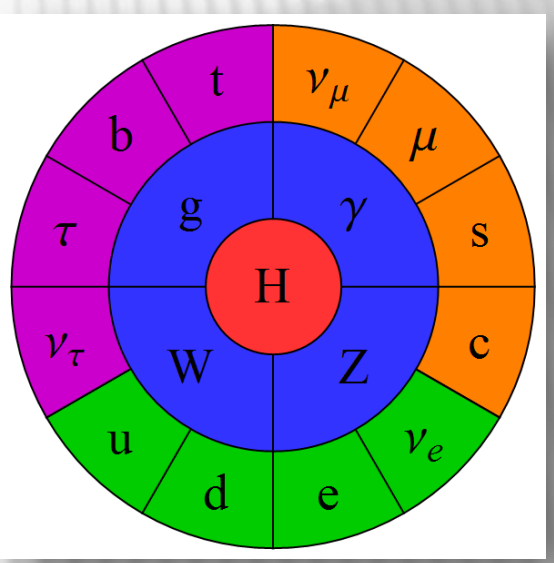
Joao Coelho

THE NOVA EXPERIMENT

BLUE SKIES?

"The beauty and clearness of the dynamical theory […] is at present obscured by two clouds." – Lord Kelvin, 1901



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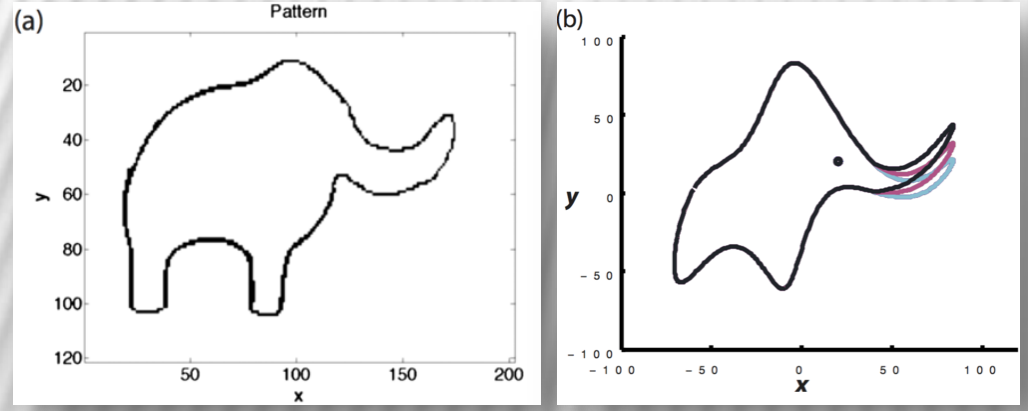
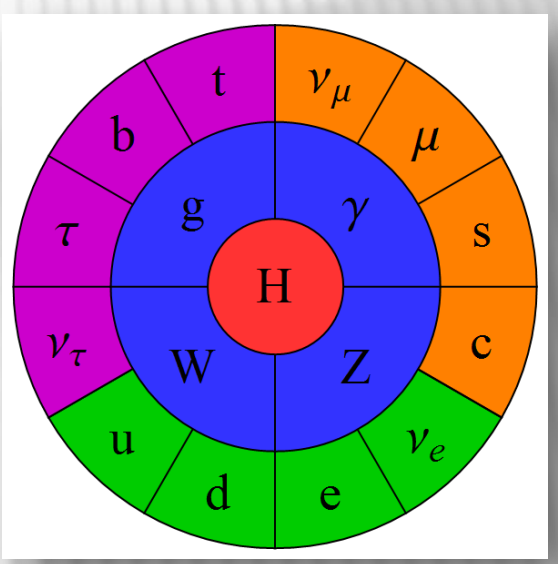
"With four parameters I can fit an elephant, and with five I can make him wiggle his trunk" – von Neumann



Am. J. Phys. 78, 648 (2010)



- 19 free parameters
- 15 related to mass
- +7 for neutrino mass and mixing

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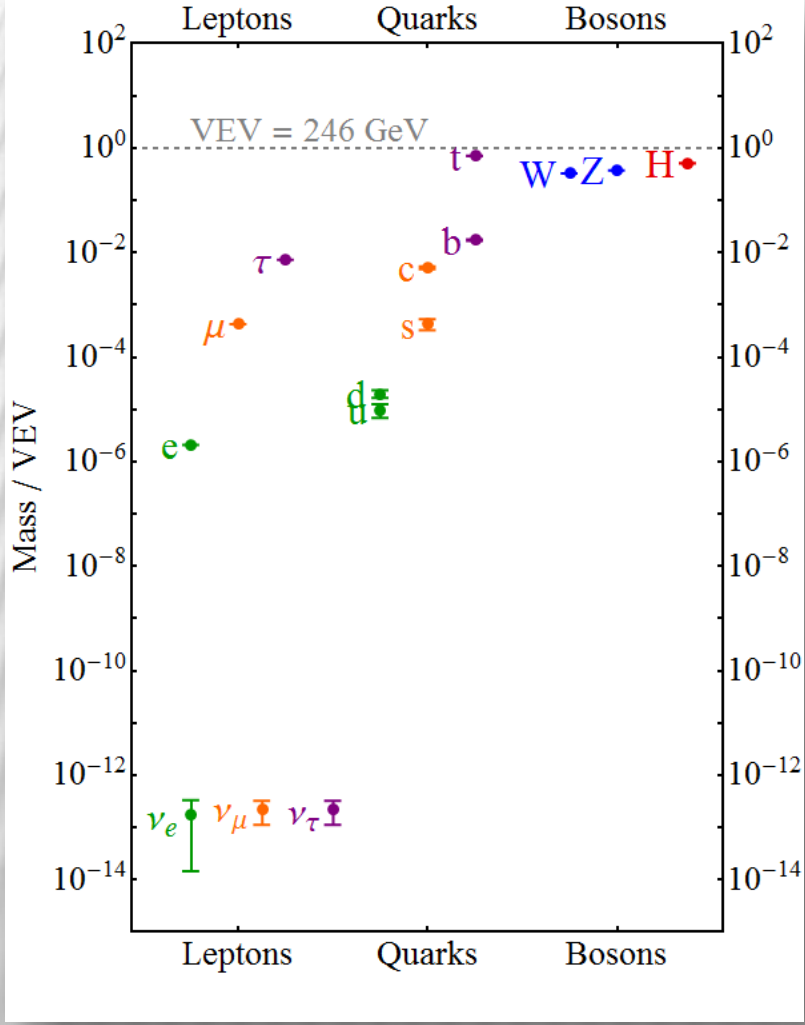

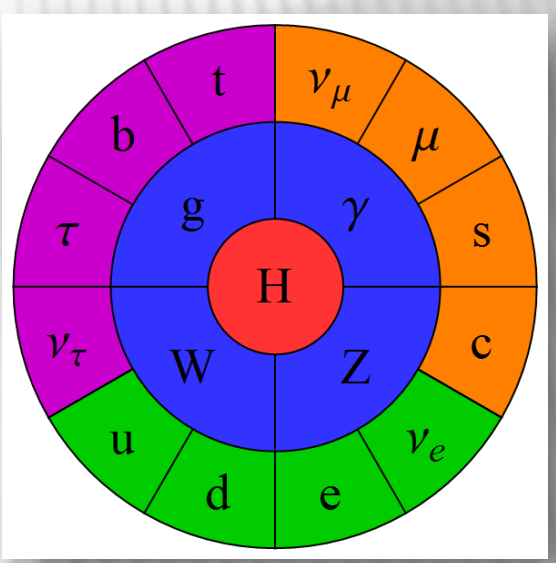

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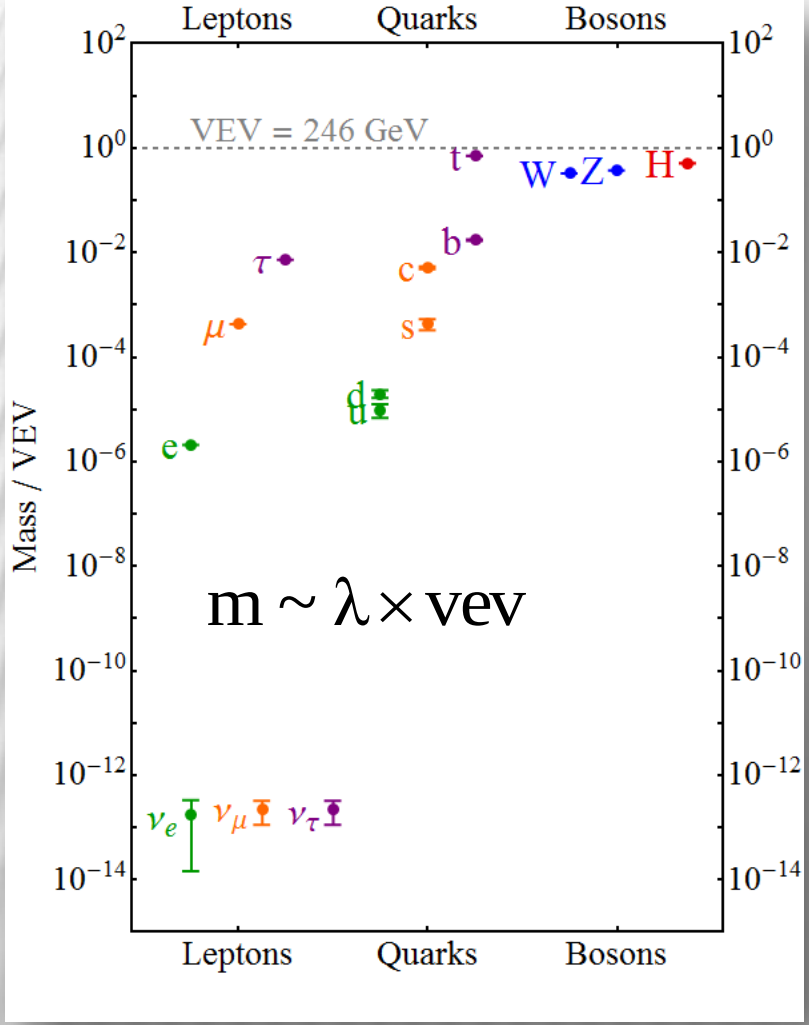

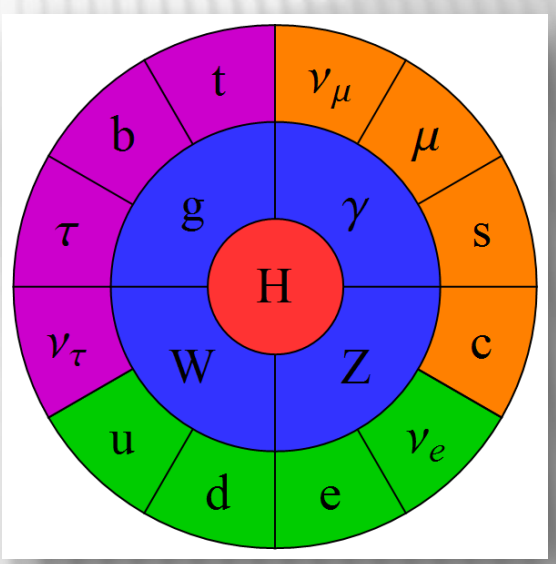

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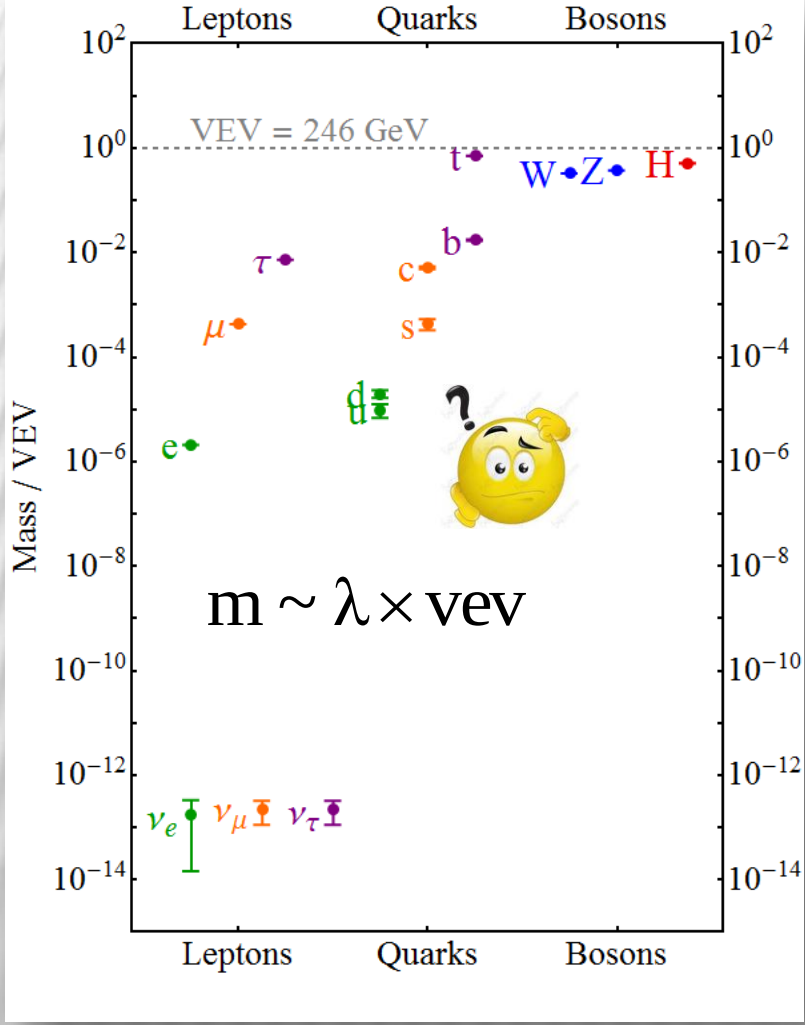

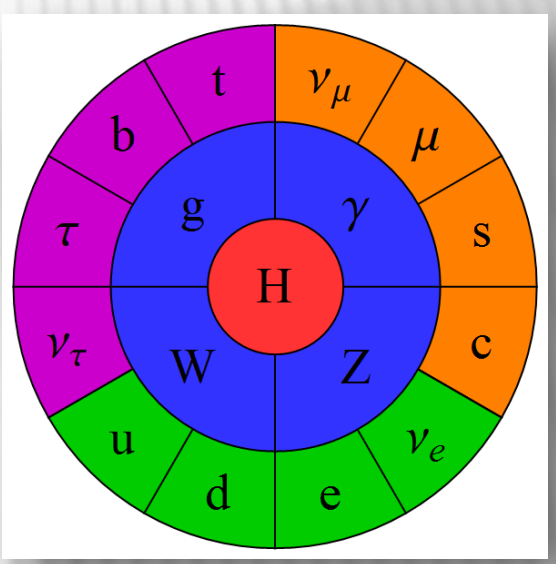

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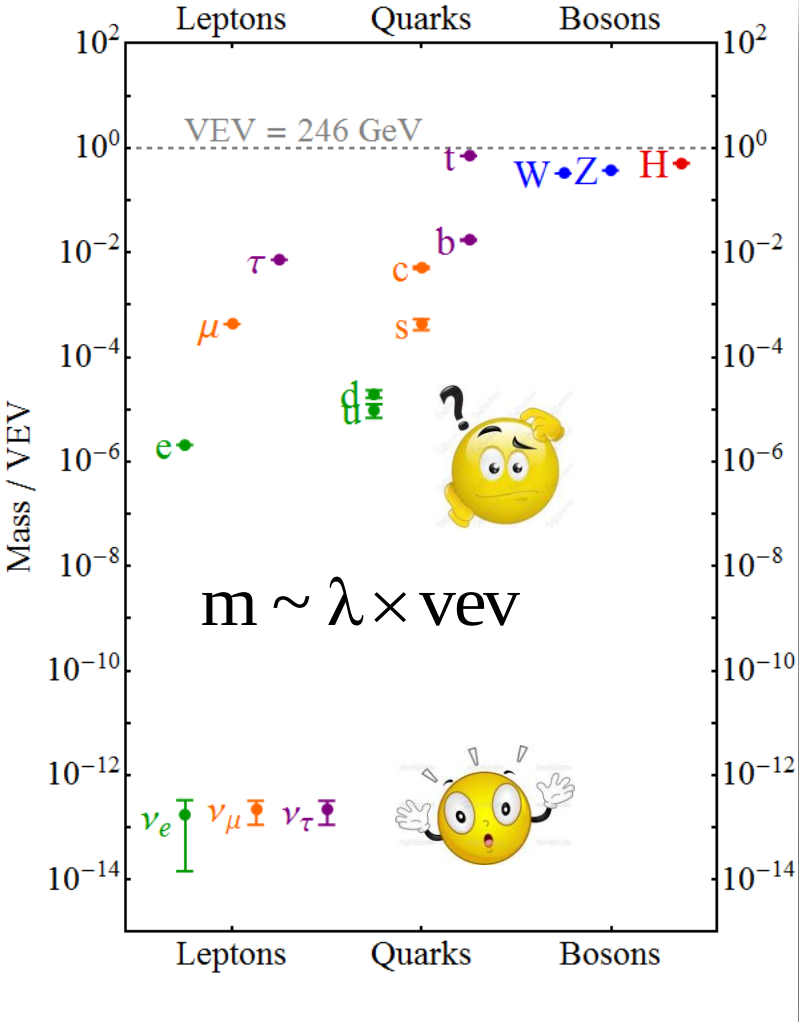

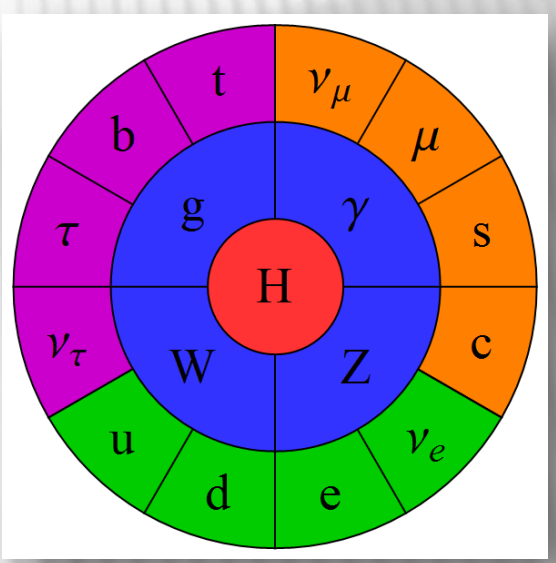

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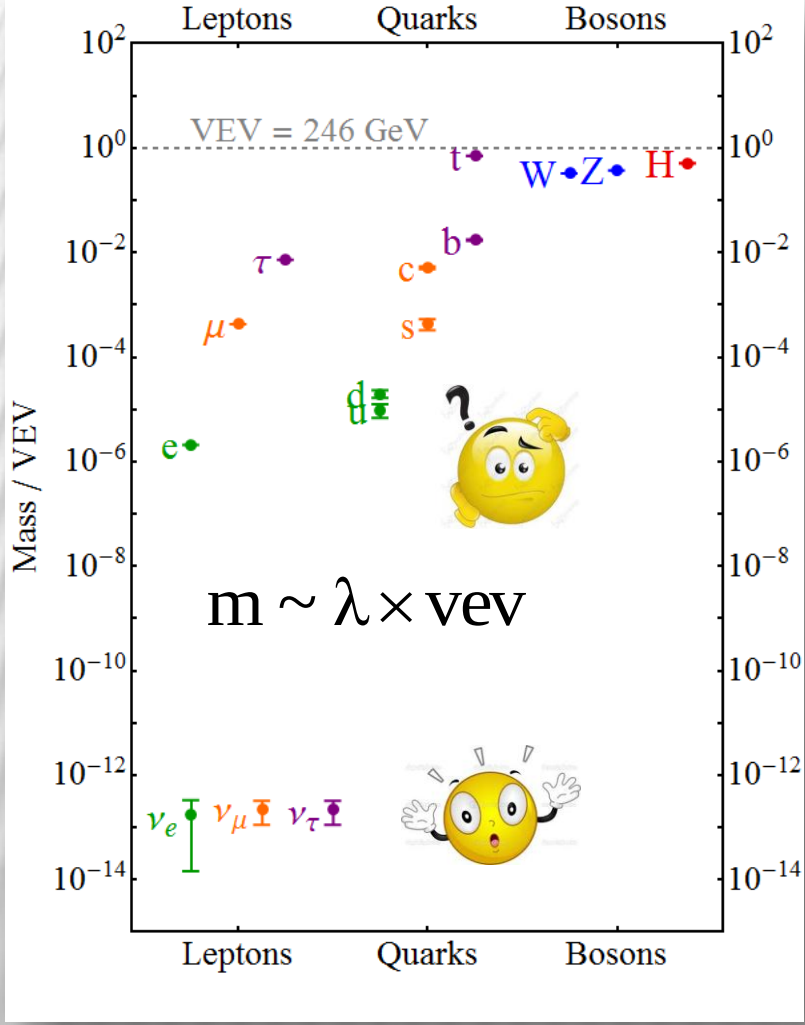
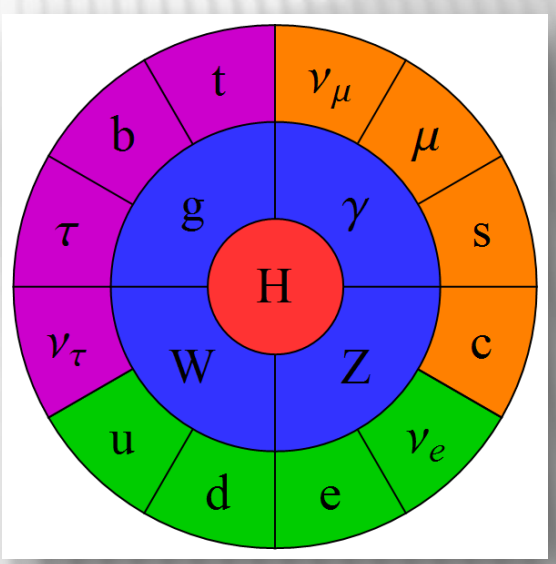
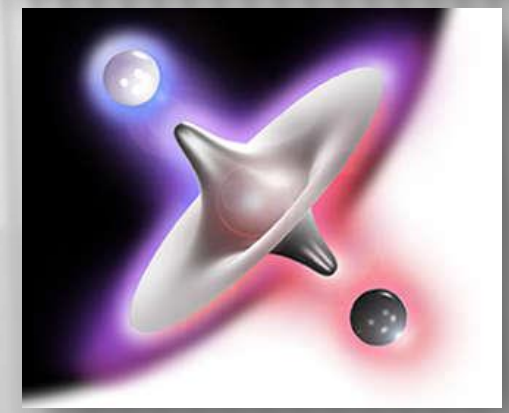


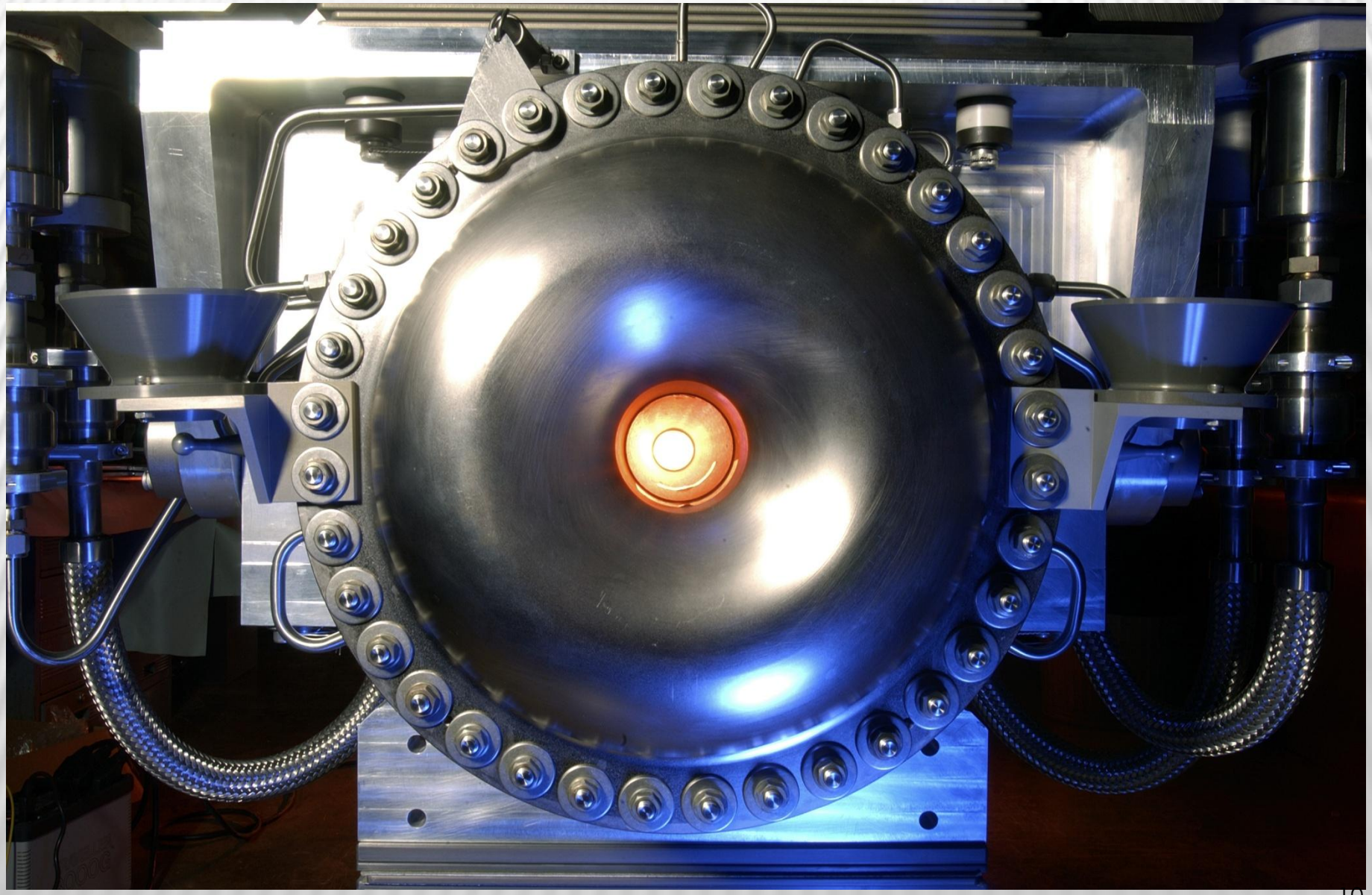




OUTLINE

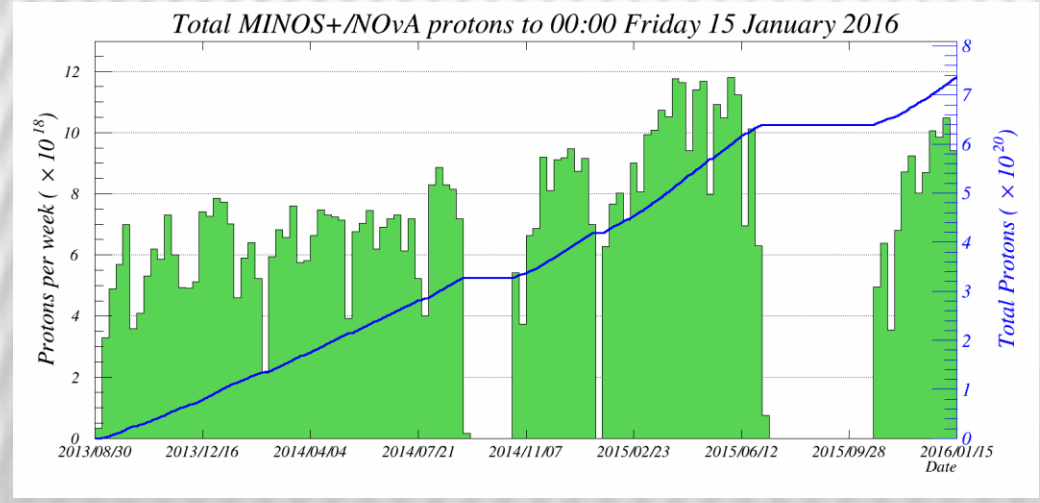
- NuMI Beam
- Neutrino Oscillations
- NOvA Experiment
- Numu Disappearance
- Nue Appearance

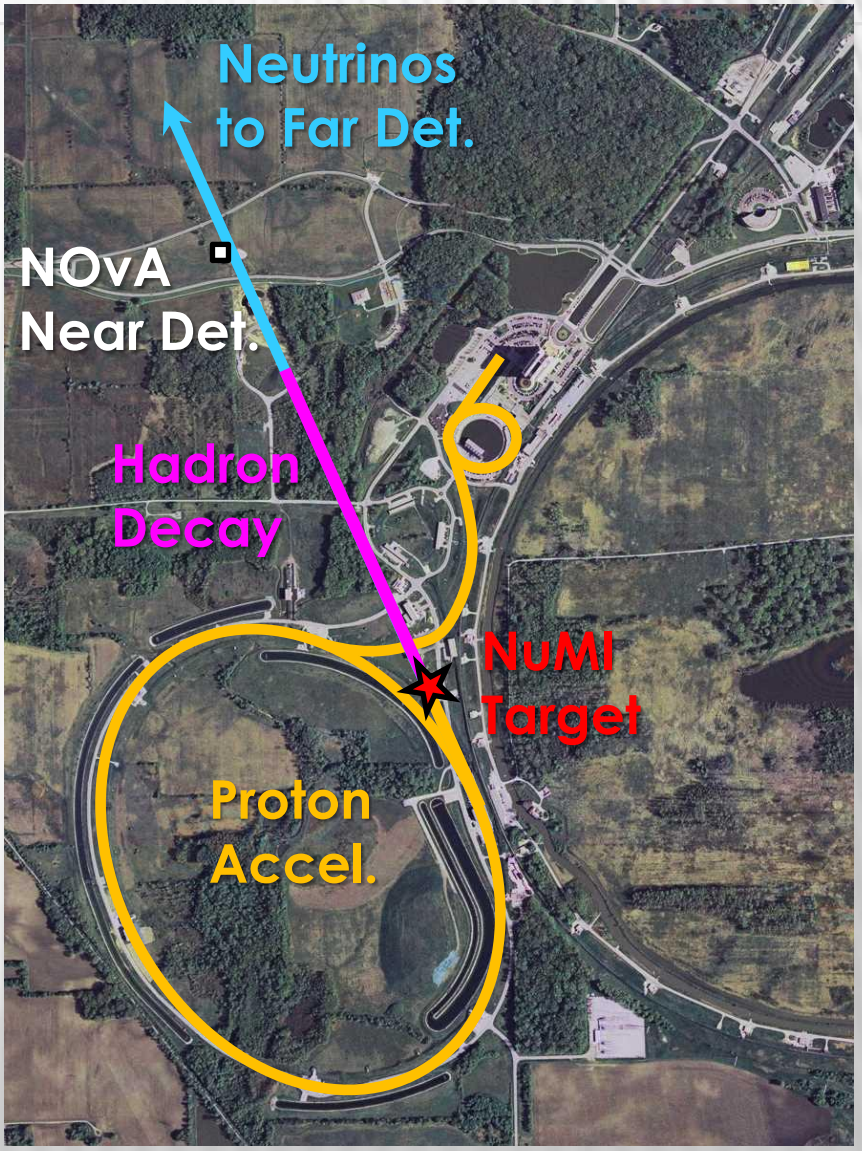
THE NUMI BEAM



RAMPING UP

- Capable of 700 kW
- Reliably ran at ~470 kW
- Record 521 kW for 1 hour
- Full power by mid 2016
- 7.4 x 10^{20} PoT delivered





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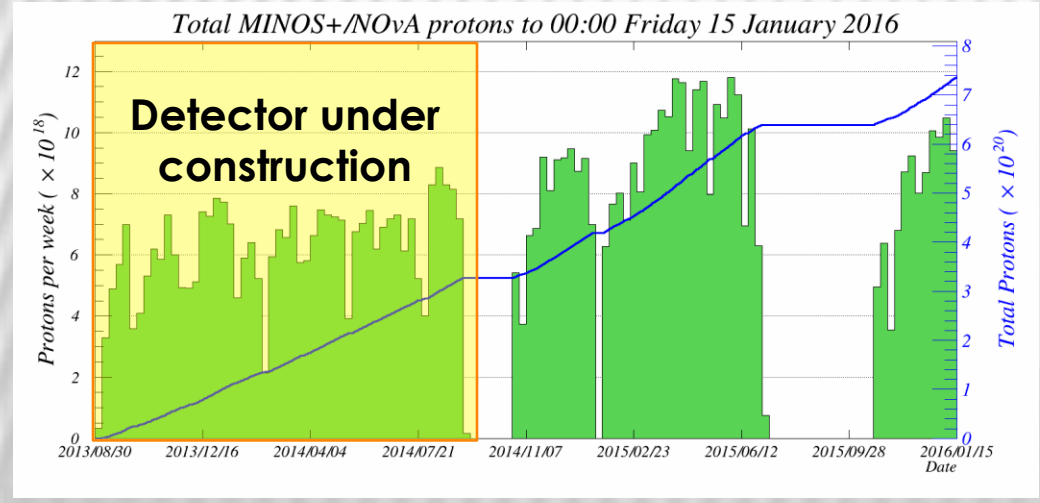

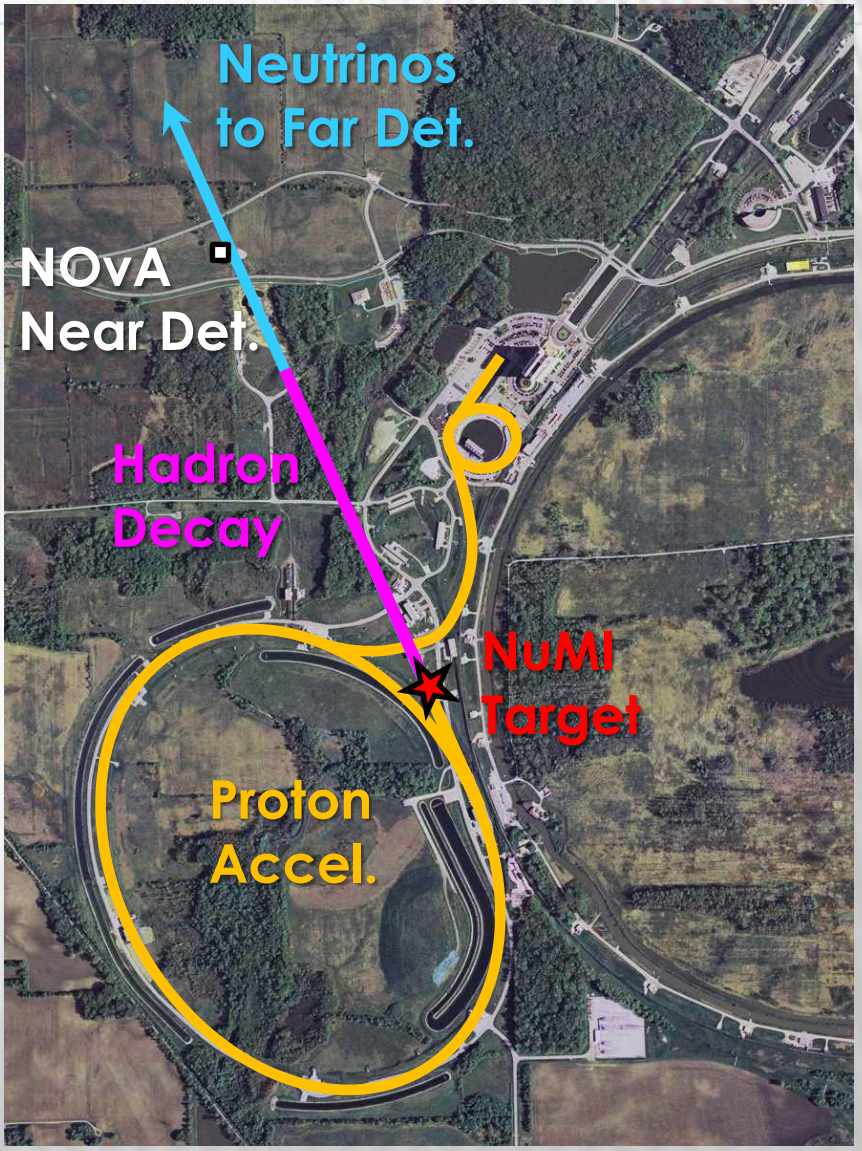

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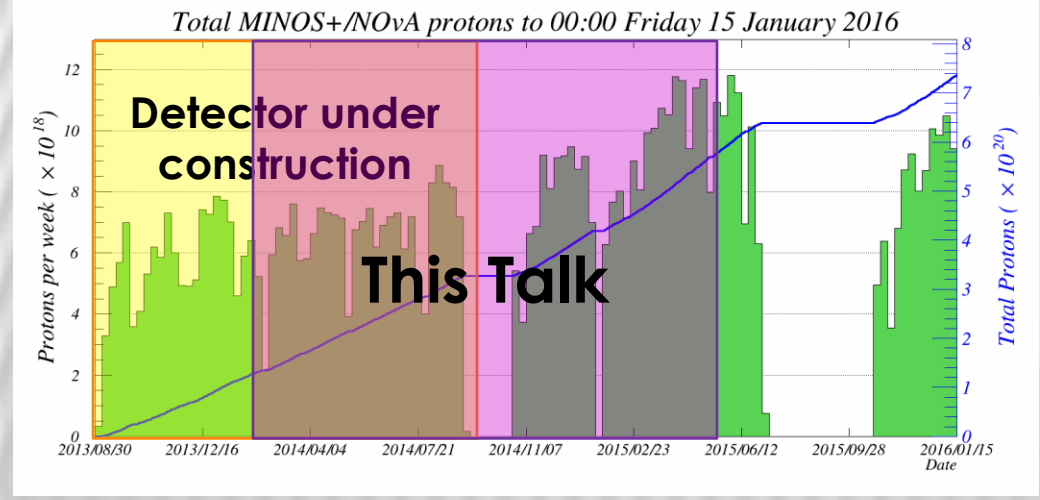
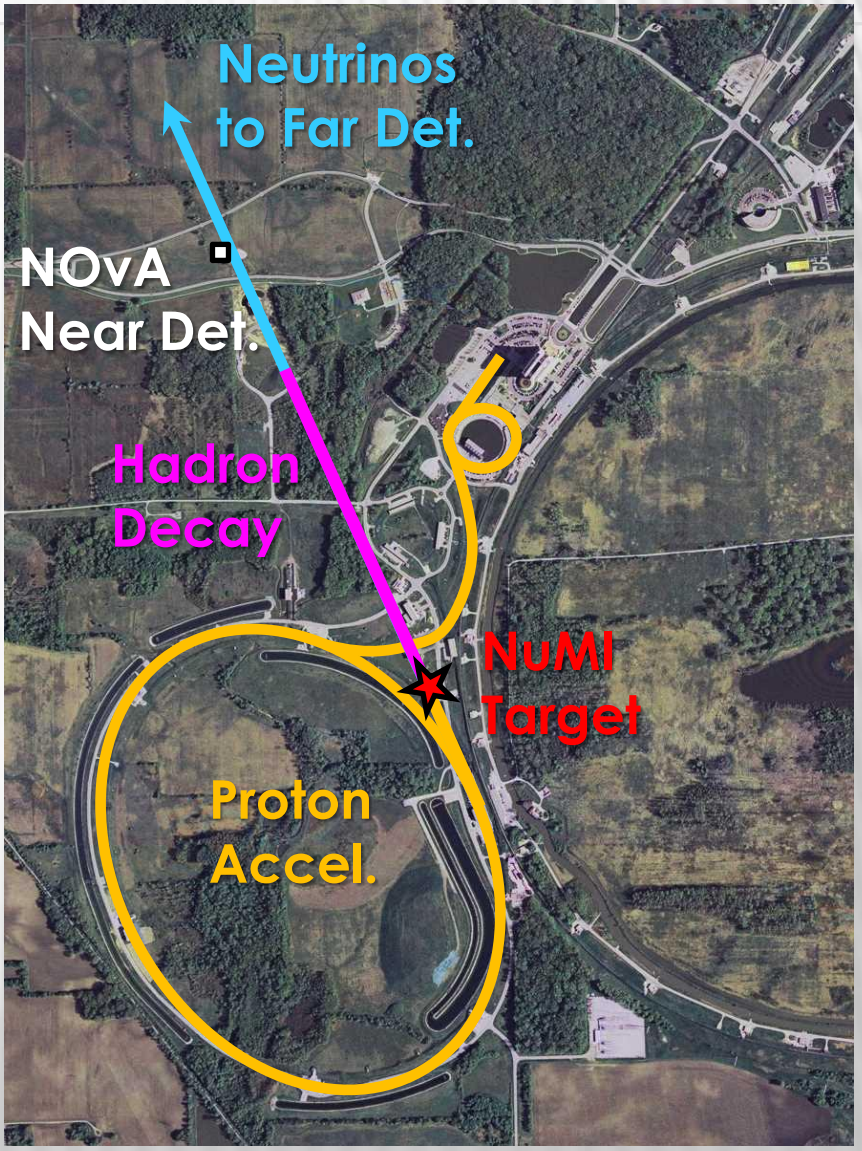
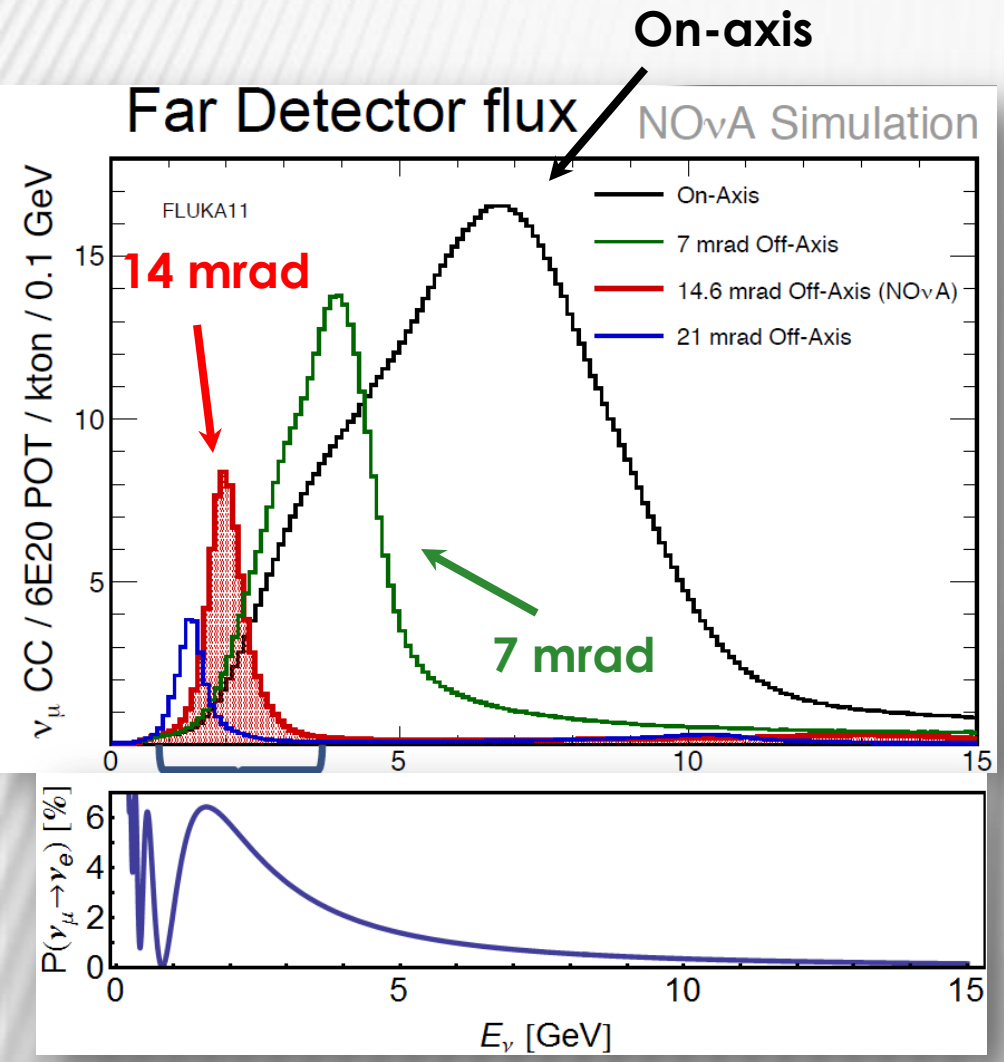


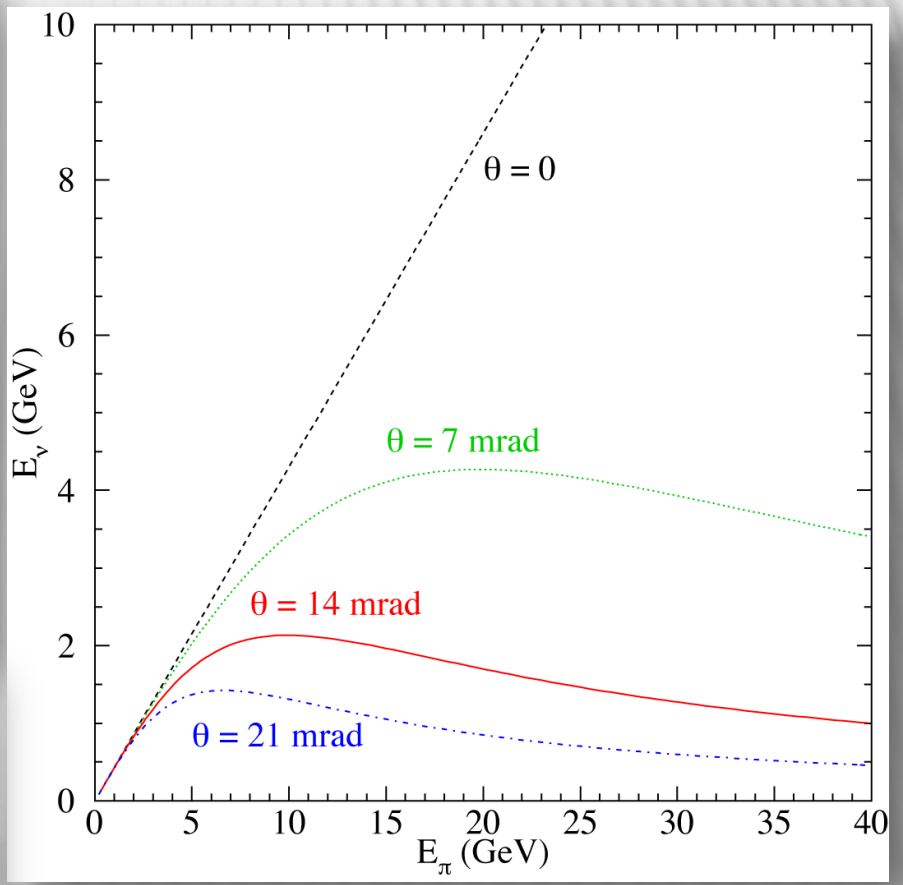


BASELINE

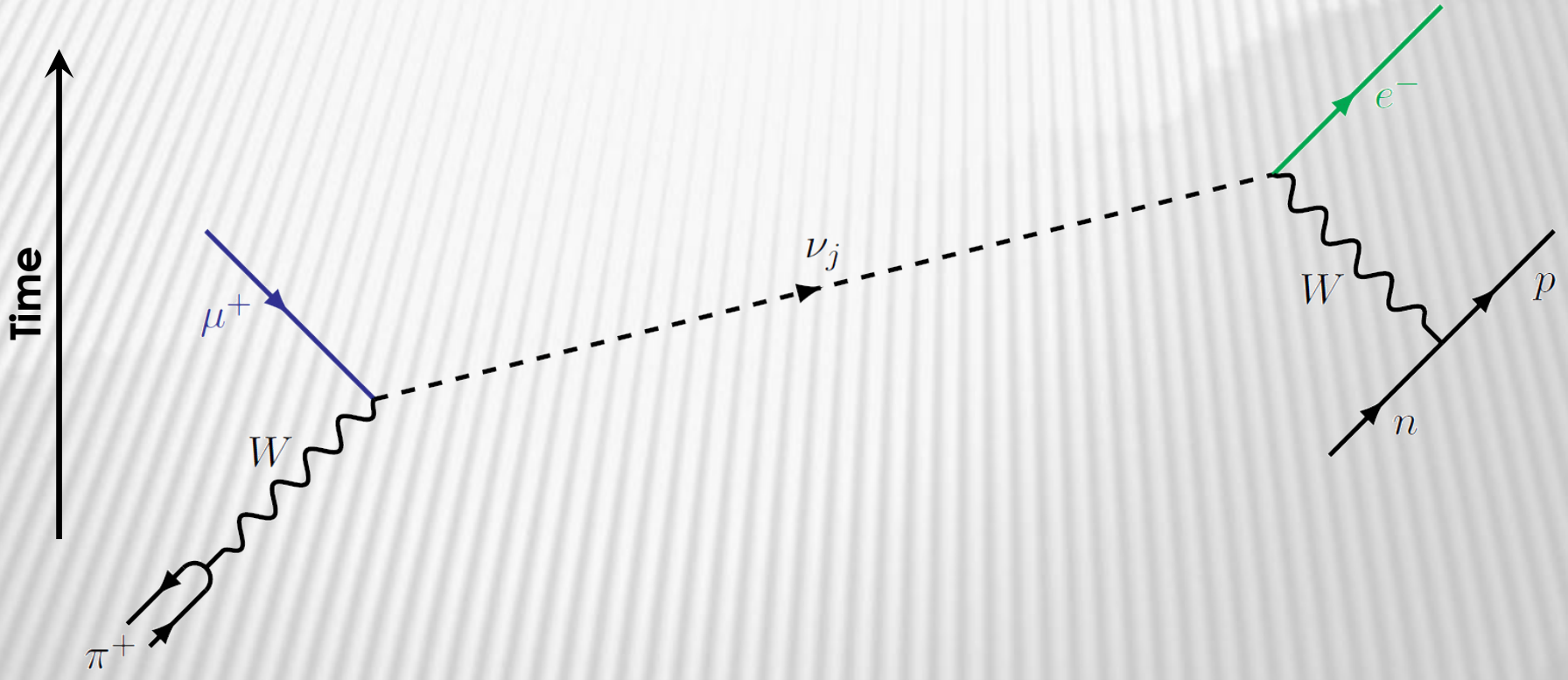

Lake Winnipeg
Canadian Shield
Hudson Bay
North Dakota
NOvA
MINOS+
Lake Nipigon
Ontario
Minnesota
Lake Superior
NOvA
810 km
0.84˚ off-axis
Beam axis
Green Bay
Wisconsin
Michigan
Lake Michigan
Iowa
Fermilab
Illinois

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]

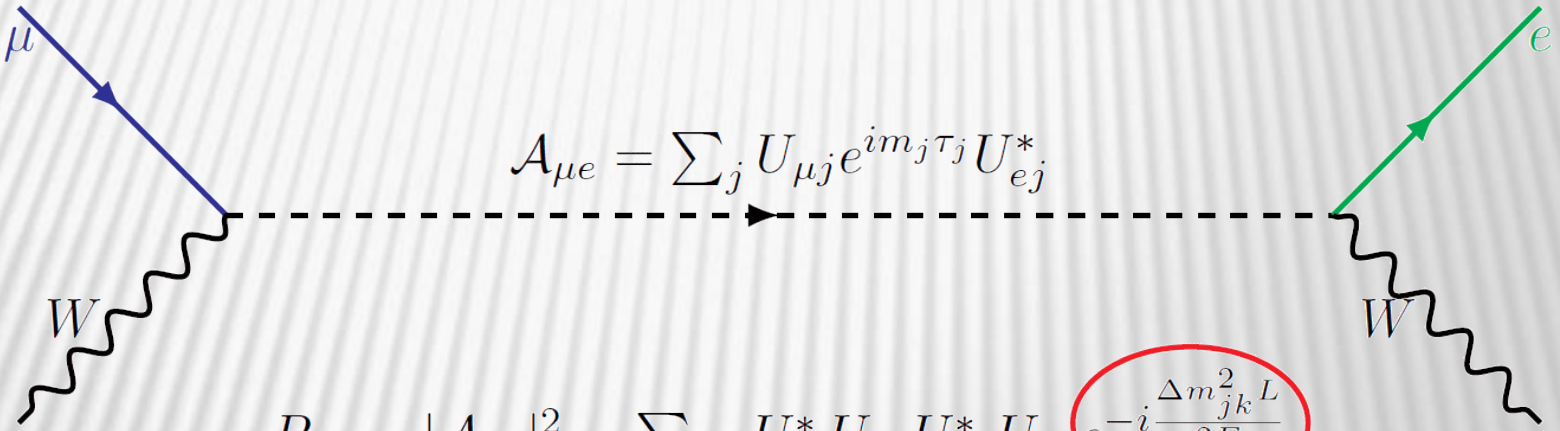

θ = 0
θ = 7 mrad
θ = 14 mrad
θ = 21 mrad
E_ν (GeV)
E_π (GeV)

