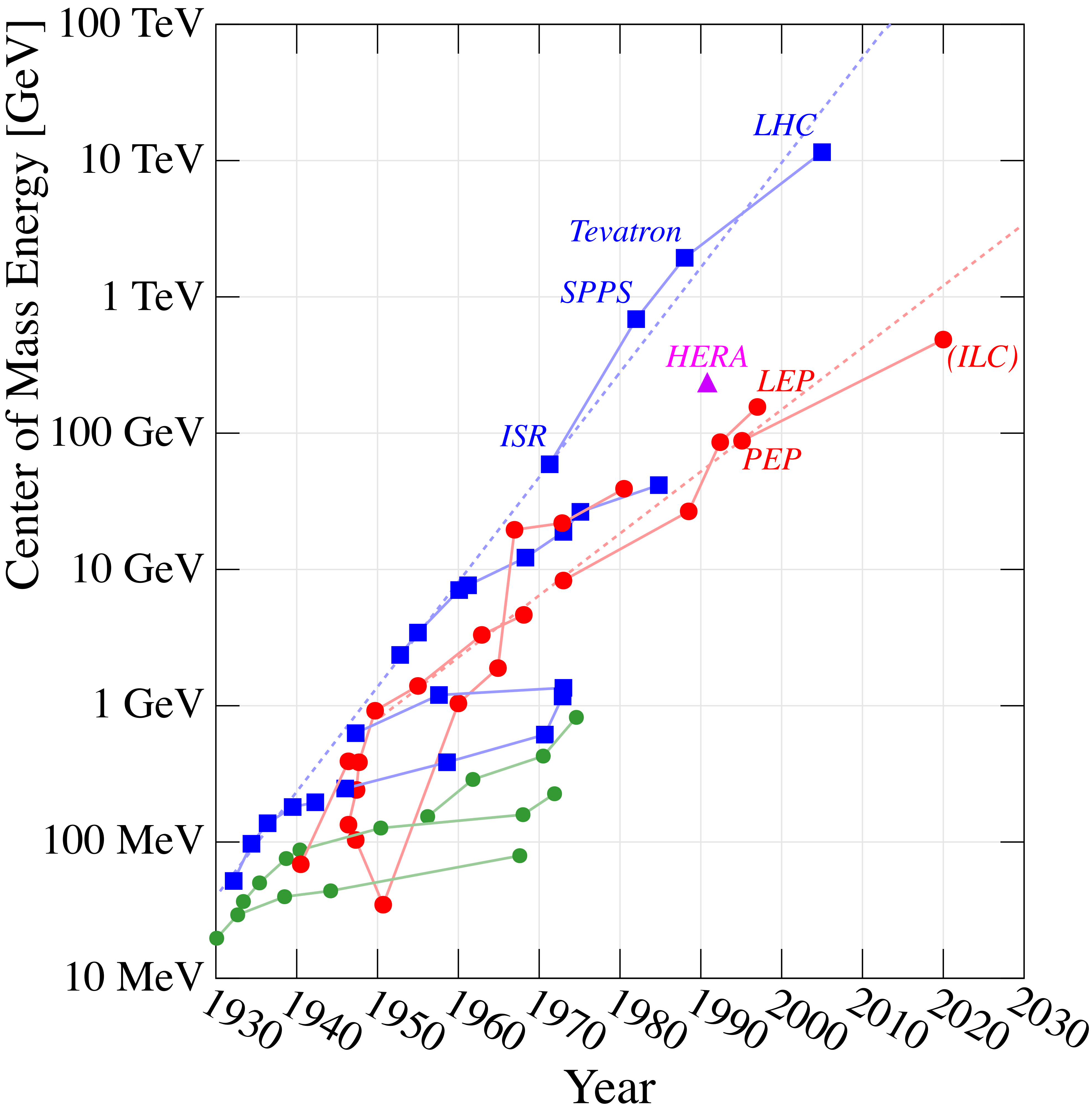
The NOvA Experiment

Mark Messier
Indiana University / Caltech

October 7, 2011

Towards CP Violation in Neutrino Physics
Institute of Physics Academy of Sciences of the Czech Republic
Prague



Center of Mass Energy [GeV]
100 TeV
10 TeV
1 TeV
100 GeV
10 GeV
1 GeV
100 MeV
10 MeV
LHC
Tevatron
SPPS
ISR
HERA
LEP
PEP
(ILC)
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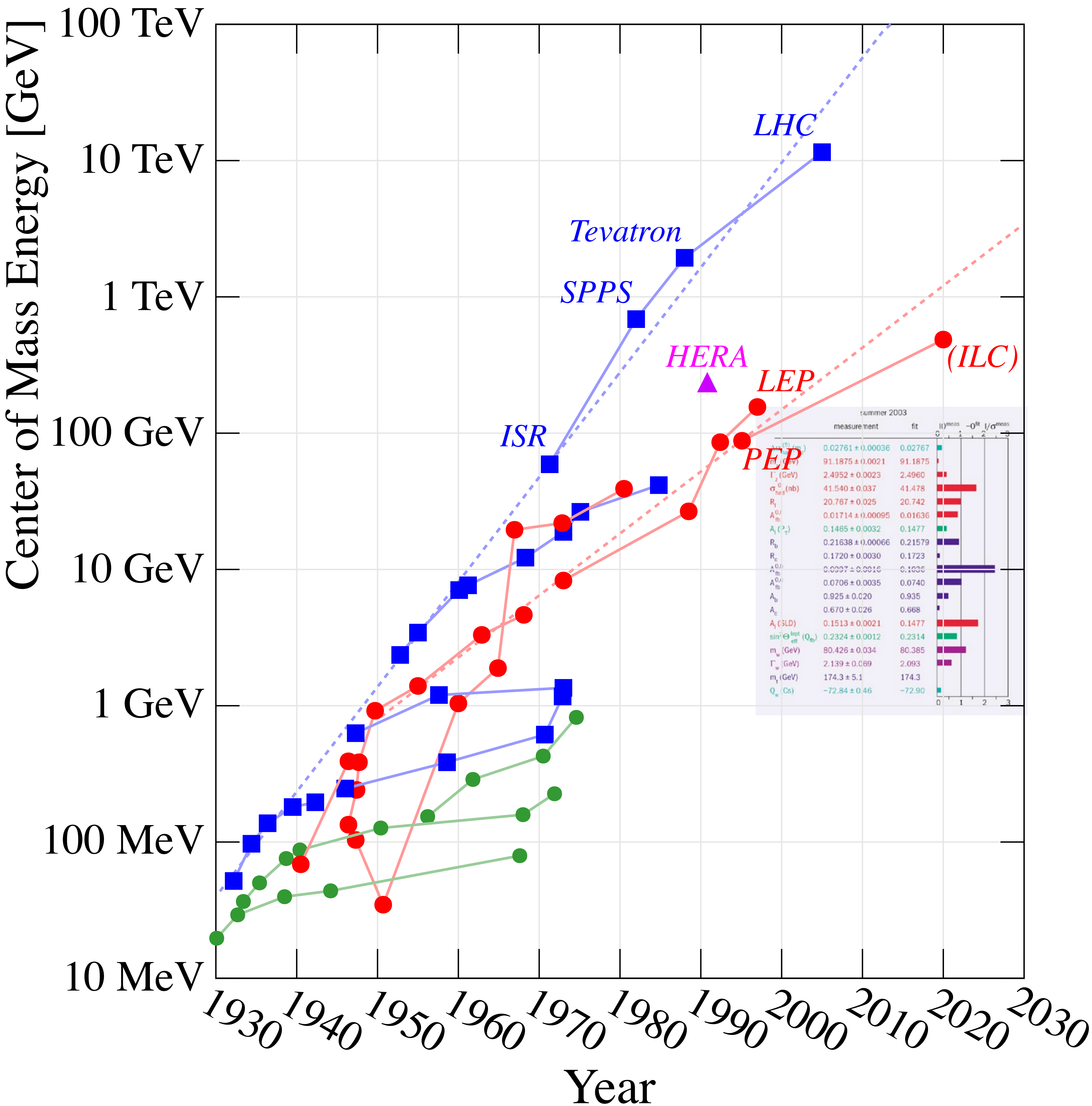
Year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summer 2003
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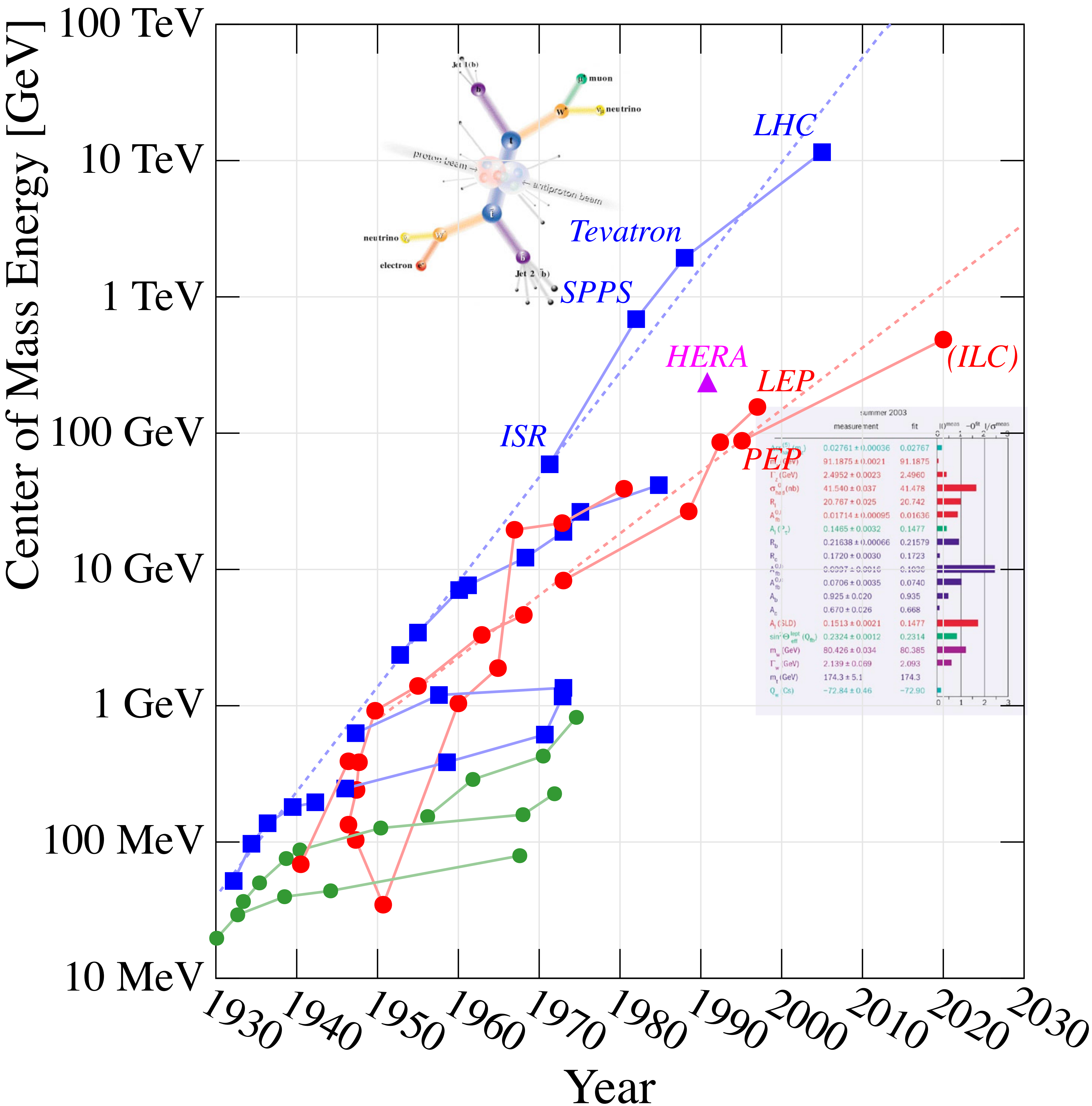
fit



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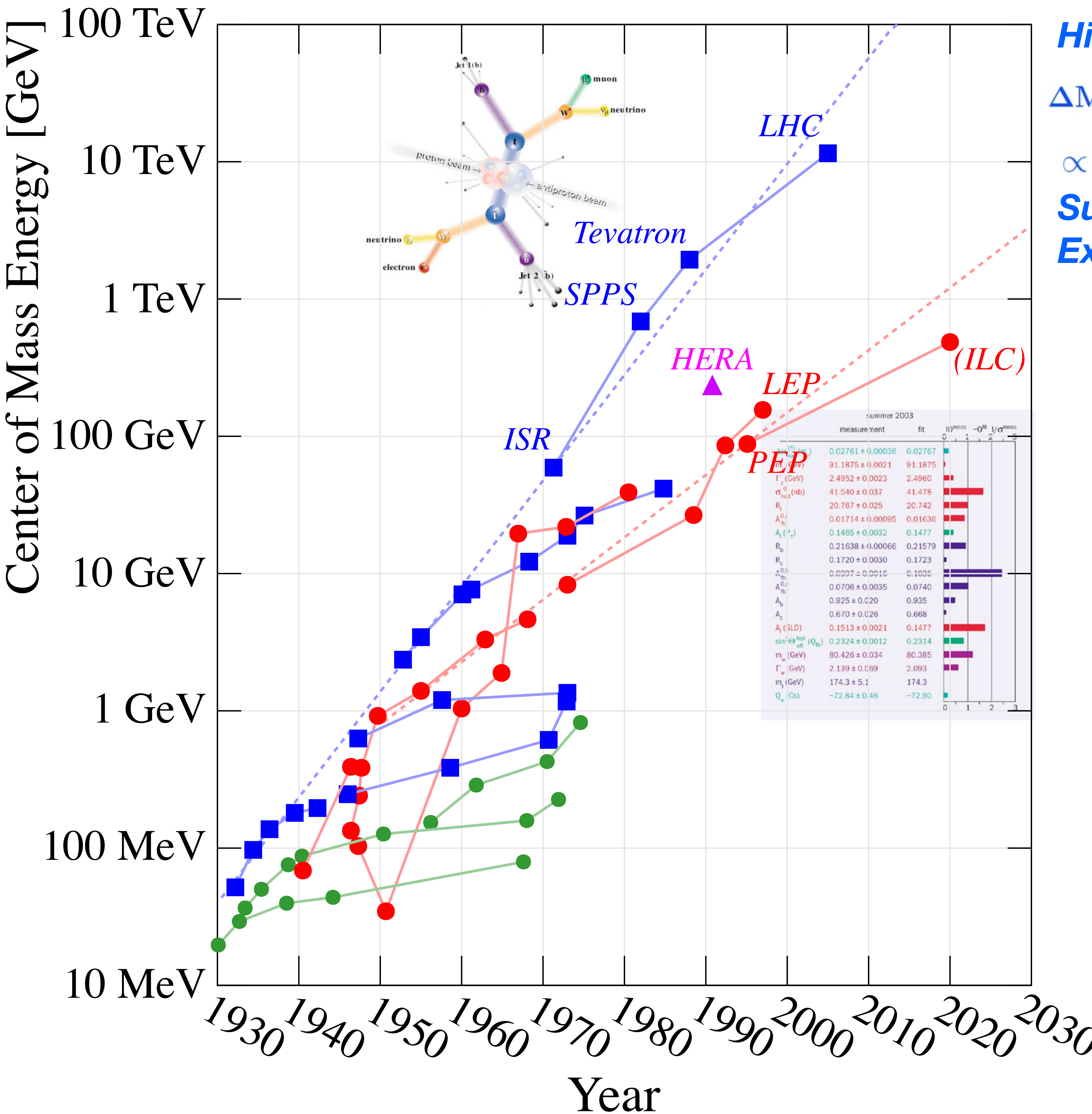
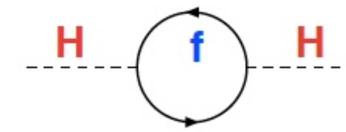


Higgs?

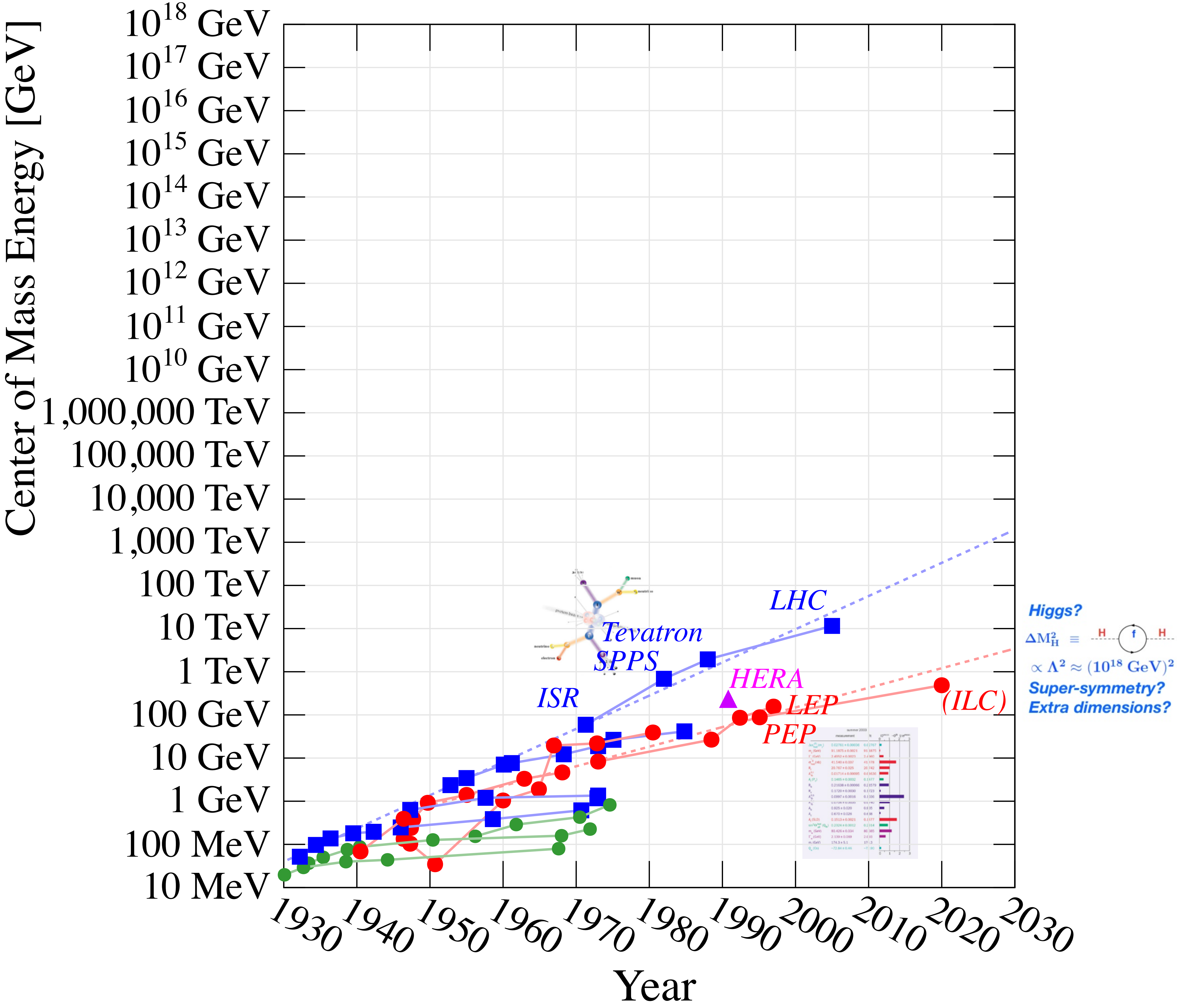
$\Delta M_H^2 \equiv$



$\propto \Lambda^2 \approx (10^{18}\ \mathrm{GeV})^2$

Super-symmetry?

Extra dimensions?



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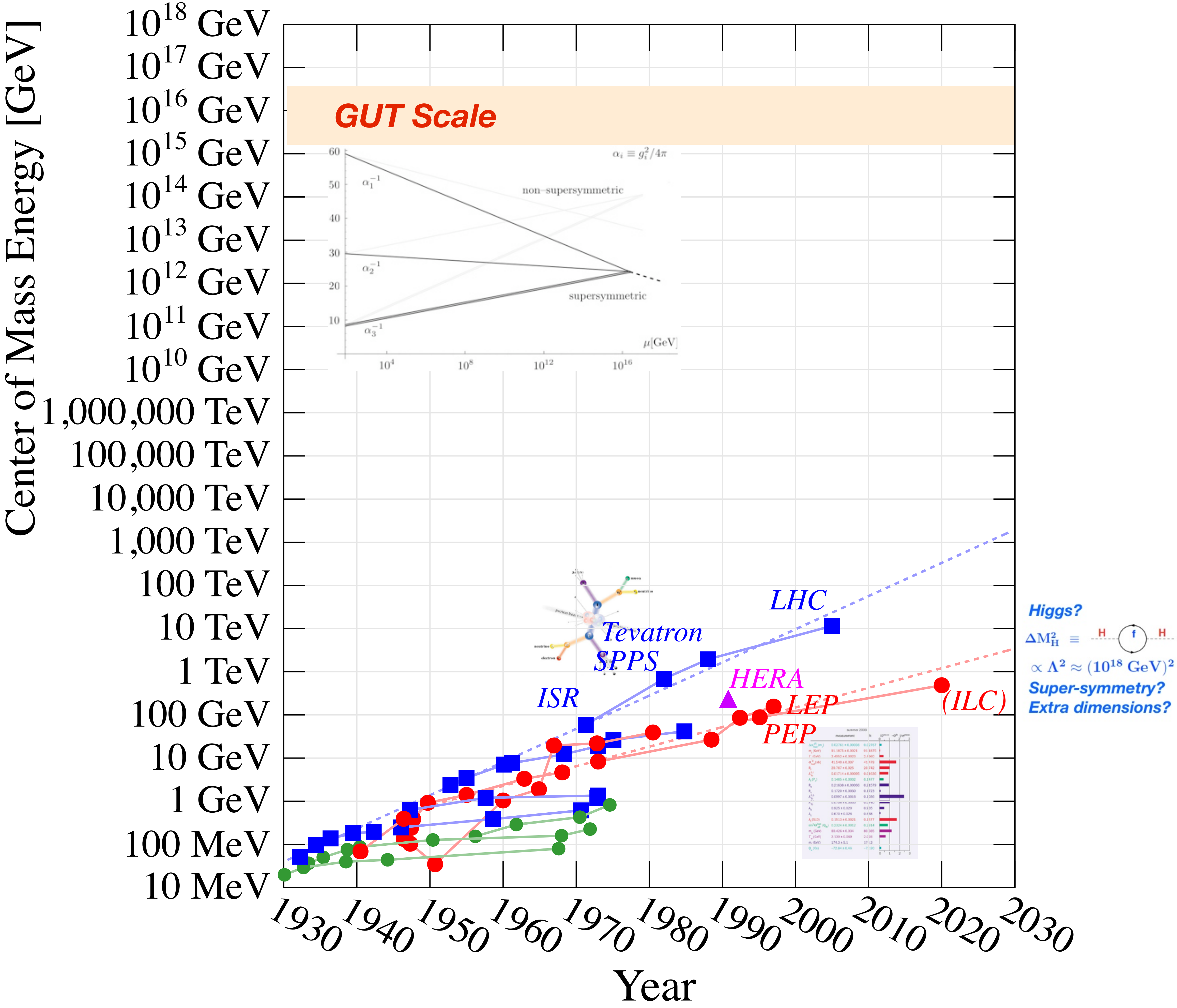

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GUT Scale
$\alpha_i \equiv g_i^2/4\pi$
non-supersymmetric
supersymmetric
α_1^{-1}
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μ[GeV]
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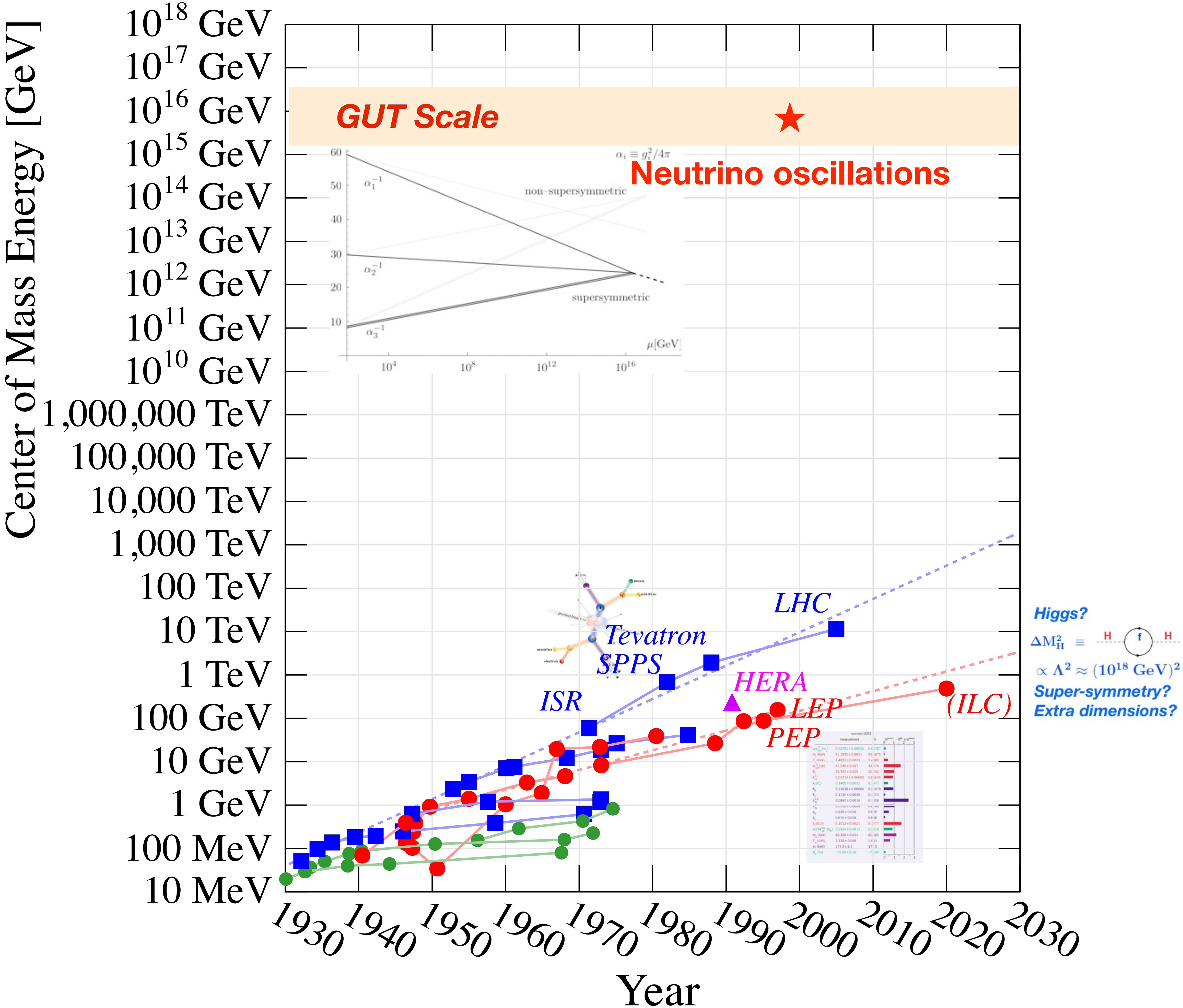

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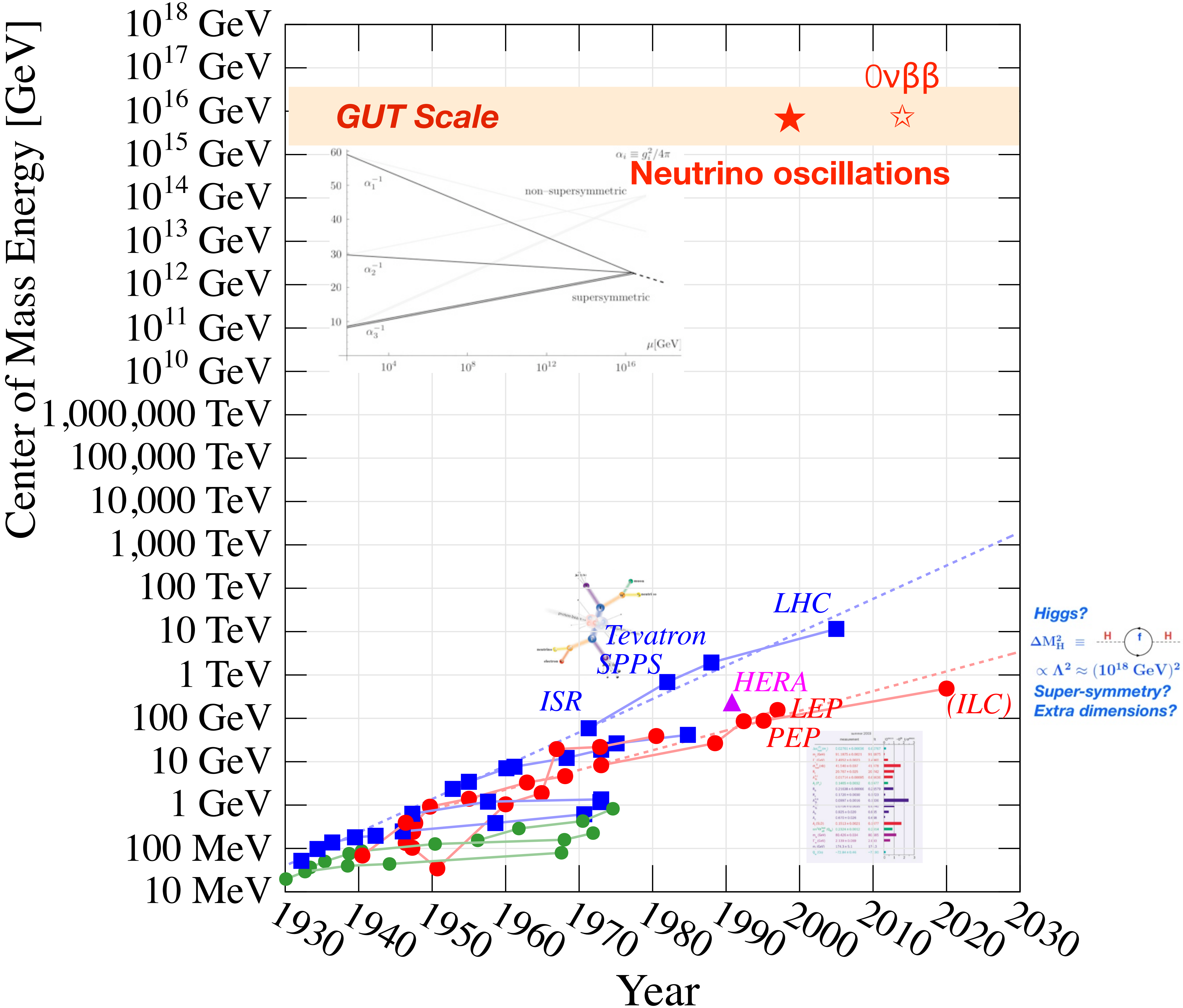

