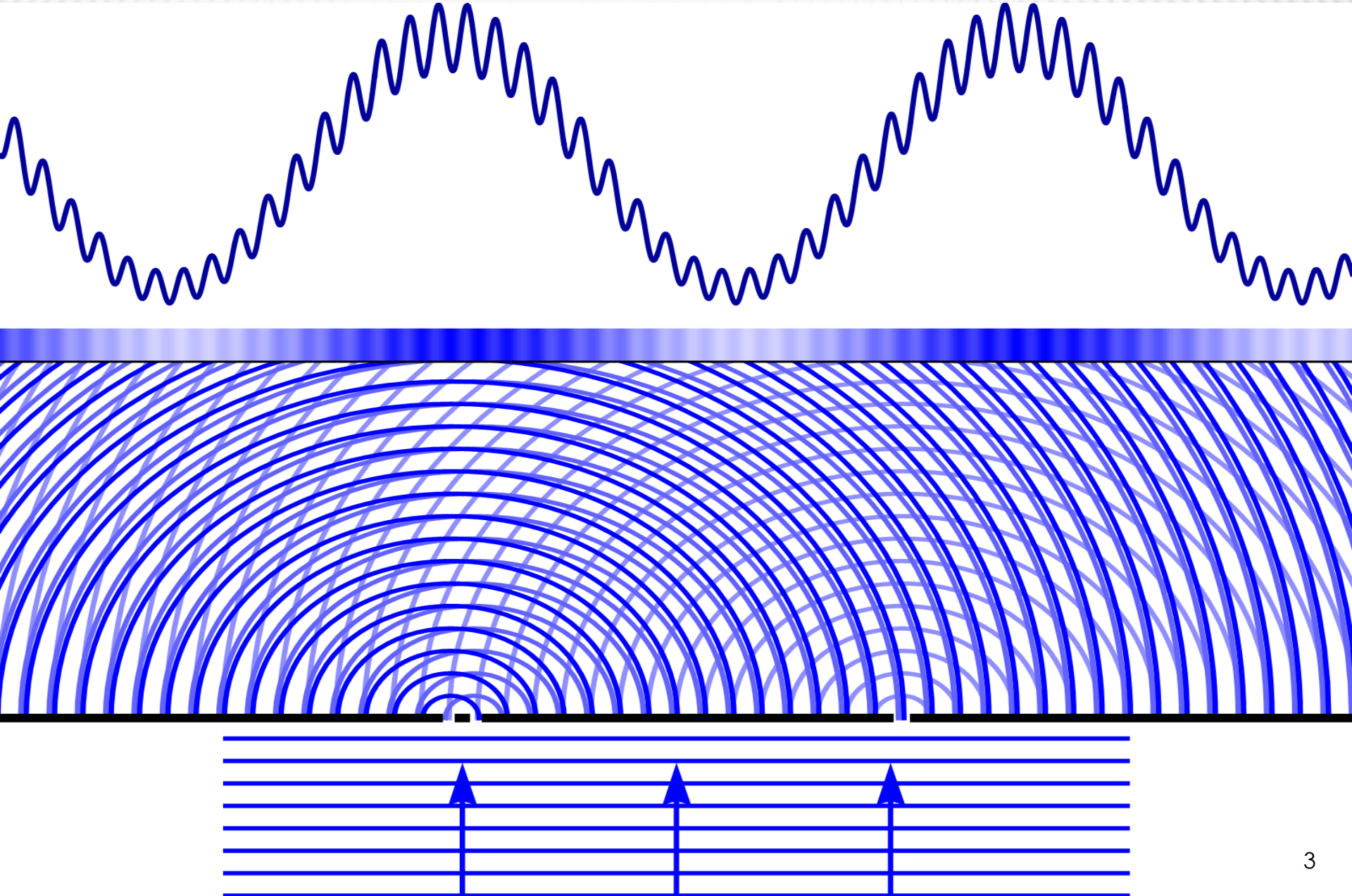
Joao Coelho
For the NOvA Collaboration

THE RISE OF NOVA

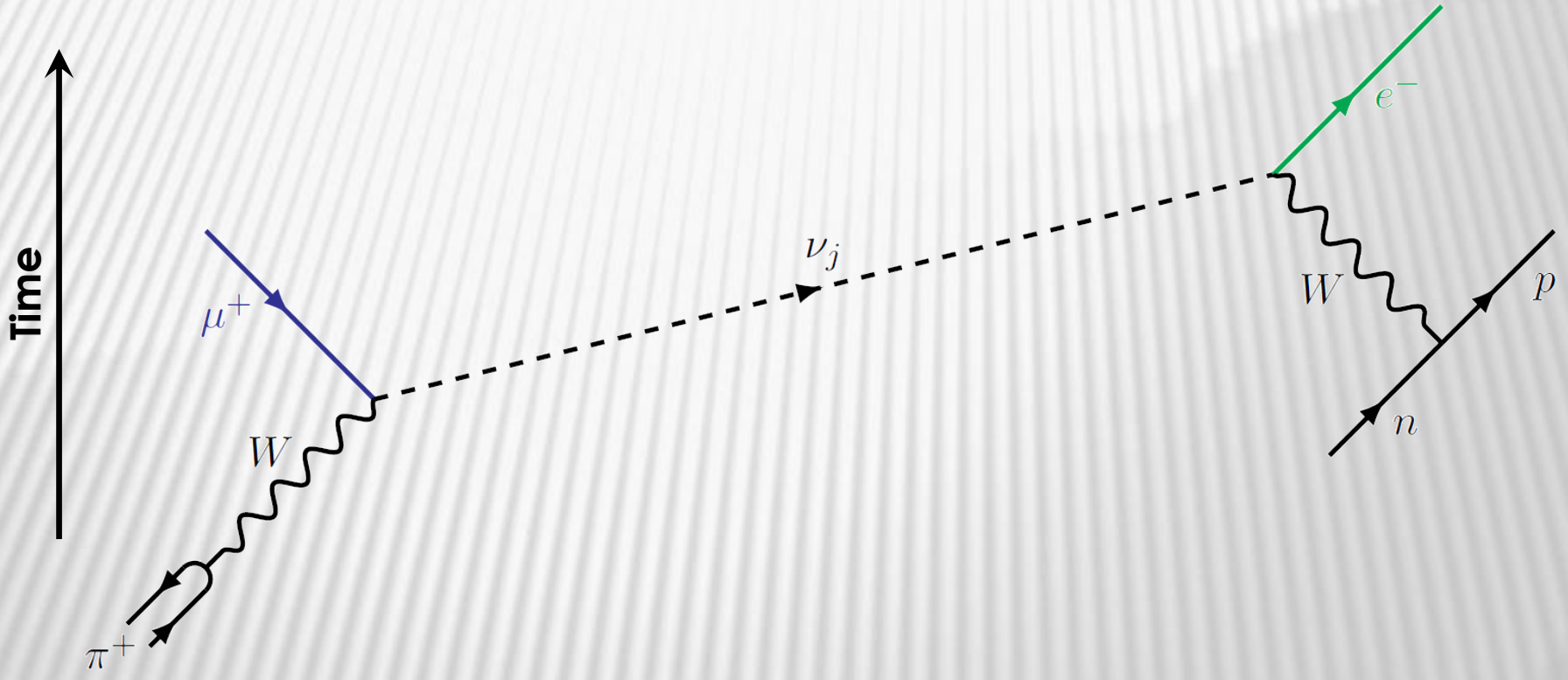
OUTLINE

- Neutrino Oscillations
- NuMI Beam
- Bi-probability plot
- NOvA Experiment
- Numu Disappearance
- Nue Appearance
- What to expect

NEUTRINO OSCILLATION

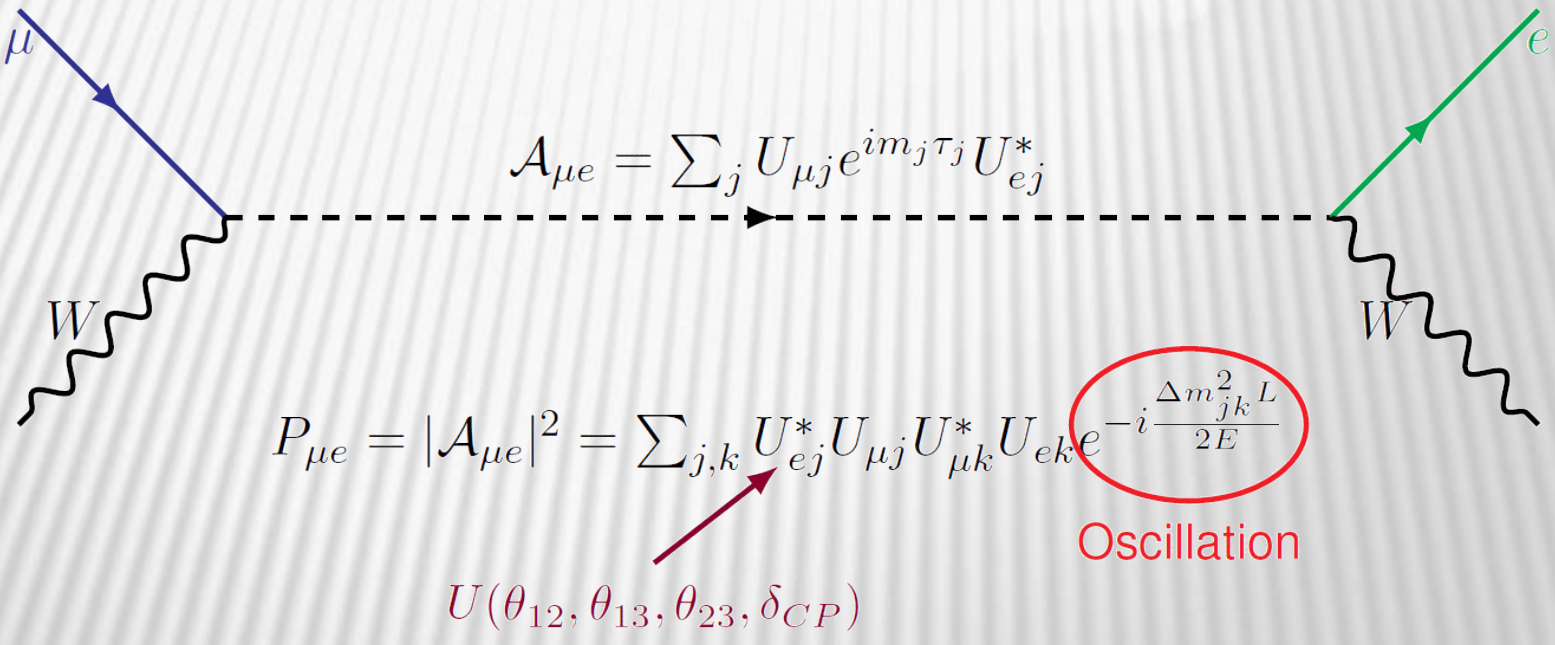


NEUTRINO OSCILLATION



NEUTRINO OSCILLATION

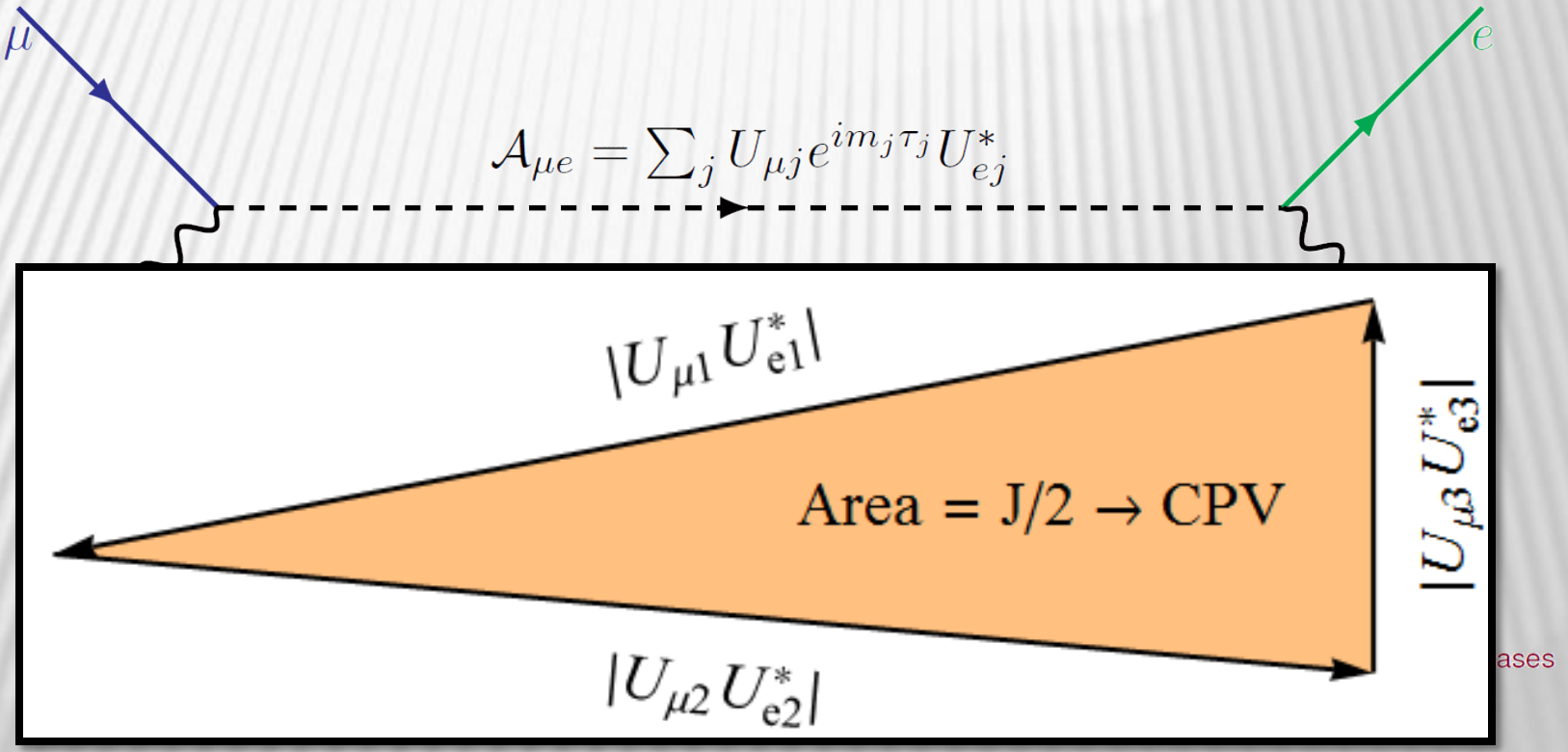
$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{23} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



In general: $n(n-1)/2$ angles and $(n-1)(n-2)/2$ phases

NEUTRINO OSCILLATION

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{23} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$



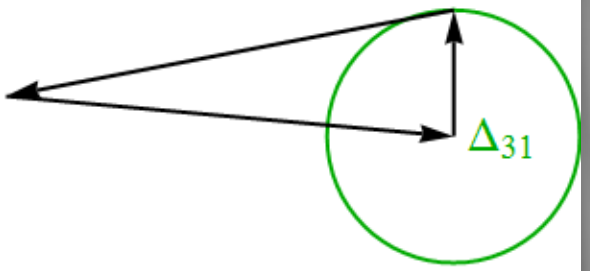
ases

NEUTRINO OSCILLATION

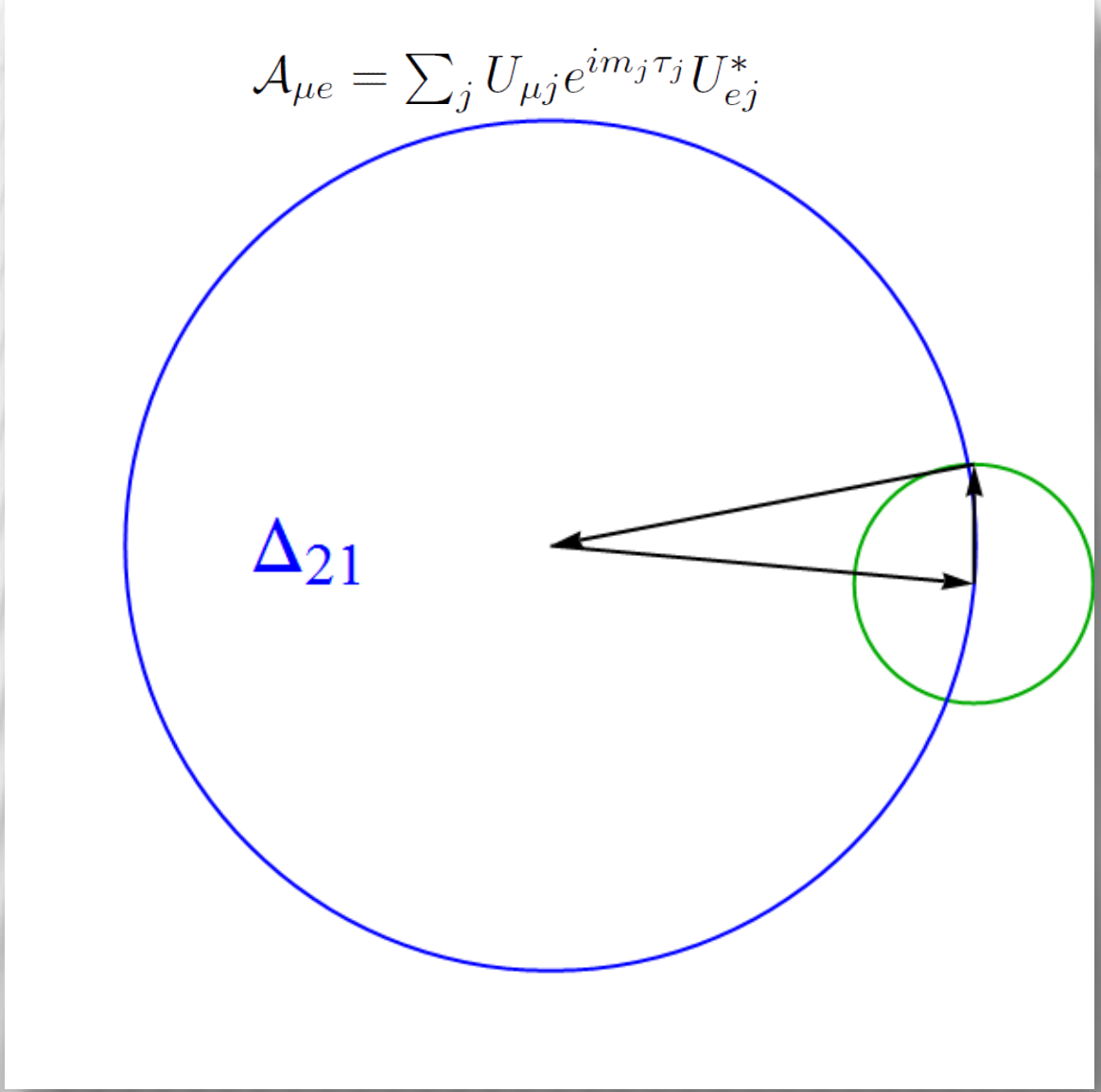
$$\mathcal{A}_{\mu e} = \sum_j U_{\mu j} e^{i m_j \tau_j} U^*_{ej}$$

