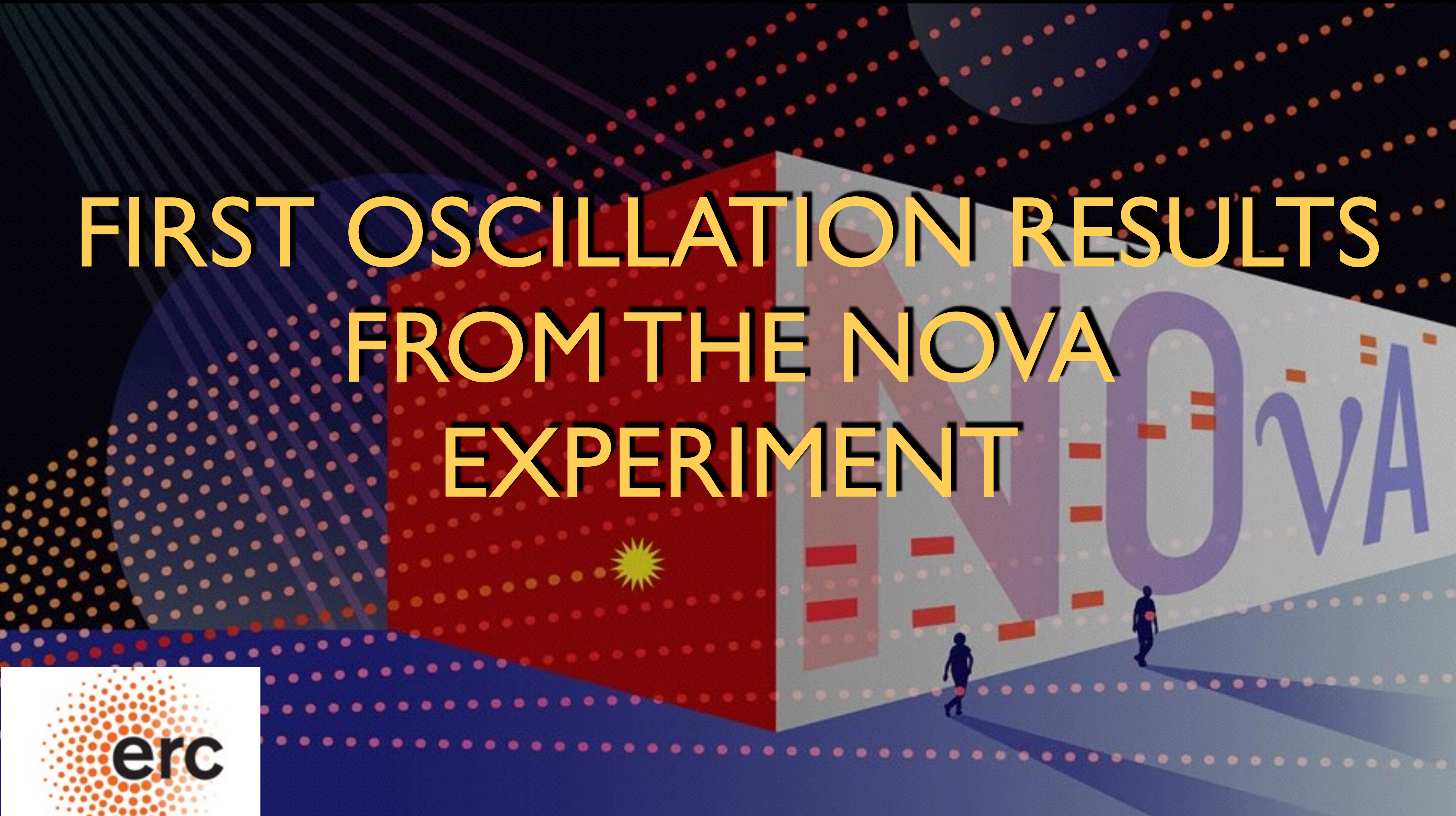
FIRST OSCILLATION RESULTS FROM THE NOVA EXPERIMENT



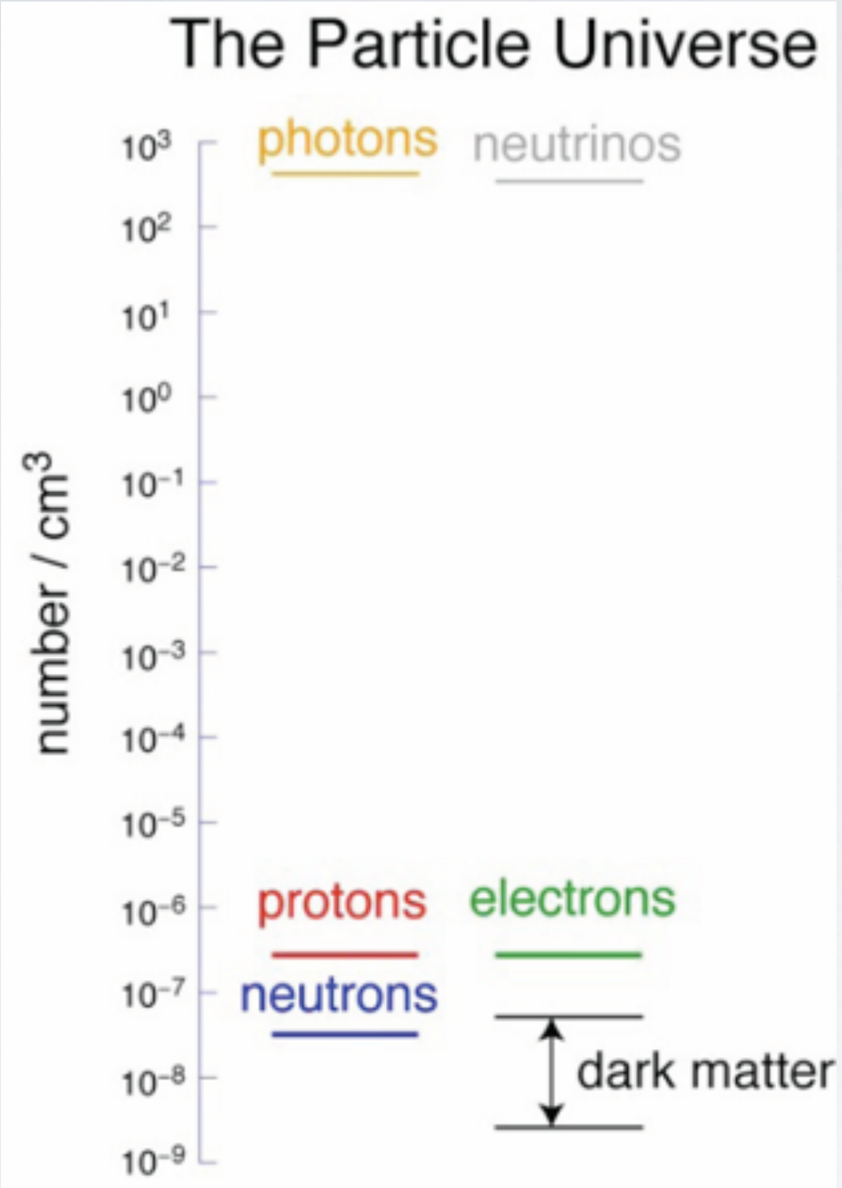
Bruno Zamorano

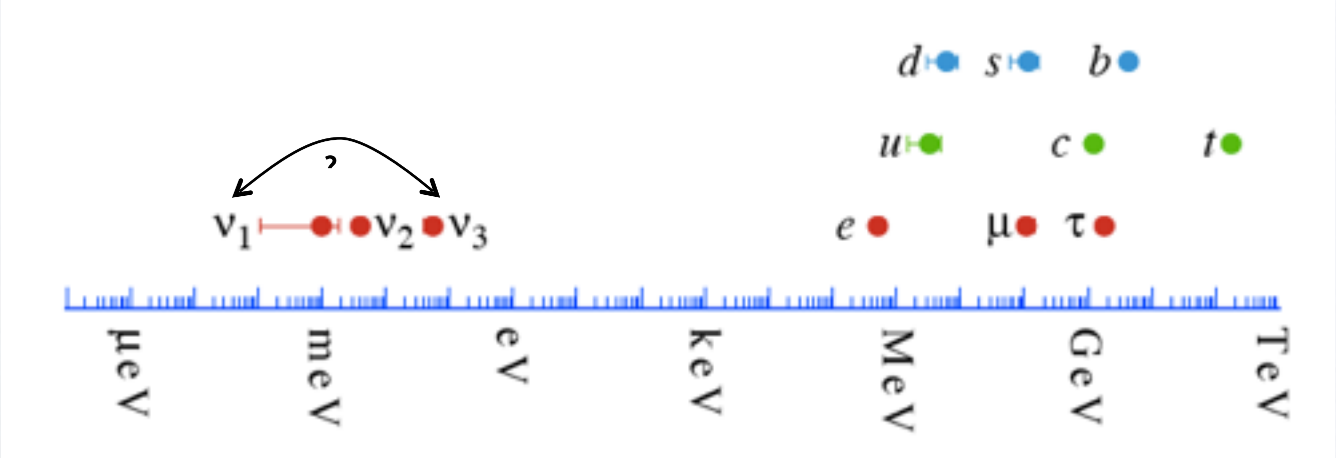
Birmingham - 20th January 2016

European Research Council
Established by the European Commission

University of Sussex

Why study neutrino oscillations?





- Second most abundant particle in the Universe and yet the worst understood
- Dark Matter aside, the only measured confirmation of Physics beyond the Standard Model
- ~20 000 neutrino papers since the discovery of neutrino oscillations
- Nobel prize 2015 and Breakthrough prize 2016
- Many open questions: CP violation (matter-antimatter asymmetry), mass ordering and mass scale, Dirac or Majorana…
- Oscillation parameters are, to our best knowledge, fundamental constants of Nature

Neutrino oscillations overview

PMNS matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\mu e} = \sum_{j,k} U^*_{ej} U_{\mu j} U^*_{\mu k} U_{ek} \boxed{\exp\left(-i\frac{\Delta m^2_{jk} L}{2E}\right)}$$

Oscillations

Neutrino oscillations overview

PMNS matrix

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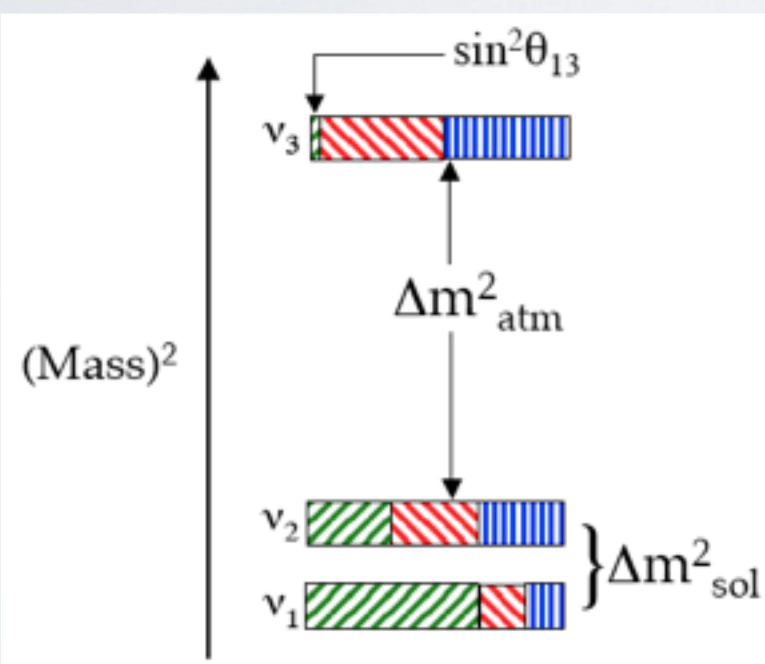
$$P_{\mu e} = \sum_{j,k} U^*_{ej} U_{\mu j} U^*_{\mu k} U_{ek} \boxed{\exp\left(-i\frac{\Delta m^2_{jk} L}{2E}\right)}$$

Oscillations

Atmospheric | Reactor | Solar

$$\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \times \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \times \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$



$$\Delta m^2_{32} \simeq \Delta m^2_{31} \xrightarrow{Osc.max} L/E \approx 500 \text{km/GeV}$$

$$\Delta m^2_{21} = m^2_2 - m^2_1 \xrightarrow{Osc.max} L/E \approx 15000 \text{ km/GeV}$$

Importance of reactor result

$$\times \begin{pmatrix} c_{13} & 0 & \boxed{s_{13}e^{-i\delta}} \\ 0 & 1 & 0 \\ \boxed{-s_{13}e^{-i\delta}} & 0 & c_{13} \end{pmatrix} \times$$

$$CP \text{ violation} \Longleftrightarrow \theta_{13} \neq 0$$

θ_{13}: from unknown to best measured

$$\sin^2\theta_{13} = 0.0219 \pm 0.0012$$

$\theta_{13} \sim 8.5°$

A new door to probing CP violation, the mass ordering and the octant of θ_{23}

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$\theta_{13} \sim 8.5°$

A new door to probing CP violation, the mass ordering and the octant of θ_{23}

ν_e appearance:

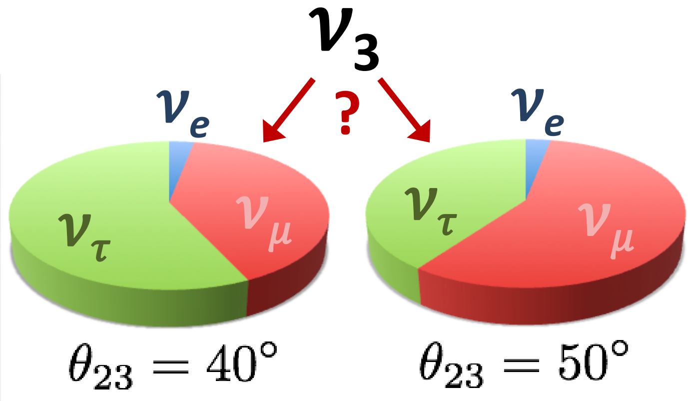
$$P(\nu_\mu \to \nu_e) \simeq \sin^2(\theta_{23})\underbrace{\sin^2(2\theta_{13})}_{\text{Daya Bay reactor experiment}}\underbrace{(\Delta m^2_{32}L/4E)}_{\text{CP-violation? and matter effect modifications}} + \ldots$$

Daya Bay reactor experiment:

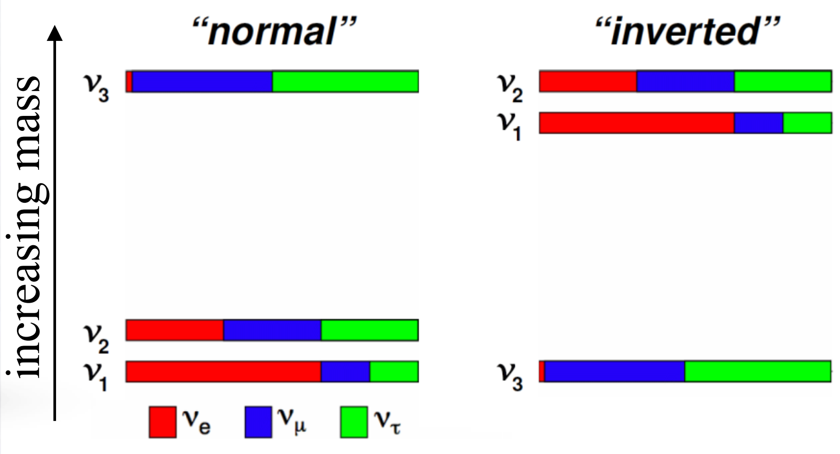
$$\sin^2(2\theta_{13}) = 0.084 \pm 0005$$

CP-violation? and matter effect modifications

θ_{23} octant



Mass hierarchy



Window to measure appearance: CP violation and mass-hierarchy

SUMMARY

The NOvA experiment

Muon neutrino disappearance

Electron neutrino appearance

Future sensitivities

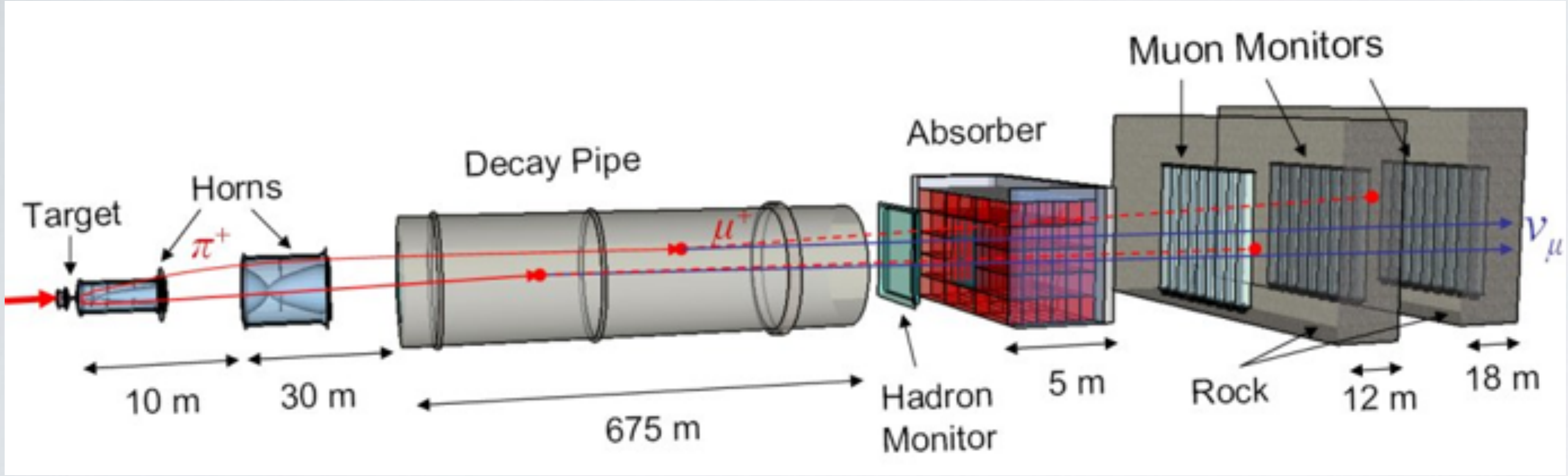
The NOvA experiment

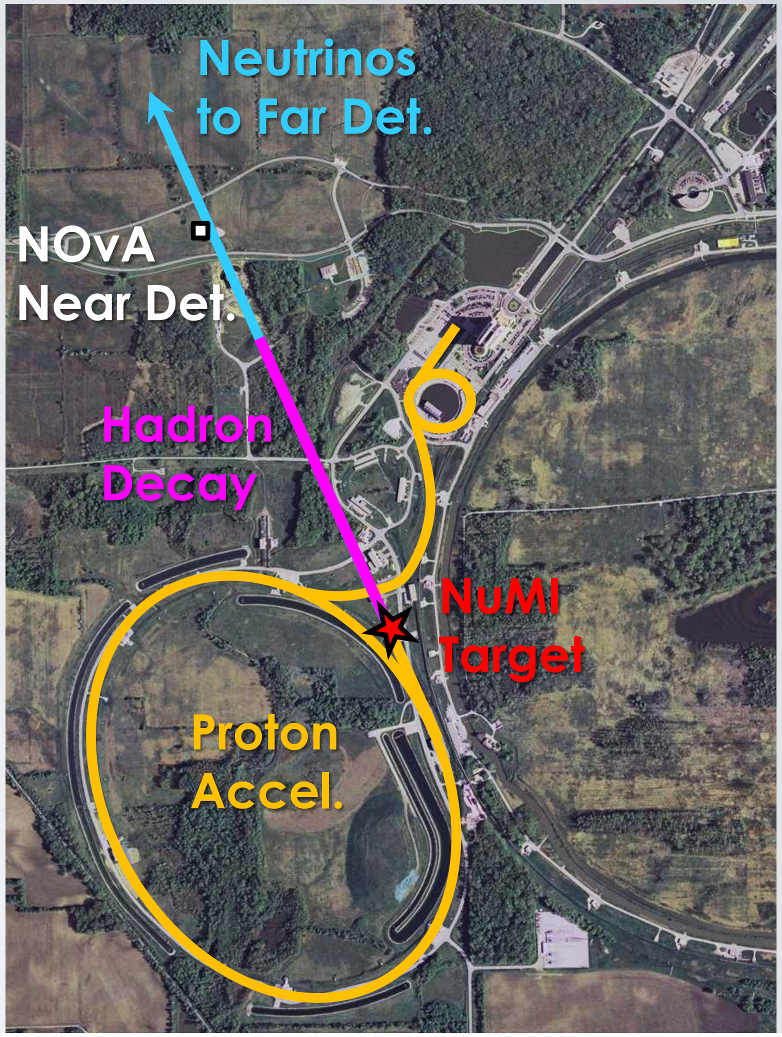
About 150 physicists from 6 countries (list growing…)

2 UK institutions: Sussex (8 people, since 2012) and UCL (6 people, just joined)

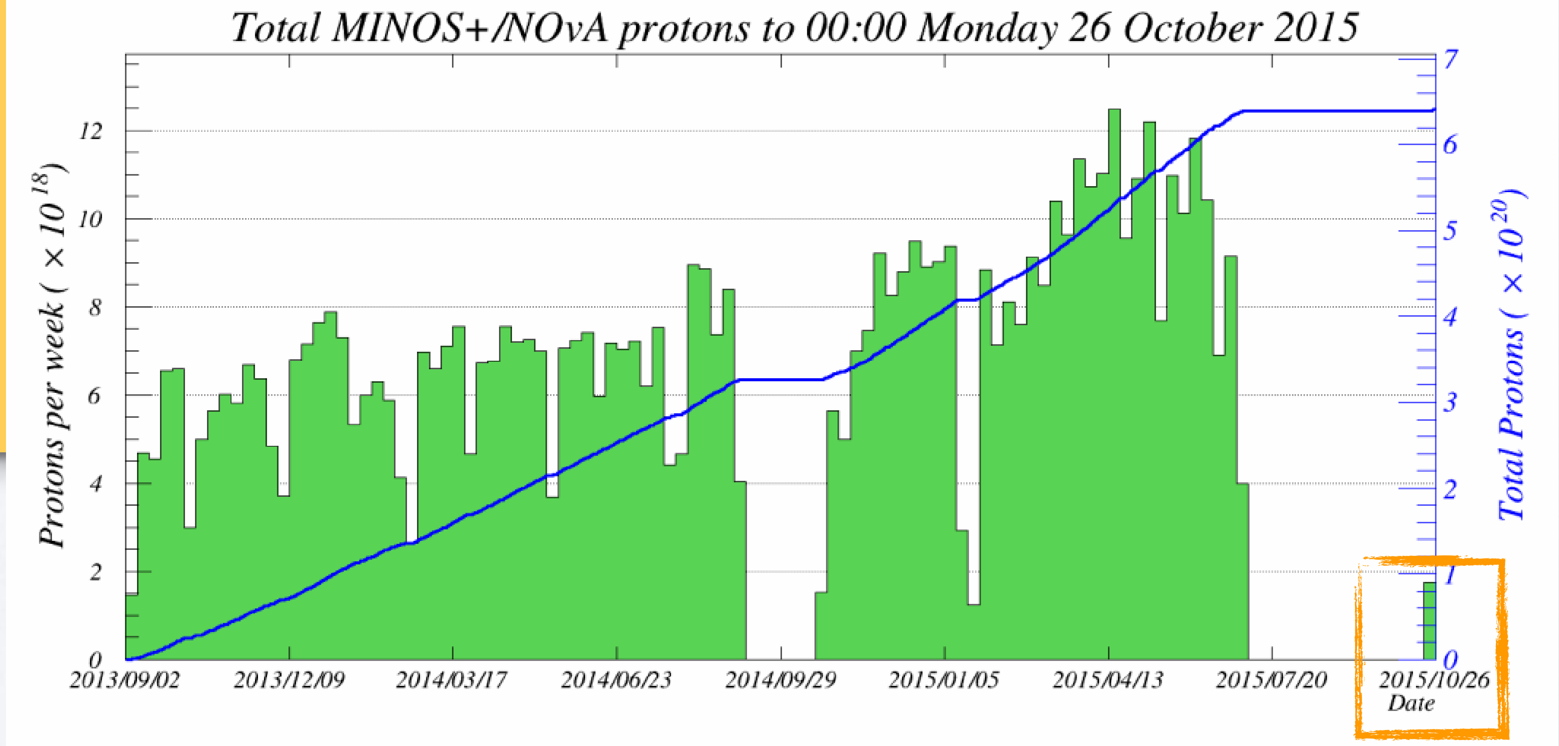
New collaborators and institutions welcome!

