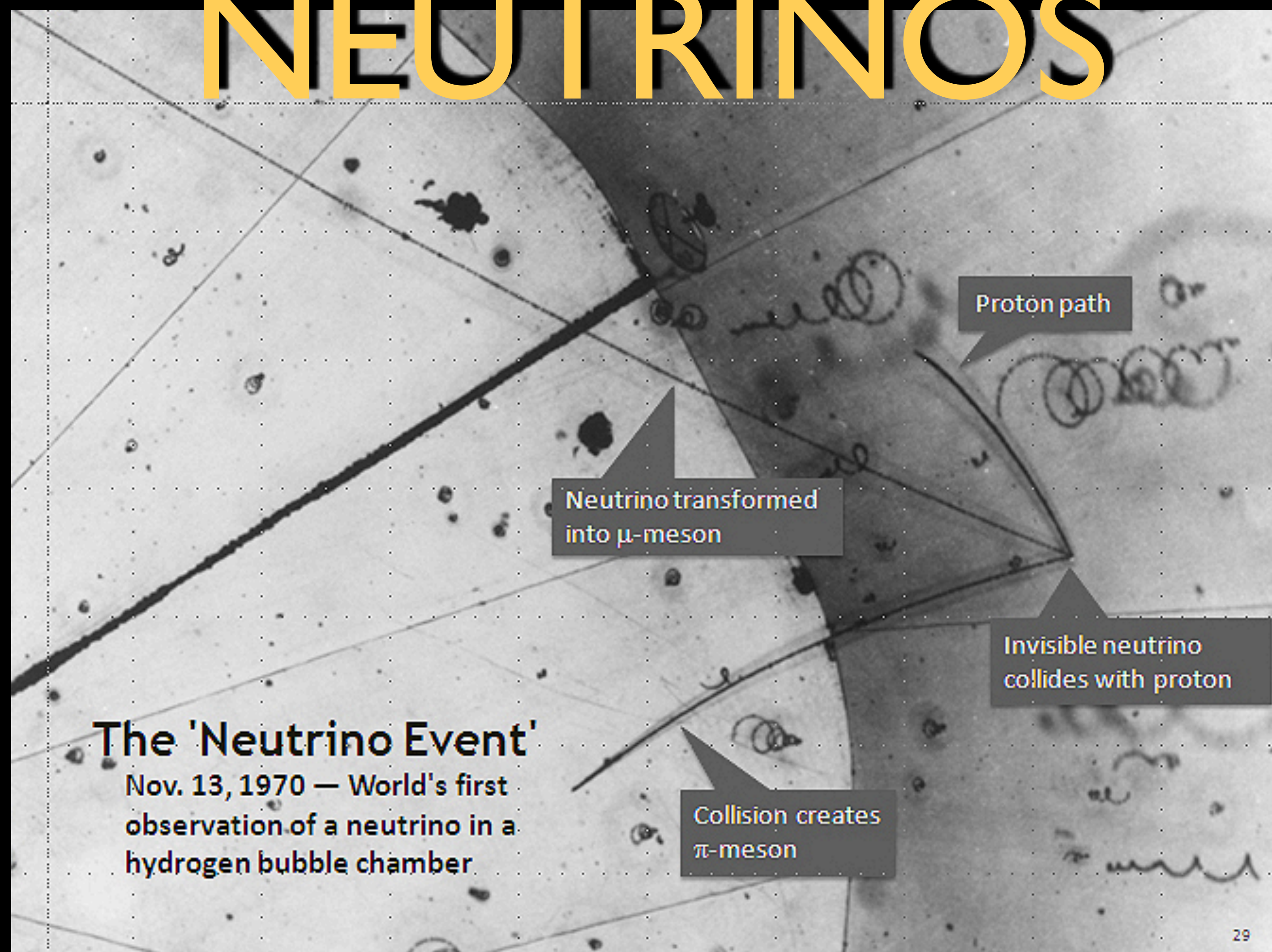
JERARQUÍA DE MASAS EN EXPERIMENTOS DE OSCILACIONES DE NEUTRINOS



Bruno Zamorano

Granada - 28 marzo 2017

European Research Council
Established by the European Commission
University of Sussex

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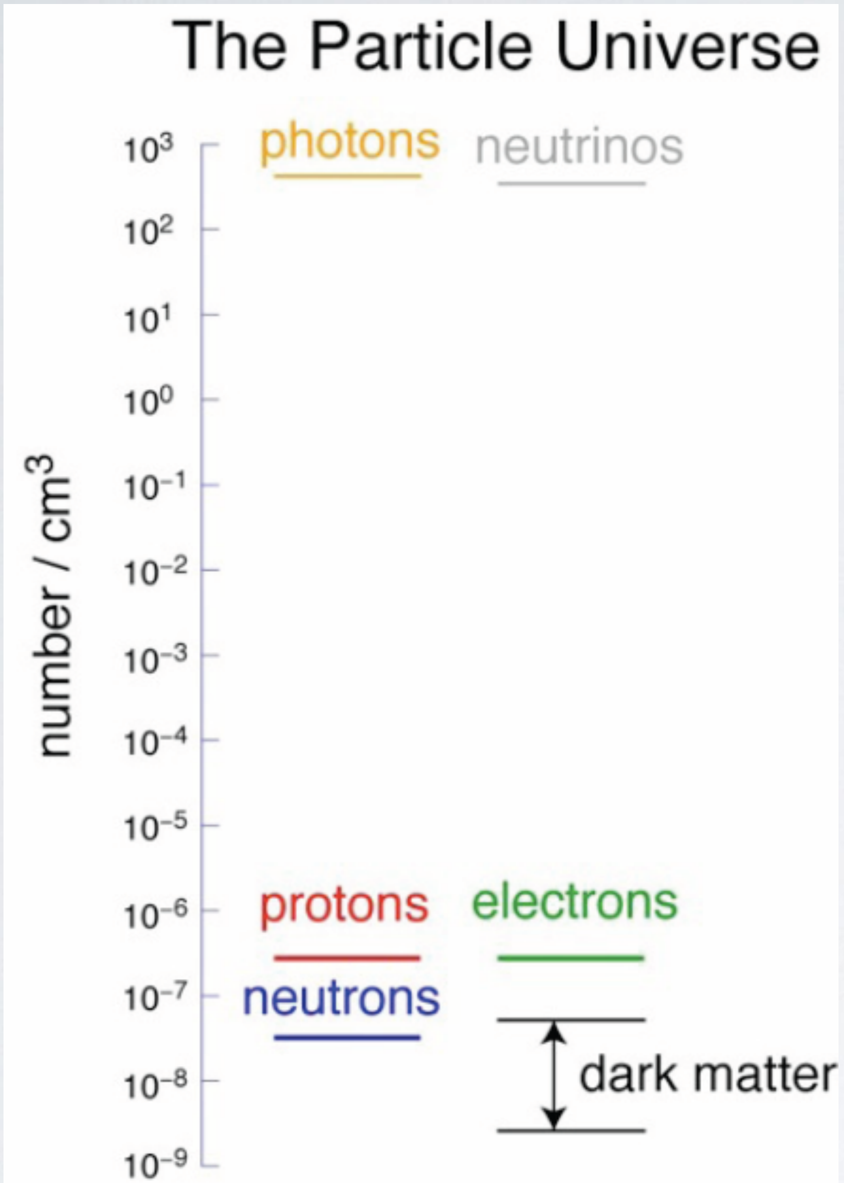
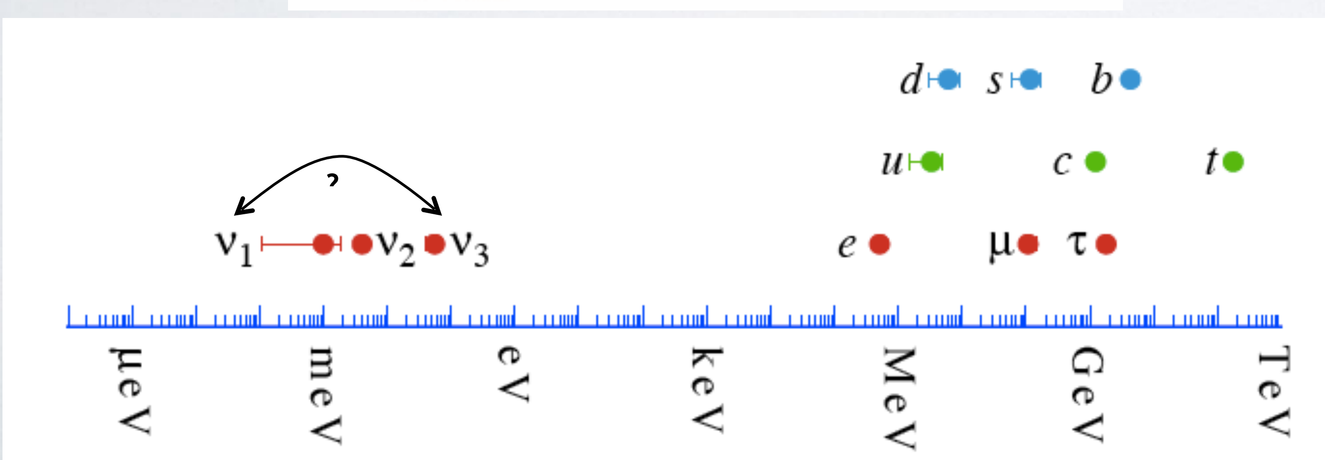
- Brief introduction to neutrino oscillations
- What do we know and how do we know it?
- What do we not know and how do we plan to find it out?
- Detailed case study: NOvA long-baseline neutrino experiment
- Future and prospects

Why study neutrino oscillations?



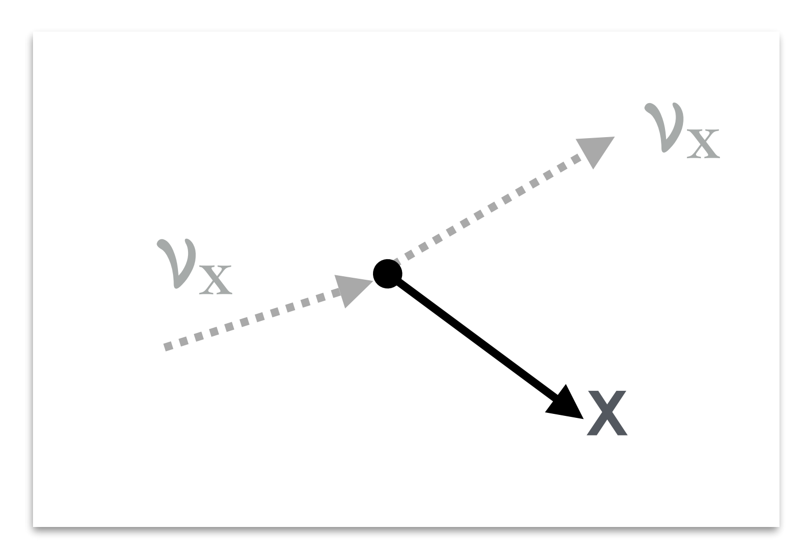


- Second most abundant particle in the Universe and yet the worst understood
- Dark Matter aside, the only measured confirmation of Physics beyond the Standard Model
- ~20 000 neutrino papers since the discovery of neutrino oscillations
- Nobel prize 2015 and Breakthrough prize 2016
- Many open questions: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

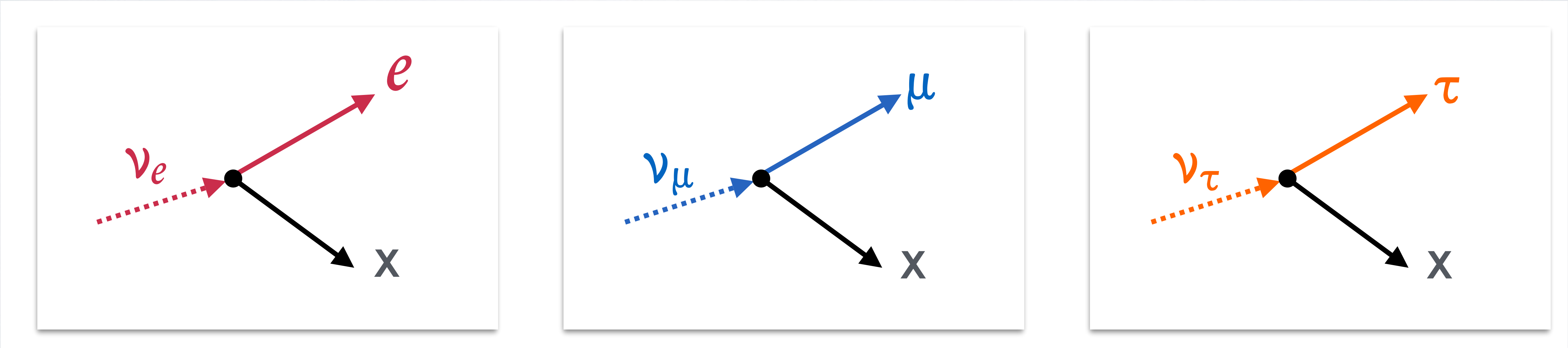
Why study neutrino oscillations?

- Weak interaction is flavour-conserving, so neutrinos can be identified via the outgoing lepton

Unless, of course, it is another neutrino

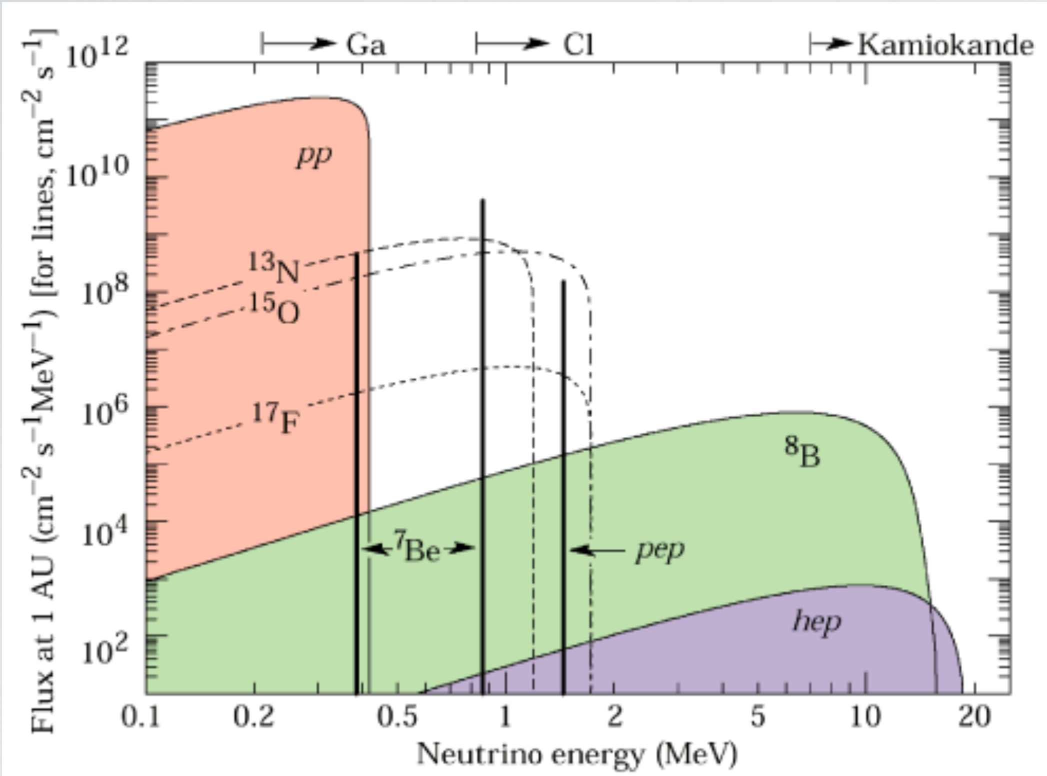


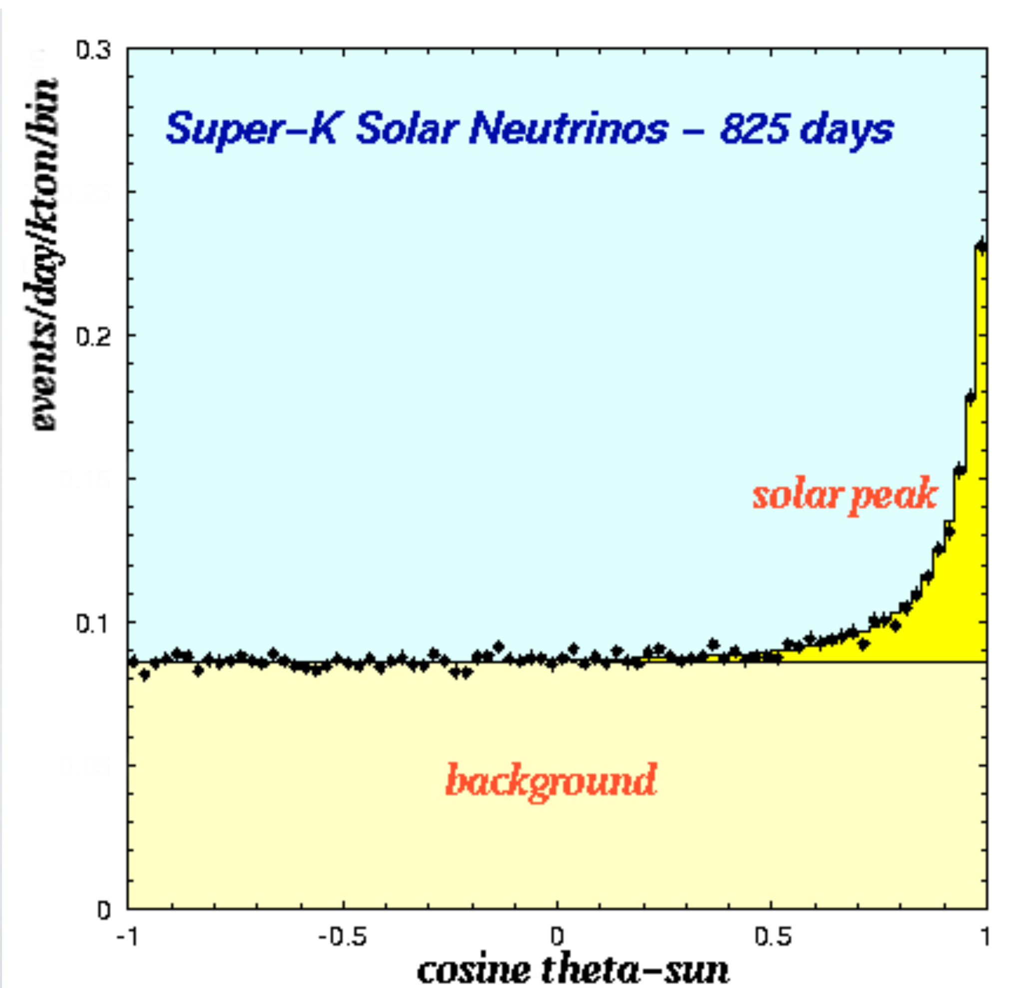
Neutral current interactions



Charged current interactions

Solar neutrinos





- Neutrinos are produced in the Sun by myriads (several million through every square cm of your body per second)
- Mostly detected through beta decay of
- B —> Be* + e^{+} + ν_e (up to 15 MeV)
- Homestake experiment, SAGE, GALLEX and esp. Super-Kamiokande detected a deficit wrt. theory: solar neutrino problem
- Because of Cherenkov directionality in SuperK, neutrinos were known to come from the Sun

- Solar neutrino problem was solved by SNO
- 1000 tons of heavy water, D_2O
- Can identify electrons, protons and photons produced in neutron capture

Designed to measure both ν_e and *total* neutrino flux

$$\text{CC rate} \propto \phi(\nu_e)$$

Only electron neutrinos

$$\text{NC rate} \propto \phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau)$$

All flavours

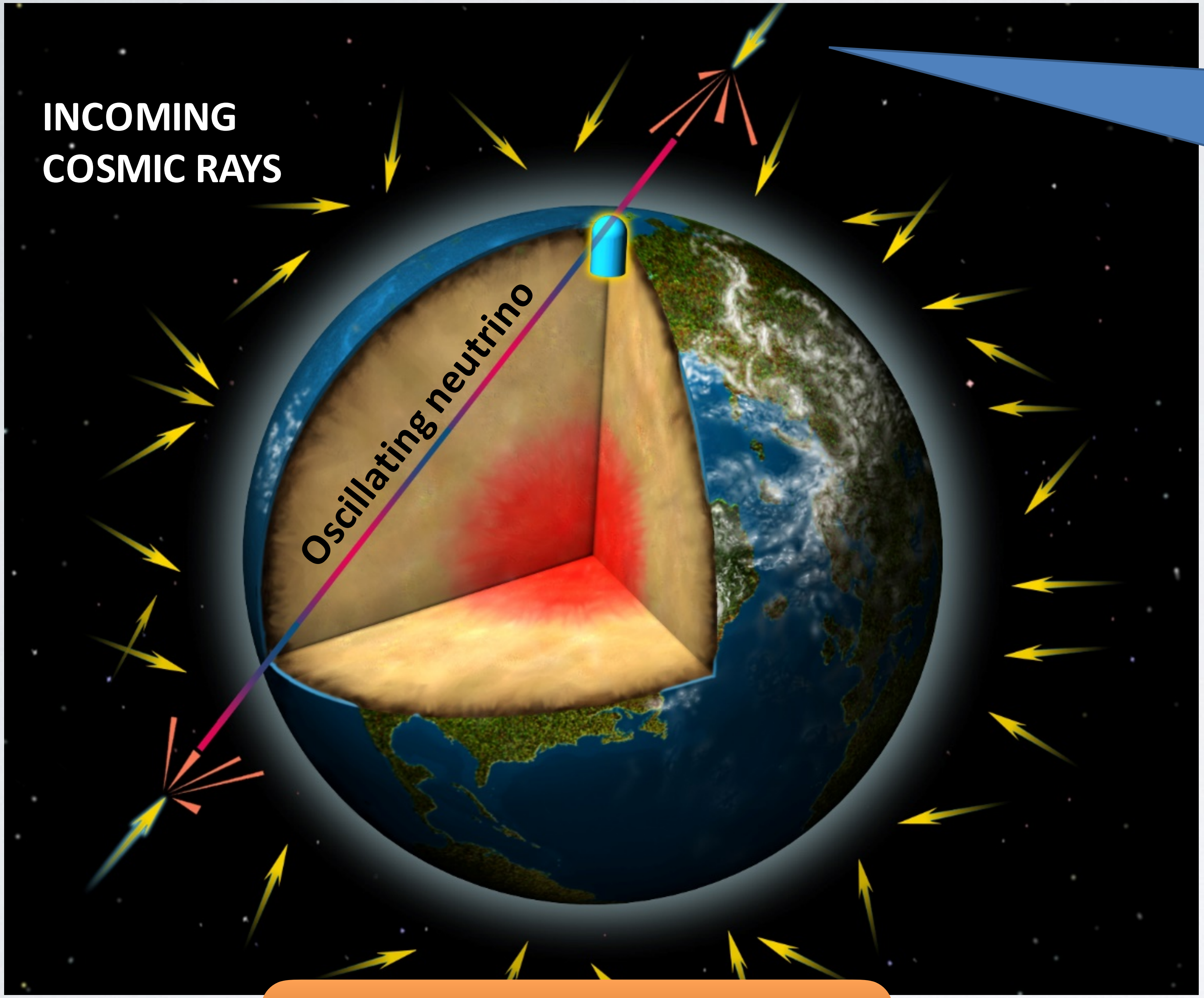
$$\text{ES rate} \propto \phi(\nu_e) + 0.154\left[\phi(\nu_\mu) + \phi(\nu_\tau)\right]$$

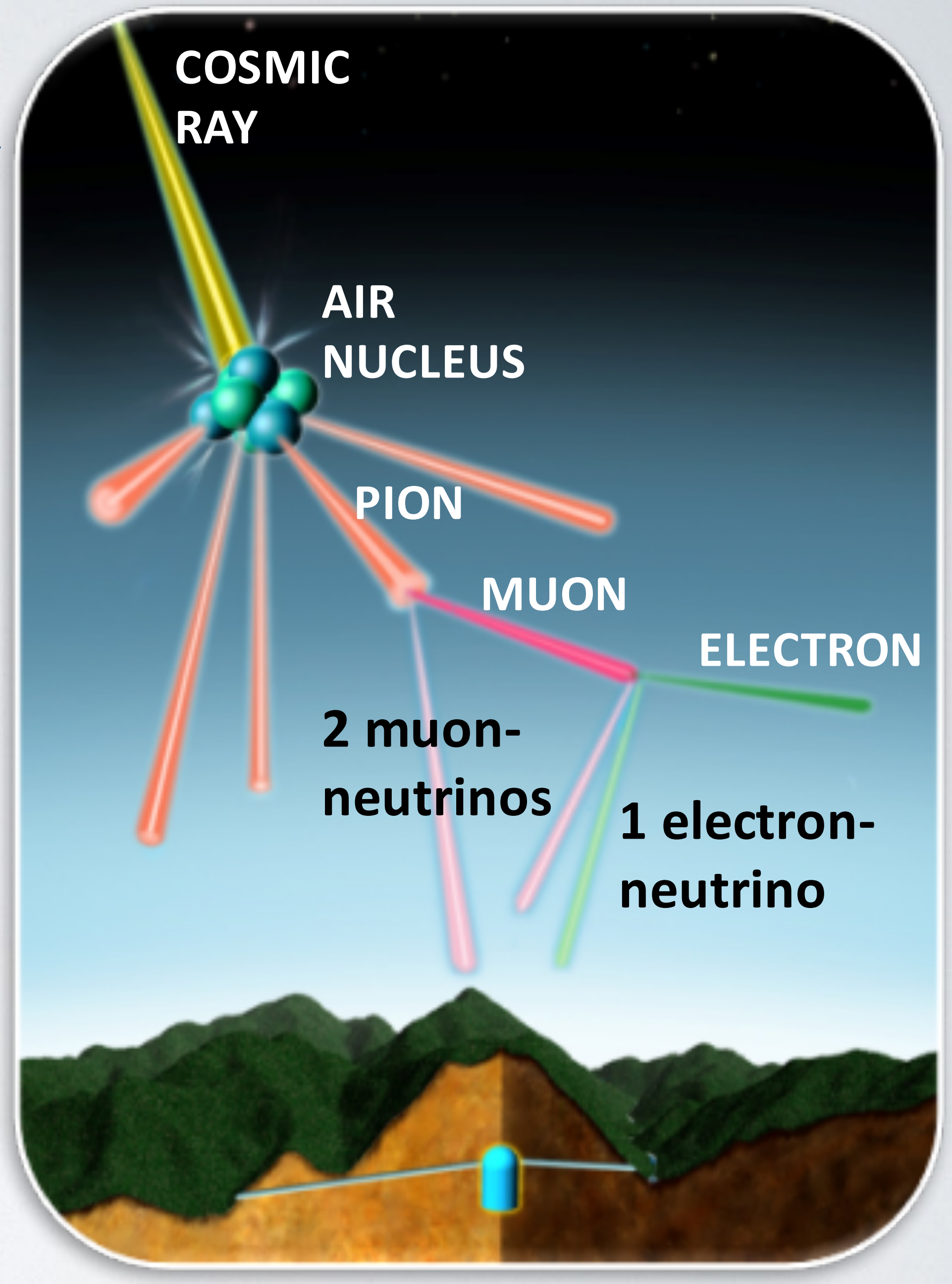
Tau and mu only via NC

$$\phi(\nu_e) = (1.76 \pm 0.10) \times 10^{-6}\text{cm}^{-2}\text{s}^{-1}$$
$$\phi(\nu_\mu) + \phi(\nu_\tau) = (3.41 \pm 0.63) \times 10^{-6}\text{cm}^{-2}\text{s}^{-1}$$
$$\phi(\nu_e)_{\text{pred}} = (5.1 \pm 0.9) \times 10^{-6}\text{cm}^{-2}\text{s}^{-1}$$

Electron neutrinos oscillate on their way from the sun!

Atmospheric neutrinos

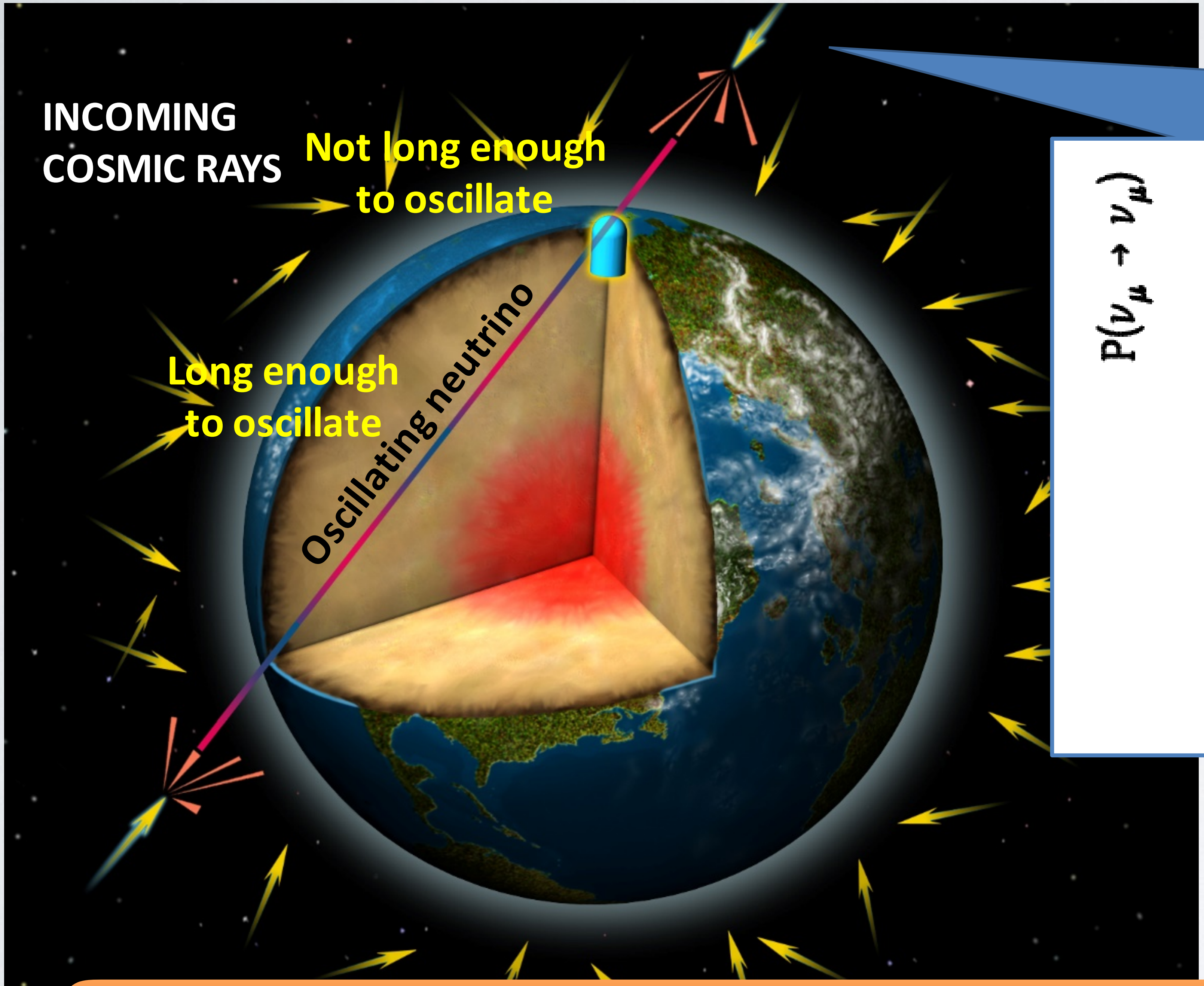


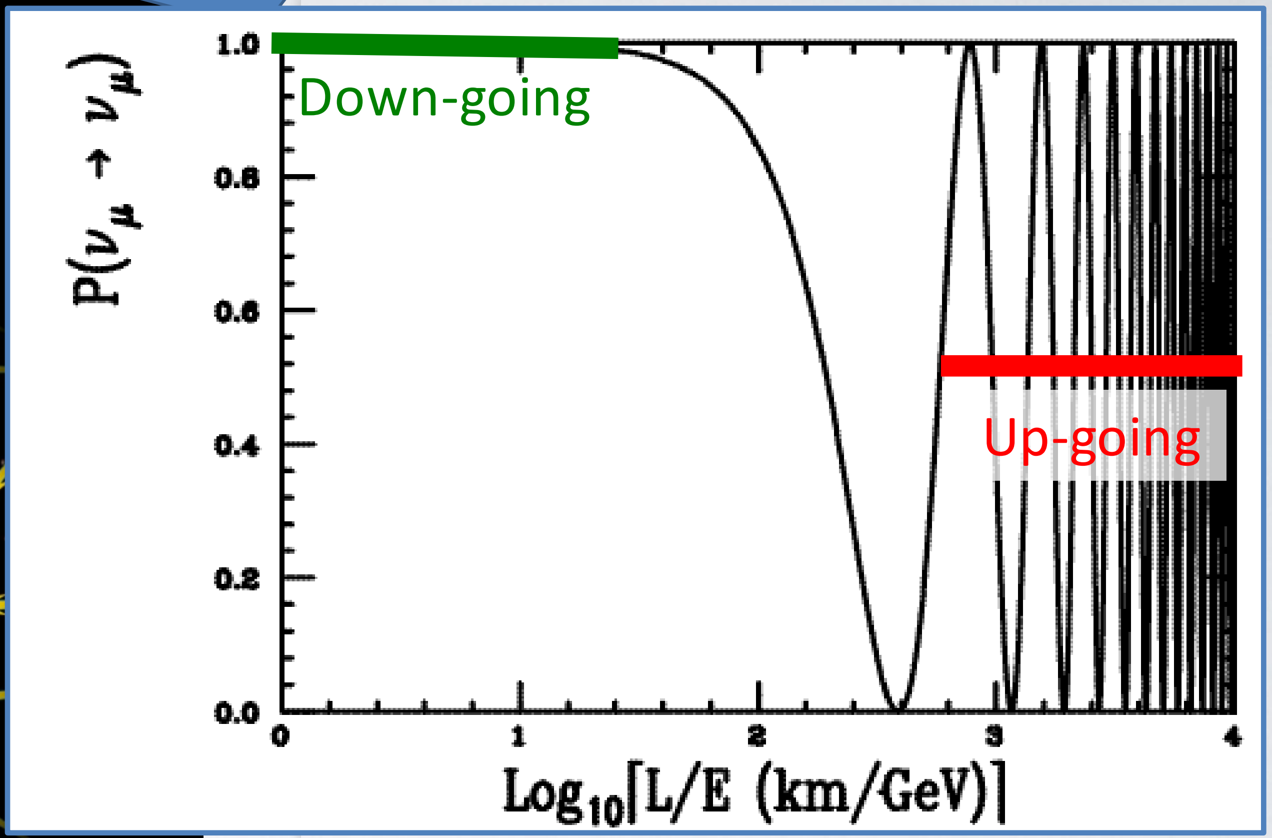


Up/down ratio ~ 1
(isotropic cosmic flux)

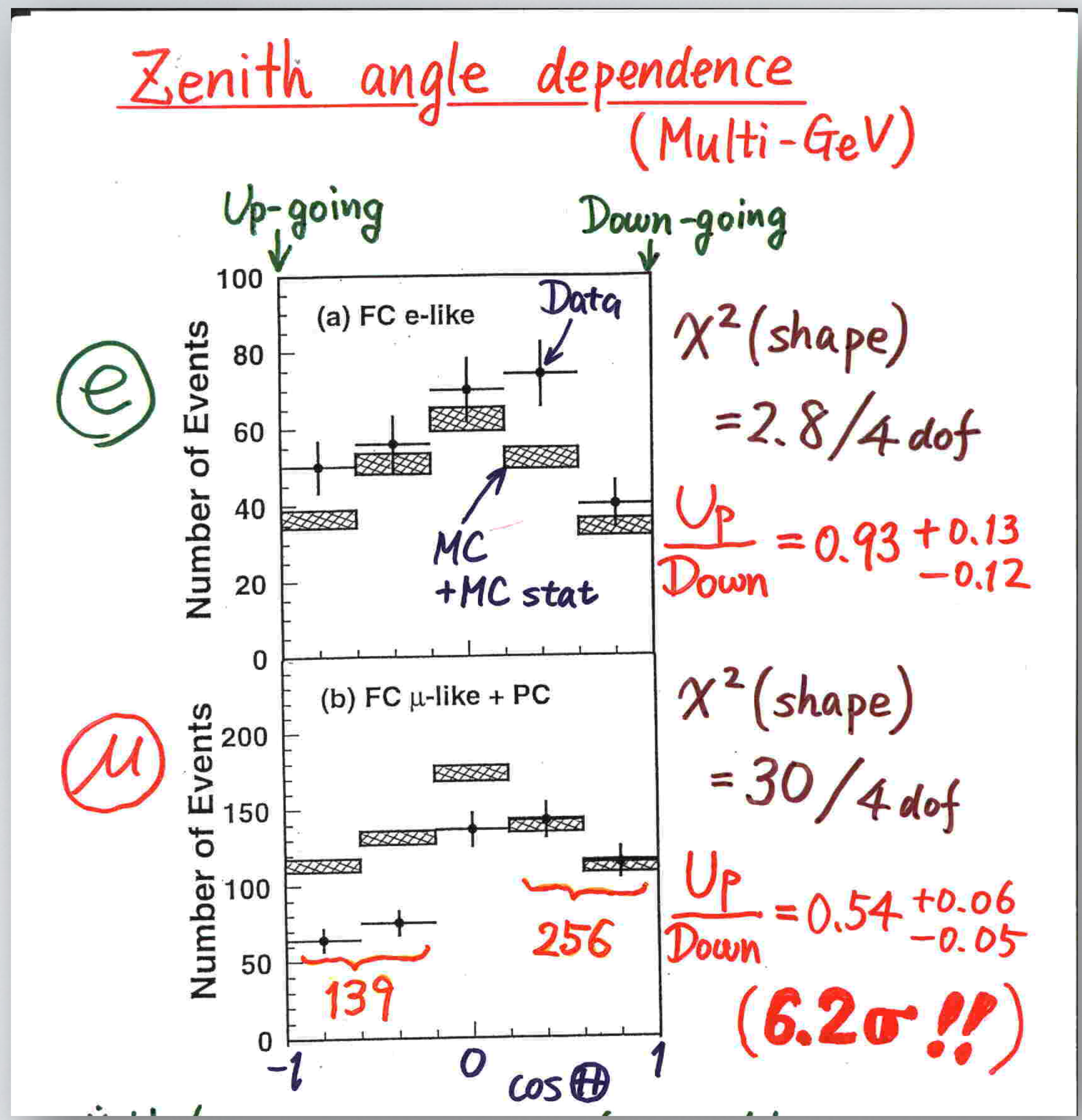
ν_μ/ν_e ratio ~2

Atmospheric neutrinos





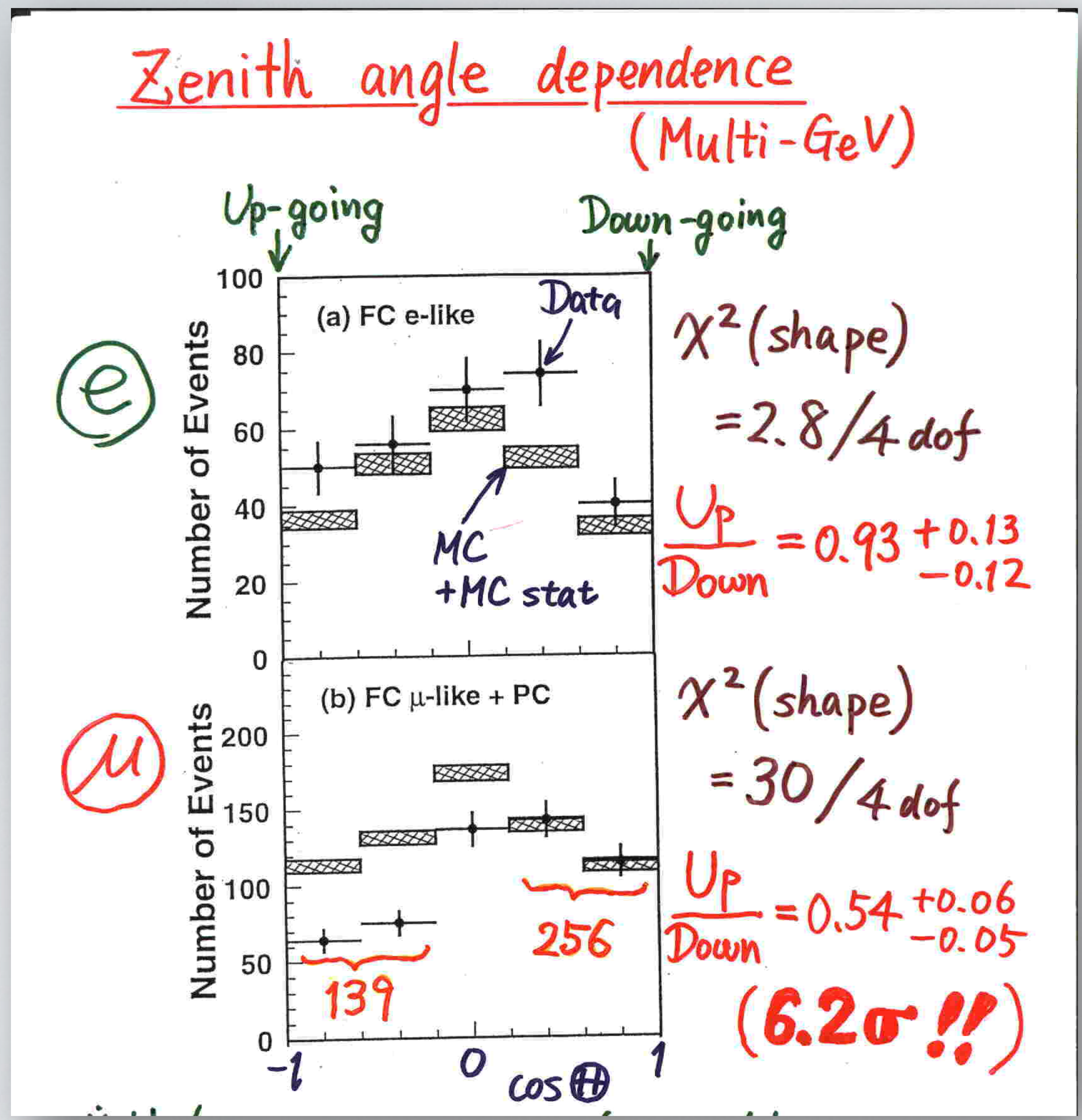
If there's oscillation, a deficit upwards-going ν_μ should be observed

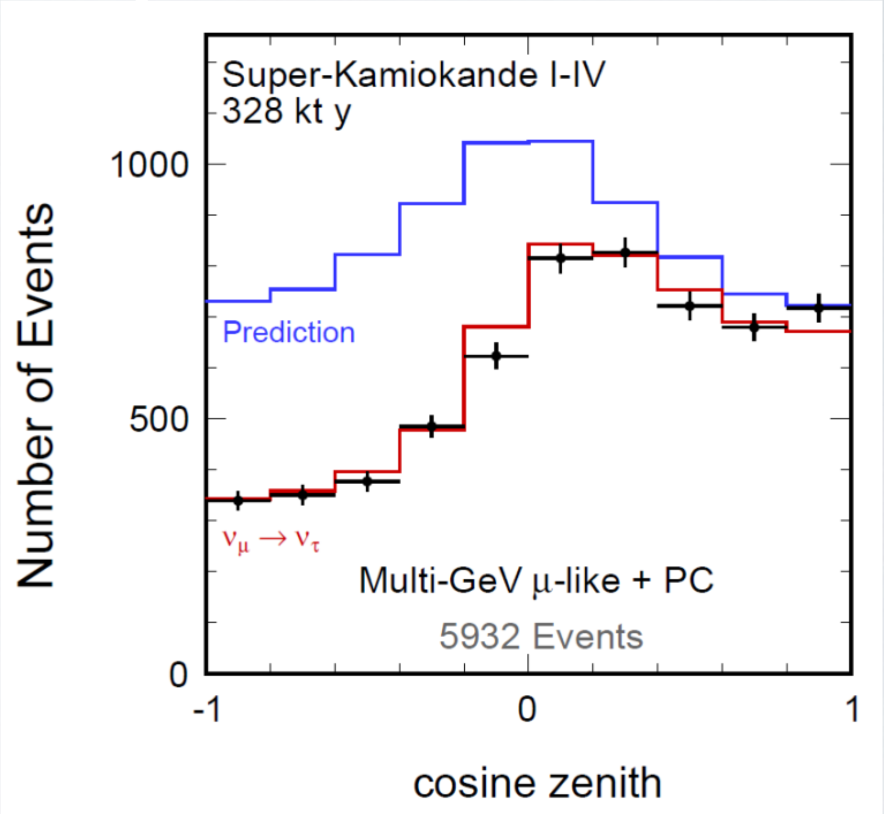


Muon neutrinos oscillate on their way through the Earth!

