

*20th Baikal Summer School on Physics of Elementary Particles and Astrophysics,
15-26 October 2020*

Neutrino Oscillations in the Accelerator Experiments

Oleg Samoylov
Joint Institute for Nuclear
Research, Dubna

Baikal summer JINR-ISU school

Almost 10 years ago

Accelerator neutrinos

Oleg Samoylov

Joint Institute for Nuclear Research

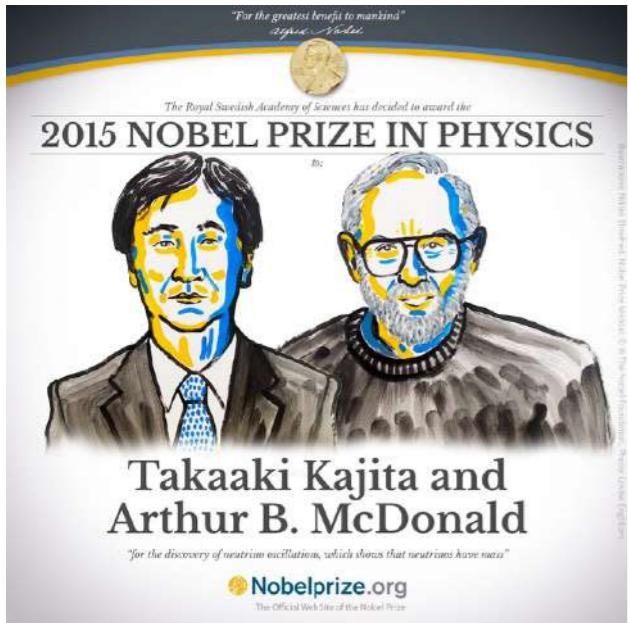
Baikal Summer School
on Physics of Elementary Particles and AstroPhysics

July 3-10, 2011

B.Koty

The Experimental Discovery of Neutrino Oscillations

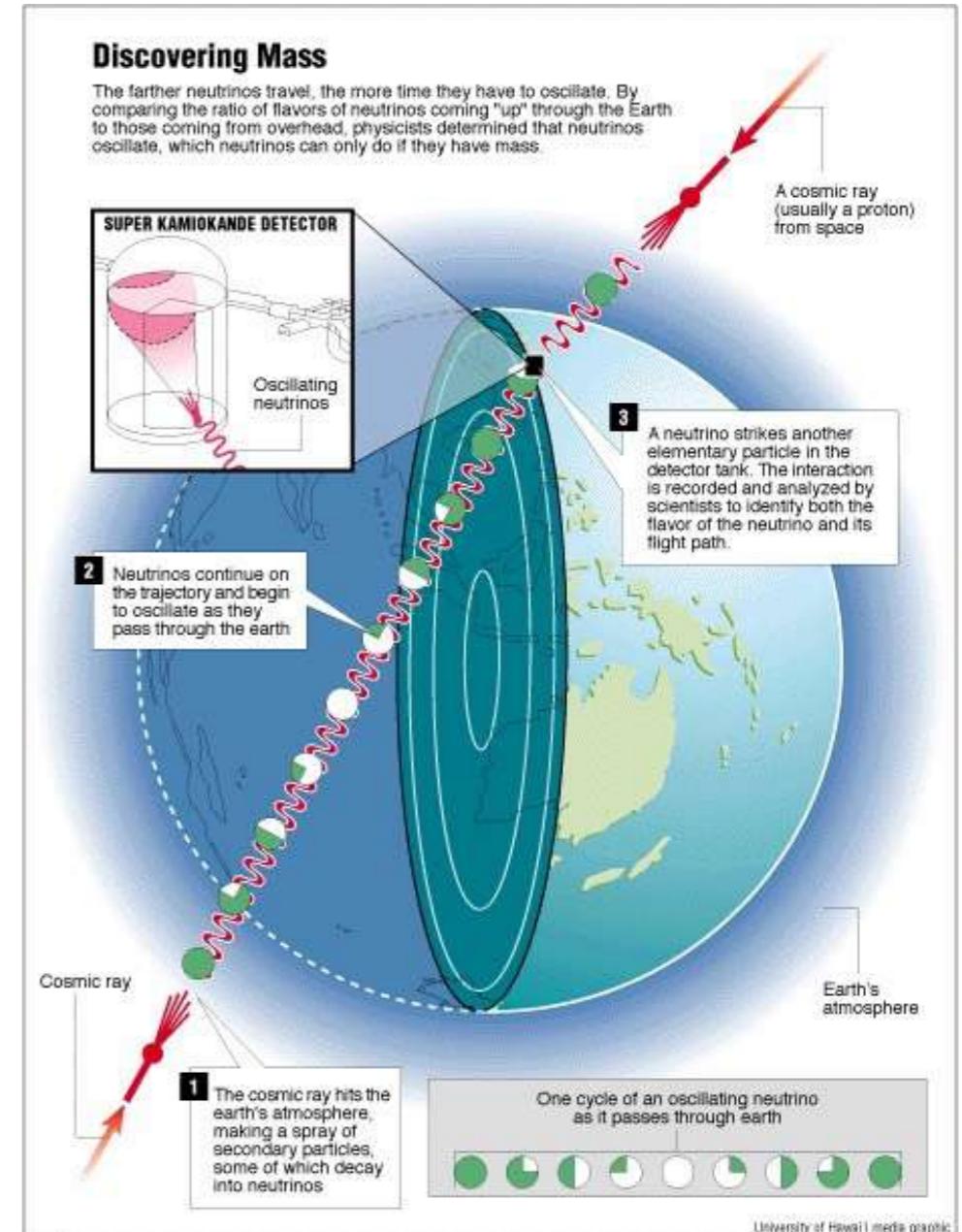
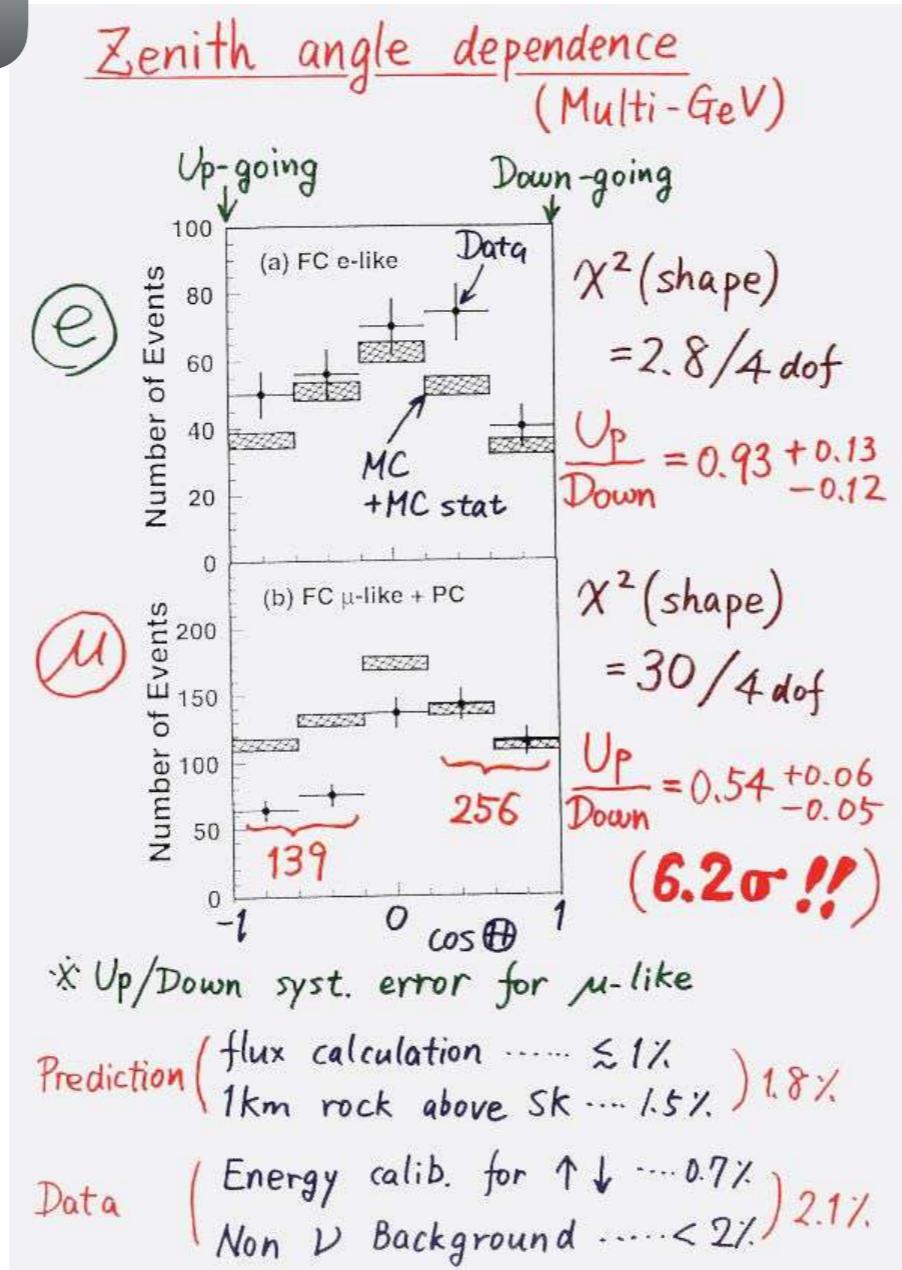
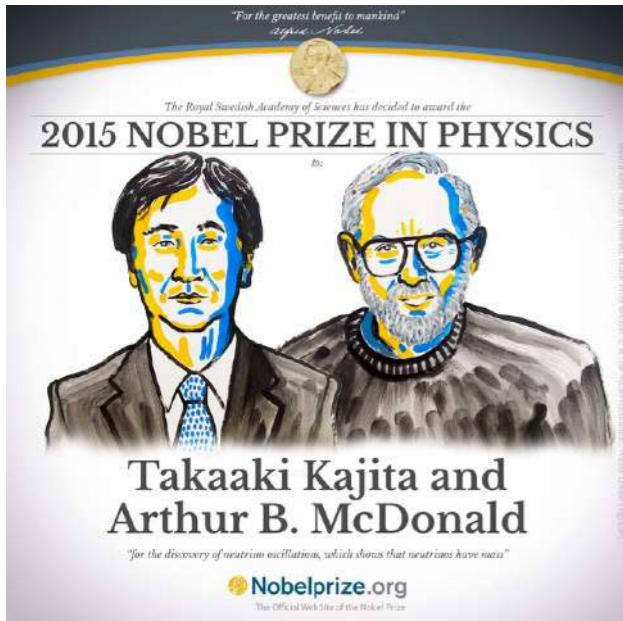
Nobel Prize 2015



«for the discovery of neutrino oscillations,
which shows that neutrinos have mass».

Evidence for oscillation of atmospheric neutrinos

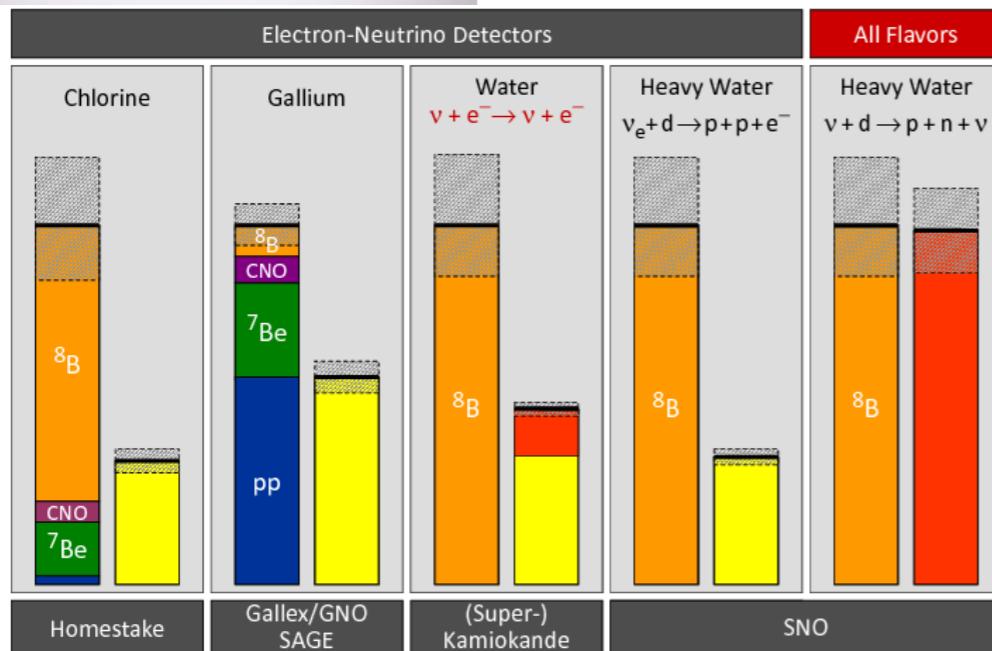
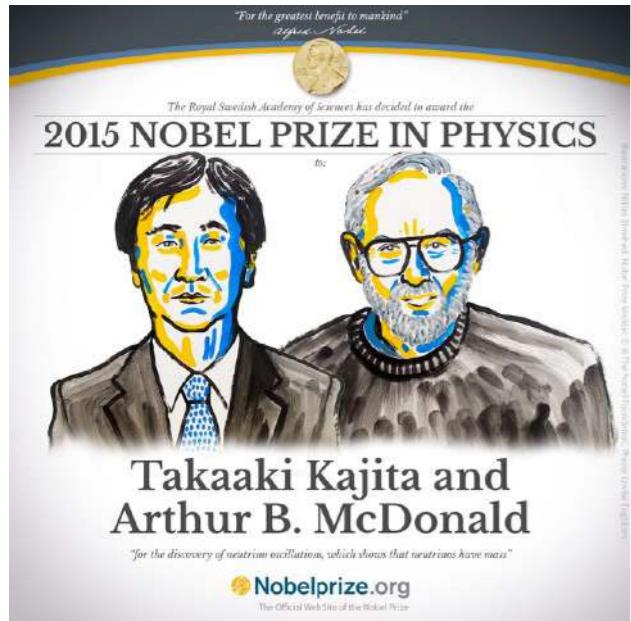
Nobel Prize 2015



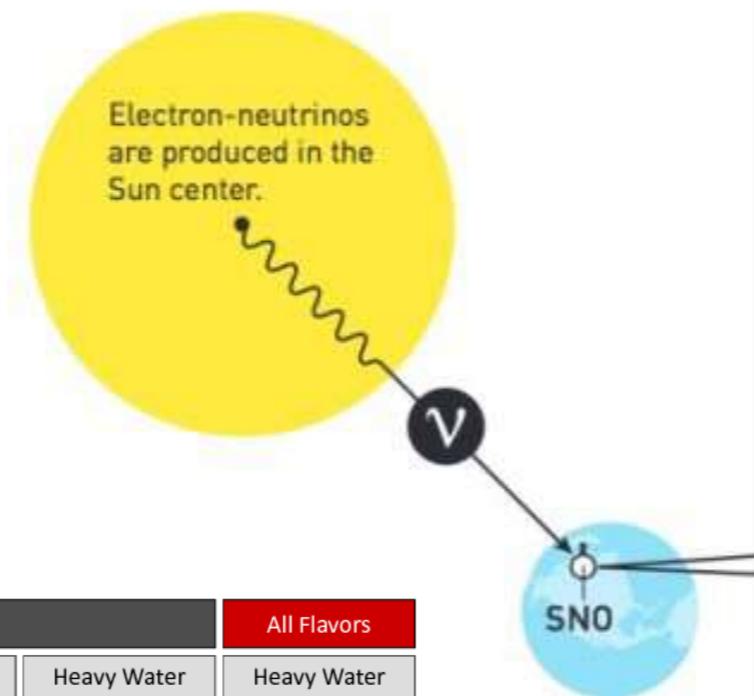
«for the discovery of neutrino oscillations, which shows that neutrinos have mass».

Evidence for oscillation of Solar neutrinos

Nobel Prize 2015



NEUTRINOS FROM THE SUN



SUDBURY NEUTRINO OBSERVATORY (SNO) ONTARIO, CANADA

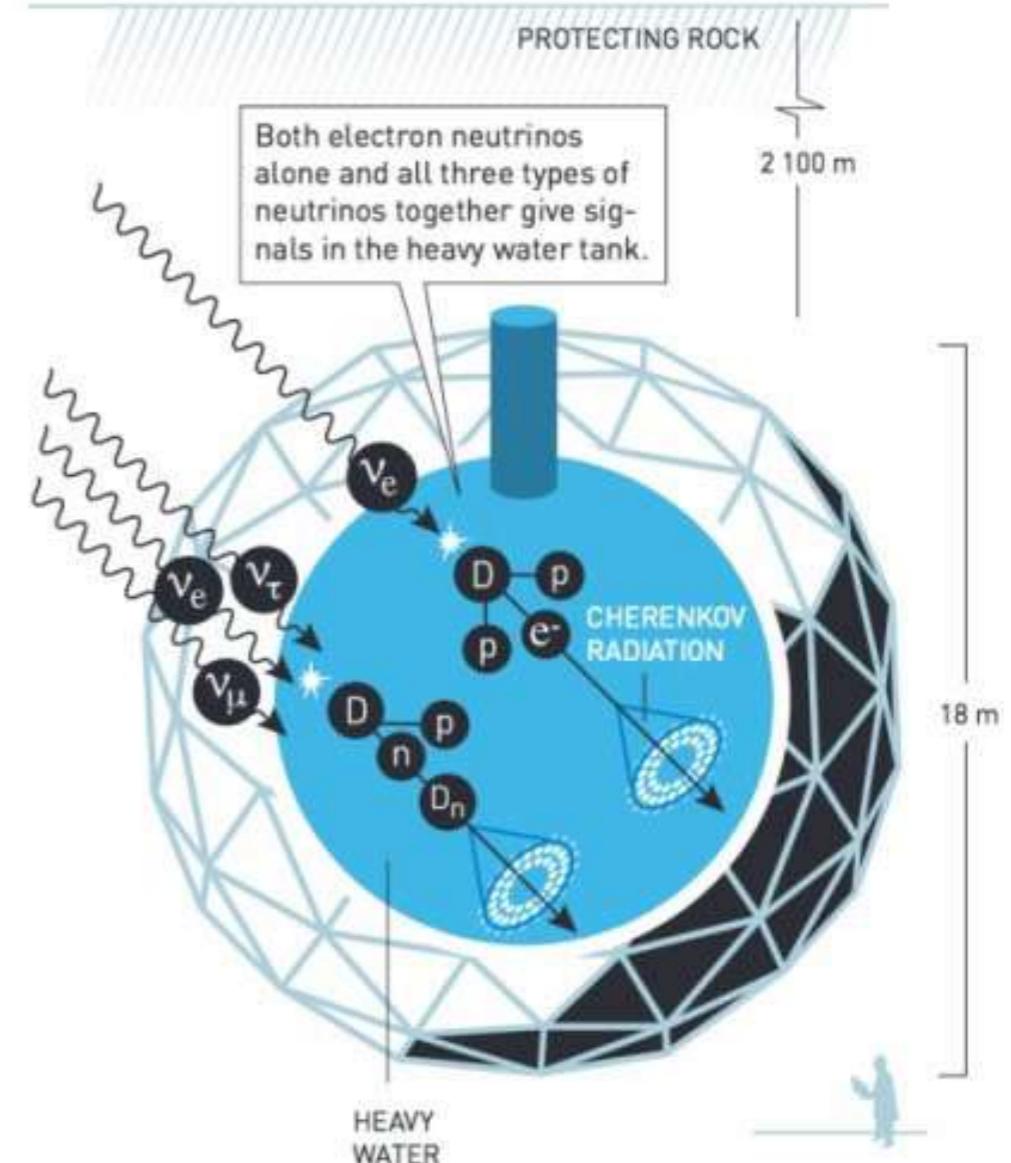
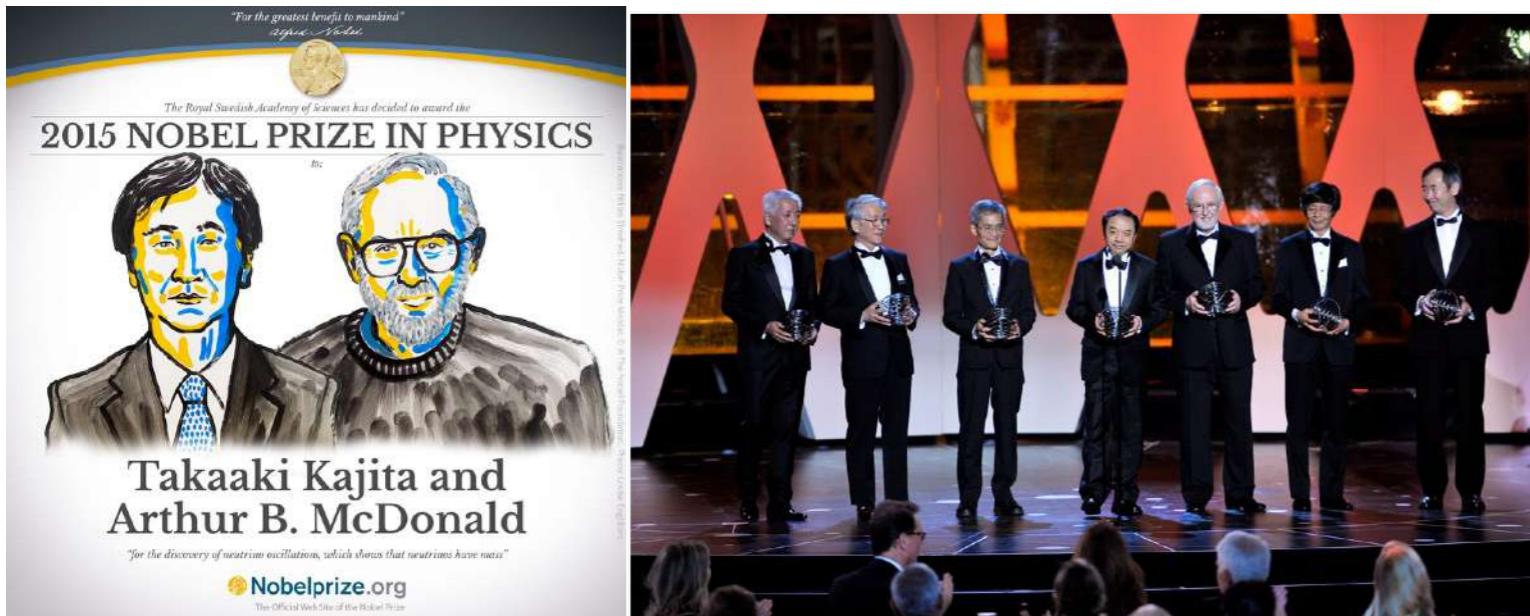


Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

«for the discovery of neutrino oscillations,
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More experimental results to neutrino oscillations

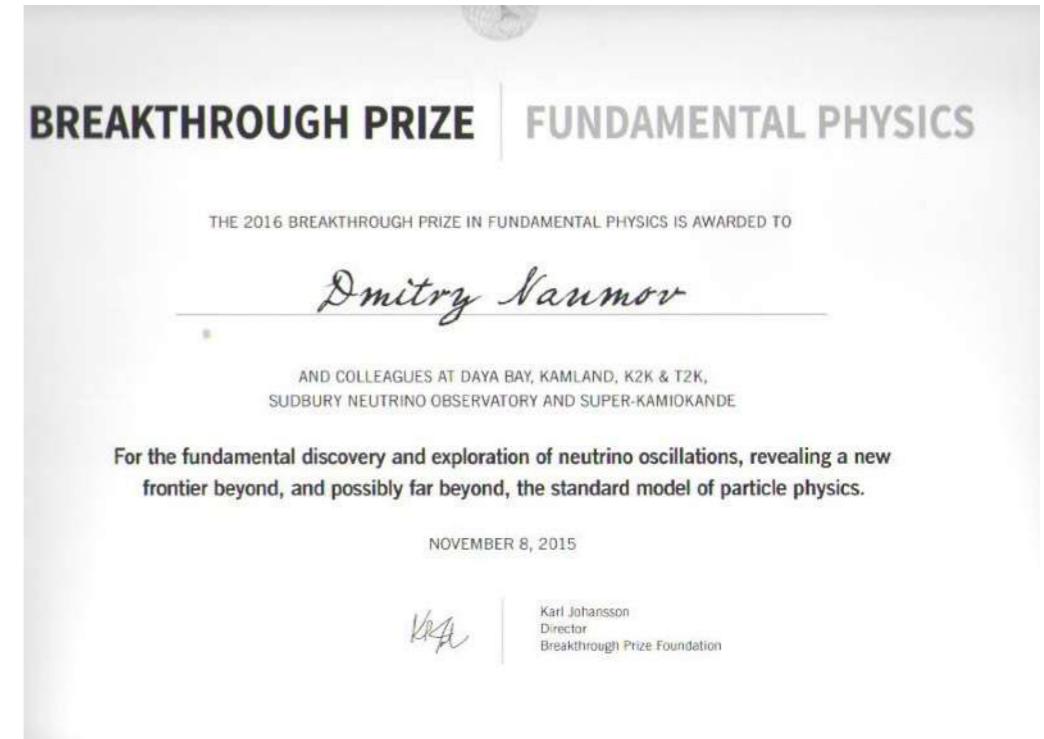
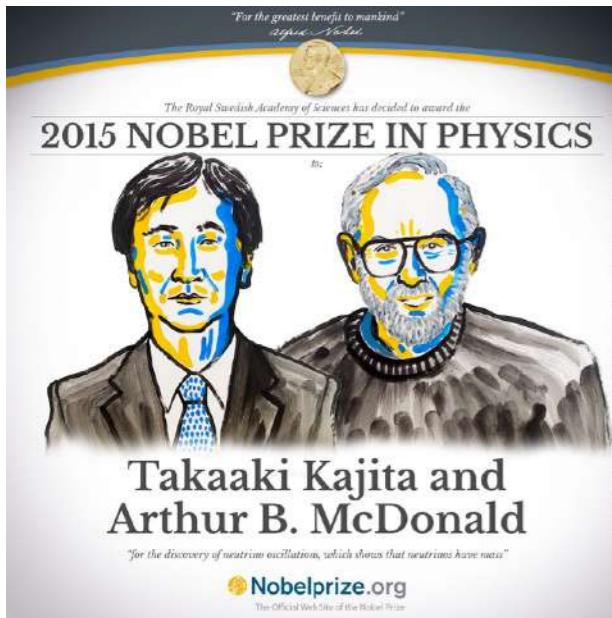
Nobel Prize 2015 and Breakthrough 2016



«The 2016 Breakthrough Prize in Fundamental Physics Awarded to 7 Leaders and 1370 Members of 5 Experiments Investigating Neutrino Oscillation: Daya Bay (China); KamLAND (Japan); K2K / T2K (Japan); Sudbury Neutrino Observatory (Canada); and Super-Kamiokande (Japan)».

More experimental results to neutrino oscillations

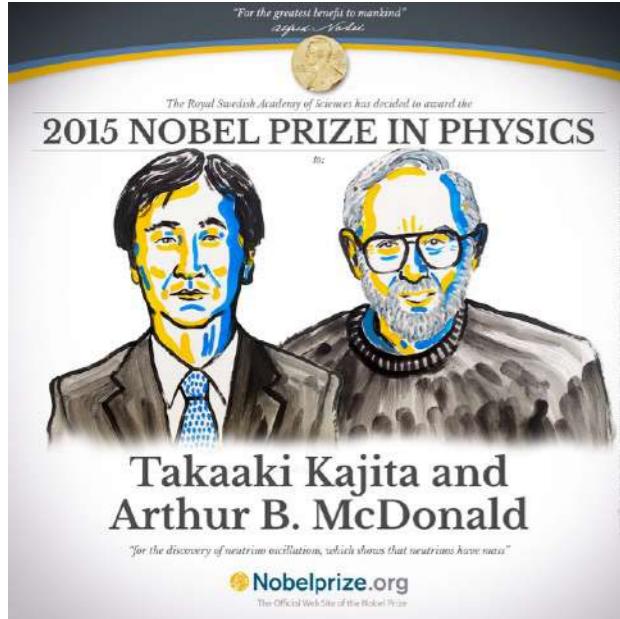
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And a short neutrino history

Nobel Prize 2015 and Breakthrough 2016



• SHORT NEUTRINO HISTORY

- 1914, James Chadwick discovered continuous β -spectrum
- 1930, Wolfgang Pauli proposed a light neutral particle of spin 1/2 emitted alongside the electron.
- 1934, Enrico Fermi published his theory of β -decay.
- 1956, Fred Reines and Clyde L. Cowan detected reactor (anti)neutrino.
- 1957, Bruno Pontecorvo proposed neutrino-antineutrino oscillations.
- 1958, Maurice Goldhaber, Lee Grodzins and Andrew Sunyar found that neutrinos are left handed.
- 1962, Leon Lederman, Melvin Schwartz, Jack Steinberger discovered muon nu.