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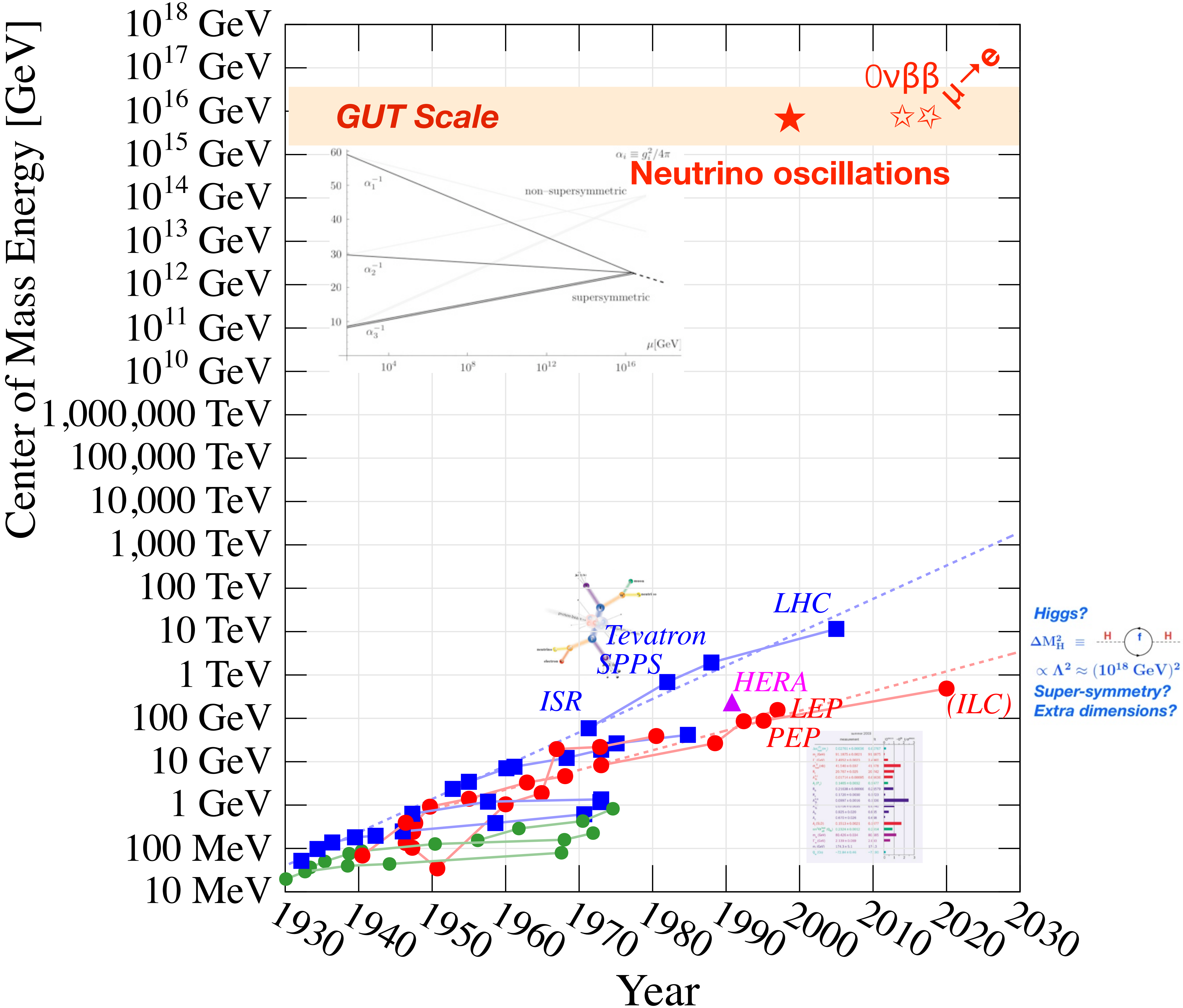

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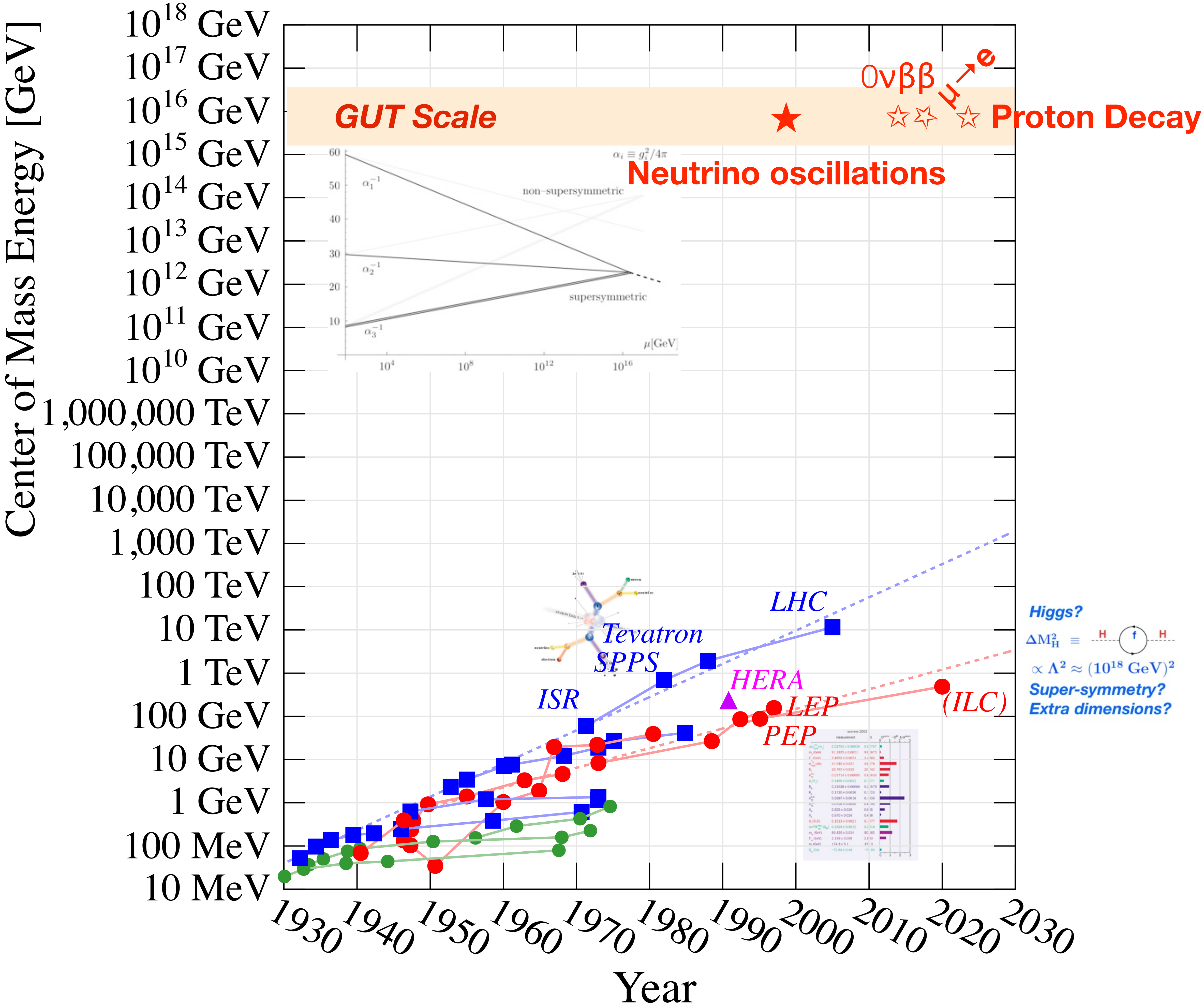
Extra dimensions?



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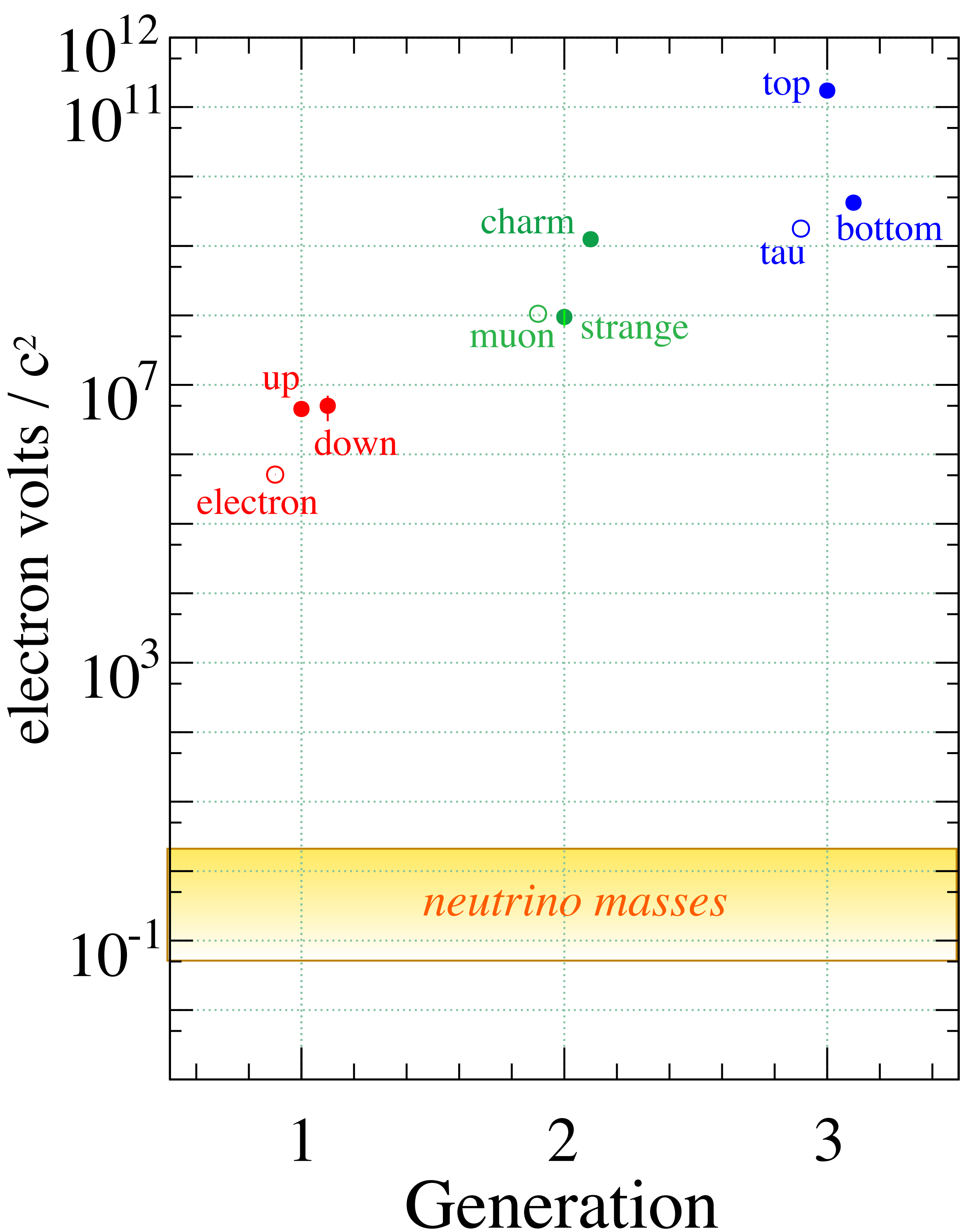
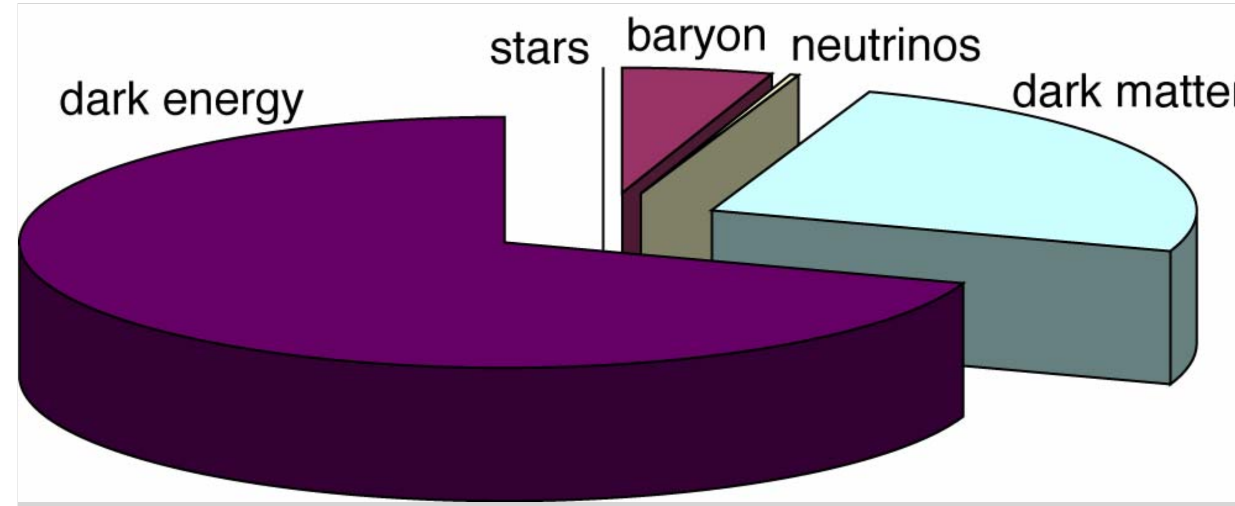




Stars and galaxies:	~0.5%
Rest of ordinary matter:	~5%
Neutrinos:	~0.3–10%
Dark Matter:	~25%
Dark Energy:	~70%

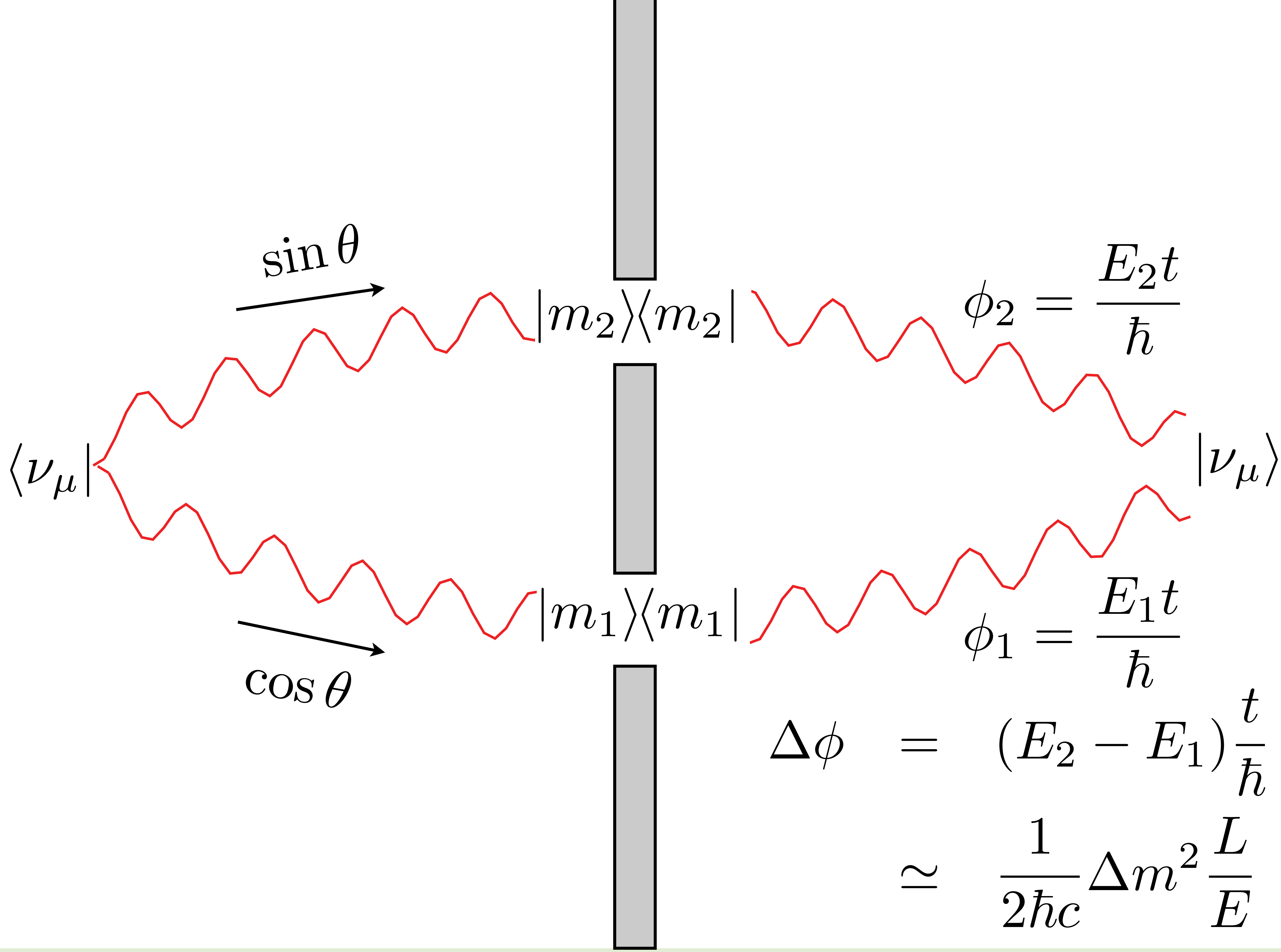
See-saw mechanism

$$\mathcal{L}_{\text{mass}} = \begin{bmatrix} \nu_L & \nu_R \end{bmatrix} \begin{bmatrix} 0 & m \\ m & M \end{bmatrix} \begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix}$$

$$\lambda \simeq \frac{m^2}{M} \simeq \frac{(100\ \text{GeV})^2}{10^{16}\ \text{GeV}} = 10^{-3}\ \text{eV}$$

Neutrino masses and mixing are a window on physics at the GUT scale

Neutrino Mass



$$\begin{aligned}\Delta\phi &= (E_2 - E_1)\frac{t}{\hbar} \\ &\simeq \frac{1}{2\hbar c}\Delta m^2 \frac{L}{E}\end{aligned}$$

$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2 2\theta \sin^2\left(1.27\Delta m^2[\mathrm{eV}^2]\frac{L[\mathrm{km}]}{E[\mathrm{GeV}]}\right)$$

Where to go from here?

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

$\nu_\mu \rightarrow \nu_\tau$

SK, K2K, and MINOS

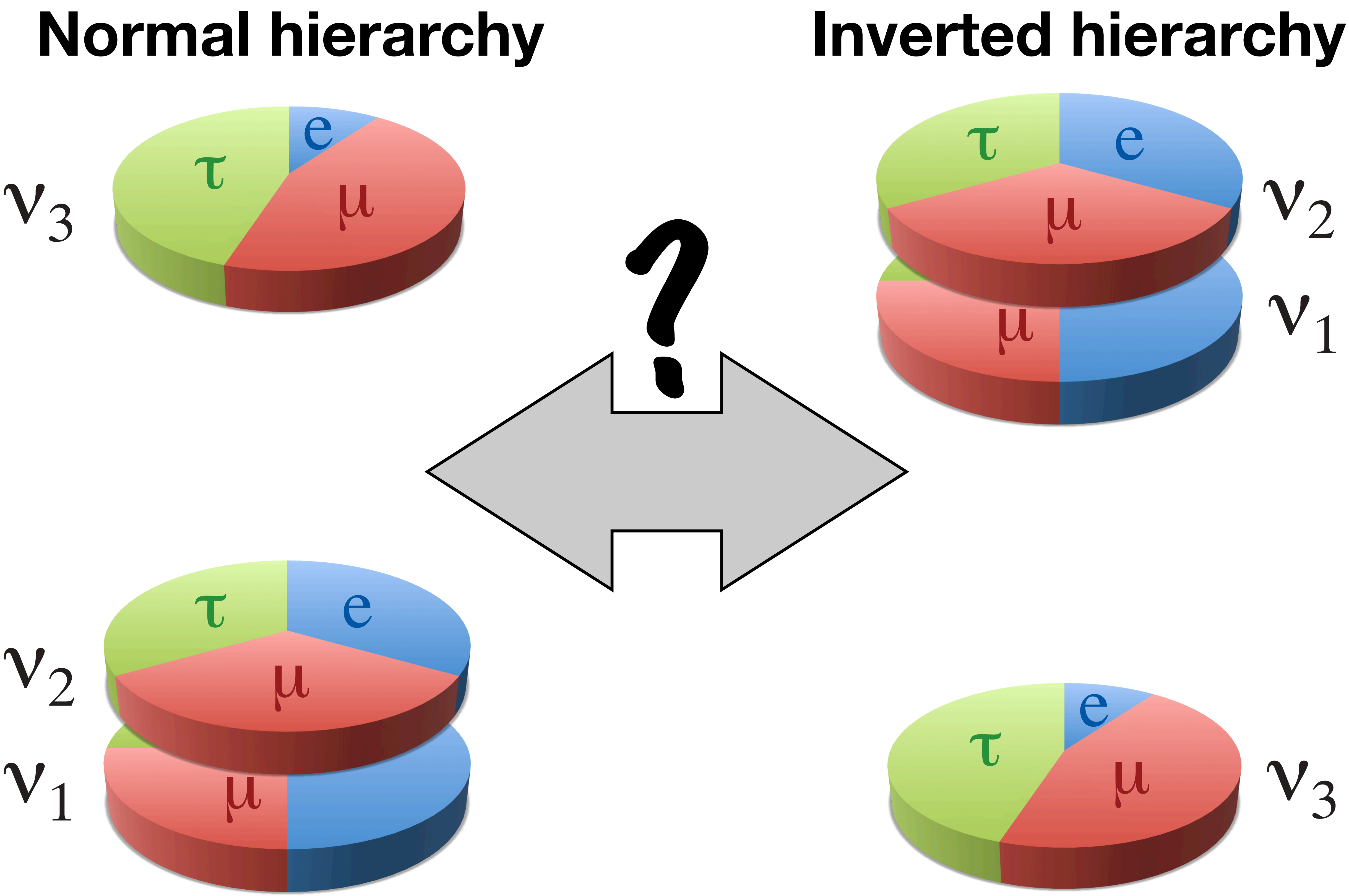
$\nu_e \rightarrow \nu_\mu + \nu_\tau$

Solar neutrinos + KamLAND

$\nu_\mu \rightarrow \nu_e$

Not observed. If this occurs opens possibility of CP violation in neutrino sector

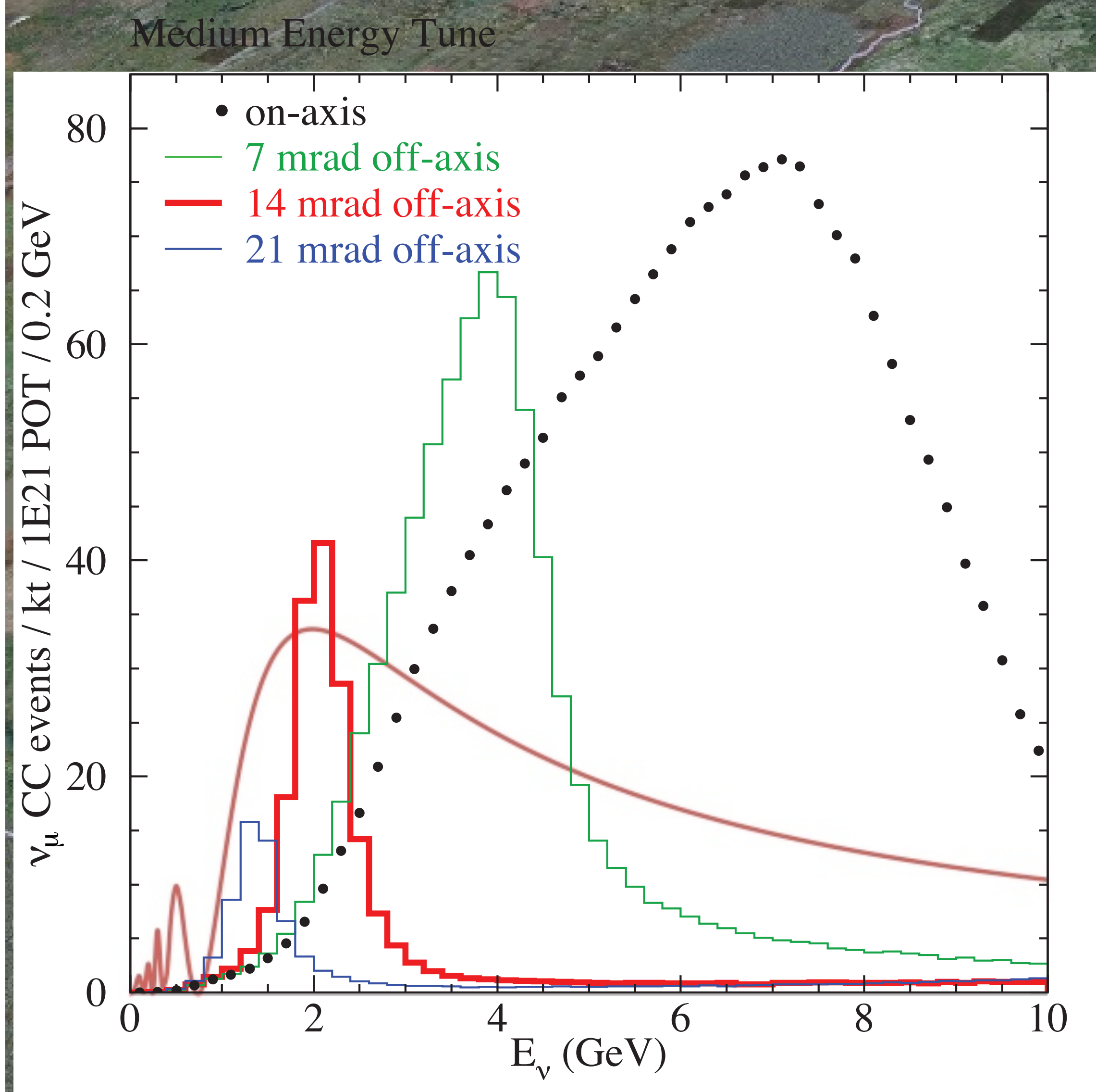
- What is θ_{13}?
- What is the pattern of masses? Is m_3 the heaviest or lightest state?
- Is the neutrino a Dirac or Majorana particle?
- Is CP violated?
- Is θ_{23} really maximal? μ-τ symmetry?
- Does the PMNS framework hold together or is there more going on?

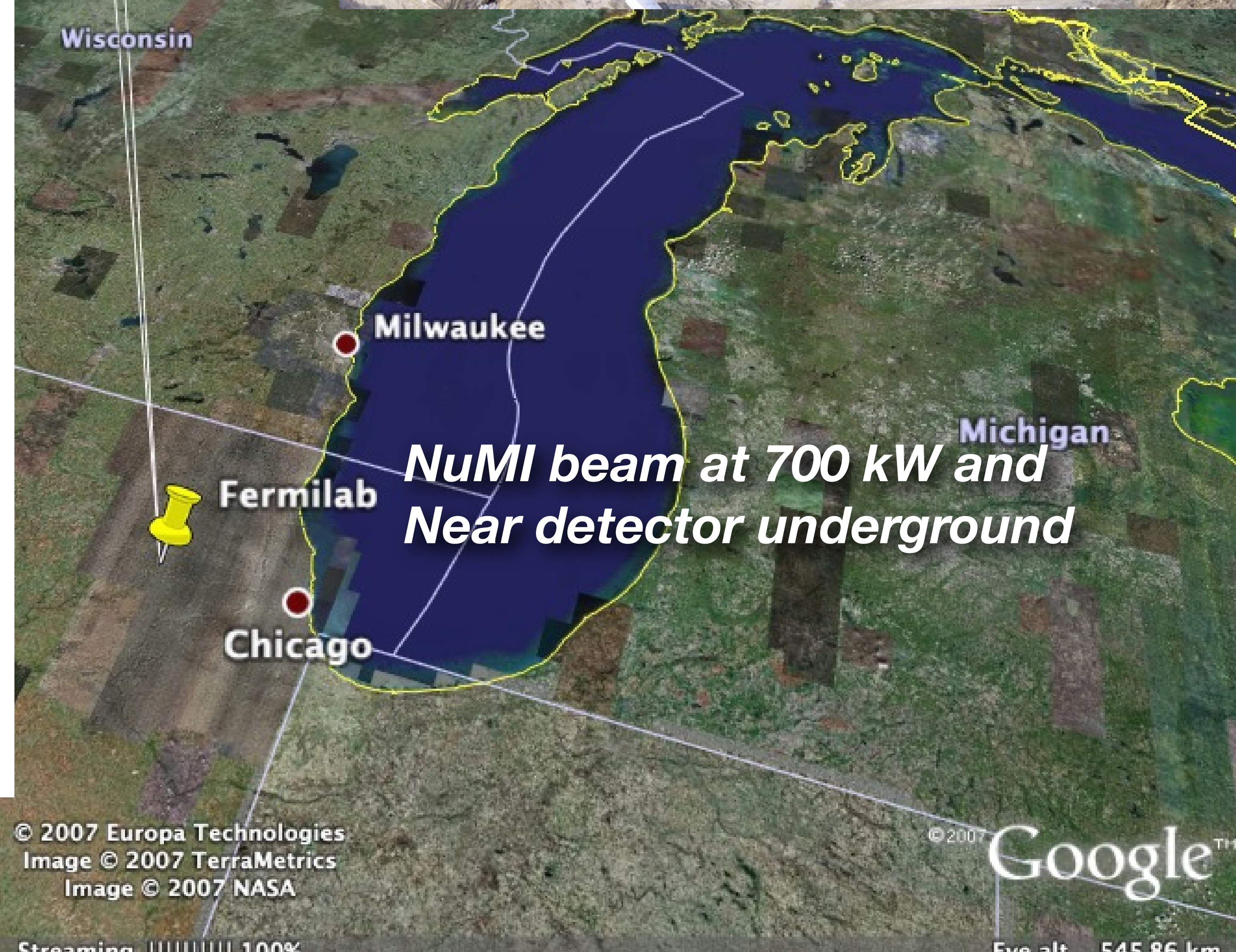


Normal hierarchy
Inverted hierarchy
ν_3
e
τ
μ
ν_2
ν_1
?