NEUTRINO OSCILLATION



NEUTRINO OSCILLATION

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



$$P_{\mu e} = |\mathcal{A}_{\mu e}|^2 = \sum_{j,k} U^*_{ej} U_{\mu j} U^*_{\mu k} U_{ek} e^{-i\frac{\Delta m^2_{jk} L}{2E}}$$

Oscillation

$$U(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{CP})$$

DISAPPEARANCE

- CPT theorem: $\nu_\alpha \rightarrow \nu_\alpha$ is T invariant, so it must be CP invariant
- 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 Disappearance

$$\mathcal{P}(\nu_e \rightarrow \nu_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \Delta_{ee} + \mathcal{O}(\Delta_{21})^2$$

Clean measure of θ_{13}

$\Delta m^2_{ee} \neq \Delta m^2_{\mu\mu}$ $[O(\Delta m^2_{21})]$

APPEARANCE

- CPT theorem: $\nu_\alpha \rightarrow \nu_\beta$ is NOT T invariant, so it CAN violate CP
- Contains odd orders in $\Delta \equiv \Delta m^2 L/E$

ν_e Appearance

$$\mathcal{P}(\nu_\mu \rightarrow \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{ee} + \tilde{J}\sin\Delta_{21}\sin\Delta_{ee}\cos(\Delta_{ee}\pm\delta) + \mathcal{O}(\Delta_{21})^2$$

Breaks θ_{23} symmetry

CP violation term

MH sensitivity but small

Only when sin $\delta \sim 0$

APPEARANCE

- CPT theorem: $\nu_\alpha \rightarrow \nu_\beta$ is NOT T invariant, so it CAN violate CP
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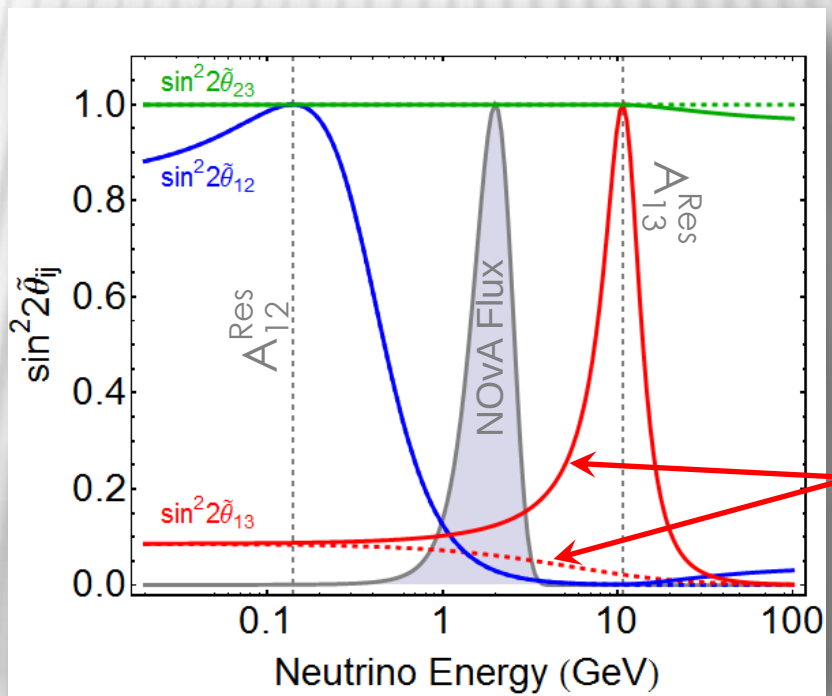
Breaks θ_{23} symmetry

CP violation term

Earth is transparent to ν's with a "refractive index"



- Apparent CP violation
- Larger MH sensitivity

- **Flips with MH**
- **Flips with CP**

APPEARANCE

- CPT theorem: $\nu_\alpha \rightarrow \nu_\beta$ is NOT T invariant, so it CAN violate CP
- Contains odd orders in $\Delta \equiv \Delta m^2 L/E$

ν_e Appearance

$$\begin{aligned}\mathcal{P}(\nu_\mu \rightarrow \nu_e) \approx & \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{ee} \\ \pm & \; 2A\cos 2\theta_{13}\sin^2\theta_{23}\sin^2 2\theta_{13}[\sin^2\Delta_{ee} - \Delta_{ee}^2 \operatorname{sinc} 2\Delta_{ee}] \\ + & \; \tilde{J}\sin\Delta_{21}\sin\Delta_{ee}\cos(\Delta_{ee}\pm\delta) + \mathcal{O}(\Delta_{21})^2\end{aligned}$$

Breaks θ_{23} symmetry

Matter effects (MH)

CP violation term

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

$$\mathcal{P}(\nu_\mu \to \nu_e) \approx \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{ee}$$
$$\pm\ 2A\cos 2\theta_{13}\sin^2\theta_{23}\sin^2 2\theta_{13}[\sin^2\Delta_{ee} - \Delta_{ee}^2\,\mathrm{sinc}\,2\Delta_{ee}]$$
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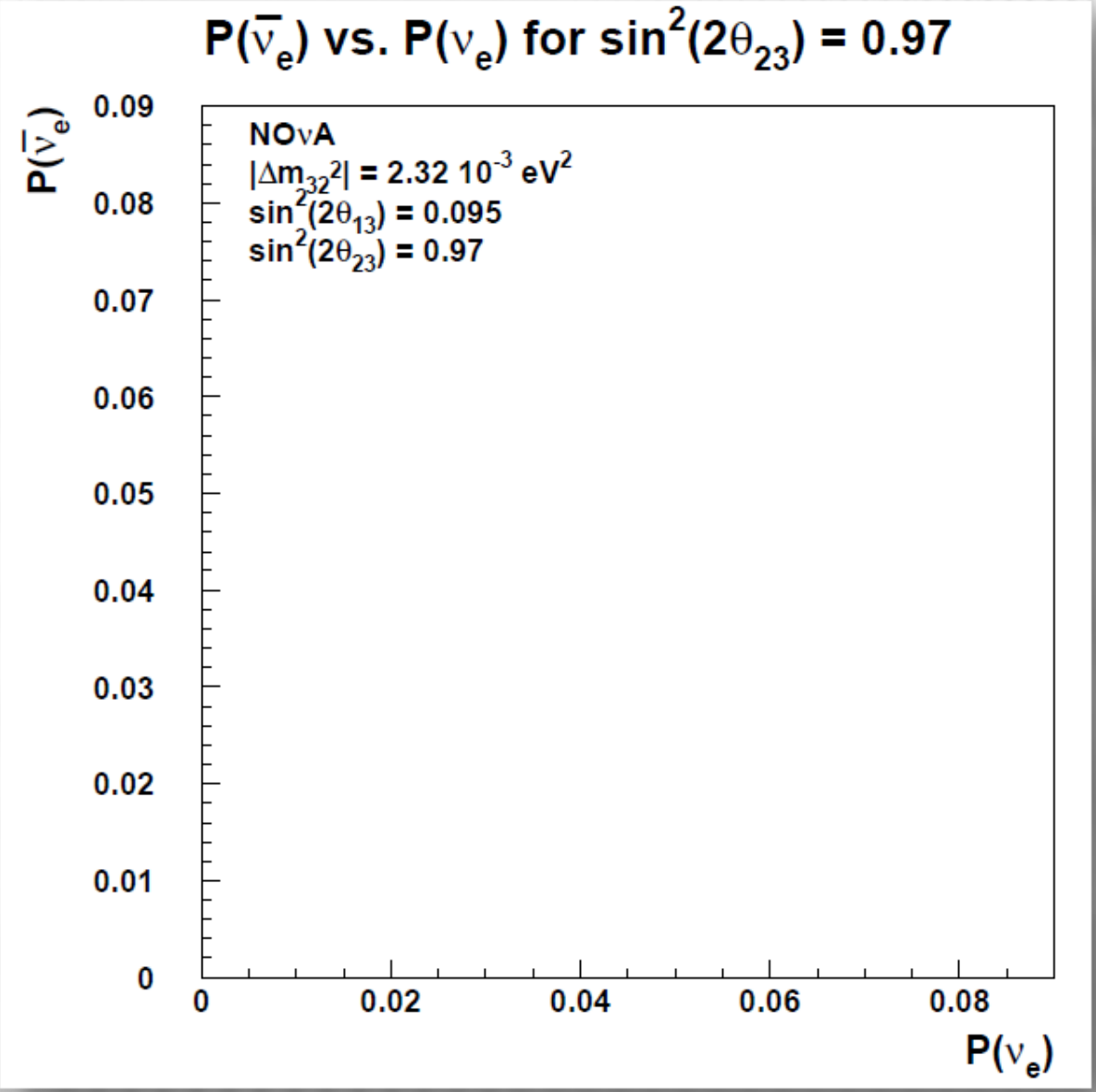

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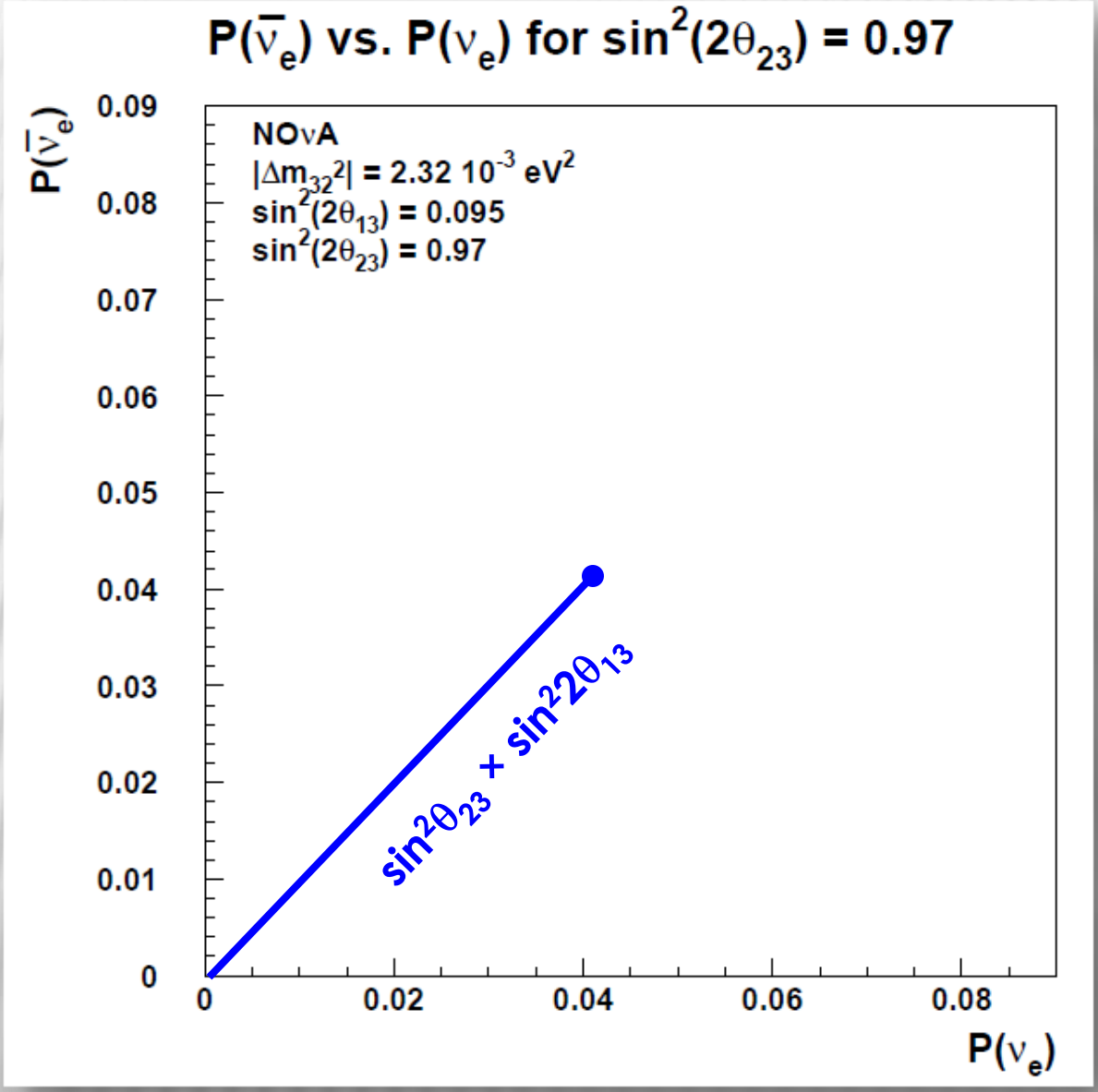

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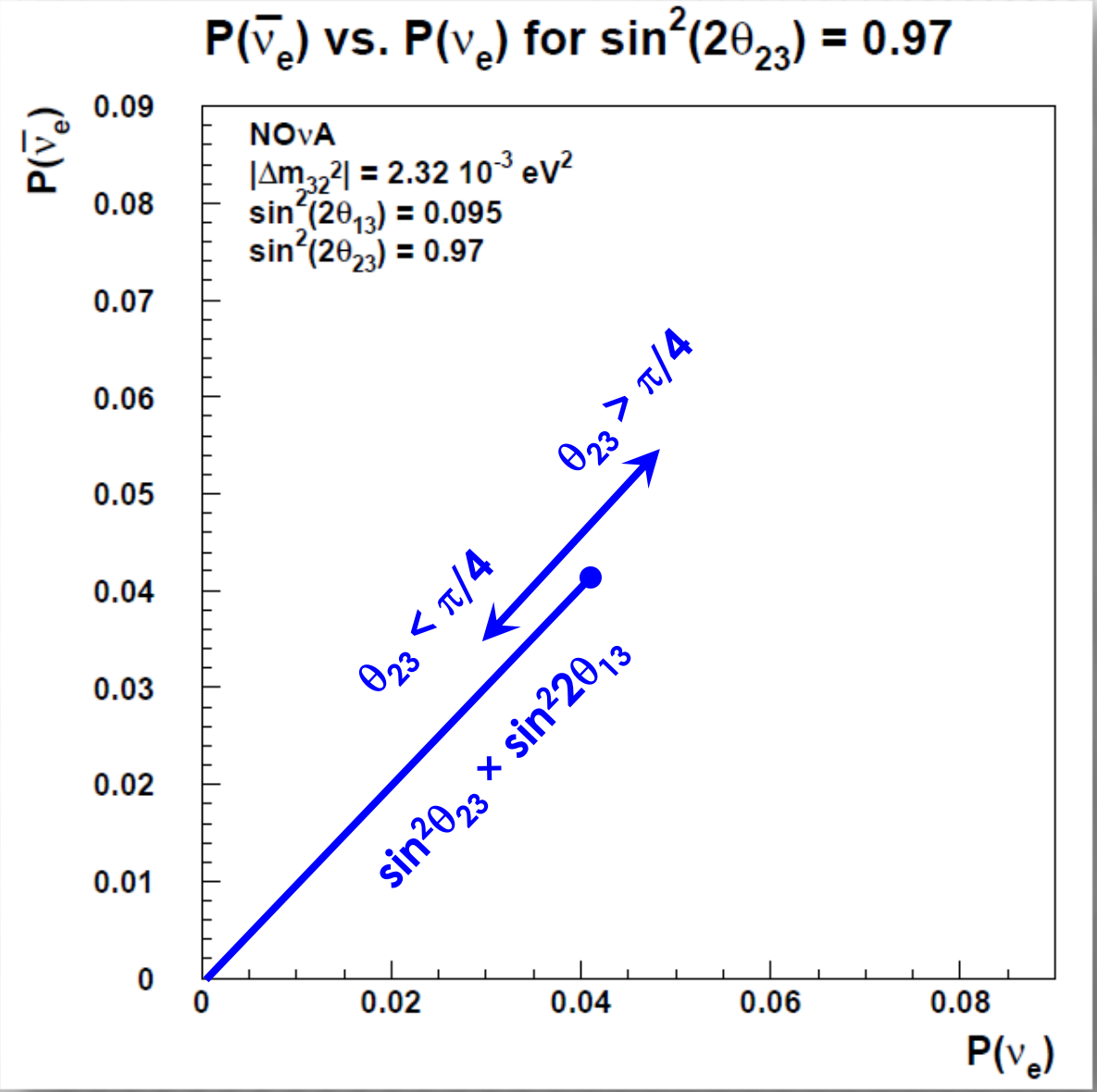

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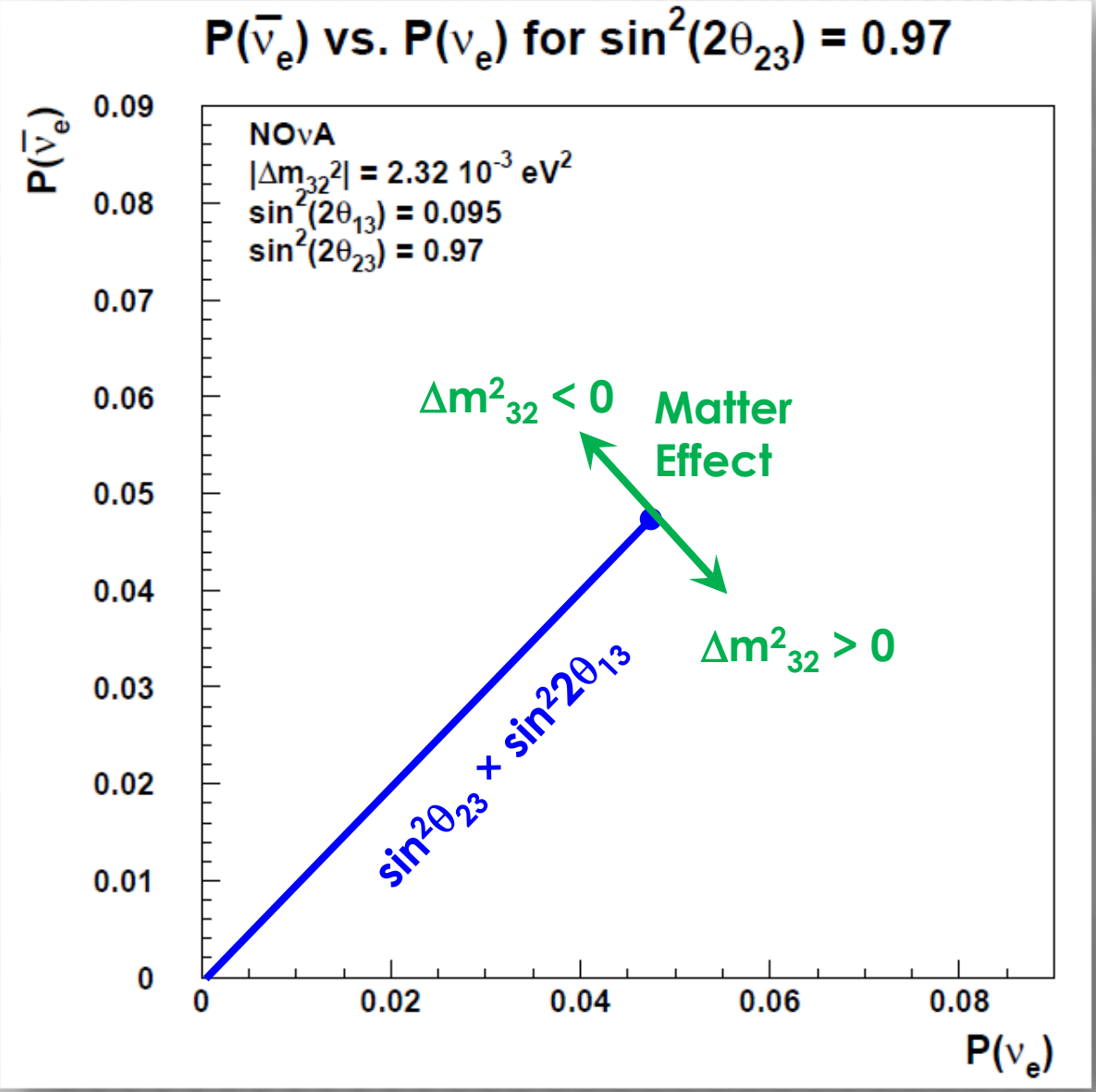

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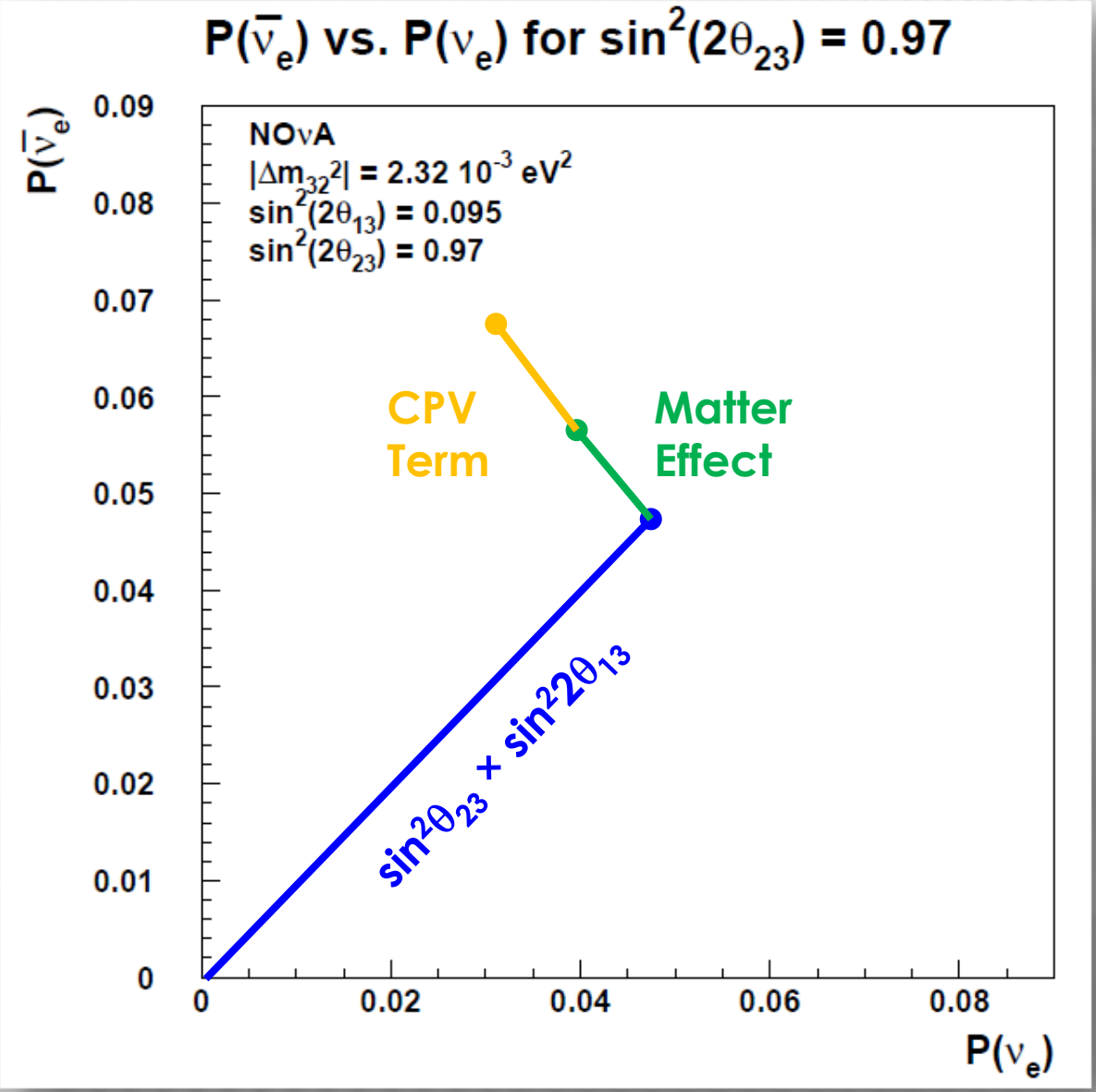

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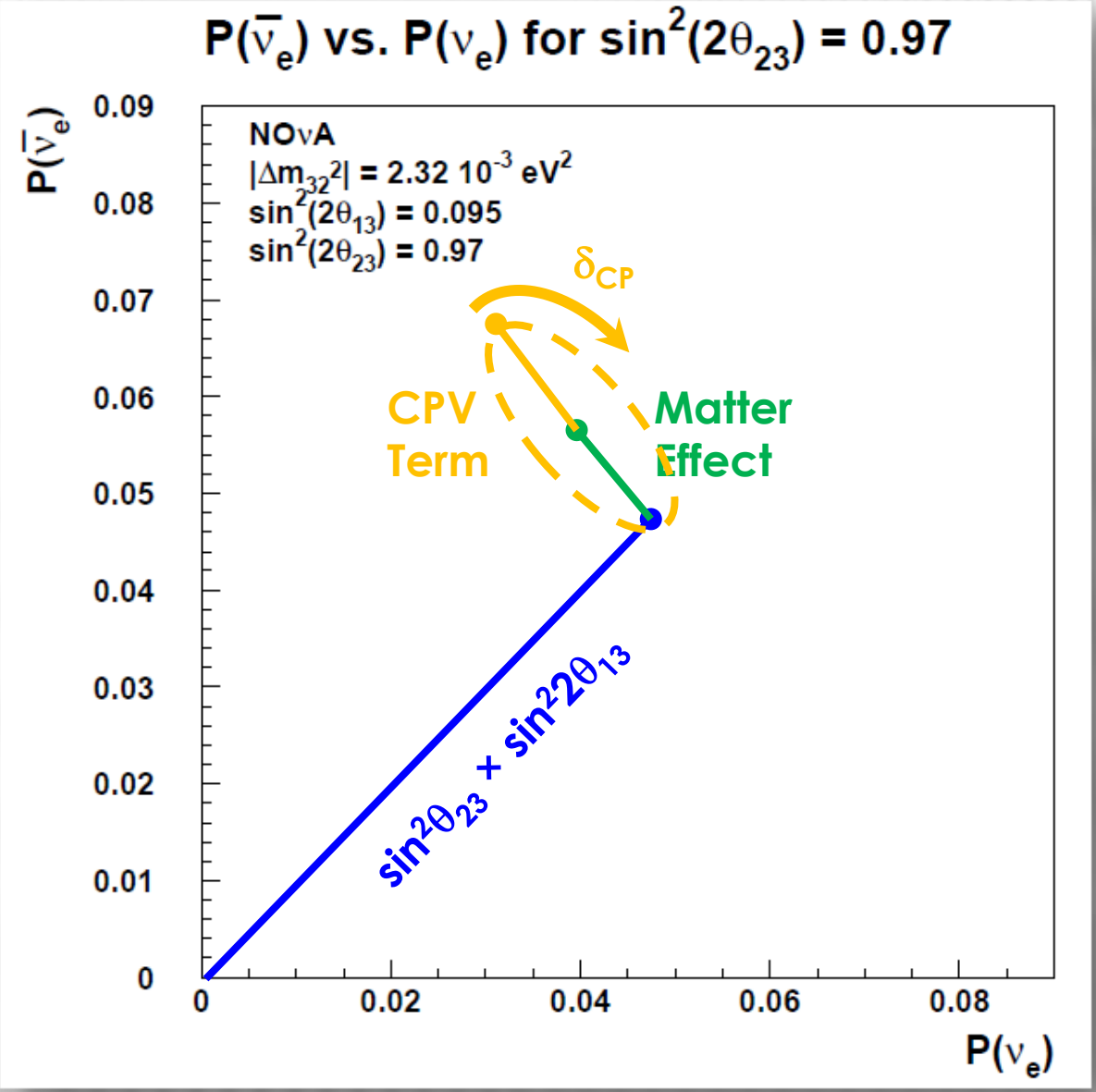
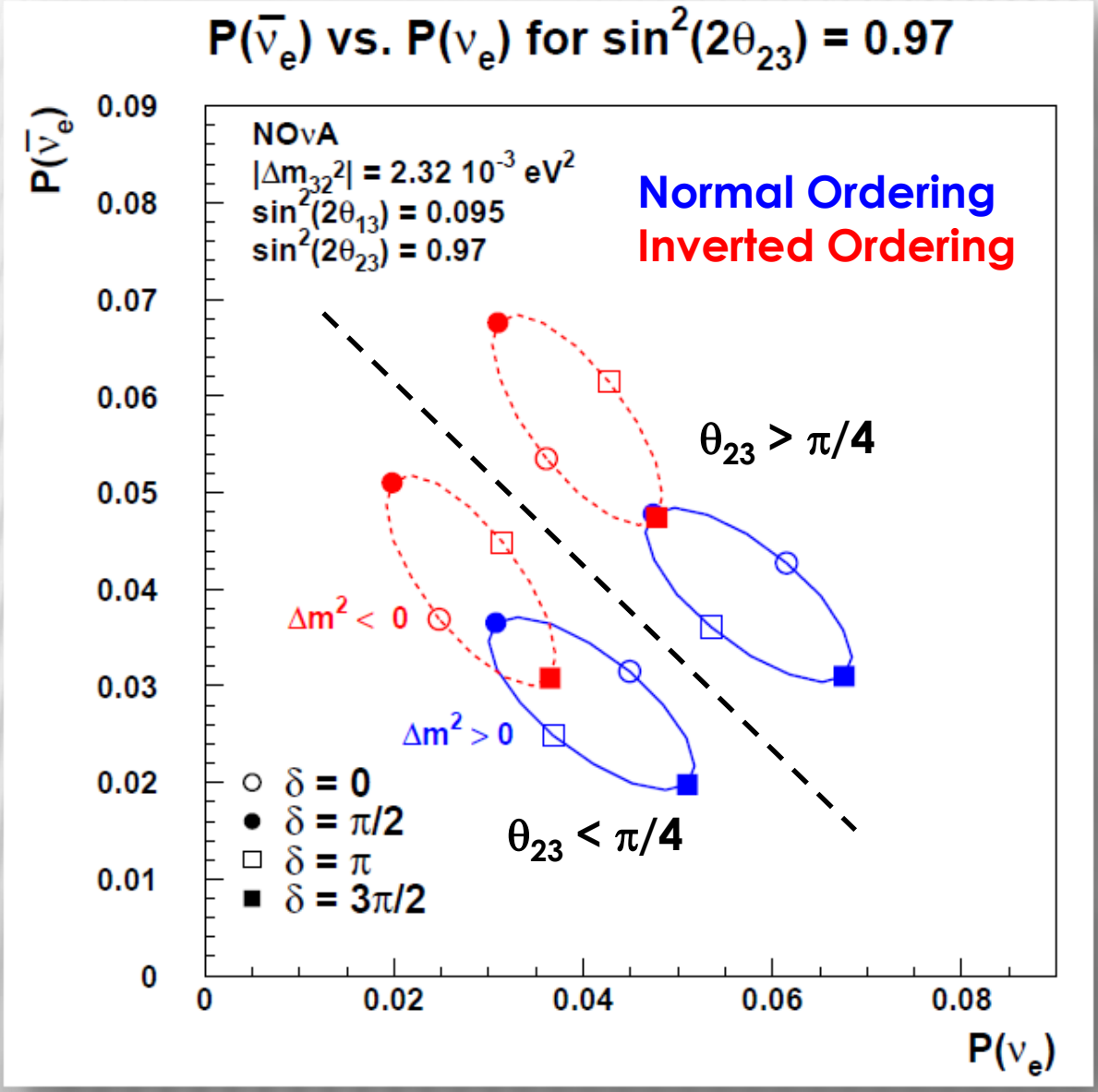


NUE APPEARANCE



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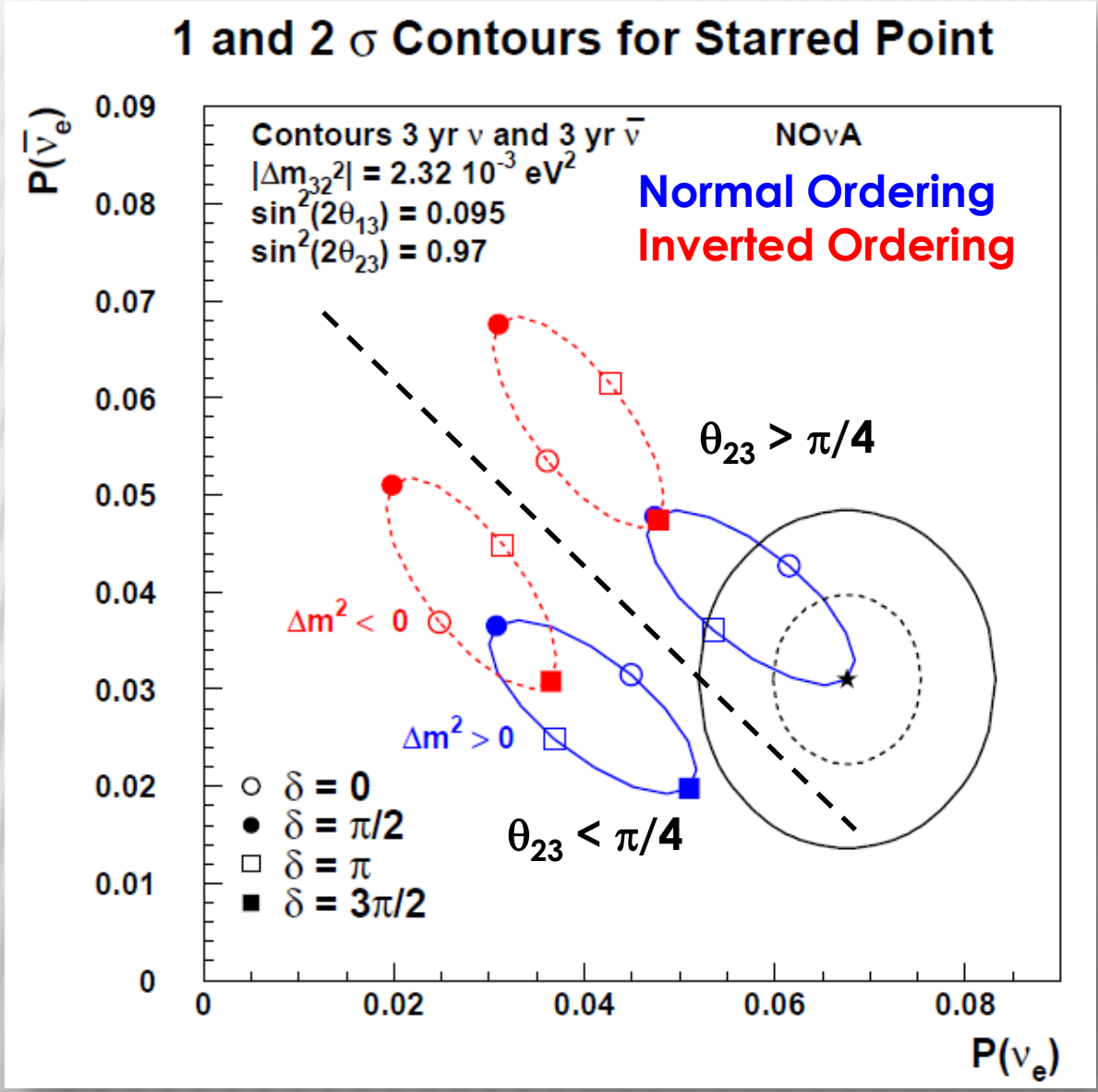
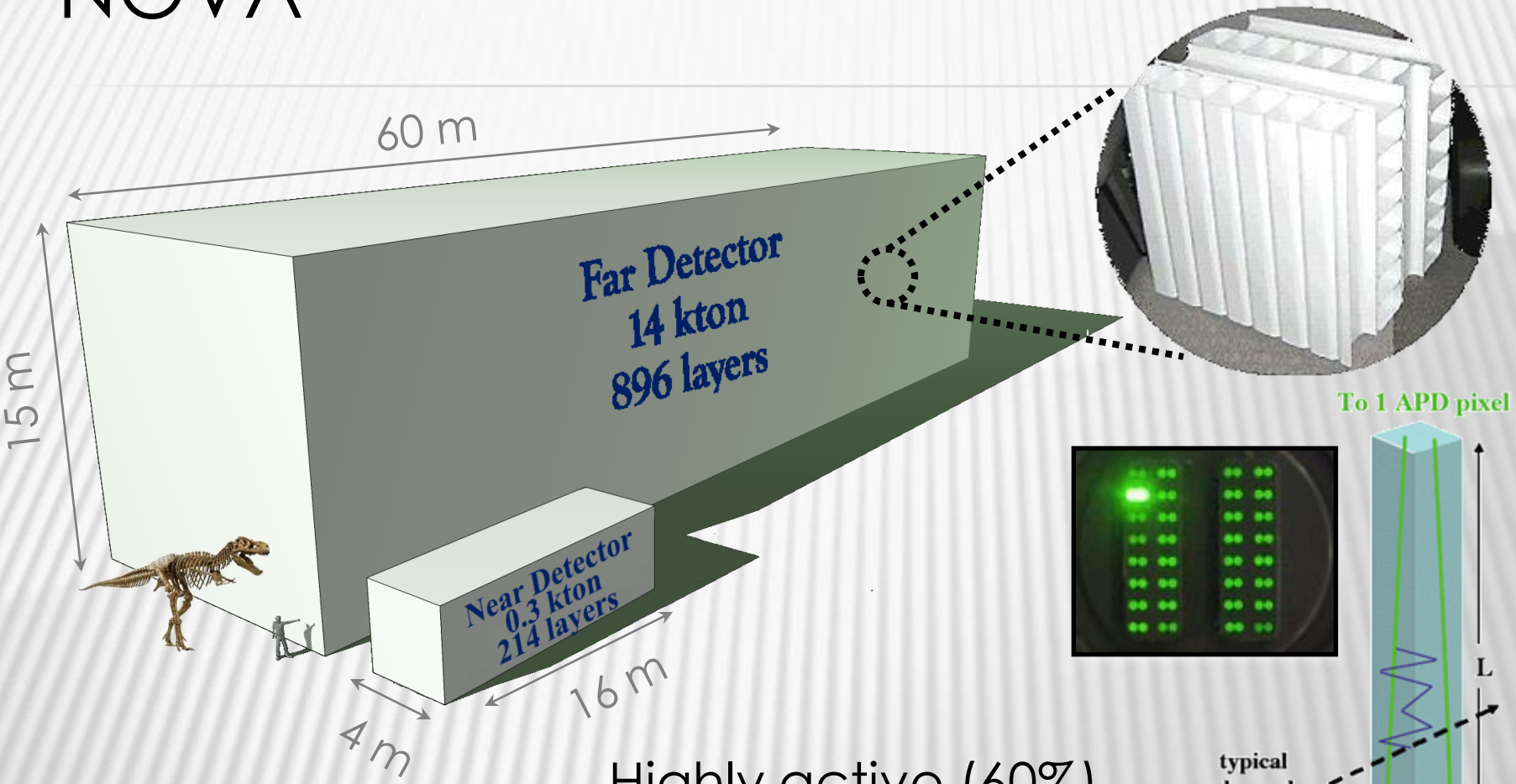


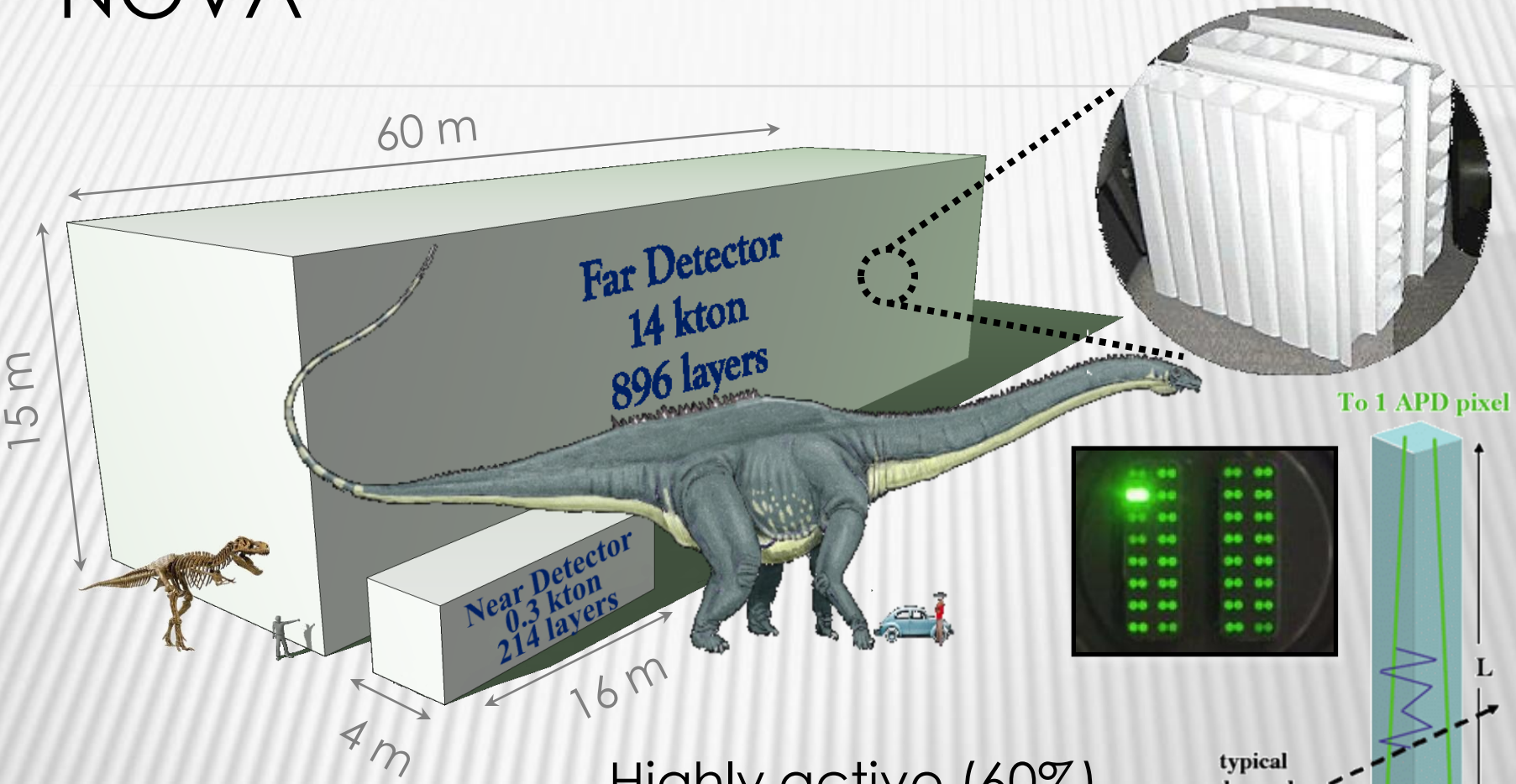
NOVA

NOVA



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

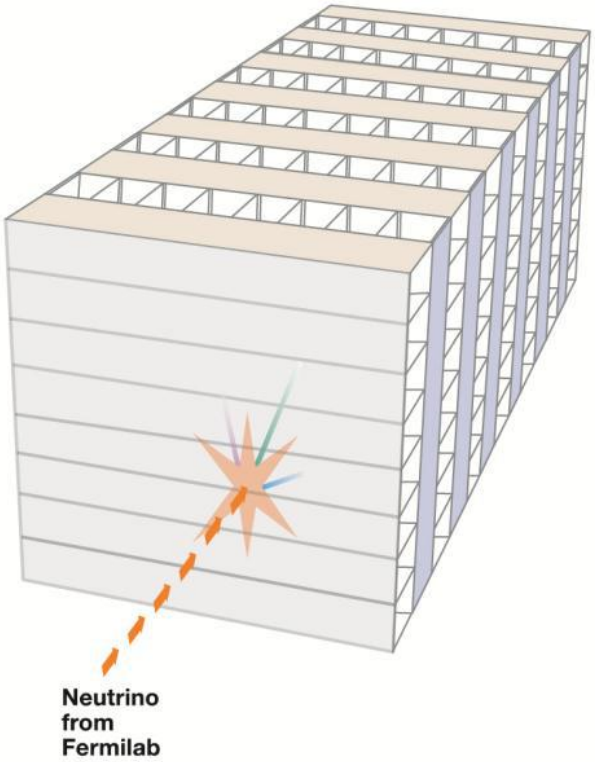
NOVA



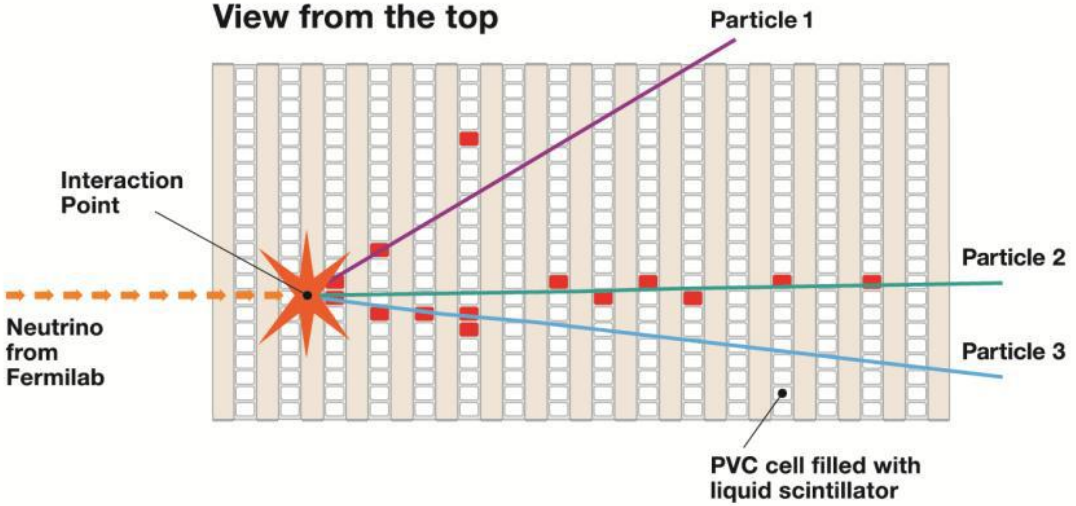
Highly active (60%)
Tracking calorimeters
Fine granularity (4x6 cm)
FD → 344,064 channels
ND → 20,192 channels