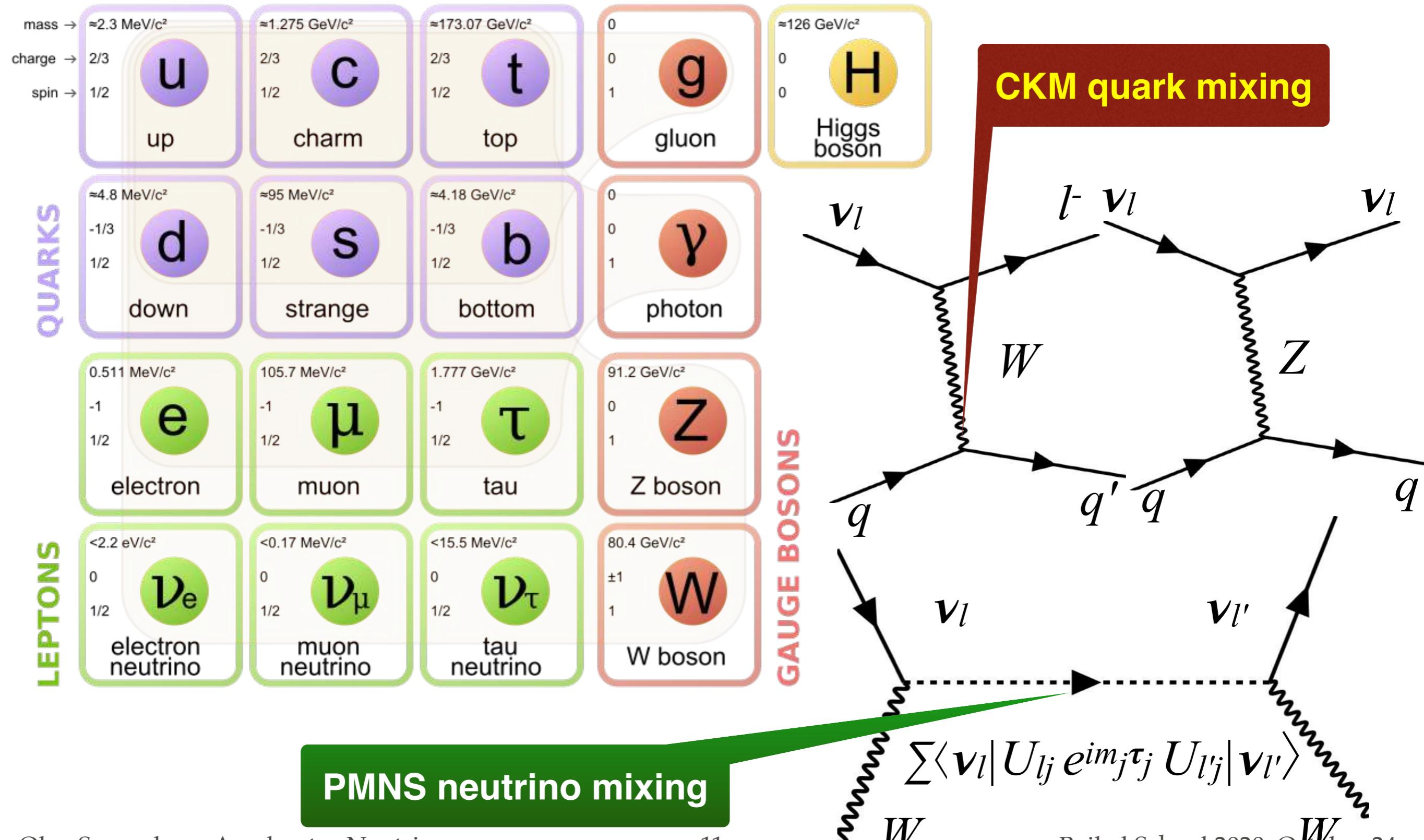
- 1962, Ziro Maki, Masami Nakagawa and Shoichi Sakata introduce neutrino flavor mixing and flavor oscillations.
- 1968, Raymond Davis got first radiochemical solar neutrino.
- 1987, Kamiokande, IMB and Baksan detectors detect burst of antineutrinos from SN1987A in Large Magellanic Cloud (51.474 kpc).
- 1989, LEP experiments determine only 3 light neutrinos (via Z-decay).
- 1998, Super-Kamiokande found muon neutrino oscillations in atmospheric neutrinos.
- 2000, DONUT observed ν_τ .
- 2001, SNO announced observation of neutral currents from solar neutrinos.
- 2002, KamLAND announces detection of a deficit of electron antineutrinos from reactors at a mean distance of 175 km.
- 2005, KamLAND announced first detection of neutrino flux from the Earth.
- 2010, OPERA announced observation of the first ν_τ from ν_μ beam.
- 2011, Borexino presented a high precision measurement of solar neutrino (Be).
- 2011, T2K announces first evidence for a nonzero mixing between the 1st and 3rd neutrino generations.
- 2012, Daya Bay announced a precision results on measuring θ_{13} with significance 5.2σ .

• NOBELS

- 1988, Leon Lederman, Melvin Schwartz, Jack Steinberger — for the neutrino beam method and the demonstration of the doublet structure of the leptons through the discovery of the muon neutrino
- 1995, Frederick Reines — for the detection of the neutrino
- 2002, Raymond Davis and Masatoshi Koshiba — for pioneering contributions to astrophysics, in particular for the detection of cosmic neutrinos
- 2015, Takaaki Kajita and Arthur B. McDonald — for the discovery of neutrino oscillations, which shows that neutrinos have mass

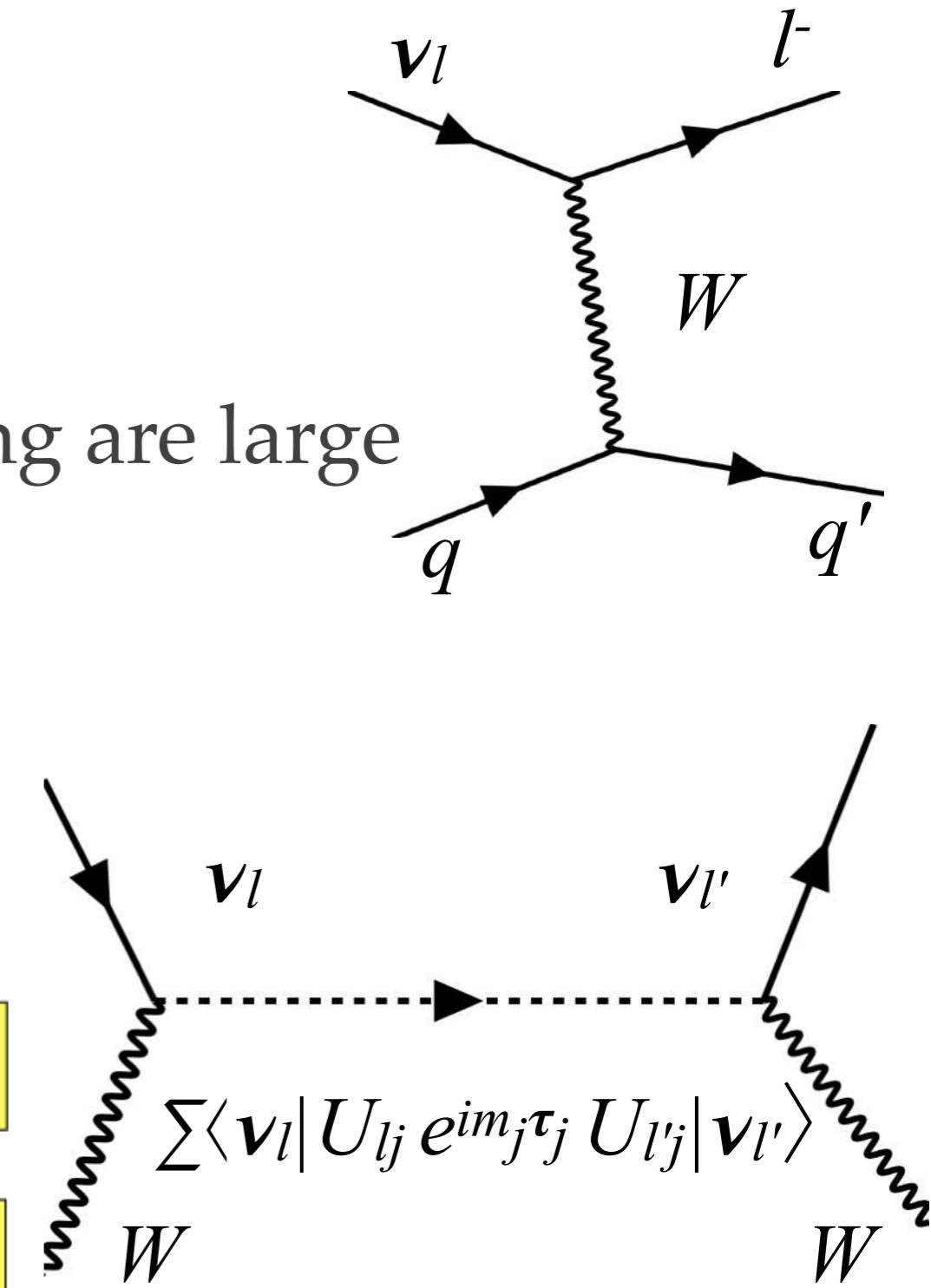
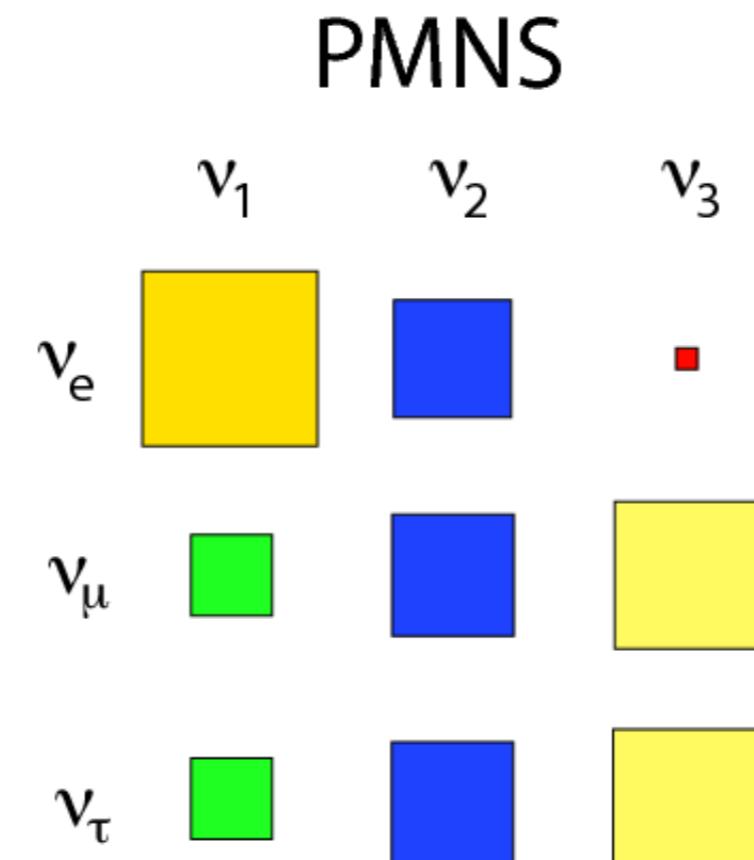
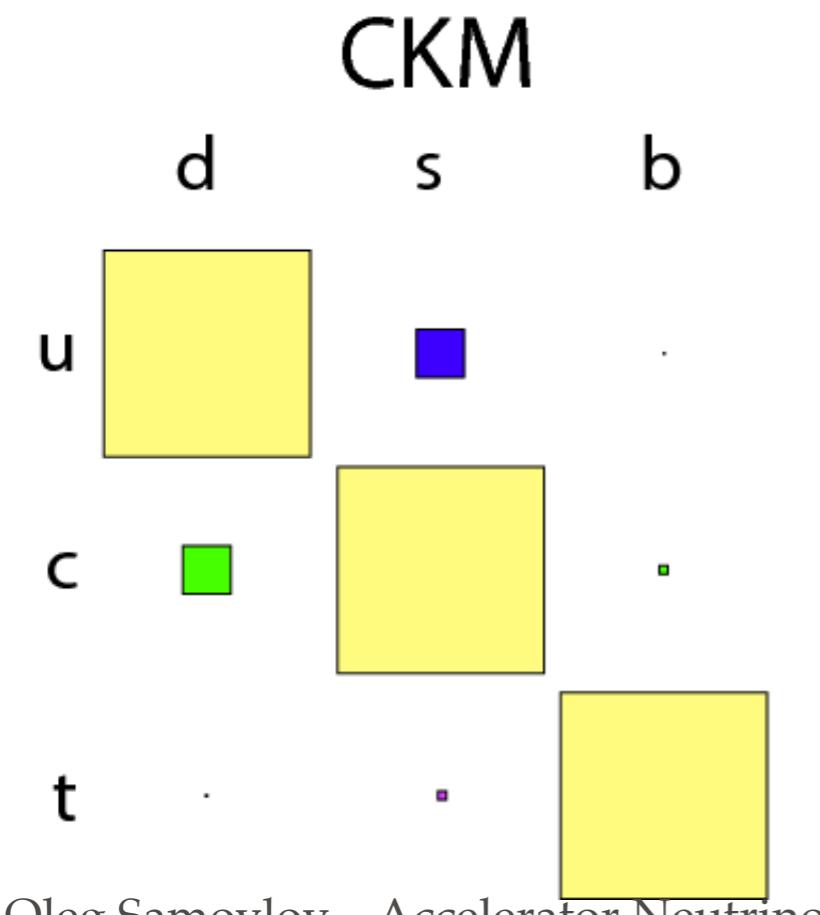
Neutrino Oscillations and Mixing

Neutrino oscillations



Neutrino mixing

- ❖ Neutrinos mix, just like quarks?
- ❖ PMNS matrix like CKM matrix?
- ❖ Unlike the quarks, neutrino mixing are large

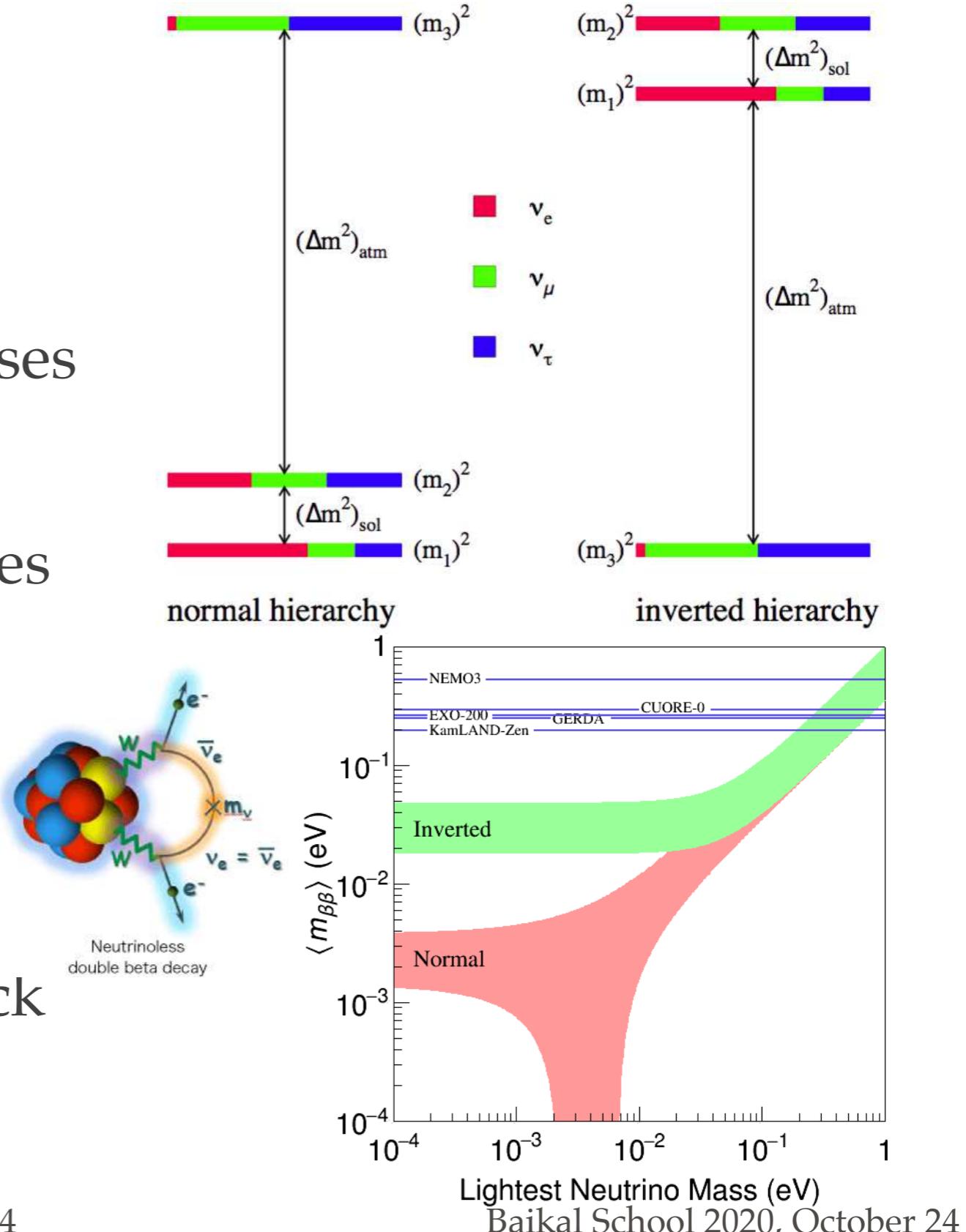


Neutrino mixing

- ❖ Neutrinos mix, just like quarks?
- ❖ PMNS matrix like CKM matrix?
- ❖ Unlike the quarks, neutrino mixing are large
- ❖ Open neutrino questions:
 - Dirac or Majorana? • Absolute masses • Mass ordering
 - CP-violation • Random mixing parameters or patterns?
 - Just 3 neutrino types?

Mass Hierarchy

- ❖ Is the most electron-like state lightest?
- ❖ i.e. Does the pattern of the masses match the charged leptons?
- ❖ Are neutrinos Majorana particles ($\nu = \bar{\nu}$)?
- ❖ Observation of $0\nu\beta\beta$ would be proof they are
- ❖ Impact of IH determination: lack of $0\nu\beta\beta$ implies Dirac nature

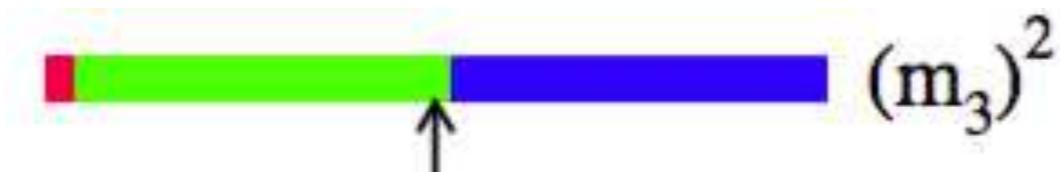


CP-violation

- ❖ Does e.g. $P(\nu_\mu \rightarrow \nu_e) = P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$?
- ❖ Insight into fundamental symmetries of the lepton sector
- ❖ Why is the universe not equal parts matter and antimatter?
- ❖ Sakharov conditions: Baryon number violation • Out of thermal equilibrium • C and CP violation
- ❖ CPV in the Standard Model, e.g. for K and B mesons, but too small
- ❖ “Leptogenesis”: generate asymmetry in neutrinos, transfer to baryons
- ❖ Require **neutrino appearance** experiment to discover

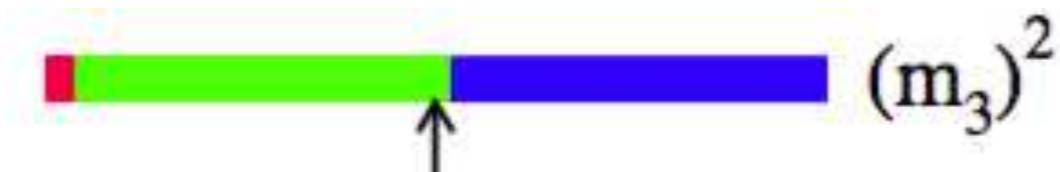
Mixing pattern

- ❖ Only a small fraction of ν_e in $|\nu_3\rangle$ (the famous $\sin^2 2\theta_{13}$)
- ❖ The remainder is split about 50/50 ν_μ / ν_τ ($\sin^2 \theta_{23}$)
- ❖ Accident? Or a sign of underlying structure?



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- ❖ Accident? Or a sign of underlying structure?



- ❖ Is θ_{23} exactly 45° ?
- ❖ If not, it is
 - $< 45^\circ$ $|\nu_3\rangle$ more ν_τ , like in quarks
 - $> 45^\circ$ $|\nu_3\rangle$ more ν_μ , unlike quarks

Neutrino oscillations

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

$\theta_{23} \sim 45^\circ$ $\theta_{13} \sim 8.5^\circ$ $\theta_{12} \sim 30^\circ$

$$|\Delta m_{32}^2| = |m_3^2 - m_2^2| \simeq 2.5 \times 10^{-3} \text{ eV}^2$$

$$\begin{aligned} \nu_\mu &\rightarrow \nu_\mu \\ \nu_\mu &\rightarrow \nu_\tau \end{aligned}$$

atmospheric and long baseline

$$\Delta m_{31}^2 \simeq \Delta m_{32}^2$$

$$\begin{aligned} \nu_e &\rightarrow \nu_e \\ \nu_\mu &\rightarrow \nu_e \end{aligned}$$

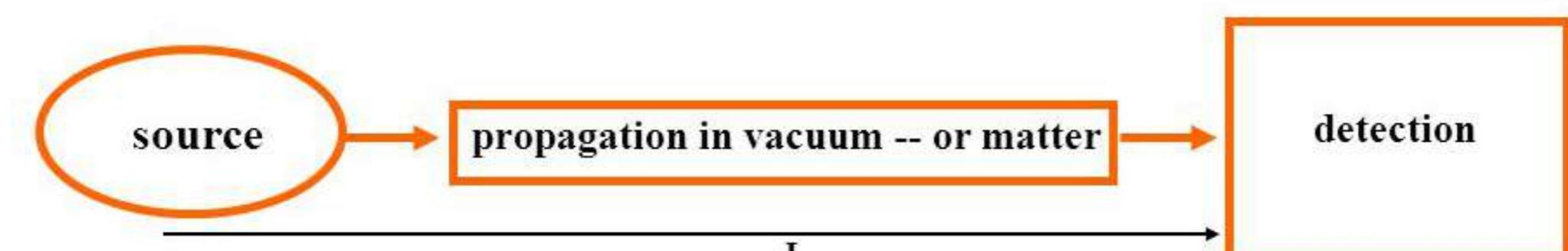
reactor and long baseline

$$\Delta m_{21}^2 = |m_2^2 - m_1^2| \simeq 7.5 \times 10^{-5} \text{ eV}^2$$

$$\begin{aligned} \nu_e &\rightarrow \nu_e \\ \nu_e &\rightarrow \nu_\mu, \nu_\tau \end{aligned}$$

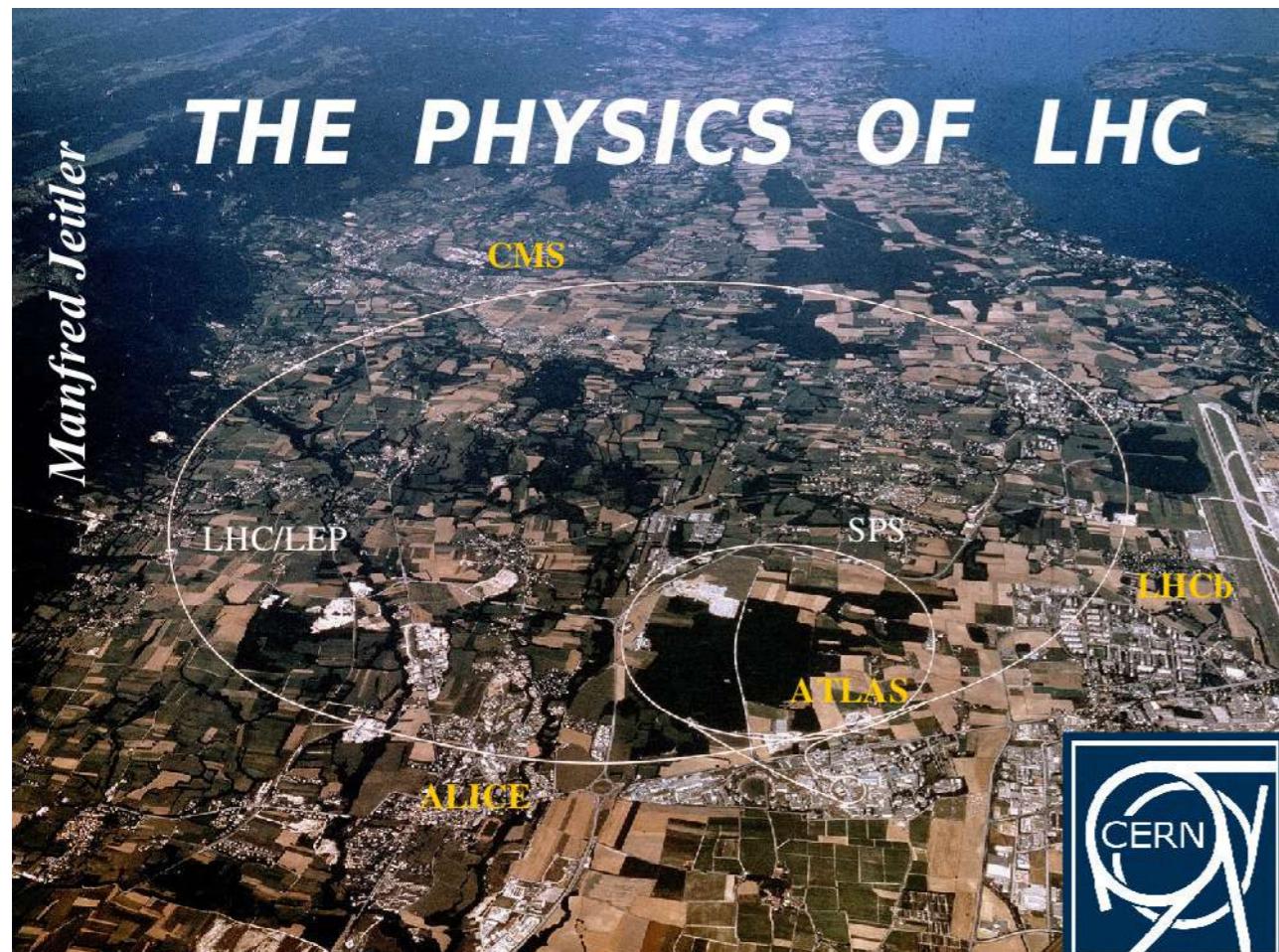
solar and reactor

Oscillation parameters: $\theta_{12}, \theta_{23}, \theta_{13}$, CP phase δ , $|\Delta m_{13}^2|$, Δm_{12}^2

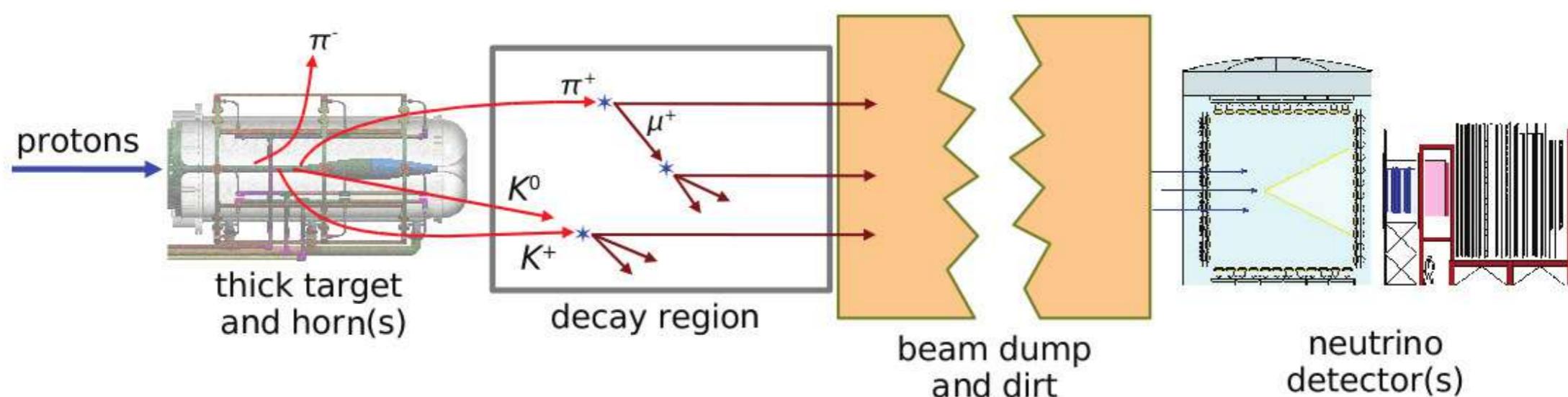


Accelerator-based Neutrino Experiments

Why accelerators?



