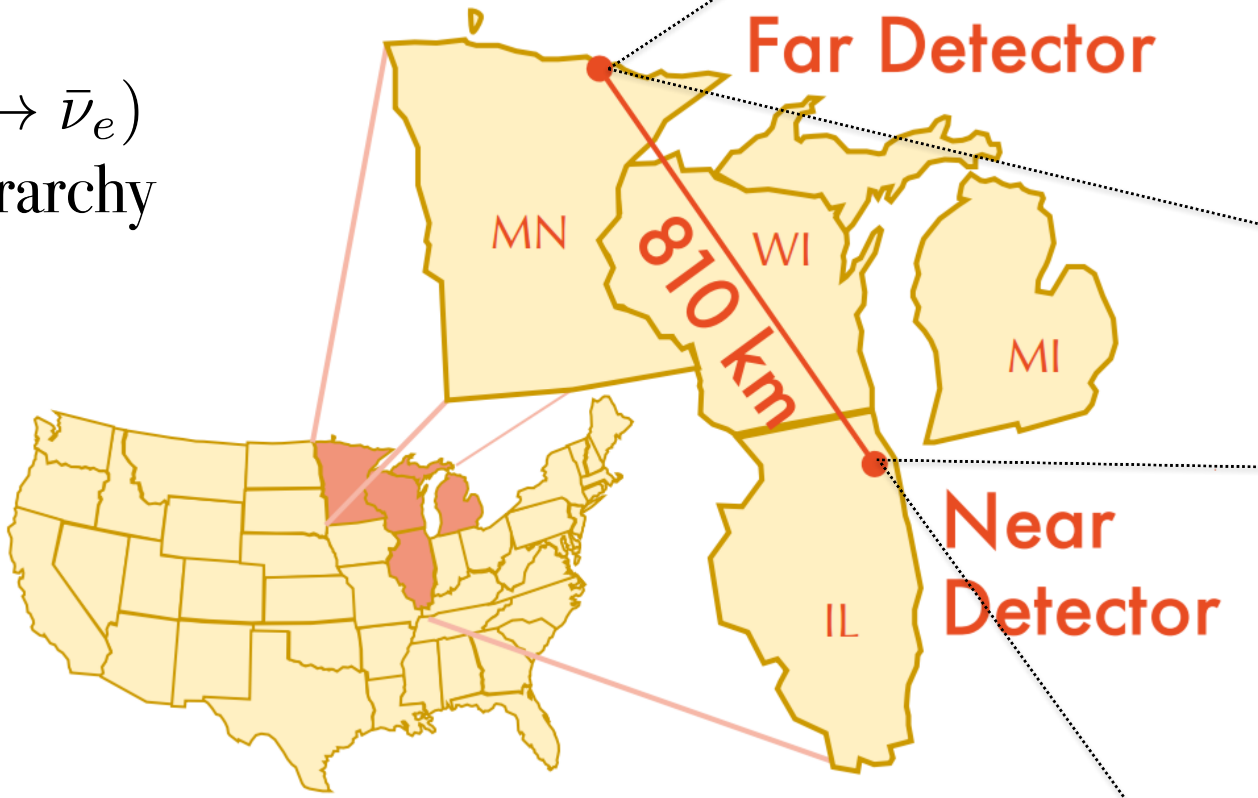
The NOvA Experiment

The NuMI Off-Axis ν_e Appearance Experiment

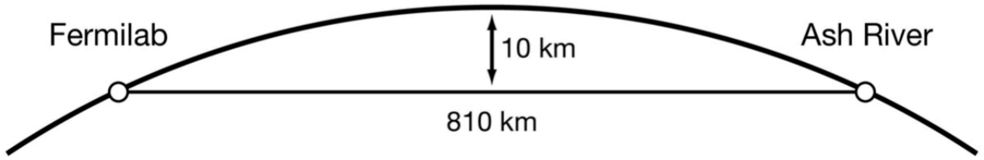
Experiment goals:

Using $\nu_\mu \to \nu_\mu$ $(\bar{\nu}_\mu \to \bar{\nu}_\mu)$
- ✳ Precise measurement Δm^2_{32}
- ✳ Mixing angle θ_{23}

Using $\nu_\mu \to \nu_e$ $(\bar{\nu}_\mu \to \bar{\nu}_e)$
- ✳ Neutrino mass hierarchy
- ✳ CP violating phase
- ✳ Mixing angle θ_{23}



Long-baseline,
beam from Fermilab,
two detectors sit at
14 mrad off-axis



Strategy

Experiment goals:

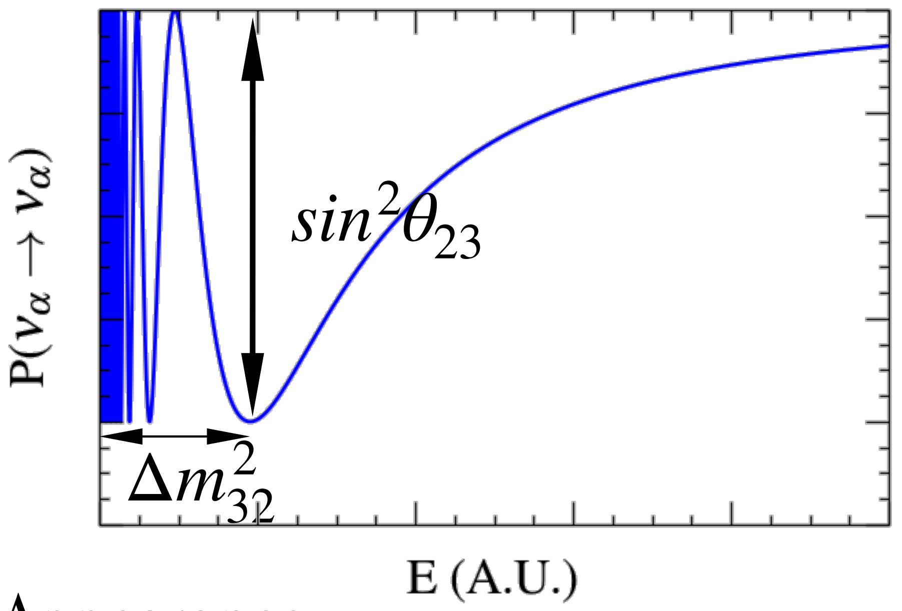
Using $\nu_\mu \rightarrow \nu_\mu$ $(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$
- ✳ Precise measurement Δm^2_{32}
- ✳ Mixing angle θ_{23}

Using $\nu_\mu \rightarrow \nu_e$ $(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$
- ✳ Neutrino mass hierarchy
- ✳ CP violating phase
- ✳ Mixing angle θ_{23}

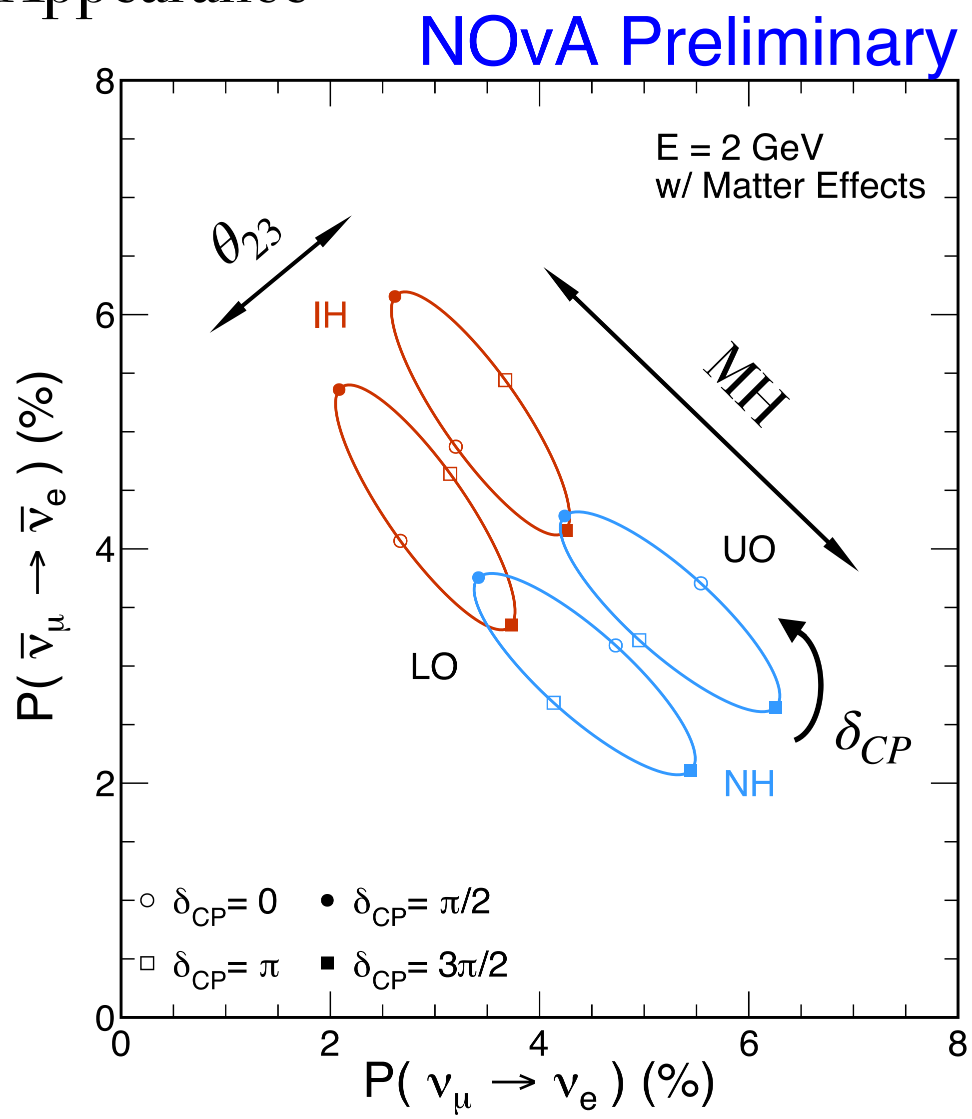
Obtain sensitivity to the mass hierarchy due to matter effects.

In order to avoid degeneracy "θ_{23} - mass hierarchy - δ_{CP}" need both neutrino and antineutrino beams

Disappearance

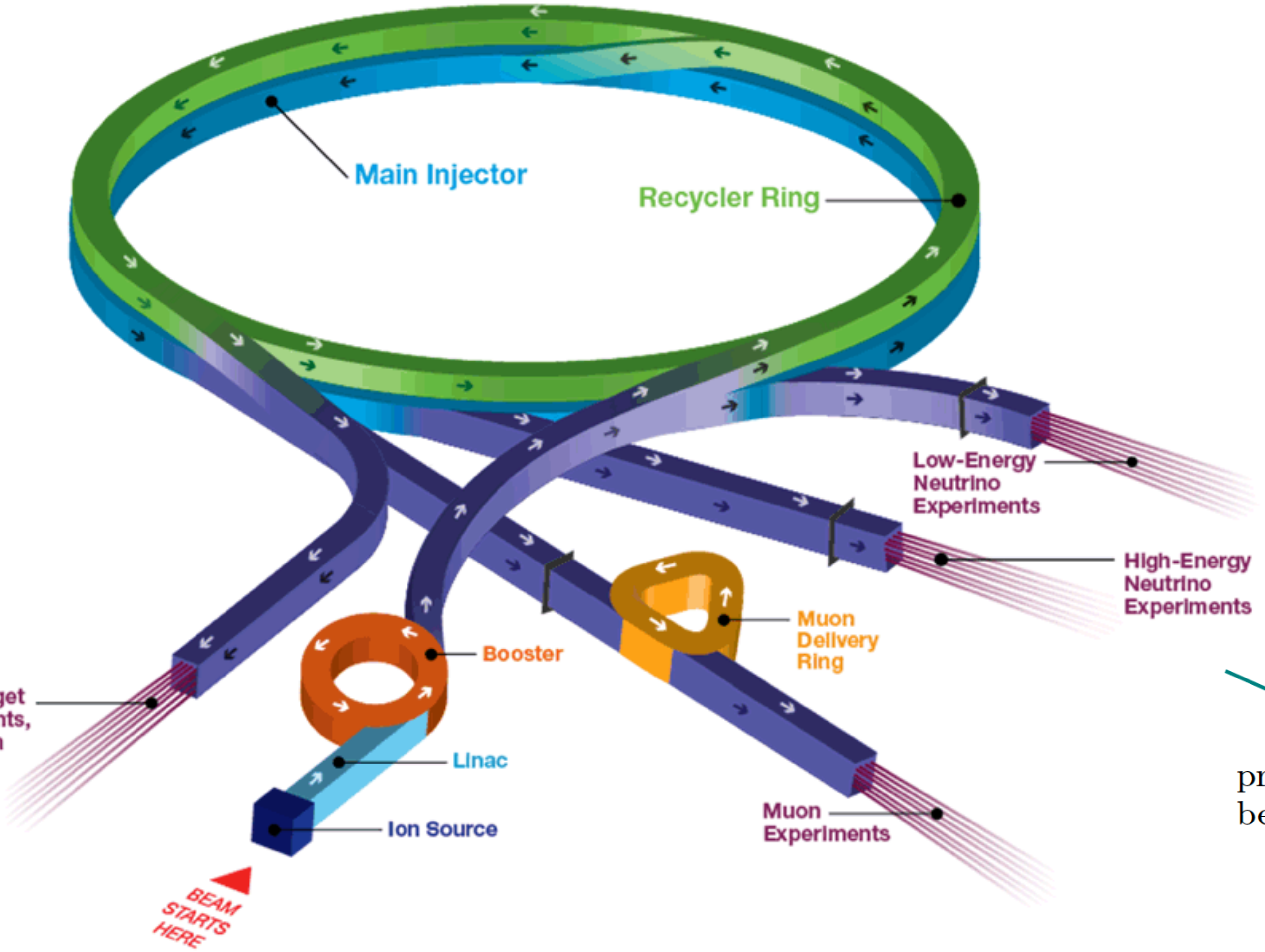


Appearance



FermiLab accelerator complex

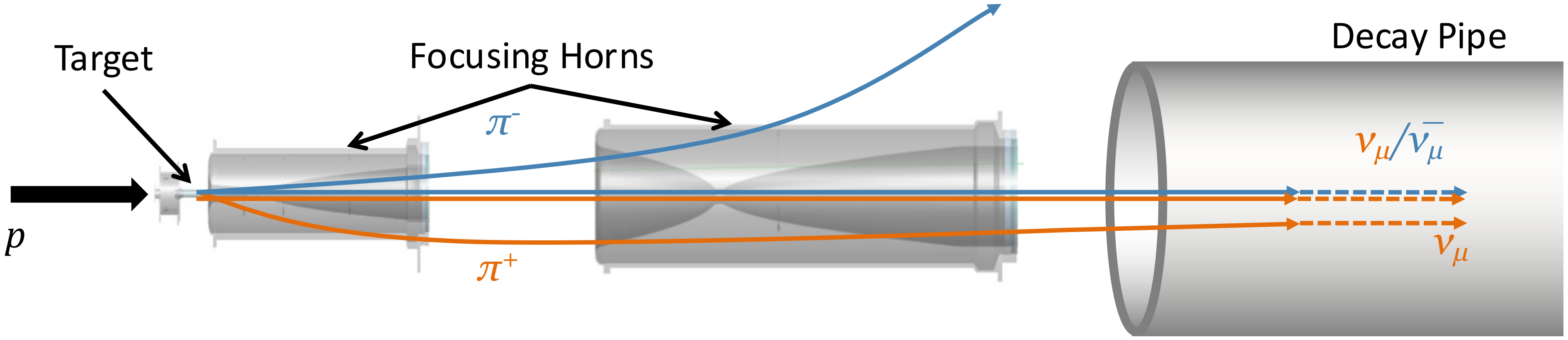
750 keV
↓
400 MeV
↓
8 GeV
↓
120 GeV
↓
to target



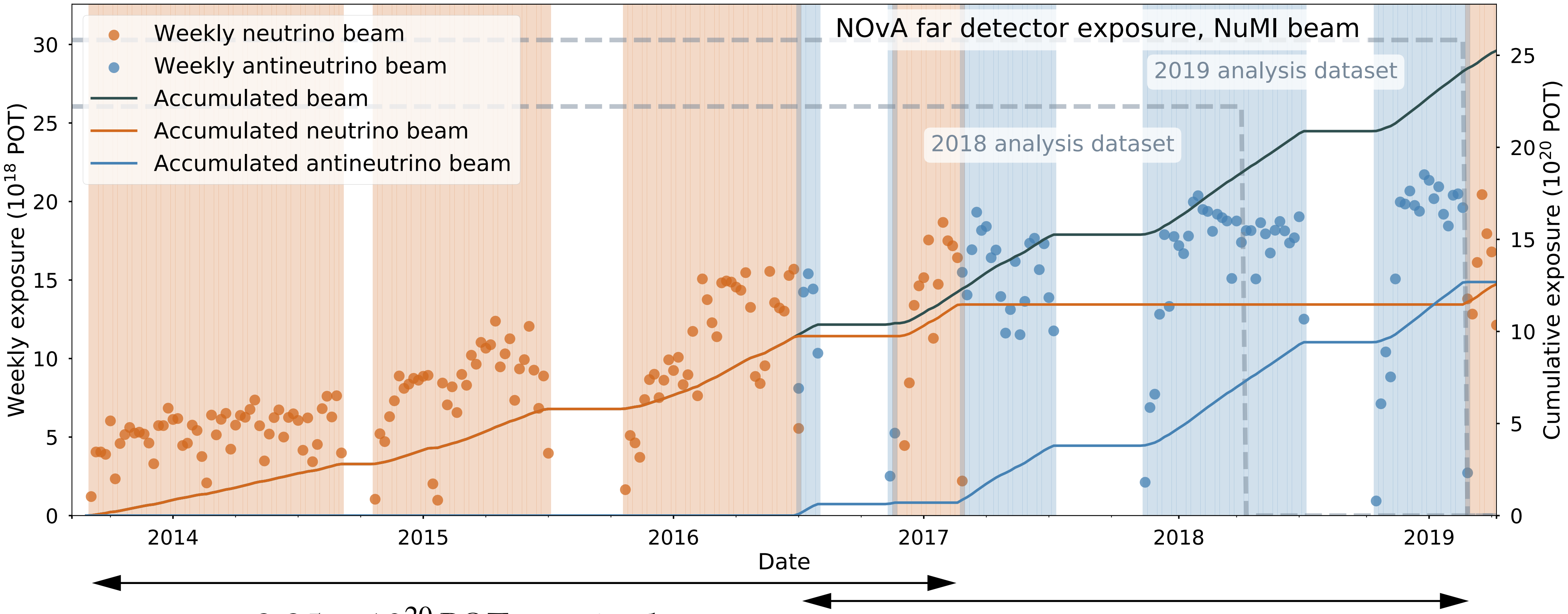
↘

proton 120 GeV beam on target

Neutrino beam



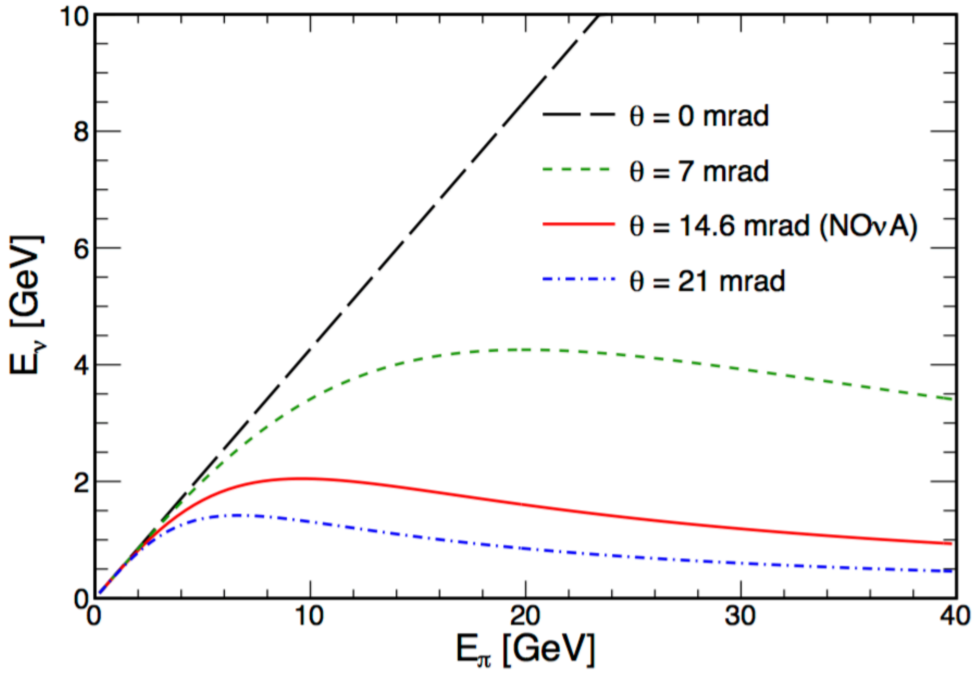
- ✳ 120 GeV protons on a carbon target, produce mesons which yield neutrinos. Beam purity with $\nu(\bar{\nu})$: $95\%\ \nu_\mu,\ 4\%\ \bar{\nu}_\mu,\ 1\%\ \nu_e\ (93\%\ \bar{\nu}_\mu,\ 6\%\ \nu_\mu,\ 1\%\ \nu_e)$.
- ✳ NOvA is designed for the 700 kW NuMI beam, with 6×10^{20} POT/year (POT = Proton On Target).

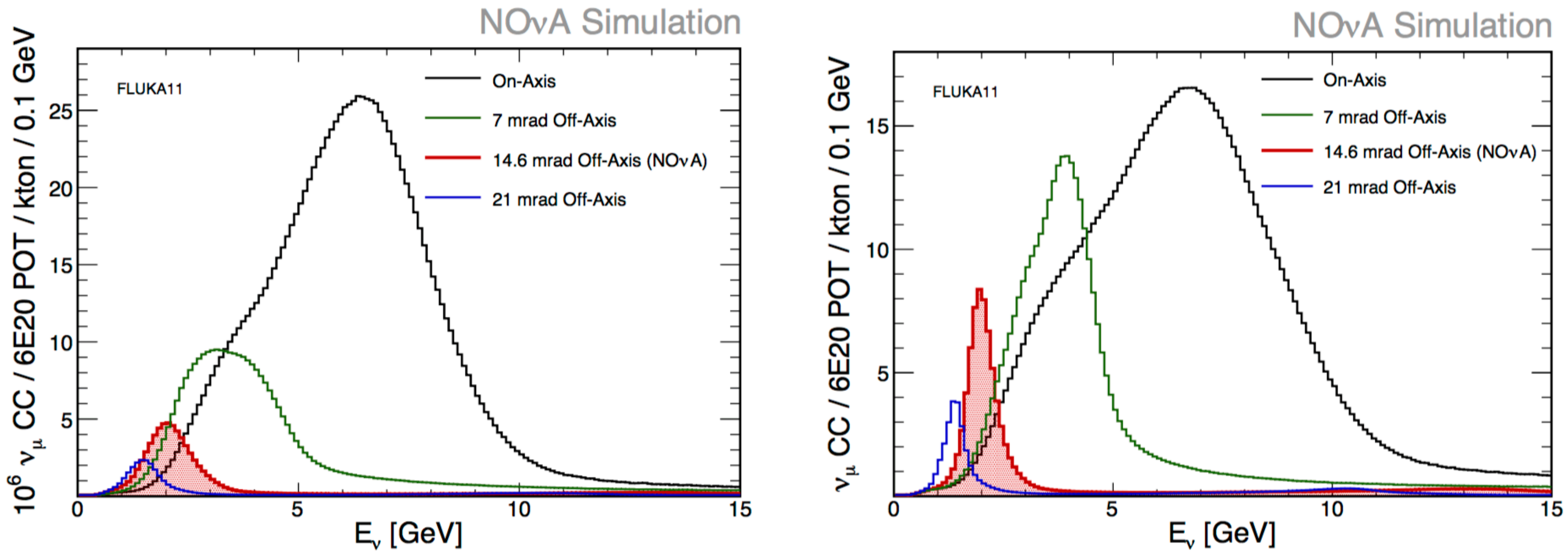


8.85×10^{20} POT neutrino beam

12.33×10^{20} POT antineutrino beam

Off-axis detector scheme



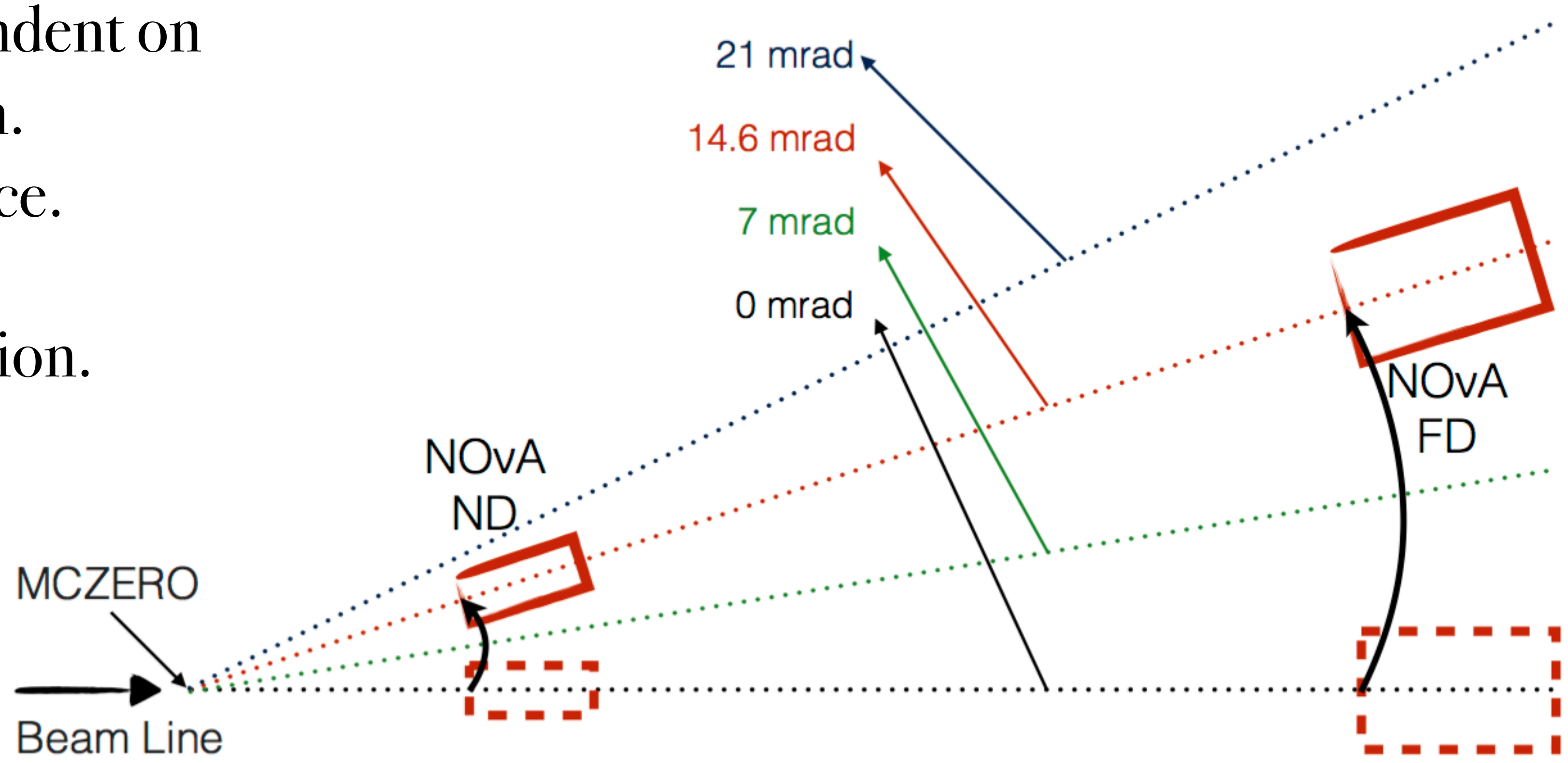


Narrowly peaked ν flux centered at 2 GeV

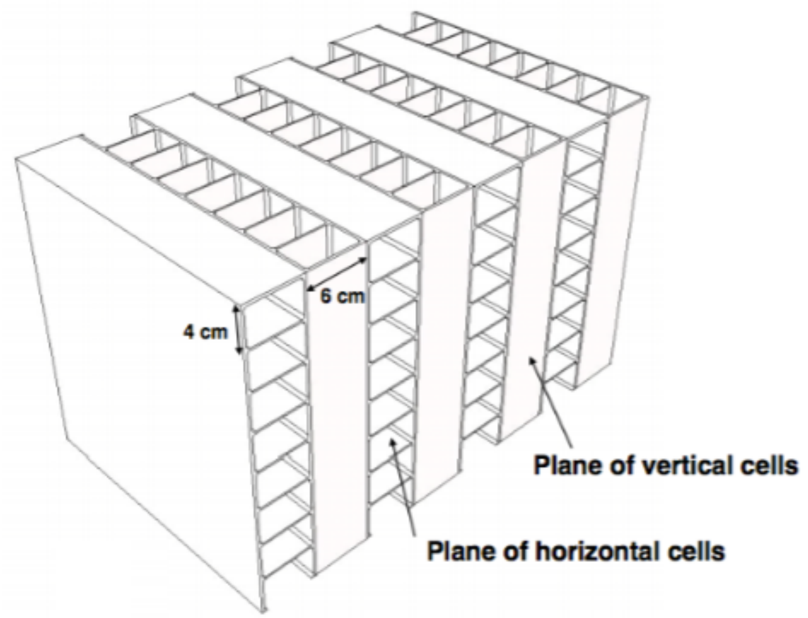
$$E_\nu = \frac{\left(1-\frac{m_\mu^2}{m_{\pi,K}^2}\right)E_{\pi,K}}{1+\gamma^2\theta^2}$$

- For π decay-in-flight, E_ν dependent on angle π decay and ν interaction.
- Off-axis have flat E_π dependence.