Super-K @Neutrino98

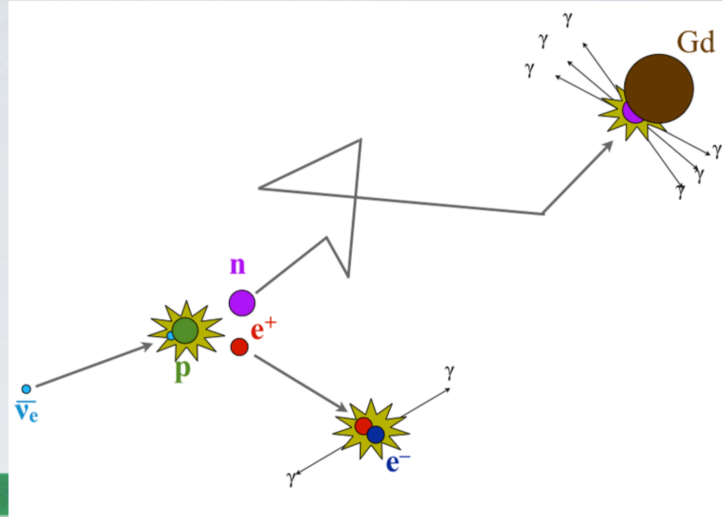
Super-K (2017)

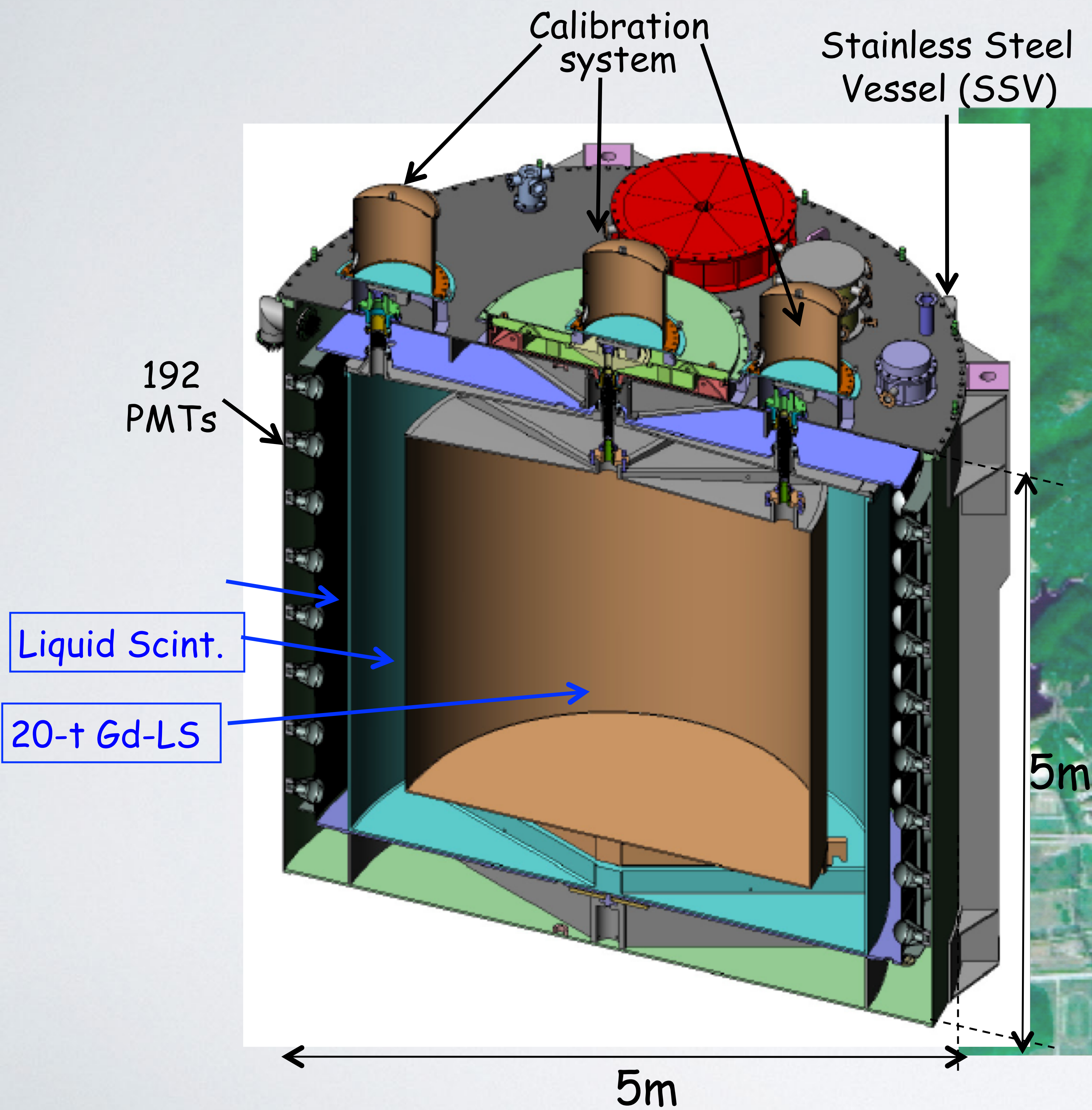




Muon neutrinos oscillate on their way through the Earth!

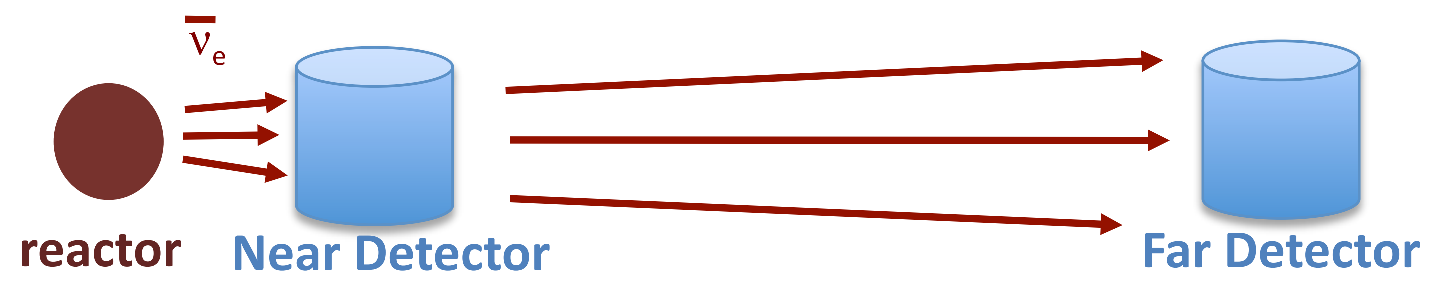
Reactor neutrinos

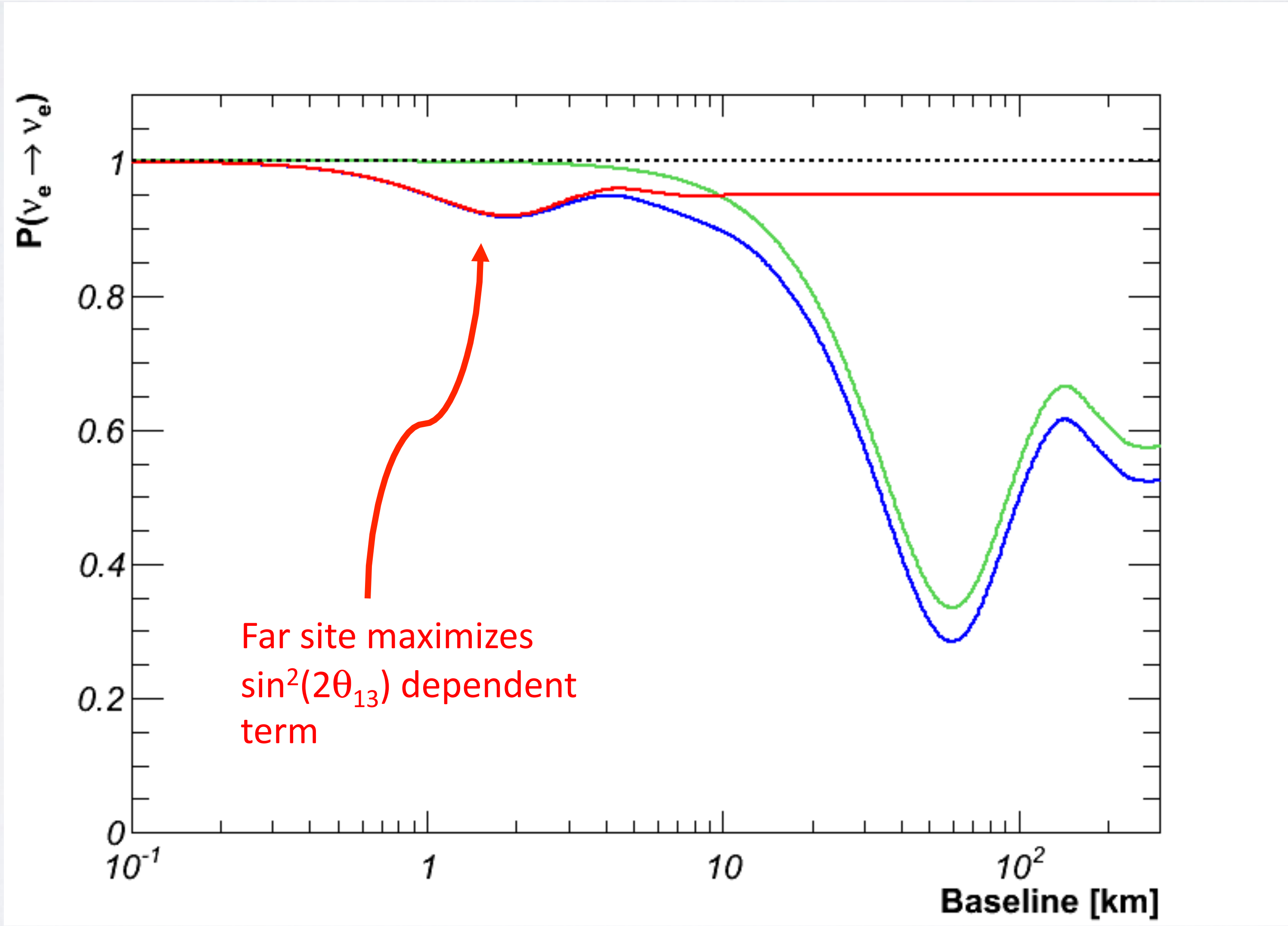


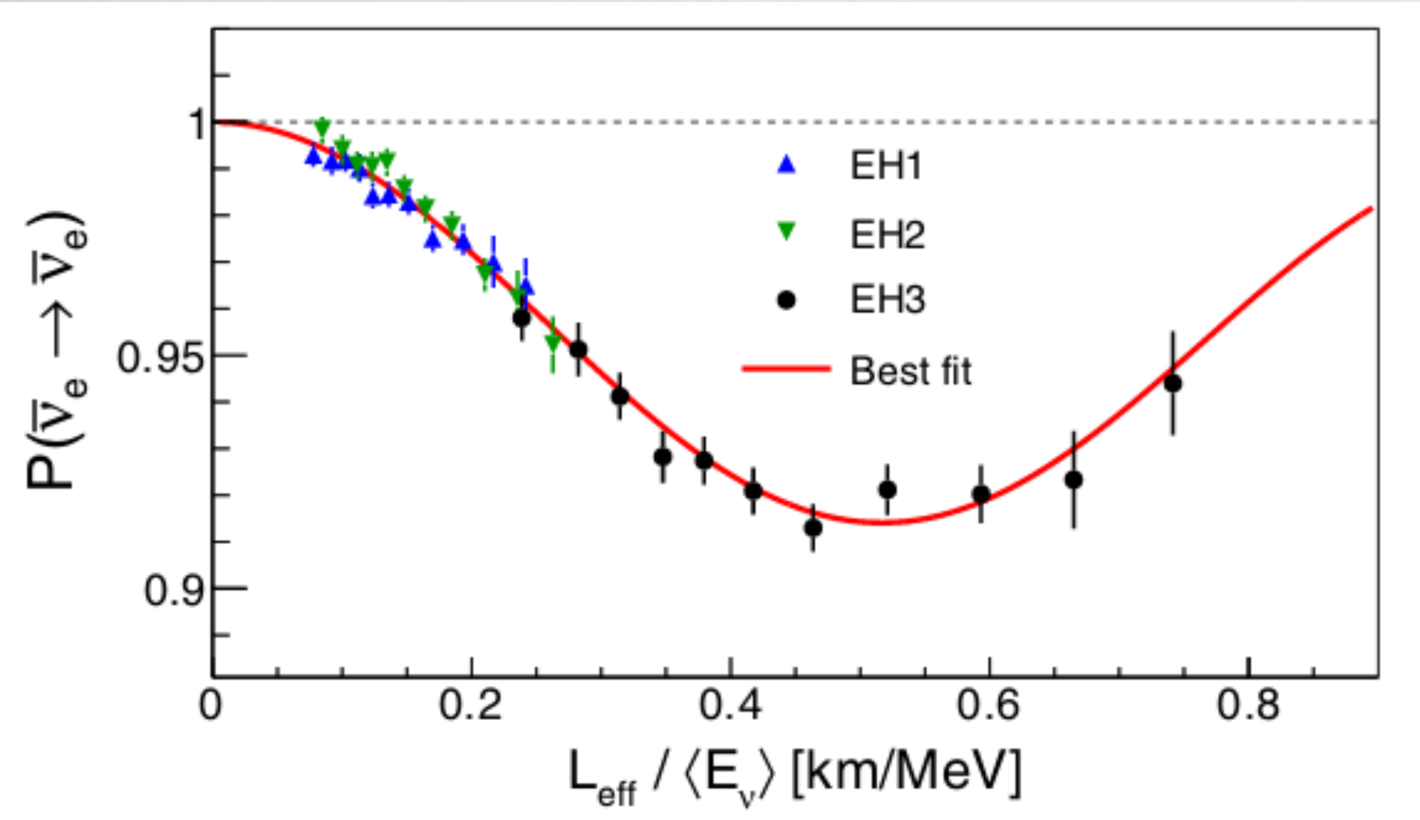


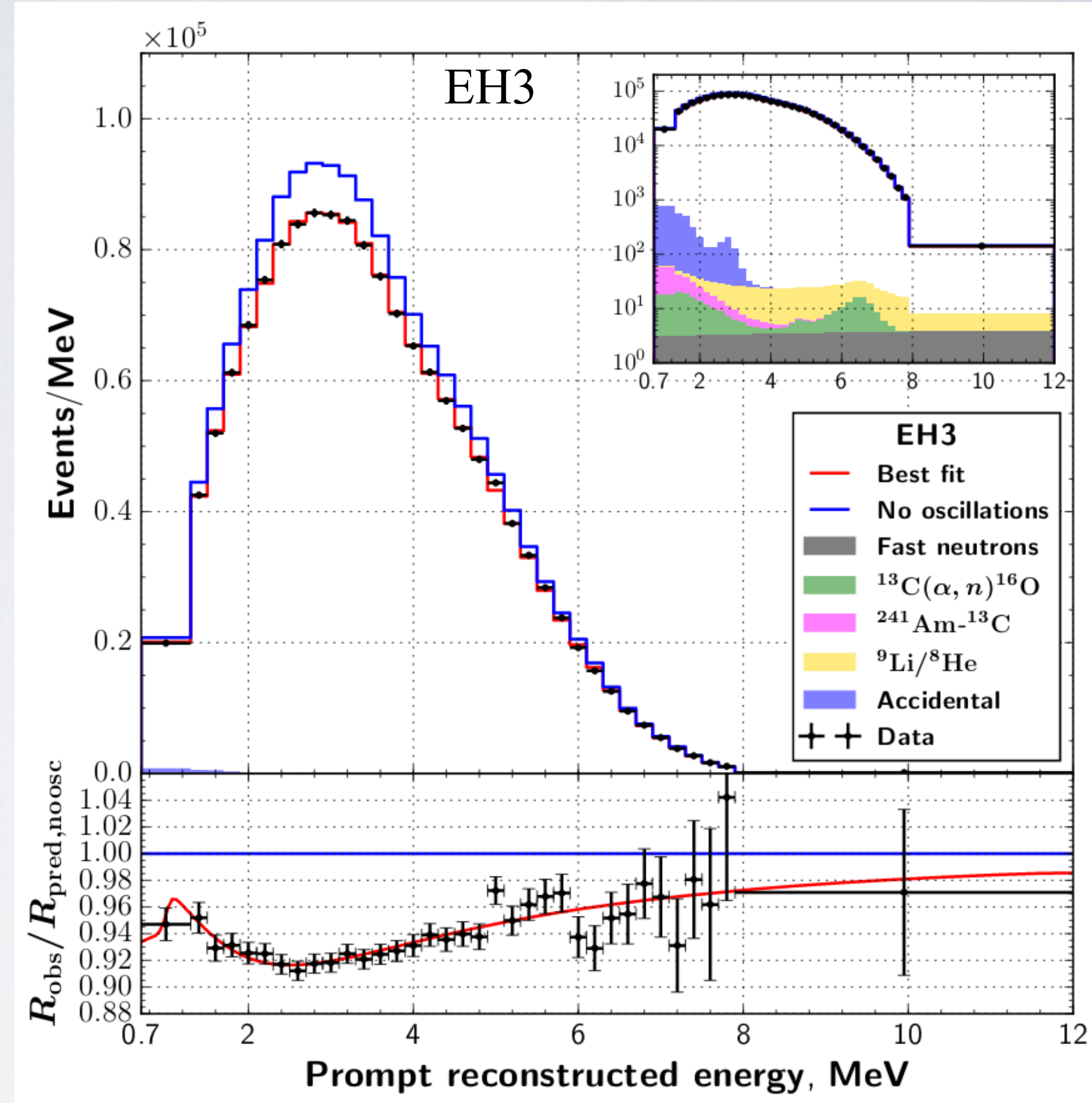
Reactor neutrinos

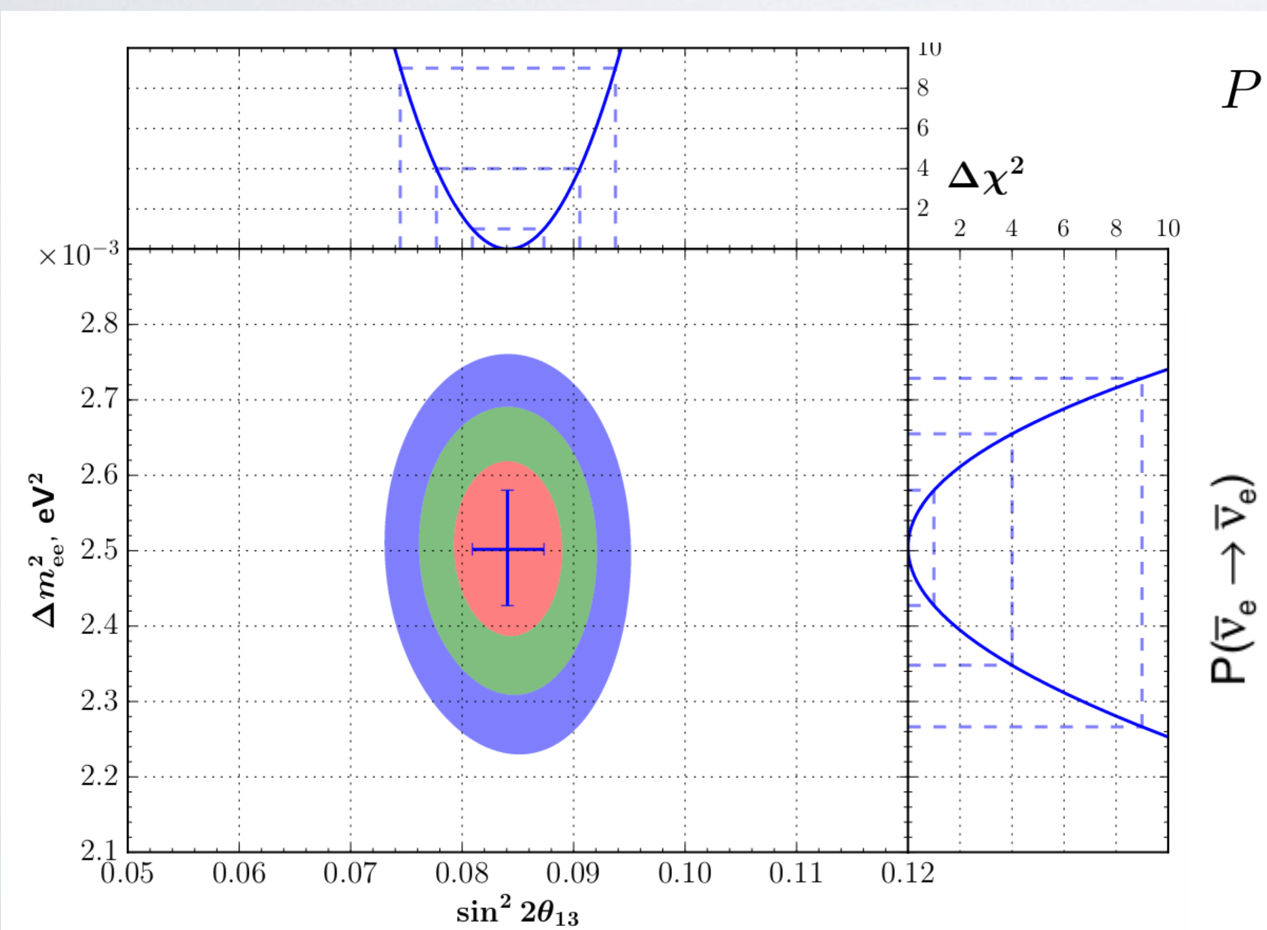
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_{\mu,\tau}) \approx \sin^2(2\theta_{13})\sin^2\left(\frac{\Delta m^2_{32} L}{4E}\right) + \sin^2(2\theta_{12})\cos^4(\theta_{13})\sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right)$$

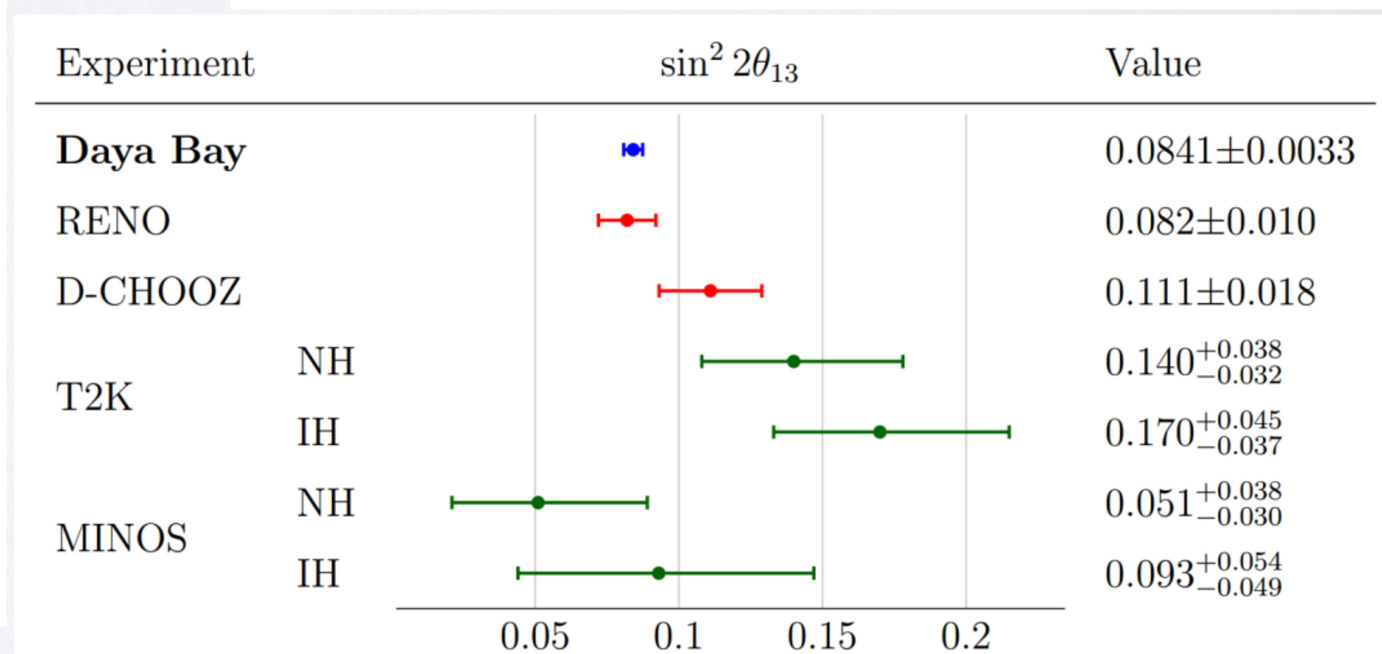




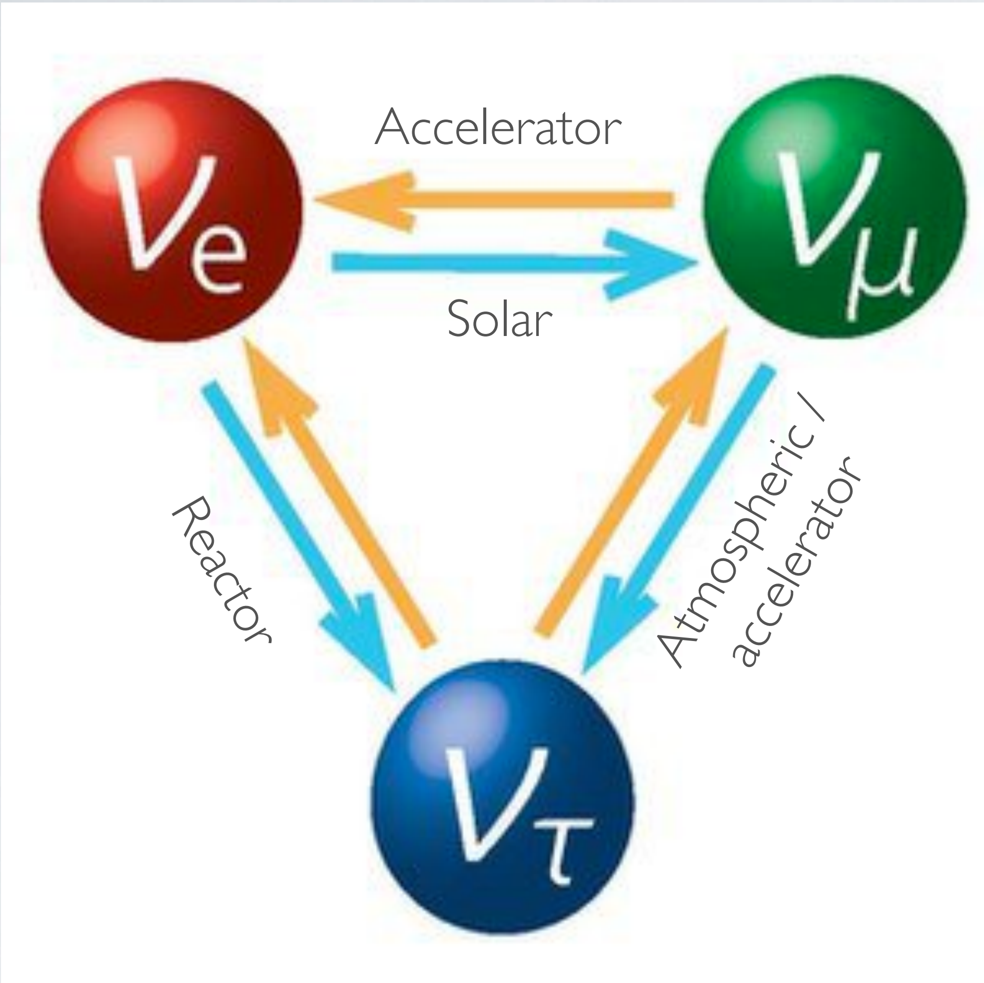

EH1
EH2
EH3
Best fit
$P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$
$L_{eff} / \langle E_\nu \rangle$ [km/MeV]


EH3
Events/MeV
×10^5
Best fit
No oscillations
Fast neutrons
$^{13}C(\alpha, n)^{16}O$
^{241}Am-^{13}C
$^{9}Li/^{8}He$
Accidental
Data
$R_{obs}/R_{pred,noosc}$
Prompt reconstructed energy, MeV

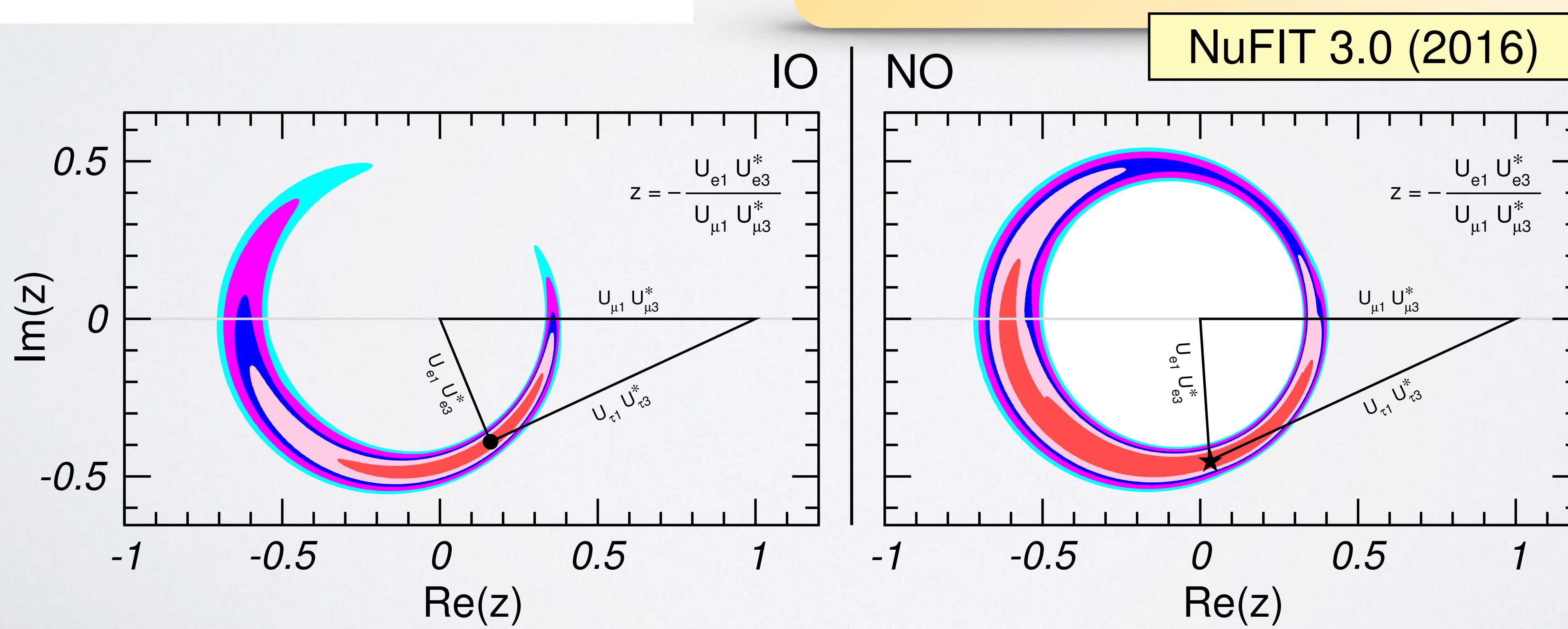

P
$\Delta\chi^2$
×10^-3
Δm^2_{ee}, eV²
$\sin^2 2\theta_{13}$
$P(\overline{\nu}_e \rightarrow \overline{\nu}_e)$


Experiment
$\sin^2 2\theta_{13}$
Value
Daya Bay
0.0841 ± 0.0033
RENO
0.082 ± 0.010
D-CHOOZ
0.111 ± 0.018
T2K
NH
$0.140^{+0.038}_{-0.032}$
IH
$0.170^{+0.045}_{-0.037}$
MINOS
NH
$0.051^{+0.038}_{-0.030}$
IH
$0.093^{+0.054}_{-0.049}$

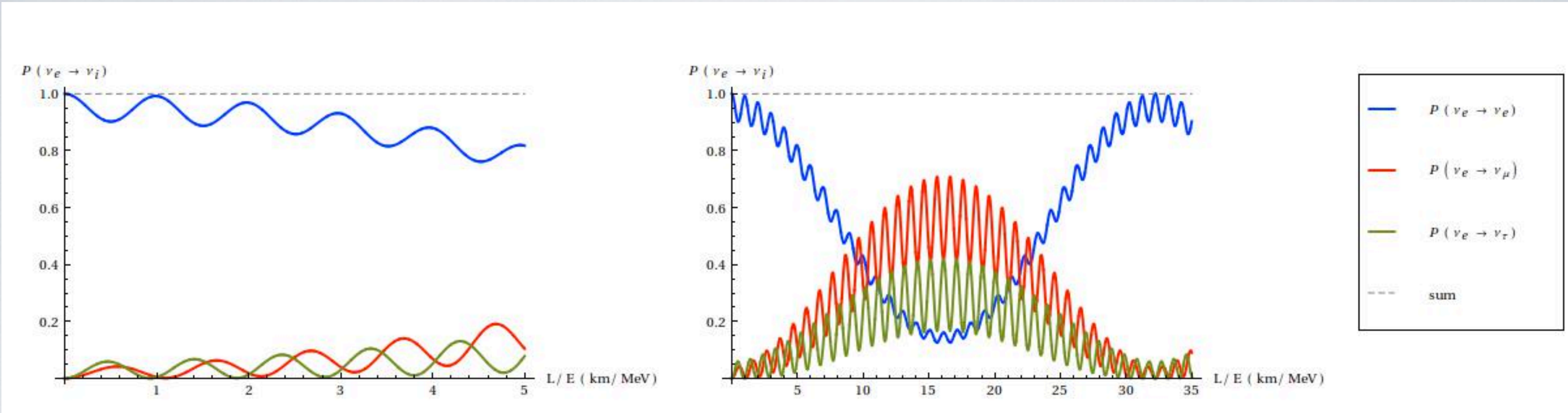
What have we measured so far?