1. $pA \rightarrow p, \pi^\pm, K^\pm, \alpha, \dots$
2. $\pi^\pm, K^\pm \rightarrow \ell^\pm \nu(\bar{\nu})$
3. $\tau_\pi = 2.6 \cdot 10^{-8} \text{ s} \ll \tau_\mu = 2 \cdot 10^{-6} \text{ s}$
– decay tunnel
4. they can be focused and charge selected by means of magnetic horns

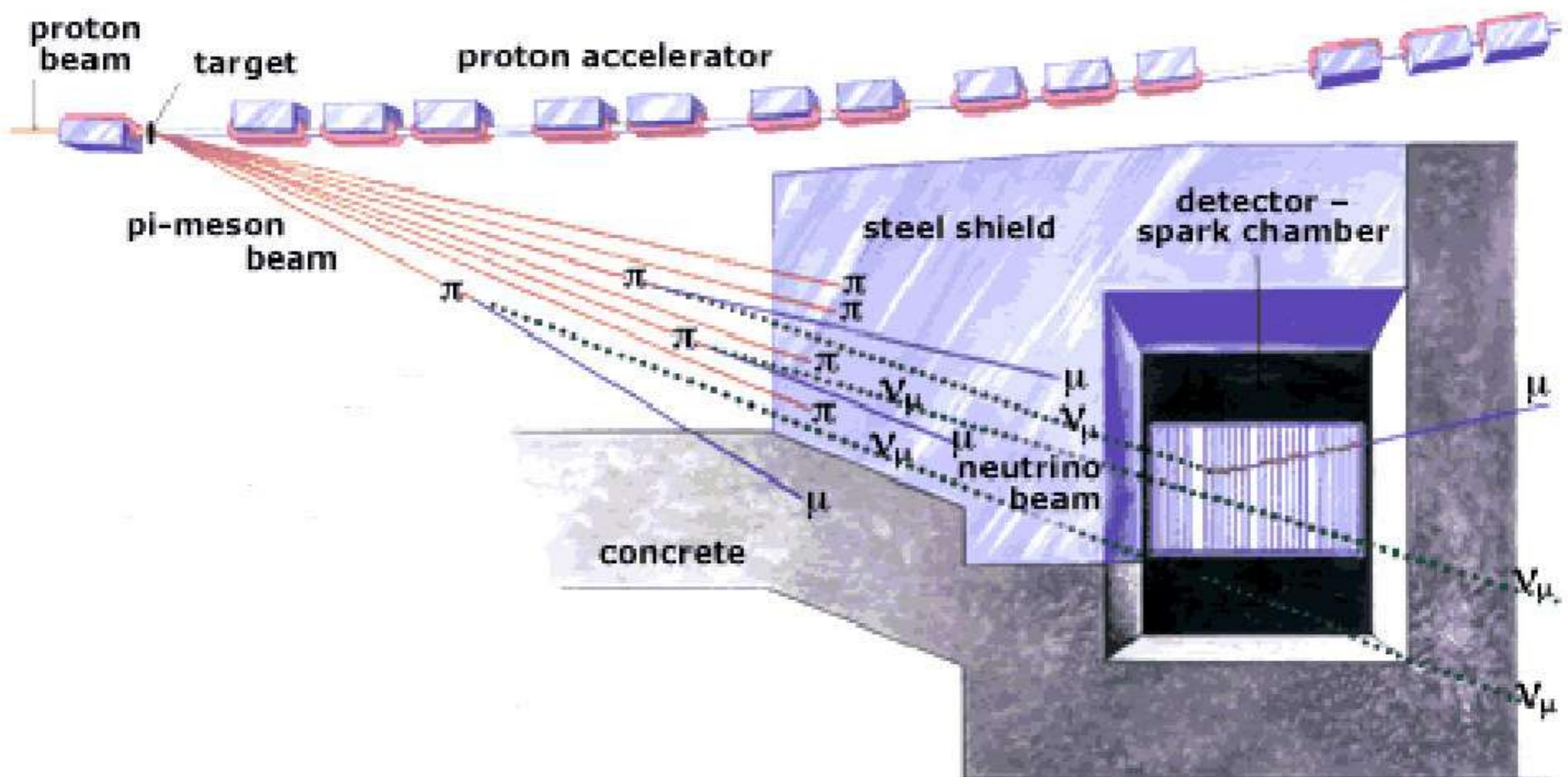


Conventional neutrino beam

First muon neutrino beam with accelerator in Brookhaven

AGS Proton Beam
Internal target

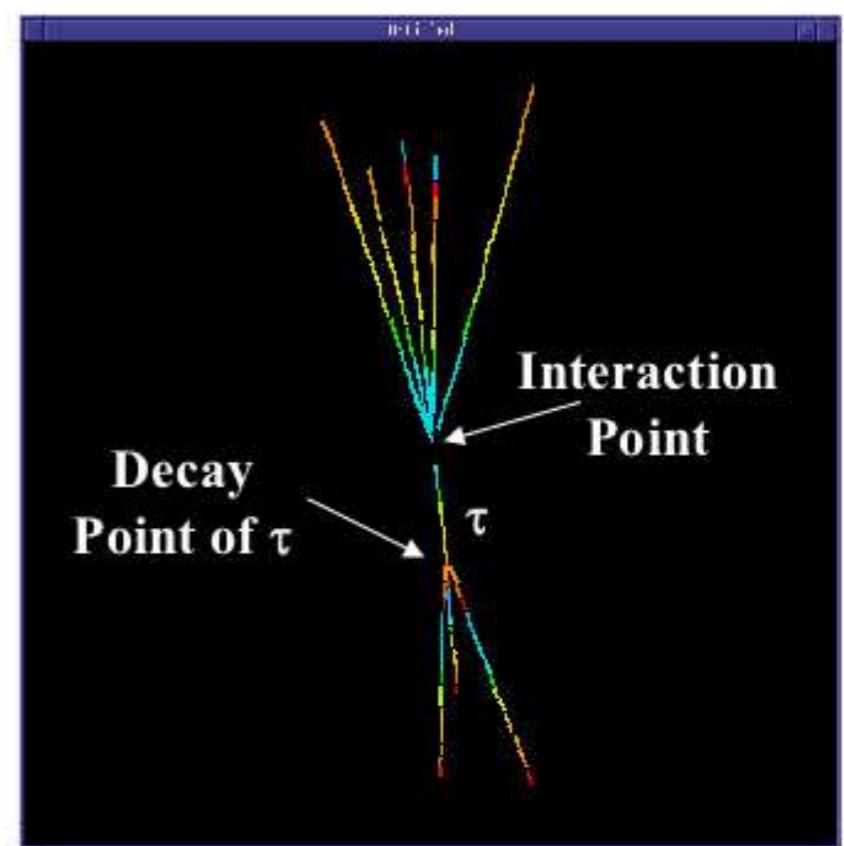
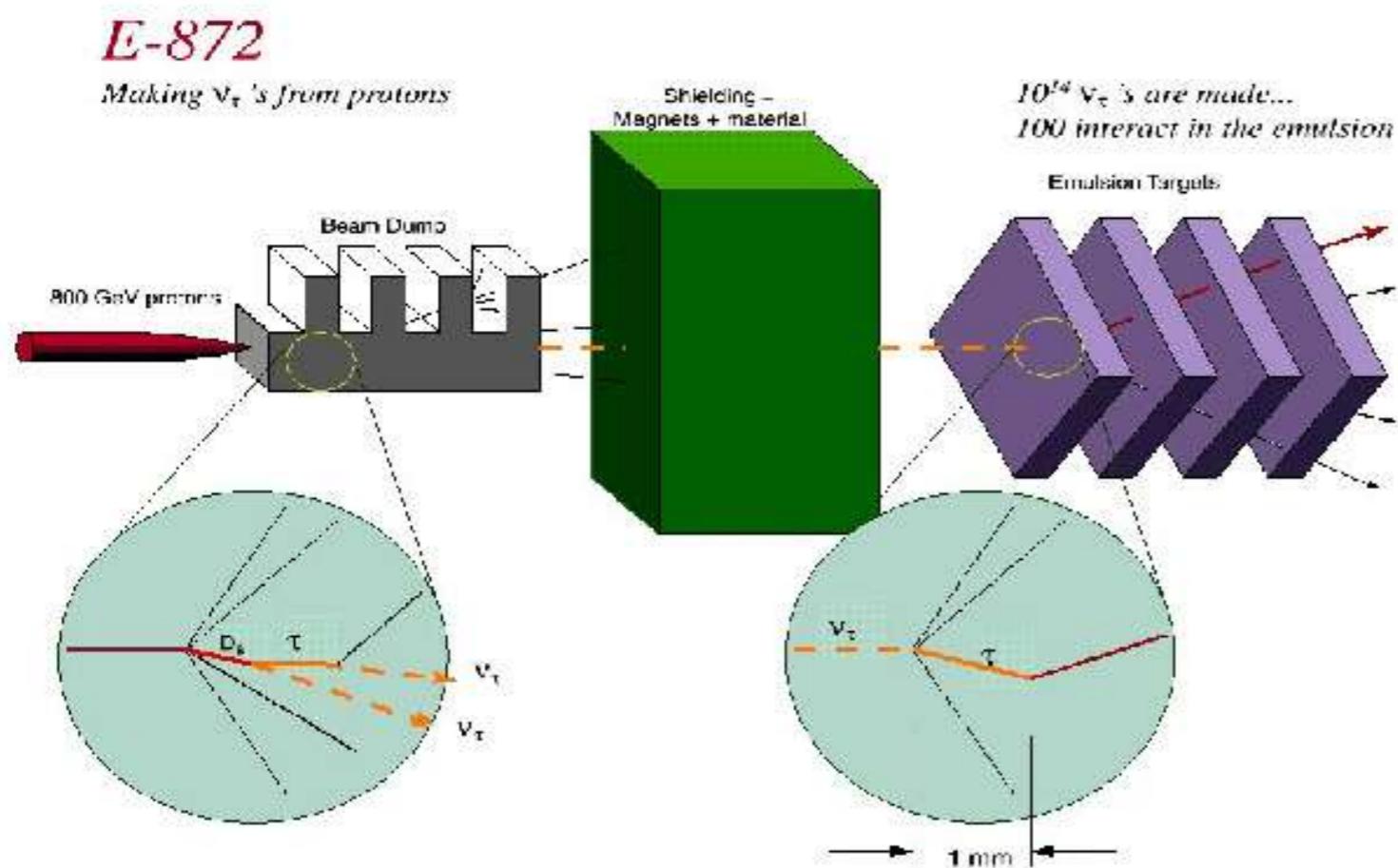
1962



The third neutrino - ν_τ

Beam dump neutrino source : suppress π , K decay and
enhance prompt decay ν source : ($D_s \rightarrow K + \tau + \nu_\tau$)

2000



Neutrino interaction and decay
of short lived particles

Facts of life for the neutrino experimenter...

Numerical example for typical accelerator-based experiment

$$N_{\text{obs}} = \left[\int \mathcal{F}(E_\nu) \sigma(E_\nu, \dots) \epsilon(E_\nu, \dots) dE_\nu d\dots \right] \frac{M}{A m_N} T$$

N_{obs} : number of neutrino events recorded

\mathcal{F} : Flux of neutrinos (#/cm²/s)

σ : neutrino cross section per nucleon $\simeq 0.7 \frac{E_\nu}{[\text{GeV}]} \times 10^{-38} \text{ cm}^2$

ϵ : detection efficiency

typical “super-beam” flux at
1000 km

M : total detector mass

A : effective atomic number of detector

m_N : nucleon mass

T : exposure time

typical accelerator
up time in one
year

$$N_{\text{obs}} = \left[\frac{1}{\text{cm}^2 \text{s}} \right] \left[0.7 \times 10^{-38} \frac{E_\nu}{\text{GeV}} \text{ cm}^2 \right] [\epsilon] [1 \text{ GeV}] \left[\frac{M}{20 \cdot 1.67 \times 10^{-27} \text{ kg}} \right] [2 \times 10^7 \text{ s}]$$

$$N_{\text{obs}} = 4 \times 10^{-6} \frac{E_\nu}{[\text{GeV}]} \epsilon \frac{M}{\text{kg}}$$

work at high energies if you can

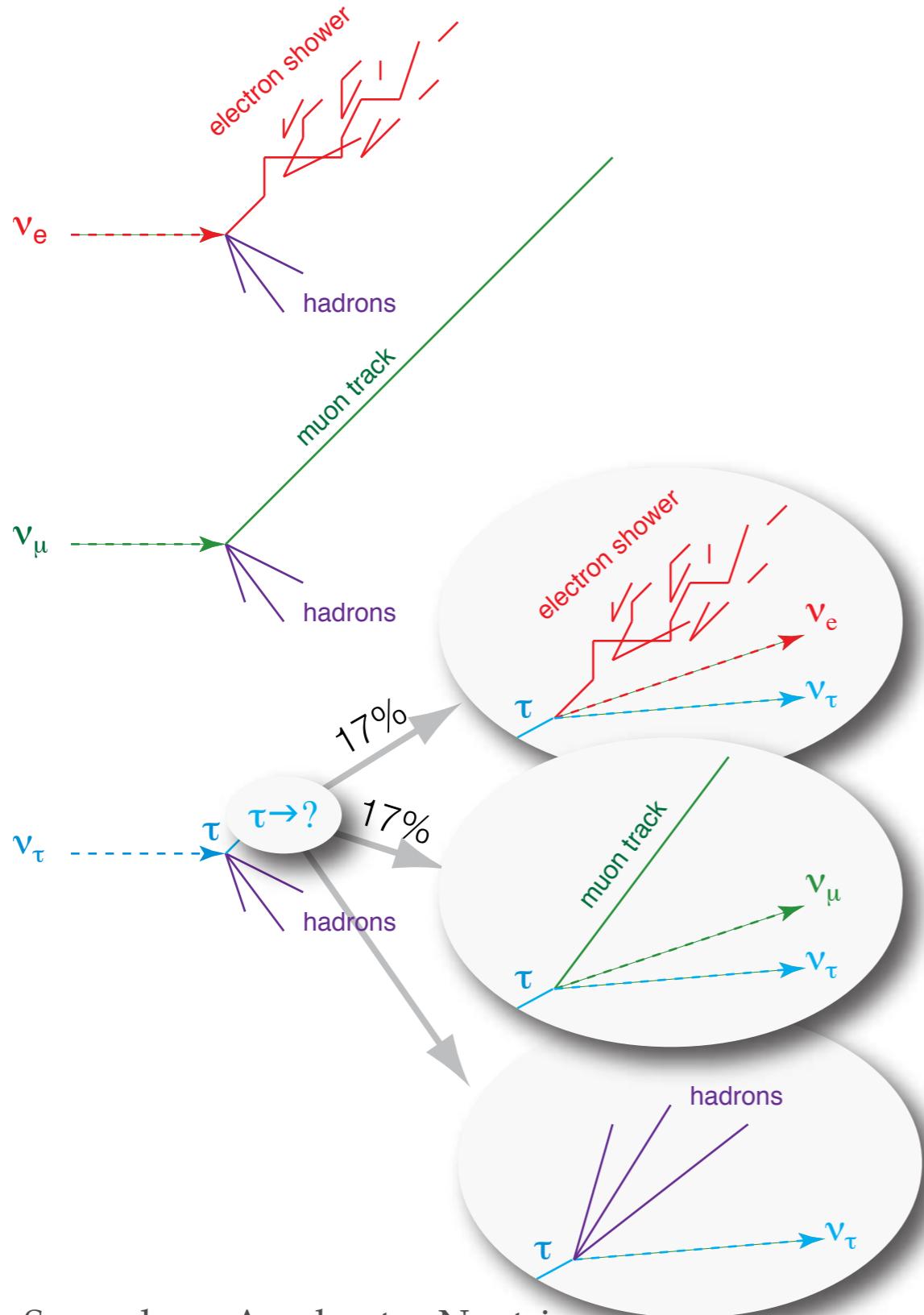
push this as high as you can

need detector masses of $10^6 \text{ kg} = 1 \text{ kton}$ to get in the game

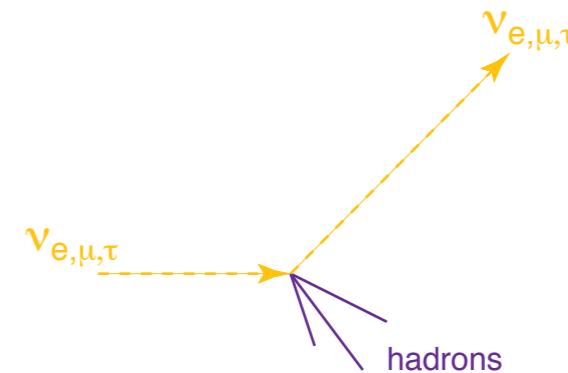
Challenge to the experimentalist: maximize efficiency and detector mass while minimizing cost

Neutrino detection channels

Charged-current

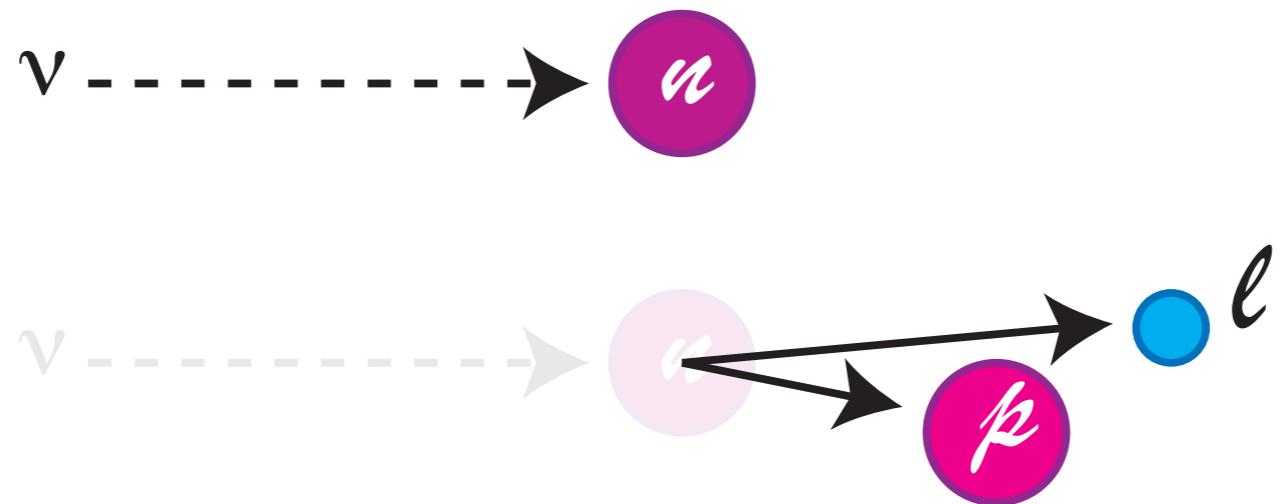


Neutral-current



- In charged-current (CC) events outgoing lepton tags incoming neutrino flavor.
 - ▶ In the case of ν_τ , the presence of a τ must be deduced from the τ decay products
- In CC events nearly all the neutrino energy is deposited in the detector
- In neutral-current events, only hadrons are present and no information about the incident neutrino flavor is available
- CC rates are affected by oscillations
- NC rates are not affected by oscillations
 - ▶ In only a few analyses are NC events considered to be signal. In most cases NC events are backgrounds to the CC processes

Production thresholds

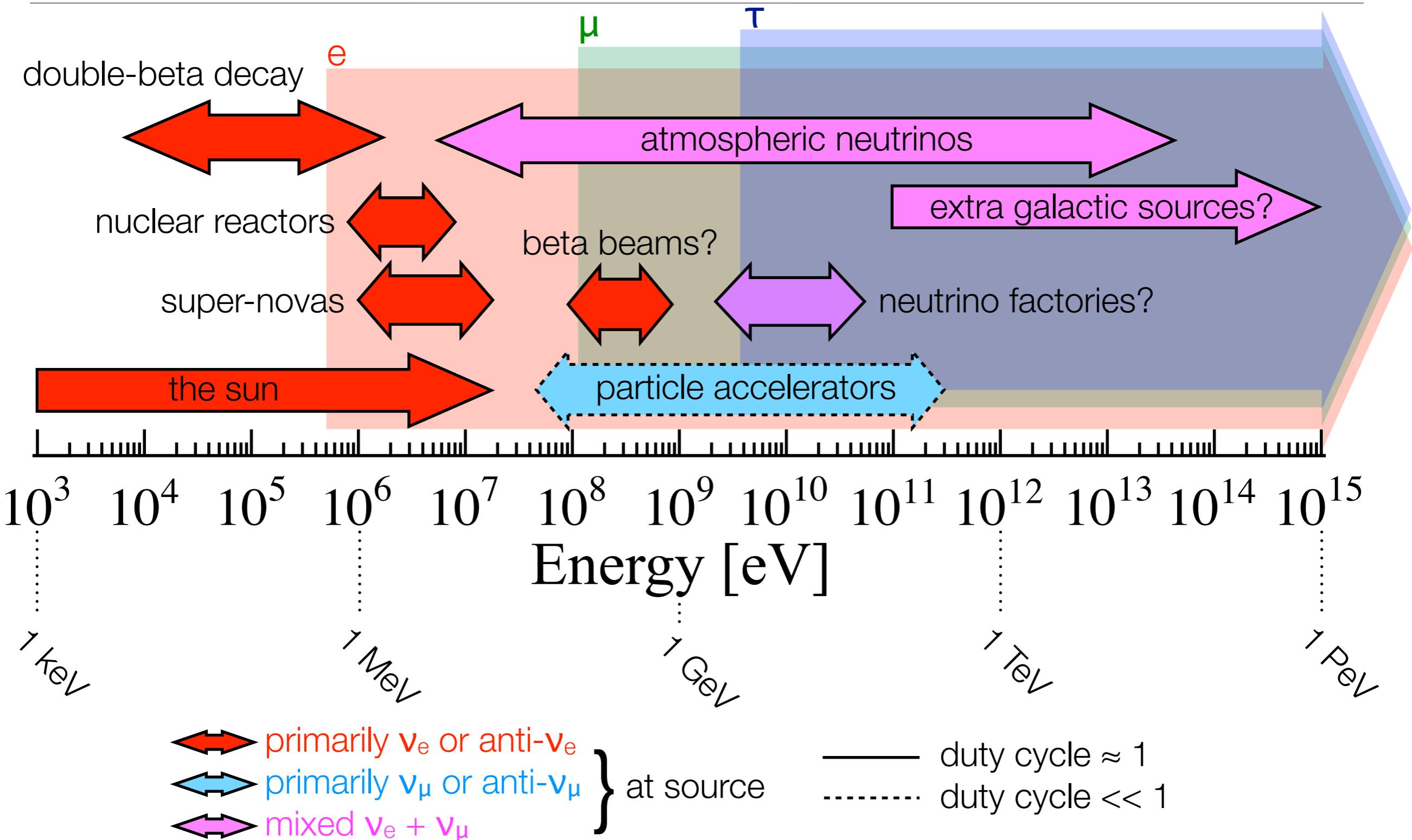


$$l = e \quad m_e = 0.511 \text{ MeV} \quad P_{\text{thresh}} = 0.511 \text{ MeV}$$

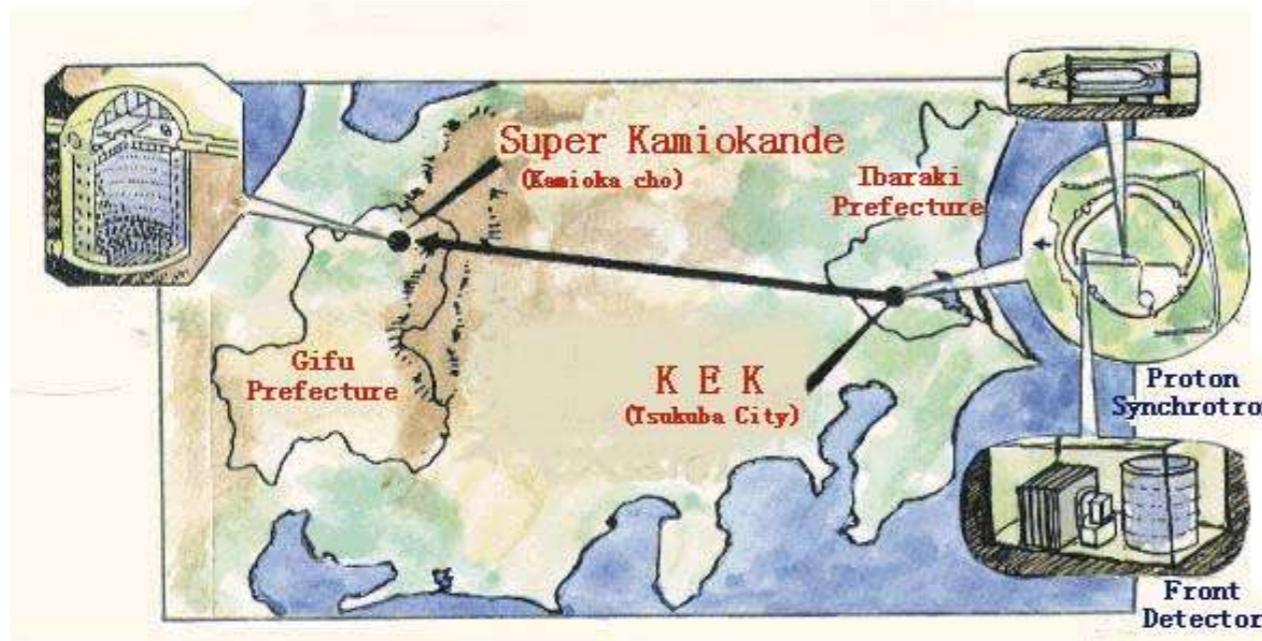
$$l = \mu \quad m_\mu = 106 \text{ MeV} \quad P_{\text{thresh}} = 112 \text{ MeV}$$

$$l = \tau \quad m_\tau = 1.78 \text{ GeV} \quad P_{\text{thresh}} = 3.47 \text{ GeV}$$