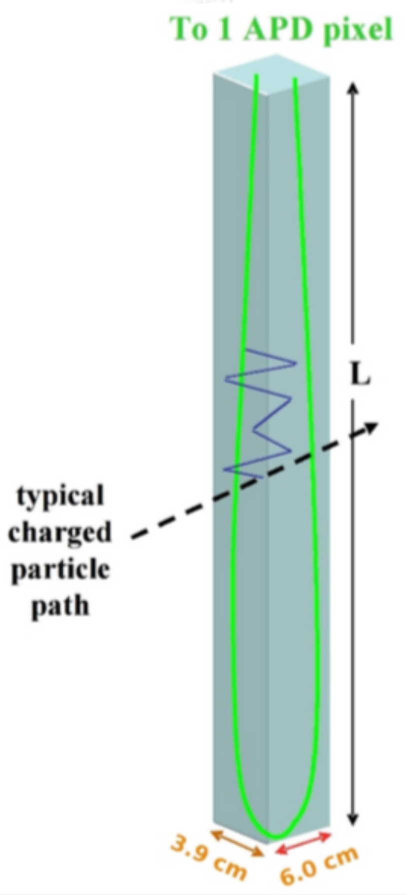
- Achieves near maximal oscillation.
- Suppresses high energy tail.
- 14 mrad off-axis.

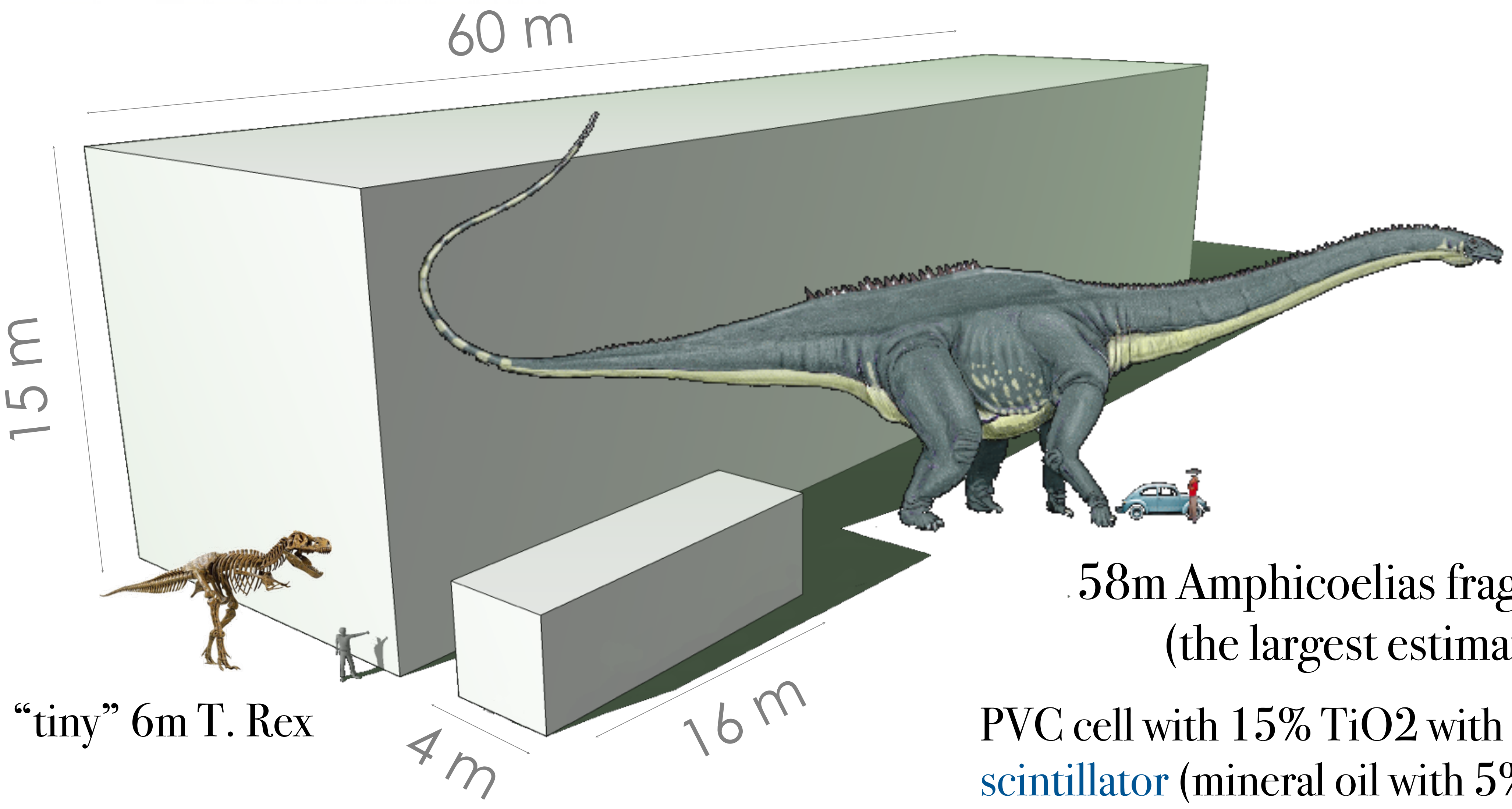


Detectors



FD: 344 064 cells
ND: 20 192 cells



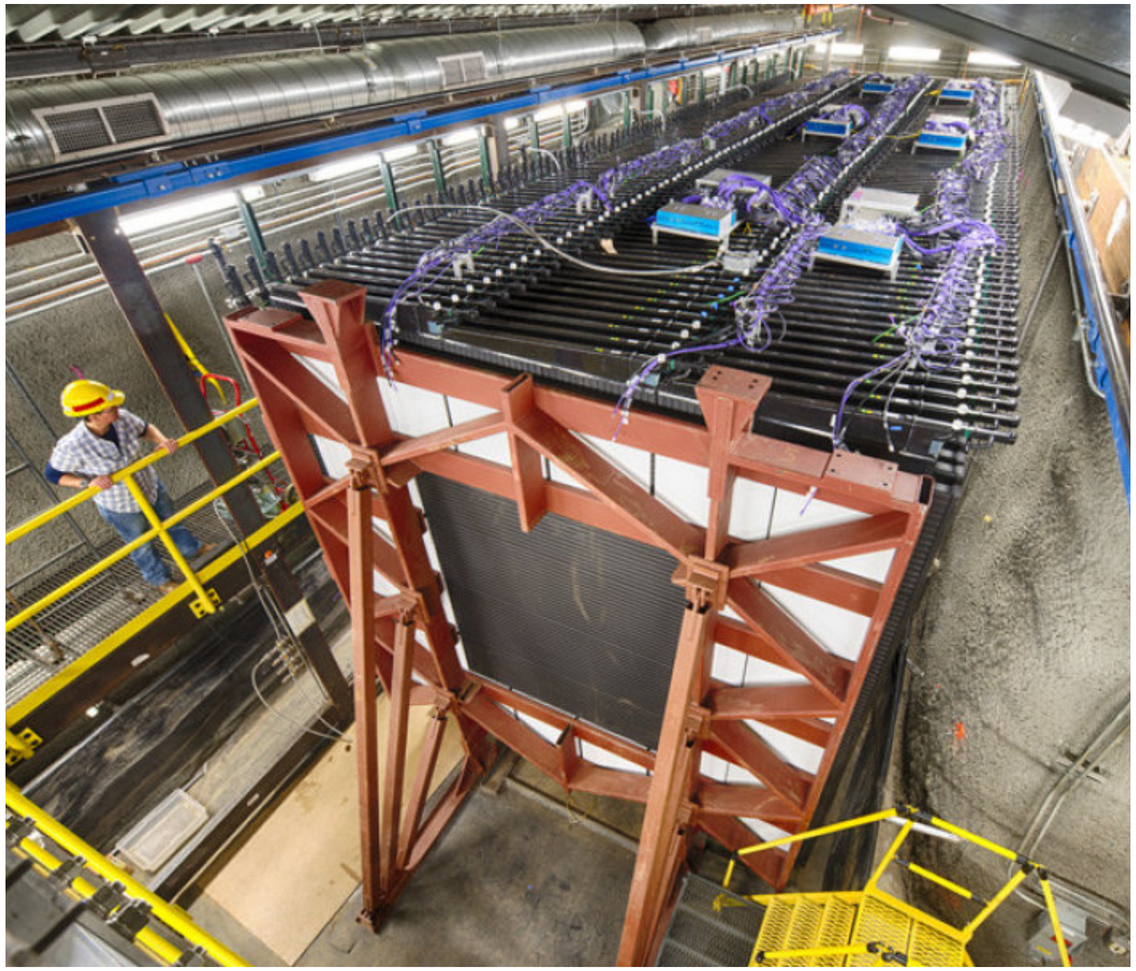


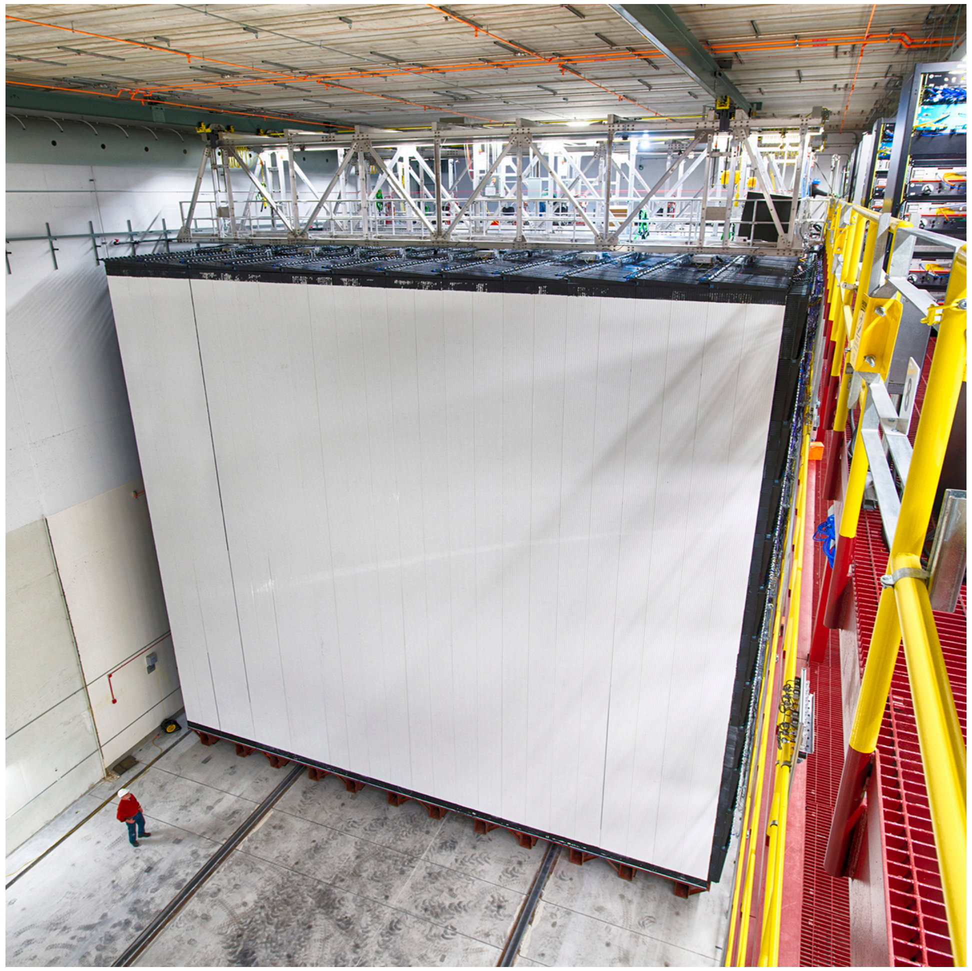
“tiny” 6m T. Rex

58m Amphicoelias fragillimus
(the largest estimate)

PVC cell with 15% TiO2 with liquid scintillator (mineral oil with 5% pseudocumene)

Two detector scheme





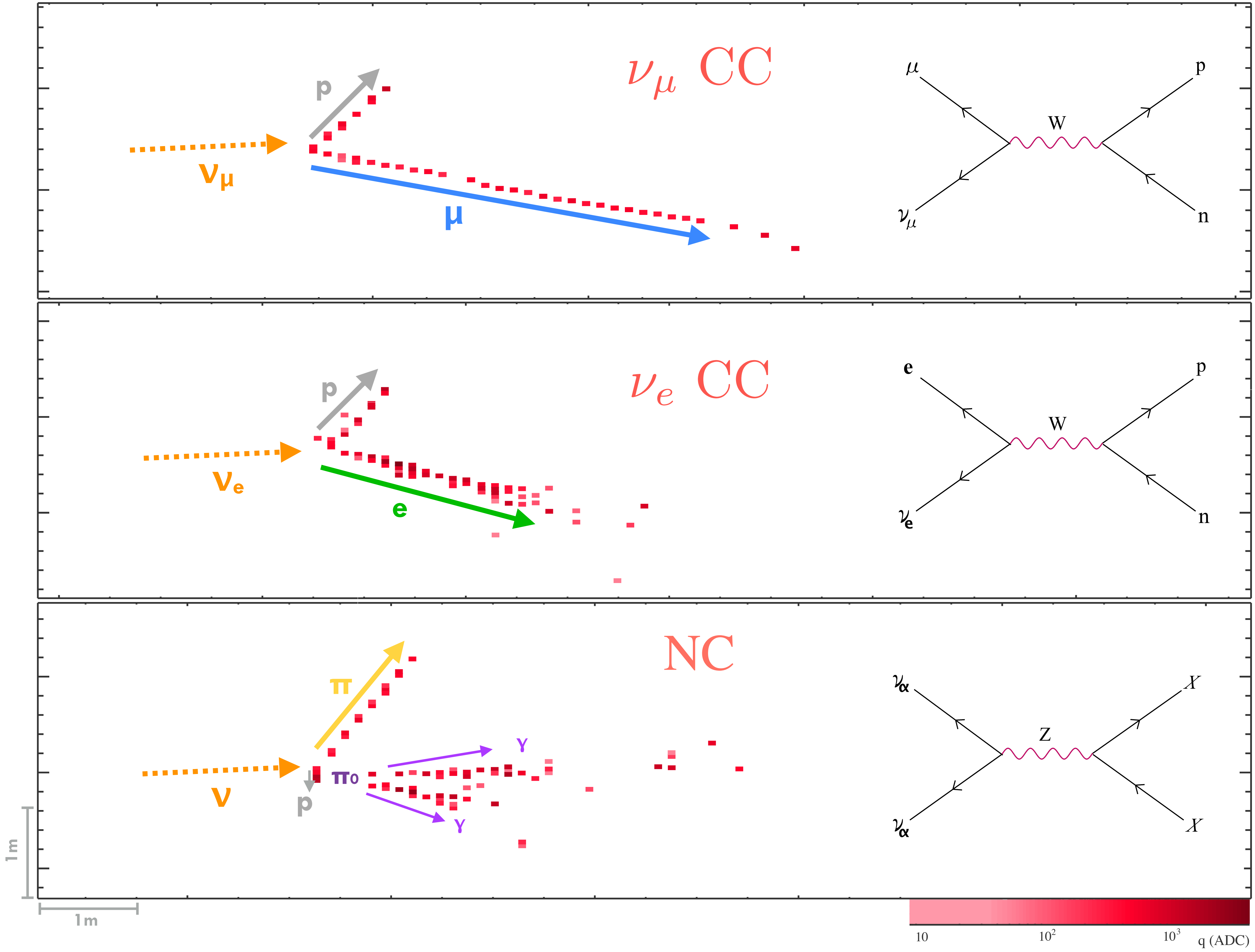
Near Detector (ND):

- 1 km after target
- measure flux composition before oscillations
- ND data used for prediction data in FD (extrapolation procedure)

Far Detector (FD):

- 810 km after target
- measure neutrino flux after oscillations
- extrapolation cancels most systematics
- FD identical to ND

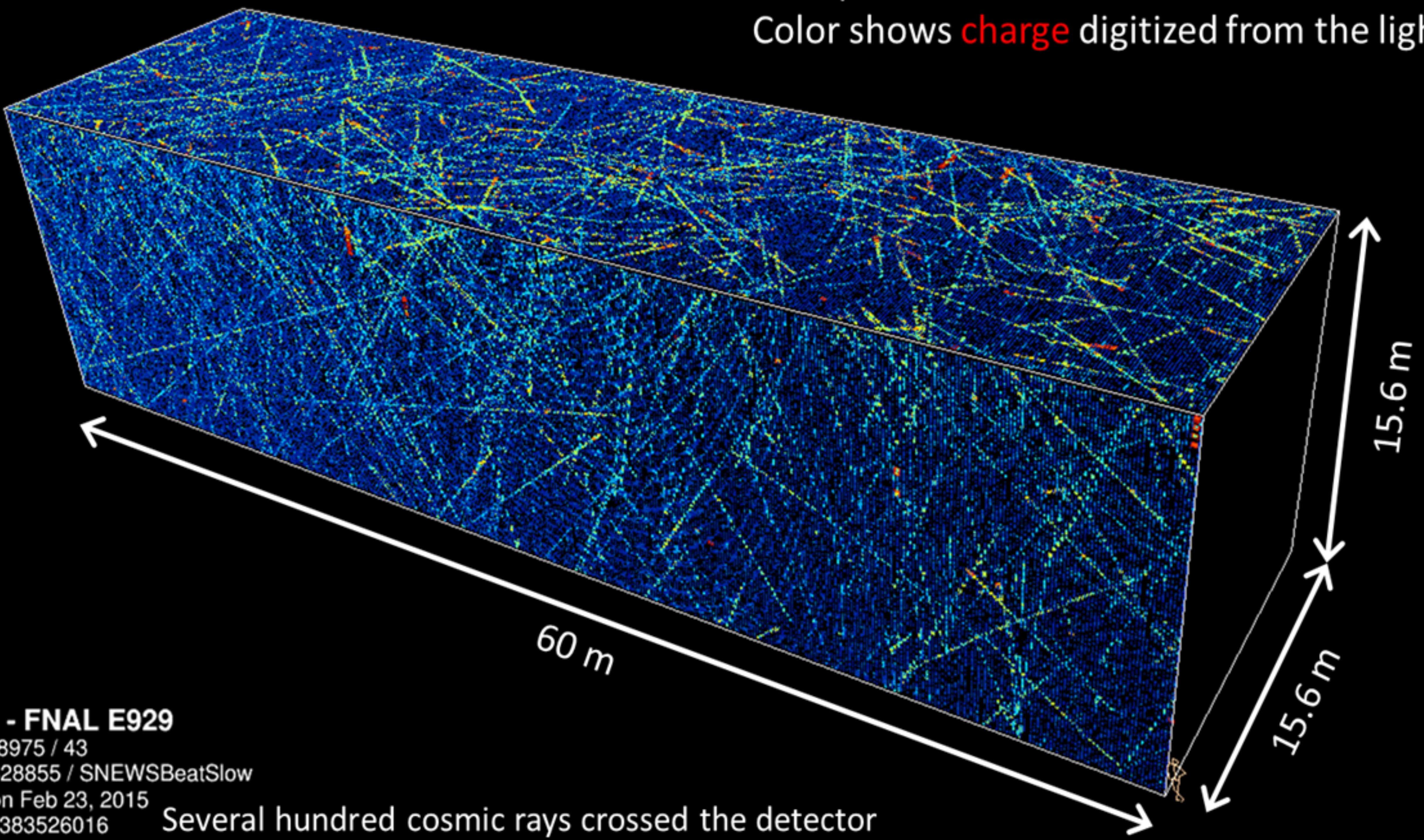
Event topologies



5ms of data at the NOνA Far Detector

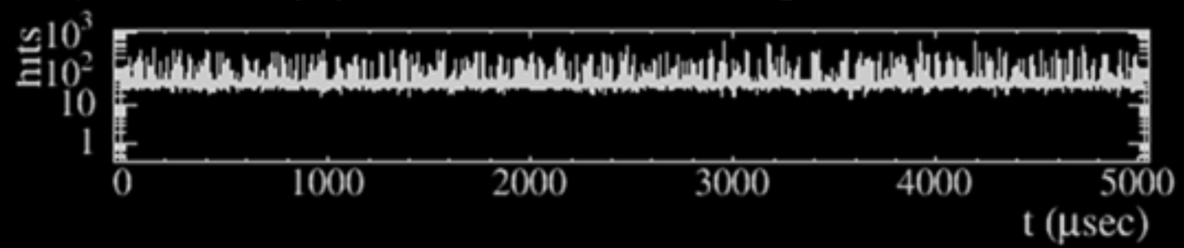
Each pixel is one hit cell

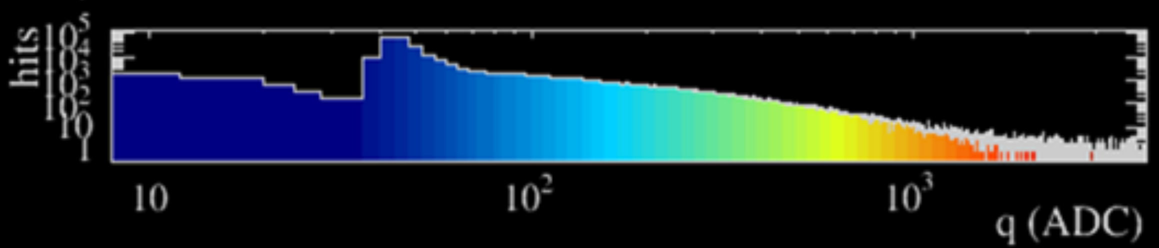
Color shows charge digitized from the light