NuMI beam

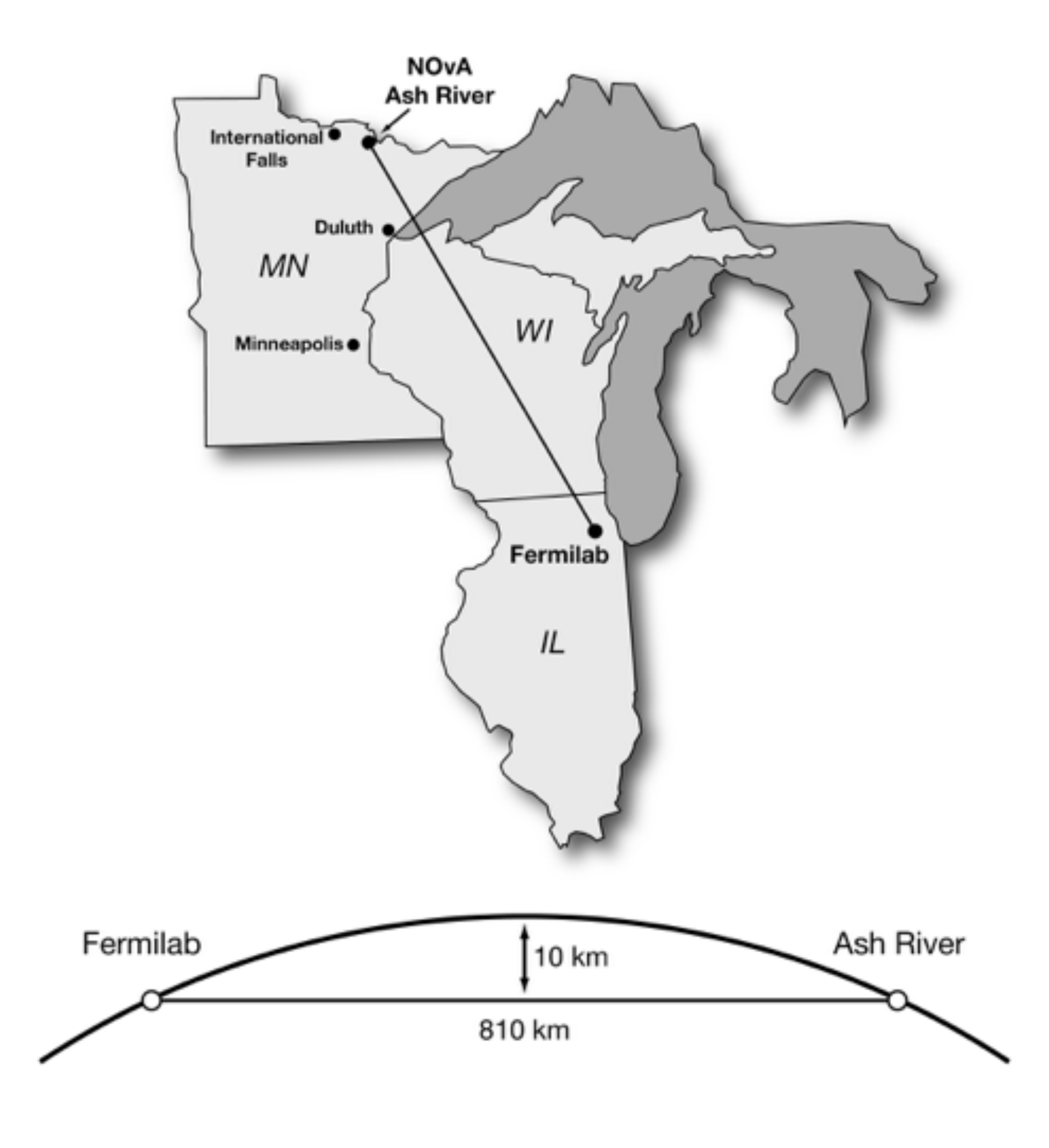




- Capable of running at 700 kW
- Reliably running at ~500 kW
- World record 521 kW for 1 hour
- Full power by mid 2016
- 6.4×10^{20} POT delivered

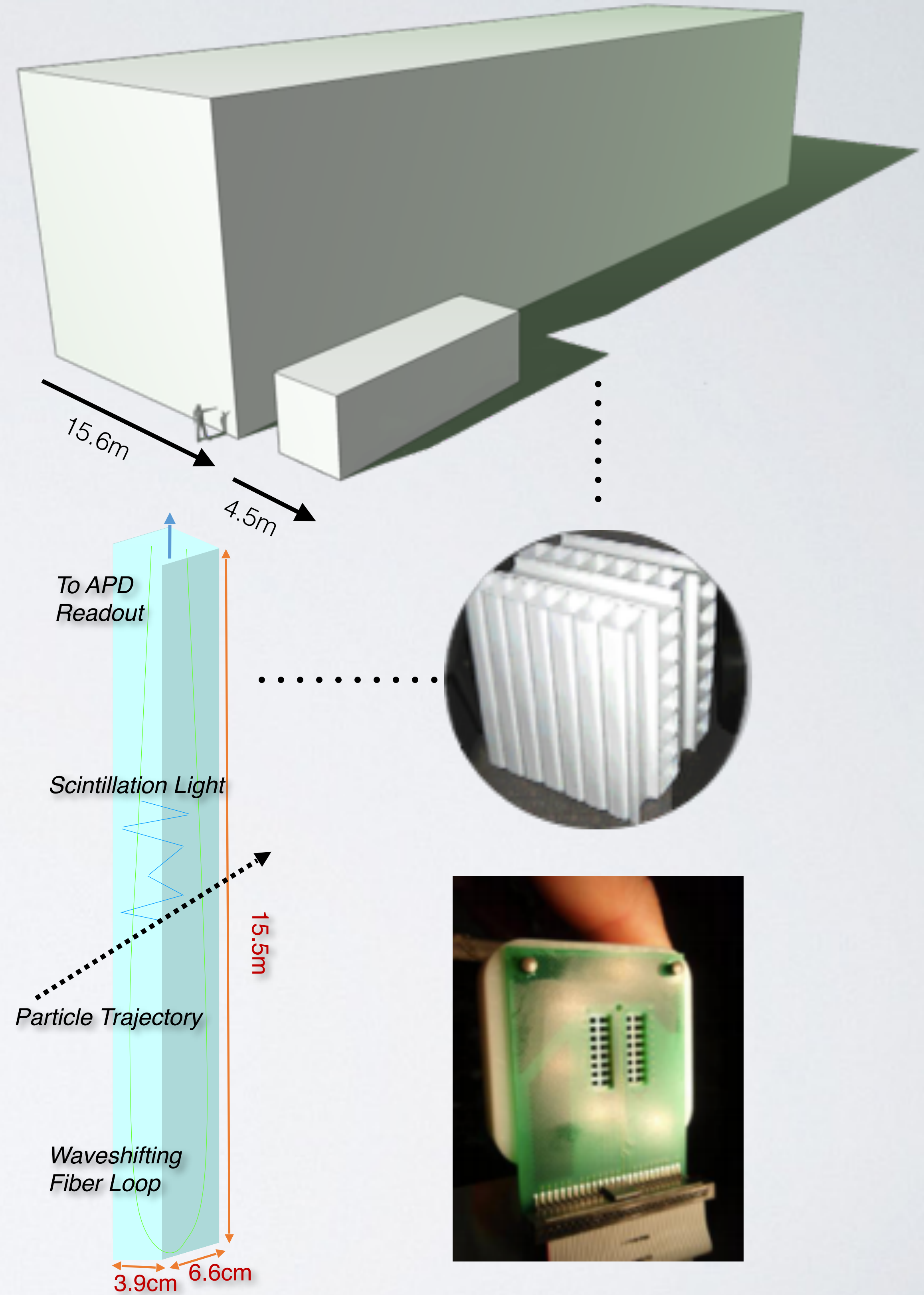


- NuMI Off-Axis ν_e Appearance, the leading neutrino oscillation experiment in the NuMI beam

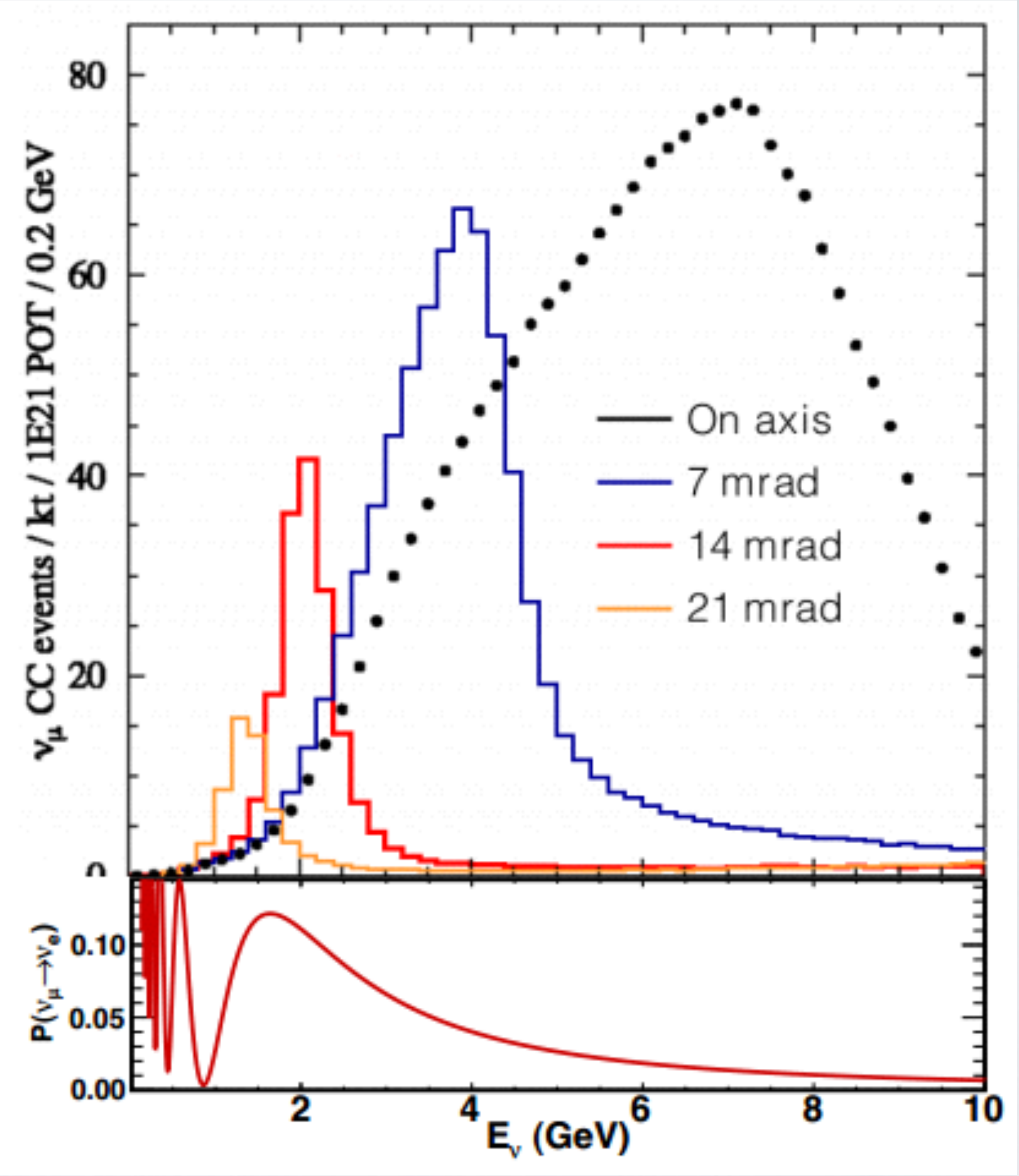


The NOvA experiment

- NuMI Off-Axis ν_e Appearance, the leading neutrino oscillation experiment in the NuMI beam
- Two highly active scintillator detectors:
  - Far Detector: 14 kT, on surface
  - Near Detector: 300 T, 105 m underground



- NuMI Off-Axis ν_e Appearance, the leading neutrino oscillation experiment in the NuMI beam
- Two highly active scintillator detectors:
  - Far Detector: 14 kT, on surface
  - Near Detector: 300 T, 105 m underground
- 14 mrad off-axis narrowly peaked muon neutrino flux at 2 GeV, L/E ~ 405 km/GeV
- ν_μ disappearance channel: θ_{23}, Δm^2_{32}
- ν_e appearance channel: mass hierarchy, δ_{CP}, θ_{13}, θ_{23} and octant degeneracy



Also: neutrino cross sections at the ND, sterile neutrinos, supernovae…

Far detector dataset

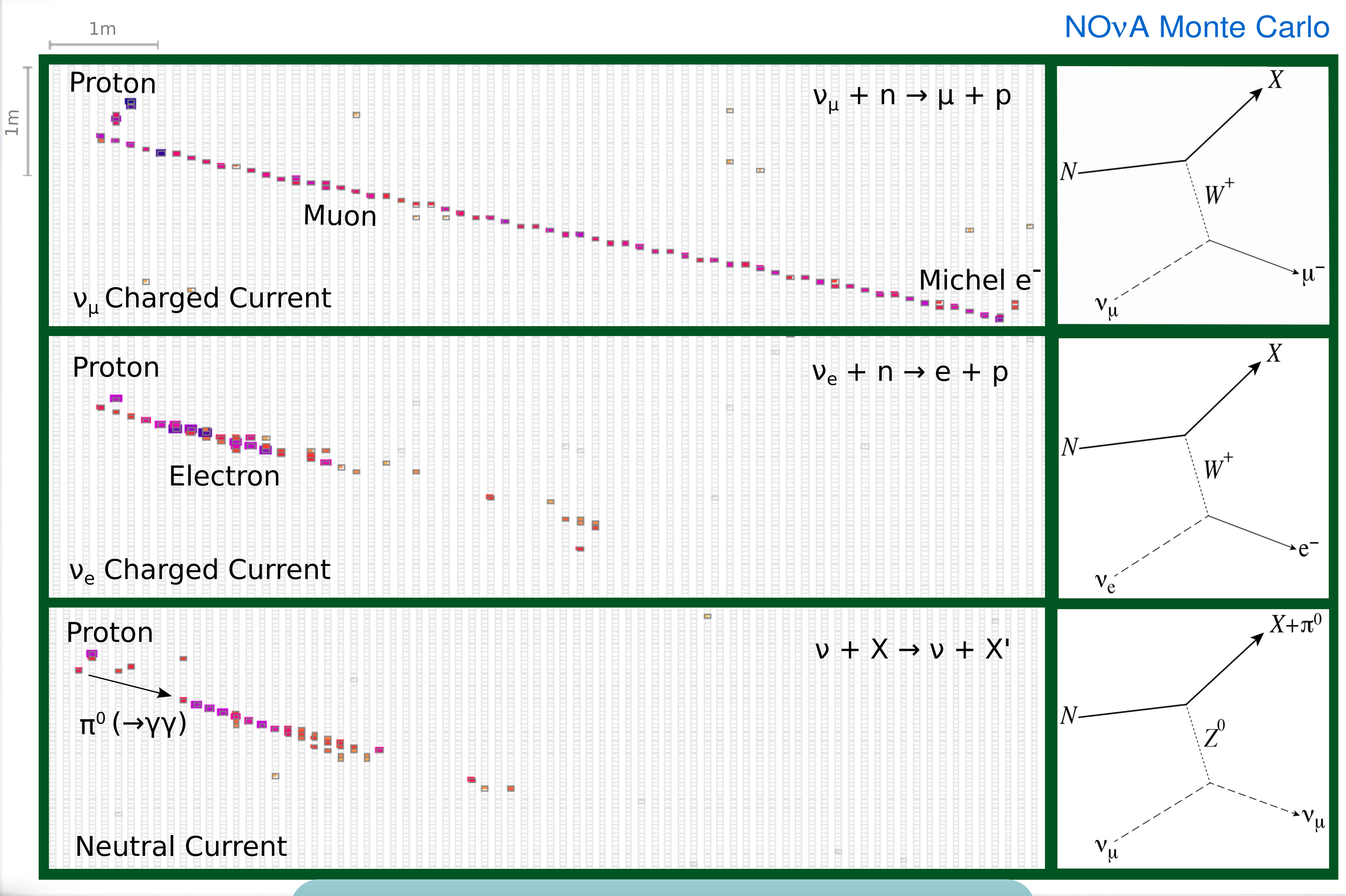
- During the construction era, we **began collecting Physics data** with each far detector "diblock" (64 detector planes) as soon as it was **fully commissioned** and Physics-ready
- Thus, the FD size is **not static** throughout our data set

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**

Partial Far Detector during construction
(6 diblock example)

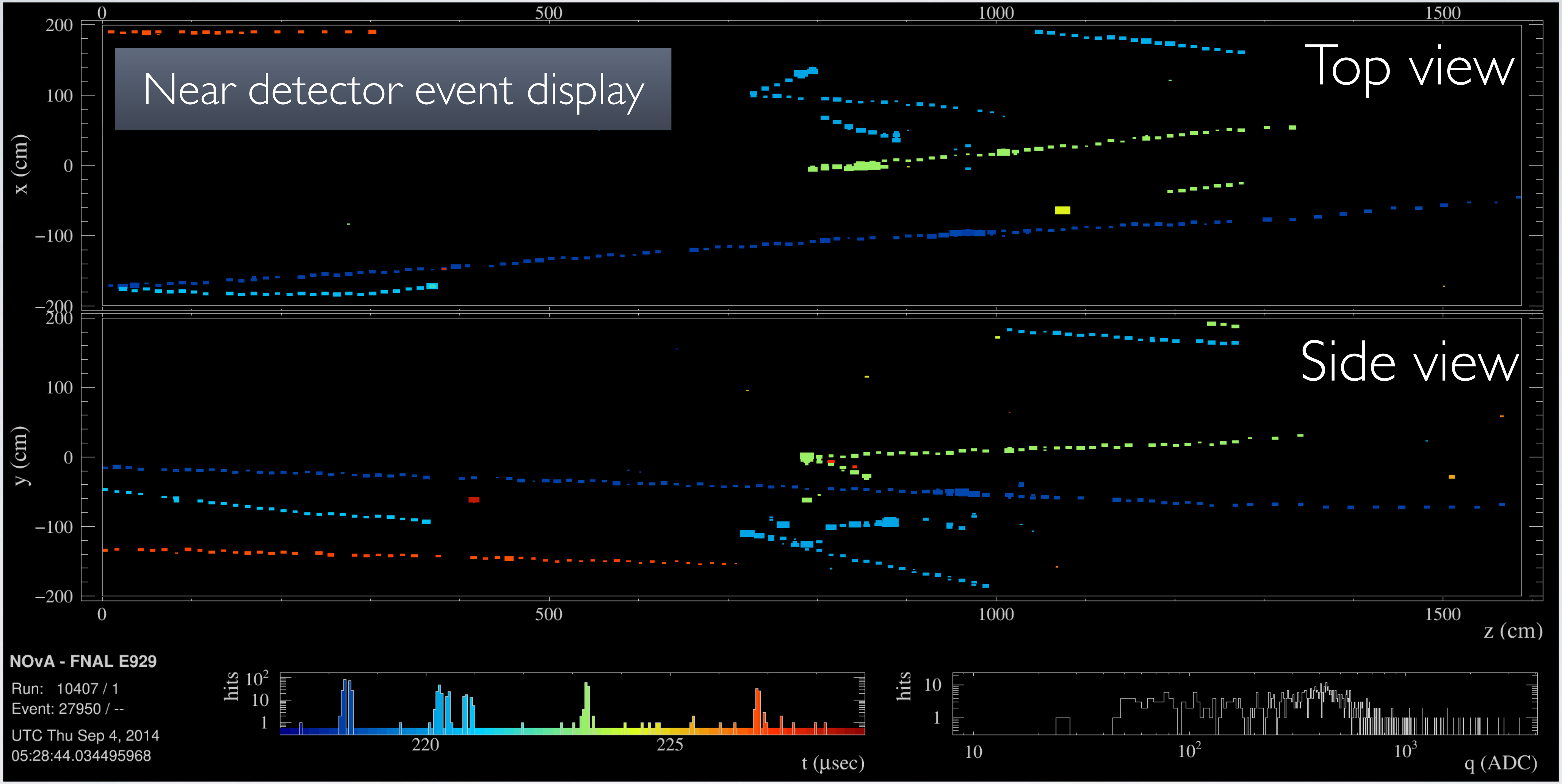
Full Far Detector
(14 diblocks)

- Superb granularity for a detector this scale
- Outstanding event identification capability

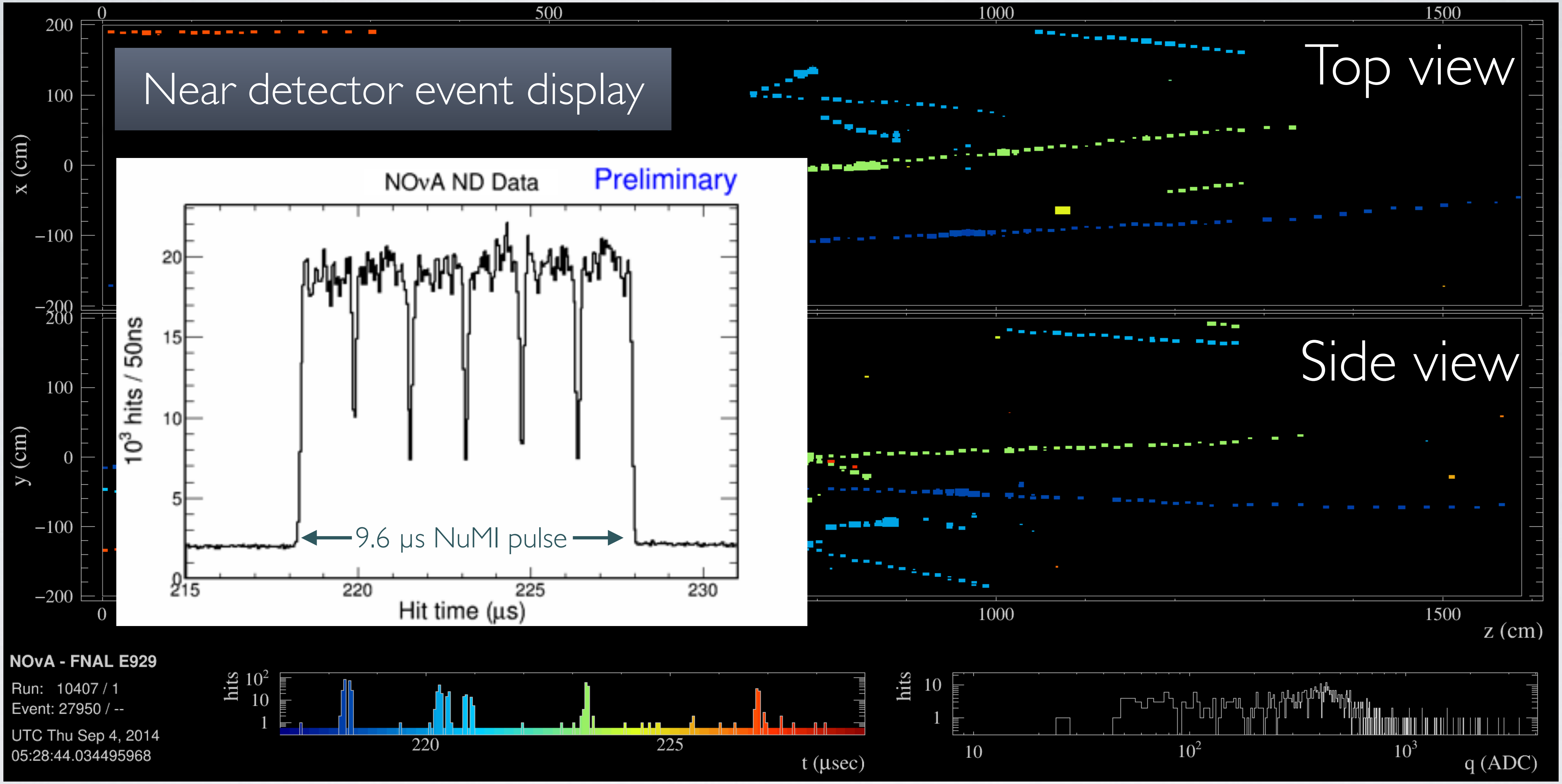


1 radiation length = 38 cm

(6 cell depths, 10 cell widths)



10 µs of readout during NuMI beam pulse



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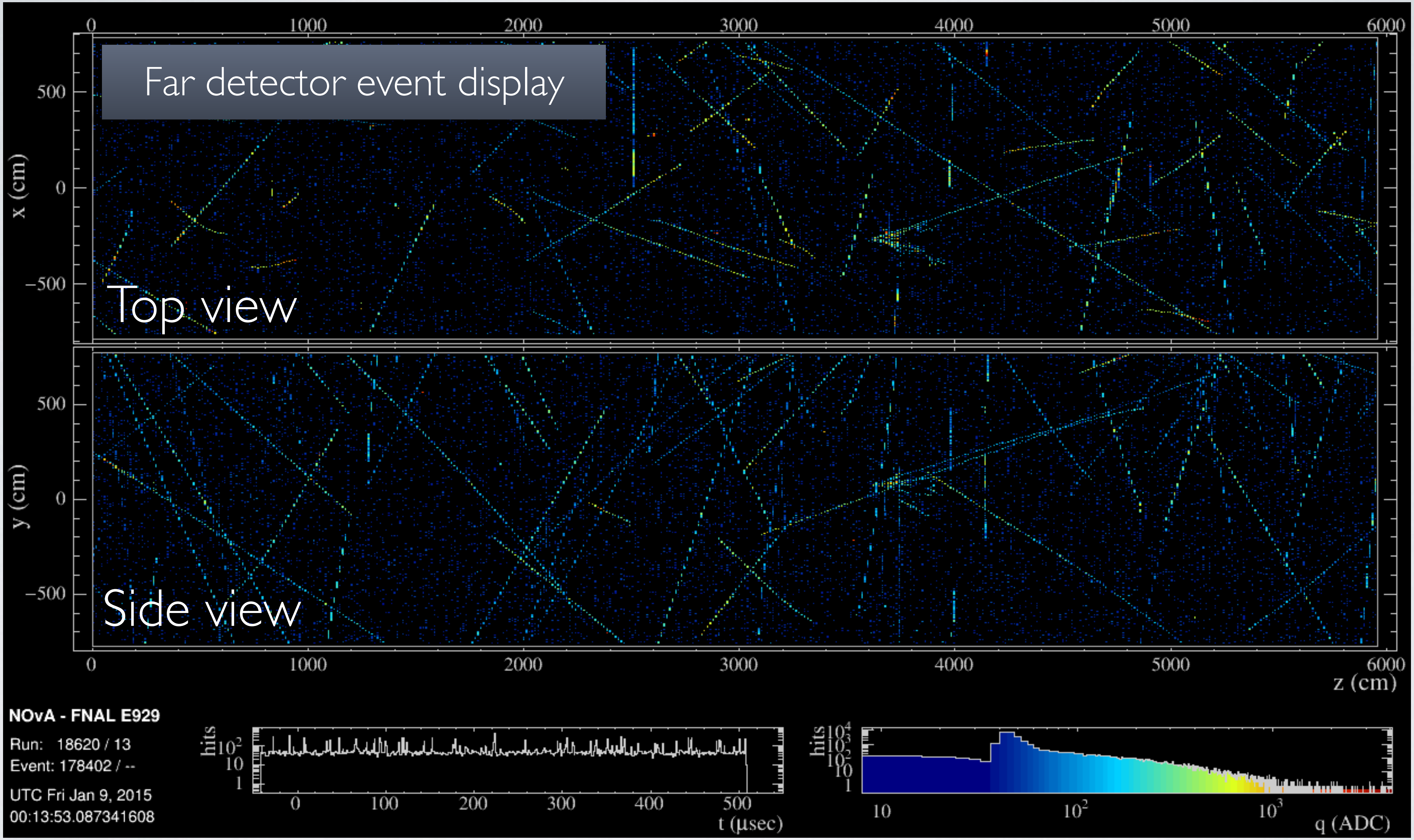
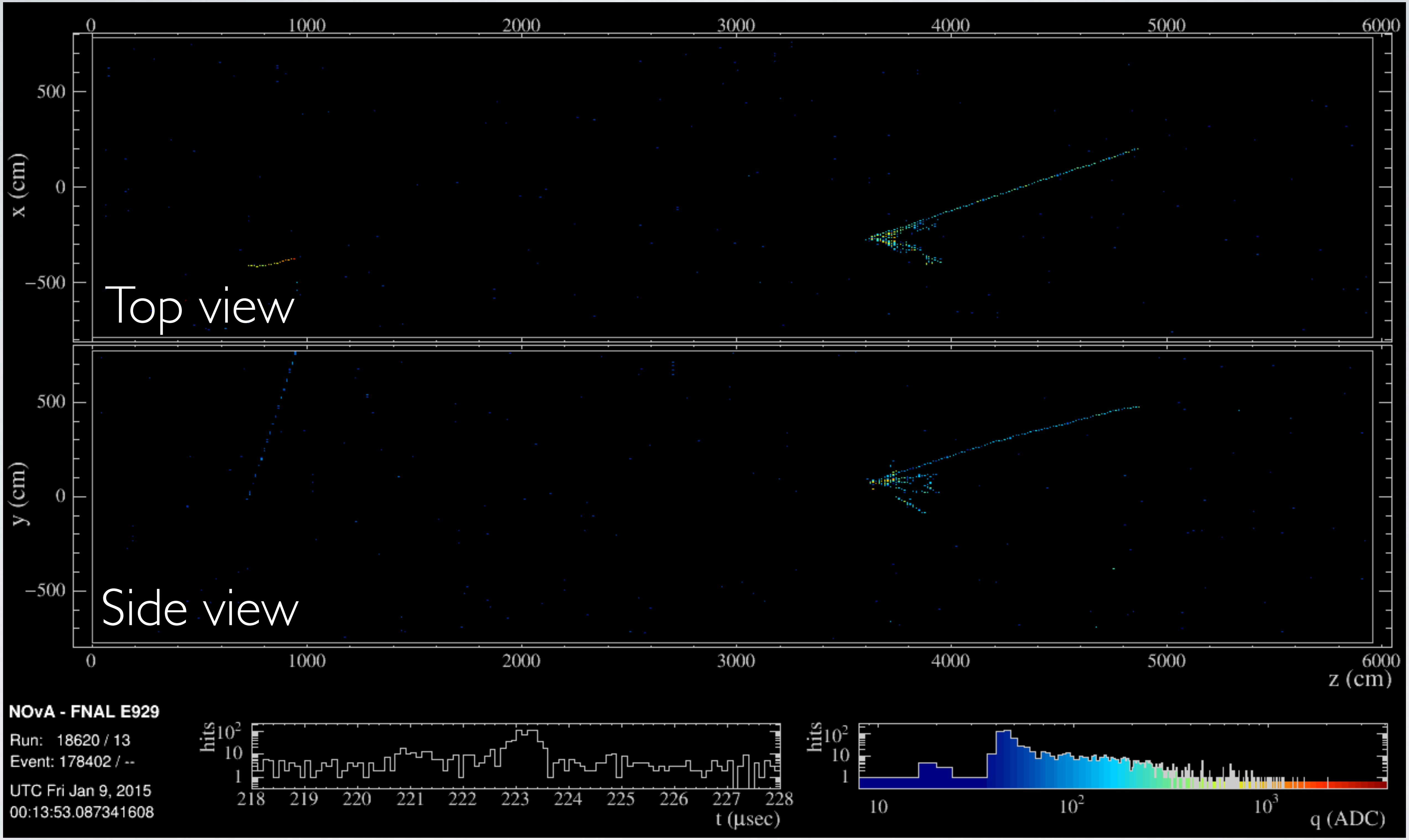
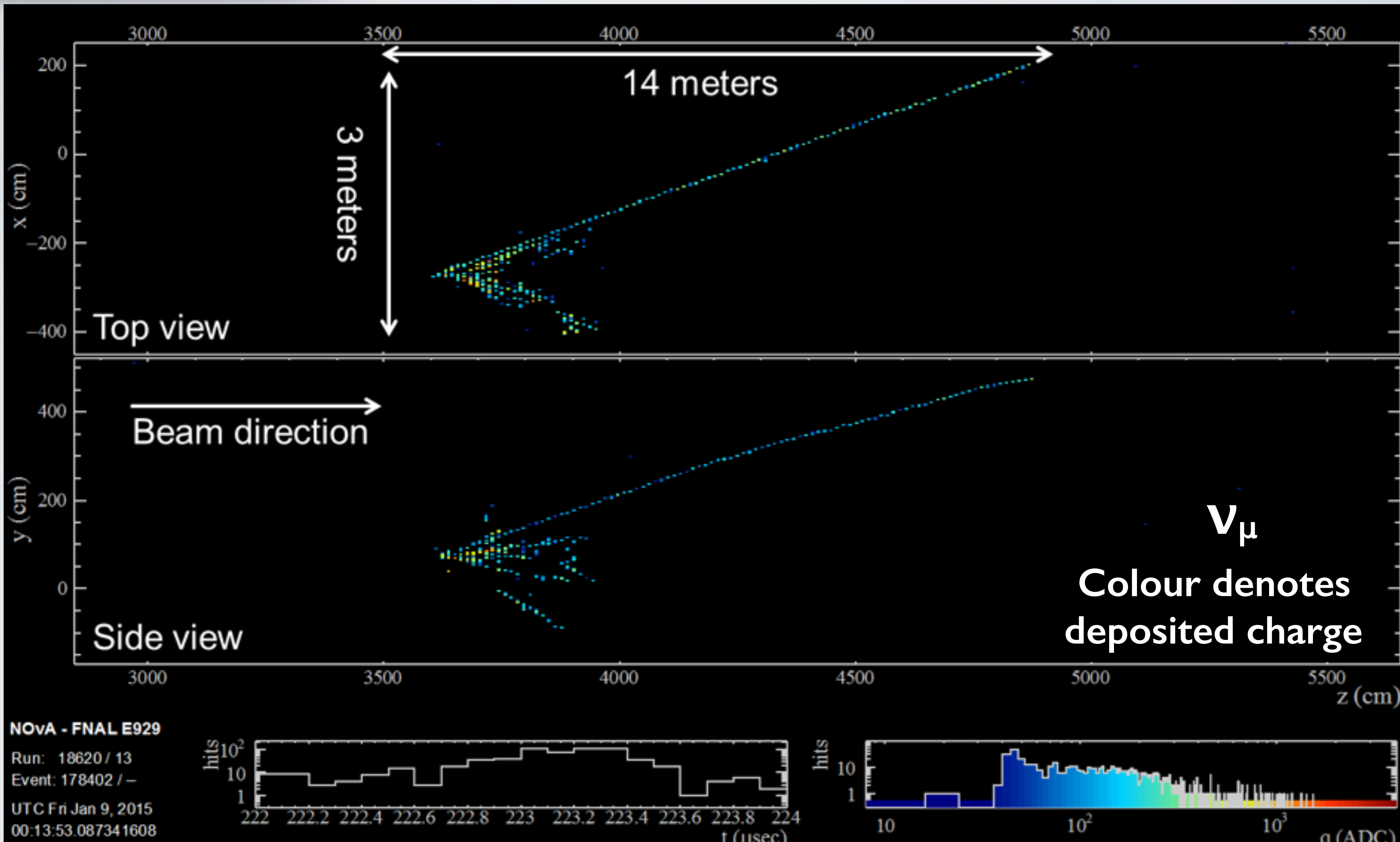