NEUTRINO OSCILLATION

$$\mathcal{A}_{\mu e} = \sum_j U_{\mu j} e^{i m_j \tau_j} U^*_{ej}$$

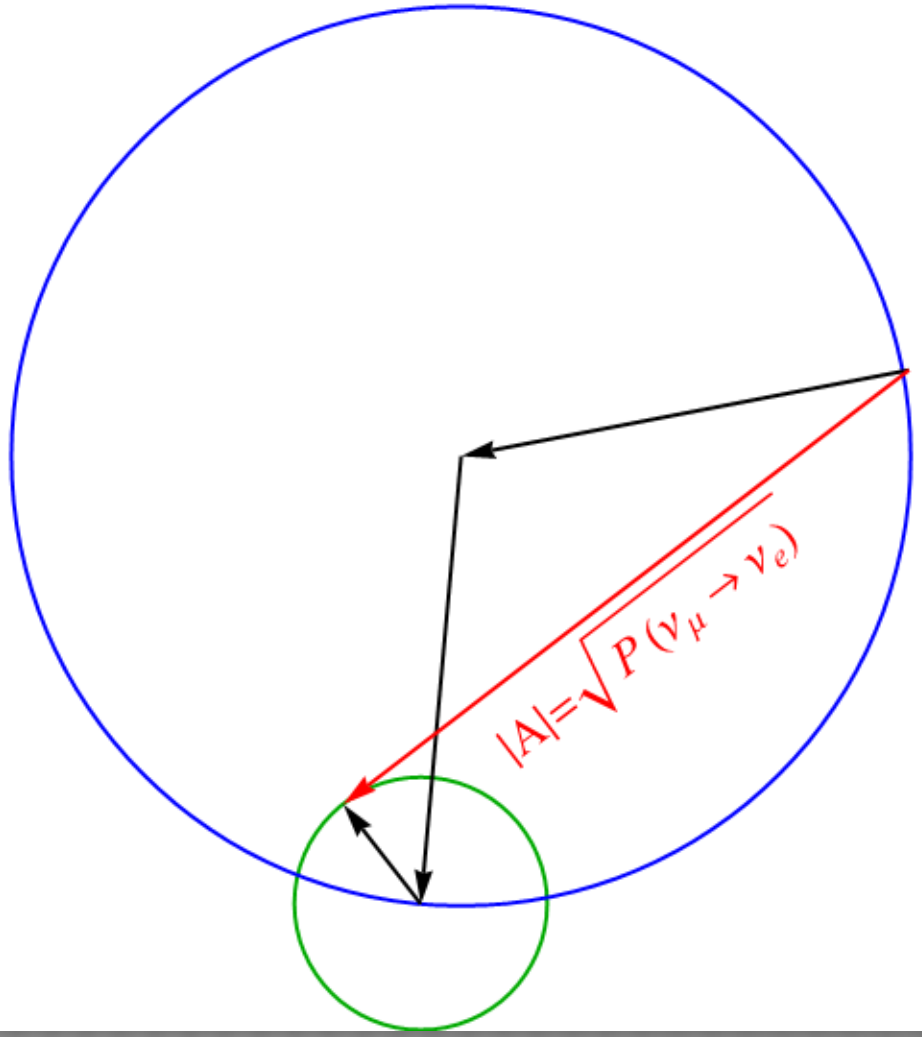


NEUTRINO OSCILLATION

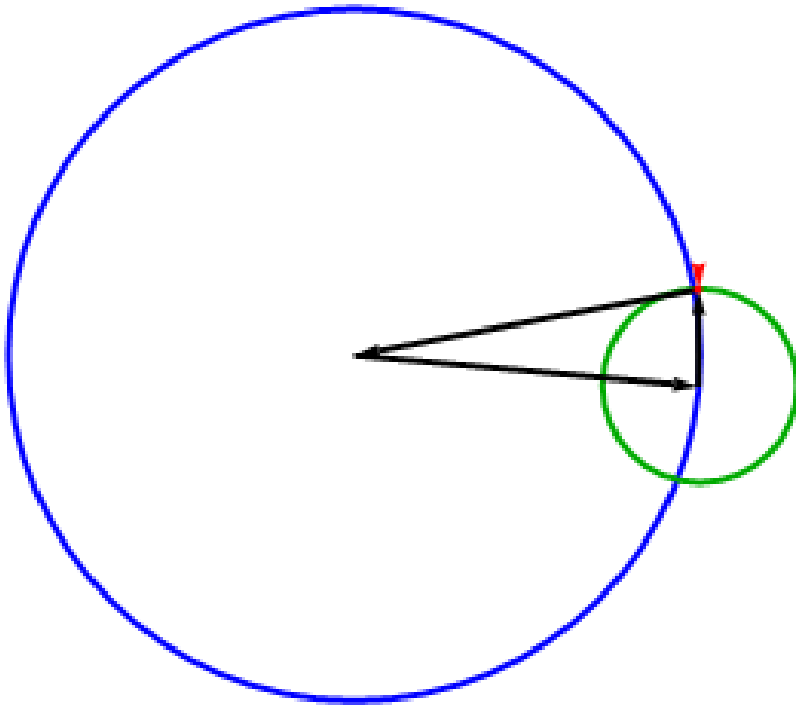


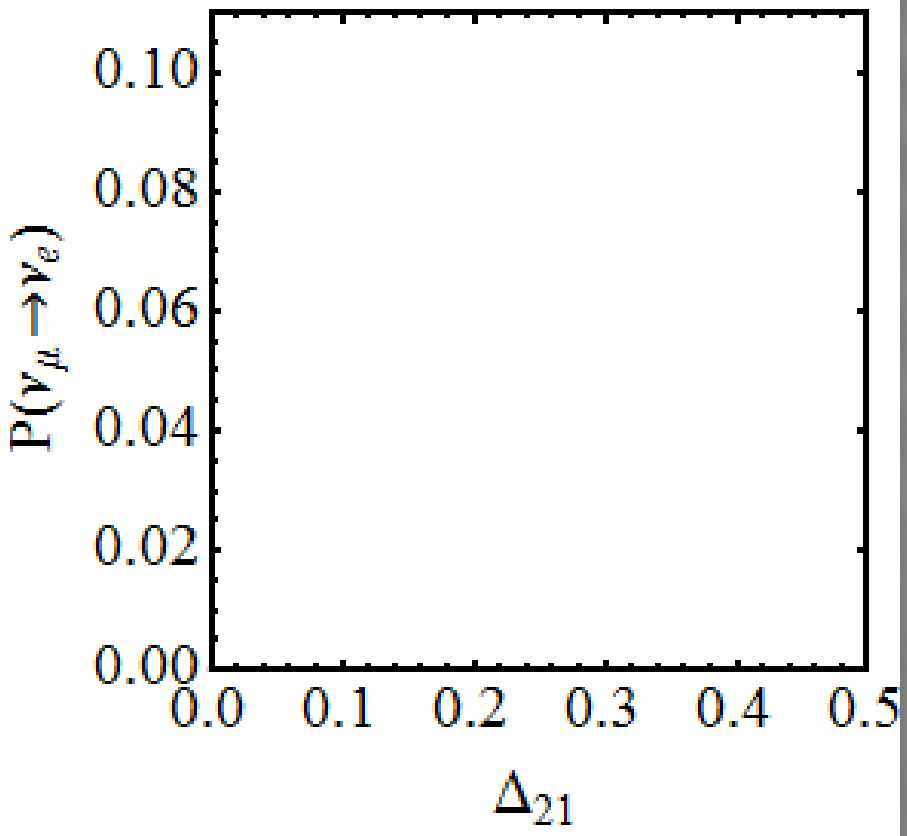
NEUTRINO OSCILLATION

$$\mathcal{A}_{\mu e} = \sum_j U_{\mu j} e^{i m_j \tau_j} U^*_{ej}$$



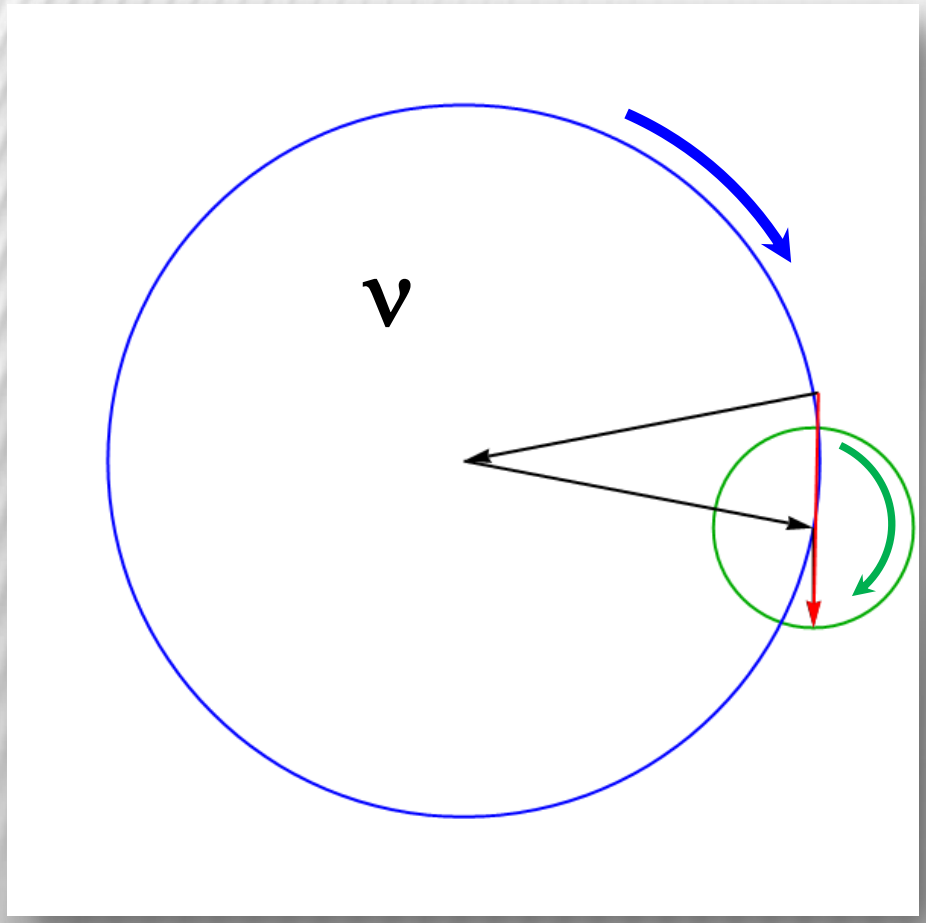
NEUTRINO OSCILLATION

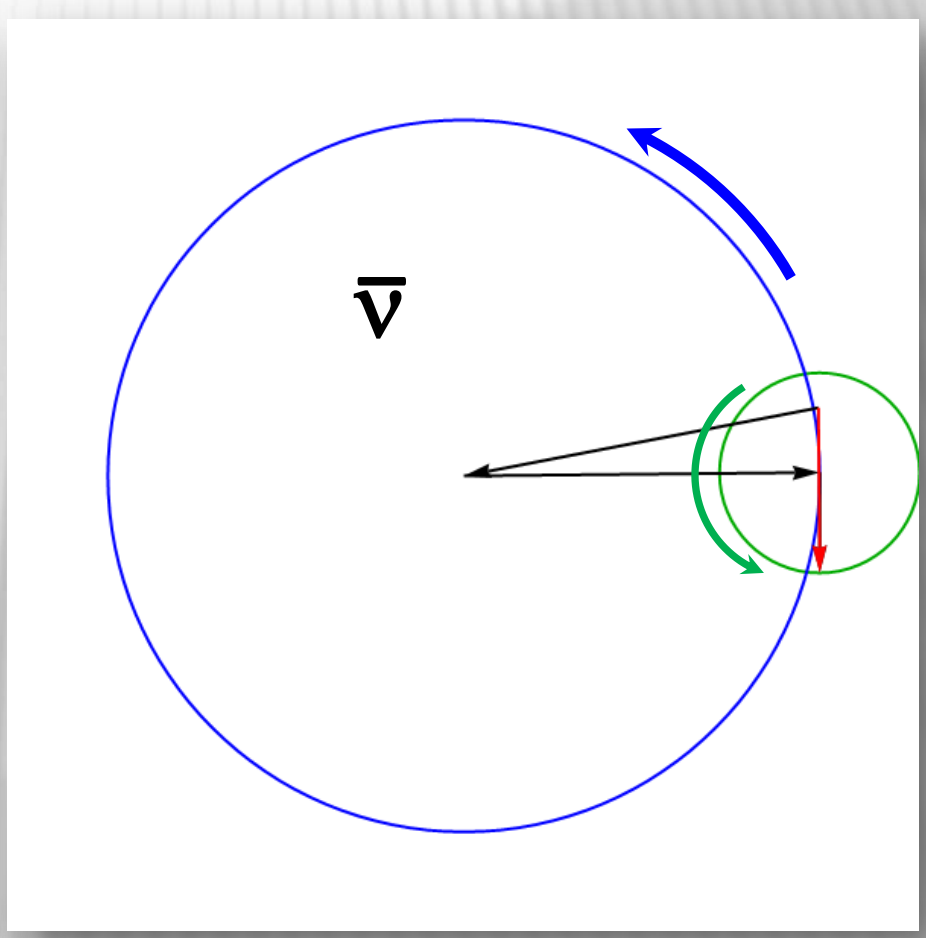




NEUTRINO OSCILLATION

- Flip CP $\Longrightarrow$ Flip T (CPT theorem)
- Triangle is not symmetric (CP violation)





NEUTRINO OSCILLATION

- $\nu_\alpha \rightarrow \nu_\alpha$ is T invariant, so it must be CP invariant (CPT theorem)
- Also, only even orders in $\Delta \equiv \Delta m^2 L/E$

ν_μ Disappearance

$$\mathcal{P}(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{\mu\mu}) \sin^2 \Delta_{\mu\mu} + \mathcal{O}(\Delta_{21})^2$$

$\theta_{\mu\mu} \sim \theta_{23}$ symmetry

$\Delta m^2_{\mu\mu} \sim \Delta m^2_{32}$ symmetry

ν_e Appearance

$$\begin{aligned} \mathcal{P}(\nu_\mu \rightarrow \nu_e) &\approx \sin^2\theta_{23} \sin^2(2\theta_{13}) \sin^2 \Delta_{\mu e} \\ &\pm \tilde{J} \sin\delta \sin\Delta_{21} \sin^2 \Delta_{\mu e} + \mathcal{O}(\Delta_{21})^2 \end{aligned}$$

CP violation ($\sin\delta$ term)

Breaks θ_{23} symmetry

Different effective Δm^2

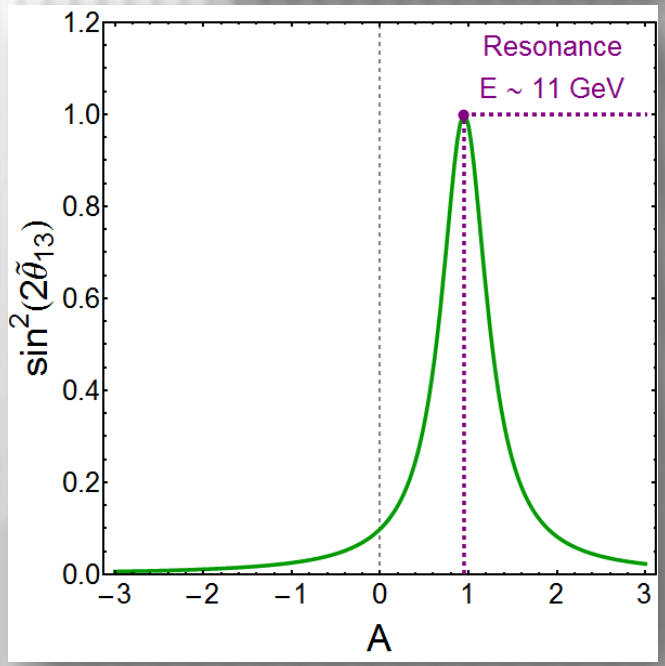
GOING THROUGH THE EARTH

- Earth is transparent to neutrinos
- It has a neutrino "refractive index"
- Main effect is change in θ_{13}

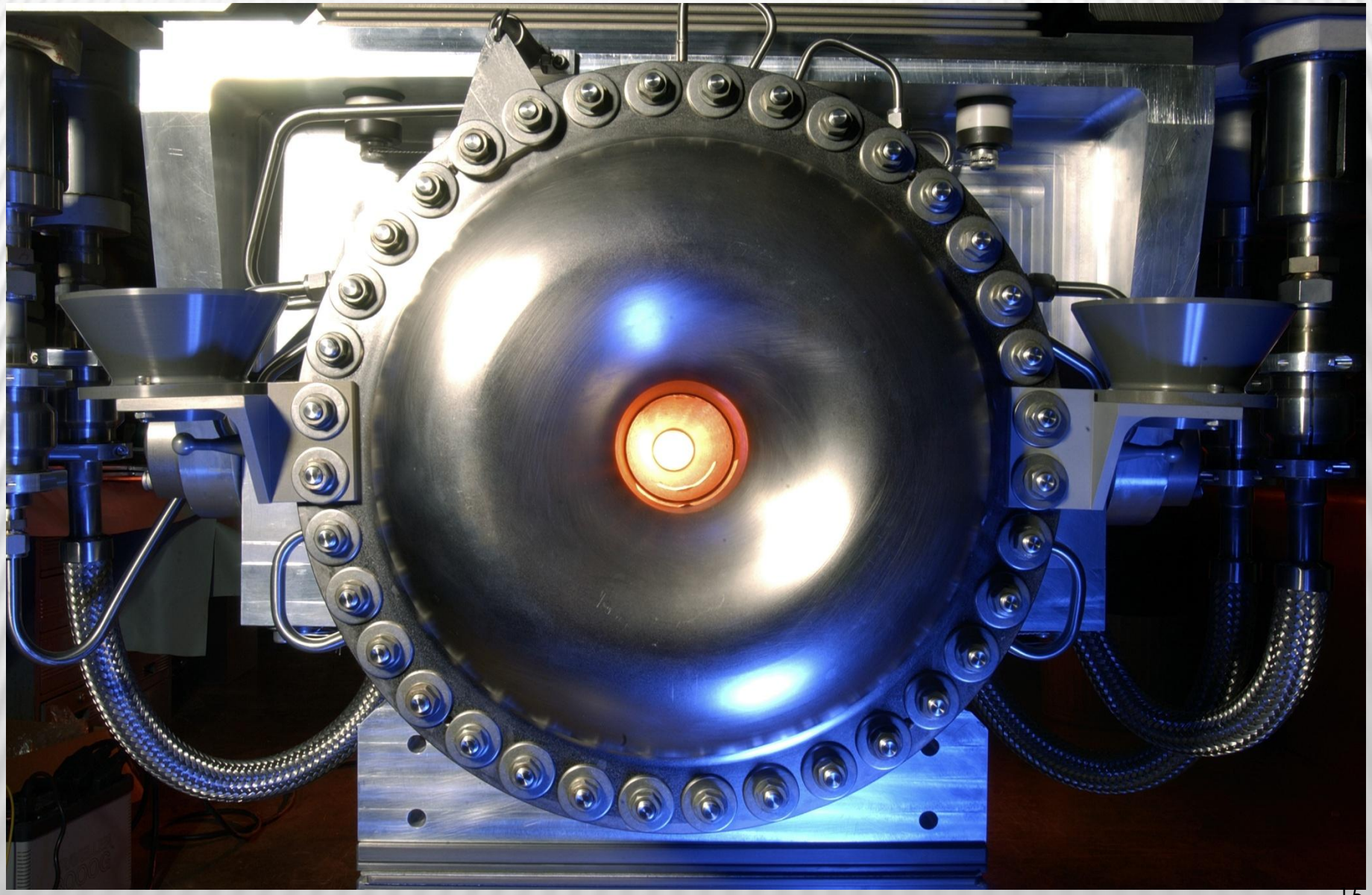
$$A \equiv \frac{\sqrt{2} G_F n_e}{\Delta m^2_{32}/2E} \sim \frac{E}{11.5\ \text{GeV}}$$

$$\tan(2\tilde{\theta}_{13}) \equiv \frac{\sin(2\theta_{13})}{\cos(2\theta_{13}) - A}$$

- Depends on sign of Δm^2_{32}
- Different signs for ν and $\bar{\nu}$
- Apparent CP violation

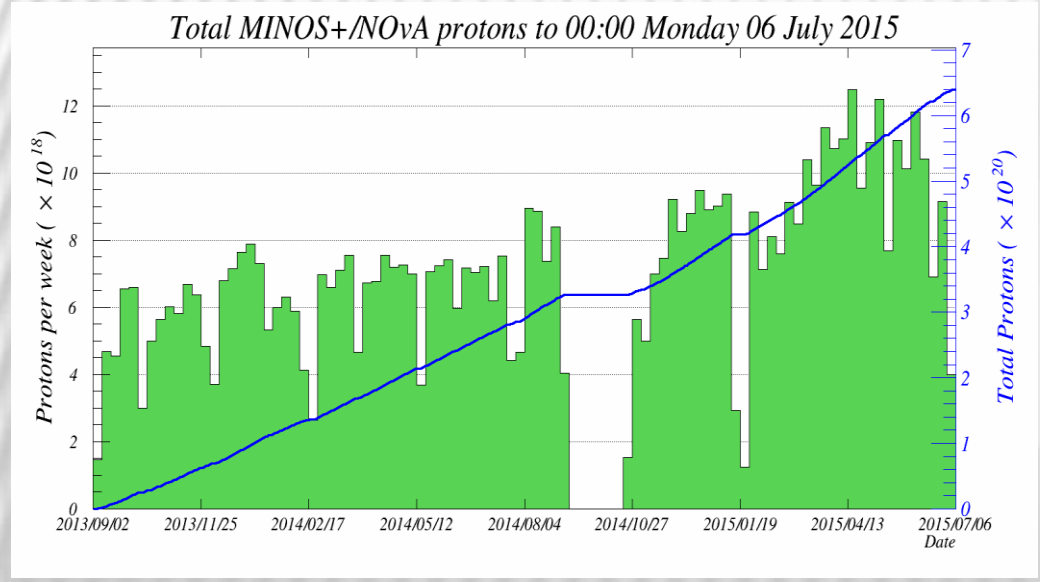


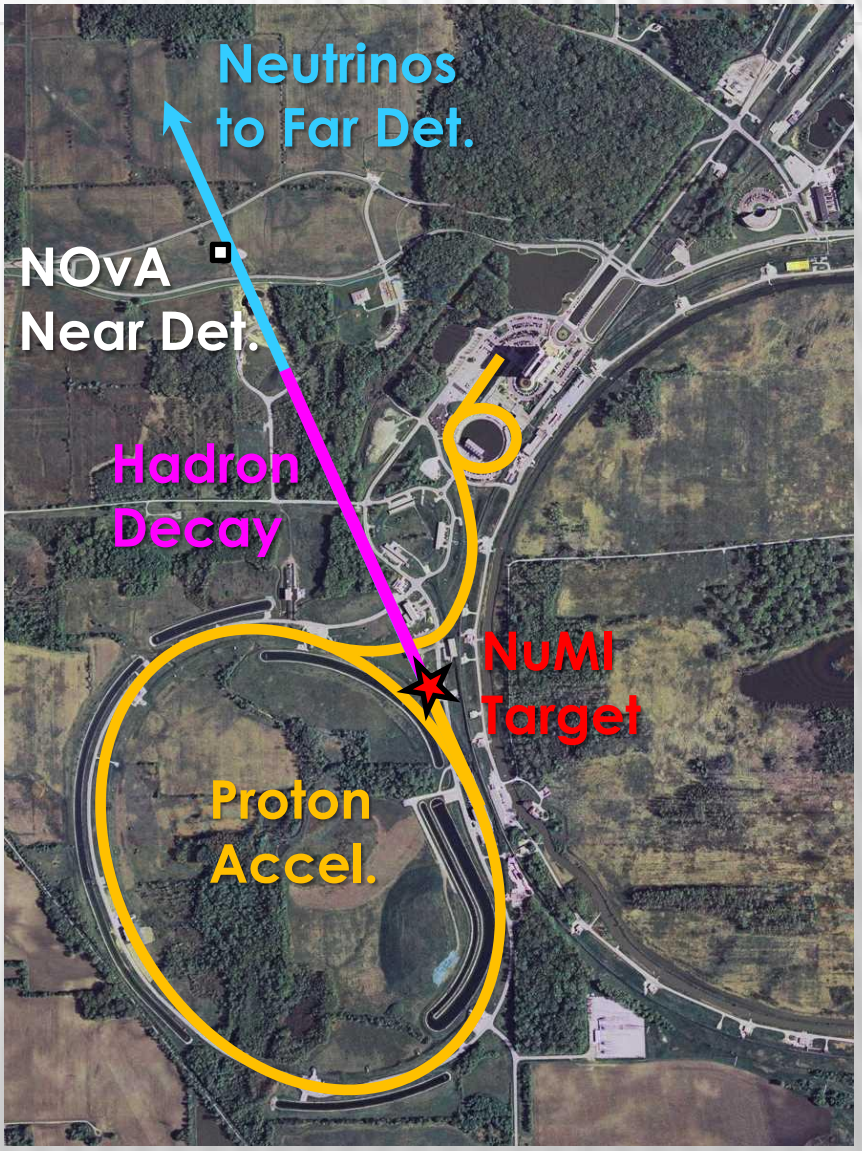
THE NUMI BEAM



RAMPING UP

- Capable of 700 kW
- Currently at ~470 kW
- Full power by mid 2016
- 6.4 x 10^{20} PoT delivered

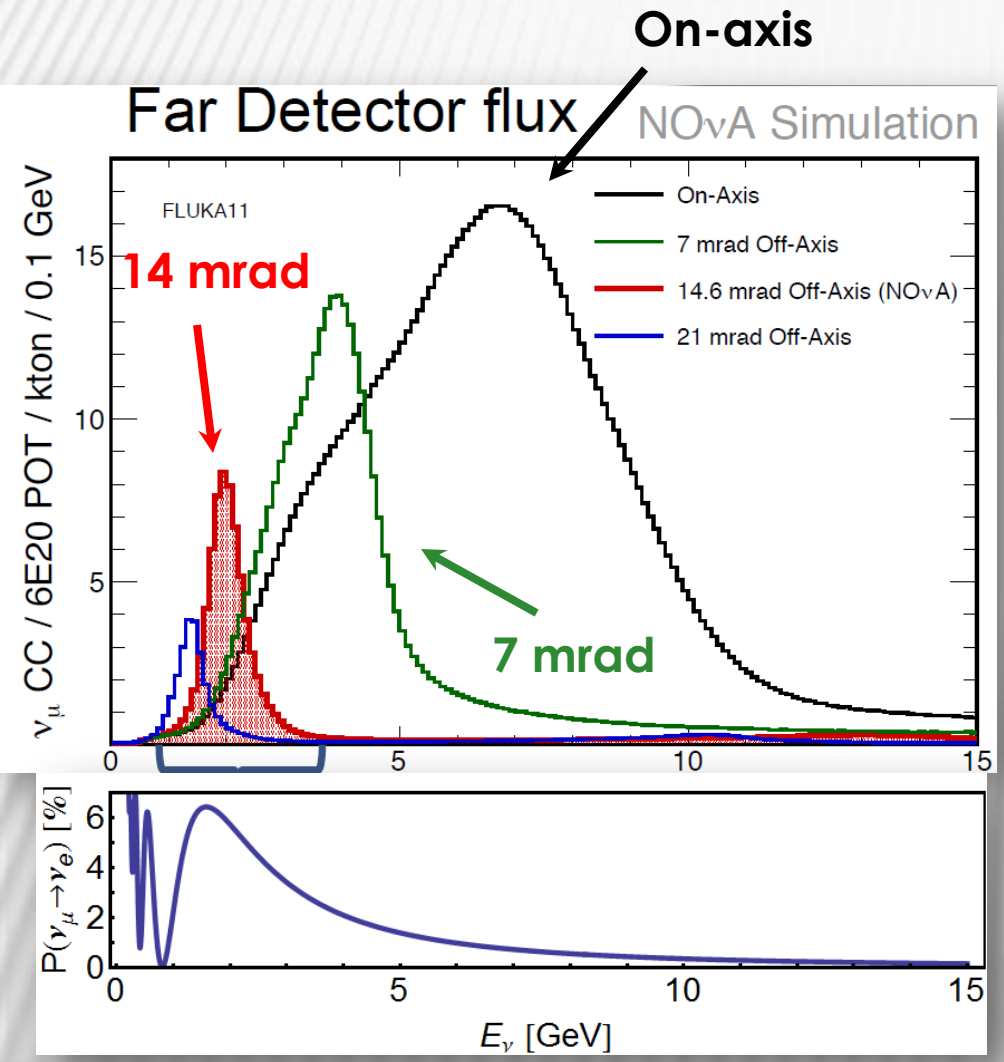


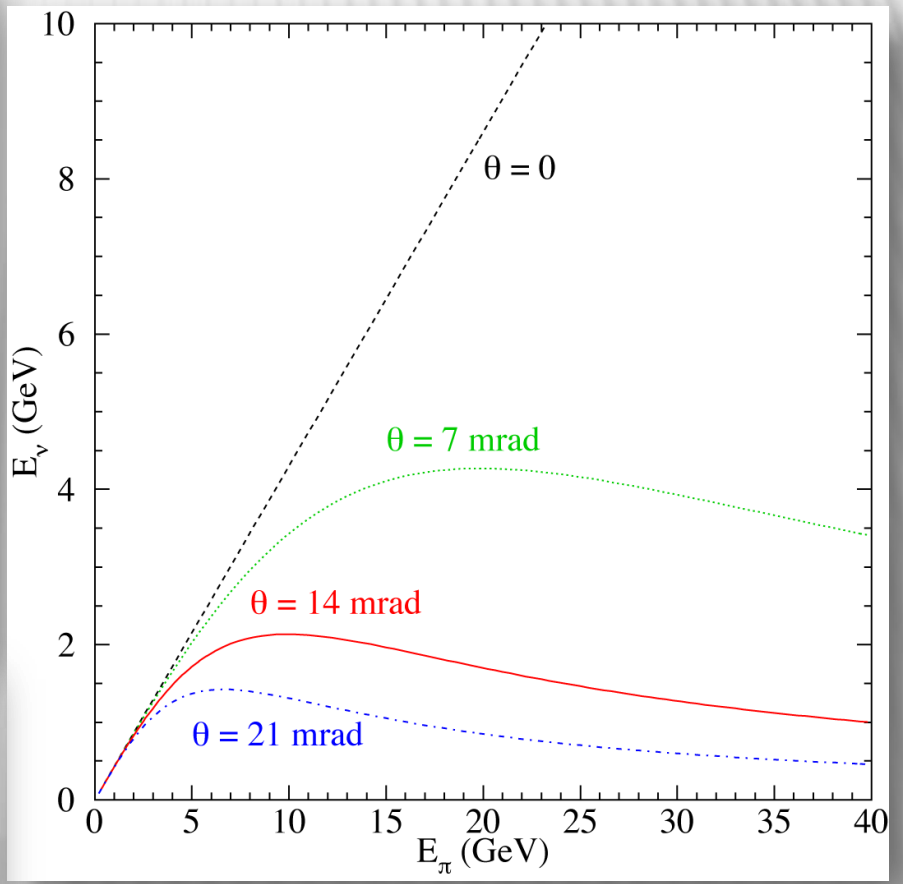


BASELINE

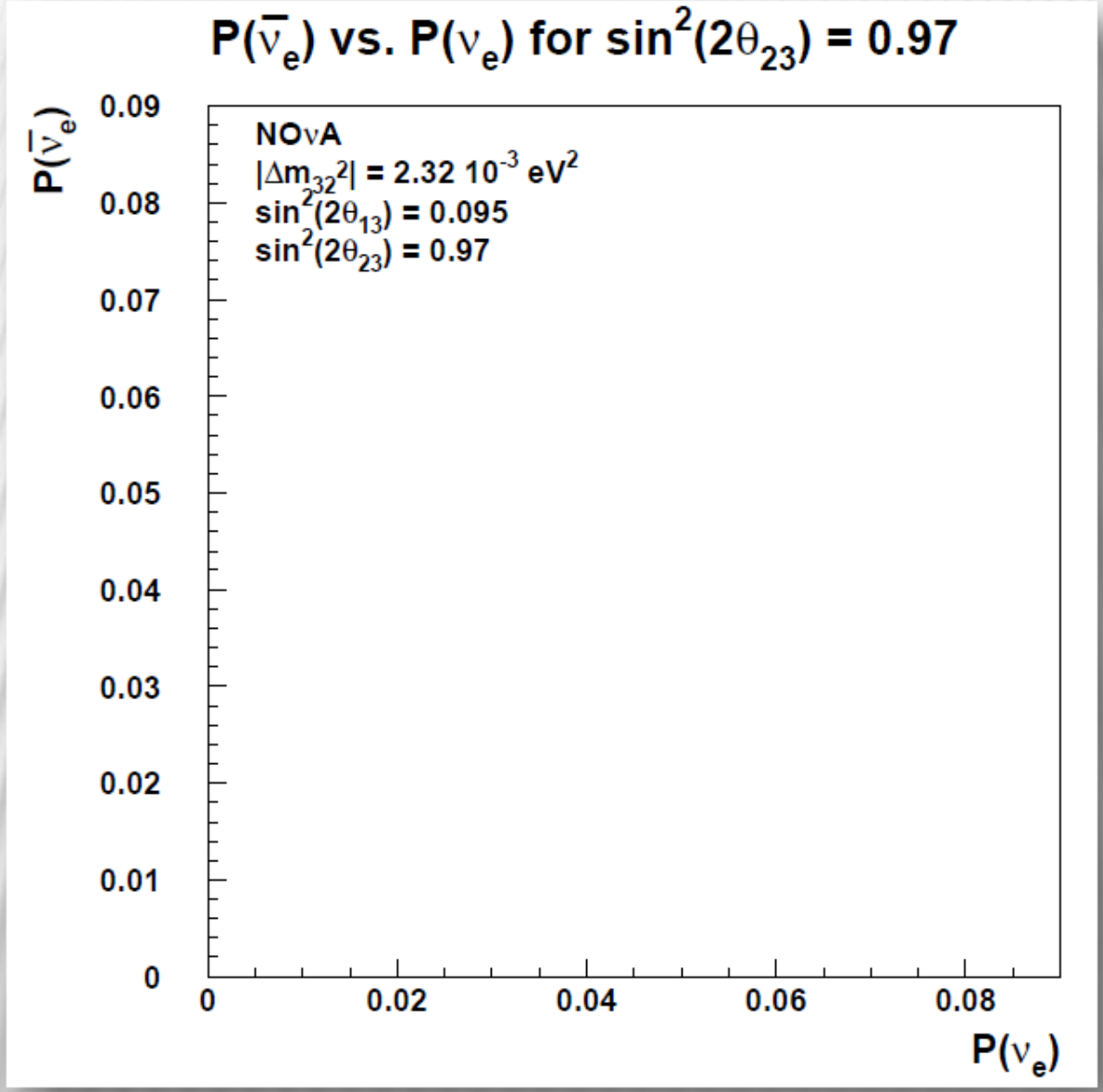
Lake Winnipeg
Canadian Shield
Hudson Bay
North Dakota
NOvA
MINOS+
Lake Nipigon
Ontario
Minnesota
Lake Superior
NOvA
810 km
0.84˚ off-axis
Beam axis
Green Bay
Wisconsin
Michigan
Lake Michigan
Iowa
Fermilab
Illinois