NOVA

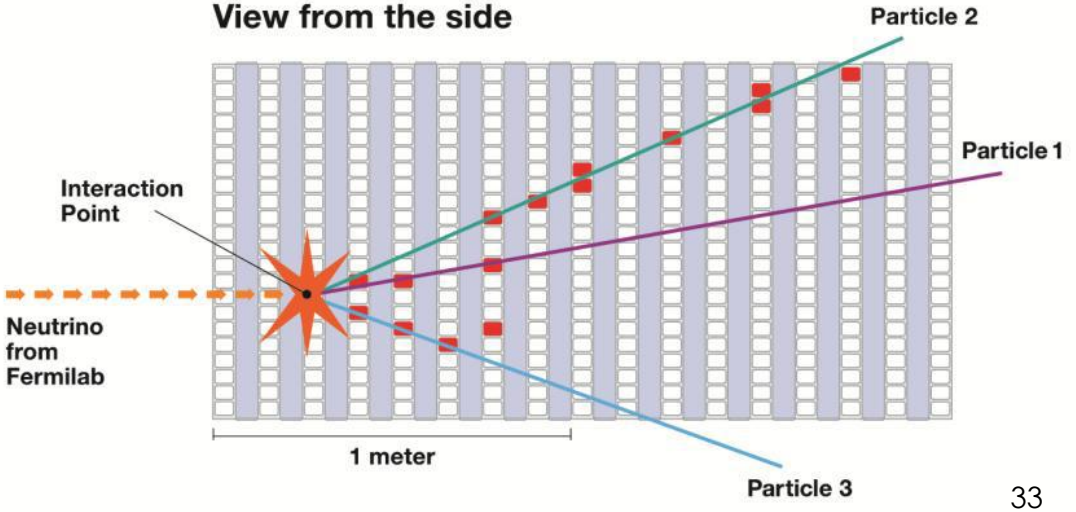
3D schematic of NOvA particle detector



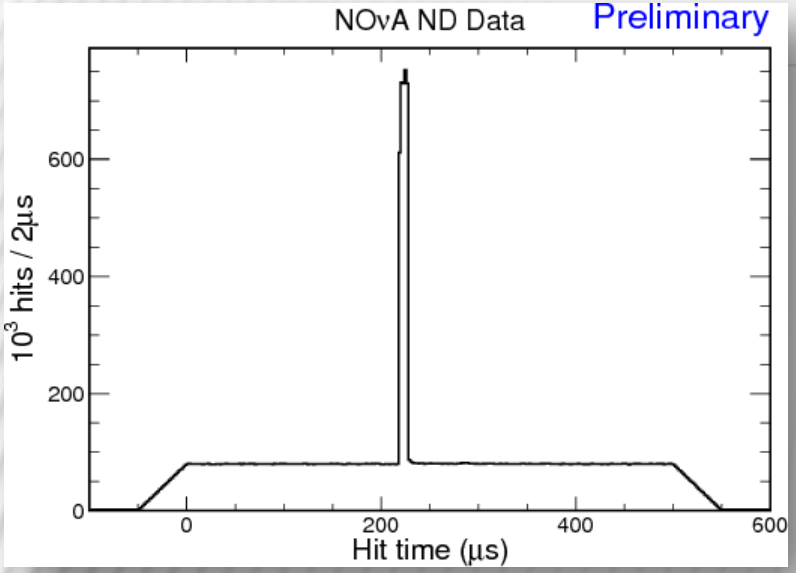
View from the top

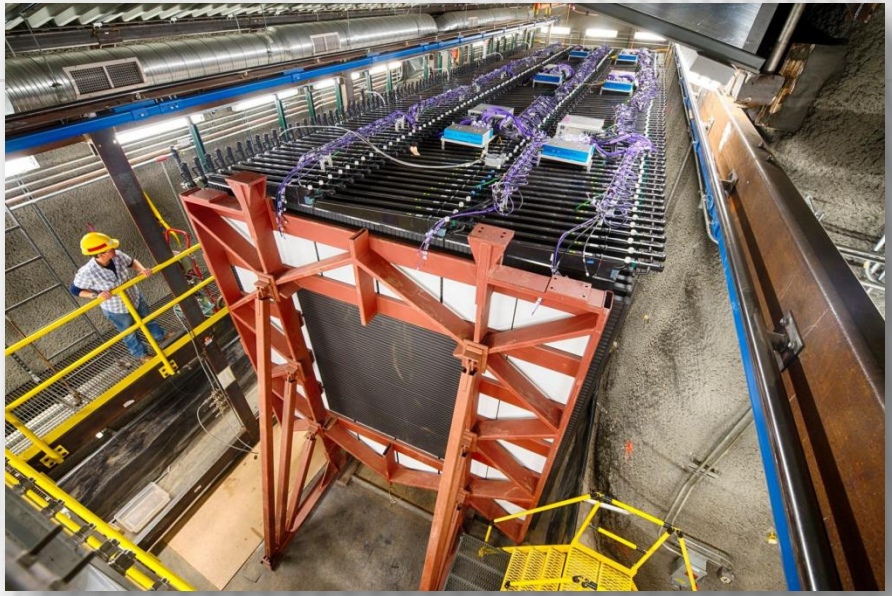


View from the side

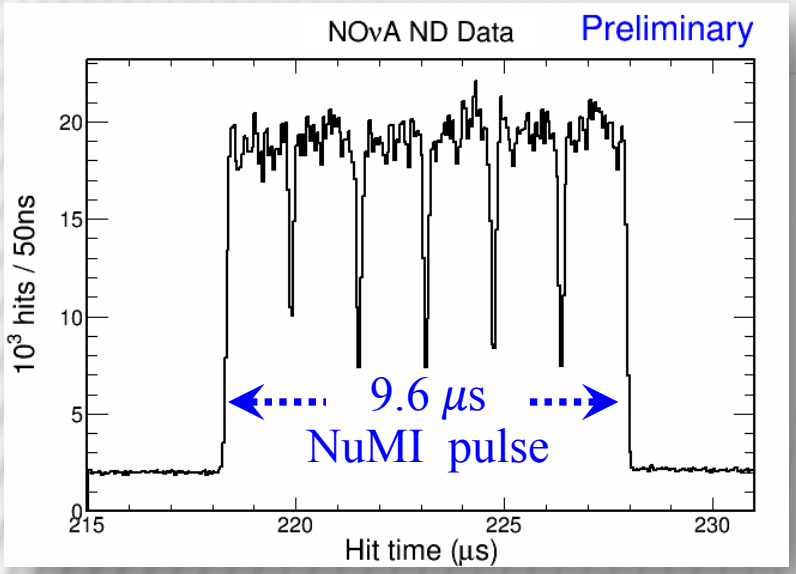


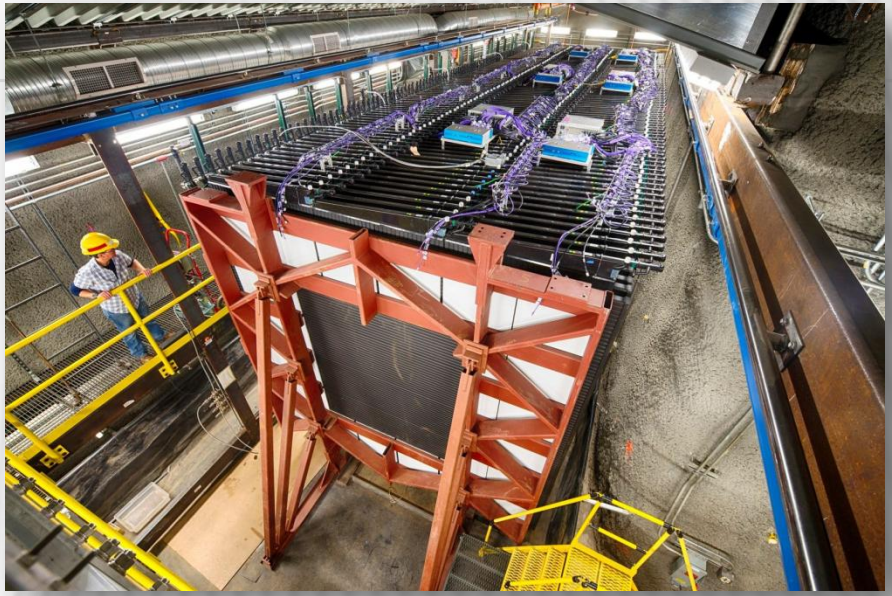
DETECTORS COMPLETE



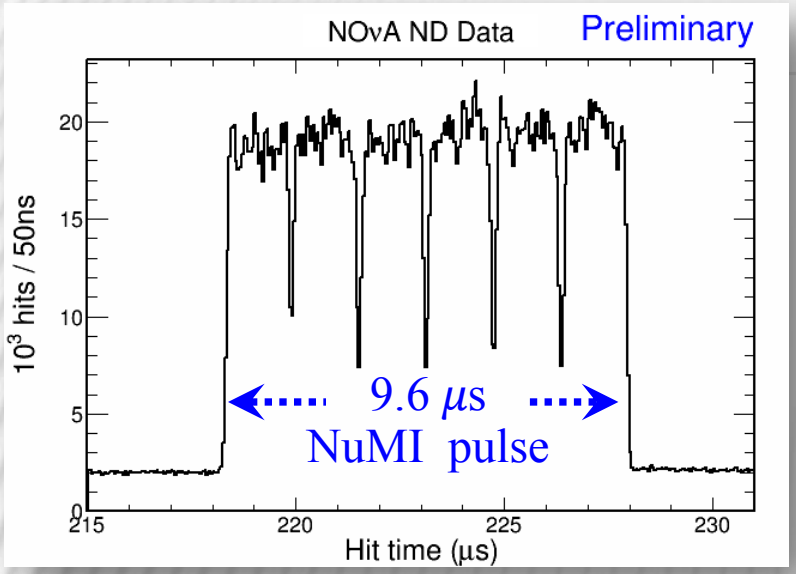


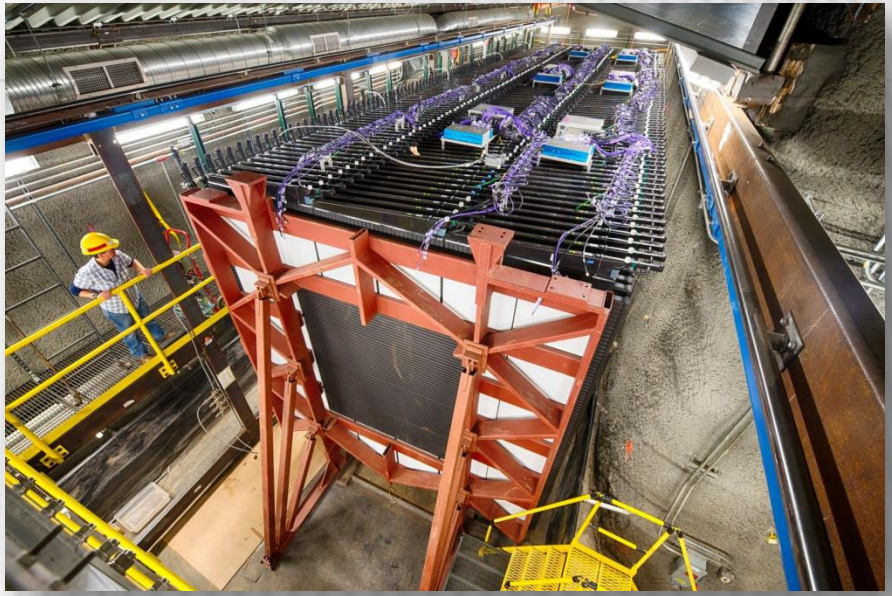
DETECTORS COMPLETE

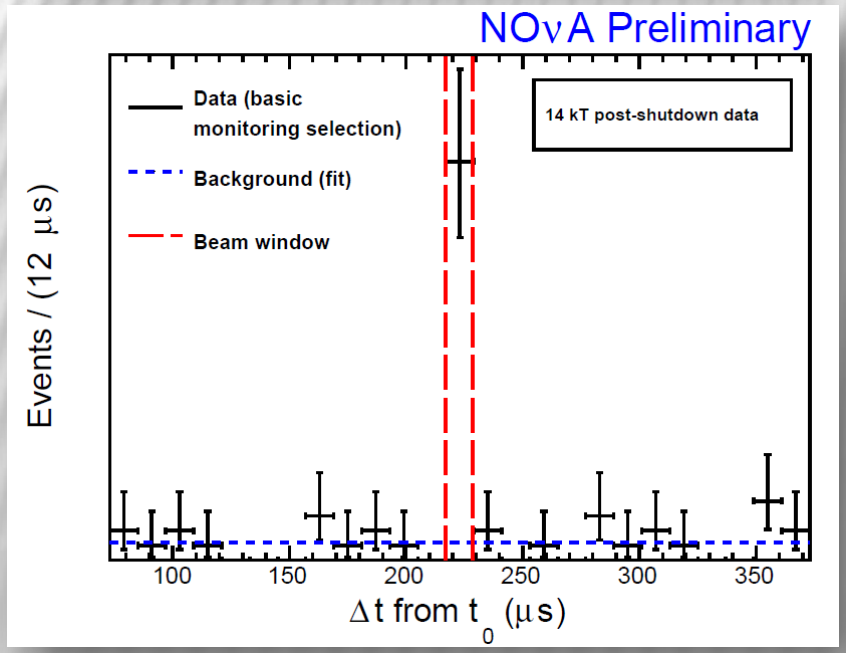




DETECTORS COMPLETE



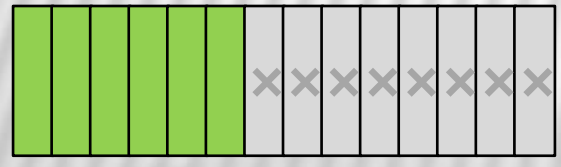




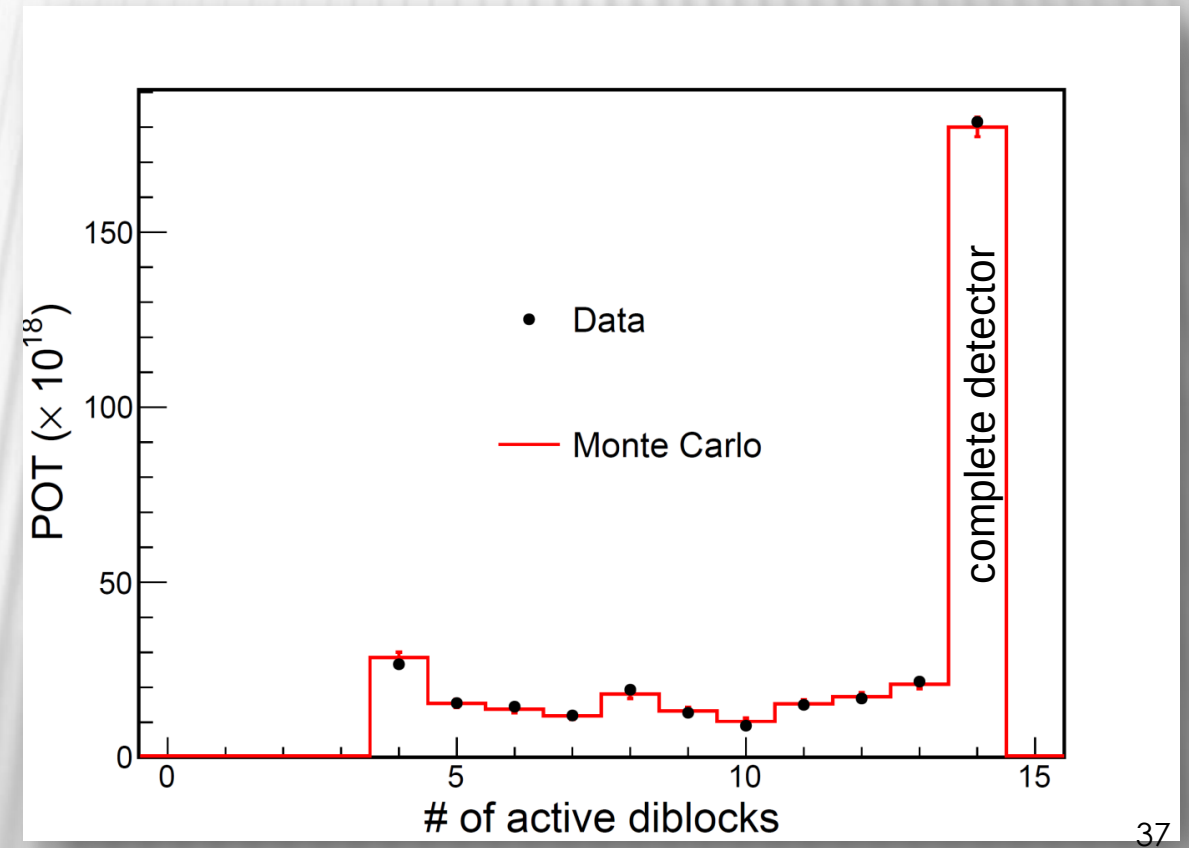
FIRST DATASET

Protons-on-target in data set:	3.45×10^{20} POT
Fraction of detector operational:	79.4% (POT-weighted average)
Full-detector-equivalent exposure:	**2.74×10^{20} POT-equiv**

- Some data was collected with partially instrumented detector during construction
- Different detector sizes are included in our simulation

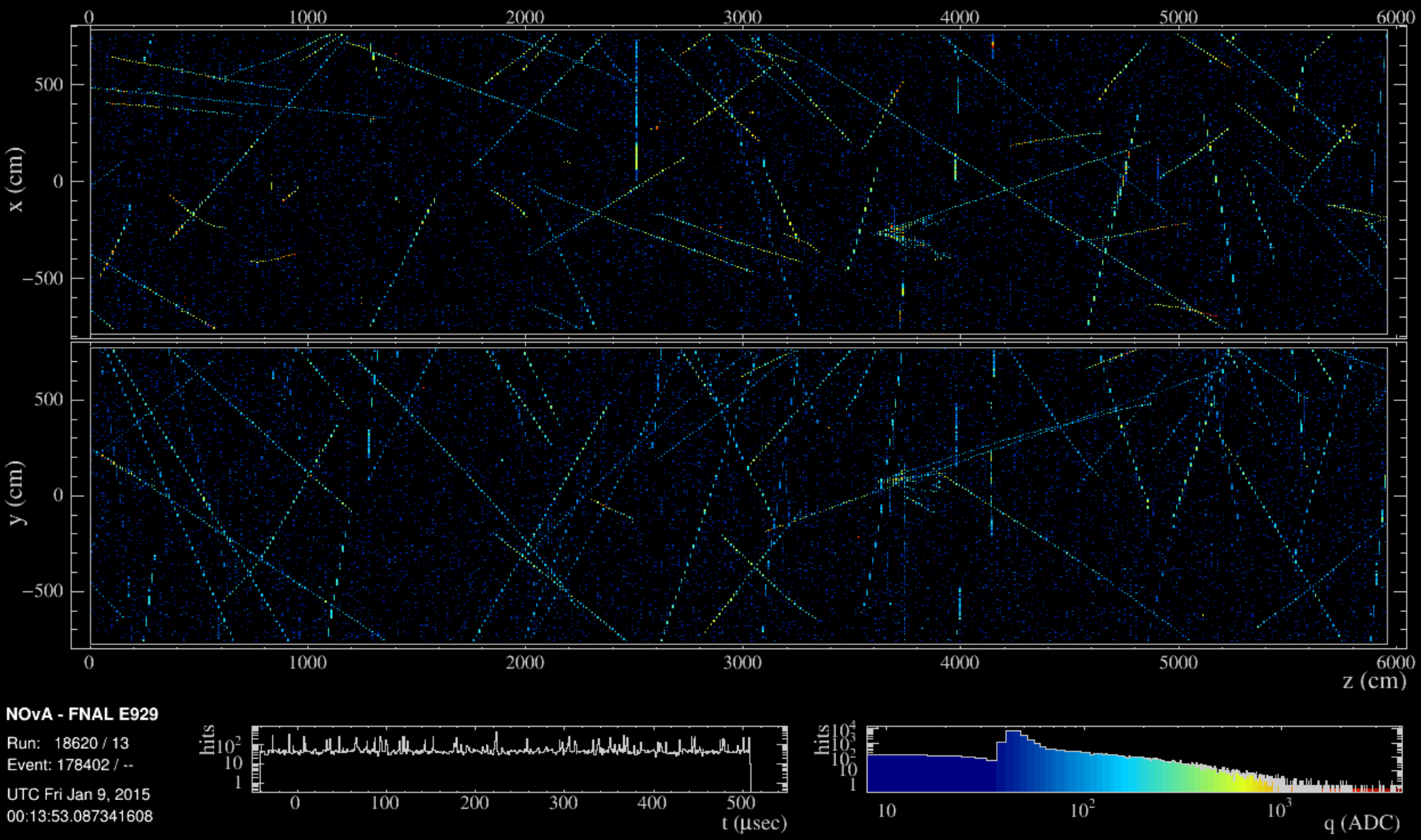


Partial Far Detector during construction
(6 diblock example)



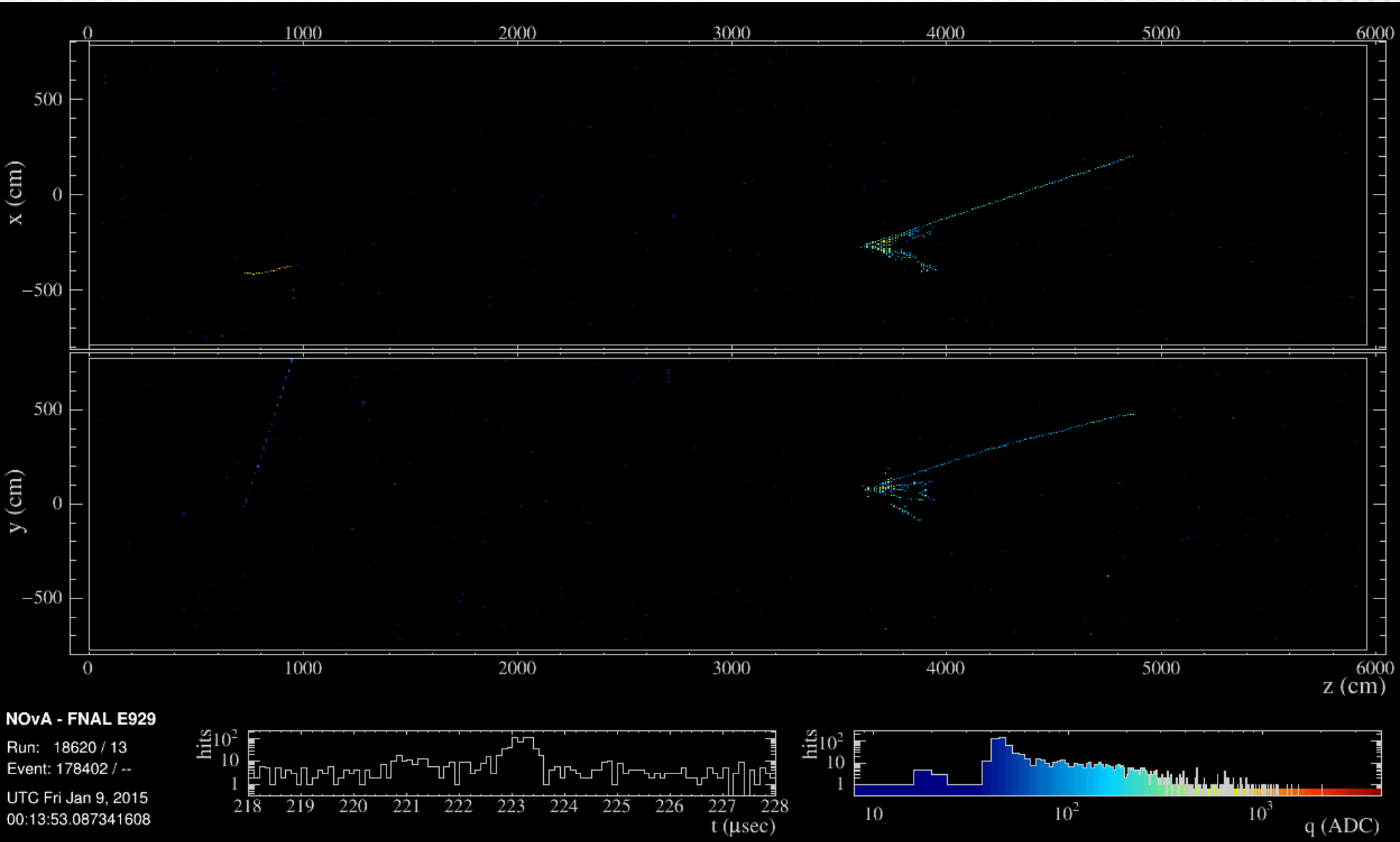
FAR DETECTOR

FD DATA



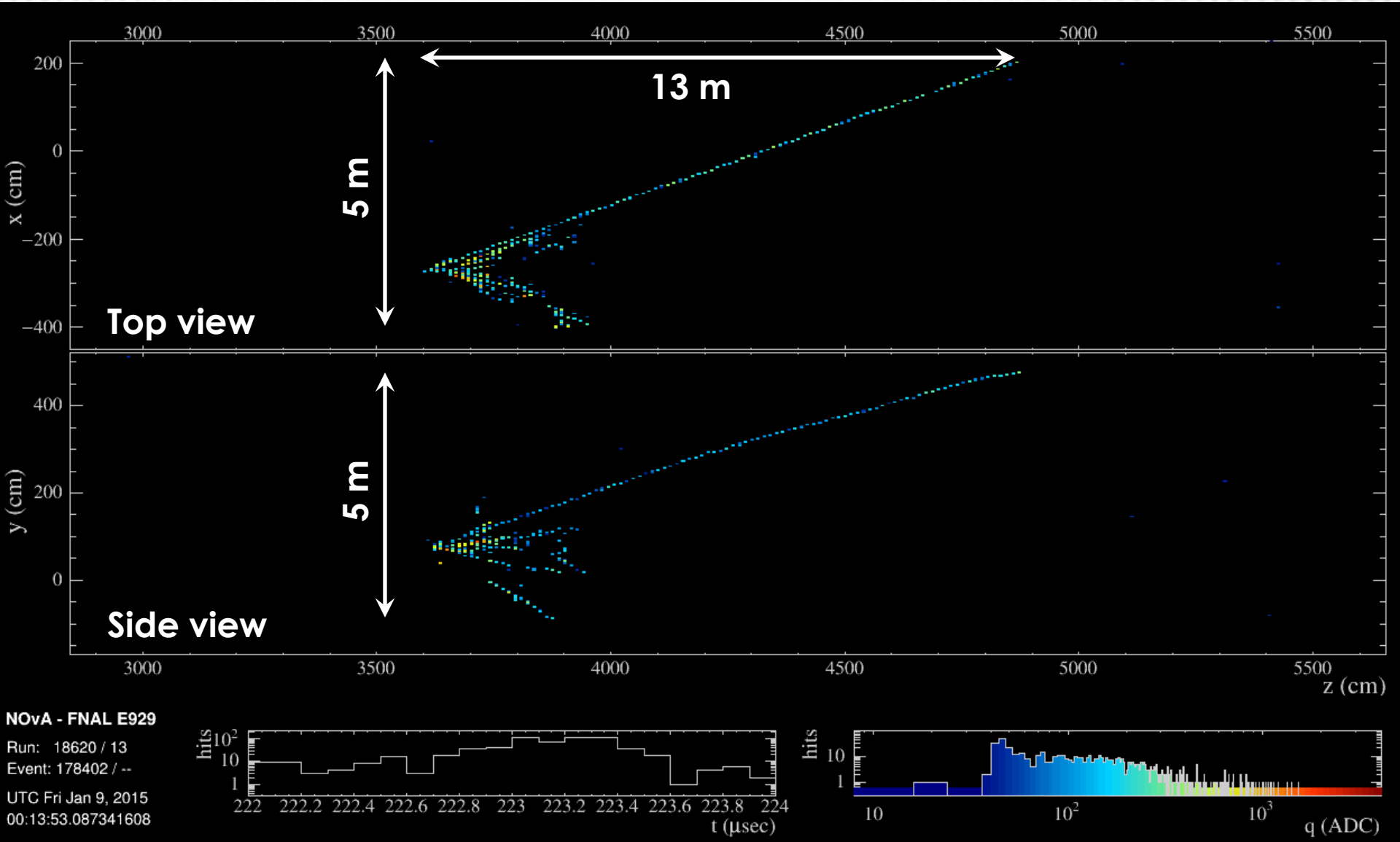
550 μs trigger window

FD DATA



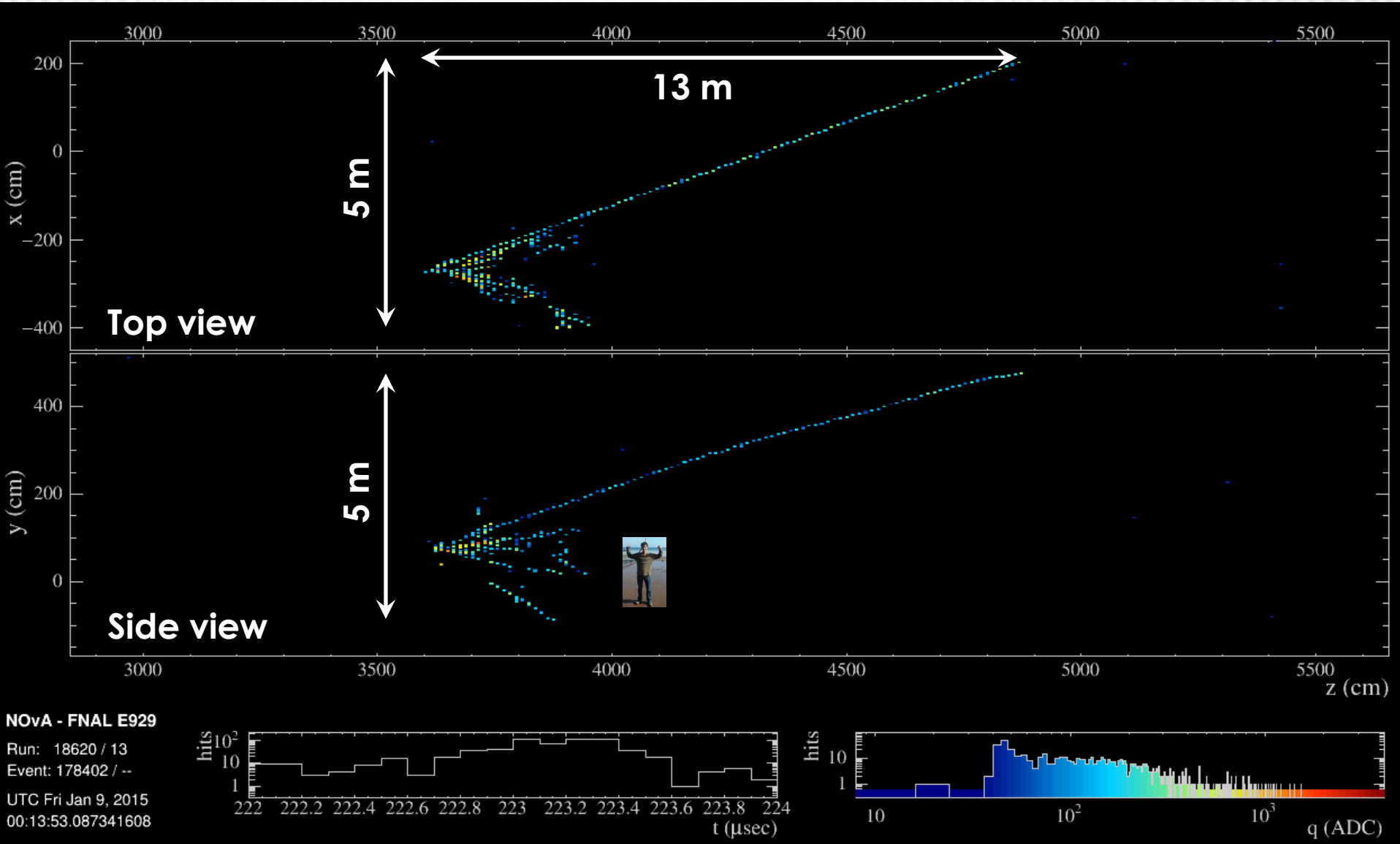
10 μs beam window

FD DATA



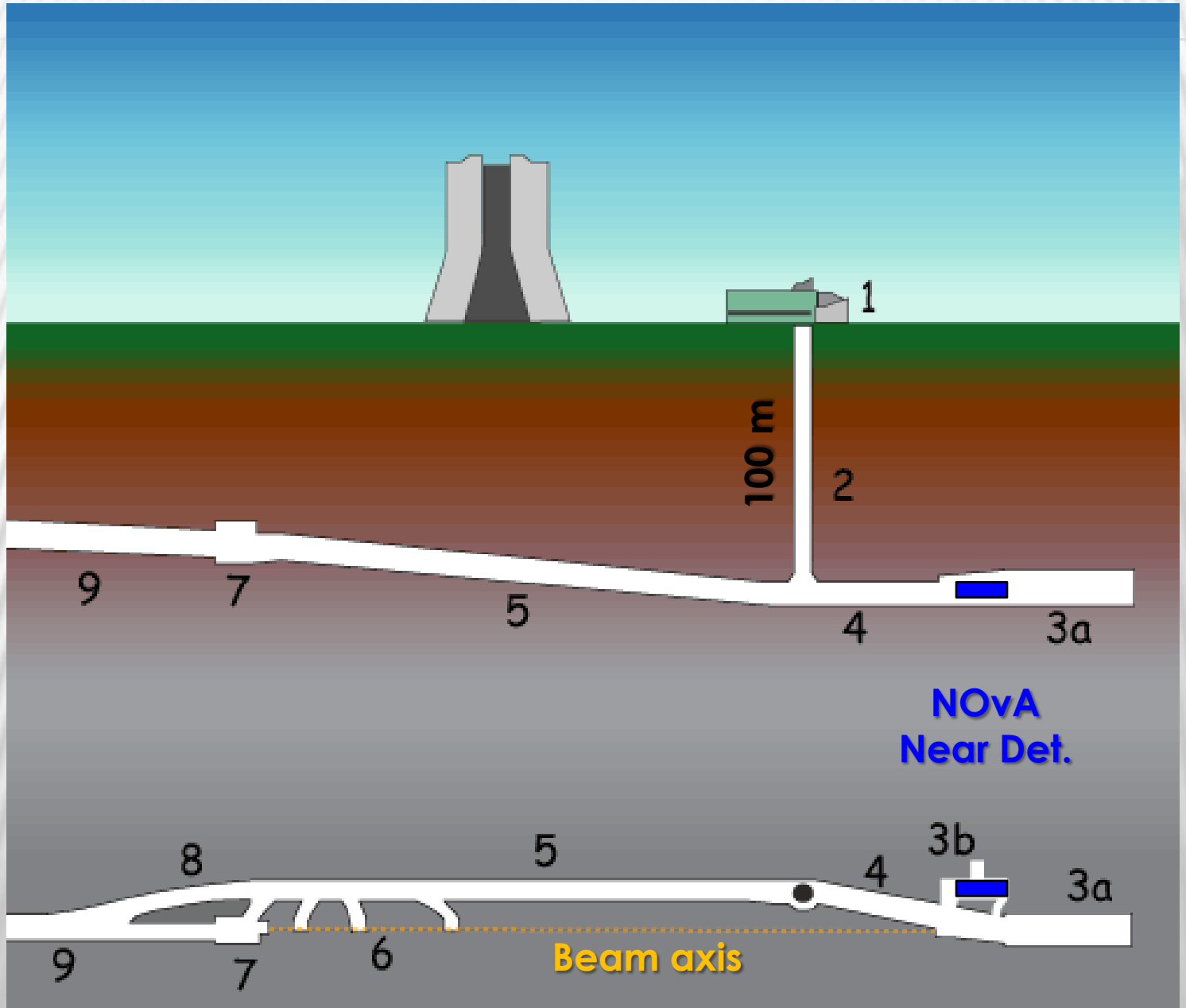
Zoom in on neutrino interaction

FD DATA

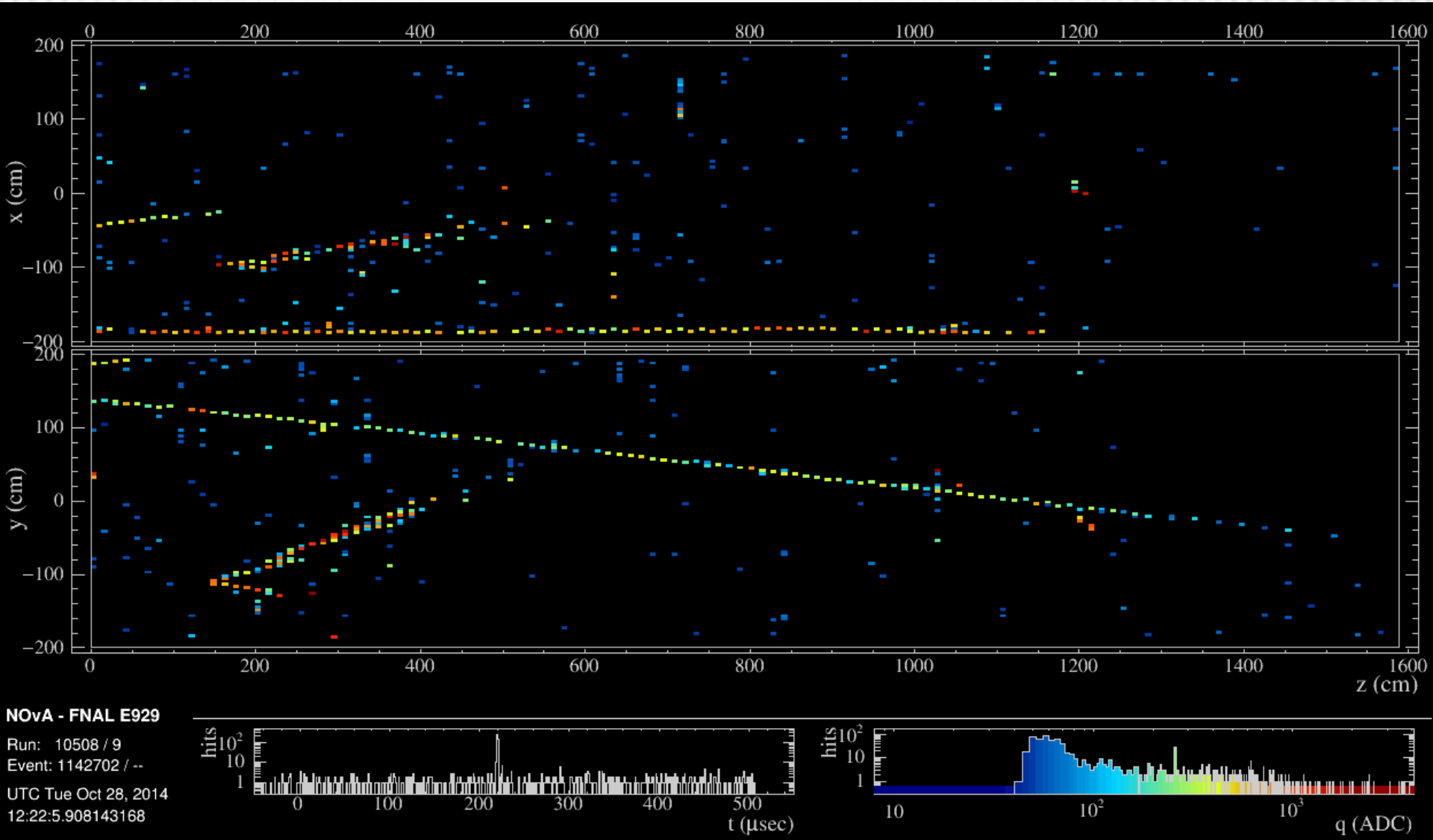


Zoom in on neutrino interaction

NEAR DETECTOR

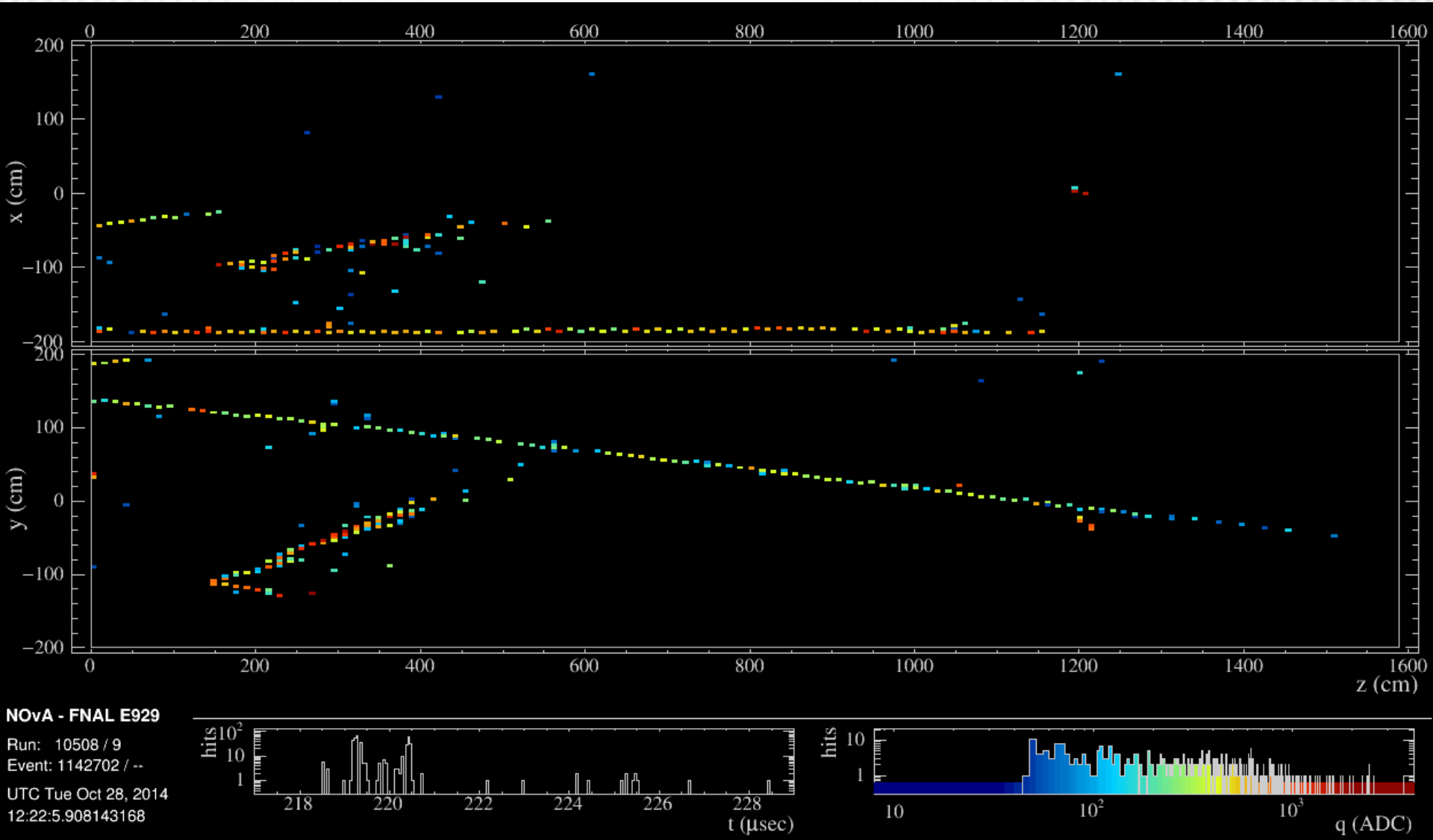


ND DATA



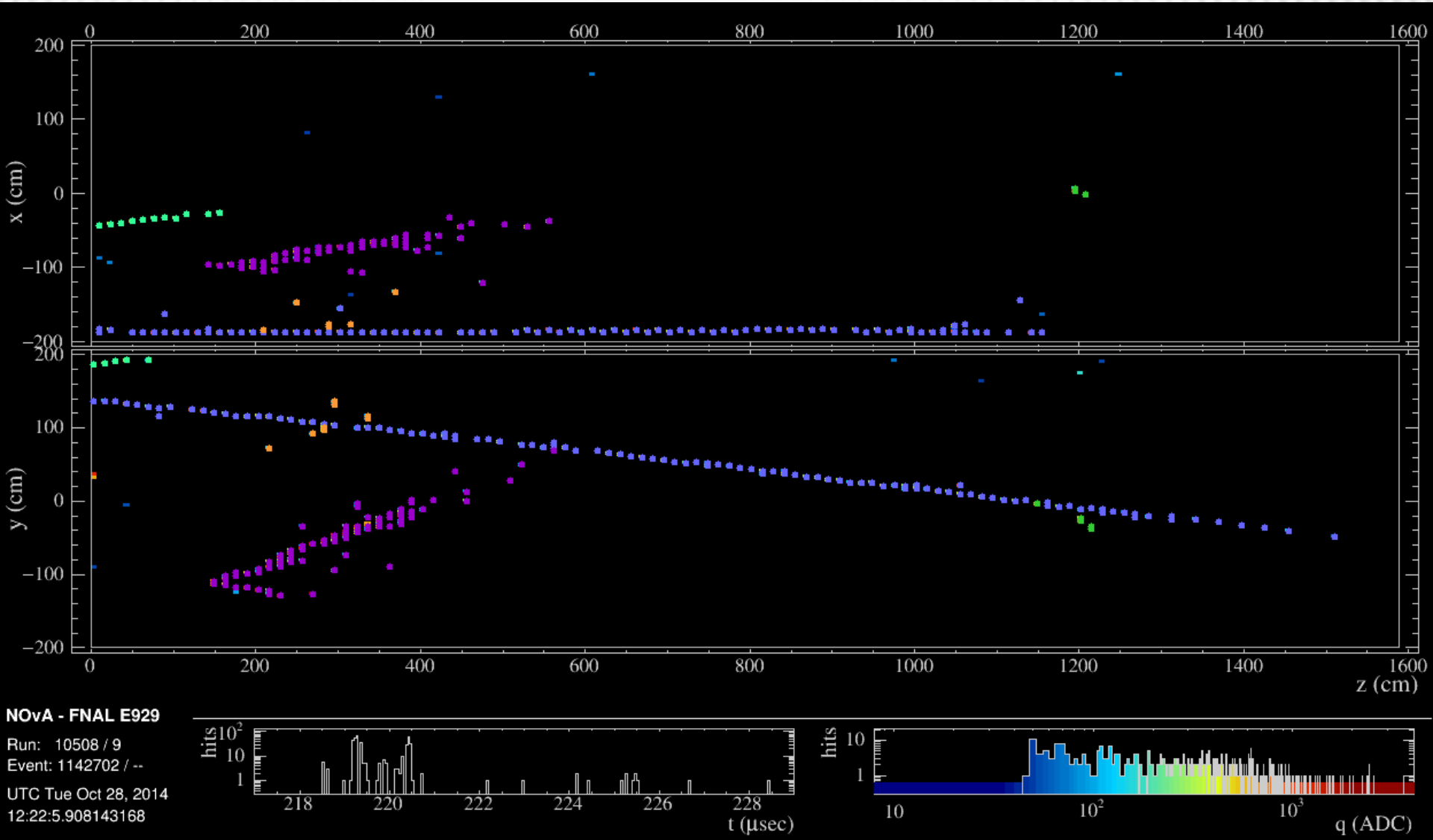
550 μs trigger window

ND DATA



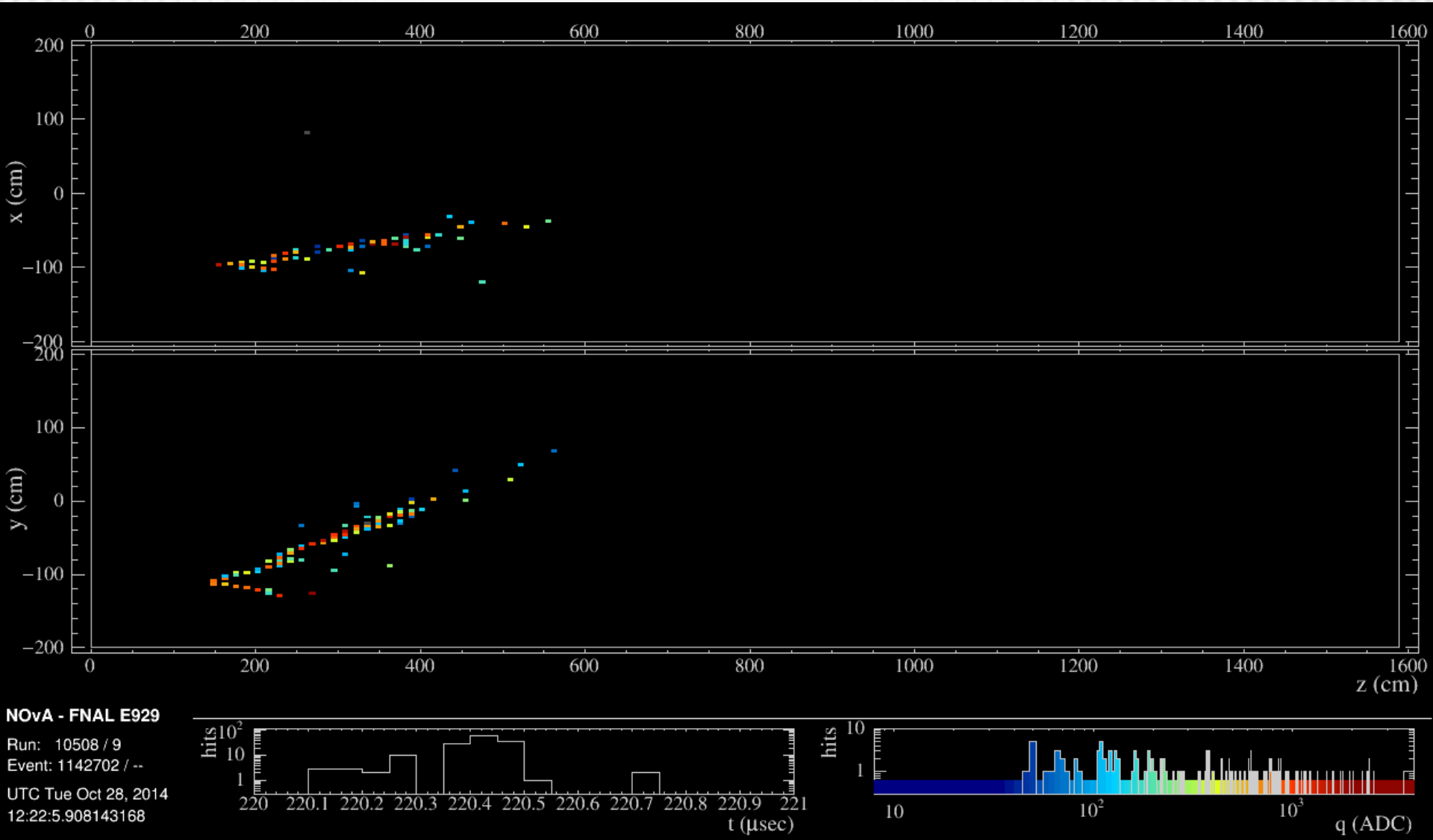
10 μs beam window

ND DATA



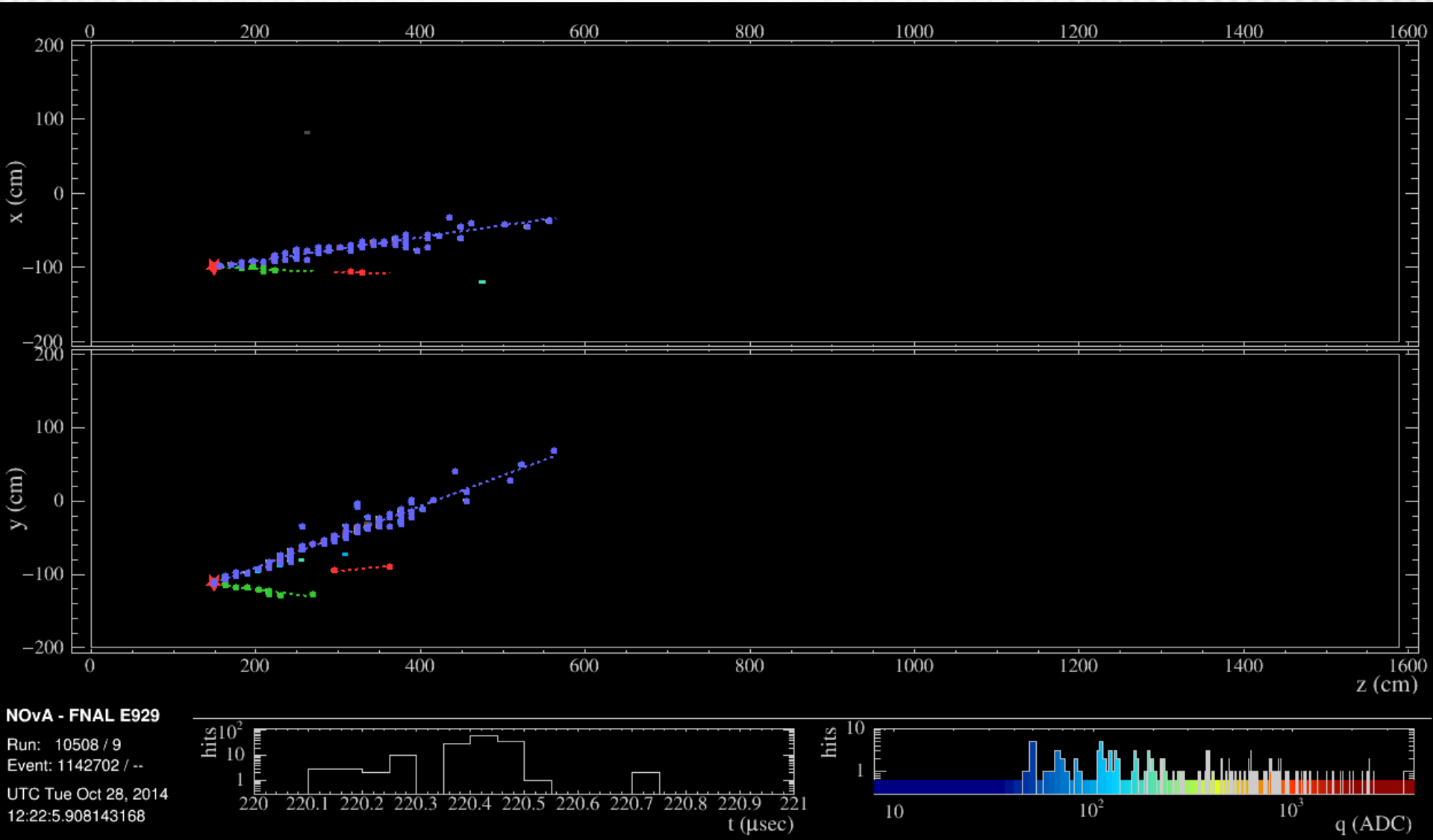
Separate into different interactions (slices)