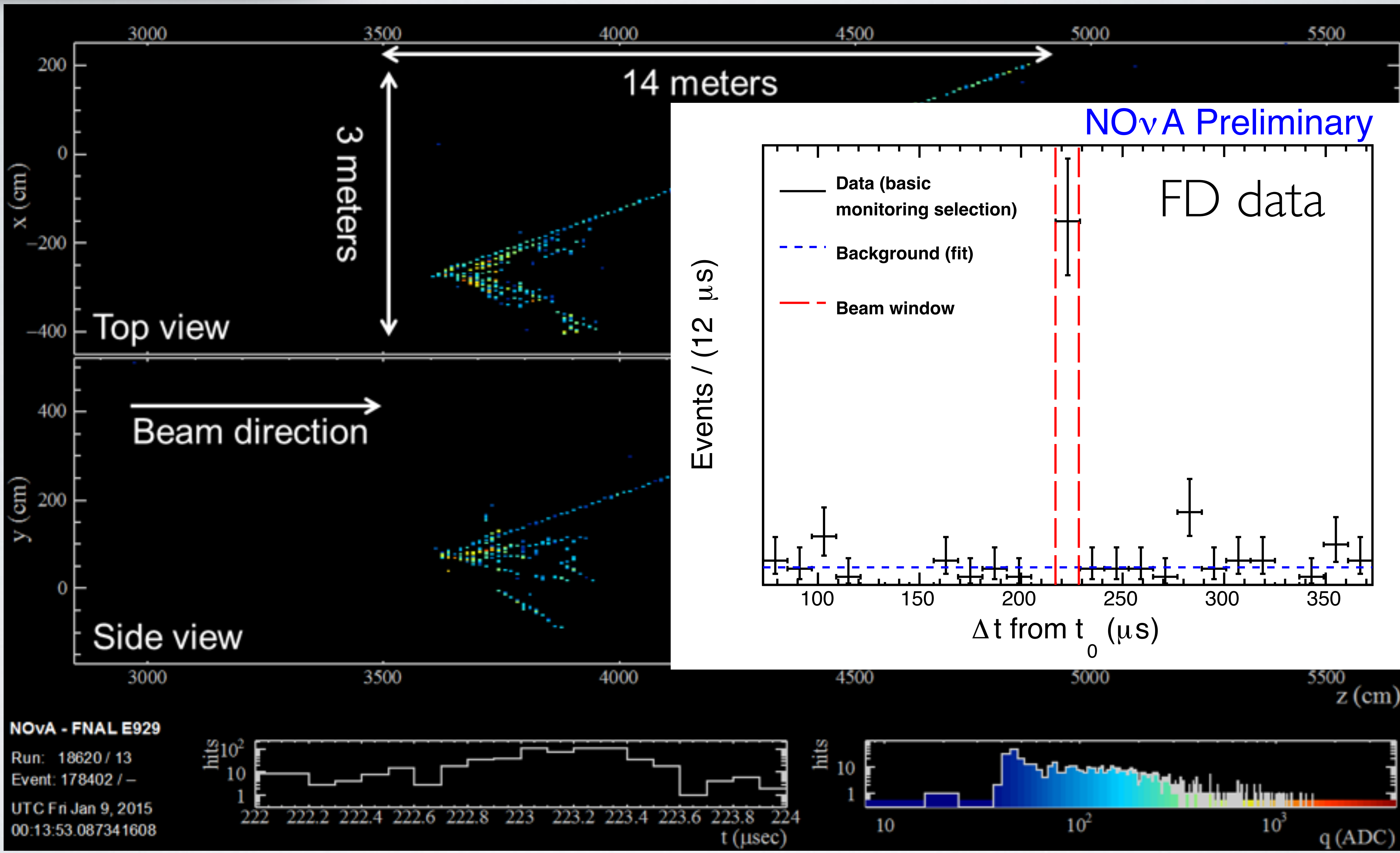
Full 550 μs readout (colours show charge)



Zoomed on the 10 µs beam spill window

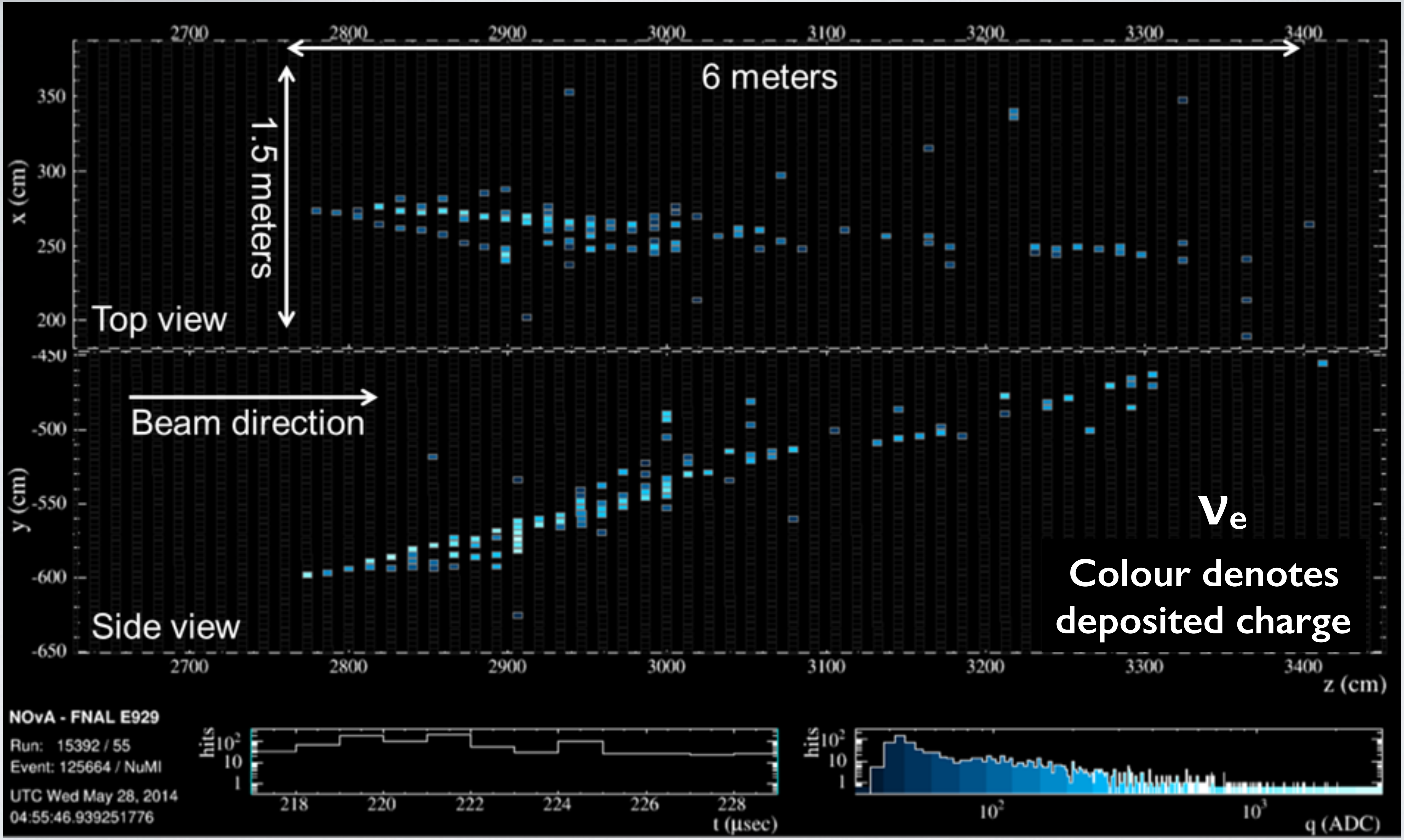


Zoomed on the time slice



Zoomed on the time slice

The NOvA experiment



Zoomed on the time slice

Disappearance analysis in a nutshell…

Identify contained ν_μ CC events in both detectors

Measure both energy spectra

Infer on the oscillation mechanism from differences between near and far energy spectra

Disappearance analysis in a nutshell…

Identify contained ν_μ CC events in both detectors

- Containment
- PID
- NC rejection
- Cosmic rejection

Measure both energy spectra

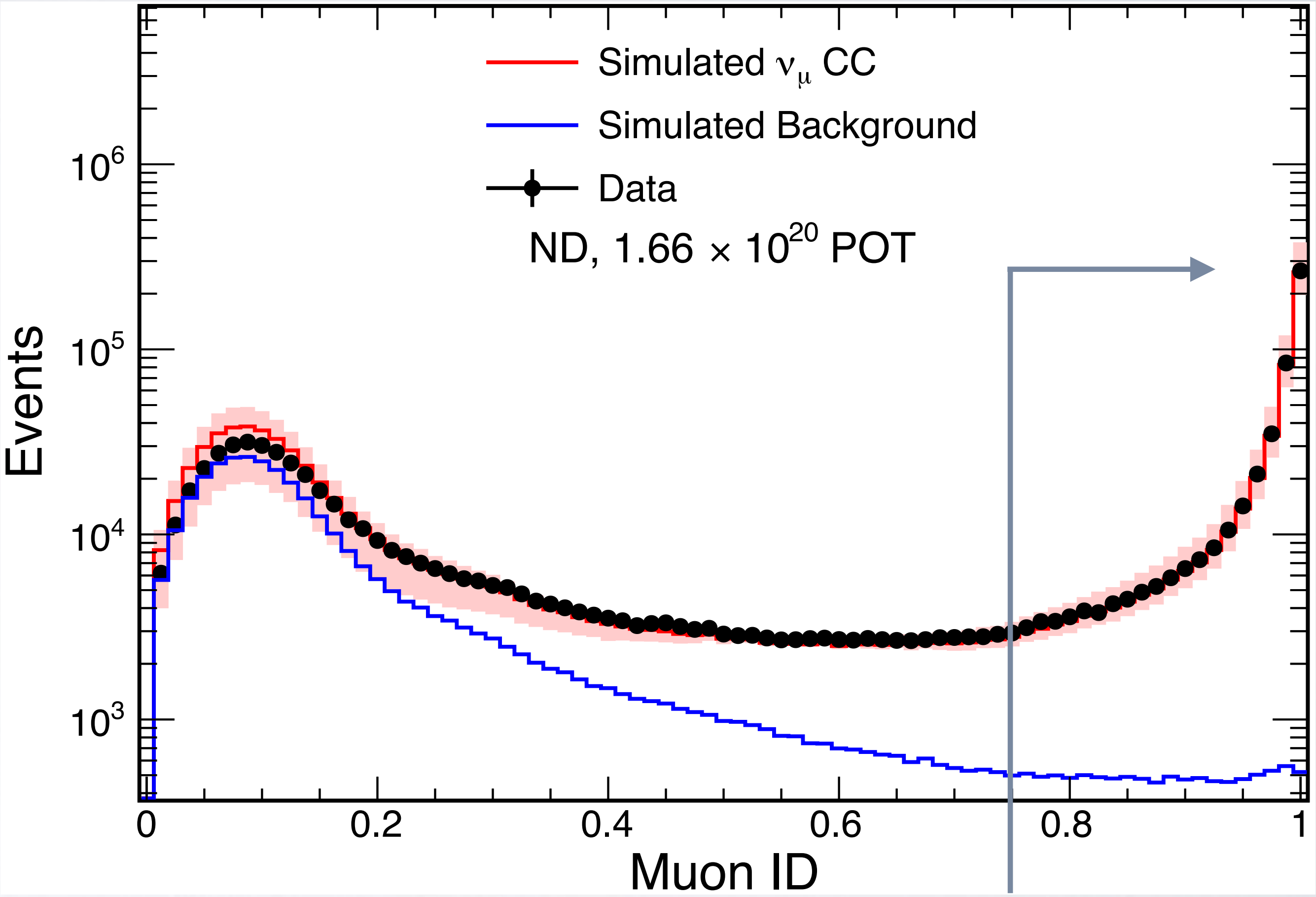
- Calibration
- Energy scale
- Hadronic energy

Infer on the oscillation mechanism from differences between near and far energy spectra

- Extrapolation
- Far / near ratio
- Best fit
- Contours
- Systematics

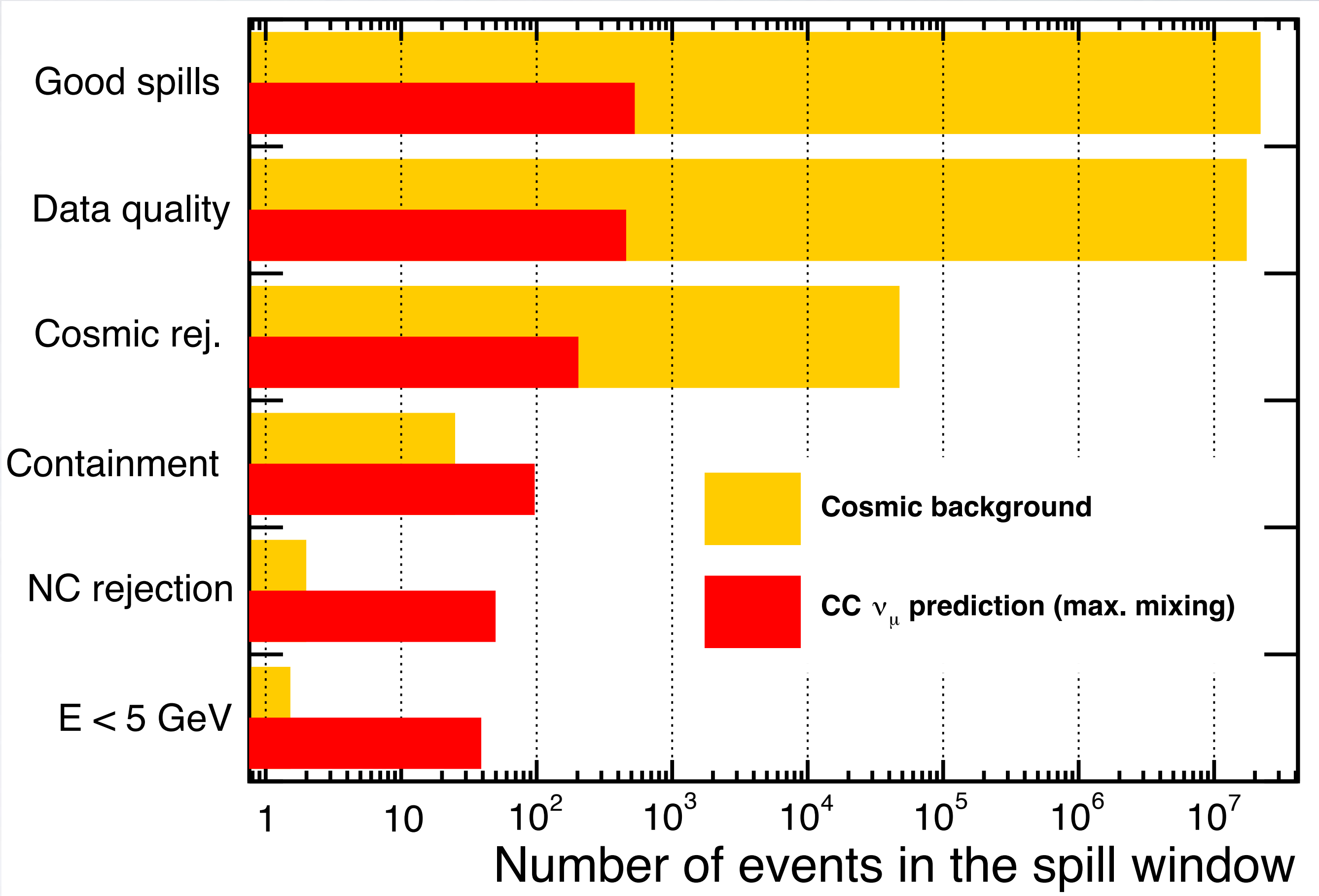
Signal selection: ν_μ CC

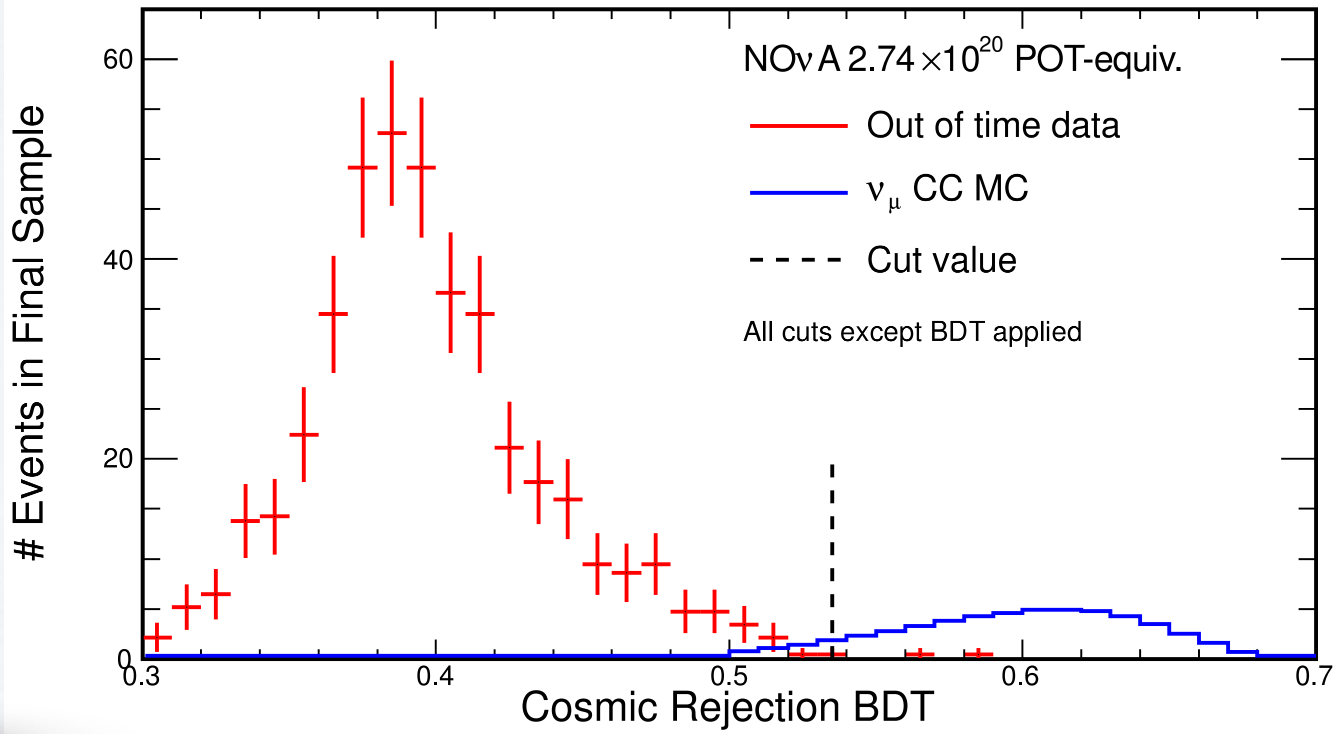
- First: basic containment cuts: require a buffer of no activity around the event
- Muon ID: 4-variable k-nearest neighbours algorithm to identify muons
  - Track length
  - dE/dx along track
  - Scattering along track
  - Track-only plane fraction
- Keep events with muon-ID > 0.75

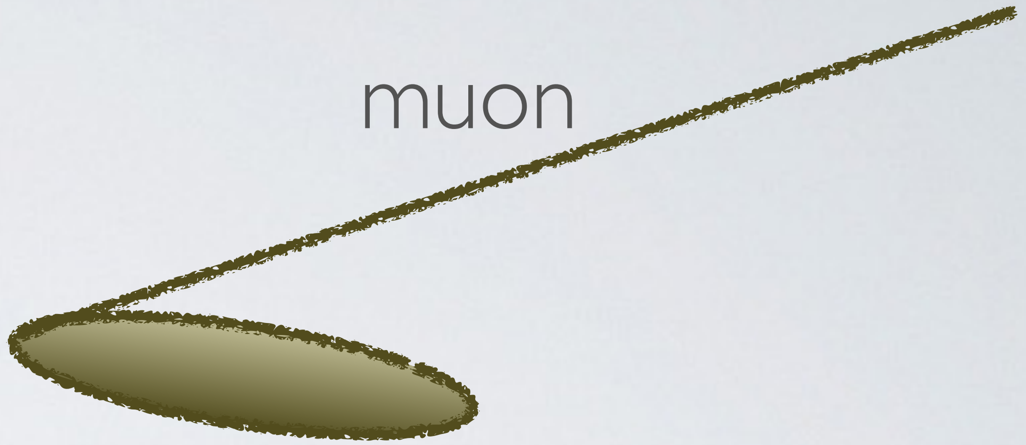


Cosmic rejection

- From beam timing: a factor 10^5 reduction
- From event topology: 10^7
- For the remaining, a boosted decision tree is trained on data without beam
  - Direction
  - Position and length
  - Energy and number of hits in event
- Keep events with BDT > 0.535
- Final rate is measured directly using out-of-time data