OFF-AXIS

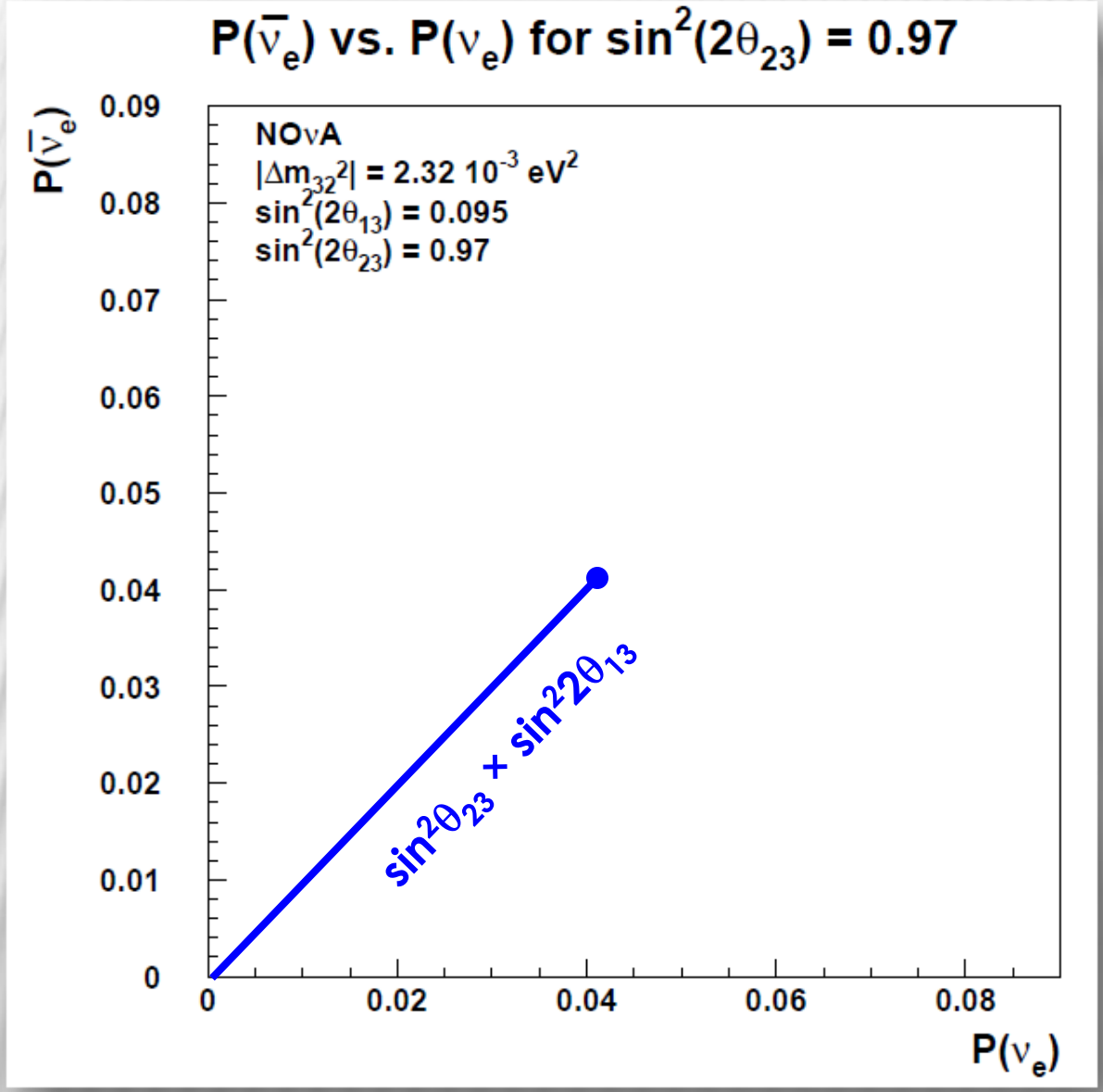

On-axis
Far Detector flux
NOνA Simulation
FLUKA11
14 mrad
7 mrad
On-Axis
7 mrad Off-Axis
14.6 mrad Off-Axis (NOνA)
21 mrad Off-Axis
ν_μ CC / 6E20 POT / kton / 0.1 GeV
$P(\nu_\mu \rightarrow \nu_e)$ [%]
E_ν [GeV]


θ = 0
θ = 7 mrad
θ = 14 mrad
θ = 21 mrad
E_ν (GeV)
E_π (GeV)