NOvA Far Detector Location

Ash River, MN
810 km from Fermilab





NuMI beam at 700 kW and
Near detector underground

Neutrino oscillations

Following presentation by Nunokawa, Parke, Valle, in "CP Violation and Neutrino Oscillations", Prog.Part.Nucl.Phys. 60 (2008) 338-402. arXiv:0710.0554 [hep-ph]

In vacuum:

$$P(\nu_\mu \to \nu_e) = |2U^*_{\mu 3}U_{e3}\sin\Delta_{31}e^{-i\Delta_{32}} + 2U^*_{\mu 2}U_{e2}\sin\Delta_{21}|^2$$

$$\Delta_{32} \equiv \frac{1.27\Delta m^2_{32}[\mathrm{eV}^2]L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]} = \frac{1.27\cdot 2.32\times 10^{-3}\cdot 810}{2.1} \simeq 1.1$$

For NOvA: $$\Delta_{31} \equiv \frac{1.27\Delta m^2_{31}[\mathrm{eV}^2]L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]} \simeq \Delta_{32}$$

$$\Delta_{21} \equiv \frac{1.27\Delta m^2_{21}[\mathrm{eV}^2]L\ [\mathrm{km}]}{E\ [\mathrm{GeV}]} = \frac{1.27\cdot 7.58\times 10^{-5}\cdot 810}{2.1} \simeq 0.04$$

$$\begin{aligned} P(\nu_\mu \to \nu_e) &\simeq |\sqrt{P_{\mathrm{atm}}}e^{-i(\Delta_{32}+\delta)} + \sqrt{P_{\mathrm{sol}}}|^2 \\ &= P_{\mathrm{atm}} + P_{\mathrm{sol}} + 2\sqrt{P_{\mathrm{atm}}P_{\mathrm{sol}}}\,(\cos\Delta_{32}\cos\delta \mp \sin\Delta_{32}\sin\delta) \end{aligned}$$

$$P_{\mathrm{atm}} \equiv \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

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long baseline experiments measure this combination

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"$-$" : ν

"$+$" : $\bar{\nu}$

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$$a = G_F N_e/\sqrt{2} \simeq \frac{1}{3500\ \rm km}$$

$$aL = 0.08\ \text{for}\ L = 295\ \rm km$$
$$aL = 0.23\ \text{for}\ L = 810\ \rm km$$

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dependence on relative sign of ***Δ_{31}*** *and* ***a***

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dependence on relative sign of ***Δ_{31}*** *and* ***a***

"fake" CP violation as ***a*** *changes sign for antineutrinos*

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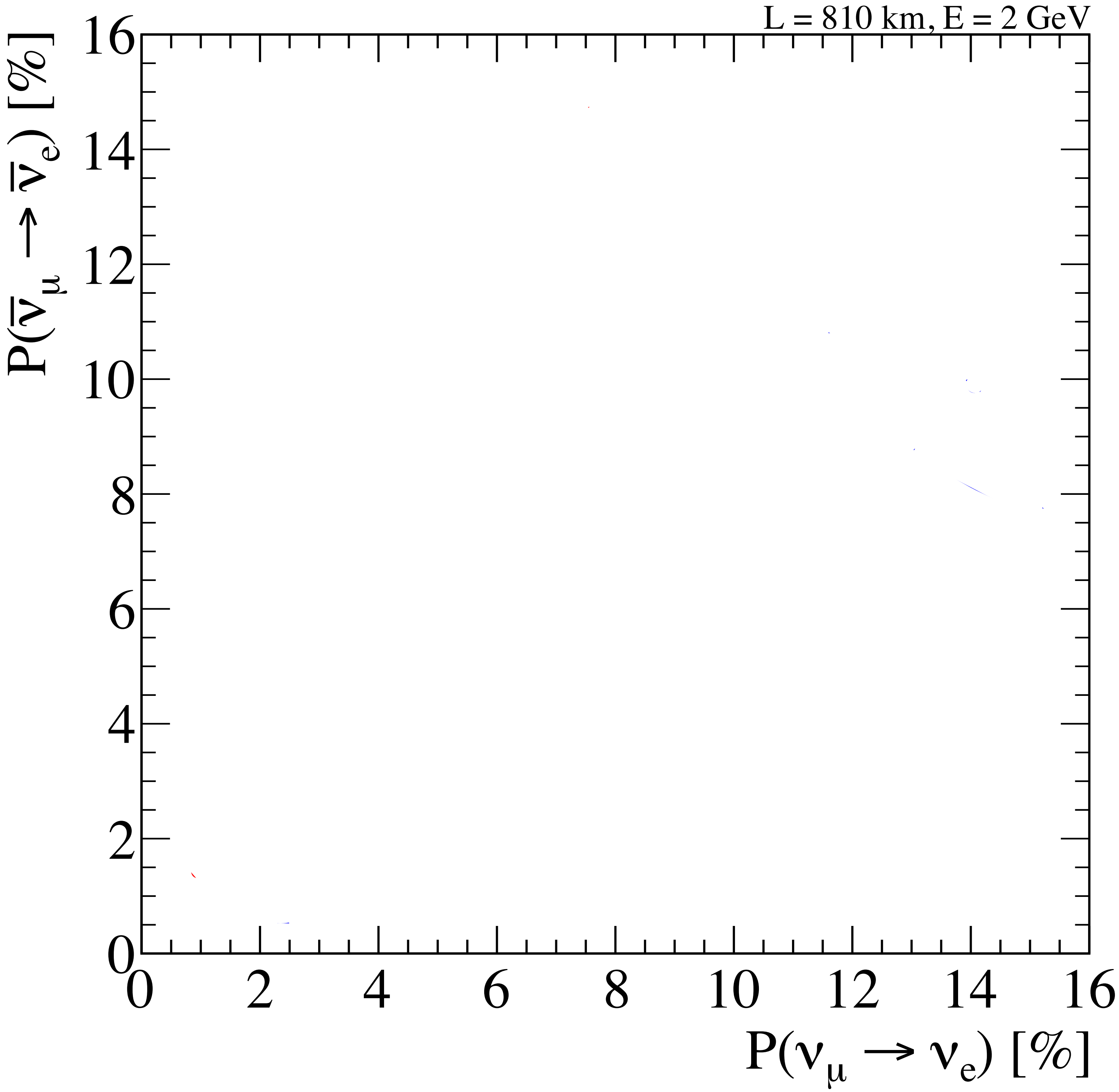
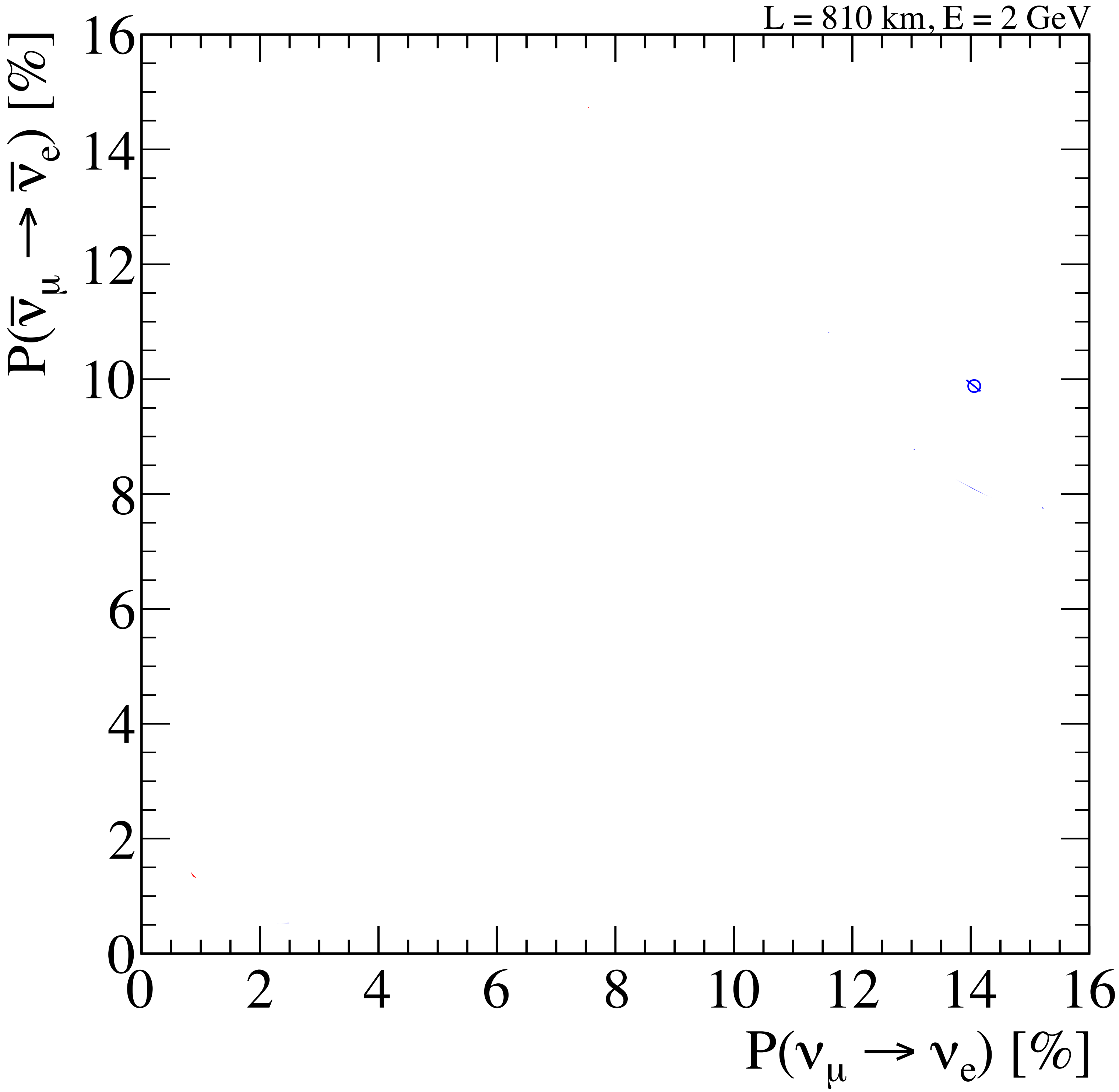


Using a muon neutrino beam, we have two basic observables

1. $P(\nu_\mu \rightarrow \nu_e)$ for neutrinos
2. $P(\nu_\mu \rightarrow \nu_e)$ for anti-neutrinos

We can plot these two observables as a function of the remaining unknowns θ_{13}, δ_{CP} , and mass hierarchy.

Principle of the NOvA Experiment



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$\Delta m^2_{31} > 0$ ("Normal hierarchy")

$\delta_{CP} = 0$

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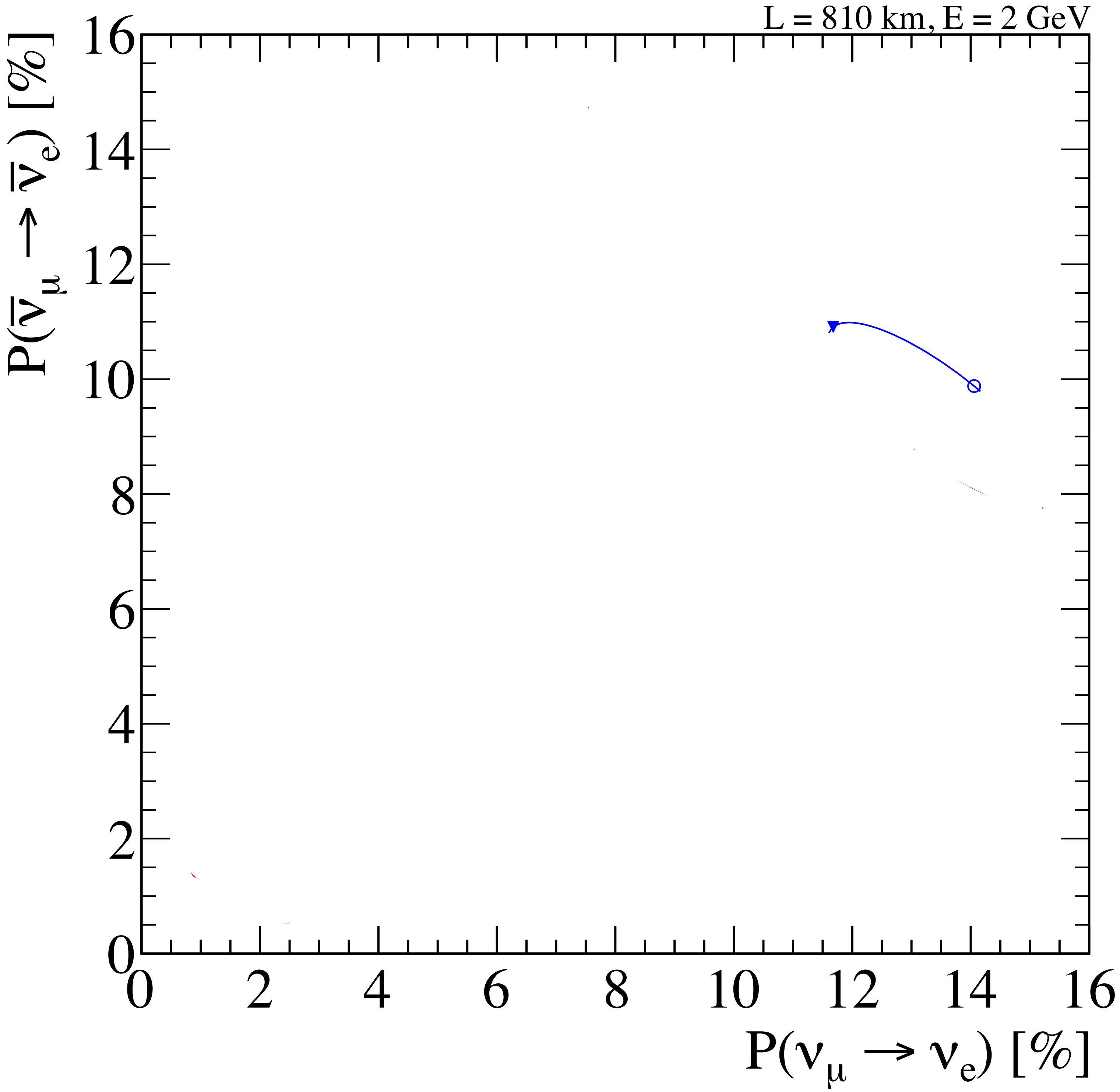

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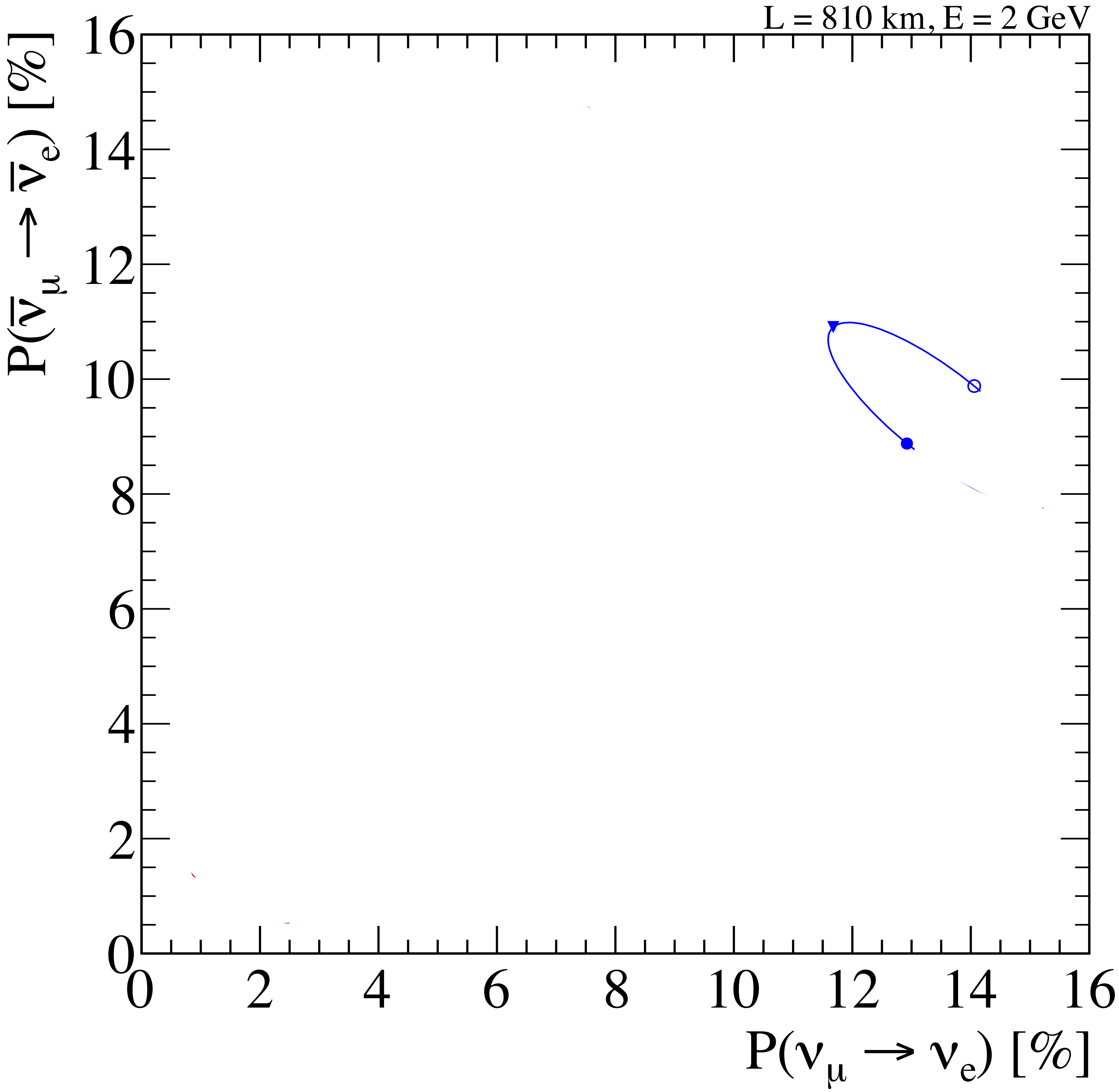
$\delta_{CP} = 0$, ▼$\pi/2$

Principle of the NOvA Experiment



Using a muon neutrino beam, we have two basic observables

1. $P(\nu_\mu \rightarrow \nu_e)$ for neutrinos
2. $P(\nu_\mu \rightarrow \nu_e)$ for anti-neutrinos

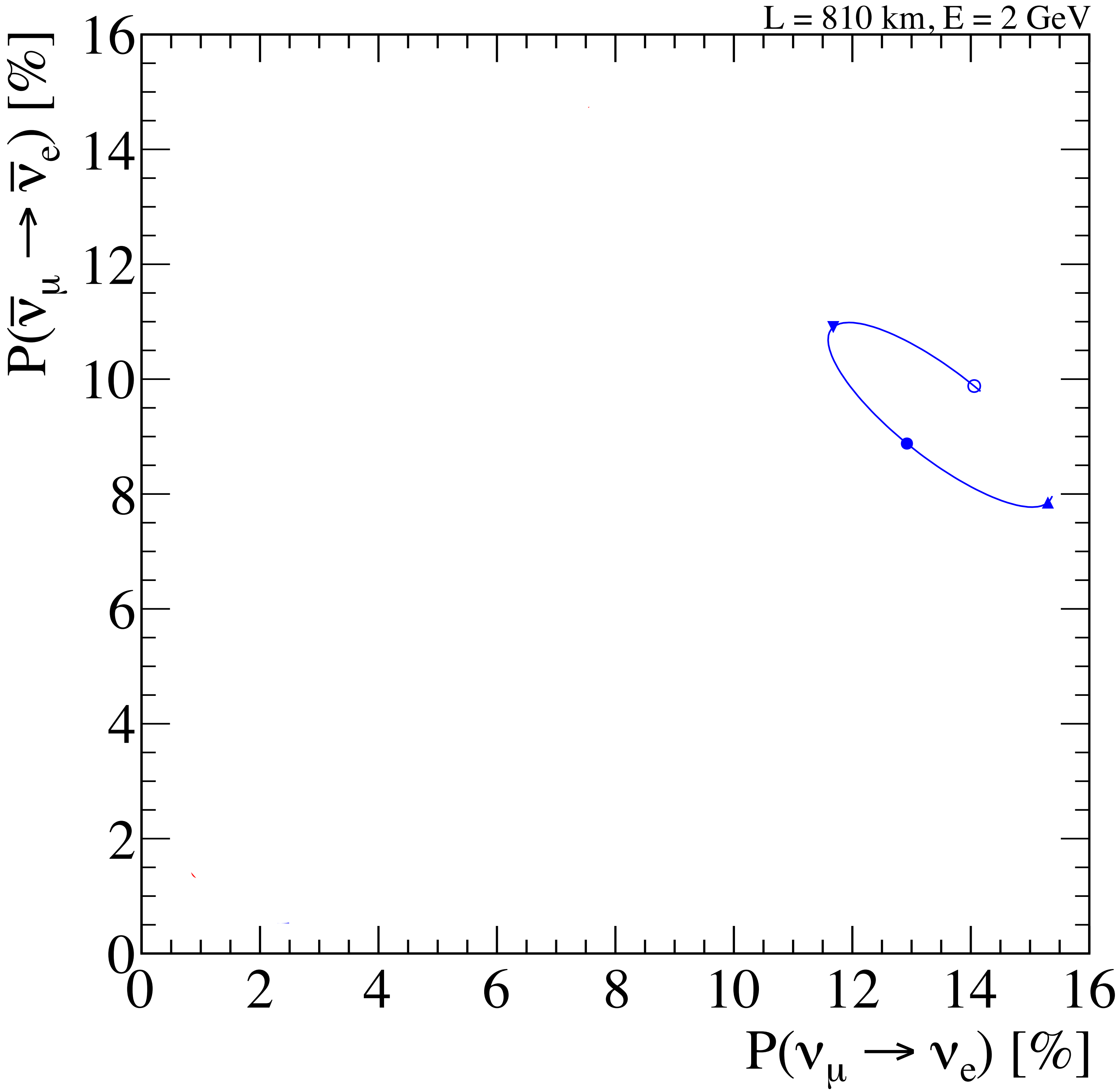
We can plot these two observables as a function of the remaining unknowns θ_{13}, δ_{CP}, and mass hierarchy.

$\theta_{13} = 15^o$

$\Delta m^2_{31} > 0$ ("Normal hierarchy")

$\delta_{CP} = 0$, ▼$\pi/2$, ● π

Principle of the NOvA Experiment



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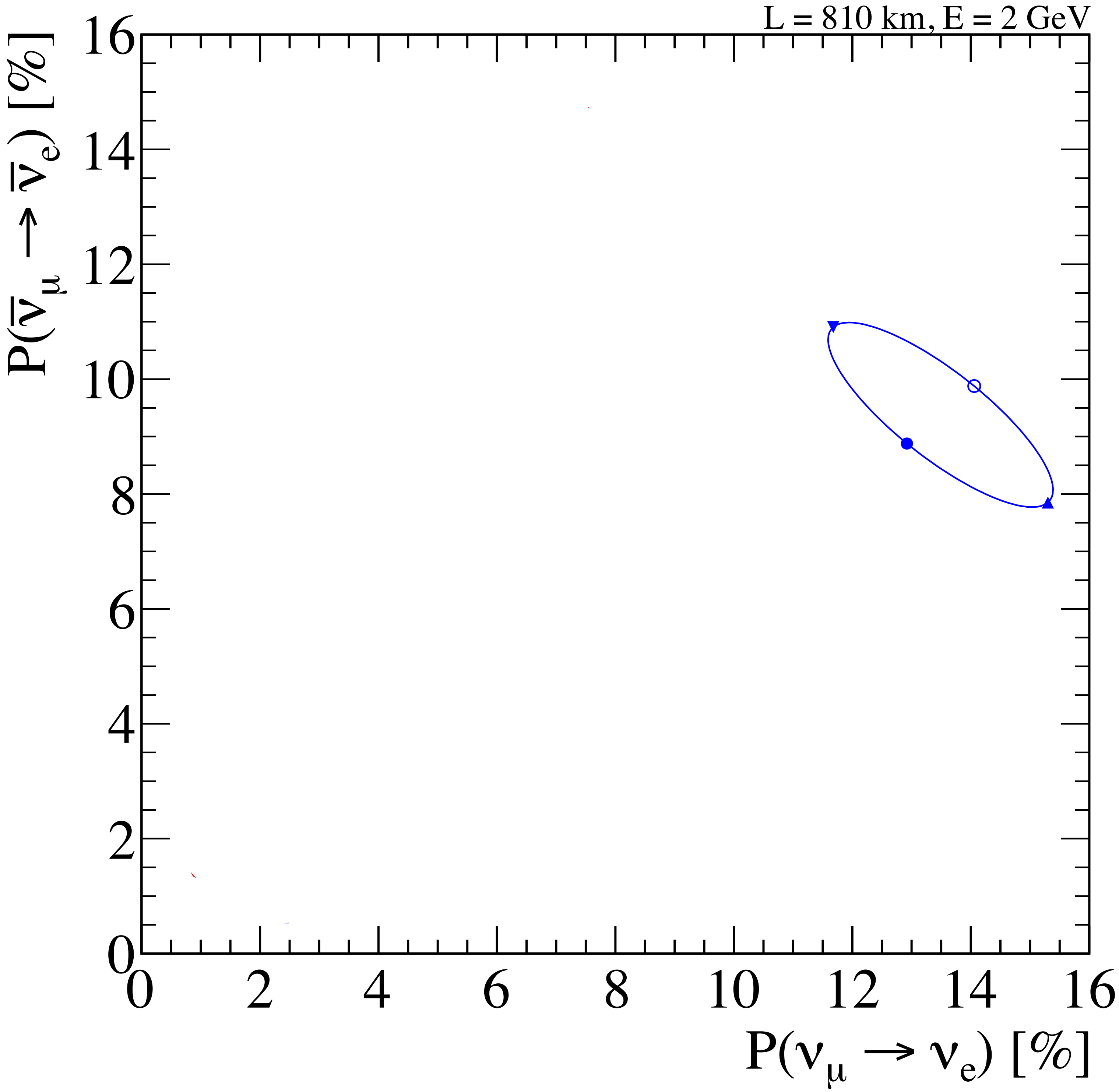

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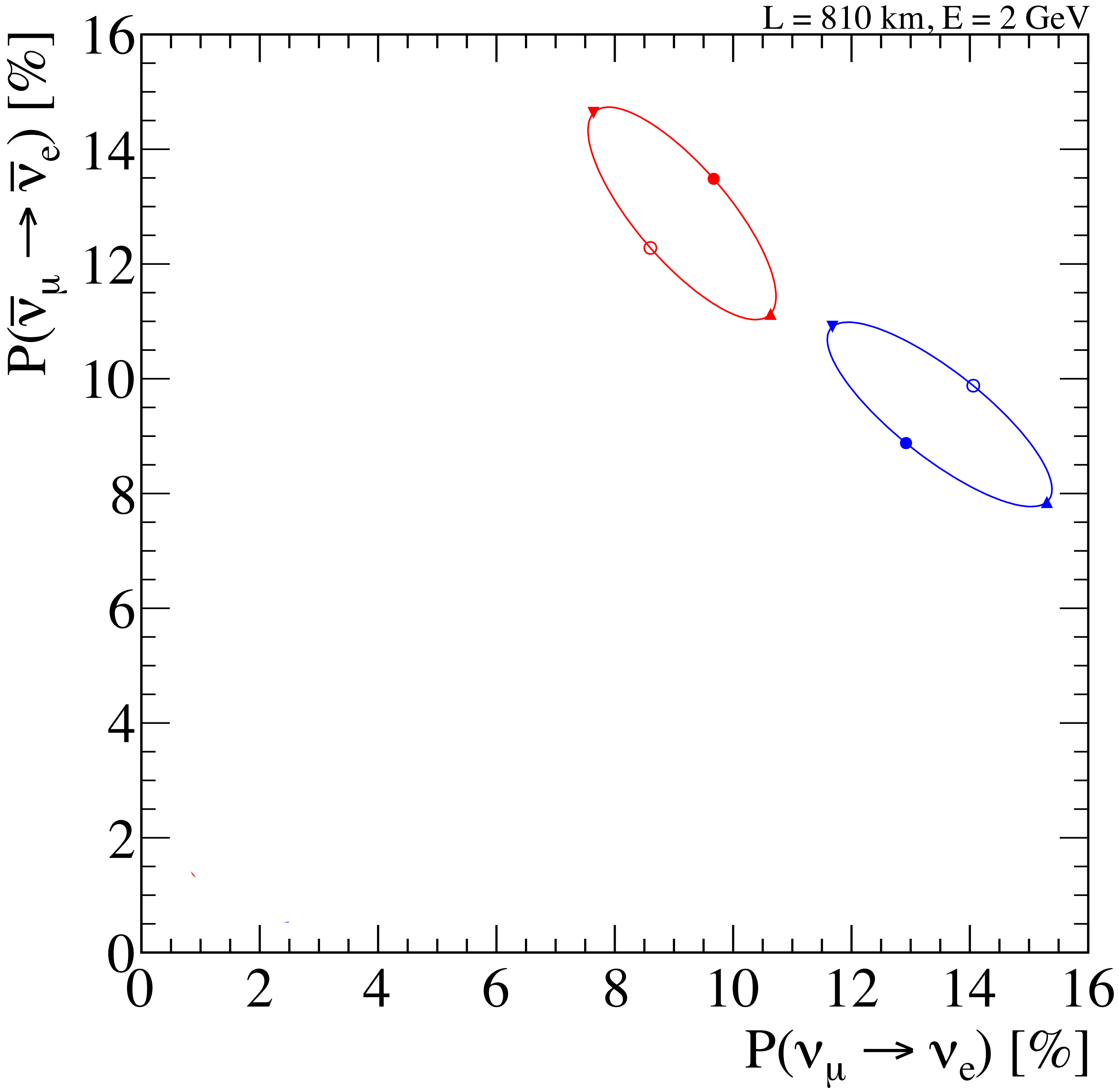

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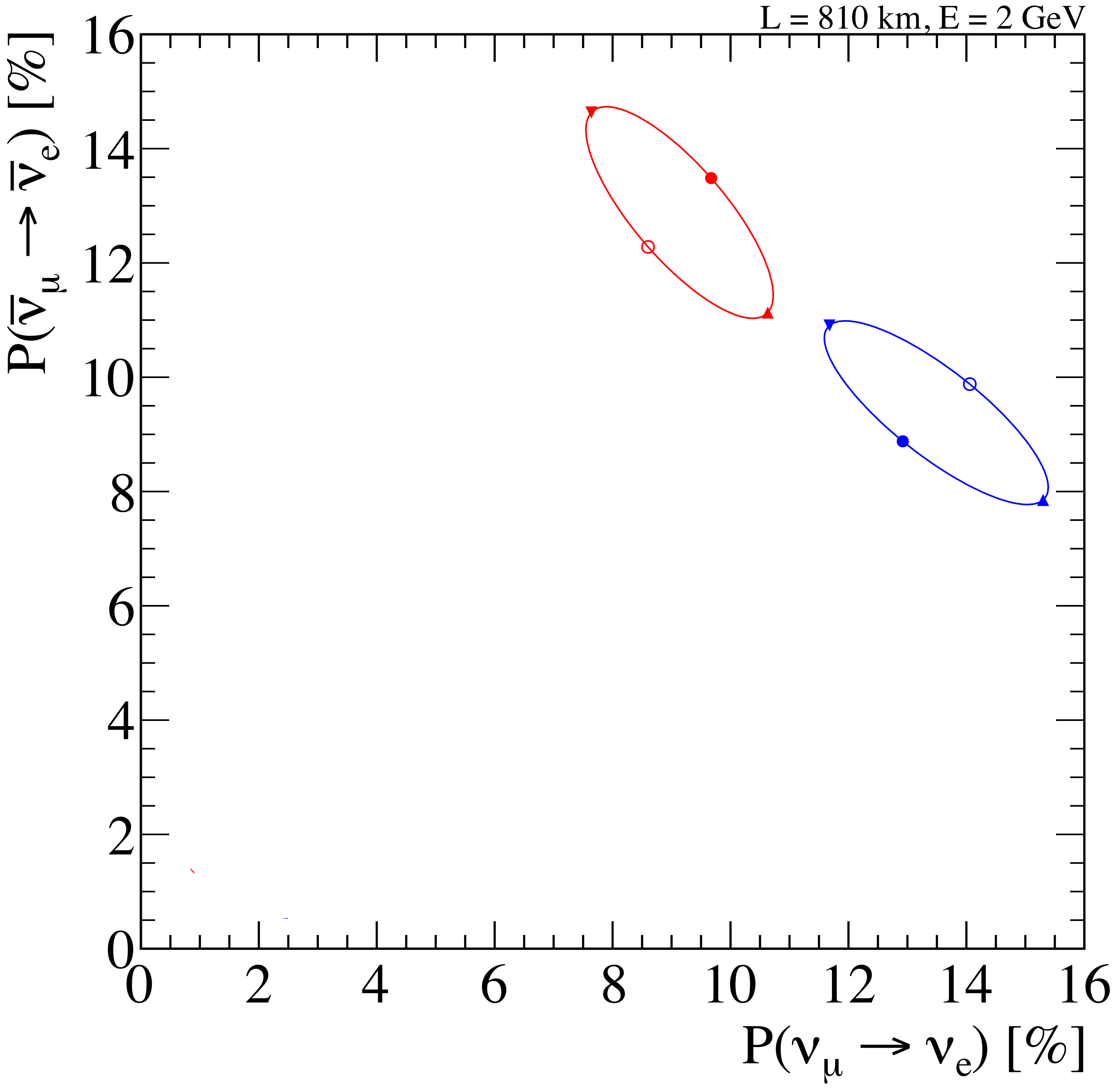

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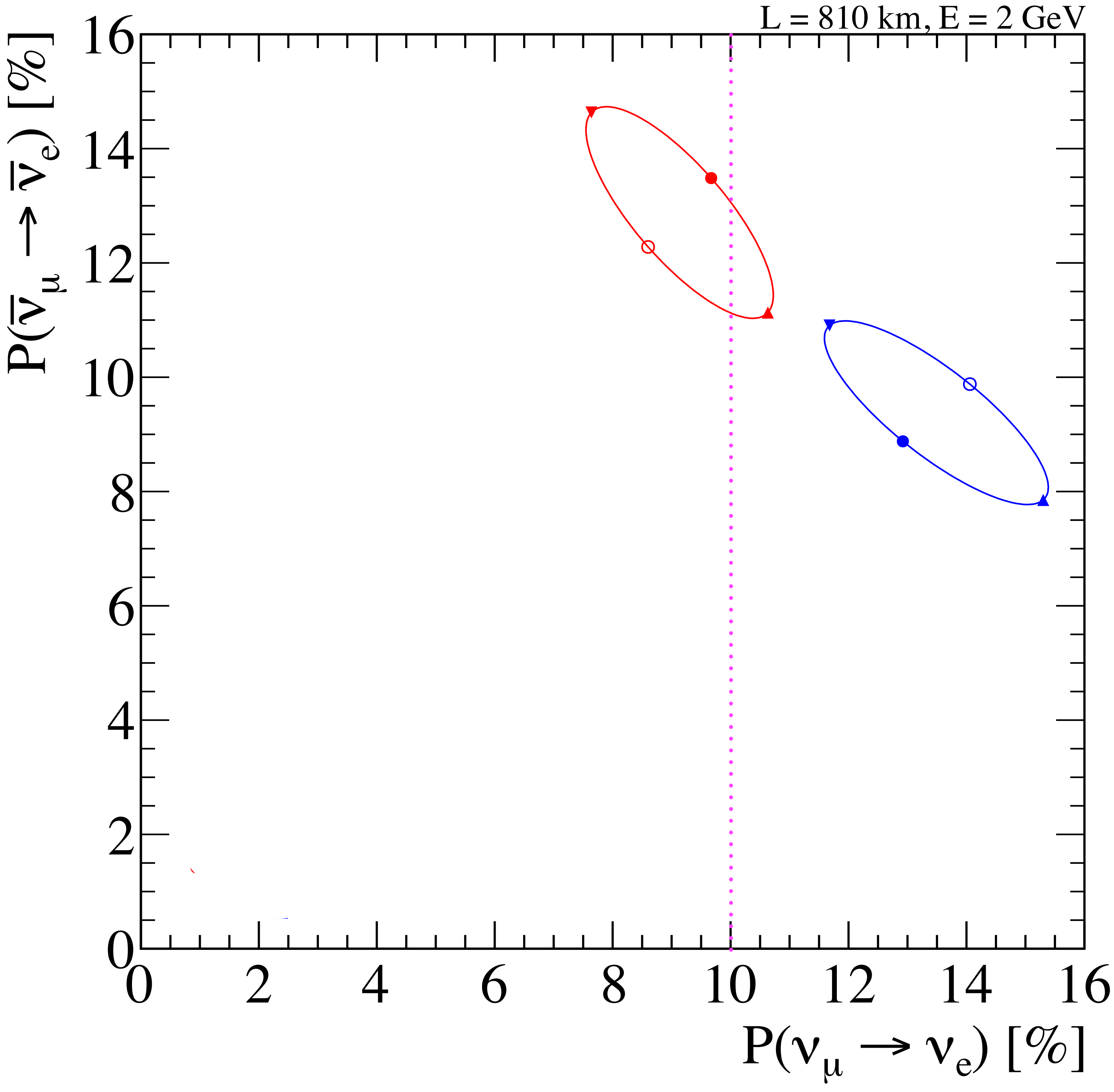
Perfect measurements of the two oscillation probabilities answer all remaining questions if θ_{13} is large enough.