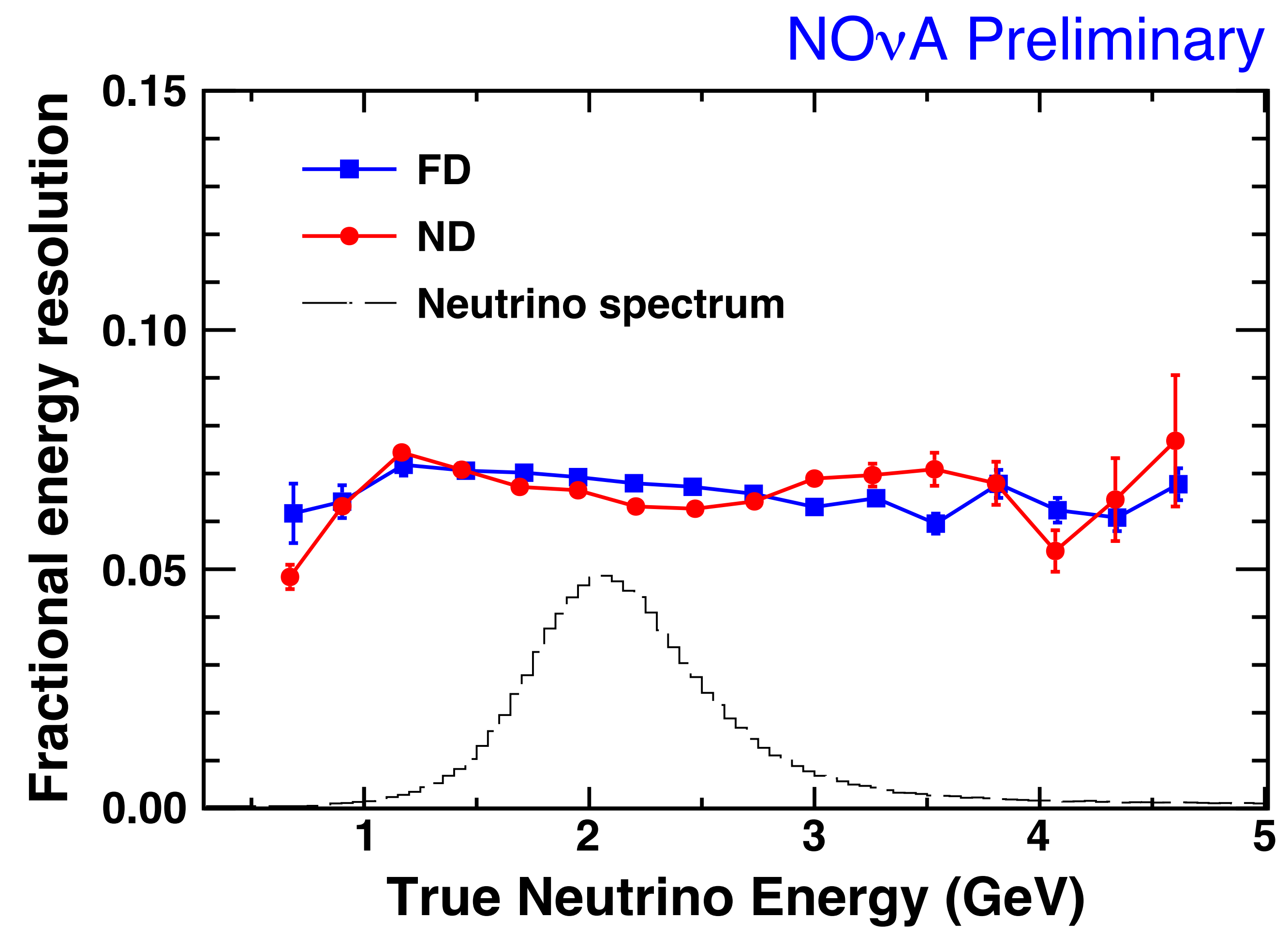






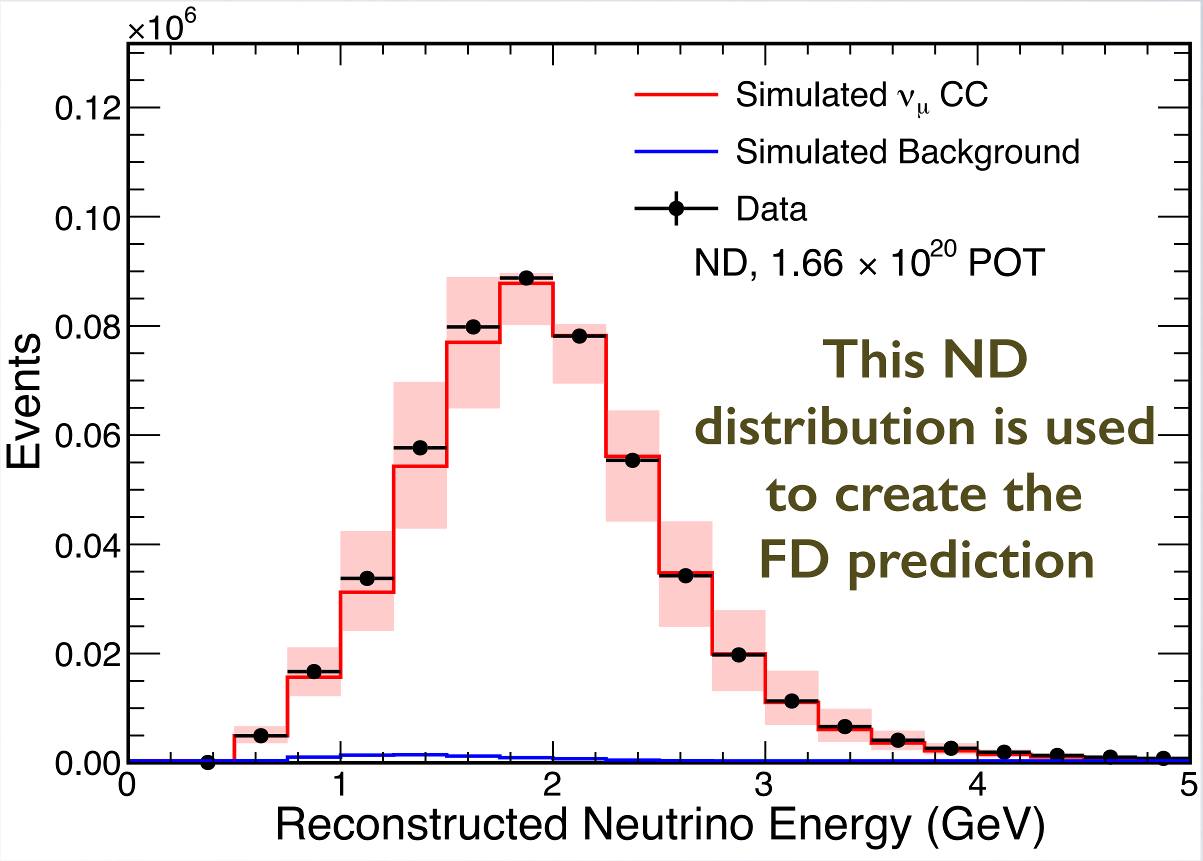
Energy estimation

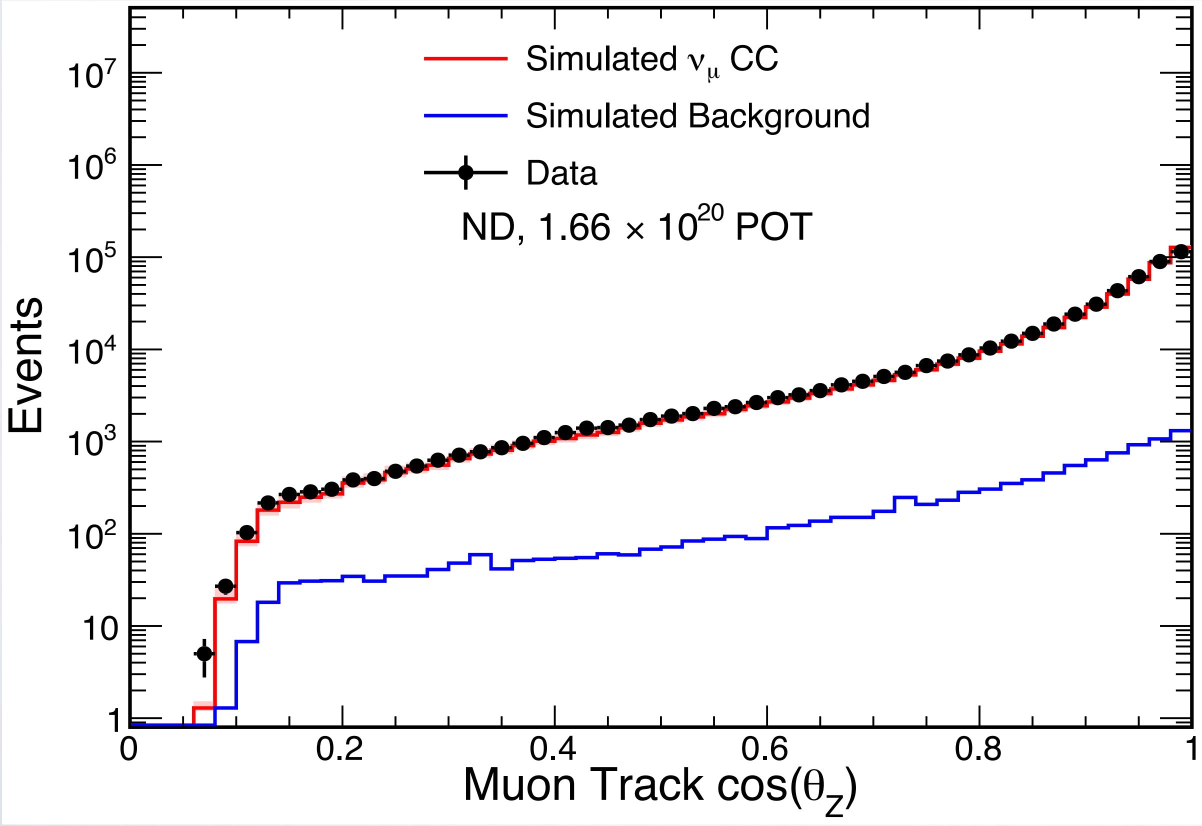
- Muon track: **length ⇒ E_μ**
- Hadronic system:
  Σ Total visible E ⇒ E_{had}
- Reconstructed neutrino energy is the sum of them: **$E_\nu = E_\mu + E_{had}$**
- Energy resolution at beam peak: ~7%

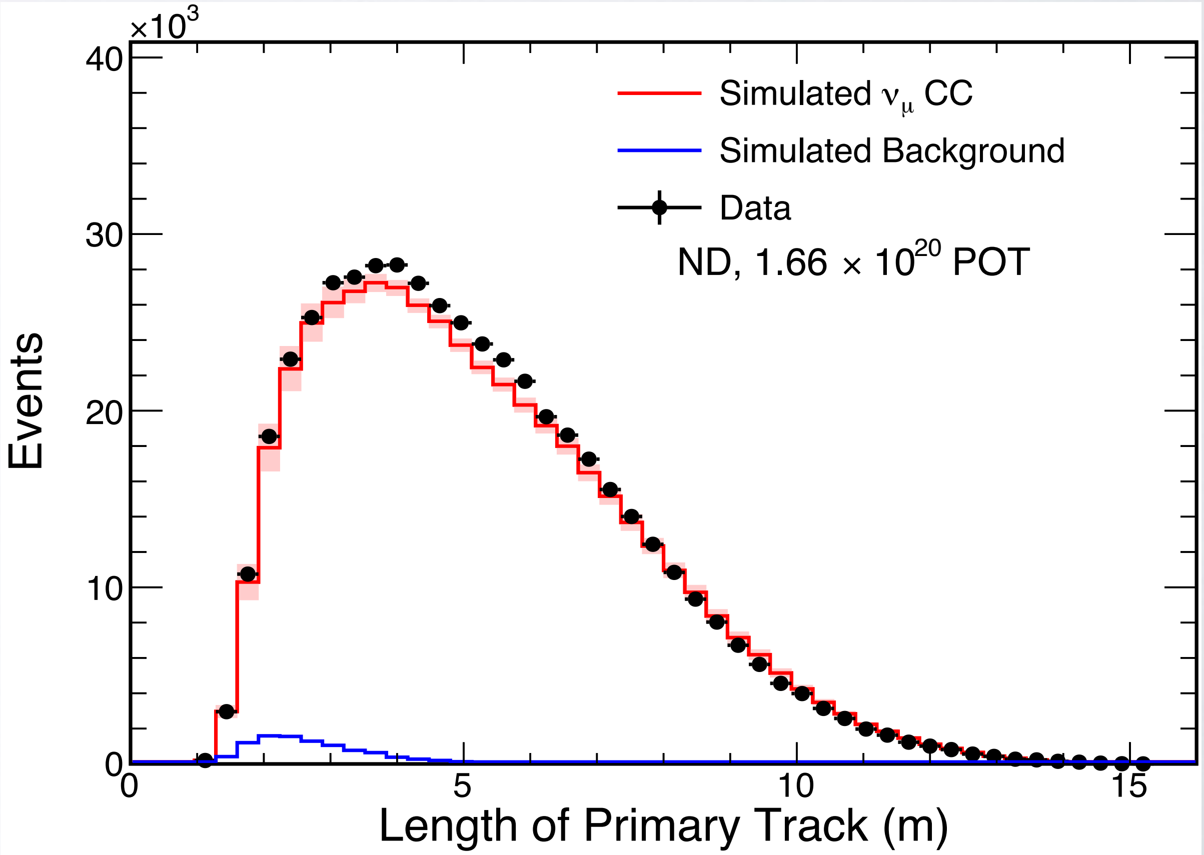


Kinematic variables in the ND after all cuts

(Sample purity in ND = 98%)



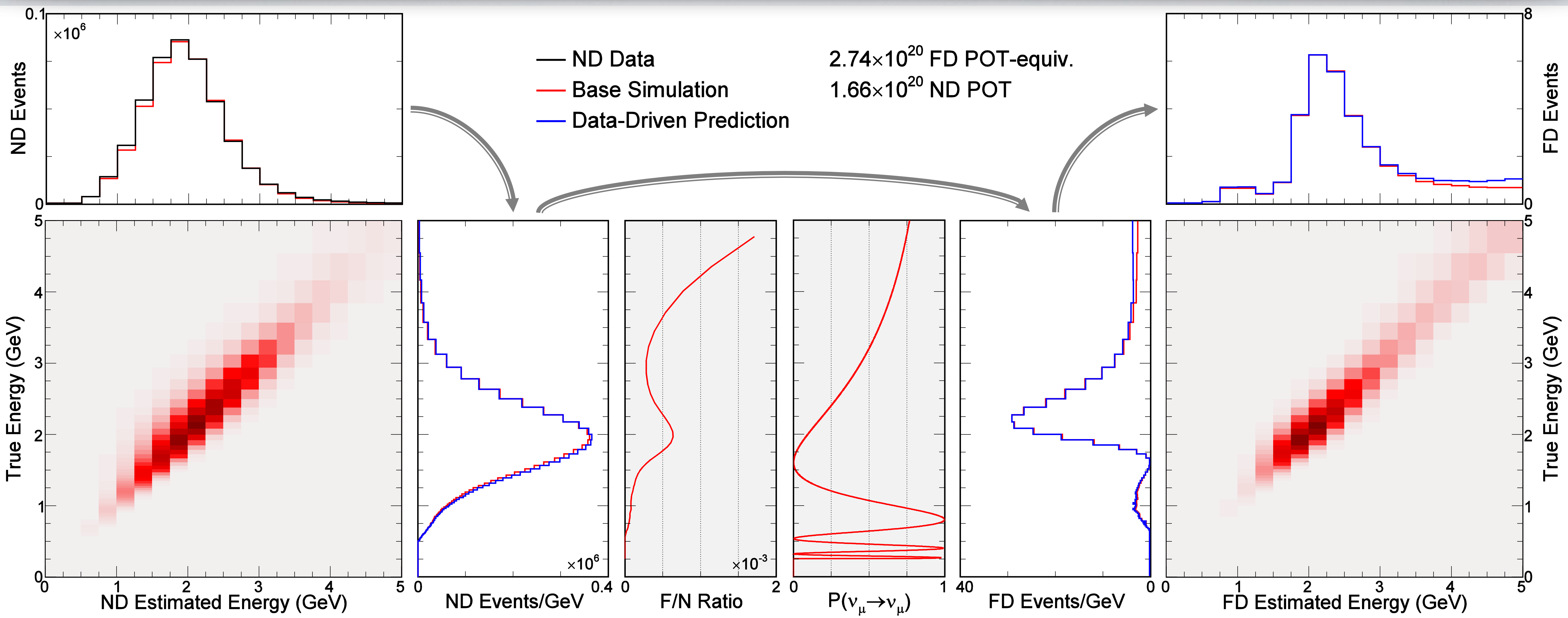




Muon neutrino disappearance

Far detector prediction

- Estimate the underlying **true energy distribution** of selected ND events
- Multiply by expected **Far/Near ratio** and $\nu_\mu \rightarrow \nu_\mu$ oscillation probability
- Convert FD true energy distribution into predicted FD reconstructed energy distribution
- Systematic uncertainties assessed by varying all MC-based steps

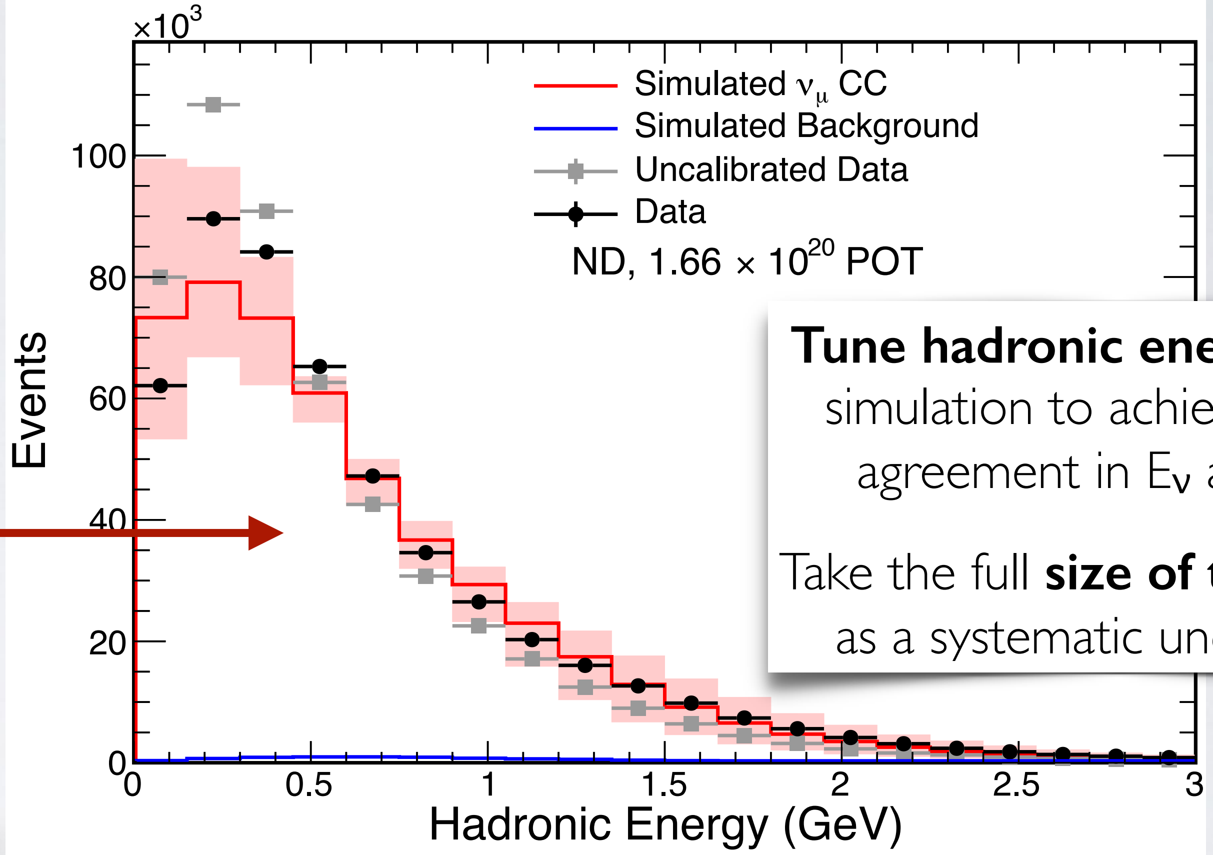


Systematics

Most of the systematic uncertainties have relatively **little influence on the result**

Hadronic energy systematic is one with a noticeable effect

(although the impact is reduced by ND-to-FD prediction procedure)



Tune hadronic energy in ND simulation to achieve better agreement in E_ν and E_{had}

Take the full **size of this tuning** as a systematic uncertainty

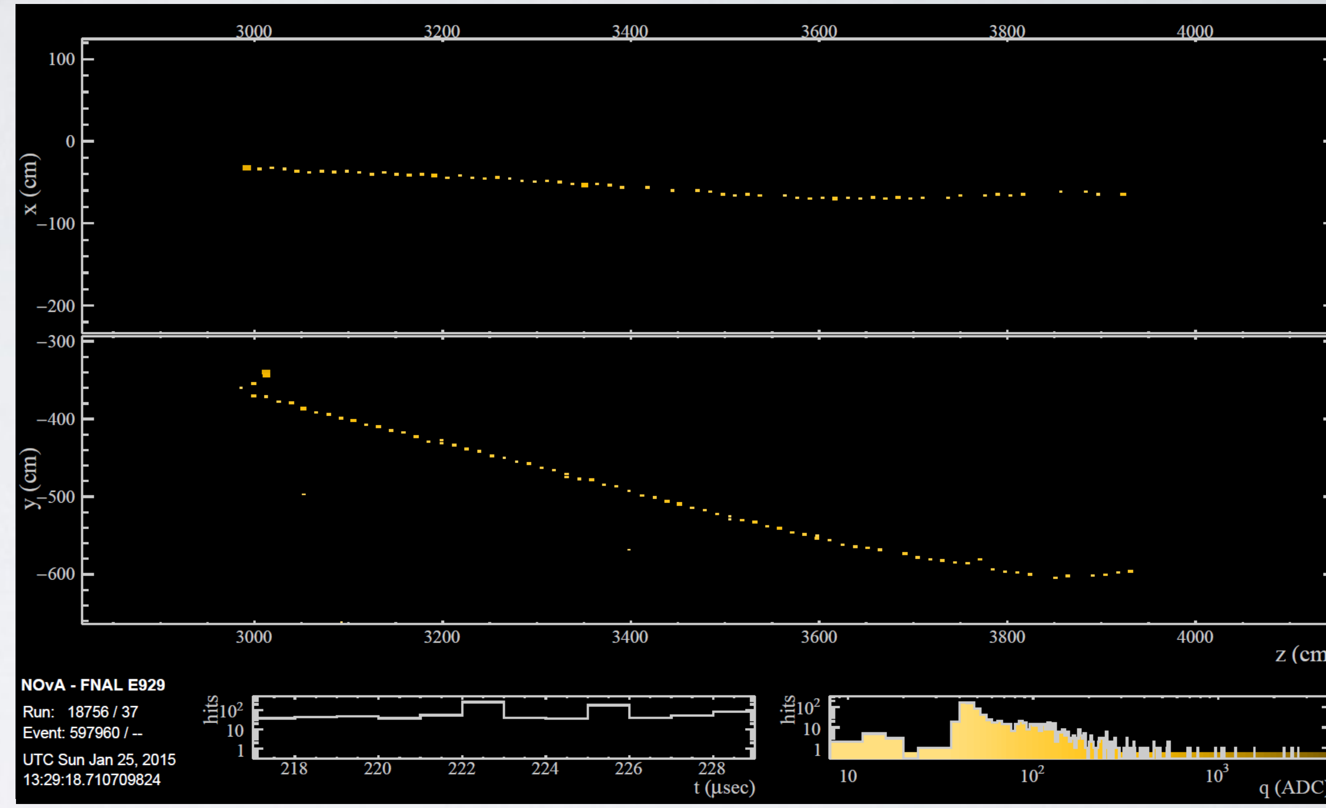
- Hadronic energy (*21%, equiv. to 6% in neutrino energy*)
- Neutrino flux (*NA49 + beam transportation model*)
- Absolute, relative normalisation (*1%, 2%*)
- Neutrino interactions (*GENIE / Intranuke model*)

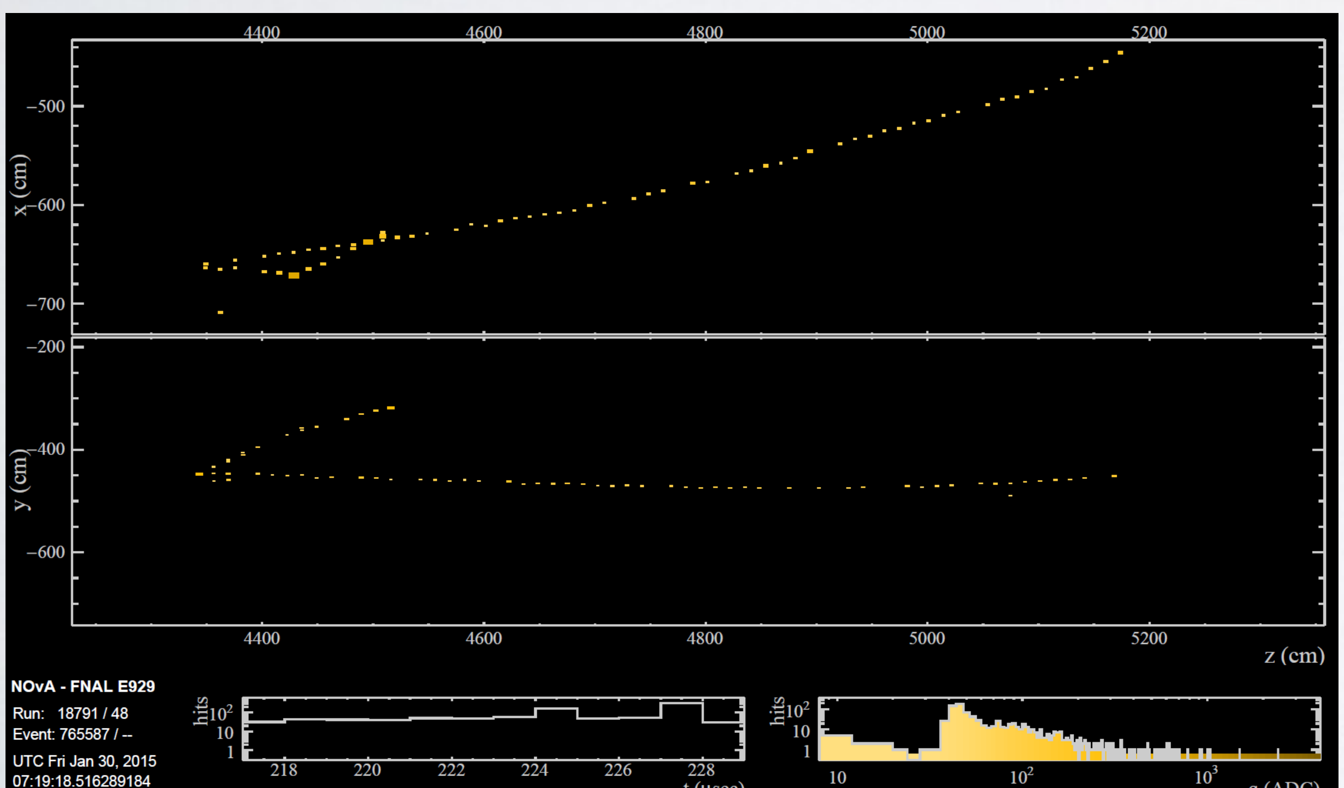
- NC and tau neutrinos (*100% each*)
- Multiple calibration and light level systs. (*Hit energy, fibre attenuation, threshold effects*)
- Oscillation parameter uncertainties (*current world knowledge*)

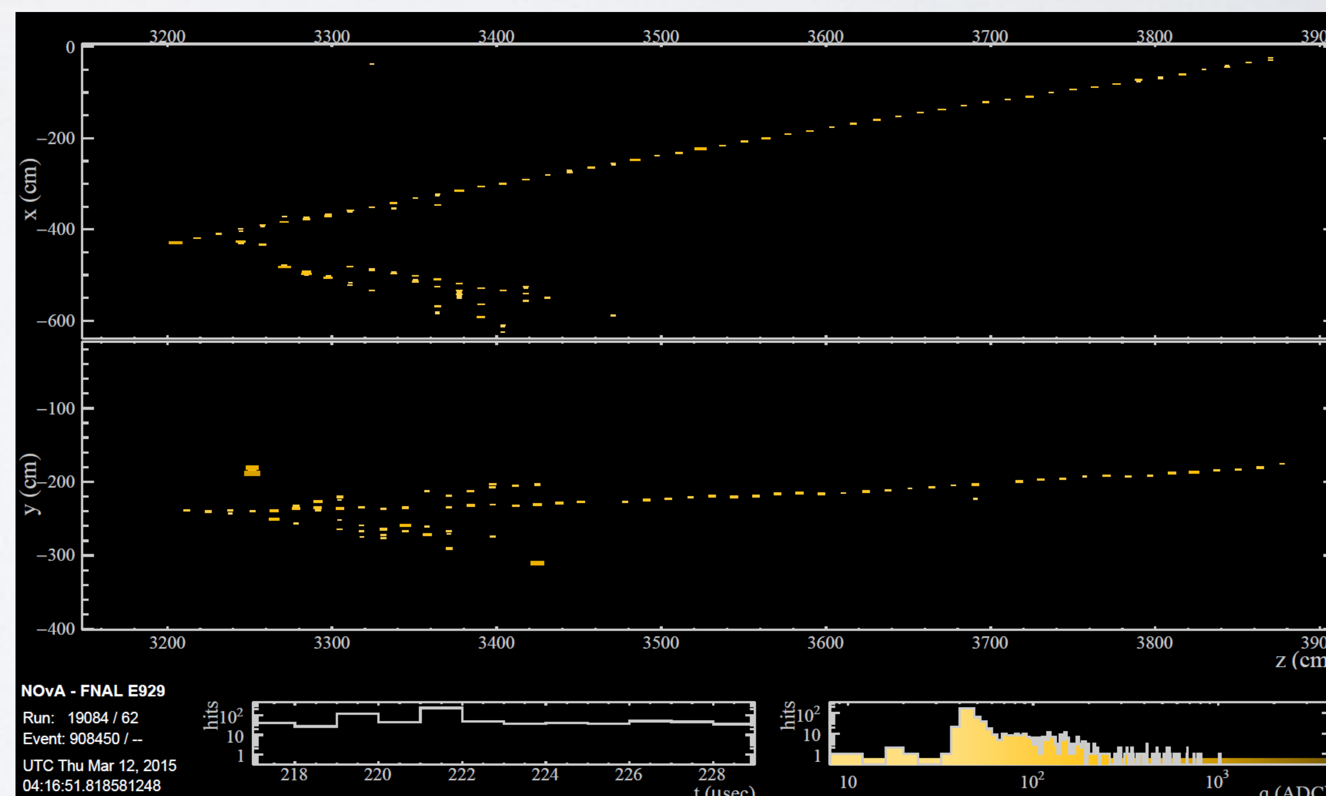
Muon neutrino disappearance

Some of the selected candidates

(zoomed views, not showing the whole detector)

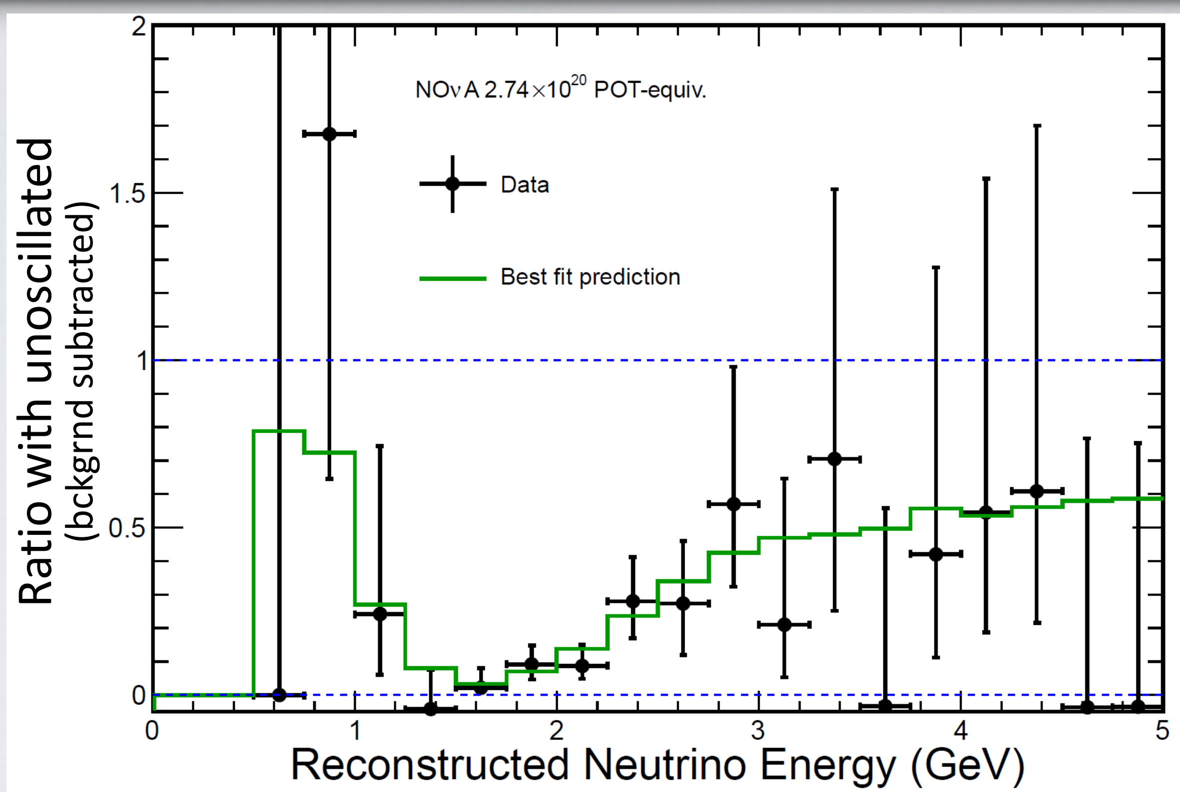


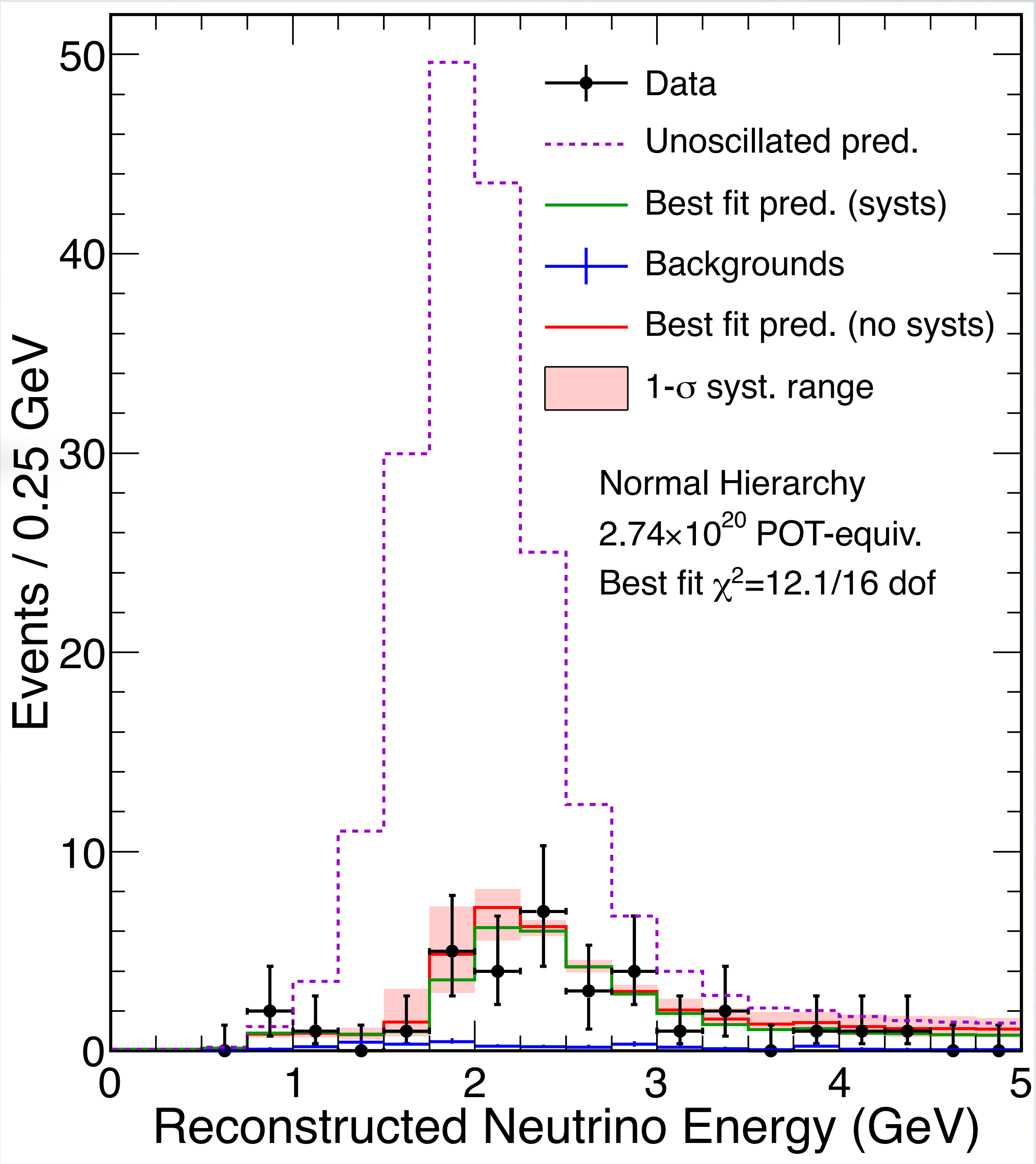




In the absence of oscillation, the expectation is 200 events (2 beam bkg., 1.4 cosmic bkg.)