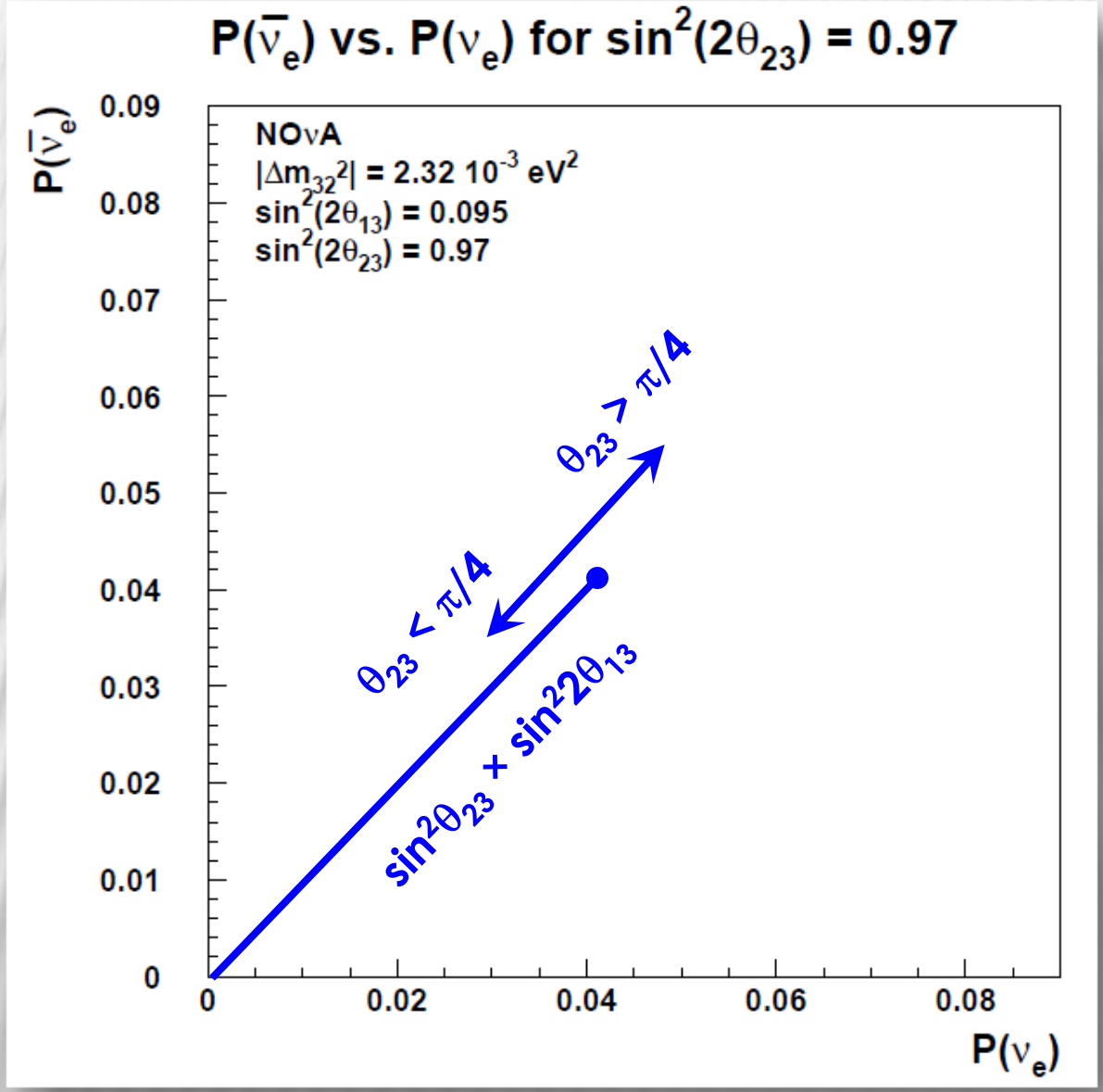
NUE APPEARANCE



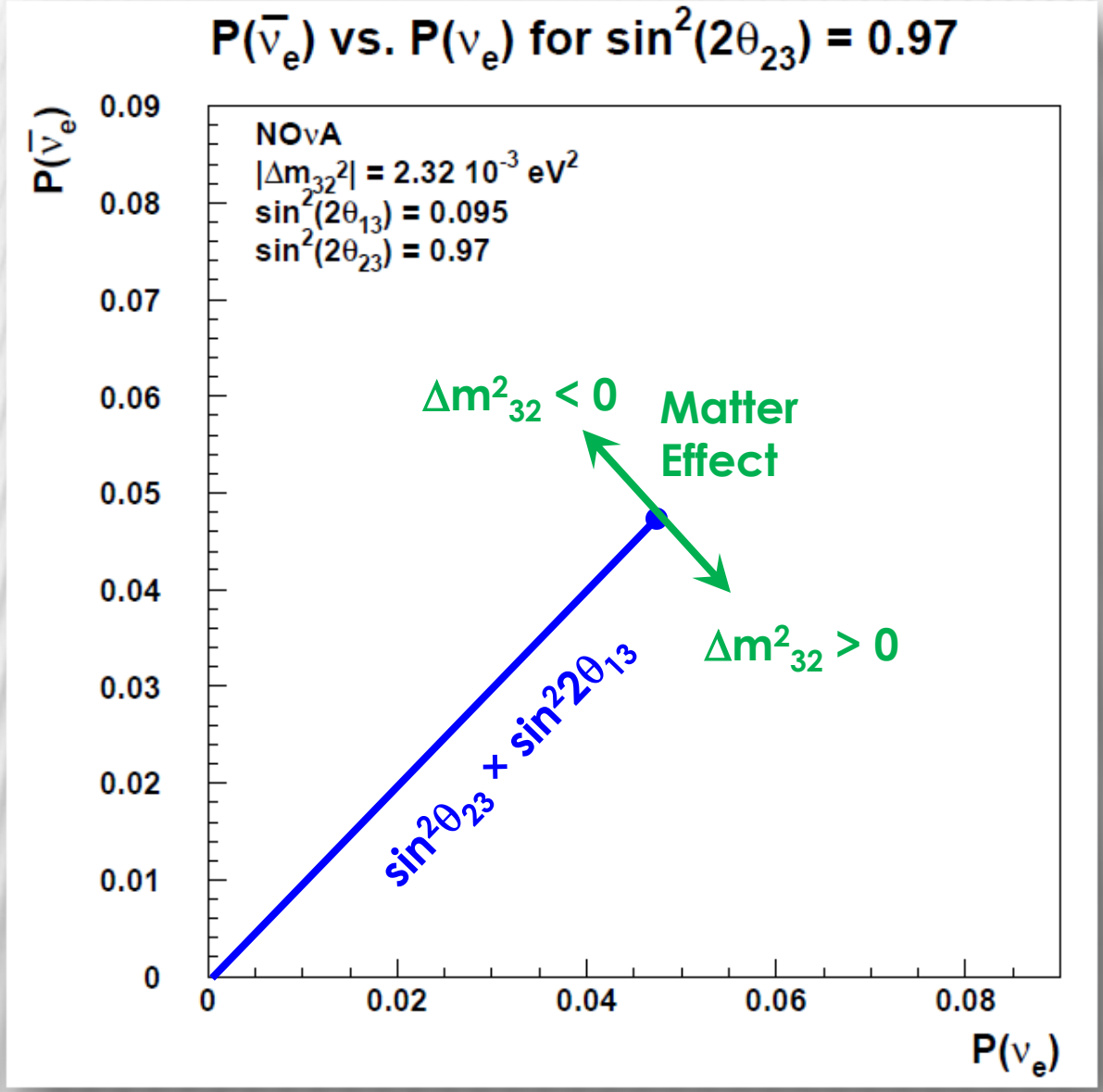
NUE APPEARANCE



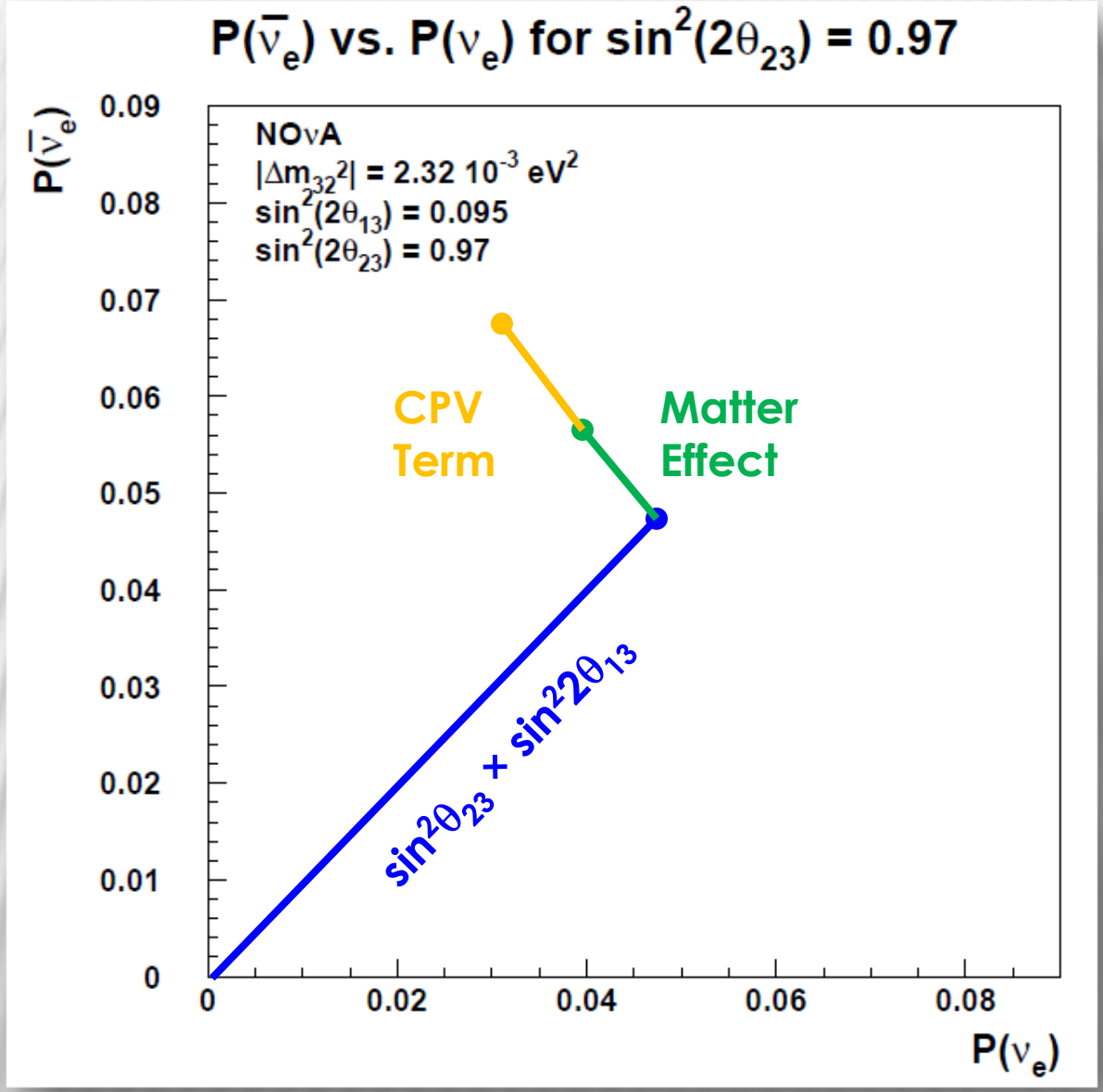
NUE APPEARANCE



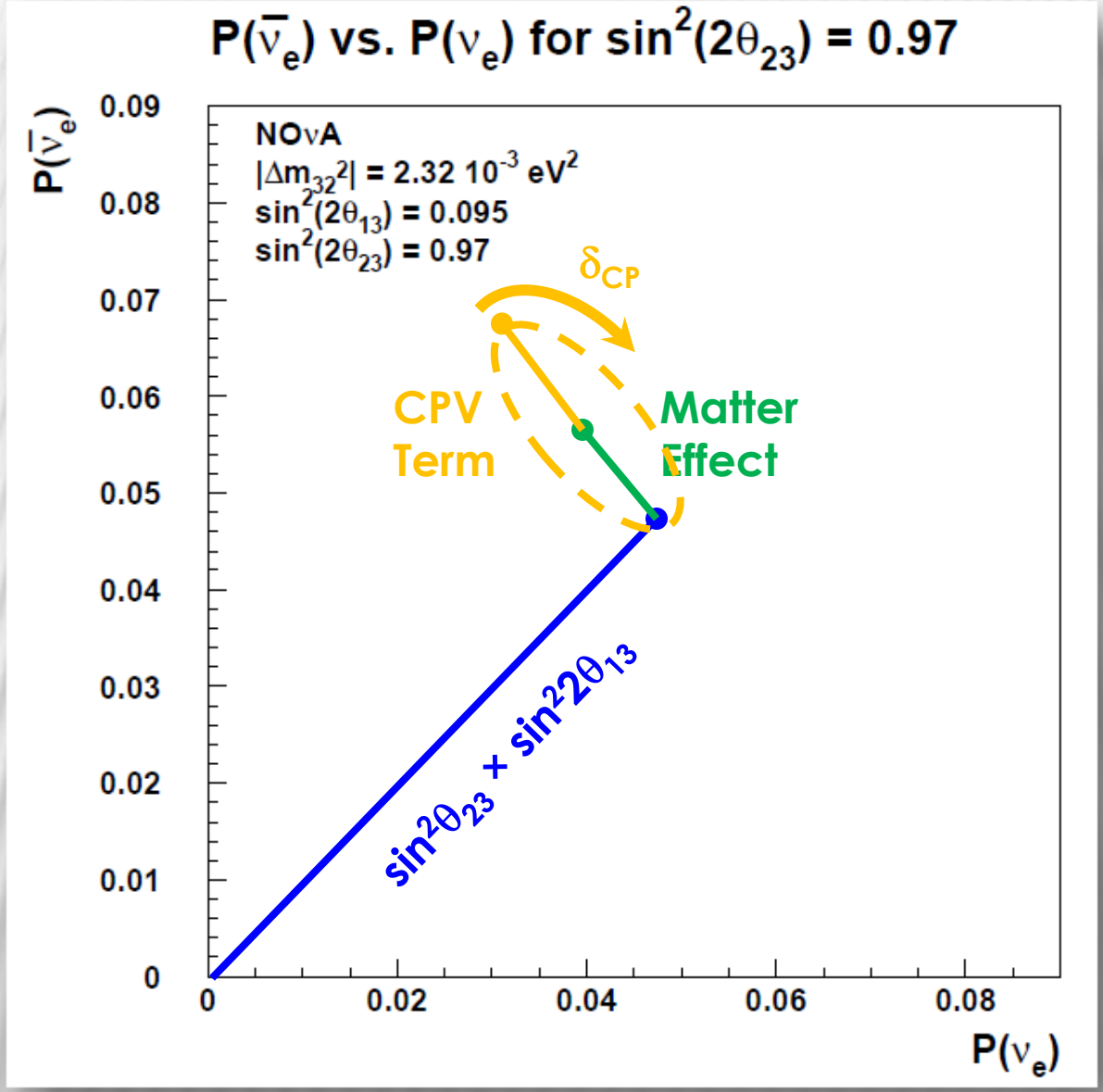
NUE APPEARANCE



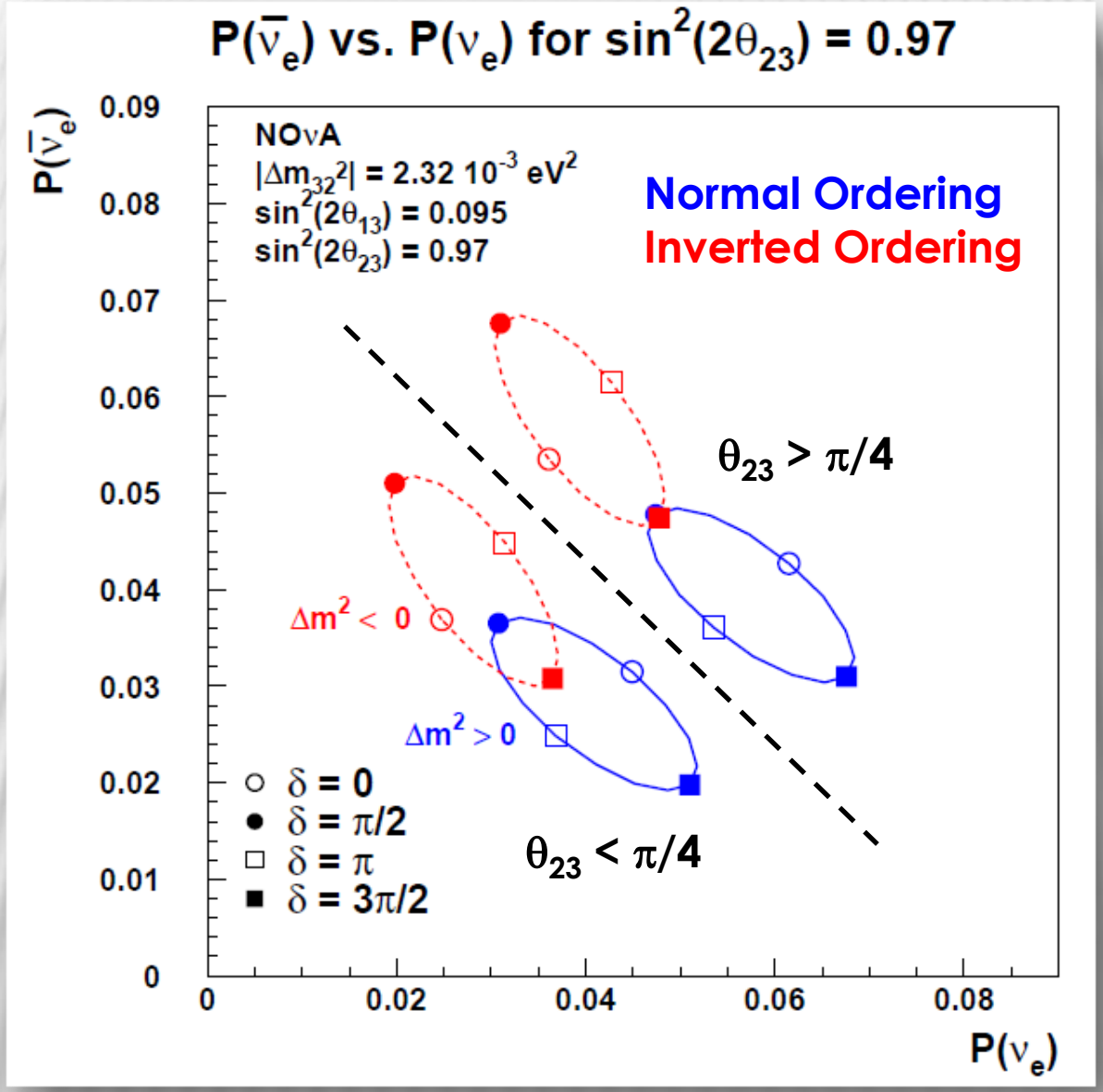
NUE APPEARANCE



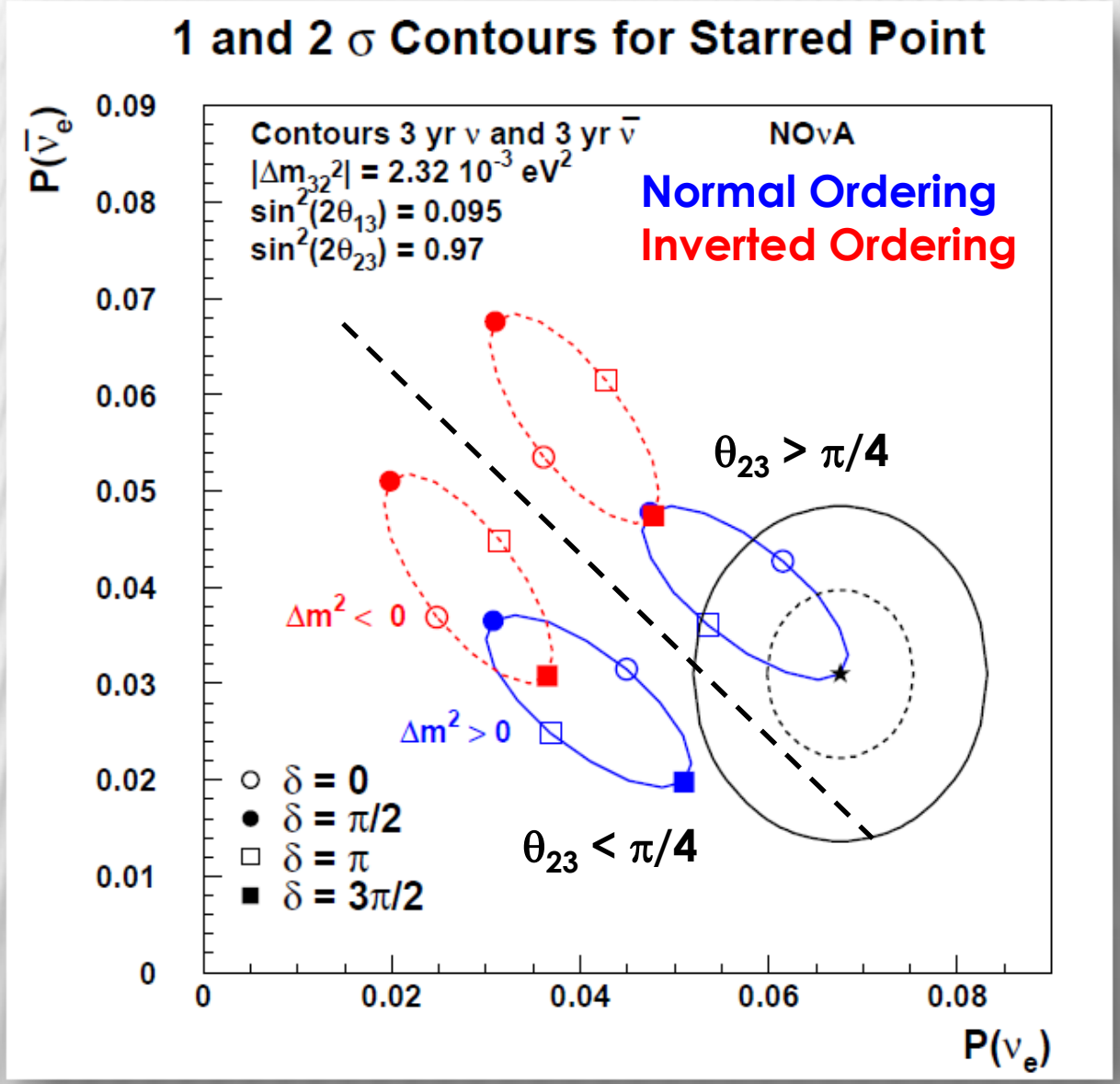
NUE APPEARANCE



NUE APPEARANCE

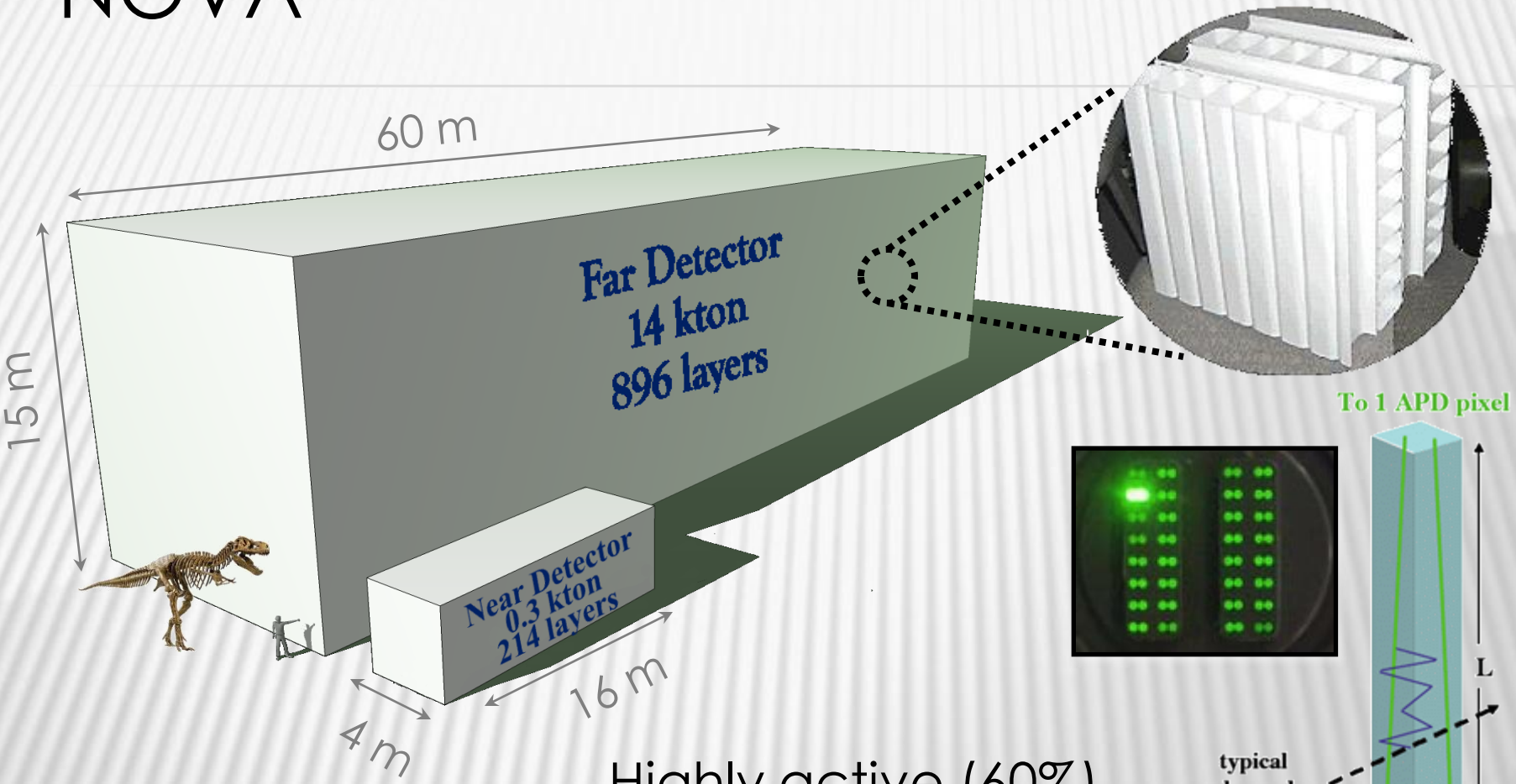


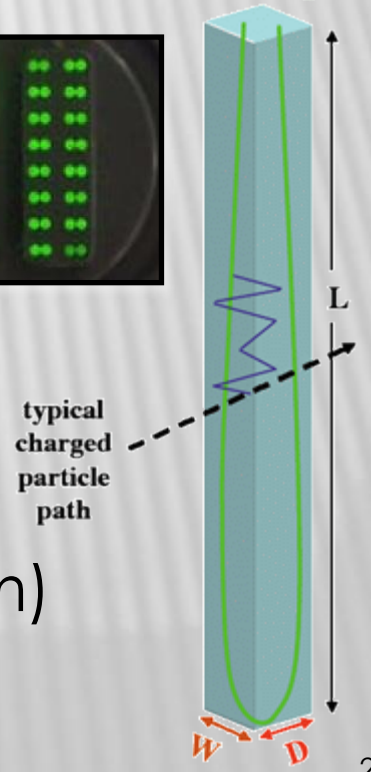
NUE APPEARANCE



NOVA

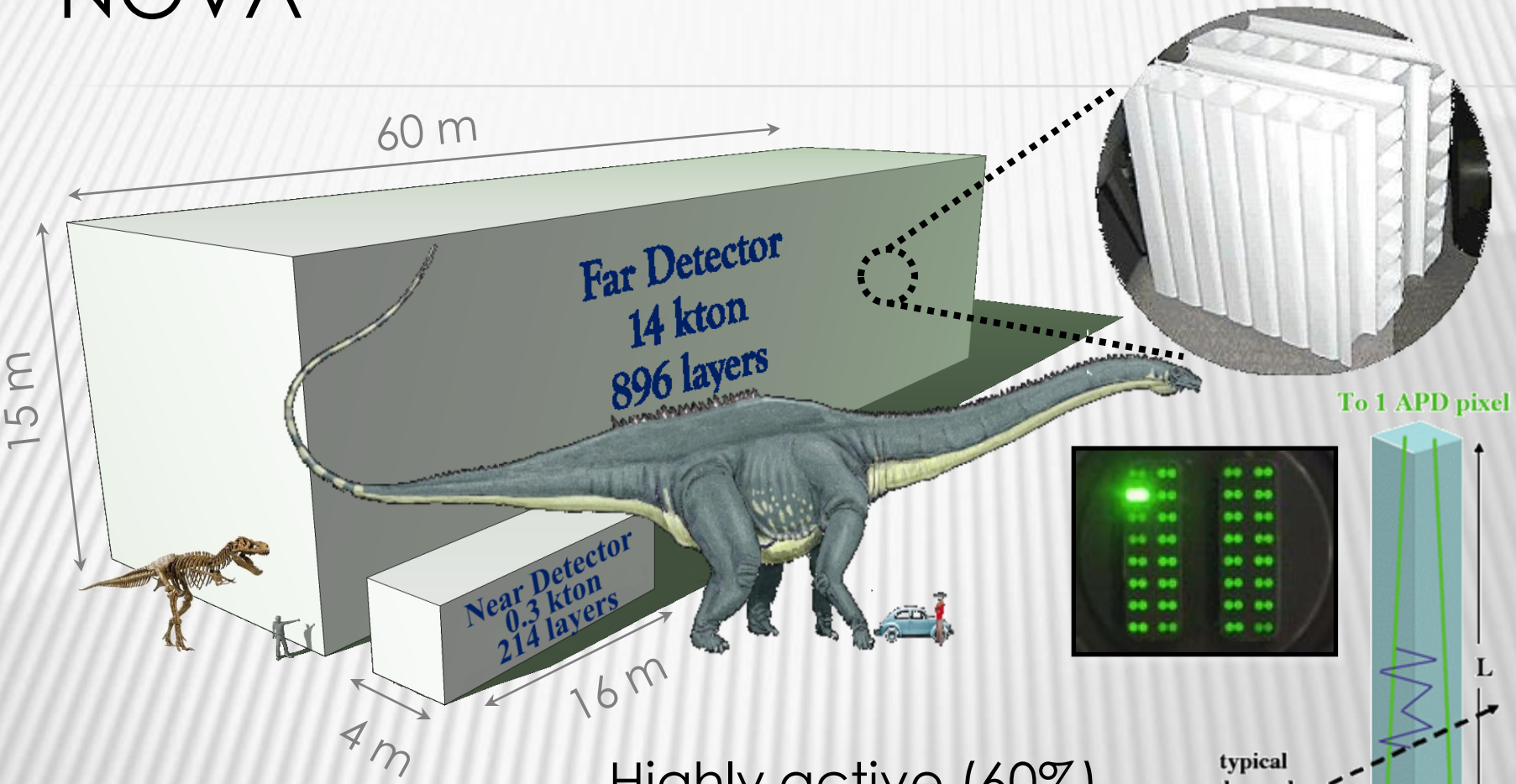
NOVA

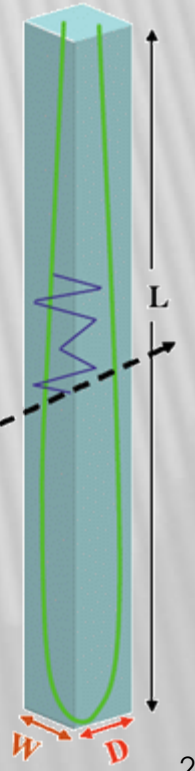




Highly active (60%)
Tracking calorimeters
Fine granularity (4x6 cm)
FD → 344,064 channels
ND → 20,192 channels

NOVA

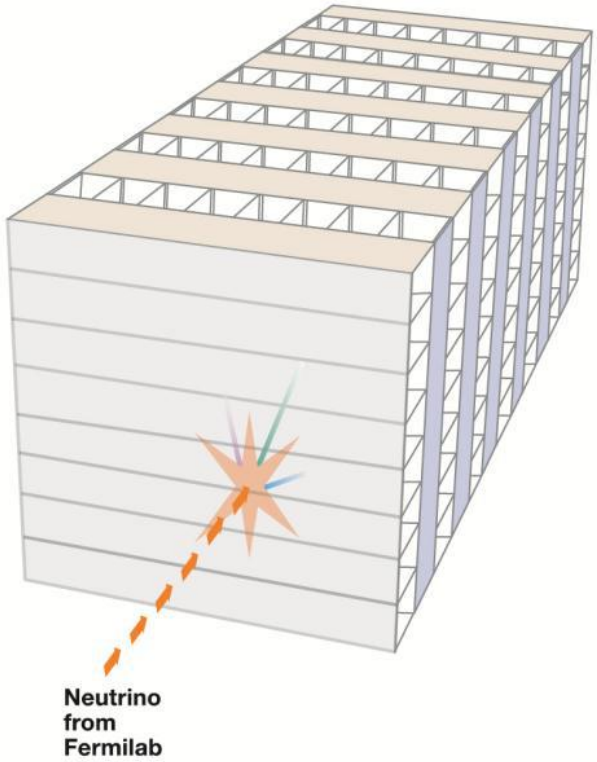




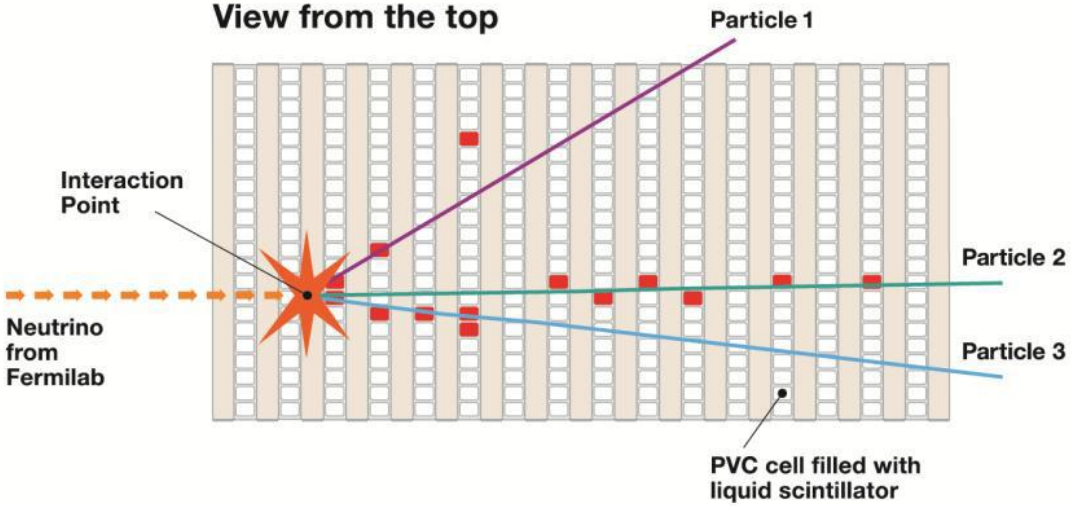
Highly active (60%)
Tracking calorimeters
Fine granularity (4x6 cm)
FD → 344,064 channels
ND → 20,192 channels