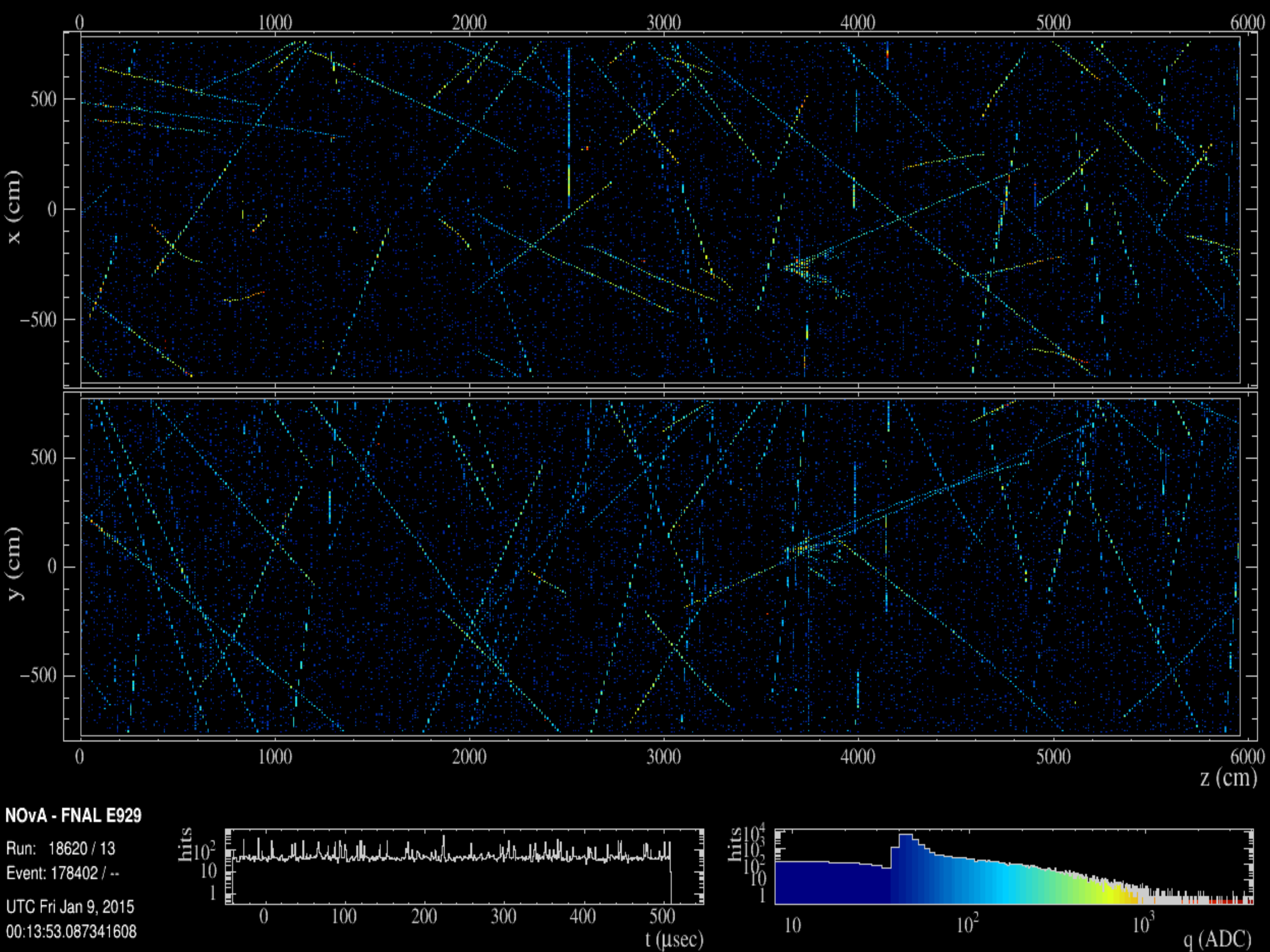


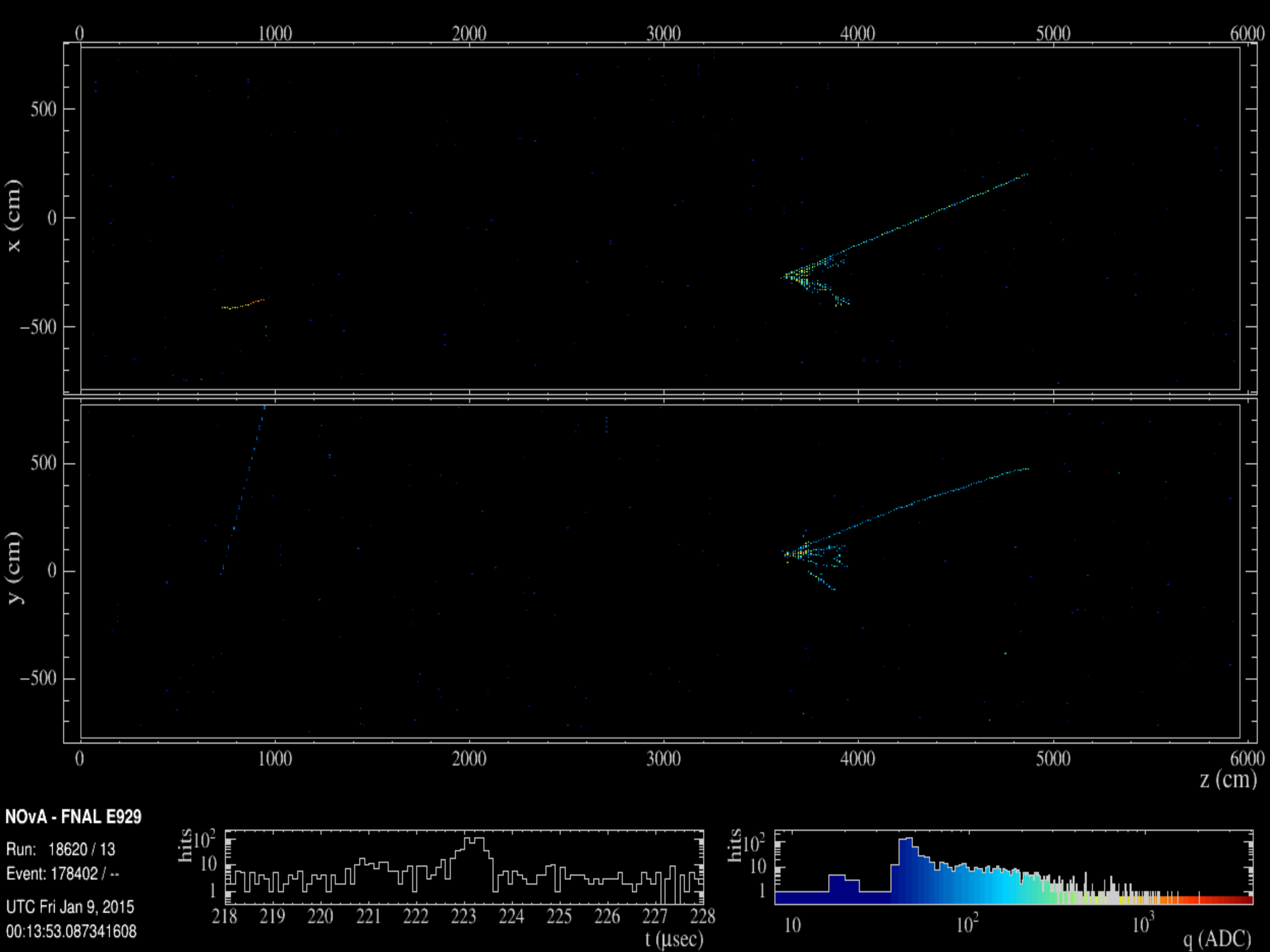
NOvA - FNAL E929
Run: 18975 / 43
Event: 628855 / SNEWSBeatSlow
UTC Mon Feb 23, 2015
14:30:1.383526016

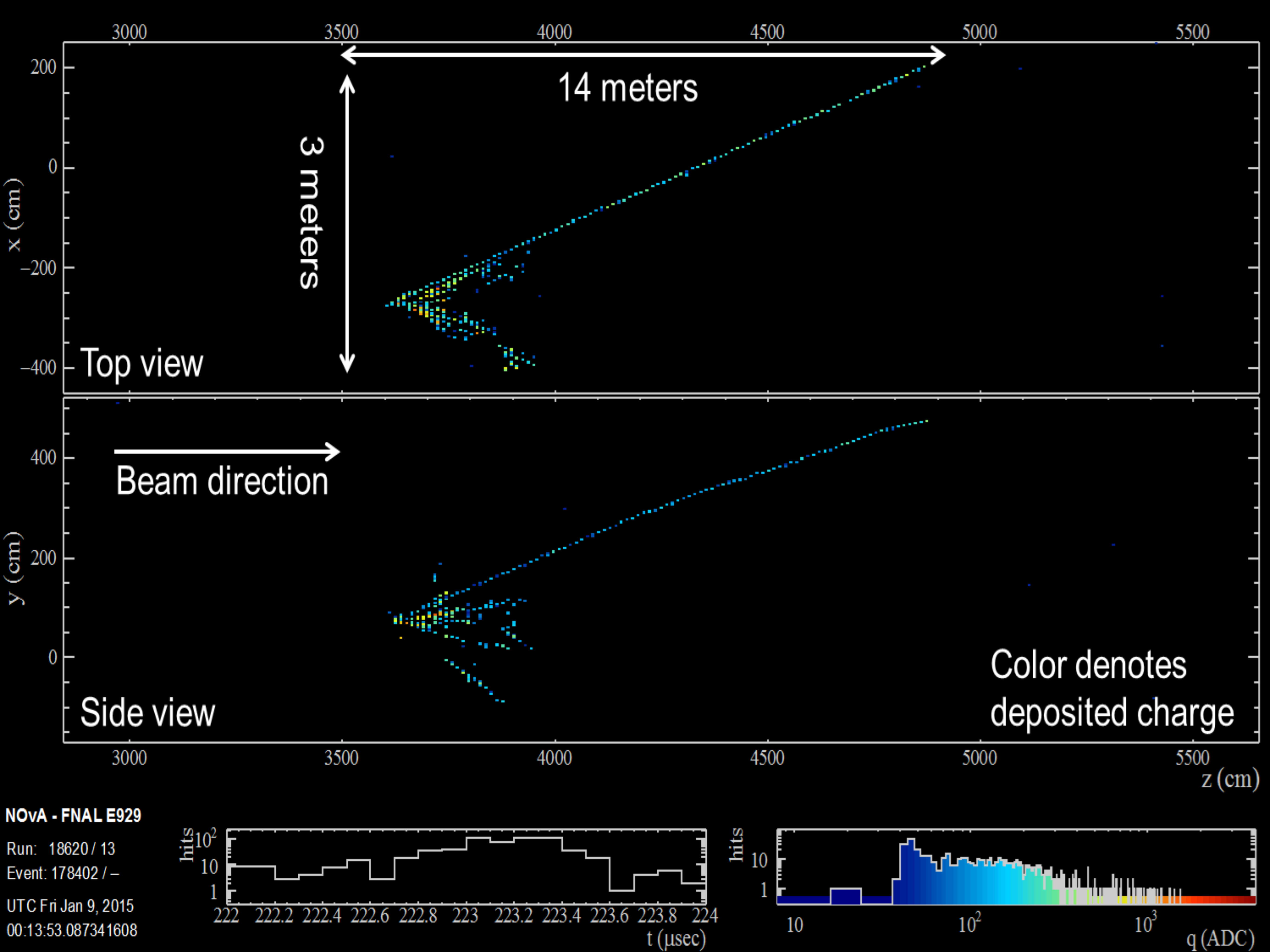
Several hundred cosmic rays crossed the detector
(the many peaks in the timing distribution below)






0
1000
2000
3000
4000
5000
6000
x (cm)
500
0
−500
y (cm)
500
0
−500
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
10^2
10
1
0
100
200
300
400
500
t (μsec)
hits
10^4
10^3
10^2
10
1
10
10^2
10^3
q (ADC)


0
1000
2000
3000
4000
5000
6000
500
0
−500
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608
hits
10^2
10
1
218
219
220
221
222
223
224
225
226
227
228
t (µsec)
q (ADC)
10^3



14 meters

3 meters

Top view

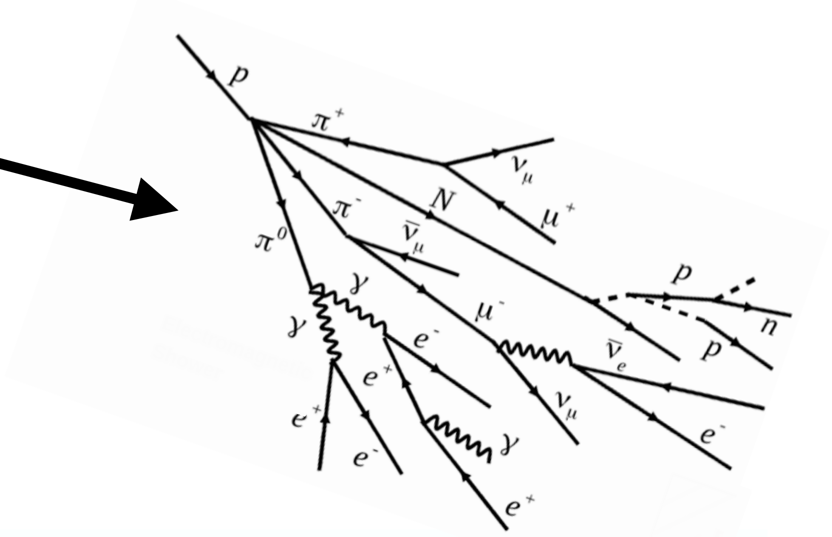
Beam direction

Side view

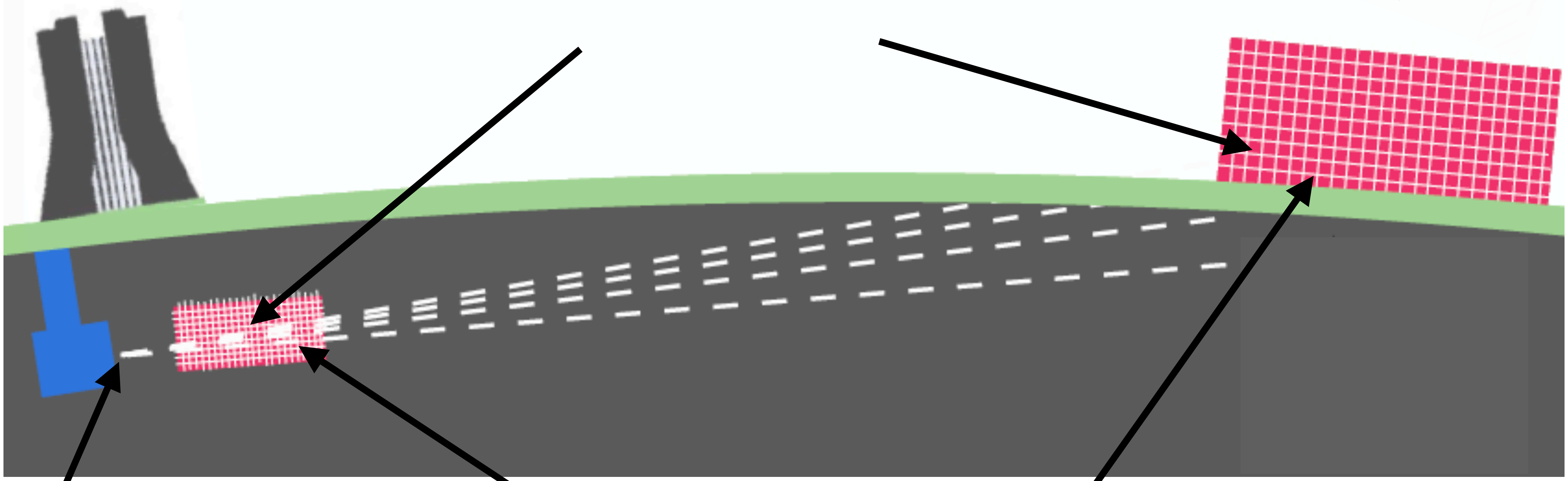
Color denotes deposited charge

Simulations

Cosmic rays: data triggers



Neutrino interactions and FSI modeling:
GENIE v2.12.2

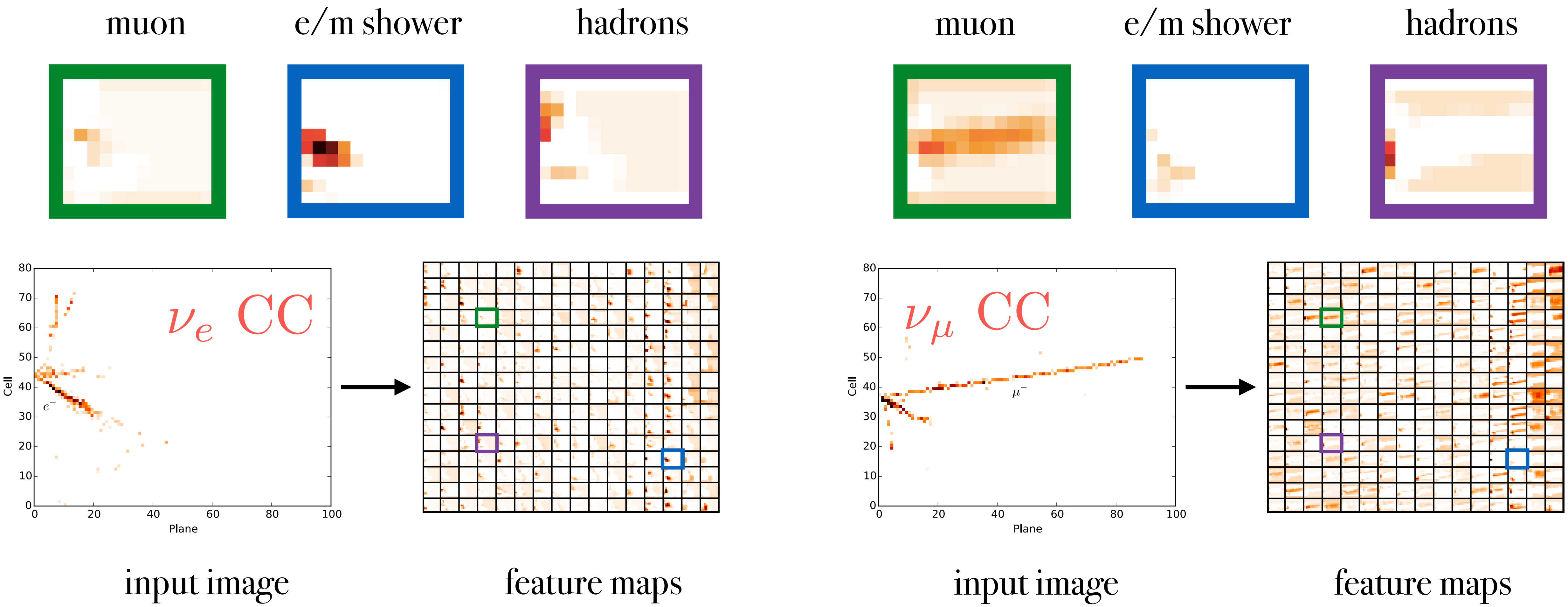


Beam hadron production:
Geant4/External data

Detector simulations: GEANT4
Readout electronics and DAQ:
custom simulation routines

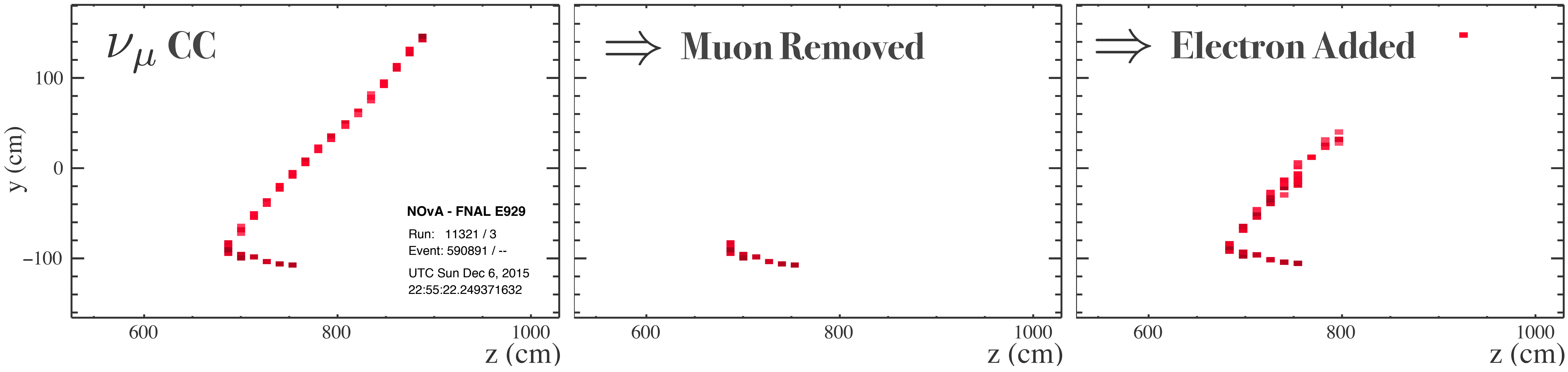
ν_e/ν_μ event selection

- ✳ Events for analysis pass various cuts: data quality, fiducial volume, BDT cosmic rejection etc. and neutrino flavor identification PID.



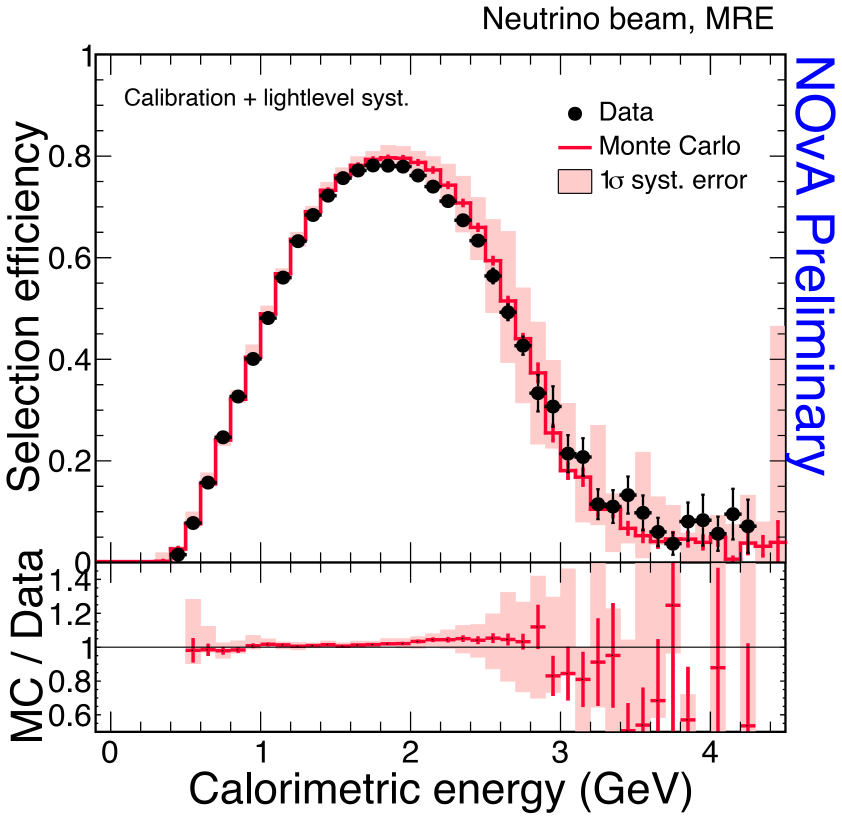
- ✳ We use convolution neural network called CVN (Convolutional Visual Network).
- ✳ Particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- ✳ Multi-label classifier – the same network used in multiple analyses: can classify ν_e, ν_μ, ν_τ, NC and cosmic.