Principle of the NOvA Experiment



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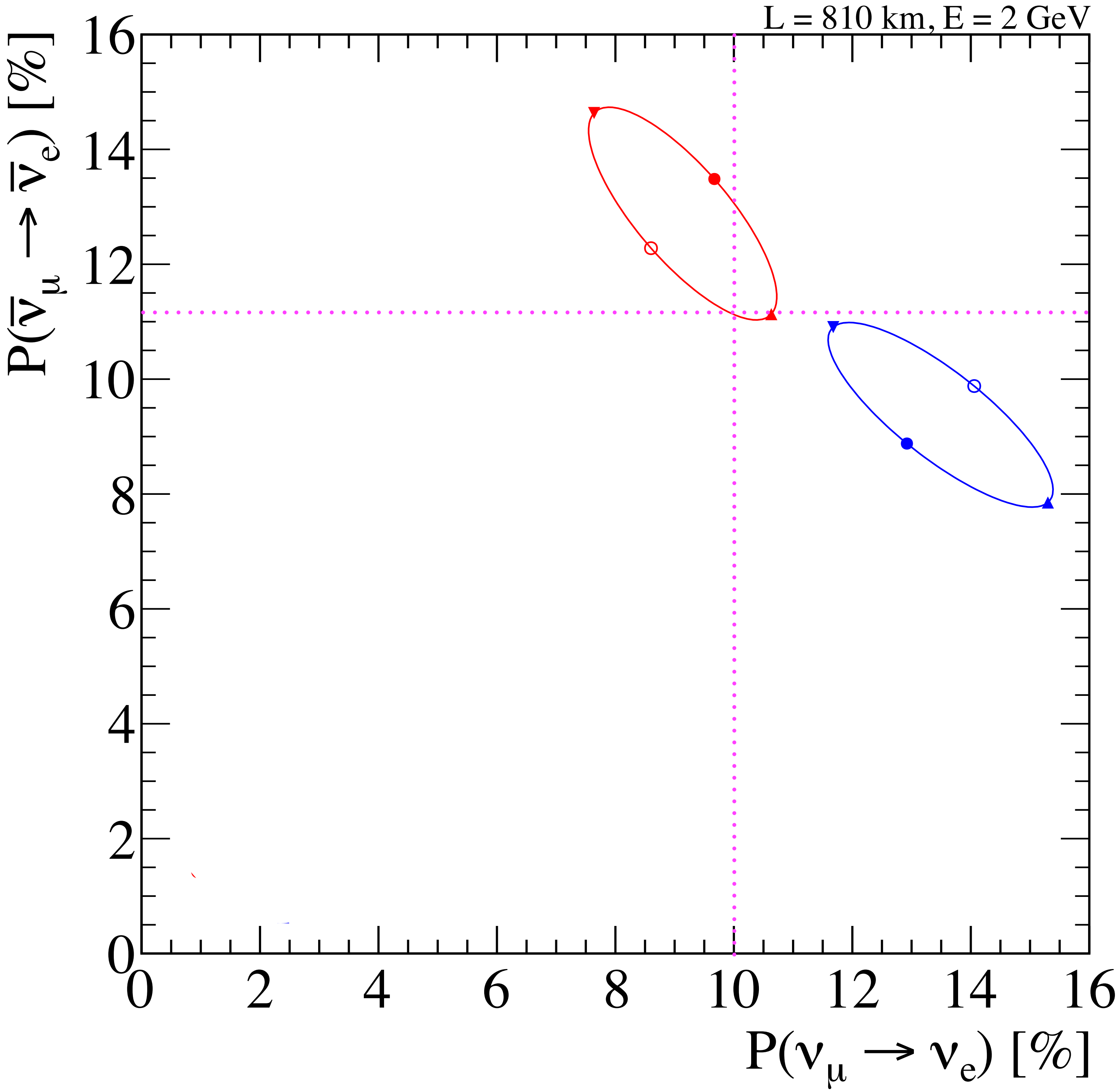

Using a muon neutrino beam, we have two basic observables

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We can plot these two observables as a function of the remaining unknowns θ_{13}, δ_{CP} , and mass hierarchy.

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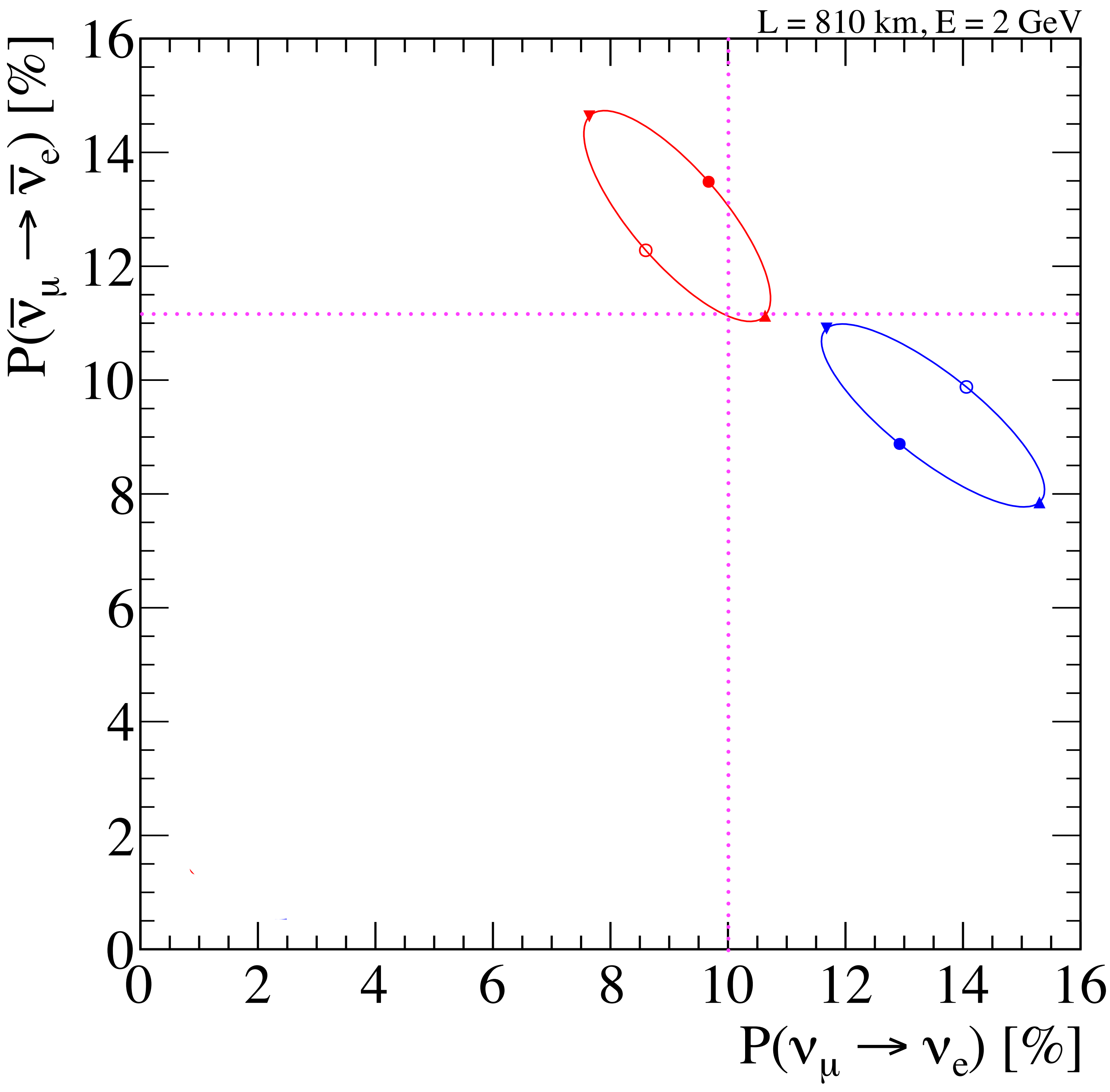

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$\theta_{13} = 15^o$

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$\delta_{CP} = 0$, ▼$\pi/2$, ● π, ▲$3\pi/2$, 2π

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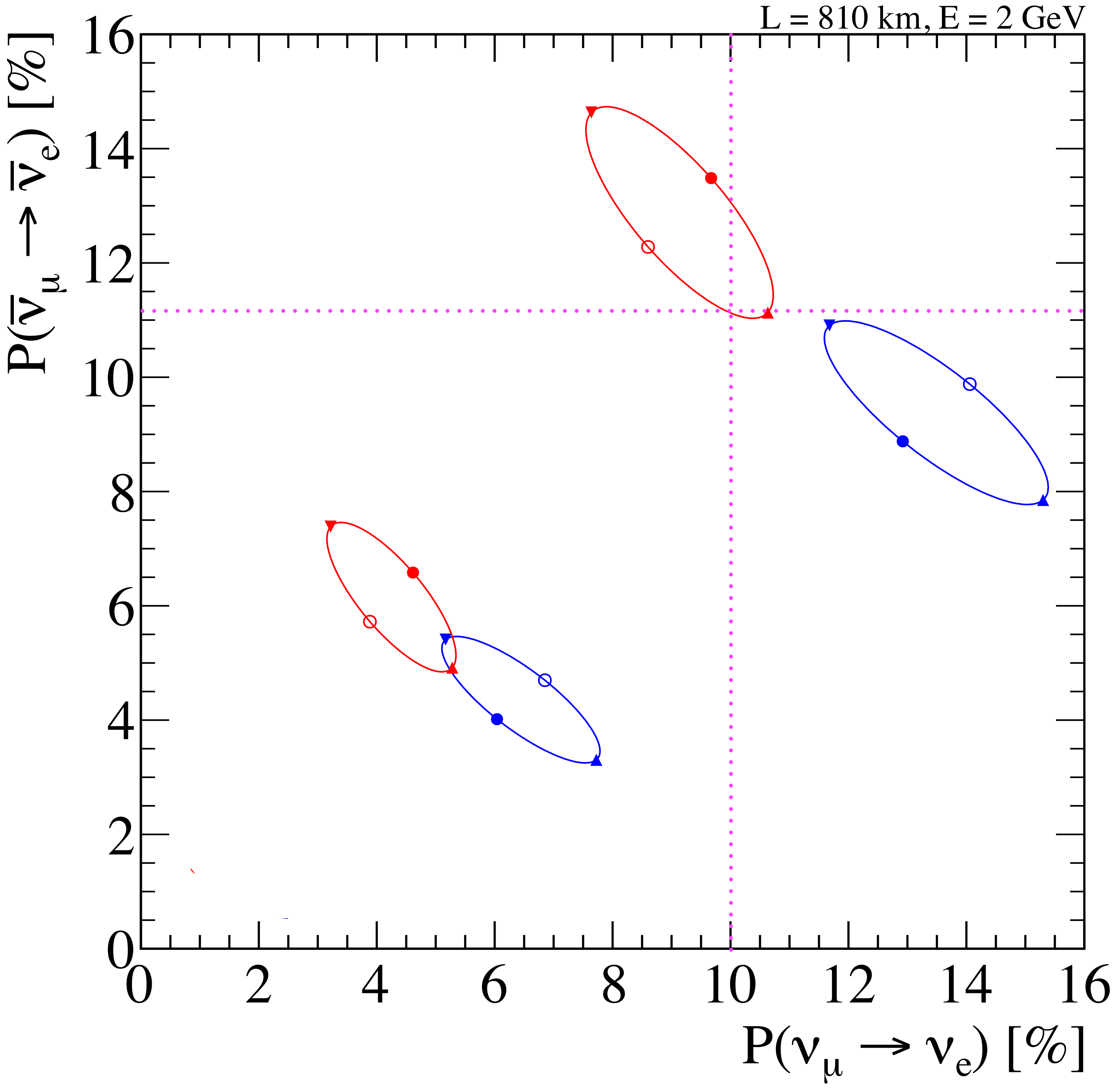
For small θ_{13} there are inherent ambiguities between hierarchy choice and δ_{CP}. However, even in these cases we learn something about δ_{CP}.



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θ_{13} = 15°, 10°

$\Delta m^2_{31}>0$ ("Normal hierarchy")

$\Delta m^2_{31}<0$ ("Inverted hierarchy")

δ_{CP} = 0, ▼π/2, ● π, ▲3π/2, 2π

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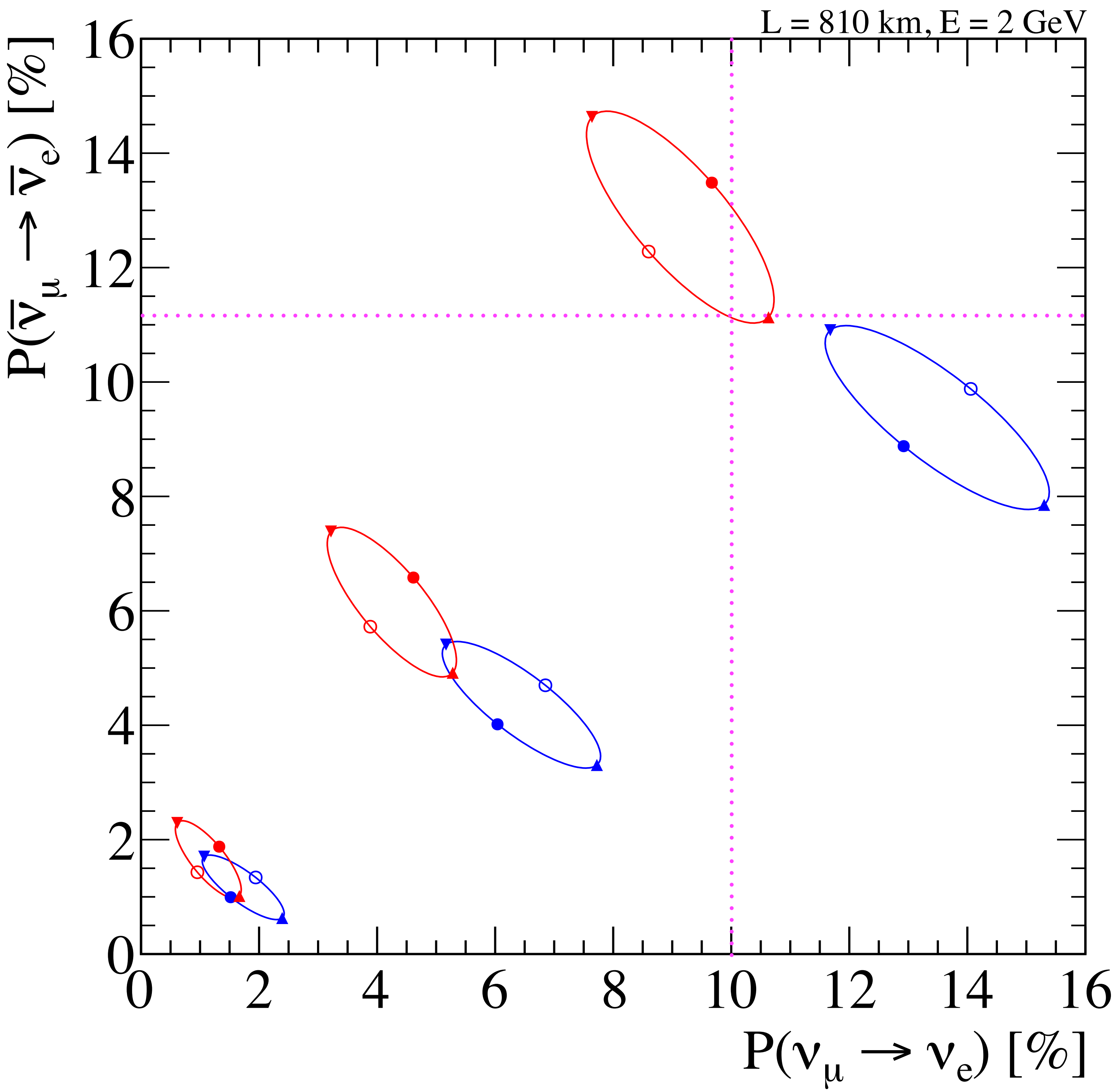

Principle of the NOvA Experiment

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We can plot these two observables as a function of the remaining unknowns θ_{13}, δ_{CP} , and mass hierarchy.

θ_{13} = 15°, 10°, 5°

$\Delta m^2_{31}>0$ ("Normal hierarchy")

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δ_{CP} = 0, ▼π/2, ● π, ▲3π/2, 2π

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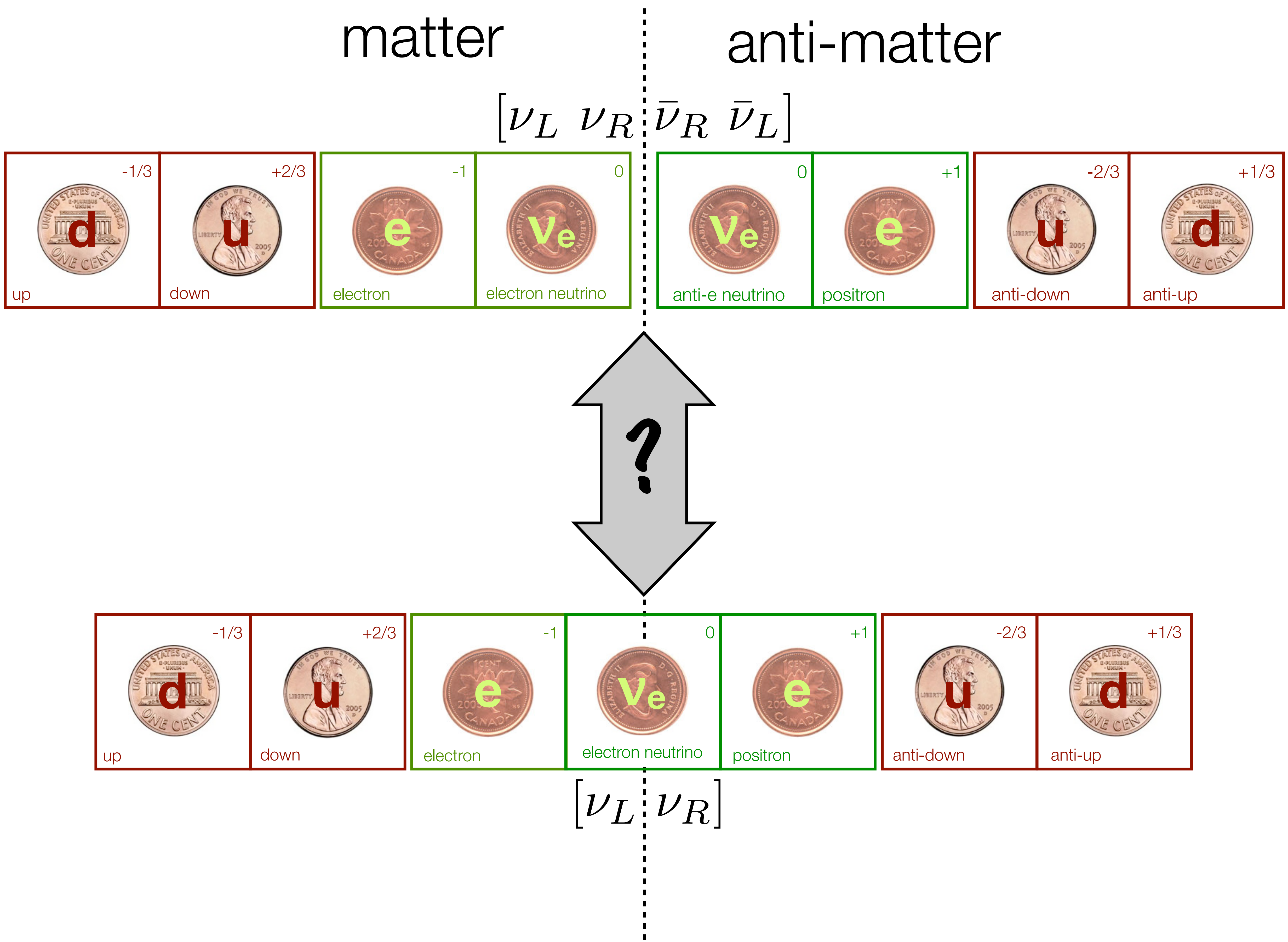
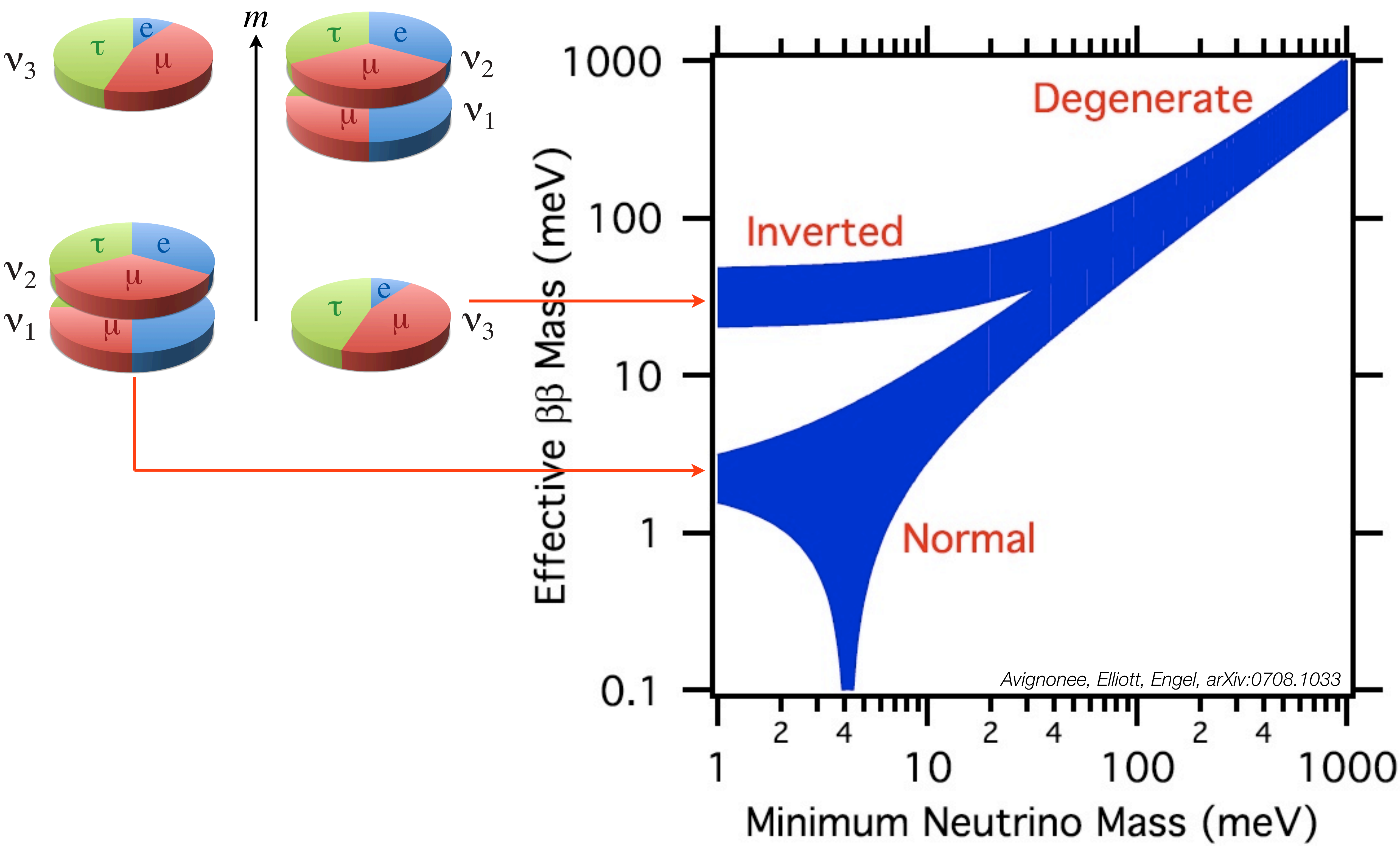
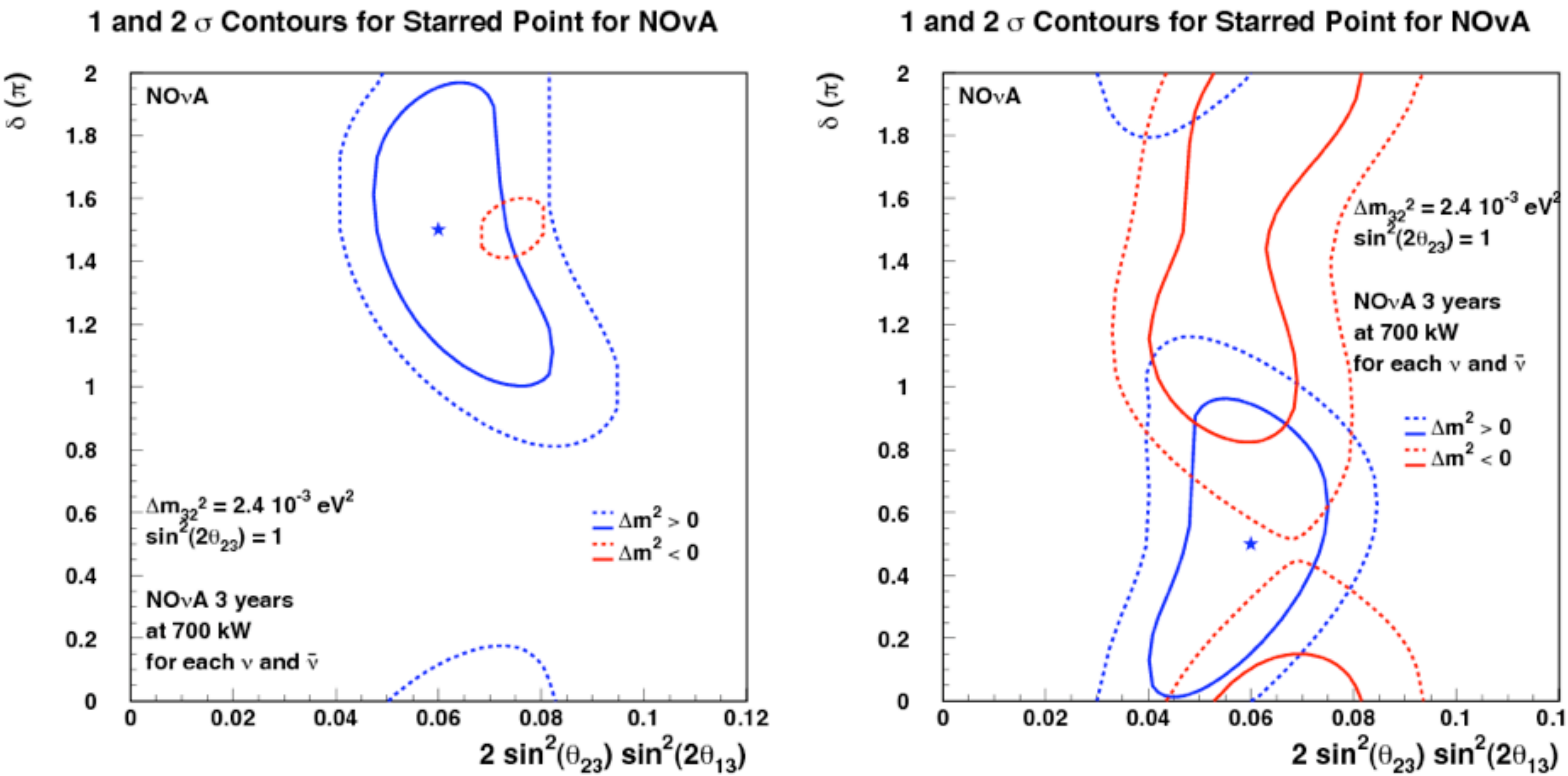
For small θ_{13} there are inherent ambiguities between hierarchy choice and δ_{CP}. However, even in these cases we learn something about δ_{CP}.

Is the Neutrino a Majorana or Dirac Particle?