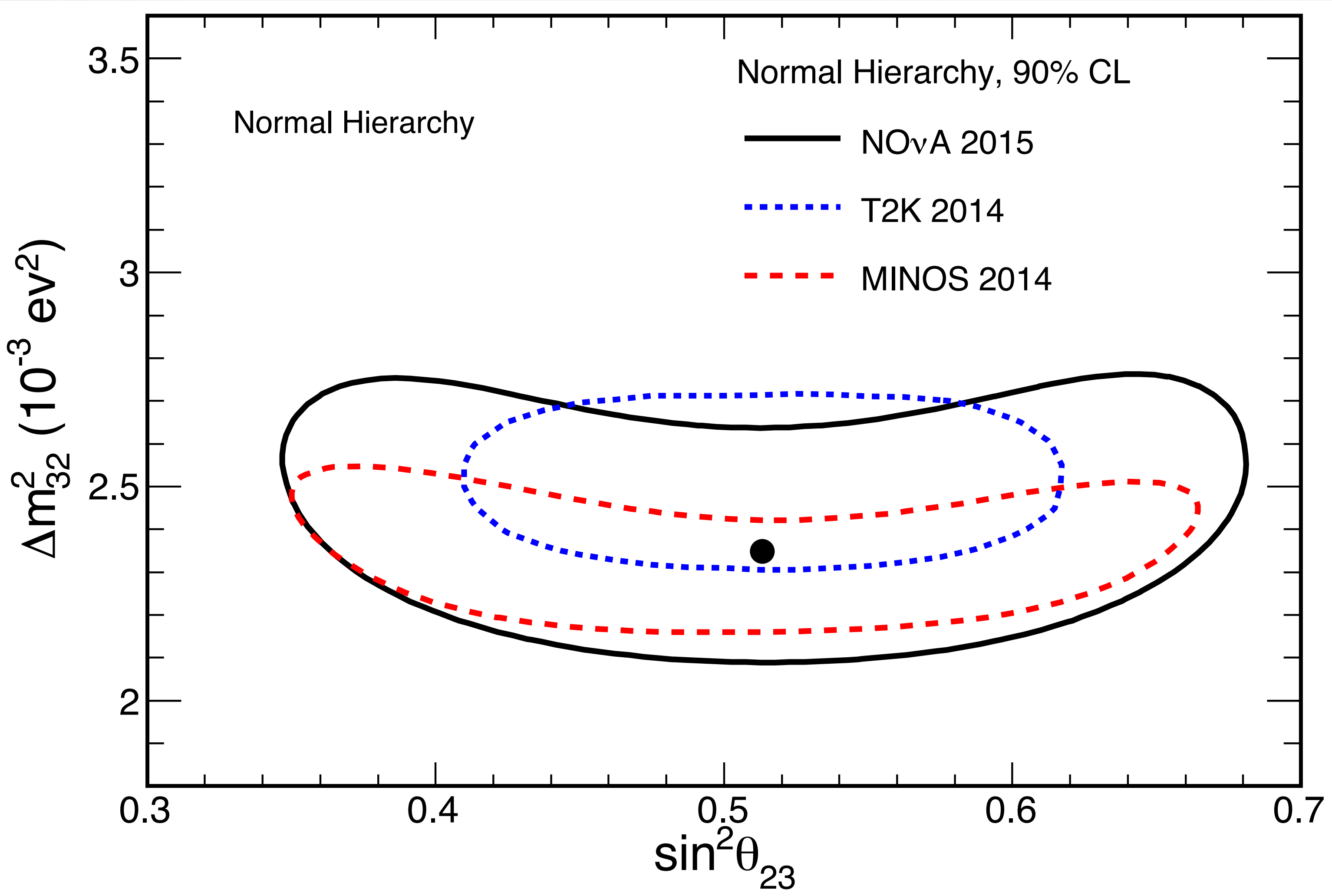
33 selected events in the FD





Clear observation of ν_μ disappearance

Oscillation parameters



Normal hierarchy

$$\Delta m^2_{32} = 2.35^{+0.19}_{-0.12} \times 10^{-3} \text{ eV}^2$$

$$\sin^2\theta_{23} = 0.513 \pm 0.106$$

Inverted hierarchy

$$\Delta m^2_{32} = -2.40^{+0.12}_{-0.18} \times 10^{-3} \text{ eV}^2$$

$$\sin^2\theta_{23} = 0.509^{+0.103}_{-0.106}$$

NOvA measurement already compelling with less than 8% of nominal exposure!

Appearance analysis in a nutshell…

Identify contained ν_e CC events in both detectors

Use ND candidates to predict beam backgrounds in the FD

Interpret any FD excess over predicted backgrounds as ν_e appearance

Appearance analysis in a nutshell…

Identify contained ν_e CC events in both detectors

- Containment
- PID
- NC rejection
- Cosmic rejection

Use ND candidates to predict beam backgrounds in the FD

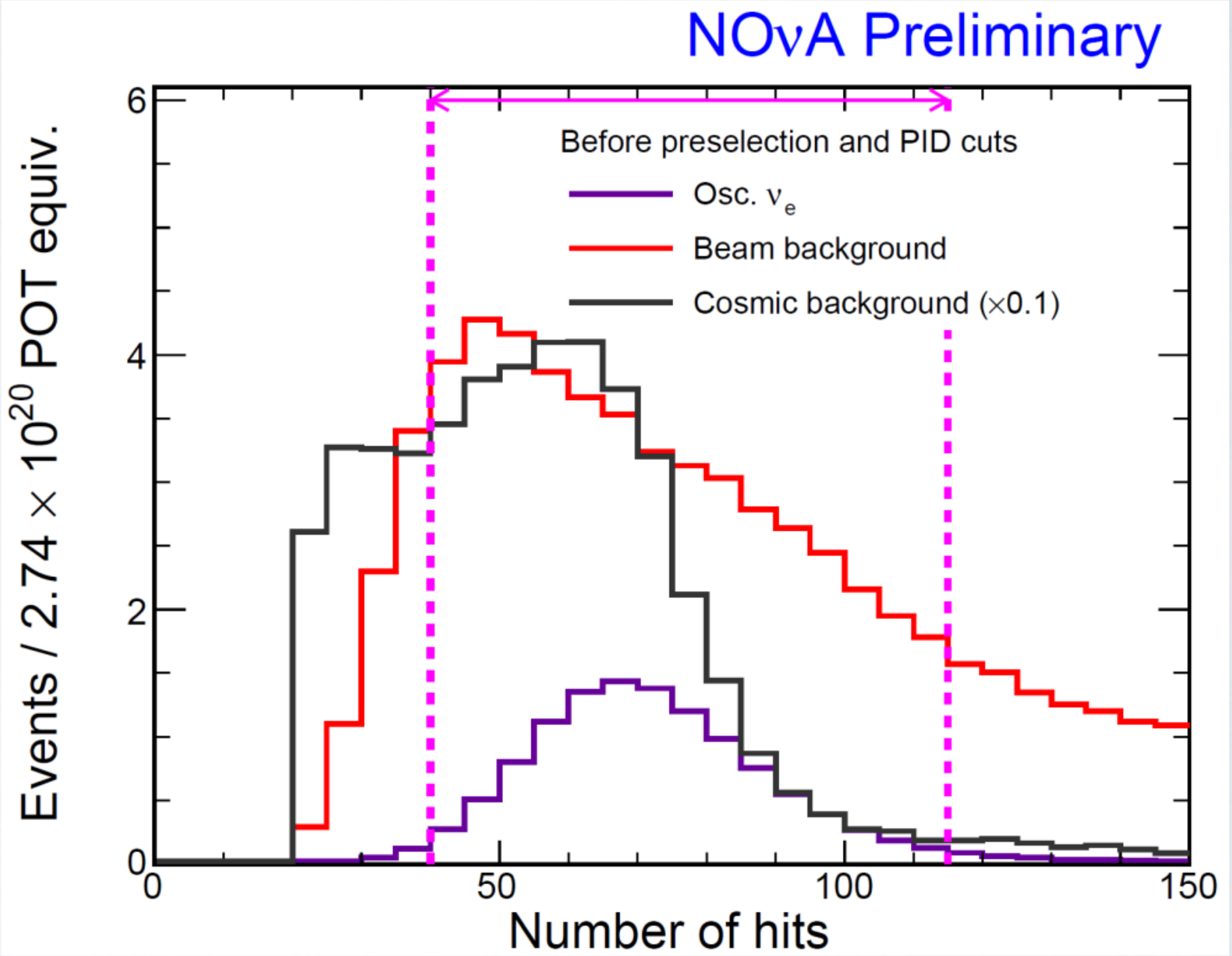
- Extrapolation
- Far / near ratio
- Systematics

Interpret any FD excess over predicted backgrounds as ν_e appearance

- Exclusions
- Significance

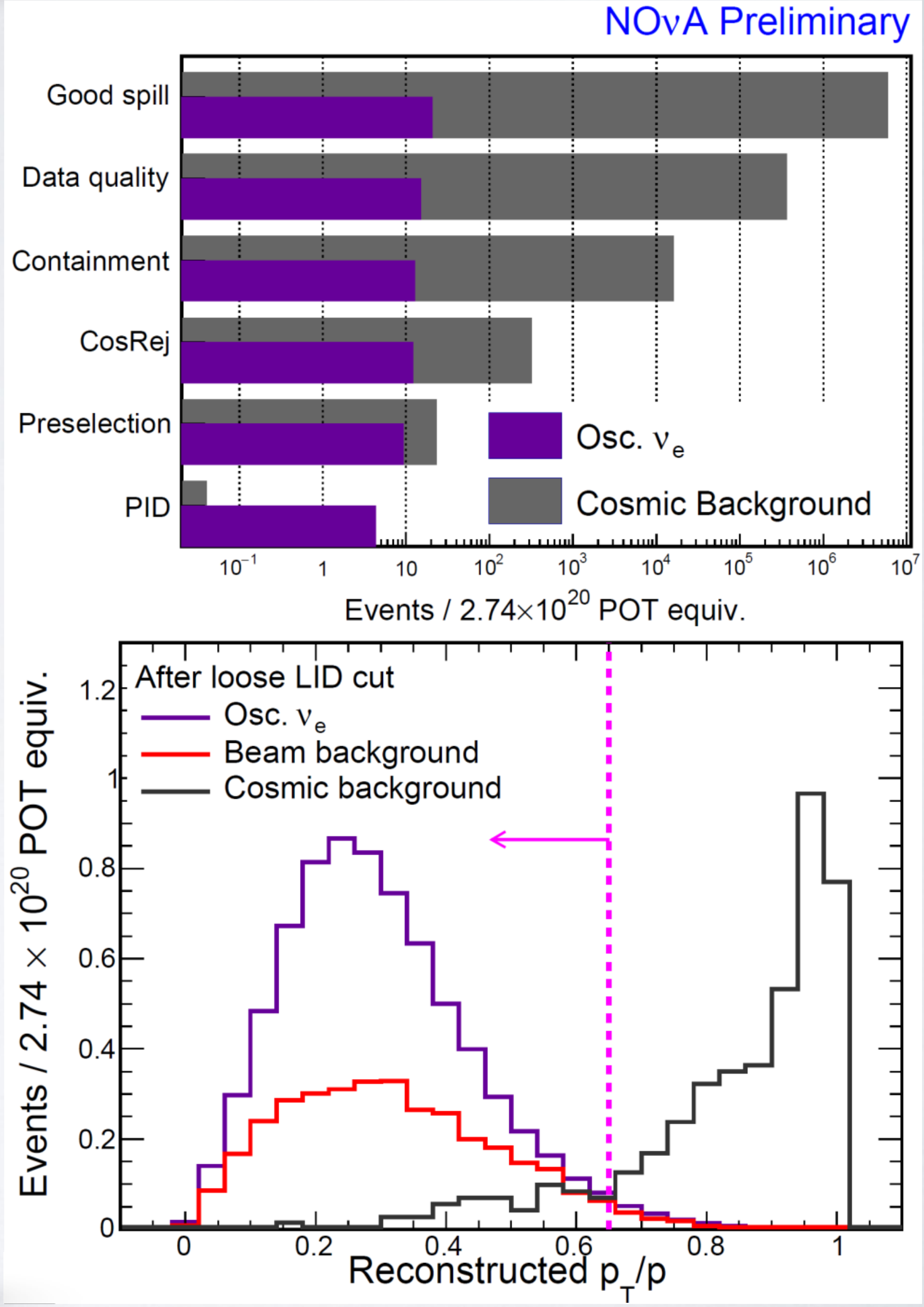
Signal pre-selection: ν_e CC

- First: basic containment cuts: require sufficient distance from the largest reconstructed shower to the edges
- 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)



Cosmic rejection

- Cut events with large transverse momentum (*Rejects downward-going cosmic showers*)
- The ν_e selectors themselves are very efficient at rejecting cosmic background
- Achieve a 1 in 10^8 rejection
- Expected cosmic background; 0.06 events, measured directly using out-of-time data



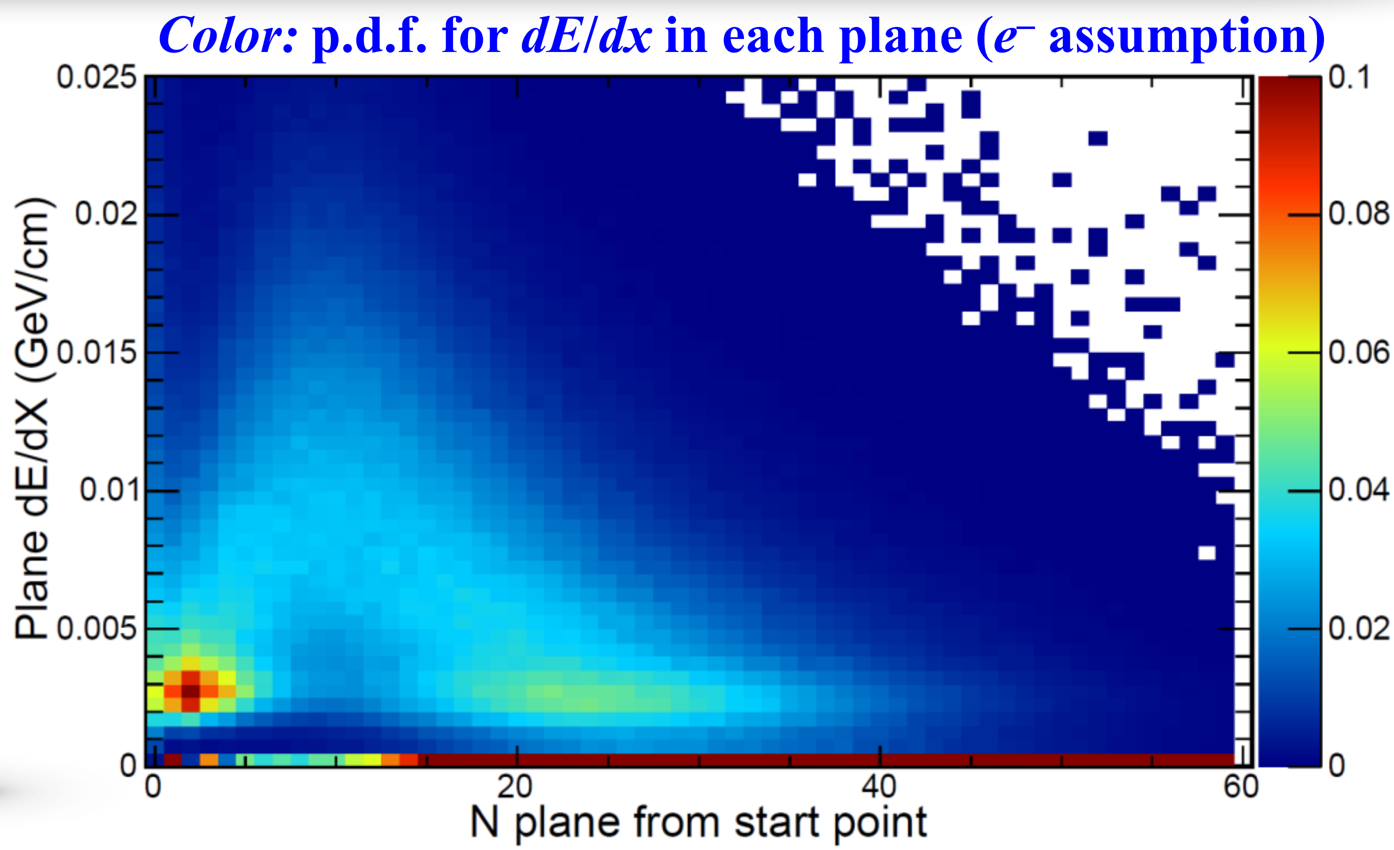
ν_e CC event identification

Two independent selection algorithms with very different designs

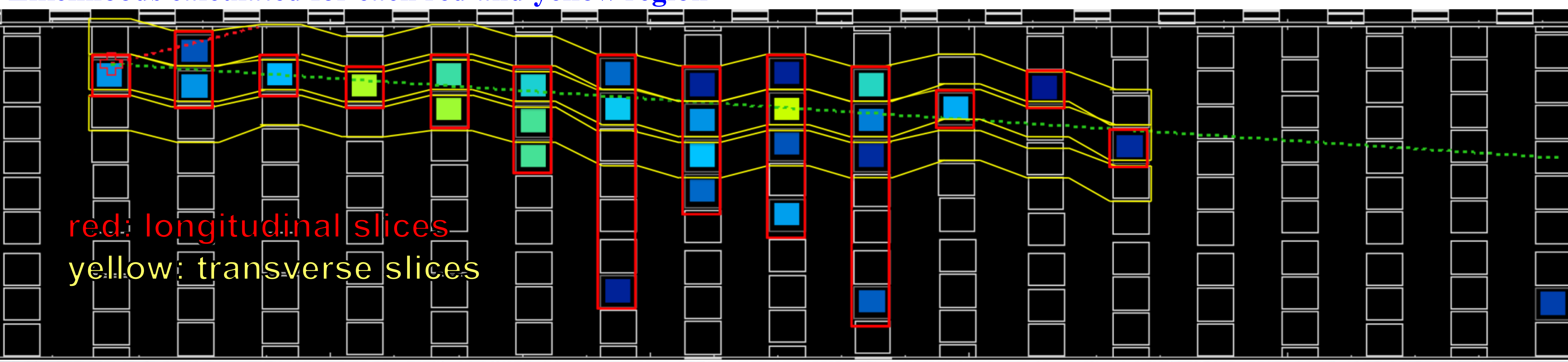
LID: Likelihood identification

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

Likelihoods feed an artificial neural network along with **kinematic and topological info**: e.g., energy near vertex, shower angle, vertex-to-shower gap, …



Likelihoods calculated for each red and yellow region

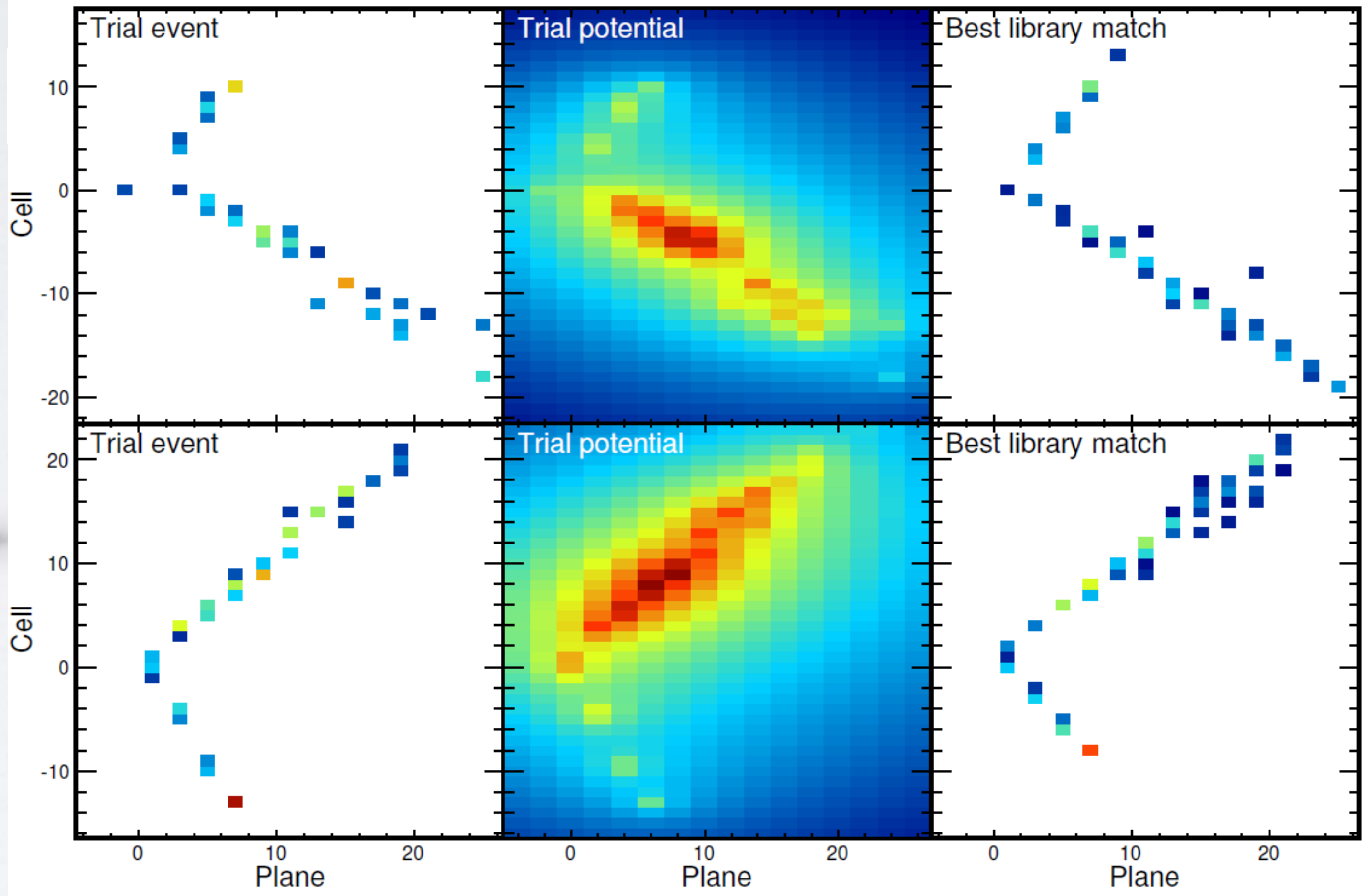


LEM: Library event matching

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

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

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



- Identical performance as measured with efficiency, $S/\sqrt{B}$ and sensitivity to oscillation parameters

Prior to unblinding, decided to **show both results and use LID as primary**

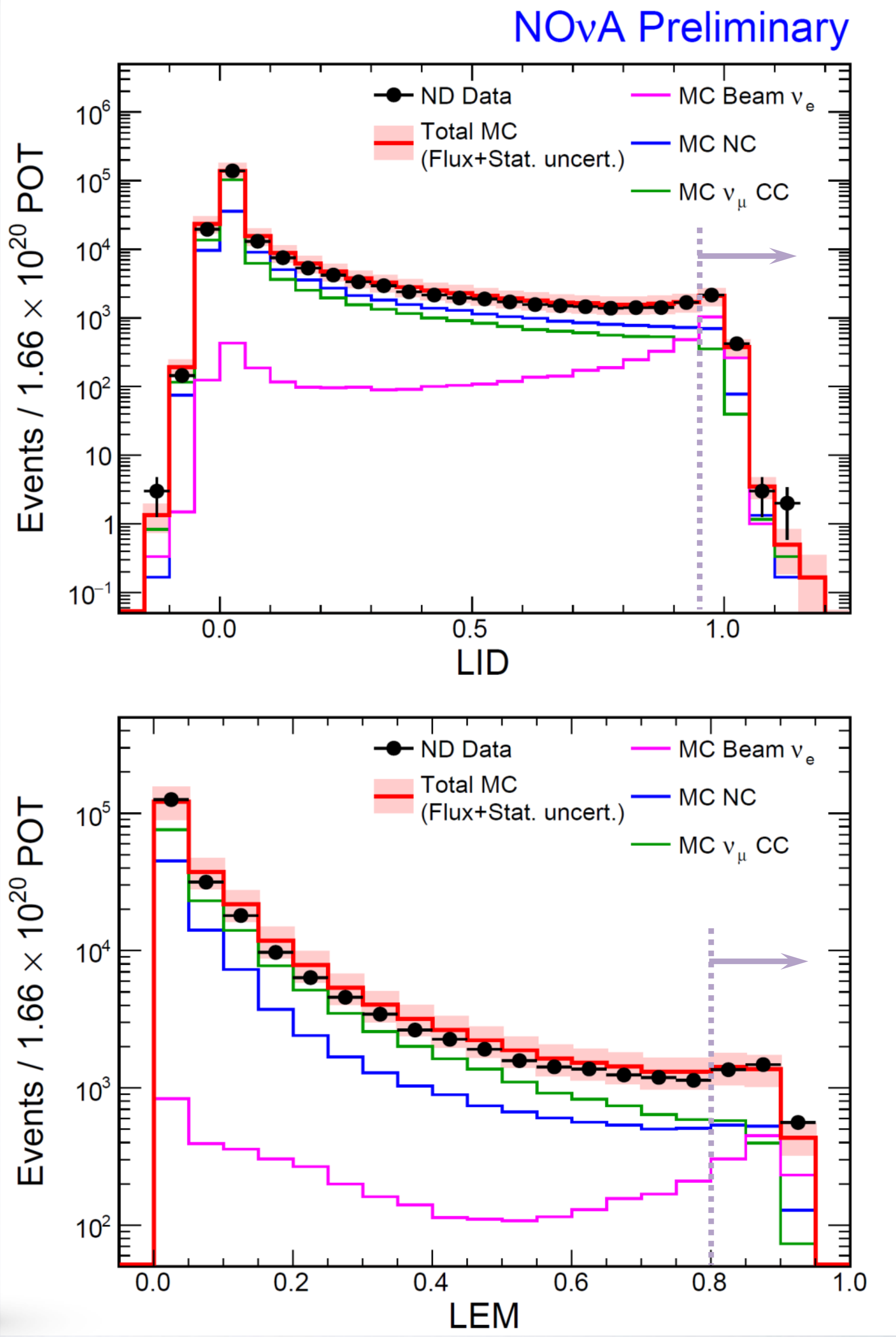
LID and LEM distributions for ND data and simulation

- Good agreement over full range

Total BKG	ν_e - CC (beam)	NC	ν_μ - CC	ν_τ - CC	Cosmic
0.94 ± 0.09	0.46	0.35	0.05	0.02	0.06
	± few % depending on osc. param.				