ND DATA



Isolate contained neutrino interaction

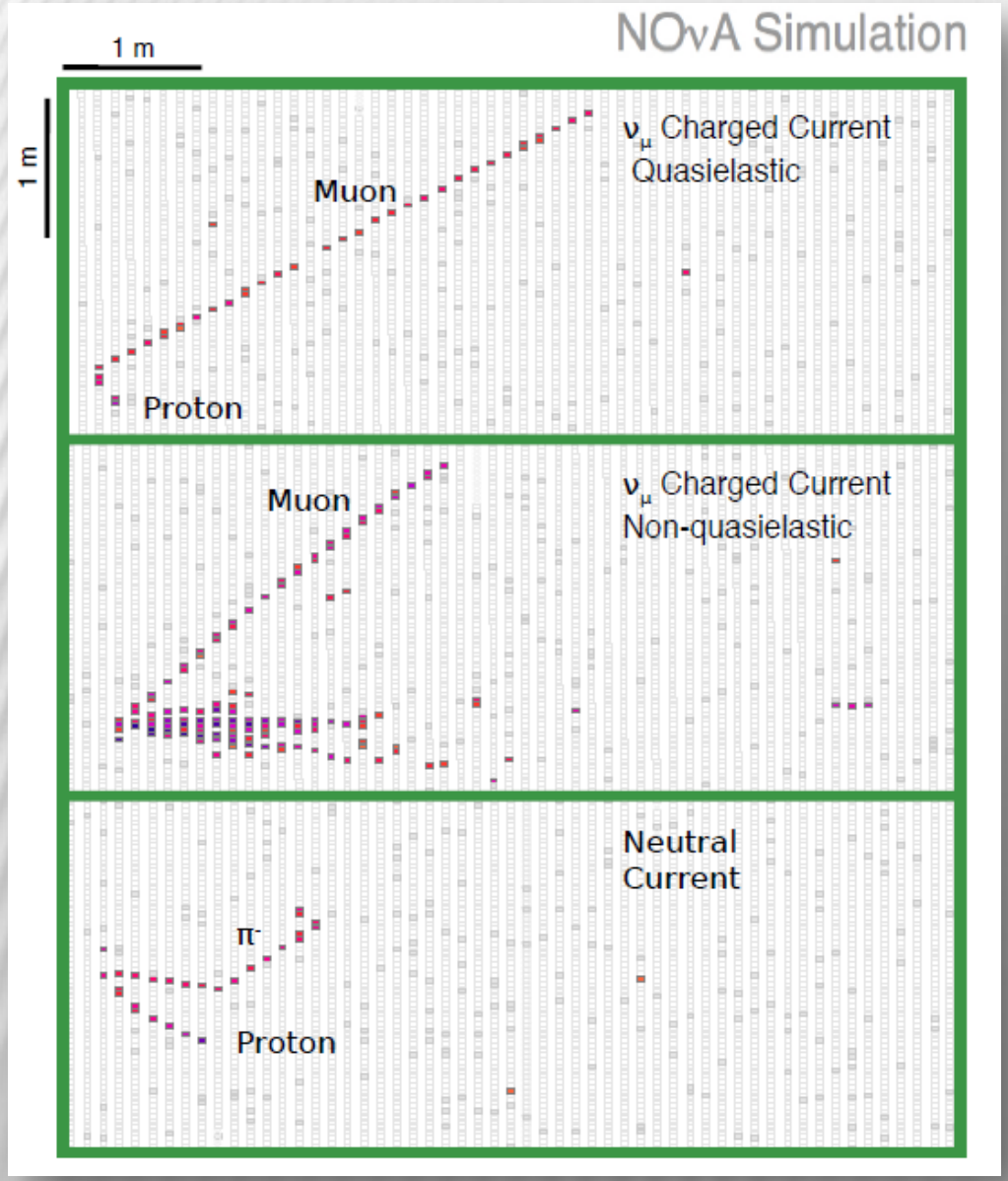
ND DATA

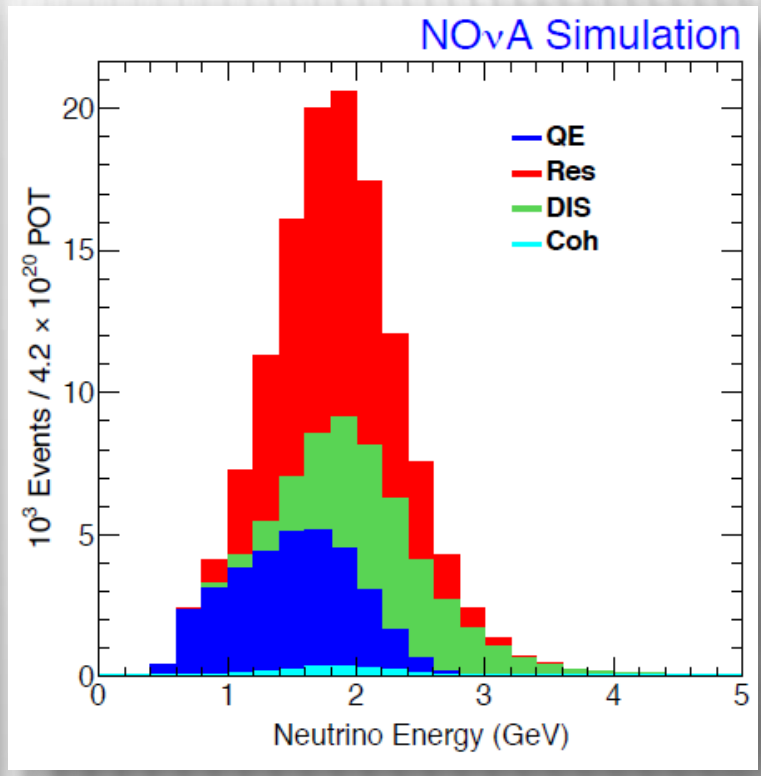


Reconstruct vertex and clusters

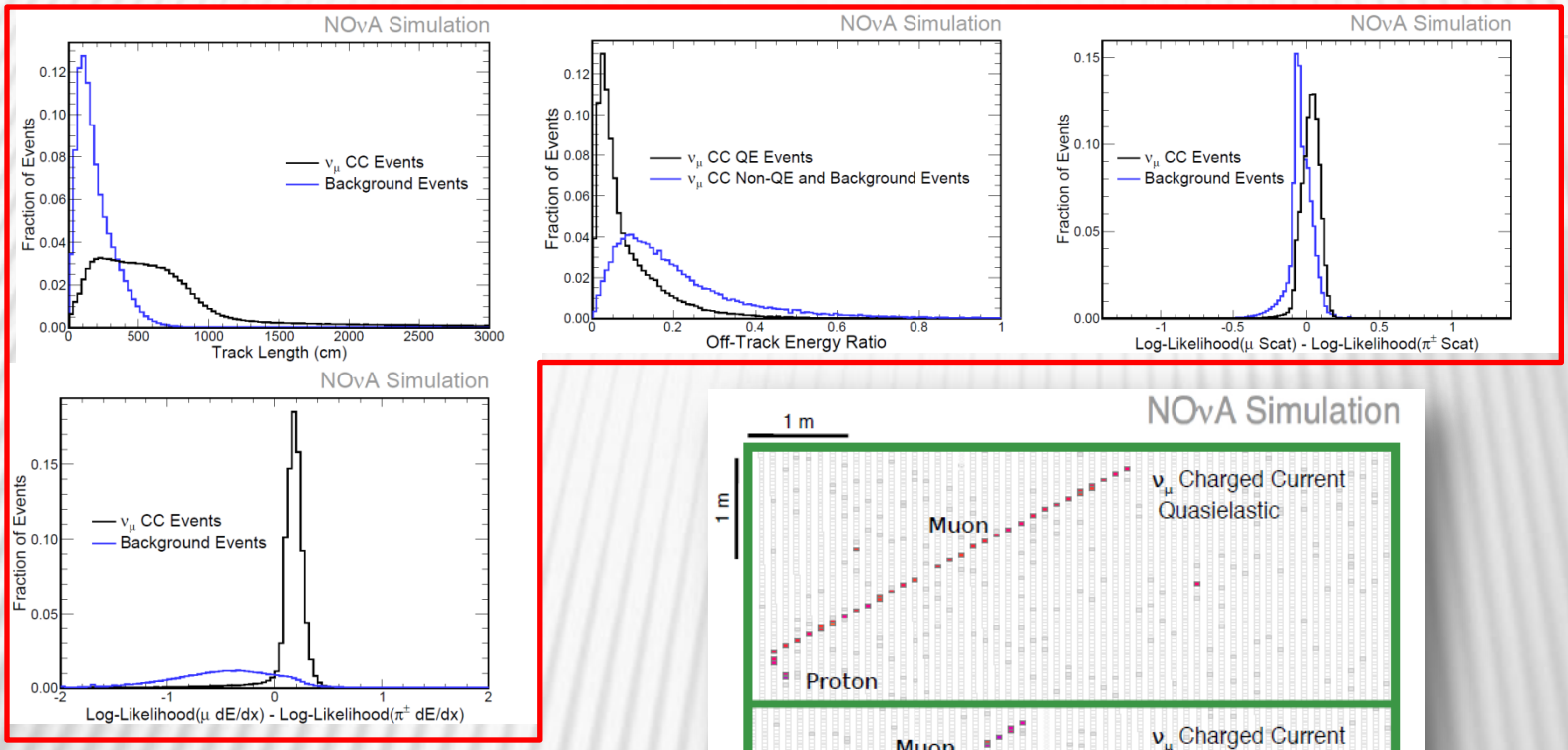
NUMU DISAPPEARANCE

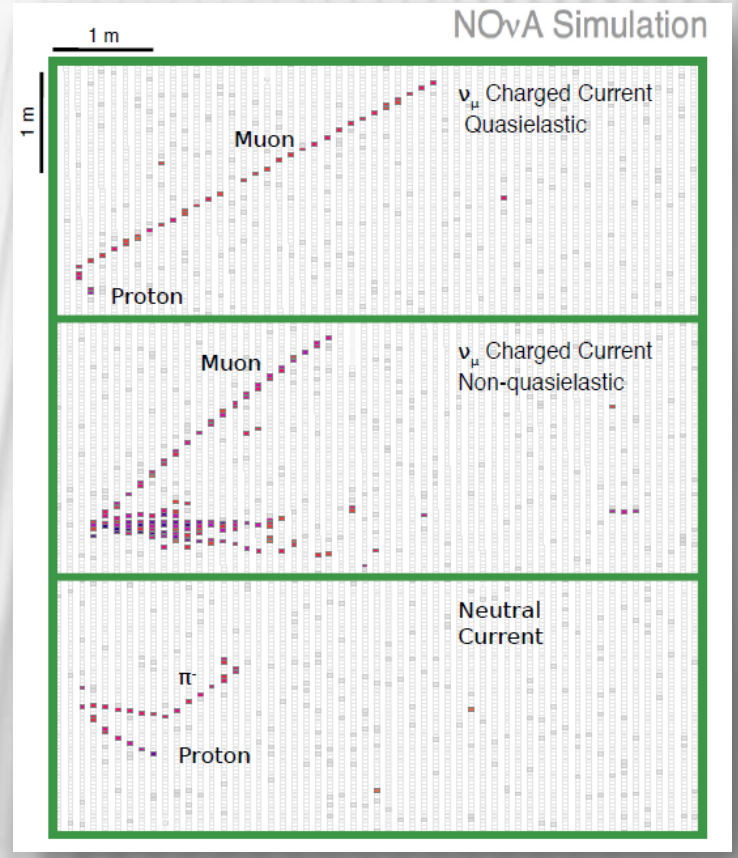
NOVA TOPOLOGIES



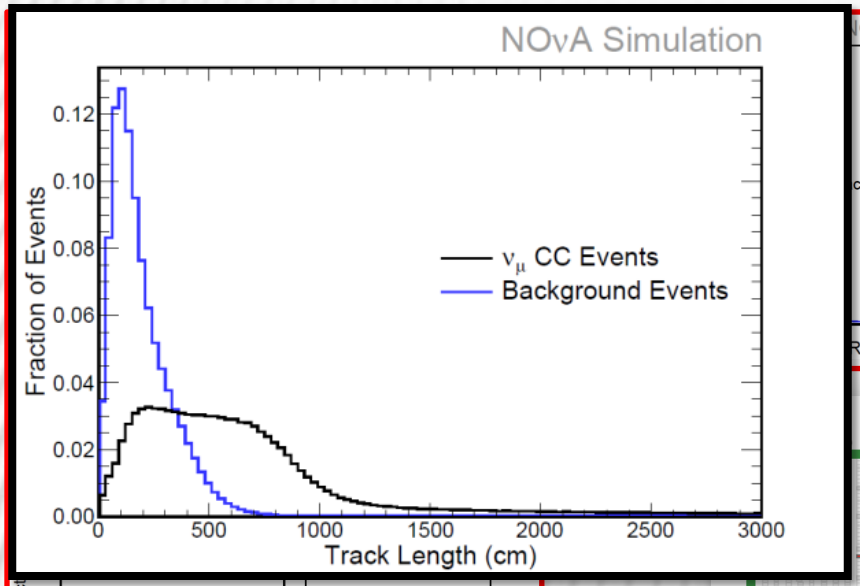


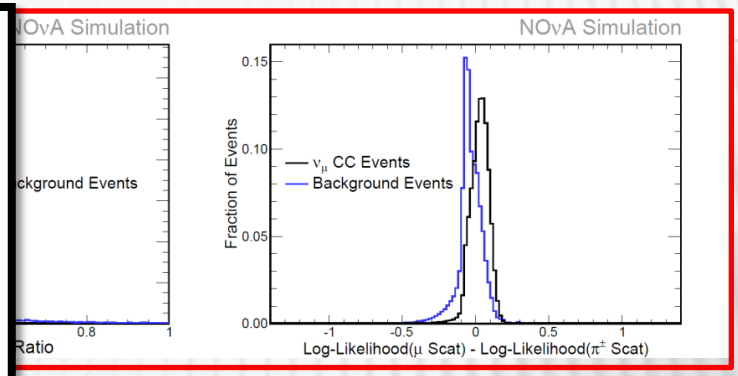
NC REJECTION

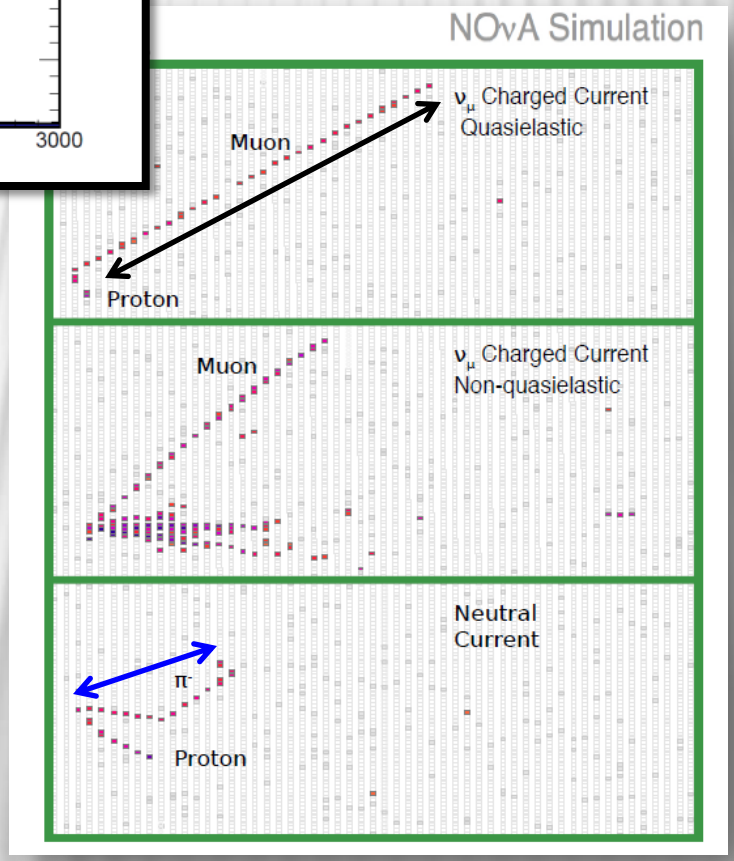




NC REJECTION







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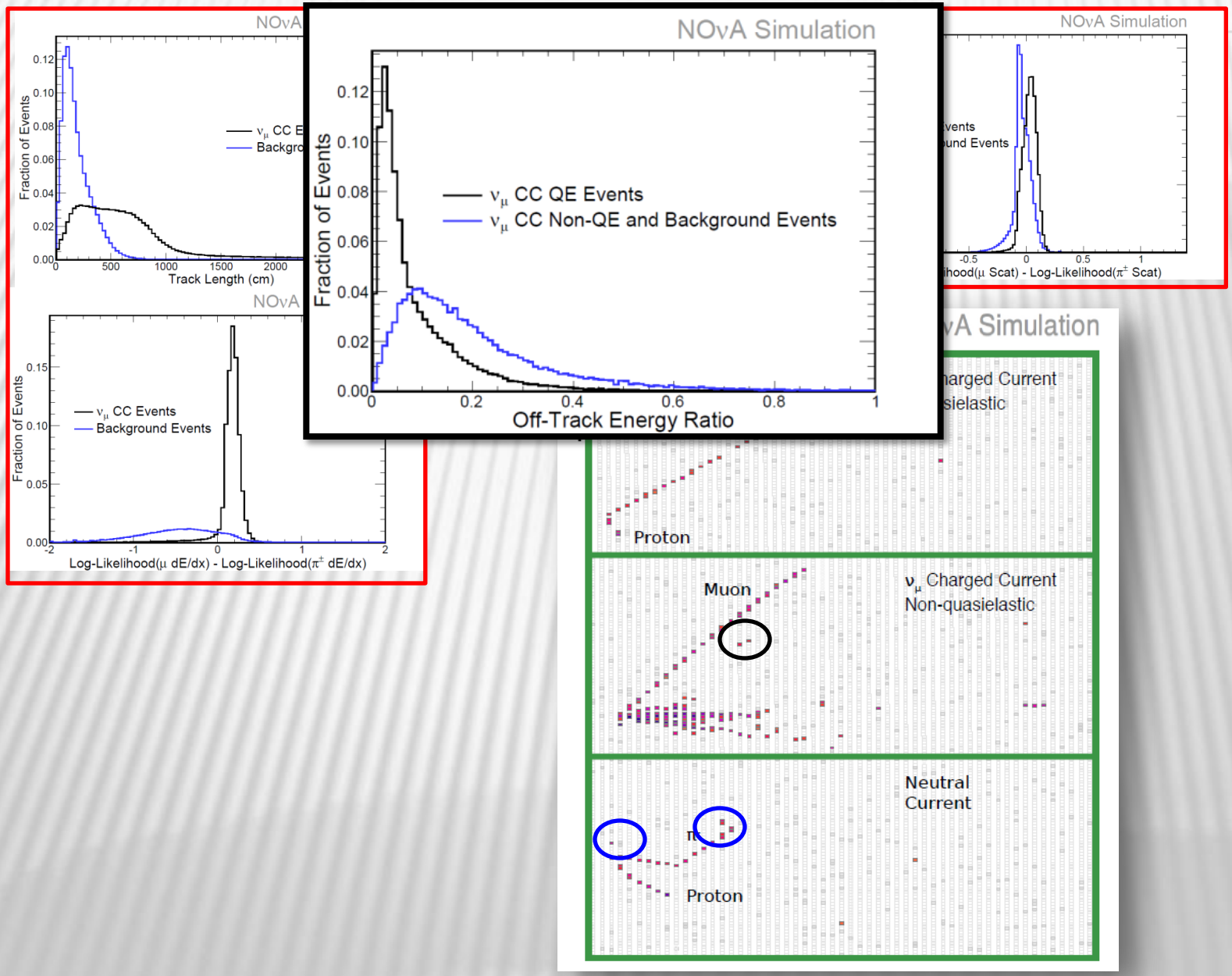
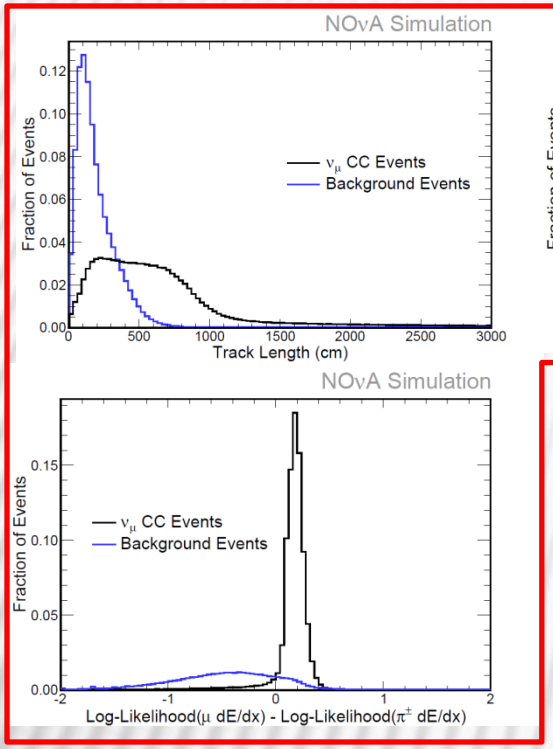
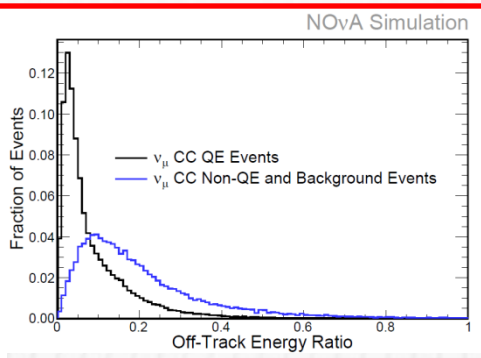
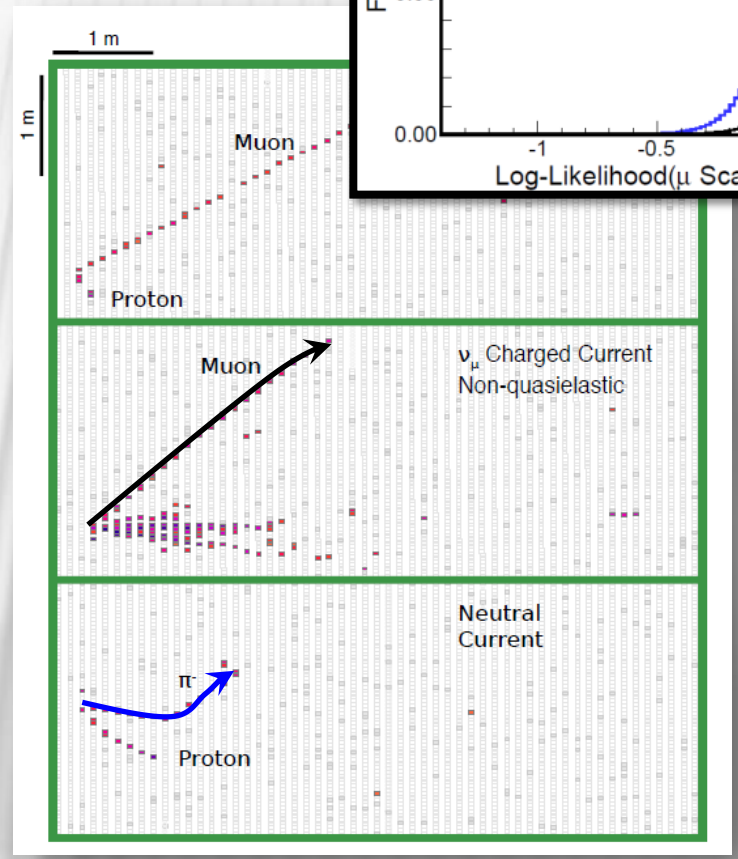
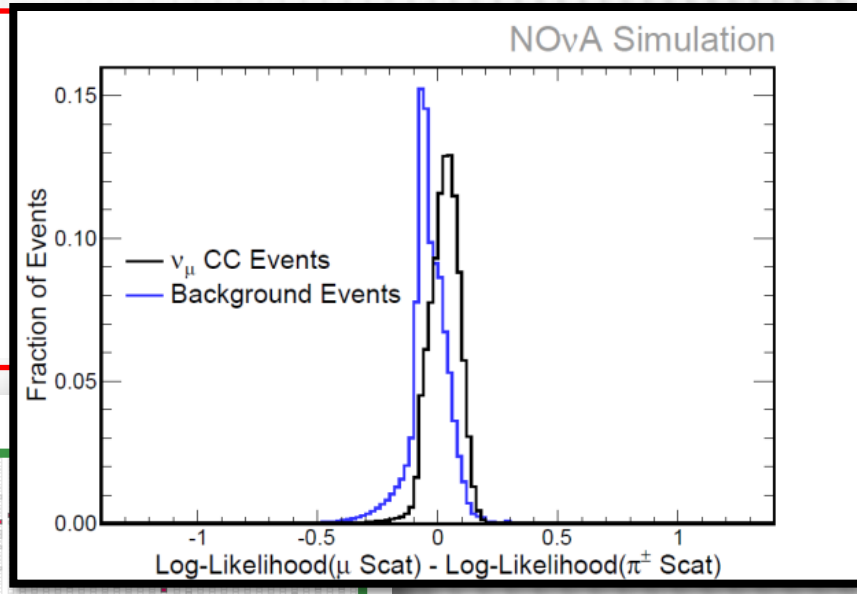


NC REJECTION









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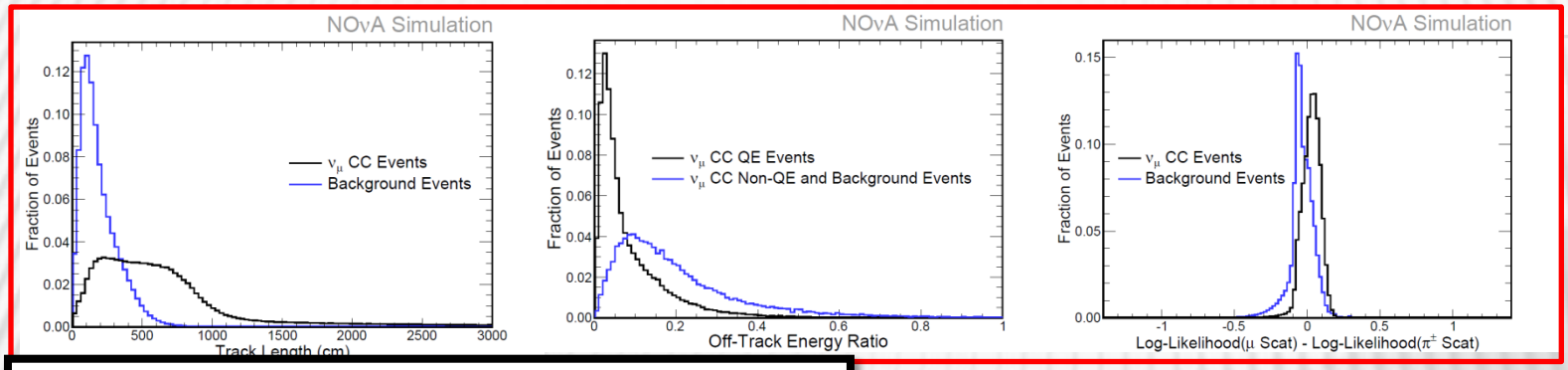

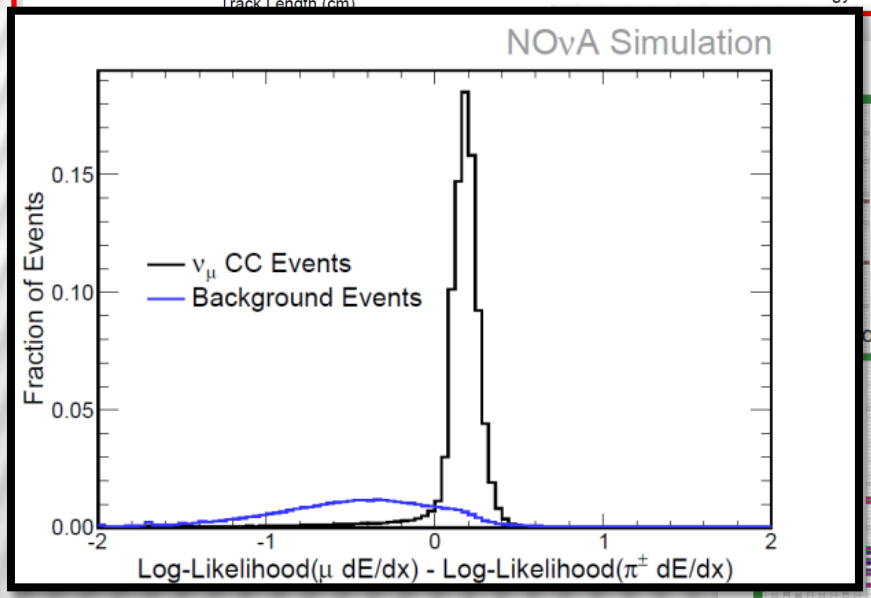

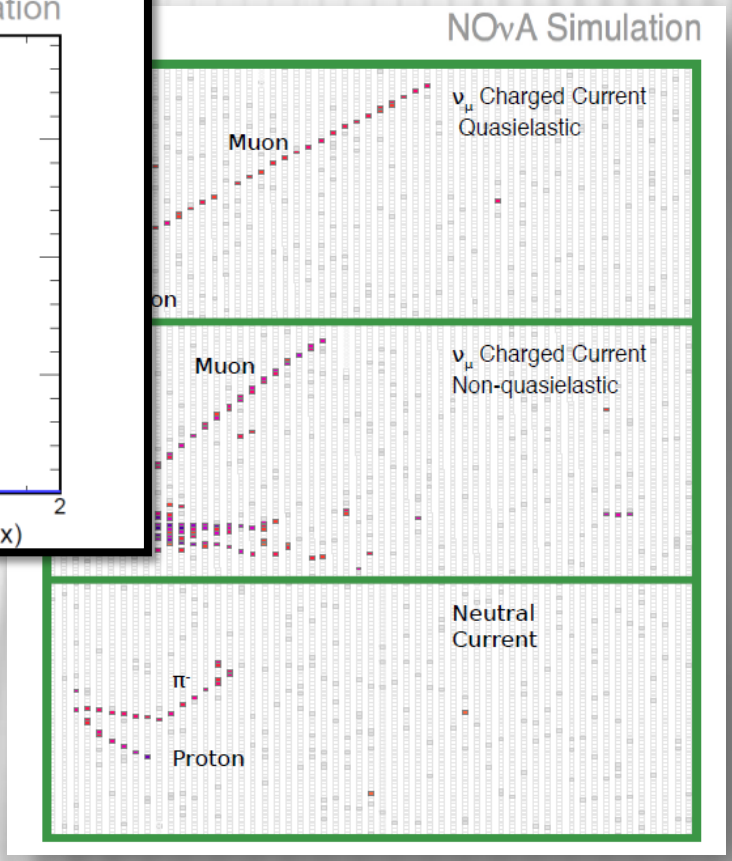

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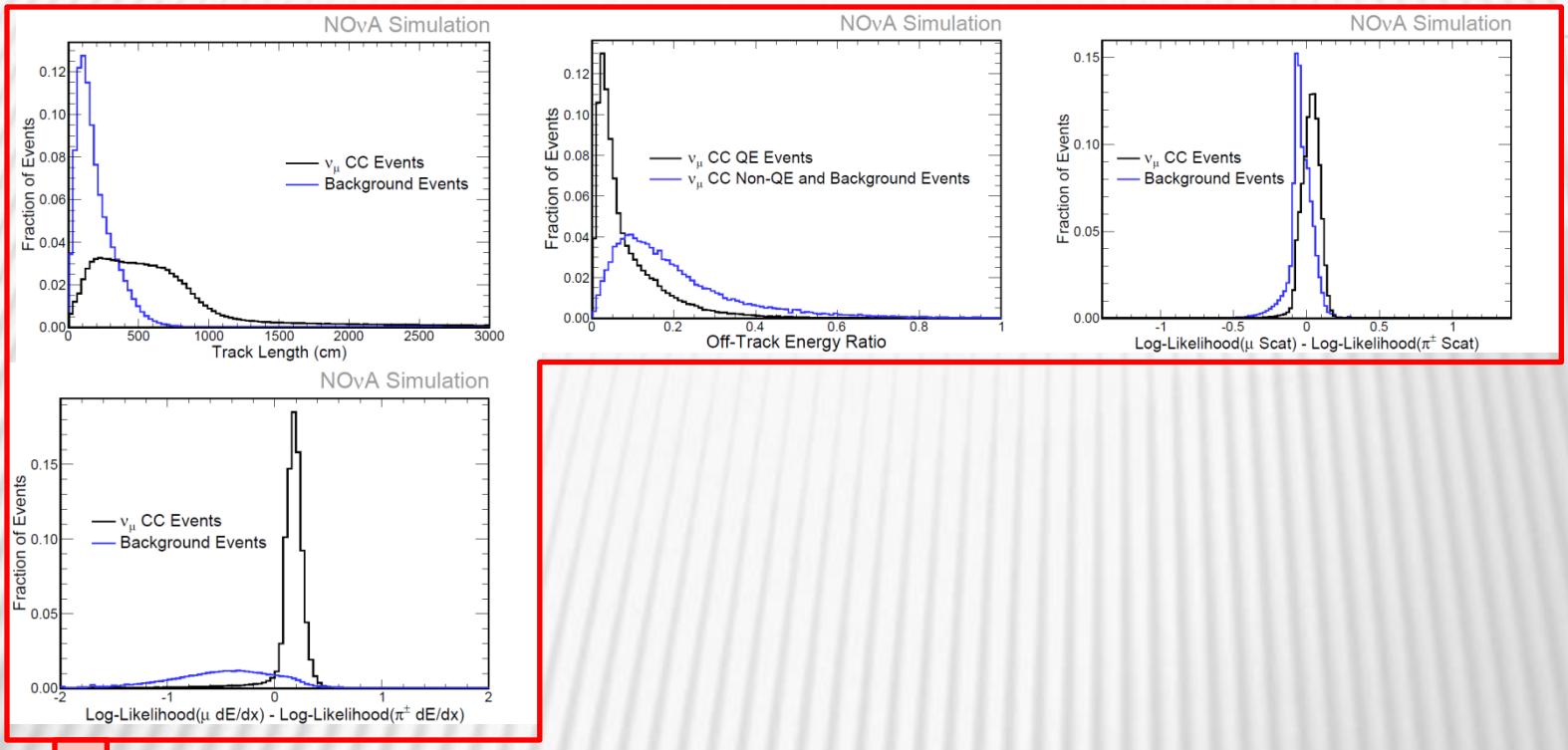

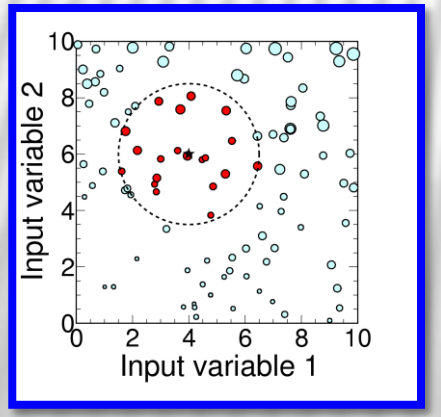

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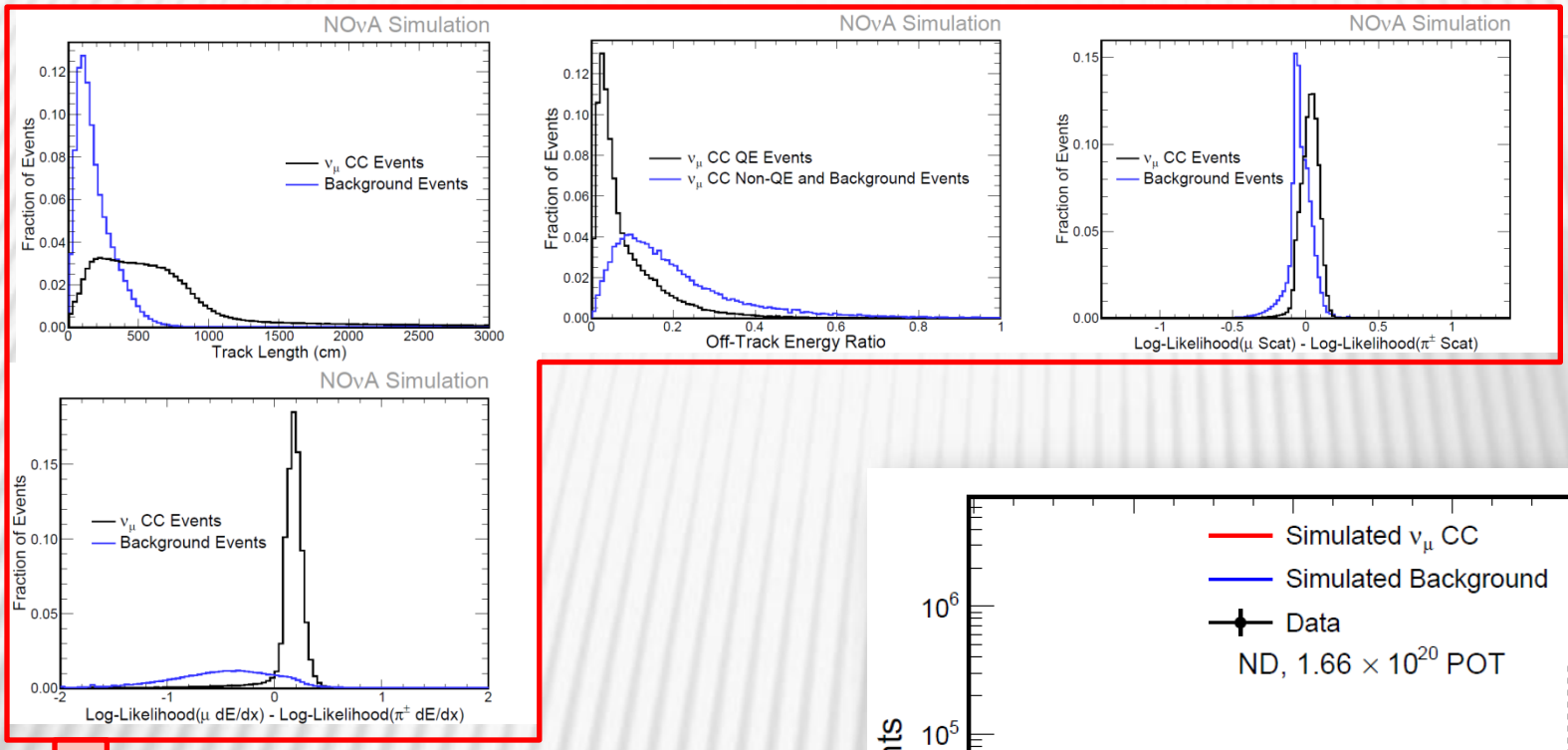
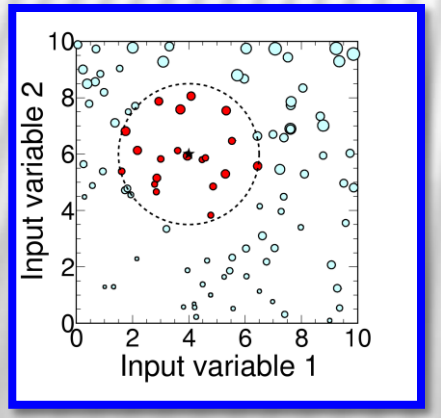
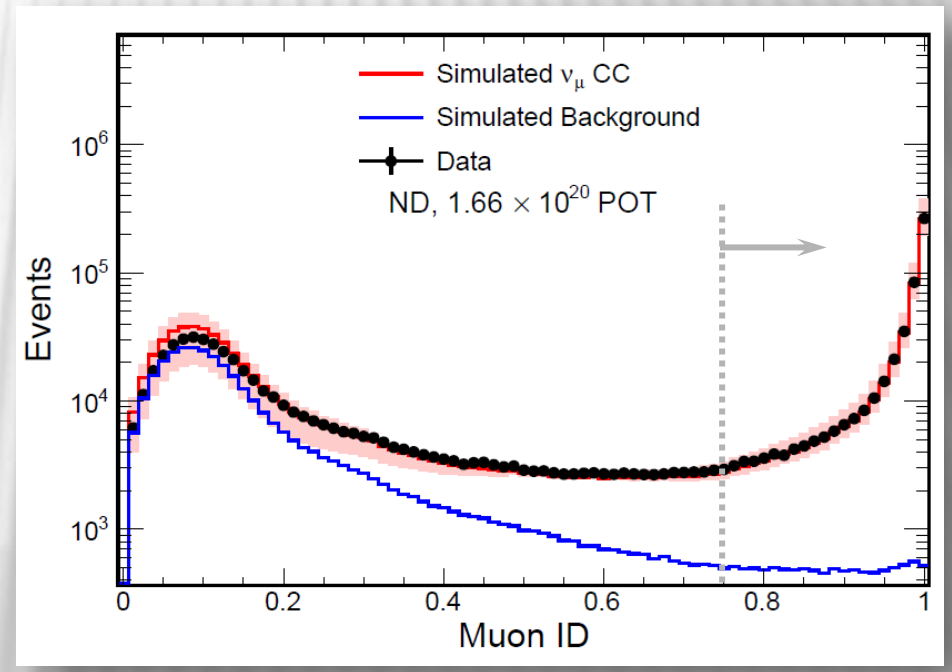
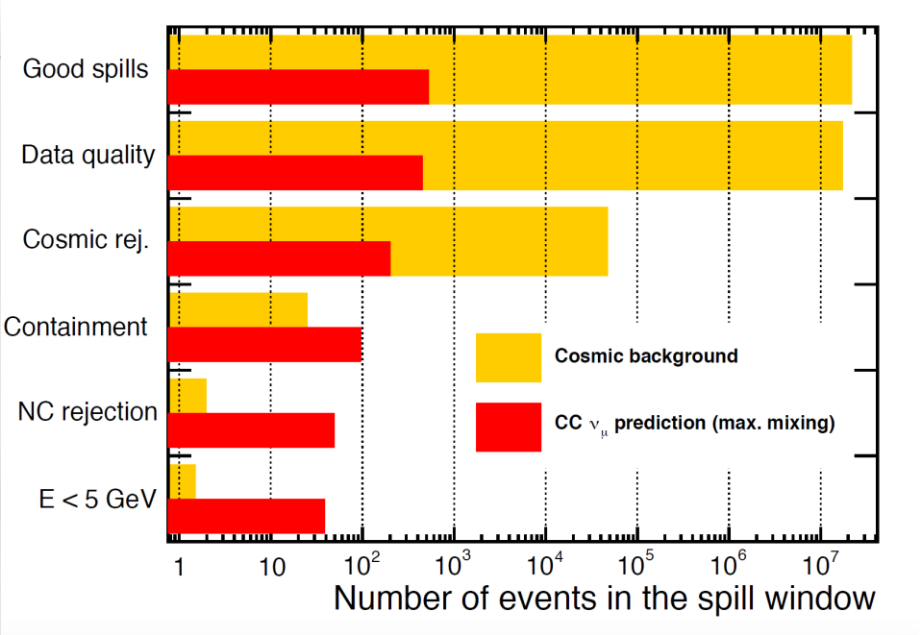


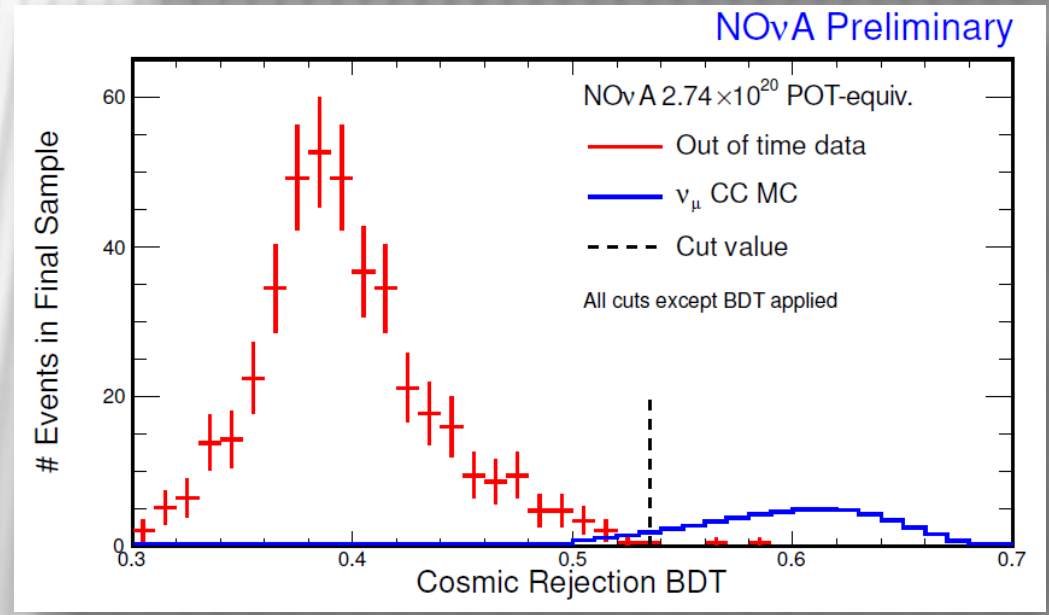




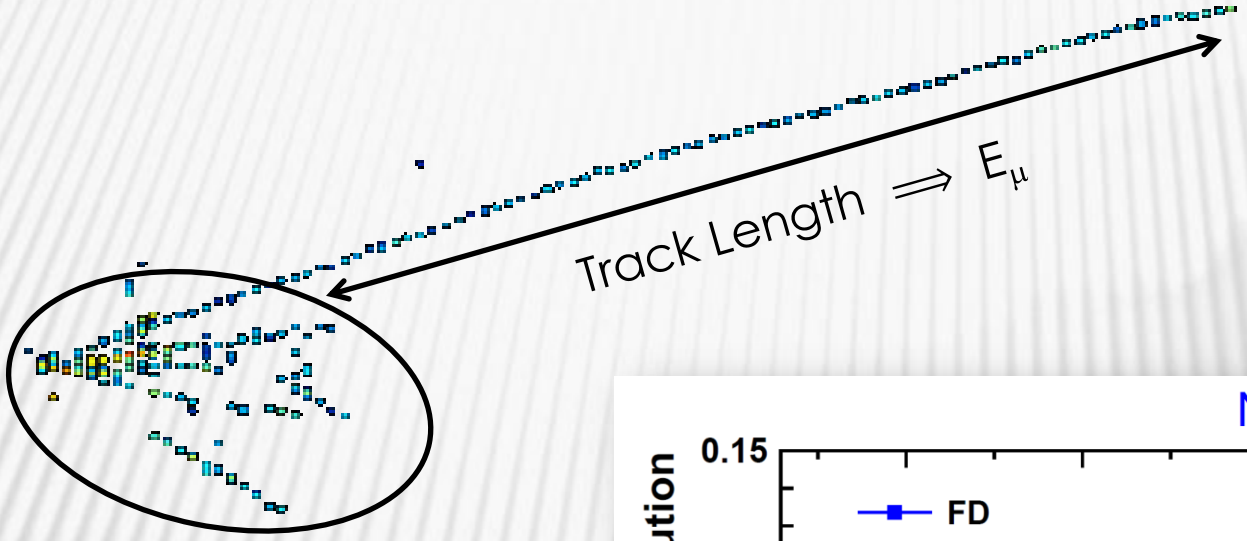
COSMIC REJECTION

- Cosmic rate is O(100kHz)
- Pulsed beam achieves a 10^5 rejection factor (9.6μs every 1.3s)
- Topology adds a 10^7 rejection factor
- Track information used in BDT



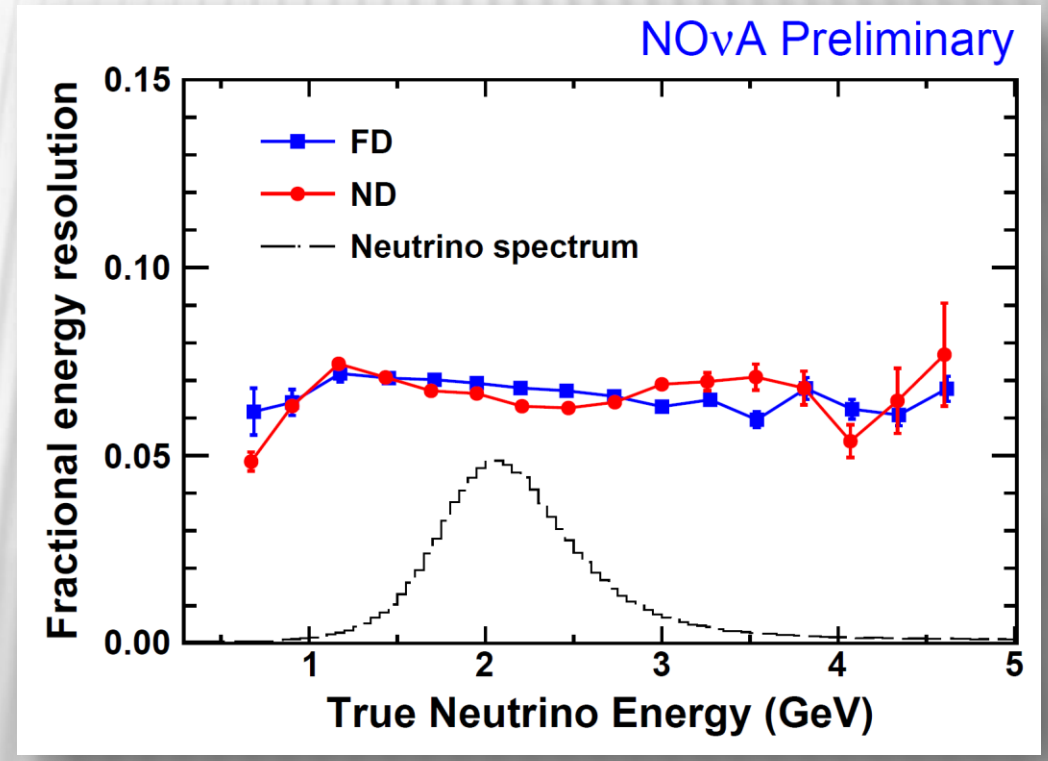


NEUTRINO ENERGY



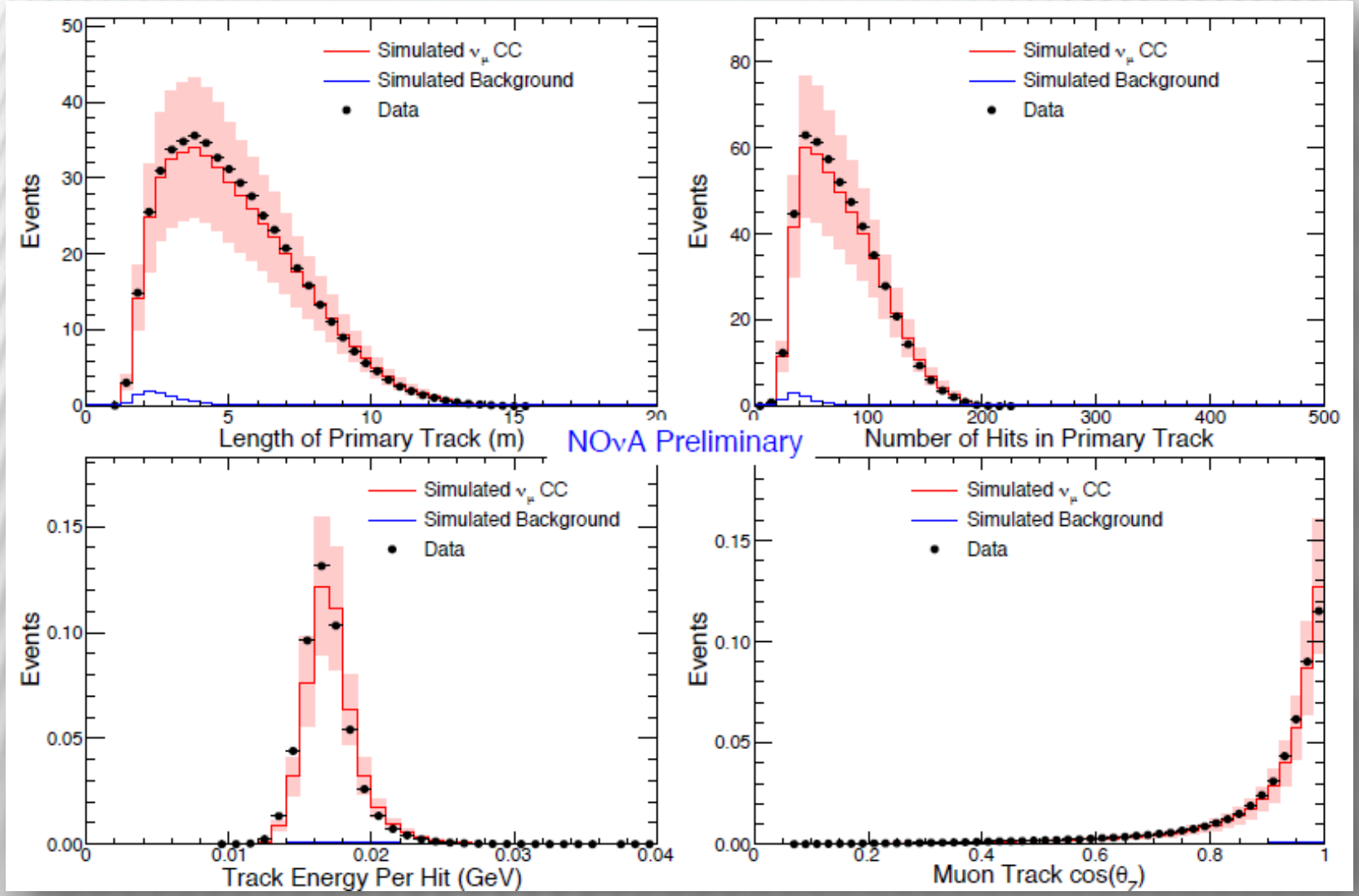
$Cal(\Sigma E_{vis}) \Longrightarrow E_{had}$

$$E_\nu = E_\mu + E_{had}$$



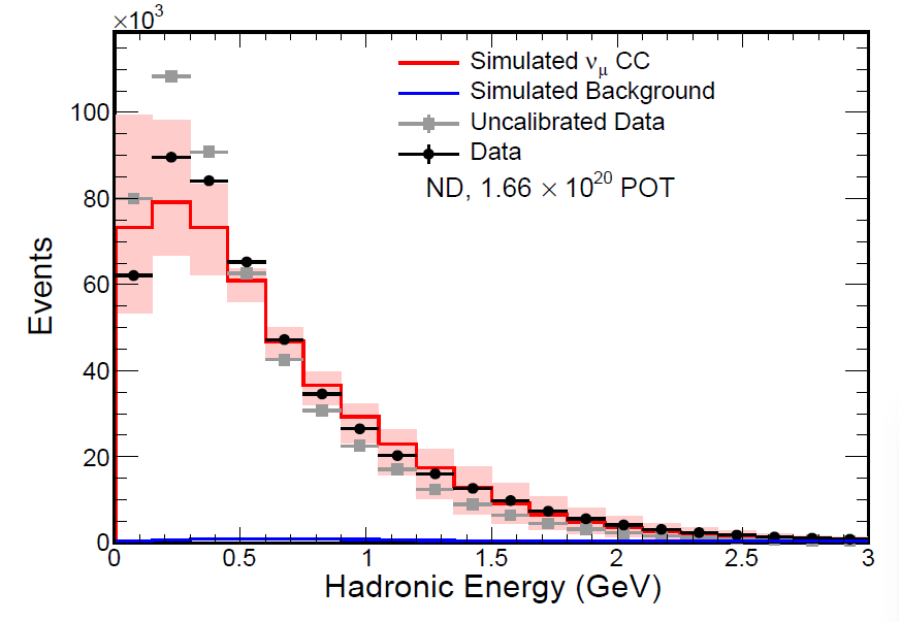
TRACK ENERGY

Muon properties are very well modeled



HADRONIC ENERGY

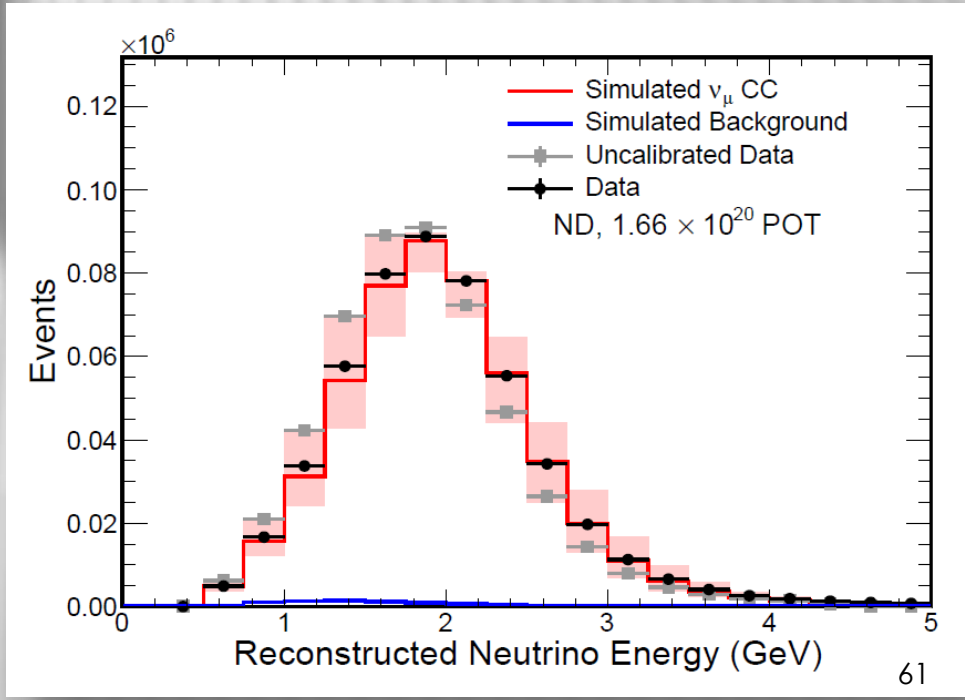
Significant discrepancies on recoil energy