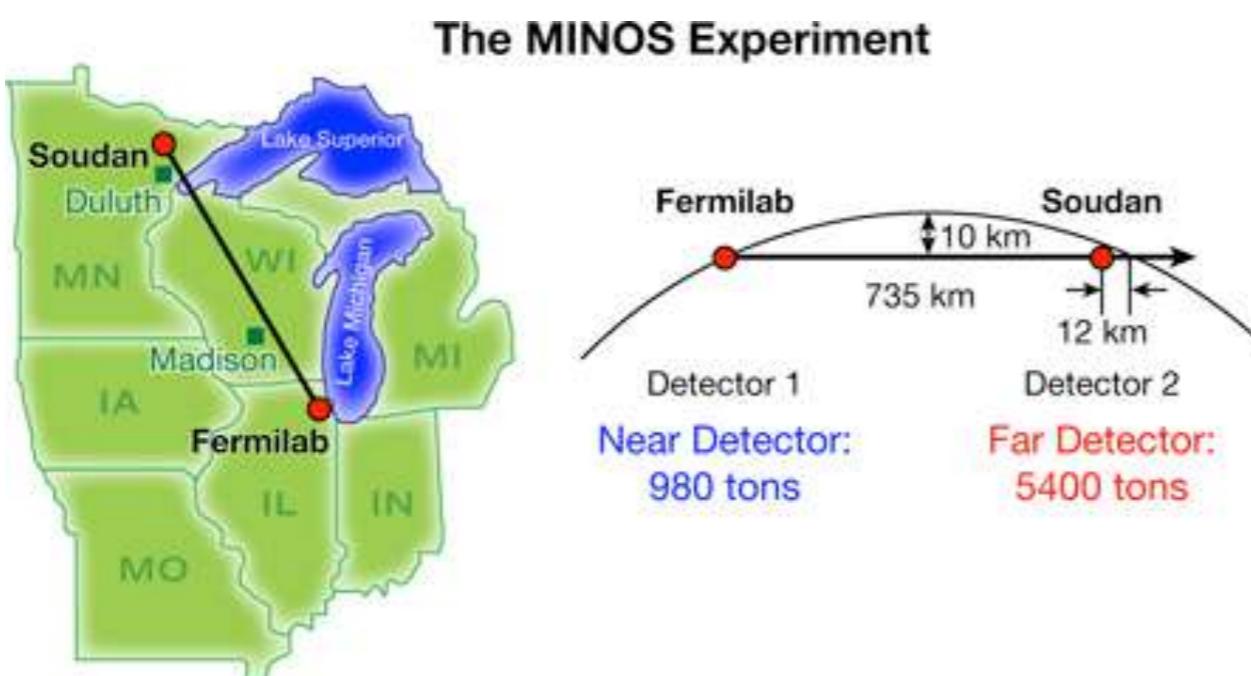
Sources for neutrino detectors



First generation accelerator-based long baseline experiments: K2K and MINOS

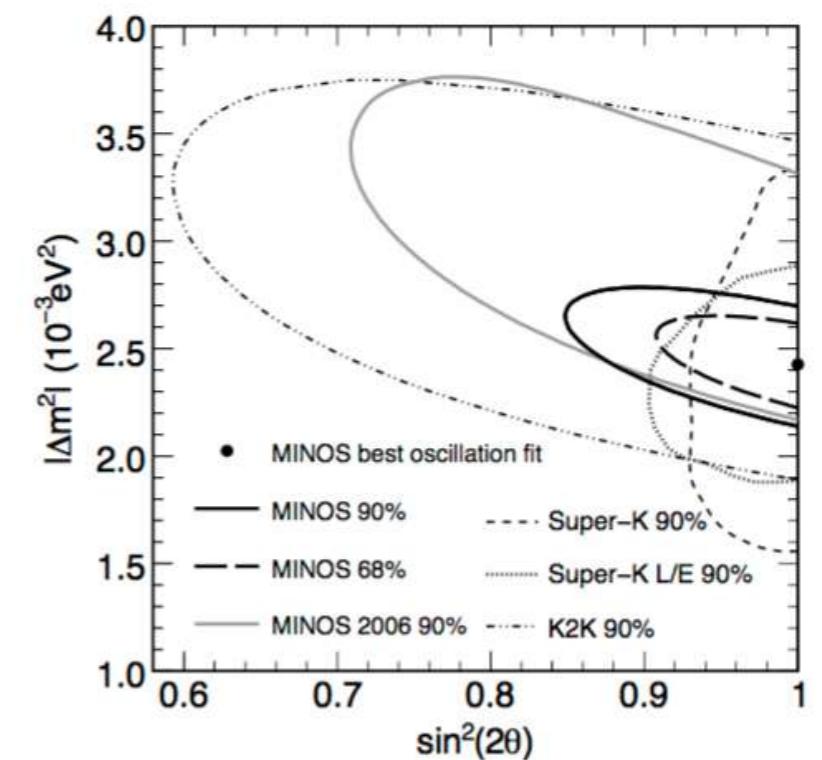
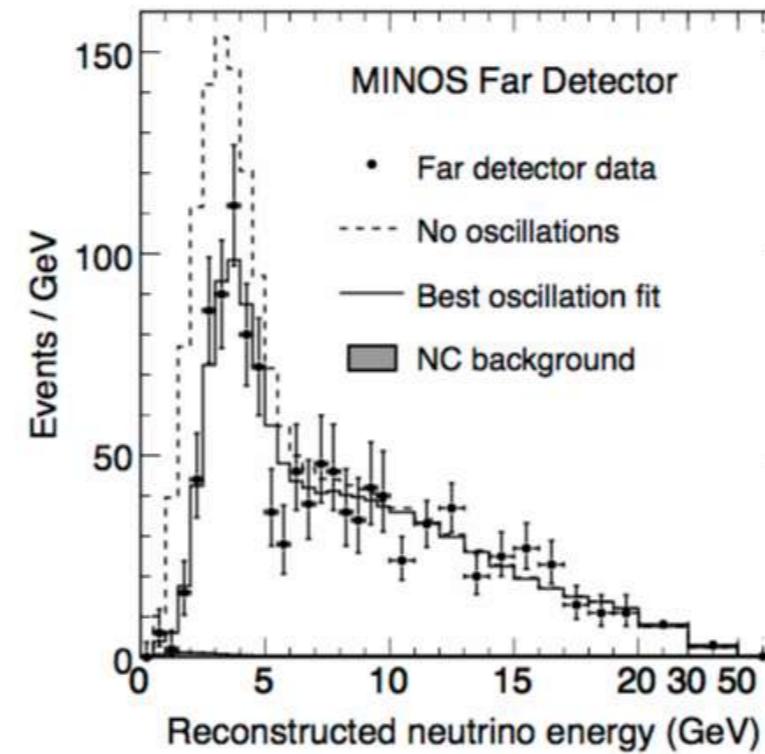
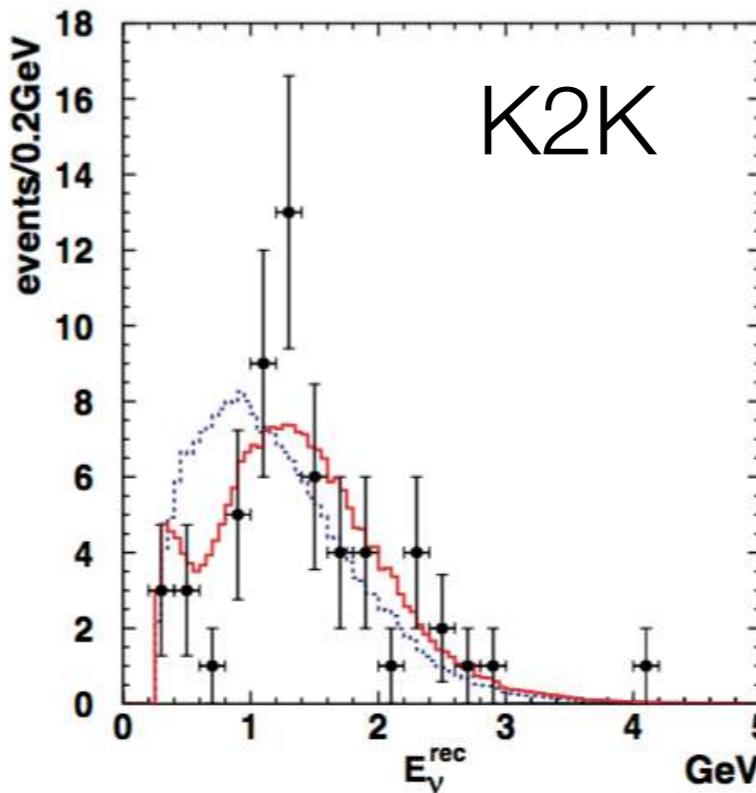


- ❖ Beam generated at KEK
- ❖ Neutrinos detected at Super-Kamiokande (Water Cherenkov Detector)
- ❖ Baseline of 250 km
- ❖ Operated 1999-2004



- ❖ Beam generated at Fermilab
- ❖ Neutrinos detected at magnetized steel far detector (5.4 kilo-ton) in Soudan mine
- ❖ Baseline of 735 km
- ❖ Operated 2005-2012(2016)

First generation accelerator-based long baseline experiments: K2K and MINOS



$$P_{\mu \rightarrow \mu} = 1 - (\sin^2 2\theta_{23} - \sin^2 \theta_{23} \cos 2\theta_{23} \sin^2 2\theta_{13}) \sin^2 \left(\frac{\Delta m_{32}^2 L}{4E_\nu} \right) + \dots$$

- ❖ The experiments were able to measure $|\Delta m_{32}^2|$
- ❖ Important for building the current generation of neutrino experiments (L/E)

Current generation accelerator-based long baseline experiments: T2K and NOvA

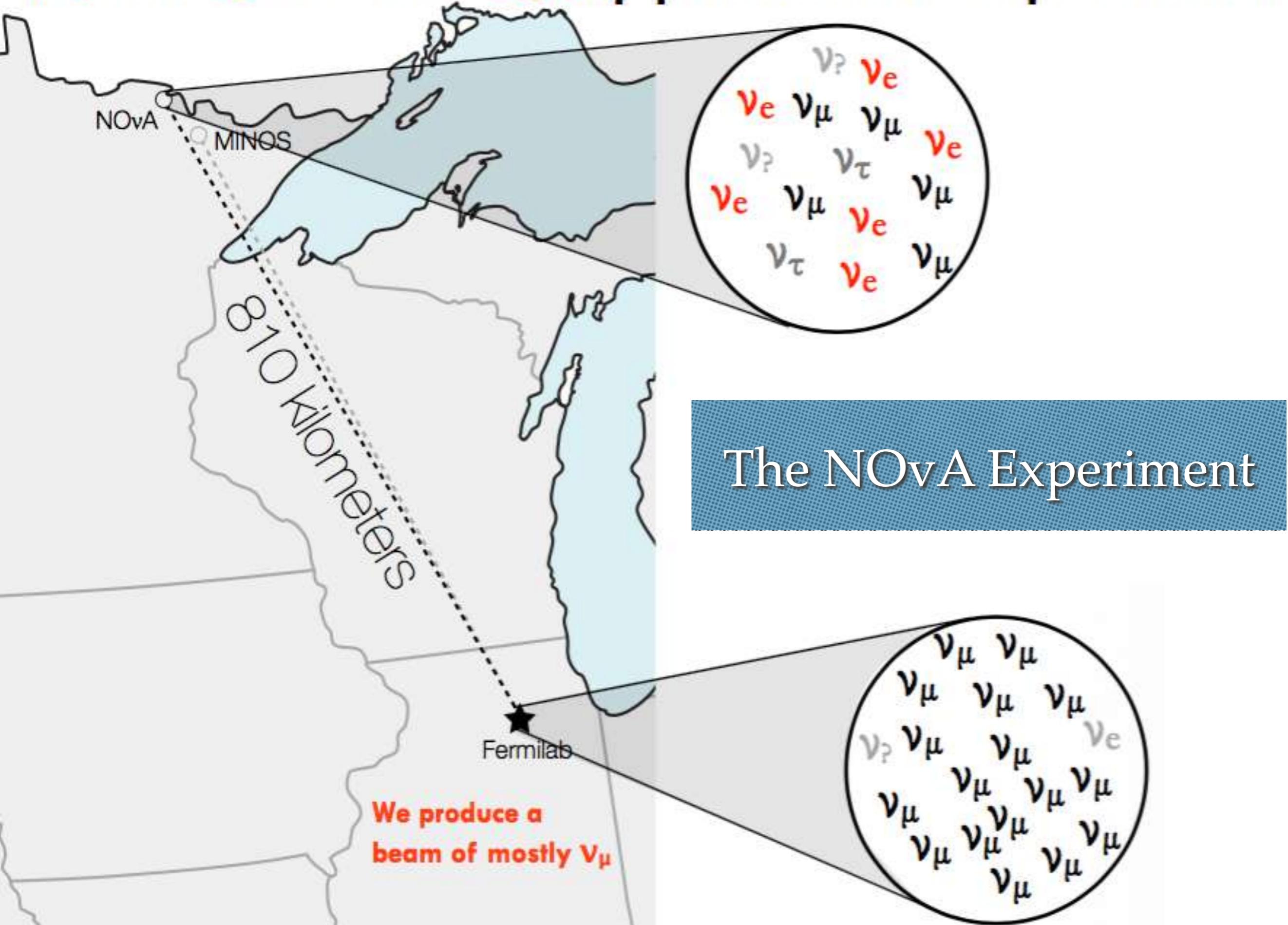


- ❖ Beam from J-PARC (Tokai)
- ❖ Neutrinos detected at Super-Kamiokande
- ❖ Baseline of 295 km
- ❖ Operating since 2009



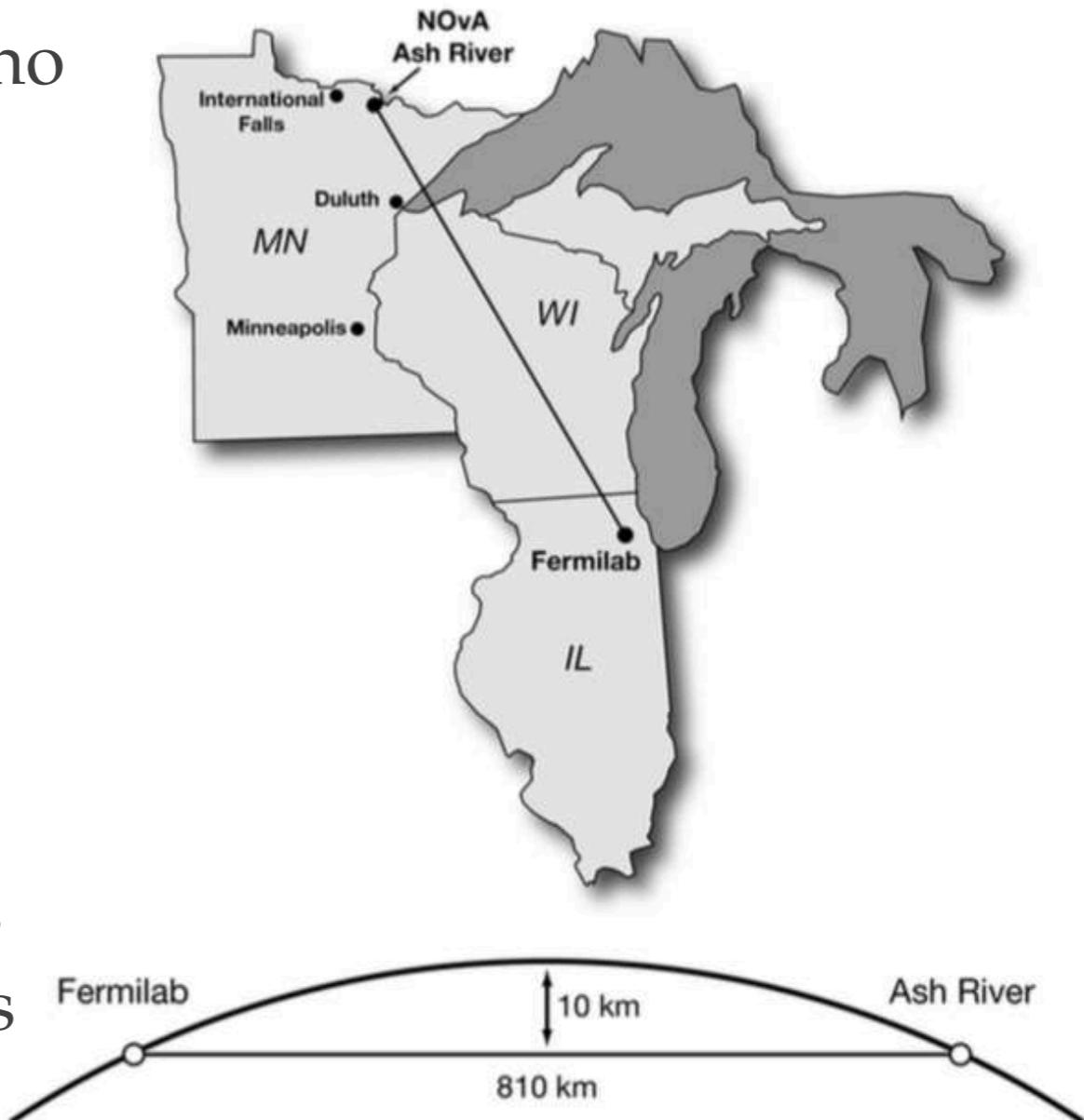
- ❖ Beam generated at Fermilab
- ❖ Neutrinos detected at segmented liquid scintillator detector in Ash River
- ❖ Baseline of 810 km
- ❖ Operating since 2014

NuMI Off-axis ν_e Appearance Experiment



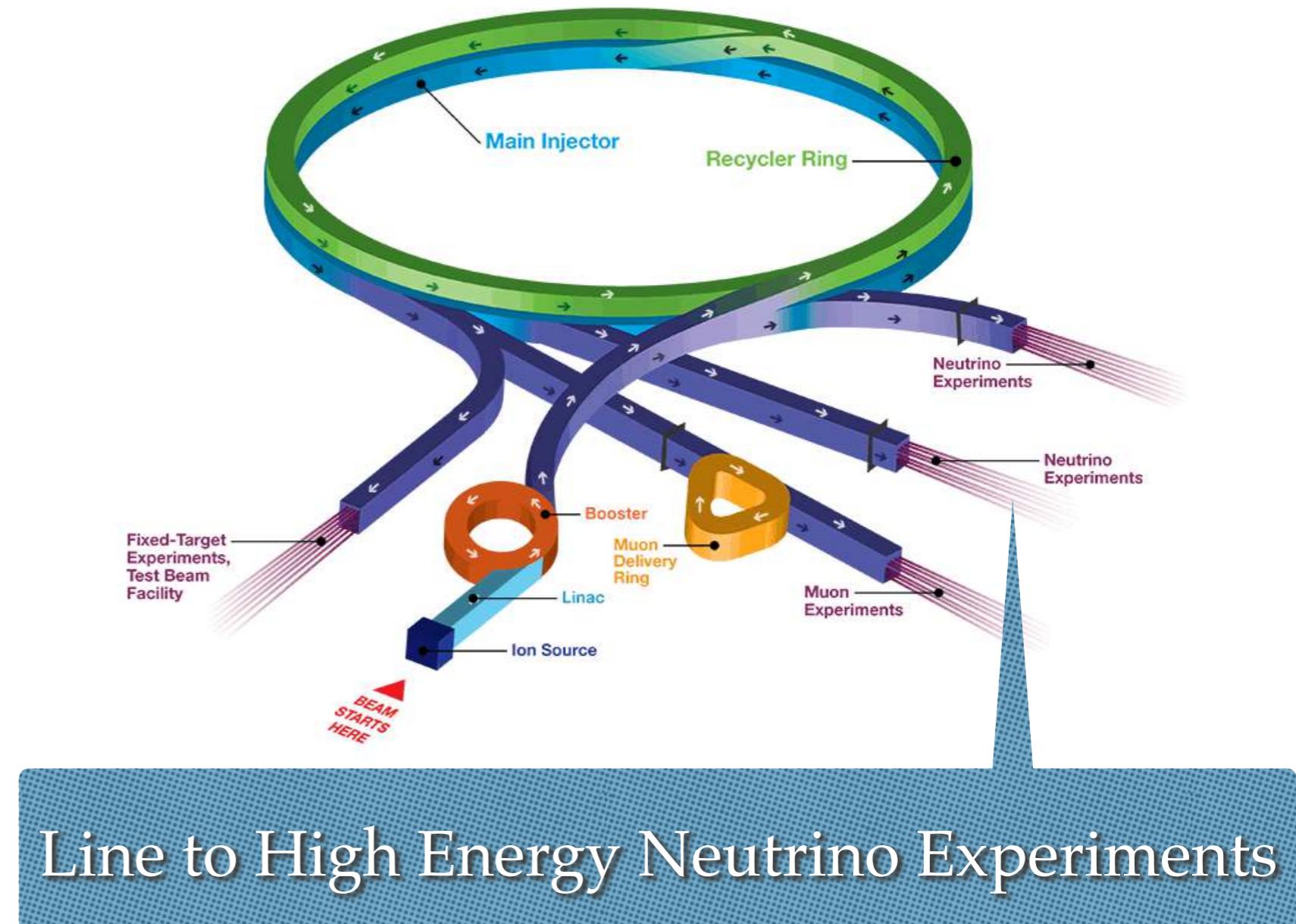
The NOvA Experiment

- ❖ NOvA experiment goals:
 - Using electron neutrino and antineutrino appearance mode
 - neutrino mass hierarchy
 - CP violating phase
 - Using muon neutrino and antineutrino disappearance mode
 - mixing angle θ_{23} octant
 - precision measurement Δm^2_{32}
 - Other tasks: search for sterile neutrinos via NC channel, neutrino cross-sections in the near detector, supernova, monopoles, dark matter, cosmic rays, etc.



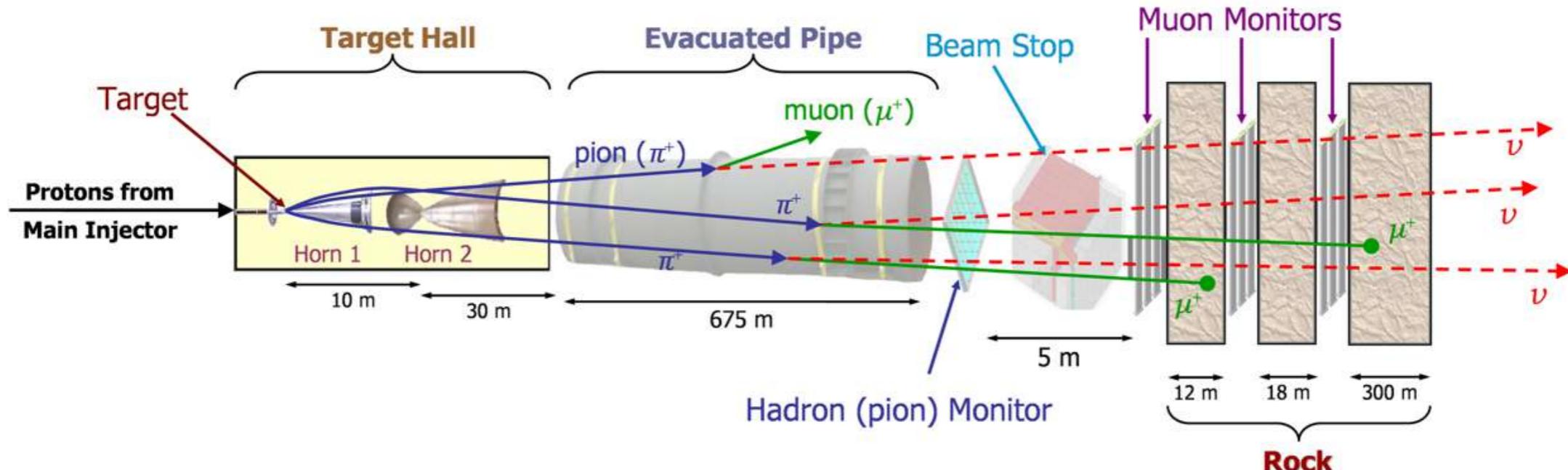
Fermilab accelerator complex

- ❖ Neutrinos produced at Main Injector (NuMI)
 - Linac 750 keV
 - Booster 400 MeV
 - Recycler 8 GeV
 - NuMI 120 GeV
 - to Carbon target



Line to High Energy Neutrino Experiments

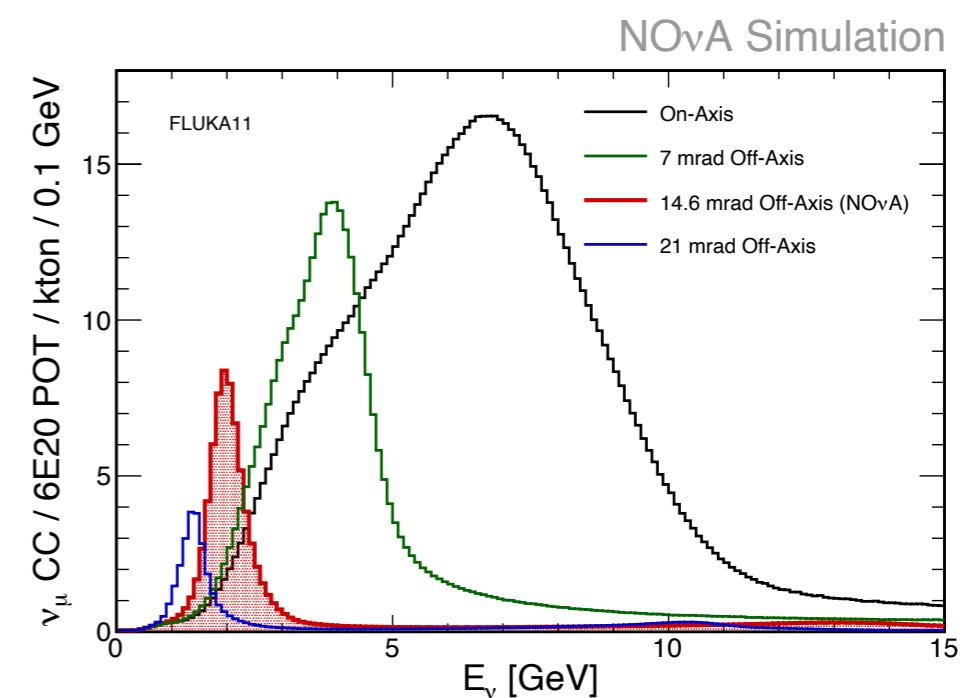
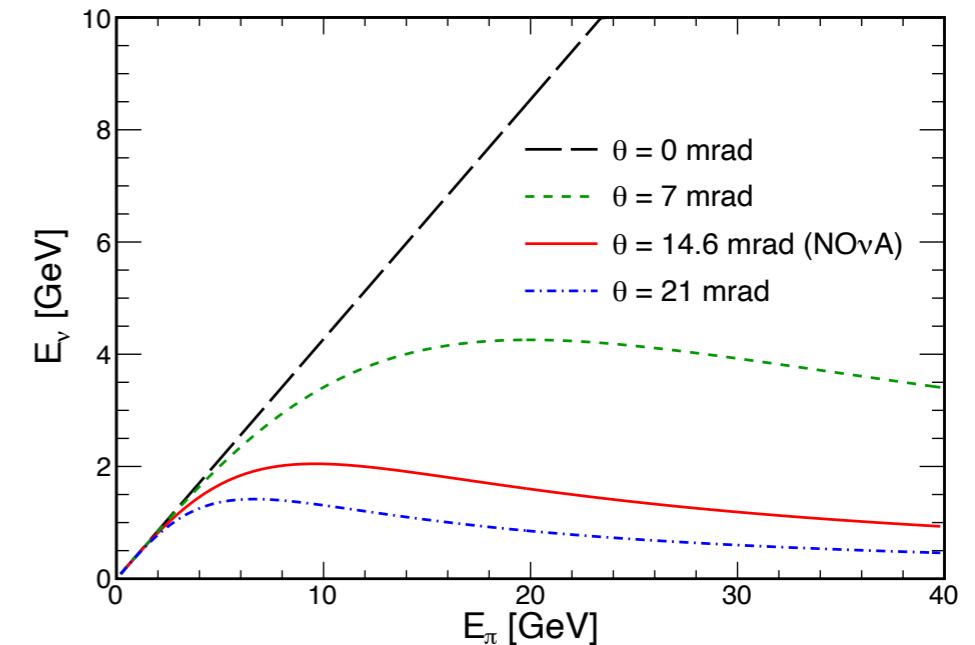
Neutrino flux



- ❖ 120 GeV protons on a carbon target, produce mesons which yield neutrinos.
- ❖ NOvA is designed for the 700 kW NuMI beam, with 6×10^{20} POT/year. (POT = Proton On Target).
- ❖ Neutrinos produced every 1.3 sec in a spill with 6 doubled batches 10 μ s time window.