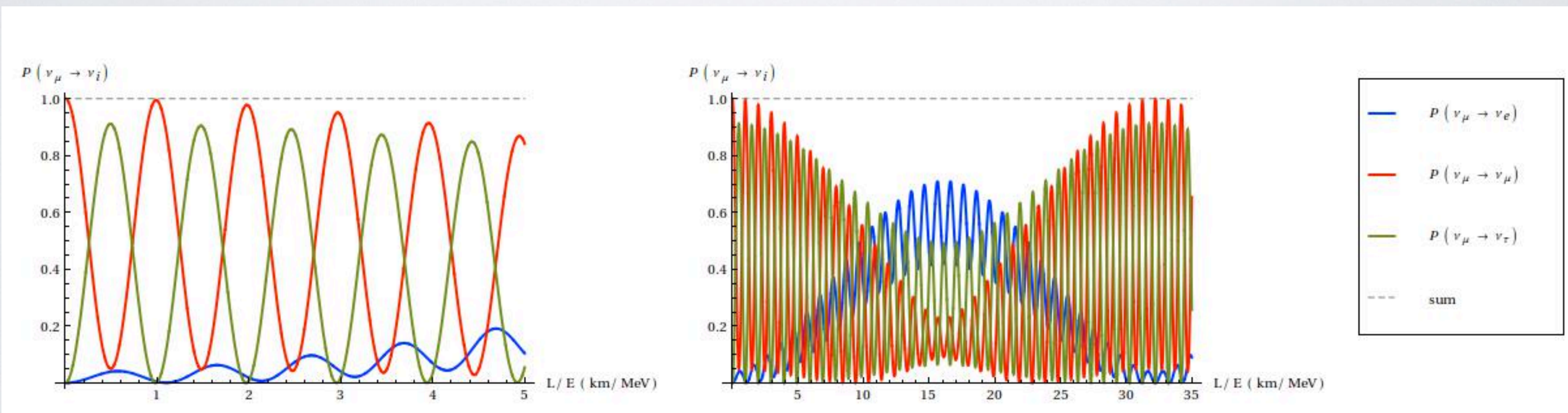


- We have now observed all the flavour oscillations except for those starting with a tau neutrino
- Energy threshold of m_τ (~1.8 GeV) makes it very difficult
- Might be important for unitarity tests in the (likely distant) future



Three-flavour oscillations





Neutrino oscillations overview

PMNS matrix

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

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

Oscillations

Neutrino oscillations overview

PMNS matrix

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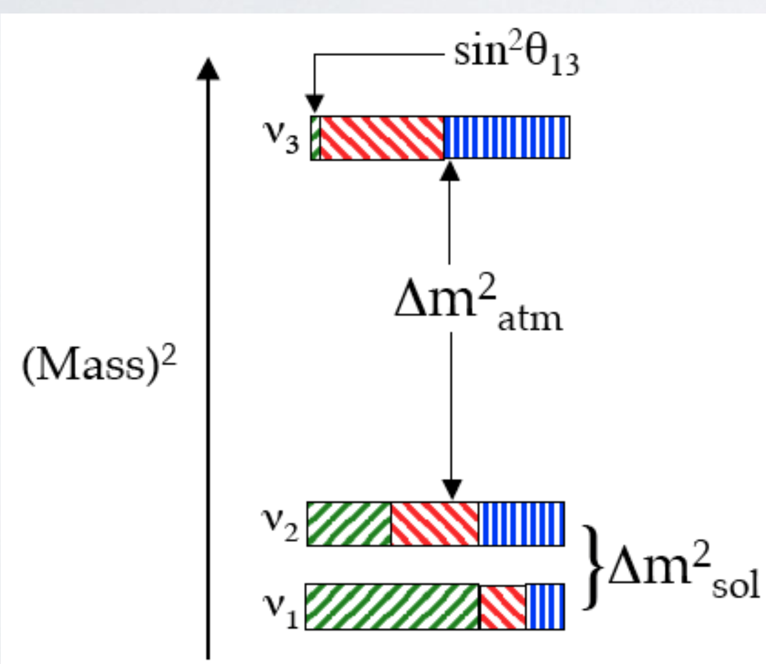
Oscillations

Atmospheric | Reactor | Solar

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

Accelerators



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

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

How well measured?

Solar →	δm^2	2.4%
Atmosp. →	Δm^2	1.8%
Solar →	$\sin^2\theta_{12}$	5.8%
Reactor →	$\sin^2\theta_{13}$	4.7%
Atmosp. →	$\sin^2\theta_{23}$	$\sim 9\%$

A. Marrone (Neutrino 2016)

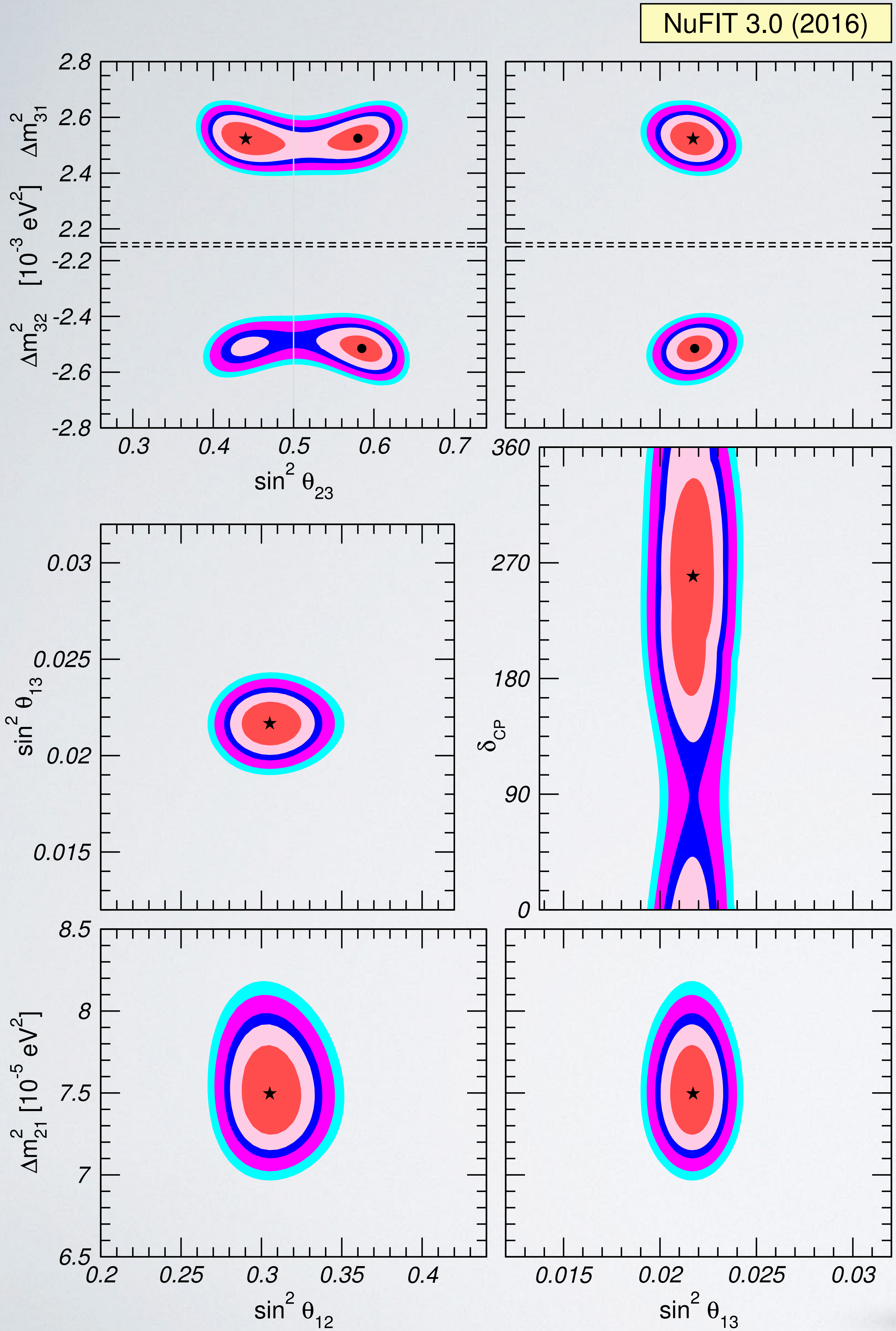
Most angles and masses have been measured using more than one experimental technique, including **accelerator-based**

Measurable with accelerator experiments

- Is $\sin^2\theta_{23}$ maximal? ($\theta_{23} = \pi/2$?)
- Is there CP violation in the lepton sector?
- What's the mass-hierarchy? (is $m_3 > m_2$ or vice versa?)
- Are there more than 3 neutrino flavours? Is there a sterile neutrino?

Not directly measurable with accelerators

- Are neutrinos Dirac or Majorana?
- What's the mass scale?



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Not directly measurable with accelerators

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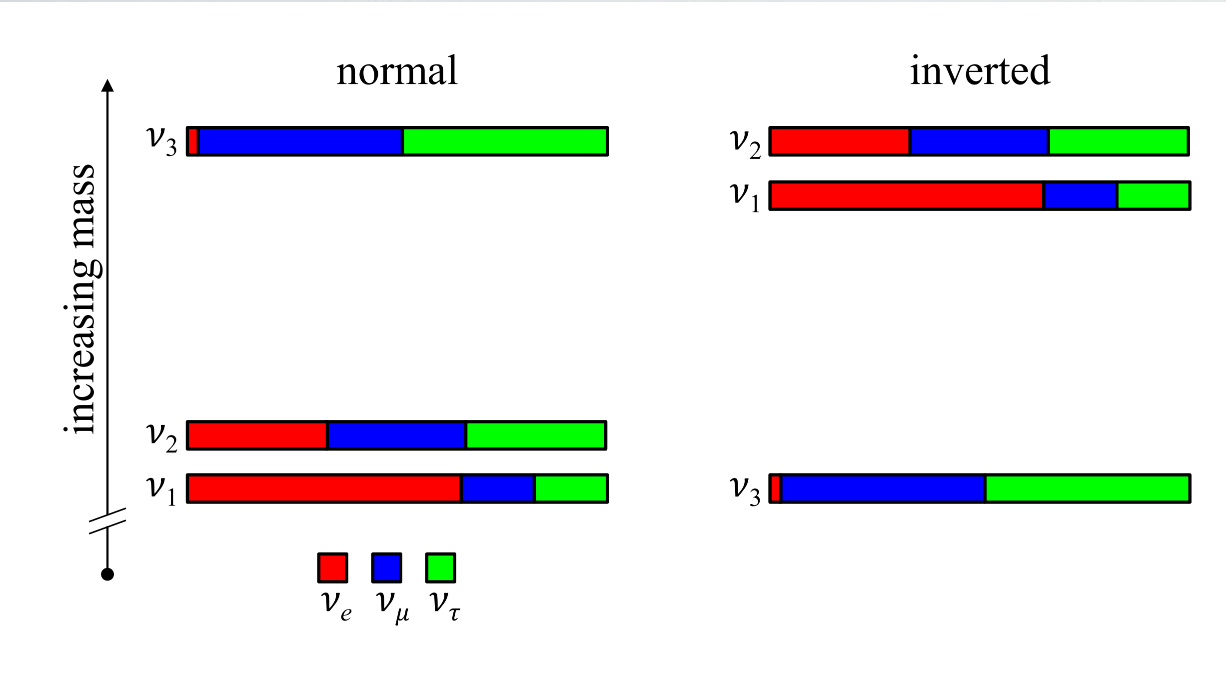
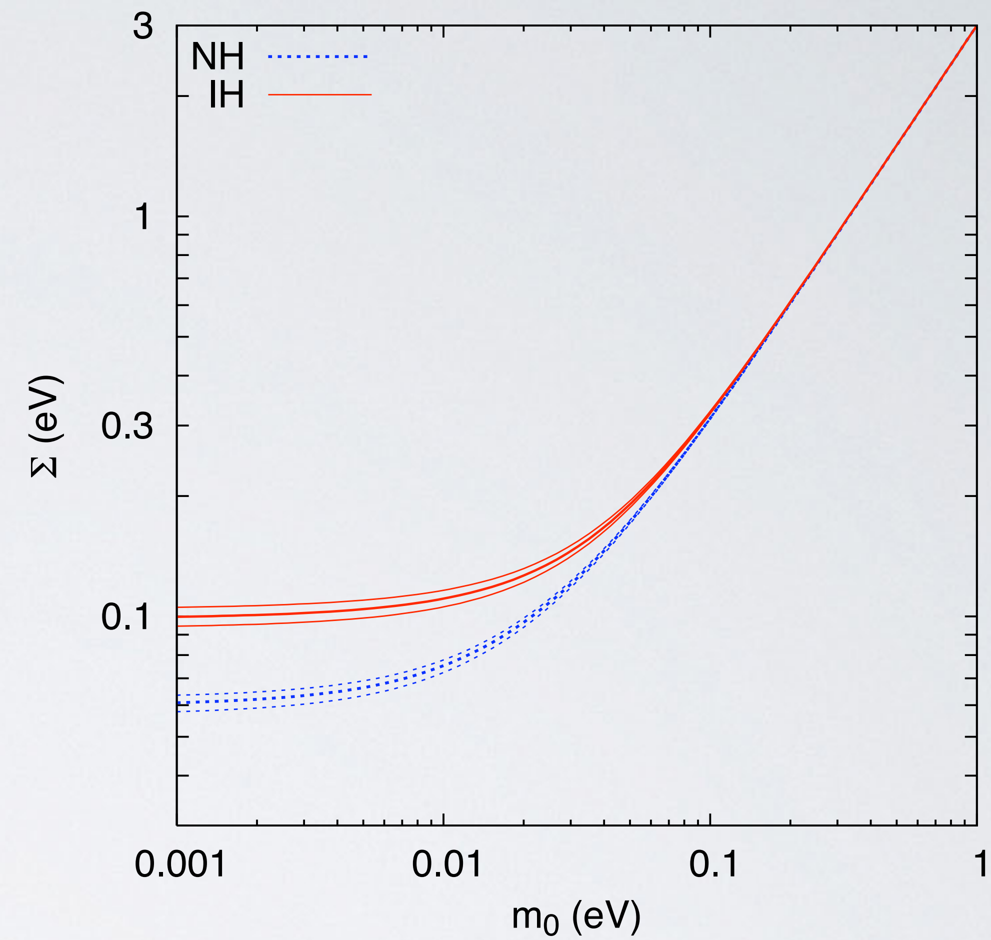
Global fits

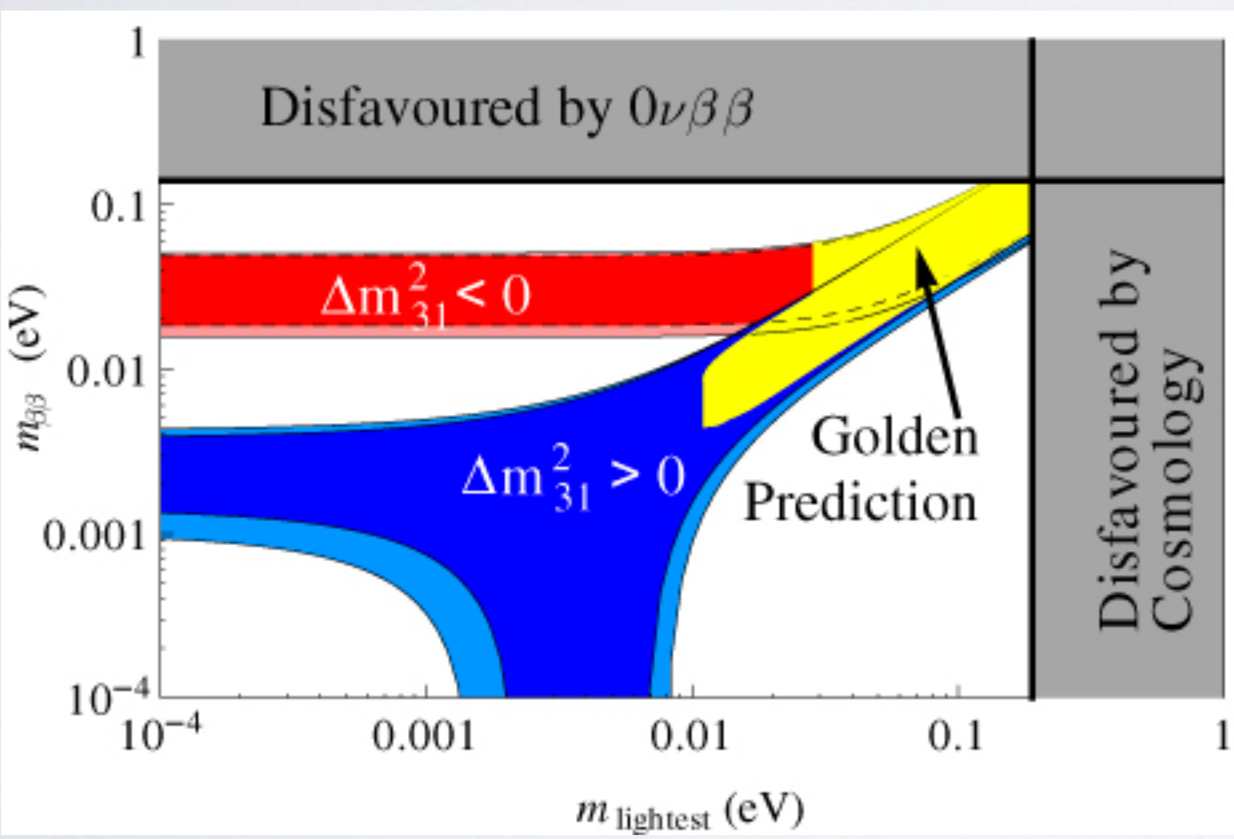
NuFIT 3.0 (2016)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 0.83$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.306^{+0.012}_{-0.012}$	$0.271 \to 0.345$	$0.271 \to 0.345$
$\theta_{12}/^\circ$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$33.56^{+0.77}_{-0.75}$	$31.38 \to 35.99$	$31.38 \to 35.99$
$\sin^2\theta_{23}$	$0.441^{+0.027}_{-0.021}$	$0.385 \to 0.635$	$0.587^{+0.020}_{-0.024}$	$0.393 \to 0.640$	$0.385 \to 0.638$
$\theta_{23}/^\circ$	$41.6^{+1.5}_{-1.2}$	$38.4 \to 52.8$	$50.0^{+1.1}_{-1.4}$	$38.8 \to 53.1$	$38.4 \to 53.0$
$\sin^2\theta_{13}$	$0.02166^{+0.00075}_{-0.00075}$	$0.01934 \to 0.02392$	$0.02179^{+0.00076}_{-0.00076}$	$0.01953 \to 0.02408$	$0.01934 \to 0.02397$
$\theta_{13}/^\circ$	$8.46^{+0.15}_{-0.15}$	$7.99 \to 8.90$	$8.49^{+0.15}_{-0.15}$	$8.03 \to 8.93$	$7.99 \to 8.91$
$\delta_{\rm CP}/^\circ$	261^{+51}_{-59}	$0 \to 360$	277^{+40}_{-46}	$145 \to 391$	$0 \to 360$
$\dfrac{\Delta m^2_{21}}{10^{-5}\ \rm eV^2}$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.50^{+0.19}_{-0.17}$	$7.03 \to 8.09$	$7.03 \to 8.09$
$\dfrac{\Delta m^2_{3\ell}}{10^{-3}\ \rm eV^2}$	$+2.524^{+0.039}_{-0.040}$	$+2.407 \to +2.643$	$-2.514^{+0.038}_{-0.041}$	$-2.635 \to -2.399$	$\begin{bmatrix} +2.407 \to +2.643 \\ -2.629 \to -2.405 \end{bmatrix}$

Why is the mass hierarchy important?



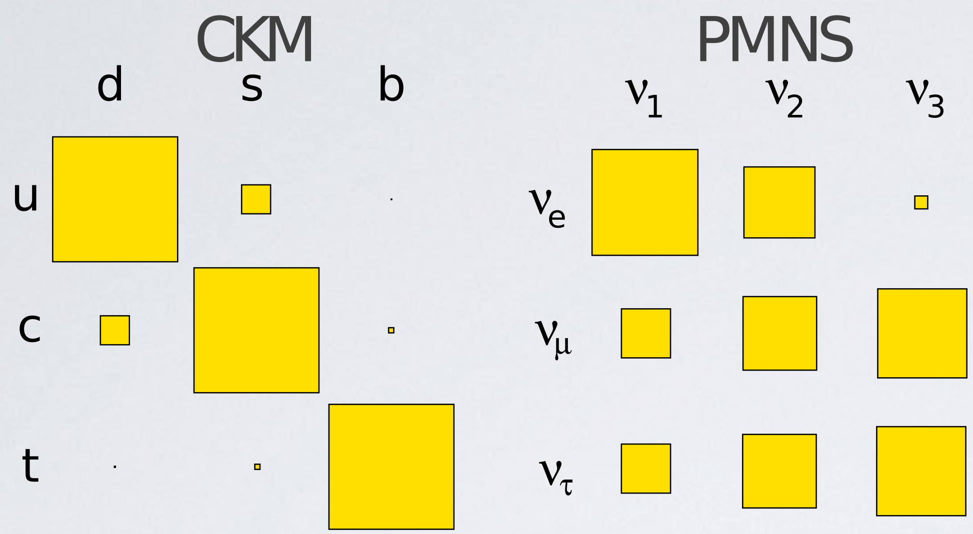




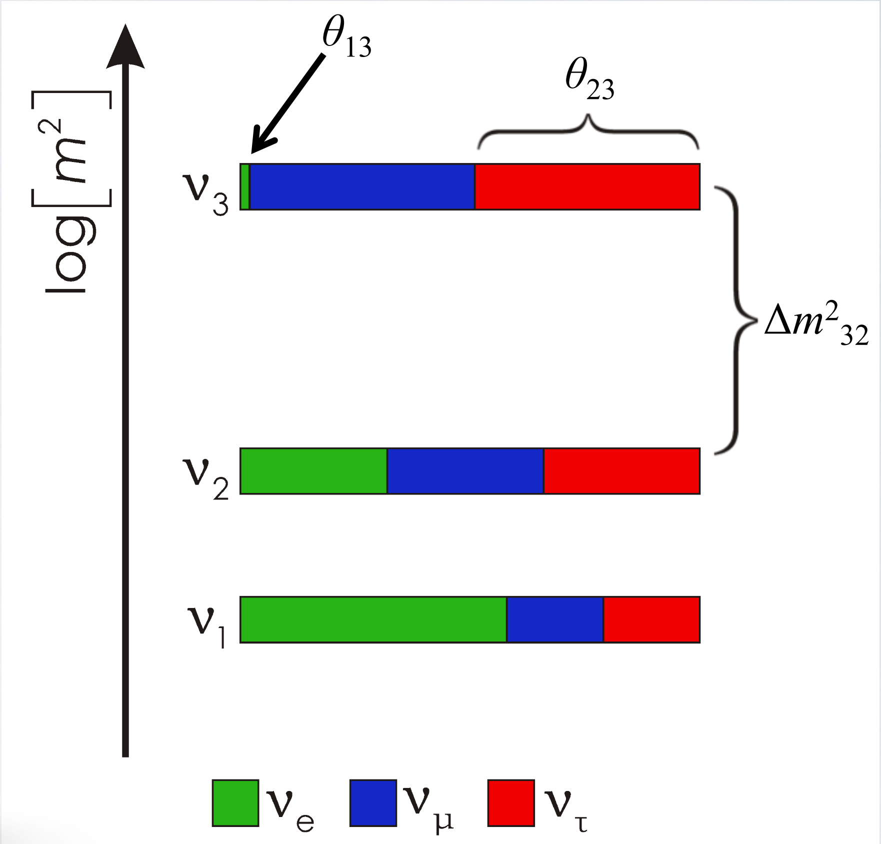
If the hierarchy is inverted, mass scale measurement is at reach from both Cosmology and $0\nu\beta\beta$ experiments.

But if it's normal it becomes much more difficult

Models for neutrino mass



Normal hierarchy



PMNS matrix is analogous to CKM in the quark sector

But, unlike quarks, mixings in the PMNS are large! Is there a pattern?

- Only a small fraction of ν_e in $|\nu_3\rangle$: $\sin^2(2\theta_{13})$
- The remainder is split ~ 50/50 between ν_μ and ν_τ
- Accident or underlying symmetry? Is it really 45° or…
  - < 45°: $|\nu_3\rangle$ more ν_τ, like the quarks
  - > 45°: $|\nu_3\rangle$ more ν_μ, unlike quarks

Importance of reactor result

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

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

θ_{13}: from unknown to best measured

$\theta_{13} \sim 8.5°$

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

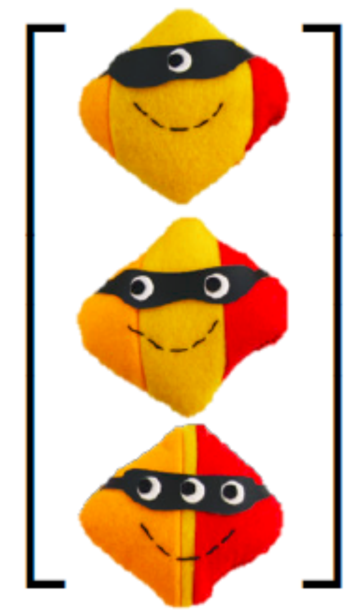
$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$
$$+2\alpha \sin\theta_{13} \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$
$$-2\alpha \sin\theta_{13} \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta + O(\alpha^2)$$

$\alpha = \Delta m^2_{12}/\Delta m^2_{31}$; $\Delta \equiv \frac{\Delta m^2_{31} L}{4E}$

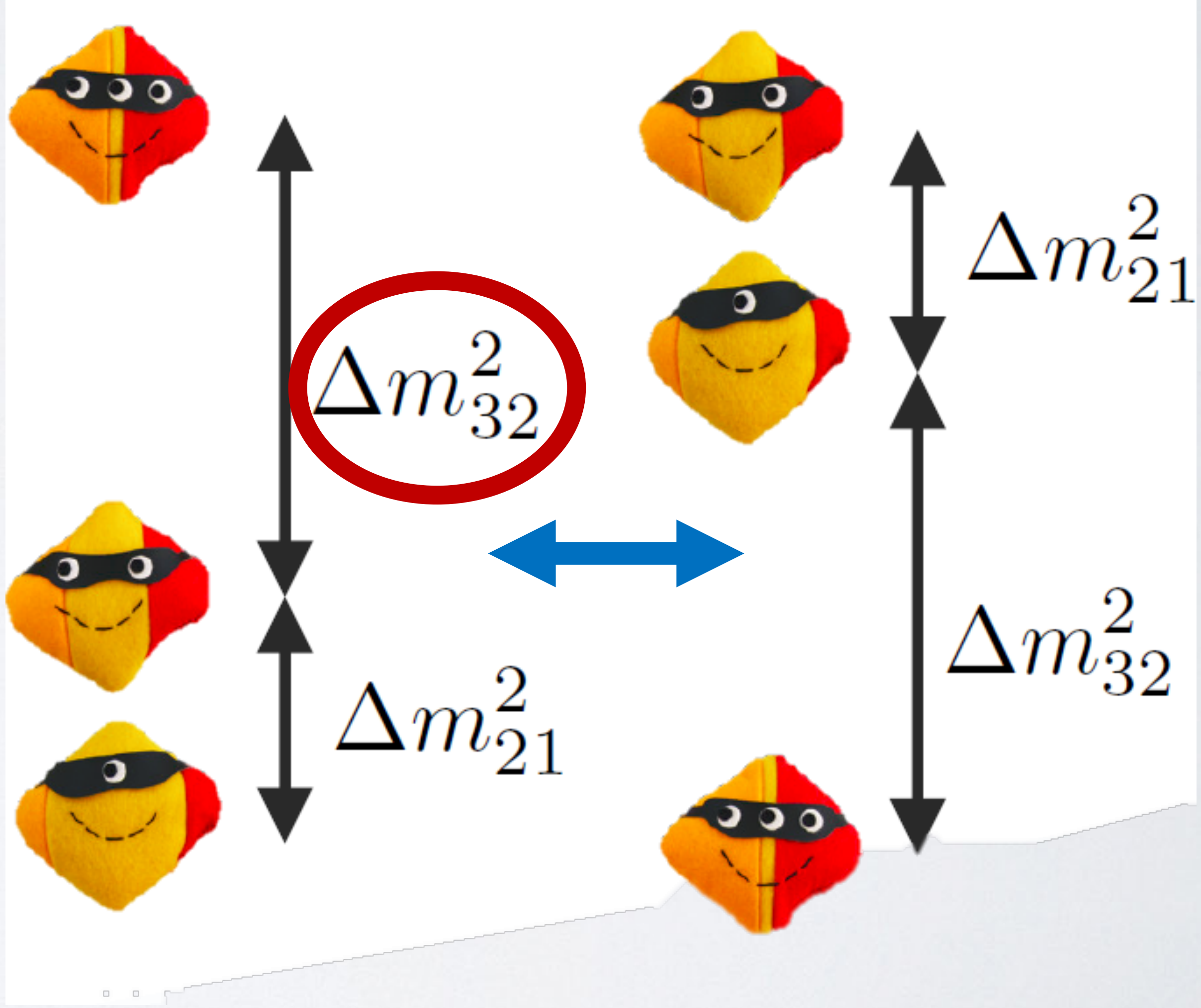
M. Freund, Phys.Rev. D64 (2001) 053003

- Proportional to $\sin^2(2\theta_{13}) \sin^2(\theta_{23})$
- Appearance enhanced/suppressed depending on value of δ_{CP} and mass hierarchy

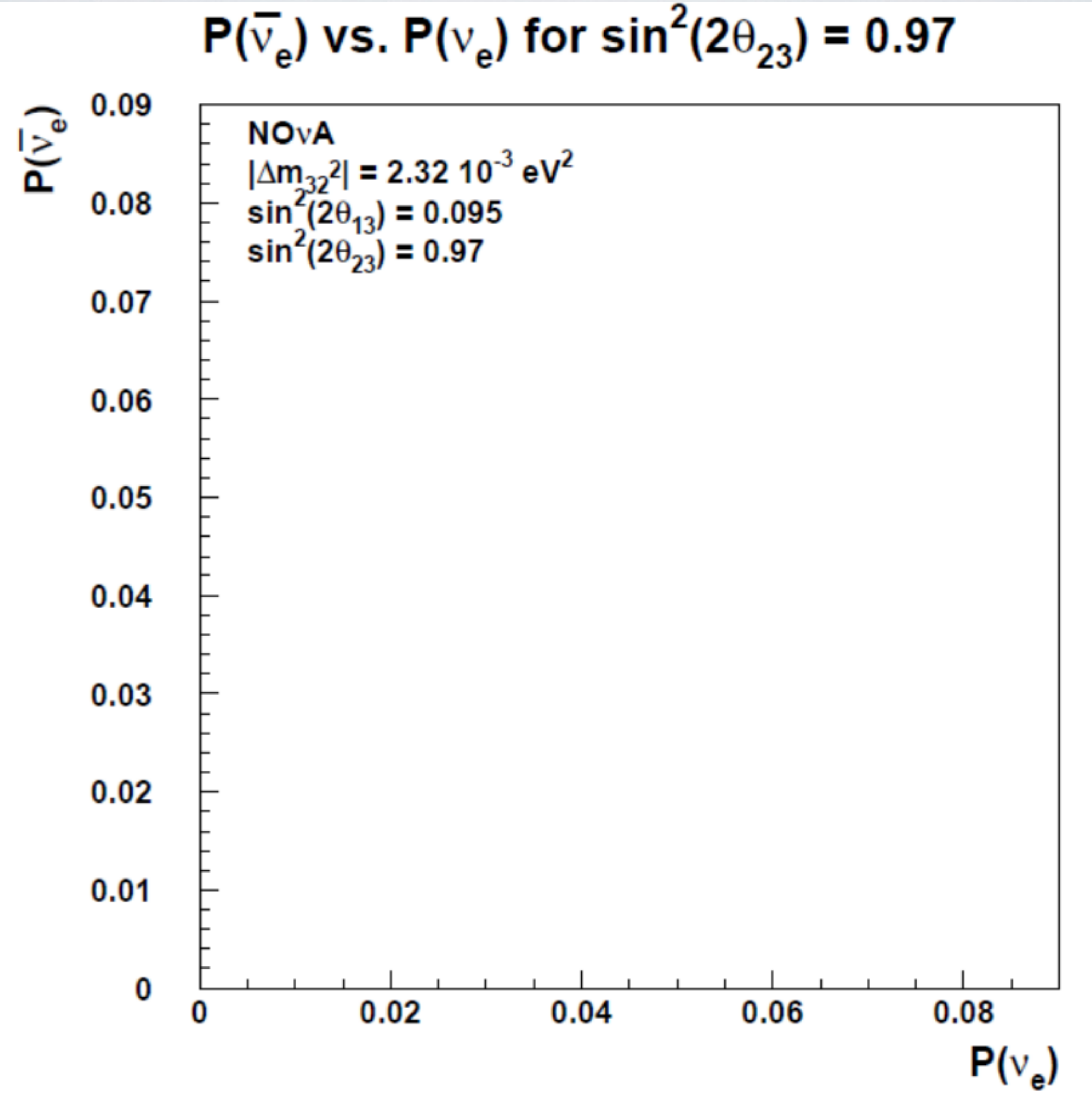
$$= R(\theta_{23}) \cdot R(\theta_{13}, \delta_{CP}) \cdot R(\theta_{12})$$



- The mixing matrix
  - θ_{23}, θ_{13}, δ_{CP}, θ_{12}
- The mass differences
  - Δm^2_{32}, Δm^2_{21}
- The mass hierarchy
  - **sign of Δm^2_{32}**



Bi-probabilities (e.g. NOvA)



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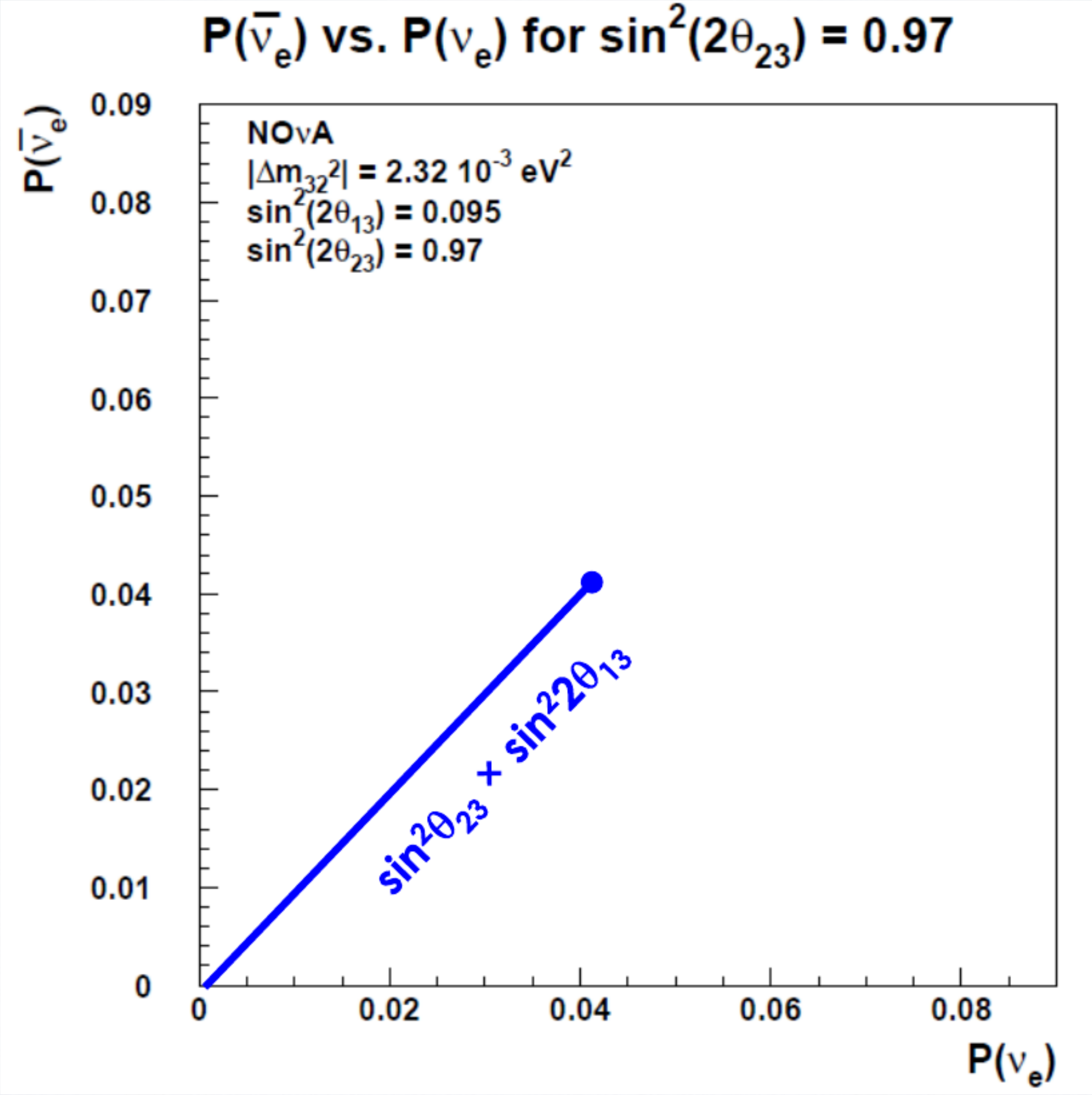

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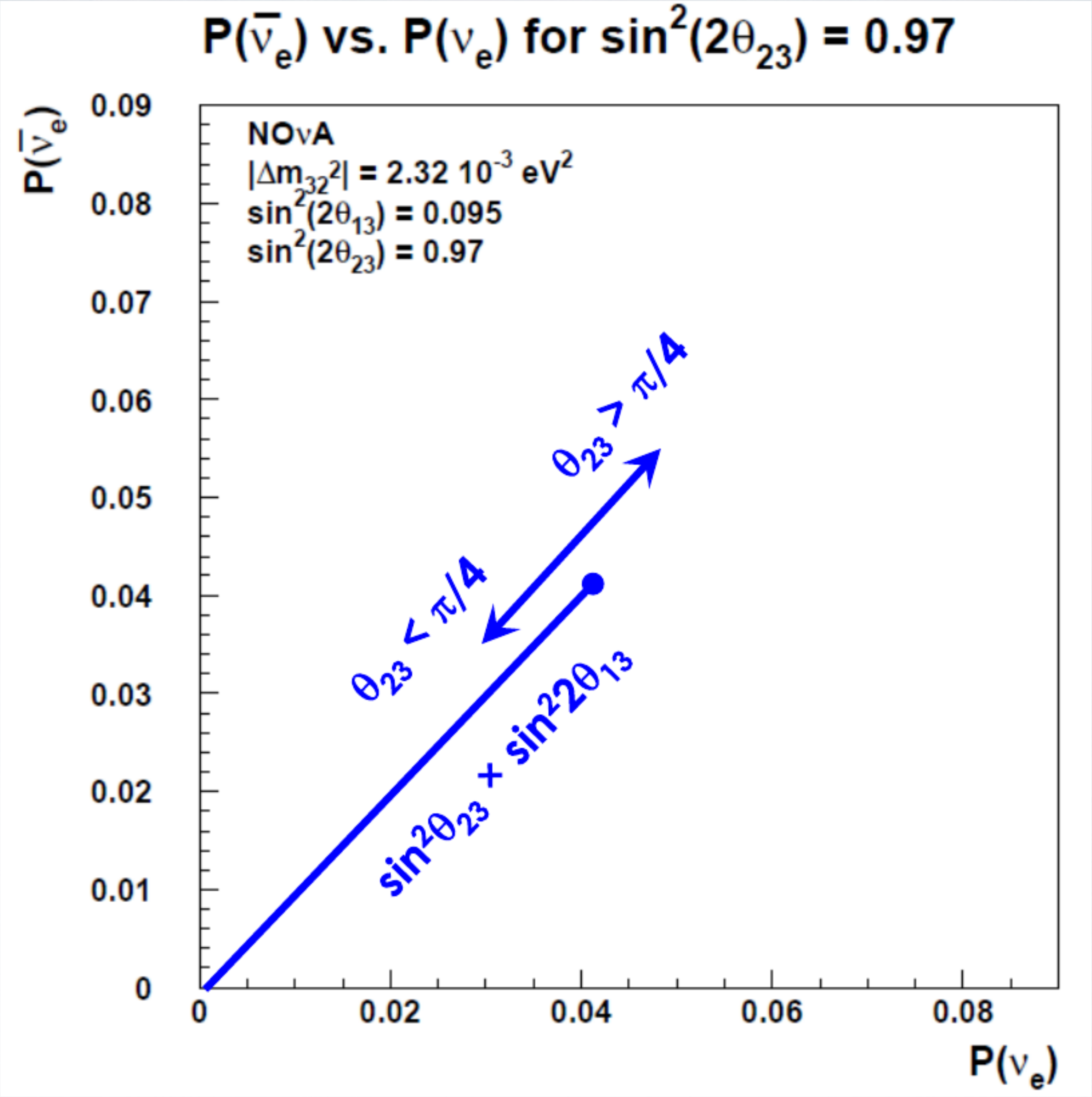