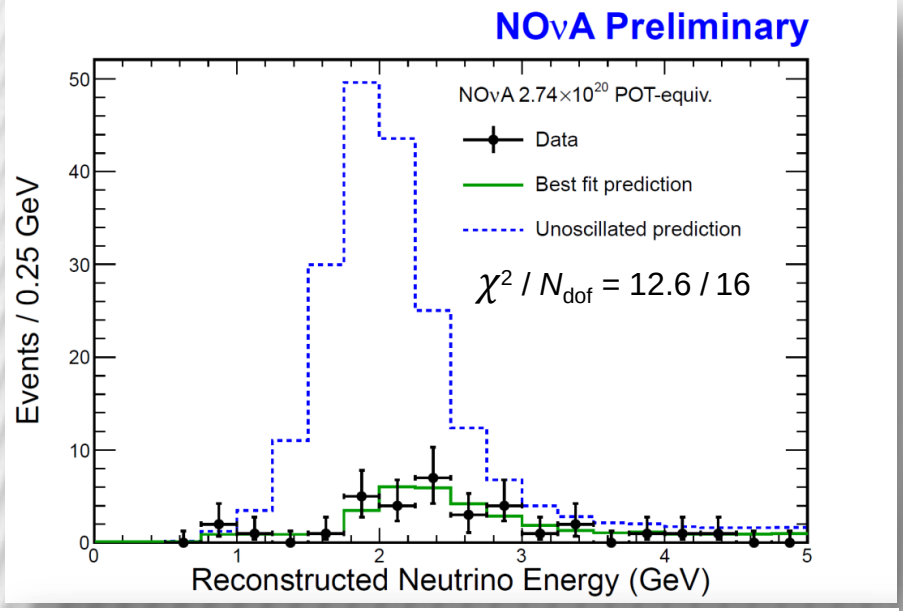
- Neutrino energy is well known from π-decay kinematics in off-axis beam

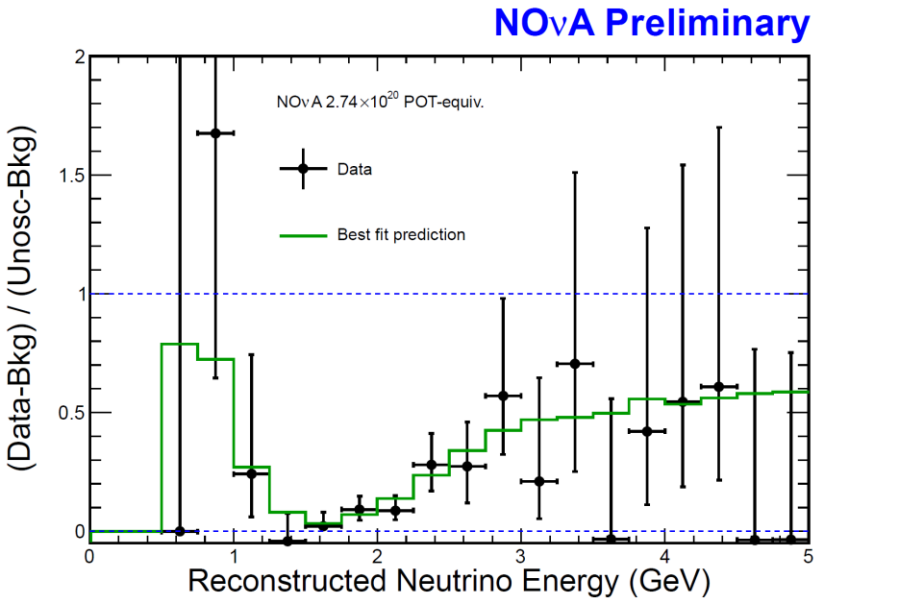
- Tune calibration of data to improve E_ν and E_{had}

- 21% shift on E_{had} taken as systematic uncertainty



NUMU DISAPPEARANCE





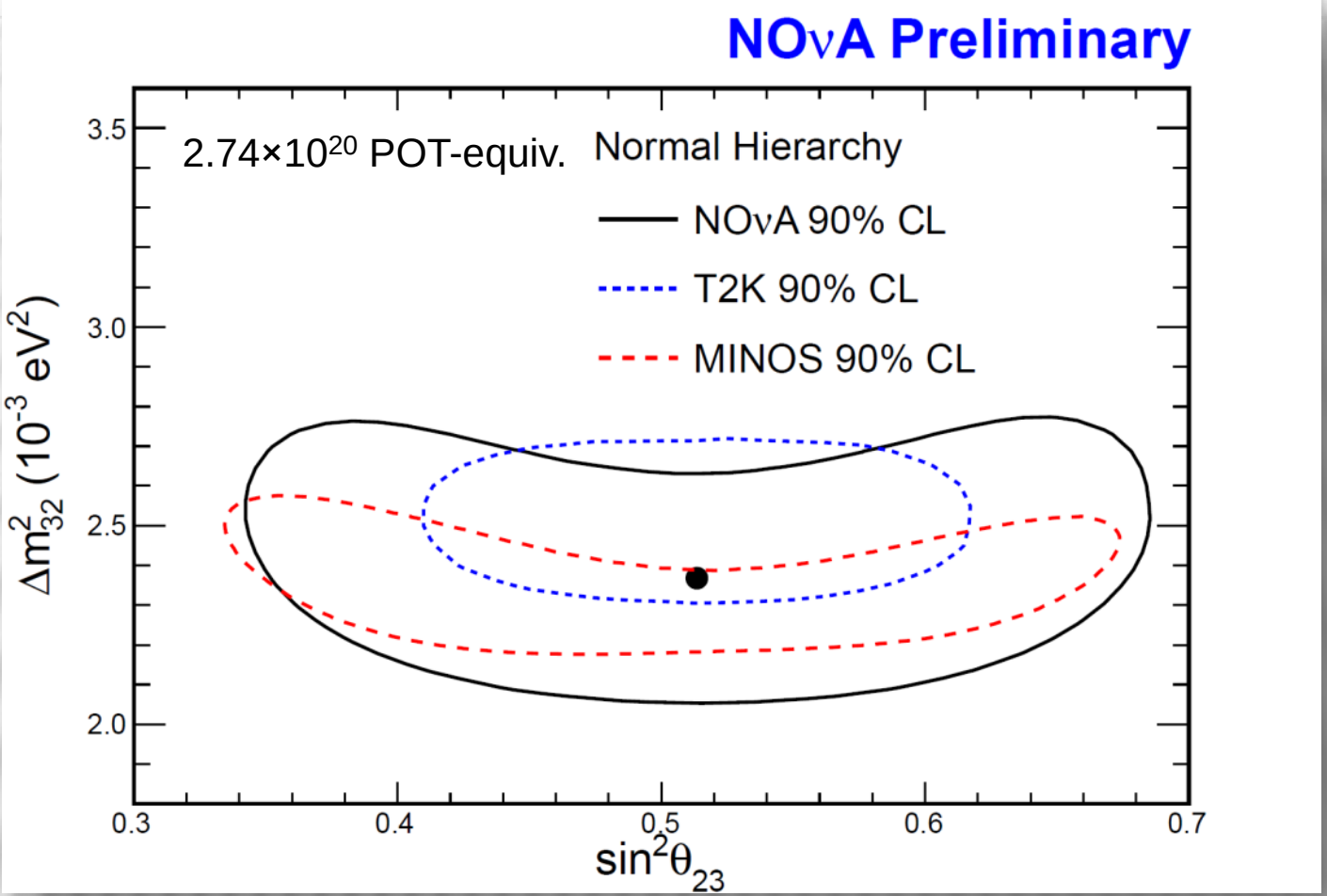
$$\Delta m^2_{32} = \begin{cases} +2.37\ ^{+0.16}_{-0.15}\ \text{[NH]} \\ -2.40\ ^{+0.14}_{-0.17}\ \text{[IH]} \end{cases} \times 10^{-3}\ \text{eV}^2$$

6.5% measurement uncertainty

$$\sin^2(\theta_{23}) = 0.51 \pm 0.10$$

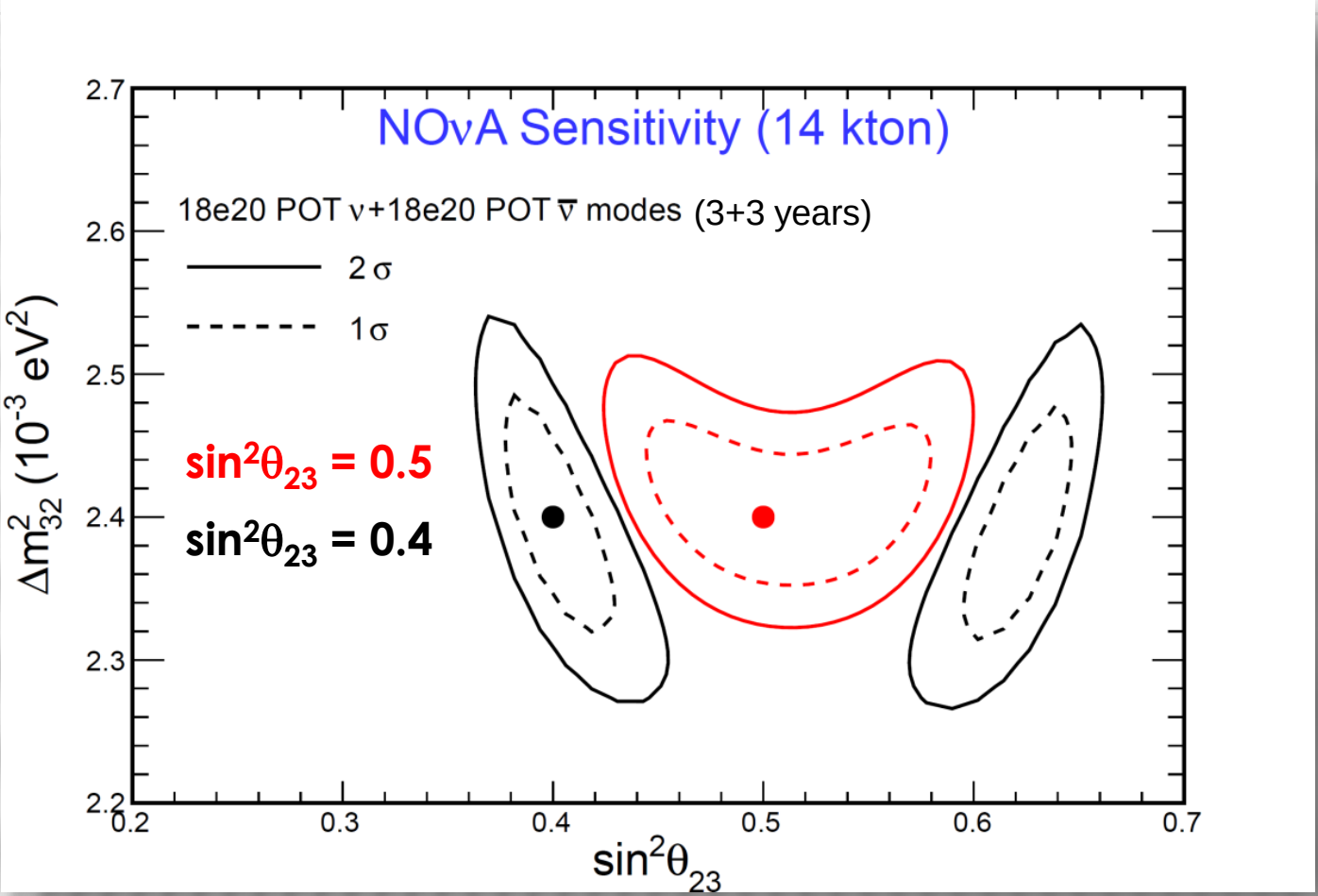
- Clear oscillation signal
- Observed **33 events**
- Expected 201 w/o osc. (including 2.0 beam bkdg. and 1.4 cosmic bkgd.

NUMU DISAPPEARANCE



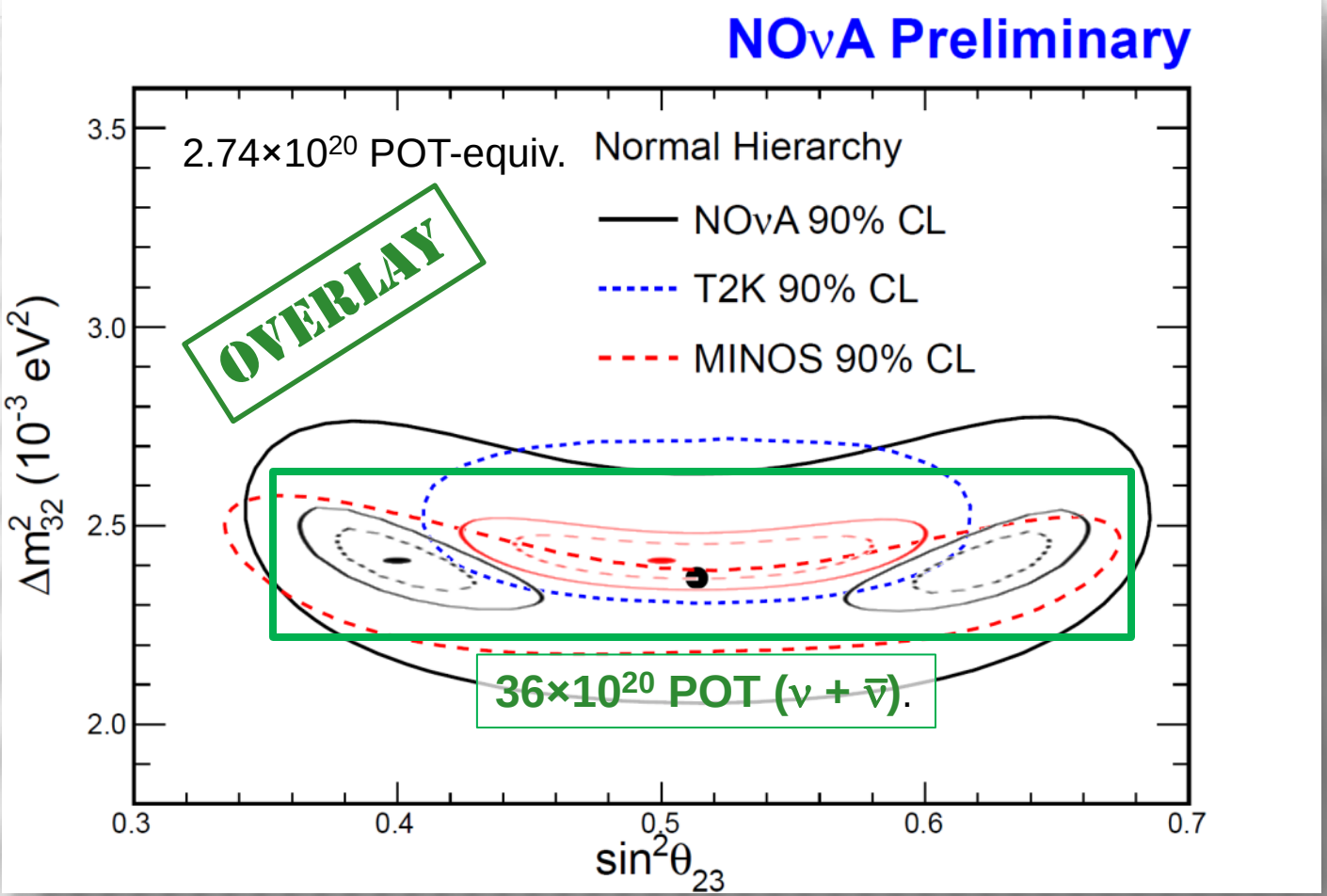
- Consistent with MINOS and T2K
- Competitive with only 7.6% of nominal exposure

NUMU DISAPPEARANCE



- Expect ~1% precision on $\sin^2 2\theta_{23}$ in 6 years
- ~2% precision on $|\Delta m^2_{32}|$ in 6 years

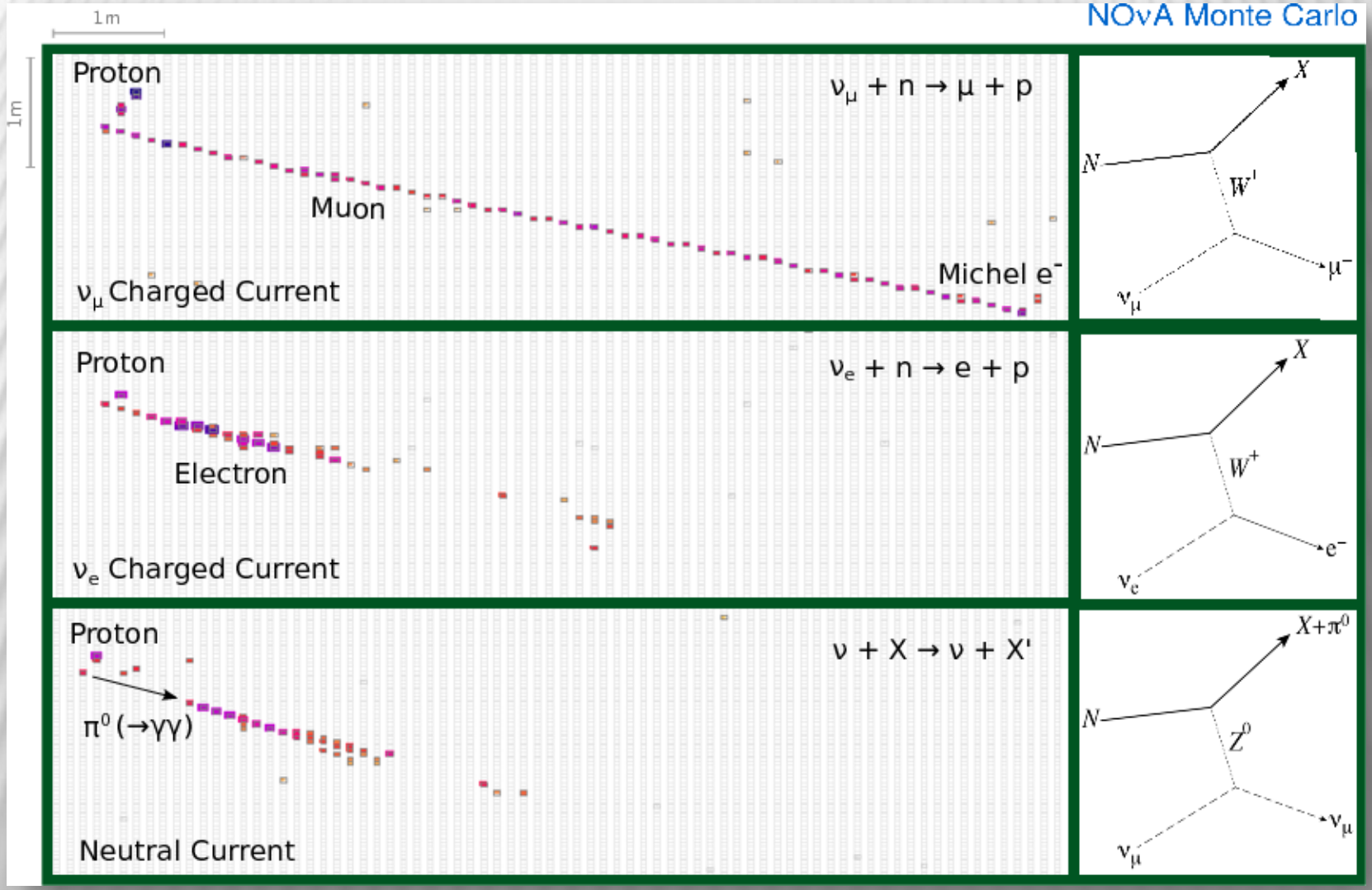
NUMU DISAPPEARANCE



- Expect ~1% precision on $\sin^2 2\theta_{23}$ in 6 years
- ~2% precision on $|\Delta m^2_{32}|$ in 6 years

NUE APPEARANCE

NOVA TOPOLOGIES



PRIMARY SELECTOR

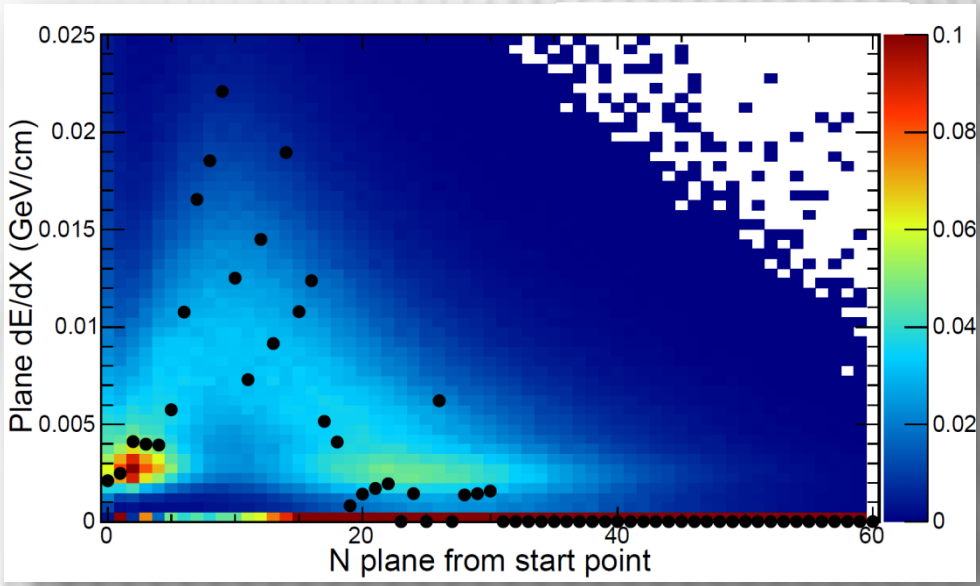
LID: Likelihood Identification

***dE/dx* likelihoods** calculated for **longitudinal and transverse** slices of leading shower under multiple particle hypotheses

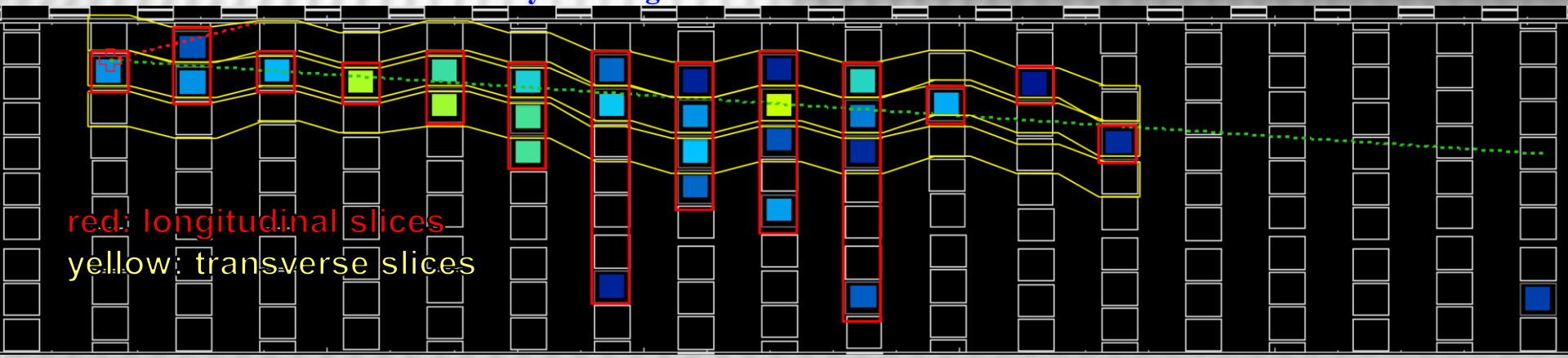
Likelihoods feed an artificial neutral network along with **kinematic and topological info**:

e.g., energy near vertex, shower angle, vertex-to-shower gap

***Points:* measured *dE/dx* in each plane (example event)**
***Color:* p.d.f. for *dE/dx* in each plane (e^- assumption)**



Likelihoods calculated for each red and yellow region



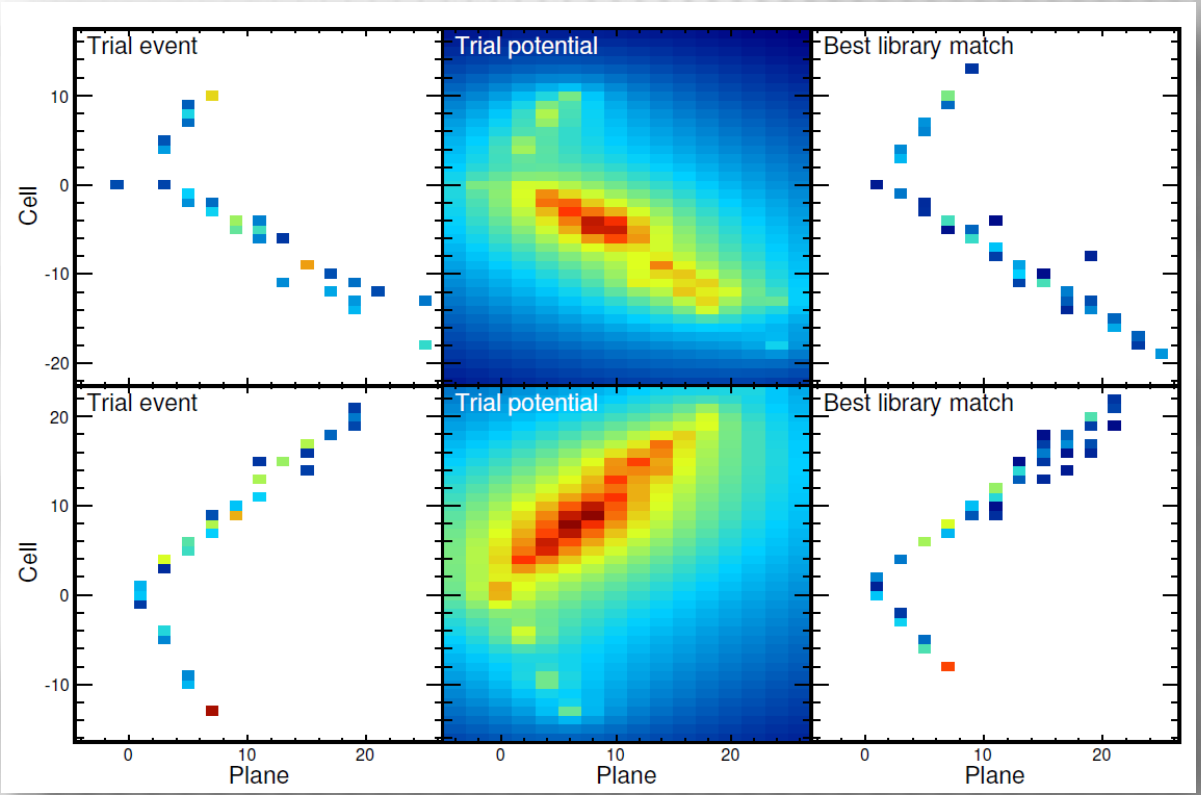
SECONDARY SELECTOR

LEM: Library Event Matching

***Left panels*: candidate event, both views**
***Right panels*: best-matched library event, both views**
***Middle panels:* an intermediate step in calculating the match quality**

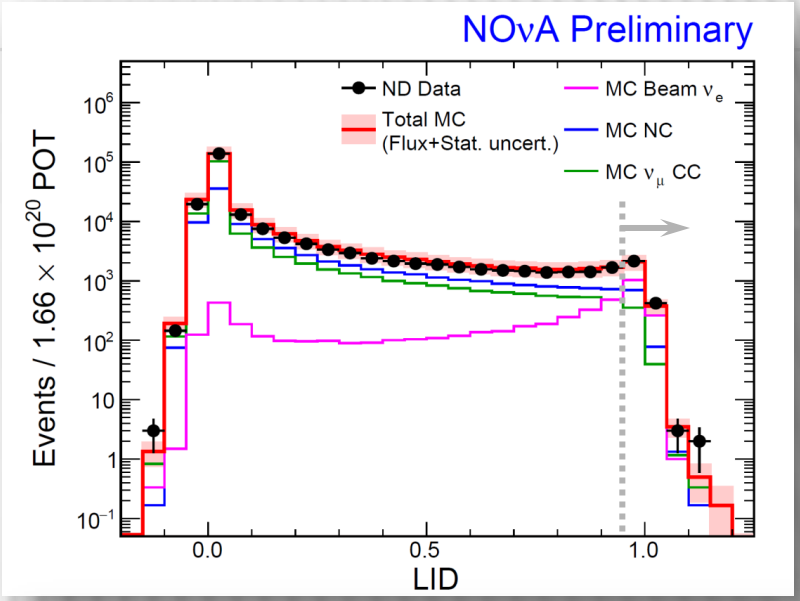
Spatial pattern of energy deposition is compared directly to that of ~10^8 simulated events ("library")

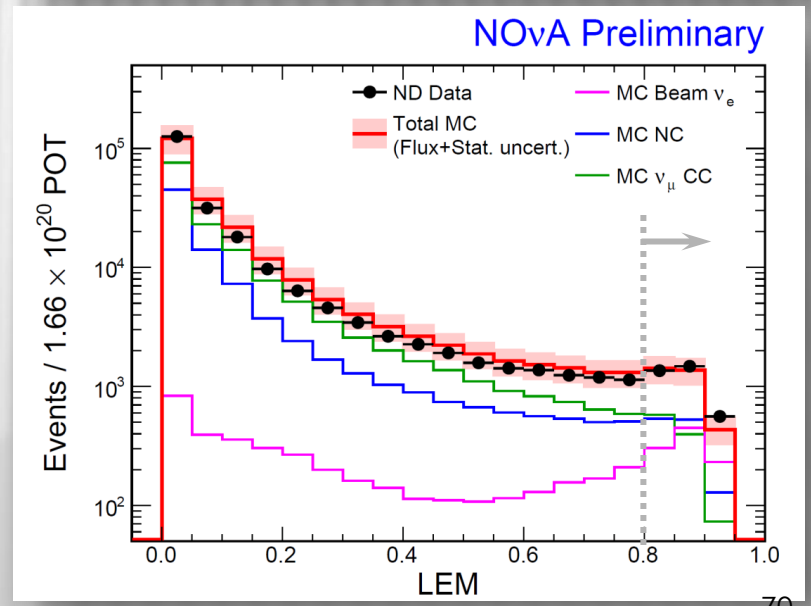
Key properties of the **best-matched library events** (*e.g.*, fraction that are signal events) are input into a decision tree to form discriminant



PERFORMANCE

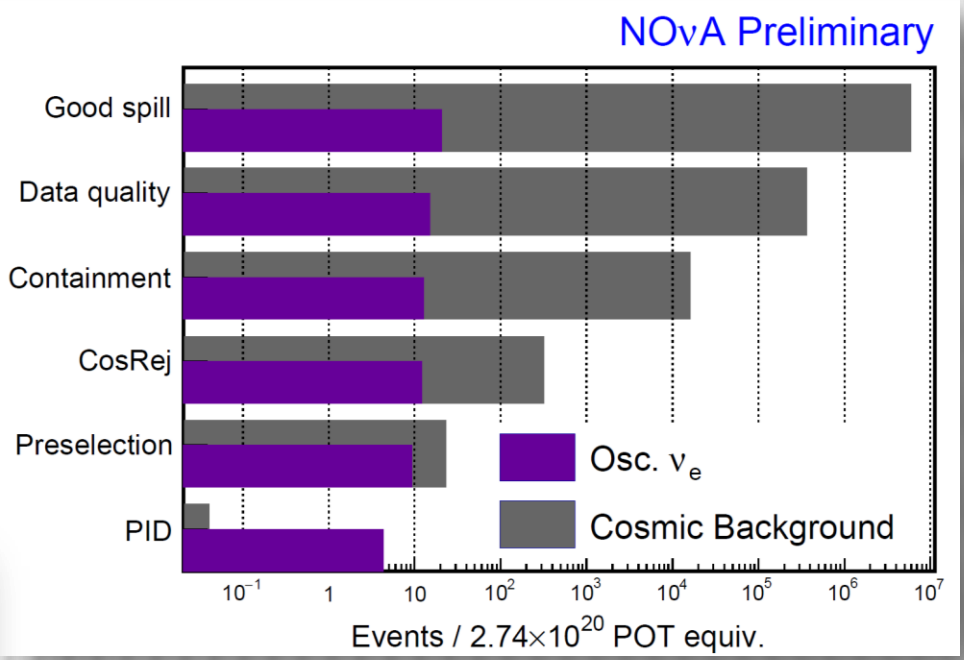
- Good data/MC agreement in both selectors
- Almost identical performance in signal efficiency, sig/bkg ratio, systematic uncertainties and physics sensitivities
- **35% signal efficiency**
- **Reject 99.3% of NC** background
- **62% overlap** in selected events between LID and LEM
- Decided, prior to unblinding, to use more traditional LID technique as primary selector, but still show both results

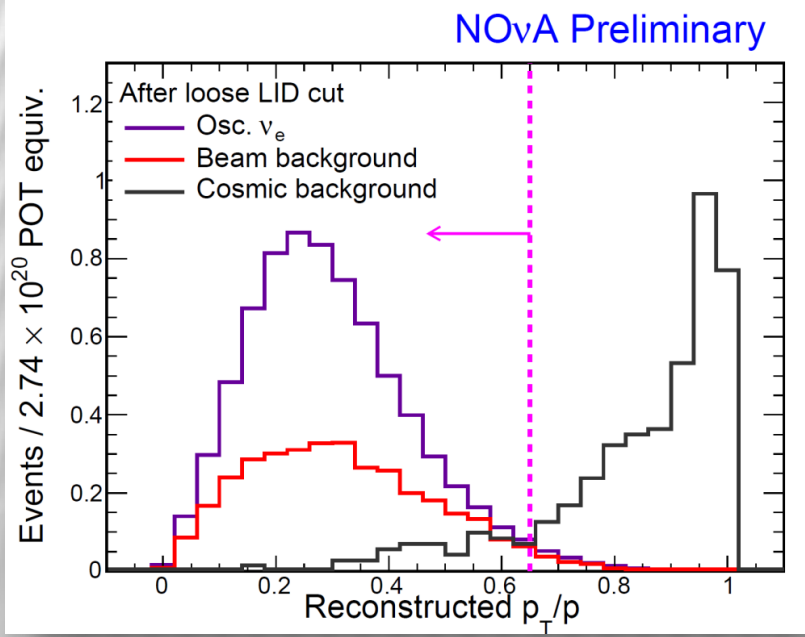




COSMIC REJECTION

- Large cosmic rejection needed
- Cut on transverse momentum to remove downward-going showers



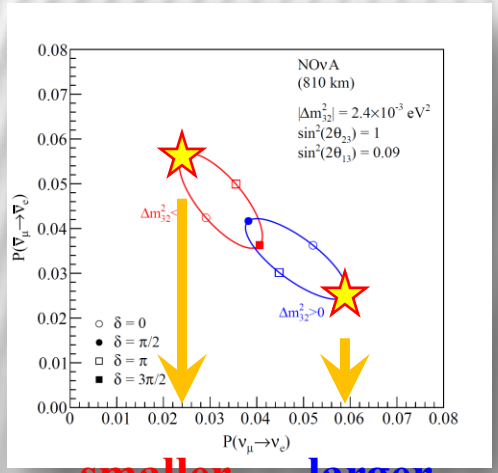


- Selectors add a lot of power
- Overall, achieve ~10^8 rejection factor

HOW MANY?

- Far detector predictions are corrected using near detector data
- Predictions correspond to a full detector exposure equivalent to 2.74×10^{20} POT (approx. 1/2 nominal year)

	Background Predictions					
	Total Bkg.	**Beam ν_e-CC**	**NC**	**ν_μ-CC**	**ν_τ-CC**	**Cosmics**
LID	**0.94 ± 0.09**	**0.47**	**0.36**	**0.05**	**0.02**	**0.06**
LEM	1.00 ± 0.11	0.46	0.40	0.07	0.02	0.06



smaller ν_e rate **larger ν_e rate**

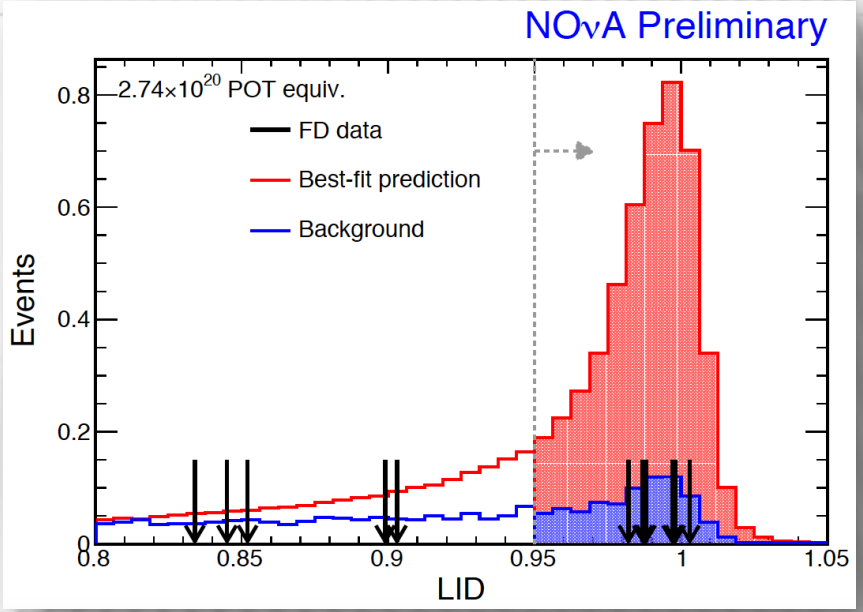
	Signal Predictions	
	IH, $\delta_{CP} = \pi/2$	**NH, $\delta_{CP} = 3\pi/2$**
LID	**2.24 ± 0.29**	**5.62 ± 0.72**
LEM	2.34 ± 0.26	5.91 ± 0.65

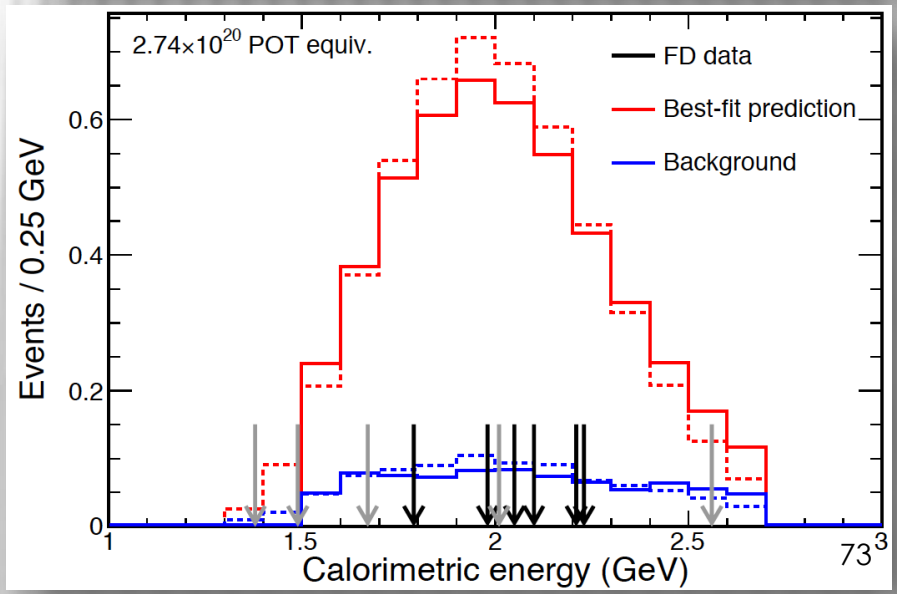
RESULTS

- **LID:**
  - **Observe 6 events**
  - **3.3σ appearance signal**
- LEM:
  - Observe 11 events
  - 5.5σ appearance signal

- **9.2%:** Probability of observing this distribution of 11 events

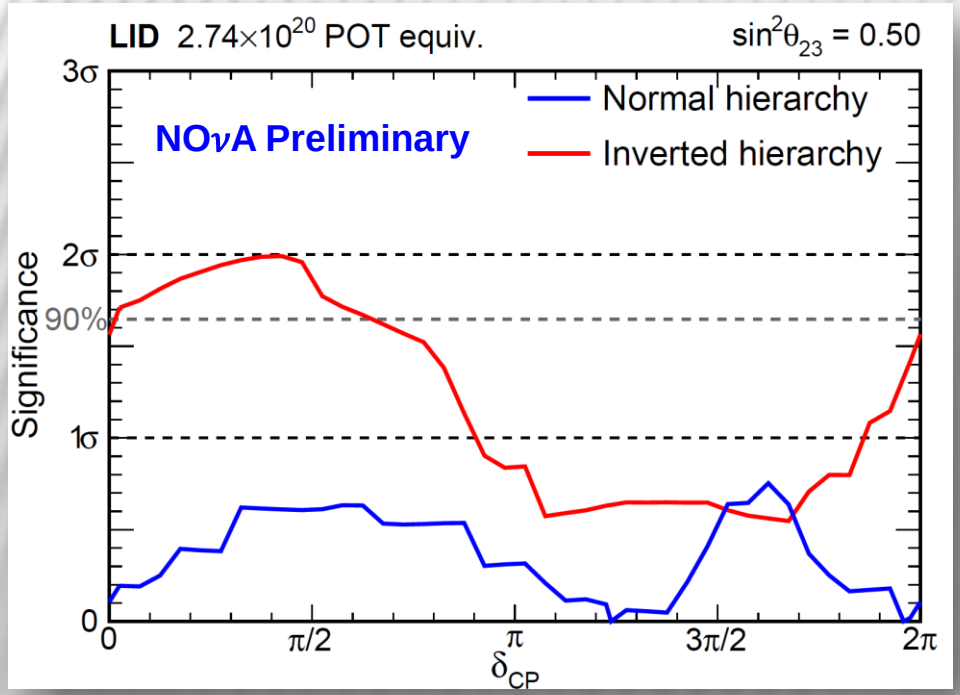
- **12%:** Probability of observing equal or worse χ^2 for LEM given NH and $\delta_{CP} = 3\pi/2$

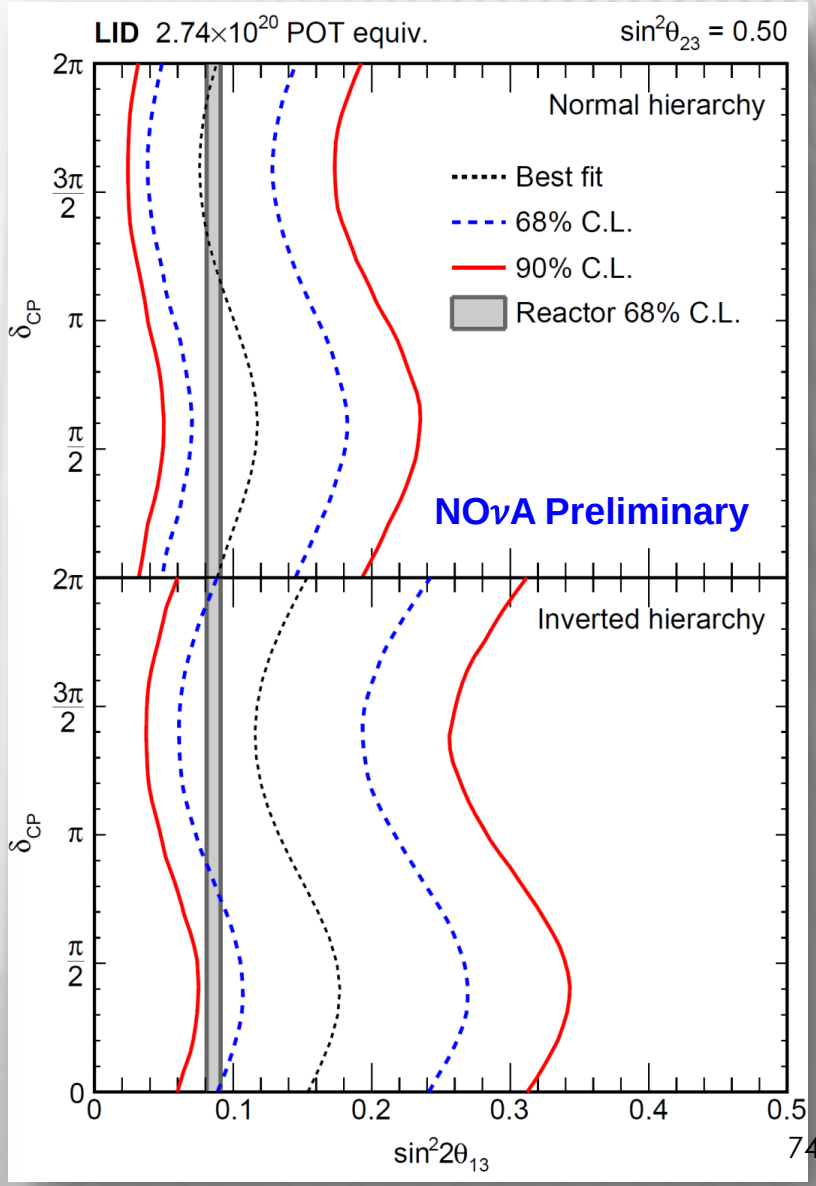




RESULTS - LID

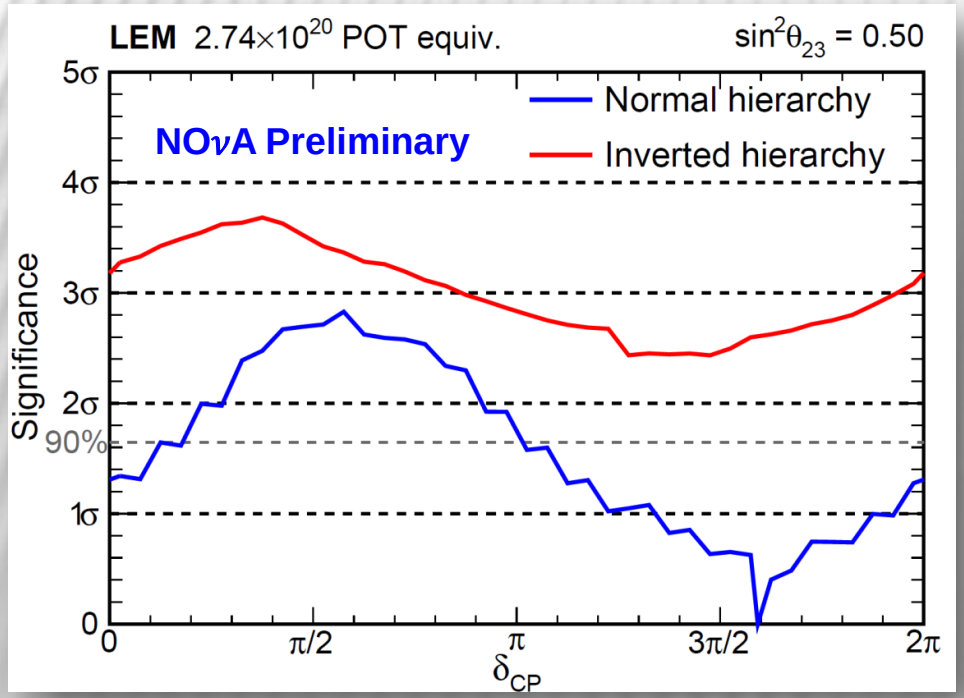
- **Consistent with reactor measurements**
- IH disfavoured at 90% CL for $0 < \delta_{CP} < 0.8\pi$, for $\sin^2 2\theta_{23} = 0.5$
- Less significant if $\sin^2 2\theta_{23} > 0.5$

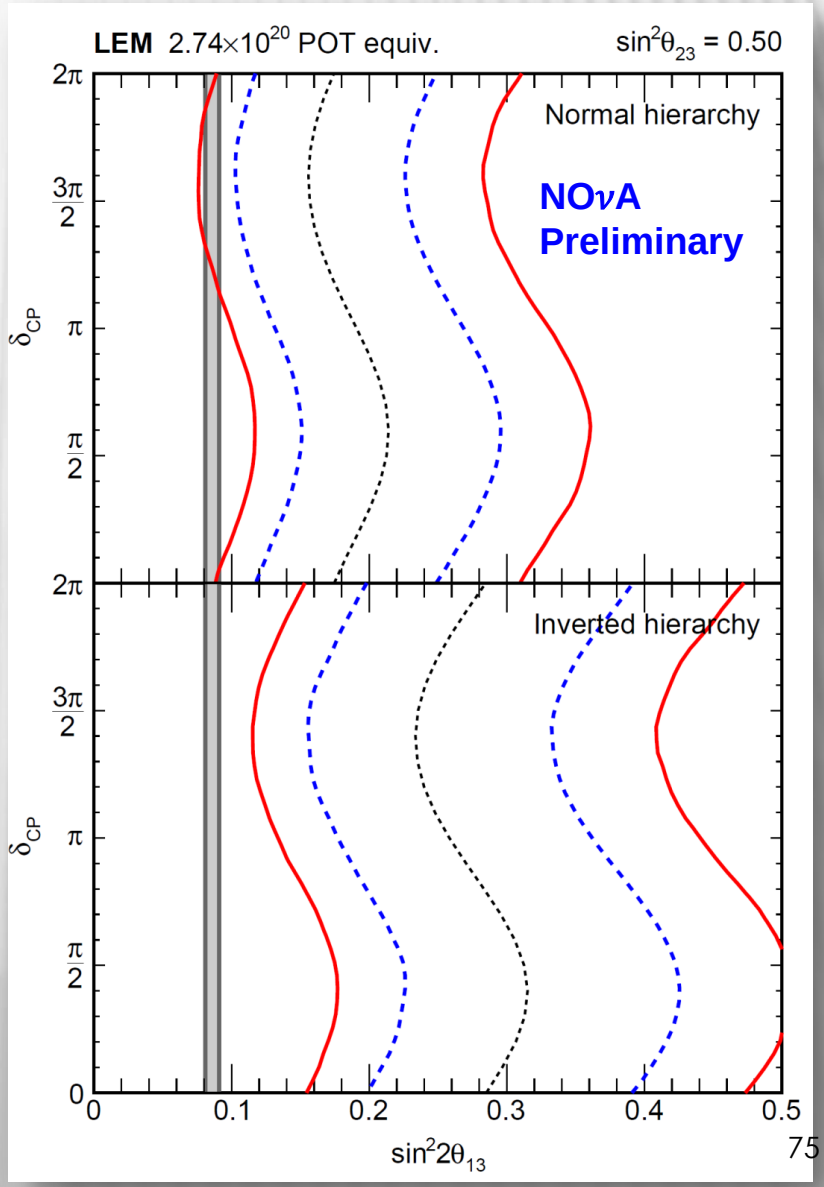




RESULTS - LEM

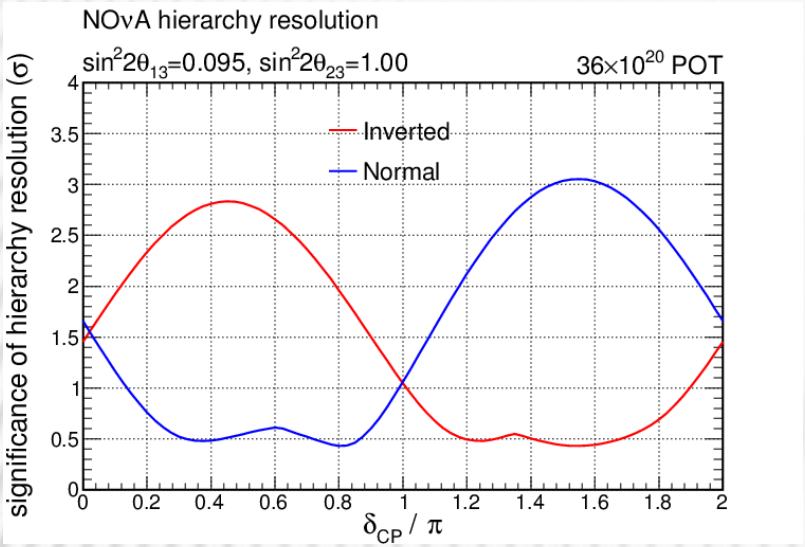
- Some tension with reactor measurements at $\sin^2 2\theta_{23} = 0.5$
- IH disfavoured at 2σ level for all values of δ_{CP} and $\sin^2 2\theta_{23}$ in [0.4, 0.6] range
- Preference for NH and $\delta_{CP} \sim 3\pi/2$