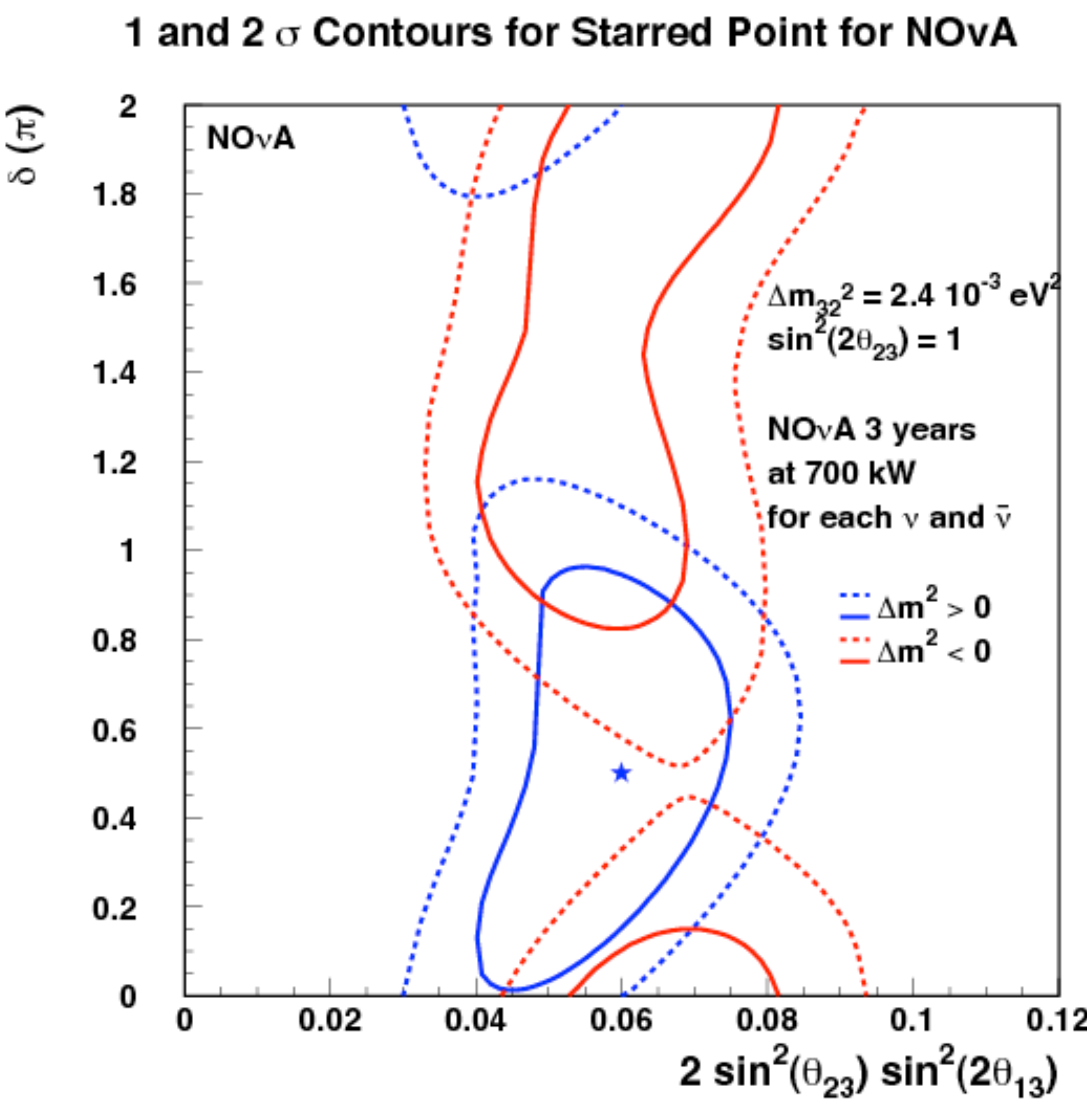
Neutrino-less double beta decay

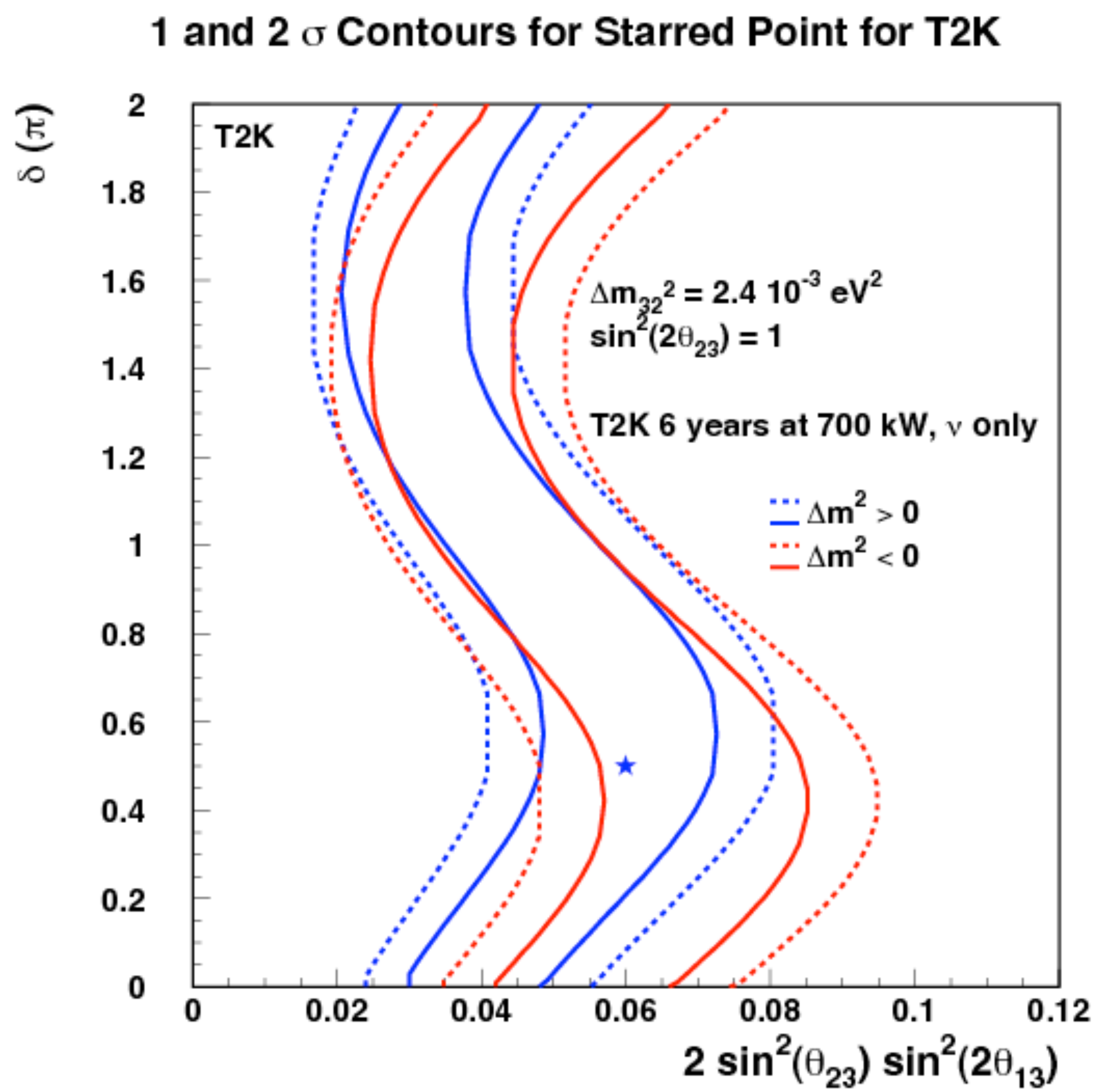




Possible NOvA measurements

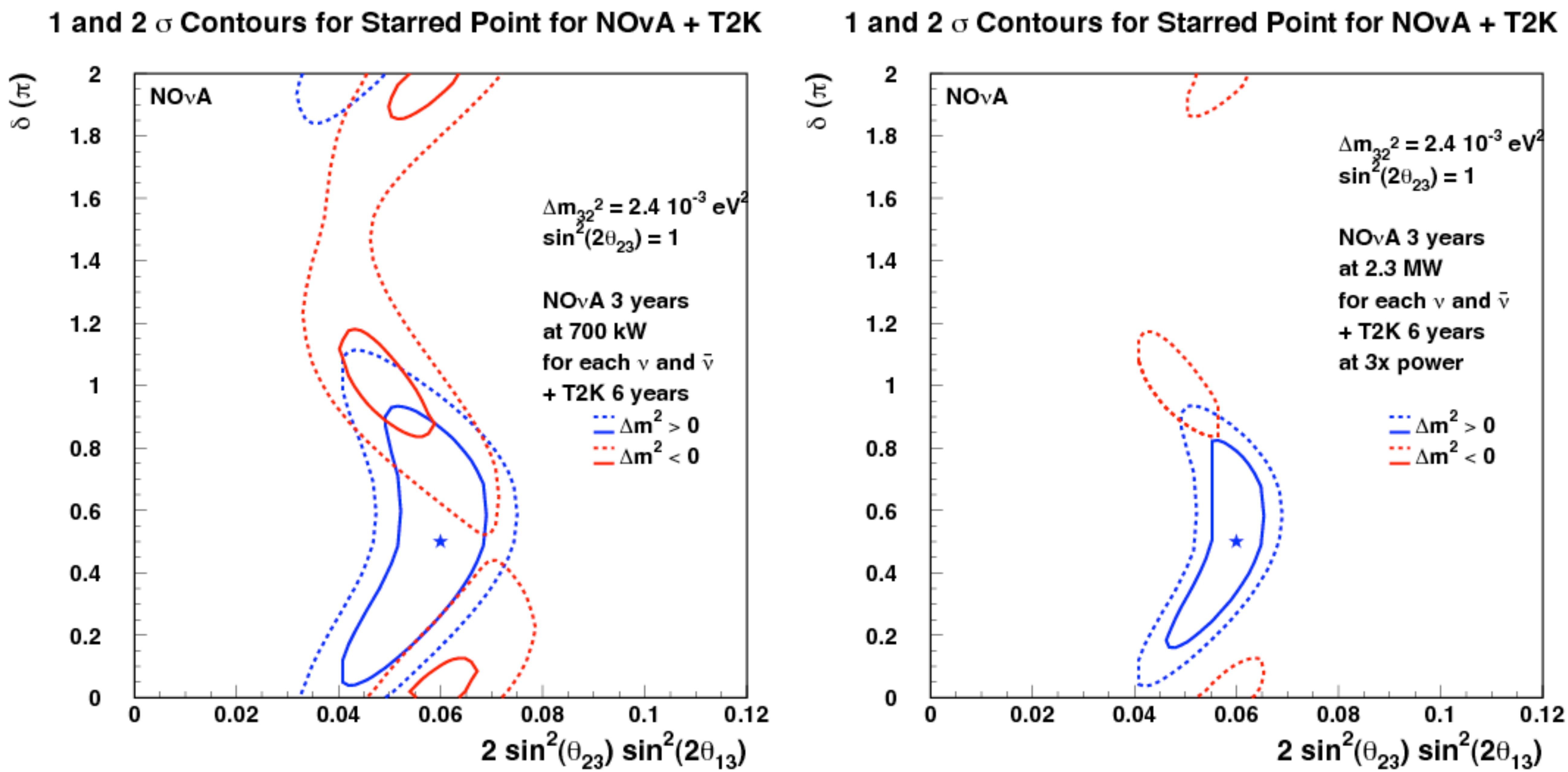
In best case NOvA measures θ_{13}, resolves the hierarchy, and learns about CPV. In worst case, NOvA measures θ_{13} and learns that hierarchy and CPV are arranged such that they cancel.





Combining NOvA with T2K in worst case

As NOvA runs both neutrinos and antineutrinos its contours are relatively straight. T2K's contours trace an "S" which intersects NOvA's contours in the lower part of the plot.

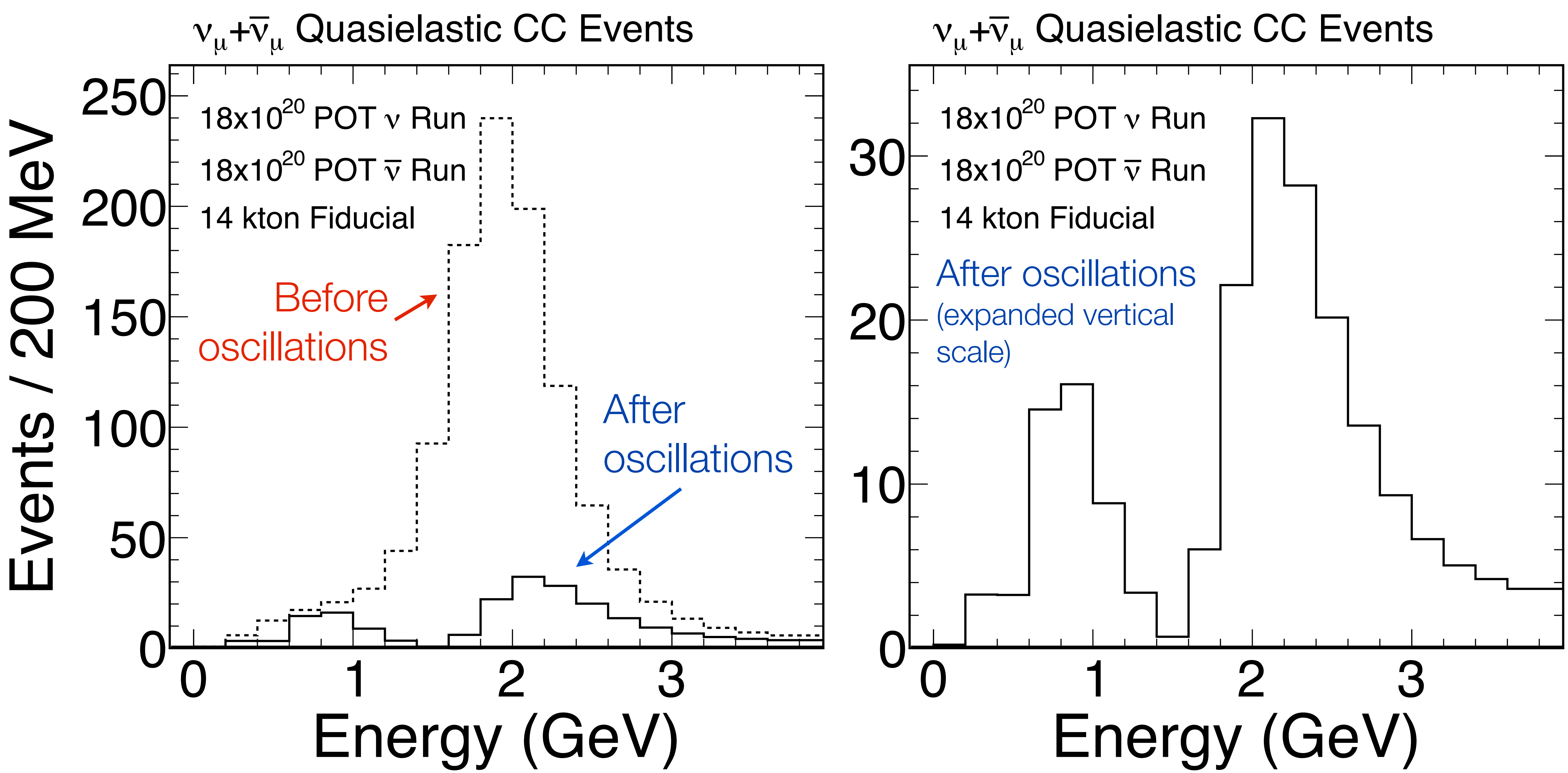


Combining NOvA with T2K

On the left we assume nominal T2K and NOvA runs. This constrains the CP phase to the lower half plane (1 sigma), but leaves the hierarchy unresolved. Increasing the statistics to each experiment by 3x resolves the hierarchy.

$\nu_\mu \to \nu_\mu$ and $\bar{\nu}_\mu \to \bar{\nu}_\mu$ Channel

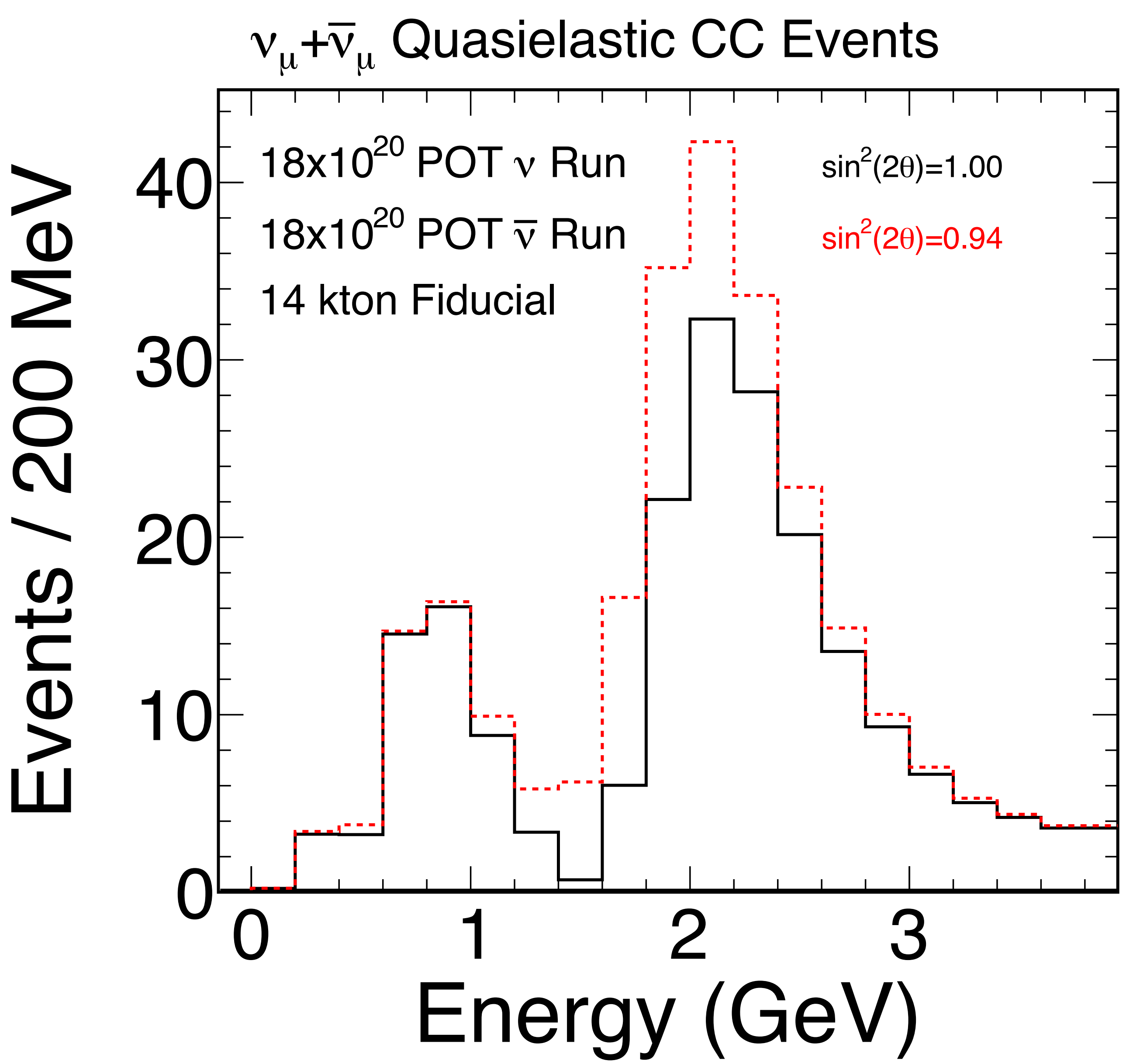
Precision θ_{23} and Δm^2_{32} measurements

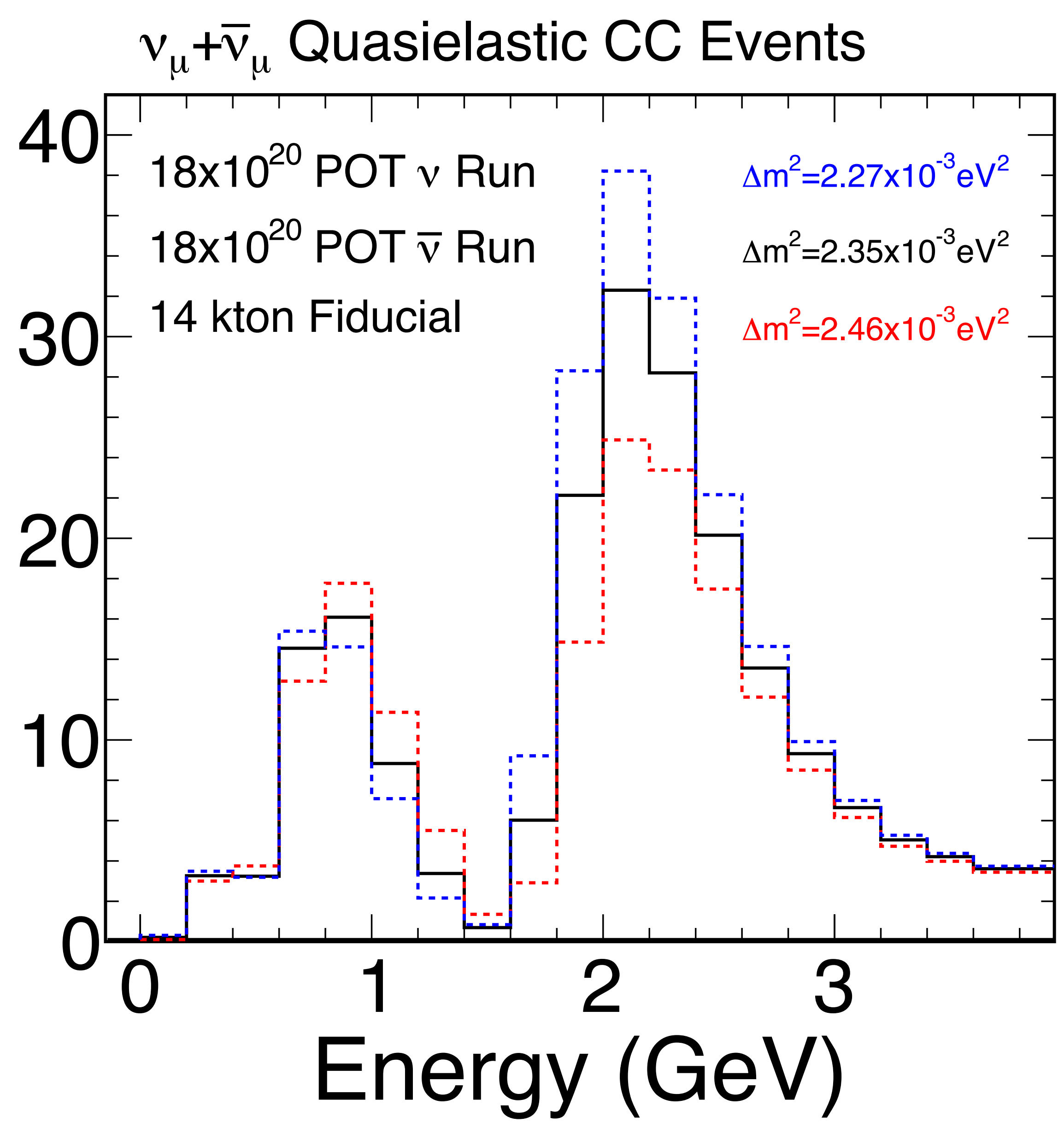


Oscillations applied using $\Delta m^2_{32} = 2.35\times10^{-3}$ eV^2, $\sin^2 2\theta_{23} = 1.0$

$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Channel

Precision θ_{23} and Δm^2_{32} measurements

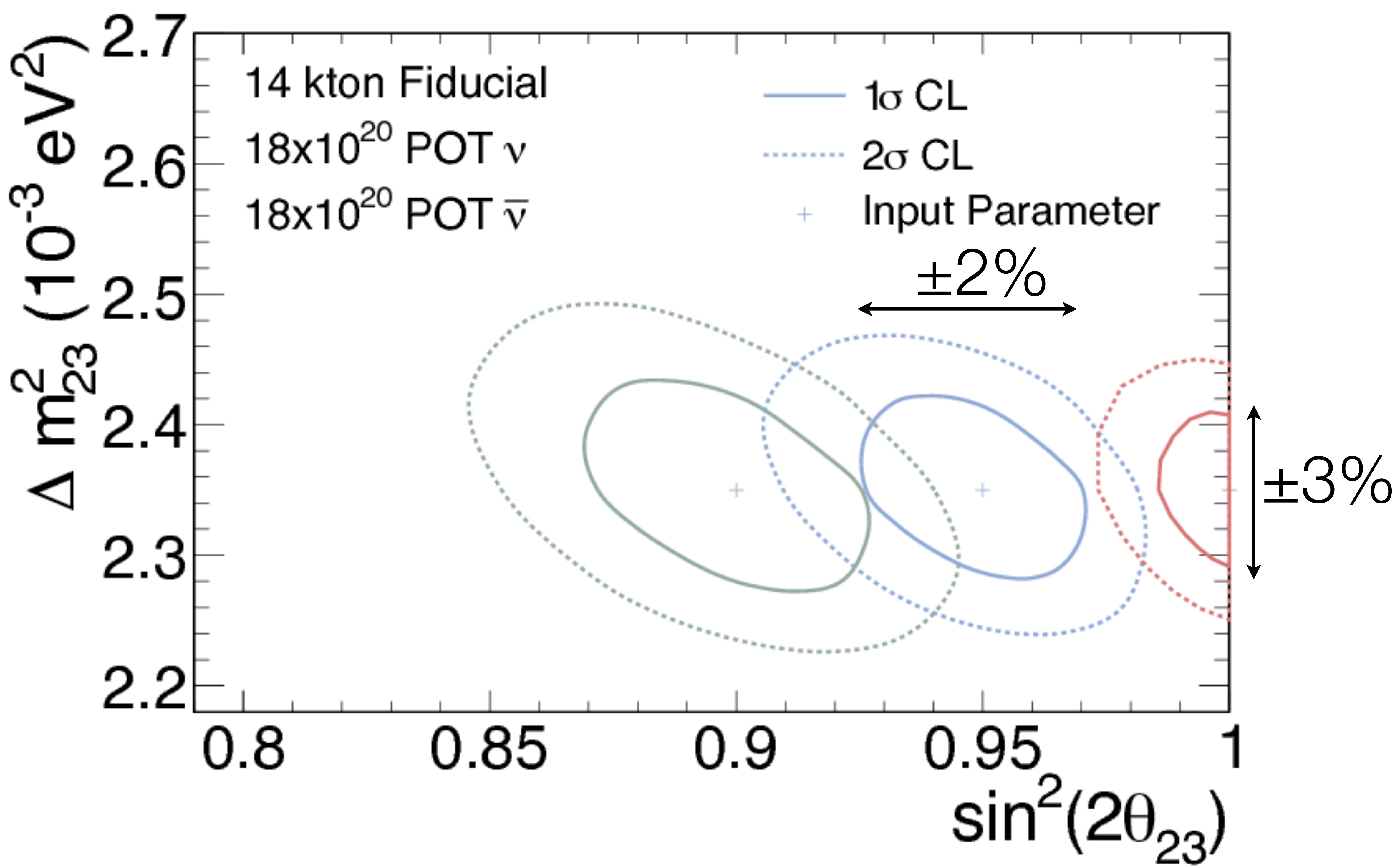




- Energy resolution (determined from simulations) is 4% for ν_μ-CC quasi-elastic events
- 10% absolute energy scale uncertainty fitted as nuisance parameter; constrained by narrow-band beam
- ~0 backgrounds due to detector performance and narrow-band beam

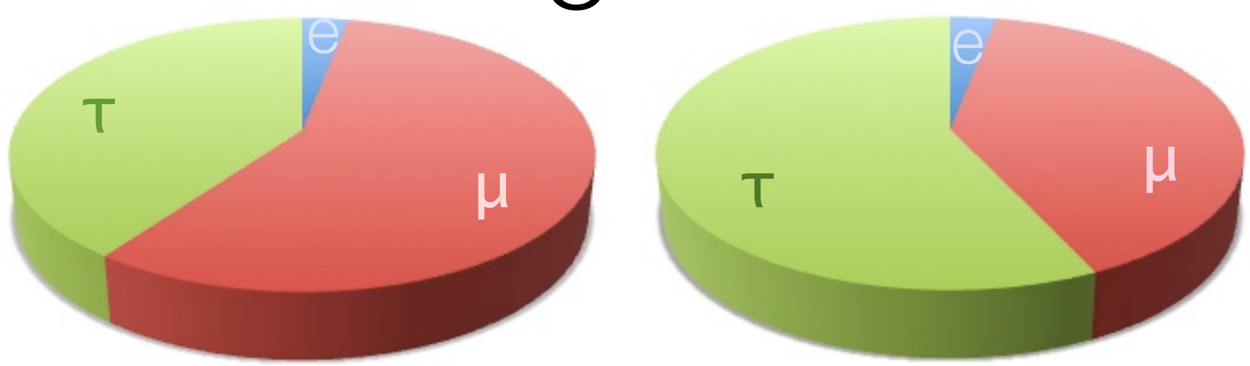
$\nu_\mu \rightarrow \nu_\mu$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$ Channel