NOVA

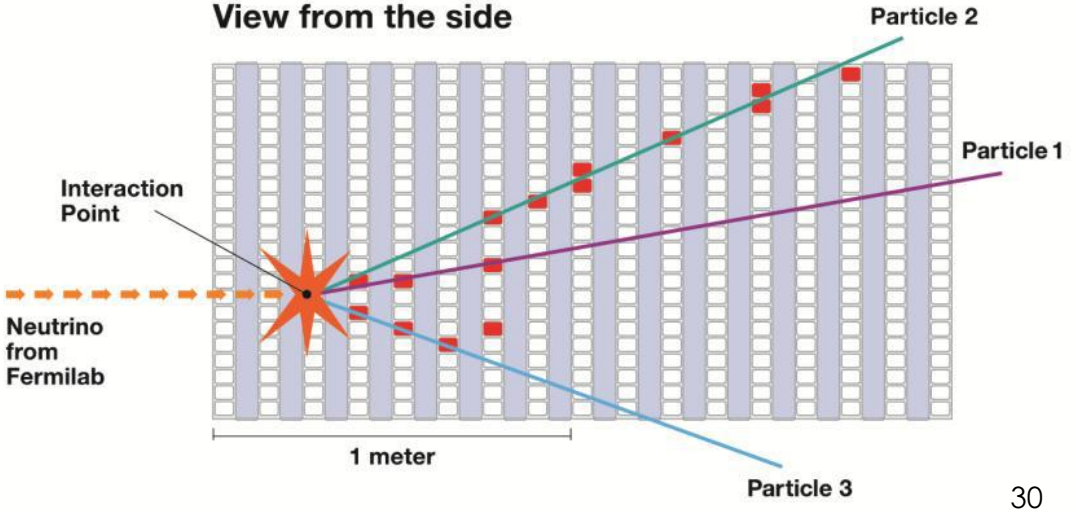
3D schematic of NOvA particle detector



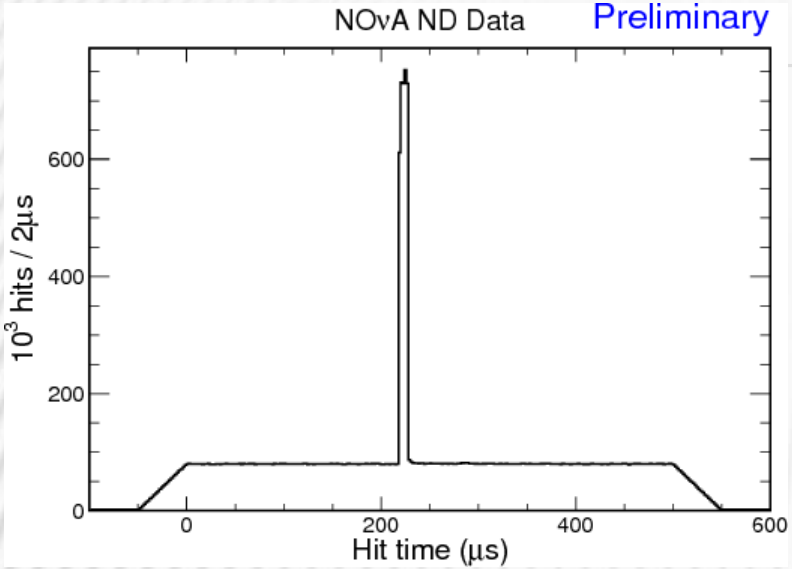
View from the top

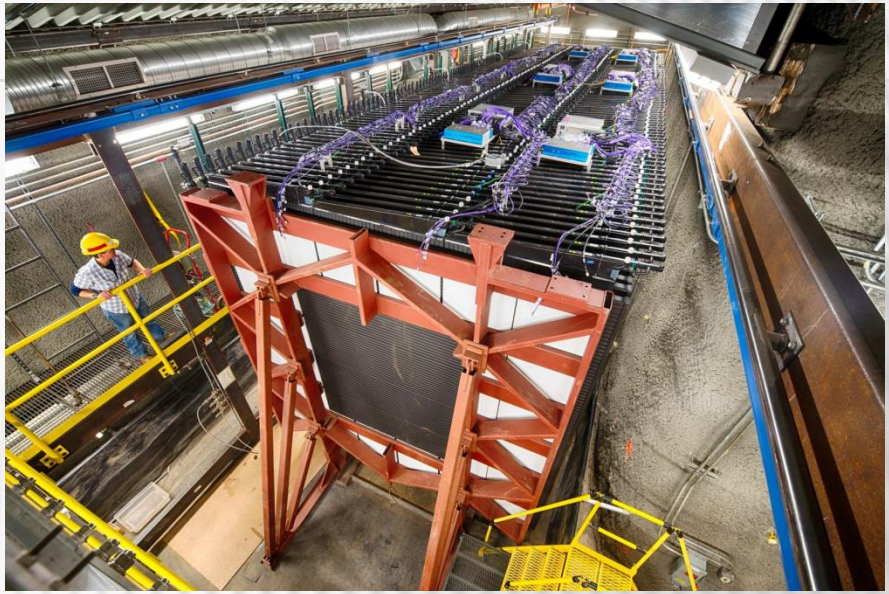


View from the side

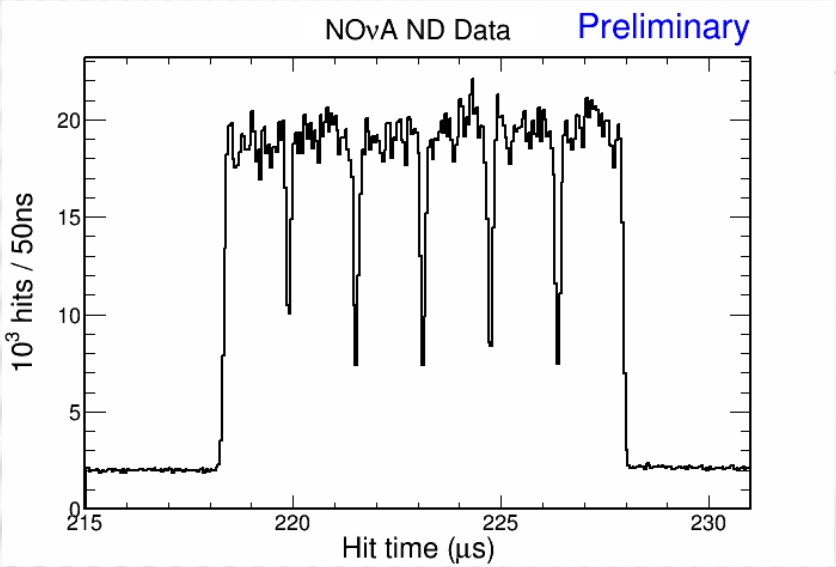


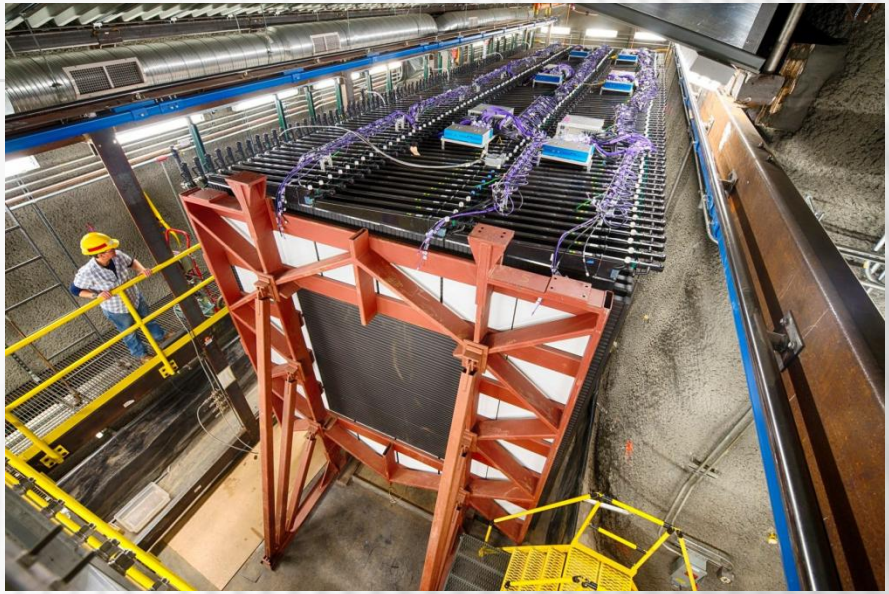
DETECTORS COMPLETE



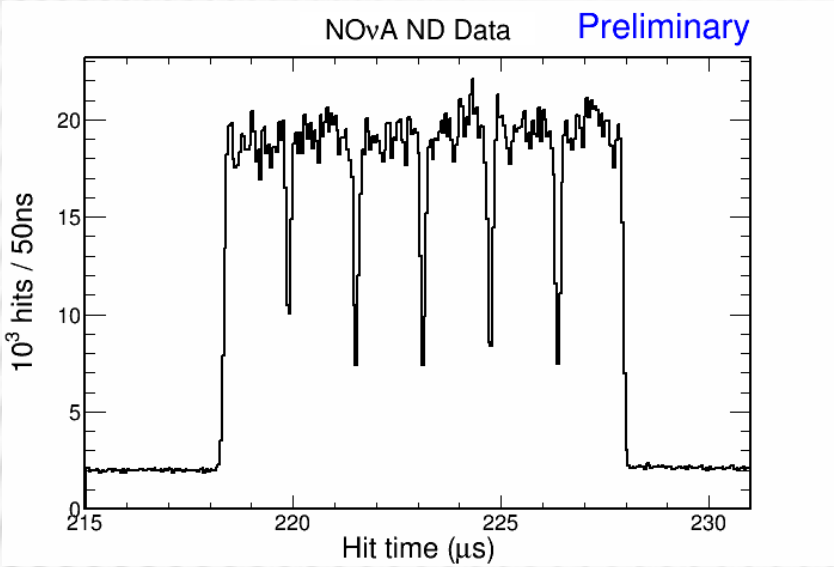


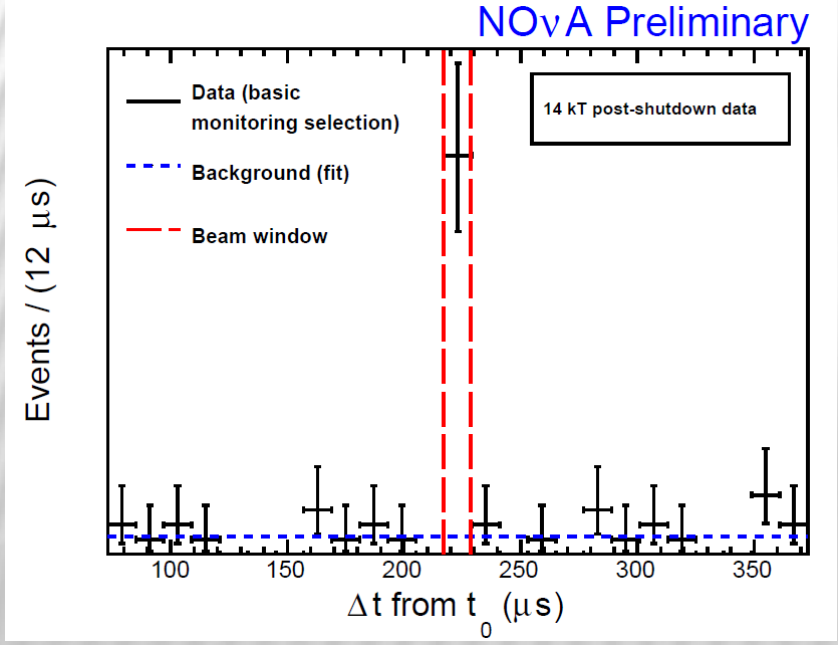
DETECTORS COMPLETE





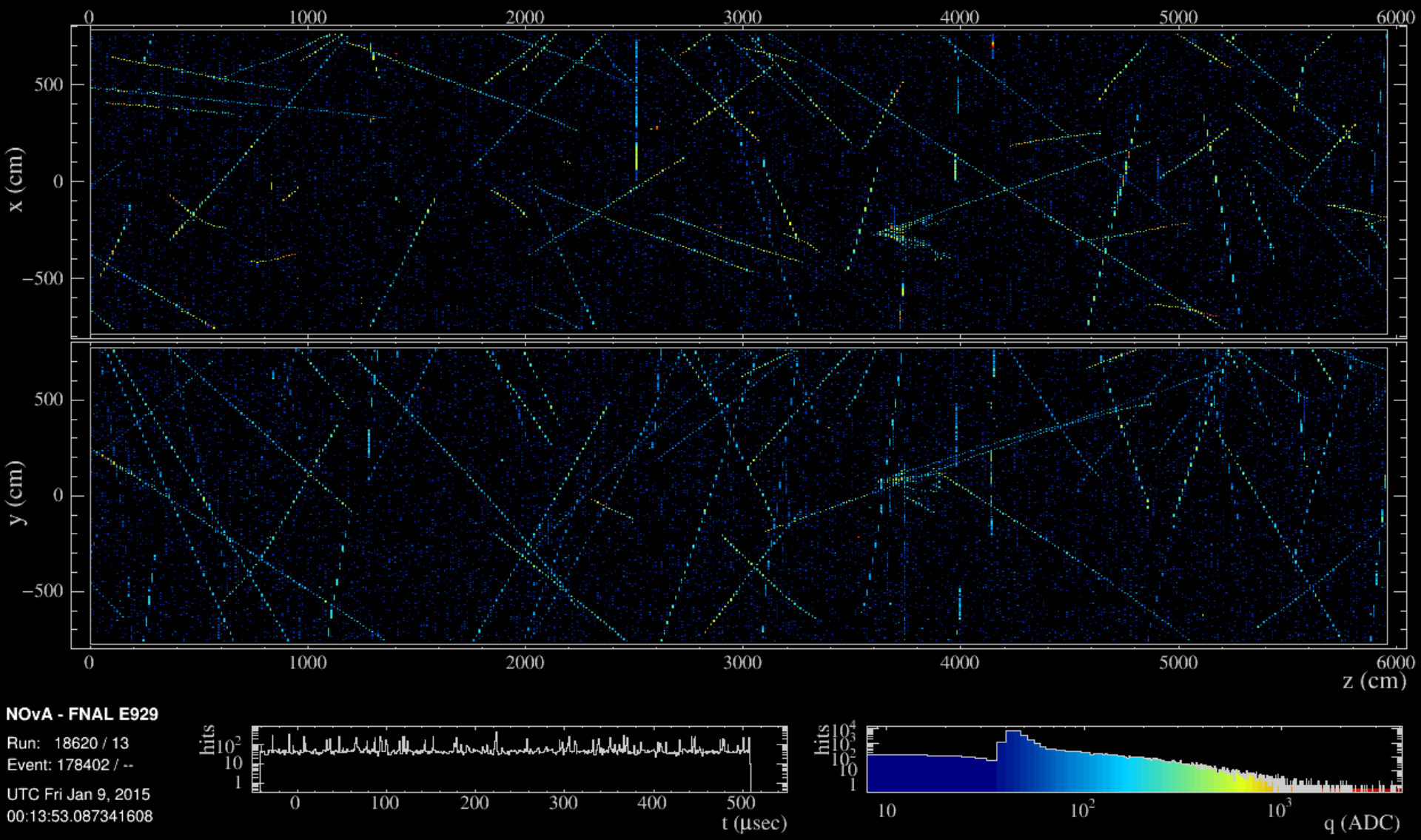
DETECTORS COMPLETE





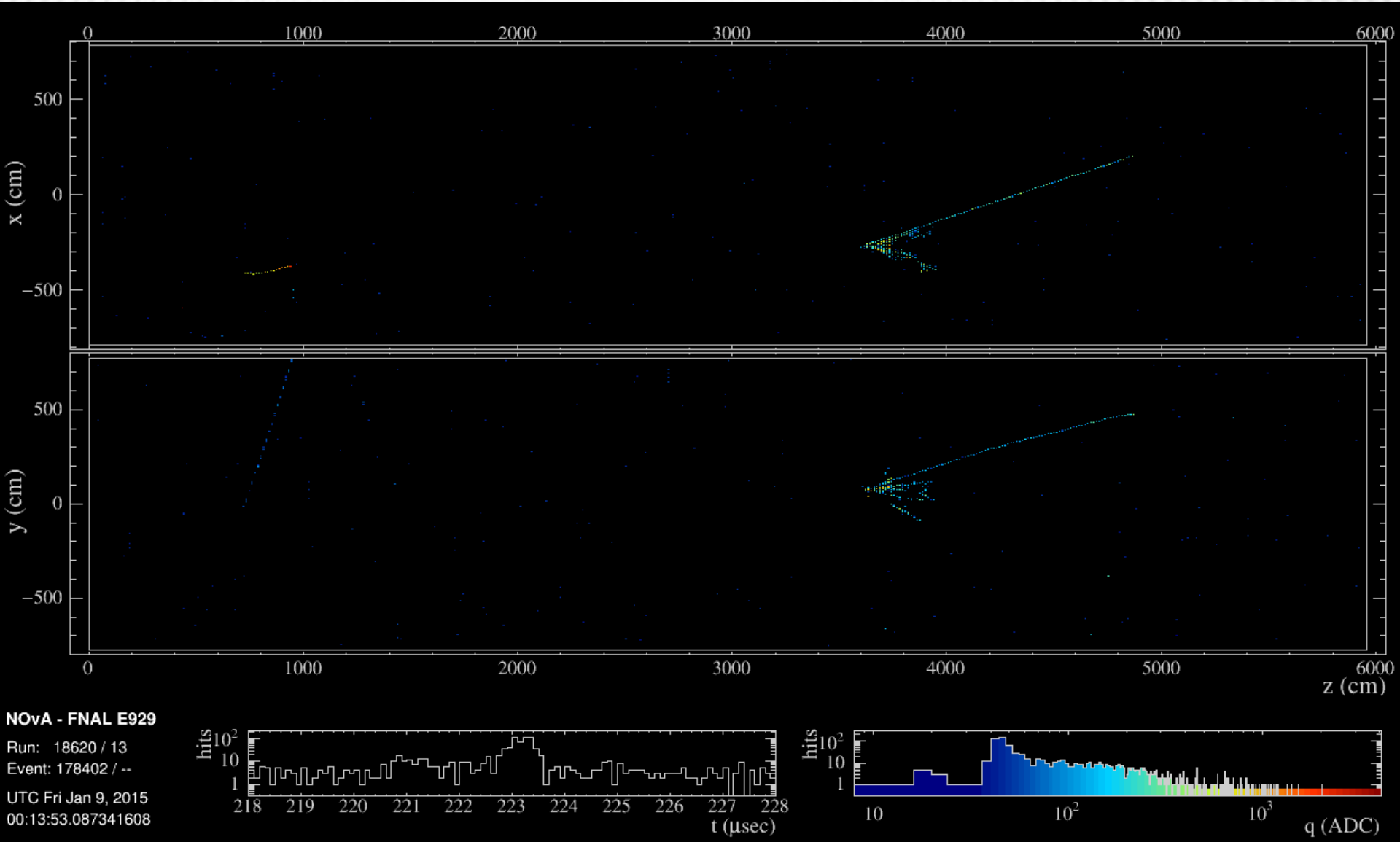
FAR DETECTOR

FD DATA



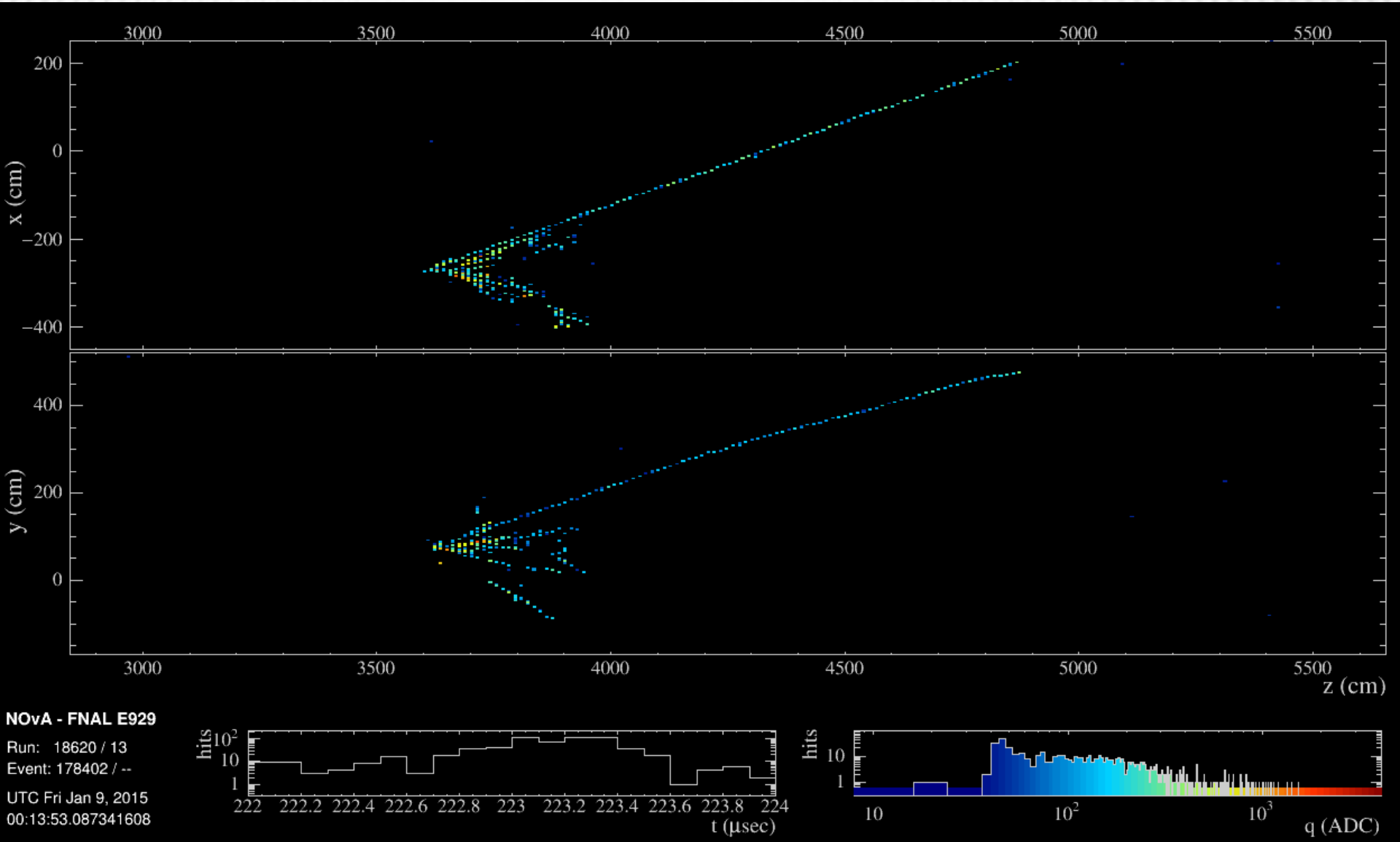
550 μs trigger window

FD DATA



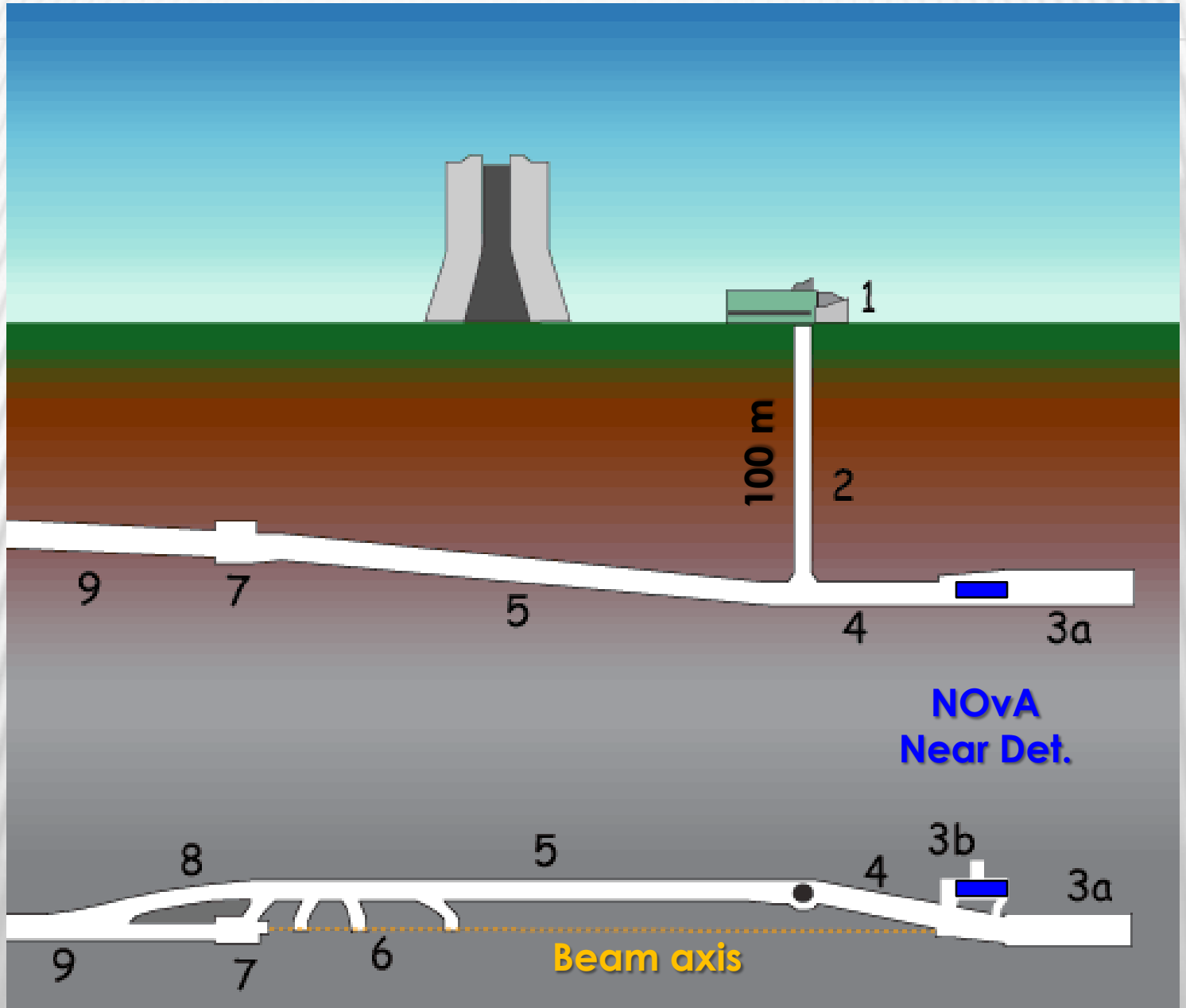
10 μs beam window

FD DATA

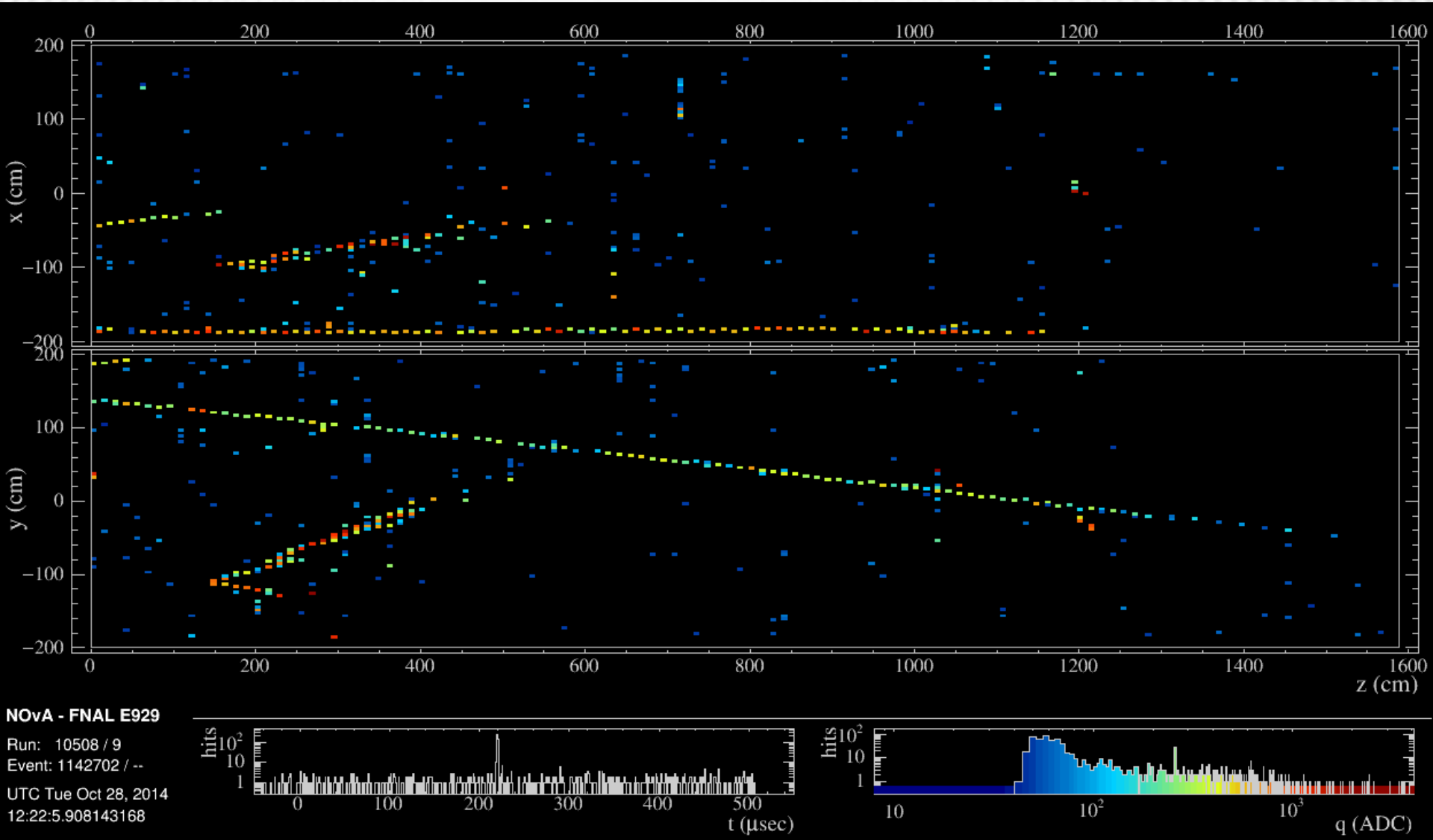


Zoom in on neutrino interaction

NEAR DETECTOR

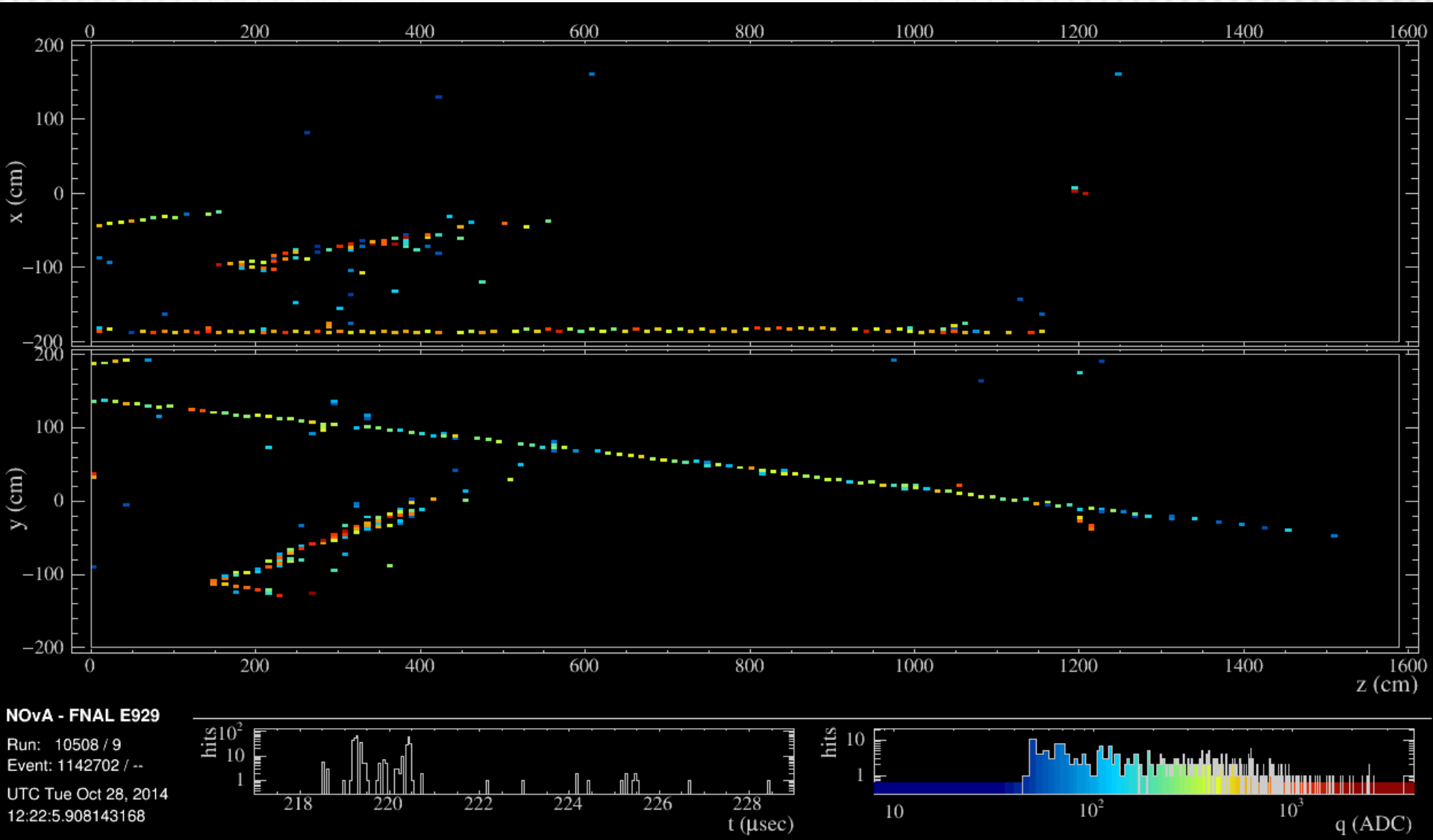


ND DATA



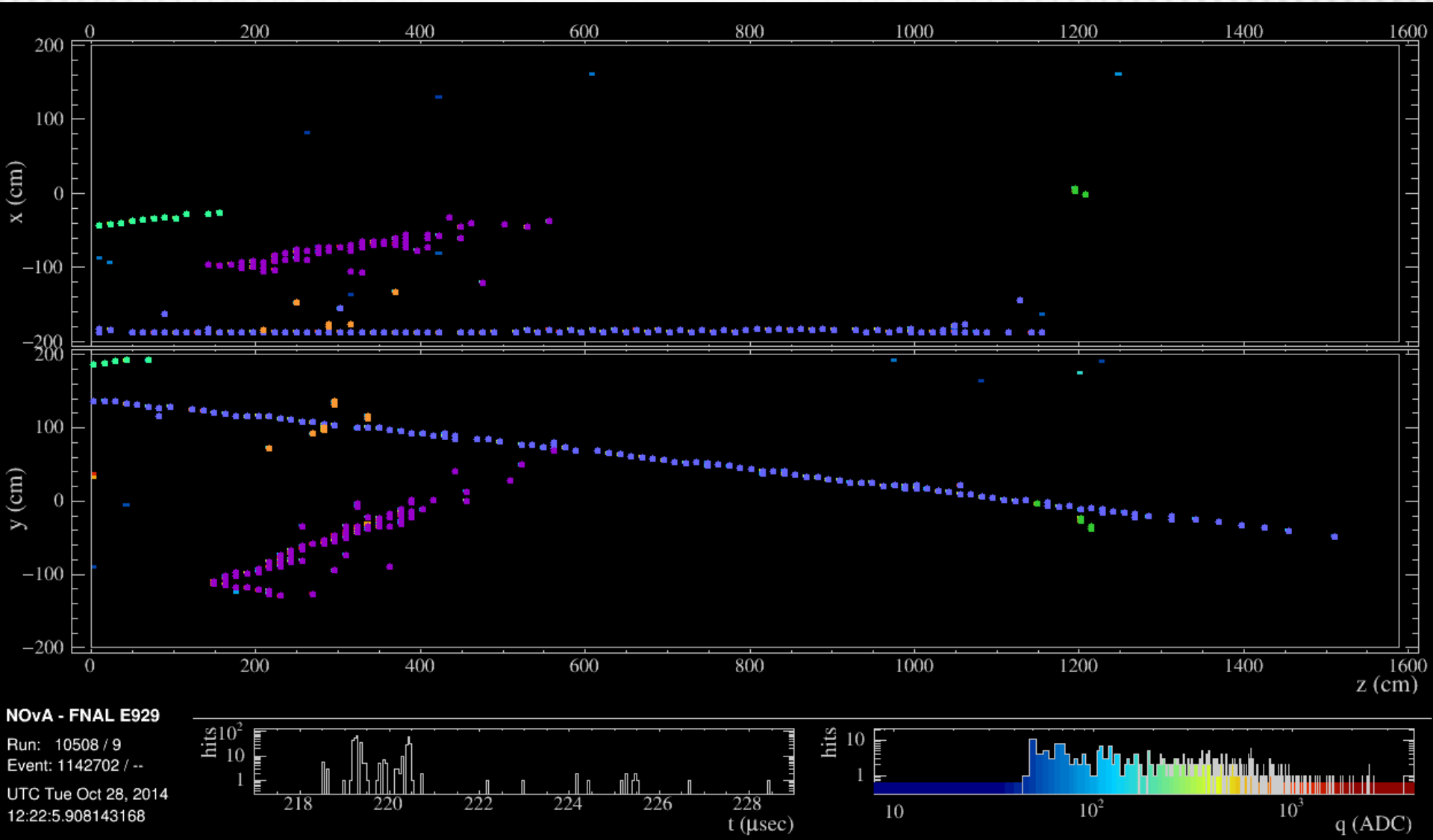
550 μs trigger window

ND DATA



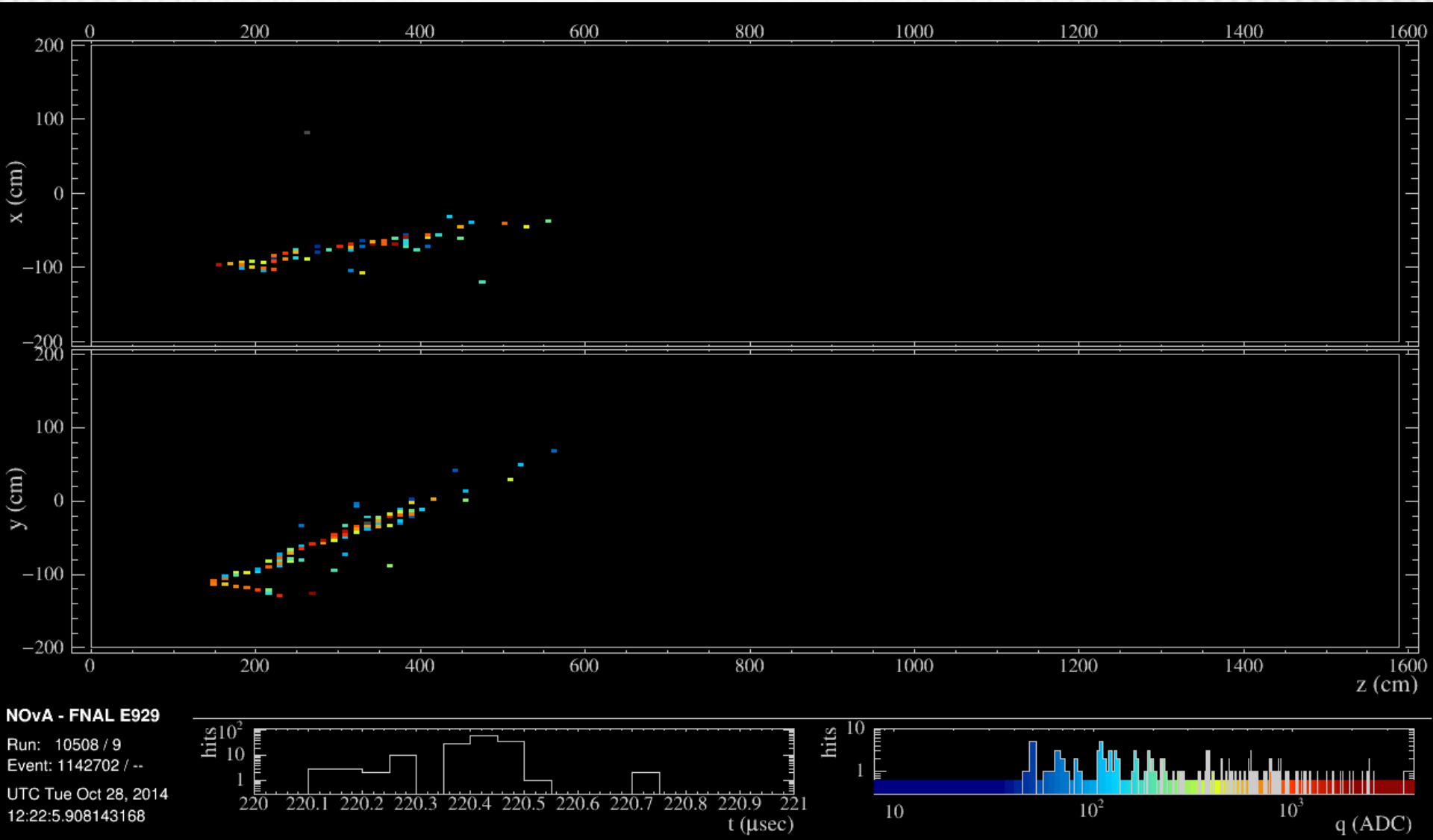
10 μs beam window

ND DATA



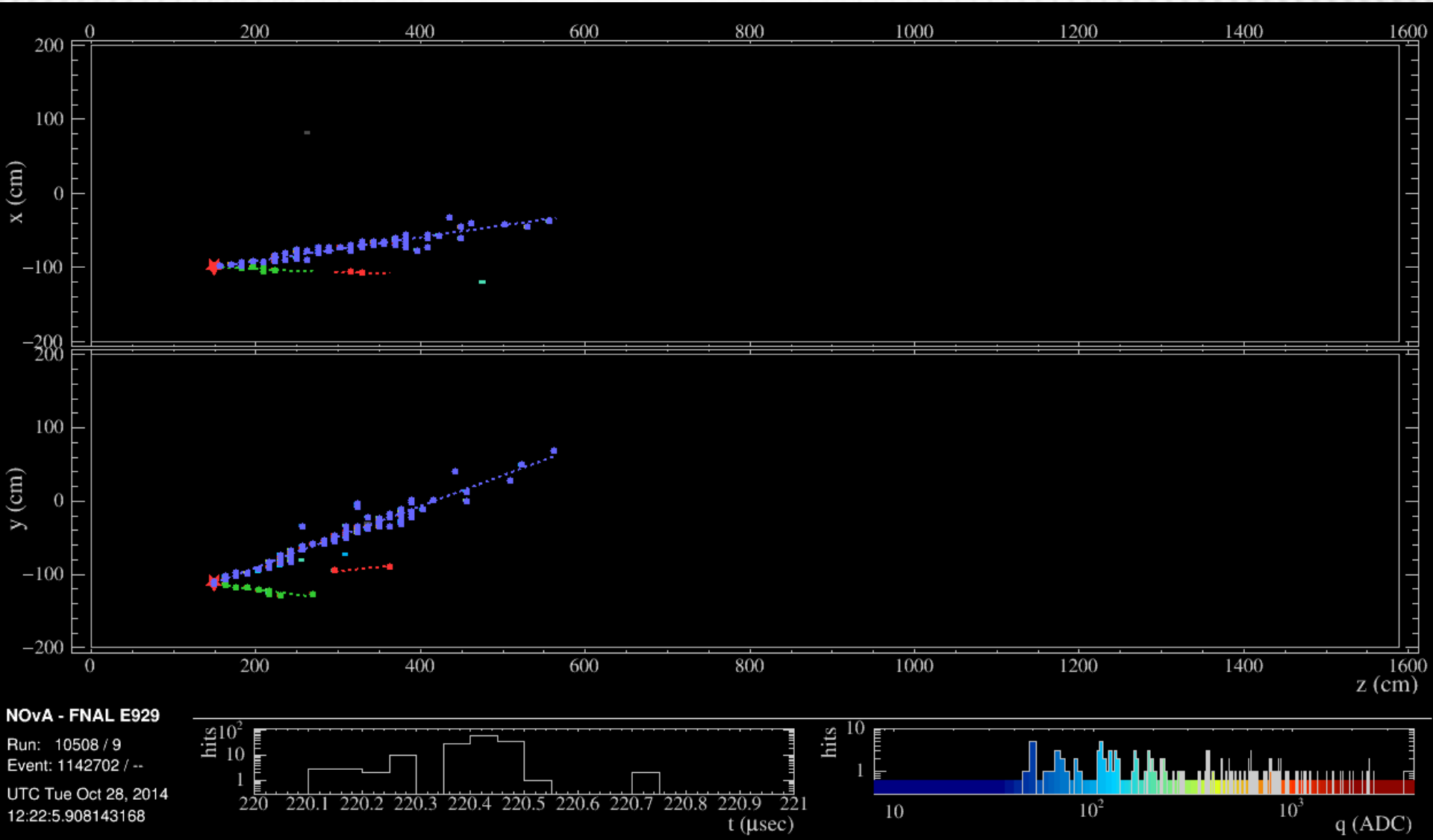
Separate into different interactions (slices)