NuMI off-axis beam

- ❖ NOvA detectors are sited 14 mrad off the NuMI beam axis
- ❖ With the medium-energy NuMI tune, yields a narrow 2-GeV spectrum at the both NOvA detectors
- ❖ Reduces NC and ν_e CC backgrounds in the oscillation analysis while maintaining high ν_μ flux at 2 GeV



Two detector scheme

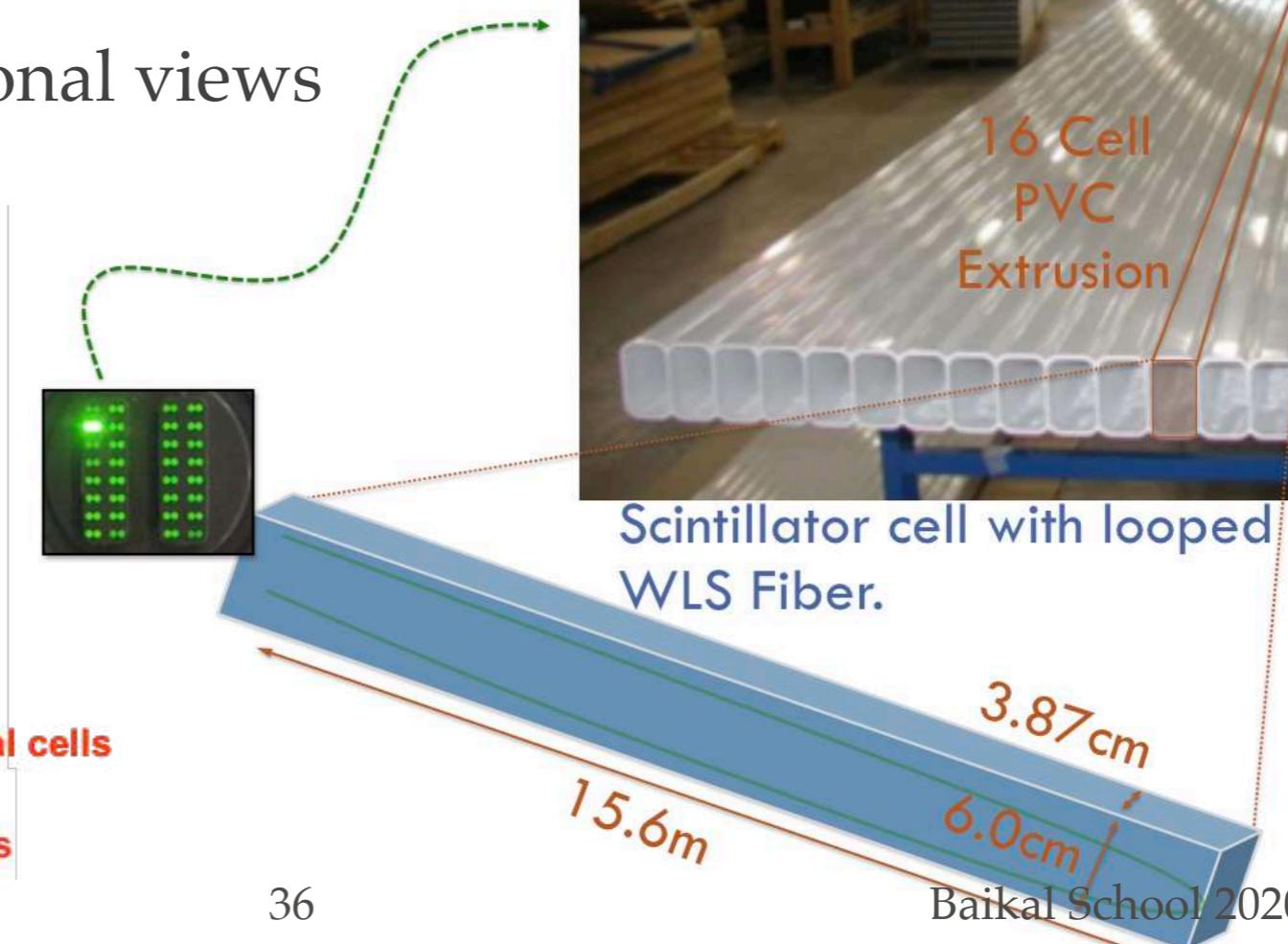
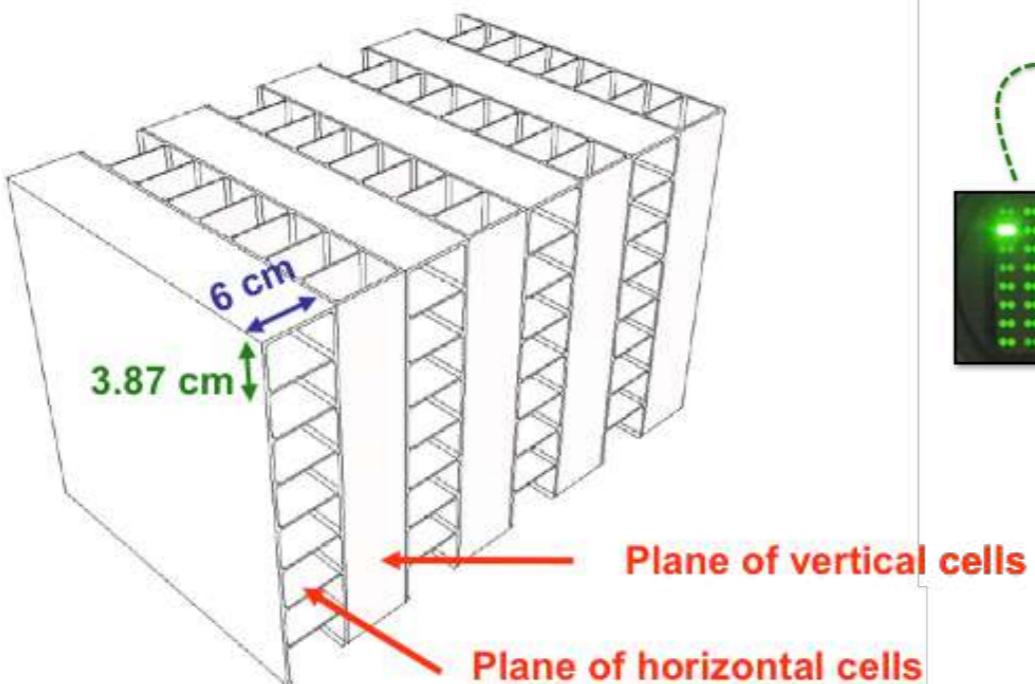
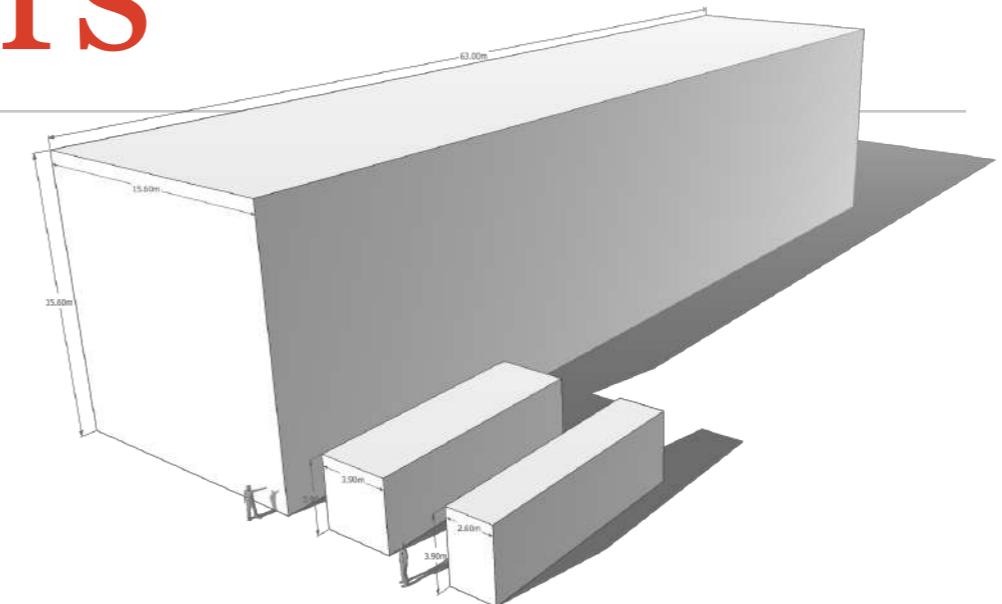


- ❖ **Near detector**
 - 1 km after target, weight 300 t
 - measure flux composition before oscillations
 - ND data used for prediction in FD (extrapolation procedure)

- ❖ **Far detector**
 - 810 km after target, weight 14 kt
 - measure neutrino flux after oscillations
 - extrapolation systematics
 - FD identical to ND

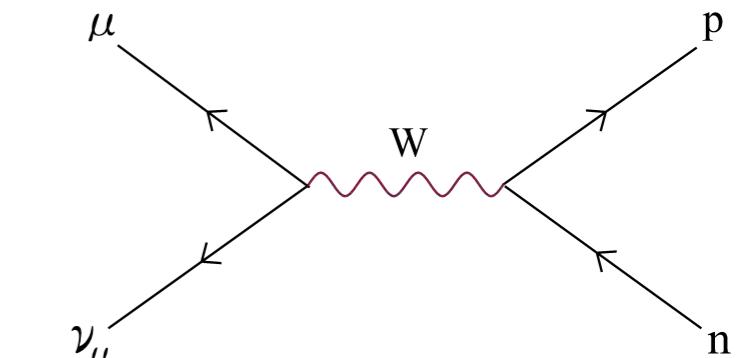
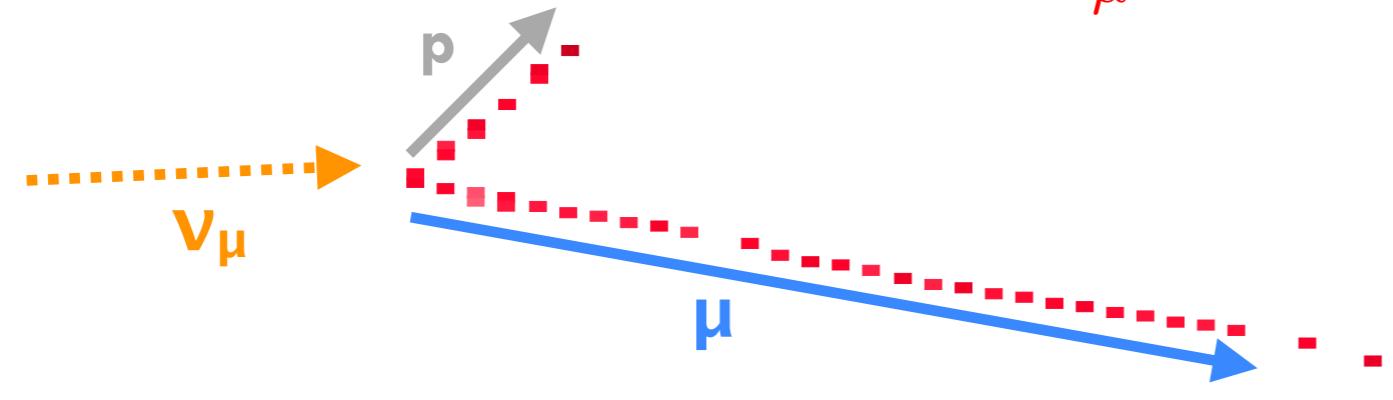
The NOvA Detectors

- ❖ PVC extrusion + Liquid Scintillator
- mineral oil + 5% pseudocumene
- ❖ Read out via WLS fiber to APD
- FD has ~344,000 channels
- muon crossing far end ~40 PE
- ❖ Layered planes of orthogonal views

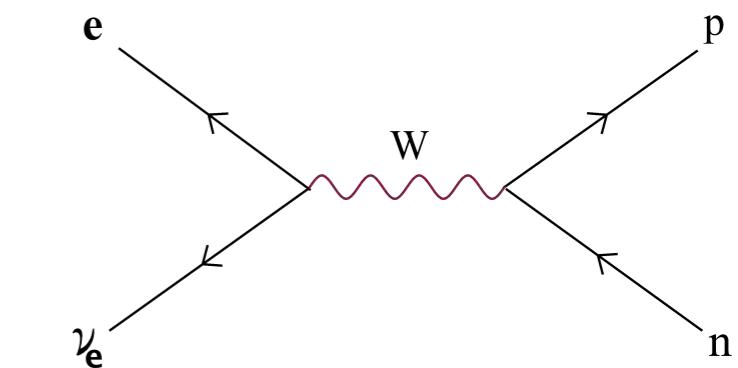
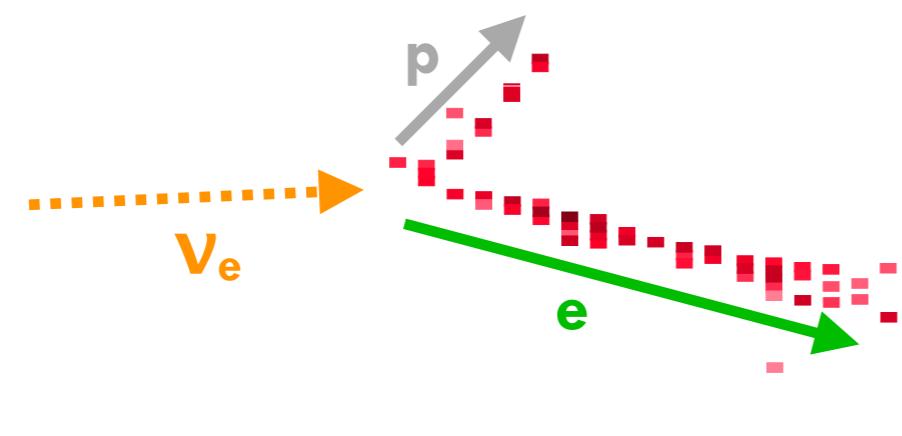


Topology of Events

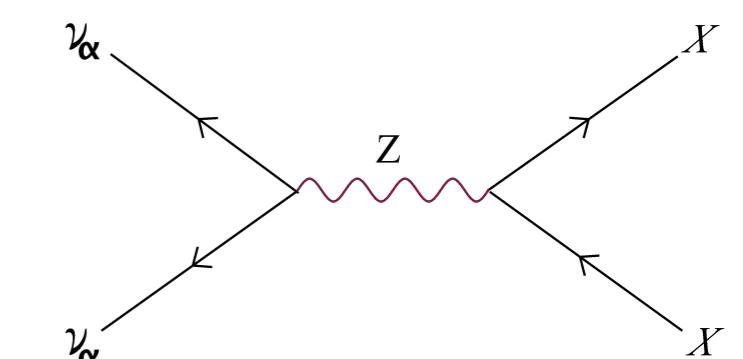
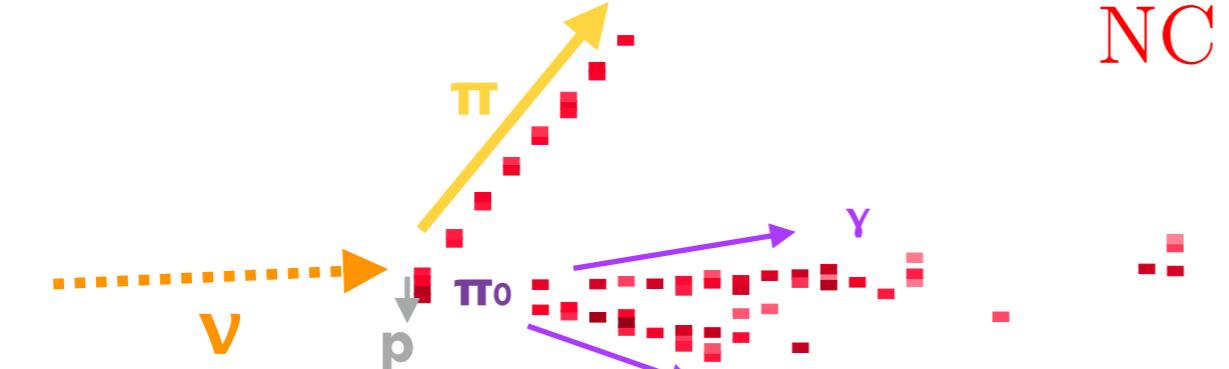
$\nu_\mu CC$



$\nu_e CC$



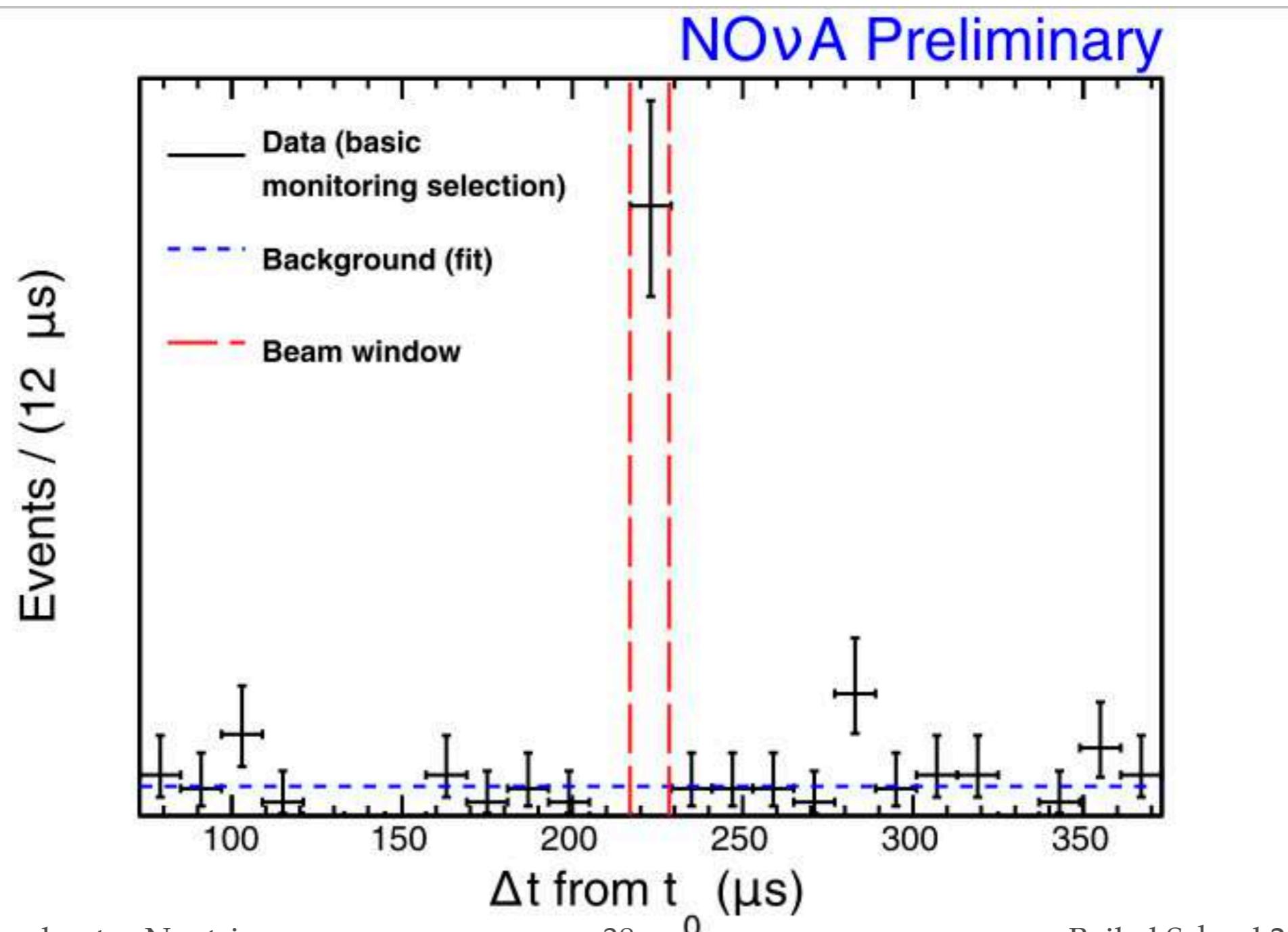
NC



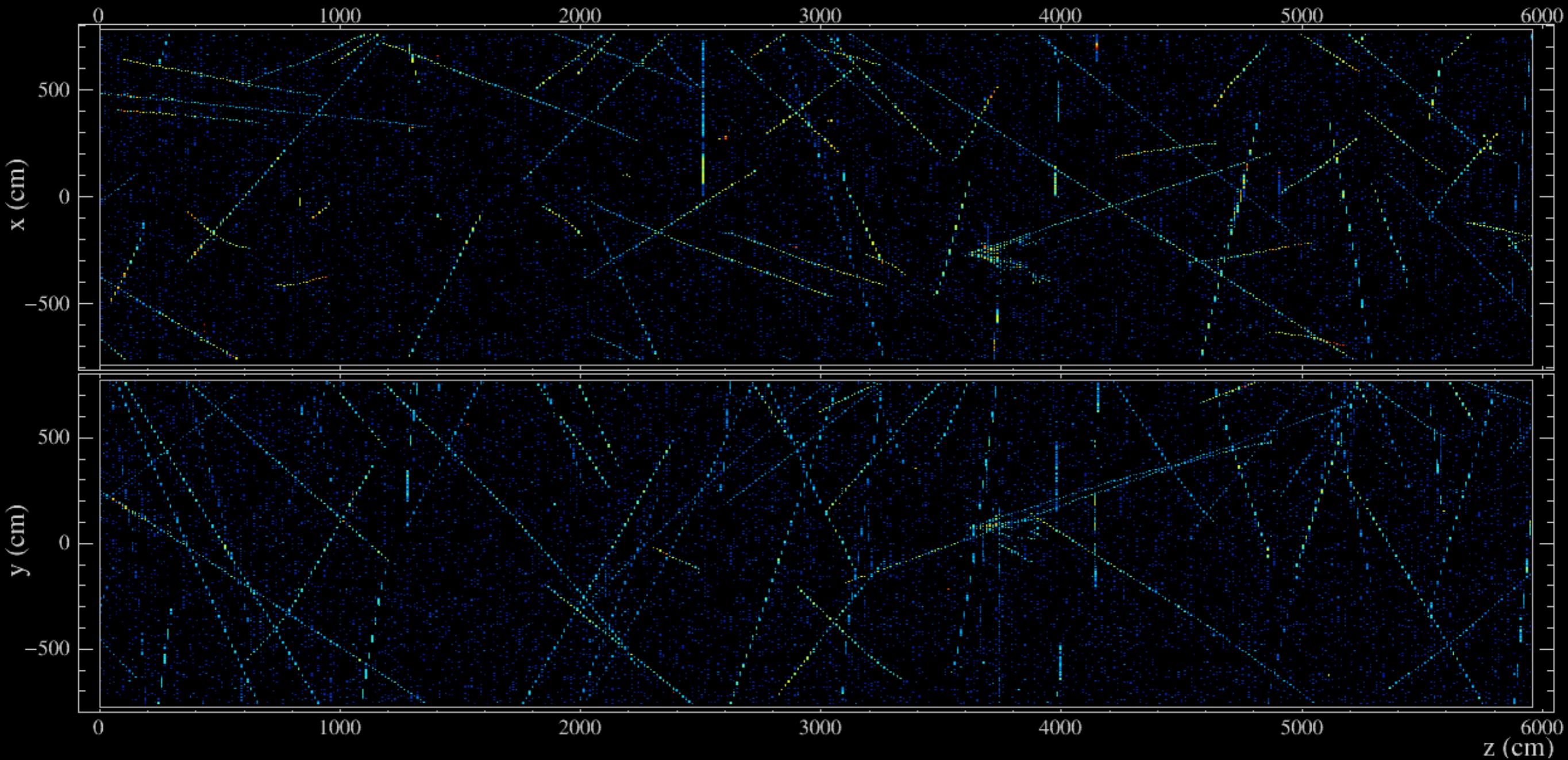
10 10² 10³ q (ADC)

FD Beam Peak

- ❖ Trigger structure: 550 μs window, NuMI neutrinos arrive for 10 μs starting at 218 μs

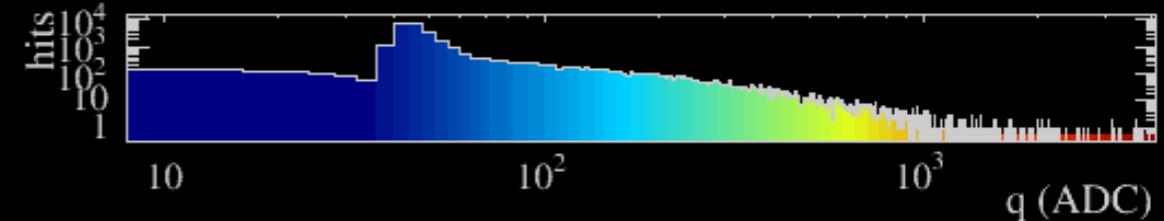
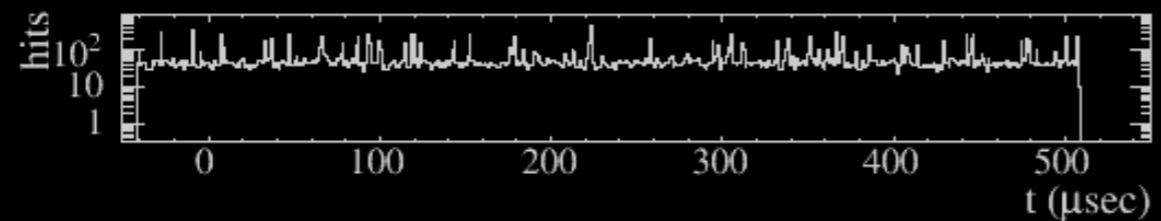


550 μ s exposure of the Far Detector

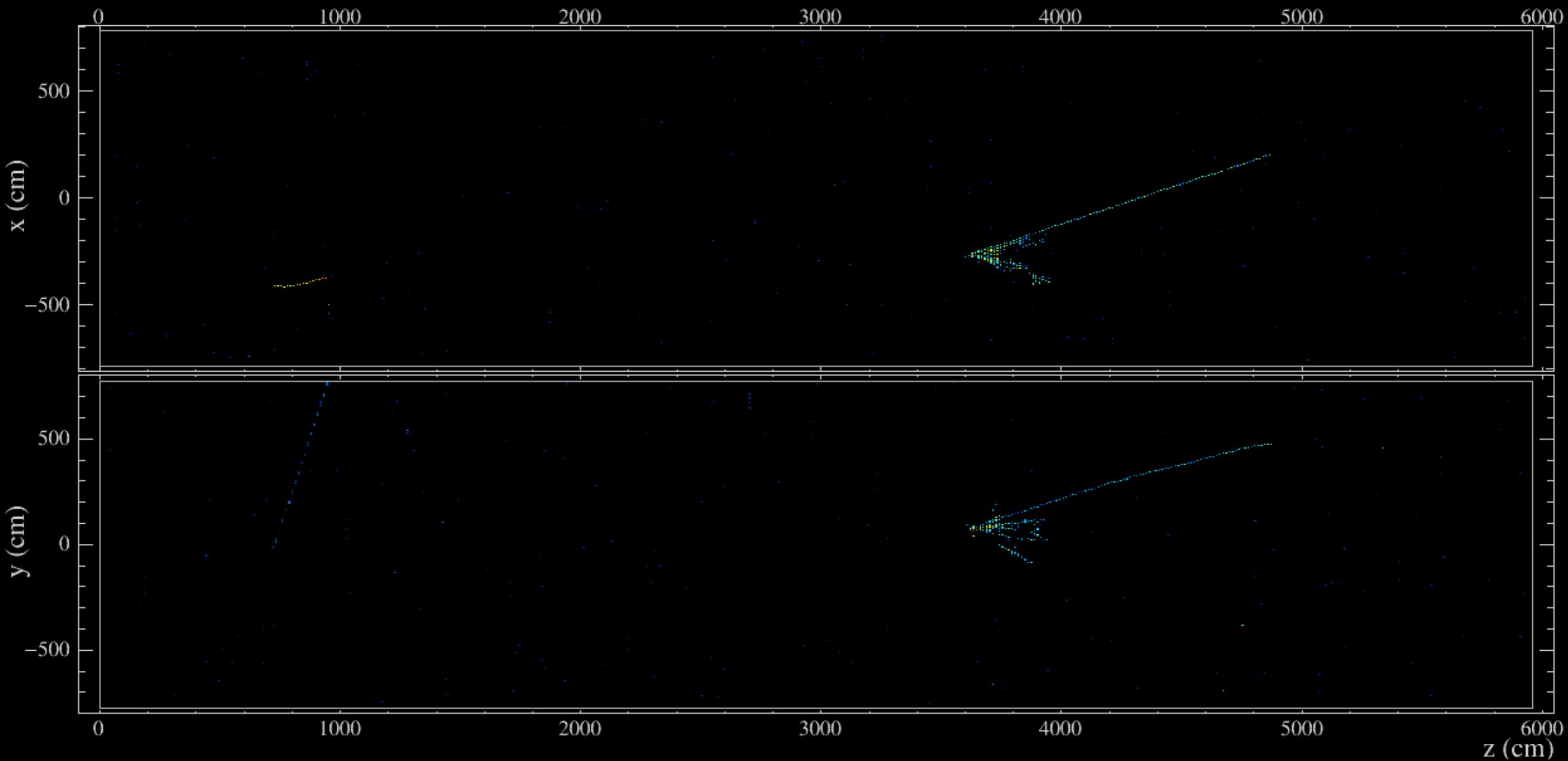


NOvA - FNAL E929

Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608

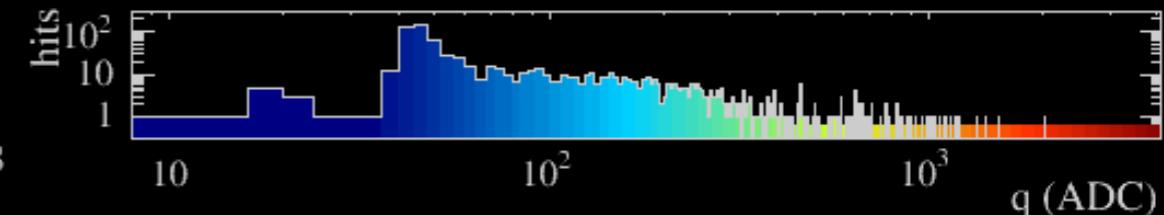
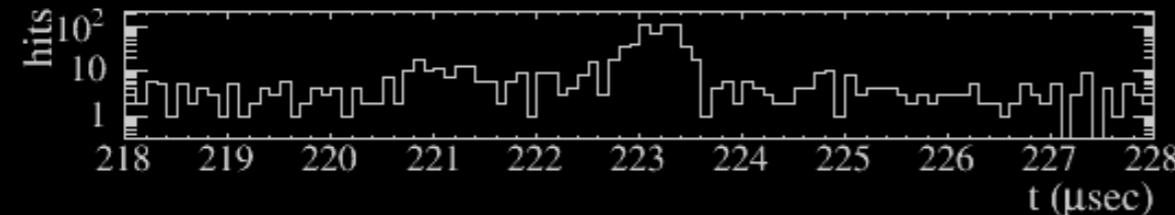