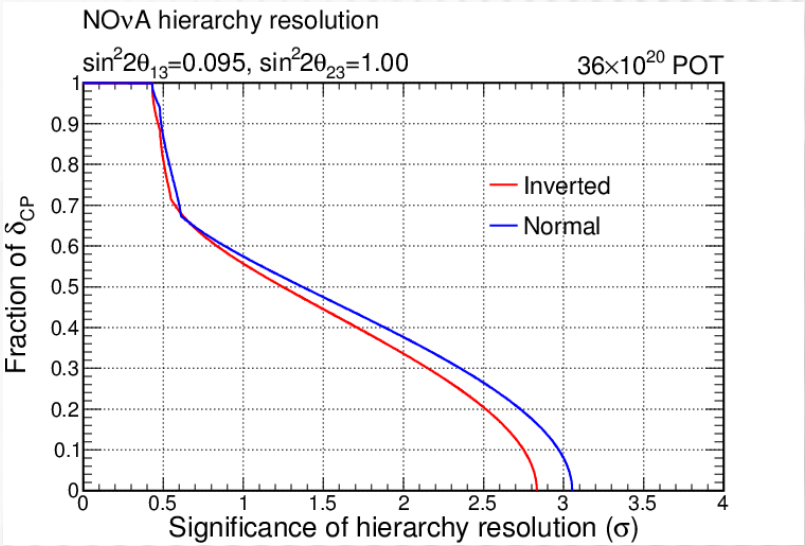


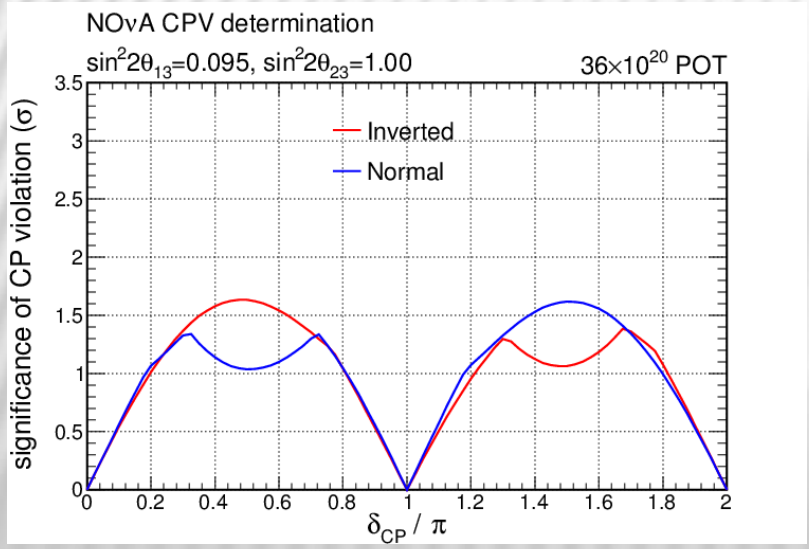


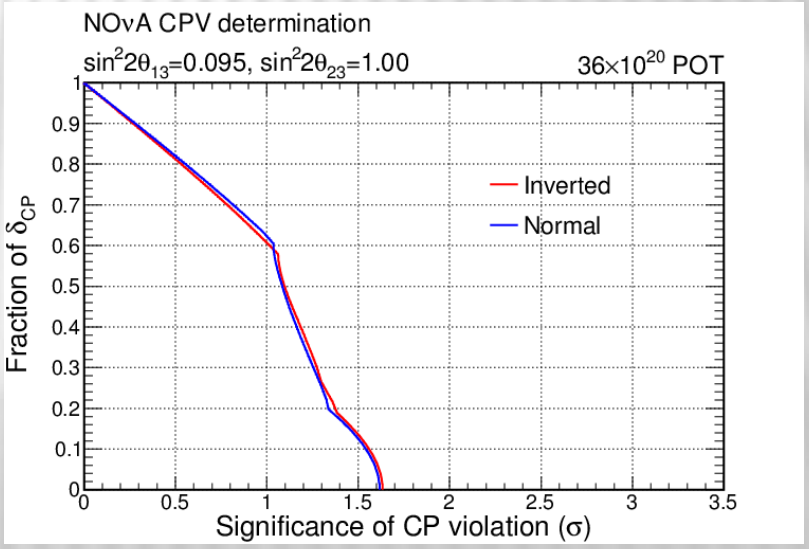
THE END GOAL

Normal Ordering
Inverted Ordering



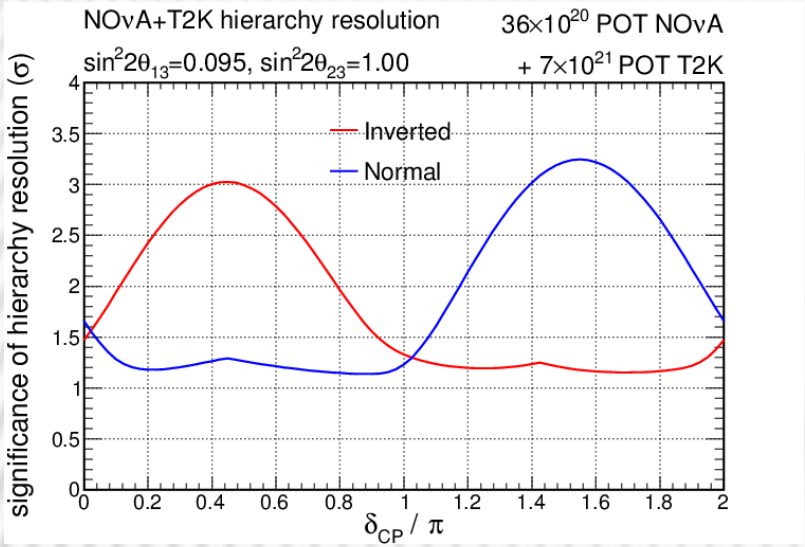


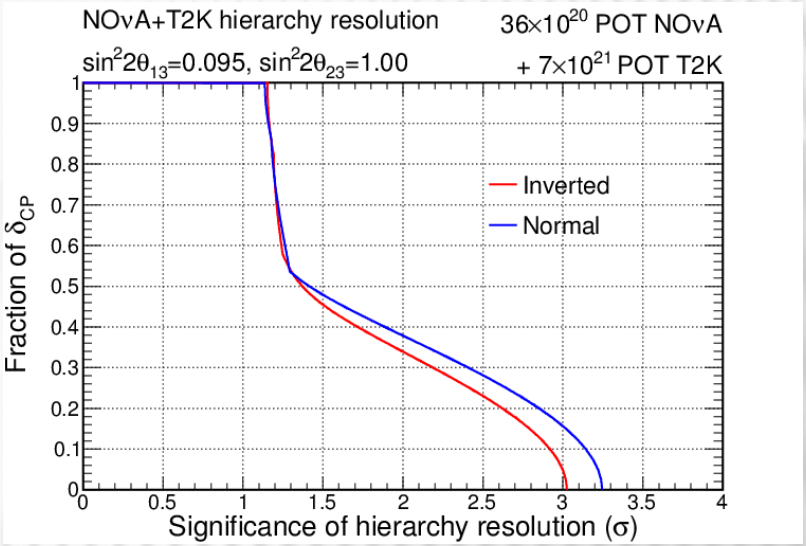


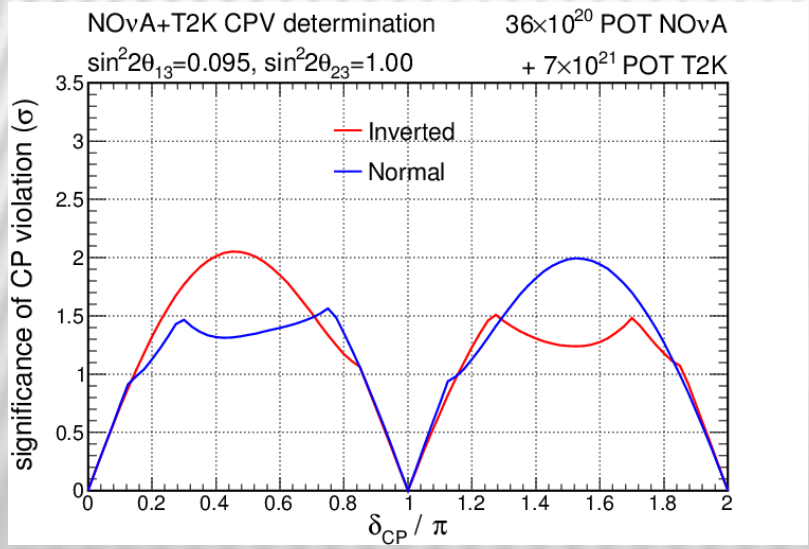


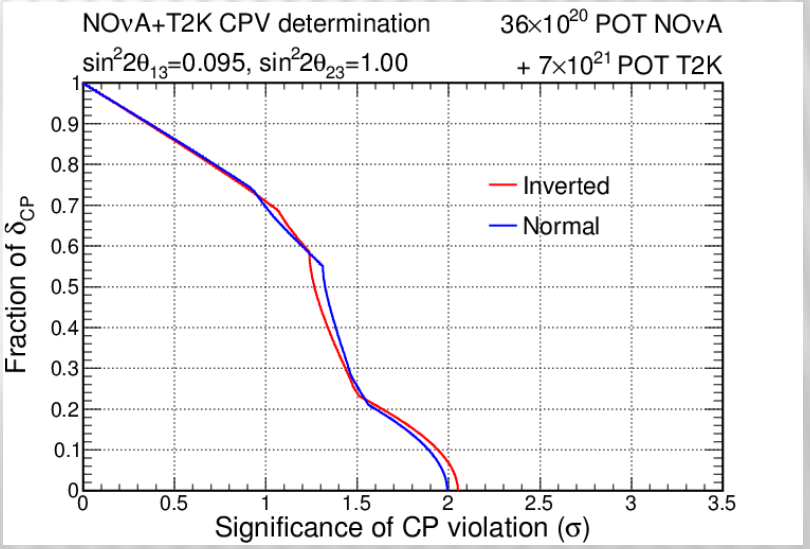
NOVA ♥ T2K

Normal Ordering
Inverted Ordering









SUMMARY

- NOvA has released first results on ν_μ disappearance and ν_e appearance

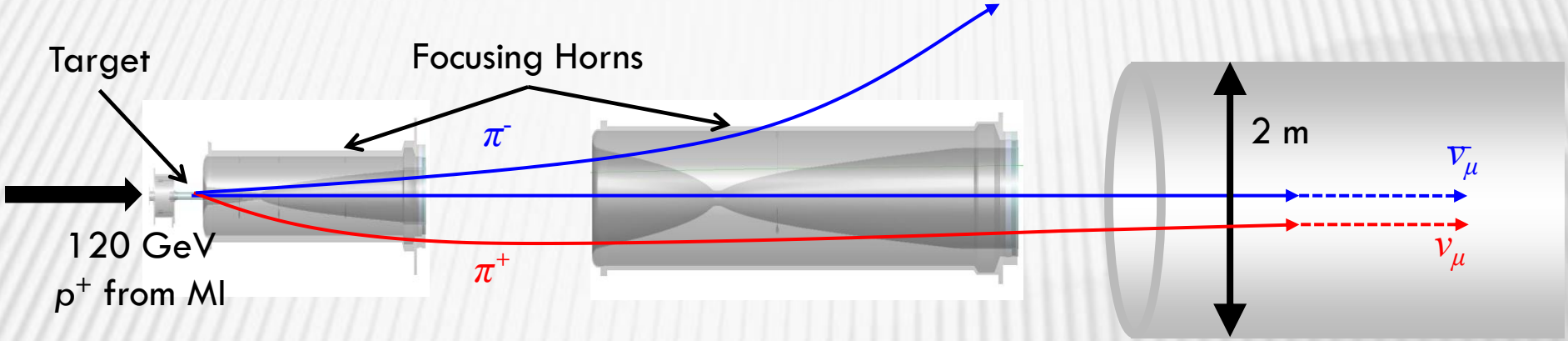
- **2.74×10^{20} POT-equiv. (~8% of total)**

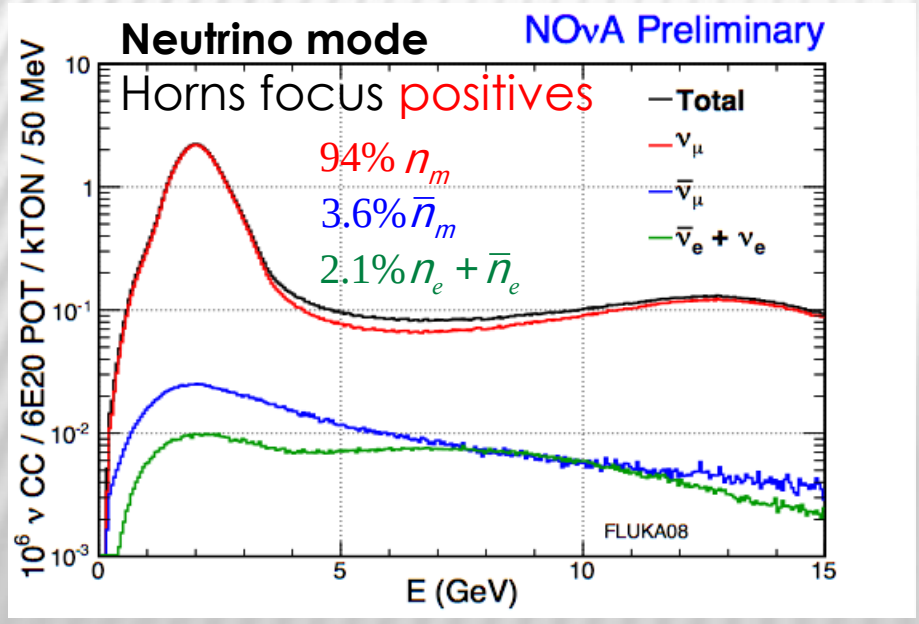
- Disappearance:
  - $\Delta m^2_{32} = \begin{cases} +2.37\ ^{+0.16}_{-0.15} \text{ [NH]} \\ -2.40\ ^{+0.14}_{-0.17} \text{ [IH]} \end{cases} \times 10^{-3}\ \text{eV}^2$
  - $\sin^2(\theta_{23}) = 0.51 \pm 0.10$

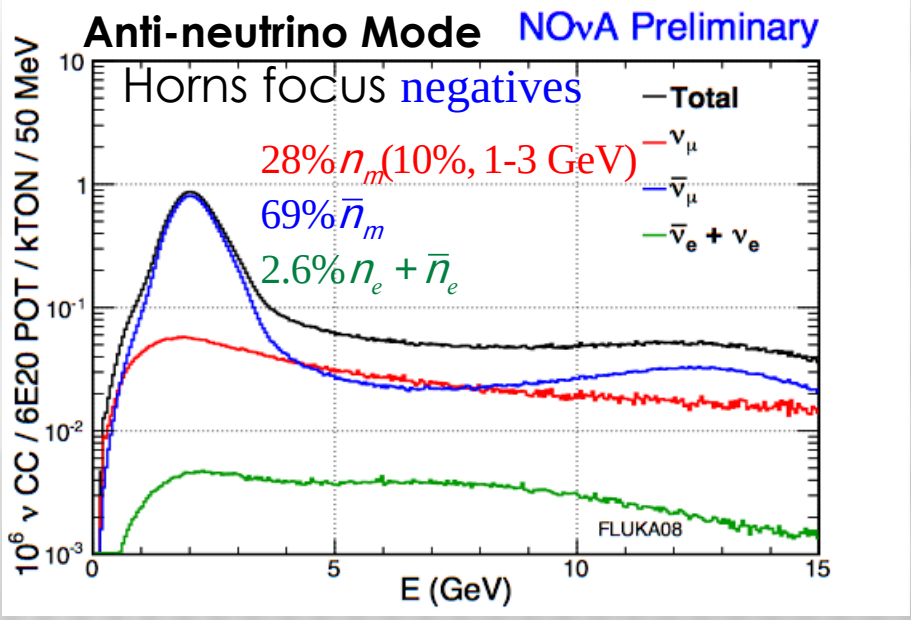
- Appearance:
  - **Observed 6 events on a bkgd of 0.94 ± 0.09**
  - **3.3σ evidence for ν_e appearance**

BACKUP SLIDES

CHARGE SELECTION



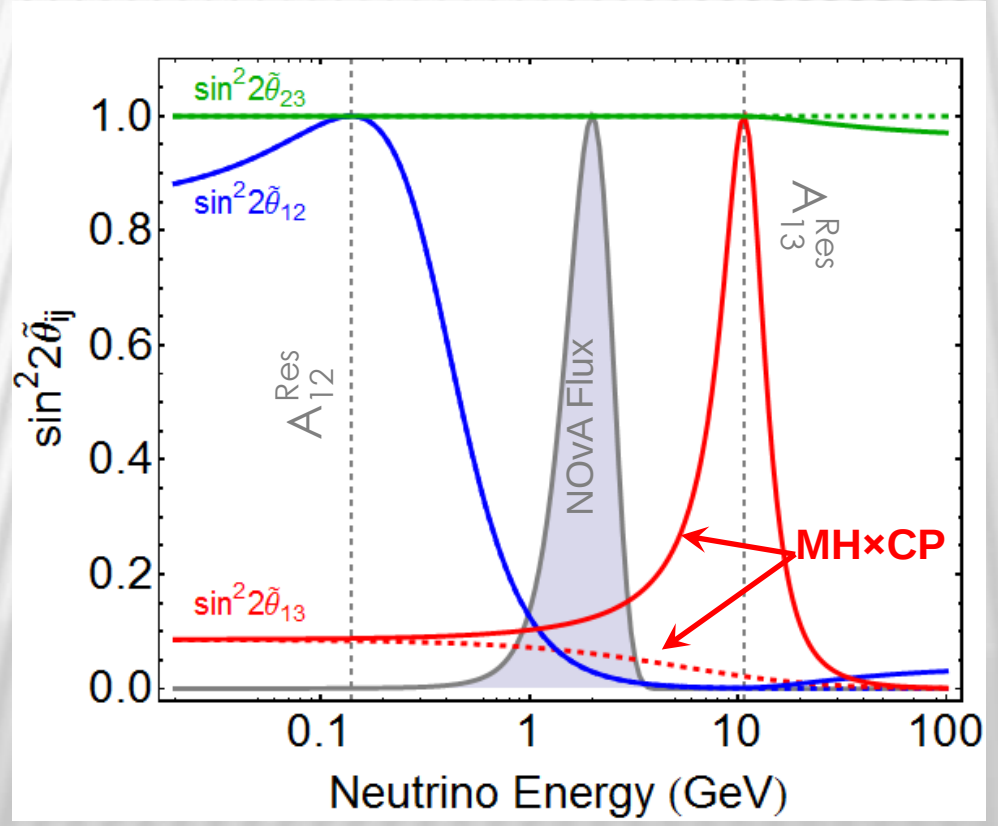




MATTER EFFETCS

$$\tan(2\tilde{\theta}_{ij}) \equiv \frac{\sin(2\theta_{ij})}{\cos(2\theta_{ij}) - A_{ij}} \quad A_{ij} \equiv \frac{\sqrt{2} G_F n_e}{\Delta m^2_{ji}/2E}$$

$$A_{13} \sim \frac{\pm E}{11\ \text{GeV}} \quad A_{12} \sim \frac{E}{0.35\ \text{GeV}}$$



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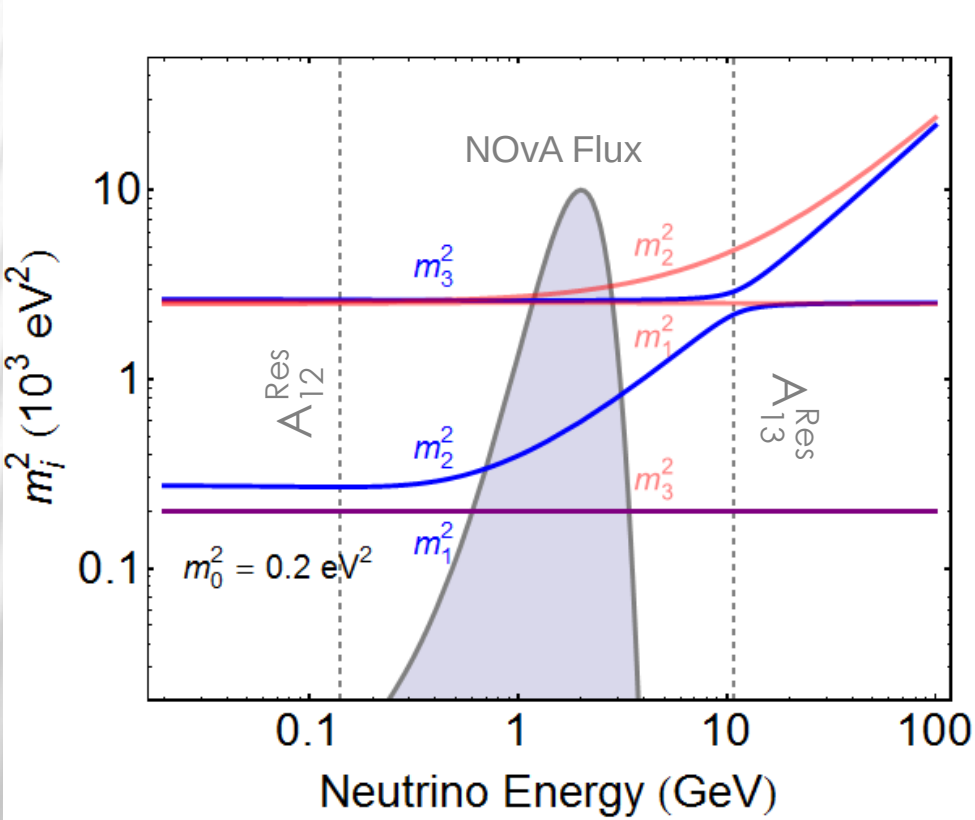

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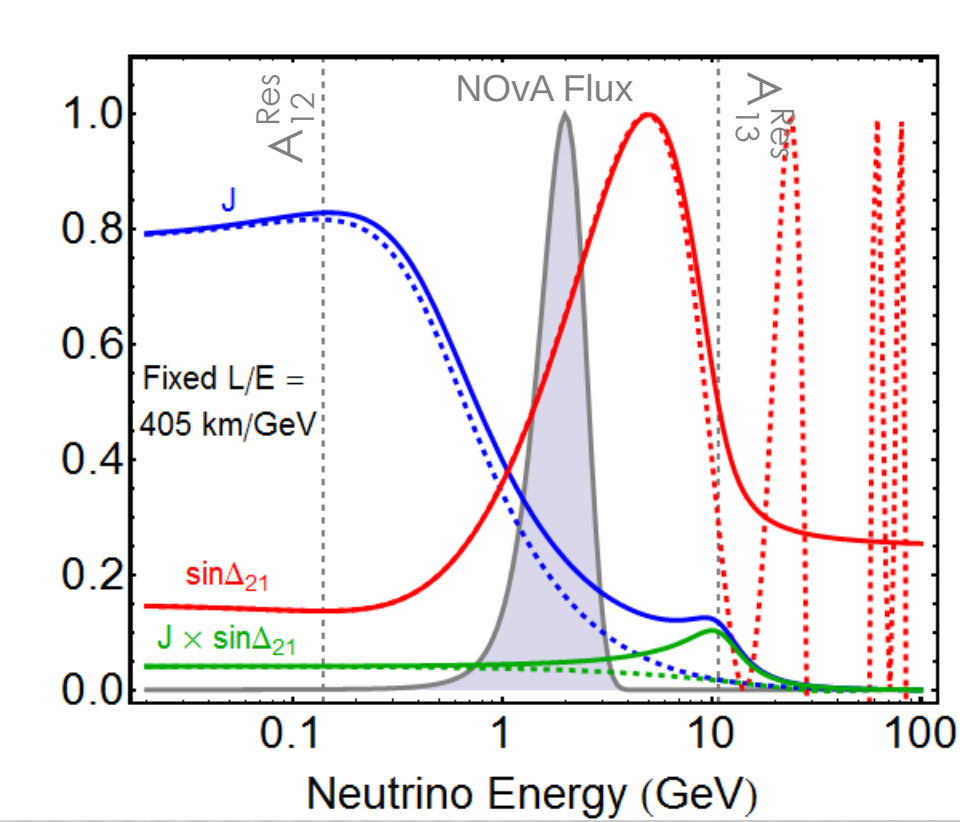
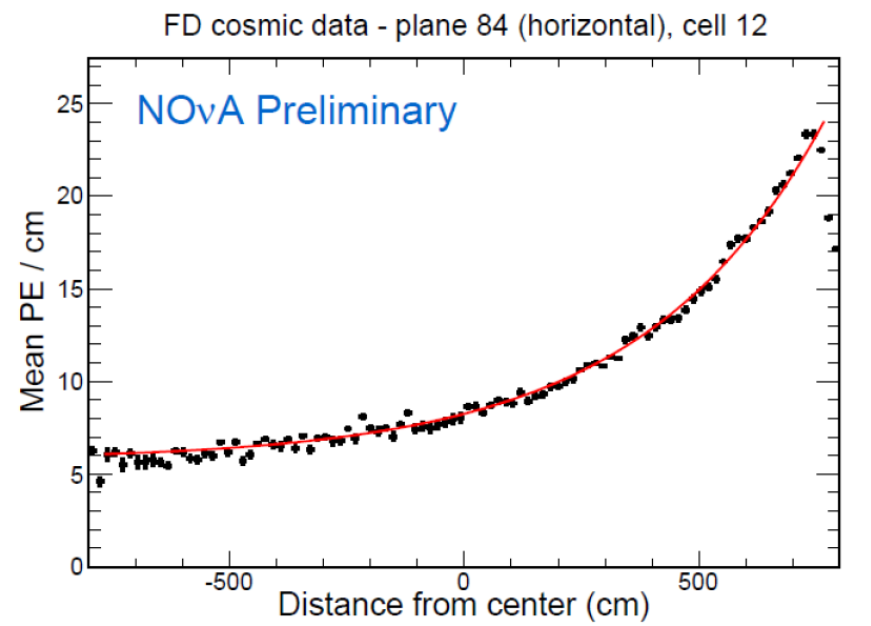
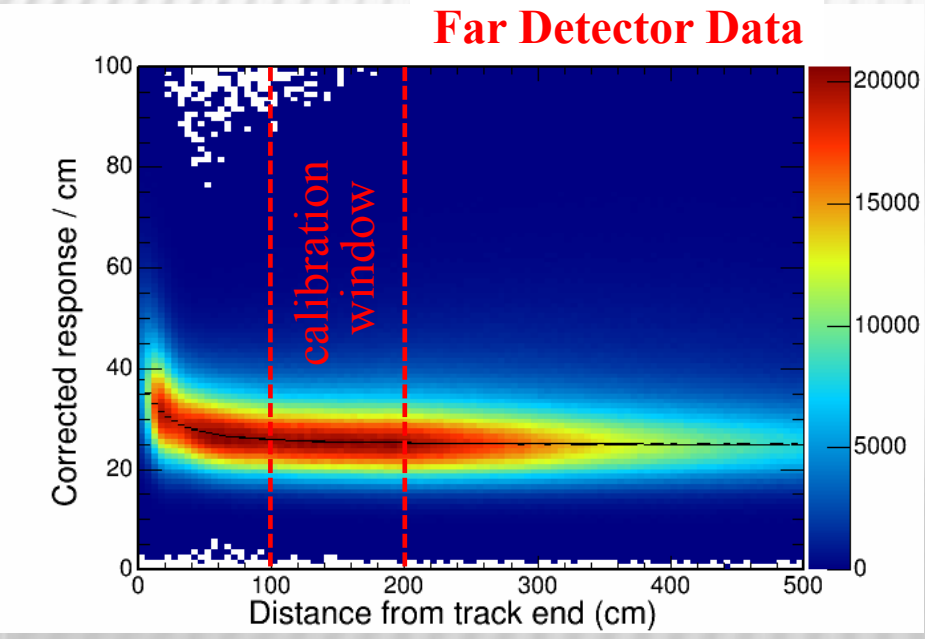


Calibration

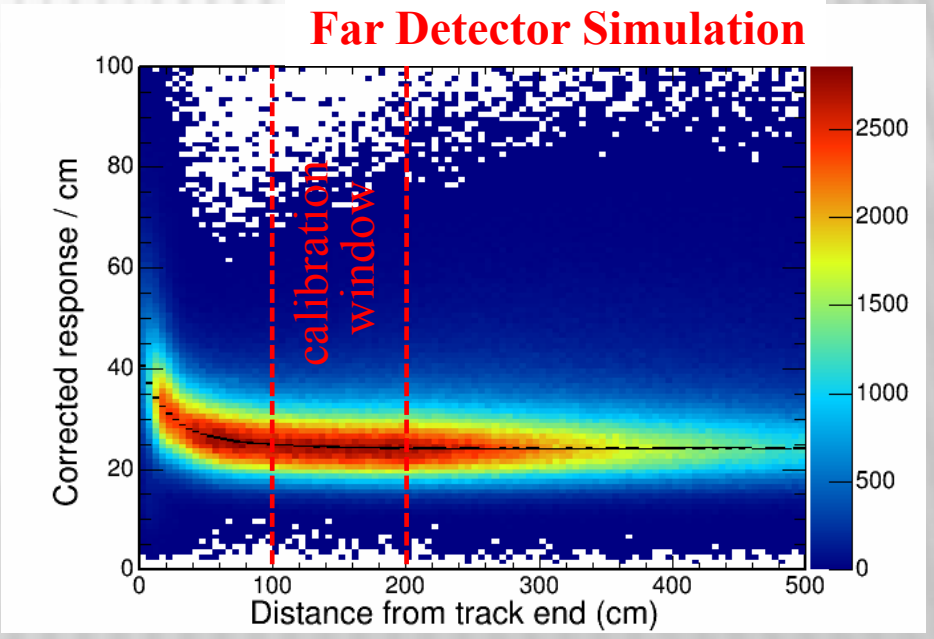
- **Biggest effect** that needs correction is **attenuation** in the WLS fiber
  Example FD cell →
- **Stopping muons** provide a standard candle for setting absolute energy scale *(below)*



Far Detector Data



Far Detector Simulation



Detector simulation pieces after energy deposition

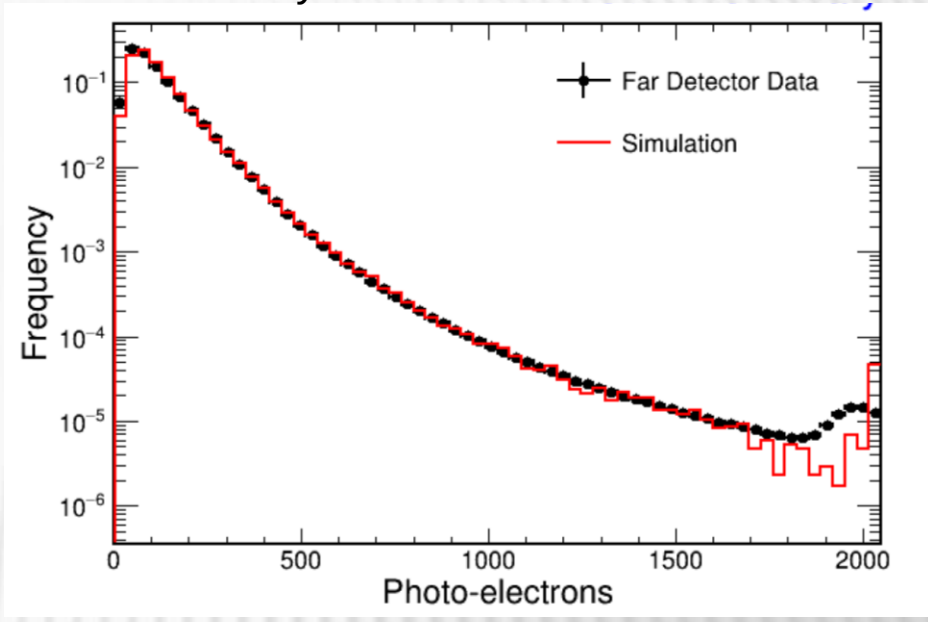
Detailed modeling includes:

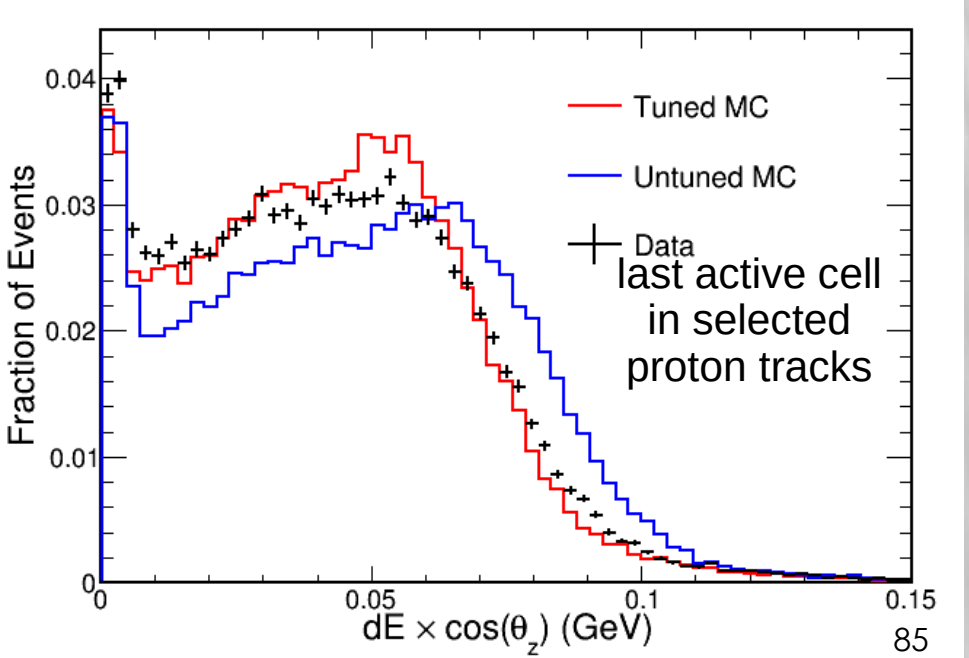
- fiber attenuation
- light collection losses at cell ends
- scintillator saturation
- fiber length variation across modules
- run-by-run matching of inactive channels
- APD characteristics
- amplifier noise
- full digitized traces
- readout electronics noise
- signal shaping, digitization, zero suppression

Top plot: distribution of photoelectrons for cosmic ray muon hits.

Bottom plot: require more scintillator saturation in simulation for high dE/dx hits than usual. Tune model to proton tracks.

cosmic ray muon hits





Multiple probes of energy scale

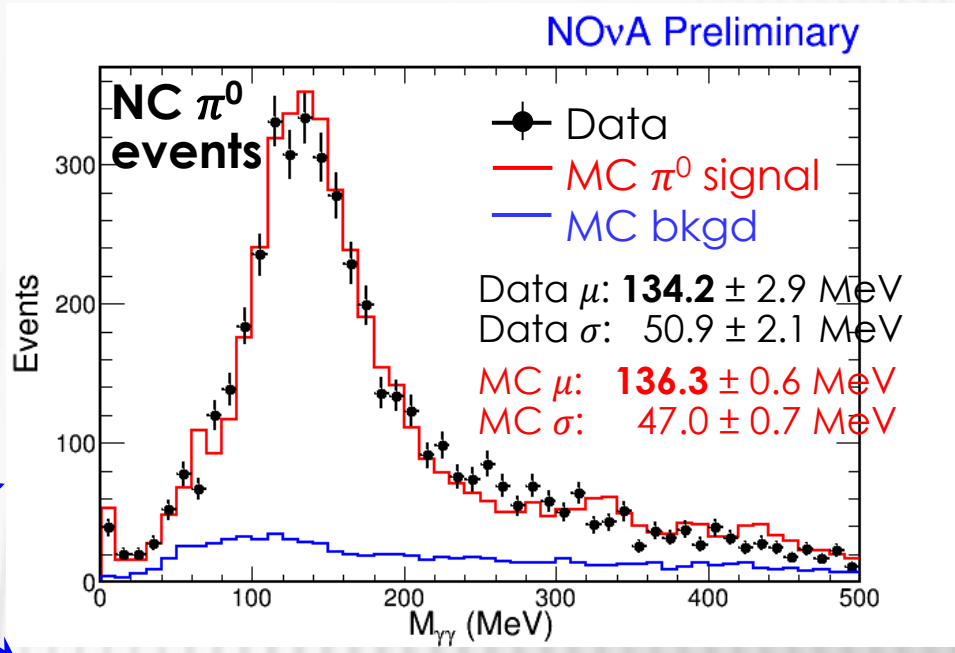
In Near Detector

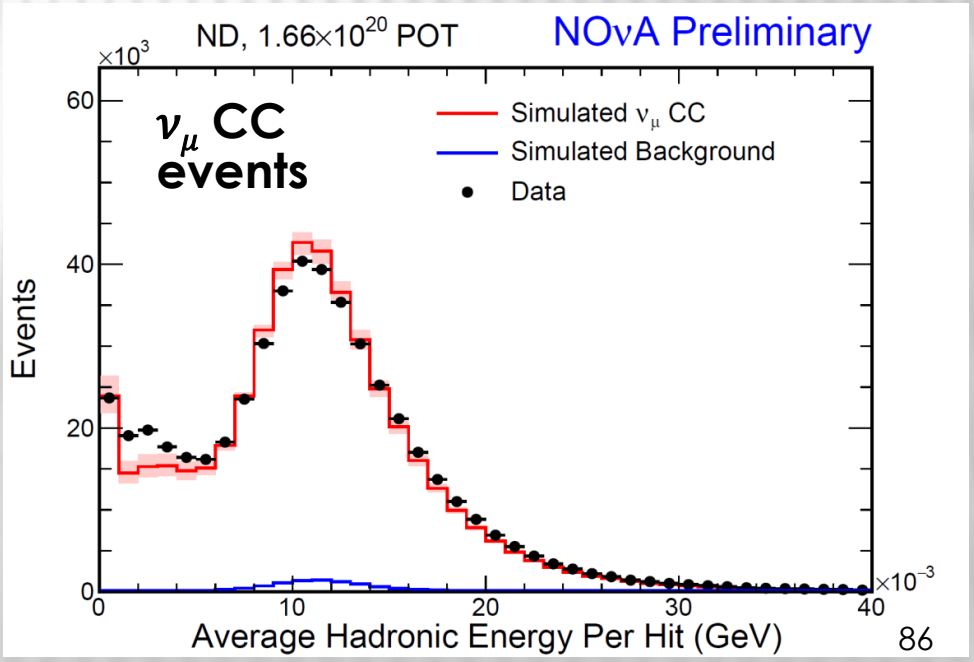
- cosmic μ dE/dx [~vertical]
- beam μ dE/dx [~horizontal]
- Michel e^- spectrum
- π^0 mass
- hadronic shower E-per-hit

In Far Detector

- cosmic μ dE/dx [~vertical]
- beam μ dE/dx [~horizontal]
- Michel e^- spectrum

All agree within ±5%



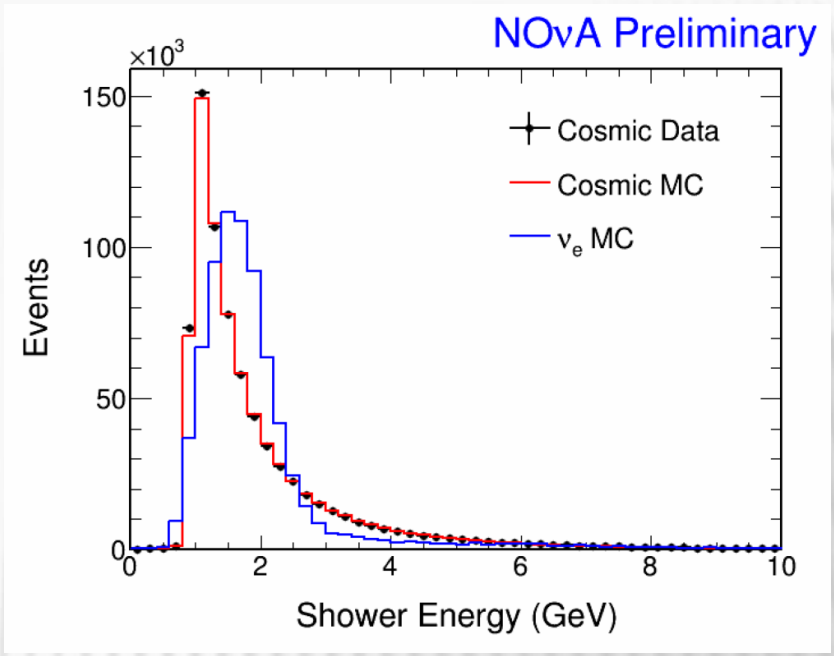


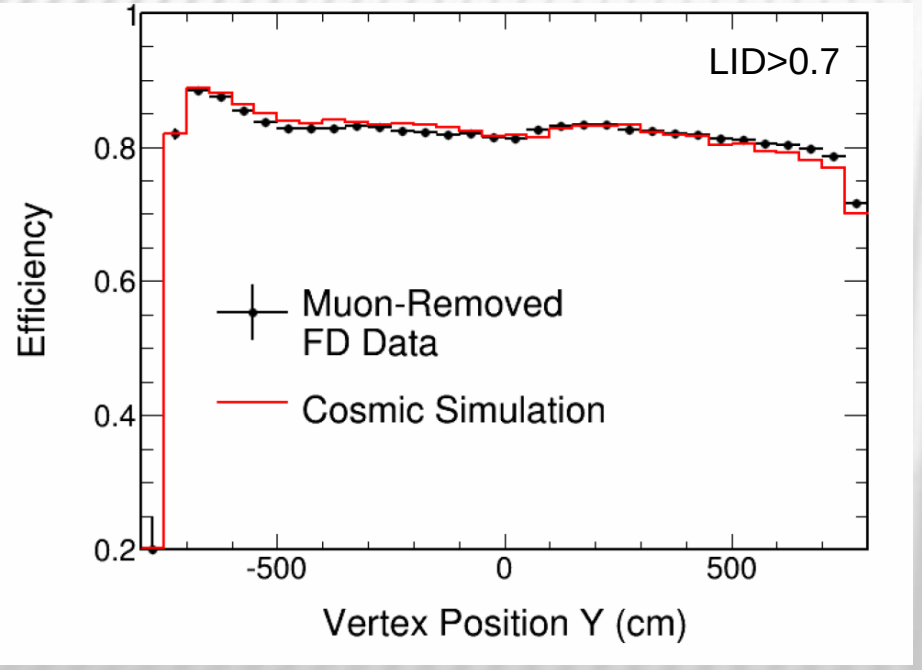
Checks of EM shower modeling

In addition to π^0 in the ND, we have **bremsstrahlung photons in ND and FD**

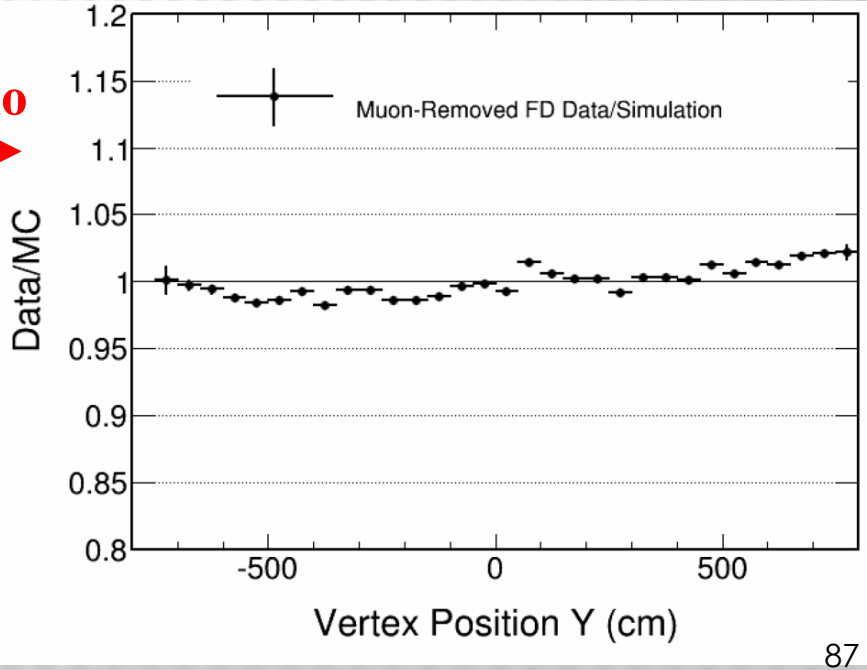
Right: **energies of brem showers** in FD
- *Excellent data/MC agreement*
- *Probes relevant E range (blue curve)*

Below: **selection efficiency** varies a bit across the large Far Detector
- ***Well modeled by simulation***





ratio



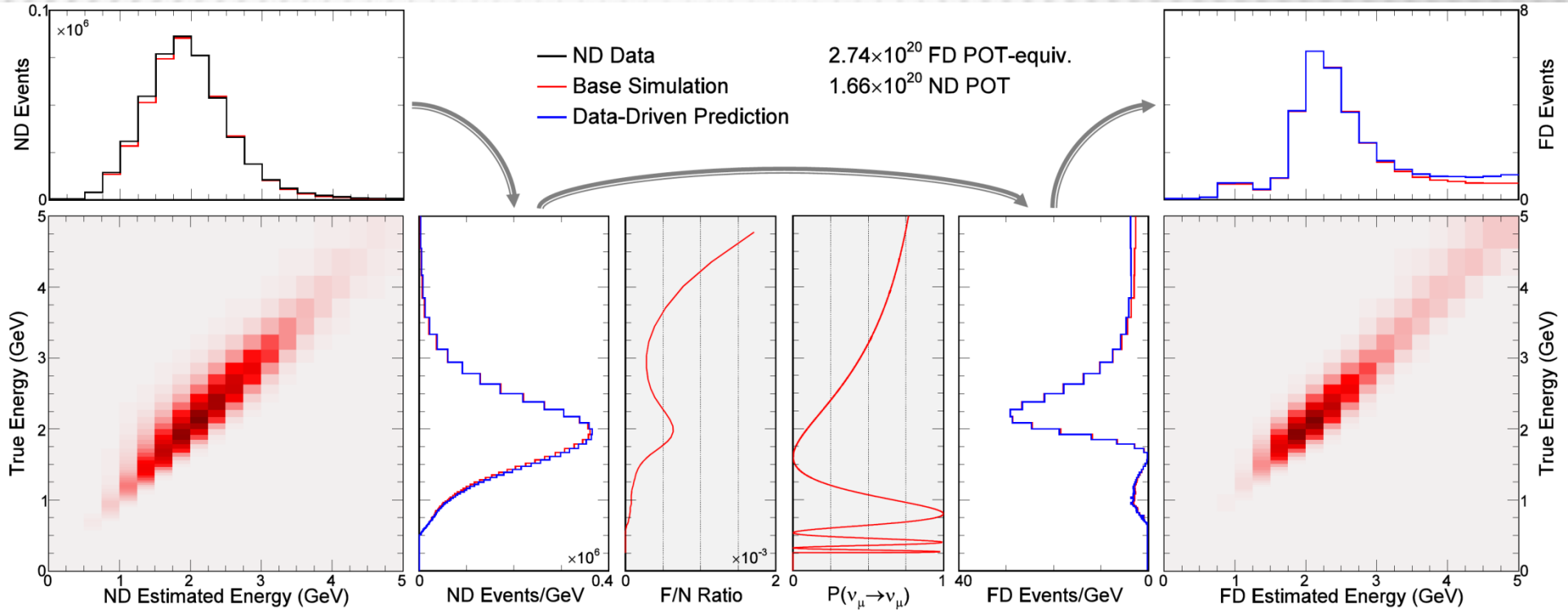
Far Detector prediction

(1) Estimate the underlying **true energy distribution** of selected ND events

(2) Multiply by expected **Far/Near event ratio** and **$\nu_\mu \rightarrow \nu_\mu$ oscillation probability** as a function of true energy

(3) Convert FD true energy distribution into **predicted FD reco energy distribution**

Systematic uncertainties assessed by **varying all MC-based steps**

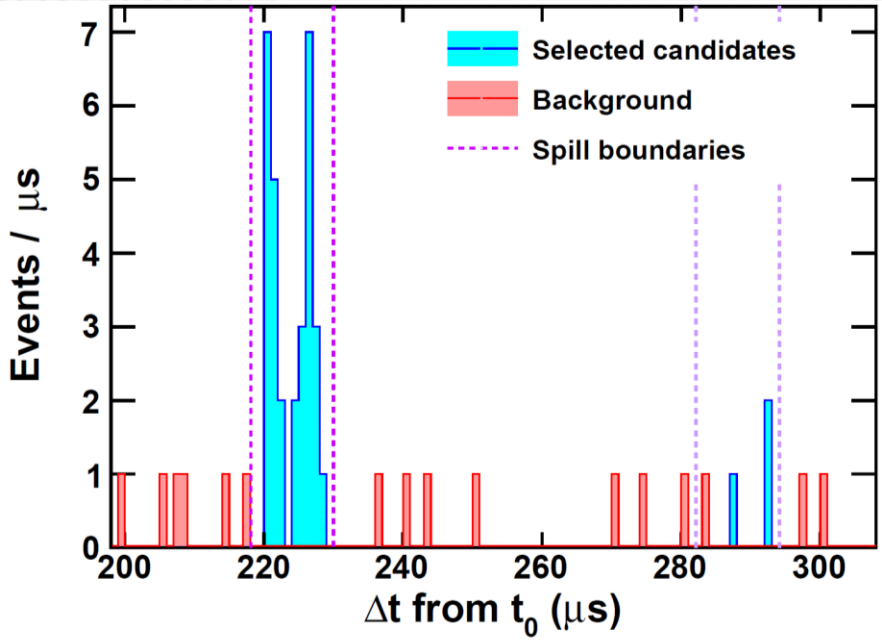


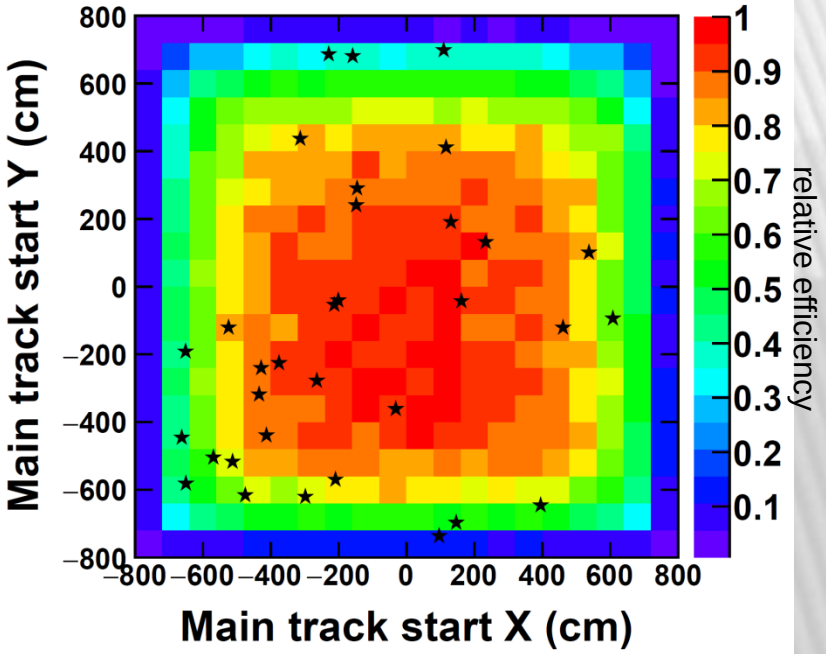
NUMU SYSTEMATICS

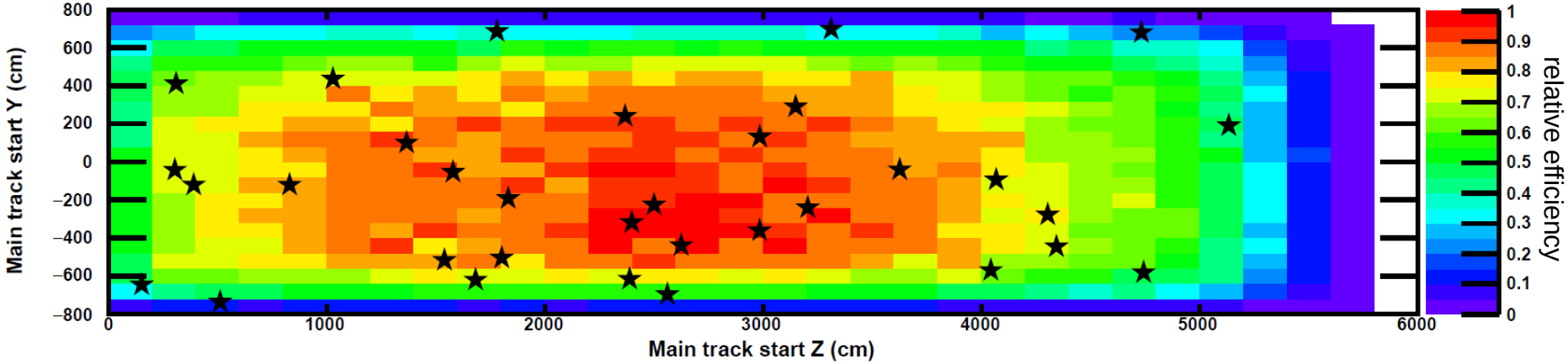
Source	$\delta(\sin^2\theta_{23})$ (±%)	$\delta(\Delta m^2)$ (±%)
Absolute Calorimetric Energy Calibration [±22%]	7.7	3.1
Relative Calorimetric Energy Calibration [±5.4%]	3.7	0.8
Cross Sections and FSI [±(15-25)%]	0.6	0.7
NC and CC Backgrounds	3.2	0.7
Detector Response	1.3	0.7
Flux [±21%]	1.6	0.4
Exposure [<±2%]	0.3	0.2
Oscillation Parameters	2.1	2.2
Total Systematic	9.2	4.1
Statistical	19	5.0