ND DATA



Isolate contained neutrino interaction

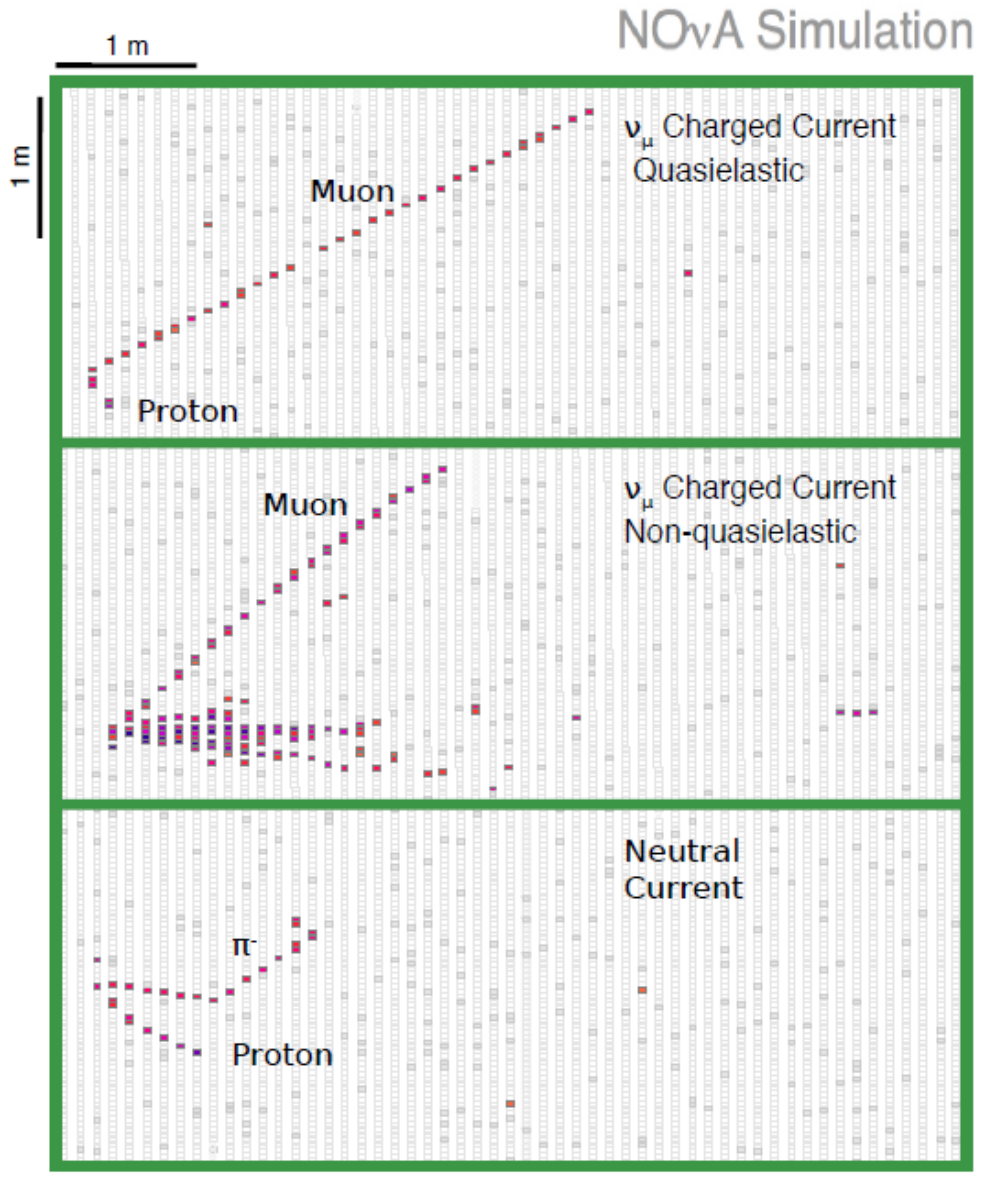
ND DATA



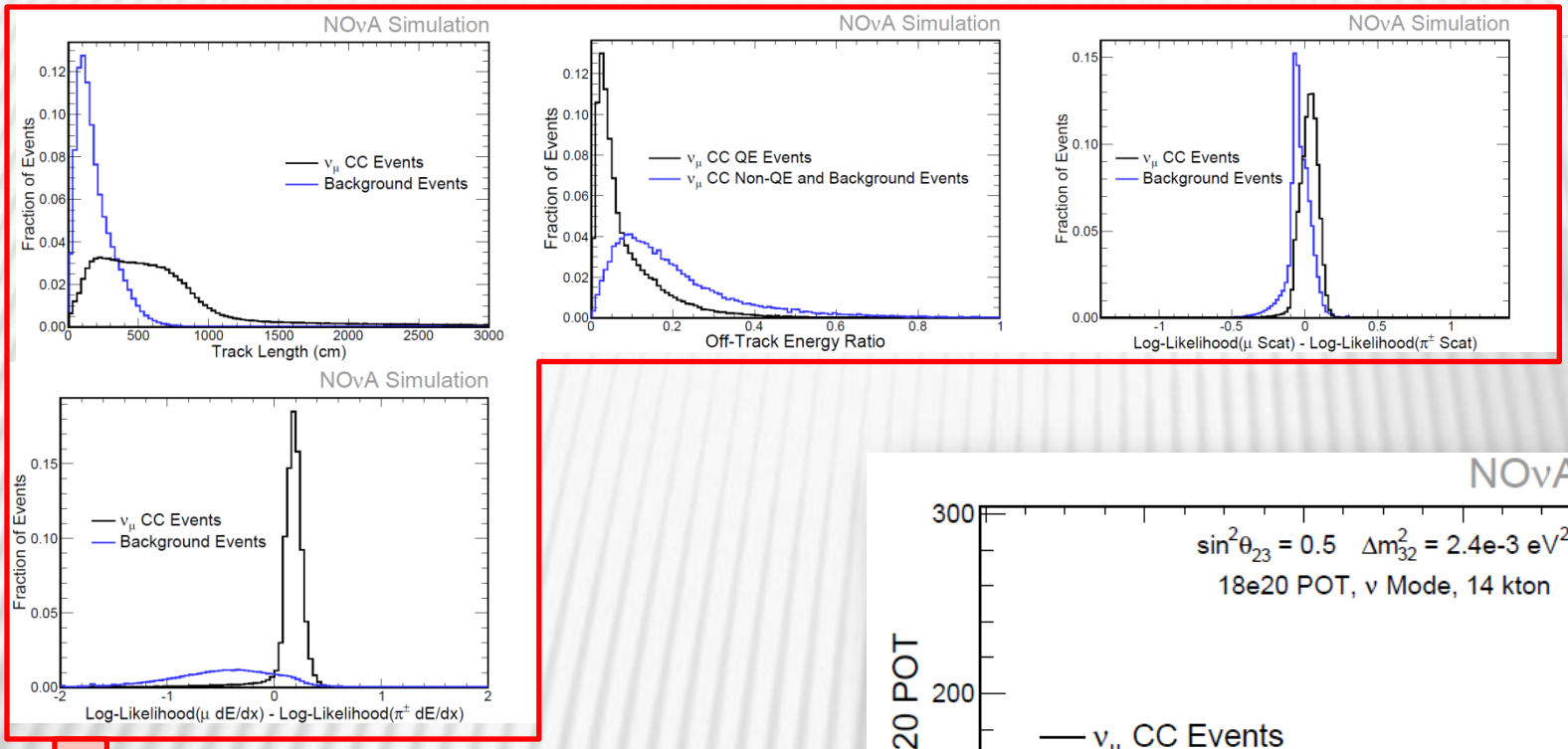
Reconstruct vertex and clusters

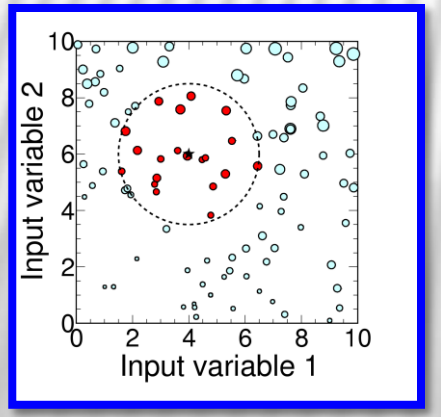
NUMU DISAPPEARANCE

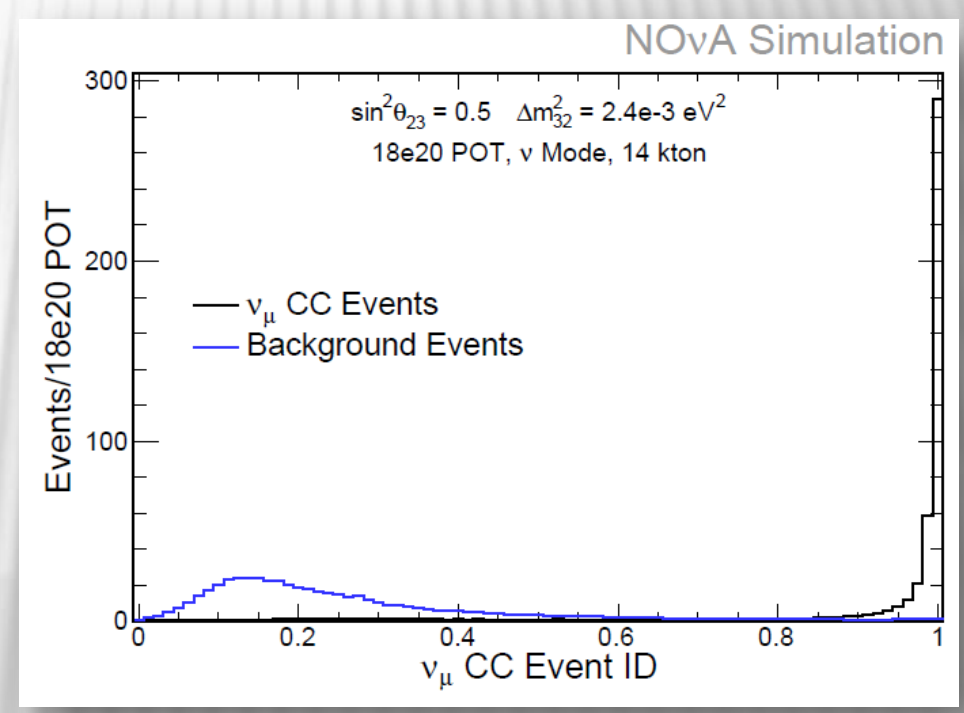
NOVA TOPOLOGIES



NC REJECTION



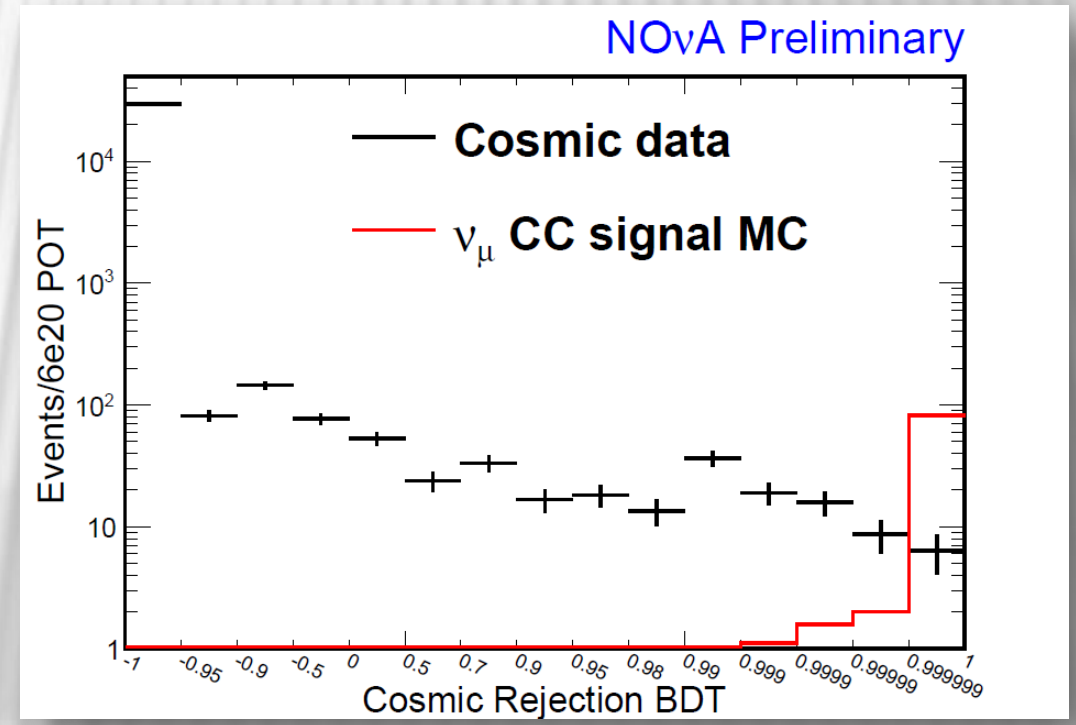




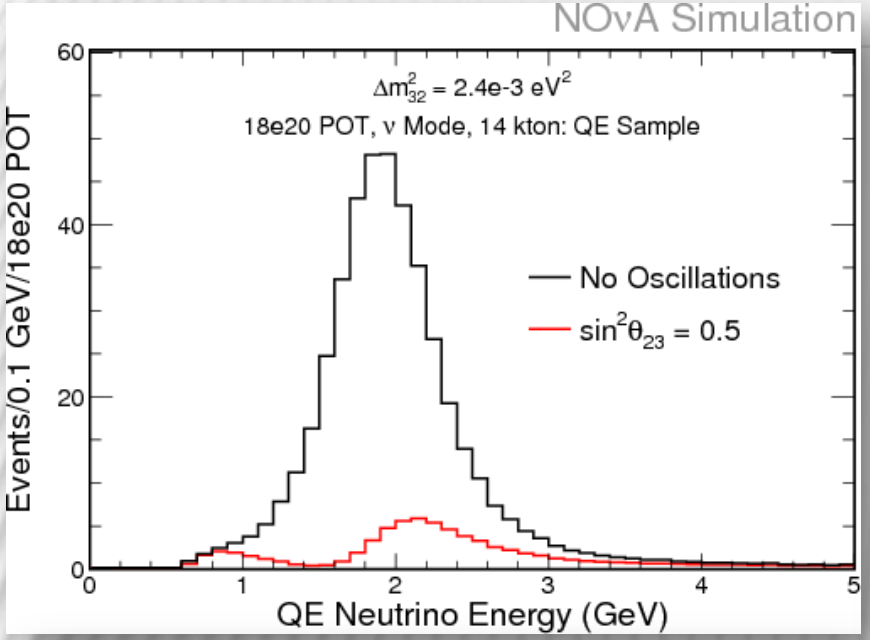
COSMIC REJECTION

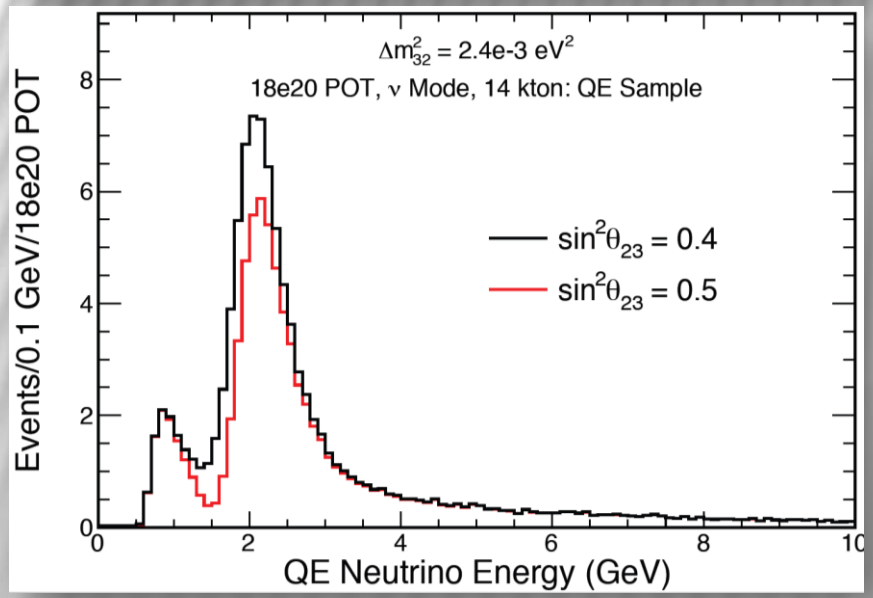
Selection	ν_μ-CC Signal	NC Background	Cosmics
No Cuts	127	380	19.1 M
Containment	109	195	120 k
NC Rejection	86	5	44 k
Cosmics Rejection	75	4	1

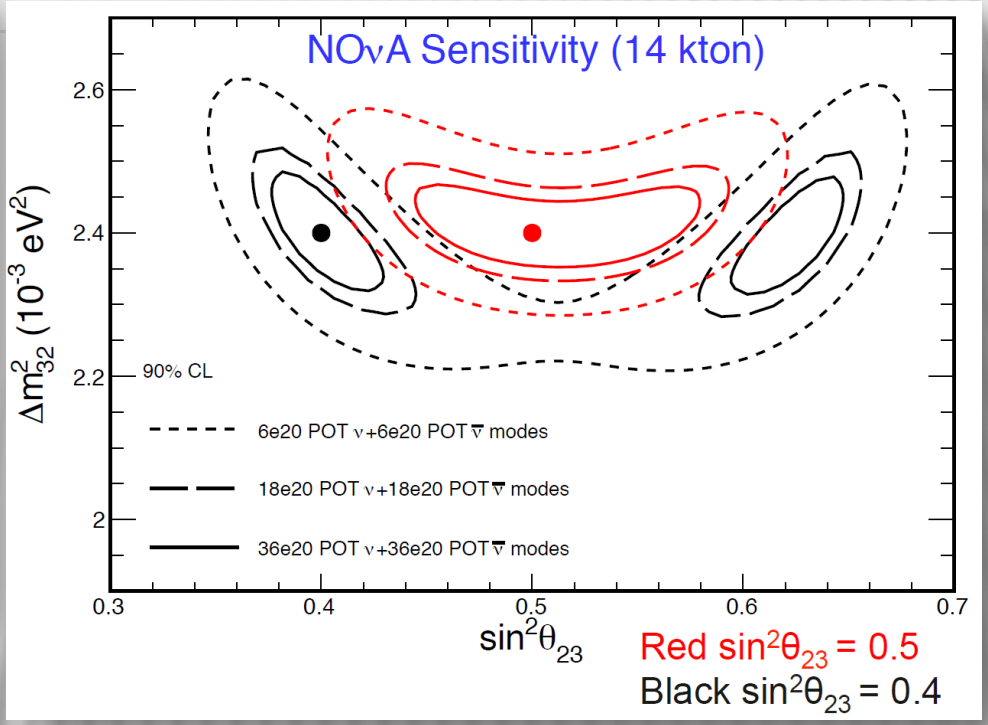
- Track information used in BDT
- Achieve a 19M : 1 rejection ratio
- Numbers based on 1 nominal year (6 x 10^{20} PoT x 14 kt)



NUMU DISAPPEARANCE

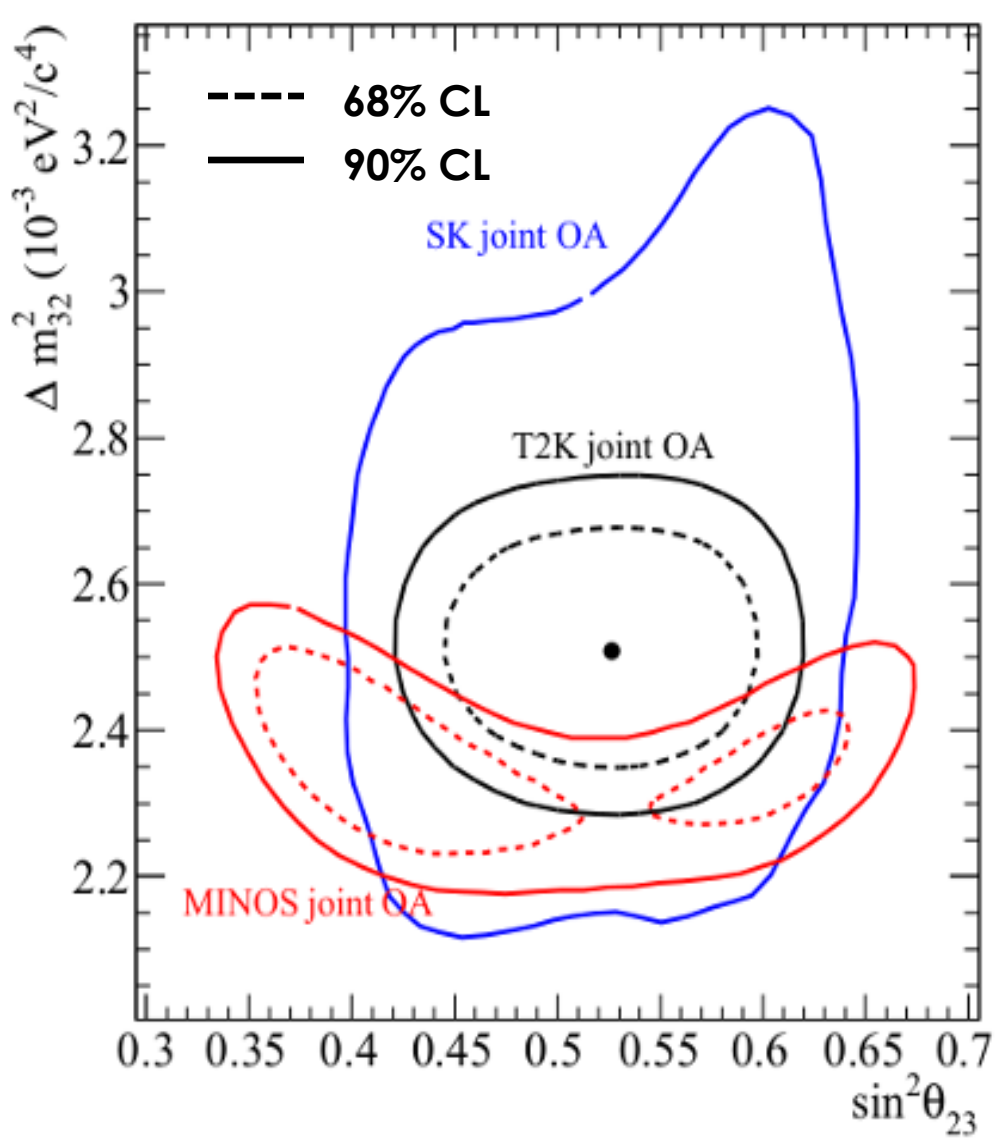




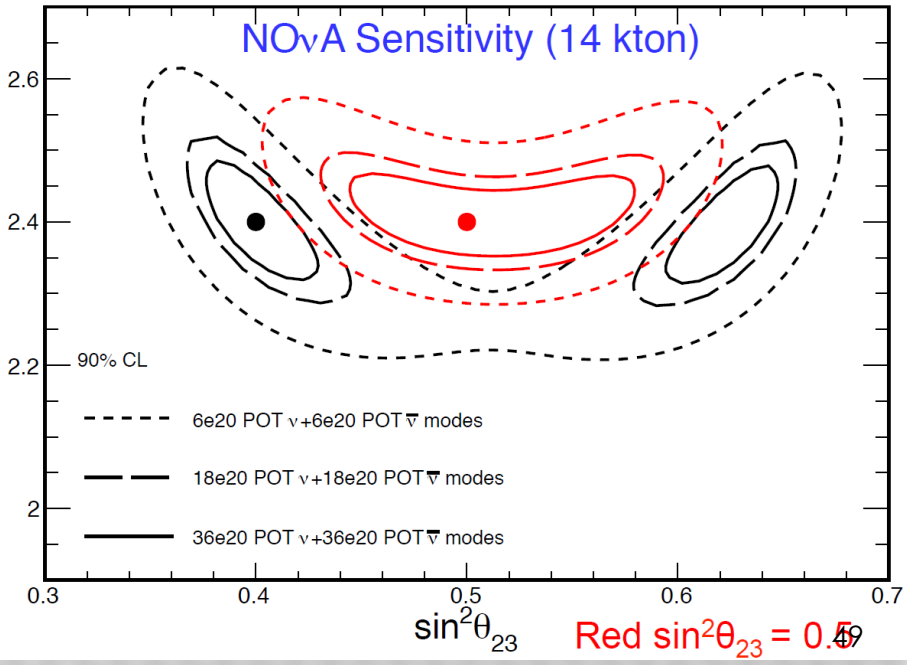


- Clear oscillation signal
- Excellent resolution of oscillation dip
- ~1% precision on $\sin^2(2\theta_{23})$