Precision θ_{23} and Δm^2_{32} measurements



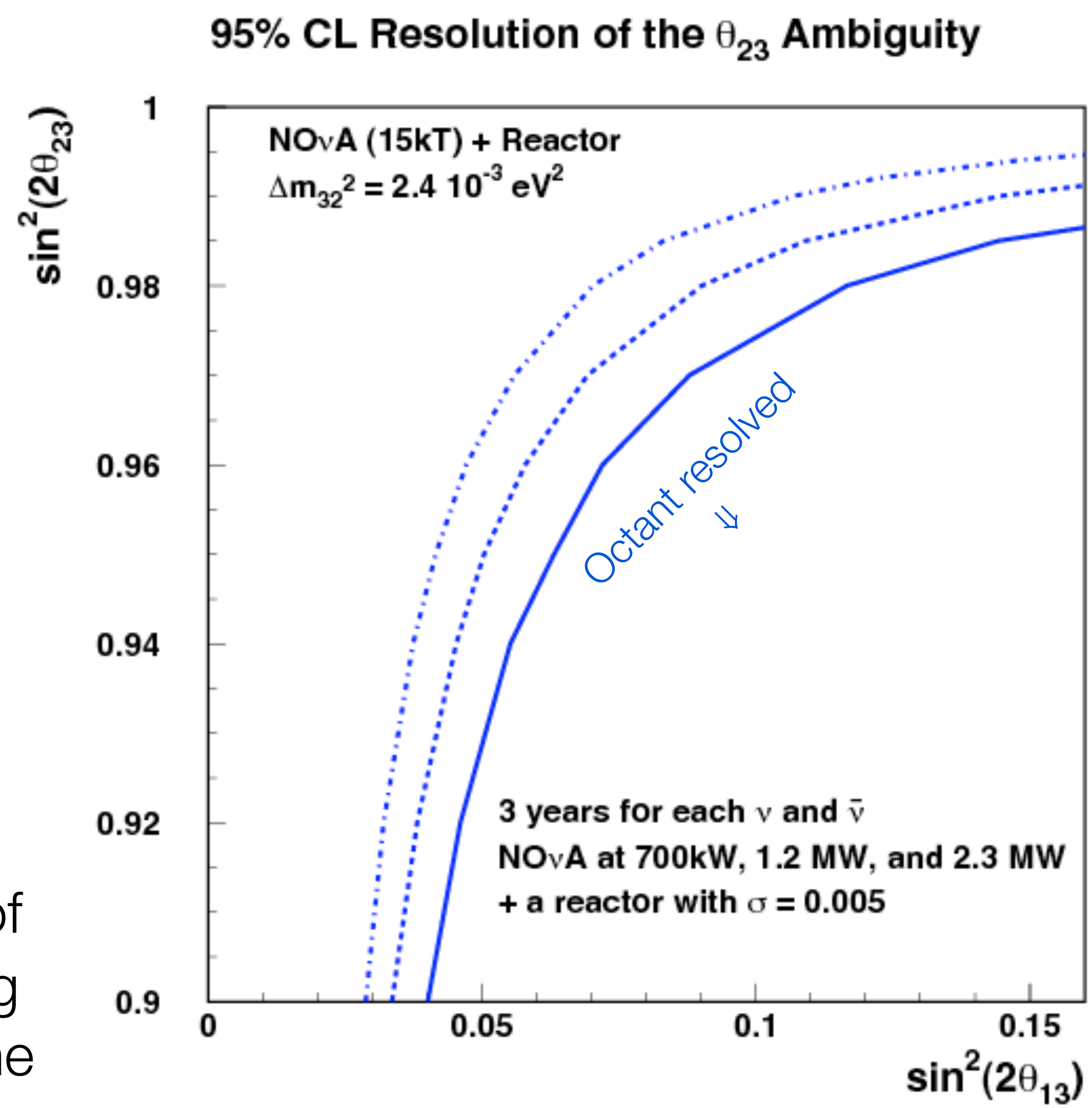
θ_{23} Quadrant: NOvA + Reactor

$\nu_3 = ?$



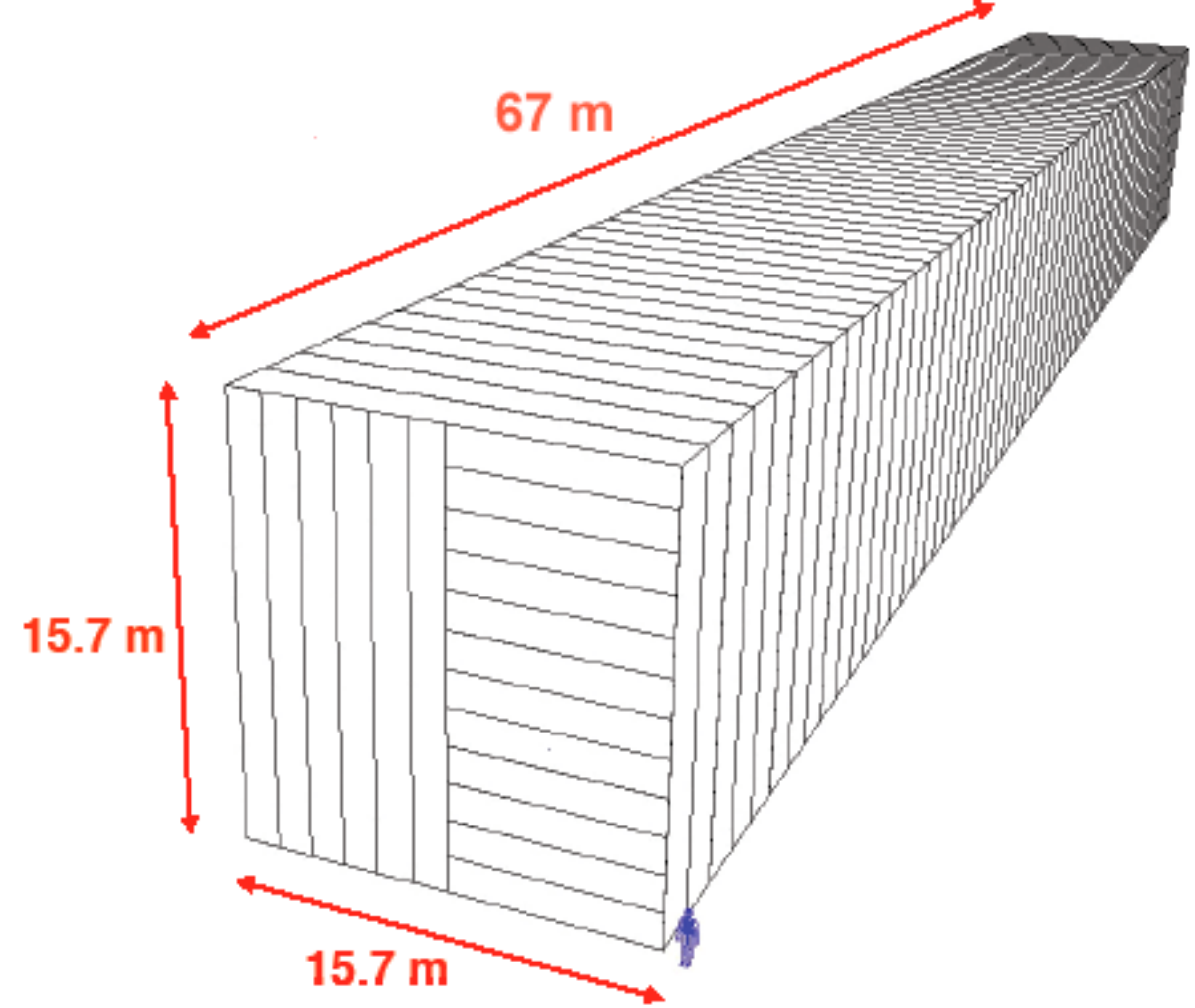
$\theta_{23} = 40^\circ$ $\theta_{23} = 50^\circ$

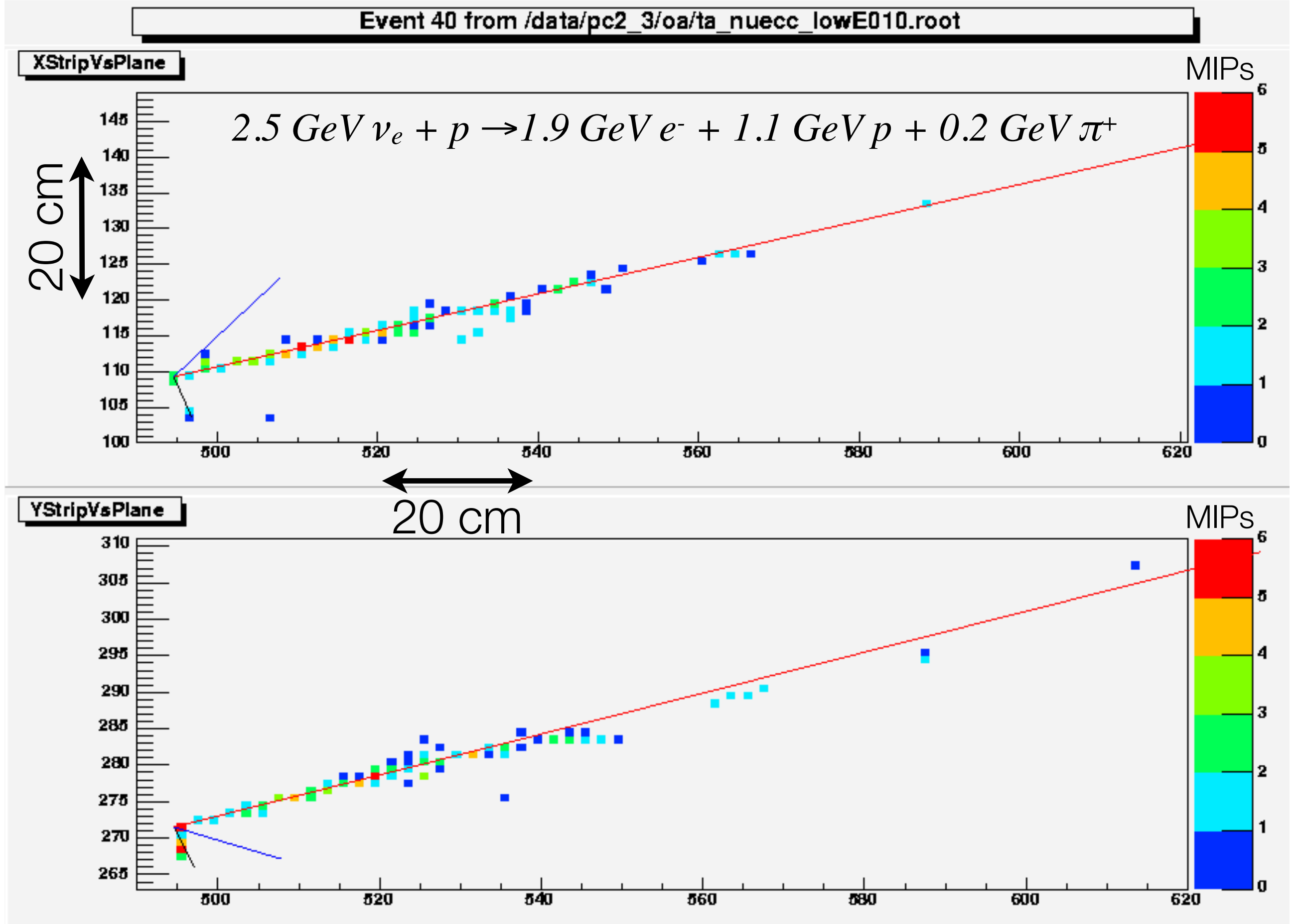
- Long baseline experiments measure $\sin^2 2\theta_{23}$ using the $\nu_\mu \rightarrow \nu_\mu$ channel and $2\sin^2\theta_{23}\sin^2 2\theta_{13}$ using $\nu_\mu \rightarrow \nu_e$
- Reactor experiments measure $\sin^2 2\theta_{13}$ using $\nu_e \rightarrow \nu_e$
- The combination allows measurement of $\sin^2\theta_{23}$ and $\sin^2 2\theta_{23}$ separately resolving the octant of the angle θ_{23} answering the question of whether ν_3 has more muon or tau content



The NOvA Experiment

- NOvA is a second generation experiment on the NuMI beamline which is optimized for the detection of $\nu_\mu \rightarrow \nu_e$ and $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillations
- NOvA is:
  - An upgrade of the NuMI beam intensity from 400 kW to 700 kW
  - A 15 kt "totally active" tracking liquid scintillator calorimeter sited 14 mrad off the NuMI beam axis at a distance of 810 km
  - A 220 ton near detector identical to the far detector sited 14 mrad off the NuMI beam axis at a distance of 1 km





Event quality

Topologies of basic interaction channels shown at right. Each "pixel" is a single 4 cm x 6 cm x 15 m cell of liquid scintillator

Top: ν_μ *charged-current*

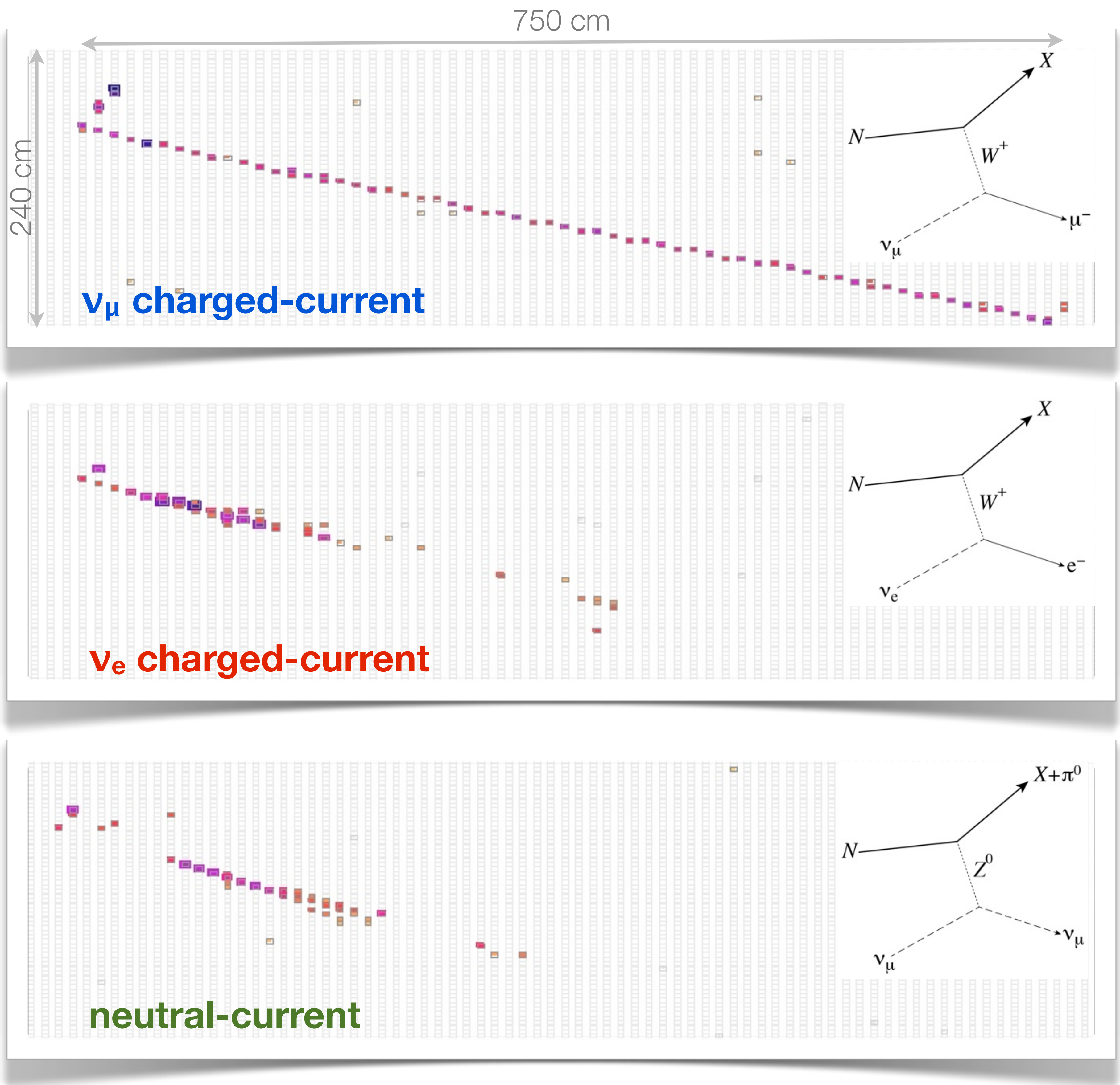
Center: ν_e *charged-current*

Bottom: *neutral-current*

Need >100:1 rejection against background

Detector challenge: Achieve large target mass (10's+ kilotons) while maintaining high granularity to avoid confusing the detection channels

NOvA achieves 35% efficiency for ν_e CC while limiting NC→ν_e CC fake rate to 0.1%



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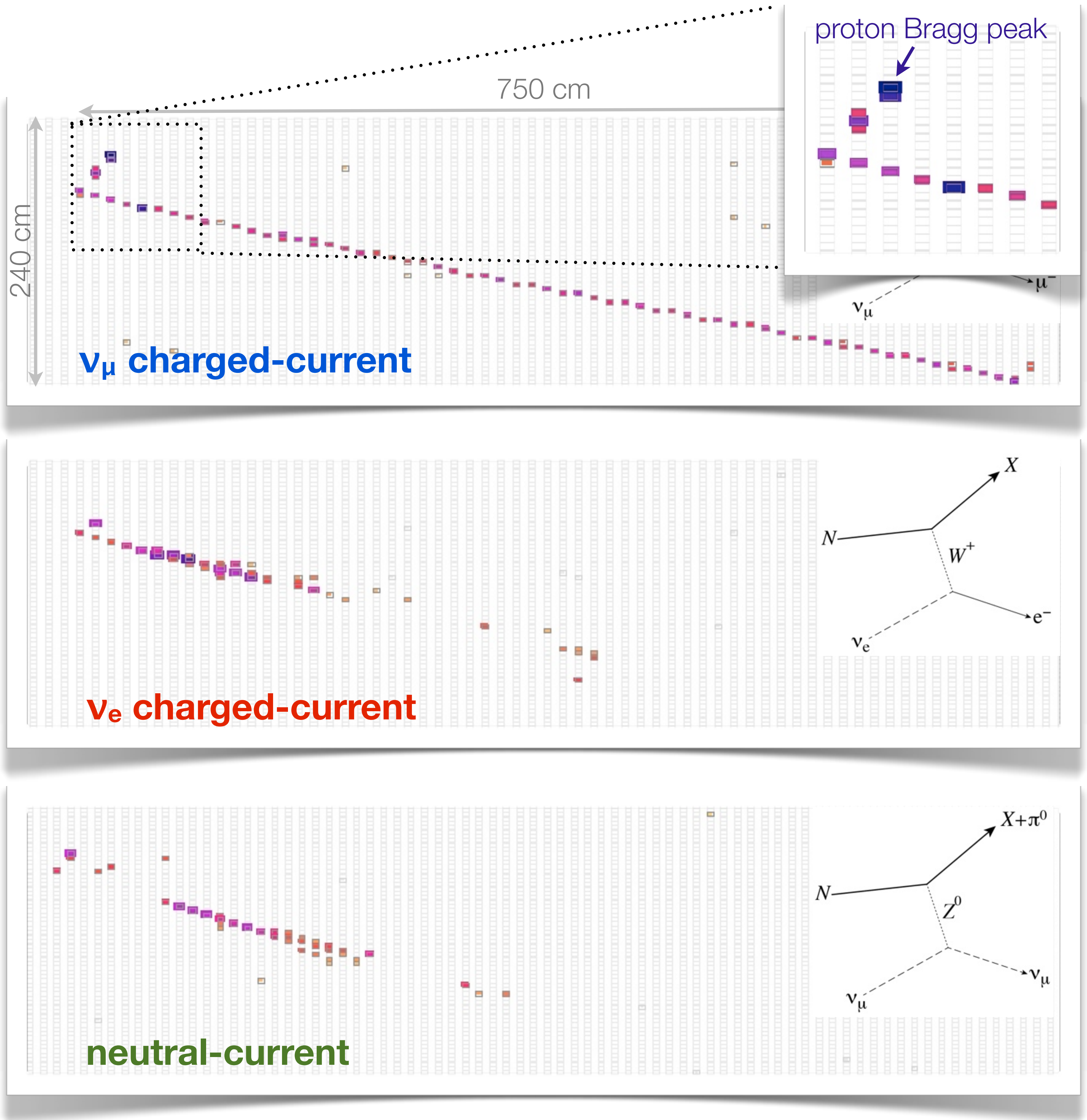

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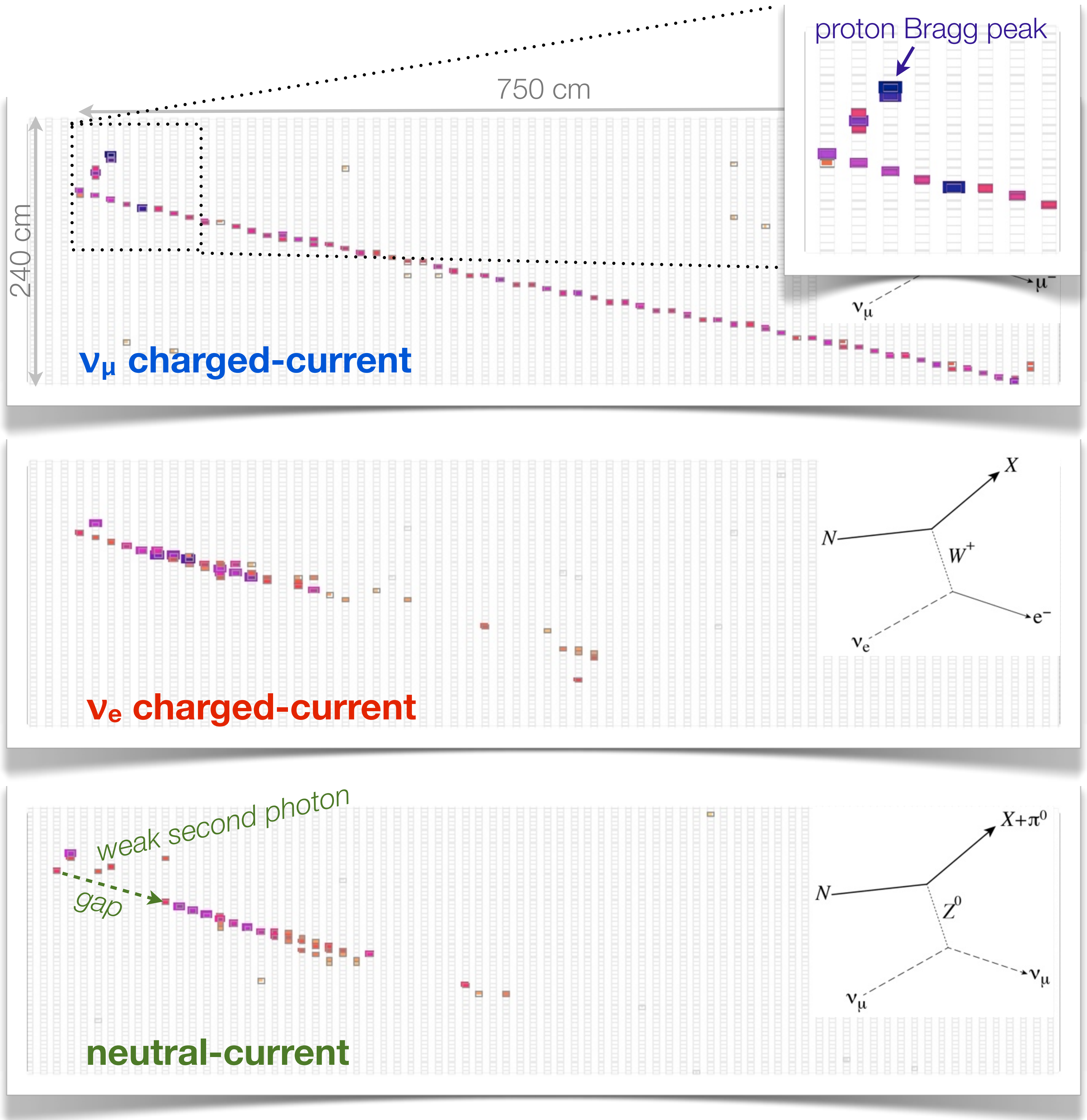
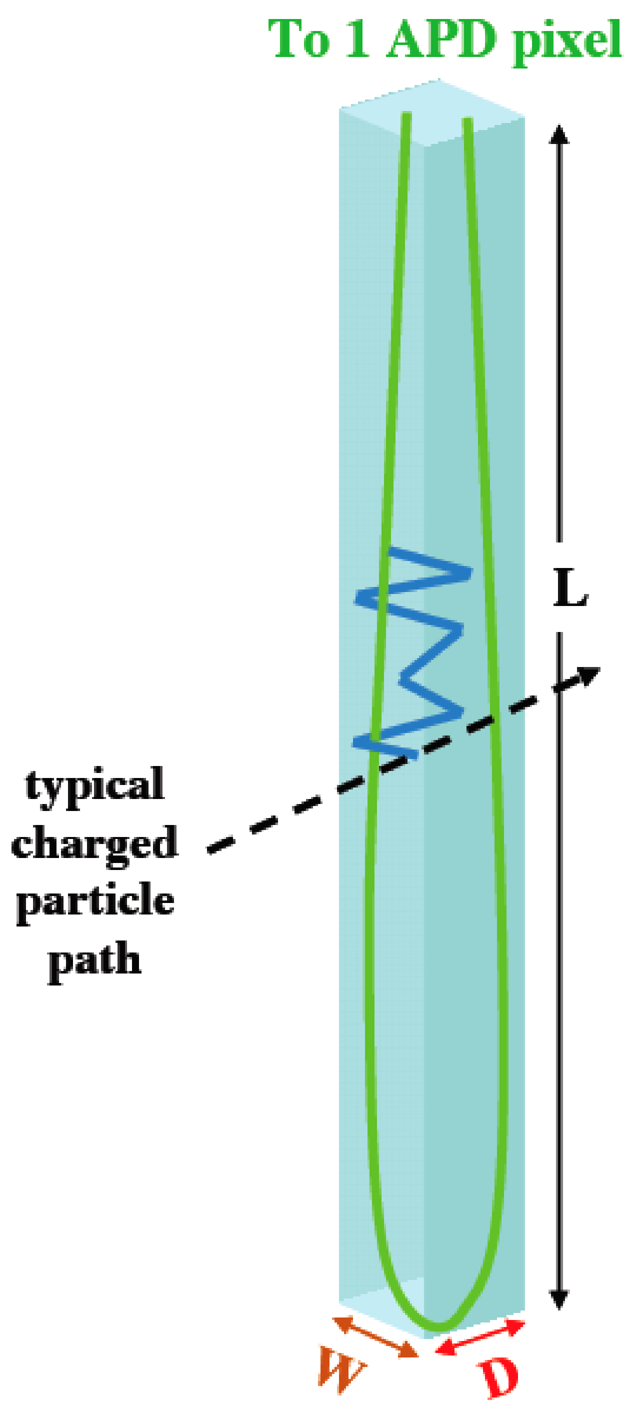
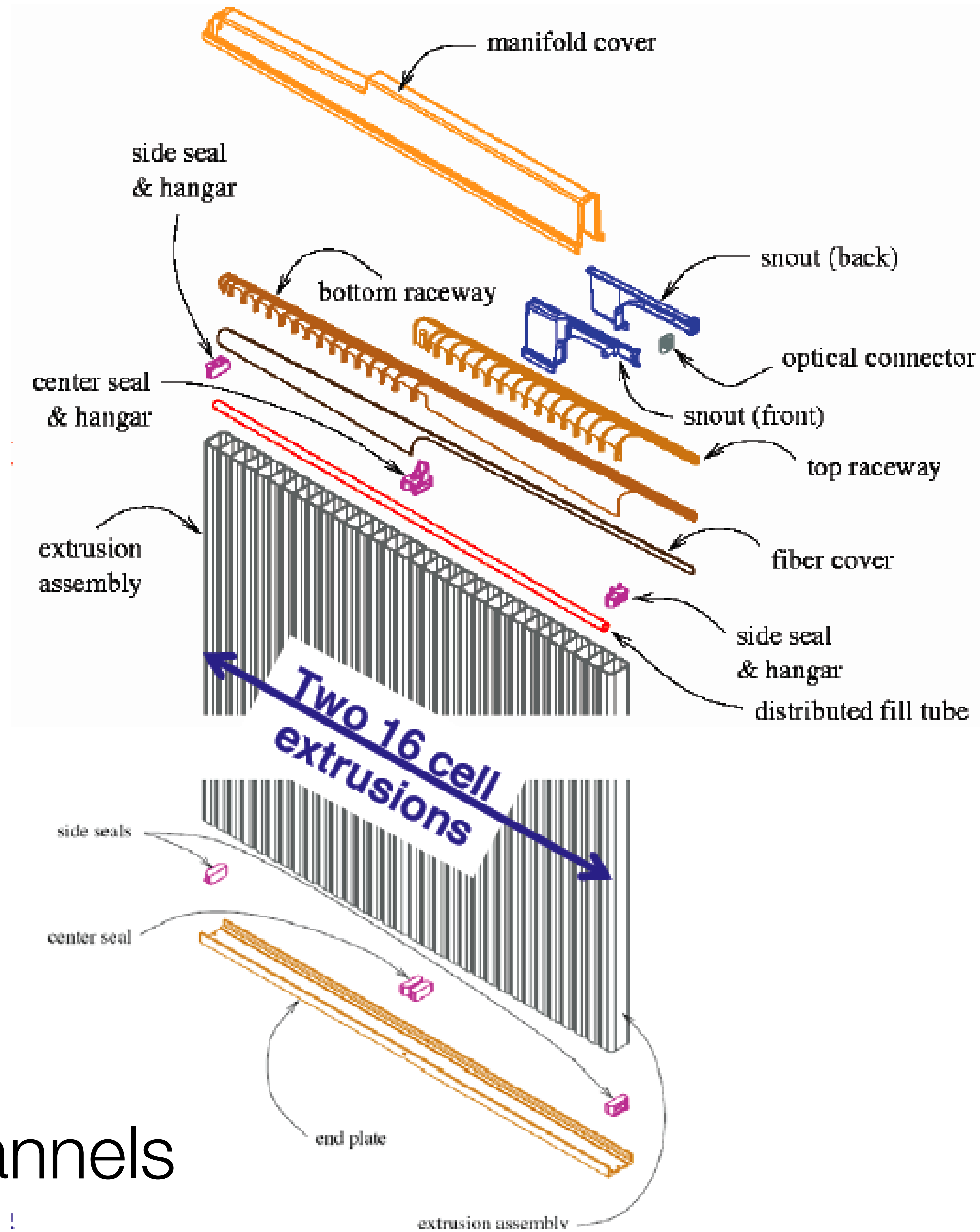






357,120 total channels

Near Detector On Surface (NDOS)

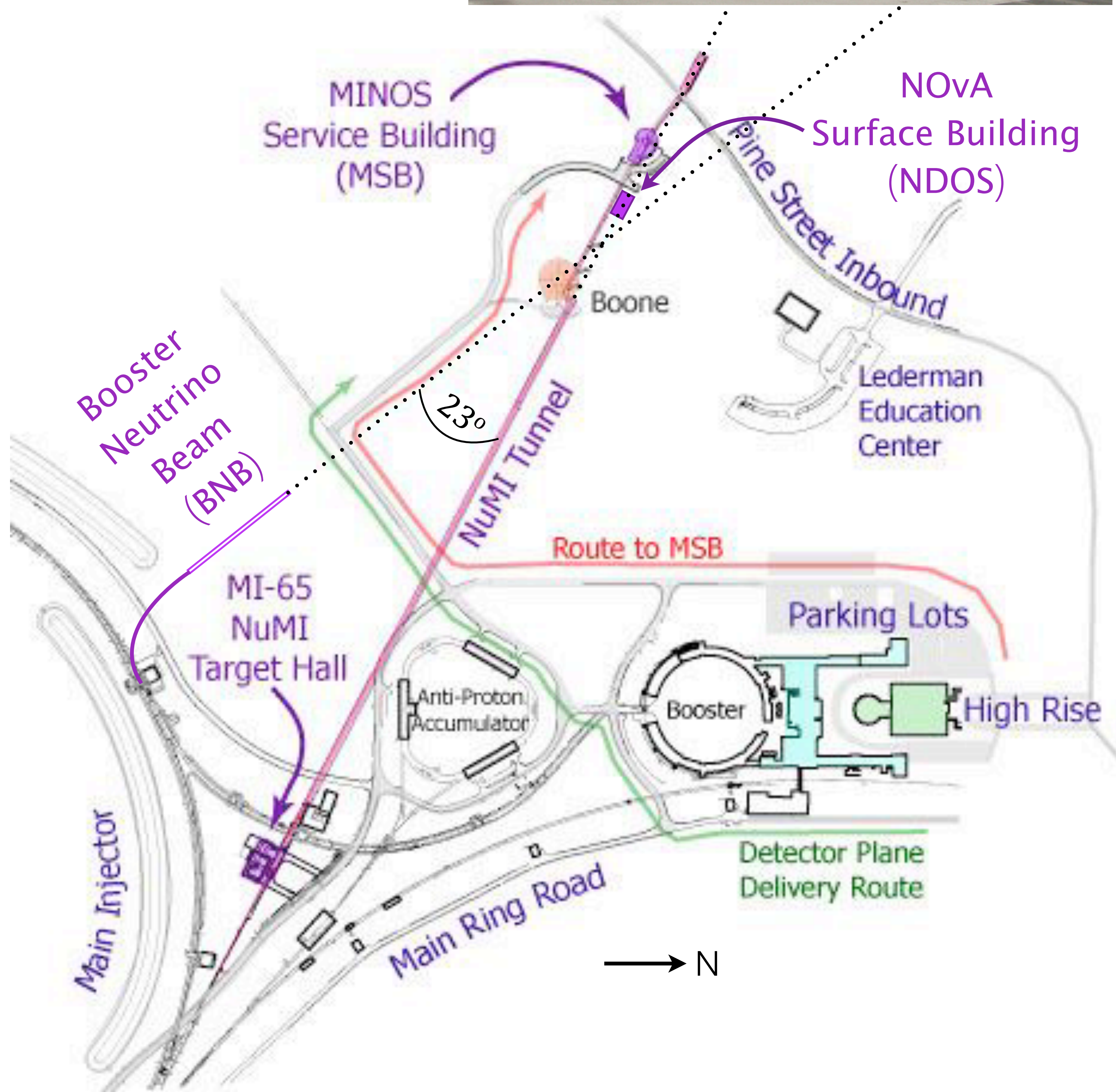
- Designed to prototype all detector systems prior to installation at Ash River as a full end-to-end test of systems integration and installation
- 2 modules wide by 3 modules high by 6 blocks long. Far detector is 12×12×30. NDOS mocks up upper corner of far detector ~exactly.
- Installation completed May 9, 2011.
- Commissioning and data collection on going 11/2010 - present