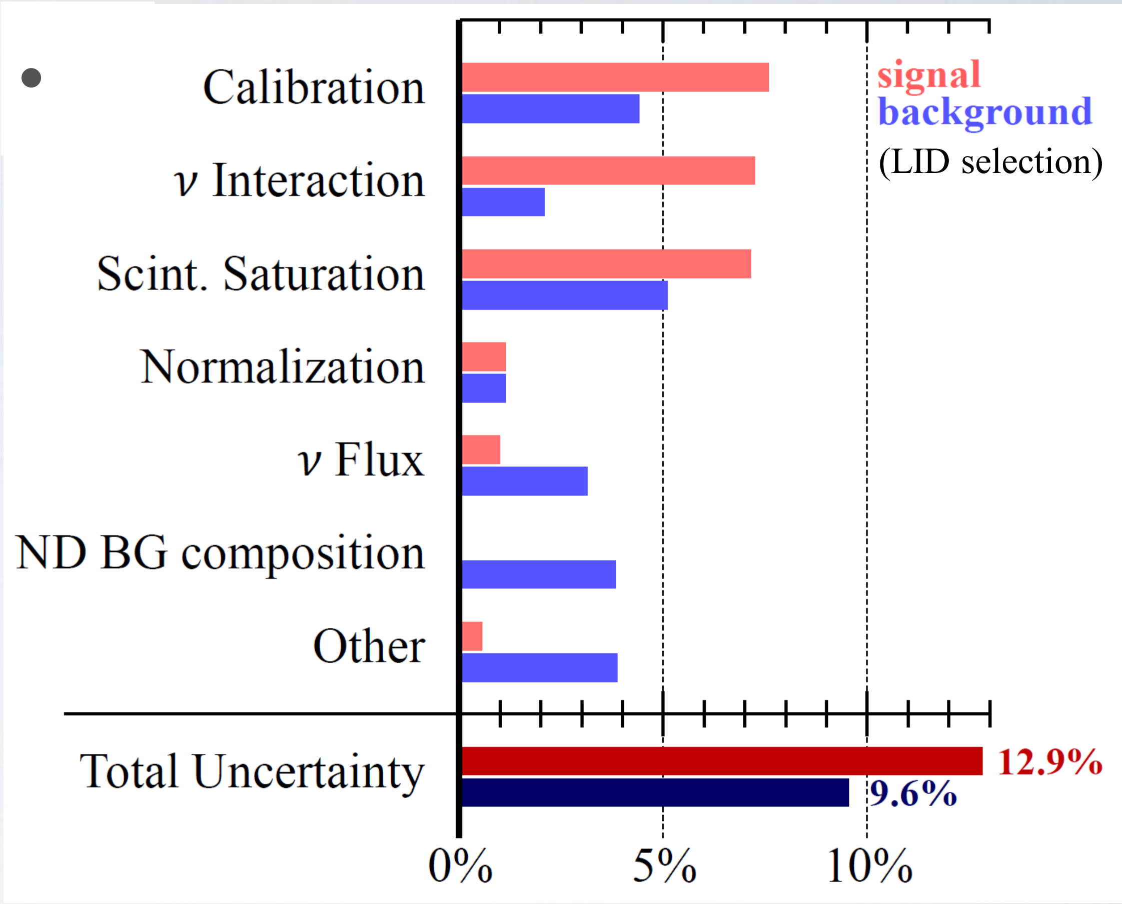
Range of signal predictions

- NH, $\delta_{CP} = 3\pi/2$, $\theta_{23} = \pi/4 \rightarrow 5.6 \pm 0.7$
- IH, $\delta_{CP} = \pi/2$, $\theta_{23} = \pi/4 \rightarrow 2.2 \pm 0.3$



Far detector prediction

- **ND data** are translated to **FD background expectation** in each energy bin, using far/near ratios from simulation
- **FD *signal* expectation** is pinned to the ND-selected νμ - CC spectrum
- Most **systematics** are assessed **via variations** in the far/near ratios



Signal efficiency relative to containment cuts: 35%

Expected overlap in LID/LEM samples of 62%

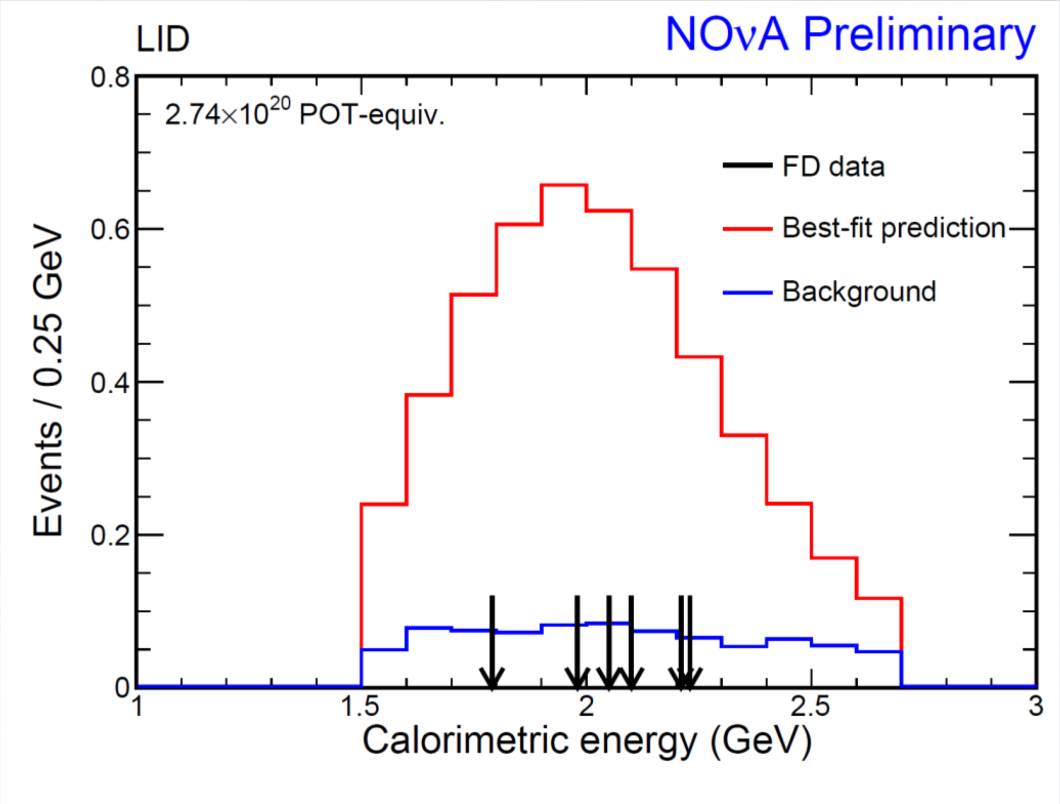
(Expected differences in which events each technique selects)

After all selection, **0.7% of NC** events remain, relative to those after containment

Far detector selected events

LID: 6 ν_e candidates

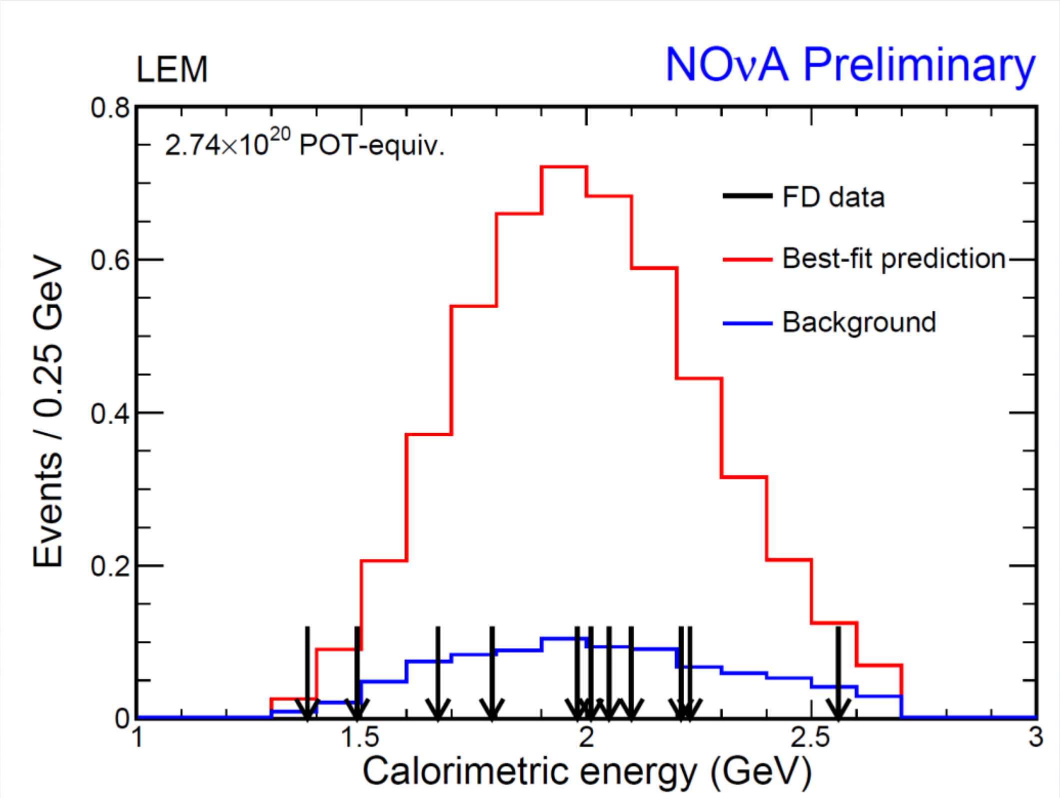
3.3σ significance for ν_e appearance



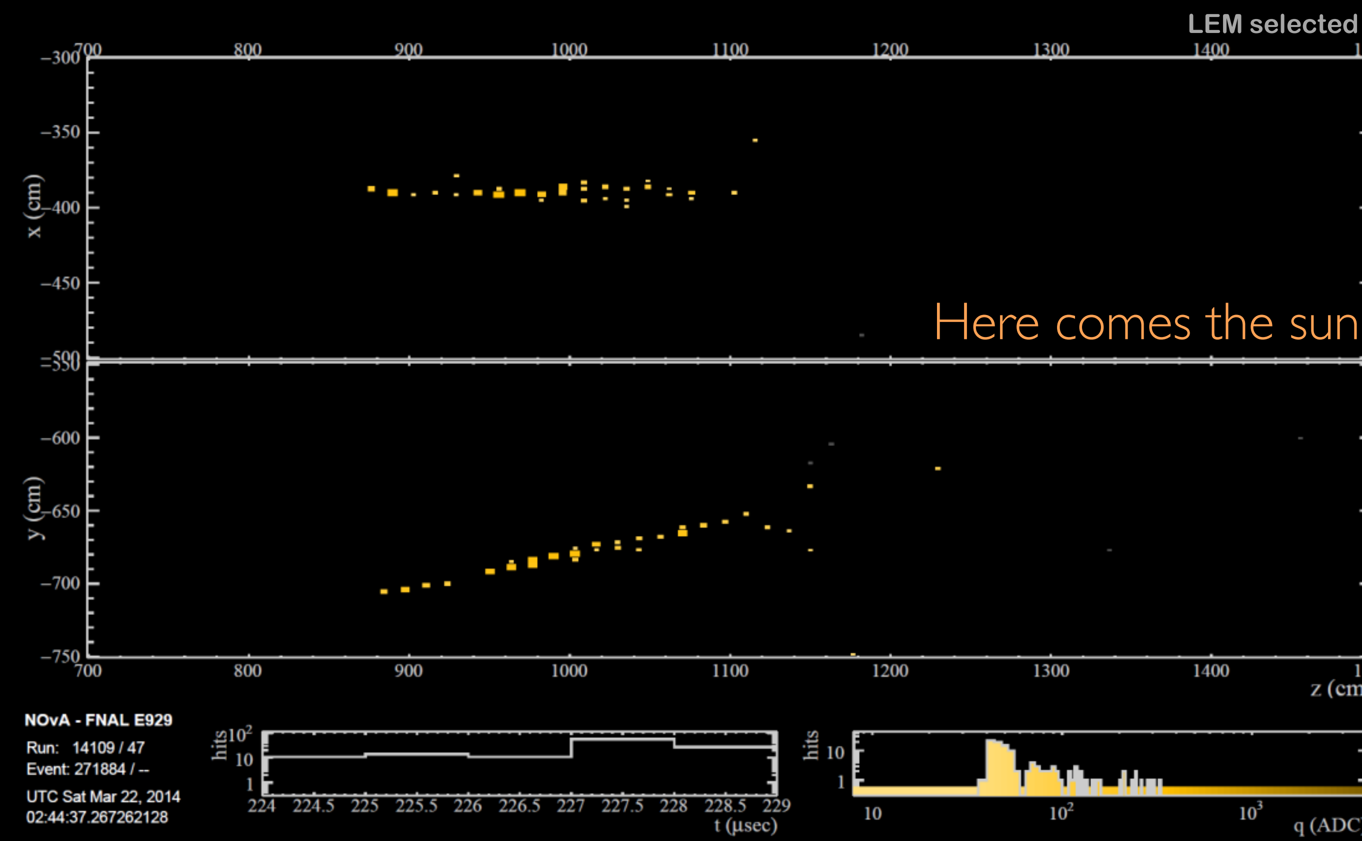
LEM: 11 ν_e candidates

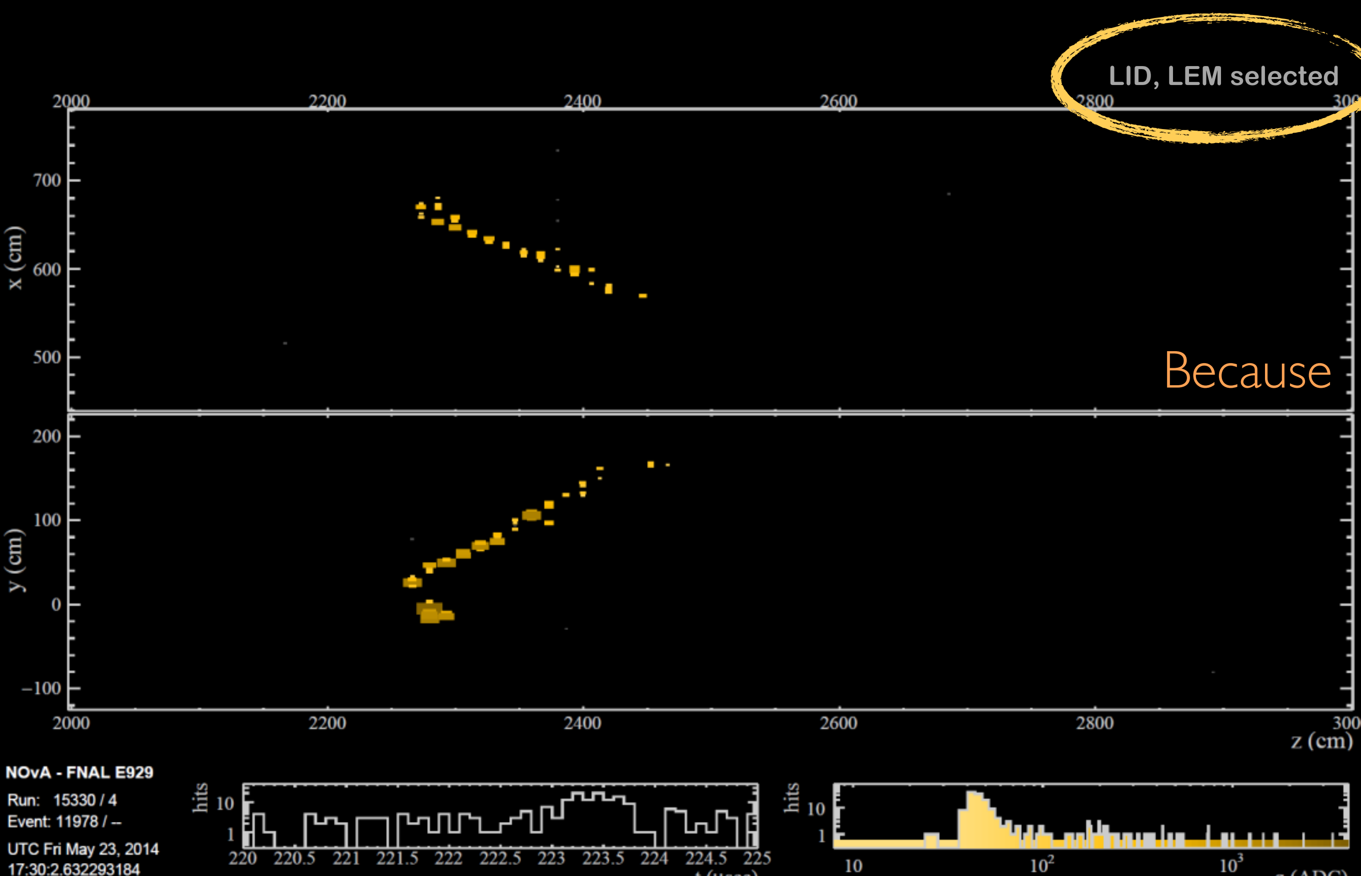
5.5σ significance for ν_e appearance

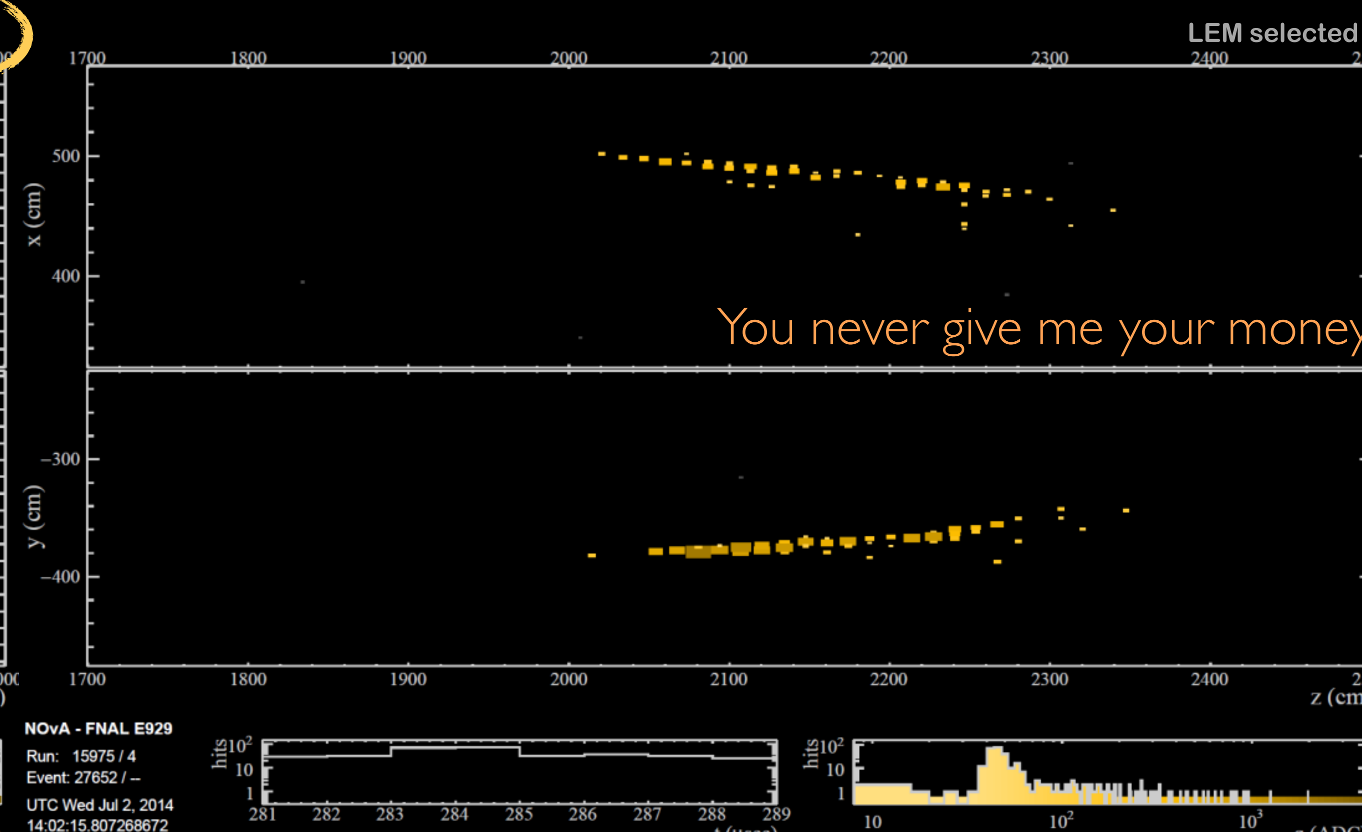
(All 6 LID events present in LEM set)



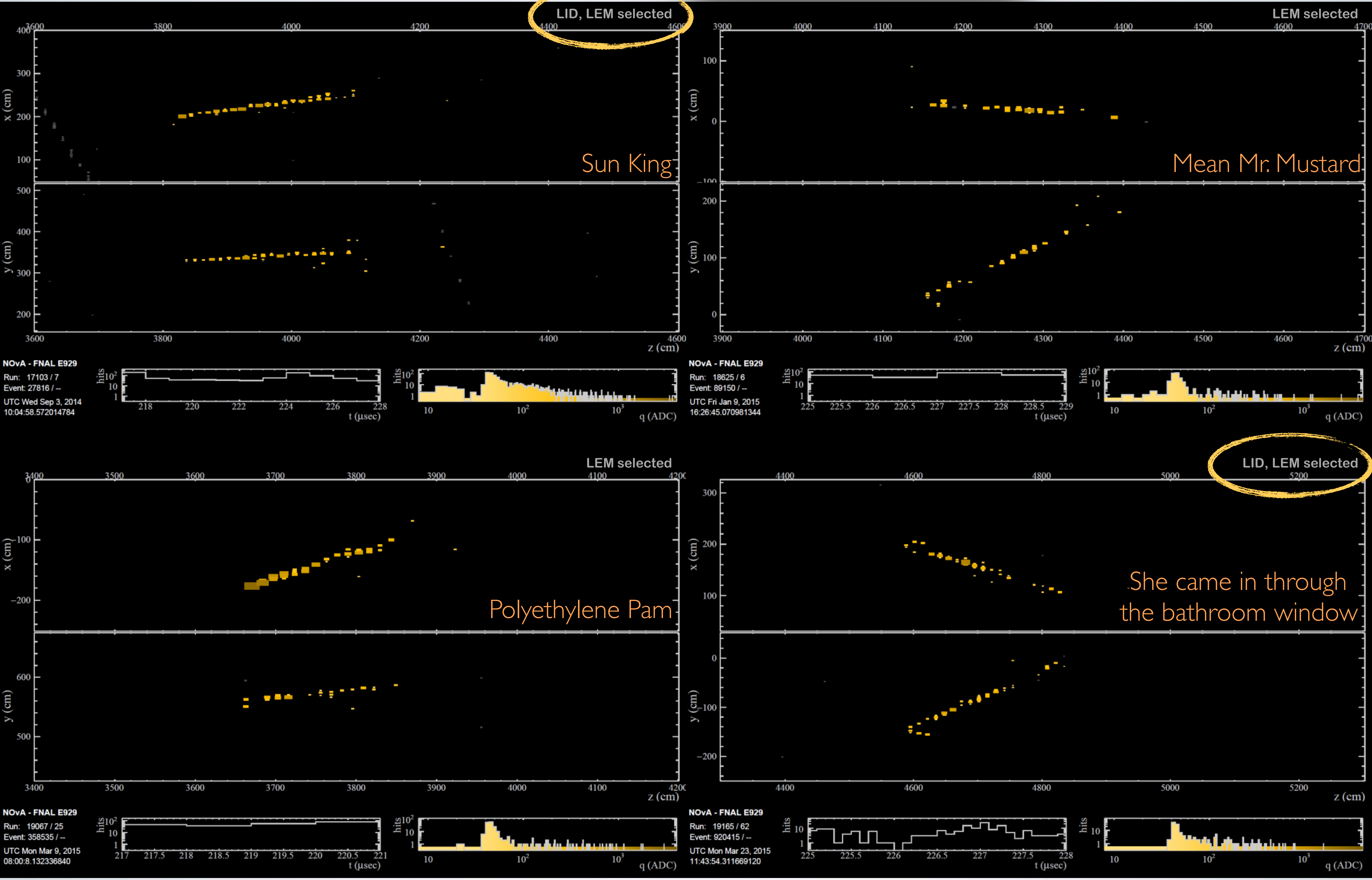

ν_e candidates

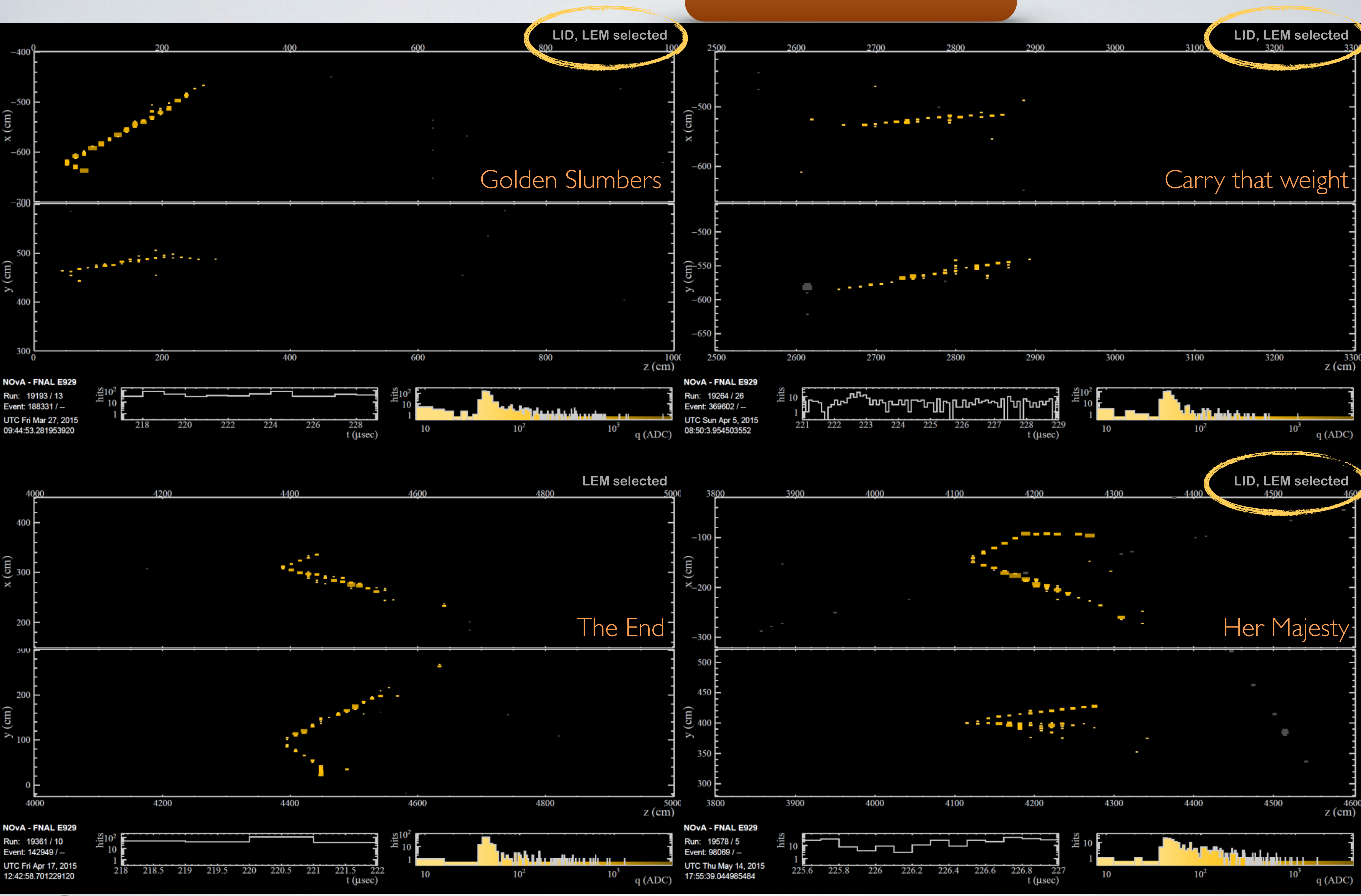

LEM selected
Here comes the sun
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 14109 / 47
Event: 271884 / --
UTC Sat Mar 22, 2014
02:44:37.267262128
hits
t (μsec)
q (ADC)