Time-zoom on 10 μ s interval during NuMI beam pulse

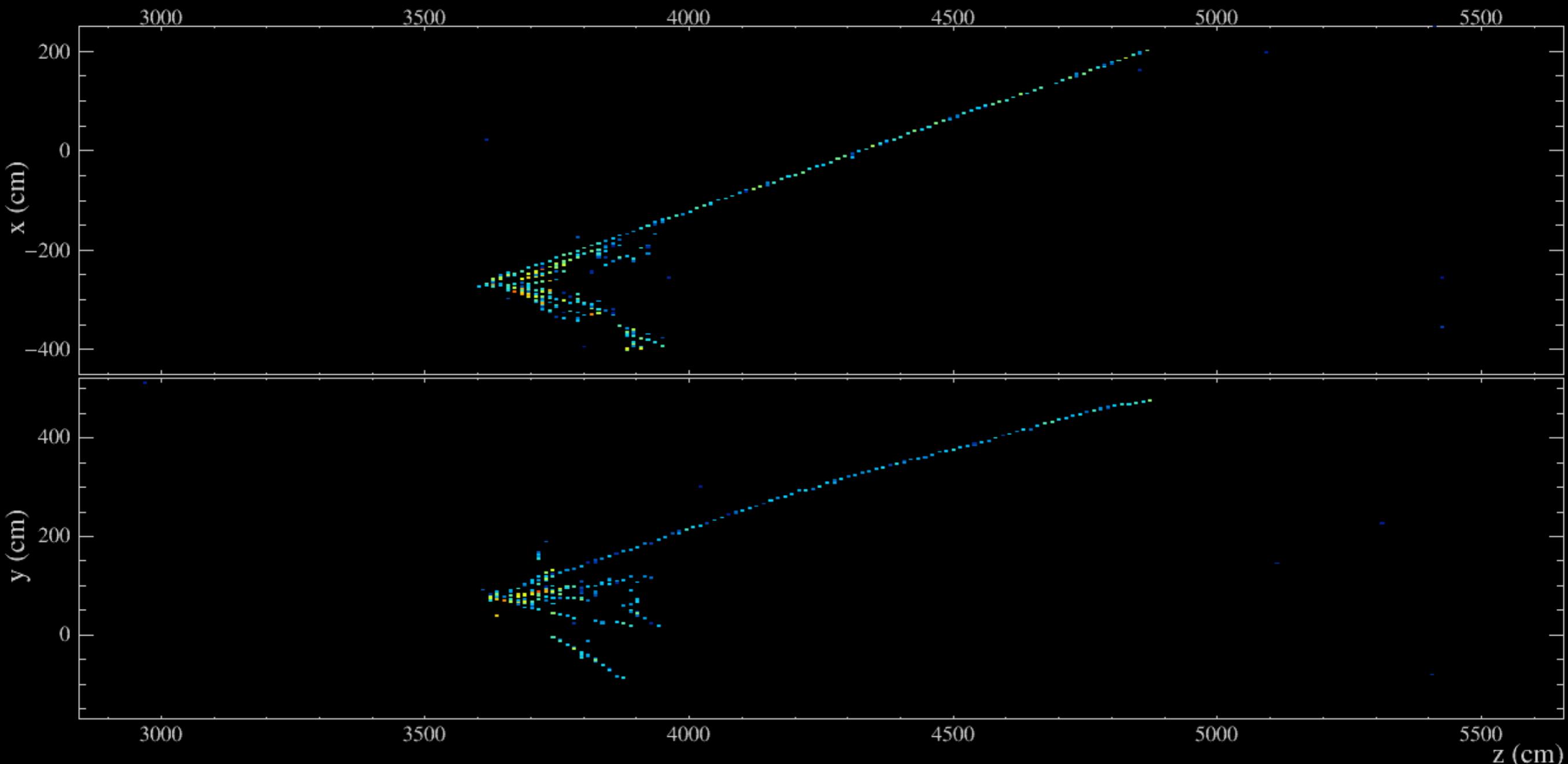


NOvA - FNAL E929

Run: 18620 / 13
Event: 178402 / --
UTC Fri Jan 9, 2015
00:13:53.087341608



Close-up of neutrino interaction in the Far Detector



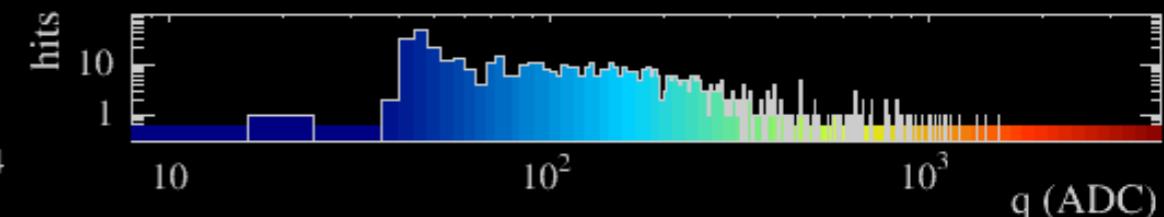
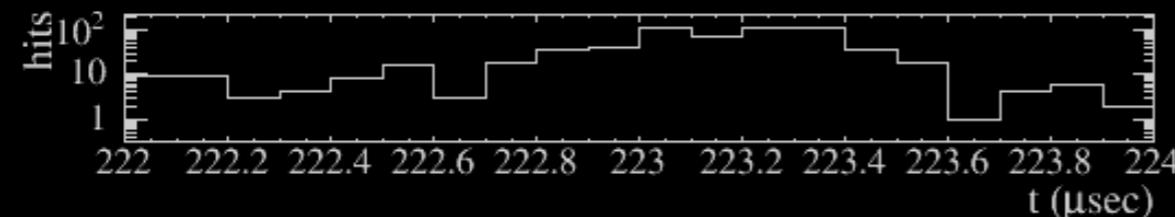
NOvA - FNAL E929

Run: 18620 / 13

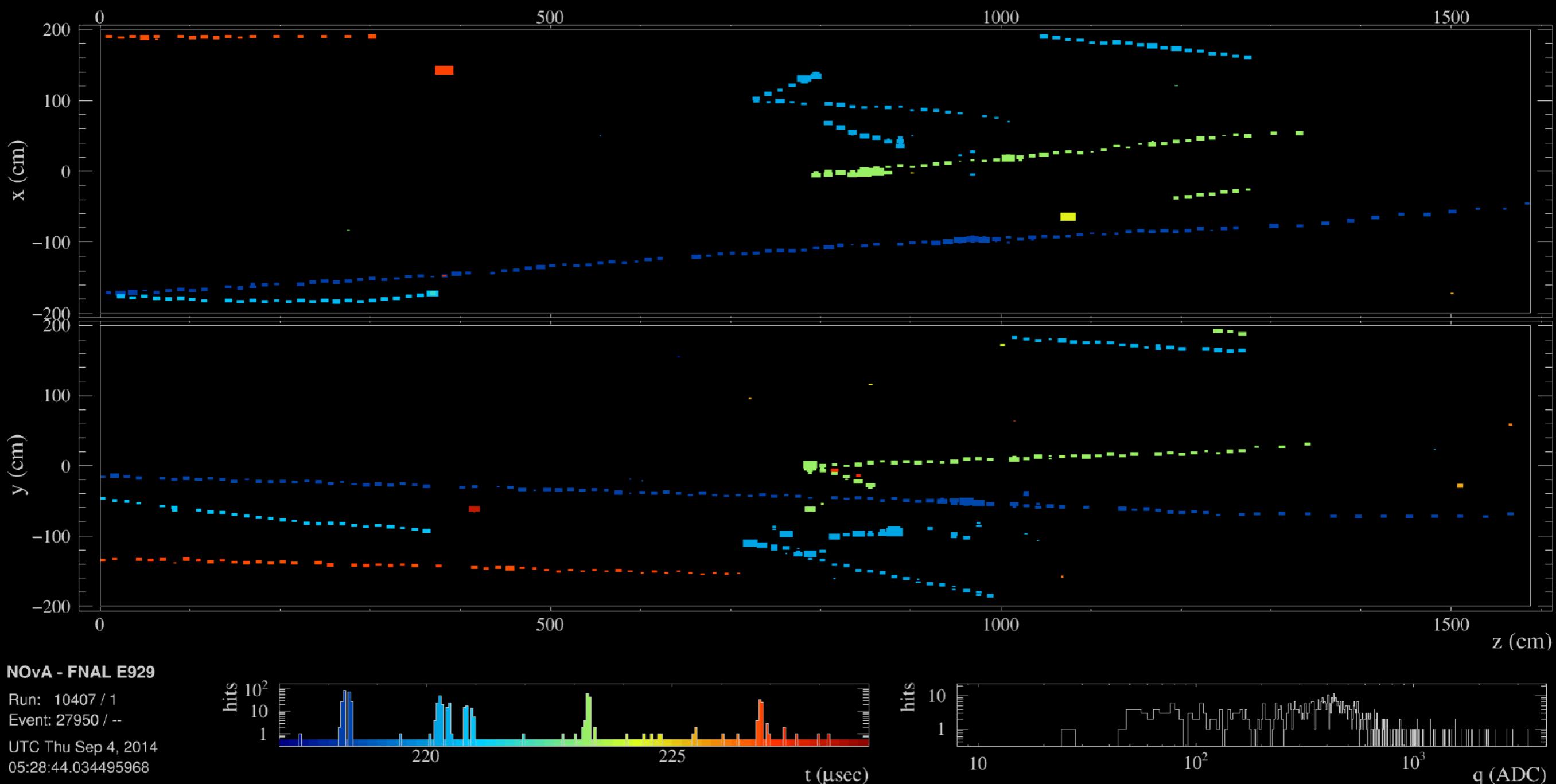
Event: 178402 / --

UTC Fri Jan 9, 2015

00:13:53.087341608



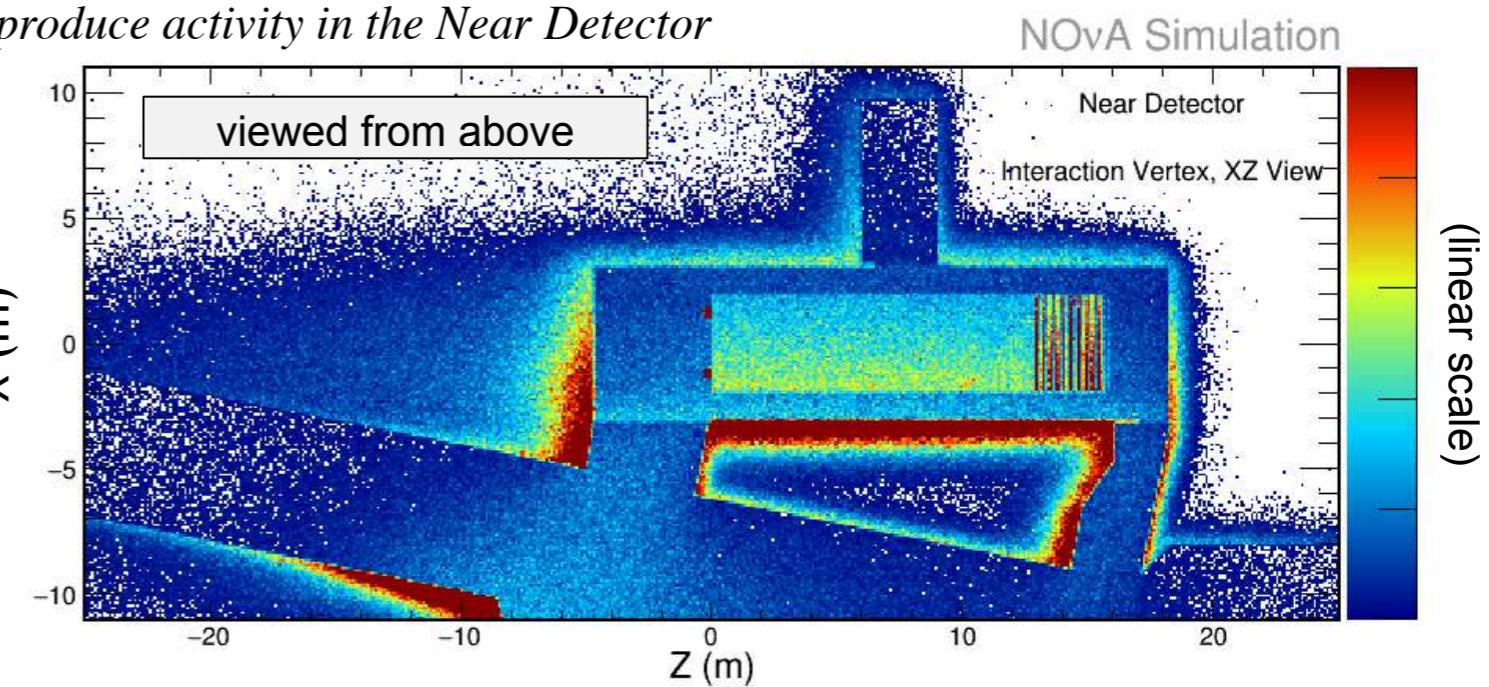
Near Detector: 10 μ s of readout during NuMI beam pulse (color \Rightarrow time of hit)



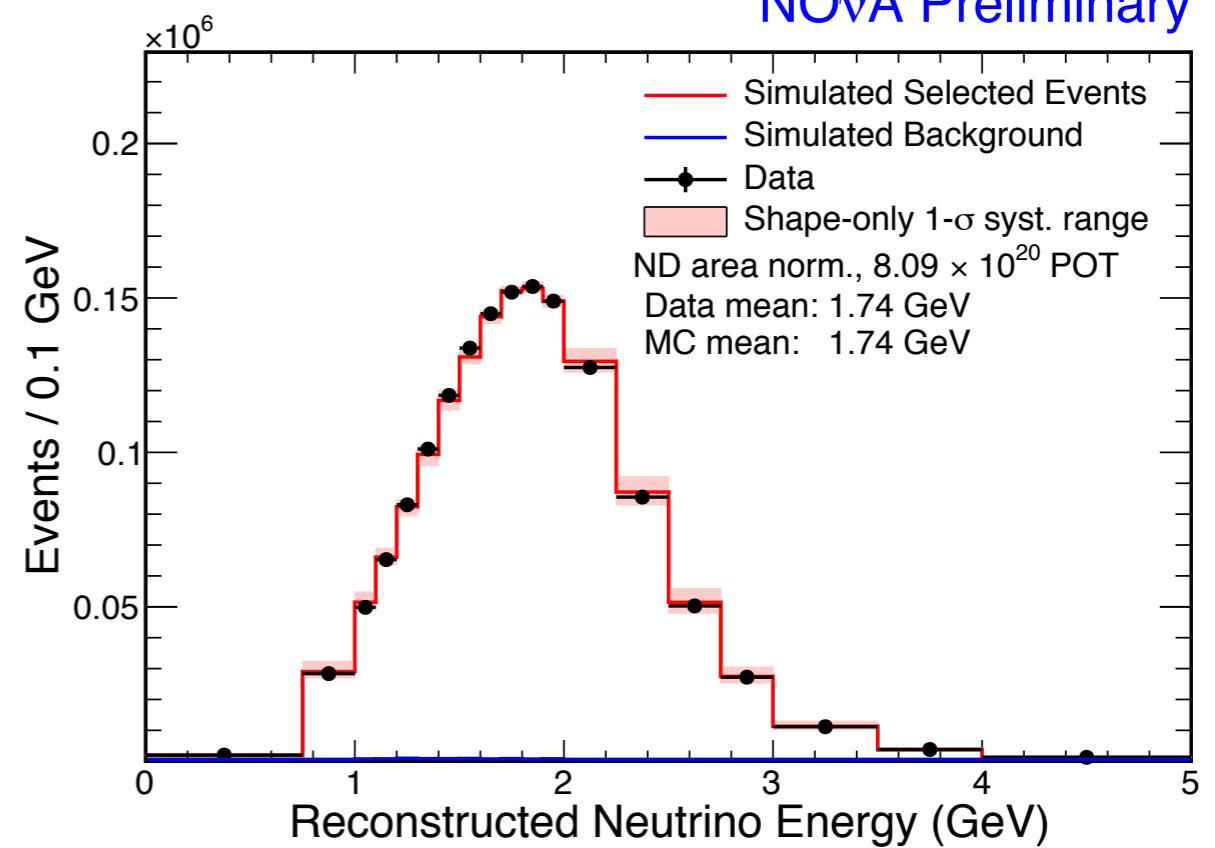
Simulations

- ❖ Beam hadron production, propagation, neutrino flux: **GEANT4/External Data**
- ❖ Cosmic ray flux: **Data Triggers**
- ❖ Neutrino Interactions and FSI modeling: **GENIE v2.12.2**
- ❖ Detector Simulation: **GEANT4**
- ❖ Readout electronics and DAQ: **Custom simulation routines**

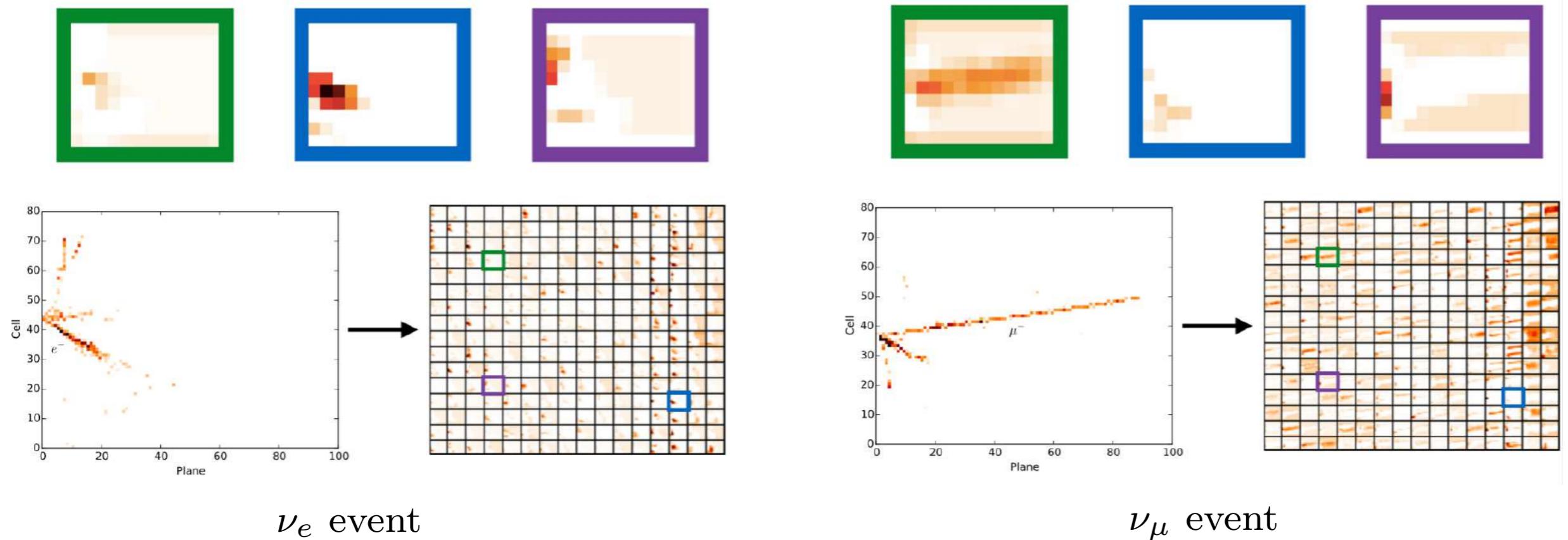
Simulation: Locations of neutrino interactions that produce activity in the Near Detector



NOvA Preliminary



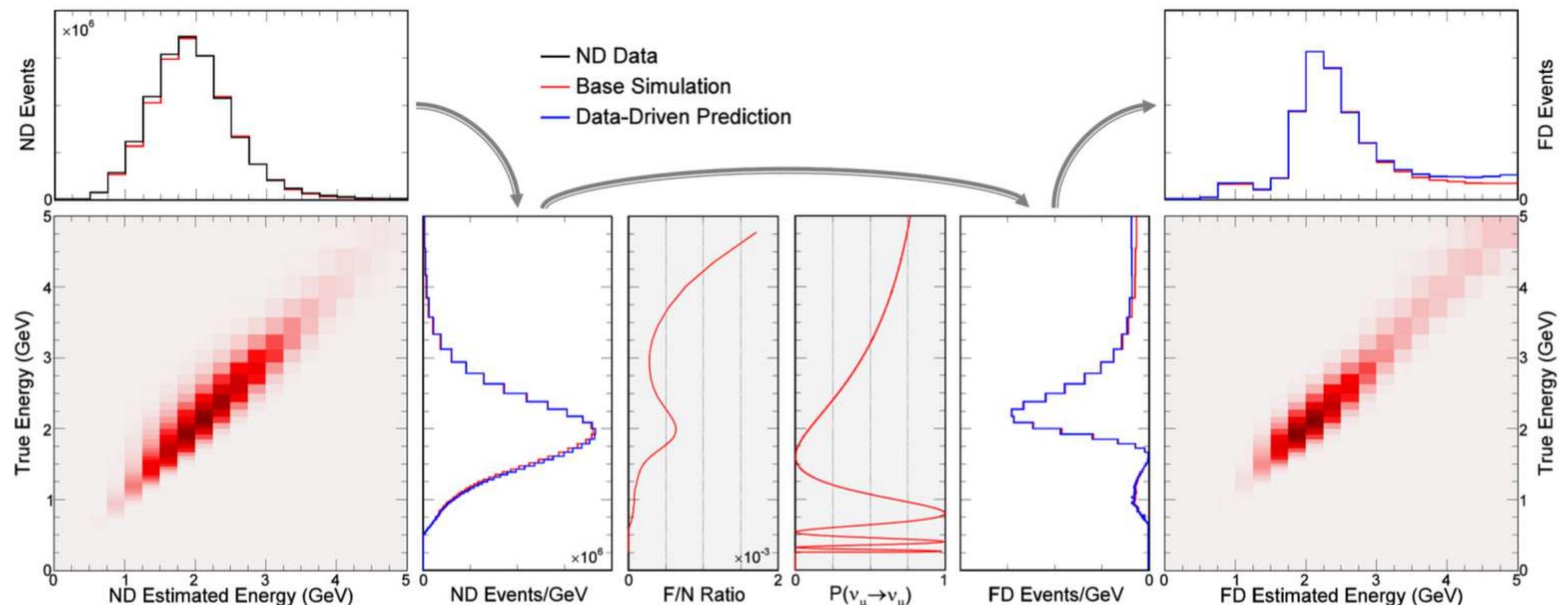
Event selector



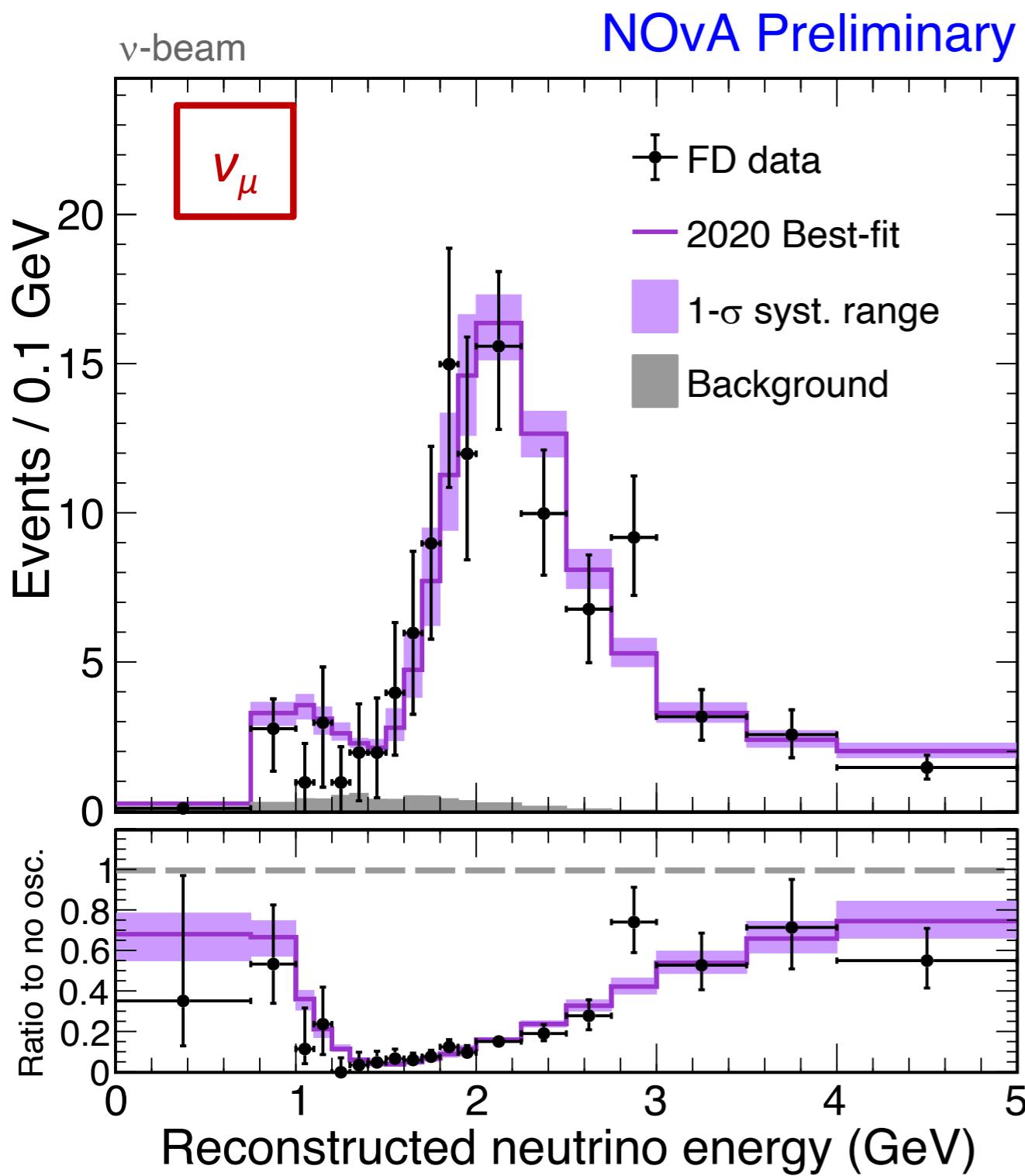
- * “Convolutional Visual Network” (CVN) - particle identification technique based on ideas from computer vision and deep learning.
- * Previously it was used only for the ν_e analysis.
- * Now ν_μ analysis also features the same event selection technique.

Extrapolation to the Far Detector

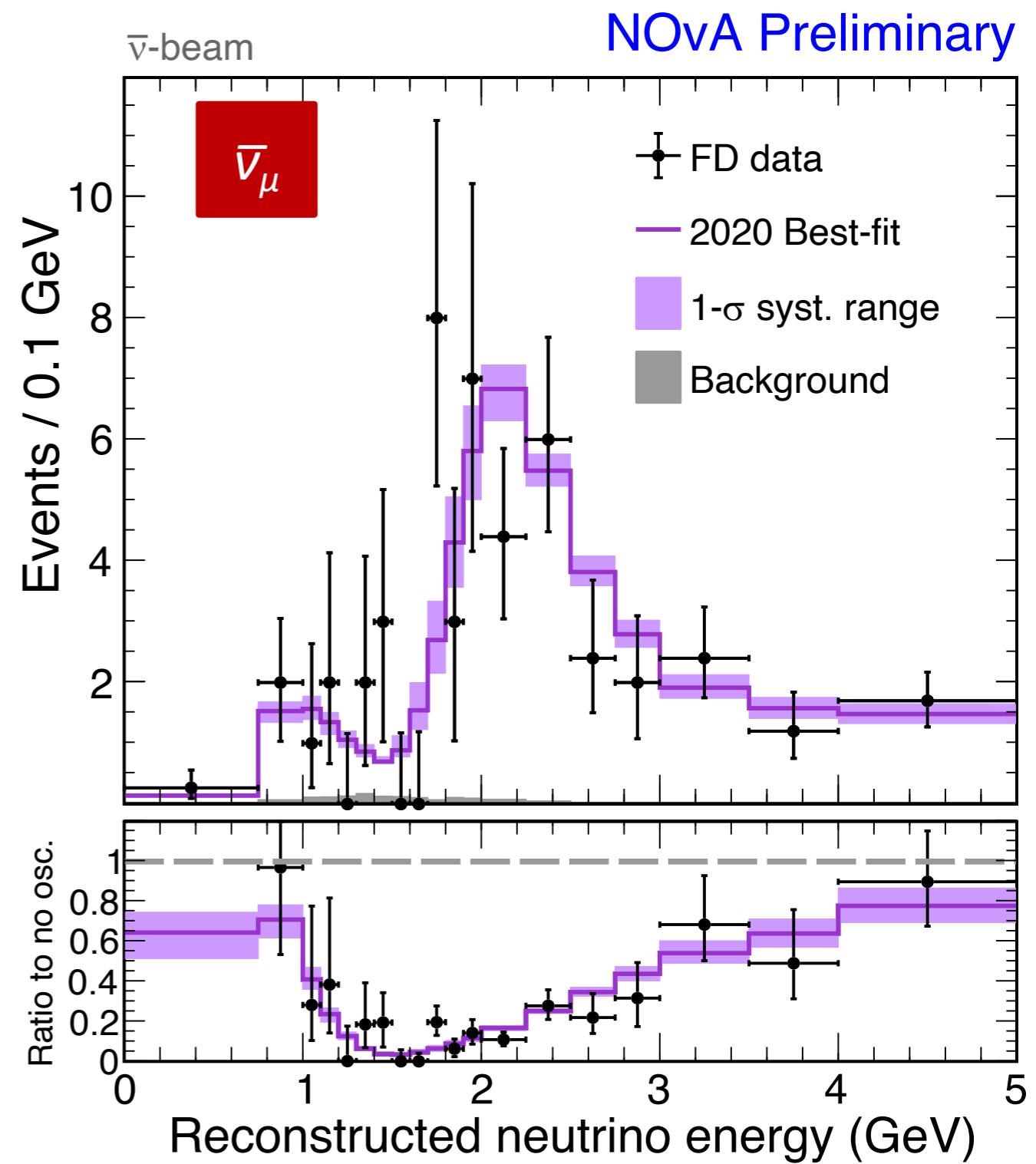
- * Estimate true energy distribution of selected ND events.
- * Multiply by expected Far/Near event ratio and oscillation probability as a function of true energy.
- * Convert FD true energy distribution into predicted FD reco energy distribution.
- * Systematic uncertainties assessed by varying all MC-based steps.