NOvA Collaboration

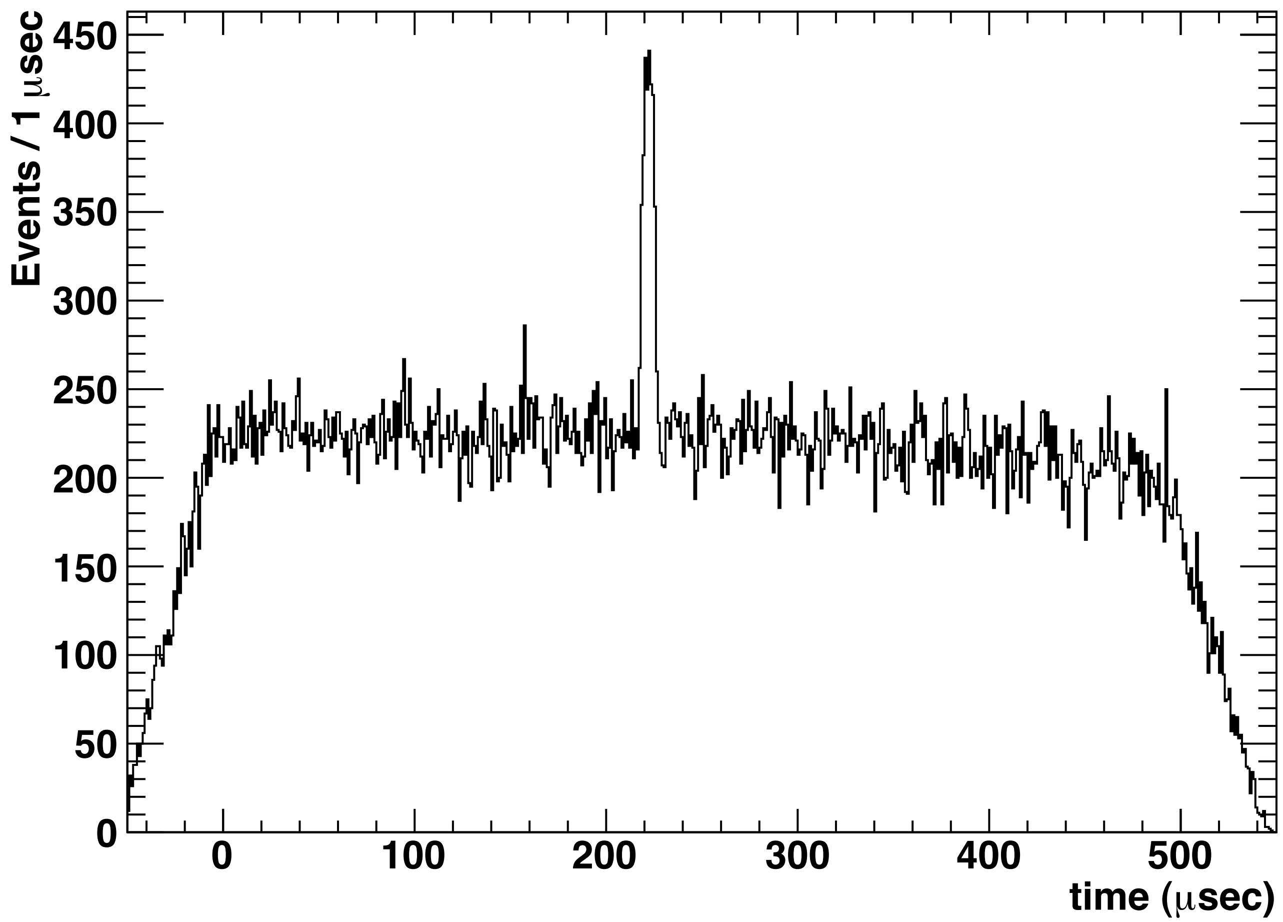
24 Institutions
110 physicists

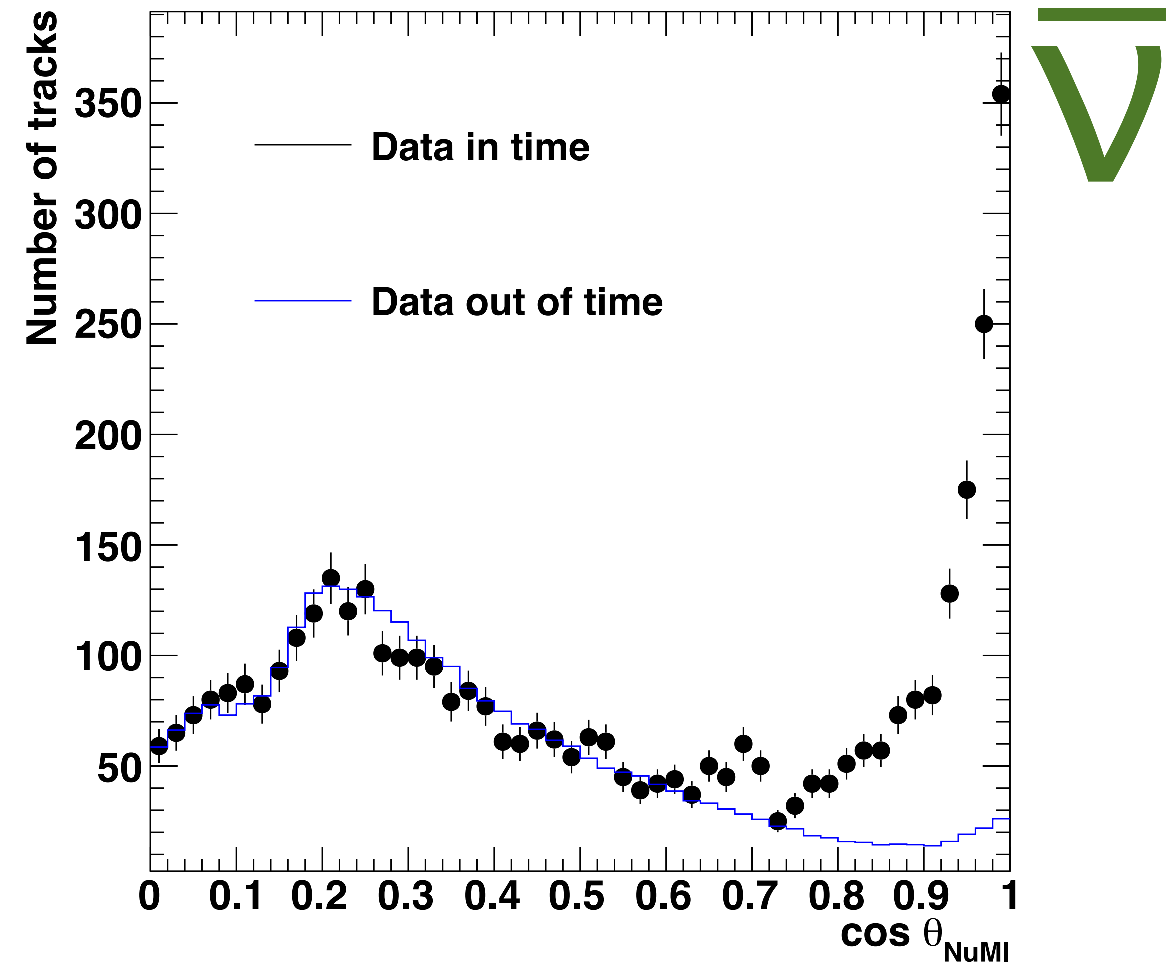
NDOS location

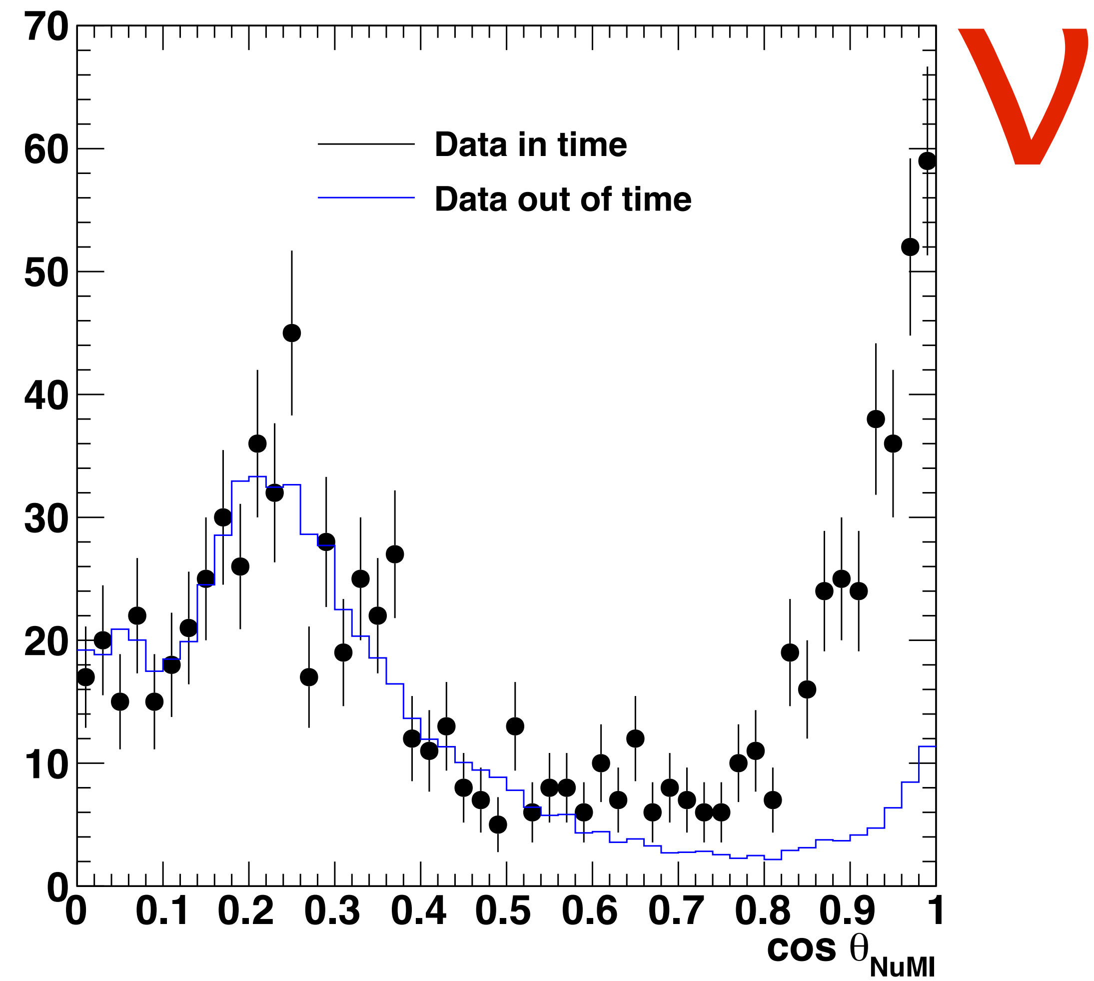
- Located in two neutrino beams providing an early look at data and a chance to tune up DAQ, calibration, reconstruction, and analysis prior to first data from Ash River
- NDOS is located directly above the NuMI neutrino beam line and is oriented parallel to the NuMI beamline. It sees neutrinos at an off-axis angle of 110 mrad.
- NDOS is located ~on the Booster Neutrino Beam (BNB) line, but the detector axis is rotated 23^{o} with respect to the BNB beamline



NuMI events

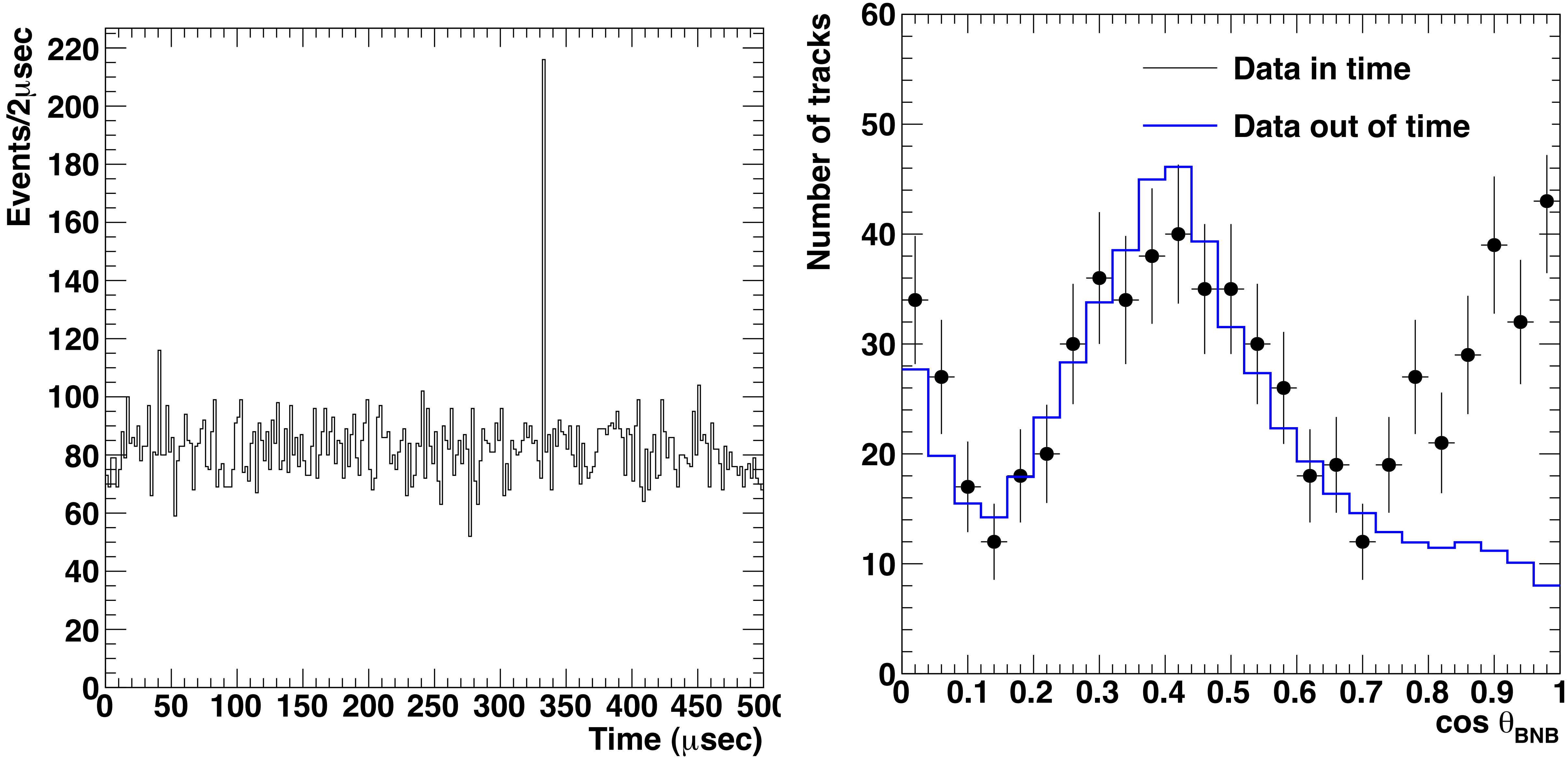




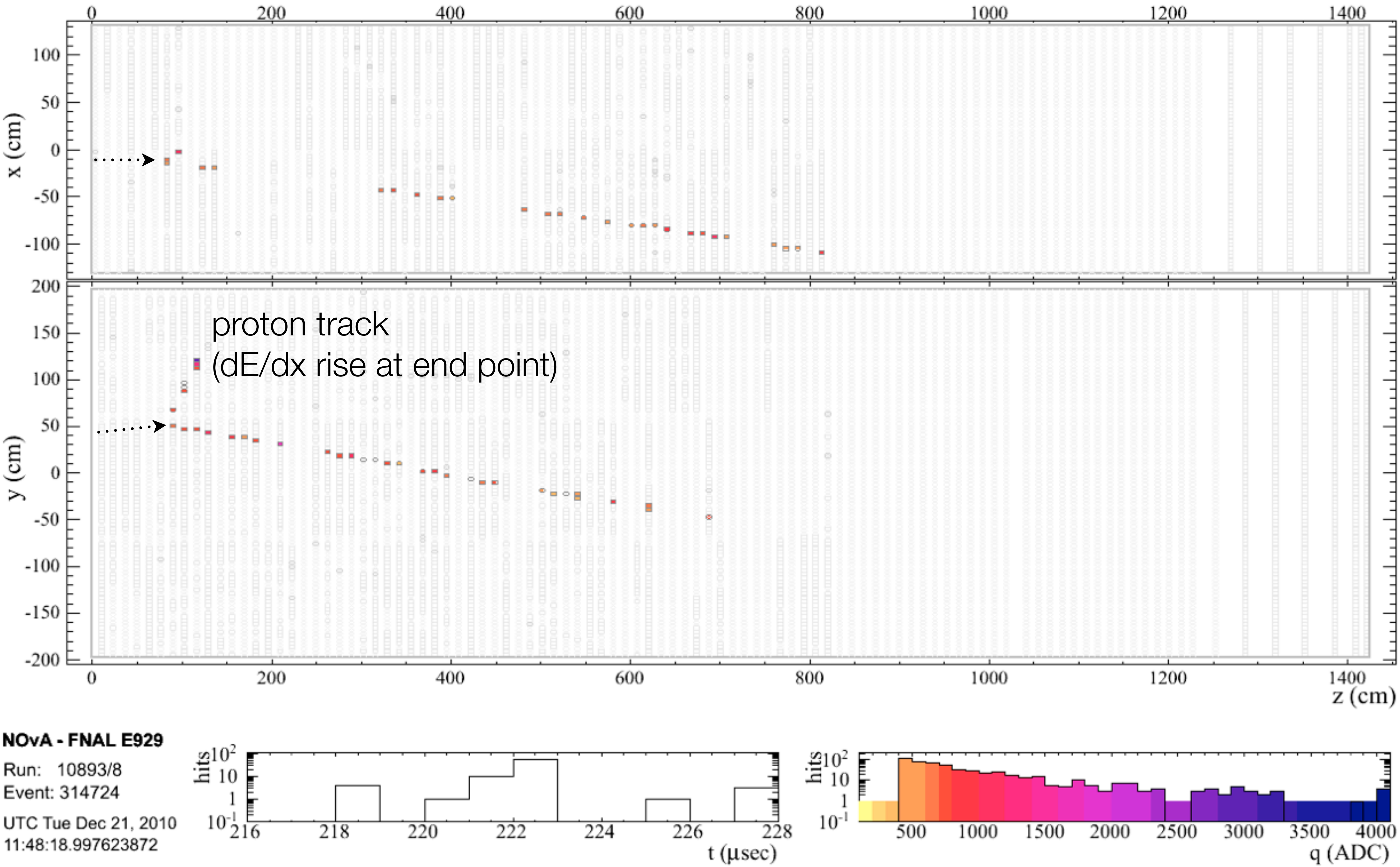


- See NuMI beam at off-axis angle of 110 mrad
- Recorded 1001 events in antineutrino mode (69 cosmic background)
- Recorded 253 events in neutrino mode (39 cosmic background)

Booster Neutrino Beam

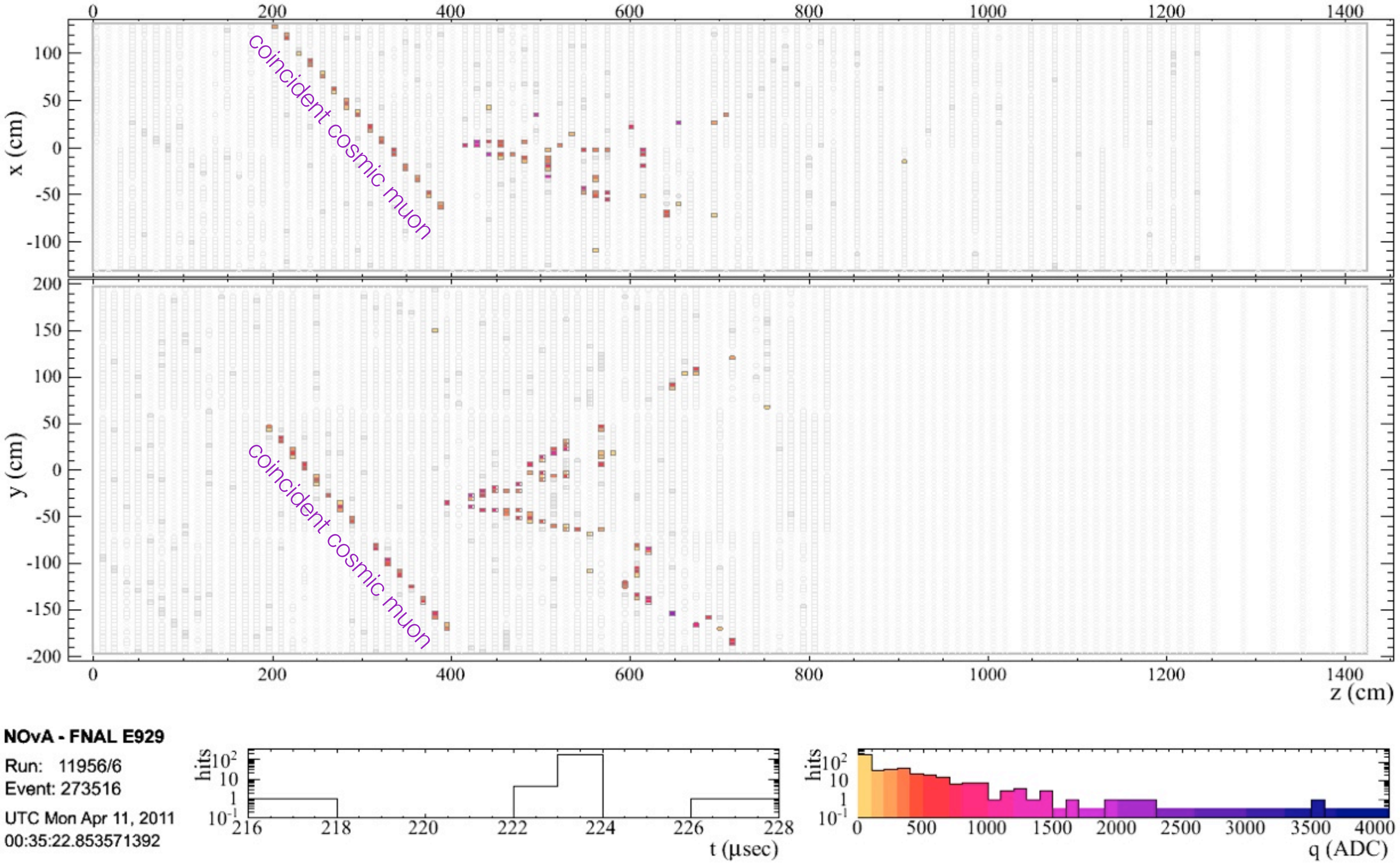


- Recorded 2.7×10^{19} protons on target. First event recorded on 12/24/2010. Last event in this sample recorded on 5/22/2010.
- 222 events on a background of 92 cosmic ray backgrounds. 5 ν's / 10^{18} POT.



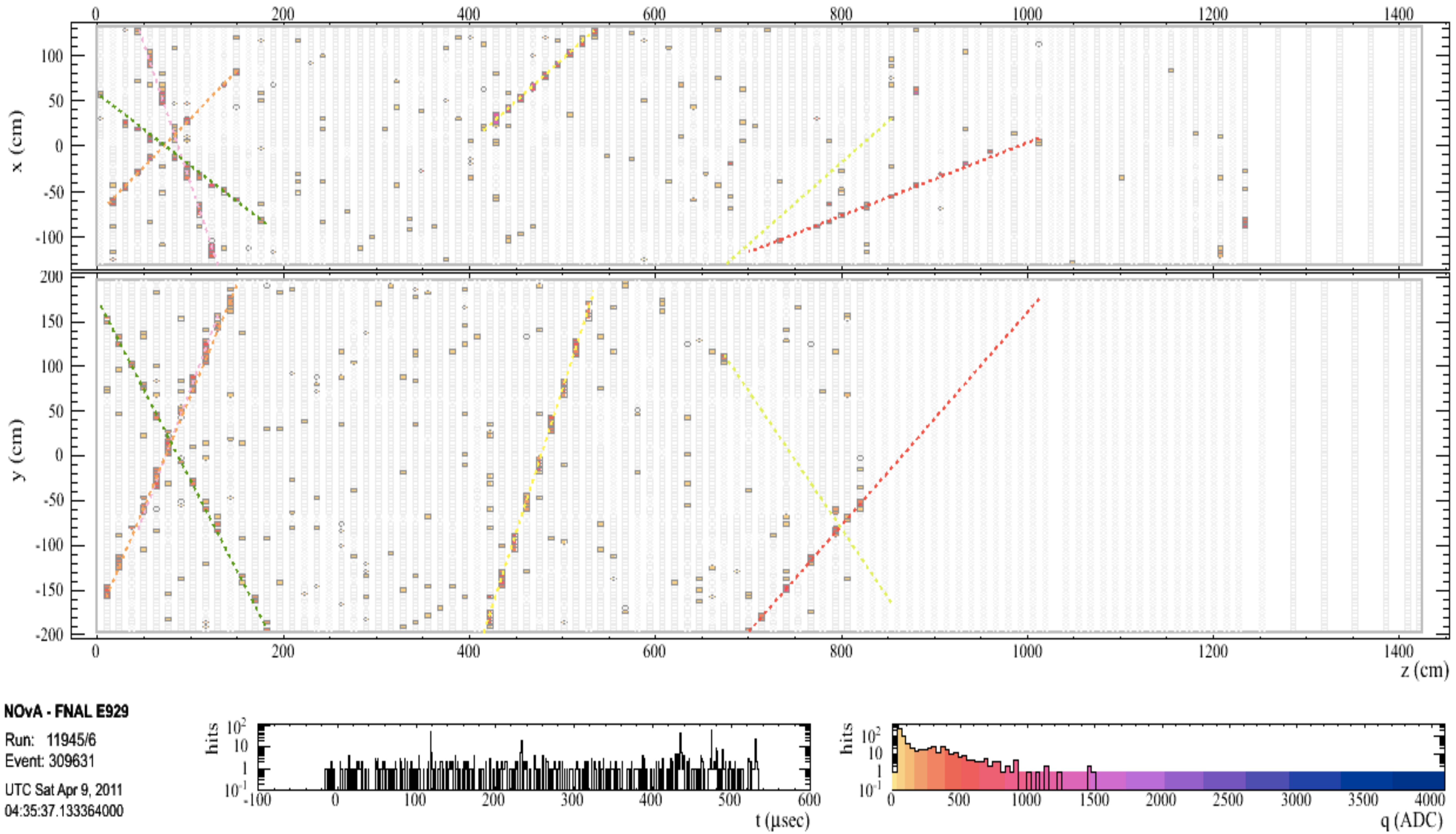
NOvA NDOS NuMI Data

ν_μ quasi-elastic candidate



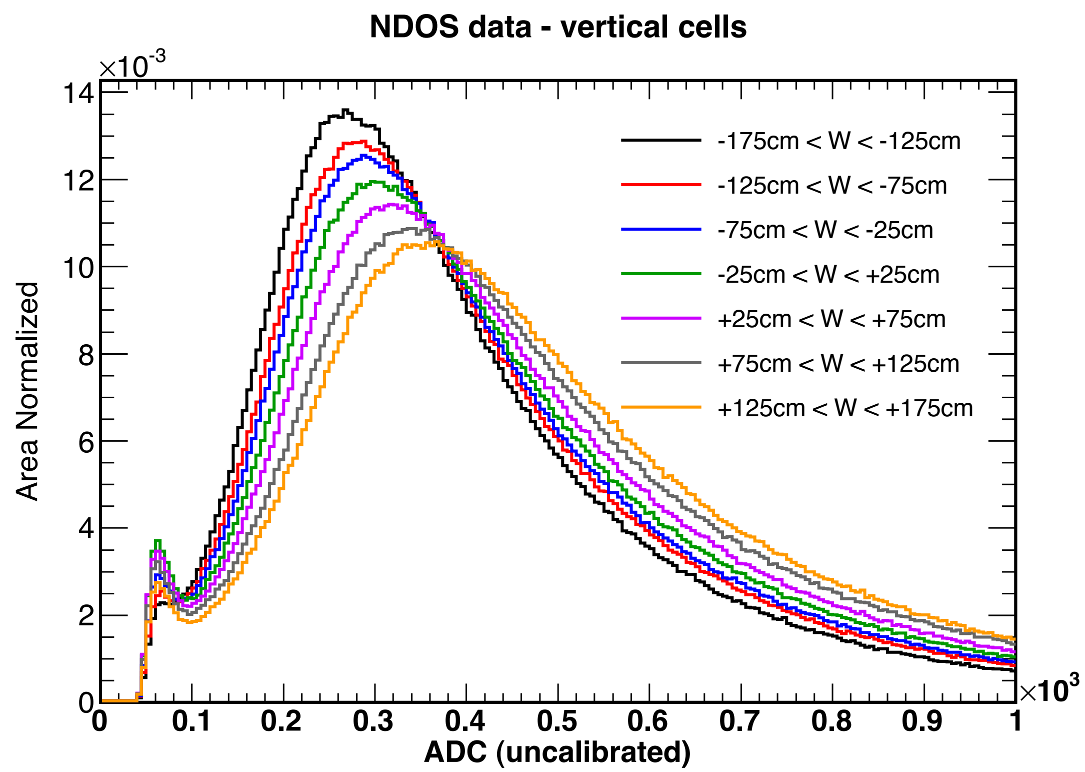
NOvA NDOS NuMI Data

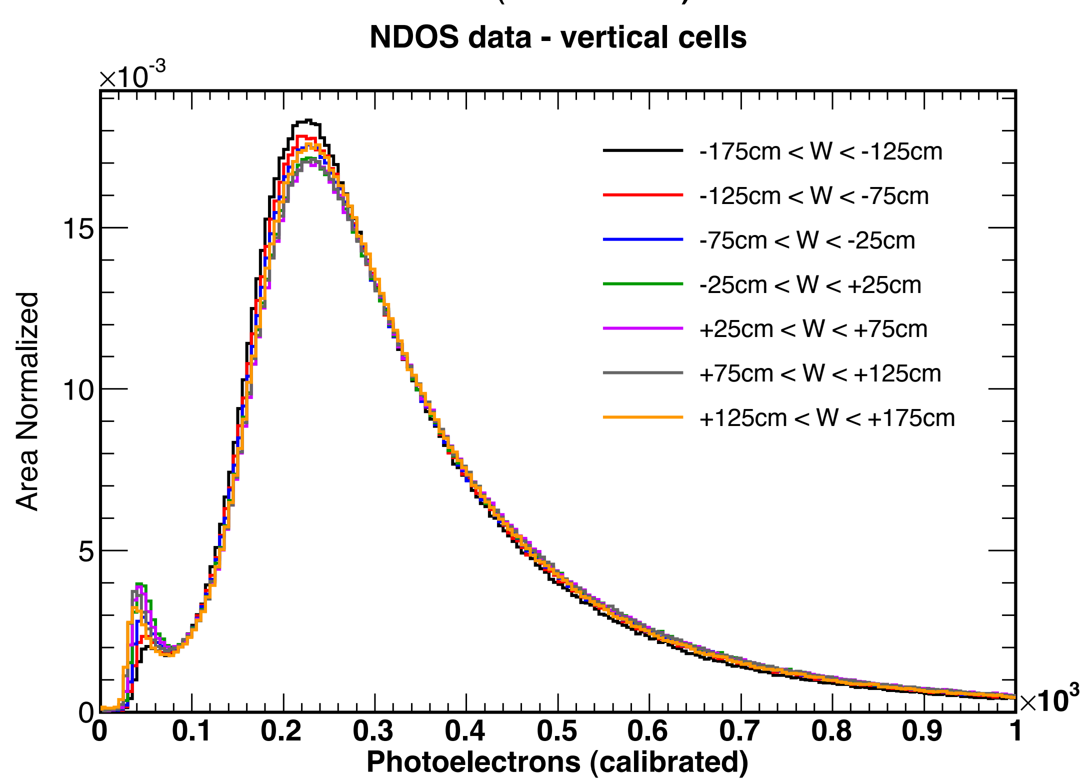
$\nu_\mu + N \rightarrow N' + \nu_\mu + \pi^0 + \pi^0$ candidate