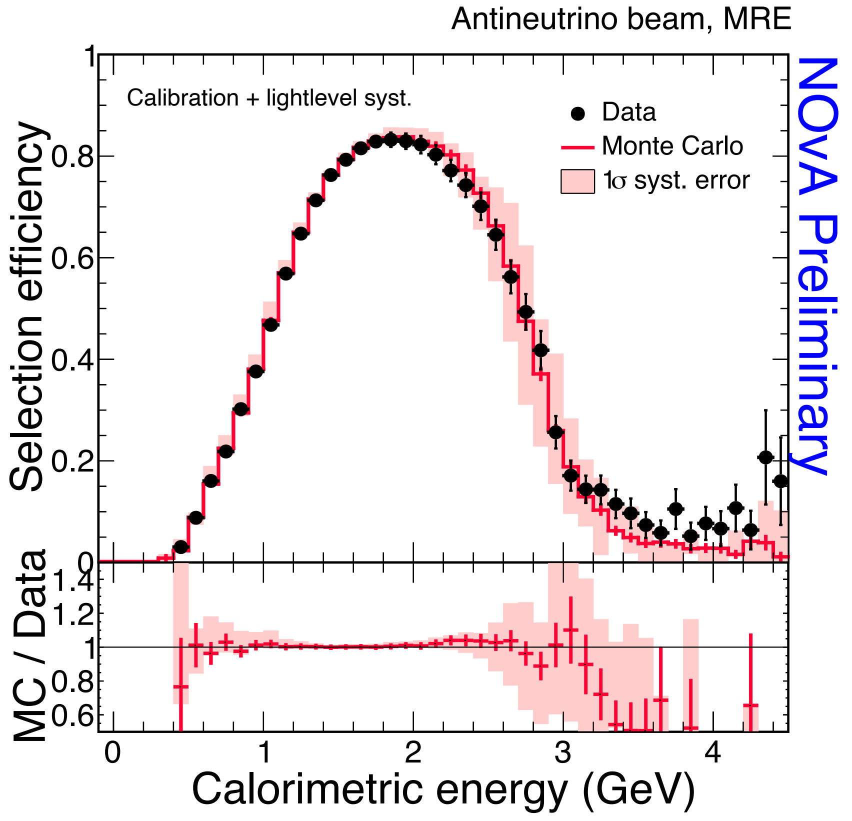
CVN crosschecks in ν_e analysis: MRE



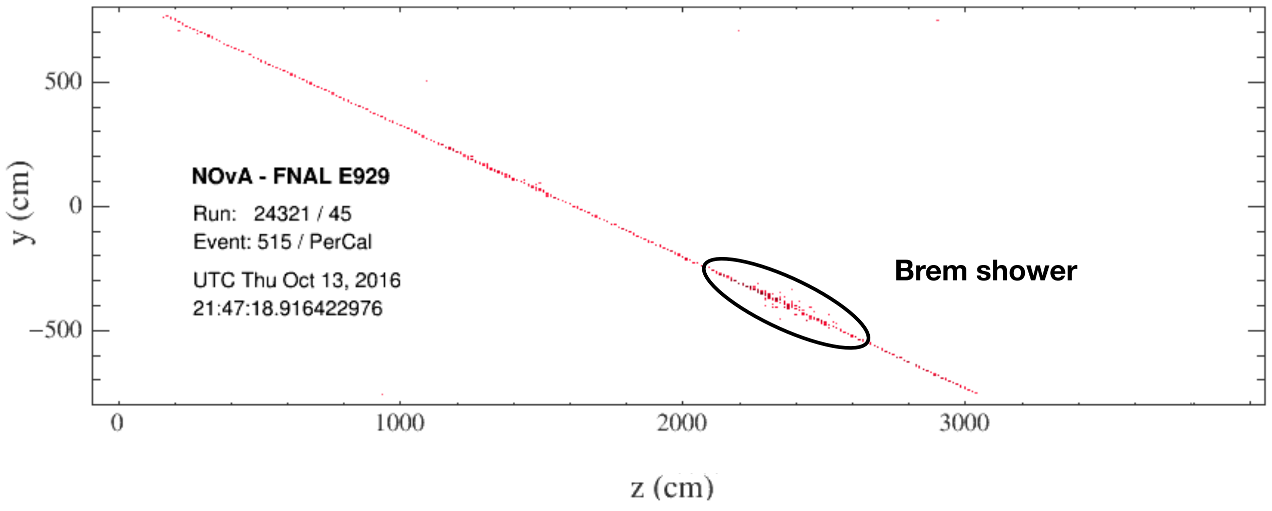
- ✳ We can create a control sample of ”electron neutrino” events by removing the muon and replacing it with simulated electron (Muon Removed Electron)

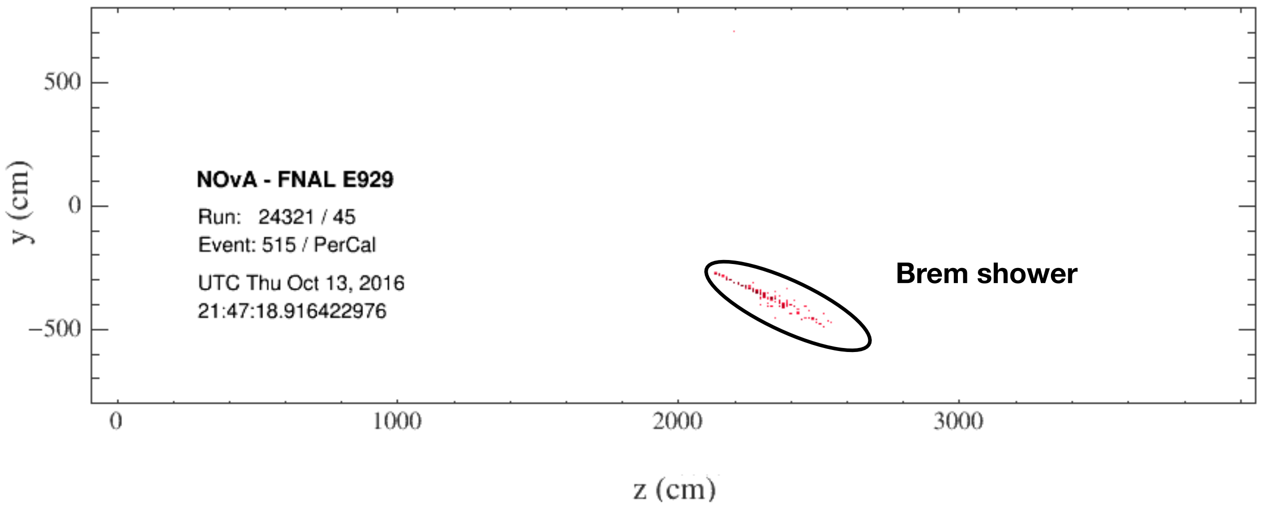
- ✳ Compare the efficiency between MRE events with real and simulated hadronic showers (allows to focus on the effect of the had. shower efficiency)
- ✳ Efficiency agrees between data and MC at the 2% level for both neutrino and antineutrino beams.





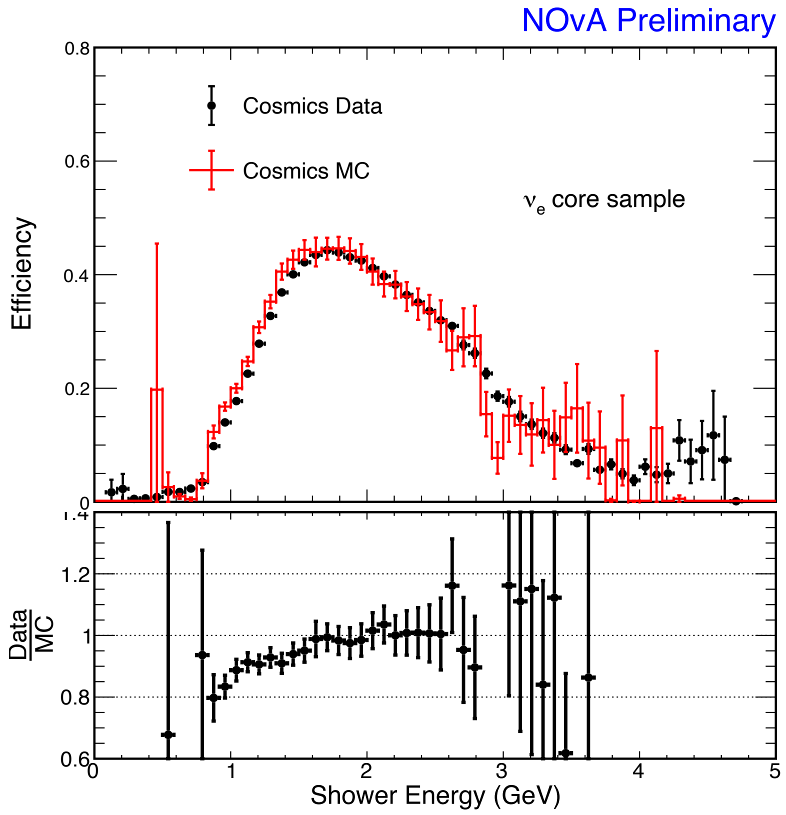
CVN crosschecks in ν_e analysis: MRBrem

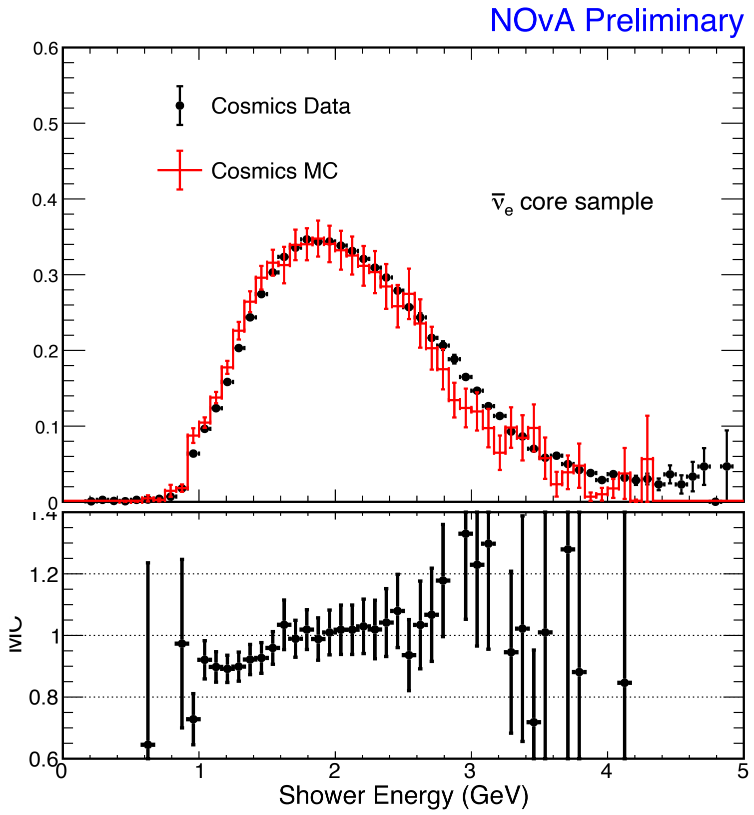




- ✳ In Muon-Removed Bremsstrahlung (MRBrem), we remove the muon from data & simulated FD cosmic muon rays, resulting in a pure selection of electromagnetic showers.

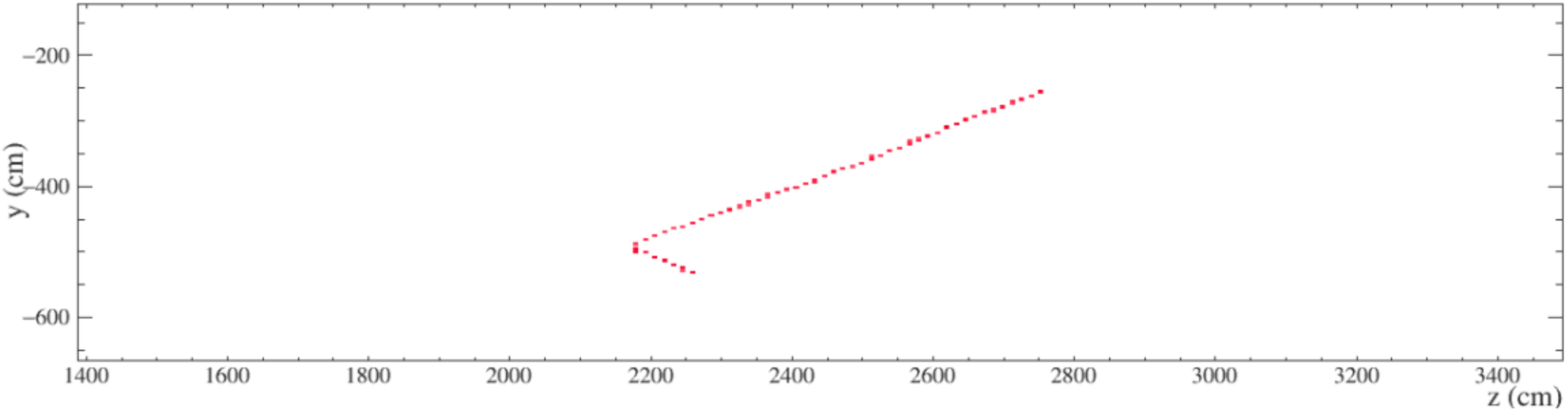
- ✳ This sample can be used to characterise the EM signature and provide valuable cross-checks of the MC simulation, reconstruction, performance of CVN algorithms at FD
- ✳ EM shower selection efficiency of data and simulated brem showers agrees within systematics for neutrino and antineutrino CVN.





ν_μ Disappearance Mode

- Select and measure ν_μ CC events in each detector;
- Extract oscillations from differences between the Far and Near energy spectra.

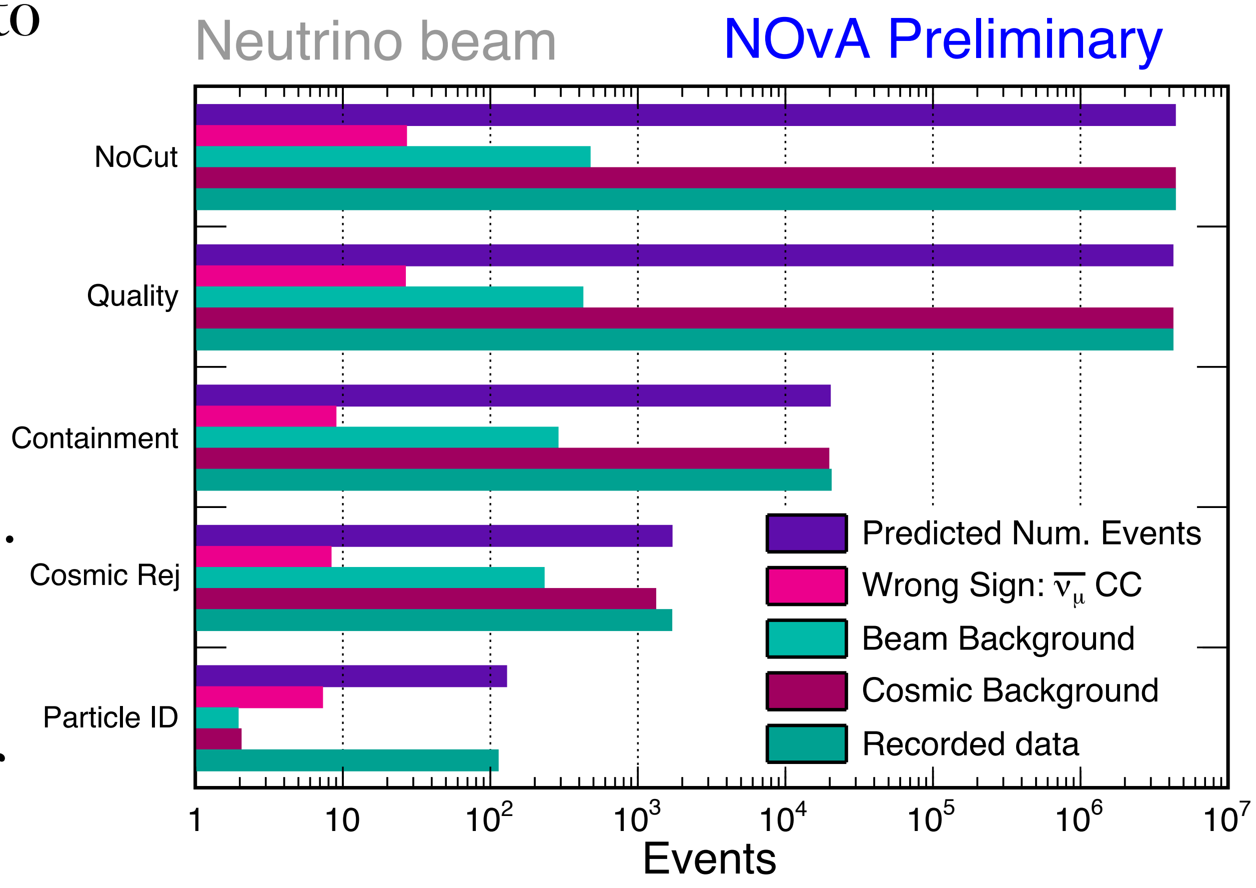


Event Selection

Cut flow for the ν_μ disappearance analysis is pretty straight forward:

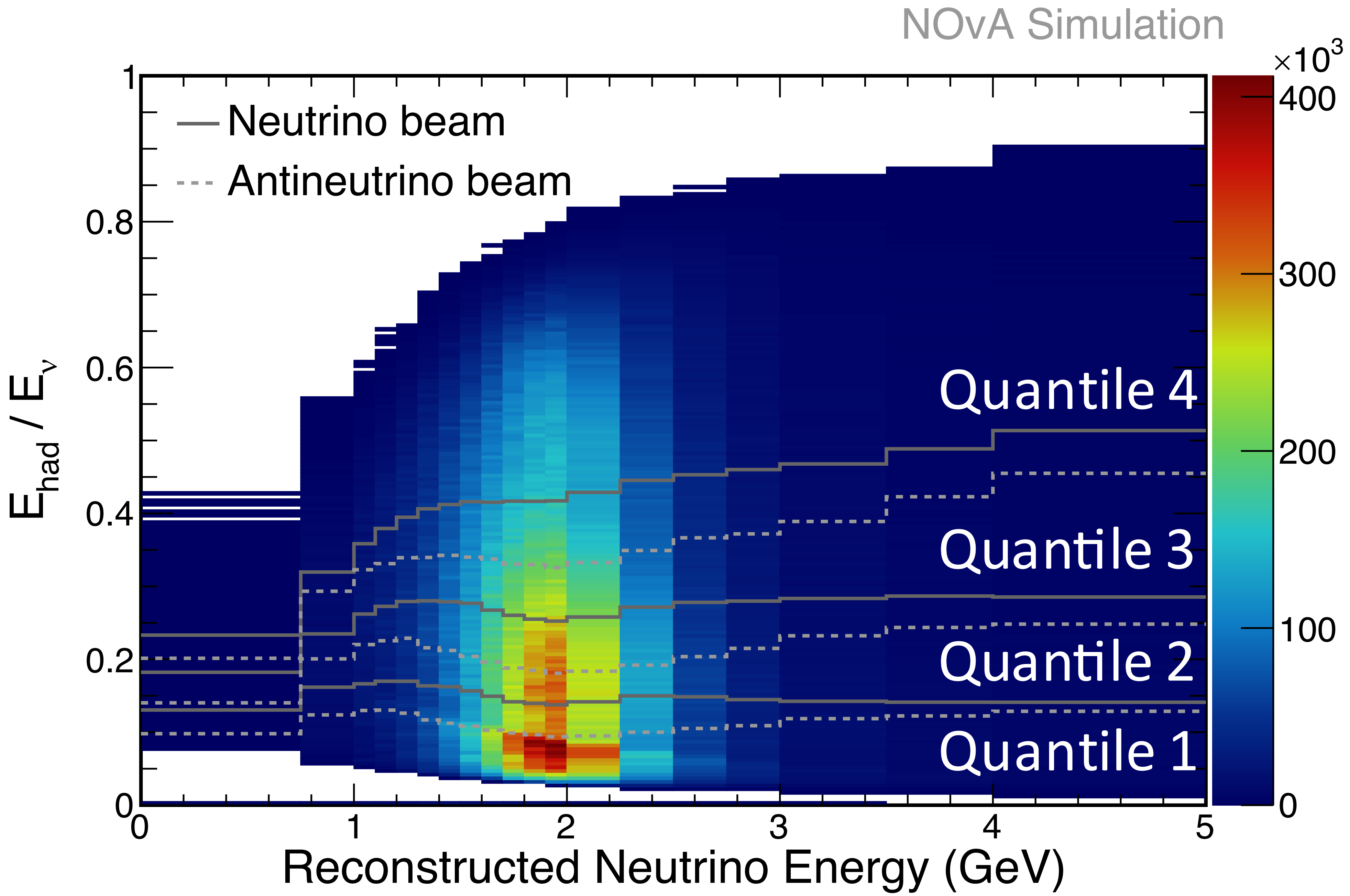
- ✳ NOvA FD places at the Earth surface → 11 billion cosmic rays/day;
- ✳ After applying timing cuts we have 10^7 events.

- ✳ 4 main groups of cuts which require event to be in fiducial volume, well-reconstructed, fully contained in the detector.
- ✳ ν_μ analysis uses CVN classifier and special kNN which identifies the muon itself.
  - ✳ kNN inputs: track length, dE/dx, scattering, fraction of track-only planes.
- ✳ ν_μ uses BDT for the cosmic rejection:
  - ✳ inputs: track length and direction, distance from the top/sides, fraction of hits in the muon and CVN.



ν_μ cut flow (similar for ν_μ-bar)

Energy quantiles

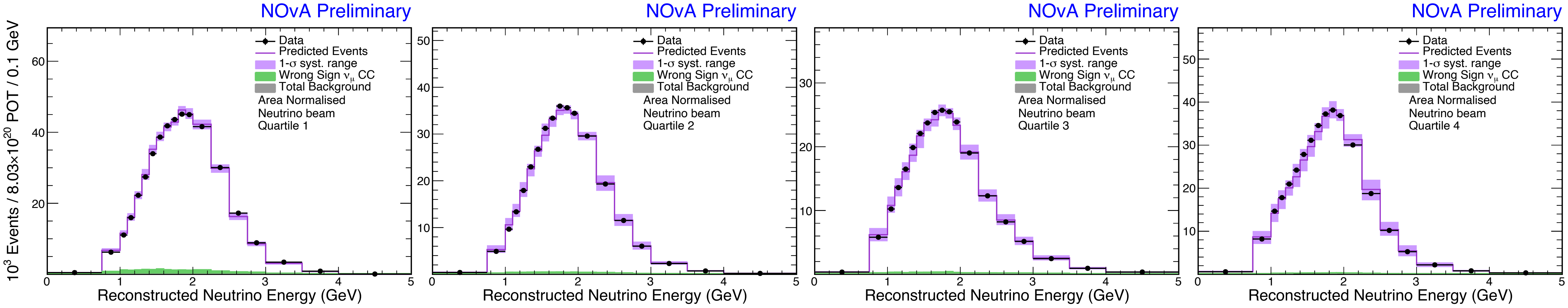


- Muon energy resolution is much better than hadronic energy resolution.
- Split into 4 equal quantiles based on hadronic energy fraction.
- Resolution varies from 6% to 12% from the best to the worst resolution

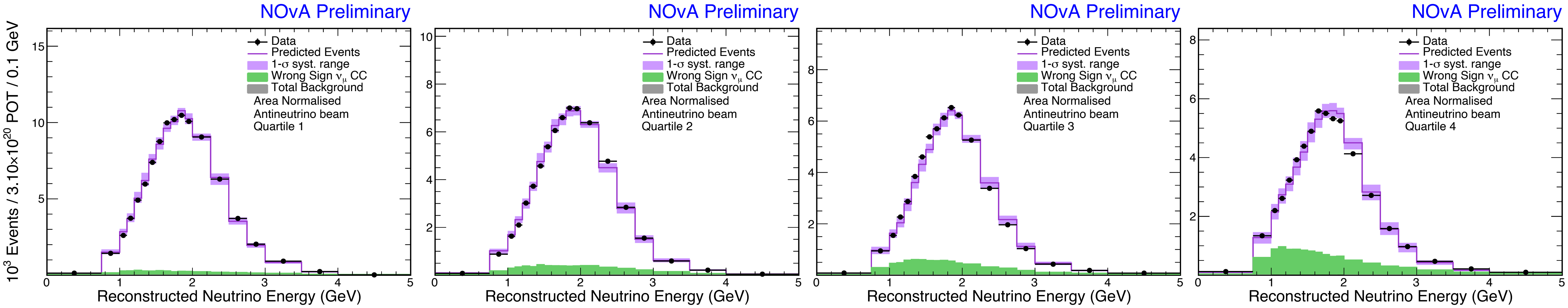
ND data for ν_μ

Quartile 1
(the best resolution ~6%) → Quartile 4
(the worst resolution ~12%)

Neutrino beam



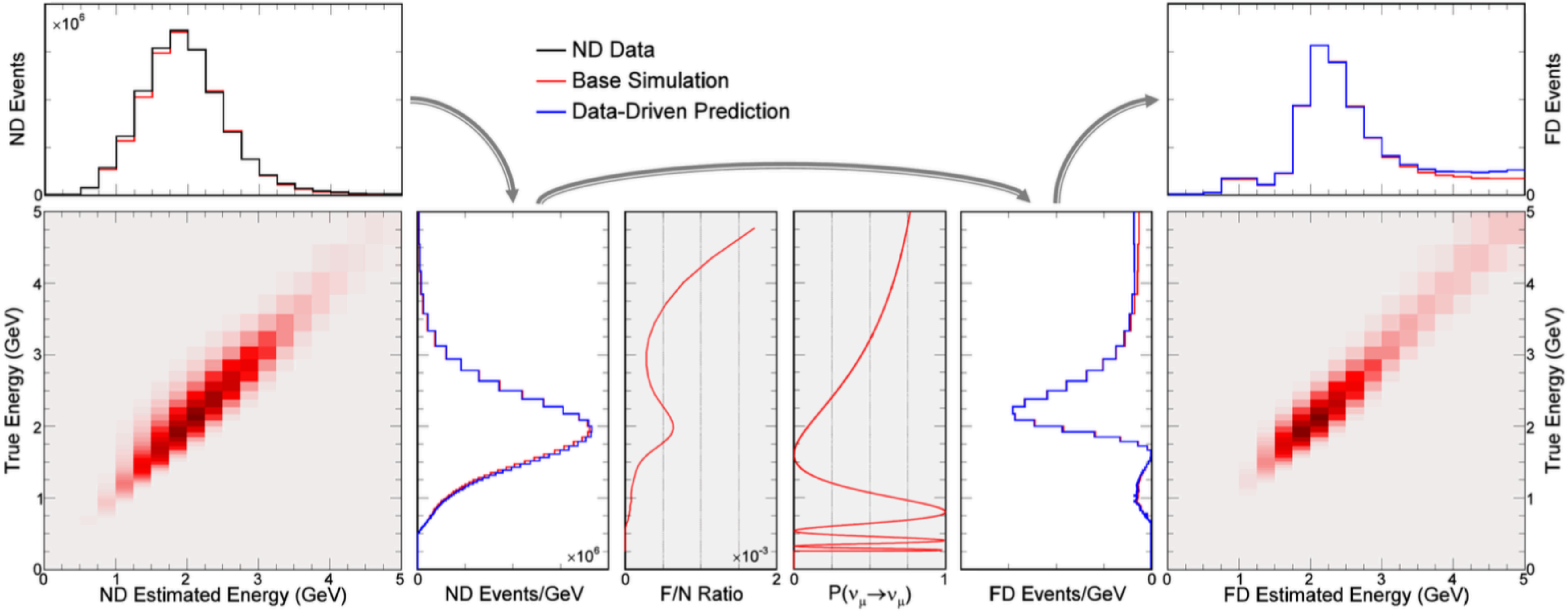
Antineutrino beam



- ✴ ν_μ sample is divided into four quartiles based on E_{had}/E_ν fraction.
- ✴ Wrong-sign background is about 3% in ν beam and 11% in $\bar{\nu}$.