- Errors on mass splitting and angle dominated by hadronic energy calibration/simulation
- NC backgrounds contribute to angle systematic uncertainty

FD ν_μ CC candidates: when and where

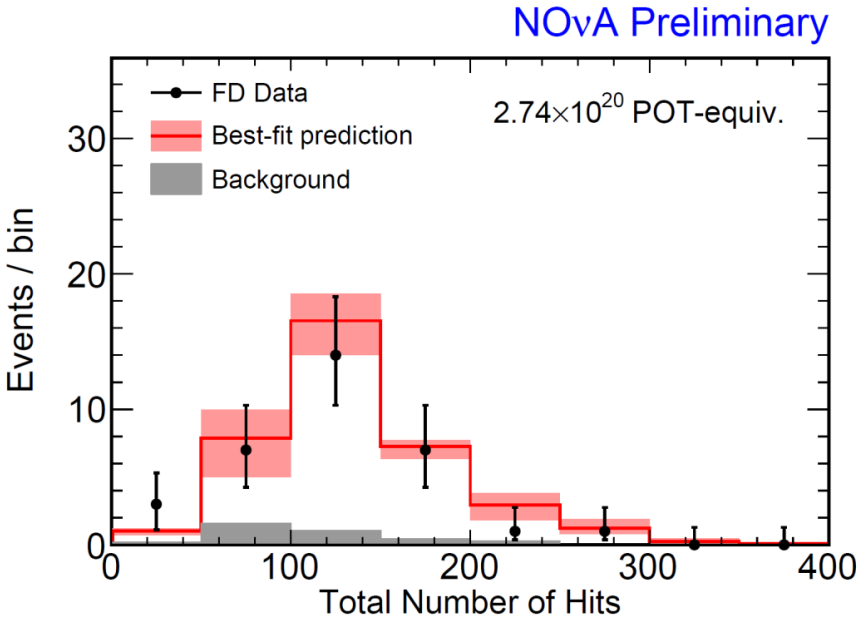


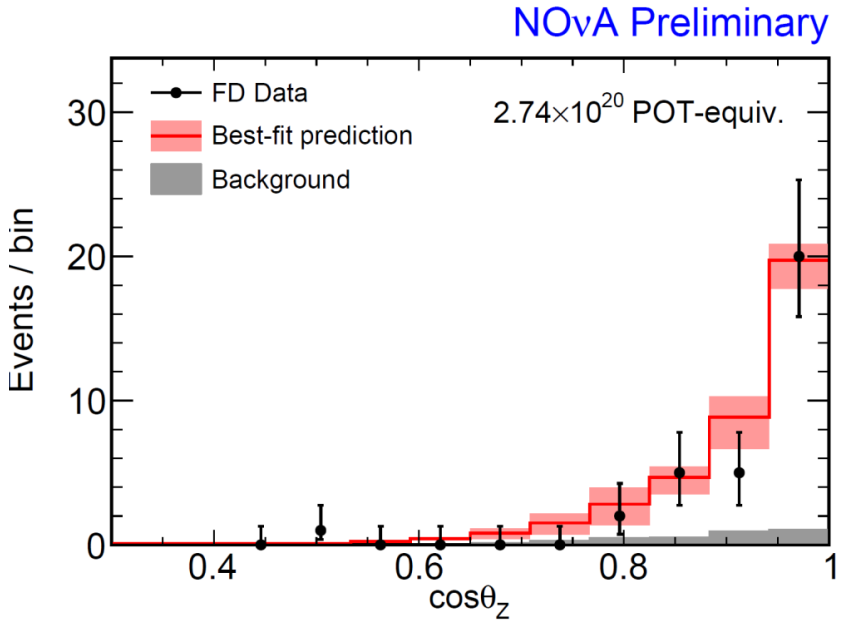


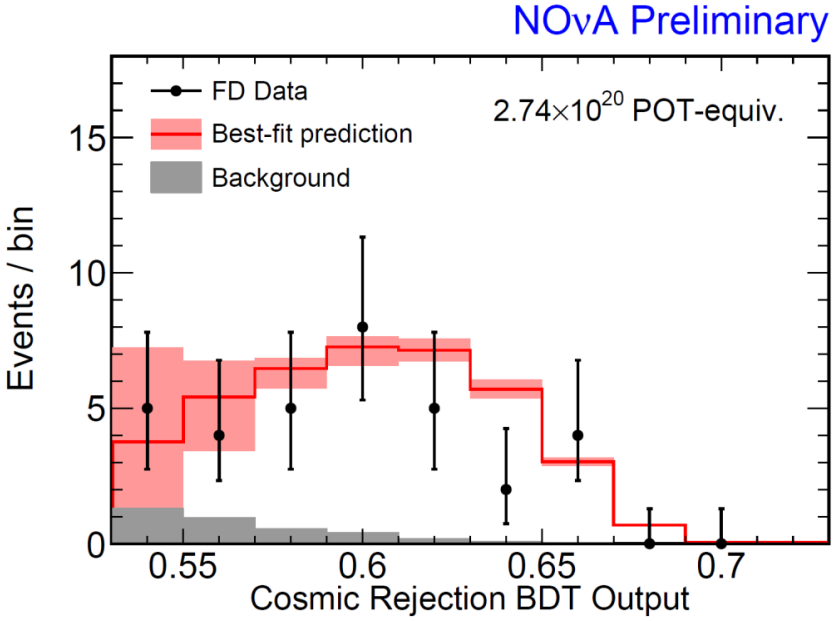


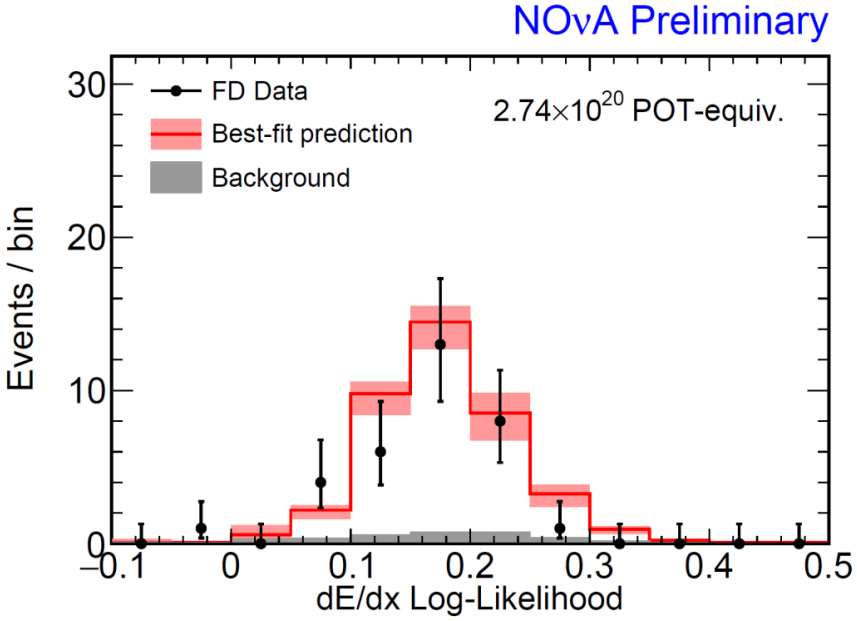
Note 1: Second timing window at +64 μs required for some of the early data
Note 2: Colors show relative efficiency. Not weighted by time variation in detector size.

FD ν_μ CC candidates: event distributions



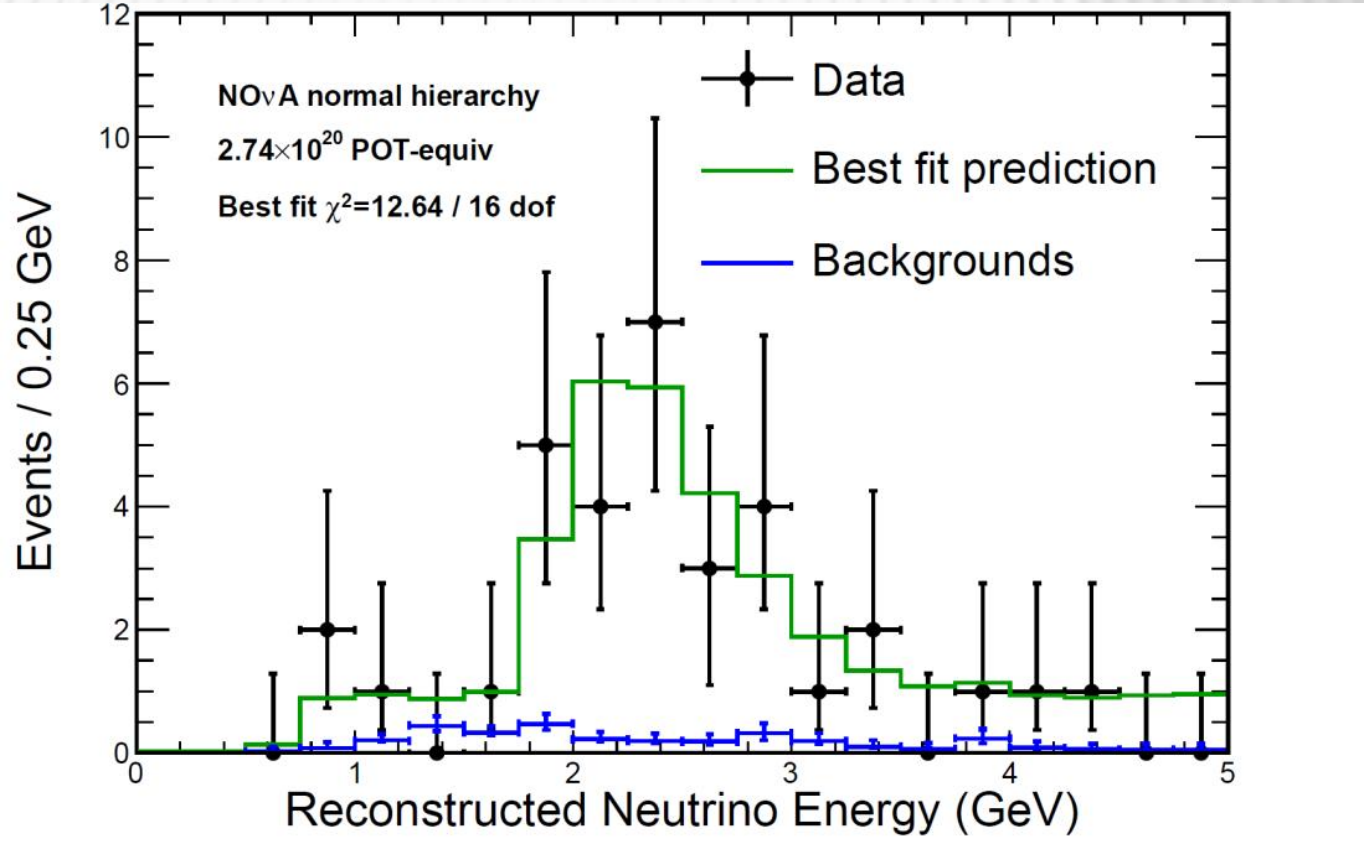






Zoomed view of Far Det. ν_μ CC energy spectrum

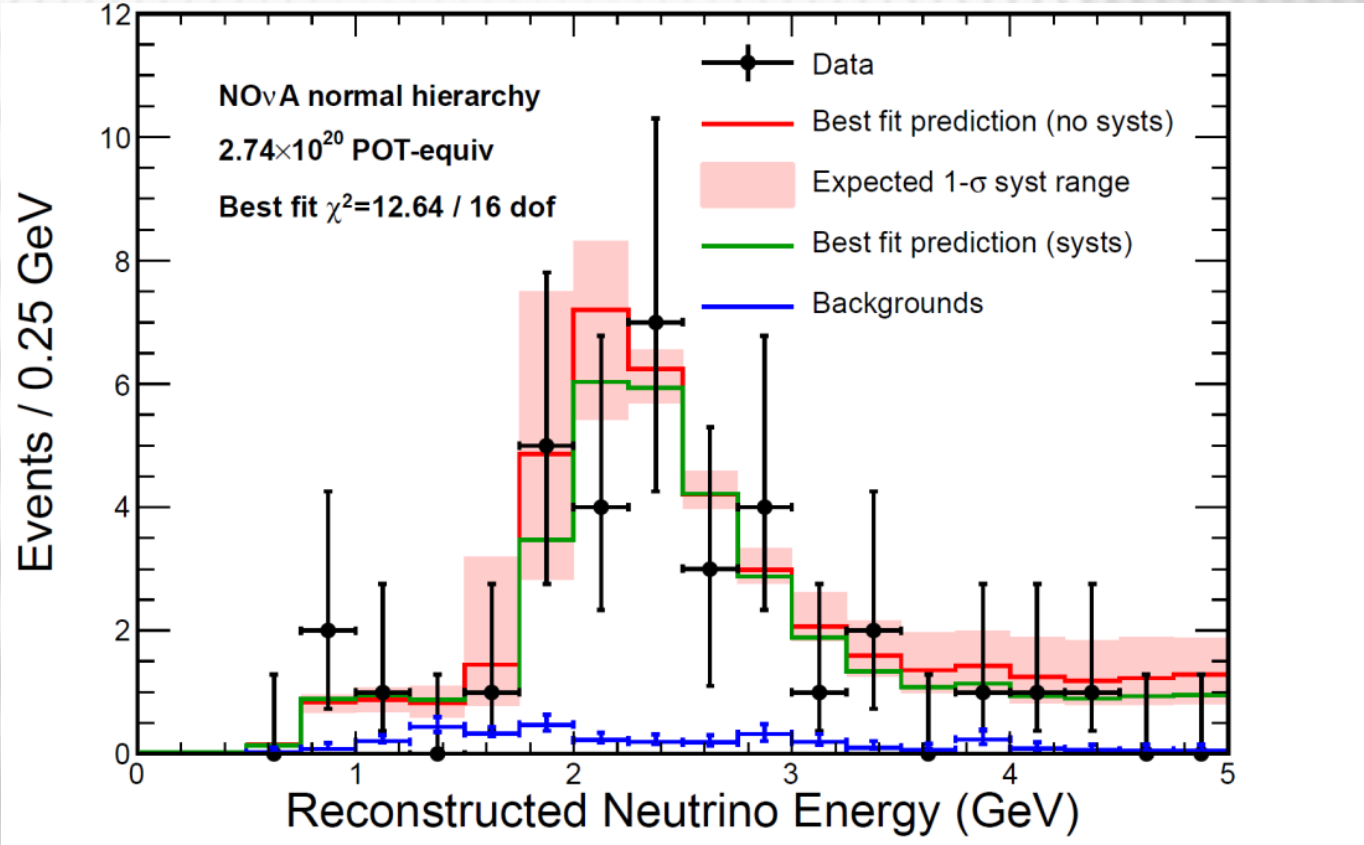
NOνA preliminary

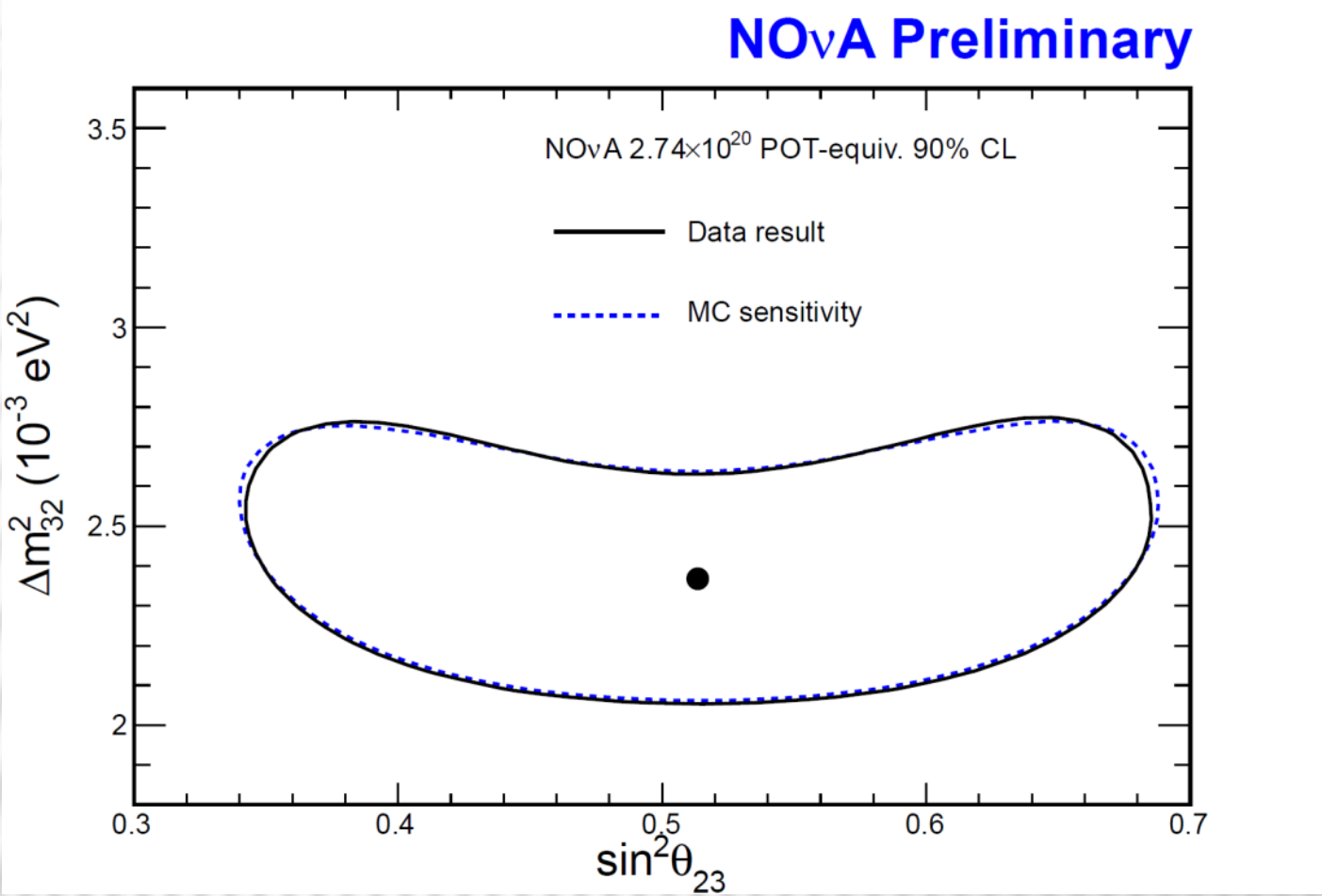


Zoomed view of Far Det. ν_μ CC energy spectrum

Also shown: the spectrum with nuisance parameters fixed at their central values and the corresponding (highly correlated) systematic error band

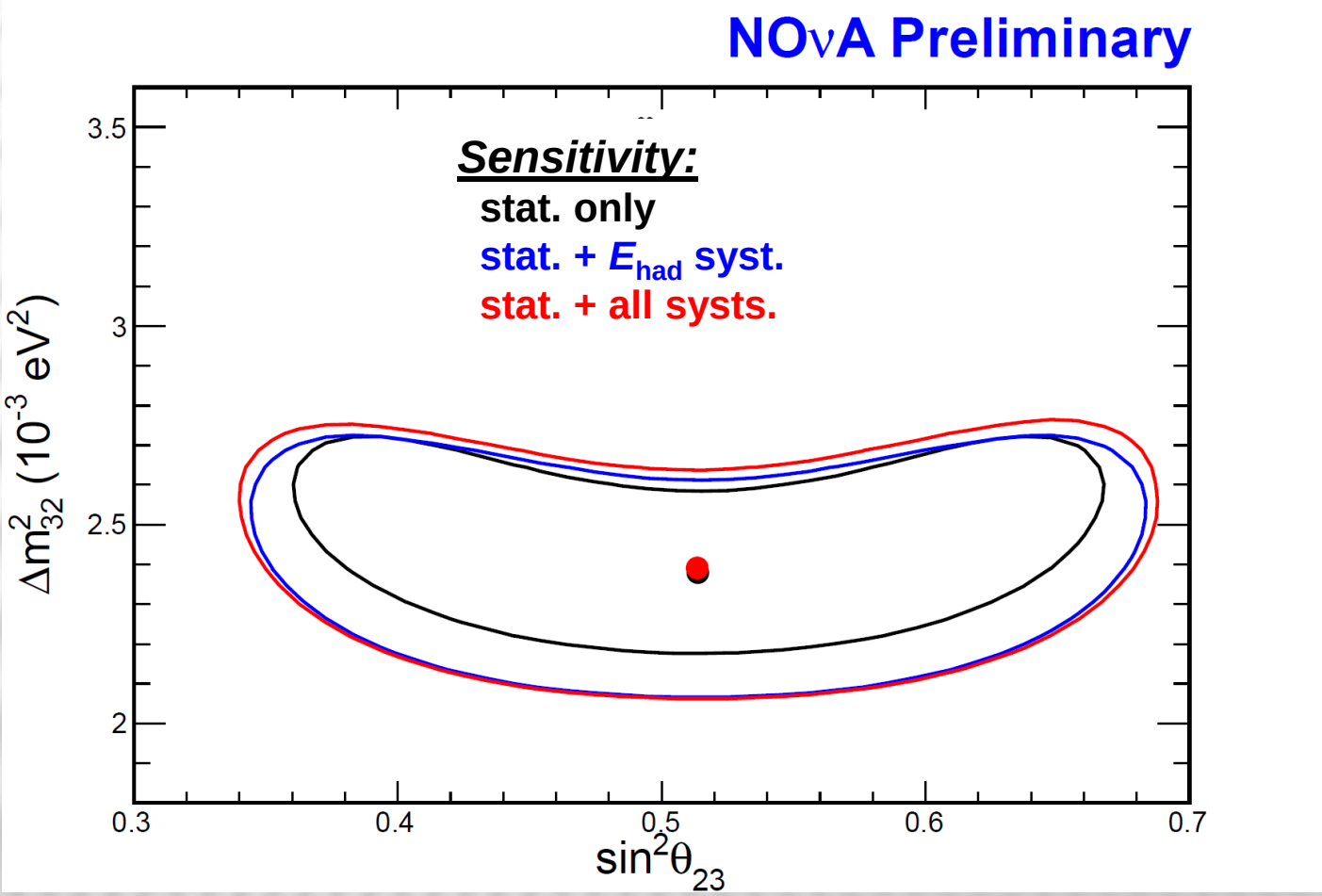
NOνA preliminary





Comparison of NOνA disppearance result to the expected sensitivity for the same best-fit parameters.

Effect of systematic uncertainties on sensitivity to atmospheric parameters in current analysis



Pre-selection

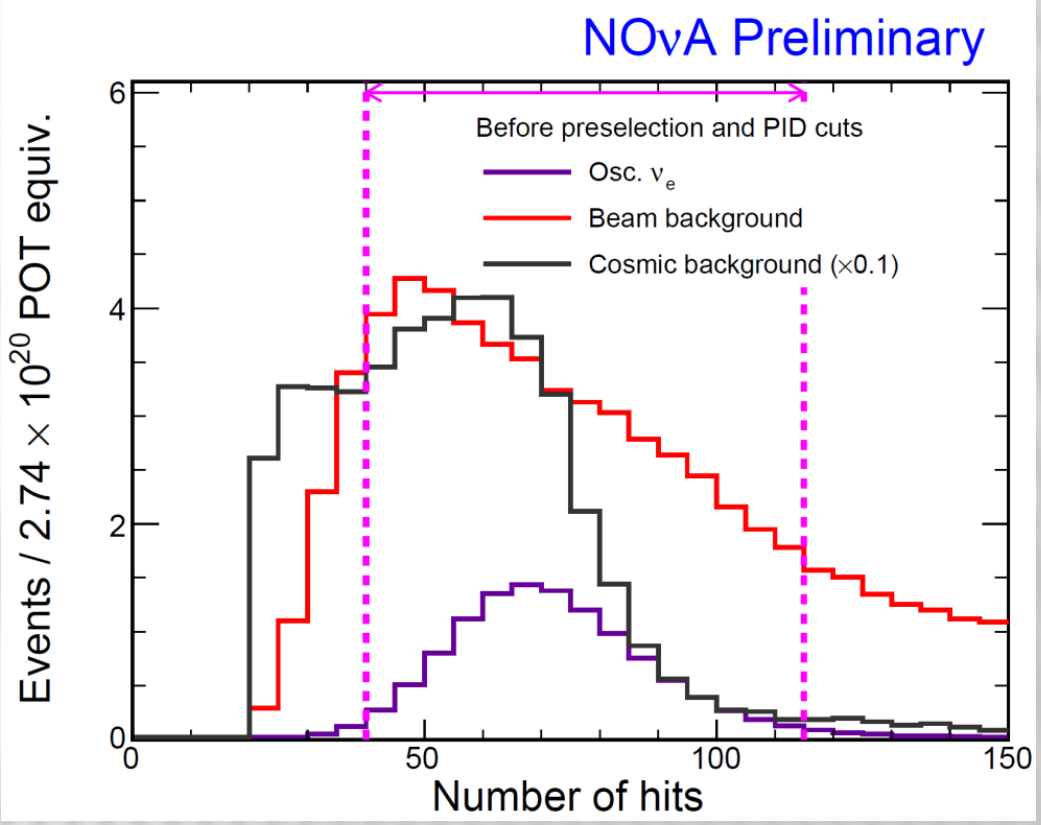
First, basic containment cuts require sufficient distance from the largest reconstructed shower to the walls.

Then, cuts applied to:

- shower length
- number of hits in event
- calorimetric energy

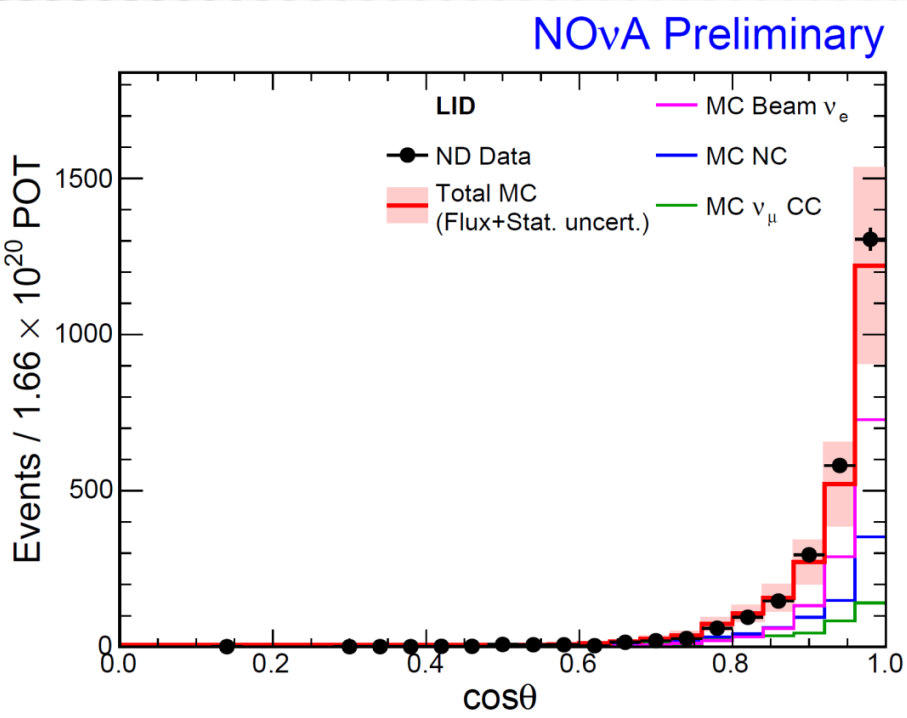
All three related to the "size" of the event

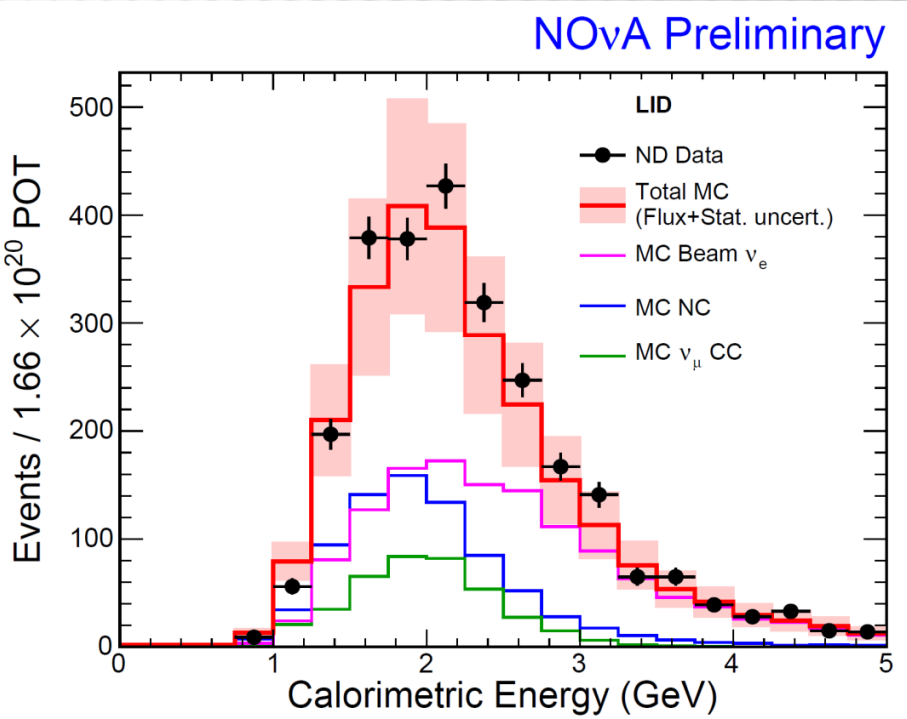
We know well the range of energies any appearing ν_e might have

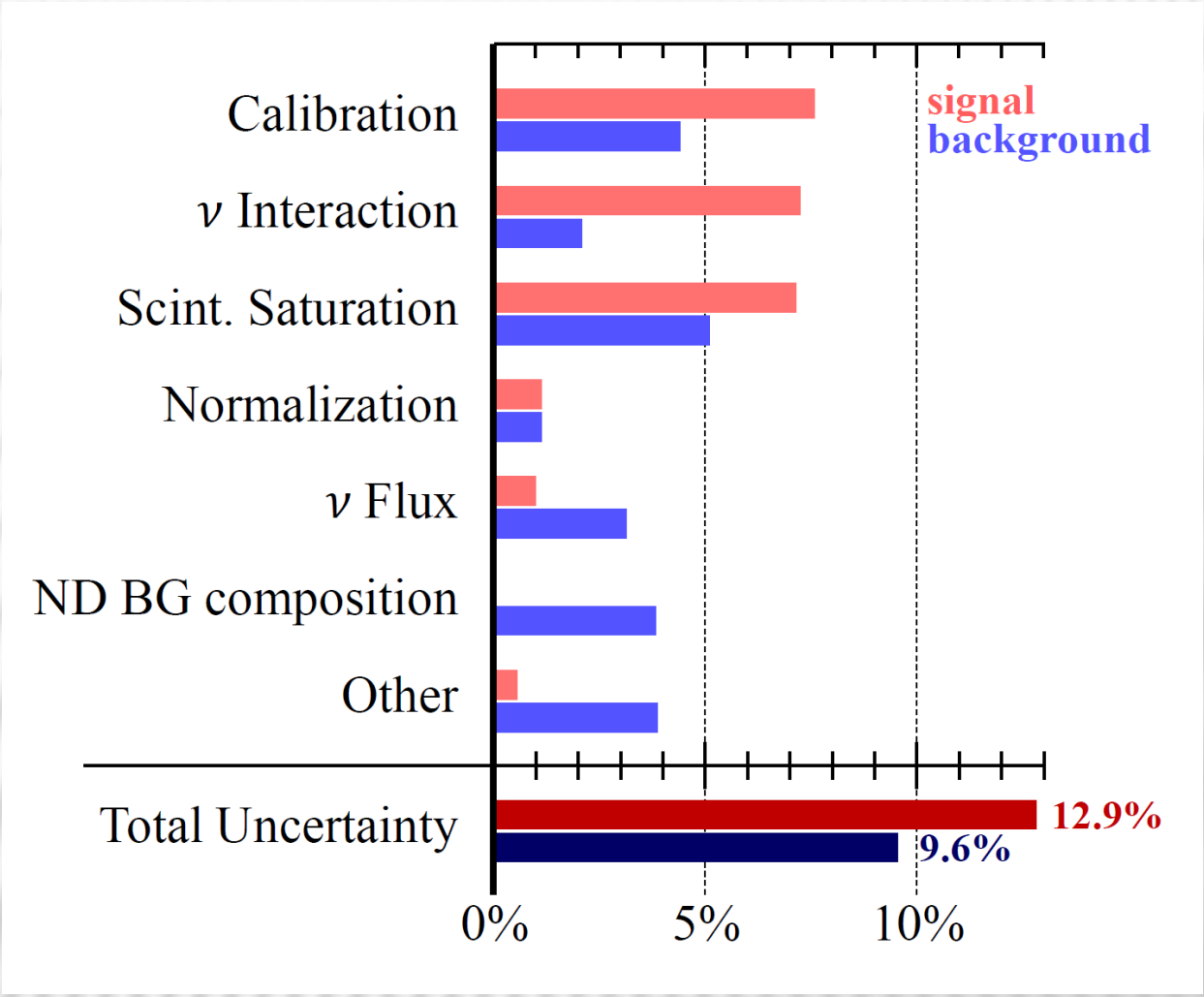


Shower direction and **event energy** distributions for **ND data** and **simulation**, *after all cuts*

This ND distribution is used to create FD background prediction



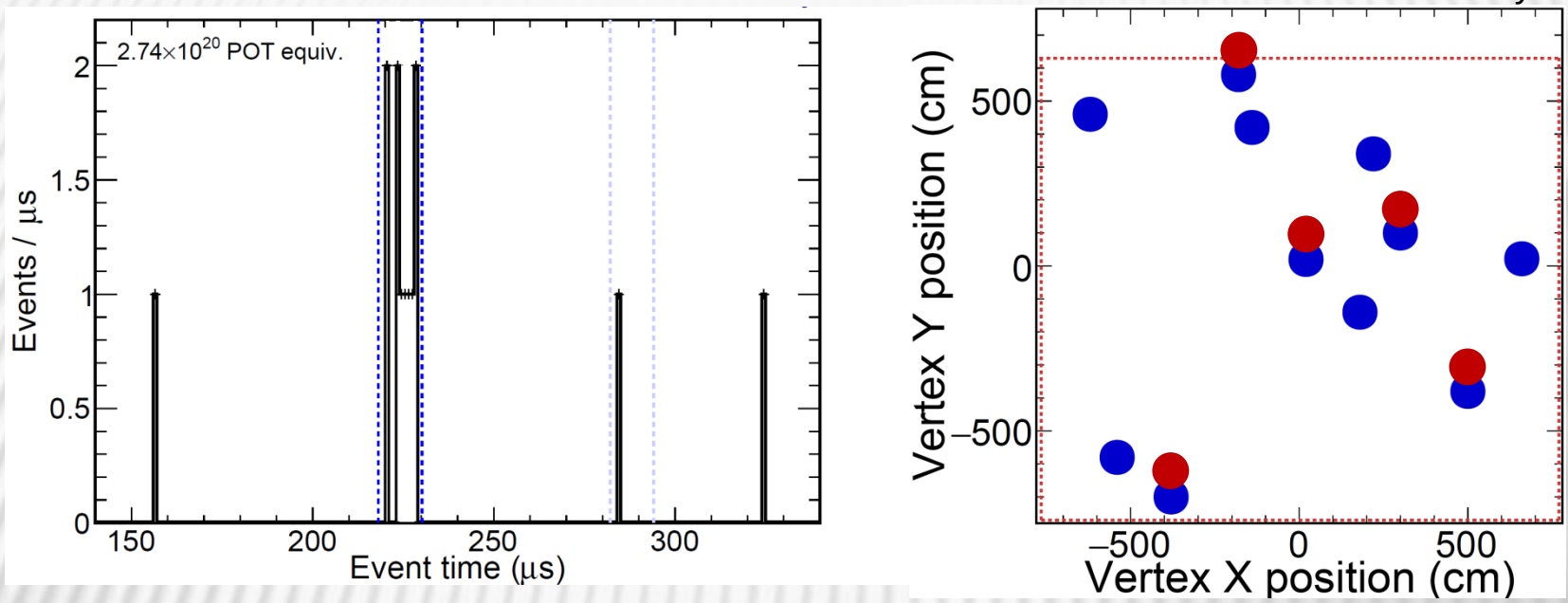


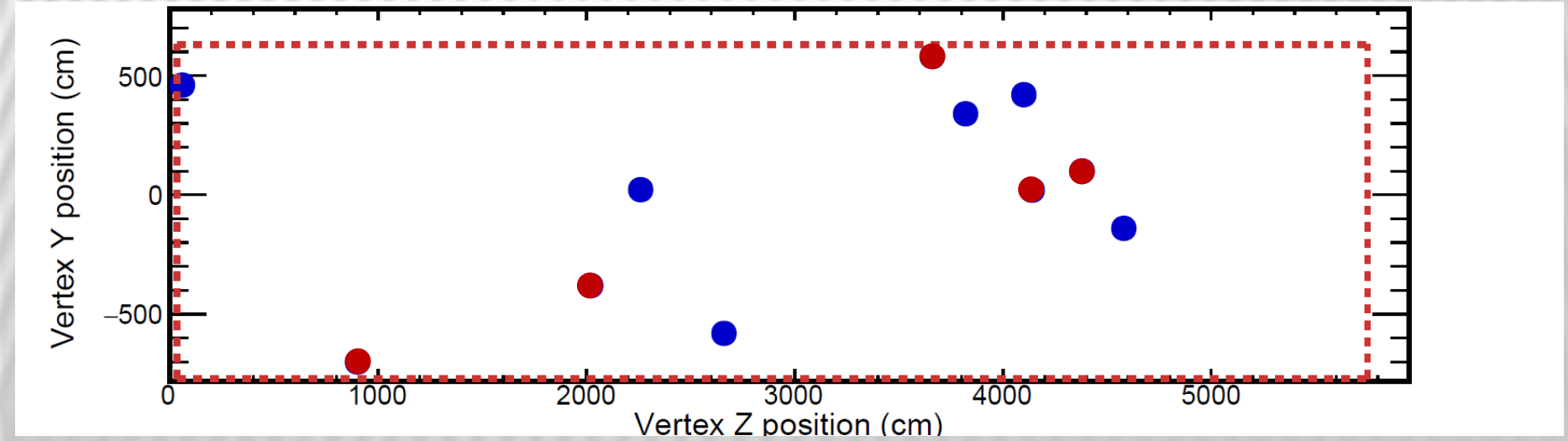


- Most systematics are assessed via variations in the Far/Near ratios

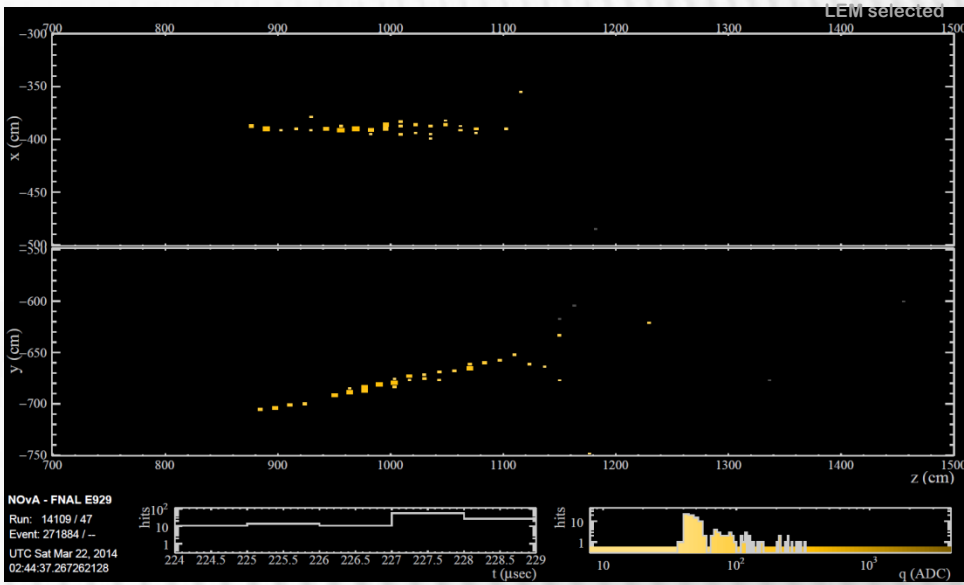
FD ν_e CC candidates: when and where

(LID + LEM events)





Note: Second timing window at +64 μs required for some of the early data.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y (cm)
z (cm)
NOvA - FNAL E929
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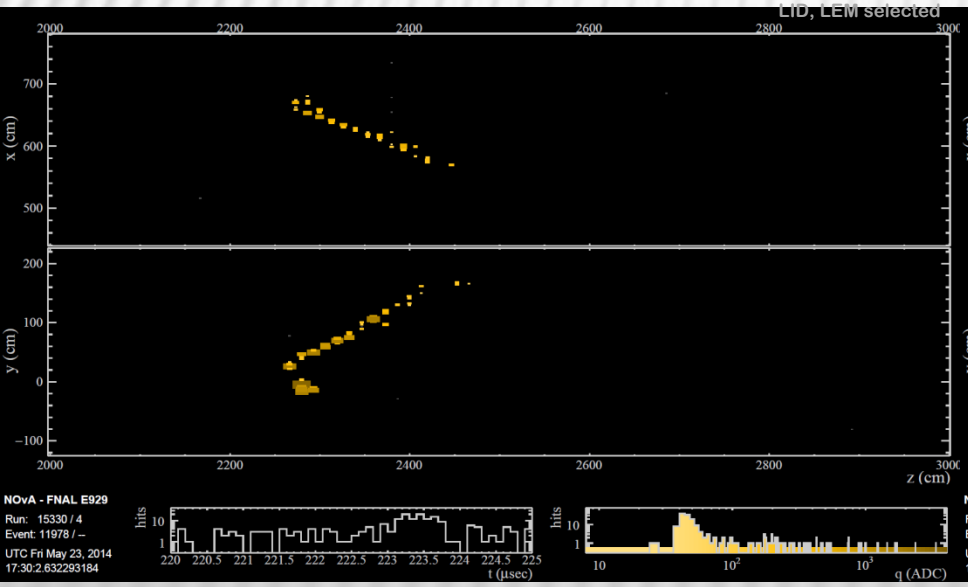
Event: 271884 / --
UTC Sat Mar 22, 2014
02:44:37.267262128
hits
t (μsec)
q (ADC)