ν_μ Far Detector spectrum

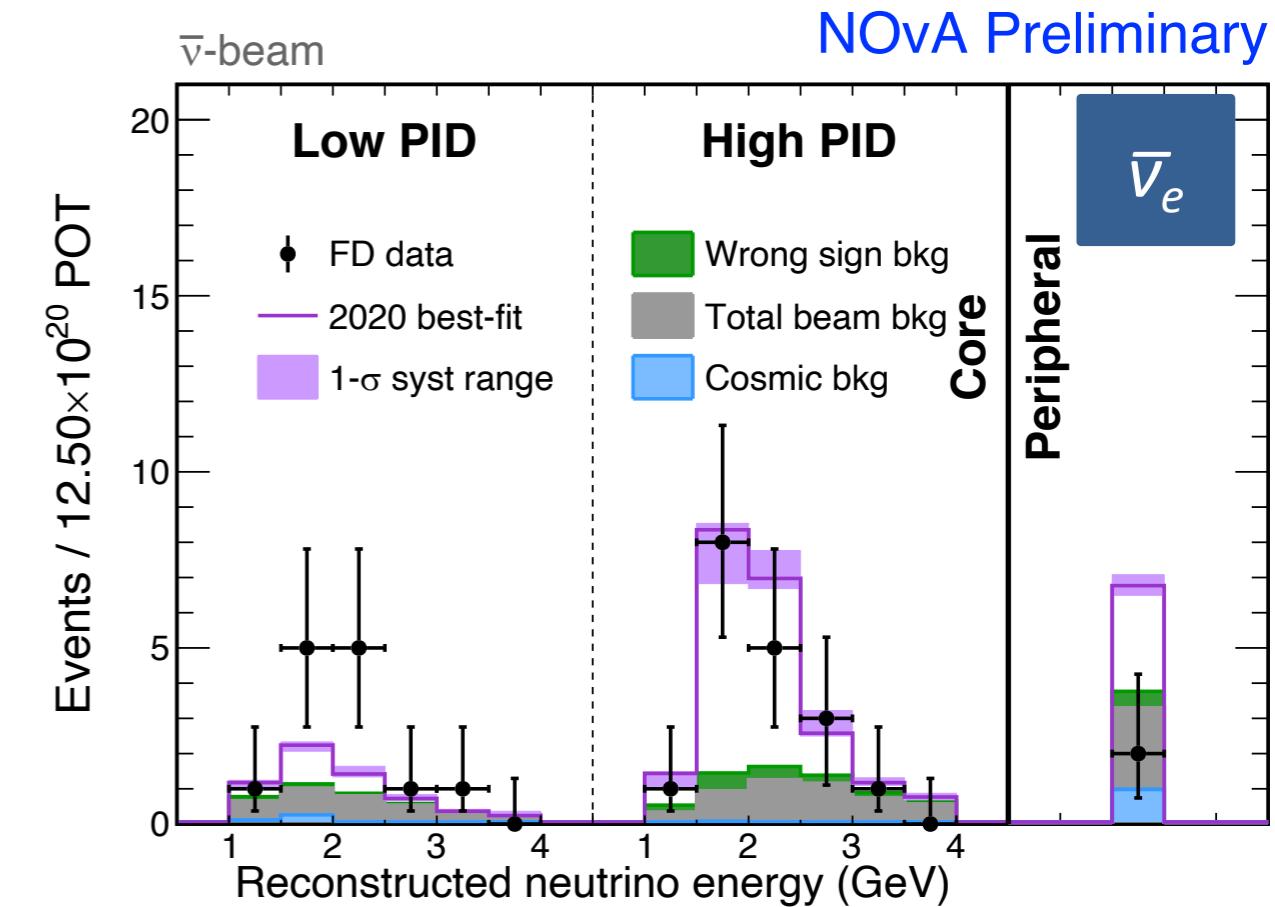
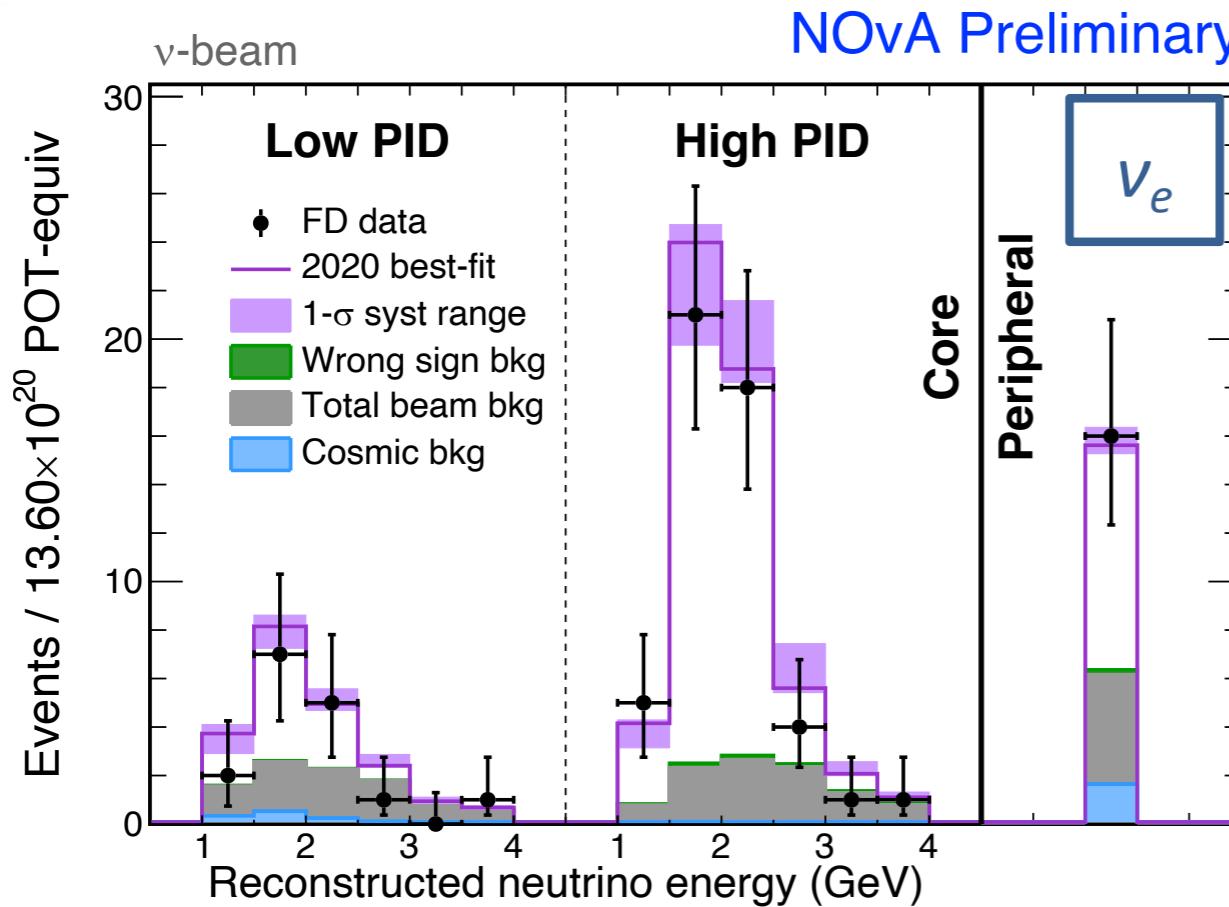


211 events, 8.2 background



105 events, 2.1 background

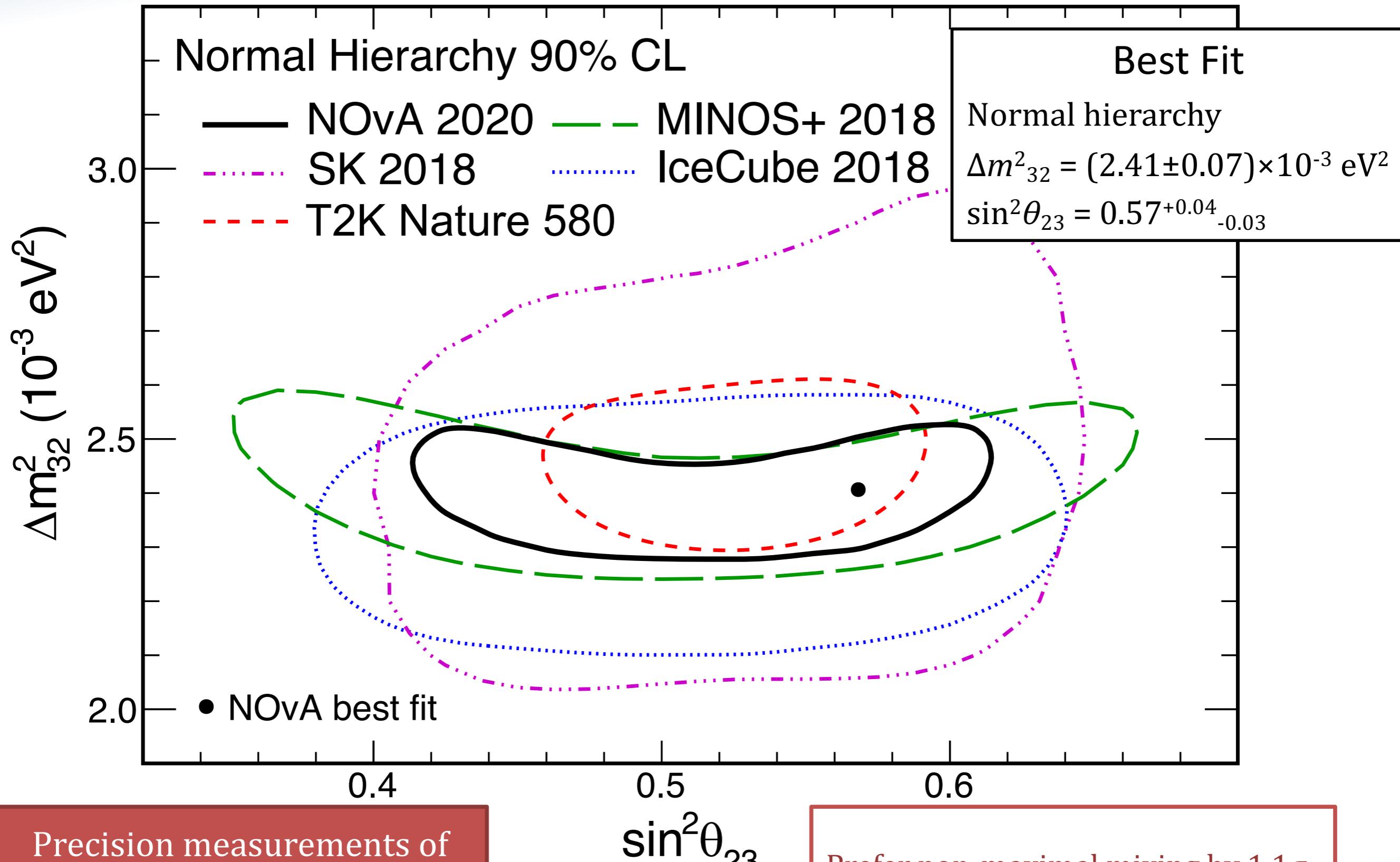
ν_e Far Detector spectrum



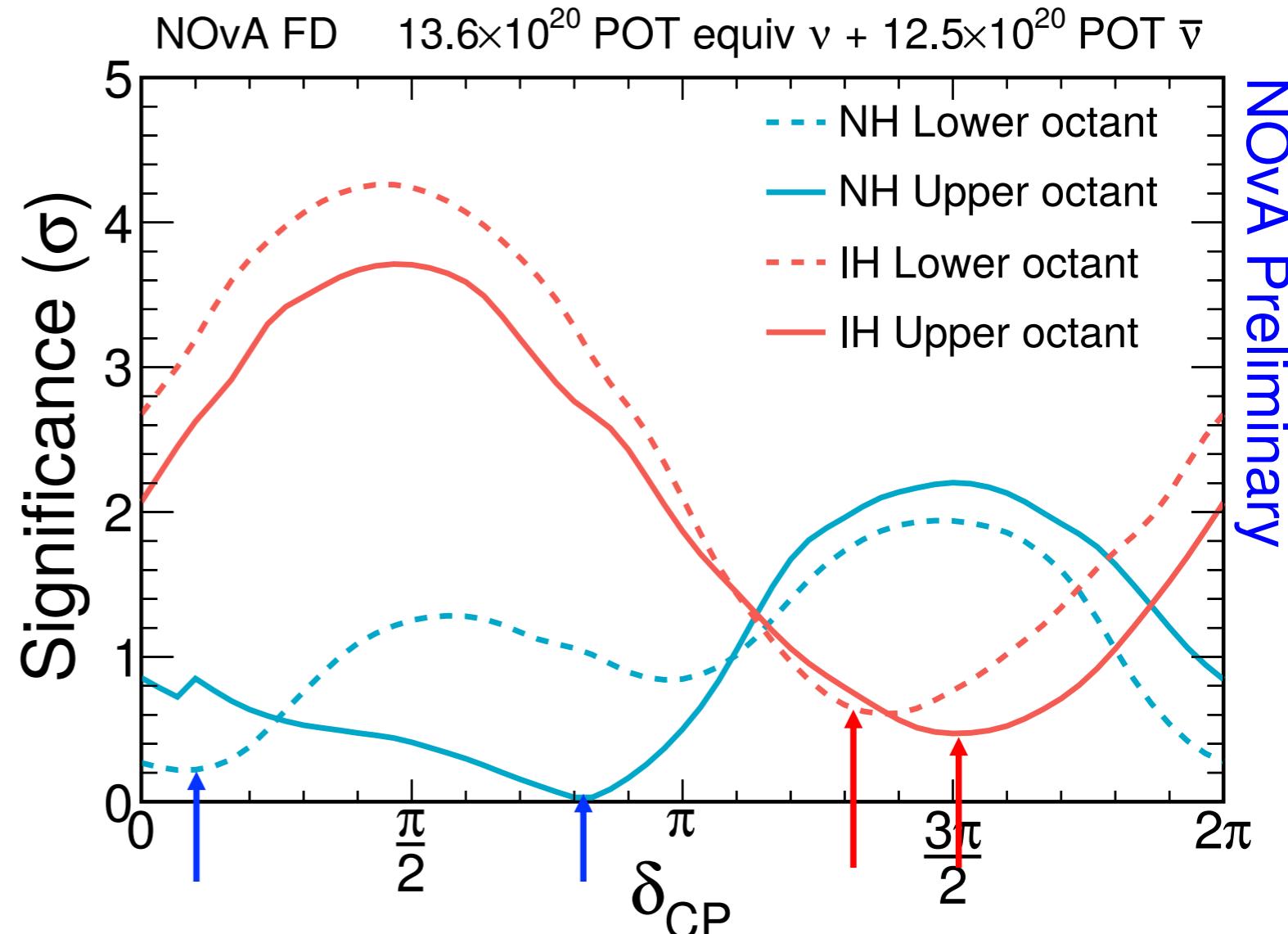
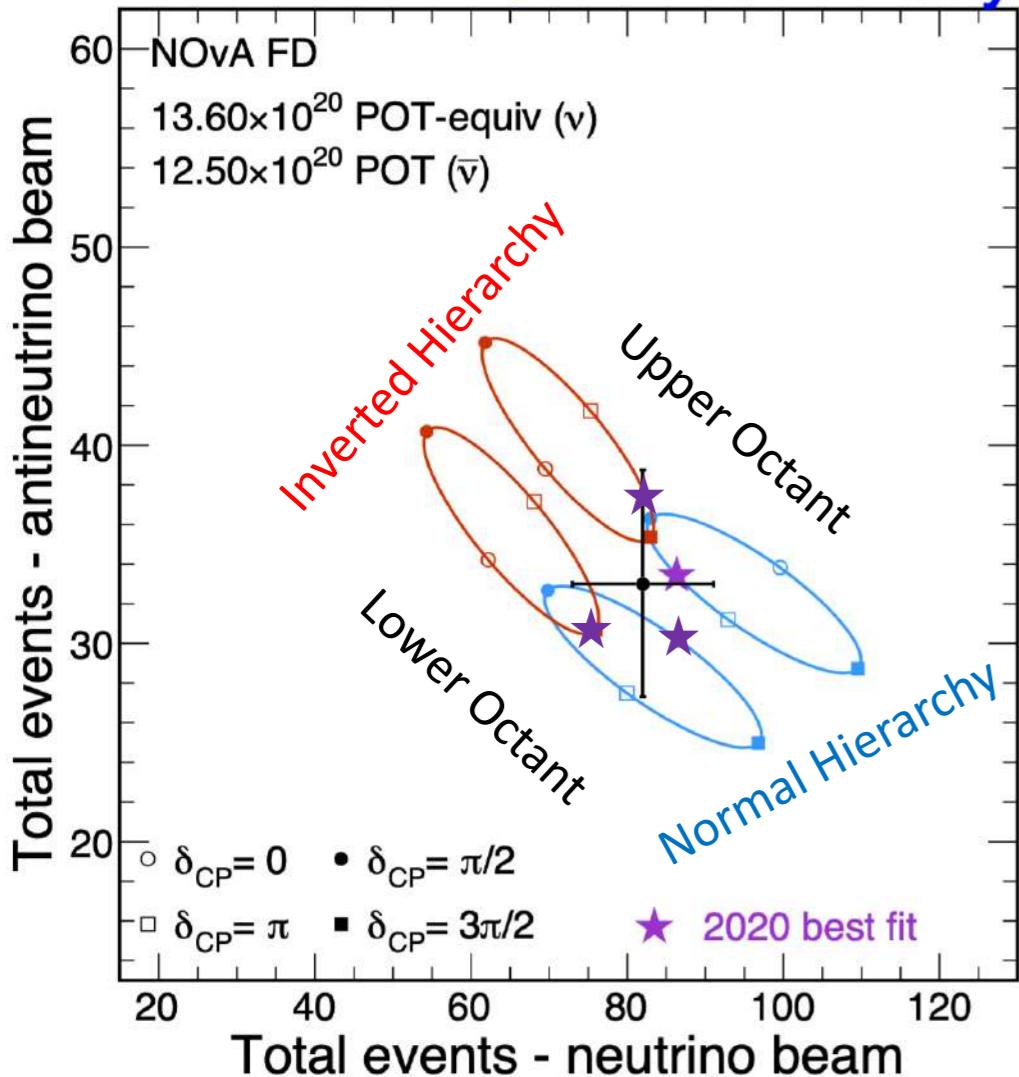
Total Observed	82	Range
Total Prediction	85.8	52-110
Wrong-sign	1.0	0.6-1.7
Beam Bkgd.	22.7	
Cosmic Bkgd.	3.1	
Total Bkgd.	26.8	26-28

Total Observed	33	Range
Total Prediction	33.2	25-45
Wrong-sign	2.3	1.0-3.2
Beam Bkgd.	10.2	
Cosmic Bkgd.	1.6	
Total Bkgd.	14.0	13-15

>4 σ evidence of $\bar{\nu}_e$ appearance



NOvA Preliminary



- We see no strong asymmetry in the rates of appearance of ν_e and $\bar{\nu}_e$
- Disfavor hierarchy- δ combinations which would produce that asymmetry
- Consistent with hierarchy-octant- δ combinations which include some “cancellation.”
 - Since such options exist for both octants and hierarchies, results show no strong preferences.

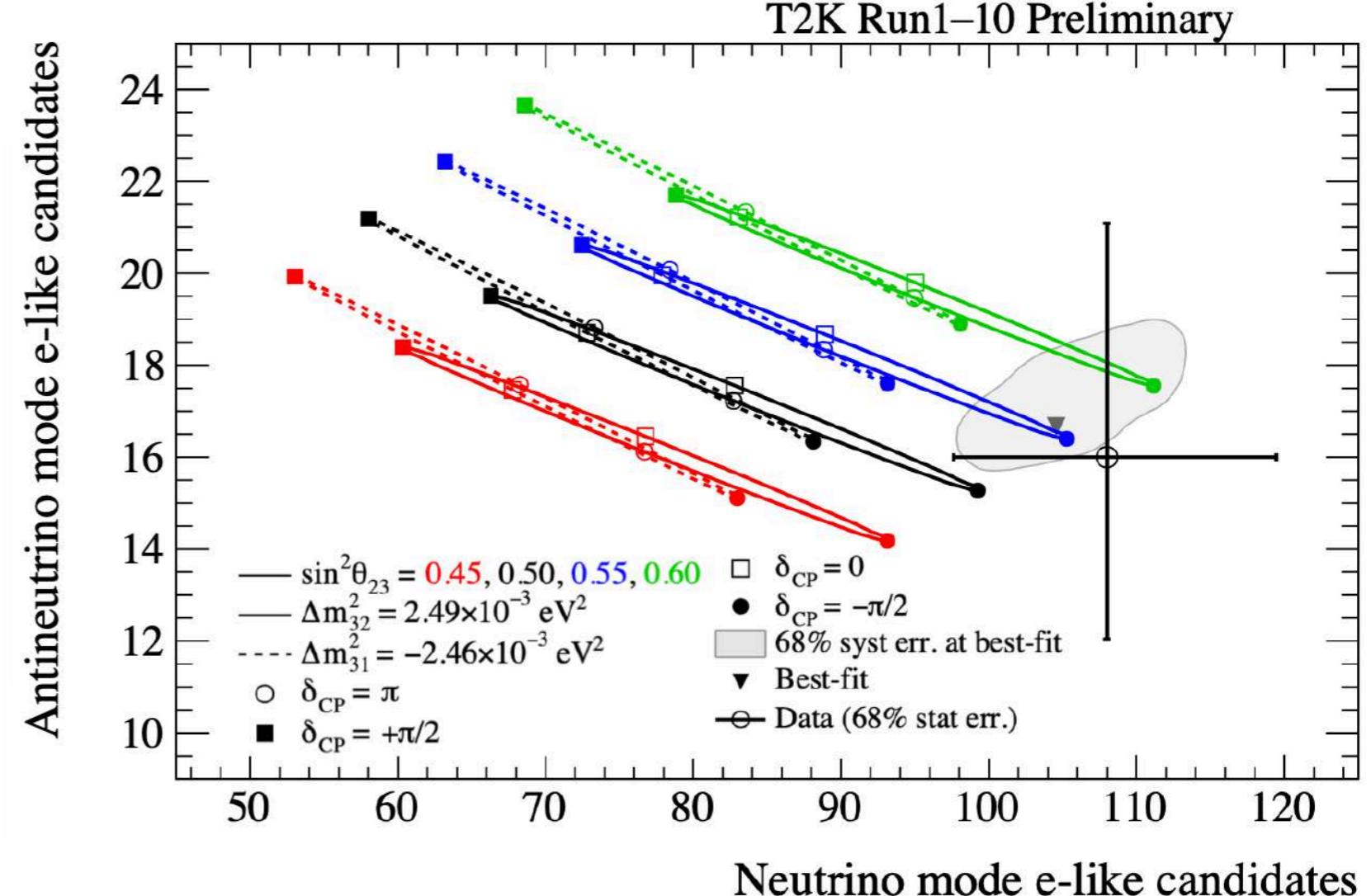
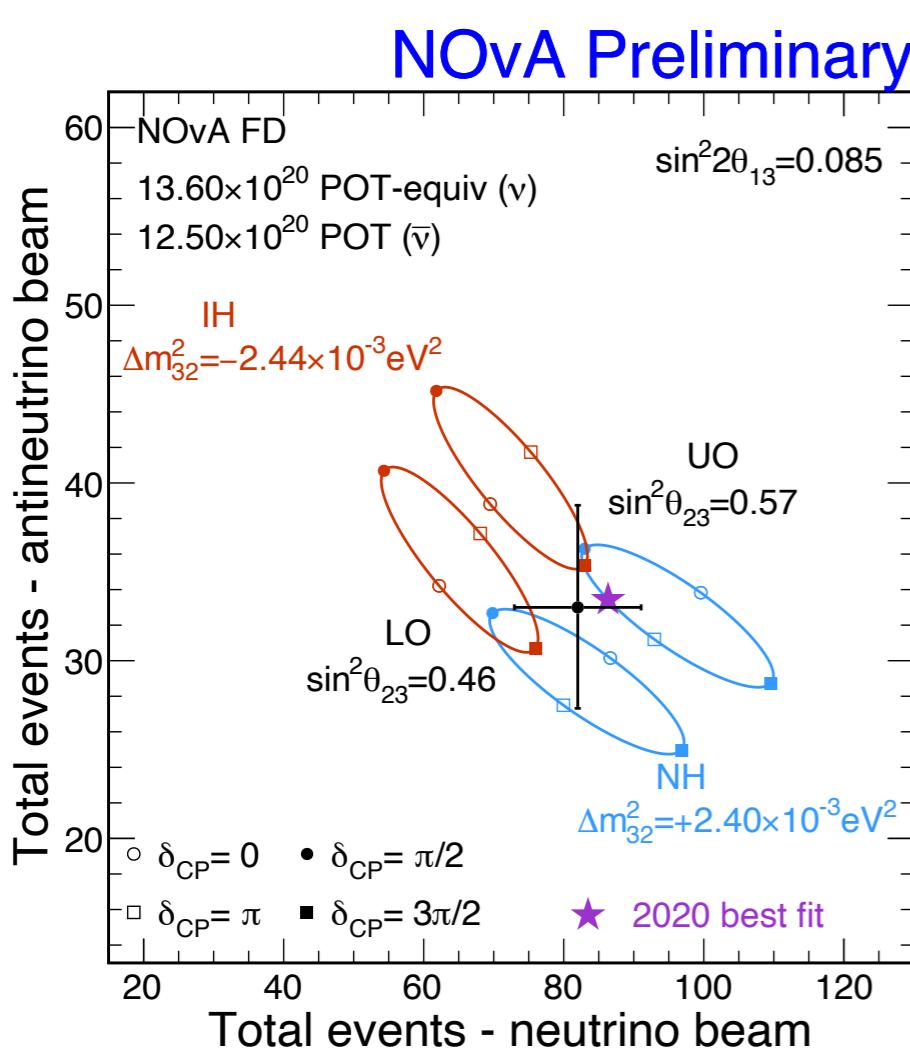
Exclude IH $\delta = \pi/2$ at $>3\sigma$

Disfavor NH $\delta = 3\pi/2$ at $\sim 2\sigma$

Prefer...