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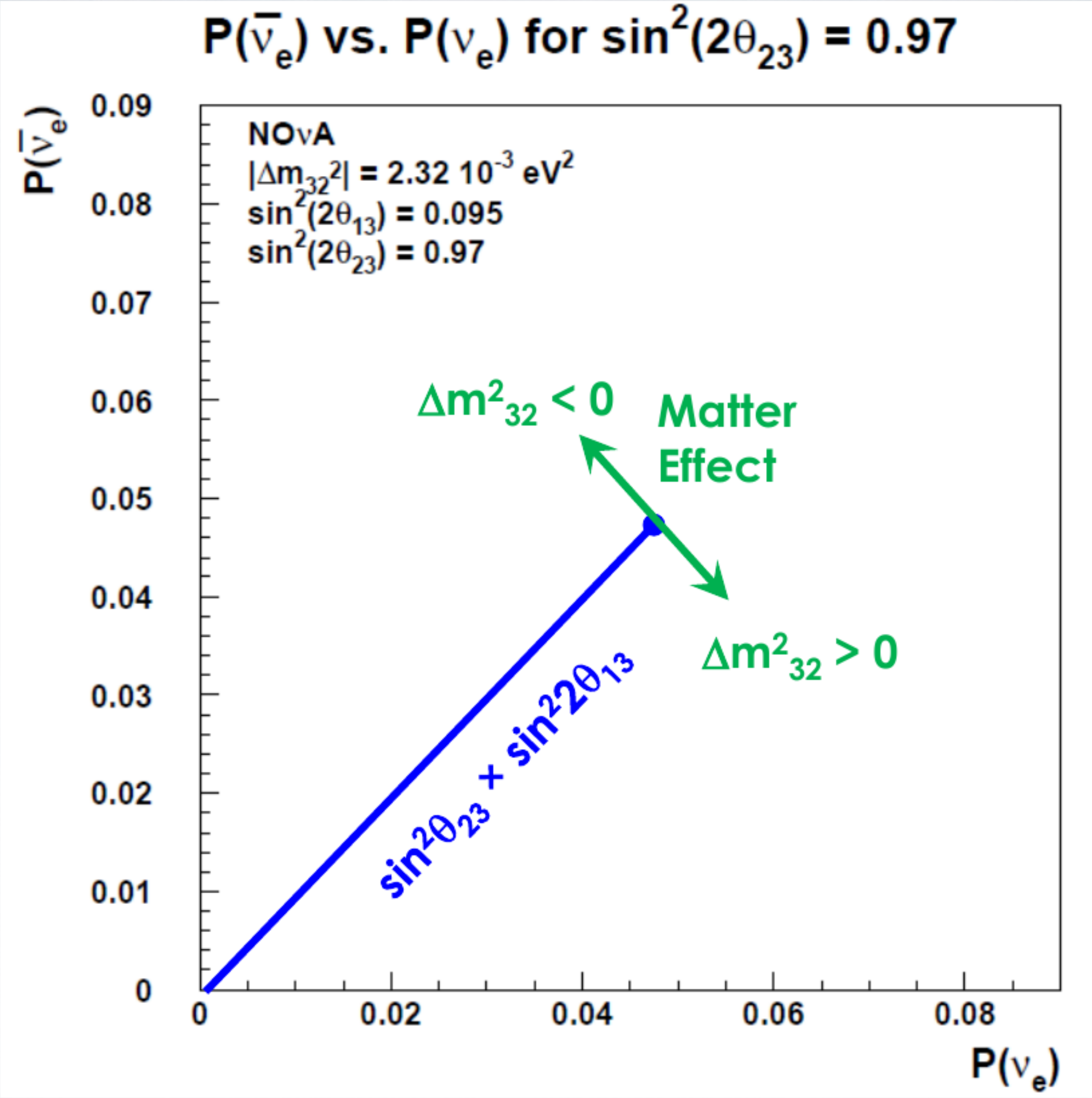

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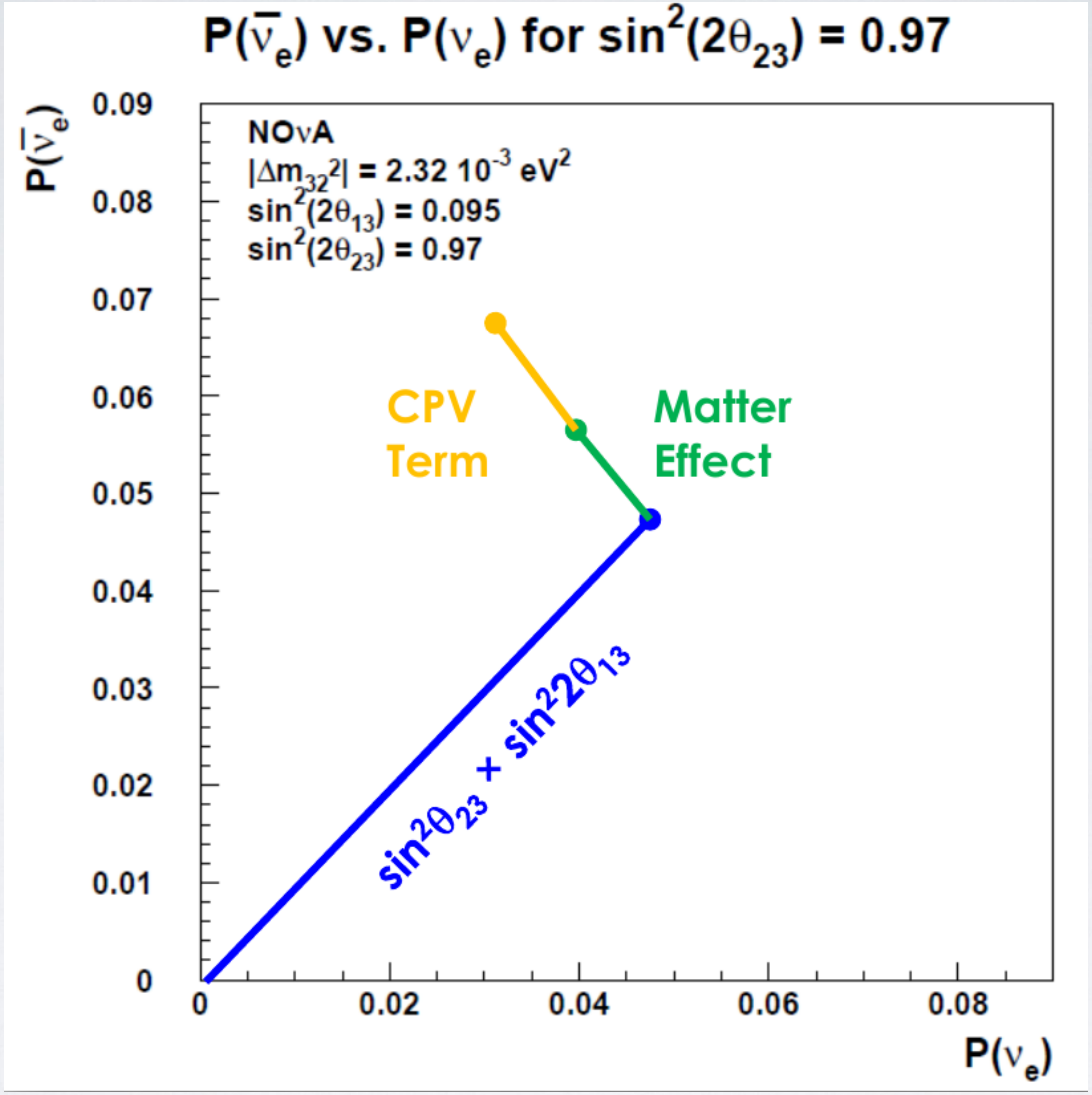
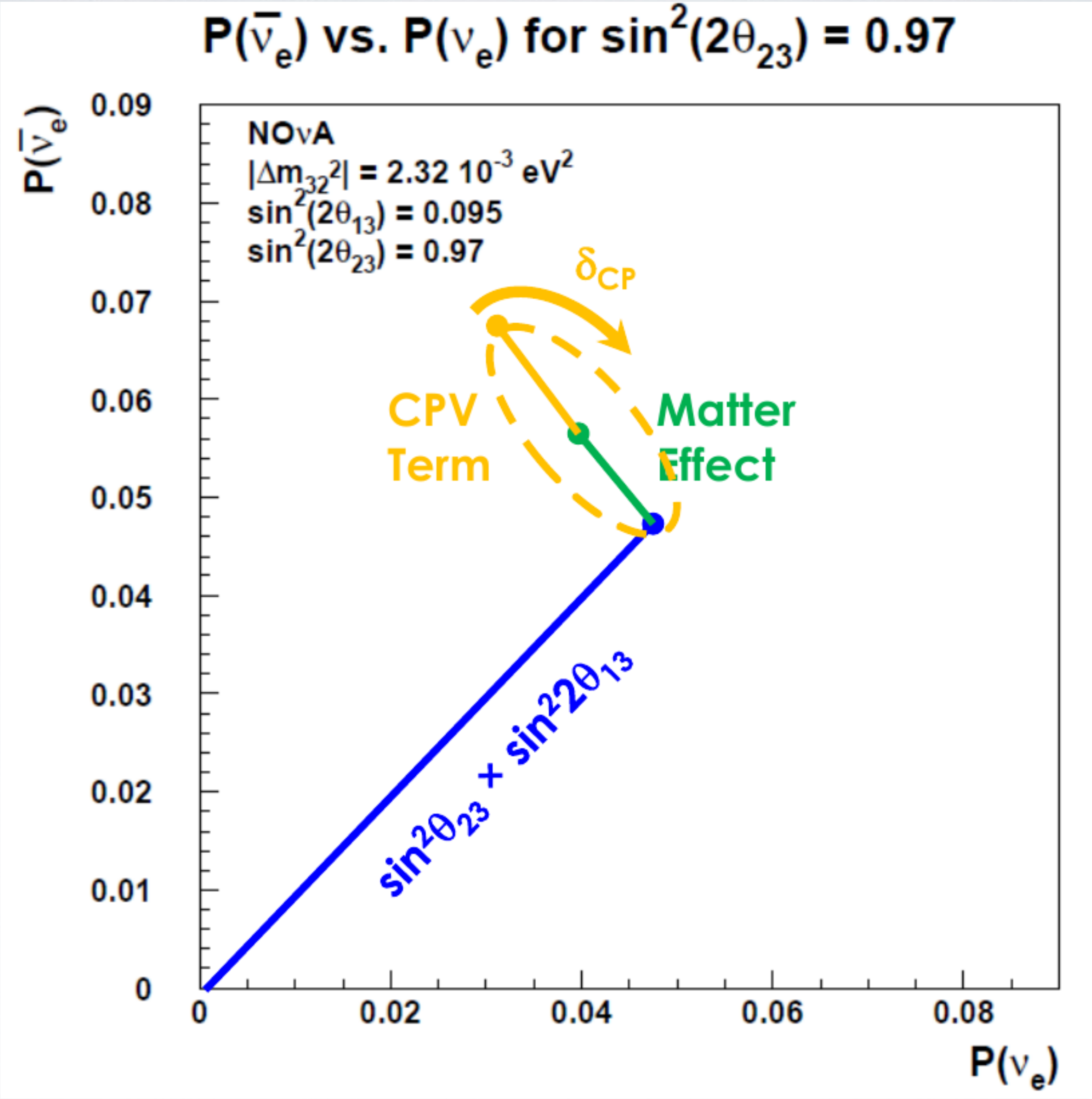
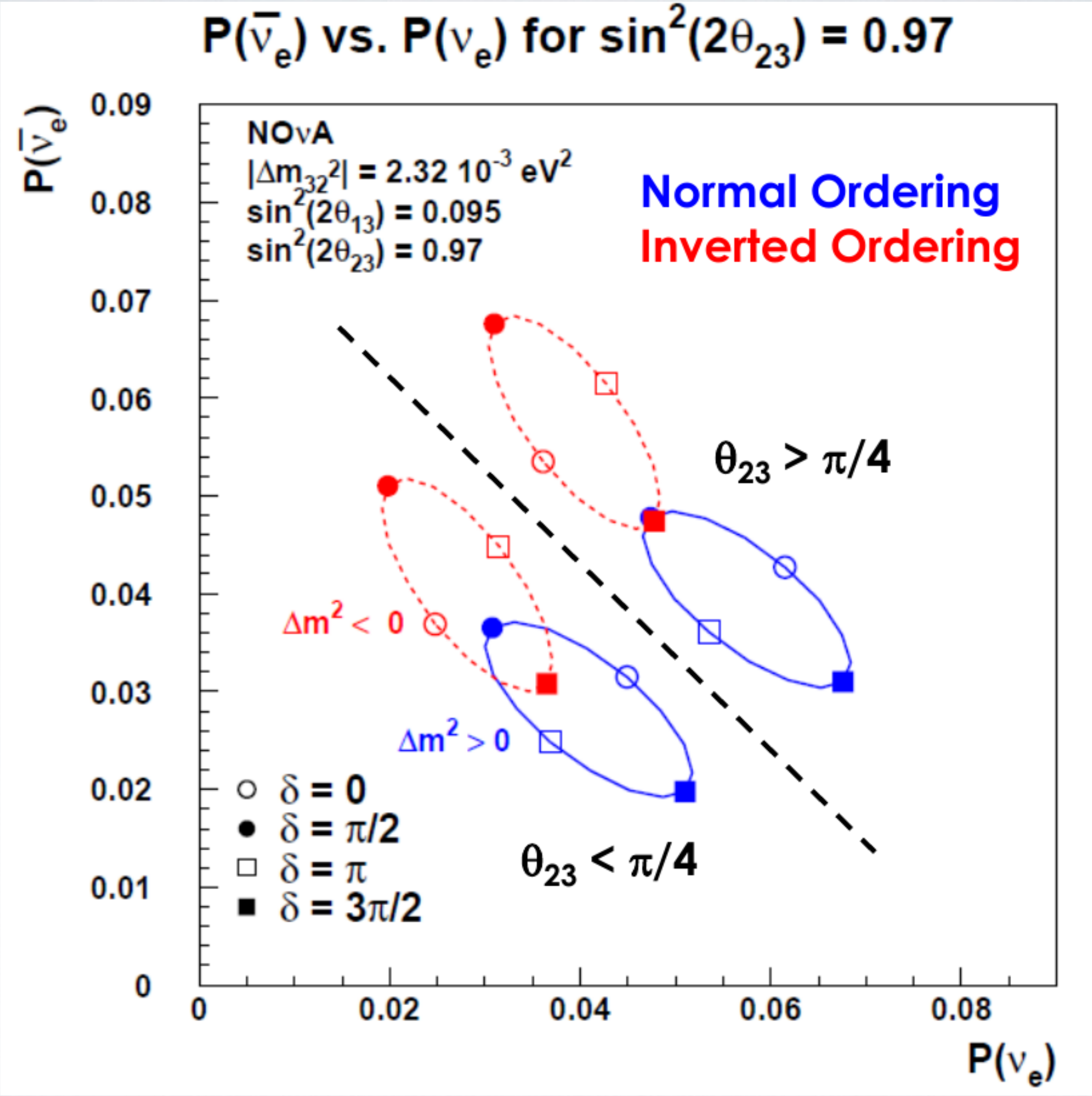


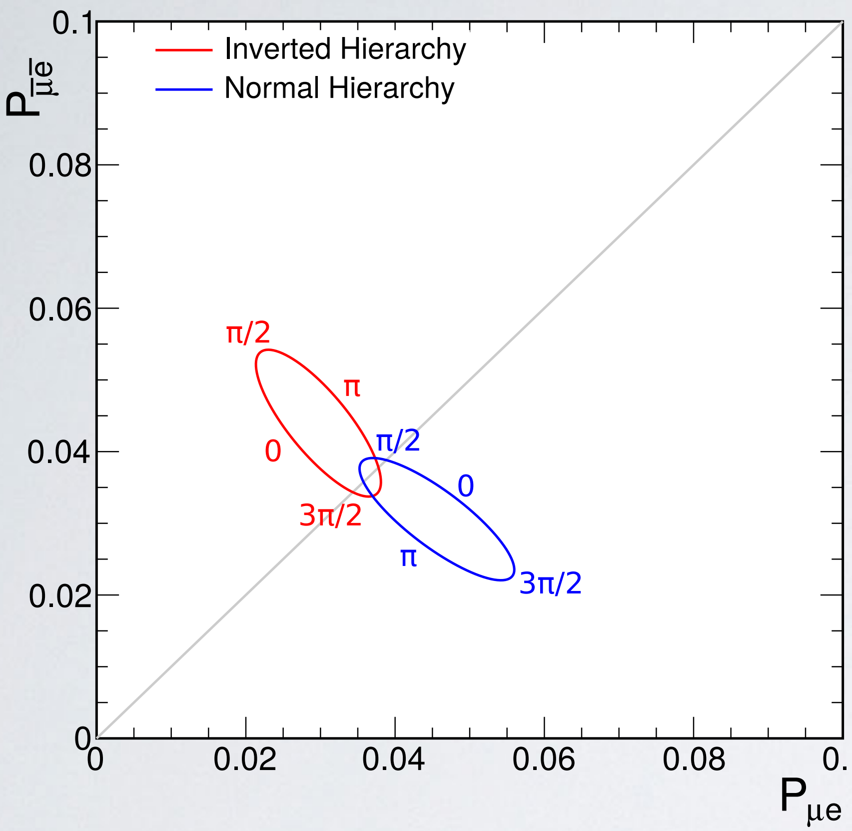
Bi-probabilities (e.g. NOvA)

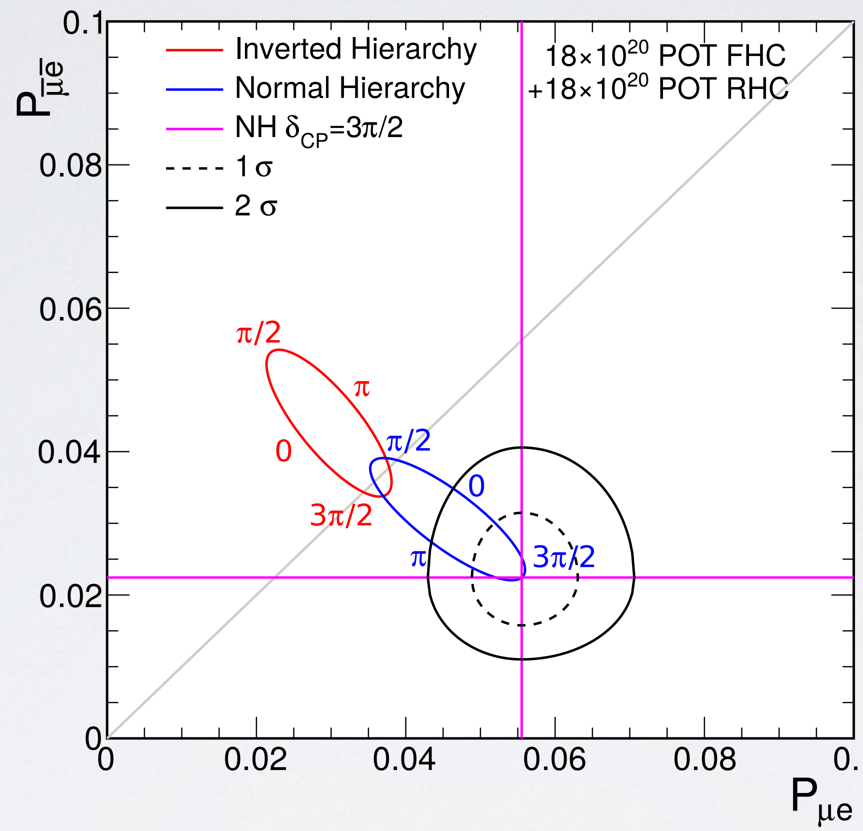


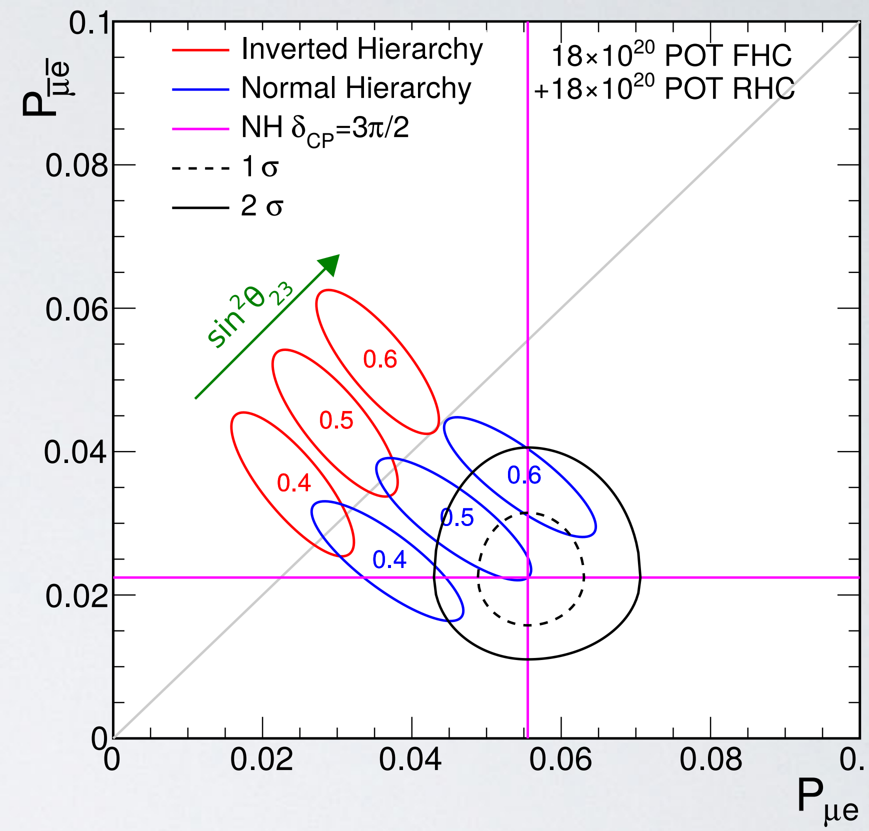
Bi-probabilities (e.g. NOvA)



Bi-probabilities (e.g. NOvA)







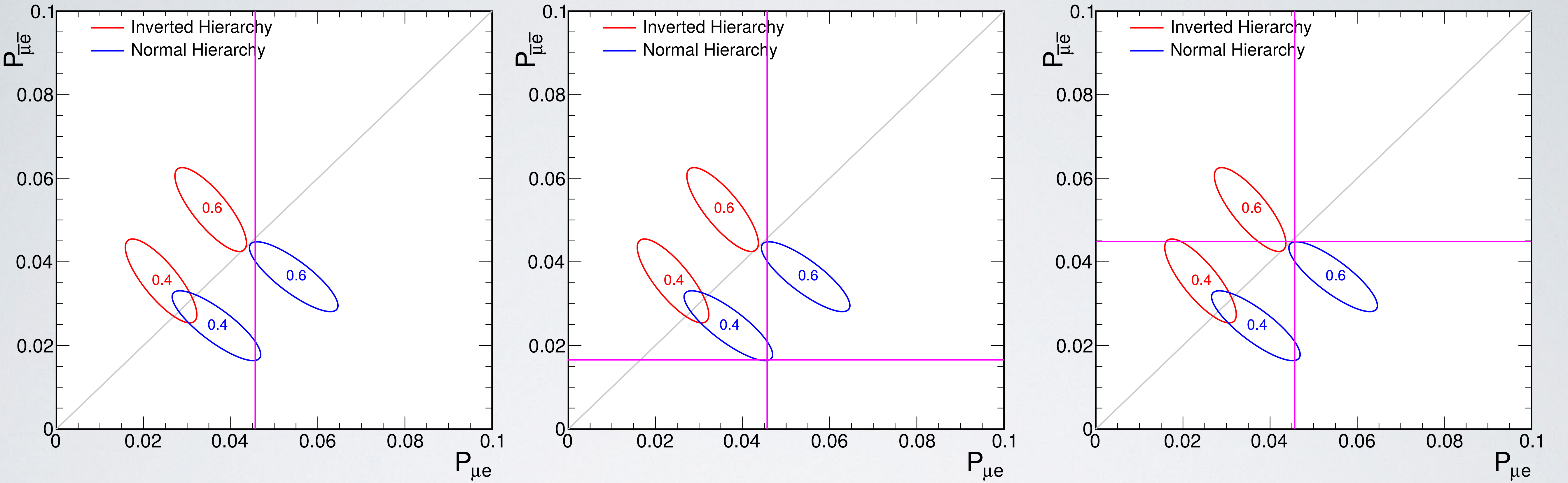
To first order, one measures $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

These depend on the MH and δ_{CP}

Measurements in neutrino and antineutrino mode provide a point with some uncertainty

Given overall dependence to $\sin^2\theta_{23}$, sensitivity to the 3 observables

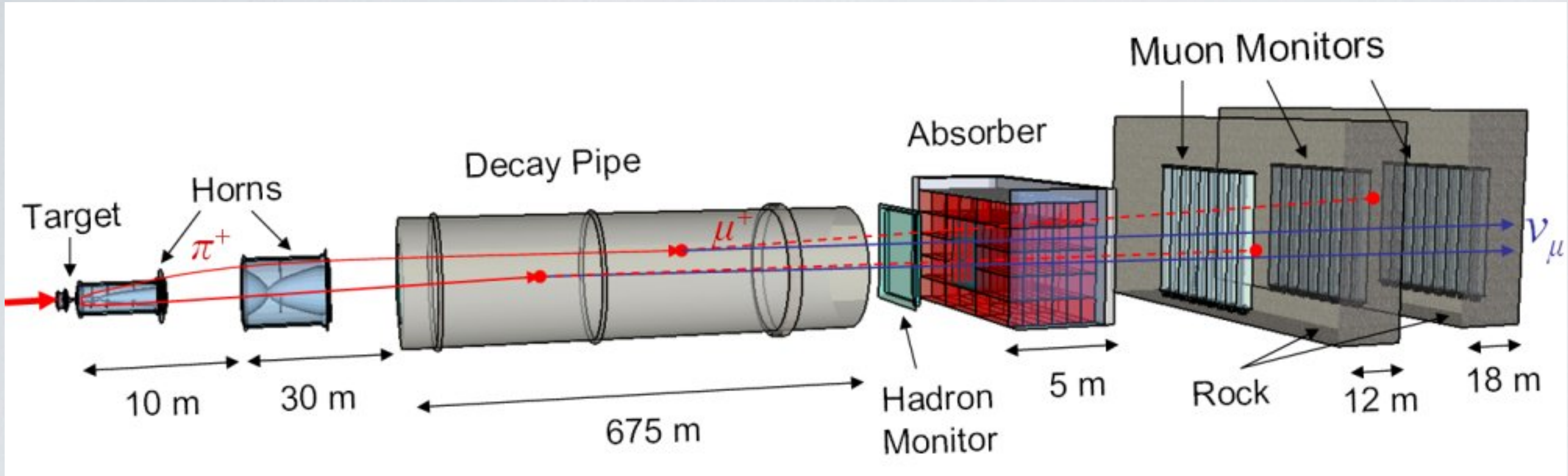
Bi-probabilities II (e.g. NOvA)



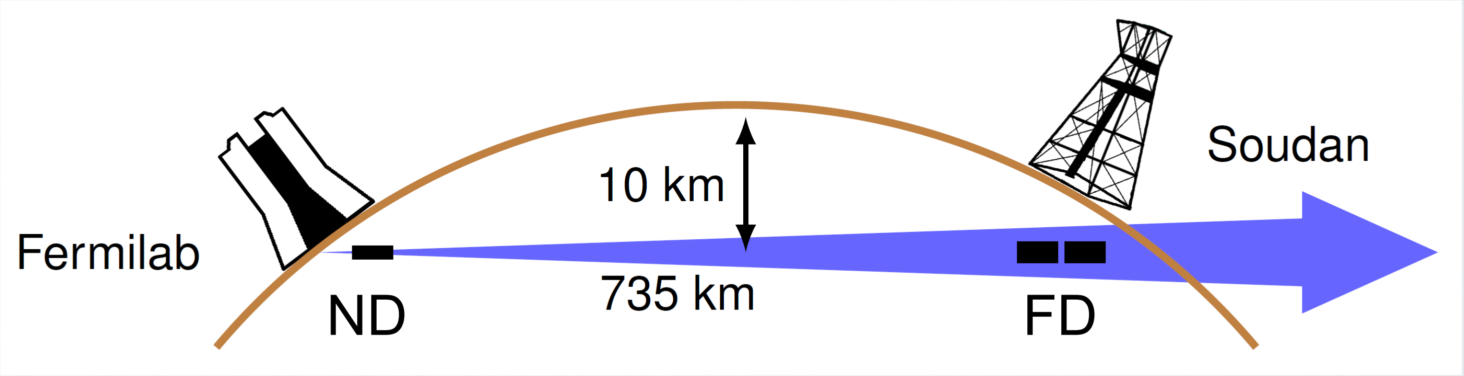
If the scenario is not so clear, antineutrino data help breaking the degeneracies

More than a factor 2 difference in the rate of antineutrinos between solutions

Long-baseline



- Highly pure ν_μ beam
- Two detectors
  - ✓ Near detector:
    - Measure beam composition
    - Determine energy spectrum
  - ✓ Far detector:
    - Measure oscillations
    - Search for new Physics



Long-baseline neutrino oscillation experiments

1st generation (past)	2nd generation (present)	3rd generation (future)
• MINOS / MINOS+ • K2K	• NOvA • T2K • OPERA	• DUNE • Hyper-K
Firmly established 3-flavour scenario Precise measurements of Δm^2_{32} and $\sin^2\theta_{23}$	Optimised for electron-neutrino appearance Constraints on δ_{CP}, mass hierarchy and octant	Precision measurement of δ_{CP} and the remaining unknowns

Key features of 2nd generation

- Narrow band (off-axis) beam
- Detectors optimised for:
  - ν_e flavour identification
  - ν_e appearance maximum (L/E)
- High-intensity neutrino beam
- Longer (or shorter) baseline to enhance (reduce) the matter effect: 10% in T2K, 30% in NOvA

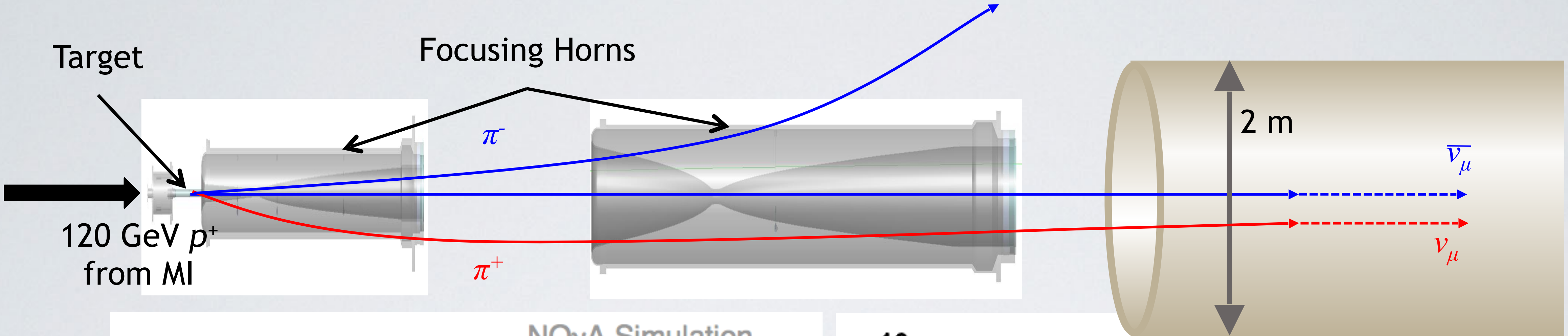
NOvA

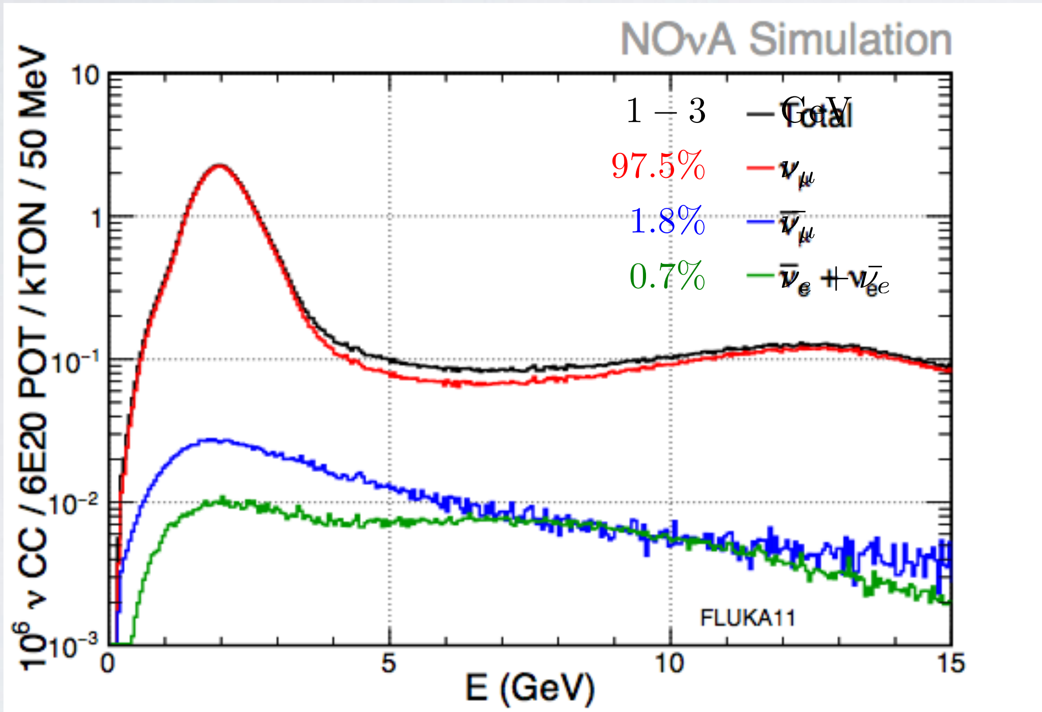
- Baseline: 810 km
- Segmented scintillation calorimeter
- 700 kW neutrino / antineutrino beam
- 14.3 mrad off-axis

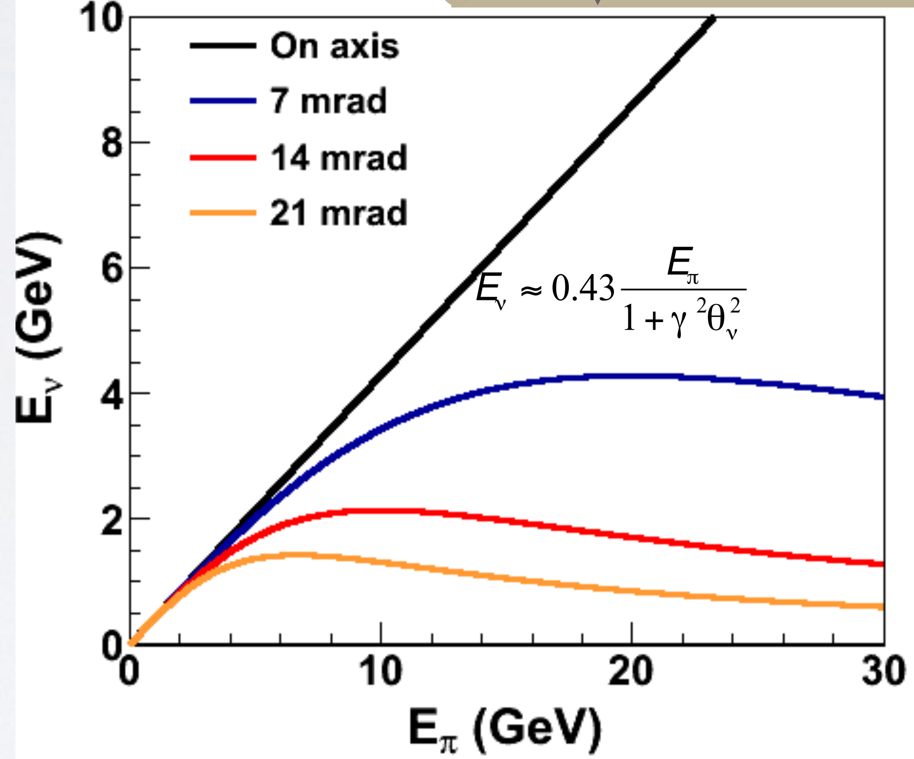
T2K

- Baseline: 295 km
- Cherenkov detector (SuperK)
- 420 kW neutrino / antineutrino beam
- 2.5° off-axis

Making an off-axis neutrino beam







- At 14 mrad off-axis, narrow band beam peaked at 2 GeV
- Near oscillation maximum
- Fewer high energy NC background events

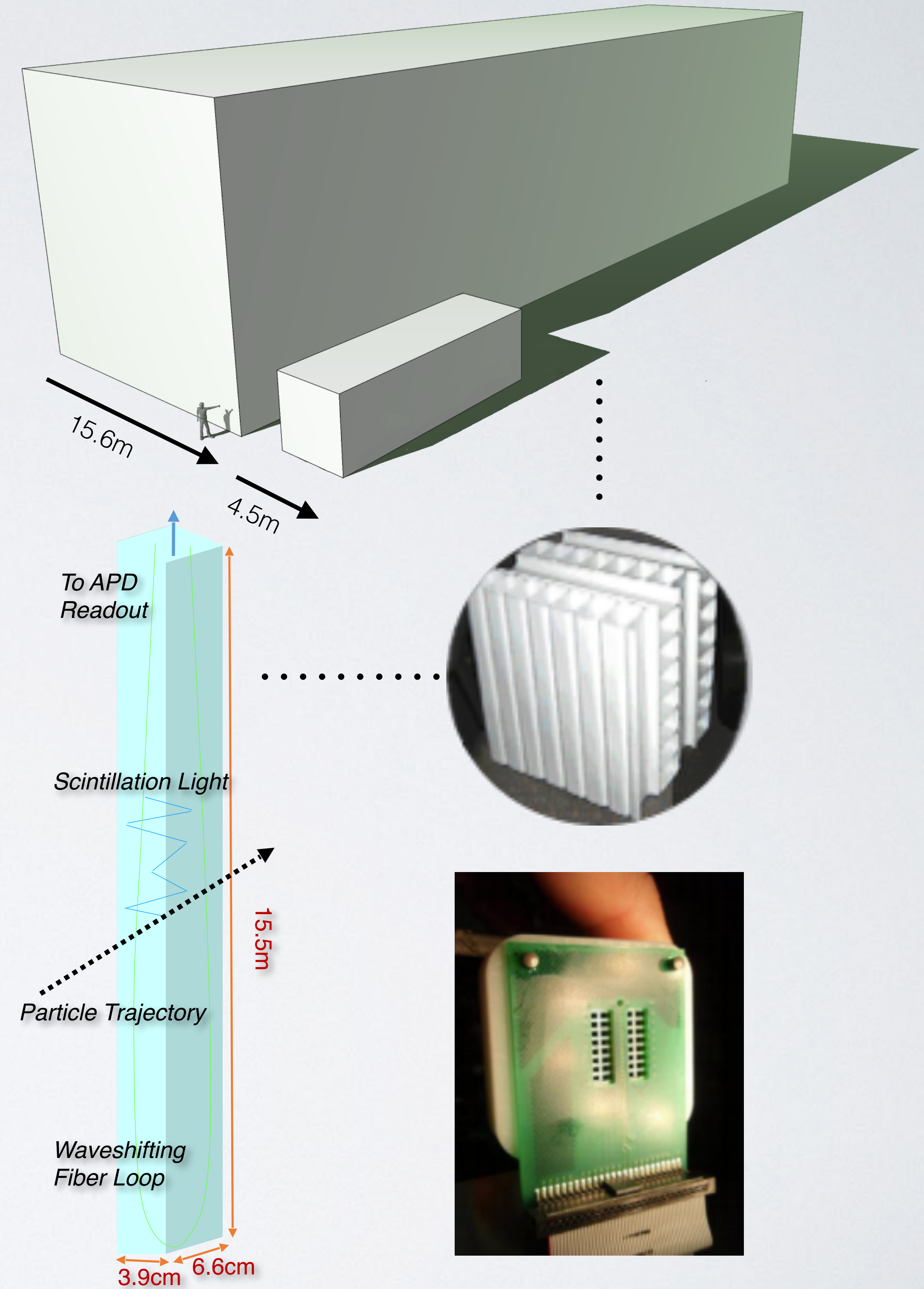
Example of optimisation: MINOS to NOvA

How to enhance the appearance measurement?