LID, LEM selected
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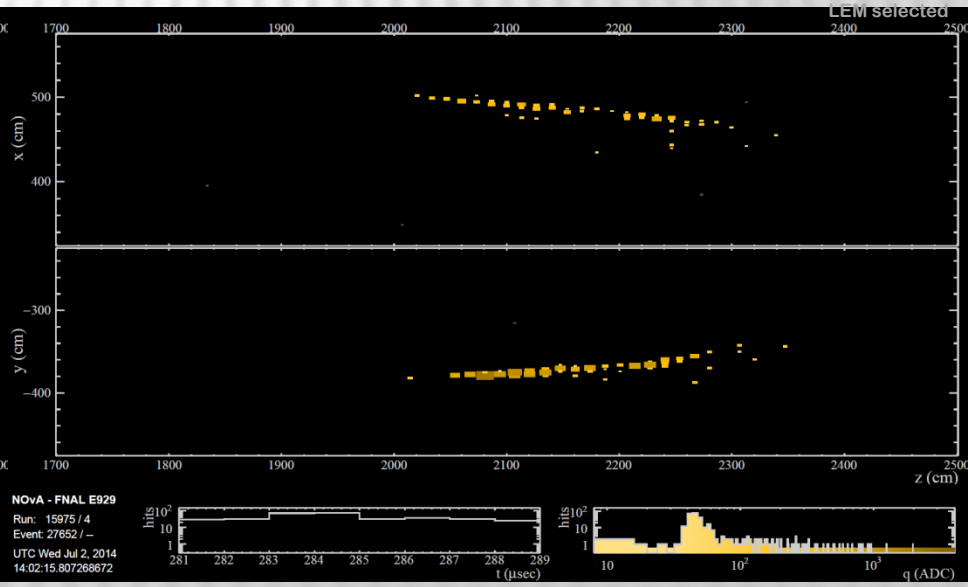
hits
t (μsec)
q (ADC)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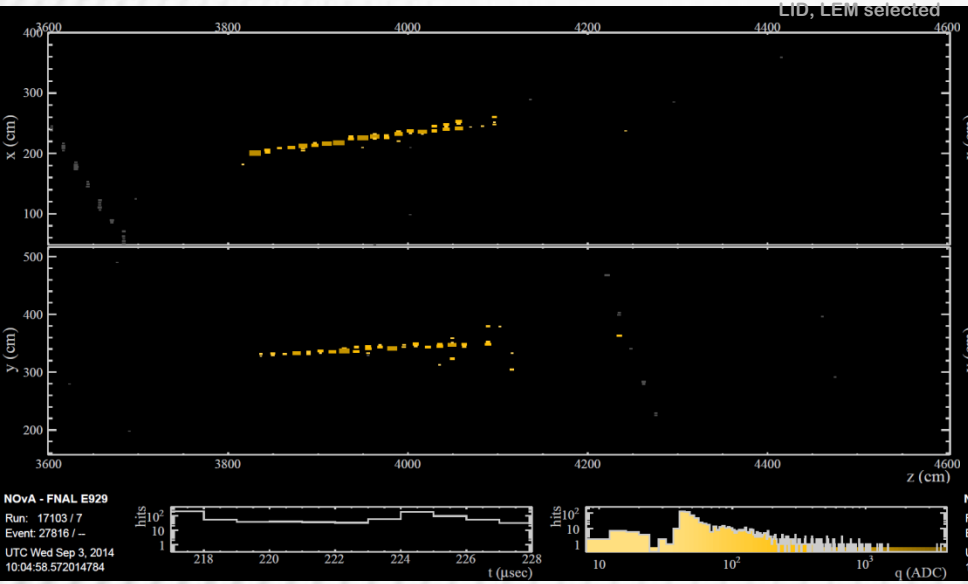
hits
t (μsec)
q (ADC)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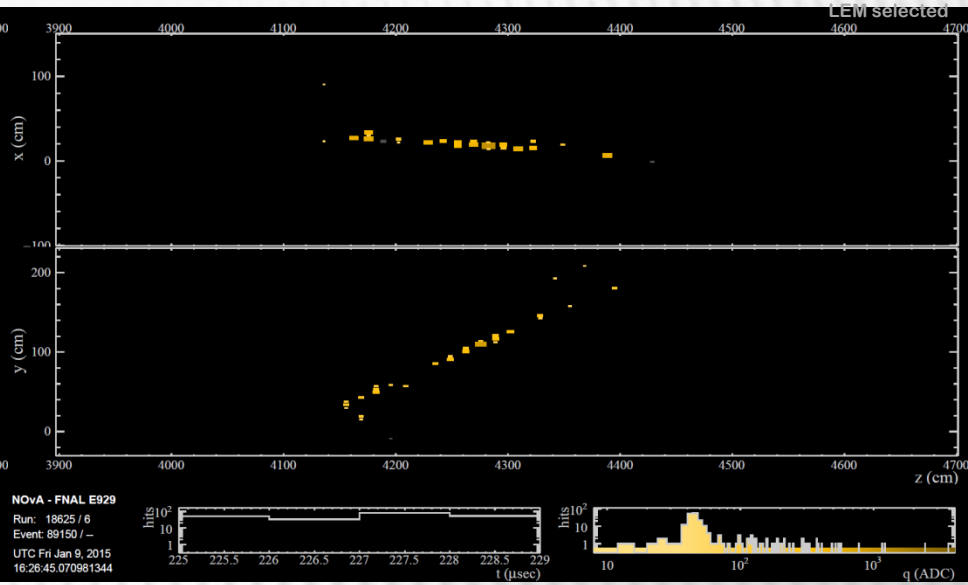
q (ADC)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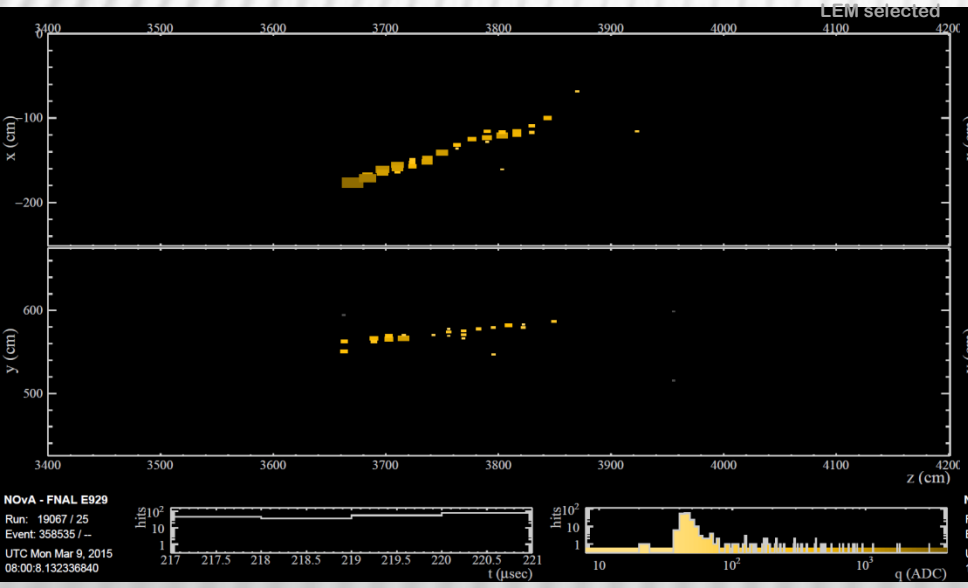
hits
t (μsec)
q (ADC)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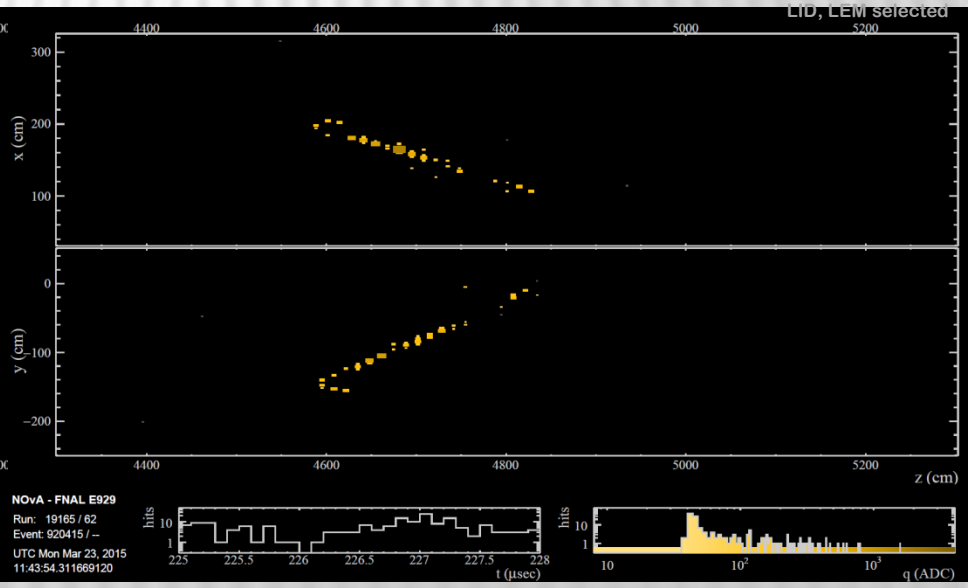
t (μsec)
q (ADC)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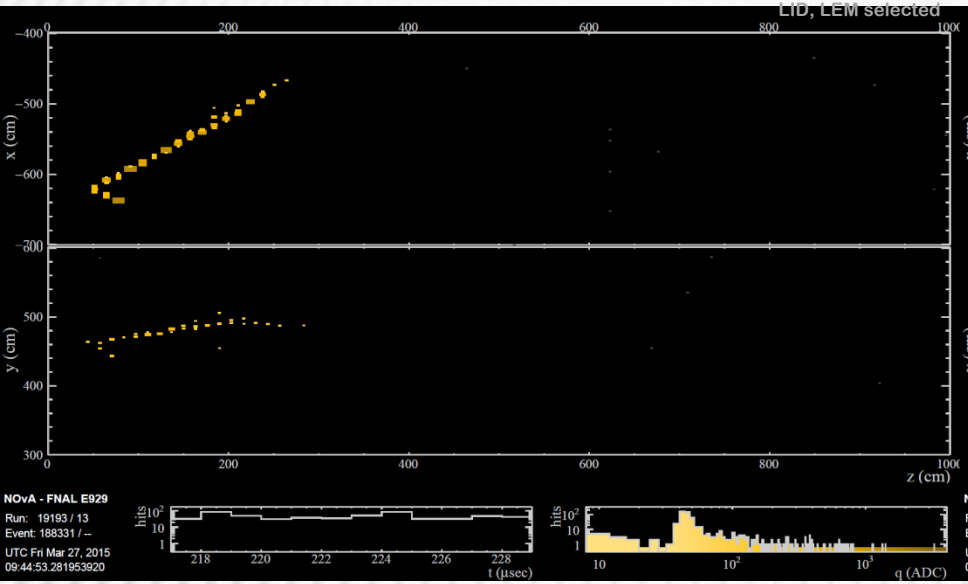
t (μsec)
q (ADC)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Event: 188331 / --
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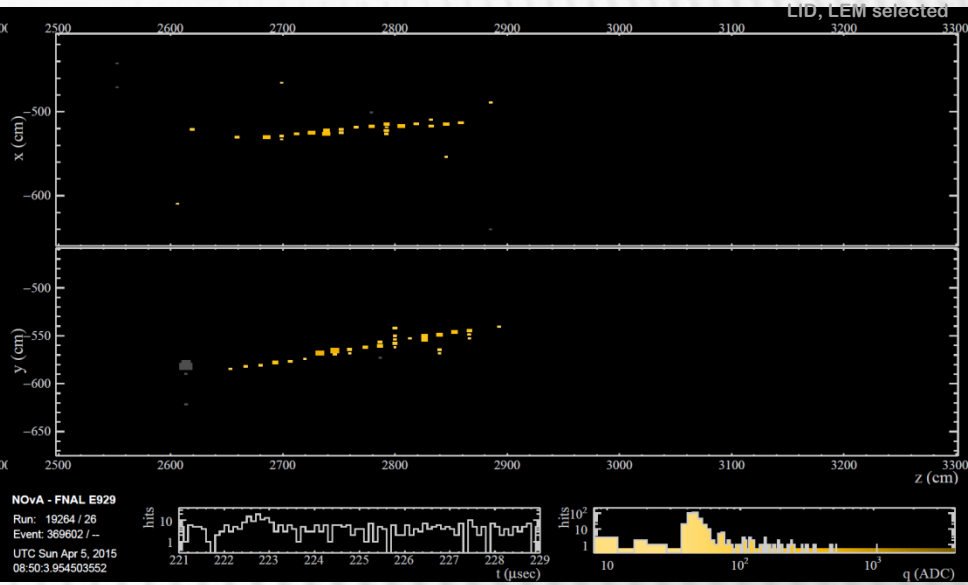
hits
t (μsec)
q (ADC)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Event: 369602 / --
UTC Sun Apr 5, 2015
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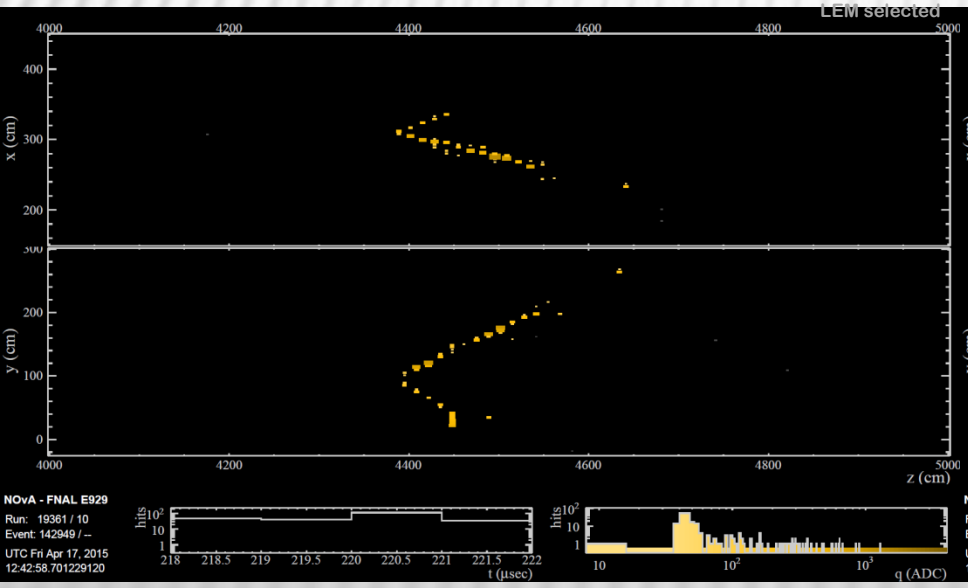
hits
t (μsec)
q (ADC)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Event: 142949 / --
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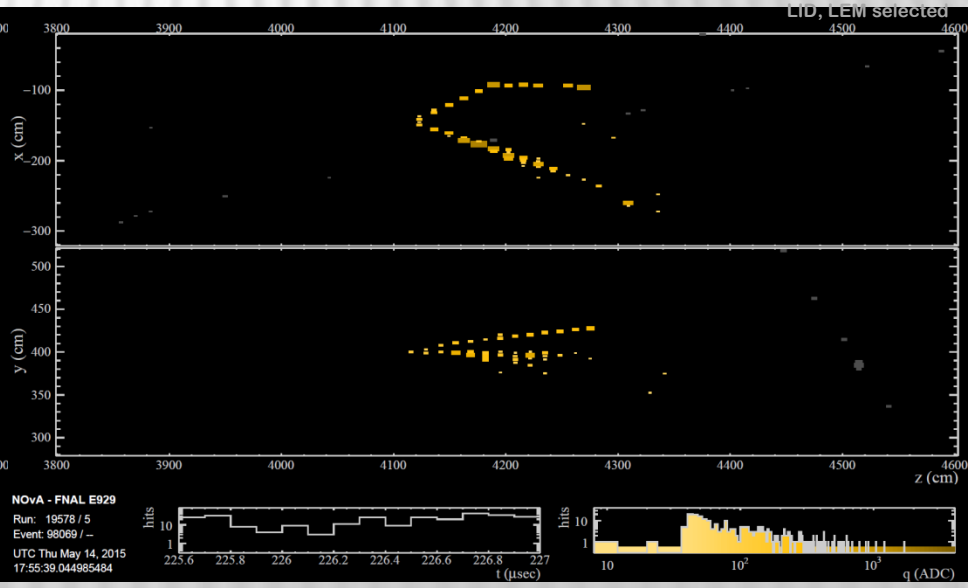
t (μsec)
q (ADC)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z (cm)
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Event: 98069 / --
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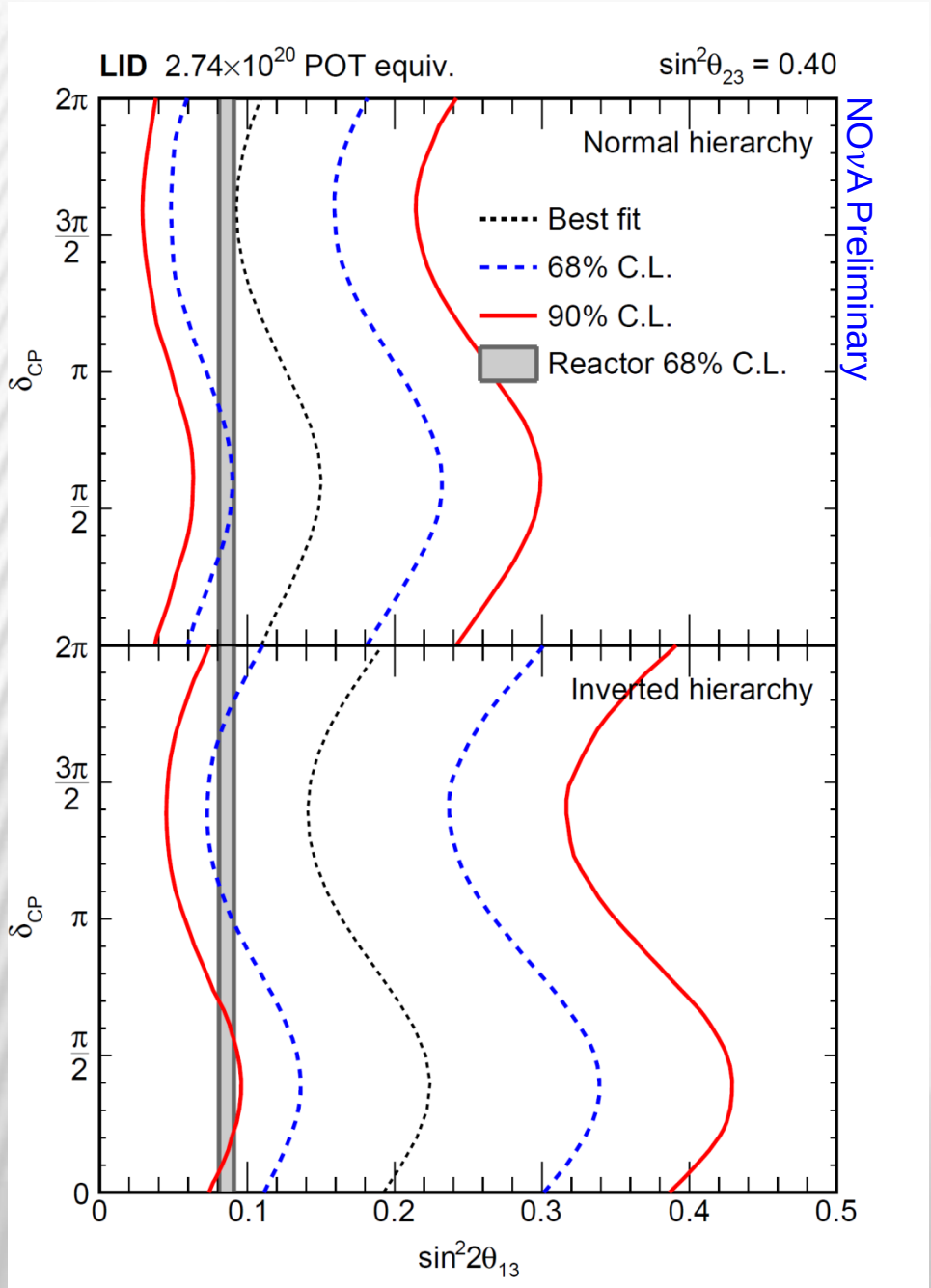
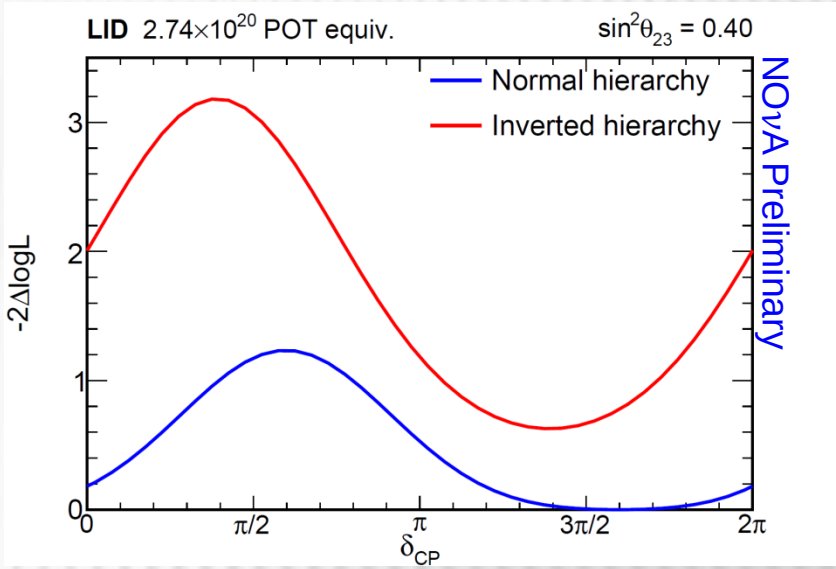
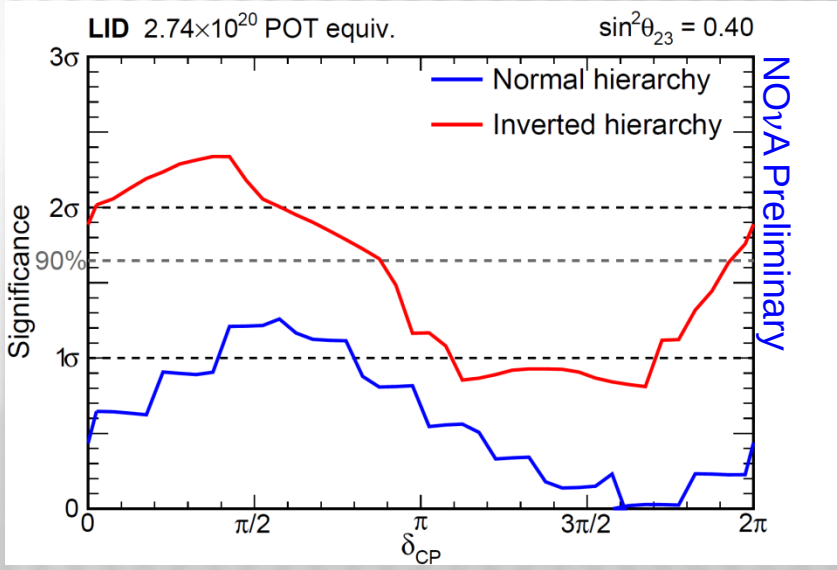
hits
t (μsec)
q (ADC)

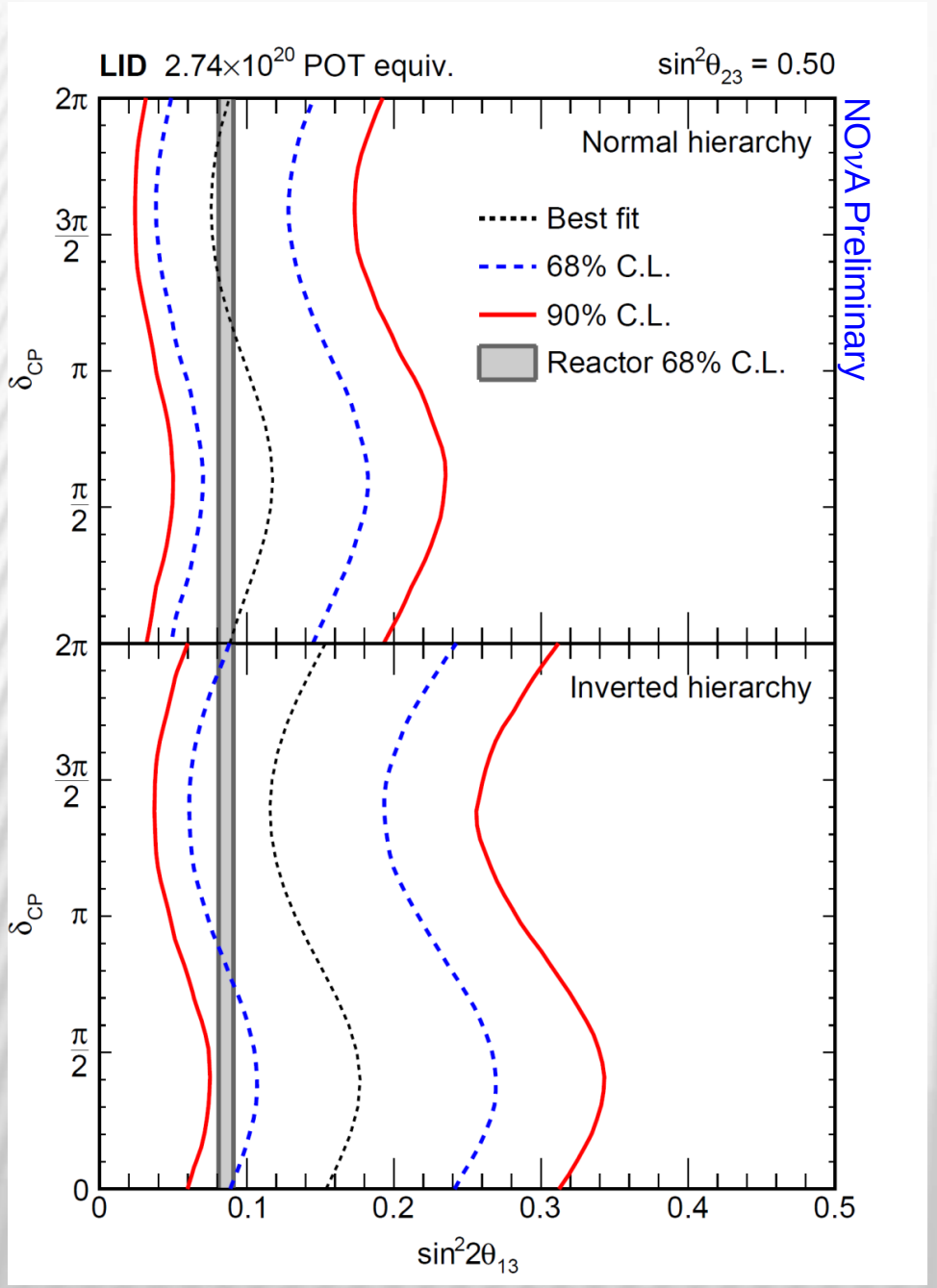
LID: Fixing $\sin^2\theta_{23} = 0.4$

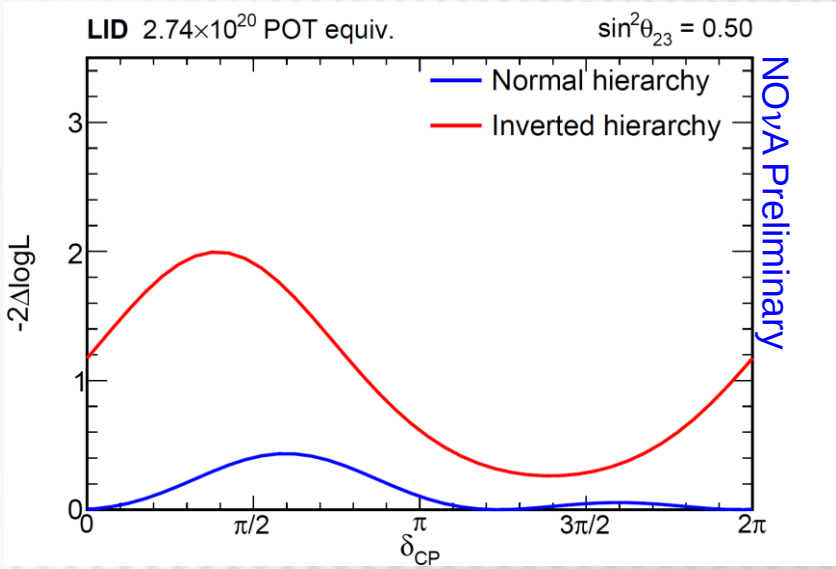


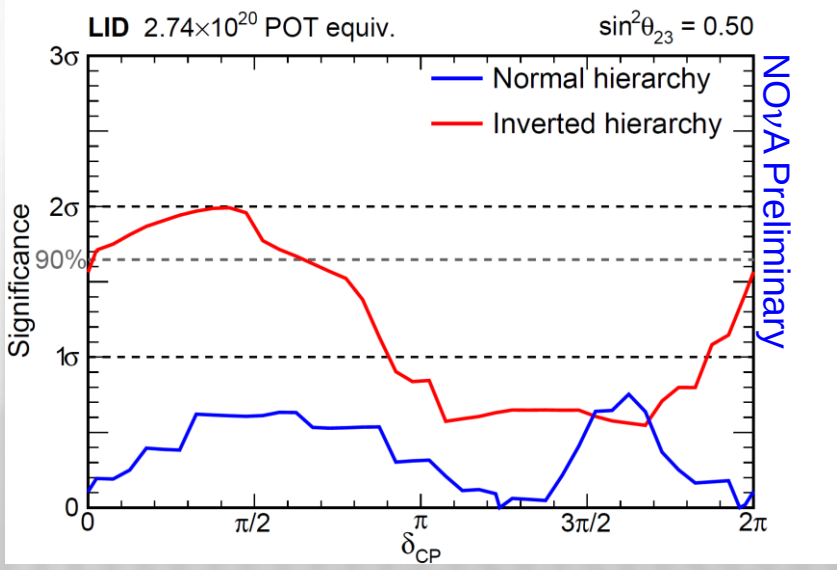




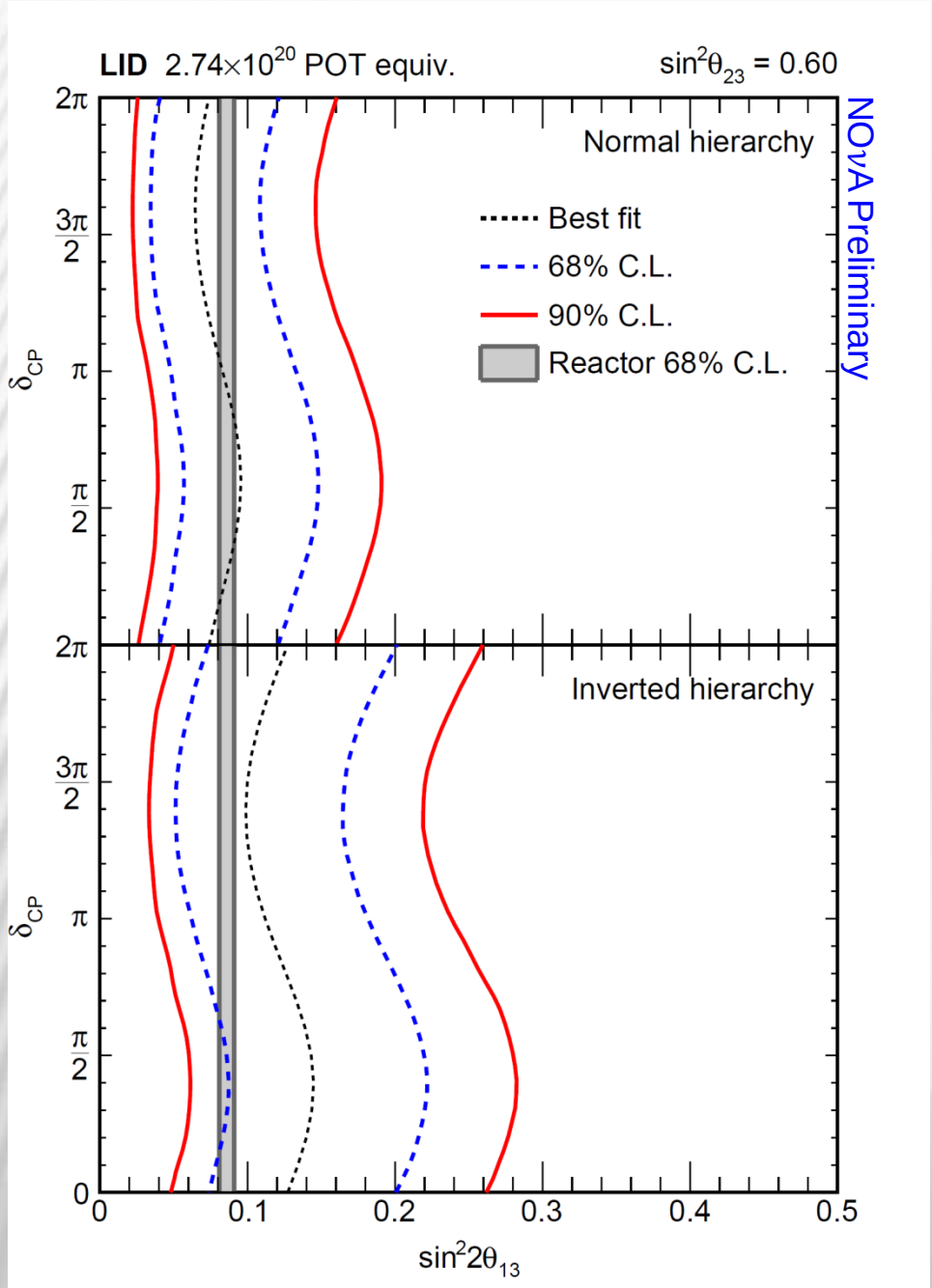
LID: Fixing $\sin^2\theta_{23} = 0.5$

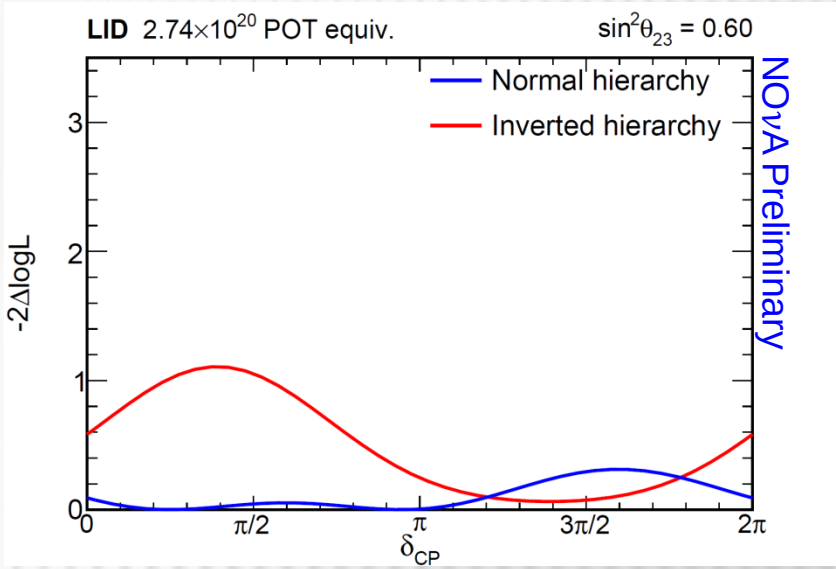


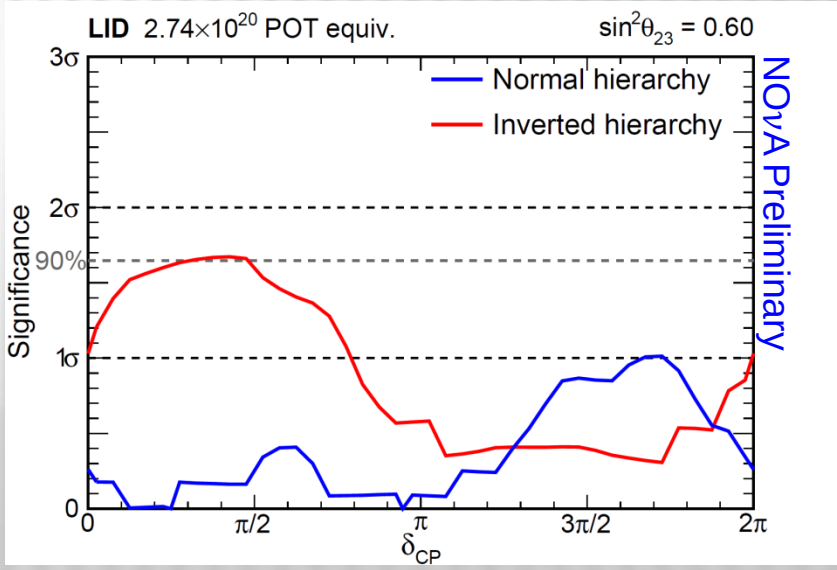




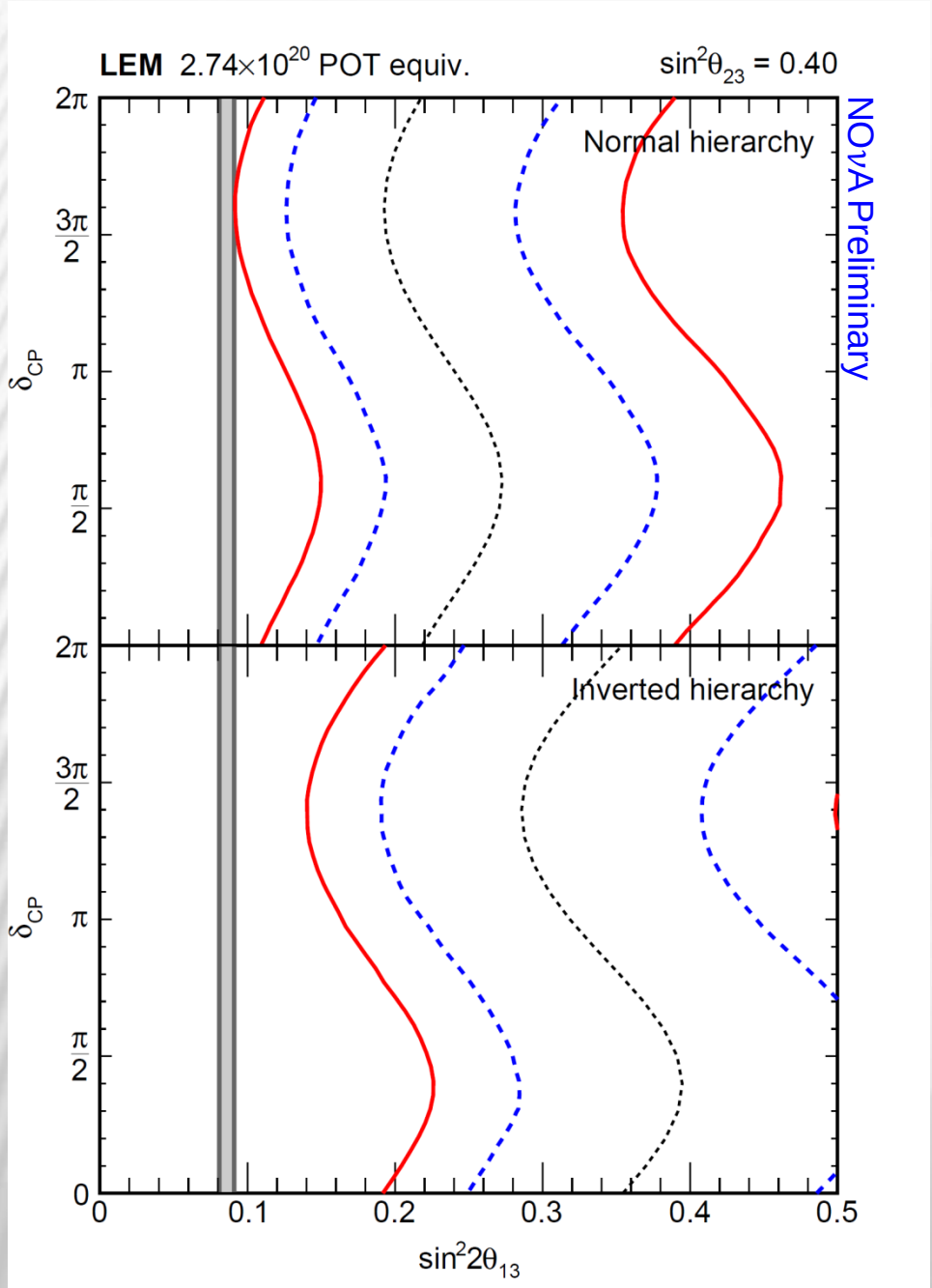
LID: Fixing $\sin^2\theta_{23} = 0.6$

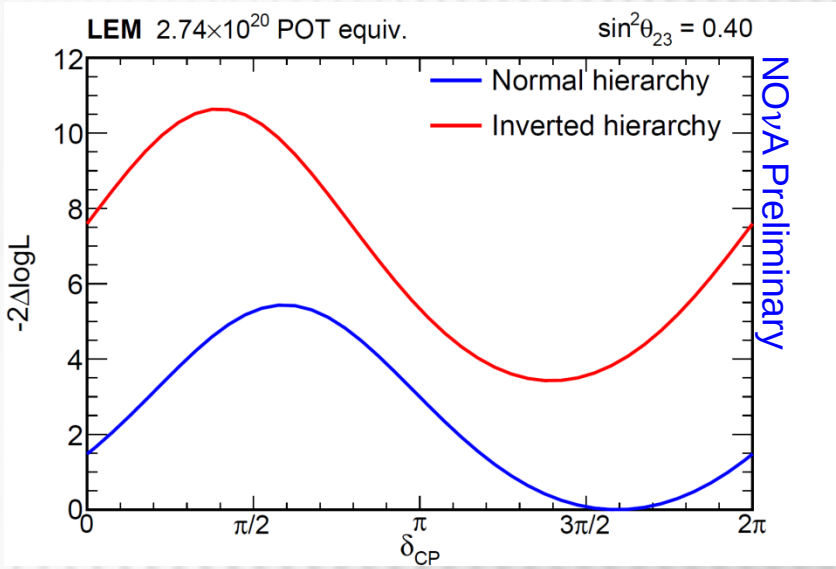


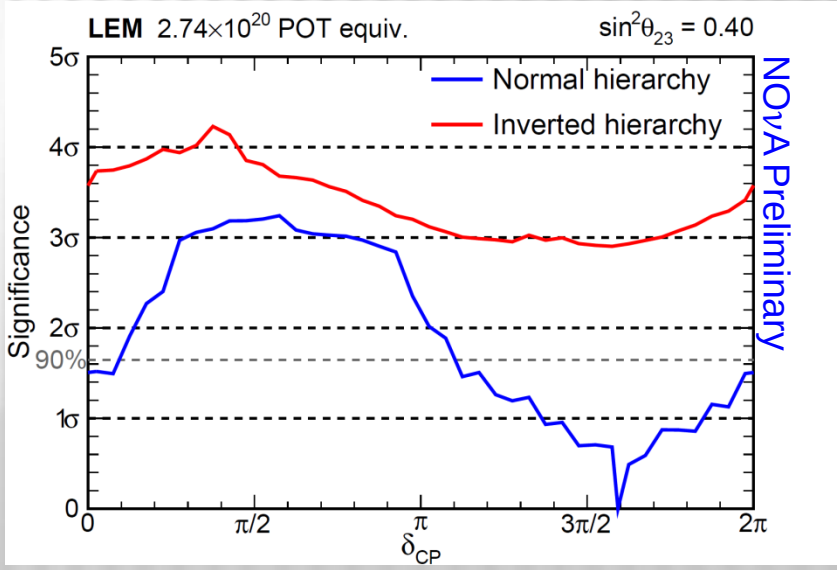




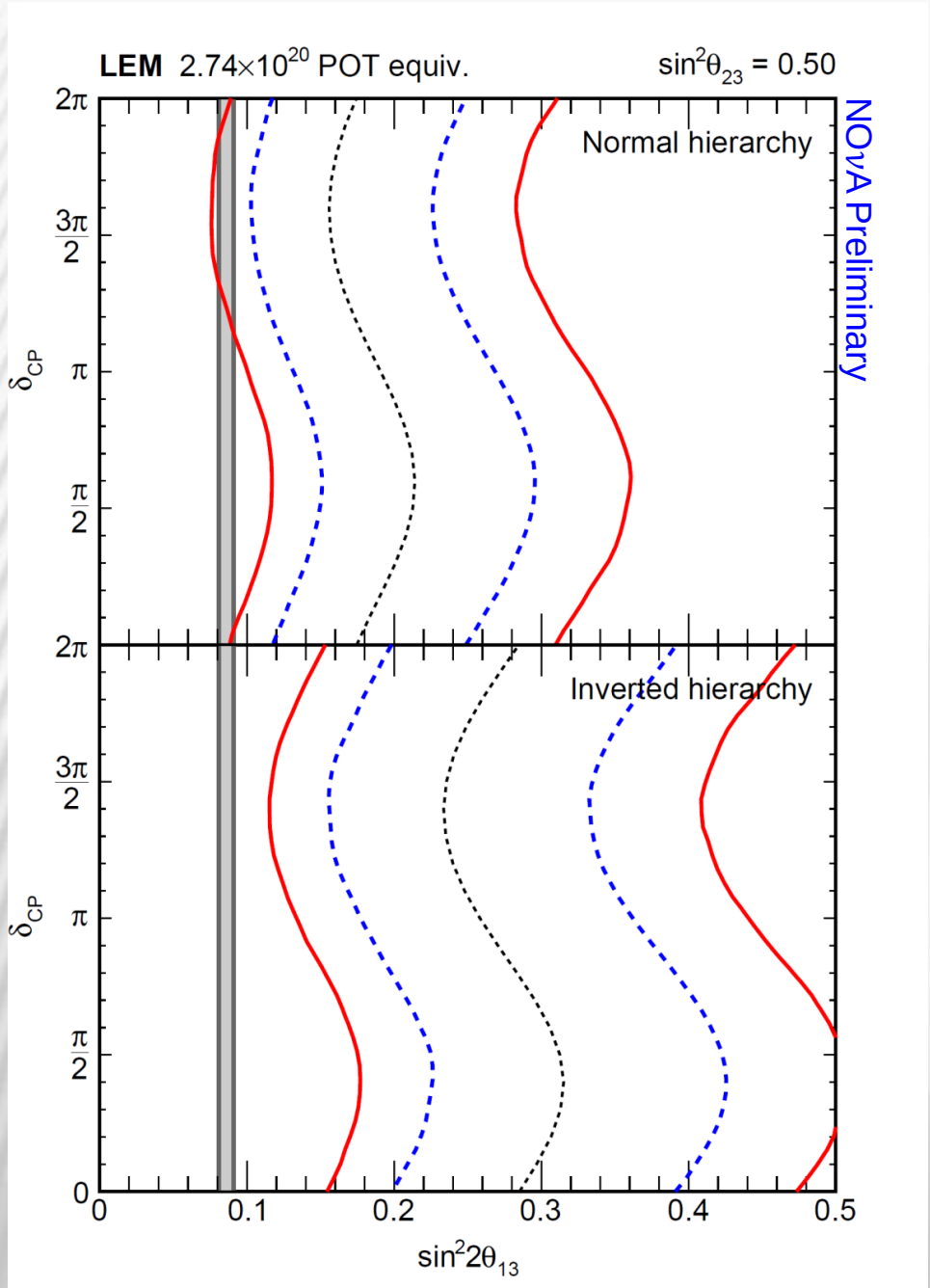
LEM: Fixing $\sin^2\theta_{23} = 0.4$

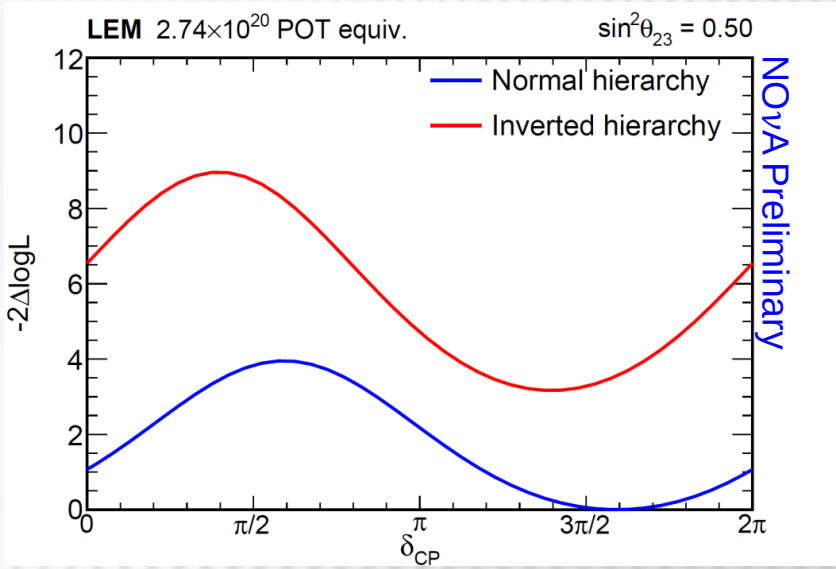


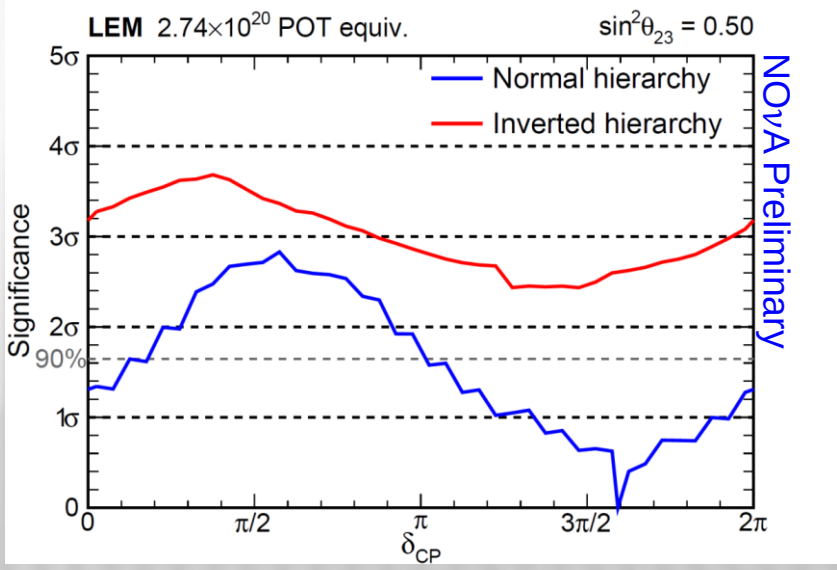




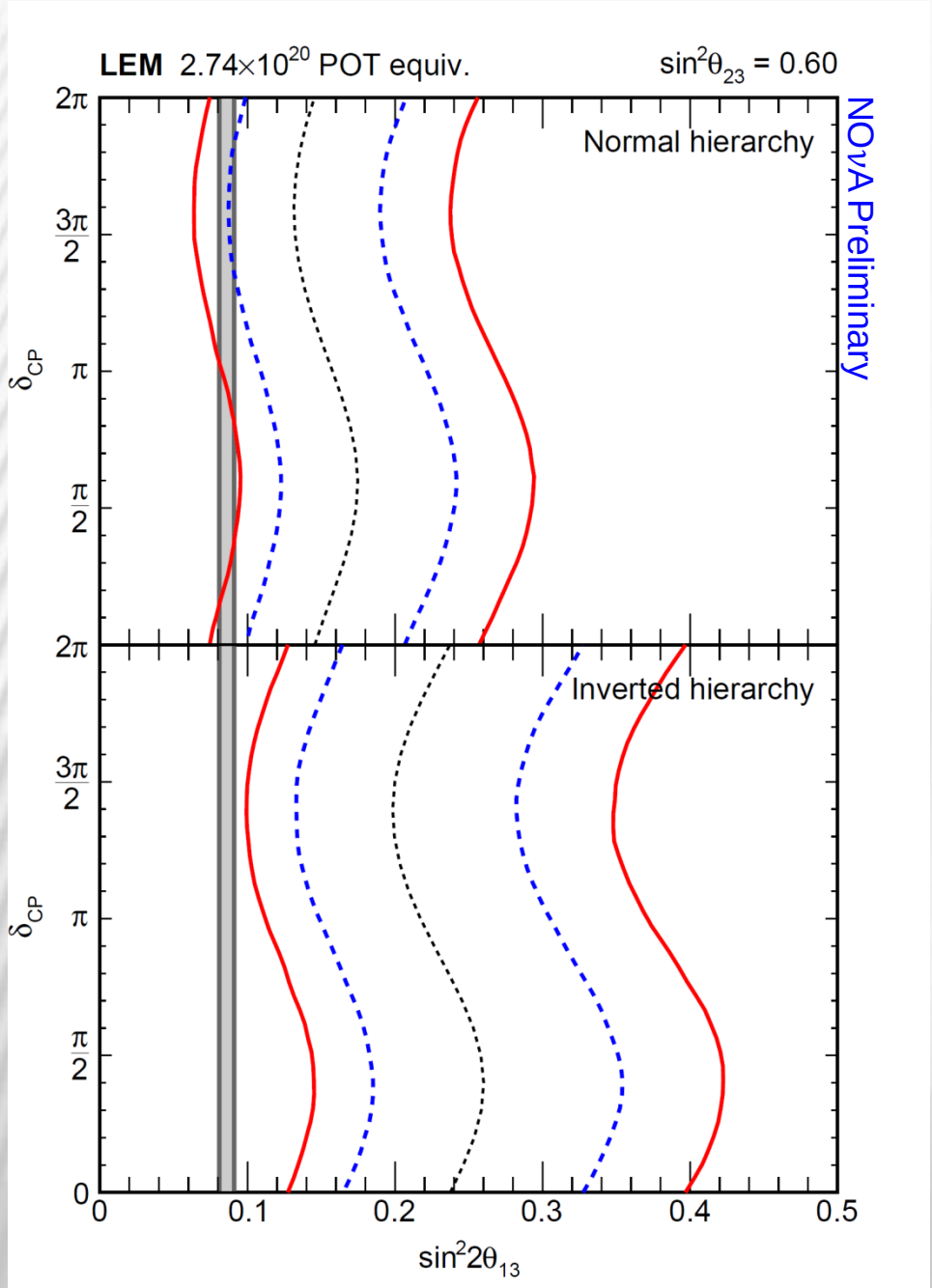
LEM: Fixing $\sin^2\theta_{23} = 0.5$

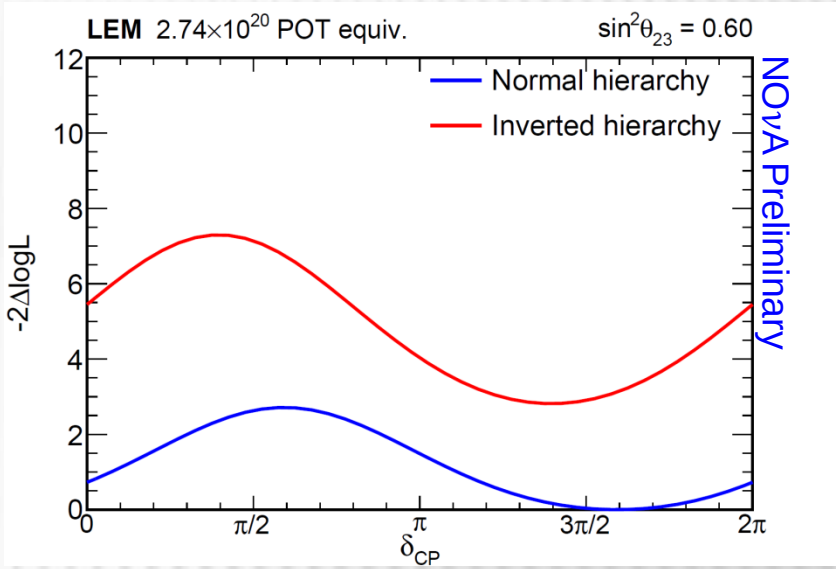


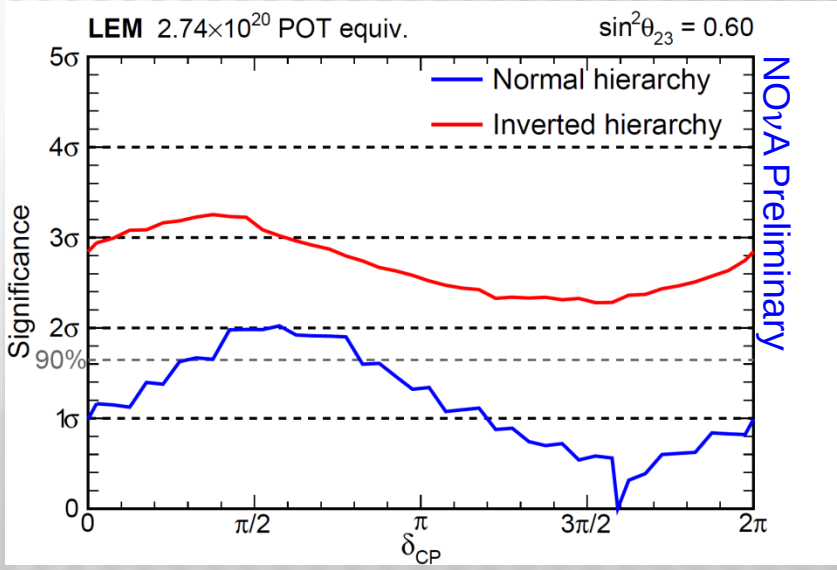




LEM: Fixing $\sin^2\theta_{23} = 0.6$

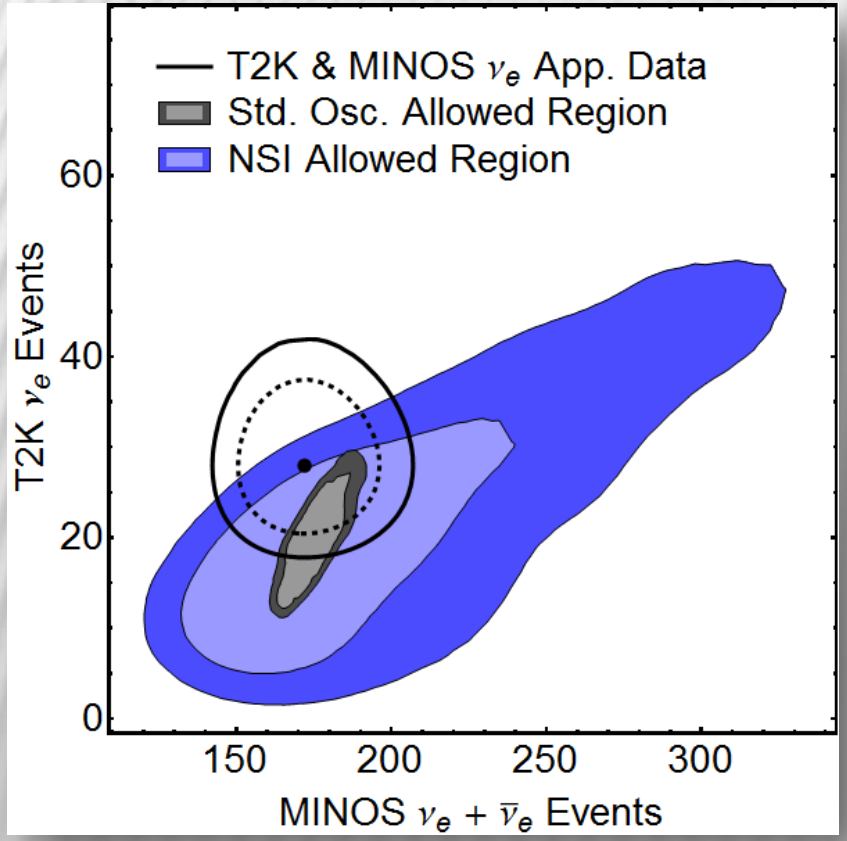






NON-STANDARD INTERACTIONS

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



- 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