Data-driven predictions

Far Detector predictions are constrained by high-stat unoscillated Near Detector data:



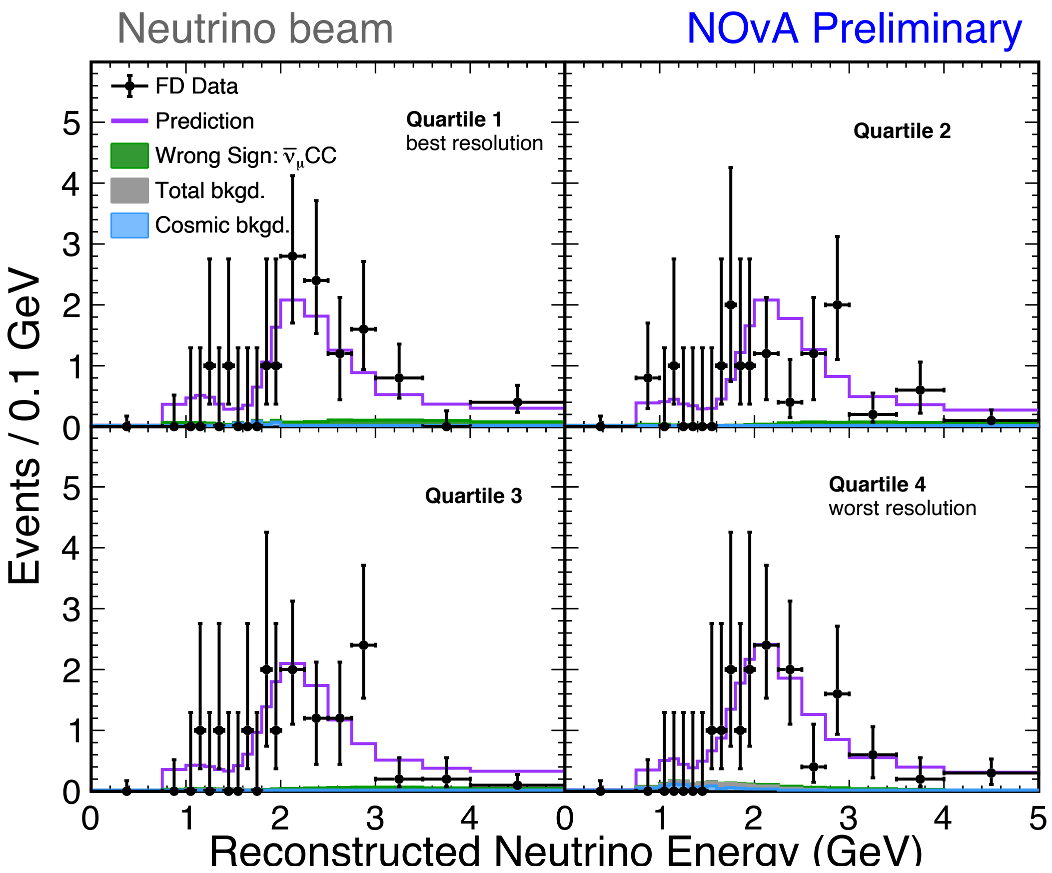
Constrain predictions with ND data

Apply oscillations and FD/ND ratio

Compare to FD data

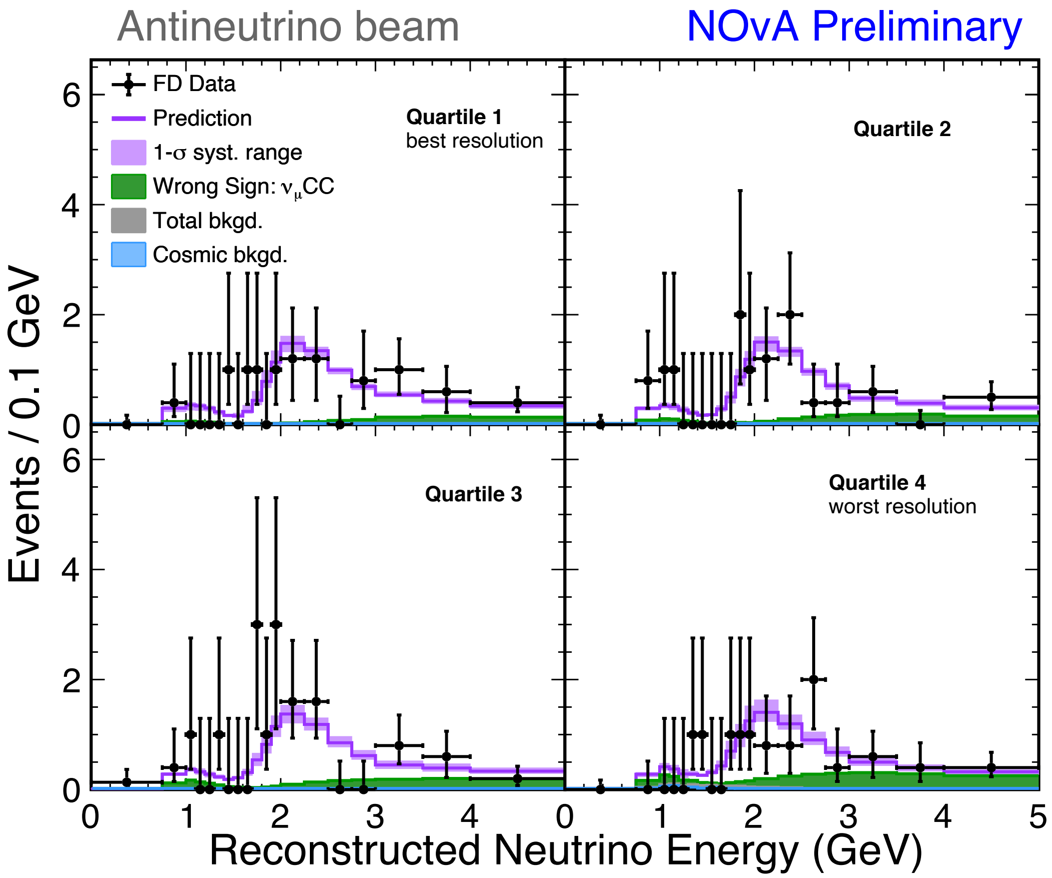
FD data. Inputs for fit - ν_μ sample

3-flavor oscillations describe data well
(goodness-of-fit p = 0.91)



Neutrino beam:

Total Observed	**113**
Best Fit prediction	124
Total bkgd	4.2
Cosmic bkg	2.1
Beam bkg	2.1
Unoscillated prediction	730

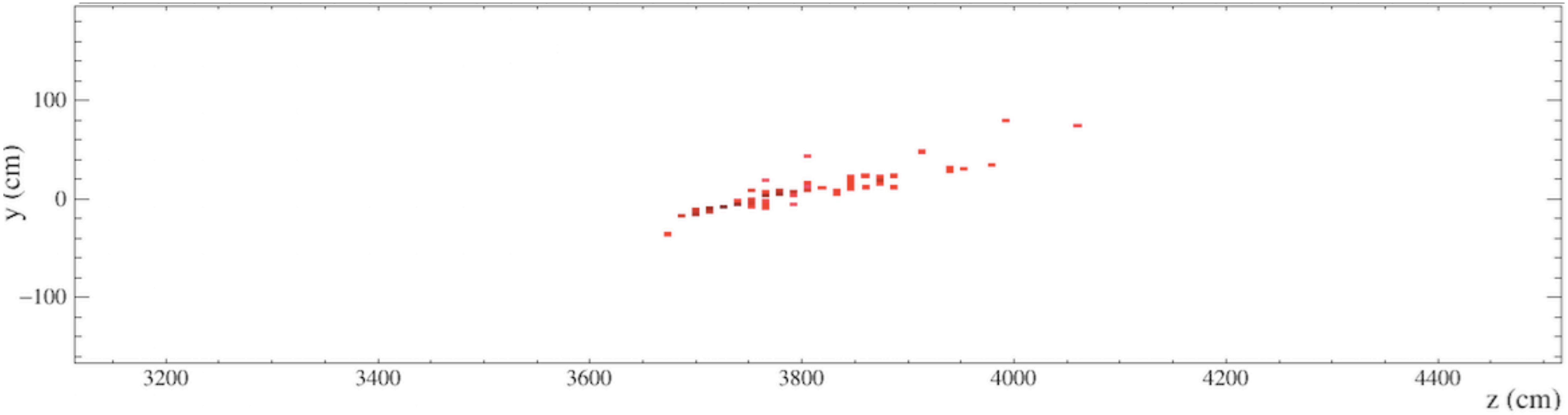


Antineutrino beam:

Total Observed	**102**
Best Fit prediction	96
Total bkgd	2.2
Cosmic bkg	0.8
Beam bkg	1.4
Unoscillated prediction	476

ν_e Appearance Mode

- ✳ Identify ν_e CC candidates in the FD;
- ✳ Use ND events to predict beam backgrounds in the FD;
- ✳ The execs over the background is signal.

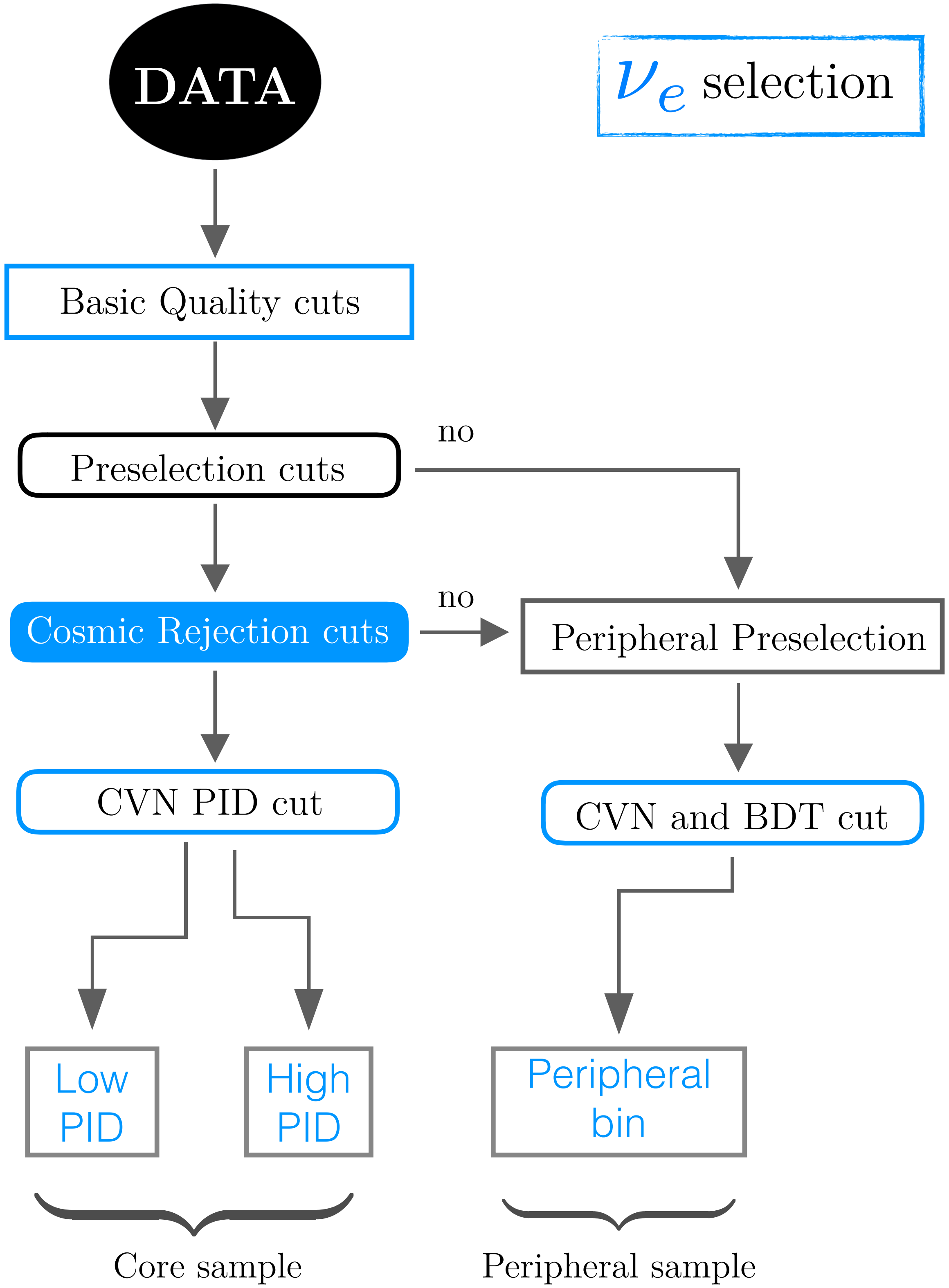


Event Selection

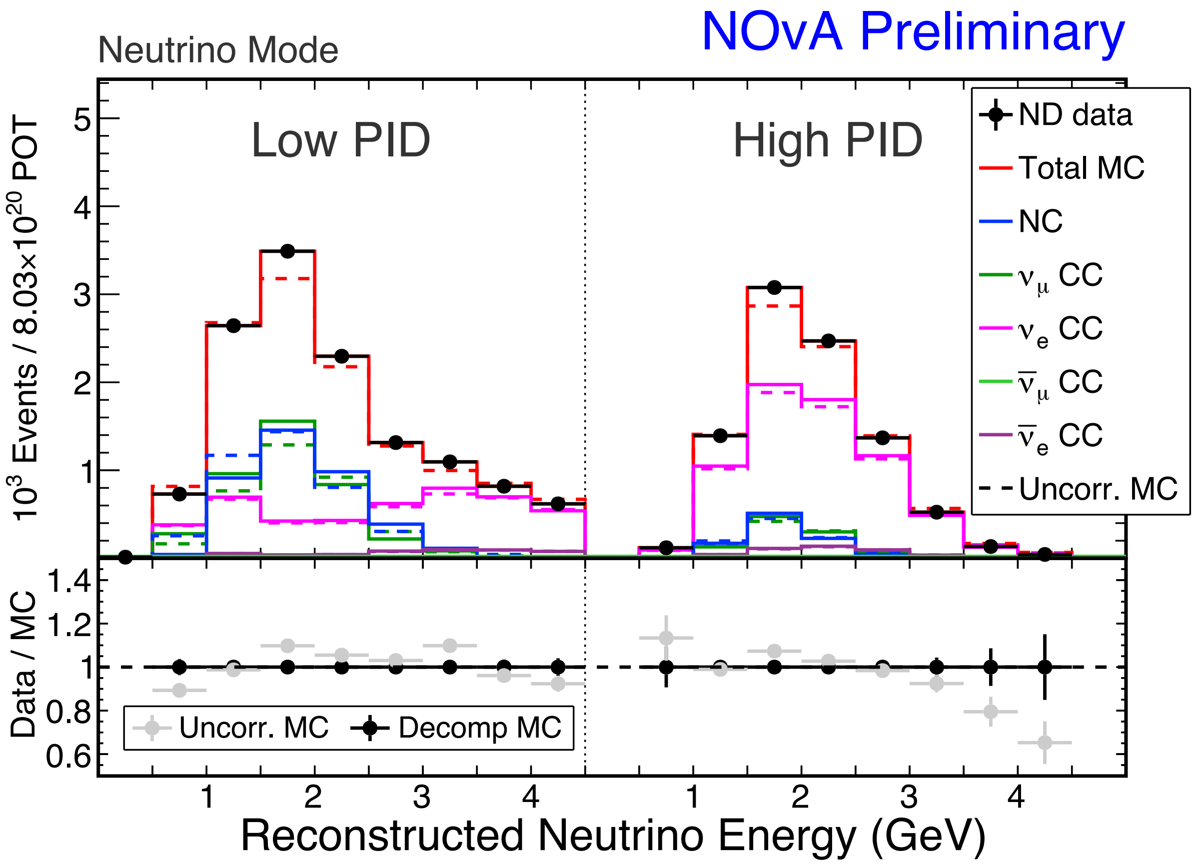
- ✴ Start with the same challenge at the FD: 10^7 events after applying timing cuts.

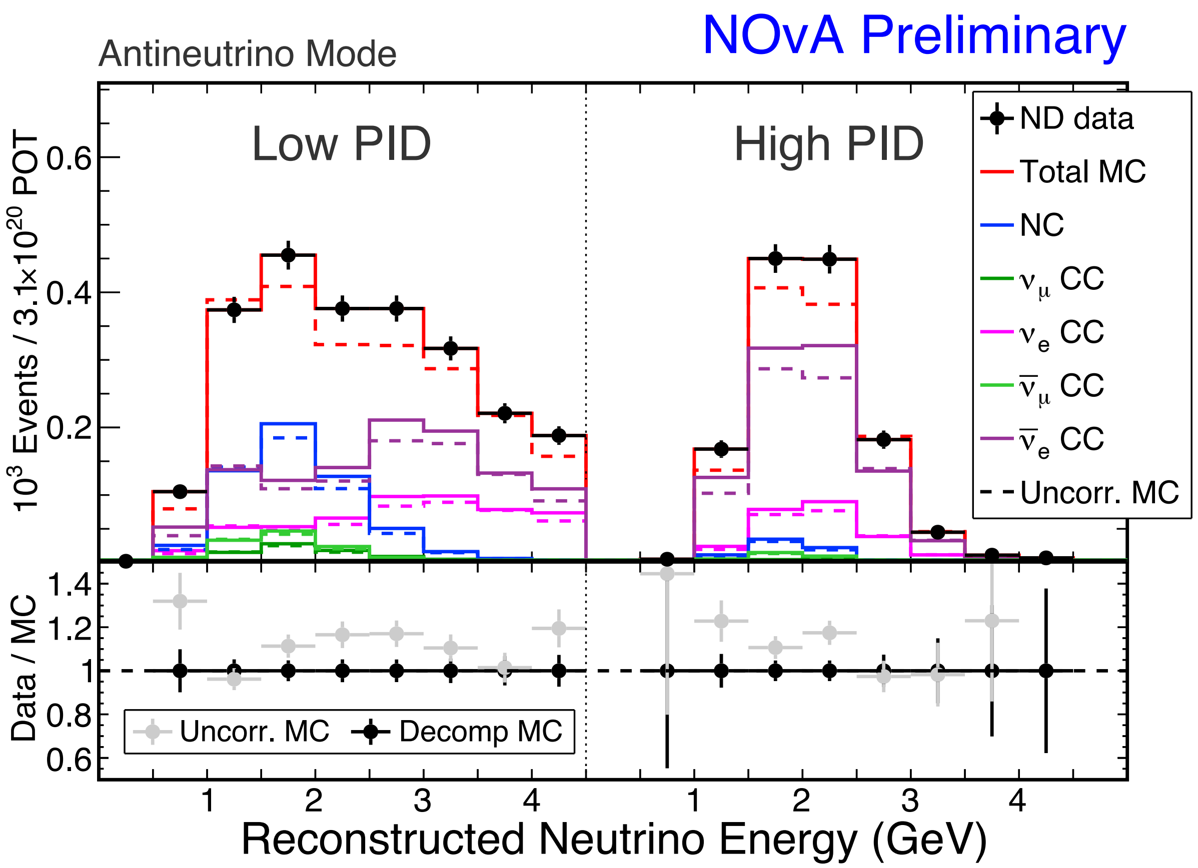
- ✴ Use CVN for PID cut.
- ✴ A bit more complicated cut flow:
  - ✴ sequence of conventional cuts on energy, event quality, positioning etc.;
  - ✴ but we reclaim events that fail main selection chain and give them one more chance in the Peripheral sample;
  - ✴ tight CVN and BDT cuts clean up this sample.

- ✴ As a result of this flow we have 3 spectra for different CVN PID binning and Peripheral sample separately.

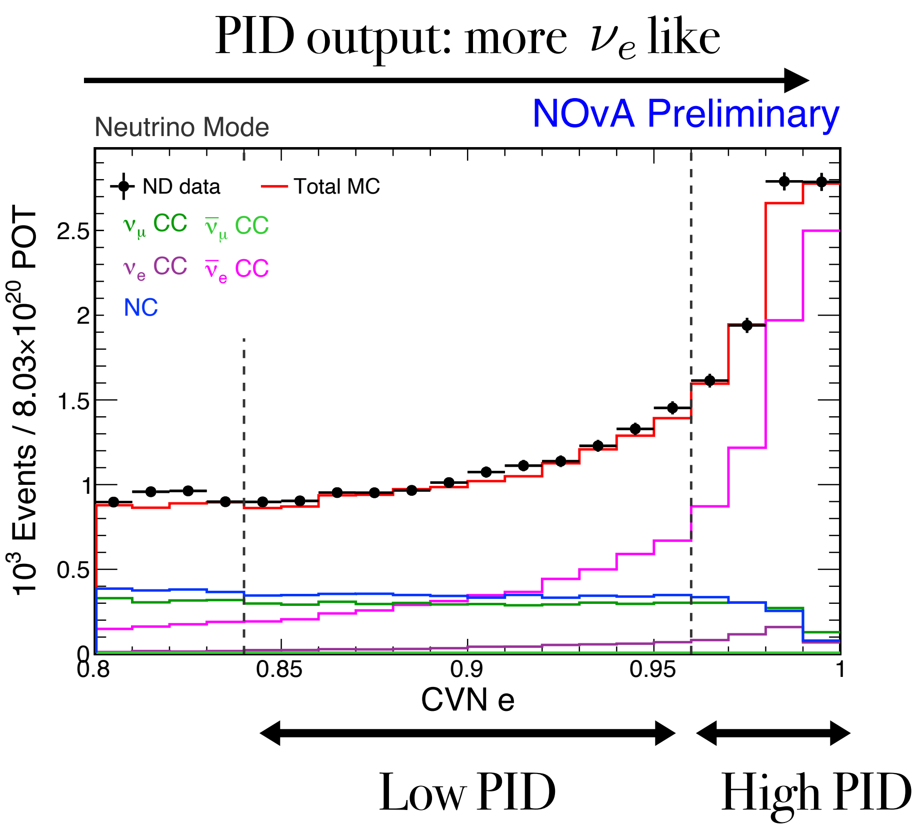


ND data for ν_e





- ✳ Split ν_e sample into Low and High PID spectra.
- ✳ All ν_e ND candidates are background sources in the FD (no oscillations in the ND).
- ✳ Use ND data to correct the predictions.
- ✳ Extrapolate each category separately to the FD.

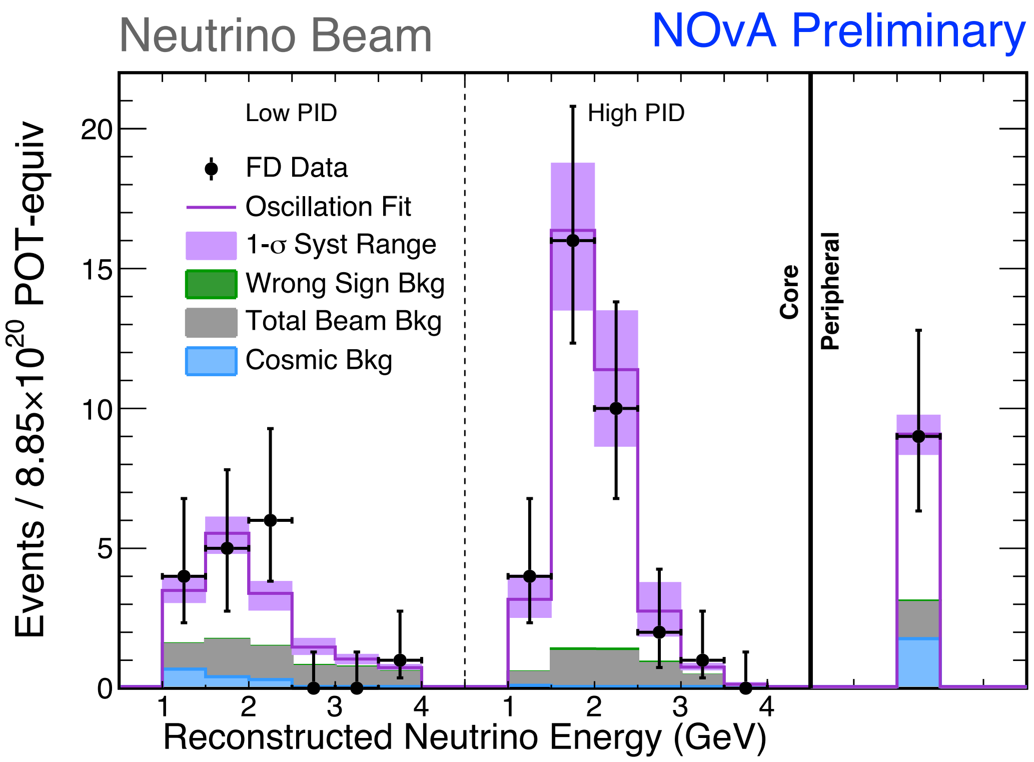


FD data. Inputs for fit - ν_e sample

3-flavor oscillations describe data well
(goodness-of-fit p = 0.91)

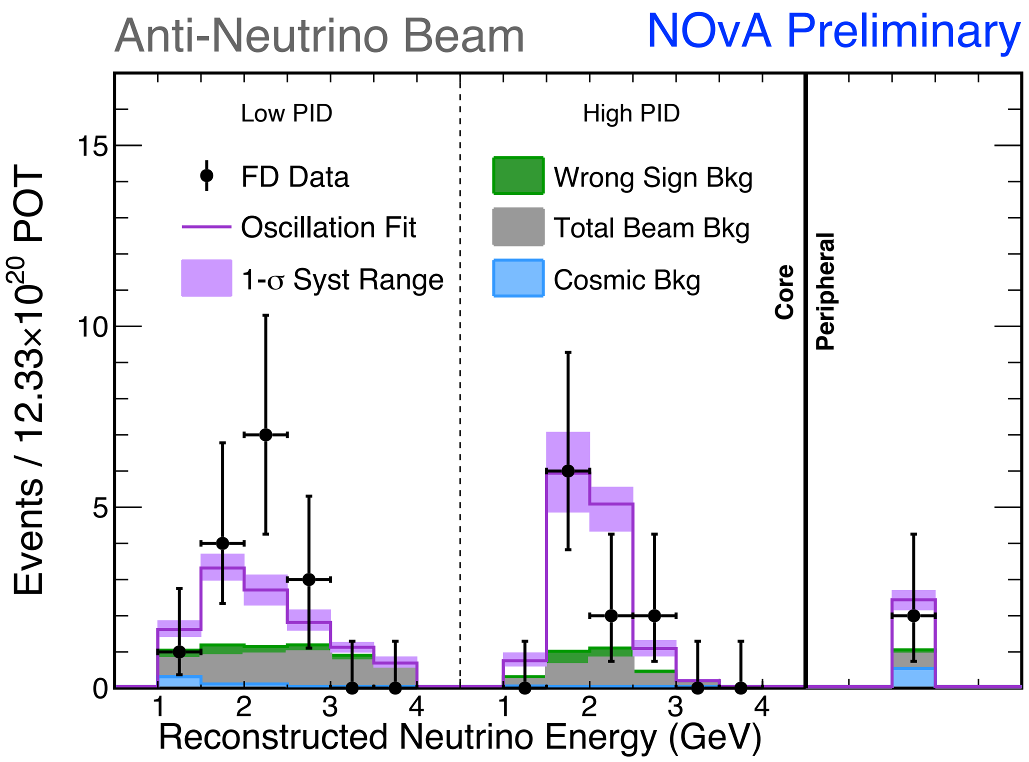
Neutrino beam:

Total Observed	**58**
Best Fit prediction	59
Total bkgd	15.0
Cosmic bkg	3.3
Beam bkg	11.1
Wrong sign ($\bar{\nu}_e$ app.)	0.7



Antineutrino beam:

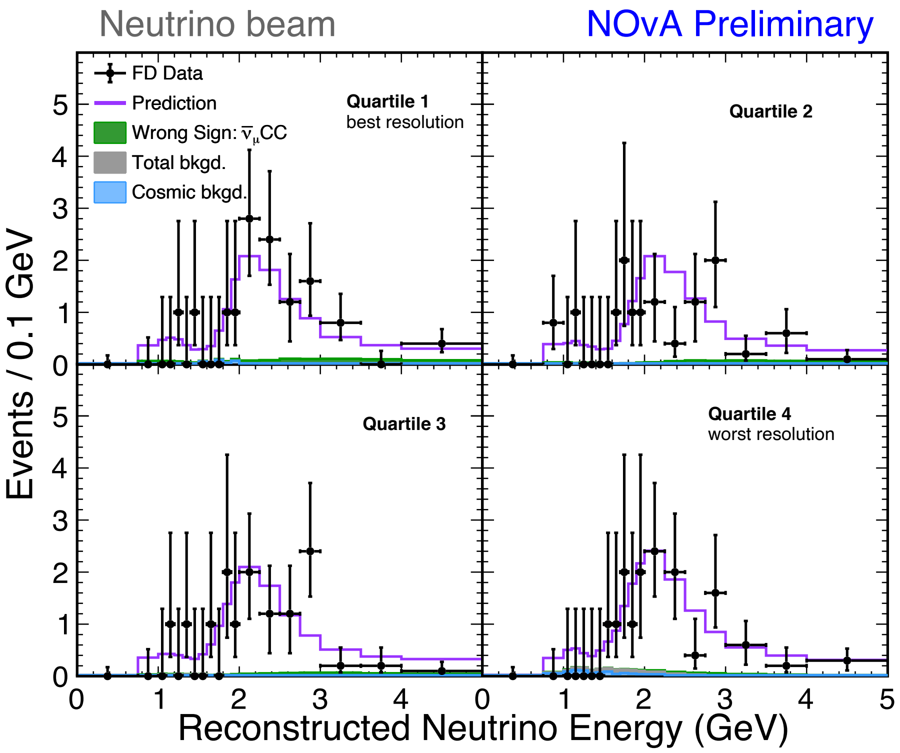
Total Observed	**27**
Best Fit prediction	27
Total bkgd	10.3
Cosmic bkg	1.1
Beam bkg	7.0
Wrong sign (ν_e app.)	2.2

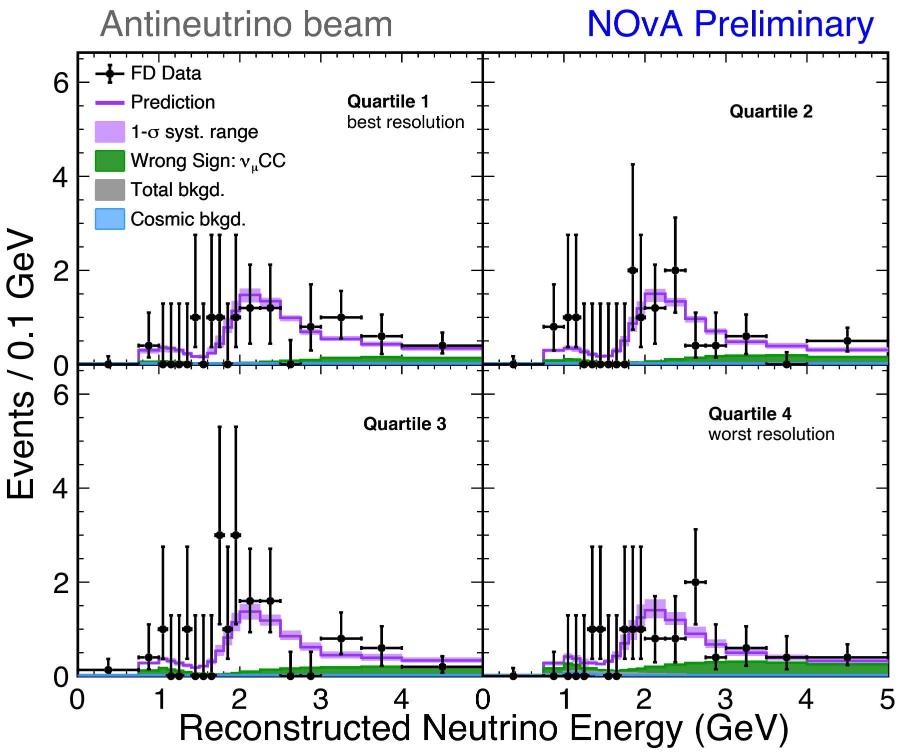


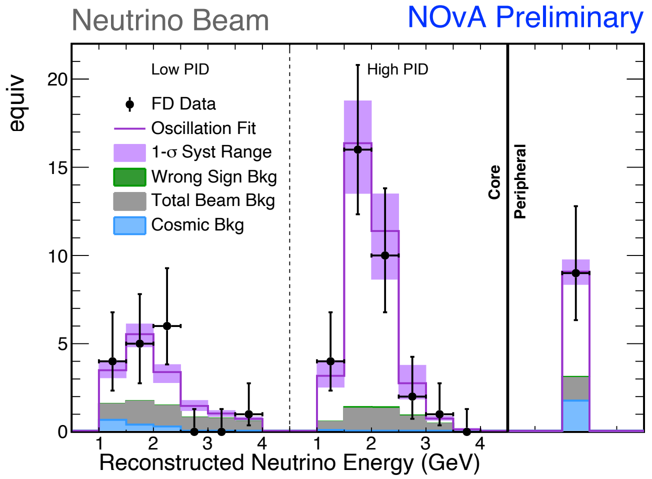
Evidence for $\bar{\nu}_e$ appearance at 4.4σ

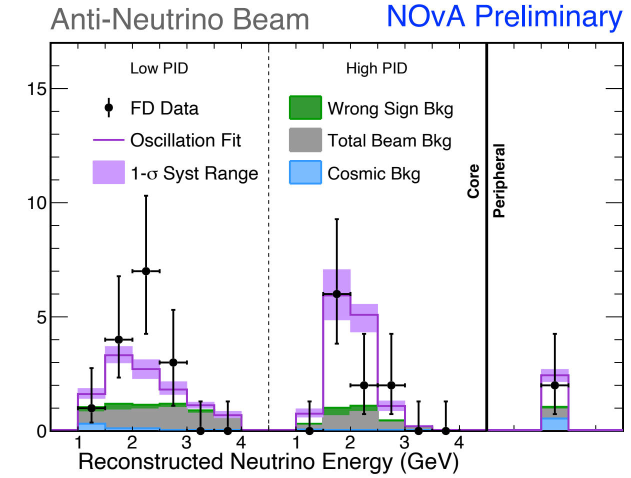
Oscillation fit results

- Joint fit of ν_μ $(\bar{\nu}_\mu)$ and ν_e $(\bar{\nu}_e)$ results.
- All systematics and oscillation pull terms shared.
- All contours and 1D ranges are Feldman-Cousins corrected.
- PDG constraint on $sin^2 2\theta_{13} = 0.082$

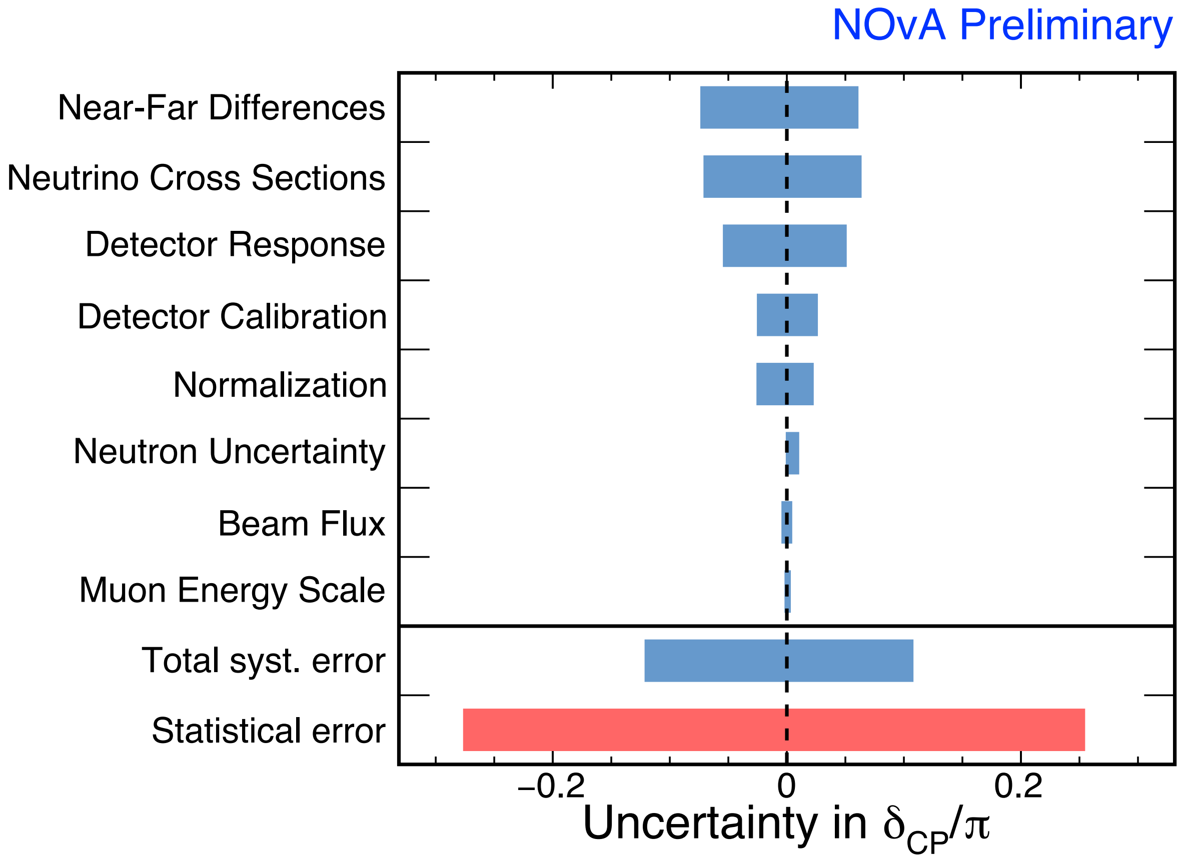


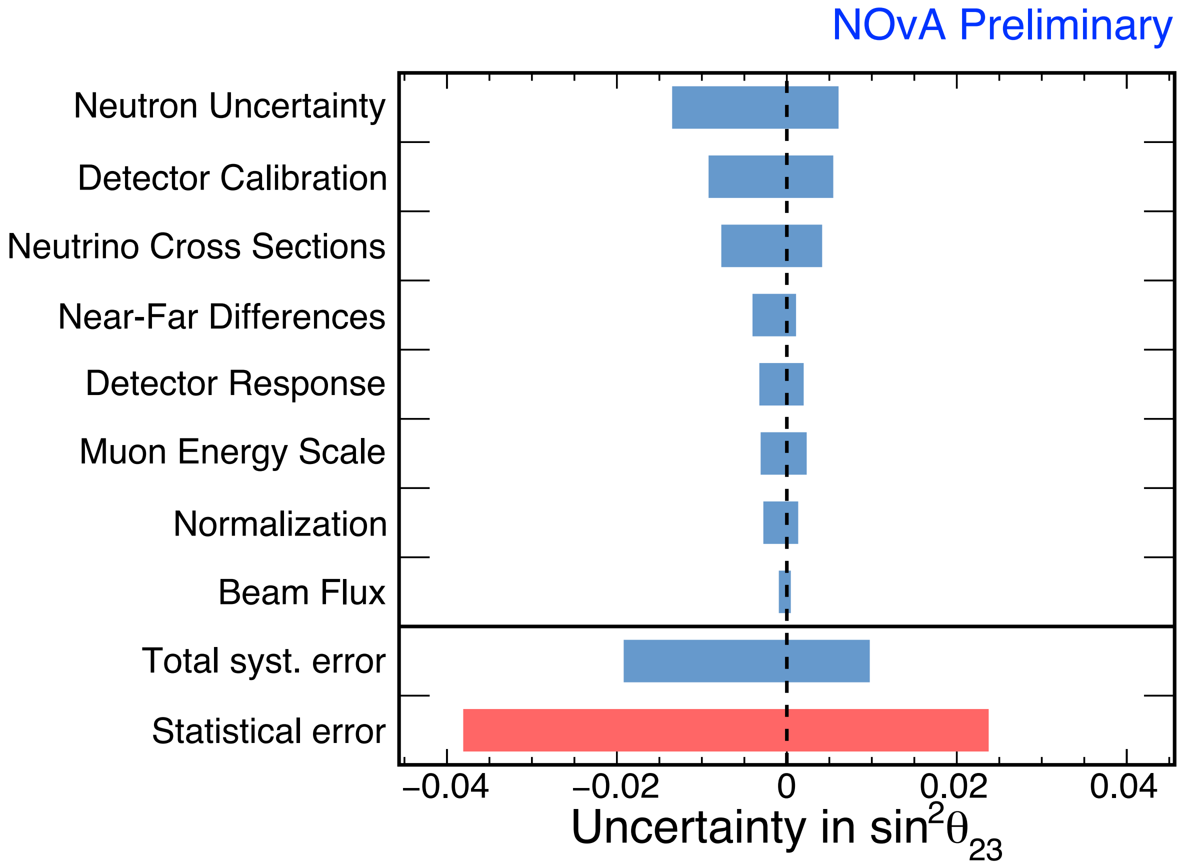


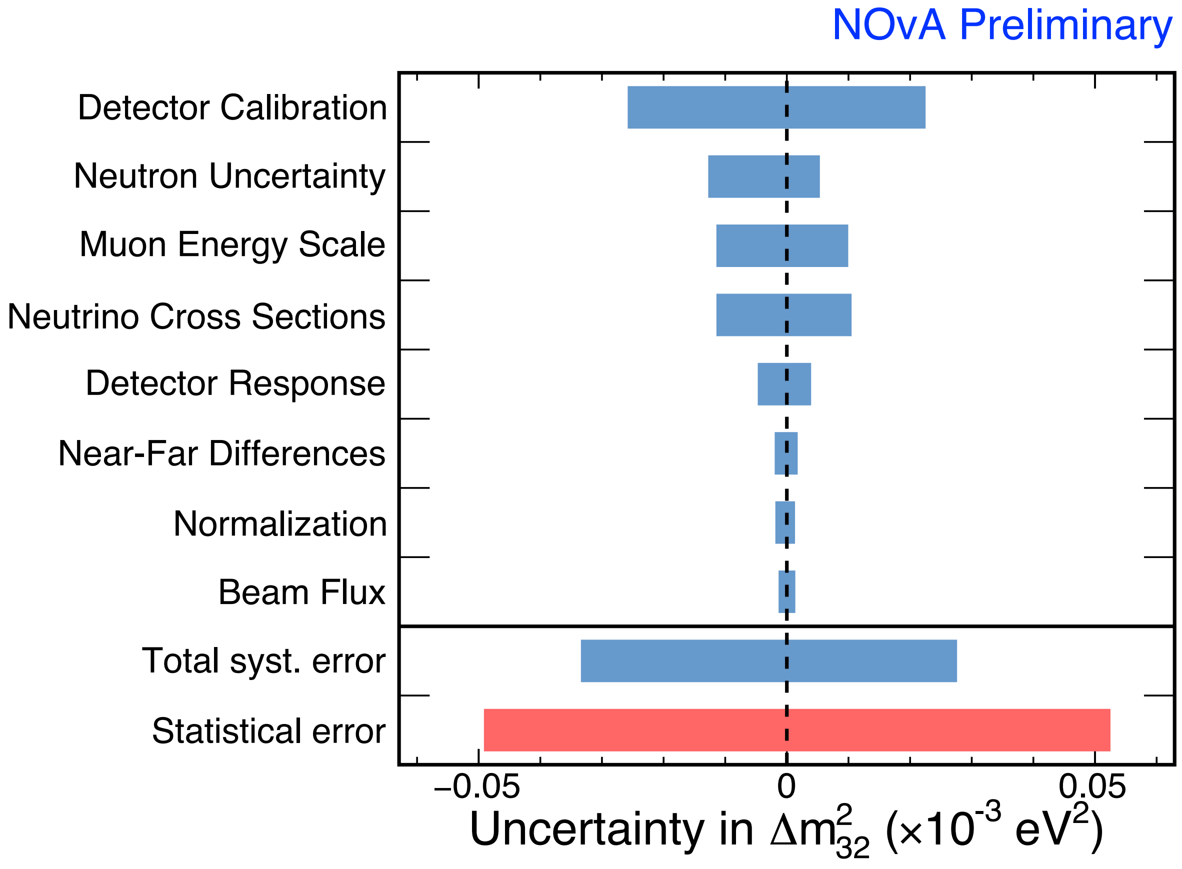




Systematics for the analysis

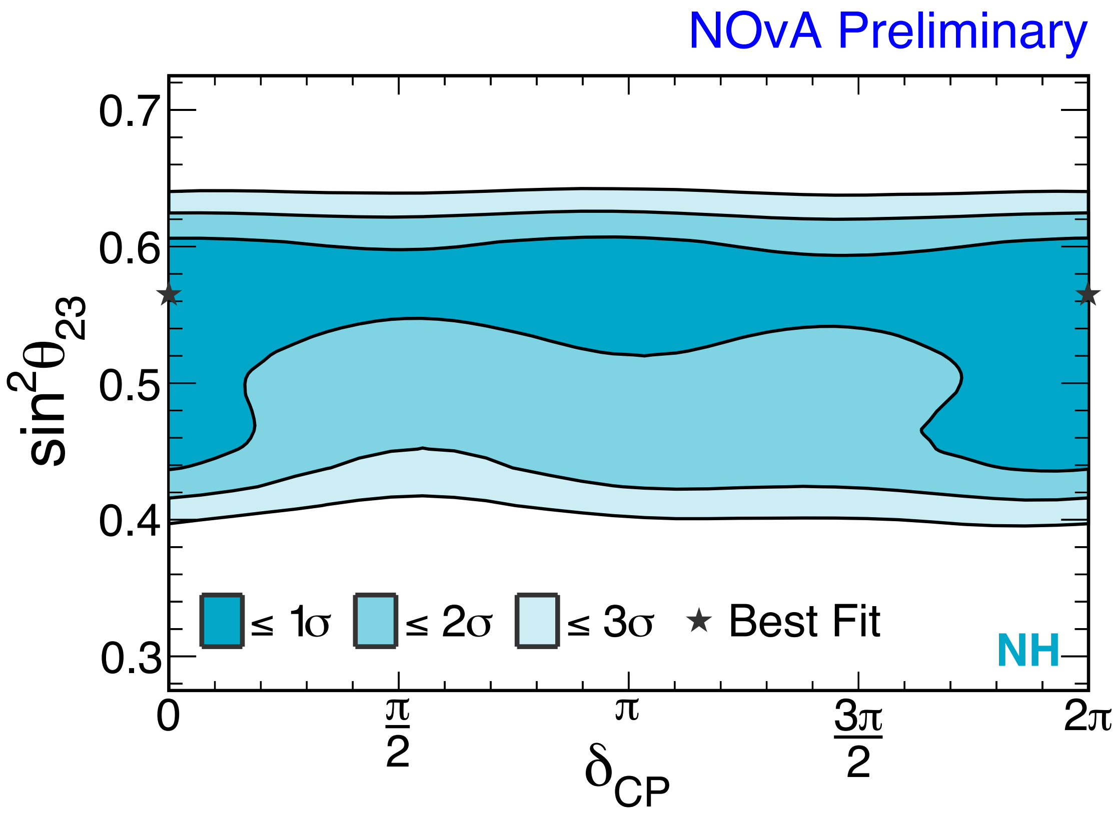


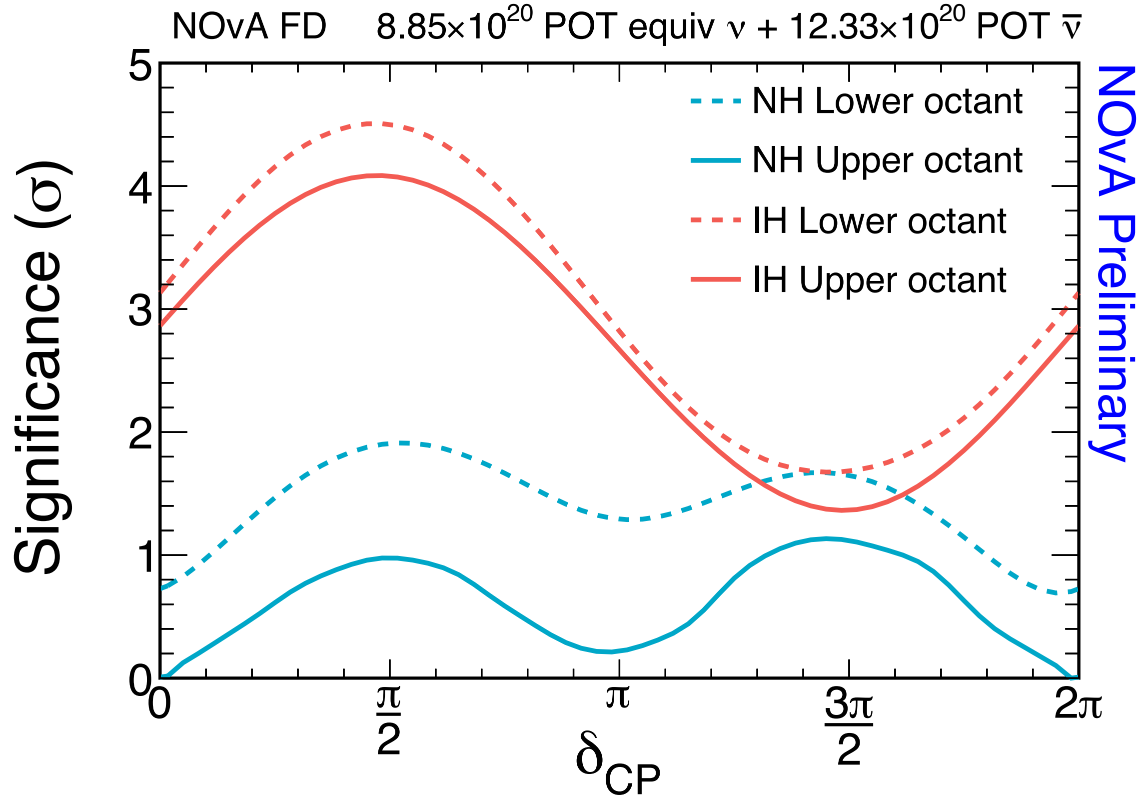


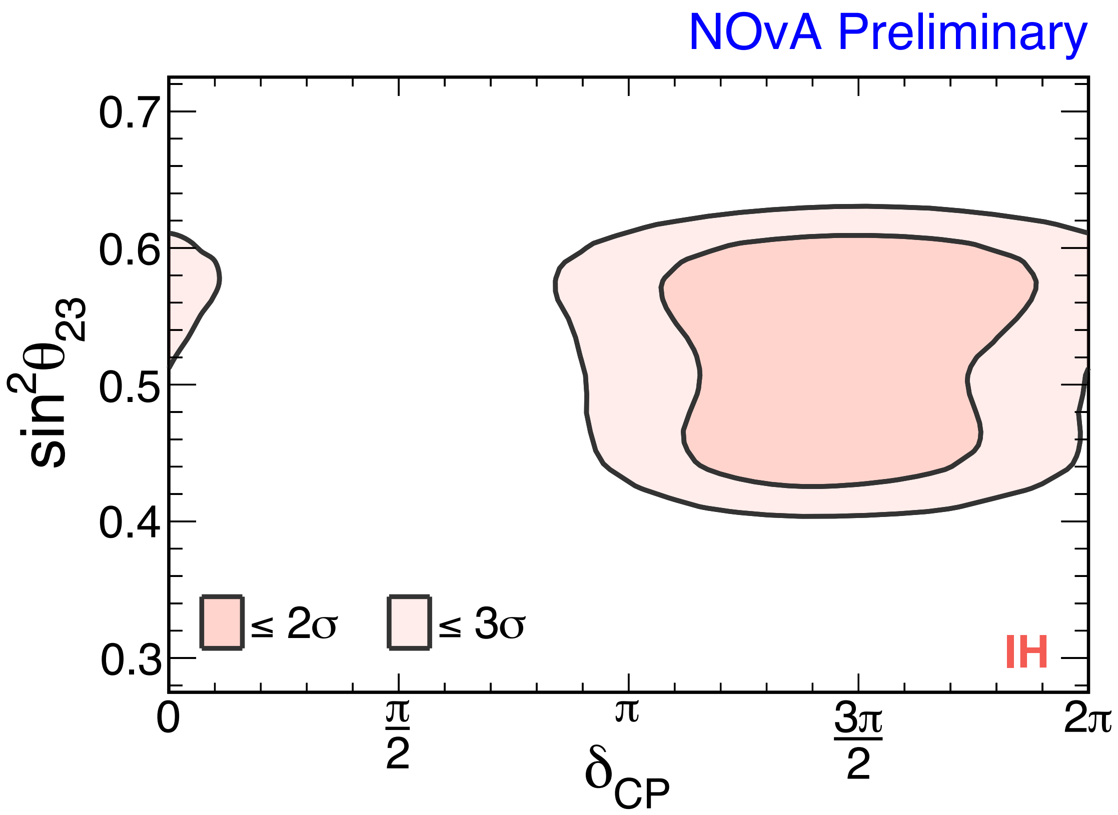


- Still statistically limited.
- The most important systematics:
  - neutrino cross sections;
  - detector calibration
  - neutron uncertainty - with $\bar{\nu}$.