Maximise signal	Reduce background	Detailed reconstruction
• Large and massive detector • Limited passive material (highly active) • High intensity beam	• Off-axis: smaller NC and ν_μ background • low Z: identify gaps and distinguish electrons from photons • Optimise L/E	• High granularity • Efficient signal collection: APDs

NOvA

- NuMI Off-Axis ν_e Appearance
- 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



NOvA

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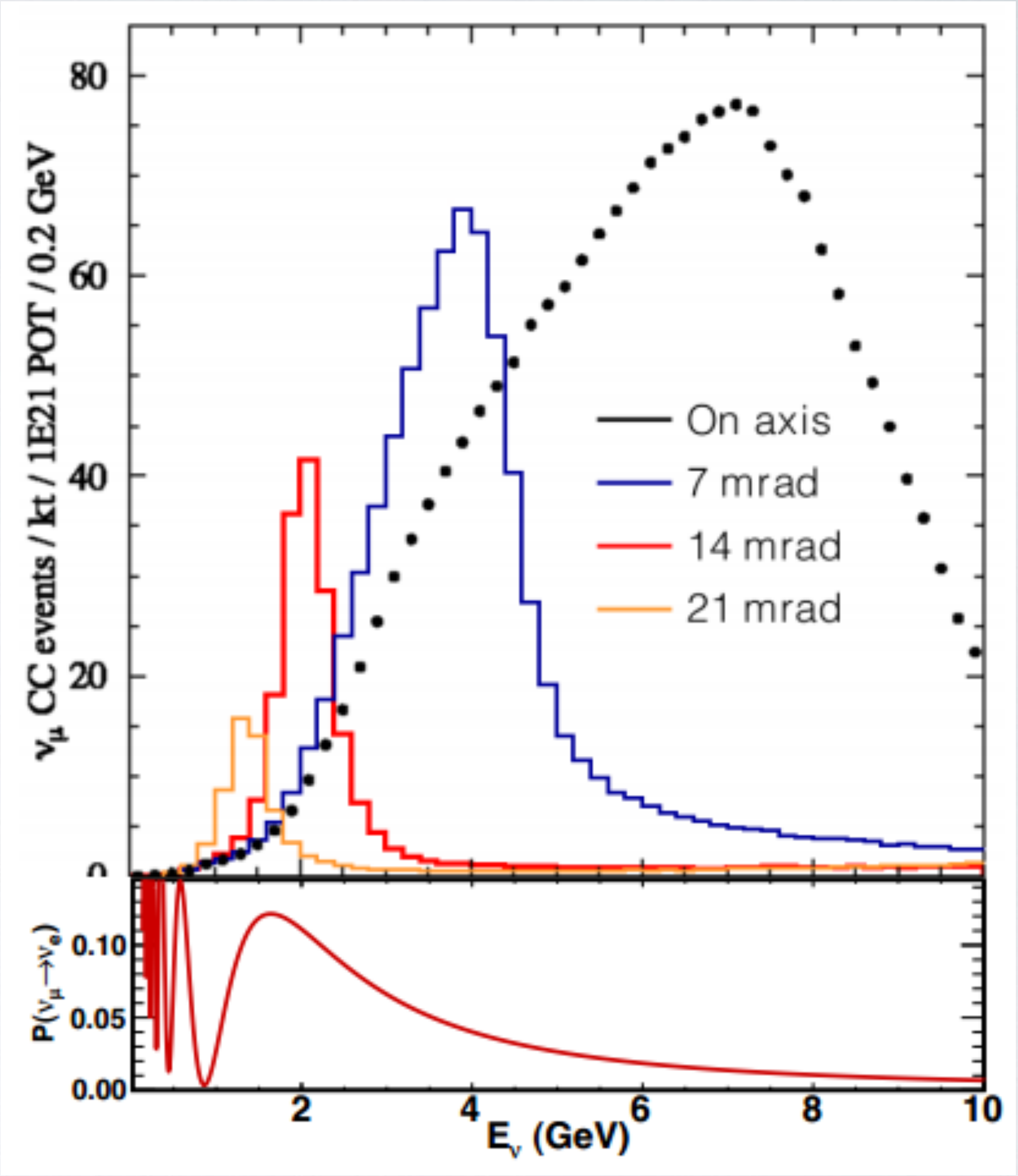
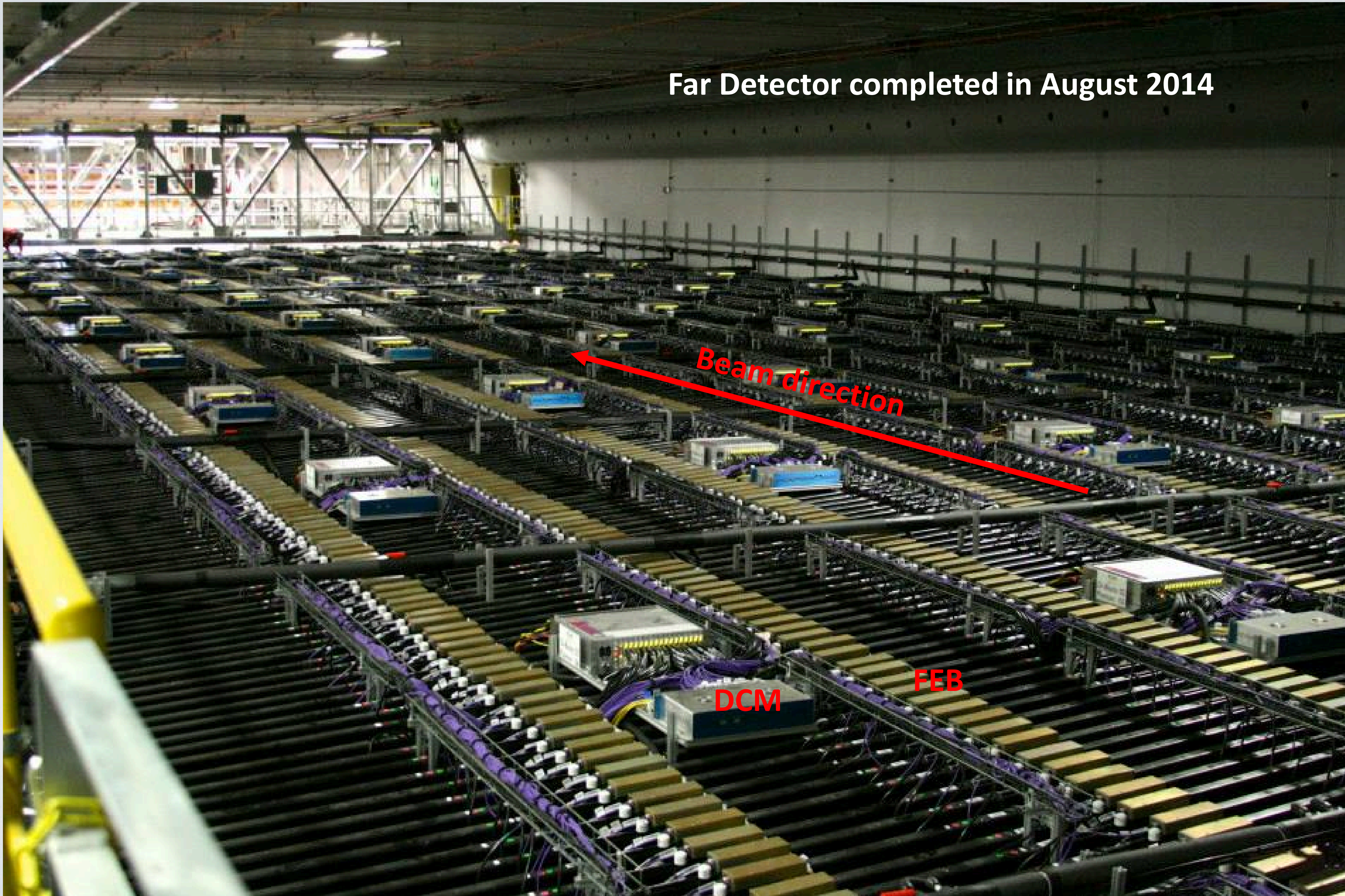


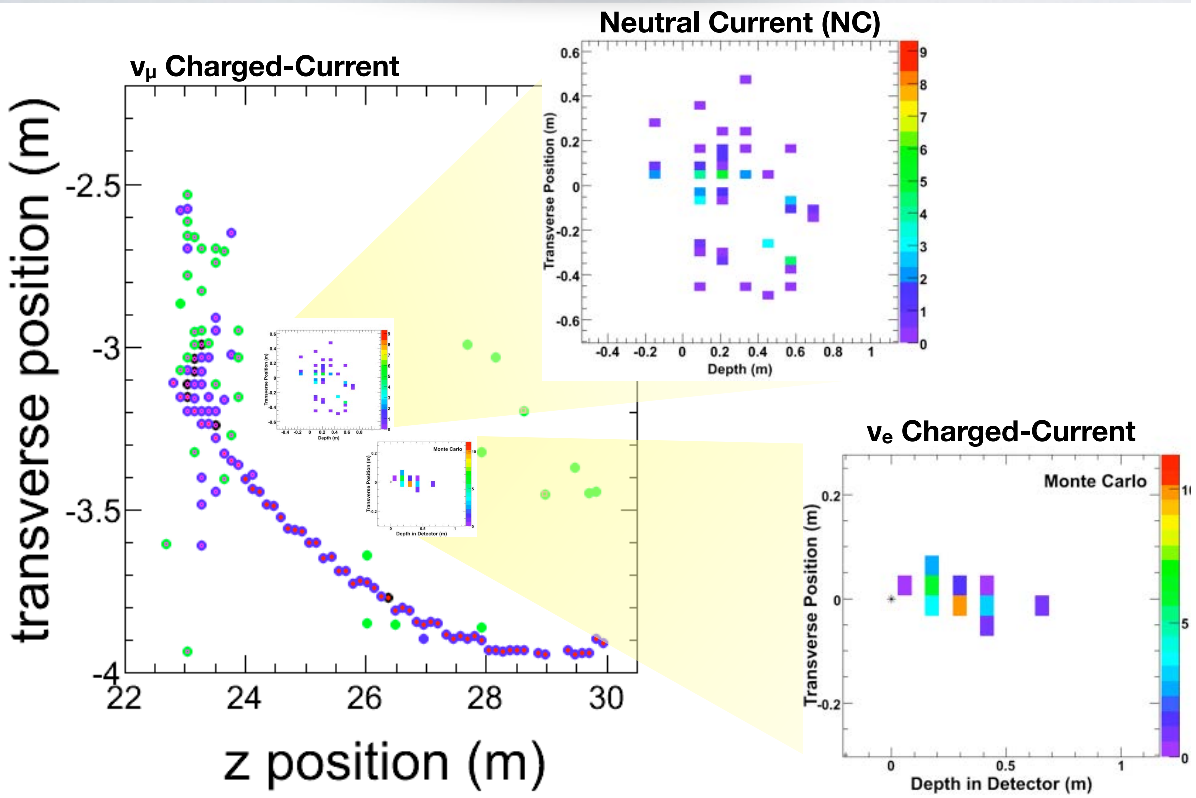
NEAR DETECTOR

FAR DETECTOR

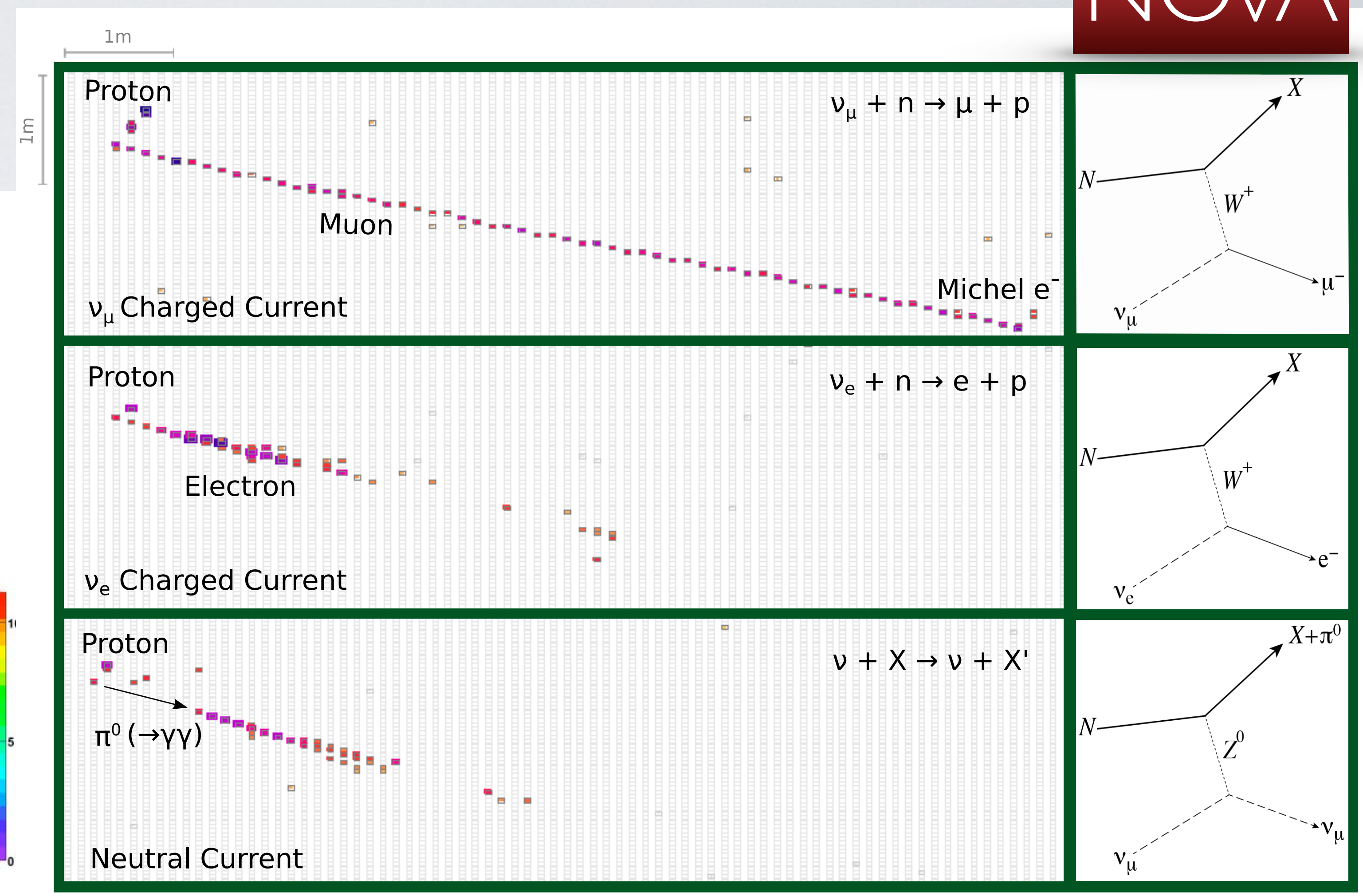


Event topologies

MINOS



NOvA

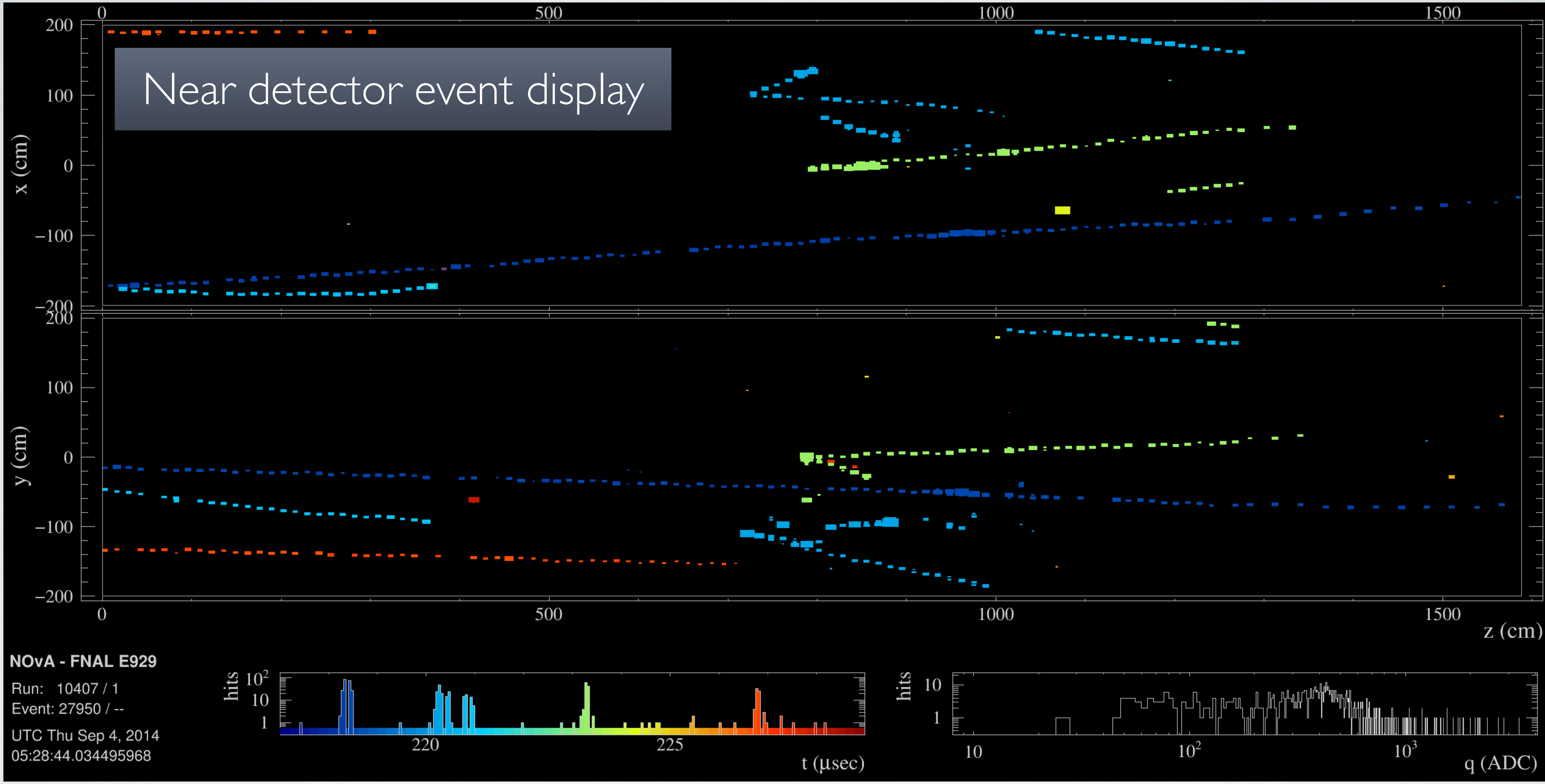


- Superb granularity for a detector this scale
- Outstanding event identification capability

1 radiation length = 38 cm

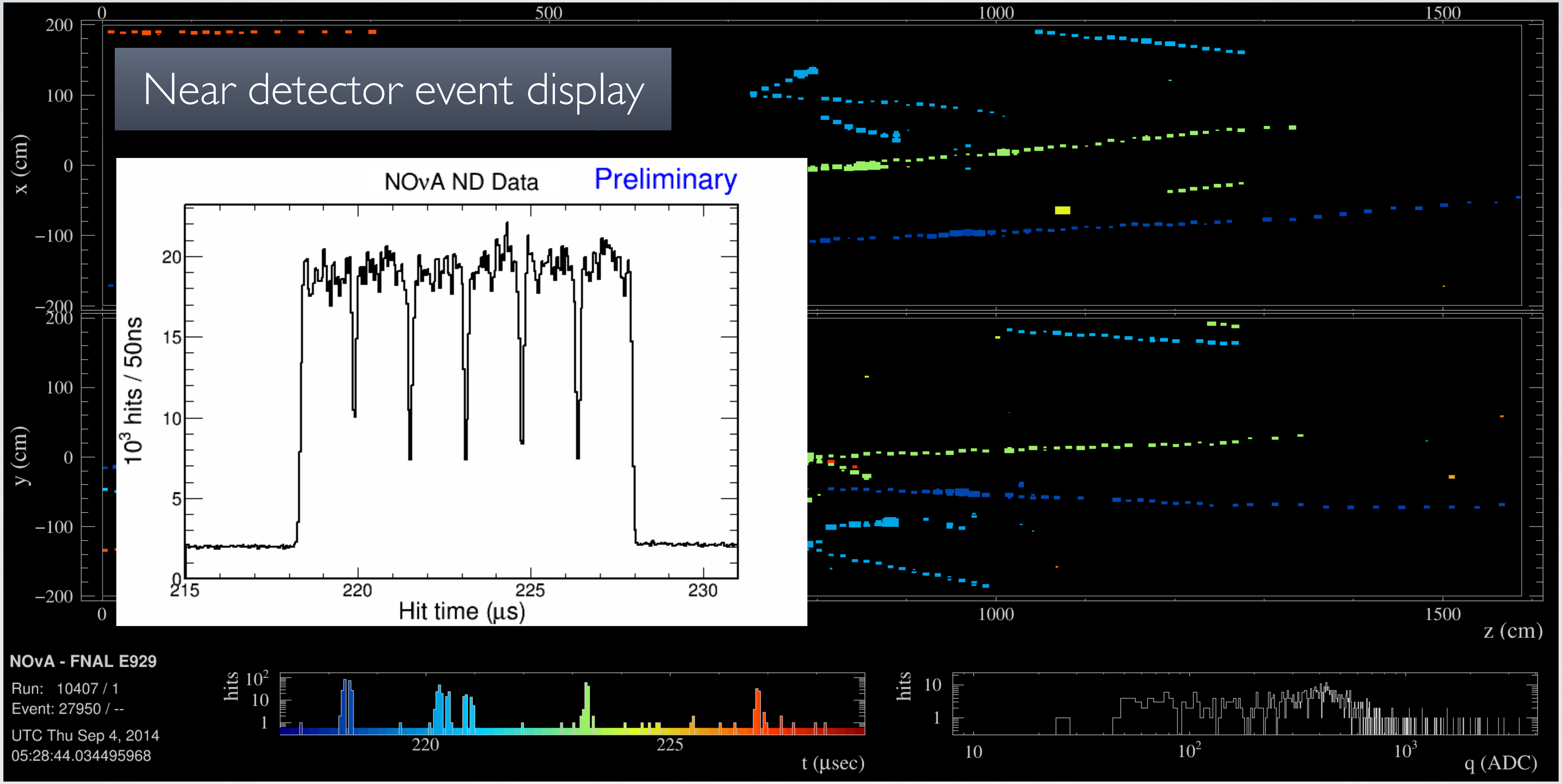
(6 cell depths, 10 cell widths)

Real events (ND)



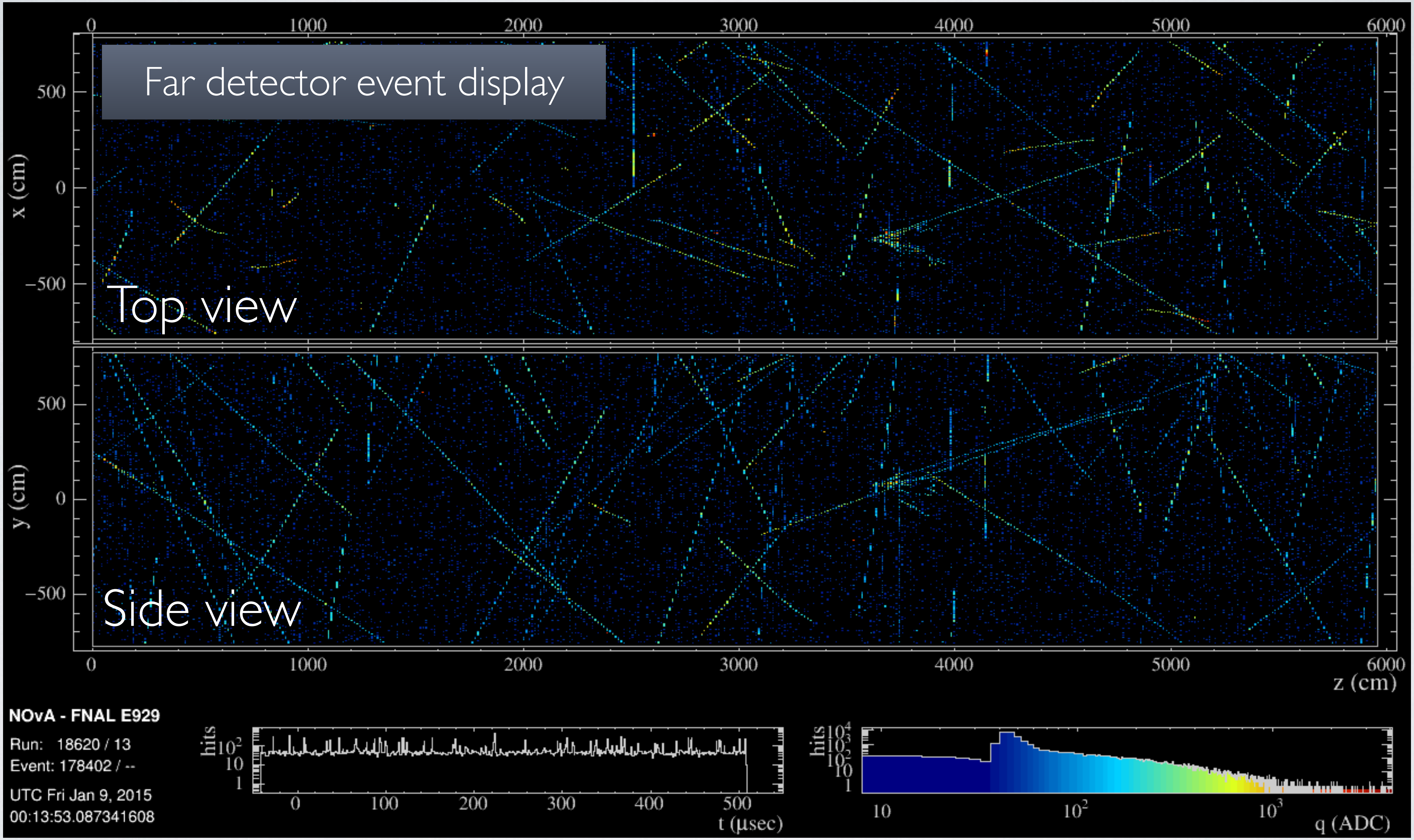
10 µs of readout during NuMI beam pulse

Real events (ND)



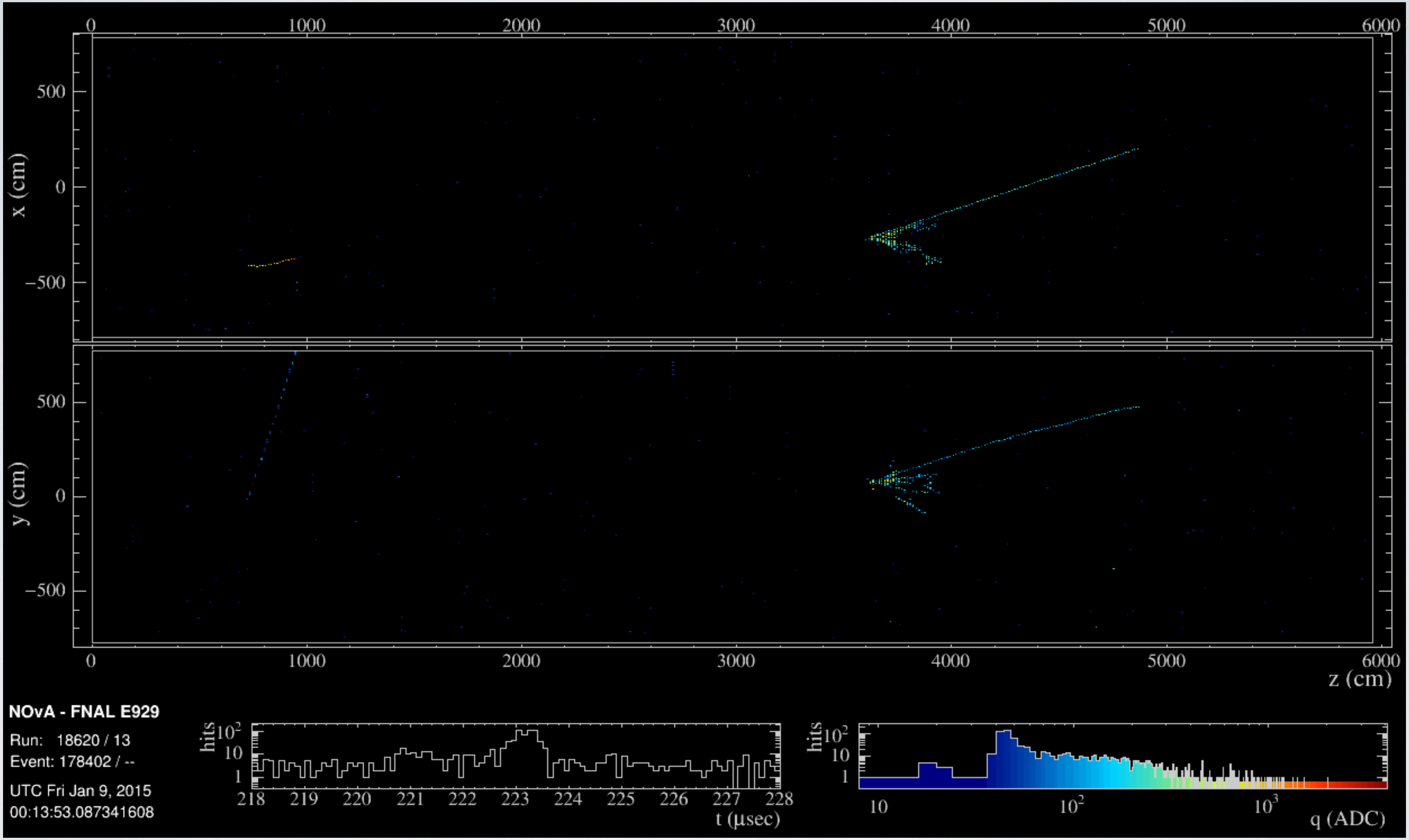
10 µs of readout during NuMI beam pulse

Real events (FD)



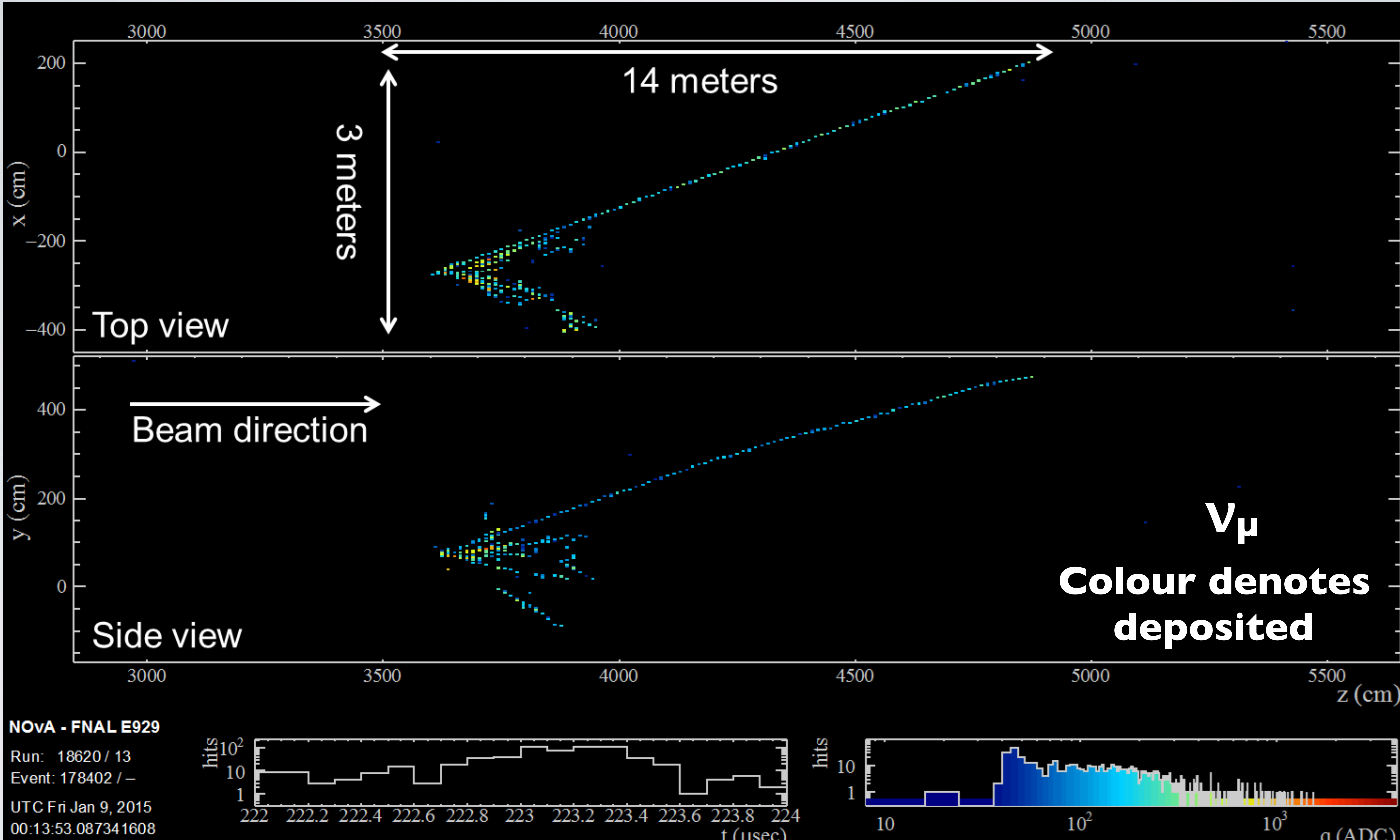
Full 550 μs readout (colours show charge)

Real events (FD)



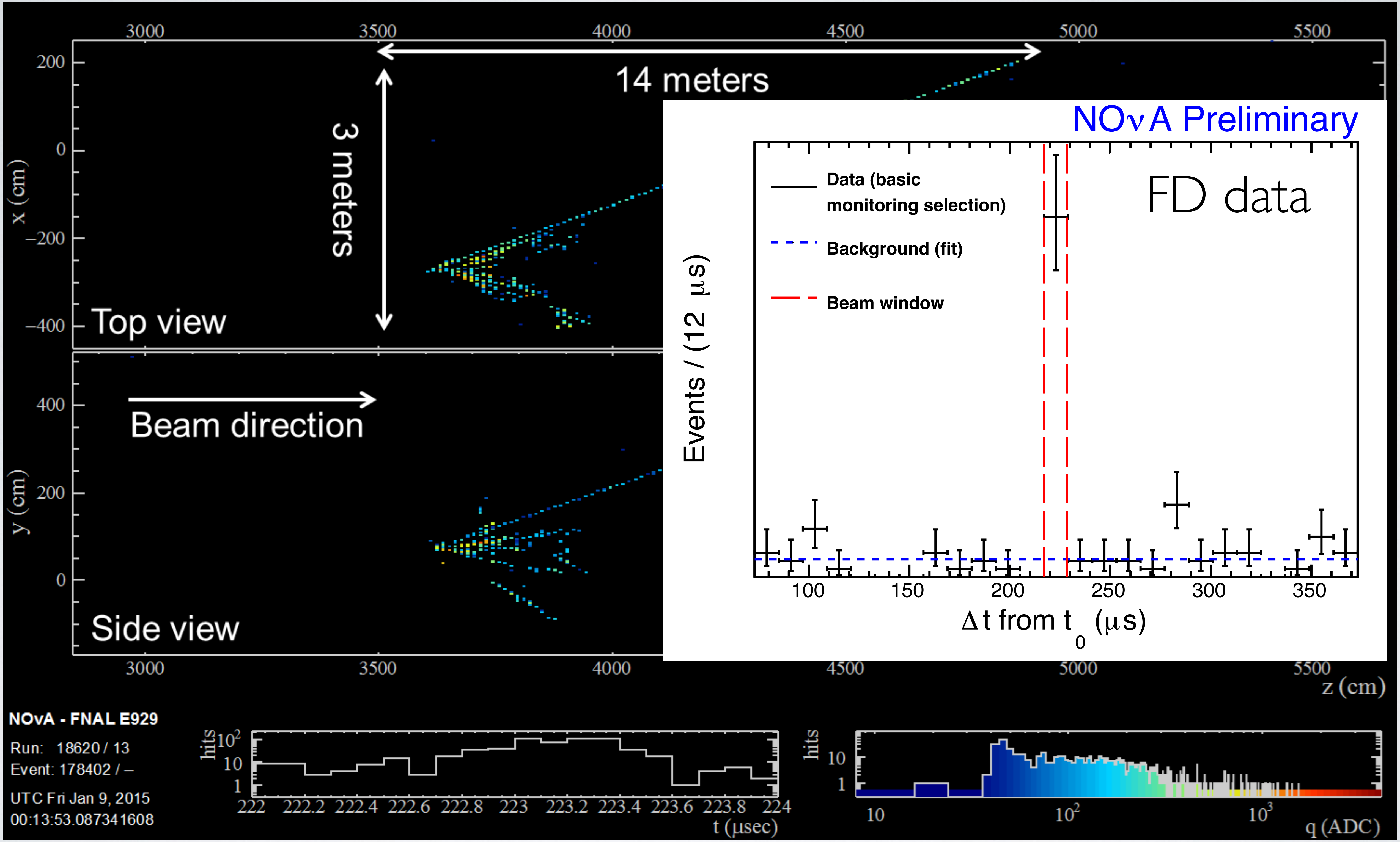
Zoomed on the 10 μs beam spill window

Real events (FD)



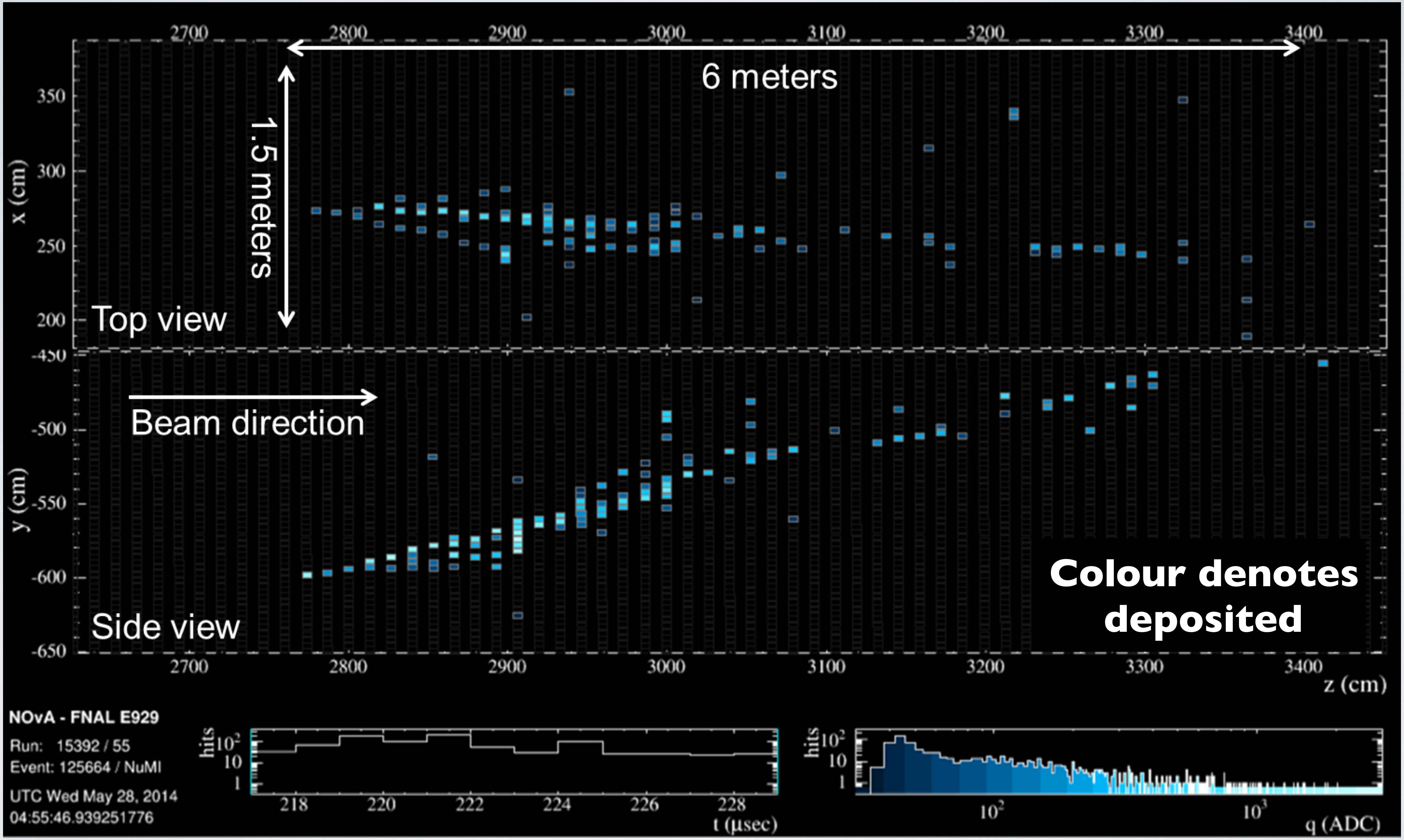
Zoomed on the time slice

Real events (FD)