LID, LEM selected
Because
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 15330 / 4
Event: 11978 / --
UTC Fri May 23, 2014
17:30:2.632293184
hits
t (μsec)
q (ADC)


LEM selected
You never give me your money
x (cm)
y (cm)
z (cm)
NOvA - FNAL E929
Run: 15975 / 4
Event: 27652 / --
UTC Wed Jul 2, 2014
14:02:15.807268672
hits
t (μsec)
q (ADC)

Electron neutrino appearance

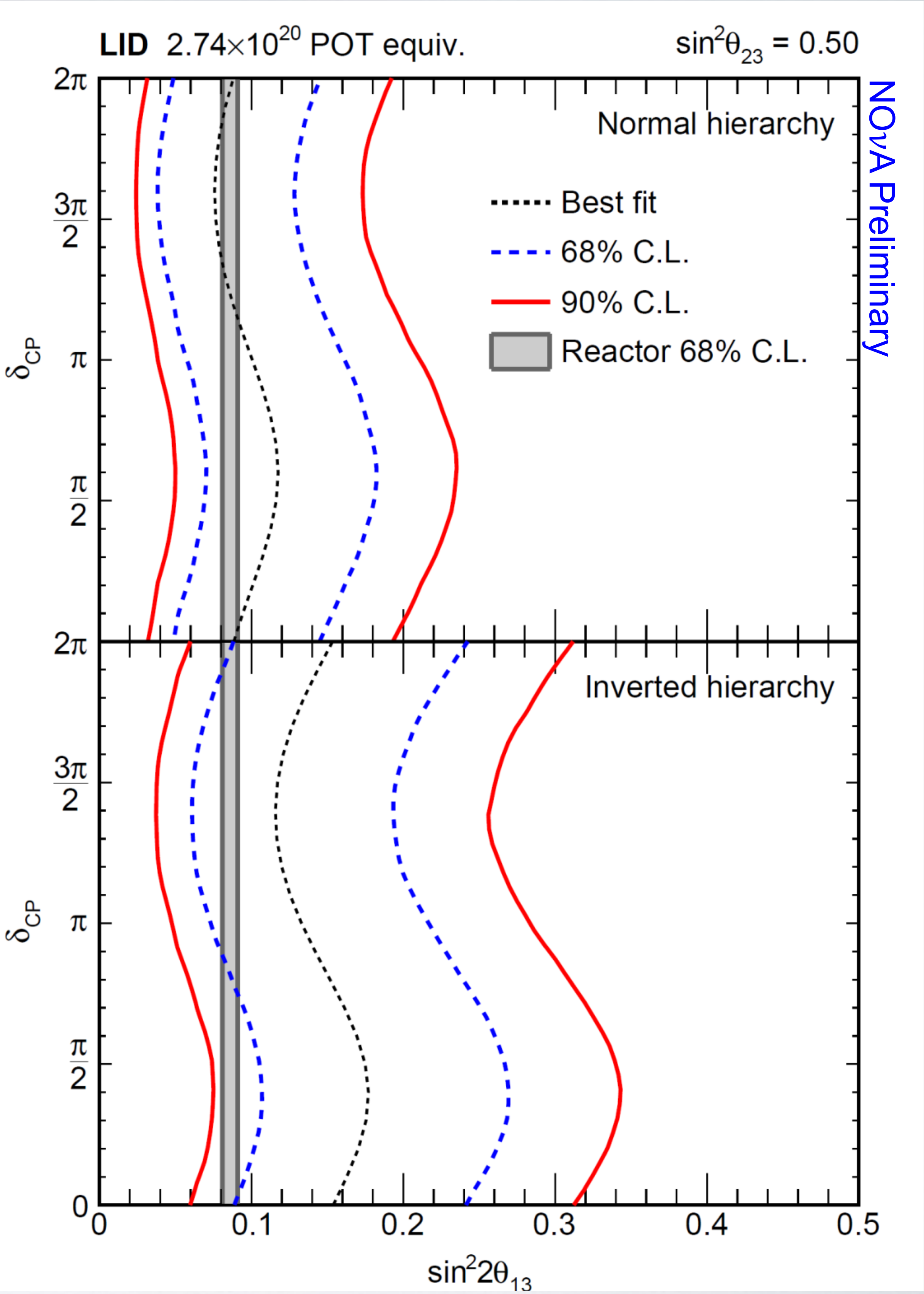



LID, LEM selected
Golden Slumbers
NOvA - FNAL E929
Run: 19193 / 13
Event: 188331 / --
UTC Fri Mar 27, 2015
09:44:53.281953920
LID, LEM selected
Carry that weight
NOvA - FNAL E929
Run: 19264 / 26
Event: 369602 / --
UTC Sun Apr 5, 2015
08:50:3.954503552
LEM selected
The End
NOvA - FNAL E929
Run: 19361 / 10
Event: 142949 / --
UTC Fri Apr 17, 2015
12:42:58.701229120
LID, LEM selected
Her Majesty
NOvA - FNAL E929
Run: 19578 / 5
Event: 98069 / --
UTC Thu May 14, 2015
17:55:39.044985484
x (cm)
y (cm)
z (cm)
hits
t (μsec)
q (ADC)

Result using LID selector

For allowed regions of δ_{CP} and θ_{13}

- Feldman & Cousins procedure applied
- Solar oscillation parameters varied
- Δm^2_{32} varied by new NOvA result
- $\sin^2\theta_{23} = 0.5$

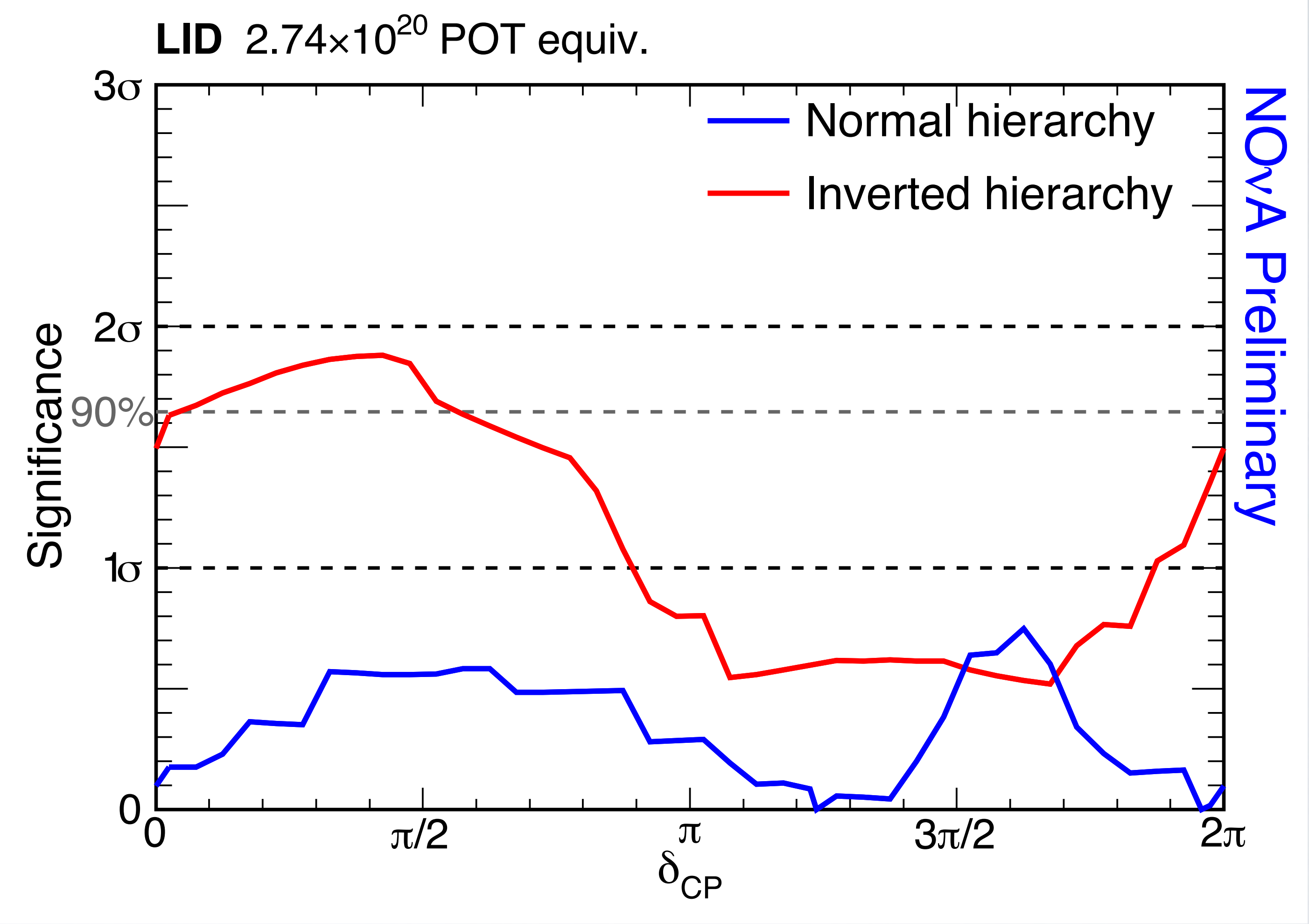


Result using LID selector

Applying global reactor constraint of

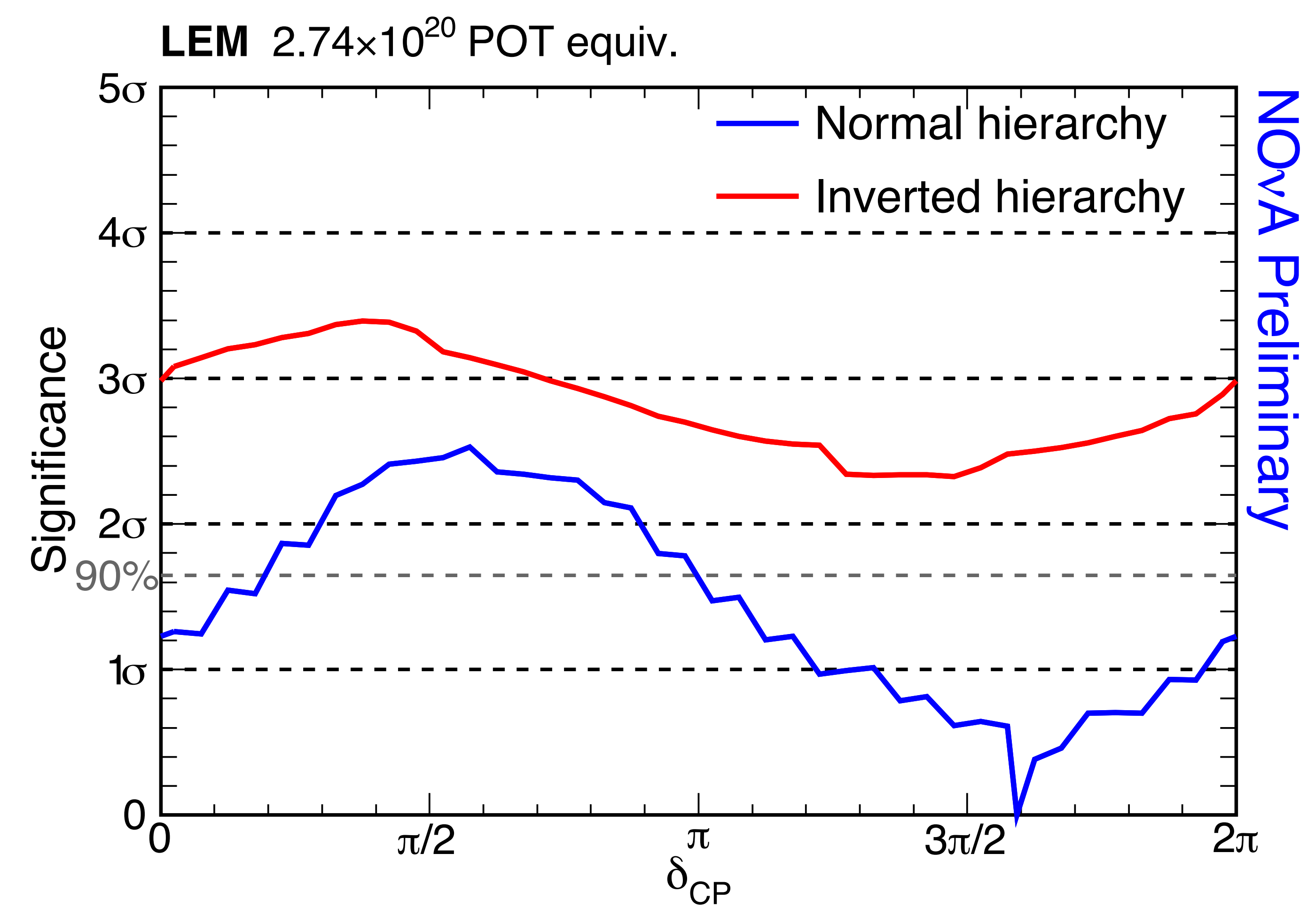
$$\sin^2\theta_{13} = 0.0219 \pm 0.0012$$

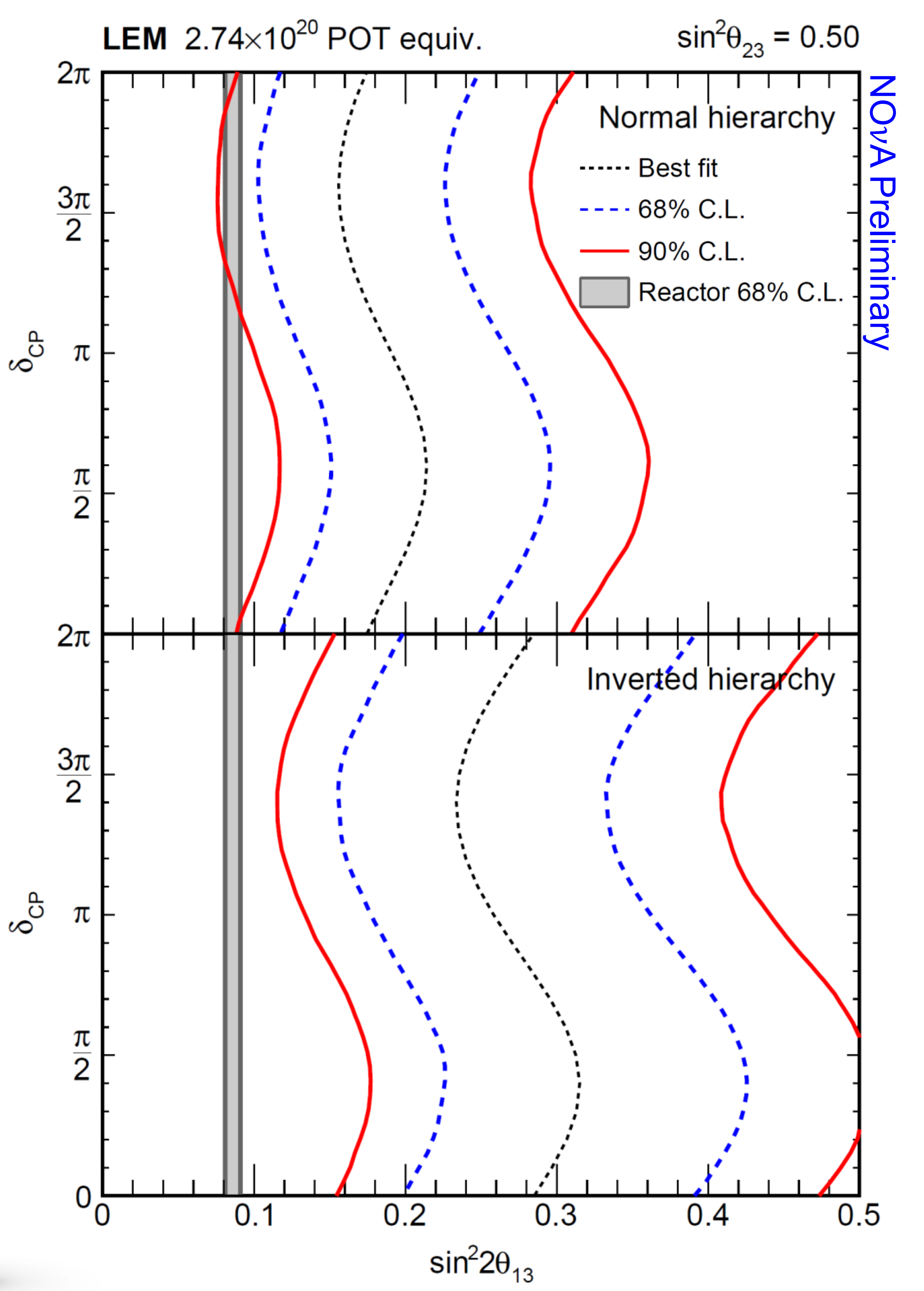
- Again, apply Feldman-Cousins to interpret -2ΔlnL
- Converted into significance (*steps due to discrete nature of counting experiment*)
- Using ν_μ constraint for $\sin^2\theta_{23}$



Inverted hierarchy for $\delta_{CP} \in [0, 0.9\pi]$ is mildly disfavoured (>1σ)

Result using LEM selector

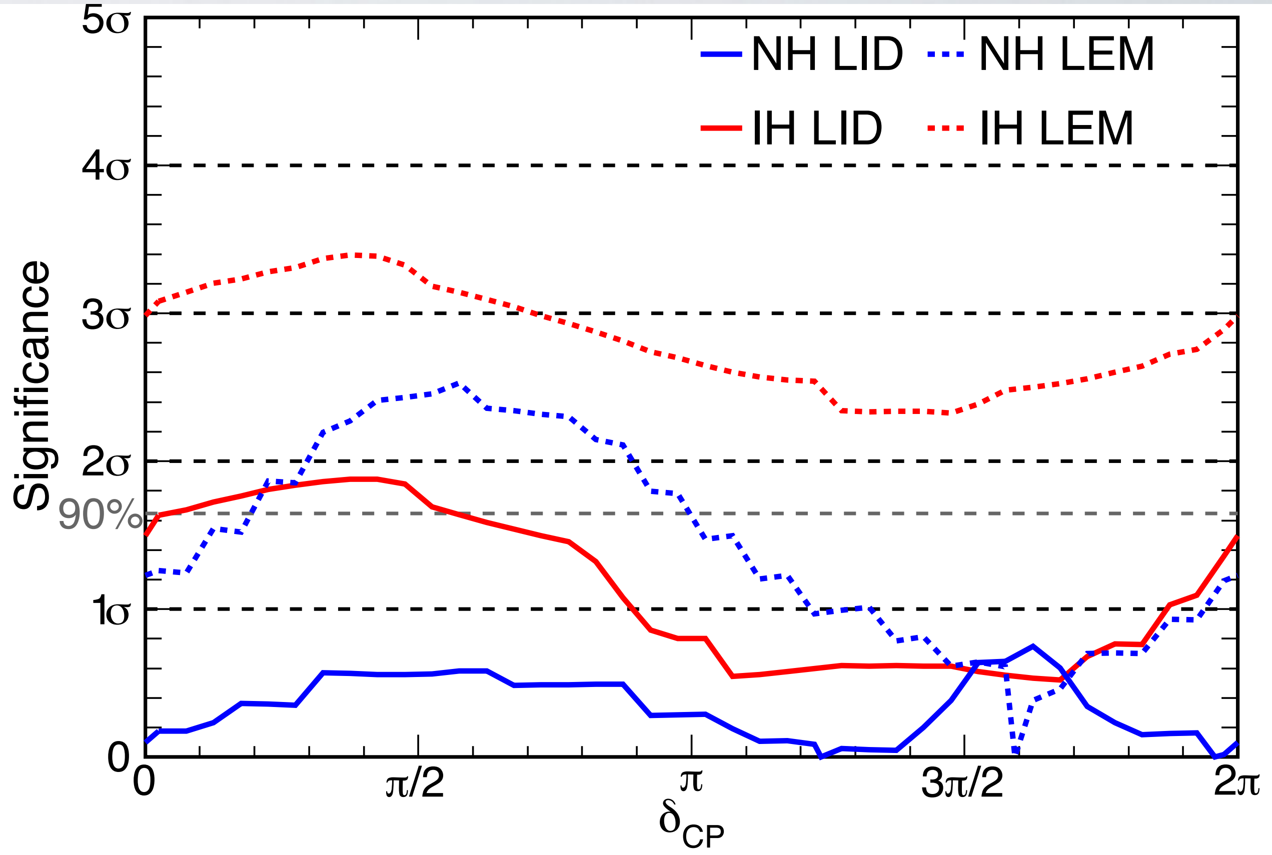




- Inverted hierarchy is disfavoured at 2.2σ for all δ_{CP}
- NH for $\delta_{CP} \in [0,\pi]$ is mildly disfavoured ($>1\sigma$)

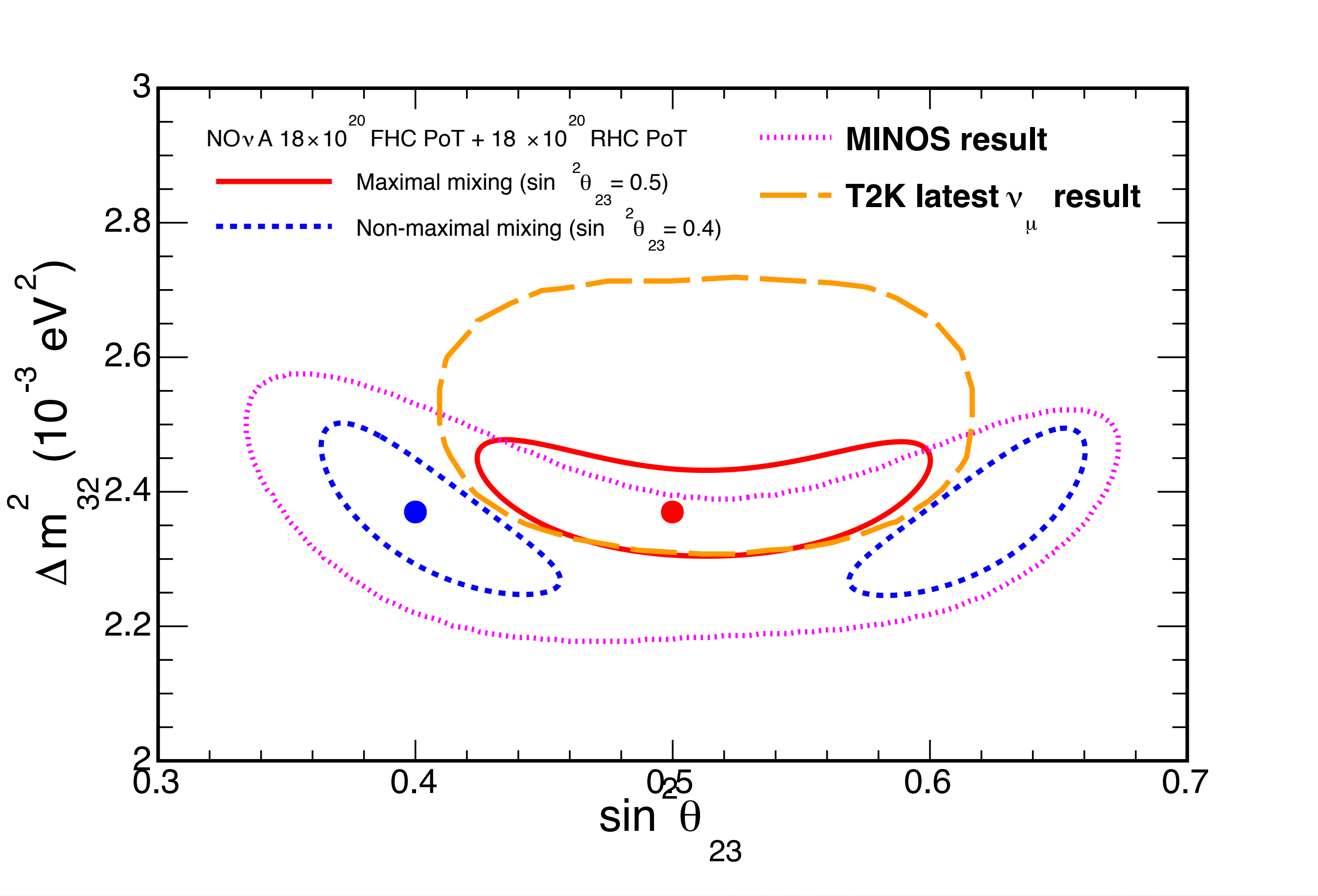
LID/LEM consistency

- Both prefer normal hierarchy
- Both prefer δ_{CP} near $3\pi/2$
- Given the expected correlations, the observed event counts yield a reasonable **mutual p-Value of 10%**