NUMU DISAPPEARANCE

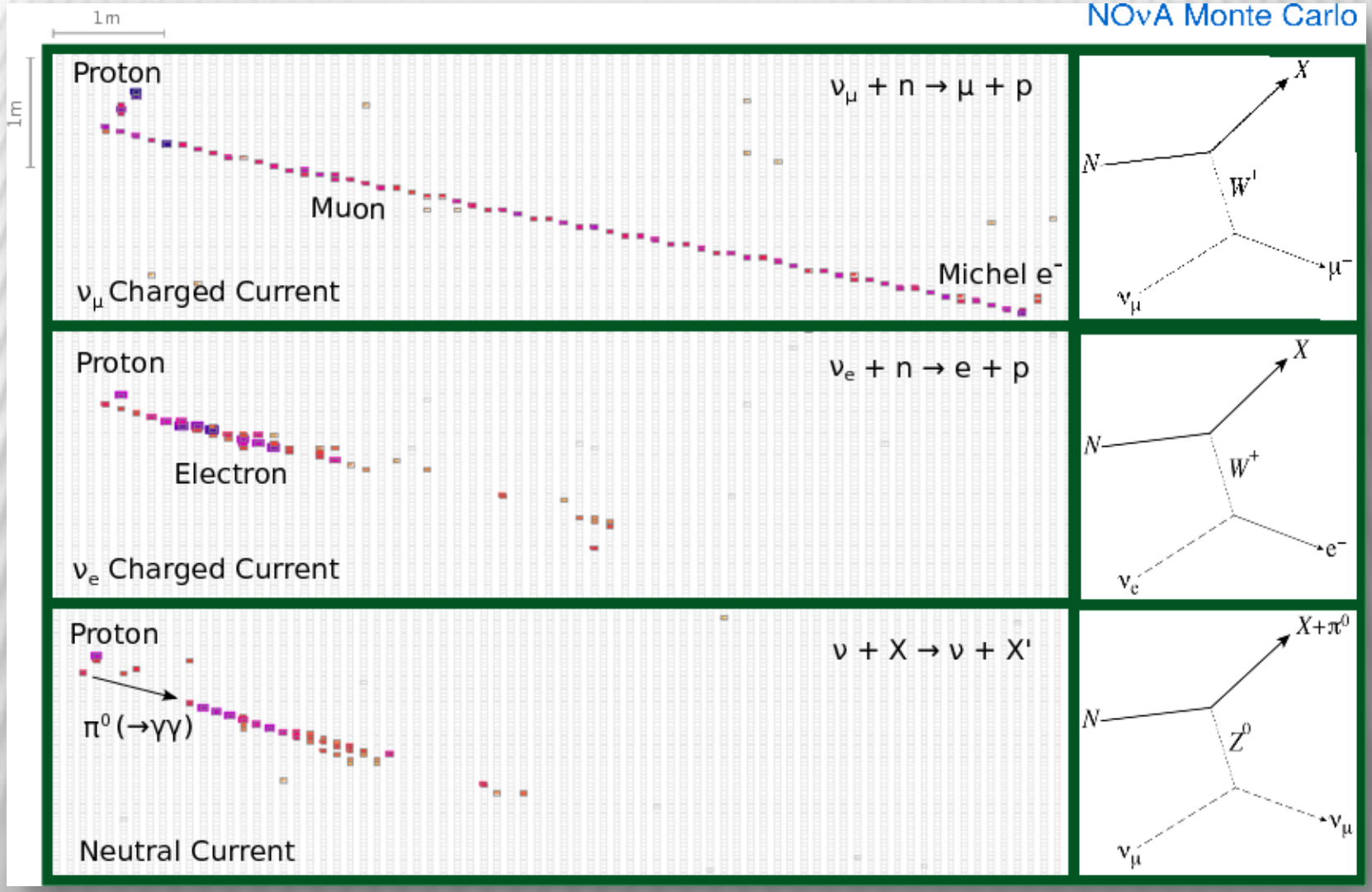


- Will test maximal mixing
- MINOS-T2K discrepancy
- First results may give some hints, but will not be conclusive



NUE APPEARANCE

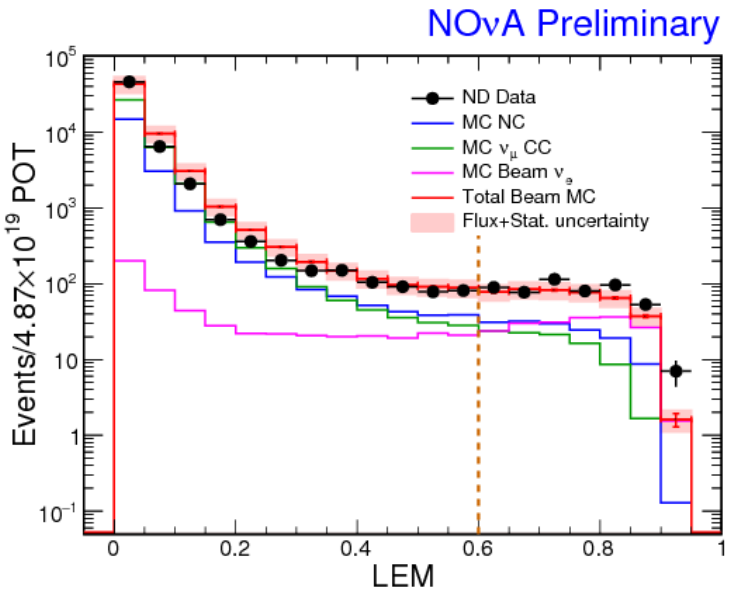
NOVA TOPOLOGIES



FINDING NUE'S

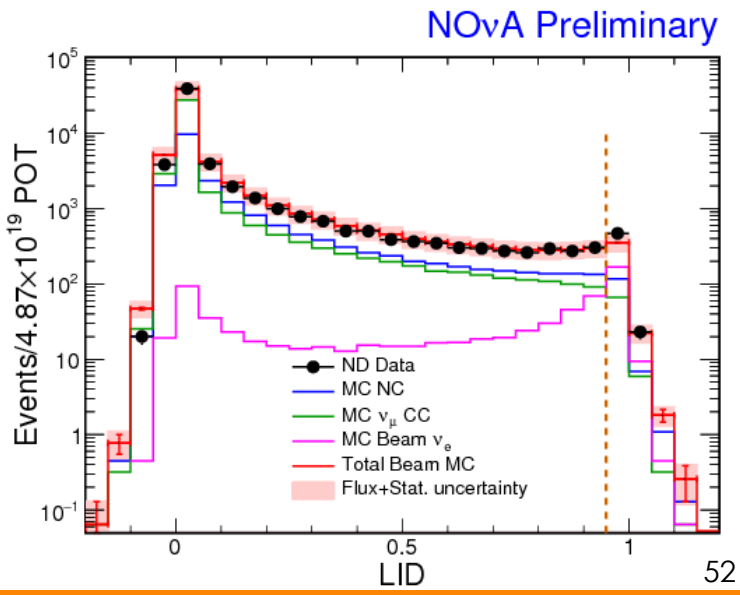
Library Event Matching

- Compare hit distribution with a library of MC simulated events
- Perform multivariate analysis on properties of best matches to event



Likelihood ν_e Identifier

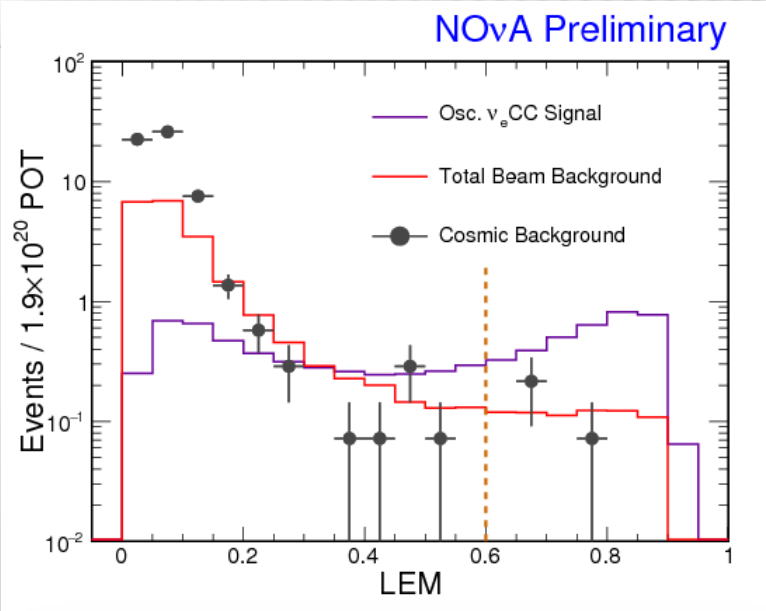
- Compare LogL of energy deposition with different particle assumptions
- Perform multivariate analysis on LogL differences and shower properties

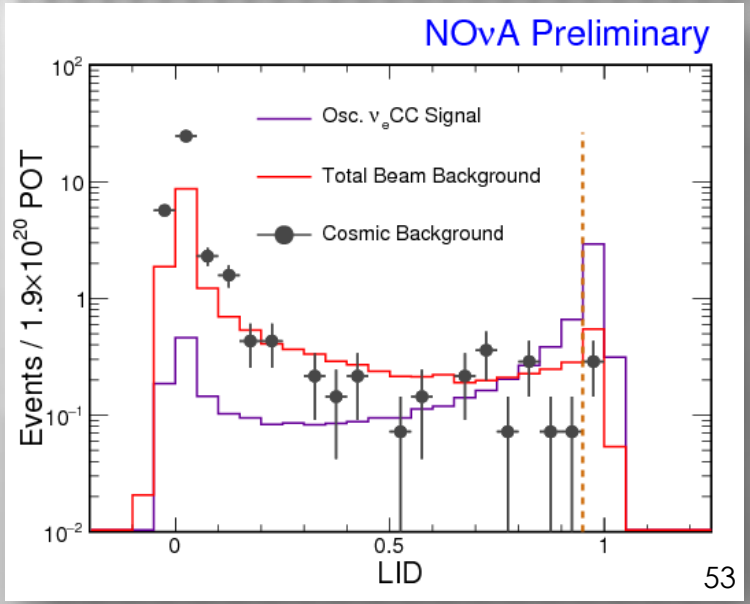


COSMIC REJECTION

Cosmic Background*	LID	LEM
No Cuts	15 M	15 M
Containment	0.6 M	1 M
Cosmics Rejection	5 k	6 k
Preselection	40	60
PID	0.3	0.3

*Based on 96 live-seconds





- Cosmic rejection essential
- Similar performance from both selection methods
- Achieve a 50M : 1 rejection ratio

HOW MANY?

- Far detector predictions are corrected using near detector data
- Predictions are scaled to a full detector exposure equivalent to approx. 1/2 nominal year, representative of expected first results
- The oscillation model assumed no matter effect and:
  - $\delta_{CP} = 0$
  - $\sin^2 2\theta_{13} = 0.095$

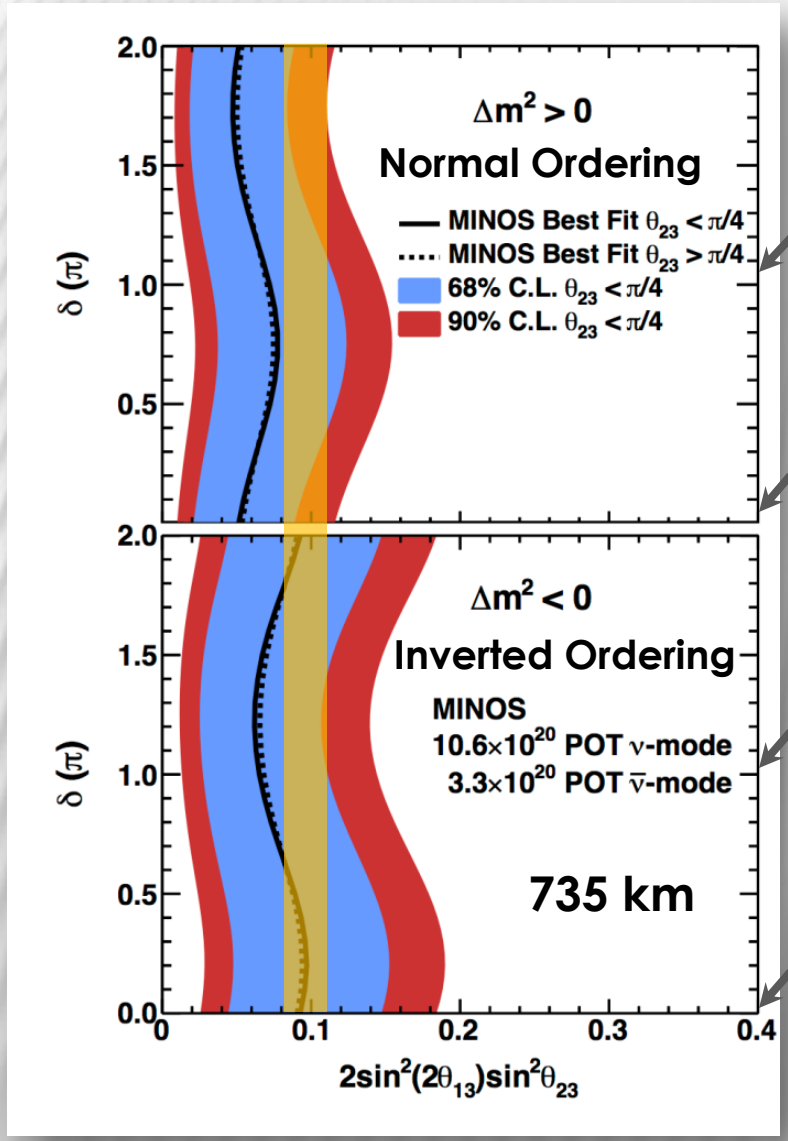
PRELIMINARY

	Osc. ν_e-CC	Total Bkg.	ν_μ-CC	NC	Beam ν_e-CC	Cosmics
LEM	**4.7**	**1.5**	**0.07**	**0.5**	**0.5**	**0.4**
LID	**4.4**	**1.3**	**0.07**	**0.4**	**0.4**	**0.4**

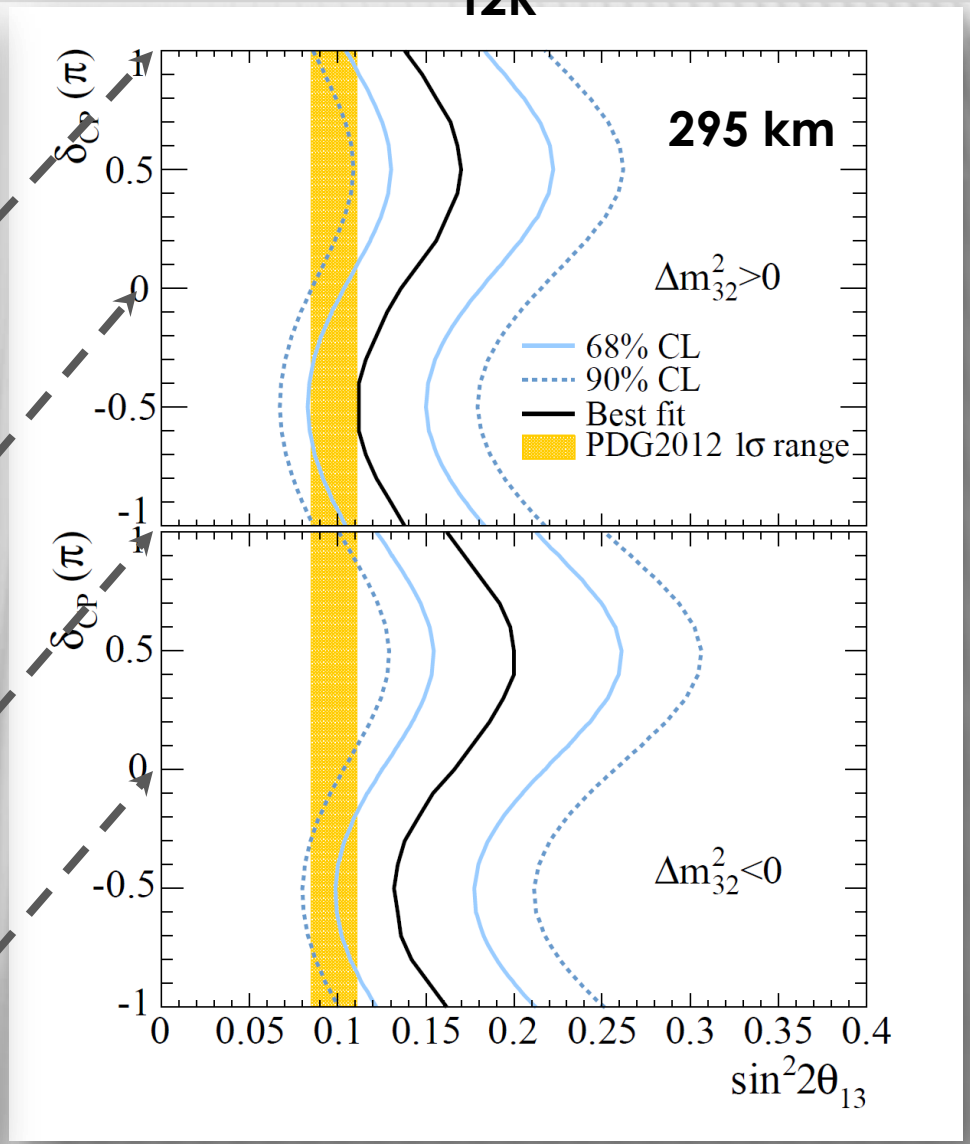
WHAT TO EXPECT

THE TENSION

$\sin^2(2\theta_{13}) \sim 0.1$



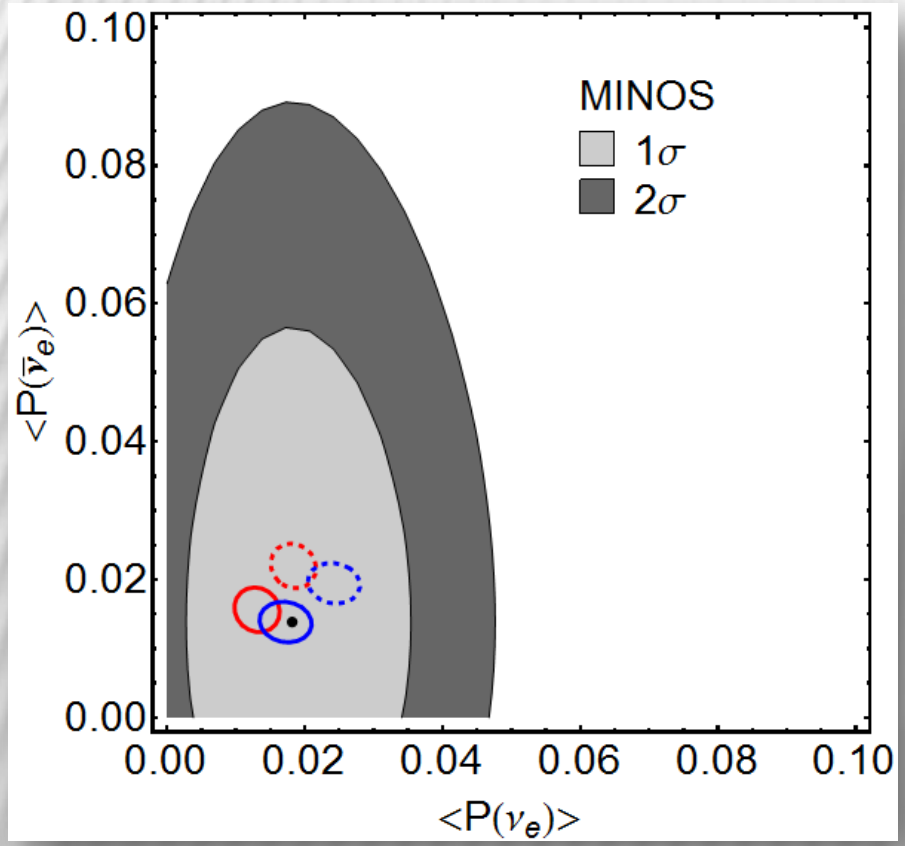
T2K

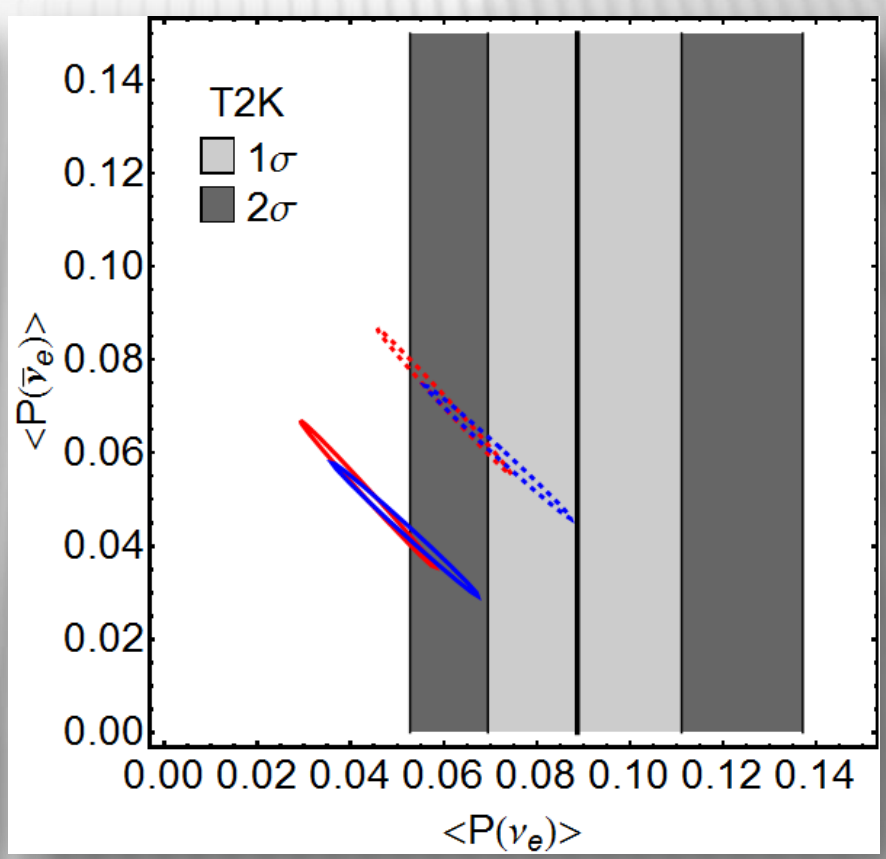


WHAT WE KNOW

Normal Ordering
Inverted Ordering

$|\Delta m^2_{32}| = 2.32\ 10^{-3}\ eV^2$
$\sin^2(2\theta_{13}) = 0.095$
$\sin^2(2\theta_{23}) = 0.97$



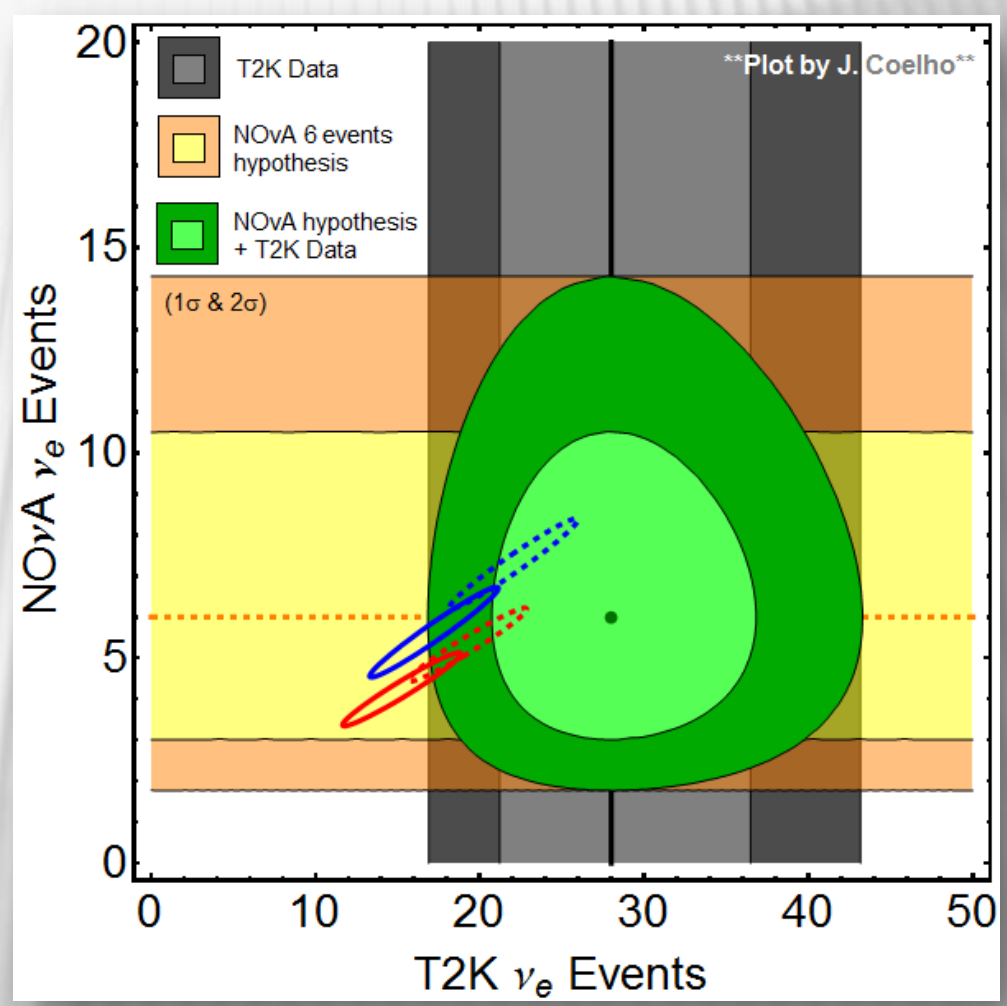


WHAT WE'LL FIND OUT

DISCLAIMER: NO OFFICIAL NOVA DATA OR SIMULATION USED IN THESE PLOTS.