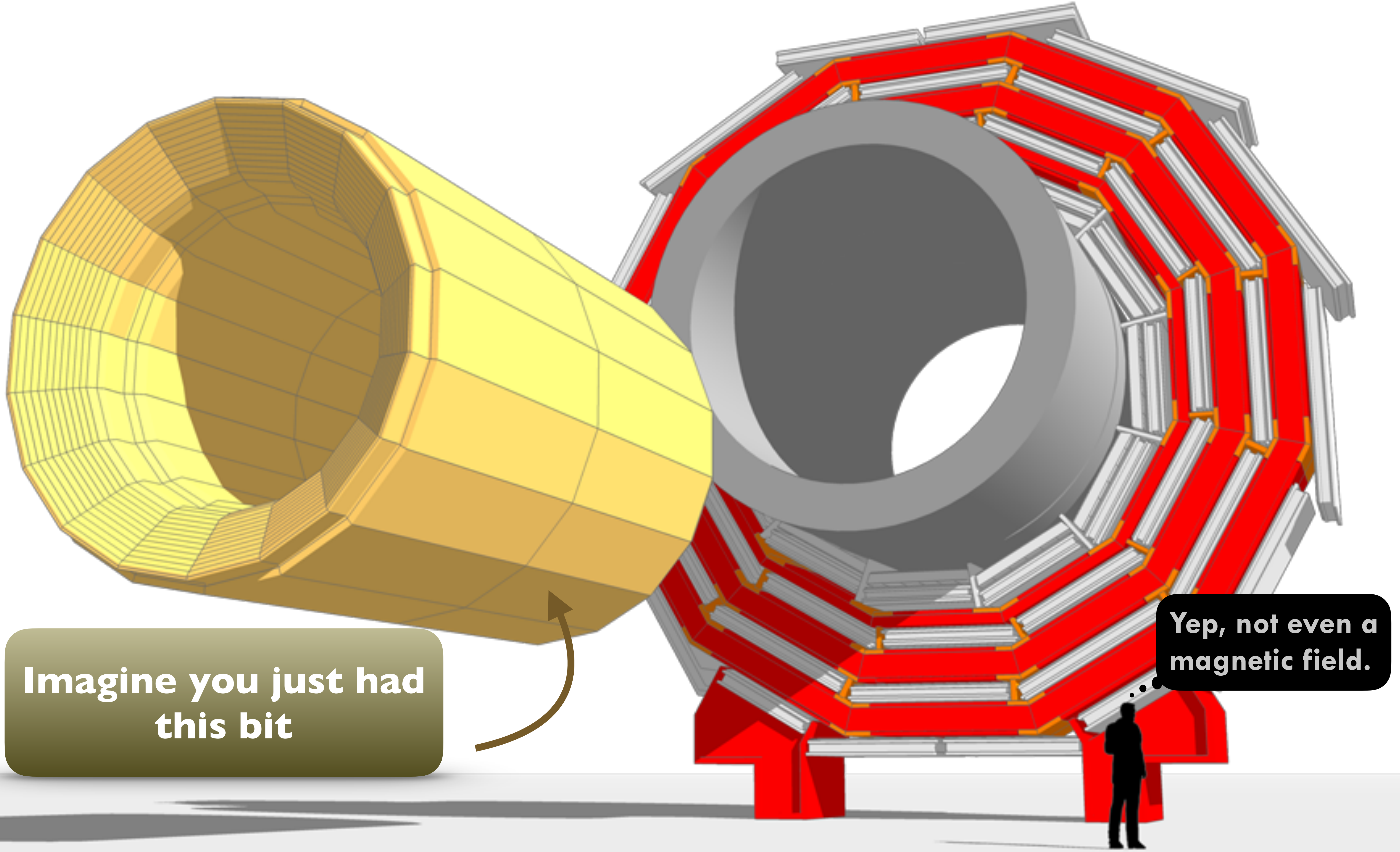
Zoomed on the time slice

Real events (FD)

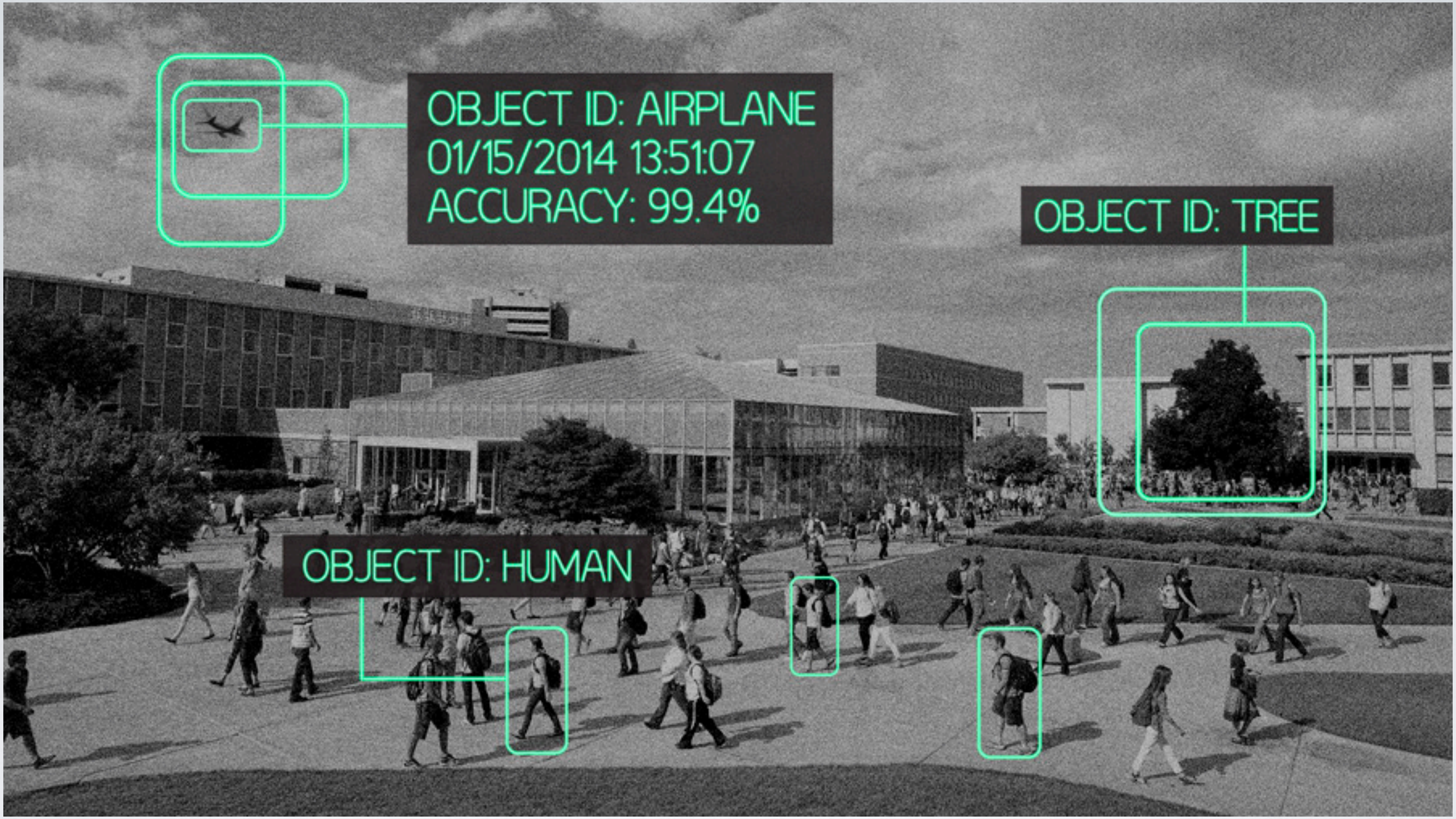


Zoomed on the time slice

Some collider context…



Convolutional neural network

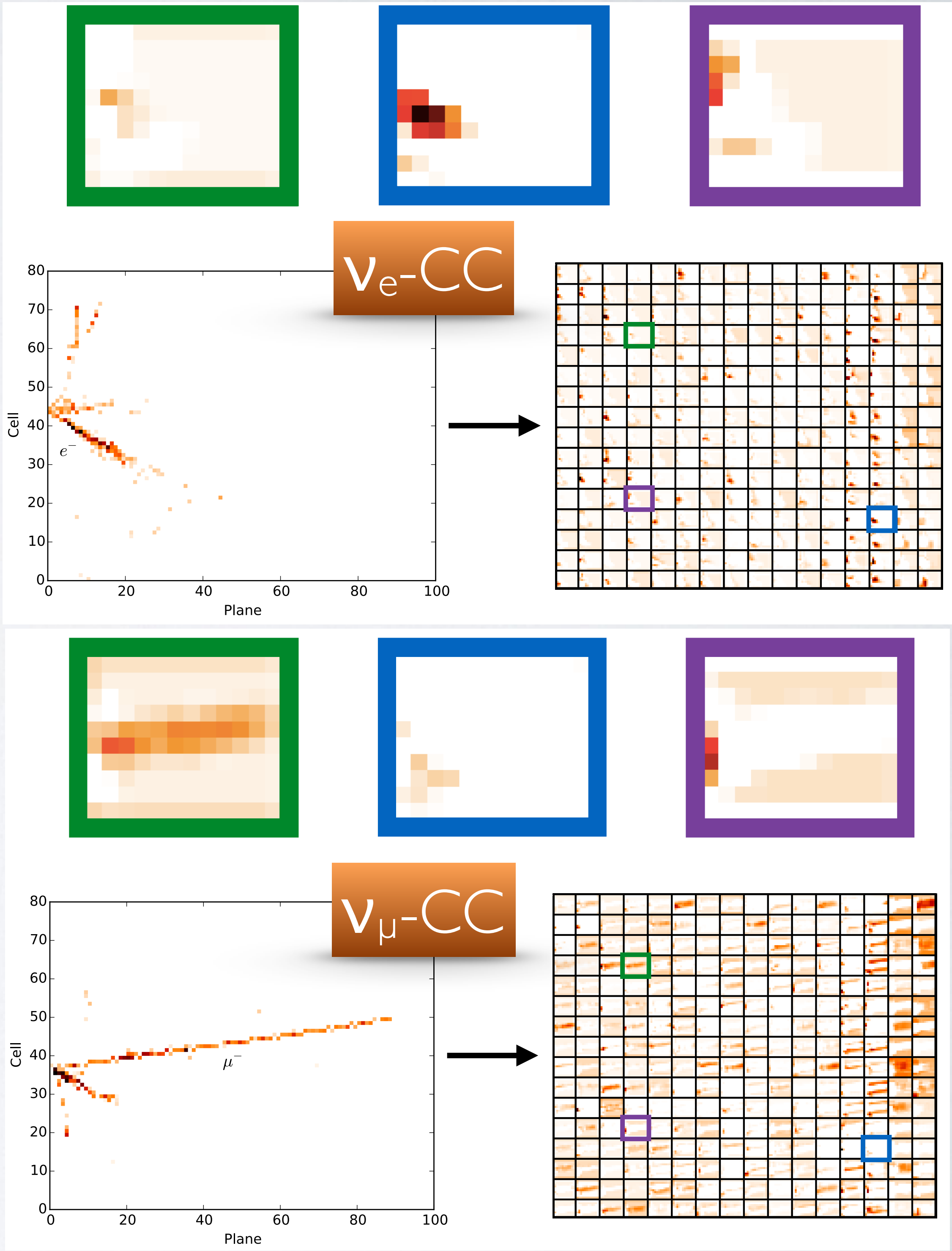


- First usage of image-recognition in particle physics
- Enormous potential both for this and the upcoming generation of experiments

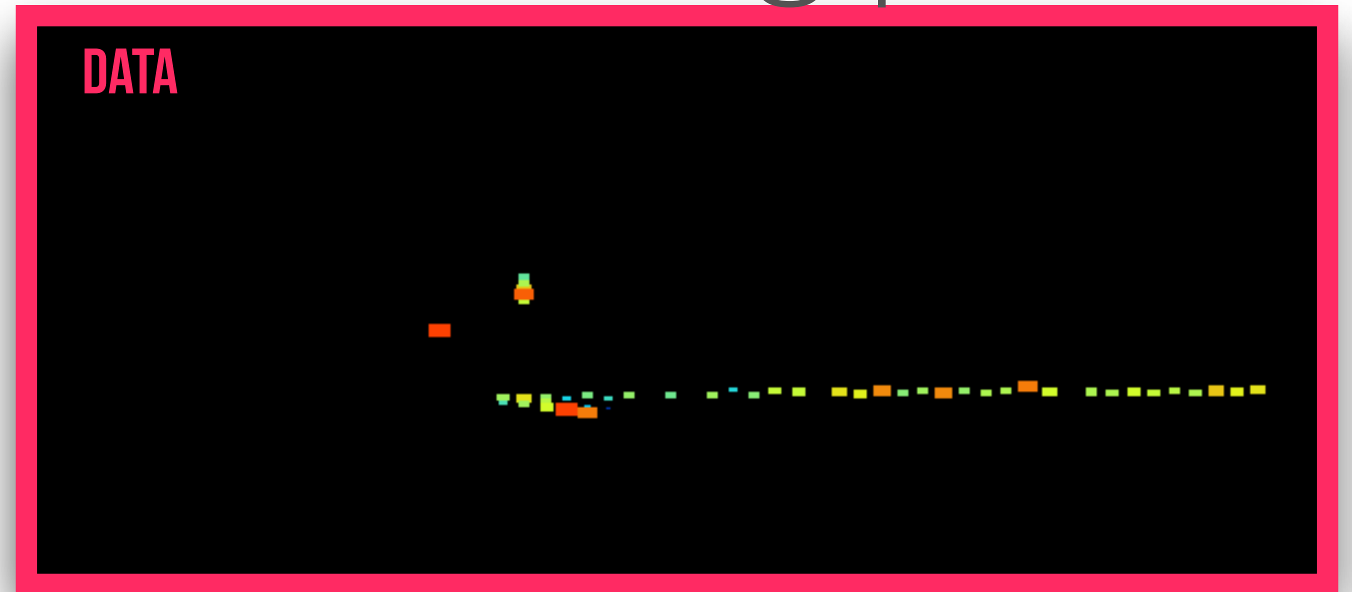
Convolutional neural network

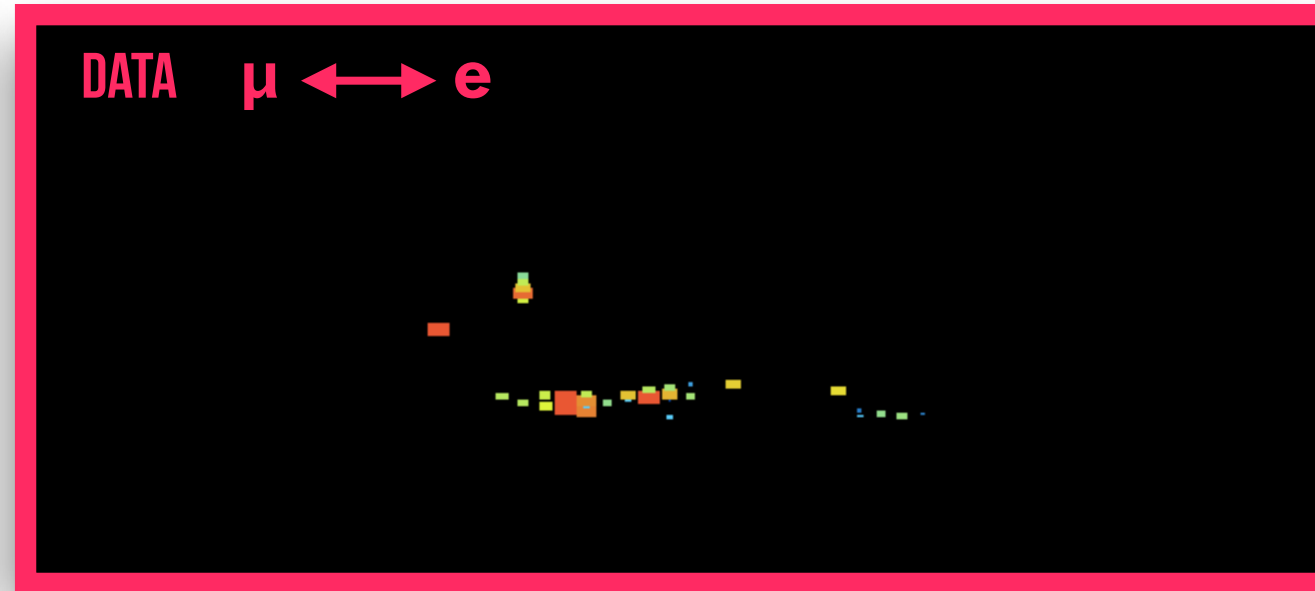
- Event selection based on ideas from computer vision and deep learning
- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Series of image processing transformations applied to extract abstract features
- Extracted features used as inputs to a conventional neural network to classify the event
- **Improvement in sensitivity from CVN equivalent to 30% more exposure**

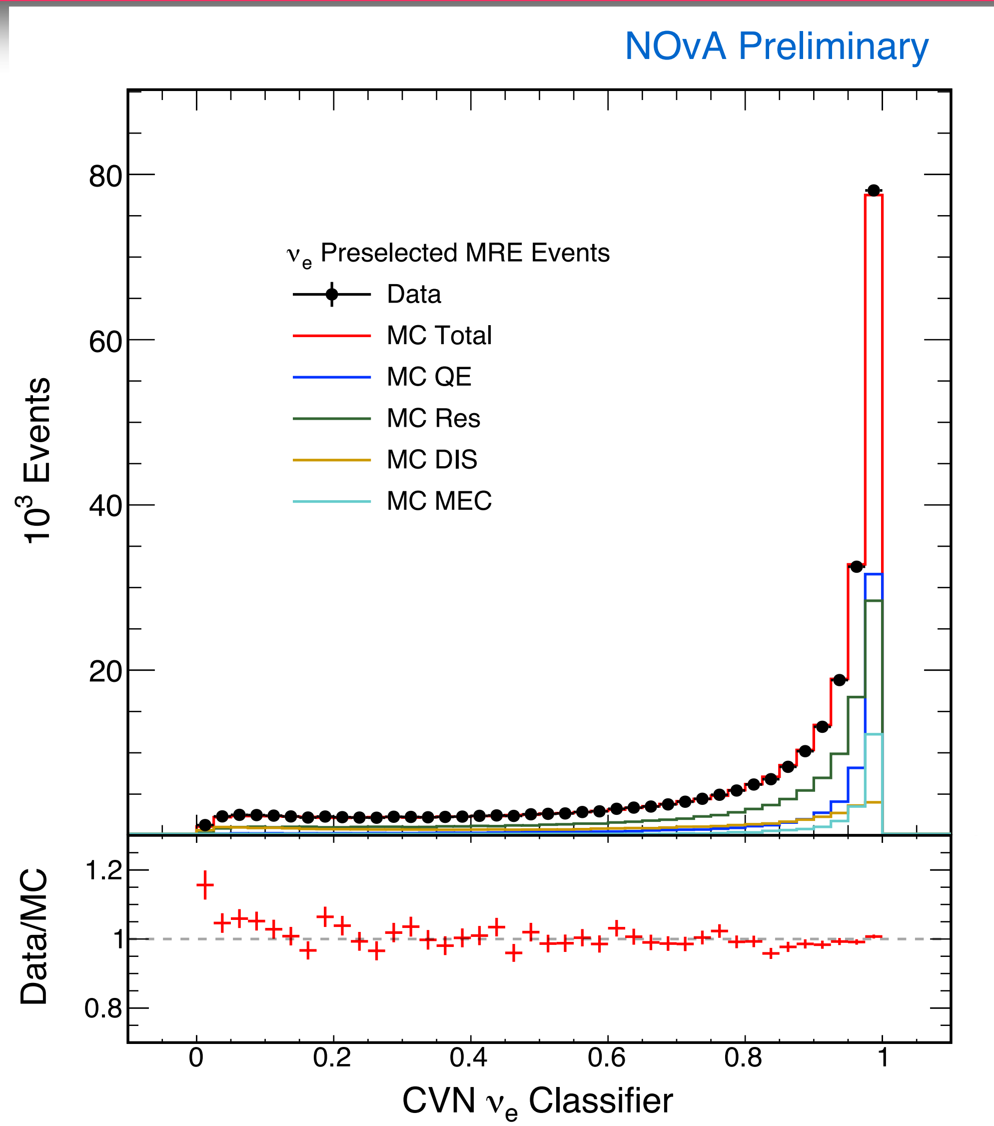
arXiv 1604.01444



Assessing performance on real data







MRE (Muon Removed - Electron):

Select a muon neutrino interaction with traditional ID methods.

Remove the muon hits and replace them with a single simulated electron of matching momentum.

Data/MC comparisons show less than 1% difference in efficiency.

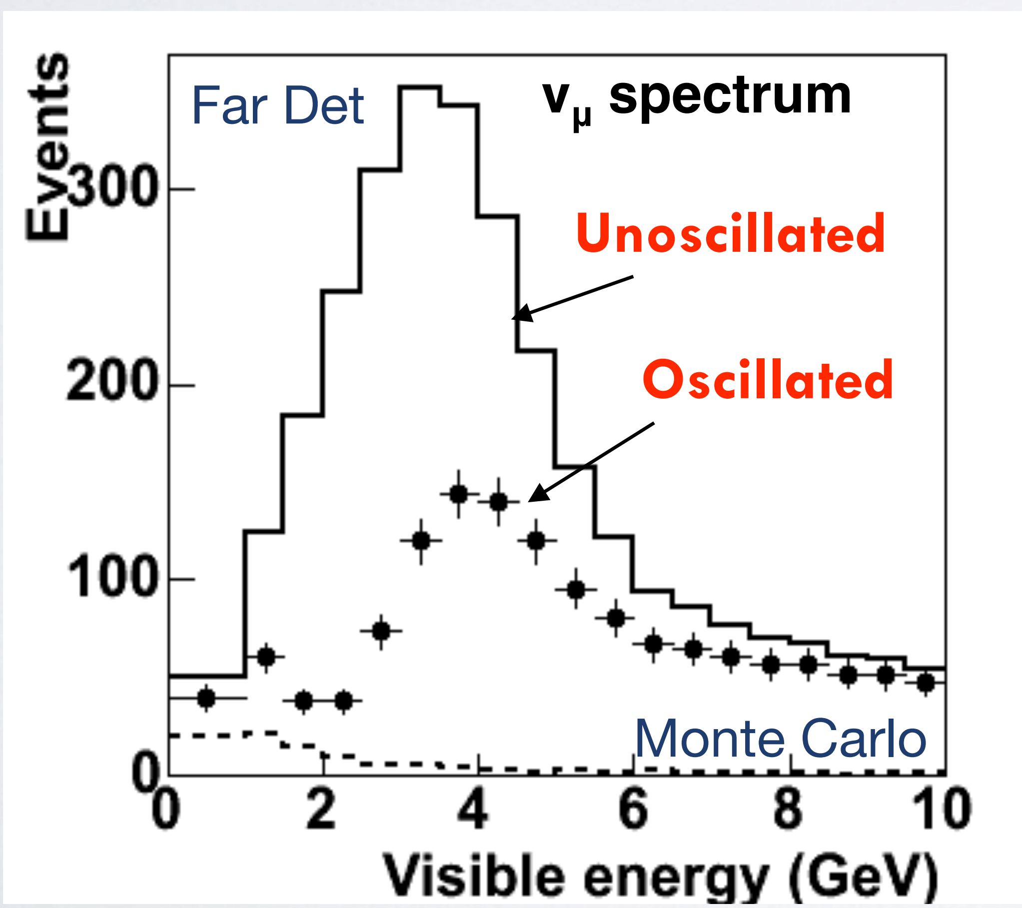
PID	Sample	Preselection	PID	Efficiency	Efficiency diff %
CVN	Data	262884	188809	0.718222	-0.36%
	MC	277320	199895	0.720809	

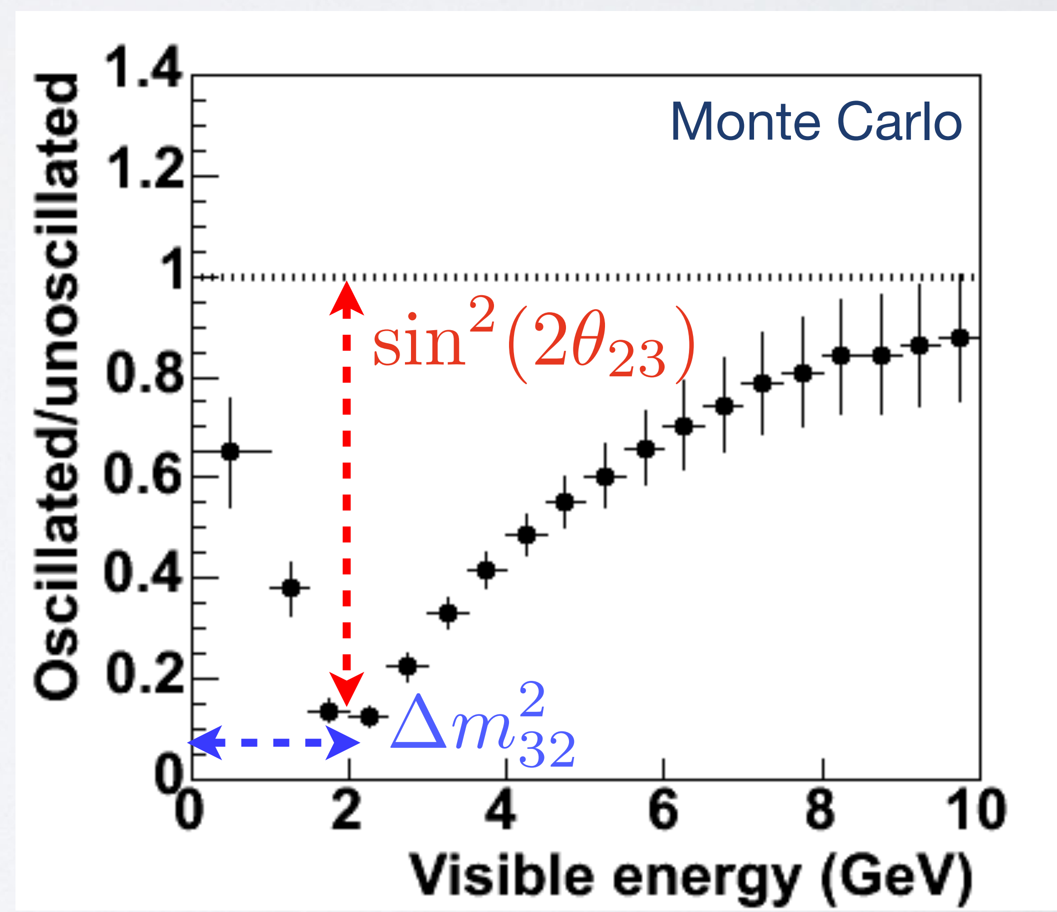
MUON NEUTRINO DISAPPEARANCE

Disappearance analysis in a nutshell…

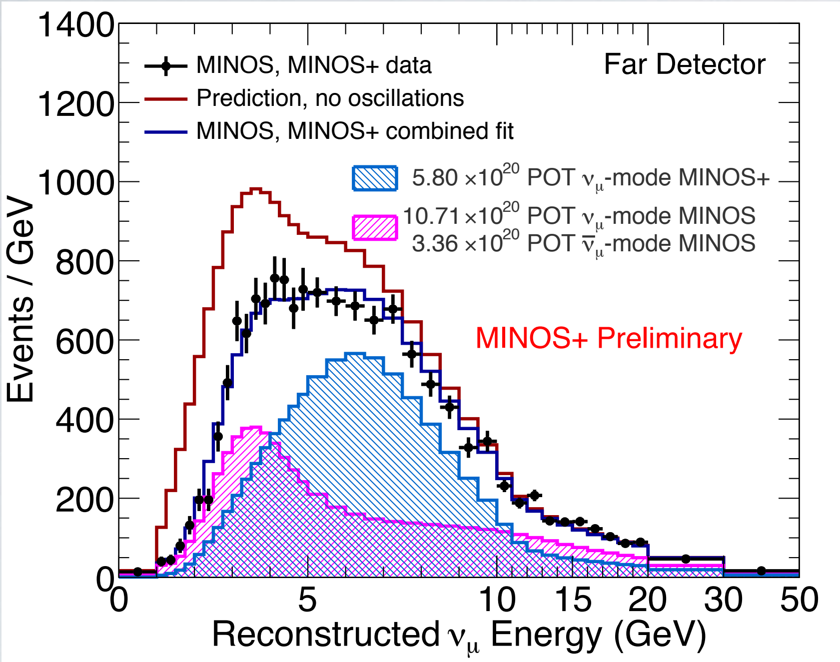
Identify contained ν_μ CC events in both detectors → Measure both energy spectra → Measure oscillation from comparison between near and far energy spectra

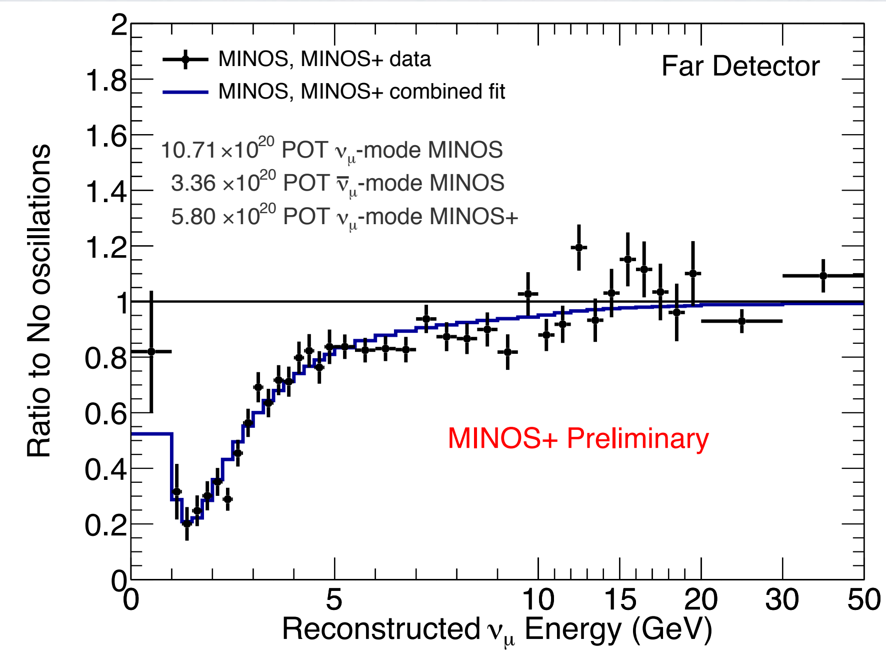
$$P(\nu_\mu \to \nu_\mu) \simeq 1 - \sin^2(2\theta_{23}) \sin^2\left(1.267\Delta m^2_{32}\frac{L}{E}\right)$$

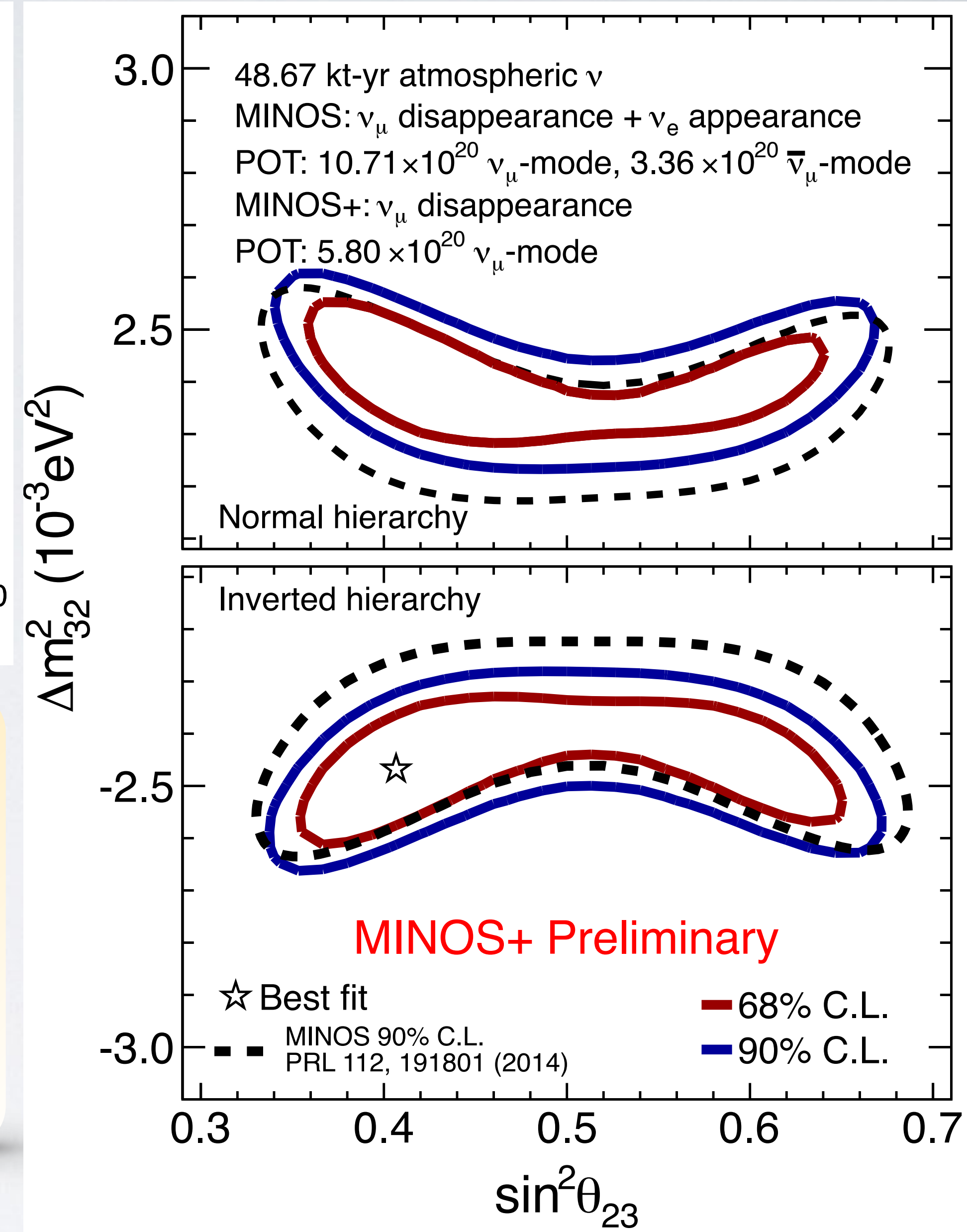




MINOS/MINOS+





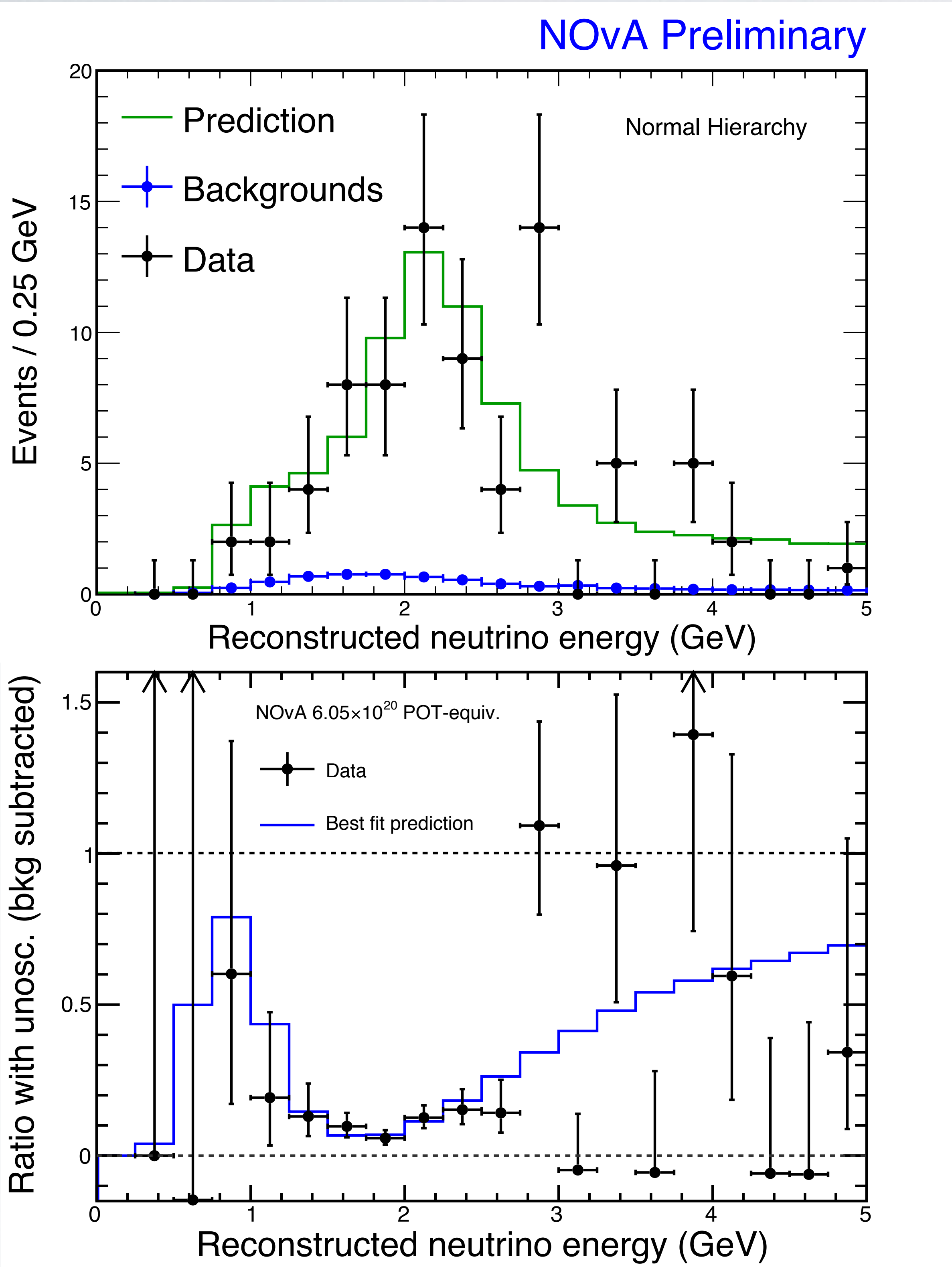


J. Evans (Neutrino 2016)

- Baseline: 735 km
- Magnetised tracker made of Fe
- On-axis (wide energy)

Slight octant preference. Best fit in the inverted hierarchy, but very small sensitivity to mass hierarchy