Oscillation results: joint $\nu_e + \nu_\mu$ fit







- All systematic uncertainties, Feldman - Cousins corrections are applied.
- Best fit:

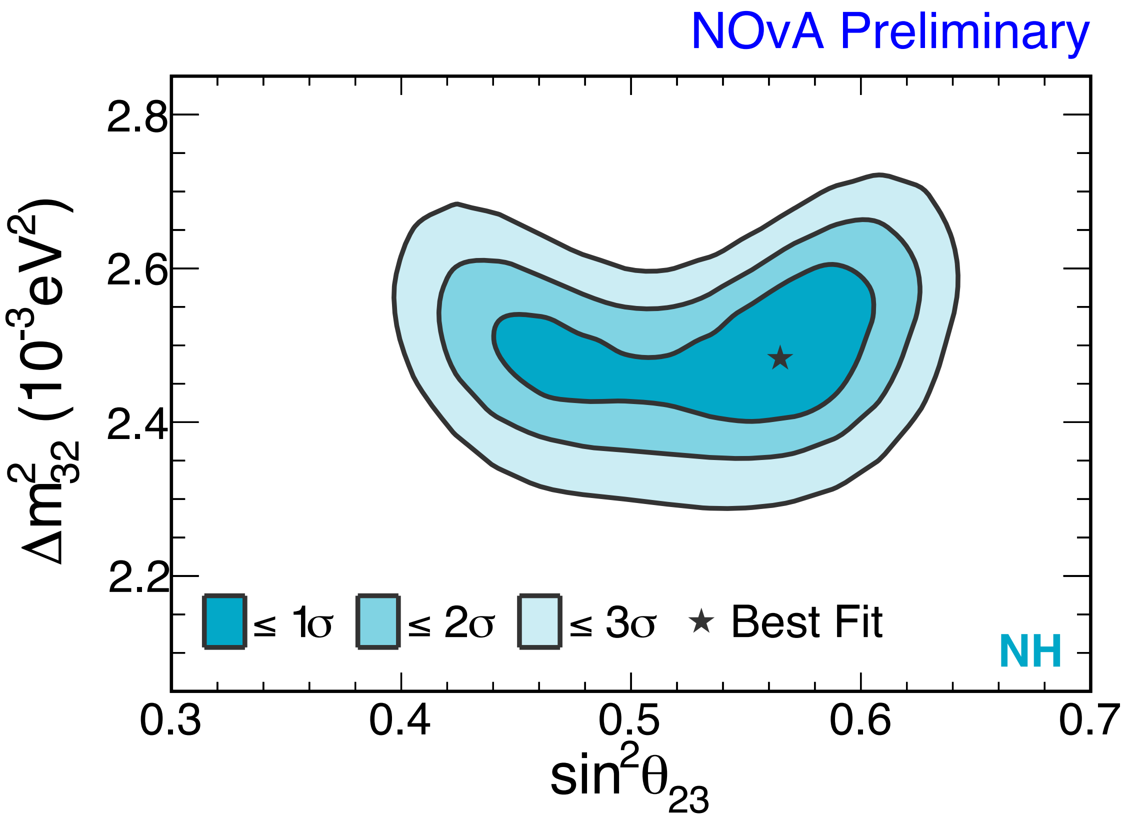
$$\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$$

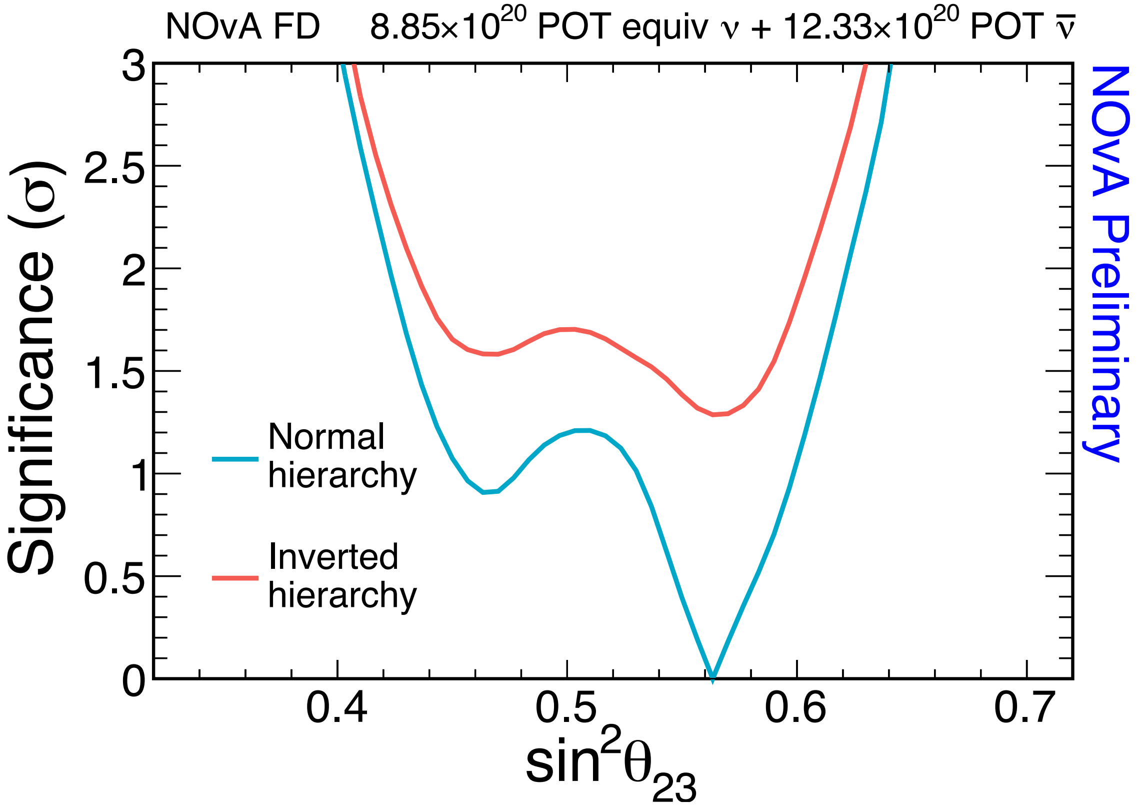
$$\Delta m^2_{32} = +\,2.48 \times 10^{-3}\,\mathrm{eV}^2\ \text{(NH)}$$

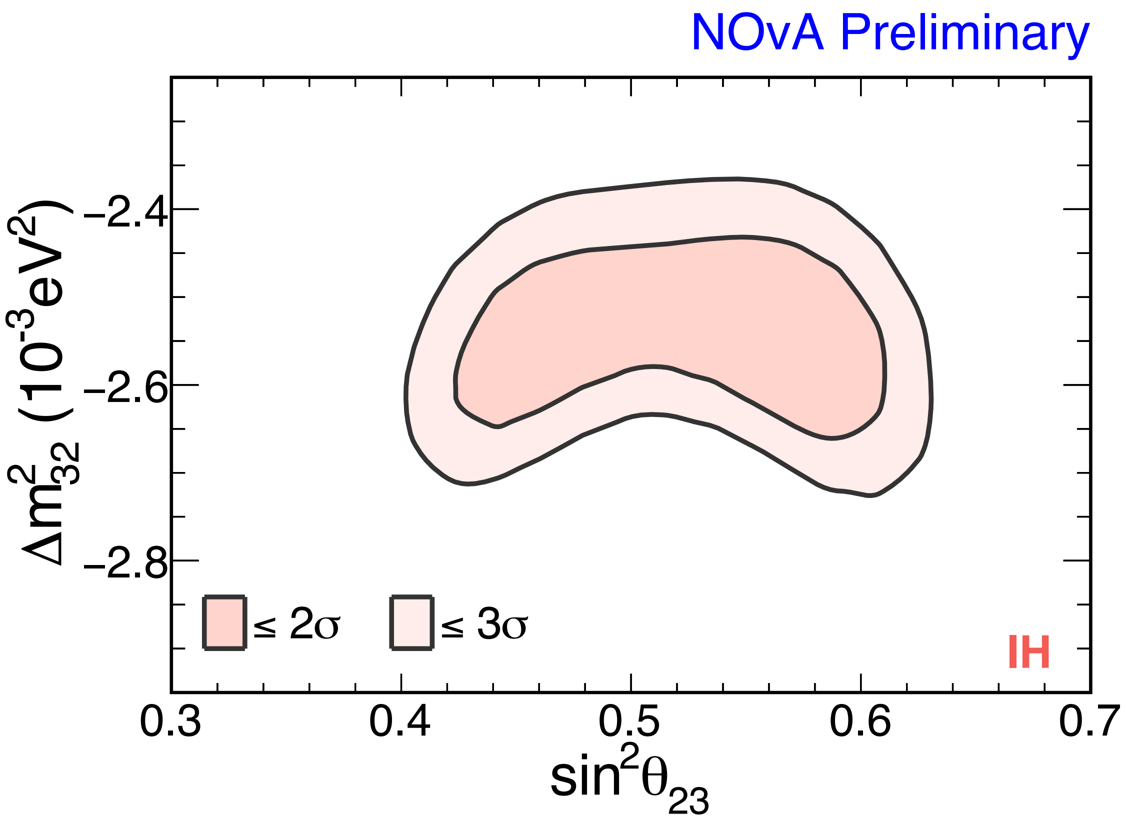
$$\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi.$$

- All values of δ_{CP} are allowed at 1.1σ (NH, Upper octant).
- IH, $\delta_{CP} = \pi/2$ is ruled out $> 4\sigma$.
- Inverted Hierarchy is disfavored at 1.9σ.

Oscillation results: joint $\nu_e + \nu_\mu$ fit







- All systematic uncertainties, Feldman - Cousins corrections are applied.
- Best fit:
  $\sin^2\theta_{23} = 0.56^{+0.04}_{-0.03}$
  $\Delta m^2_{32} = +2.48 \times 10^{-3}\ \mathrm{eV}^2$ (NH)
  $\delta_{CP} = 0.0^{+1.3}_{-0.4}\pi.$
- $\sin^2\theta_{23} < 0.5$ (lower octant) is disfavored at 1.6σ

Future

Currently running with neutrino beam.

- Plan is to run 50:50 $\nu : \bar{\nu}$;
- NOvA is expected to run until 2025.

With current analysis, expect:

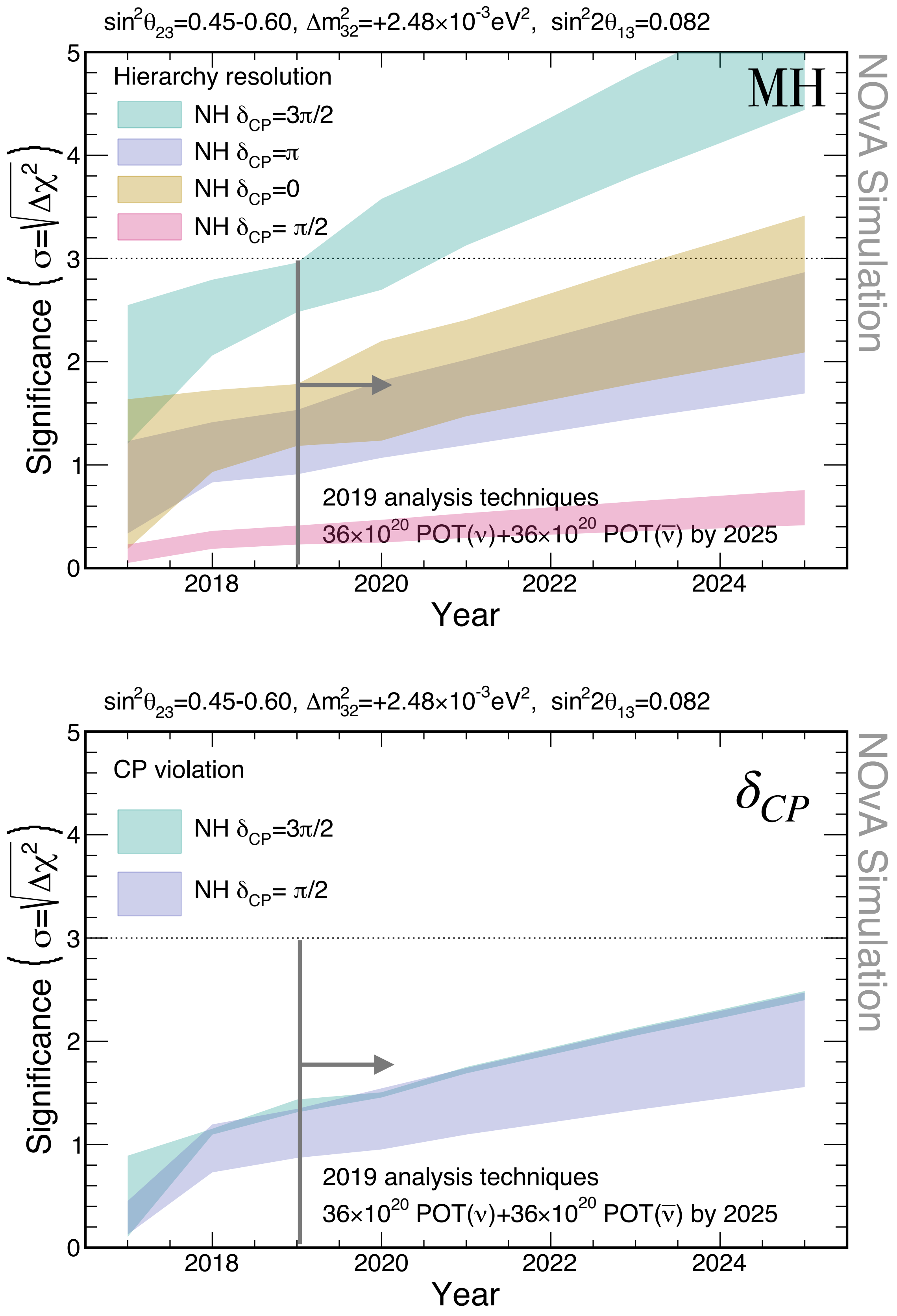
- potential 3-5σ sensitivity to hierarchy with favorable parameters;
- possible >2σ sensitivity to CP violation.

Note: sensitivity depends strongly on the true values in nature.

Expected improvements for upcoming analyses:

- accelerator → $\nu/\bar{\nu}$ beam intensity;
- det. response model;
- cross section models.

Projected sensitivities



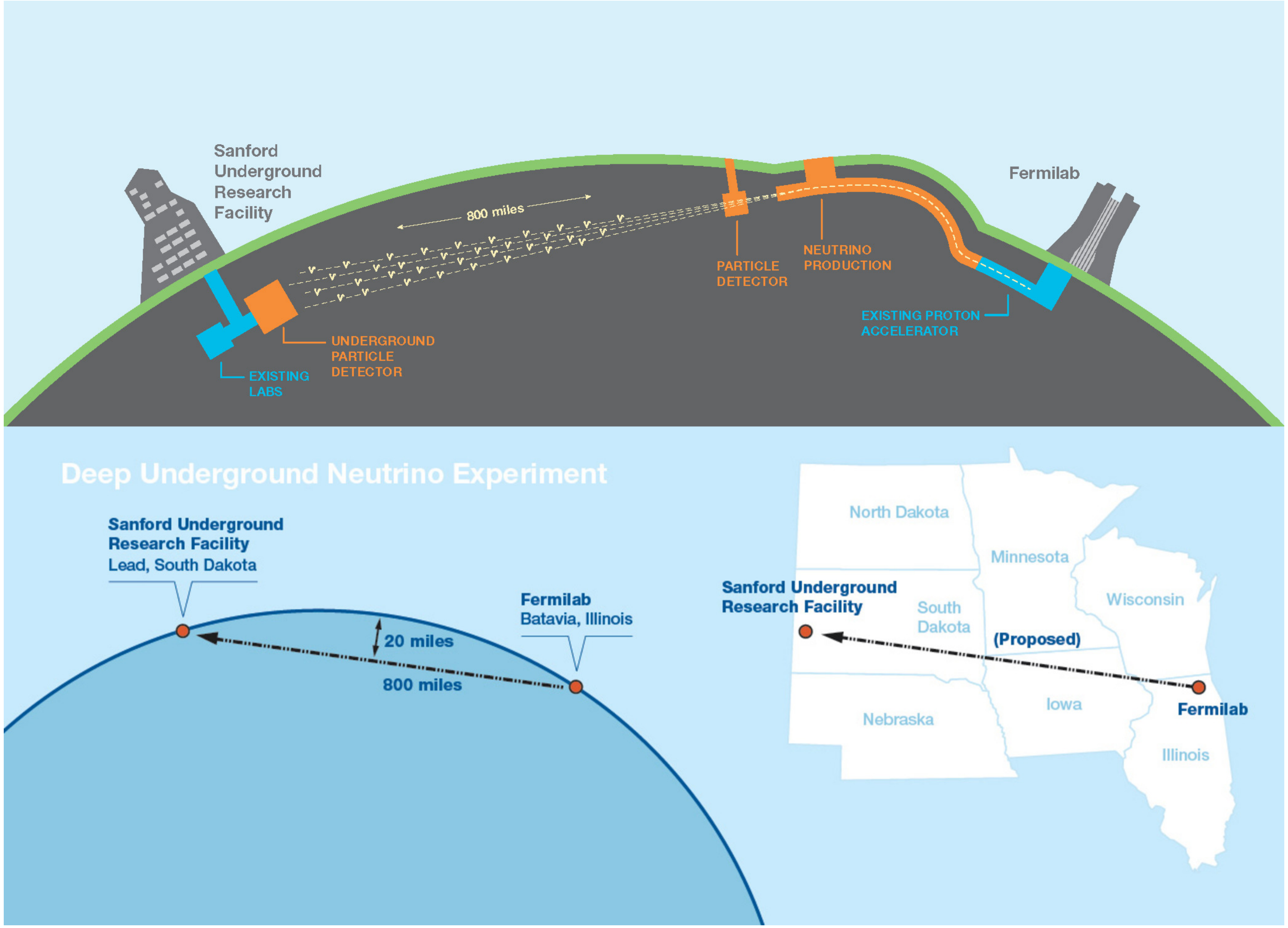
JINR participation in NOvA

Group leader: A. Olshevskiy
Deputy at JINR: O. Samoylov

24 JINR collaborators (13 authors) out of 240 in NOvA with the following activities:

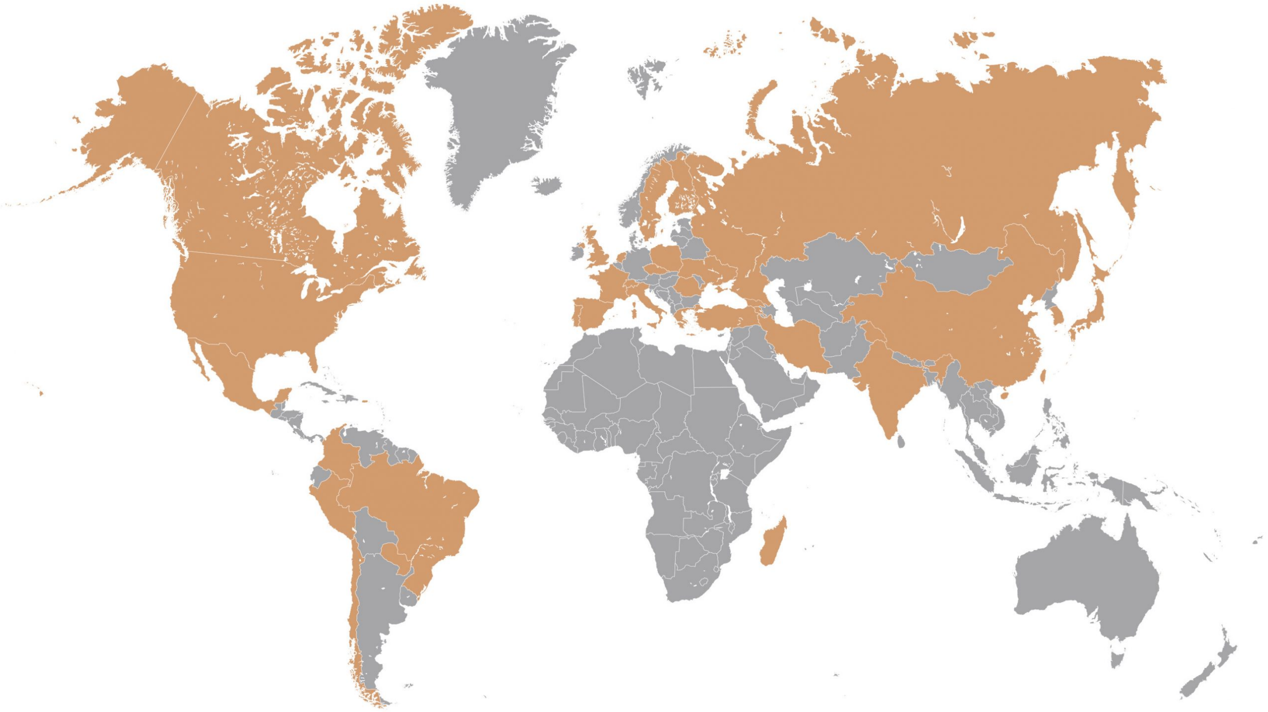
- scintillator filling and APD testing (N.Anfimov, O. Samoylov, A. Sotnikov)
- detector construction and response; NOvA test benches at JINR (A. Antoshkin, N.Anfimov, O.Klimov, O. Samoylov, A. Sotnikov)
- Dubna Remote Operation Center for NOvA (A.Antoshkin, N. Anfimov, A.Balandin and A. Dolbilov (emergency contacts), Ch. Kullenberg, O. Samoylov, A. Sheshukov)
- JINR data center for NOvA and IT support (N. Balashov, A. Baranov, A. Dolbilov, N. Kutovskiy, E. Kuznetsov)
- theoretical group (I. Kakorin, K. Kuzmin, V. Naumov)
- detector simulation and calibration (O. Samoylov, O. Petrova)
- cross-section measurements:
  - coherent pion production (Ch. Kullenberg)
  - strange particle production (V. Allakhverdian)
- exotics:
  - atmospheric muons (A. Morozova, O. Petrova)
  - supernova detection (M. Petropavlova, A. Sheshukov)
  - monopole search (A. Antoshkin)
- oscillation analysis:
  - sterile neutrino searches (V. Korsunov)
  - 3 flavor paradigm (A. Kalitkina, L. Kolupaeva)

Deep Underground Neutrino Experiment (DUNE)



- **1.2 MW** neutrino beam from FNAL to SURF (South Dakota, USA)
- Far Detector: Liquid argon TPC (**1300** m km baseline)
- Near Detector: composite (574m baseline)

DUNE collaboration



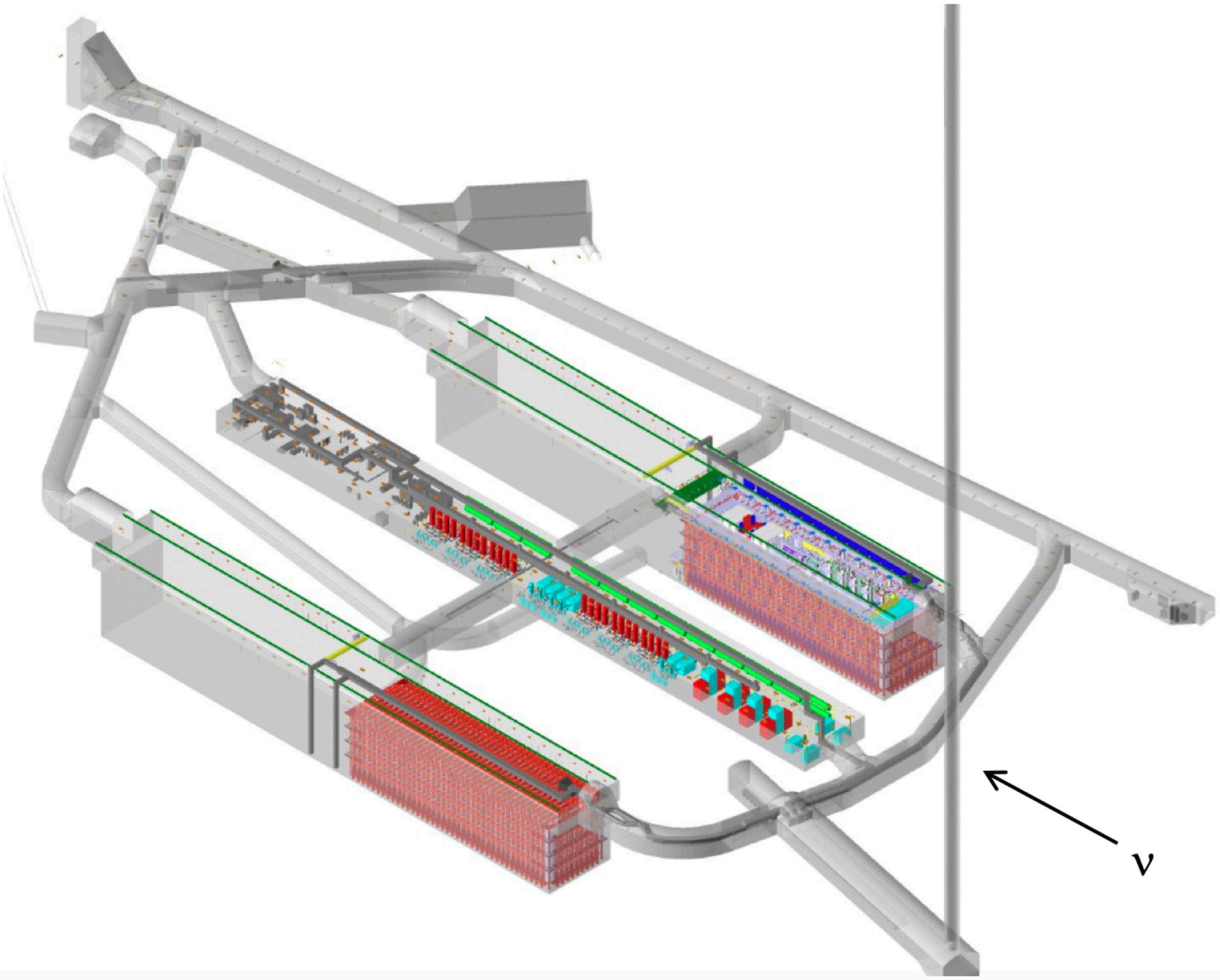
34 countries
192 institutions
1104 collaborators

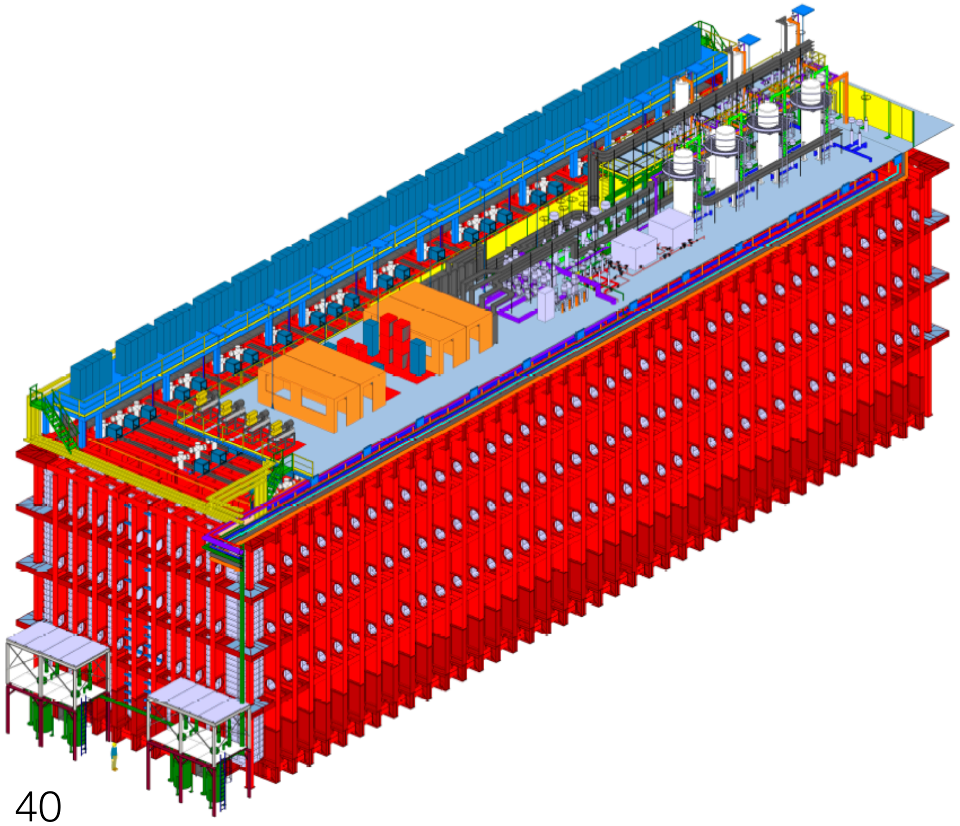
DUNE far-site facility

- 5 main caverns
  - 4 detector caverns and one support cavern (cryogenics and DAQ).