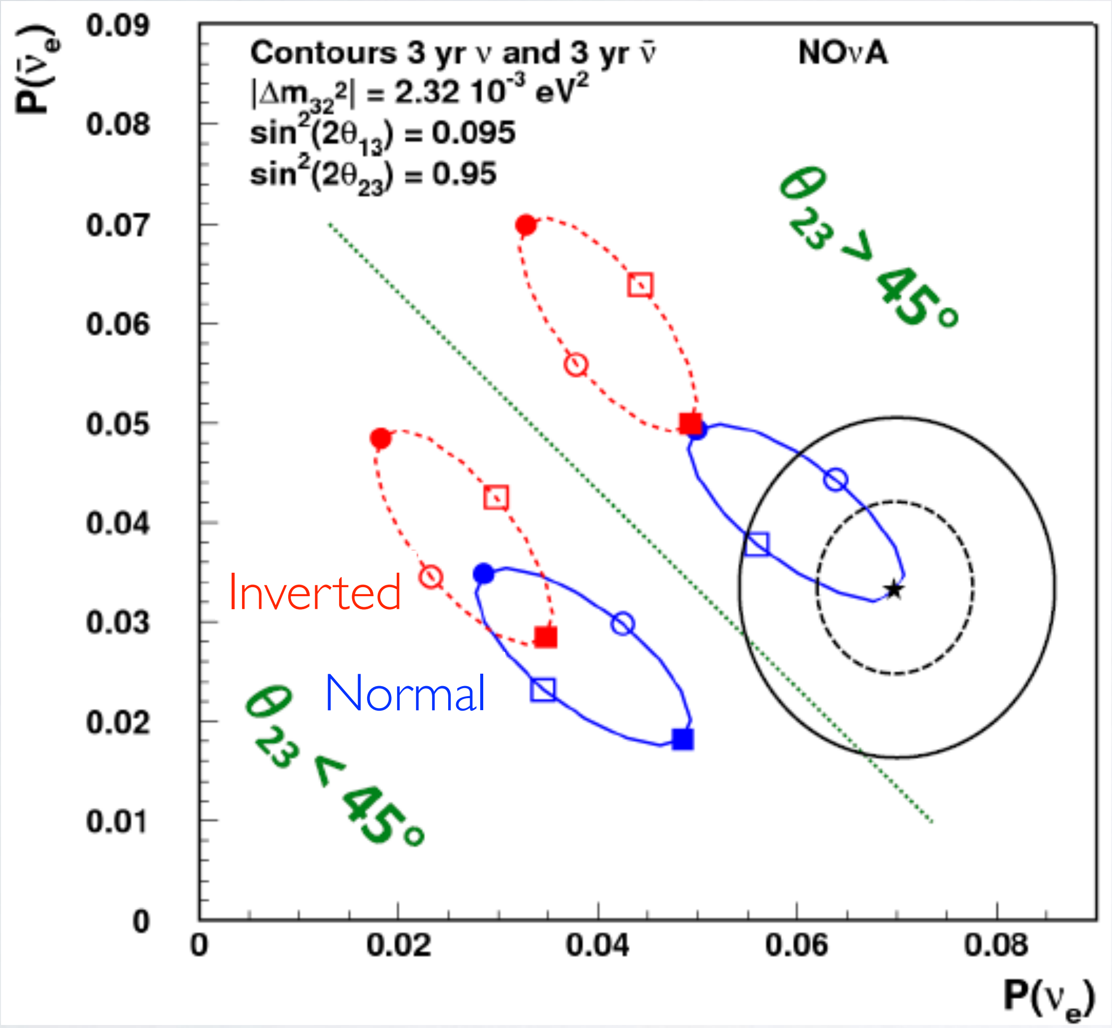


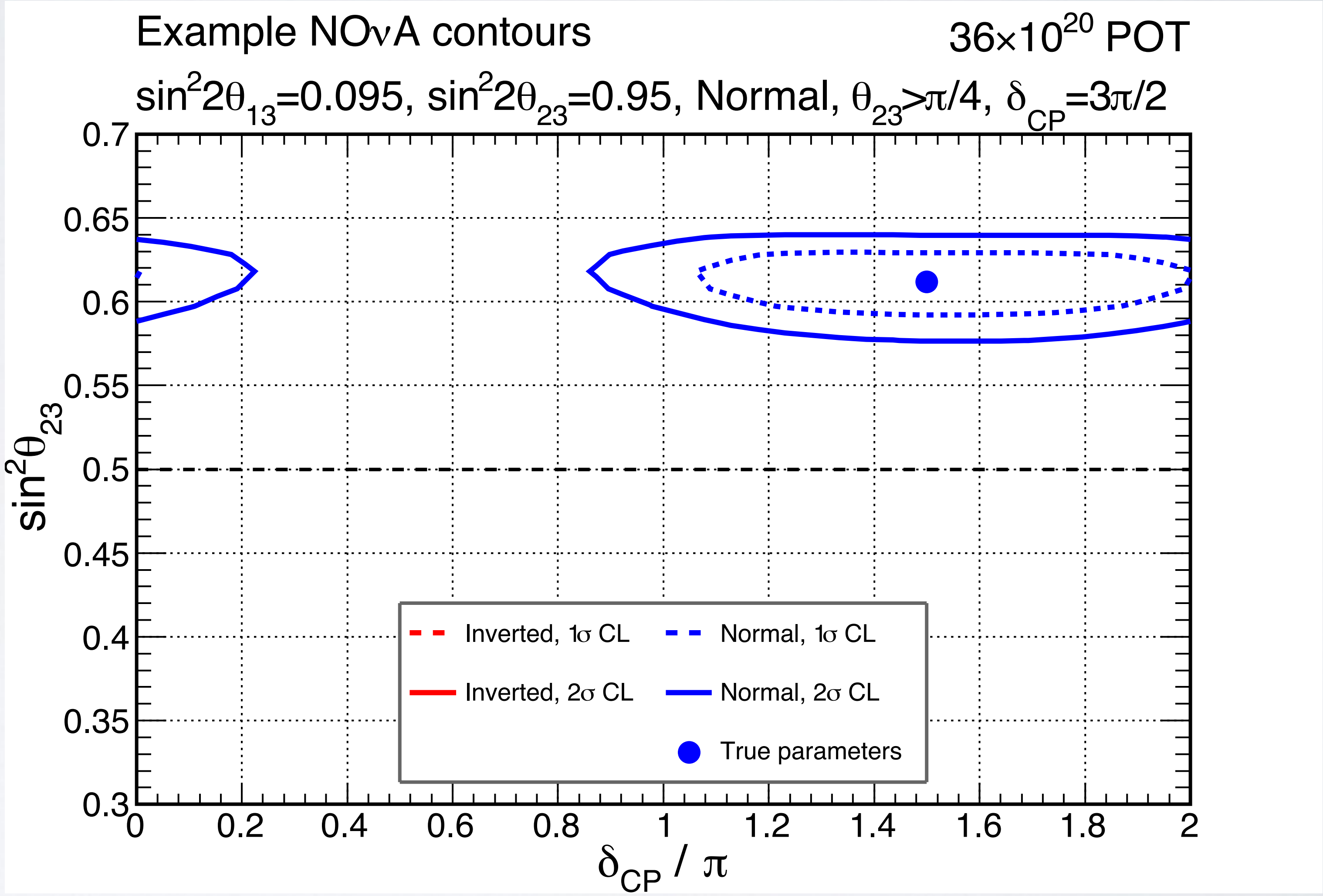
The specific point IH, $\delta_{CP} = \pi/2$ is disfavoured at 1.6σ (LID), 3.2σ (LEM) for $\sin^2\theta_{23} \in [0.4, 0.6]$

- Potential to exclude maximal mixing, depending on Nature's choice
- Leading measurement in both Δm^2_{32} and $\sin^2\theta_{23}$ for nominal sensitivity
- Measurements in the anti-neutrino channel: CPT tests



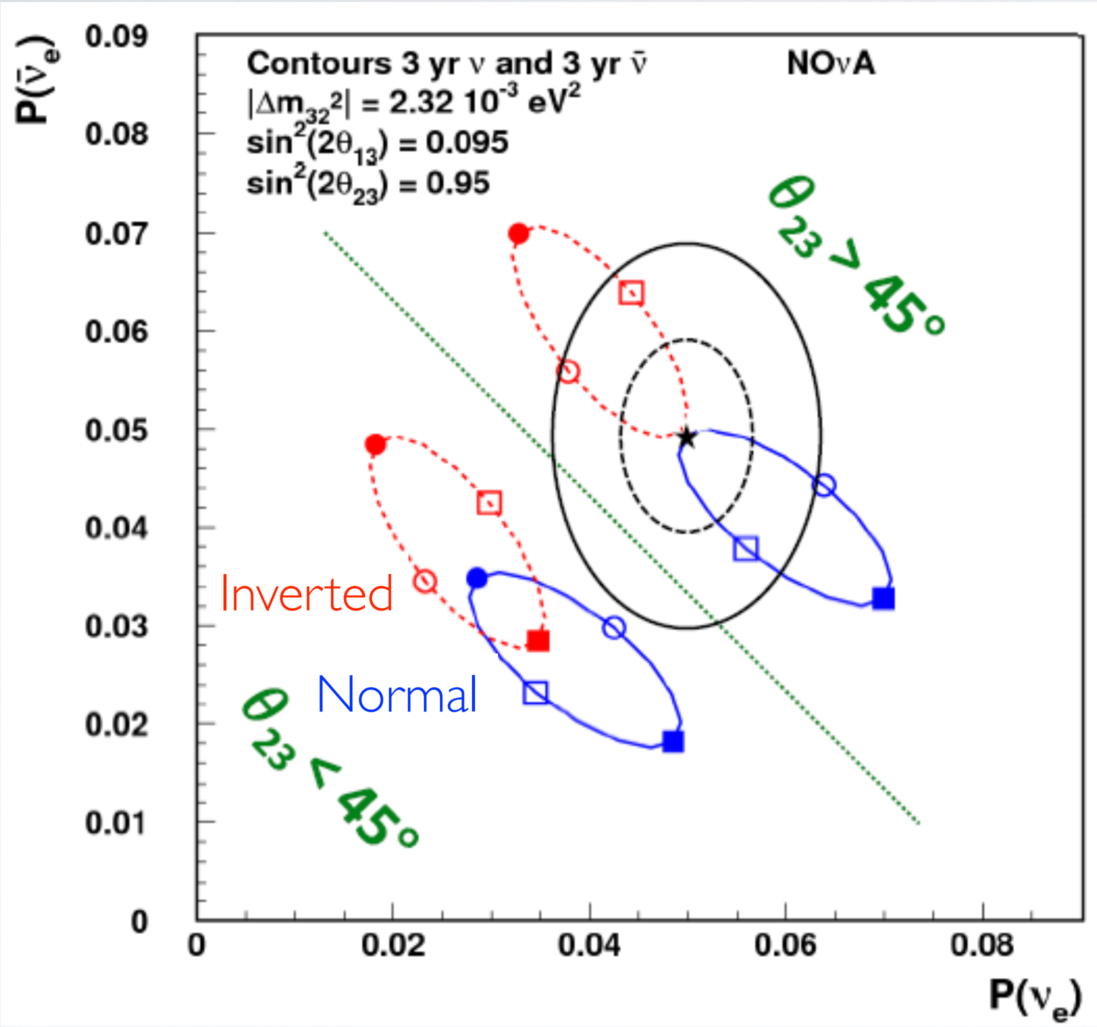
COMBINING MUON AND ELECTRON NEUTRINO ANALYSES

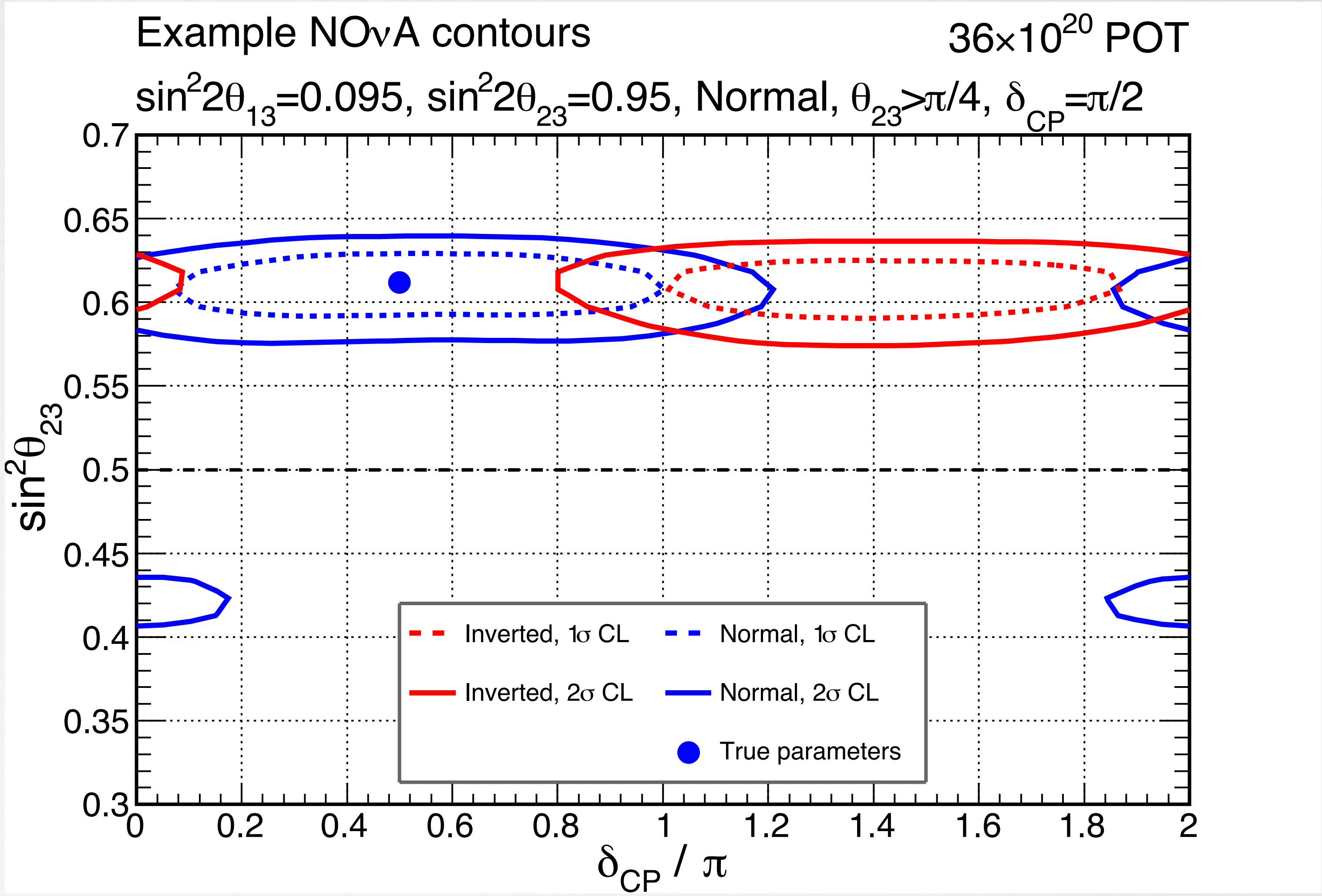




Best case scenario: NOvA simultaneously measures the mass ordering, CP violation and octant information!

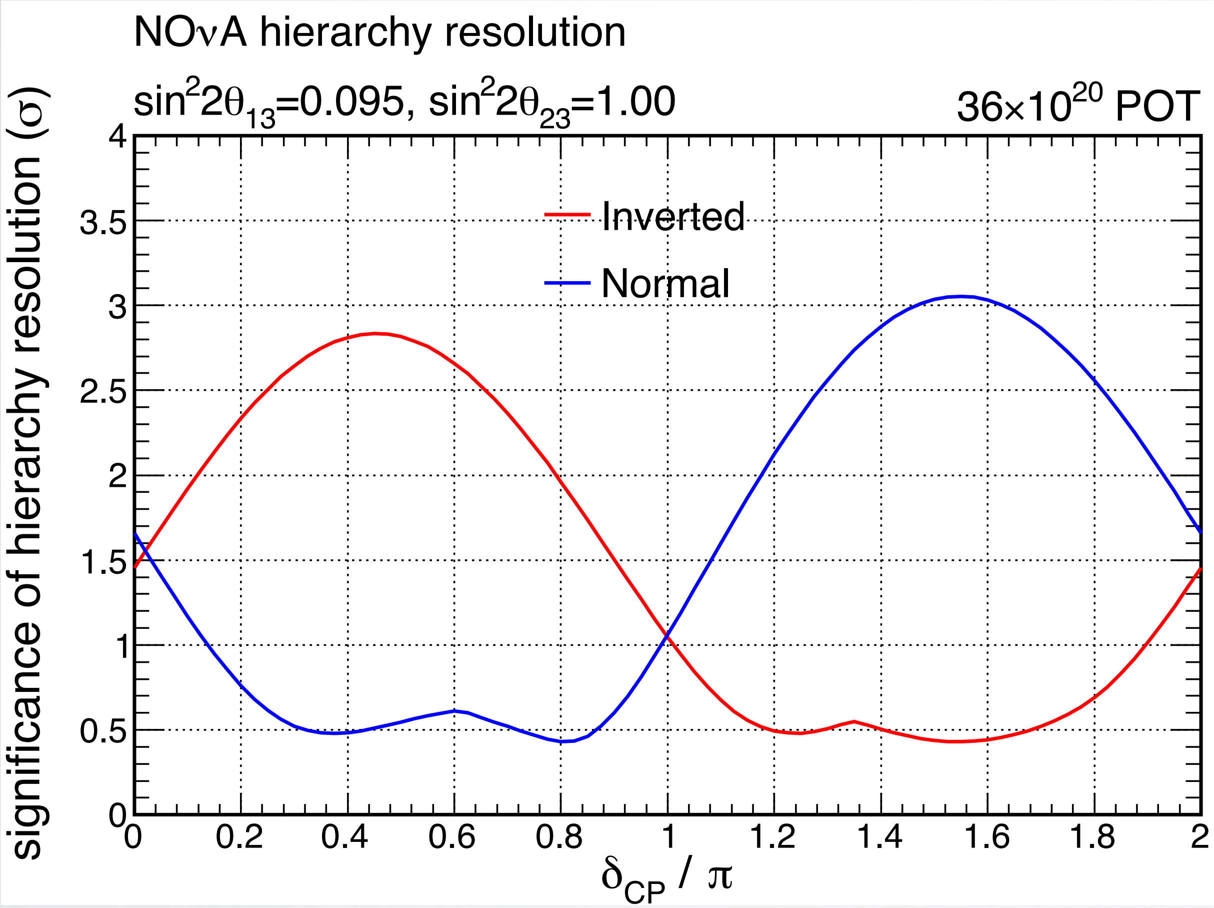
COMBINING MUON AND ELECTRON NEUTRINO ANALYSES

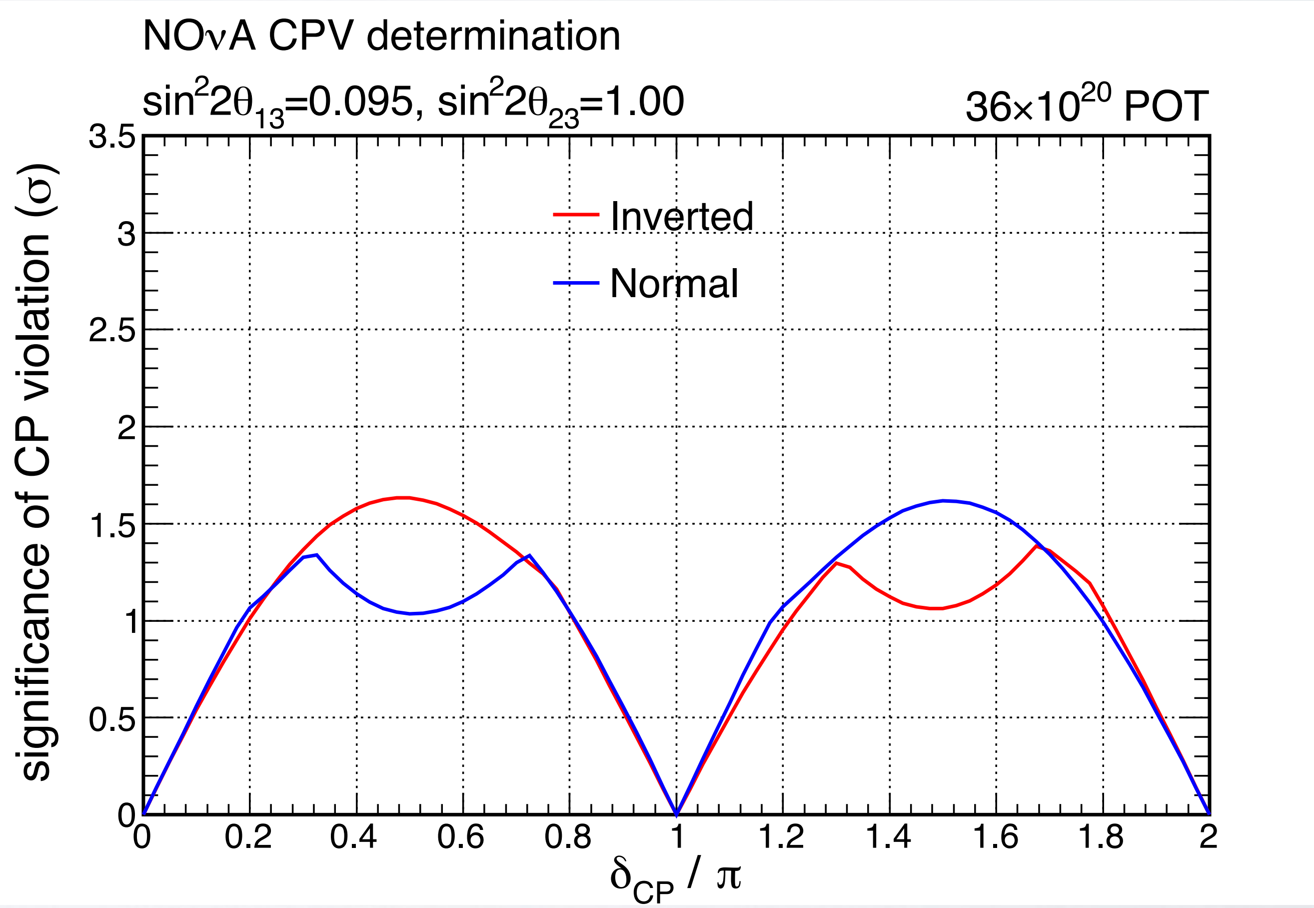




Degenerate case: mass ordering and CP violation are coupled, but the octant information is not

MASS HIERARCHY AND CP-VIOLATION

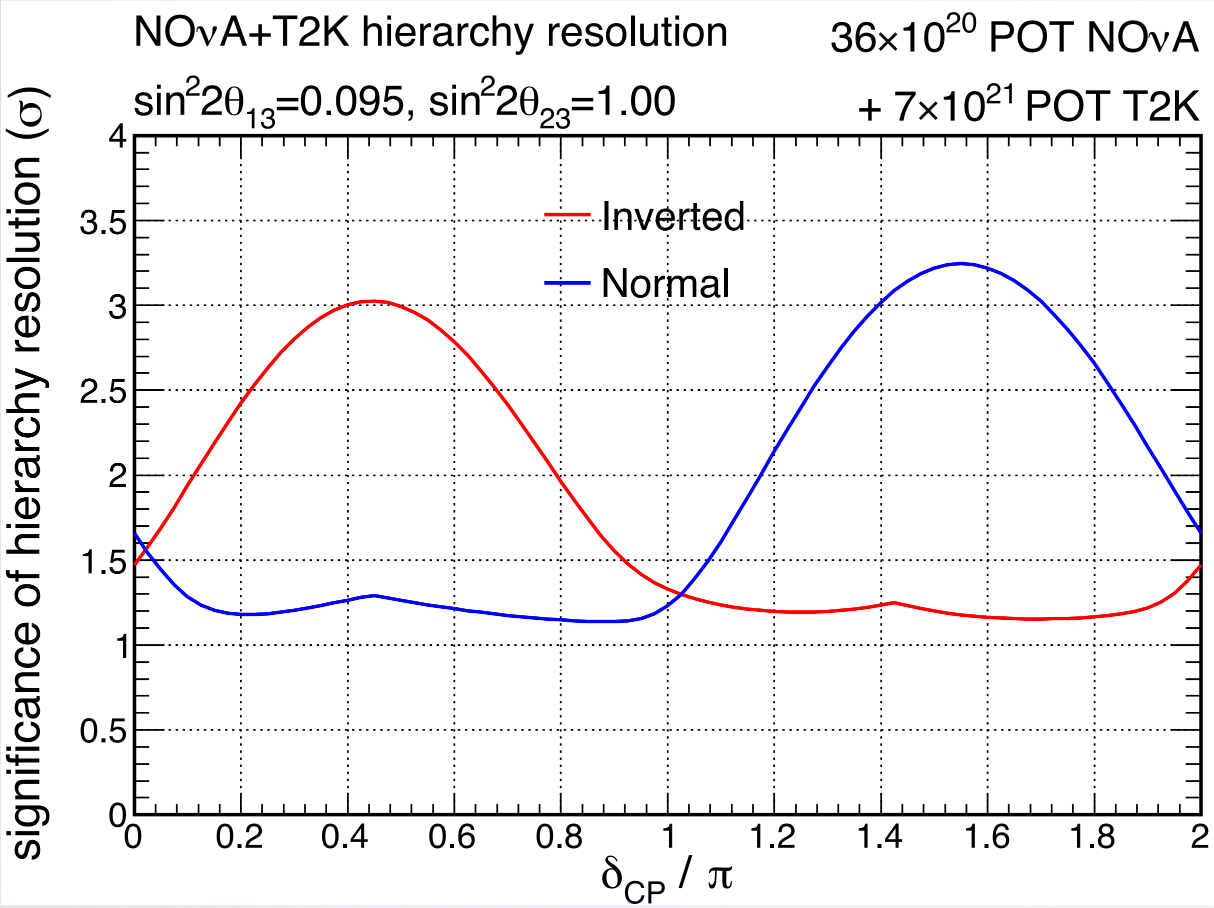


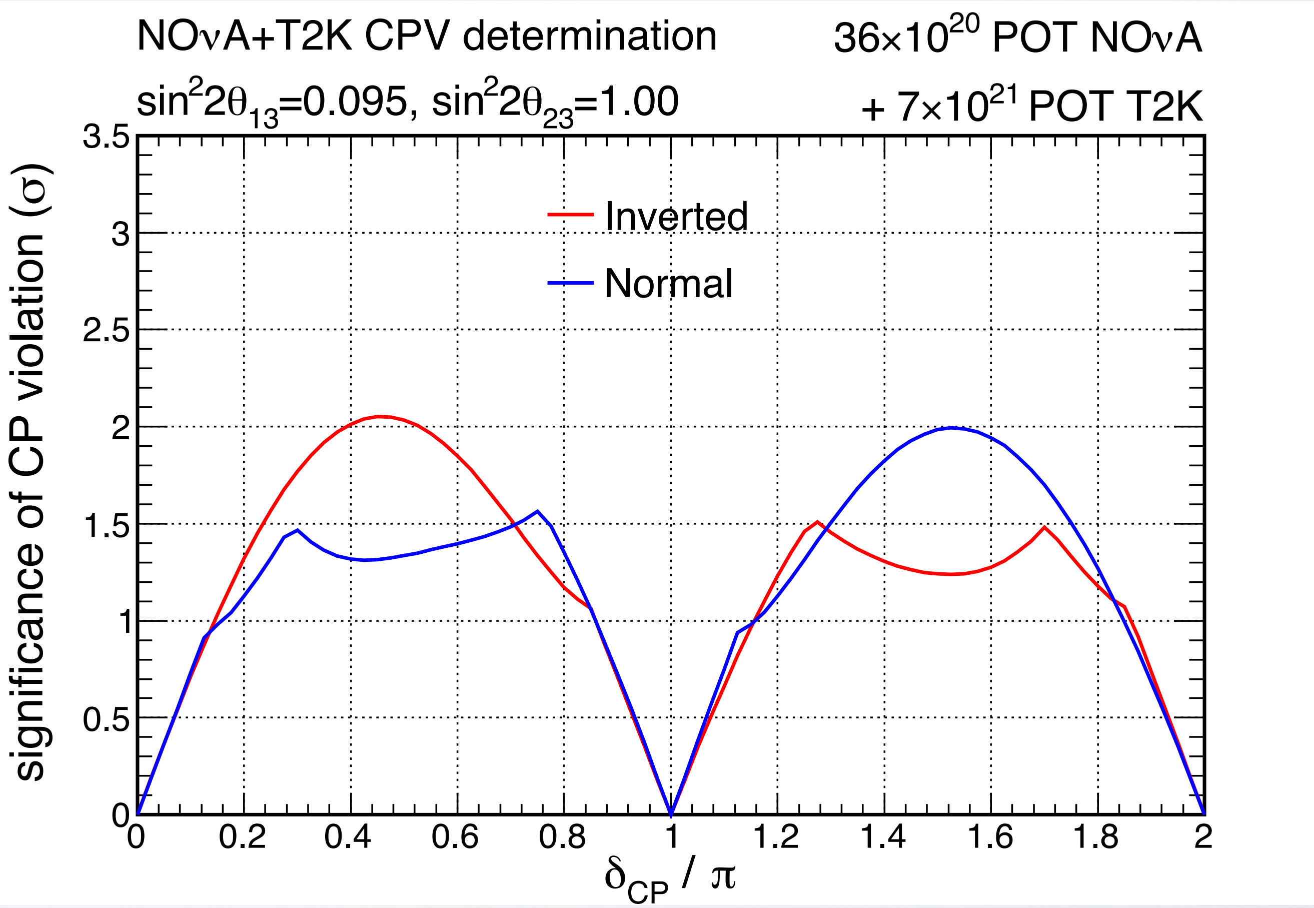


3+3 years (ν_μ +anti-ν_μ): 2 sigma in about 30% of the δ_{CP} range

Only 1.5 sigma in 10% of the range

COMBINATION WITH T2K





Combining with T2K: At least 1 sigma for the whole δ_{CP} range

With T2K: 1.5 sigma in 25%

- Far and near detector completed in August 2014
- The NuMI beam intensity is steadily increasing, setting new records on a weekly basis
- First analysis dataset included 7.8% of full exposure (40% of a standard running year)
- Other NOvA physics: programme underway
  - Neutrino cross-sections
  - Sterile neutrinos, non-standard interactions, CPT tests
  - Supernova neutrinos
  - Dark matter and monopole searches
  - *And more…*

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  - *And more…*

With 2.74 x 10^{20} POT exposure…

- Unambiguous ν_μ disappearance signature
- 6.5% measurement of atmospheric mass splitting
- Consistent with maximal mixing
- ν_e appearance signal at 3.3σ for primary selector, 5.5σ for secondary selector
- At max mixing, disfavour IH for $\delta_{CP} \in [0,0.6\pi]$ at 90% with primary selector. Further preference for NH with secondary selector

Much more to come!

SUMMARY

- Both NOvA detectors are operational and taking high quality data in the NuMI beam

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SUMMARY

- Both NOvA detectors are operational and taking high quality data in the NuMI beam

- Compelling measurement of muon neutrino disappearance with 8% of nominal exposure

- NOvA will use both appearance and disappearance channels to provide constraints on δ_{CP}, and leading measurements on the mass ordering and the θ_{23} octant

- Full FD with higher beam power: at least 2 x data next summer

THANK YOU FOR YOUR ATTENTION

Public live event display:
http://nusoft.fnal.gov/nova/public/

www-nova.fnal.gov