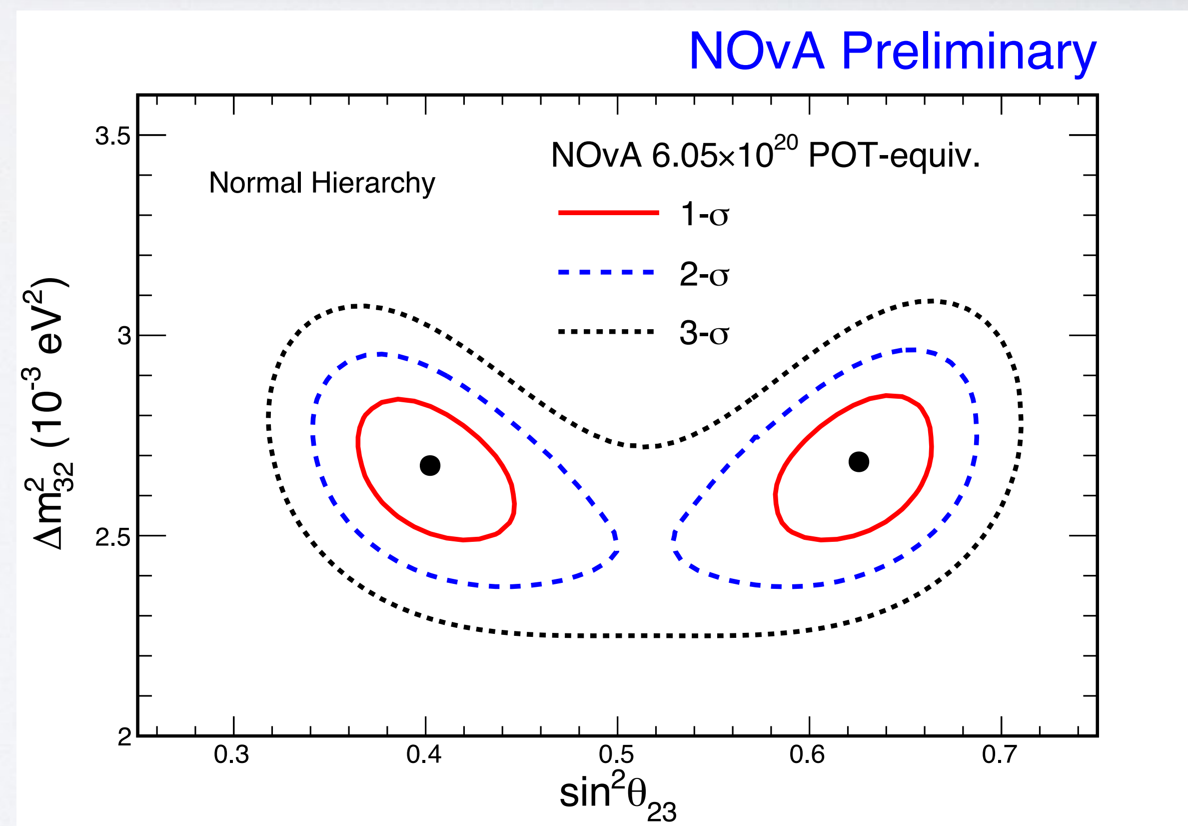
NOvA



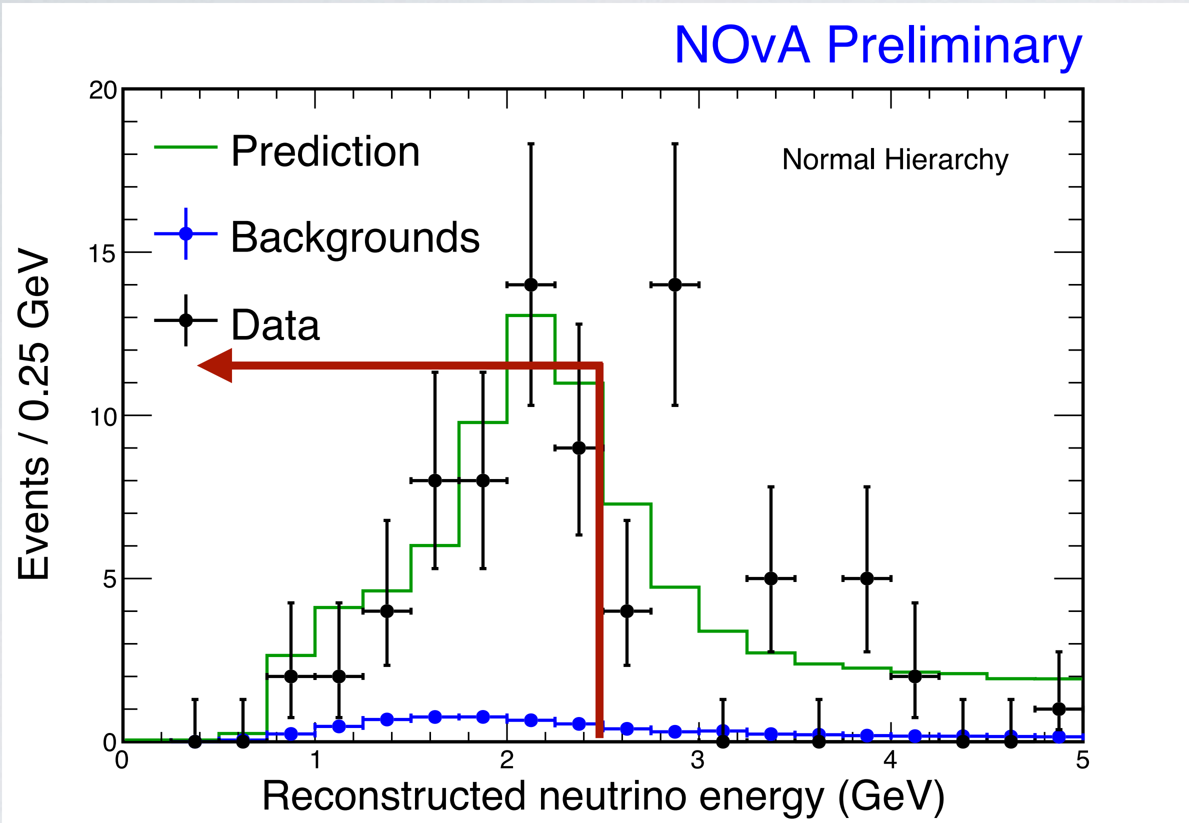
- 473 expected without oscillations
- 82 with oscillations. 78 observed

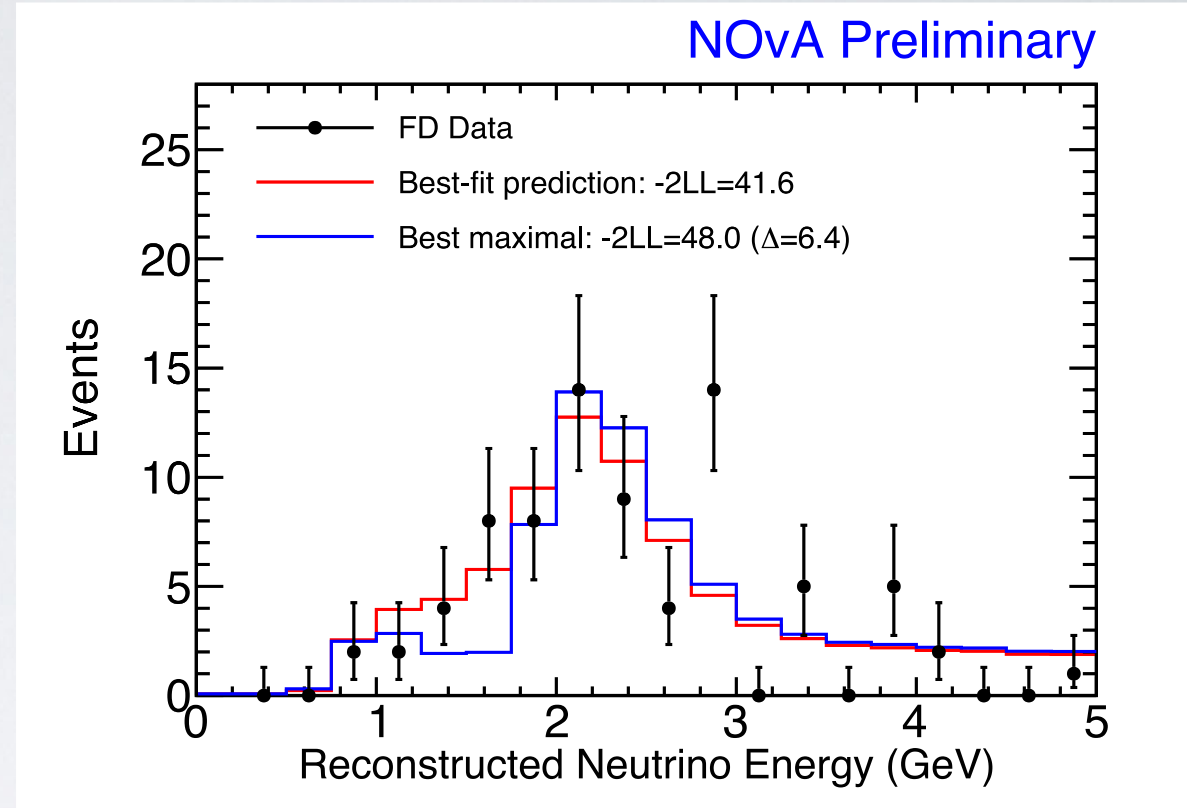
$$\Delta m^2_{32} = (2.67 \pm 0.12) \times 10^{-3} \mathrm{eV}^2 \text{ (NH)}$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} \; (0.63^{+0.02}_{-0.03})$$

Maximal mixing disfavoured at 2.5σ

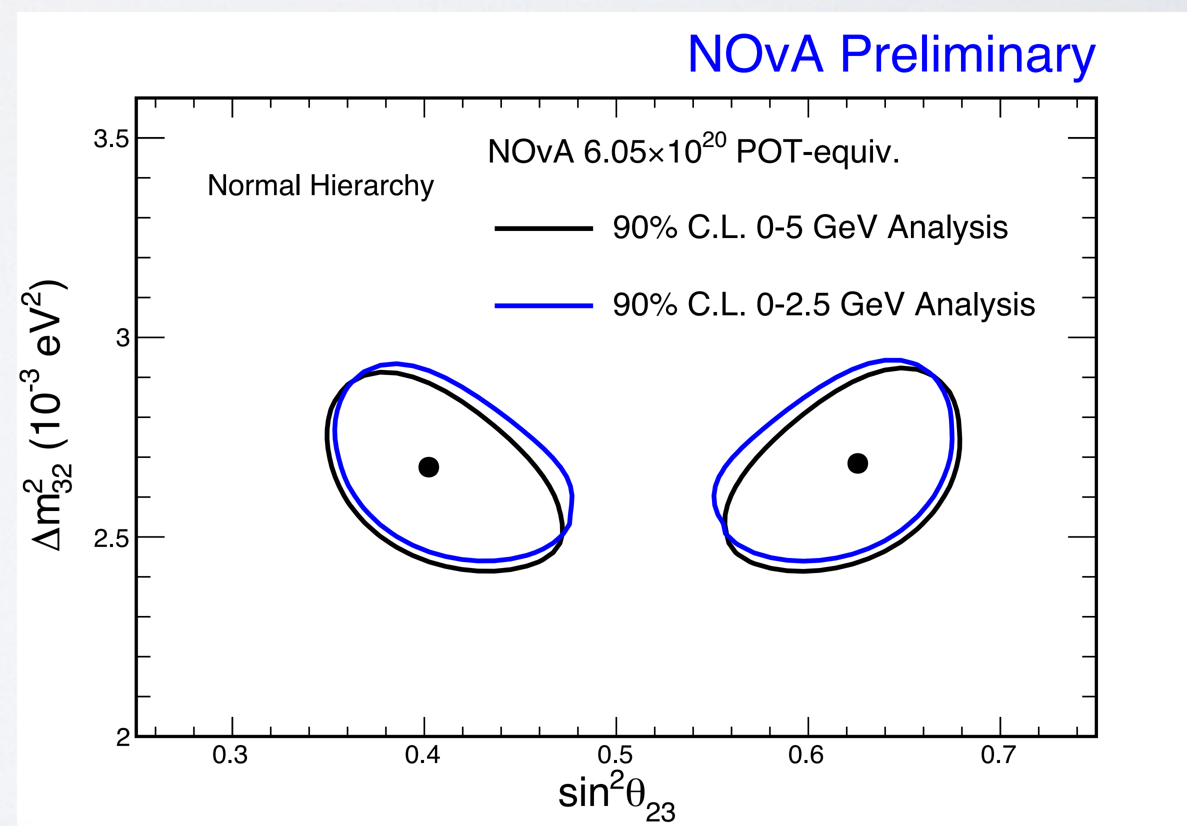


NOvA

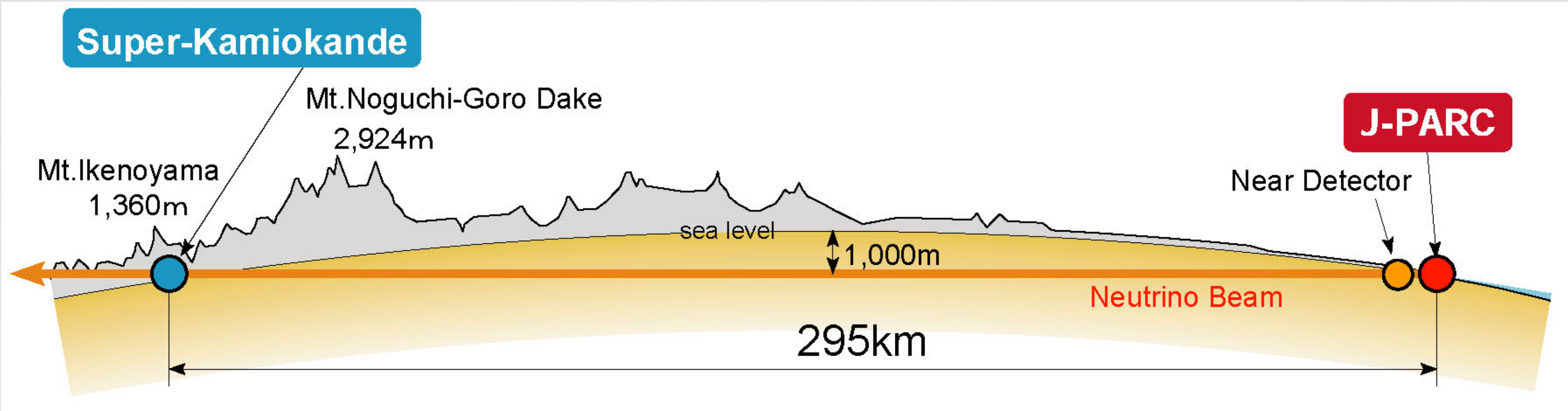




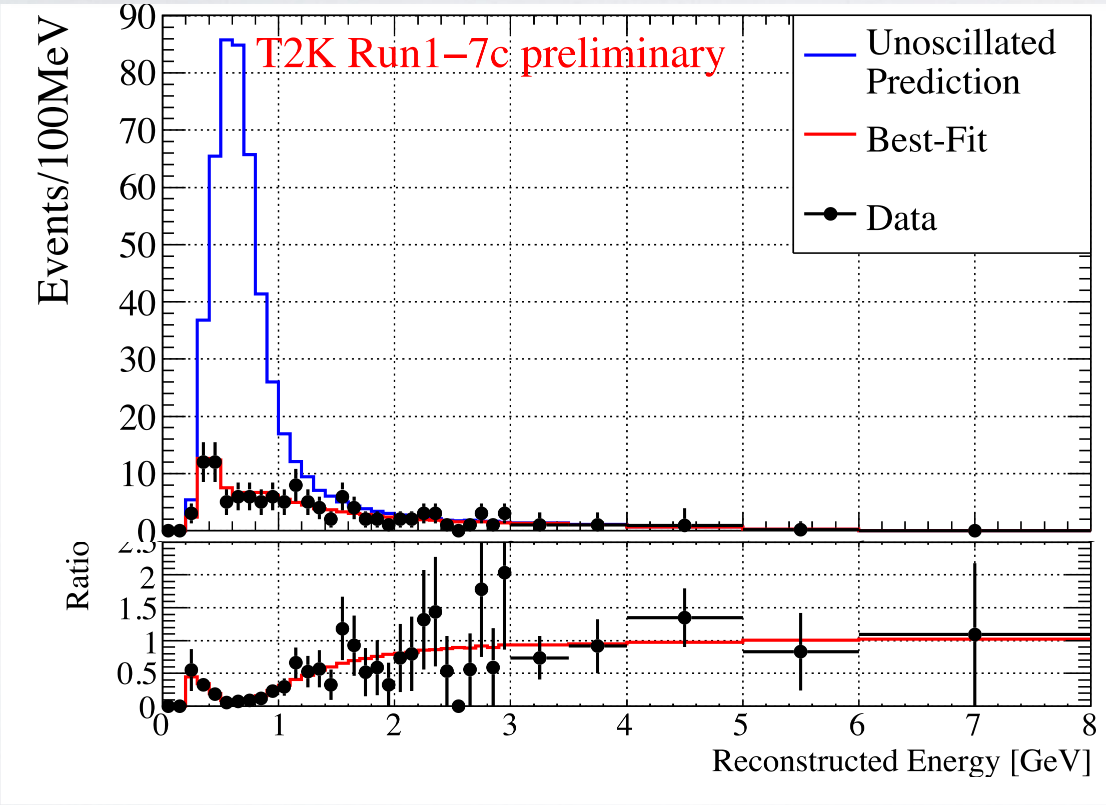
- X^2/ndf = 41.5 / 17 driven by fluctuations on the tail
- Fitting below 2.5 GeV yields X^2/ndf = 3.2/7 but negligible change on result (and same maximal mixing rejection)
- Best fit at forced maximal mixing has ΔX^2 = 6.4

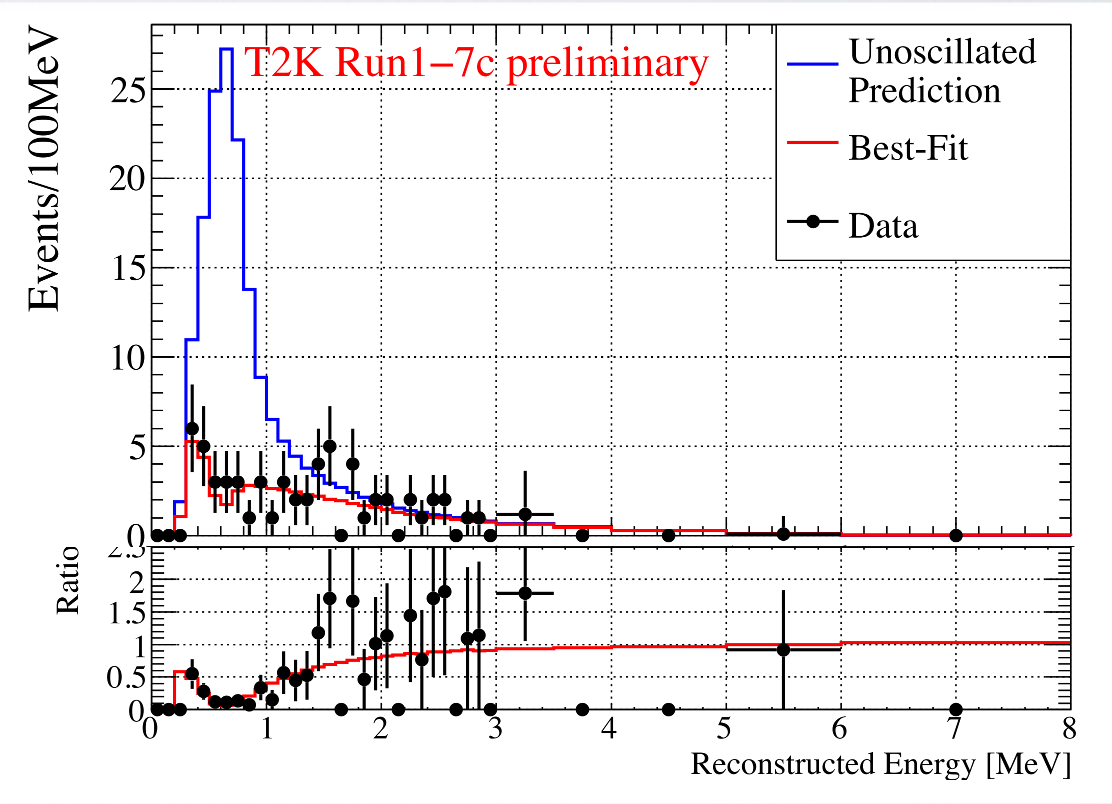


T2K



- It has run in both neutrino and antineutrino modes
- 135 neutrino candidates with a prediction of 135.8
- 66 antineutrino candidates with a prediction of 64.2



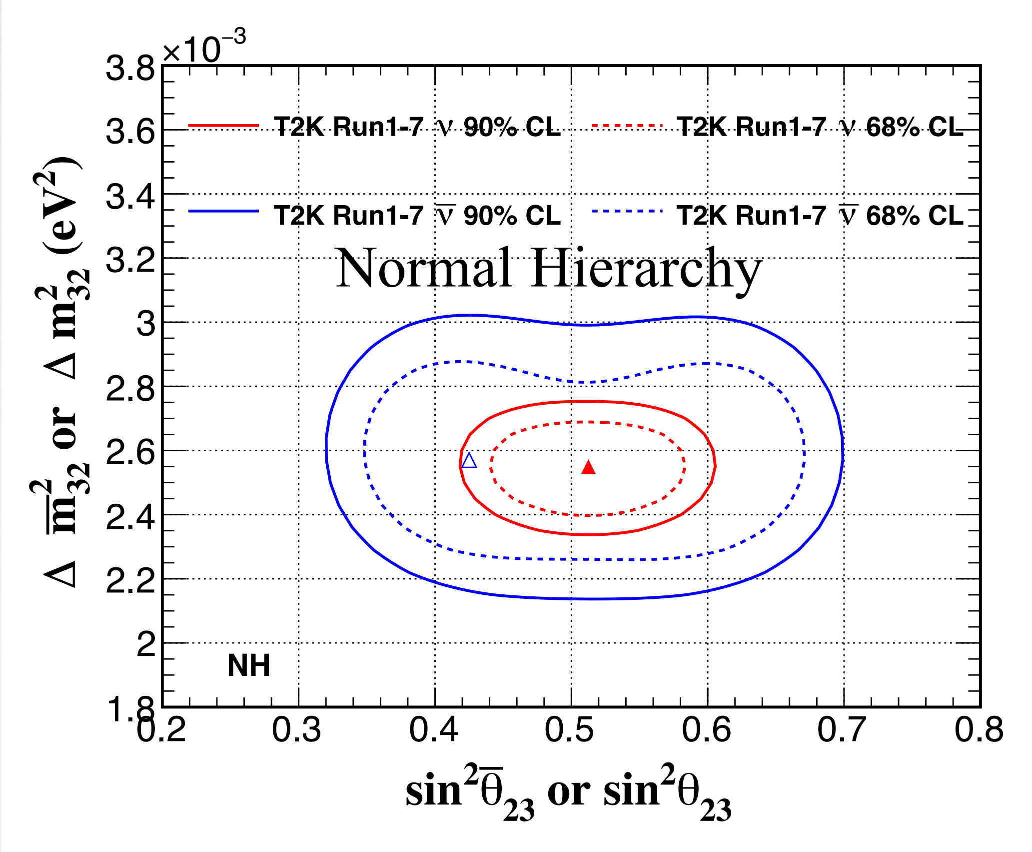


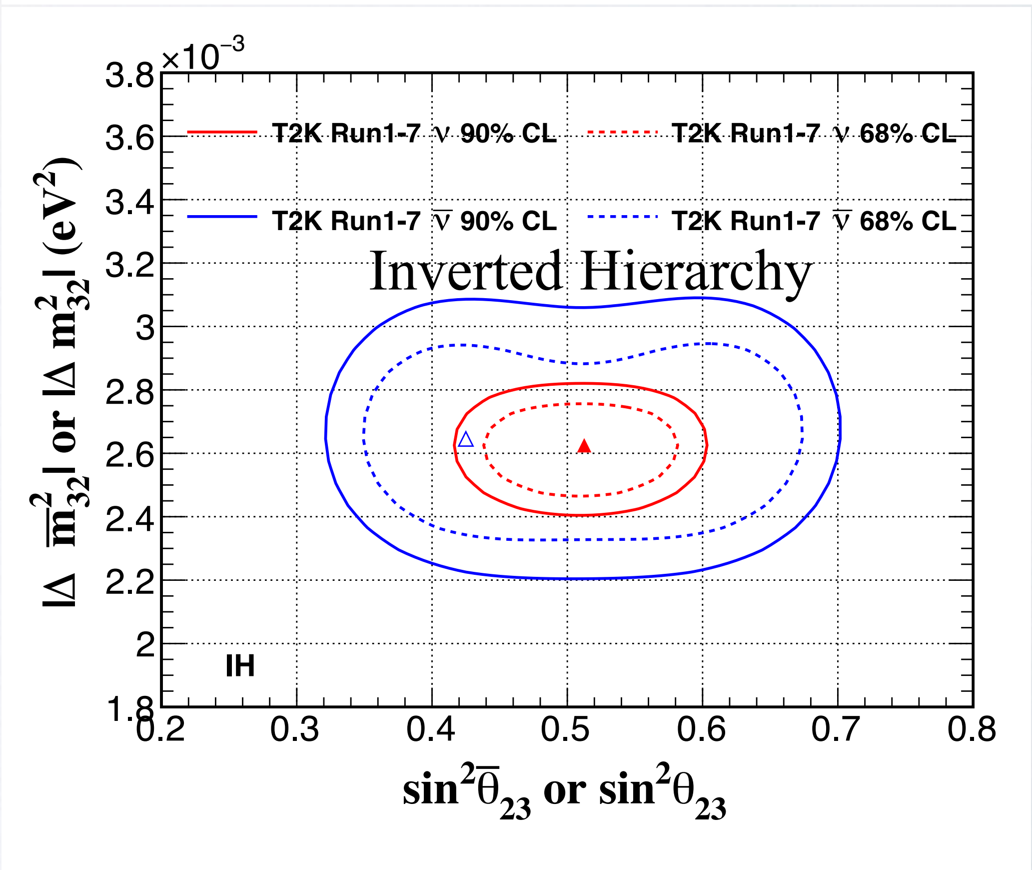
K. Iwamoto (ICHEP 2016)

T2K

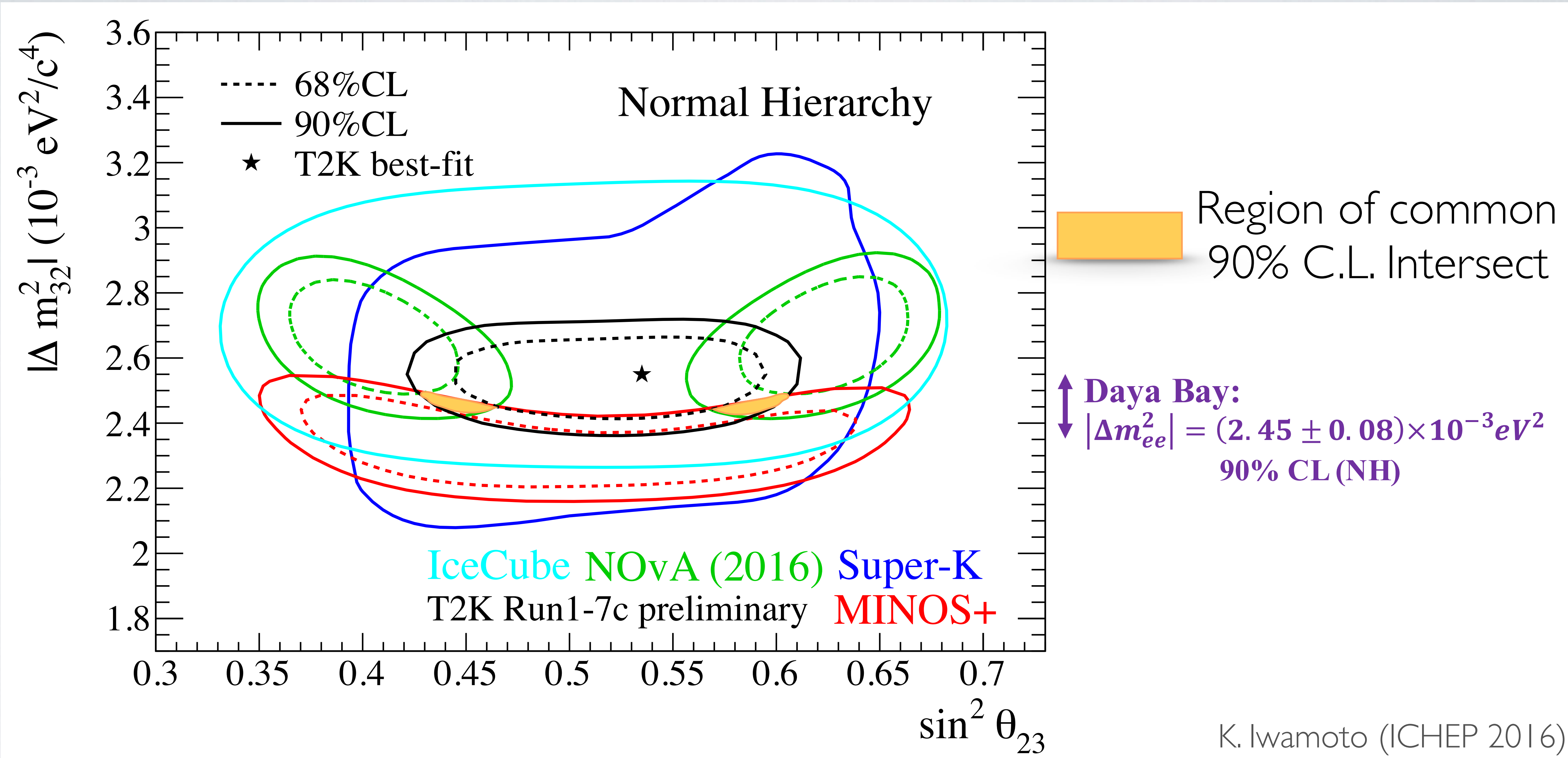
- T2K results are consistent with maximal mixing for both neutrinos and antineutrinos
- No evidence of CPT violation within errors
- Best fit for antineutrinos is slightly non-maximal

	NH	IH
$\sin^2\theta_{23}$	$0.532^{+0.046}_{-0.068}$	$0.534^{+0.043}_{-0.066}$
$\lvert\Delta m^2_{32}\rvert[10^{-3}\text{eV}^2]$	$2.545^{+0.081}_{-0.084}$	$2.510^{+0.081}_{-0.083}$



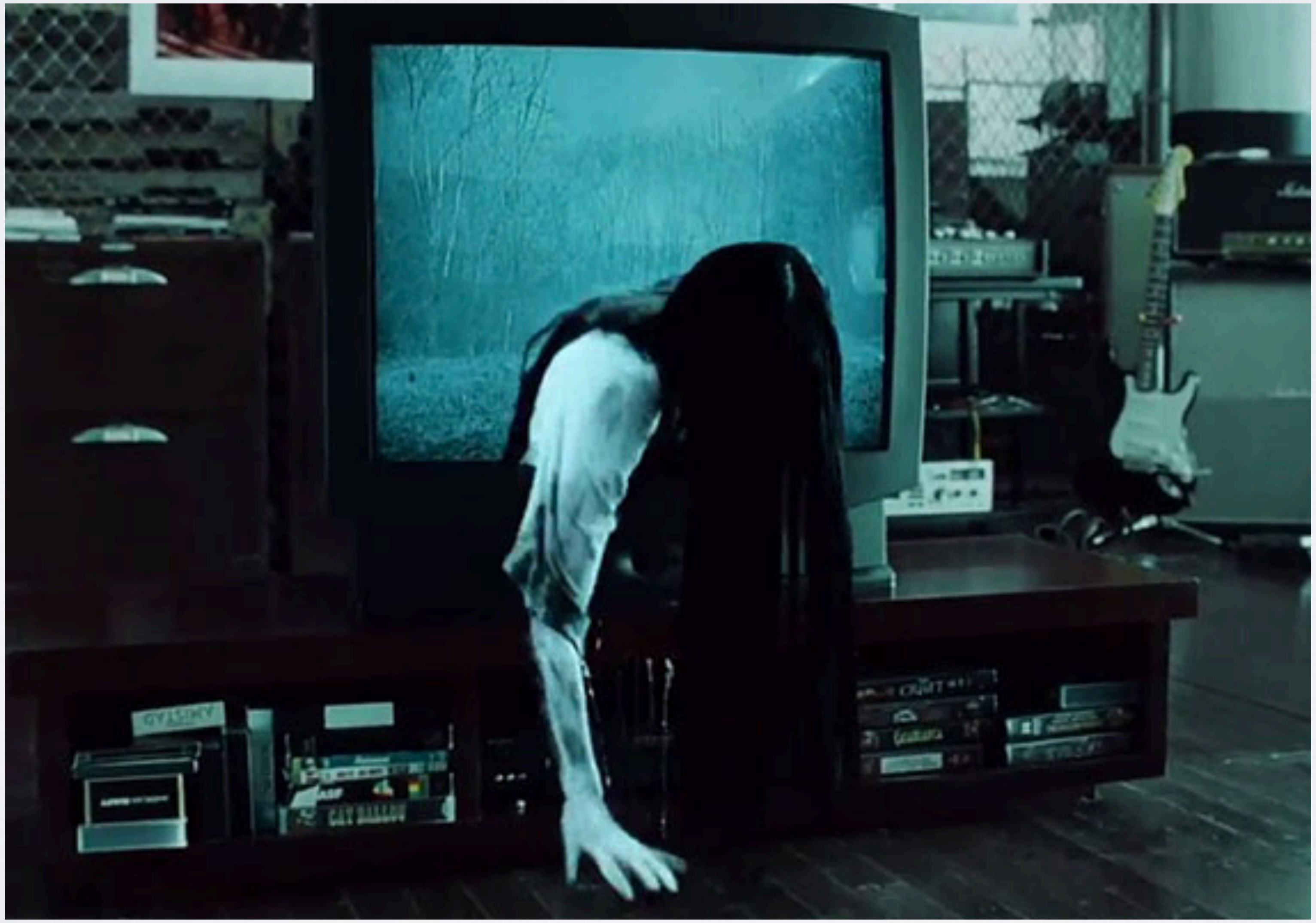


Comparison



- Small tension across accelerator experiments
- More data should shed light on whether it's just a statistical fluctuation

ELECTRON NEUTRINO APPEARANCE

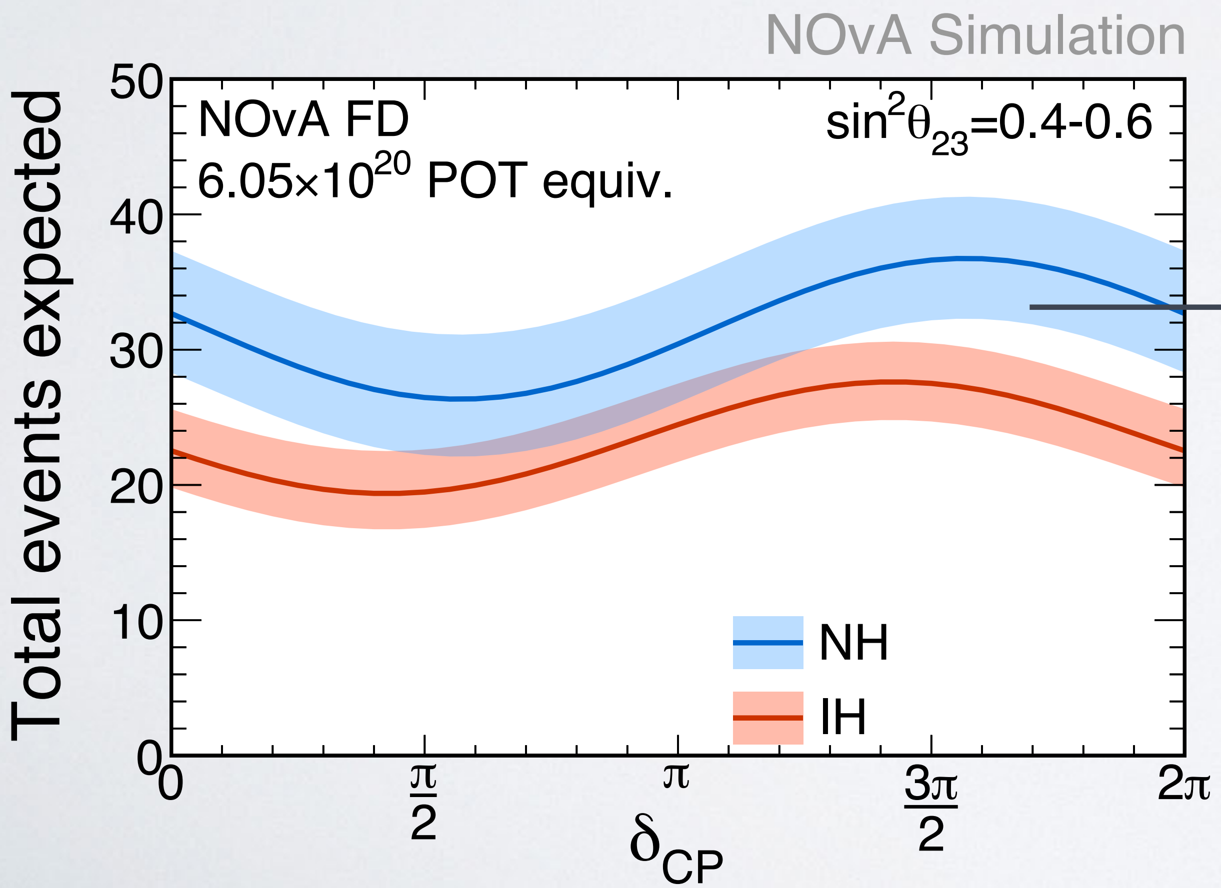


Appearance analysis in a nutshell…

Identify ν_e CC events in both detectors

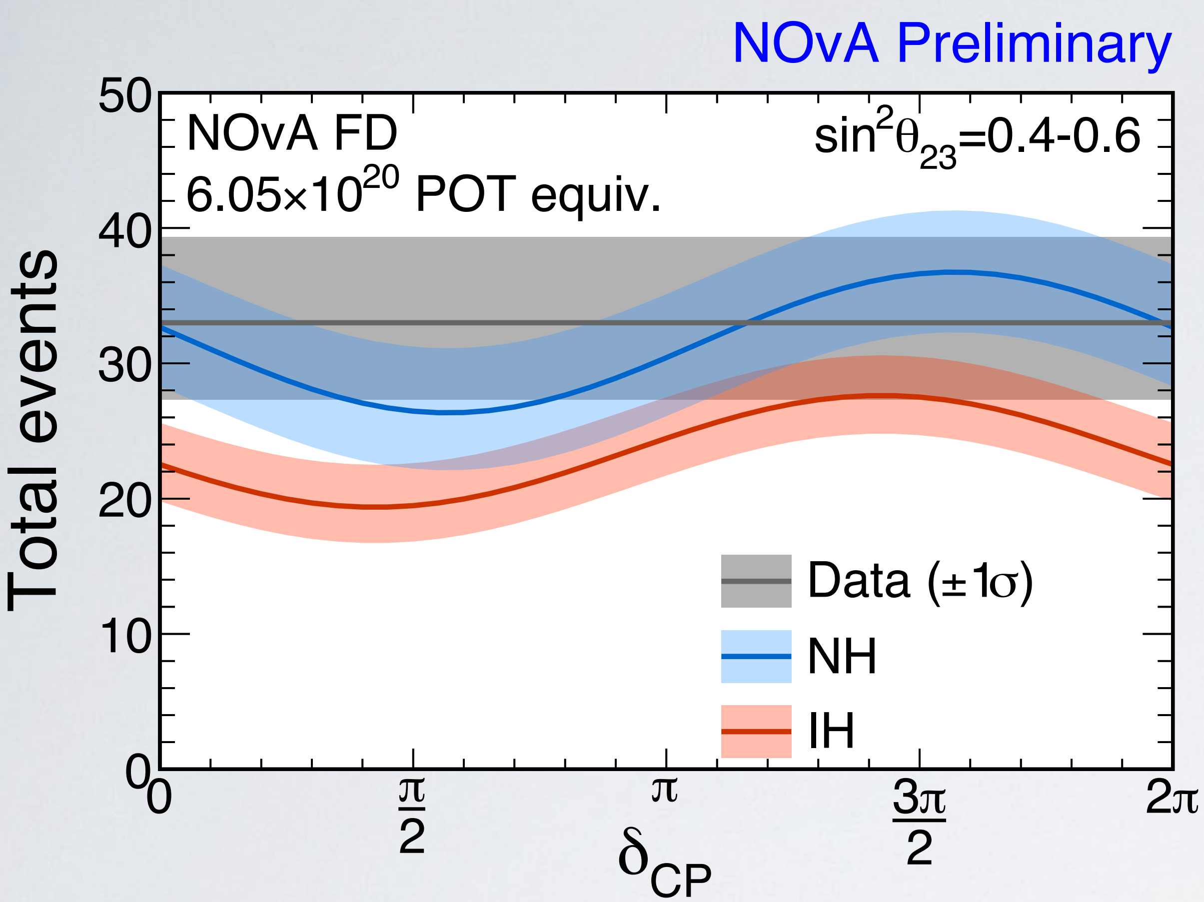
Use ND measurements to predict backgrounds in the FD