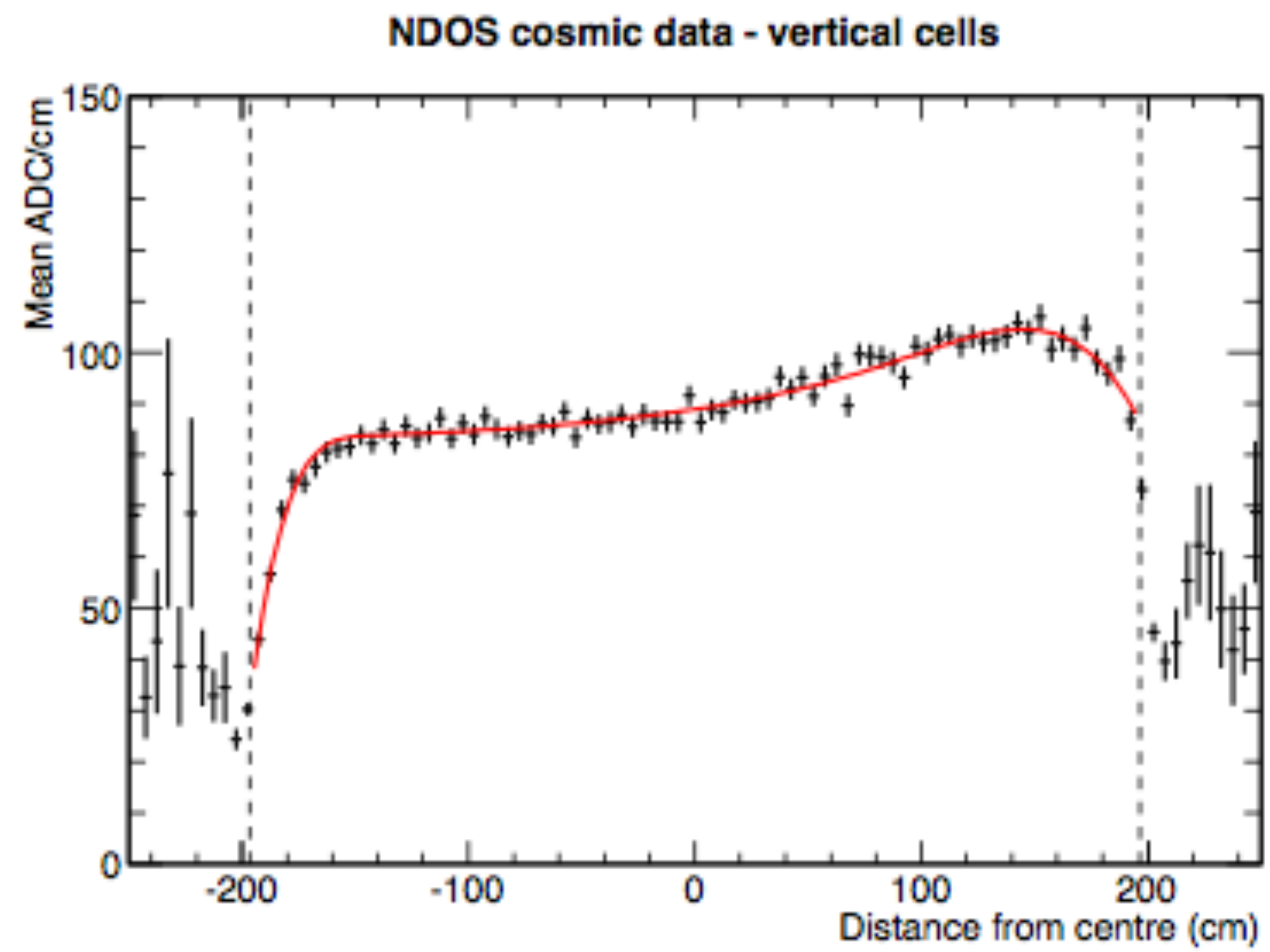


Cosmic rays in NDOS

Using cosmic rays:
Cell-by-cell calibration

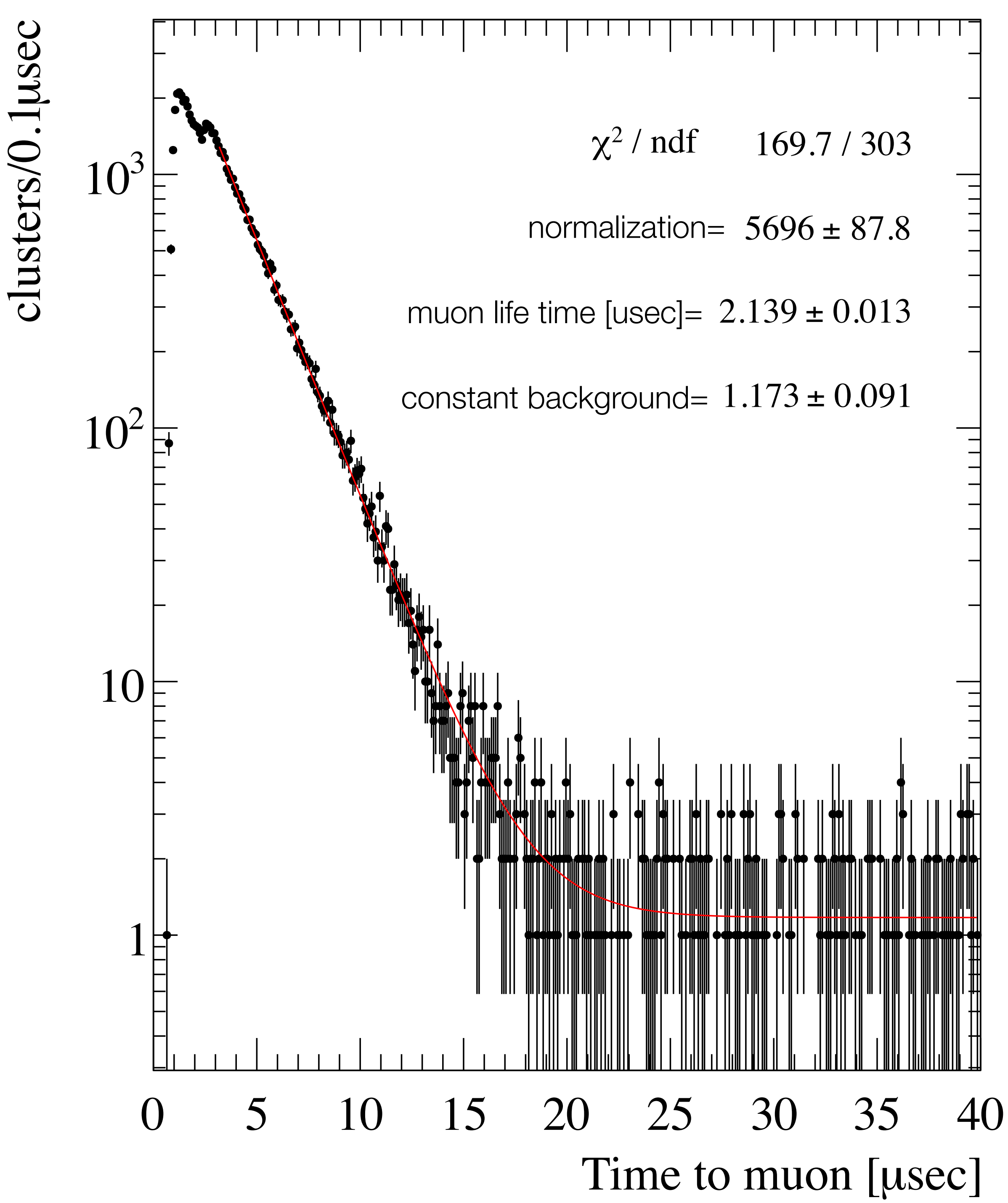


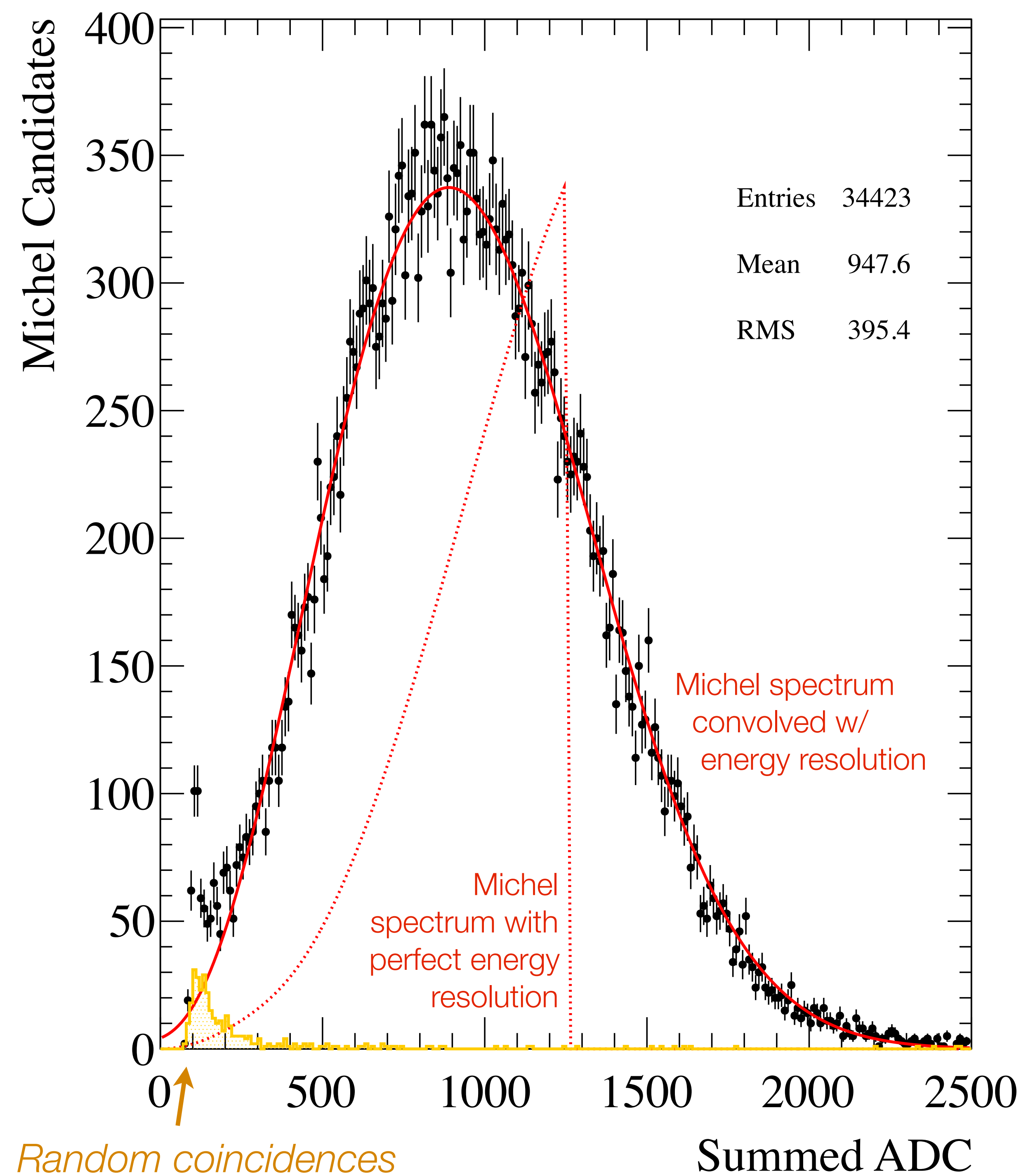




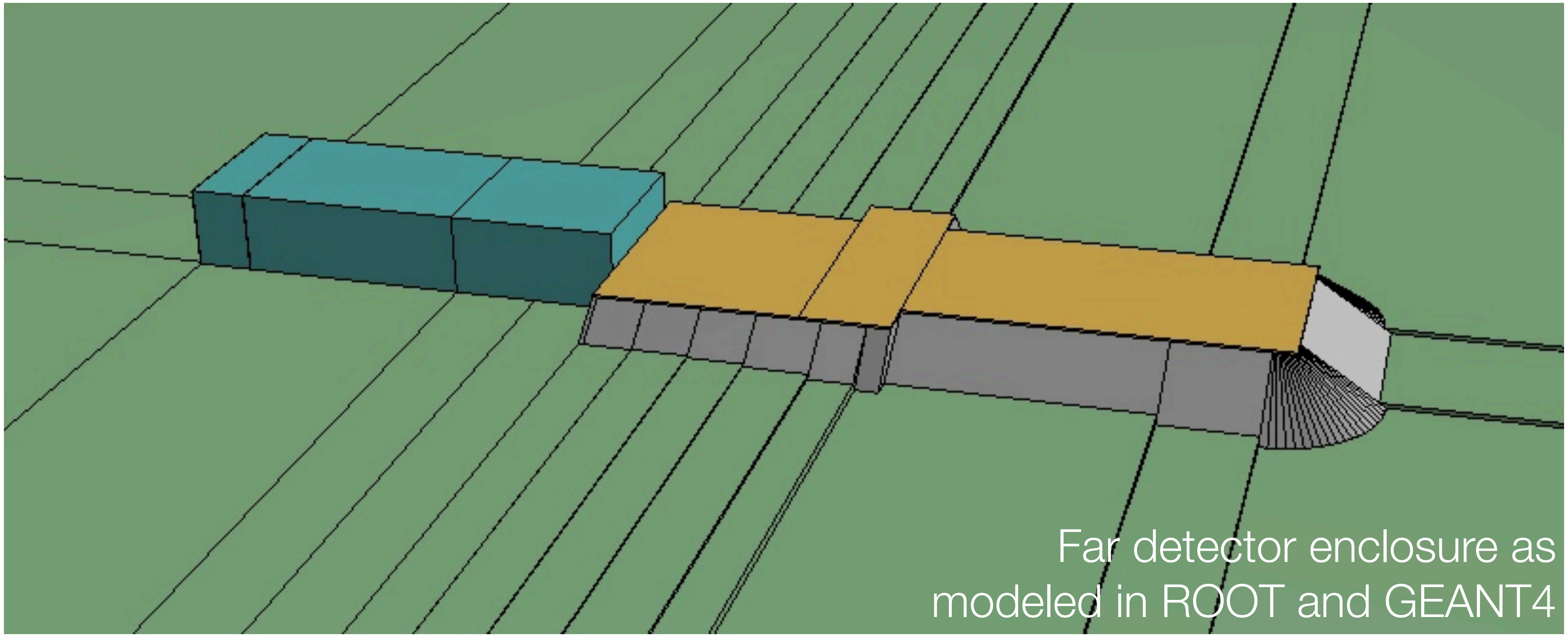
- Top left: Path length-corrected muon response for different distances from fiber end for a single example cell
- Above: Measured and fitted fiber attenuation for the example cell
- Bottom left: Muon response after attenuation corrections

Using cosmic rays:
Michel electrons from muon decay





Random coincidences
These are clusters that are matched to muons recorded 20 seconds prior to event



Experiment progress:

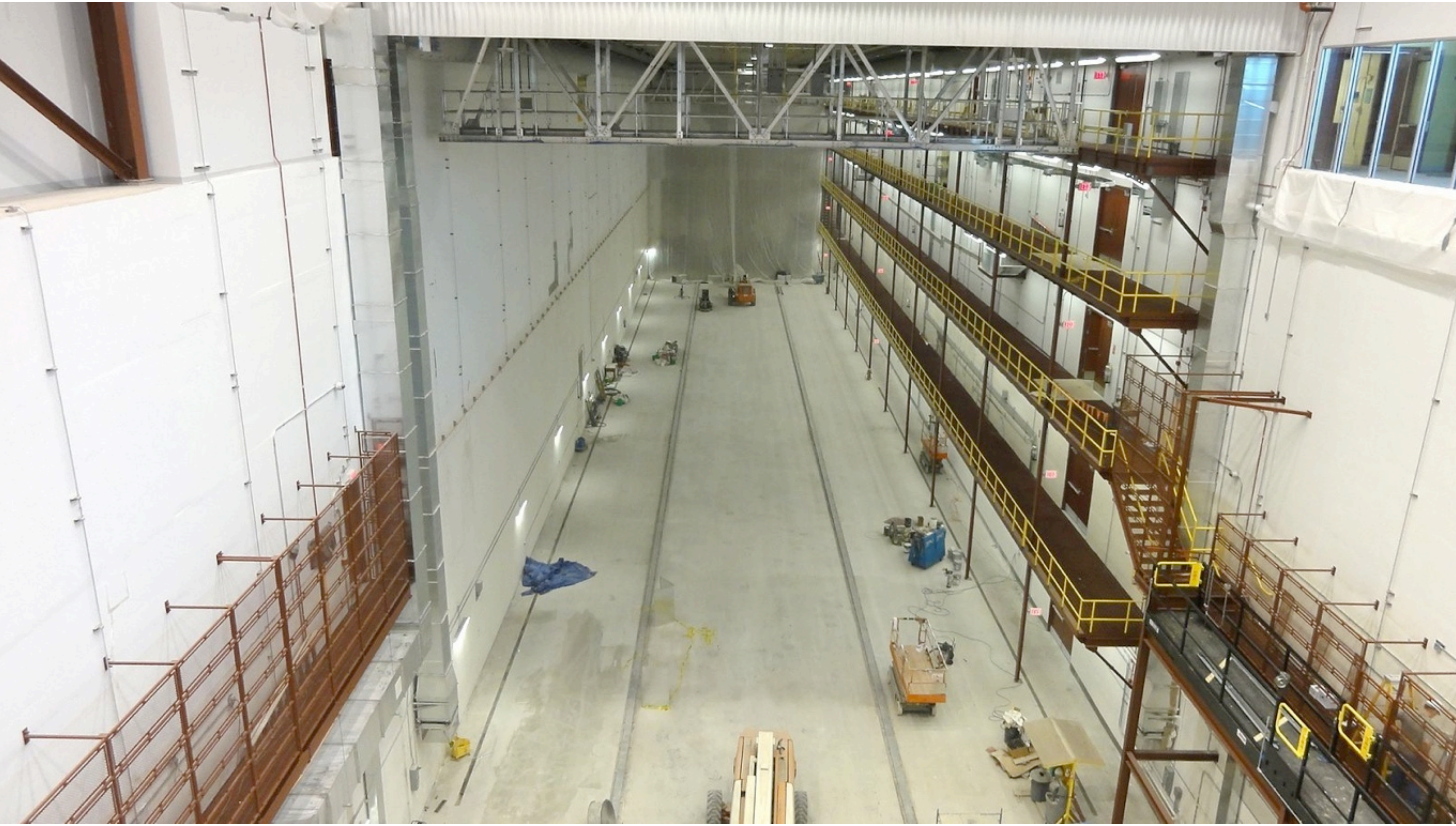
Far detector laboratory complete

After many years of looking at this. We can now look at this...

Experiment progress:

Far detector laboratory complete

Beneficial occupancy of Ash River laboratory on April 13, 2011

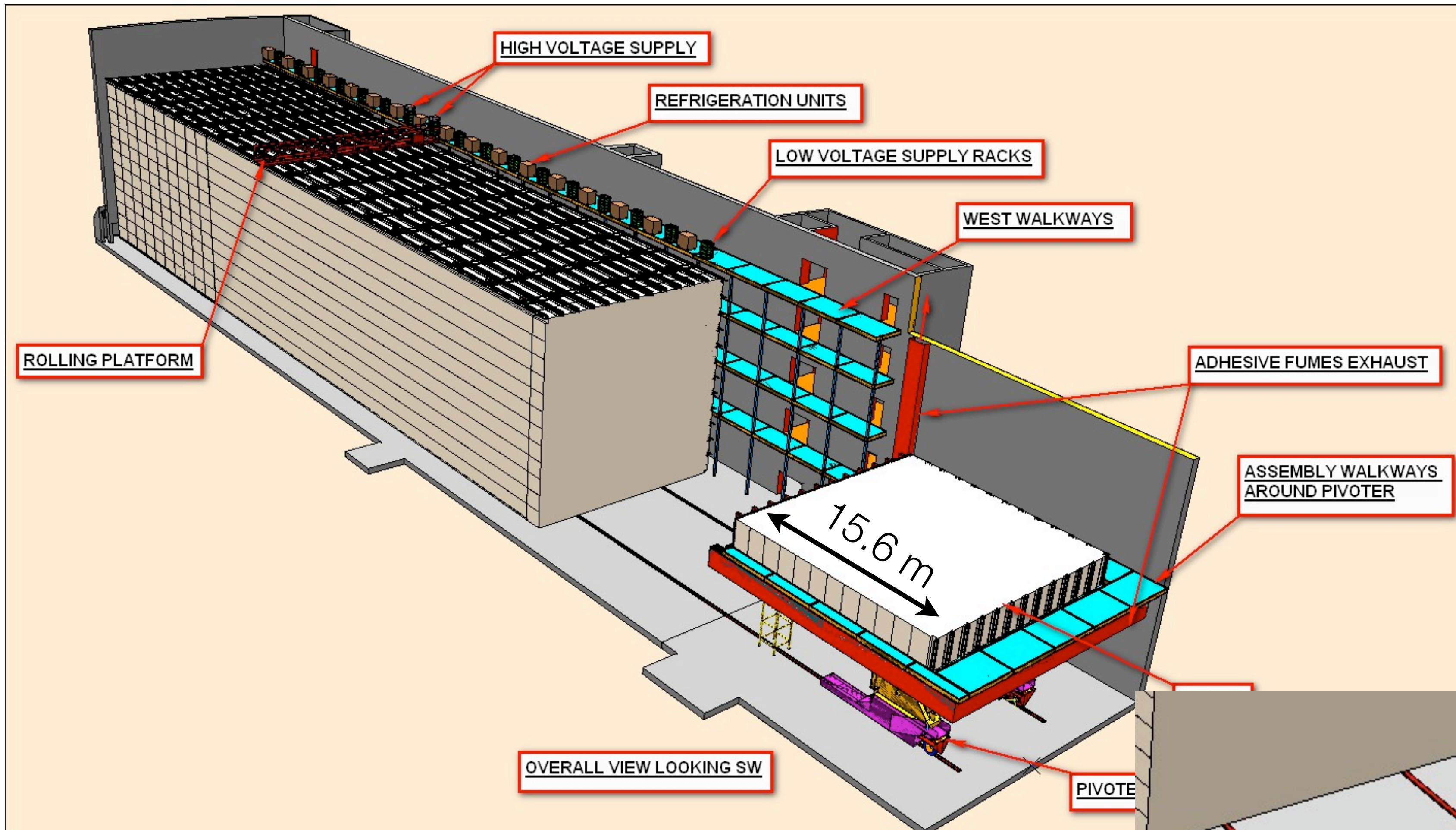


Experiment progress:

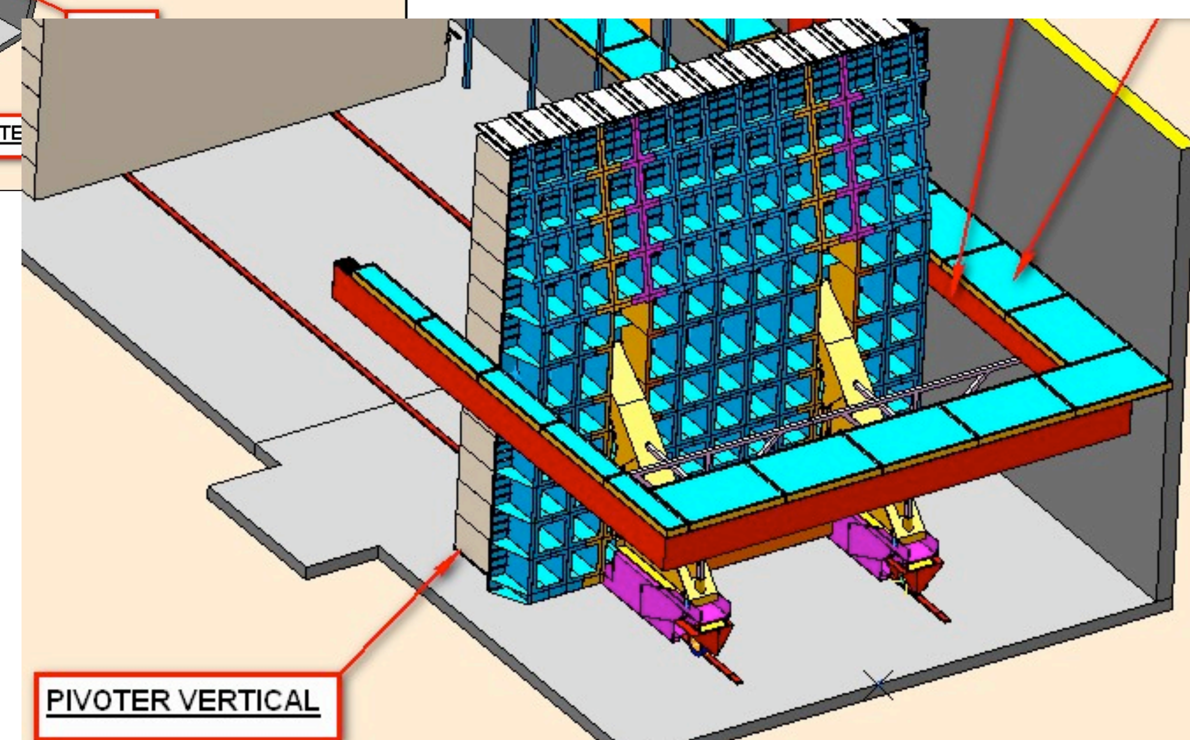
Far detector laboratory complete

Inside the detector enclosure looking south

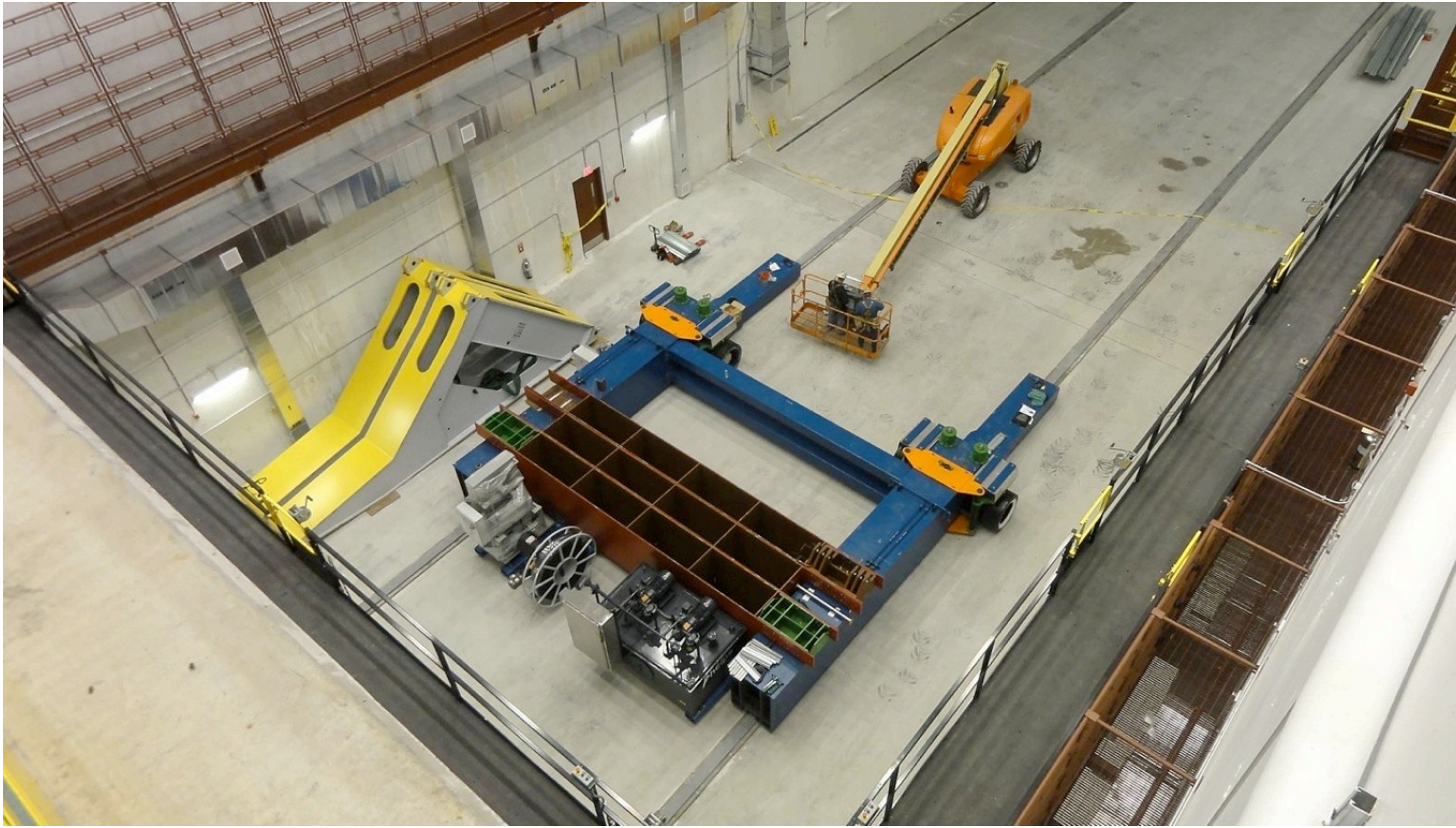
Block Pivoter



work platform



Block Pivoter Prototype



Block pivoter assembly at Far Detector

First pieces in place on their rails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Each section above is ~5 kt of detector mass
Beam is off to upgrade Main Injector and NuMI to 700 kW

Summary

- NOvA addresses 7 of 8 “compelling issues” in neutrino physics
- Far detector construction is underway.
  - Far detector laboratory complete
  - NuMI upgrades begin in March of 2012
  - Plan to have first far detector block in place by then
  - Commissioning of 700 kW beam begins in 2013 with ~5 kt of far detector in place
  - 15 kt complete by end of 2013
- Prototype near detector operational on surface at Fermilab
  - Extremely valuable preparation for construction at Ash River
  - Early look at real cosmic rays and neutrinos