- Detectors based on LArTPC technologies
  - Same cryostat dimensions 62m x 19m x 18m;
  - 17 kt total LAr mass;
  - 10 kt fiducial LAr mass .

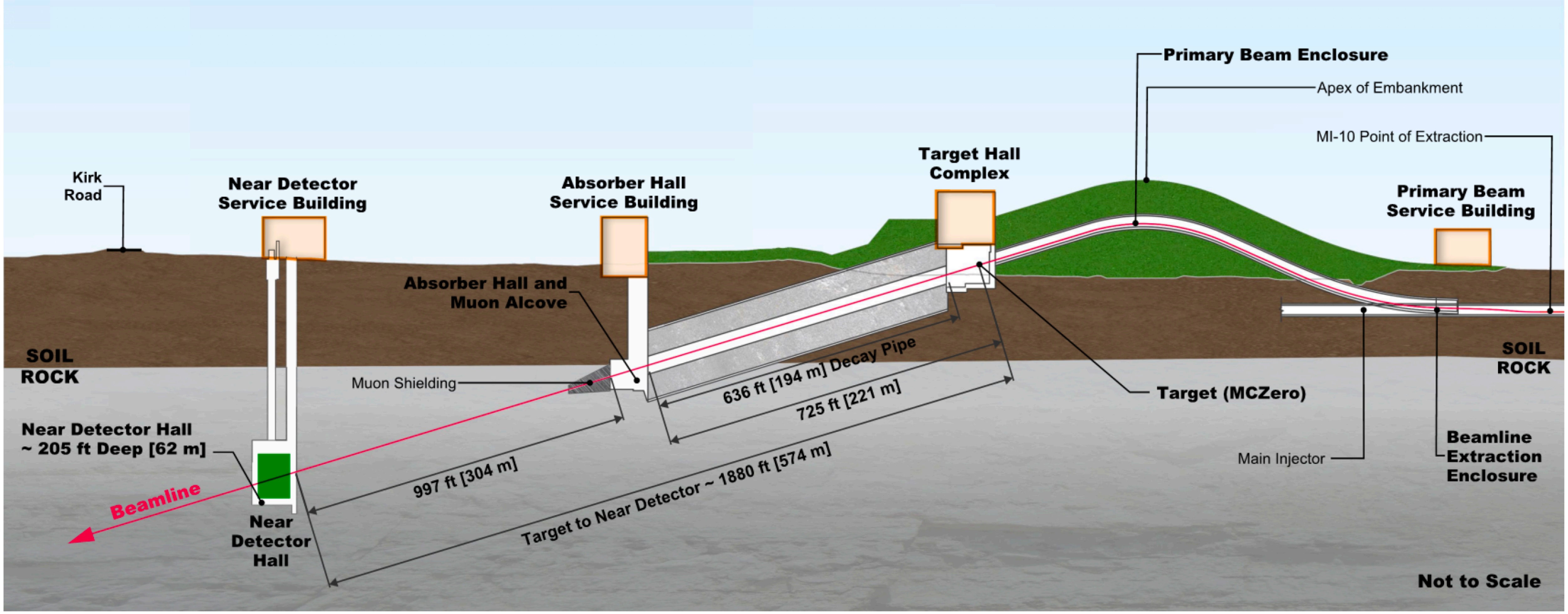
- Detectors installed in a staged approach over some years
  - 2 detectors installed before beam starts.



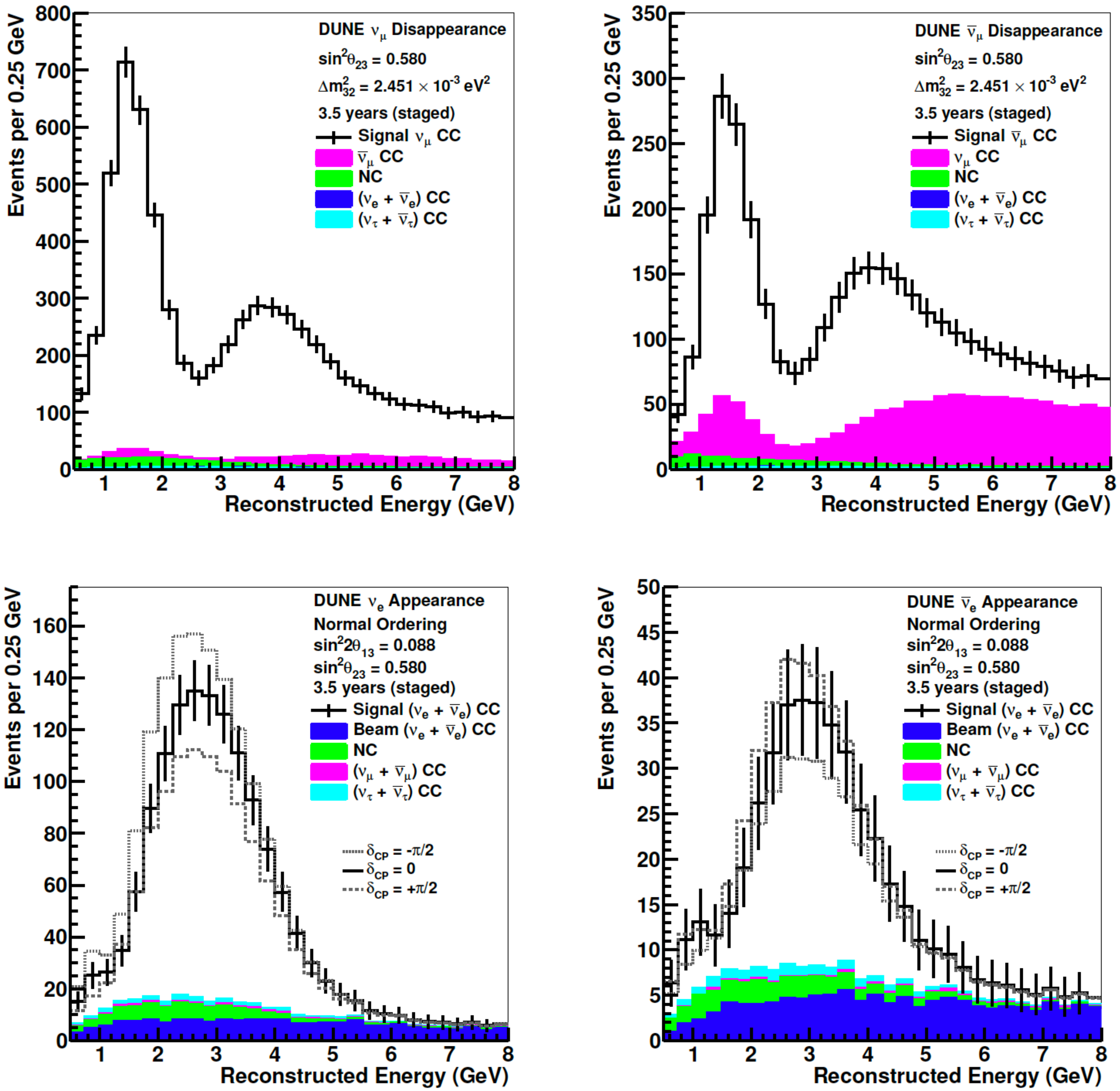


DUNE beamline

- 1.2 MW proton beam at 60-120 GeV (10^{20} POT/ year);
  - Up to 2.4MW of beam power by 2030.
- Oriented 5.8° down



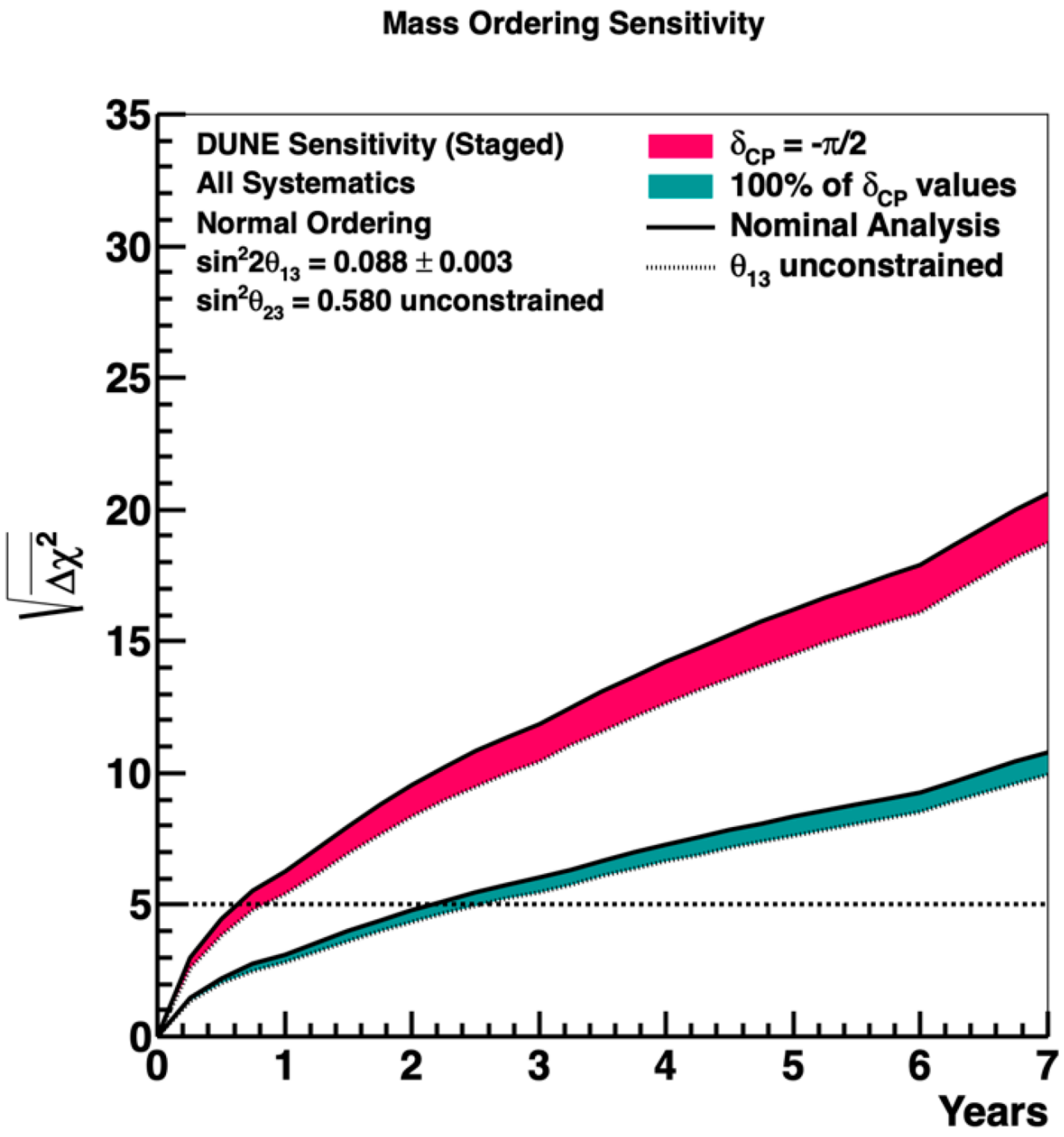
Expected number of events



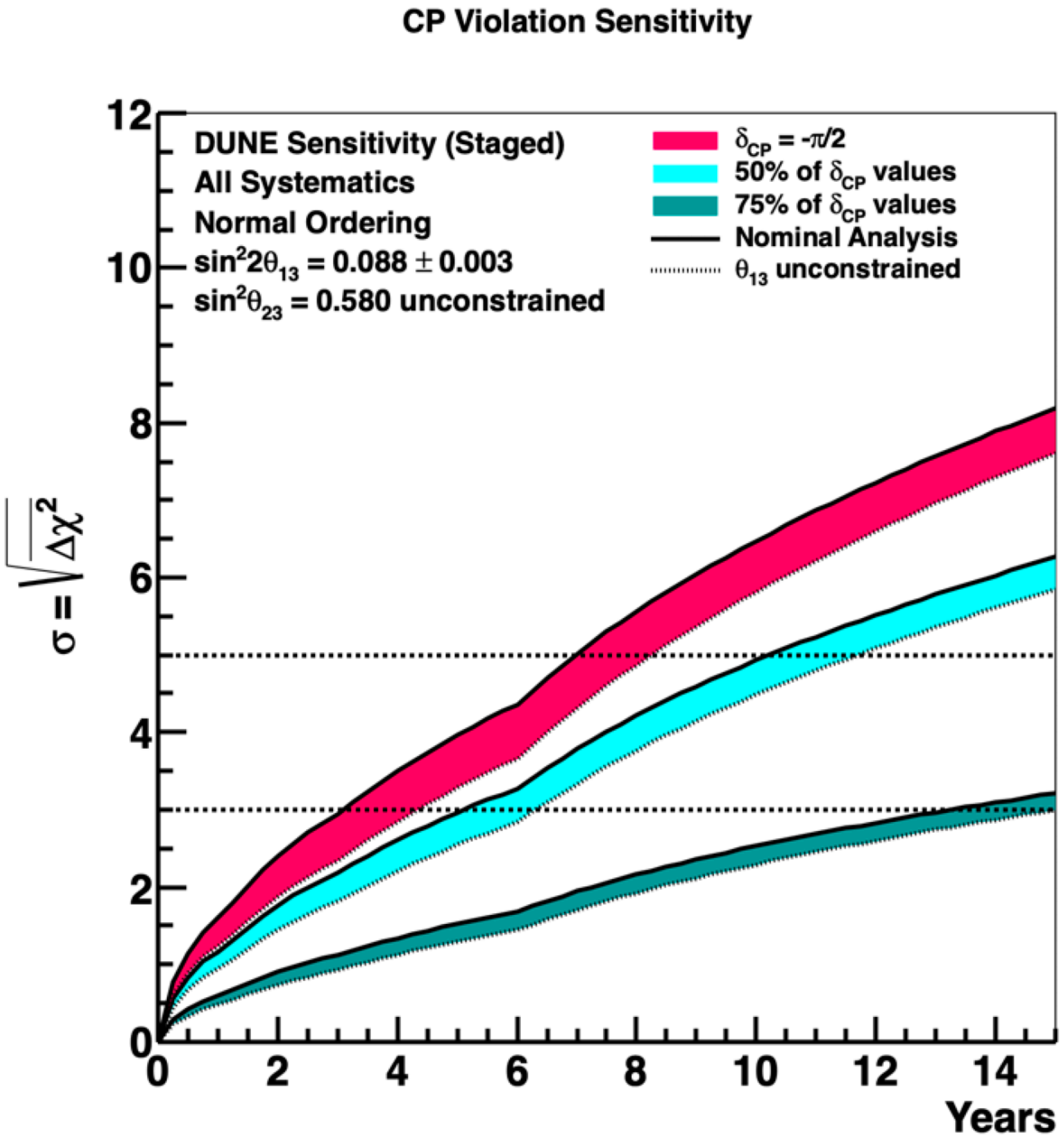
About 10 000 ν_μ events
after 7 years

About 1 000 ν_e events
after 7 years

DUNE sensitivities



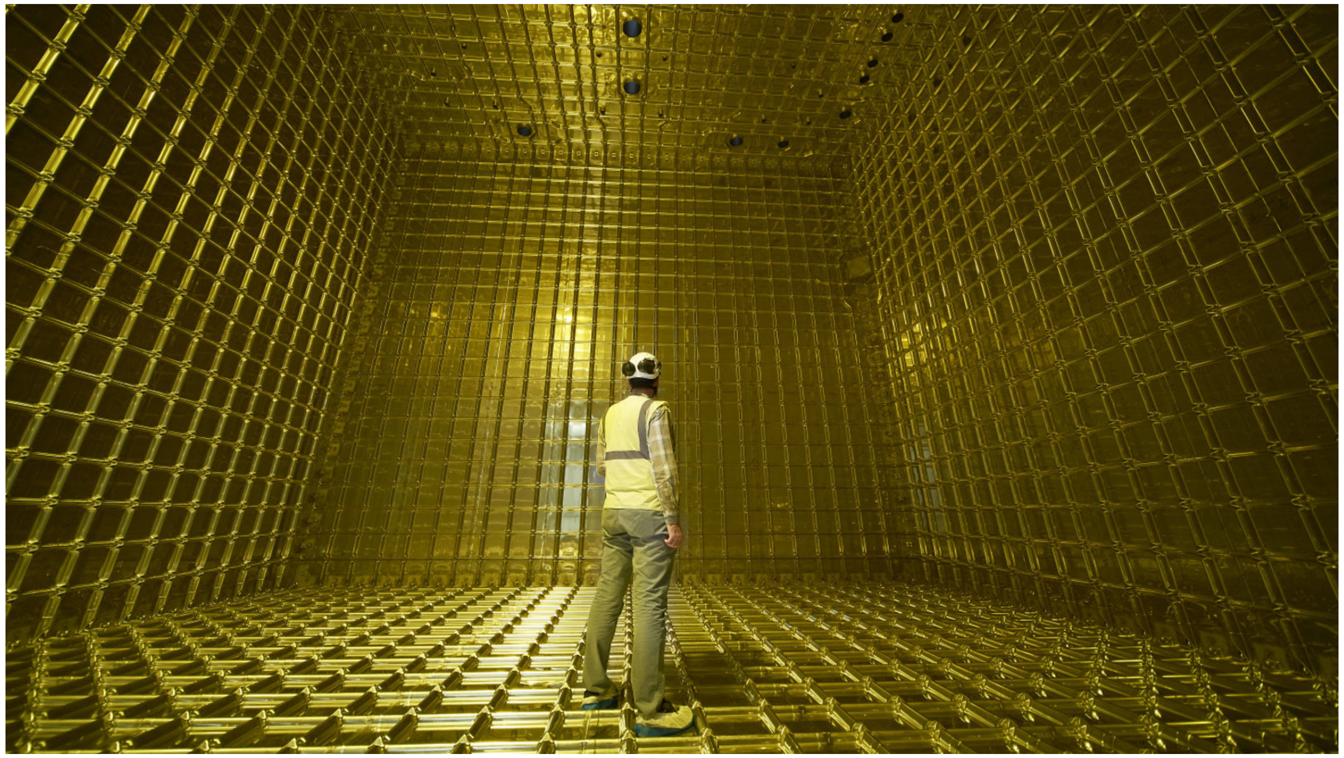
Mass Ordering Sensitivity

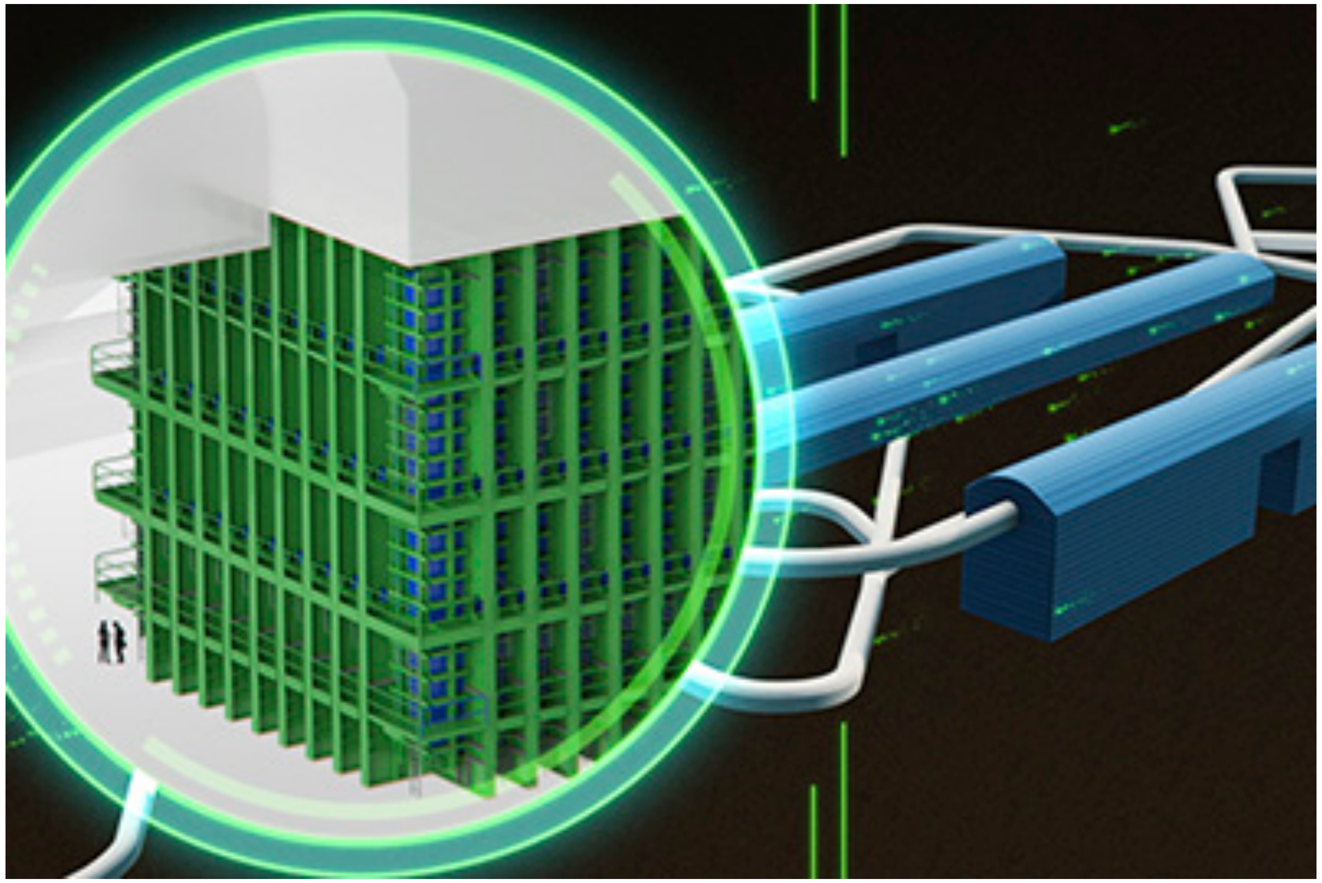


CP Violation Sensitivity

- 5σ sensitivity to mass ordering after 2 years of beam running (for any value of δ_{CP})
- 5σ sensitivity to 50% of δ_{CP} values after 10 years of beam running.

DUNE planned timeline





2024: Start installing first module (SP)

2025: Start installing second module, total fiducial mass of 20 kt
- physics data taking starts with atmospheric neutrinos

2026: Beam operational at 1.2MW,
- physics data taking with beam starts

2027: Add third FD module, total fiducial mass of 30 kt

2029: Add fourth FD module, total fiducial mass of 40 kt

2030: upgrade to 2.4 MW beam

Conclusions

Strong participation of JINR group in NOvA in all essential parts of experiment.

With 8.85×10^{20} $(\nu) + 12.33 \times 10^{20}$ $(\bar{\nu})$ POT exposure the following results were obtained:

✳ 4.4σ evidence for $\bar{\nu}_e$ appearance in $\bar{\nu}_\mu$ beam;

✳ the best fit is in the Normal Hierarchy,
$\delta_{CP} = 0\pi$, $\sin^2\theta_{23} = 0.56$, $\Delta m^2_{32} = +2.48 \times 10^{-3}\,\mathrm{eV}^2$;

✳ 1.9σ preference for the Normal neutrino mass hierarchy, exclude $\delta_{CP} = \pi/2$ in Inverted hierarchy at $> 4\sigma$;

✳ prefer upper octant of $\sin^2\theta_{23}$ at 1.6σ (consistent with maximal mixing at 1.2σ).

With operation through 2025 NOvA expects:

- ✳ possible 3 - 5σ sensitivity to mass hierarchy;
- ✳ potential sensitivity to CP violation phase $> 2\sigma$.

The next generation experiment DUNE is expected to start in 2025:

- ✳ ambitious and rich physics program;
- ✳ 5σ sensitivity to MH after 2 years of beam data taking.