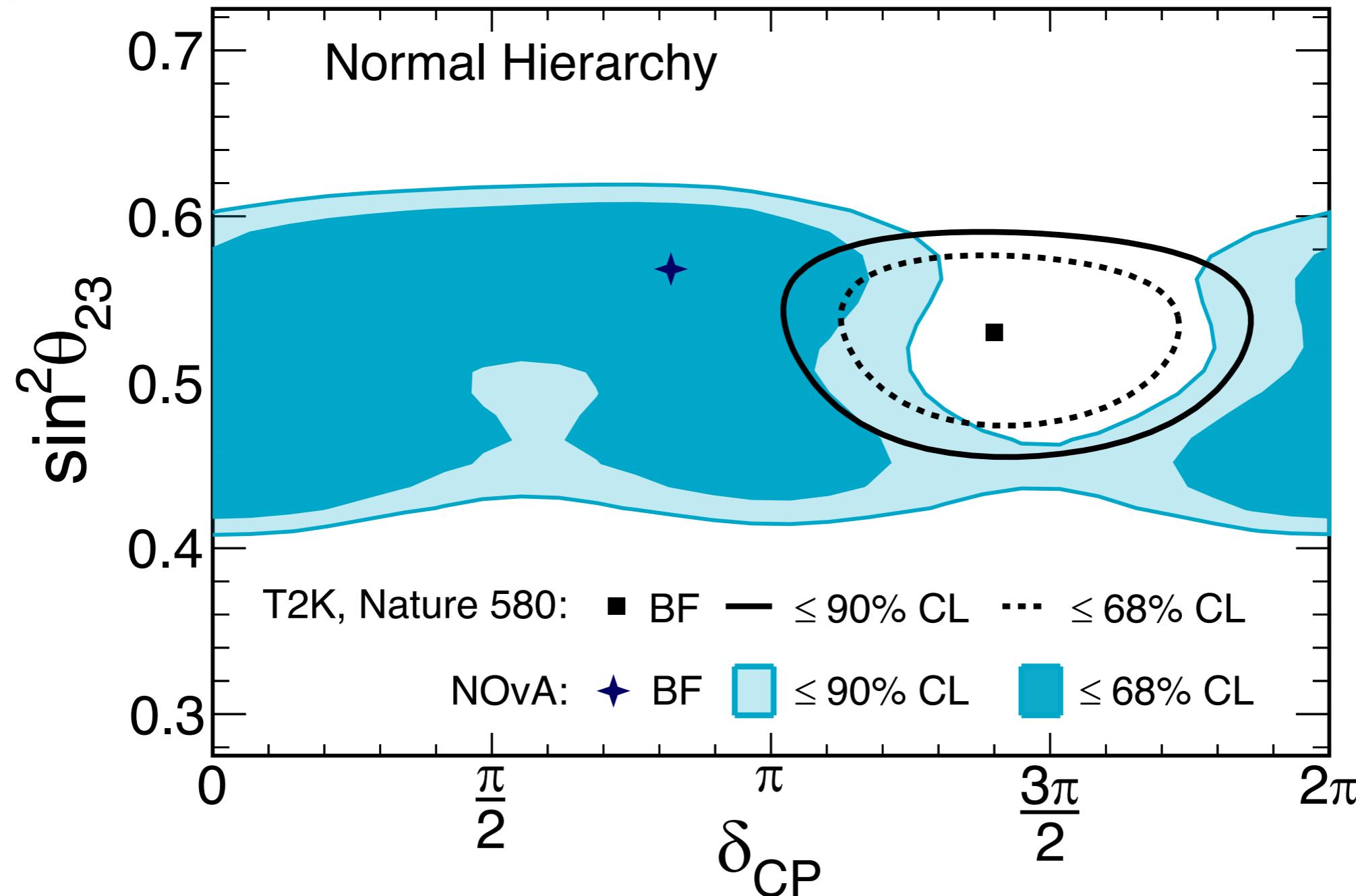
Normal Hierarchy at	1.0σ
Upper Octant at	1.2σ

T2K and NOvA latest results



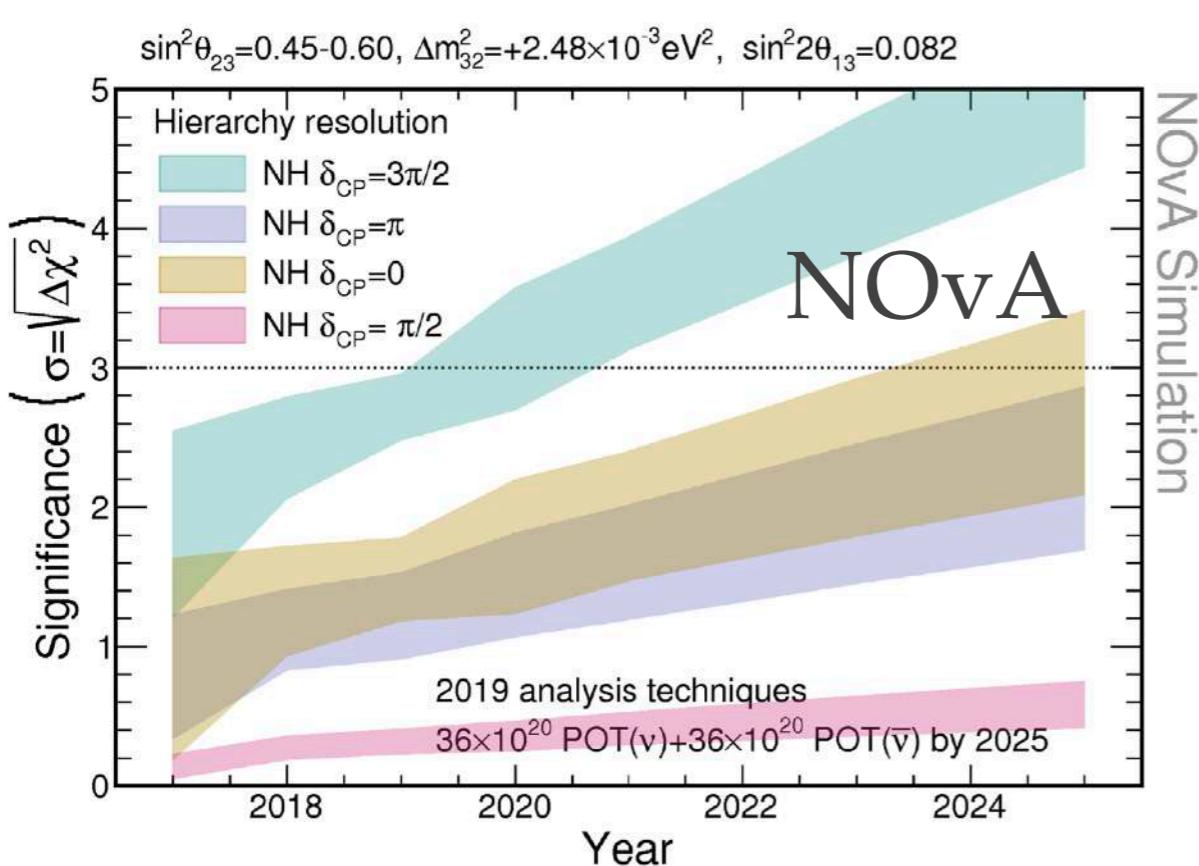
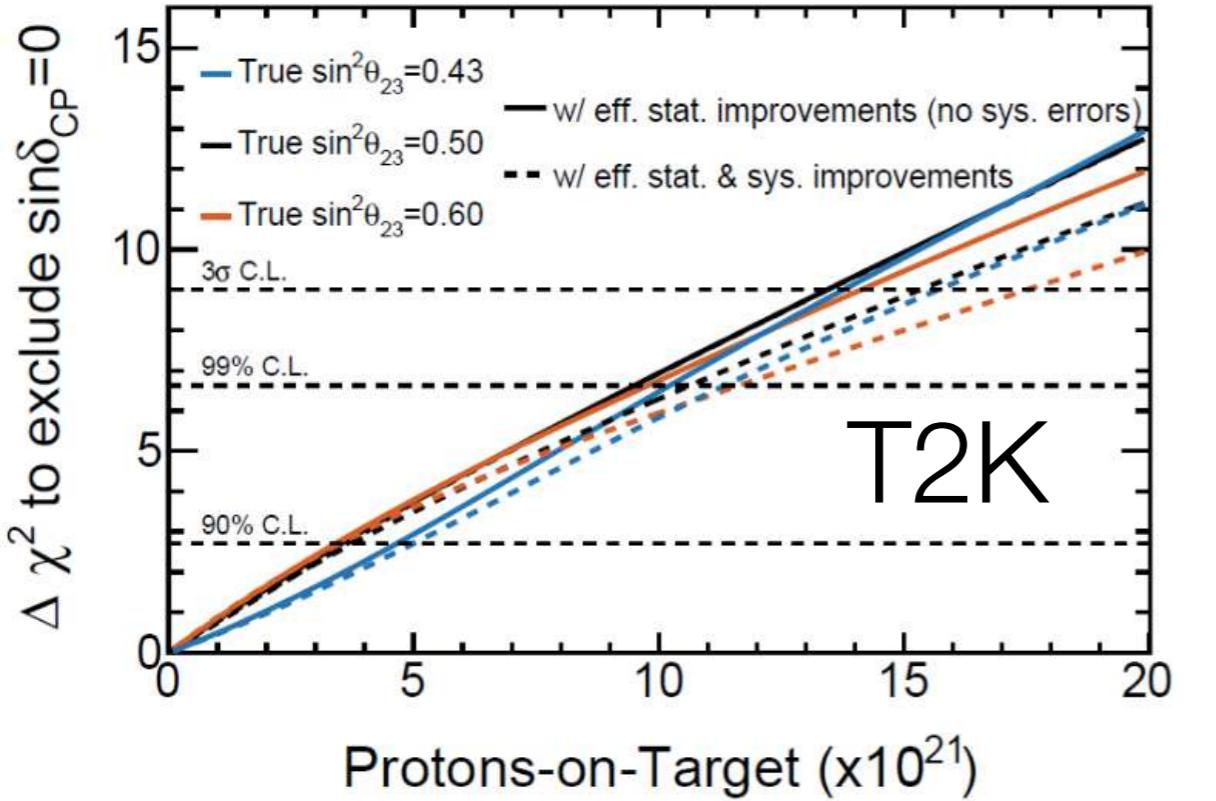
Excitement at Neutrino-2020 !

T2K and NOvA latest results



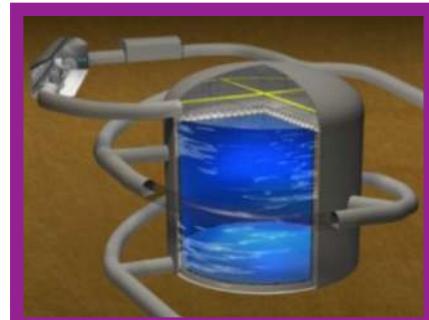
- ❖ Quantifying consistency requires a joint fit of the data from the two experiments

T2K and NOvA future



- ❖ T2K : operation to 2026
- ❖ NOvA : operation to 2025
- ❖ T2K may reach 3 σ CP violation sensitivity if CPV is near maximal
- ❖ NOvA will have $\sim 2\sigma$ sensitivity under similar assumptions
- ❖ NOvA can reach 3 σ hierarchy sensitivity for 30-50% of δ values, with the full dataset and an upgraded beam

Next generation experiments: T2HK and DUNE



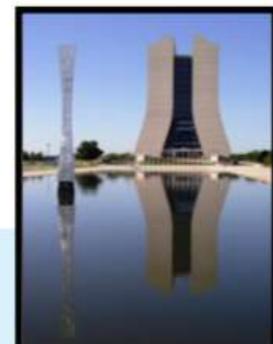
Hyper-Kamiokande



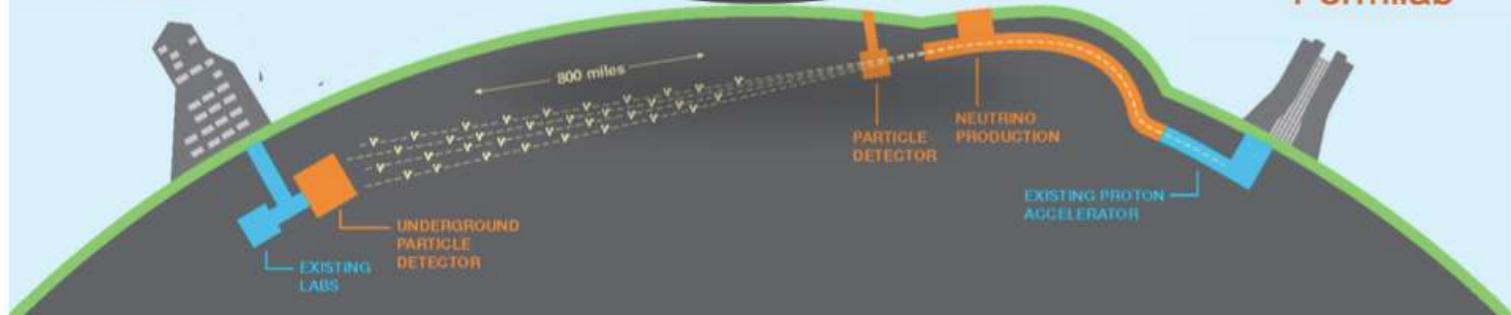
- ❖ Hyper-K
- ❖ Natural evolution of Super-K and T2K
- ❖ Water Cherenkov detector
- ❖ 8x larger fiducial mass
- ❖ 2.5 times more beam power



SURF



Fermilab

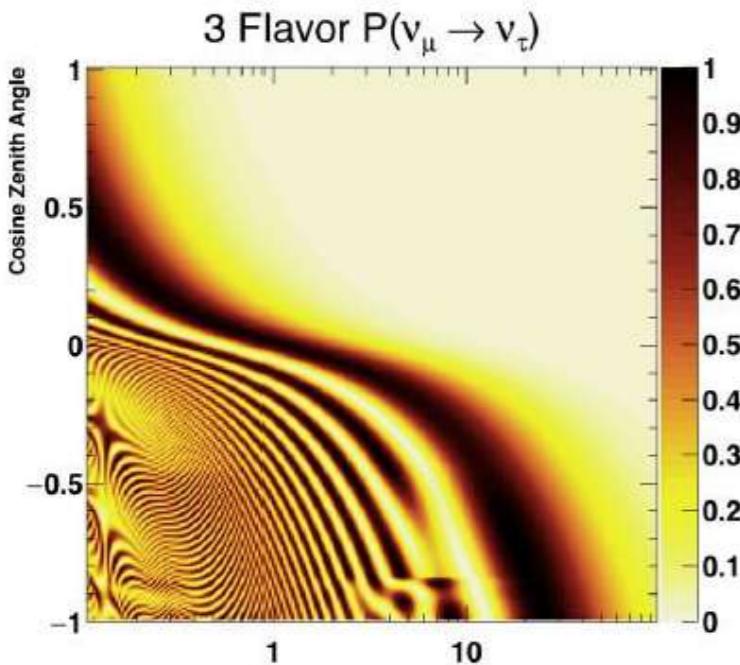


- ❖ DUNE
- ❖ More dramatic change from current experiments
- ❖ Broad band on-axis beam
- ❖ 1300 km baseline
- ❖ Liquid Ar detector
- ❖ Located in Homestake mine

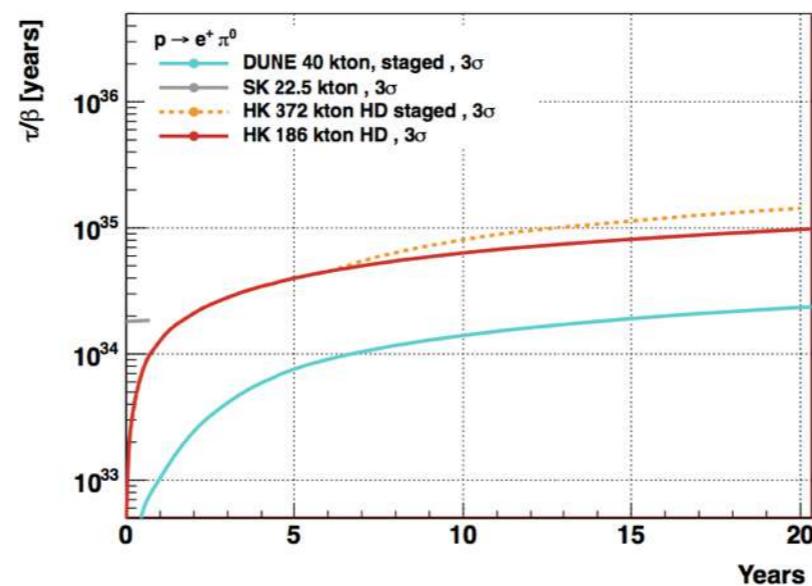
Next generation experiments: T2HK and DUNE

- Hyper-K and DUNE have broad physics programs beyond long baseline neutrino oscillations

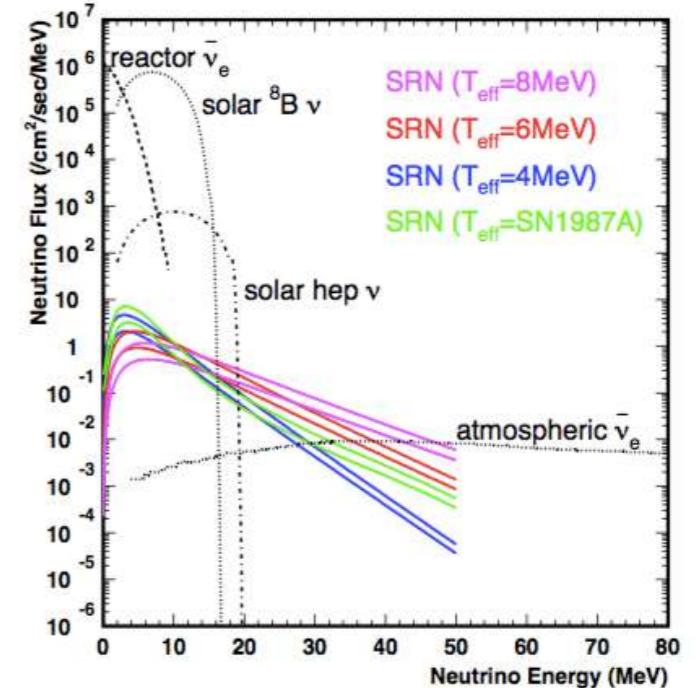
Atmospheric neutrinos



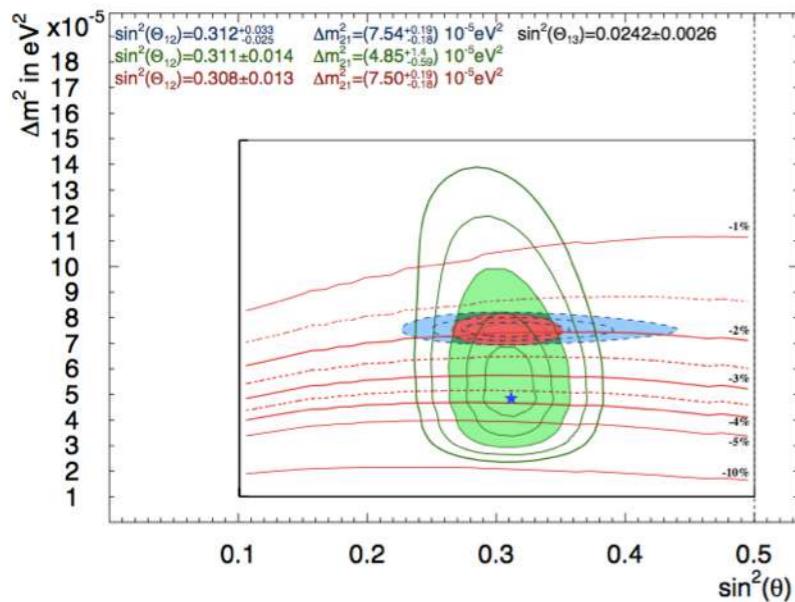
Nucleon decay



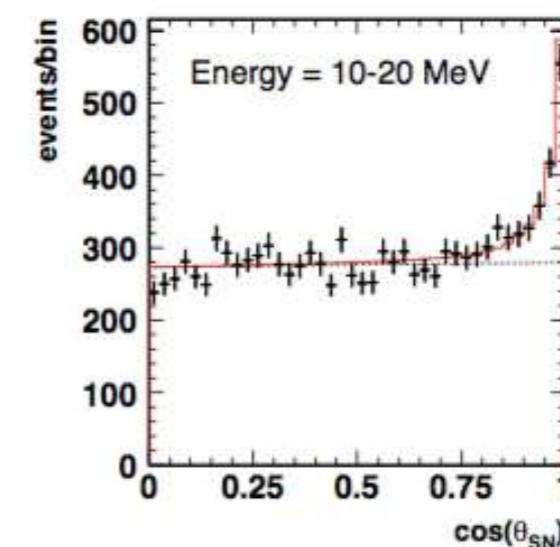
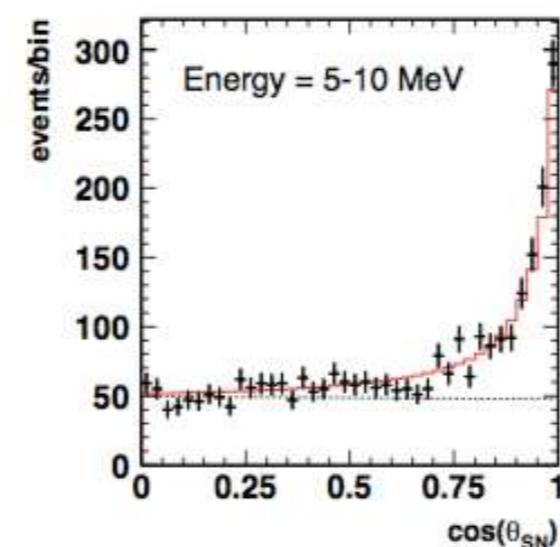
Supernova relic neutrinos



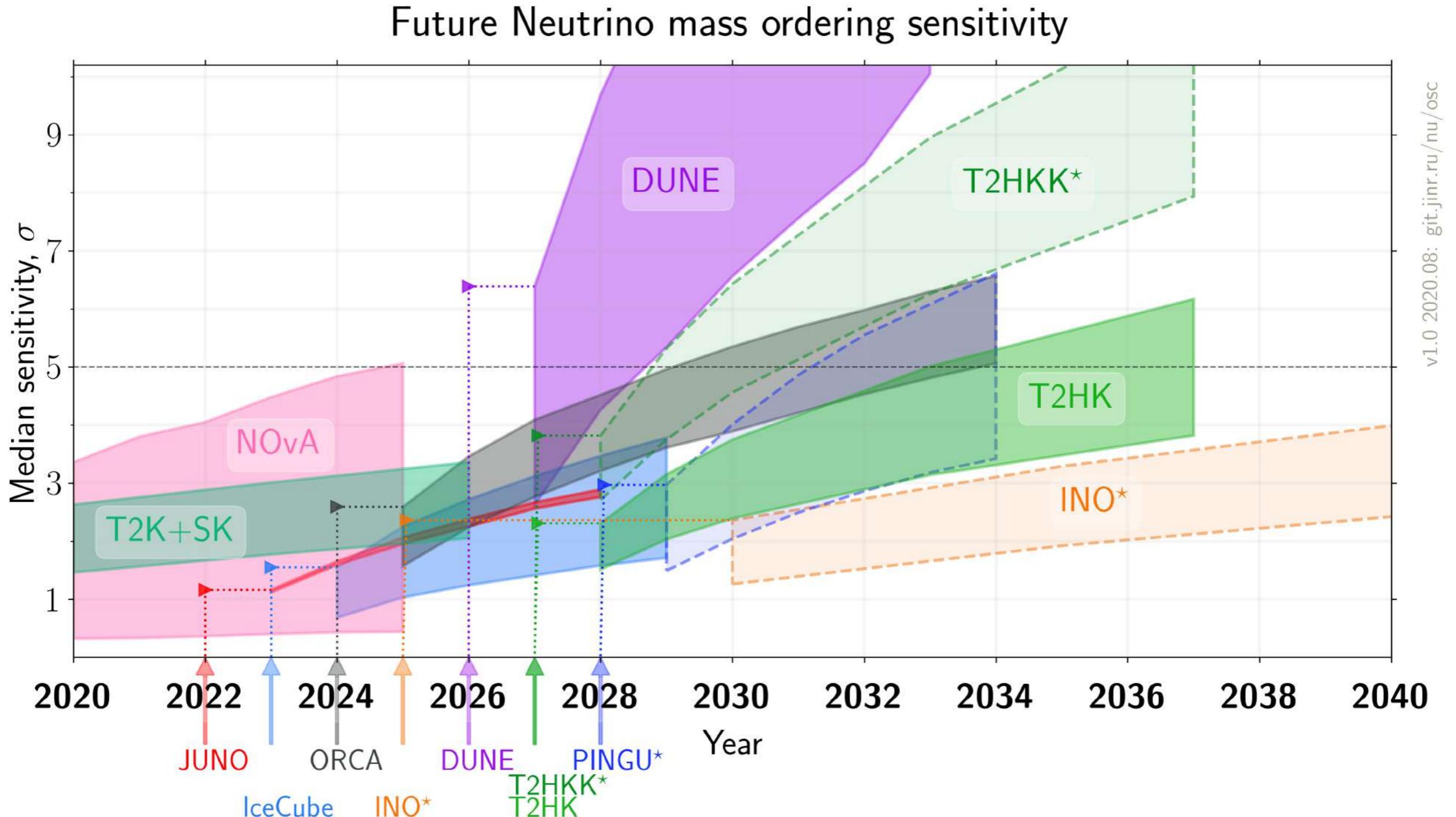
Solar neutrinos



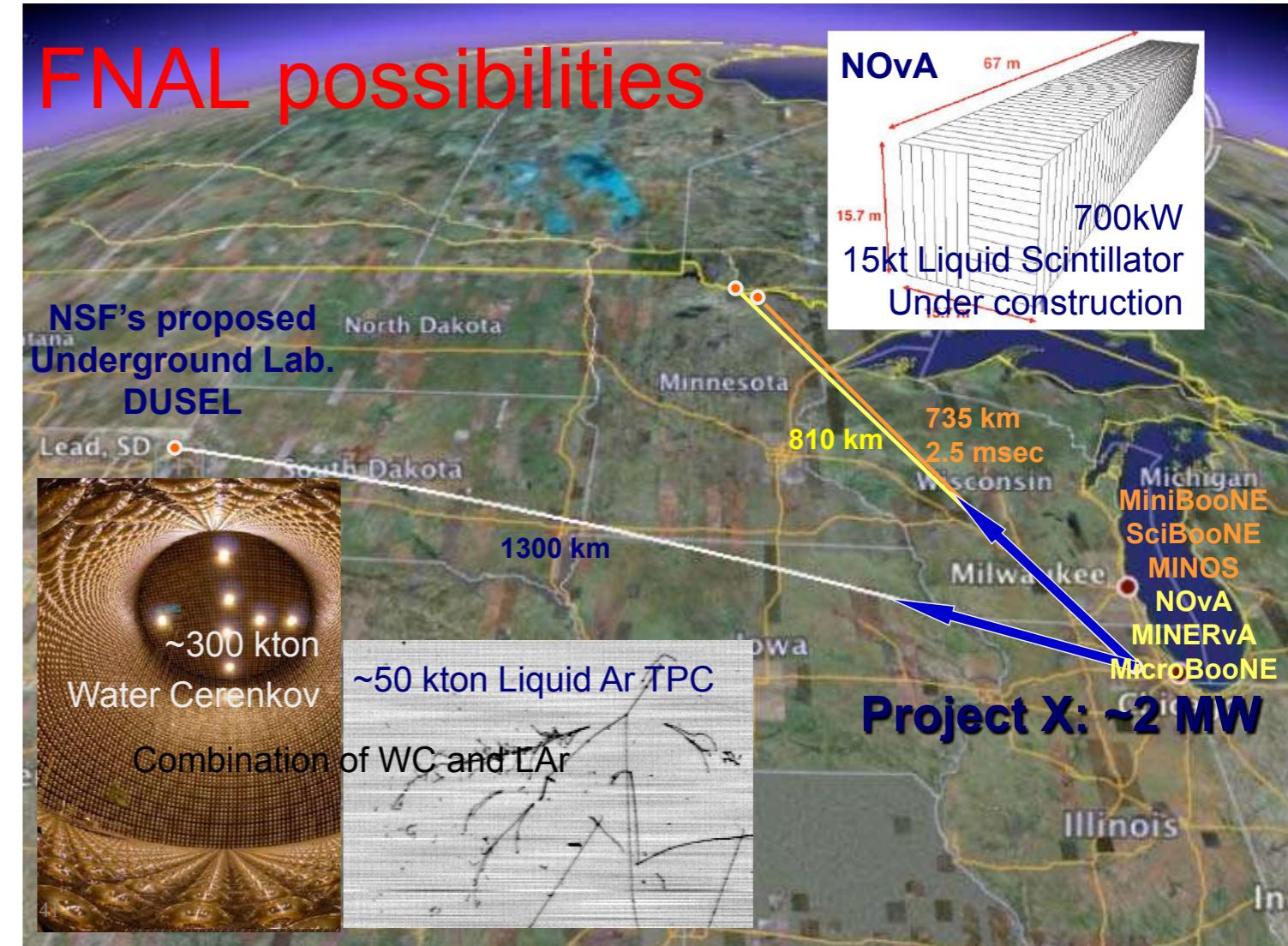
Supernova burst



Next generation experiments



Historical remark from 10 years ago



- ❖ The next generation of Hyper-K and DUNE will determine the mass ordering and make more sensitive searches for CP violation

Summary

- ❖ The discovery of neutrino oscillations shows that neutrinos have mass and the presence of physics beyond the Standard Model.
- ❖ With the discovery of a non-zero θ_{13} mixing angle the neutrino physics has entered a new era of tackling the problems of neutrino mass hierarchy and lepton CP violation.
- ❖ Both questions can be addressed in accelerator-type long baseline experiments through the measurement of matter effects in atmospheric-regime neutrino oscillations.
- ❖ The current generation of accelerator based experiments, NOvA and T2K, along with atmospheric neutrino experiments, IceCube and Super-K, and reactor neutrino experiments are making precise measurements of neutrino oscillation parameters.
- ❖ The next generation of long baseline neutrino experiments, DUNE and Hyper-K, will make even more precise measurements of neutrino oscillation parameters that probe the origin of flavor, aim for unprecedented sensitivity to CP violation, and search for new physics beyond the 3-neutrino mixing paradigm.