- **What if NOvA sees 6 events?**
- Average expectation
- Lower than T2K
- **No clear answer** on mass ordering, but still prefer maximal CP violation due to T2K

Normal Ordering
Inverted Ordering

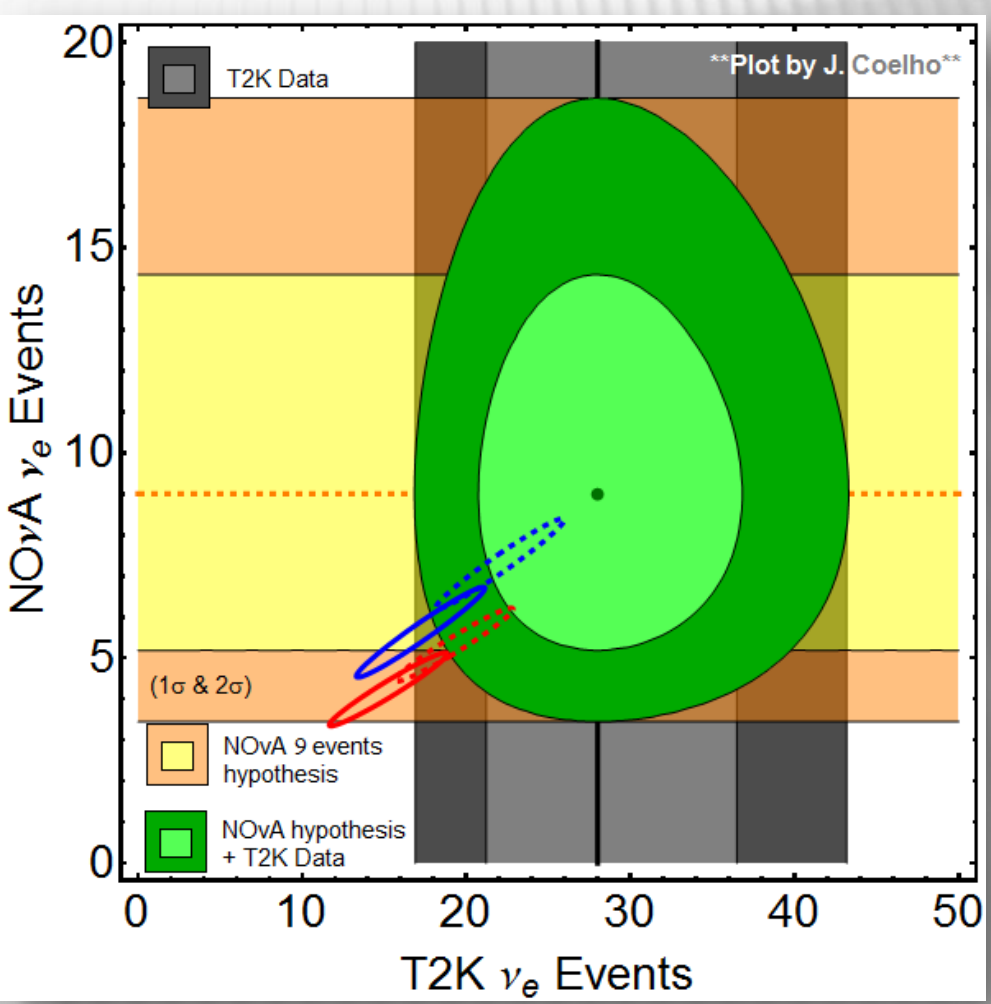


WHAT WE'LL FIND OUT

DISCLAIMER: NO OFFICIAL NOVA DATA OR SIMULATION USED IN THESE PLOTS.

- **What if NOvA sees 9 events?**
- Higher than expected
- Similar to T2K
- Some tension with standard oscillation
- **Improved sensitivity** to mass ordering, θ_{23} octant and CP violation

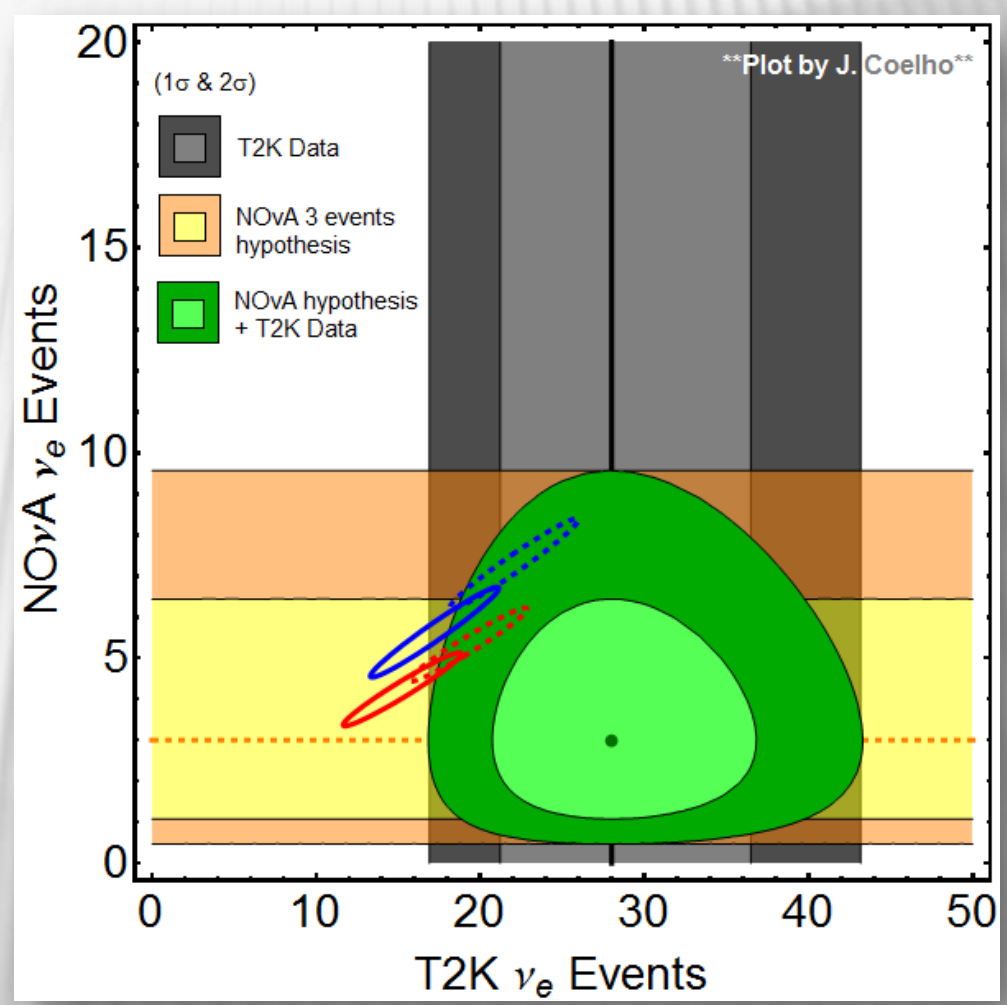
Normal Ordering
Inverted Ordering



WHAT WE'LL FIND OUT

DISCLAIMER: NO OFFICIAL NOVA DATA OR SIMULATION USED IN THESE PLOTS.

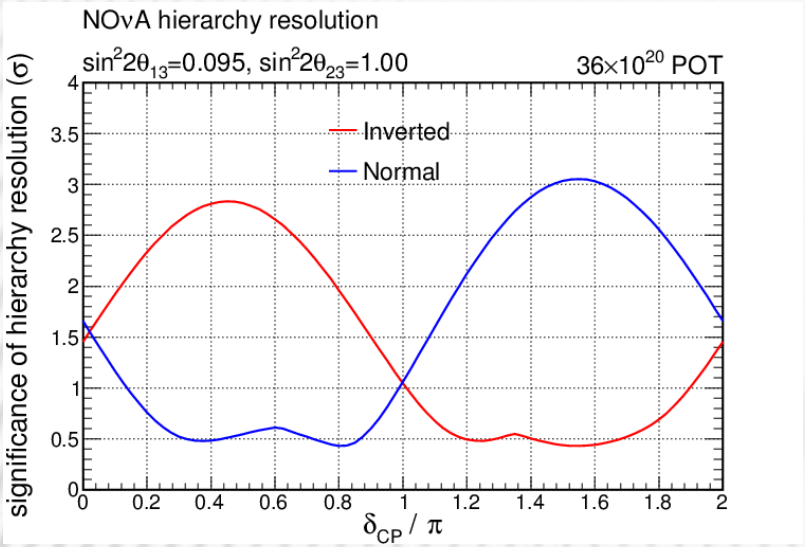
- **What if NOvA sees 3 events?**
- Lower than expected
- Opposite of T2K
- Relatively strong **tension** with standard oscillation picture

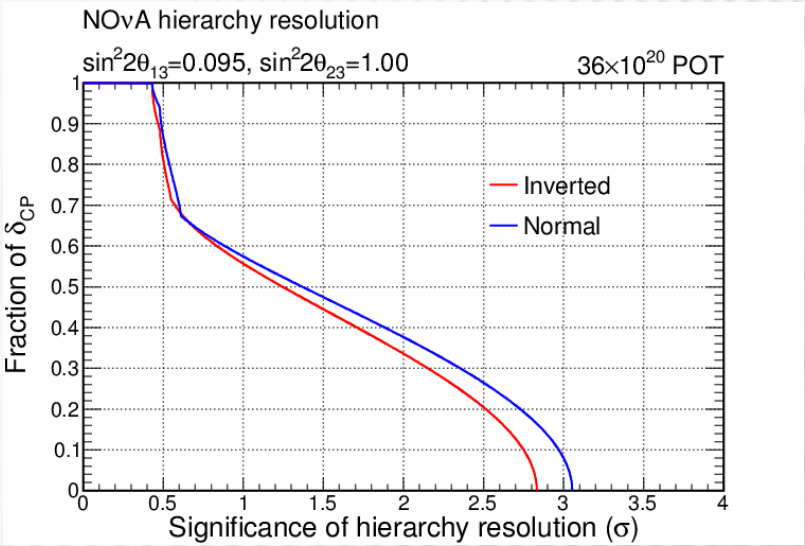


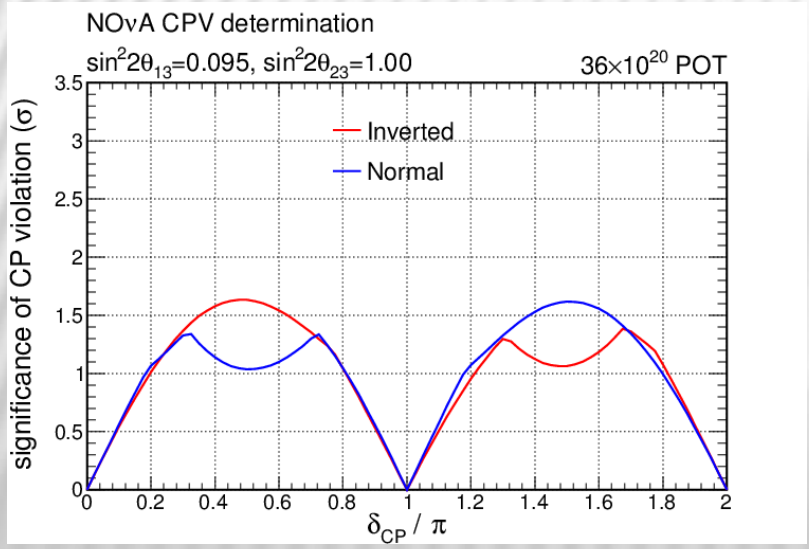
Normal Ordering
Inverted Ordering

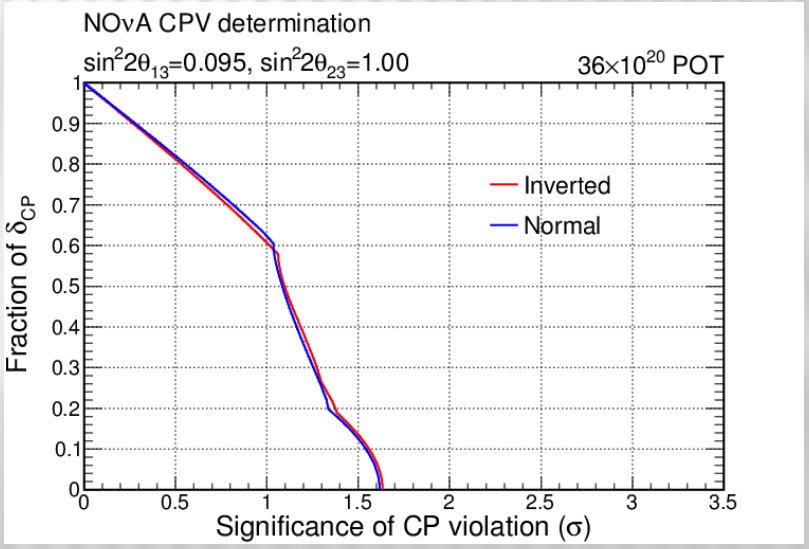
THE END GOAL

Normal Ordering
Inverted Ordering



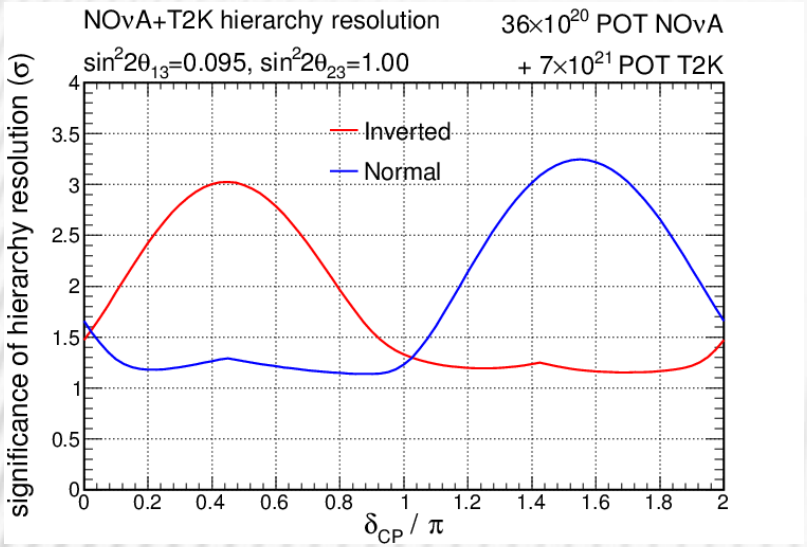


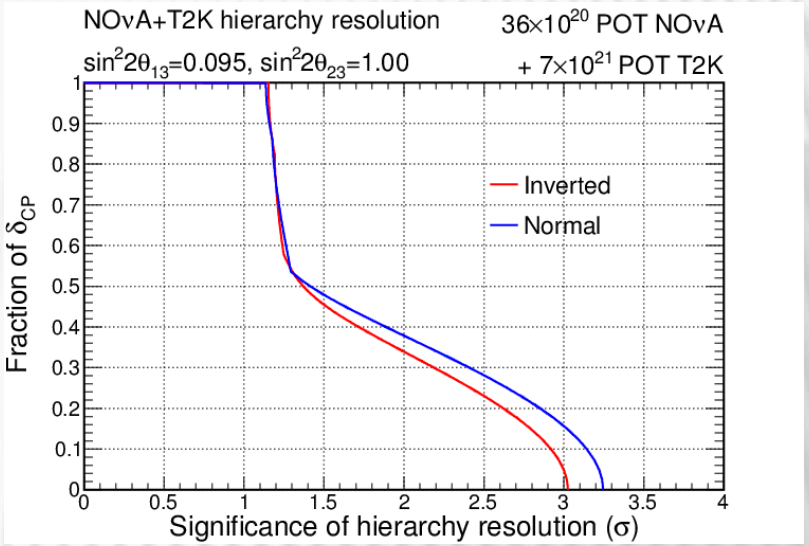


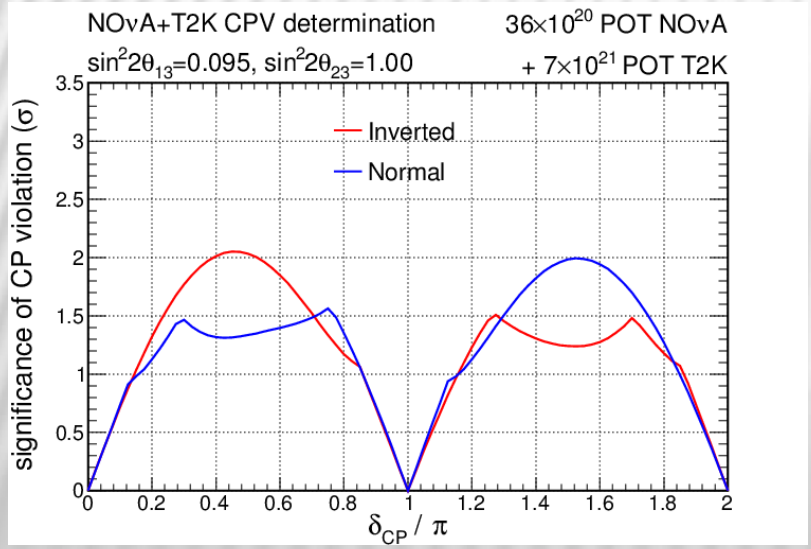


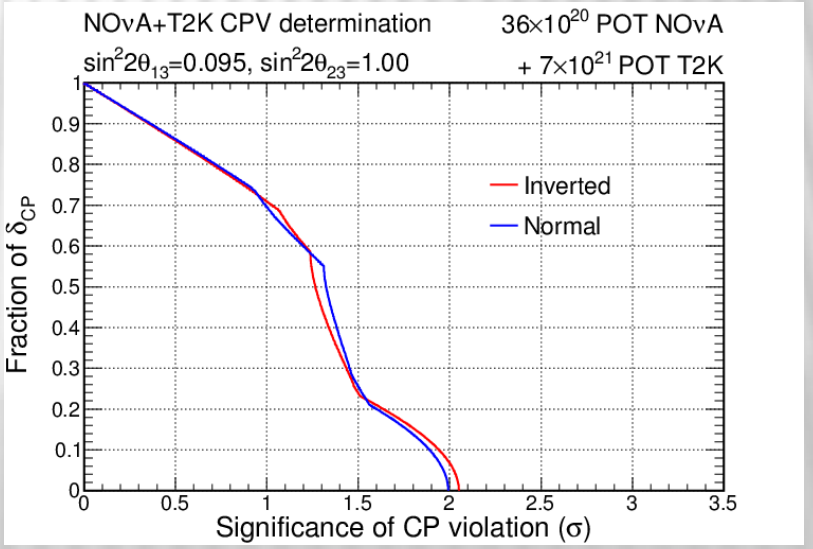
NOVA ♥ T2K

Normal Ordering
Inverted Ordering









SUMMARY

- NOvA will be releasing exciting first results in the upcoming weeks

- About half a nominal year of full detector equivalent data already collected (~3 x 10^{20} PoT)

- Predict anywhere from 3 to 9 candidate ν_e events depending on exact oscillation parameters

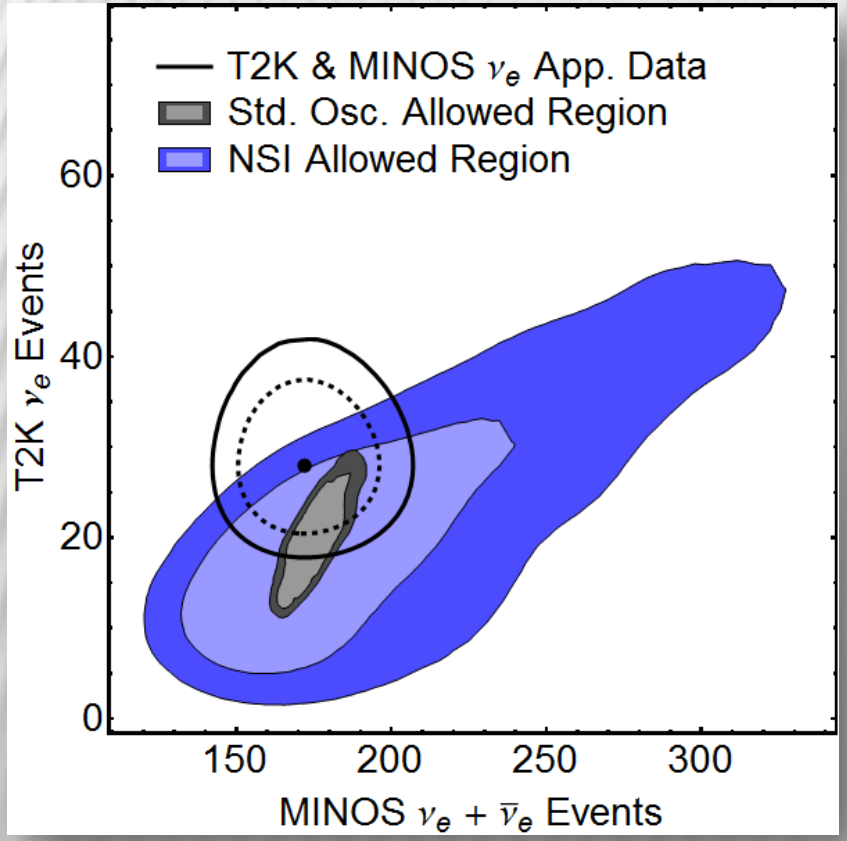
- Will NOvA prefer MINOS or T2K?

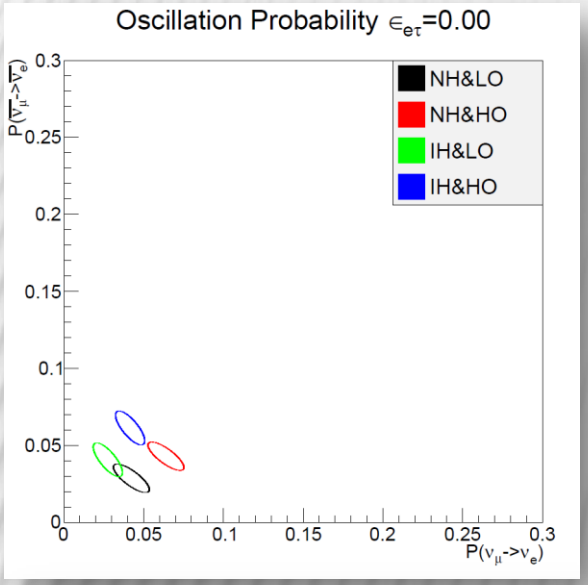
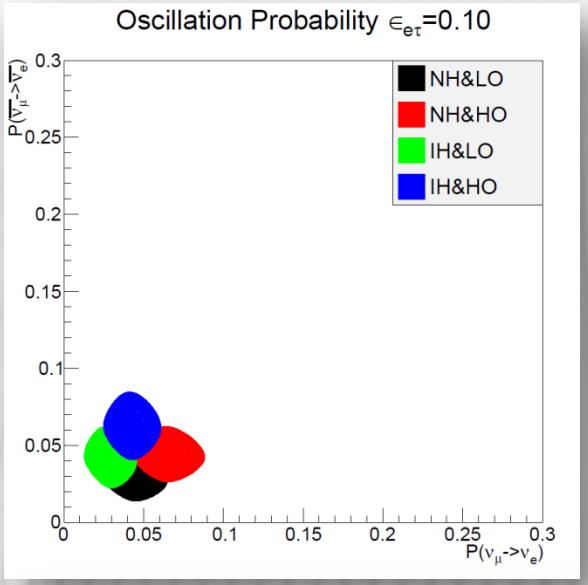
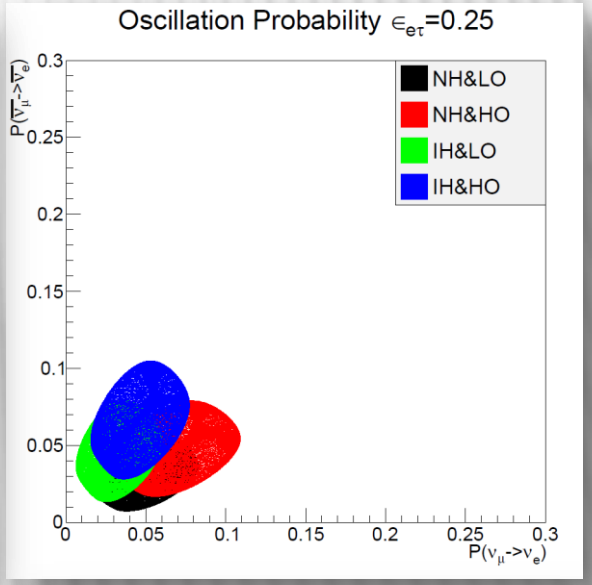
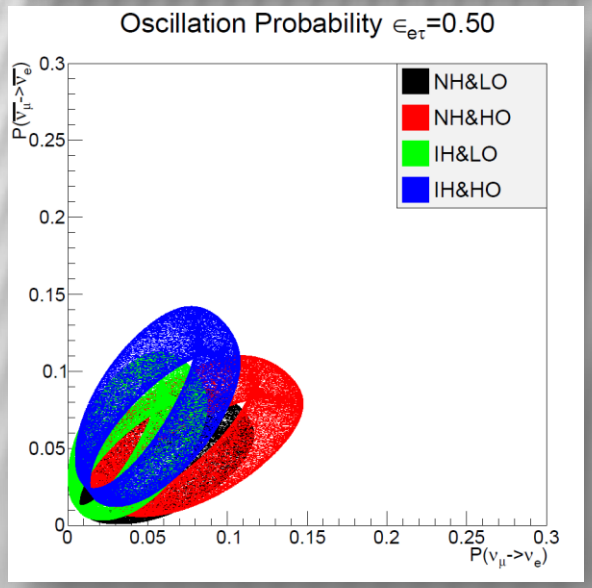
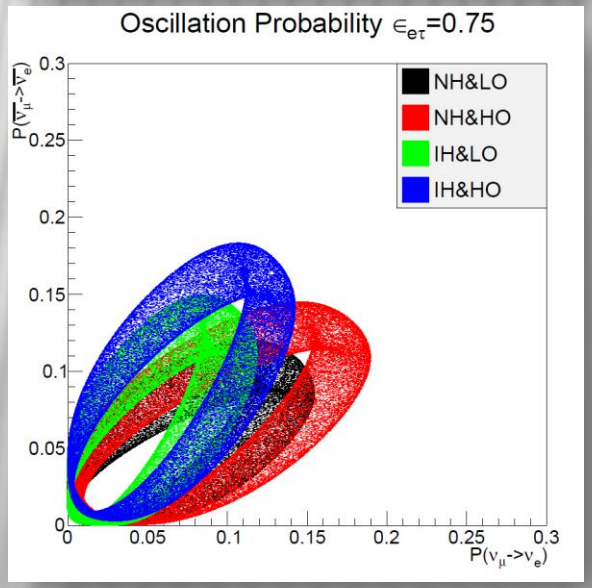
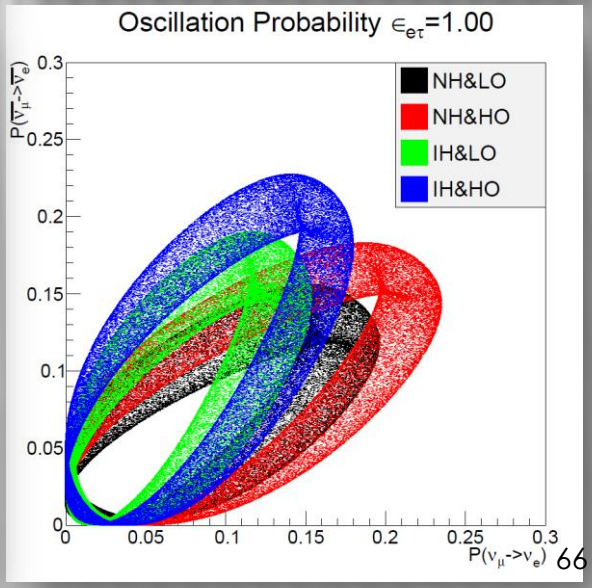
- Place your bets!

BACKUP SLIDES

NON-STANDARD INTERACTIONS

$$H = U_{PMNS} \begin{bmatrix} 0 & 0 & 0 \\ 0 & \frac{\Delta m^2_{21}}{2E} & 0 \\ 0 & 0 & \frac{\Delta m^2_{31}}{2E} \end{bmatrix} U^{\dagger}_{PMNS} + V_e \begin{bmatrix} 1+\epsilon_{ee} & \epsilon_{e\mu} & \epsilon_{e\tau} \\ \epsilon^*_{e\mu} & \epsilon_{\mu\mu} & \epsilon_{\mu\tau} \\ \epsilon^*_{e\tau} & \epsilon^*_{\mu\tau} & \epsilon_{\tau\tau} \end{bmatrix}$$



- What if there are new interactions?
- Change in refractive index
  - Extra CP violation
  - Larger parameter space
- NOvA will have world leading sensitive to these NSI effects

NON-STANDARD INTERACTIONS