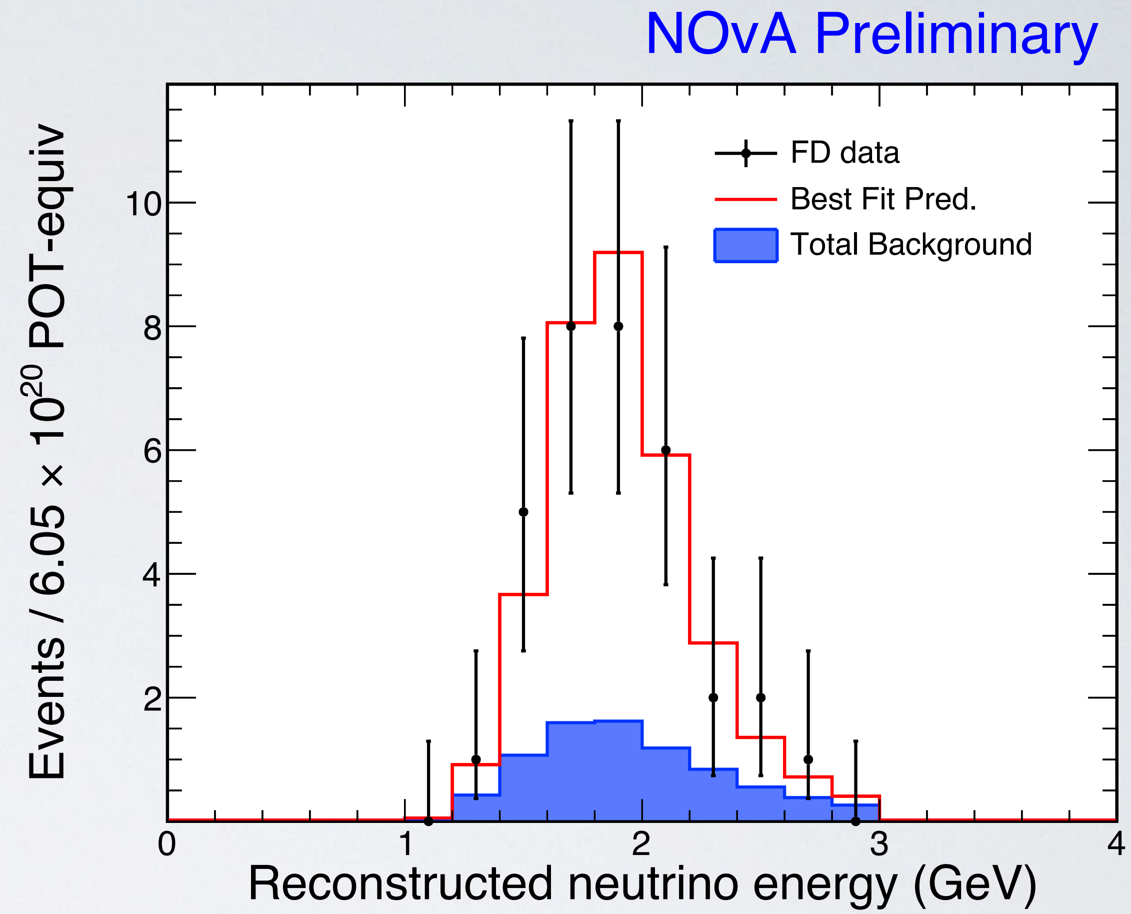
Interpret any FD excess over predicted backgrounds as ν_e appearance



Number of observed events constraints δ_{CP} and mass hierarchy

NOvA





Signal events
(±5% systematic uncertainty):

NH, $3\pi/2$,	IH, $\pi/2$,
28.2	11.2

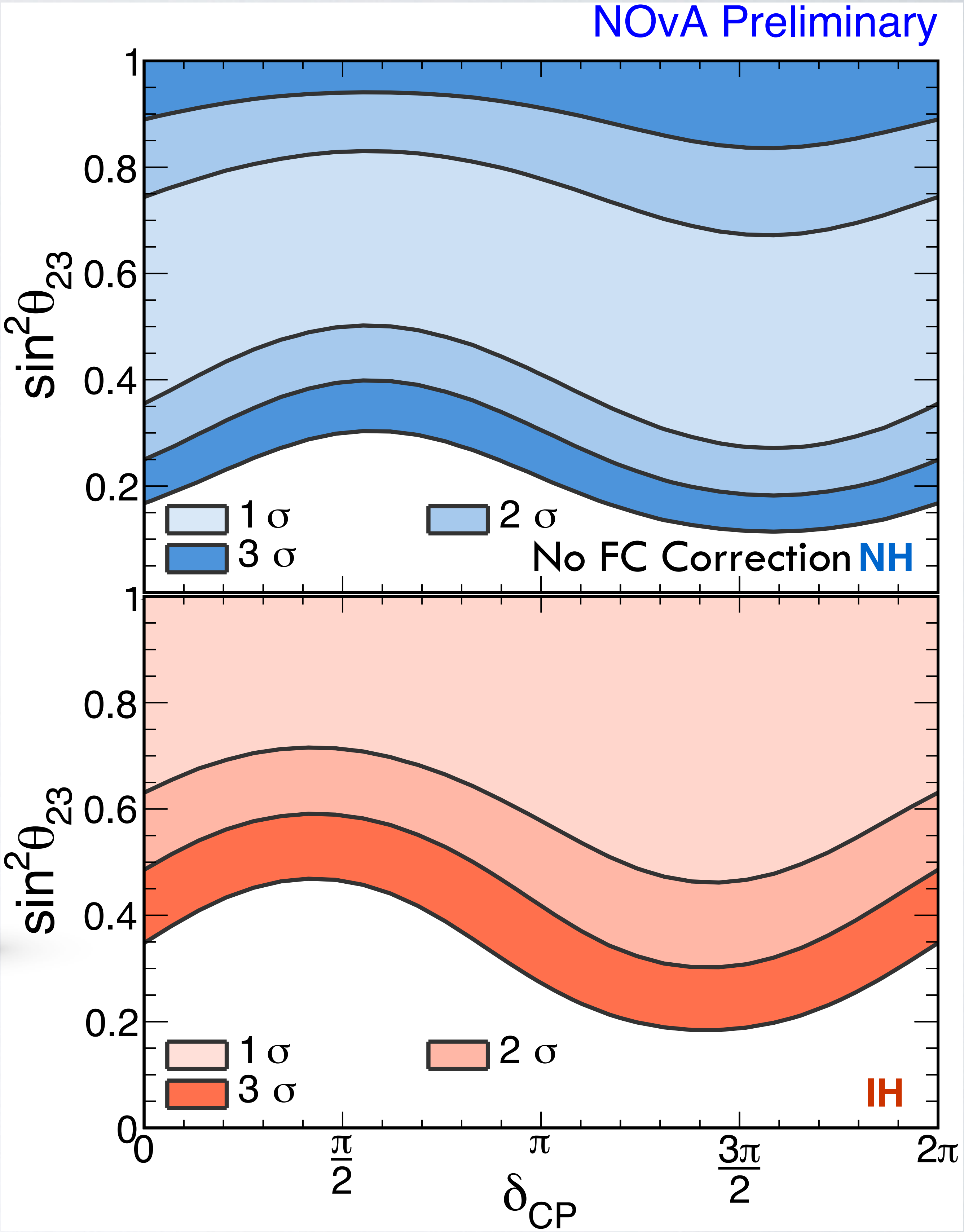
- Observe 33 events over a background of 8.2
- Towards the higher end of the expectation

Background by component
(±10% systematic uncertainty):

Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5

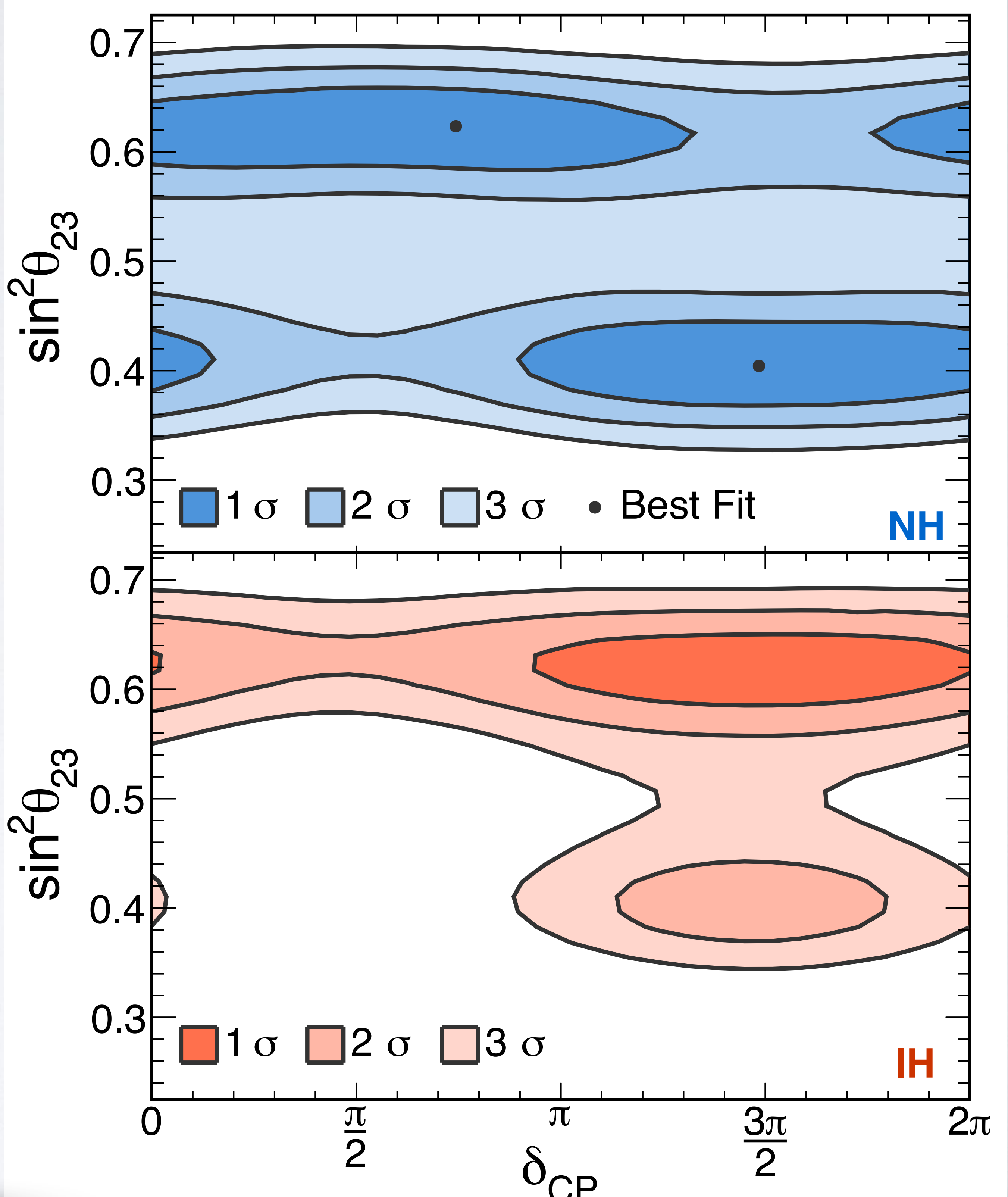
NOvA

- Fit for hierarchy, δ_{CP}, $\sin^2\theta_{23}$
- Include reactor constraints $\sin^2(2\theta_{13})=0.085\pm0.05$



NOvA

- Include θ_{23} and Δm^2_{32} from disappearance analysis
- Fully joint analysis including all systematic correlations
- Best fit to NH, δ_{CP} = 1.49π and $\sin^2(\theta_{23})$ = 0.40
- But best fit IH-NH has ΔX^2 = 0.47
- IH, lower octant around $\delta_{CP} = \pi/2$ disfavoured at 3σ
- Antineutrino data planned for Spring 2017 will help resolve degeneracies



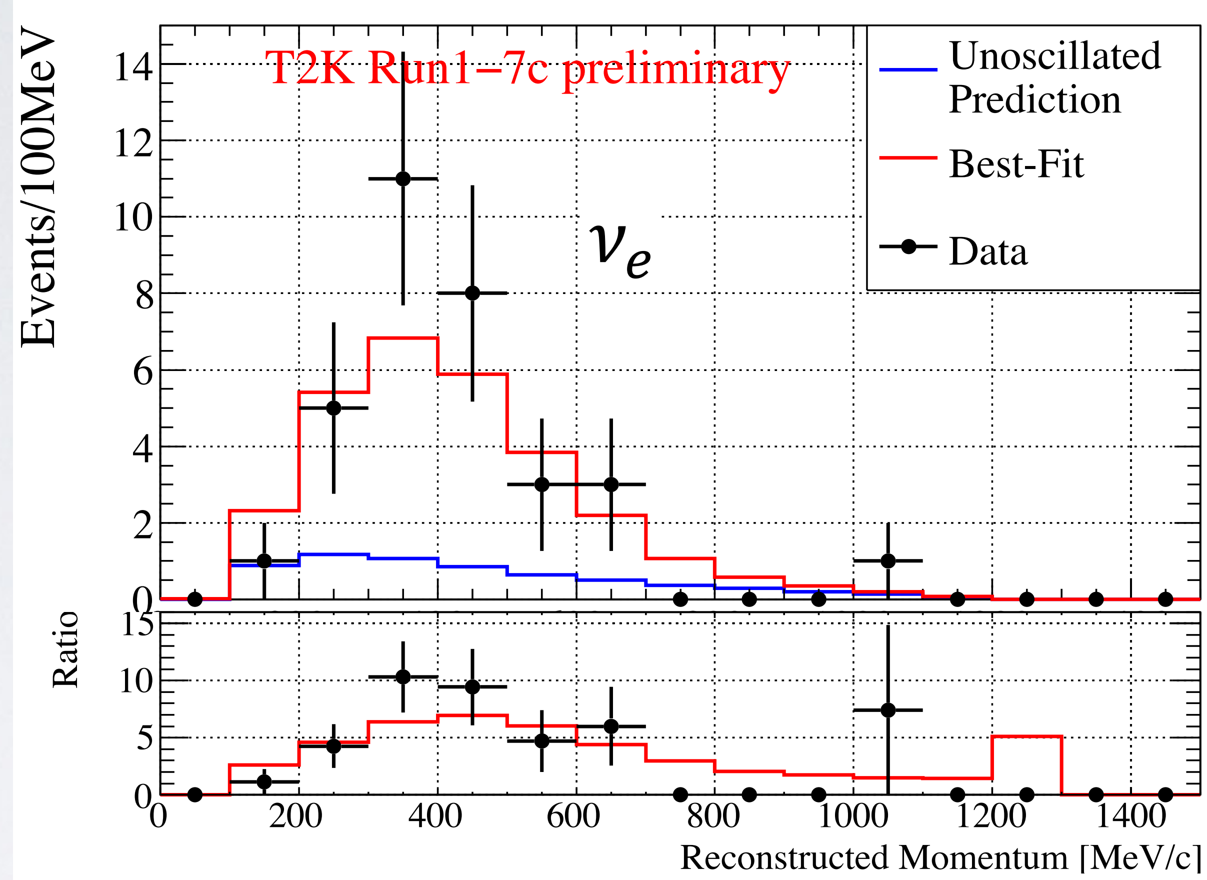
T2K

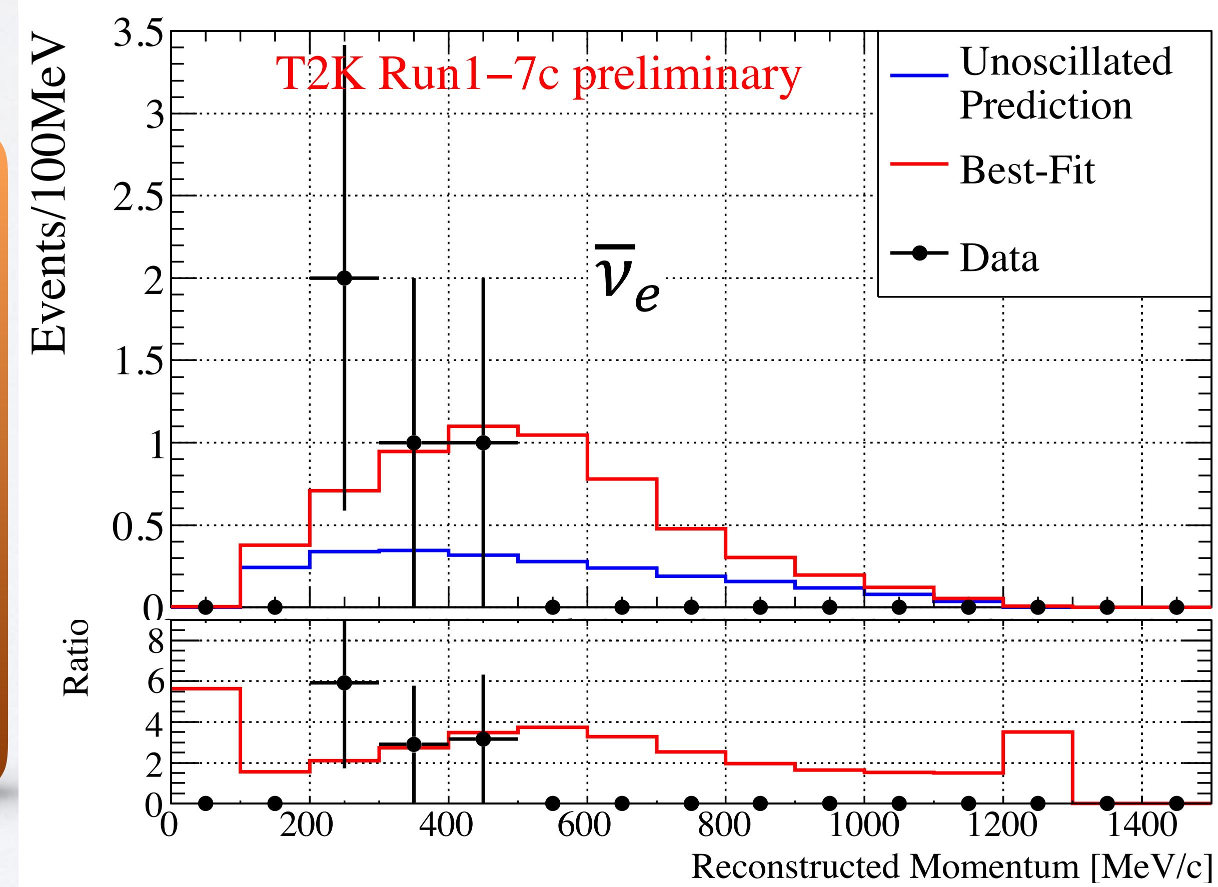
K. Iwamoto (ICHEP 2016)

		EXPECTED (NH, $\sin^2\Theta_{23}$=0.528)			
	OBS.	δ_{CP}=-π/2	δ_{CP}=0	δ_{CP}=+π/2	δ_{CP}=π
ν_e	32	27.0	22.7	18.5	22.7
$\overline{\nu}_e$	4	6.0	6.9	7.7	6.8

↑

Favoured at
$\delta_{CP} = -\pi/2$





T2K has observed 32 neutrino candidates and 4 antineutrino candidates

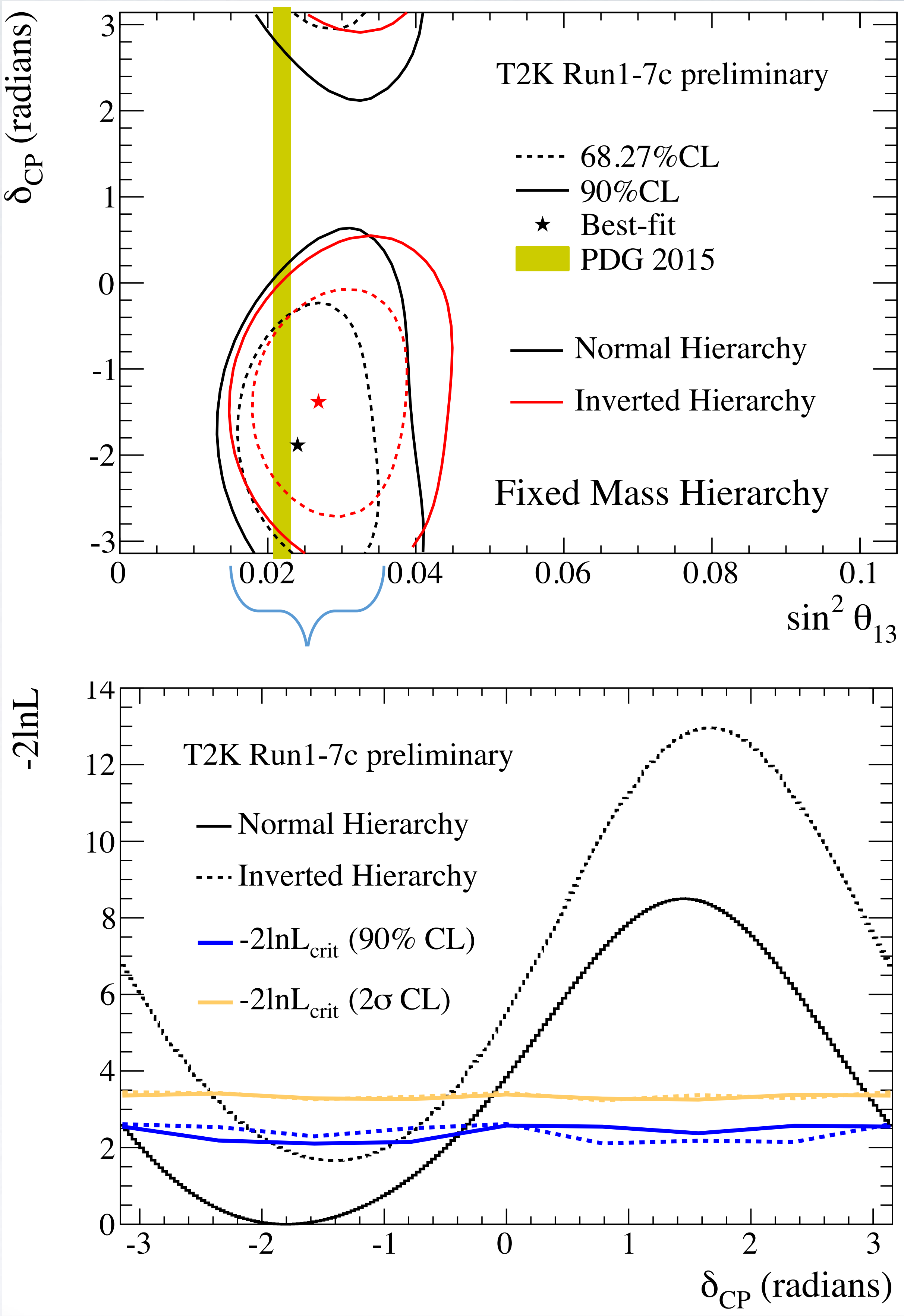
Some small tension:

Neutrinos too high (upper octant?)

Antineutrinos too low (lower octant?)

T2K

- Results consistent with the amount of appearance expected from information in rector experiments
- Combining with reactor and T2K muon neutrino disappearance data:
- **Claim 90% exclusion of no CP violation (dCP = 0 or π)**
- Exclusion depends on T2K's observed maximal mixing angle



Next generation experiments

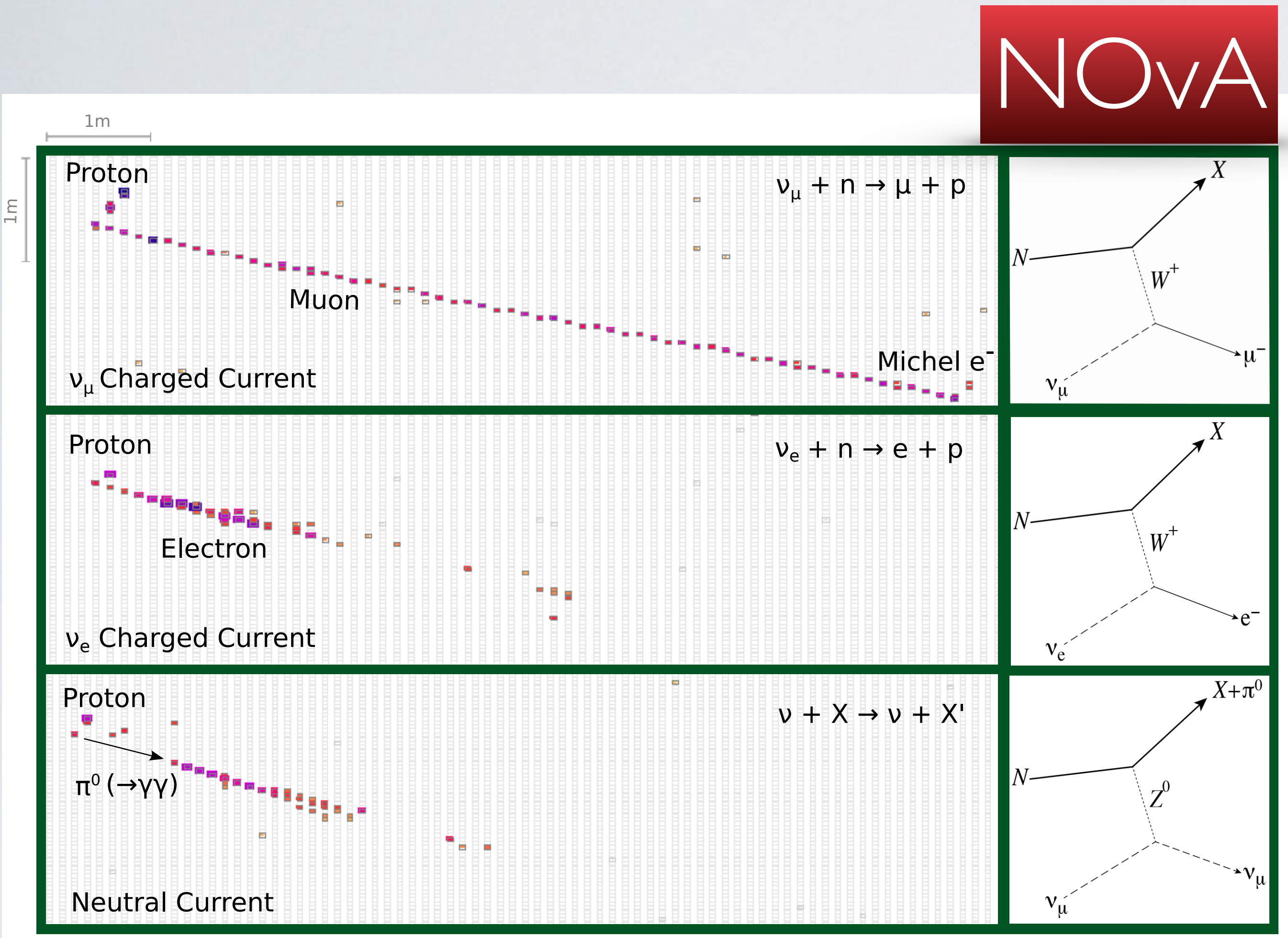
1st generation | 2nd generation | 3rd generation

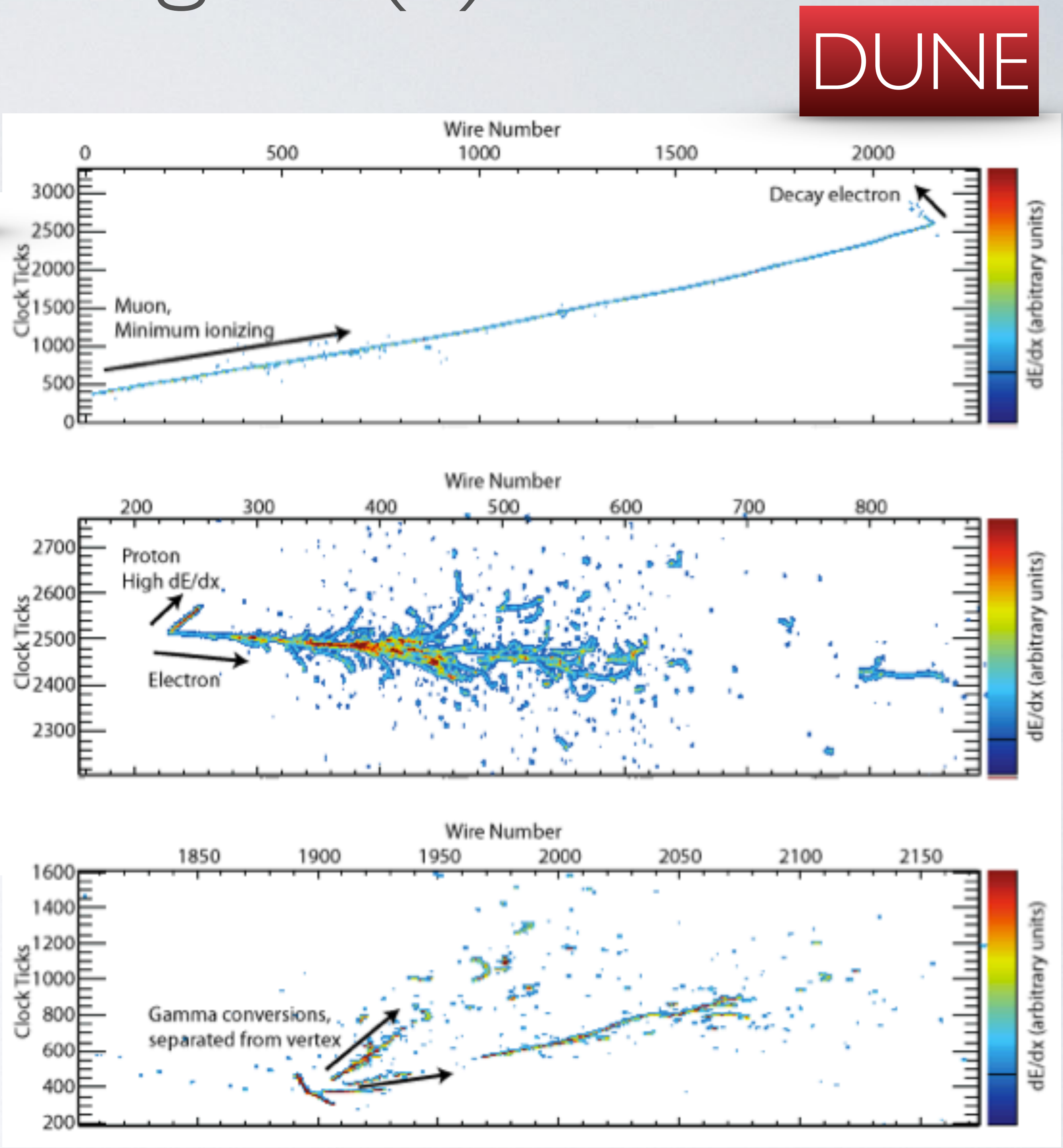
- Higher intensity beams can provide more neutrinos and allow for a longer baseline
- Similarly, larger mass can allow to collect more neutrinos
- Finally, higher detector resolution allows for better background rejection

In the US, DUNE is being planned with a baseline of 1300 km, a new 2.3 MW beam and high resolution liquid argon detectors

In Japan, HyperK is also being planned with an upgrade to 1.3 MW beam and 500 kton detector

Event topologies (II)



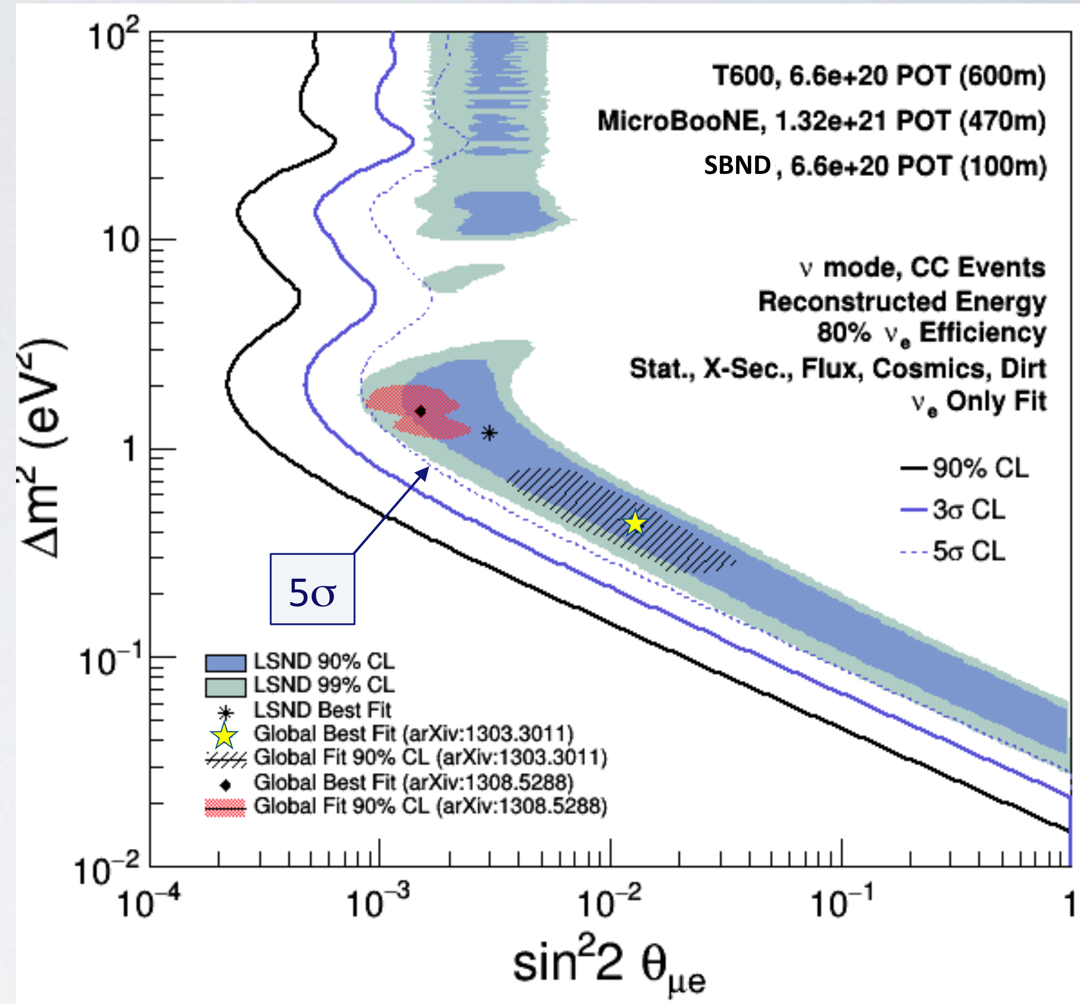


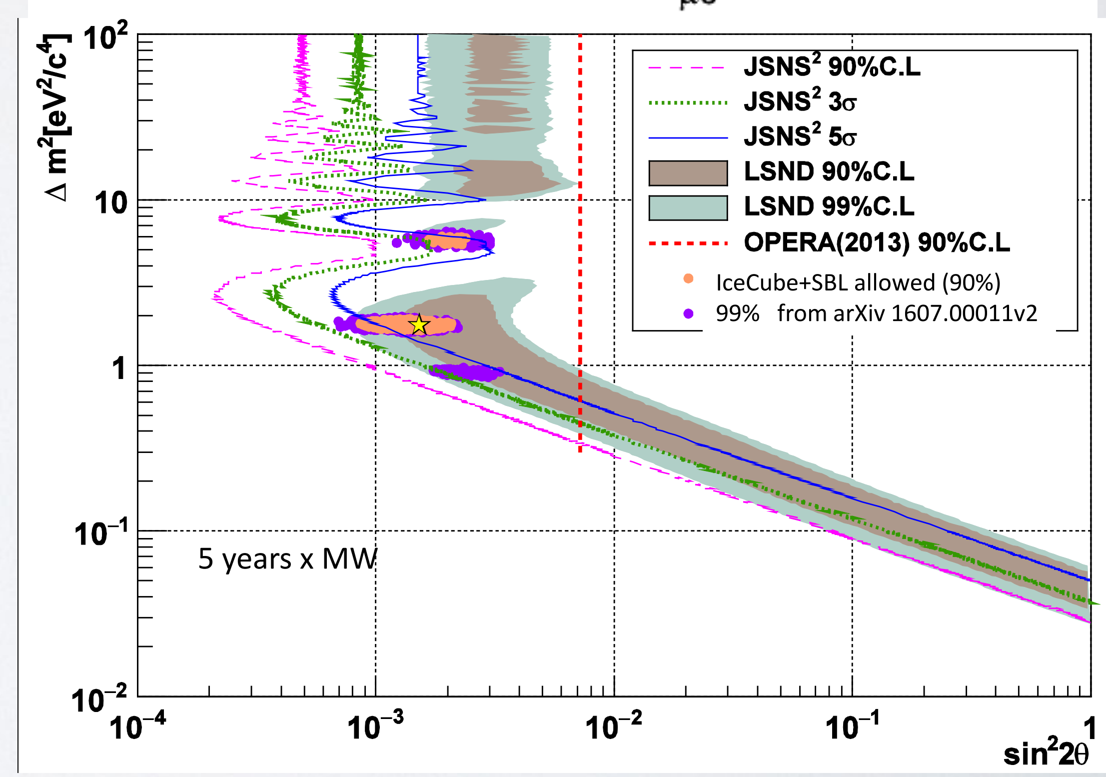
"Like going from a set of pictures to 3D HD video"

Sterile neutrinos?

D. Schmitz (Neutrino 2016)

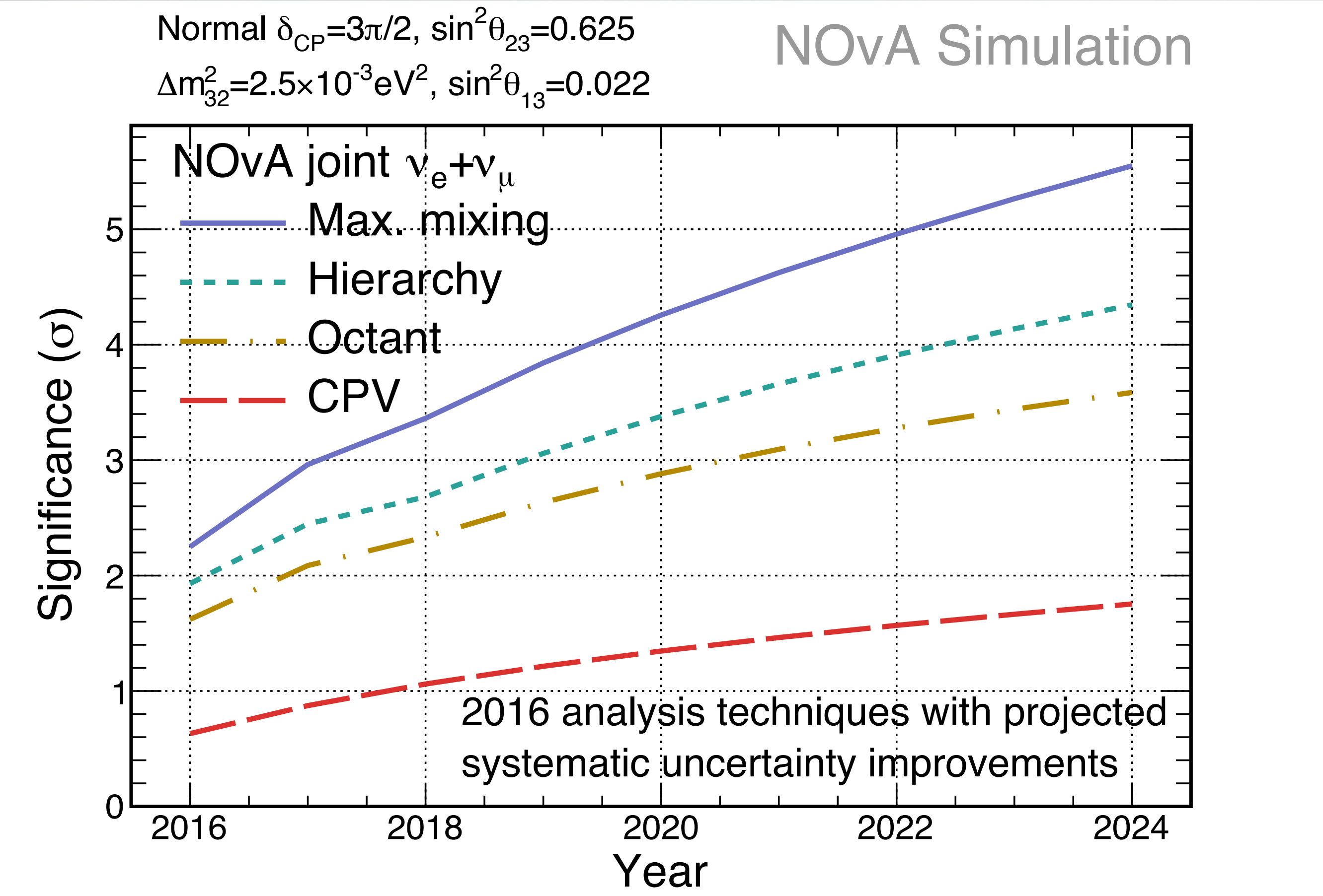
- Tantalising evidence of additional, sterile neutrinos, coming from short-baseline experiments: LSND (decay at rest) and MiniBooNE (deca in flight), but no evidence from long-baseline experiments
- A short baseline (SBN) program has been established at Fermilab using the booster beam. A 3-detector system (all liquid-argon based) will explore the anomalous hints at > 5**σ**
- In Japan, JSNS[2] will use decay at rest to reproduce LSND results. Sensitivity to exclude LSND region at 3**σ**

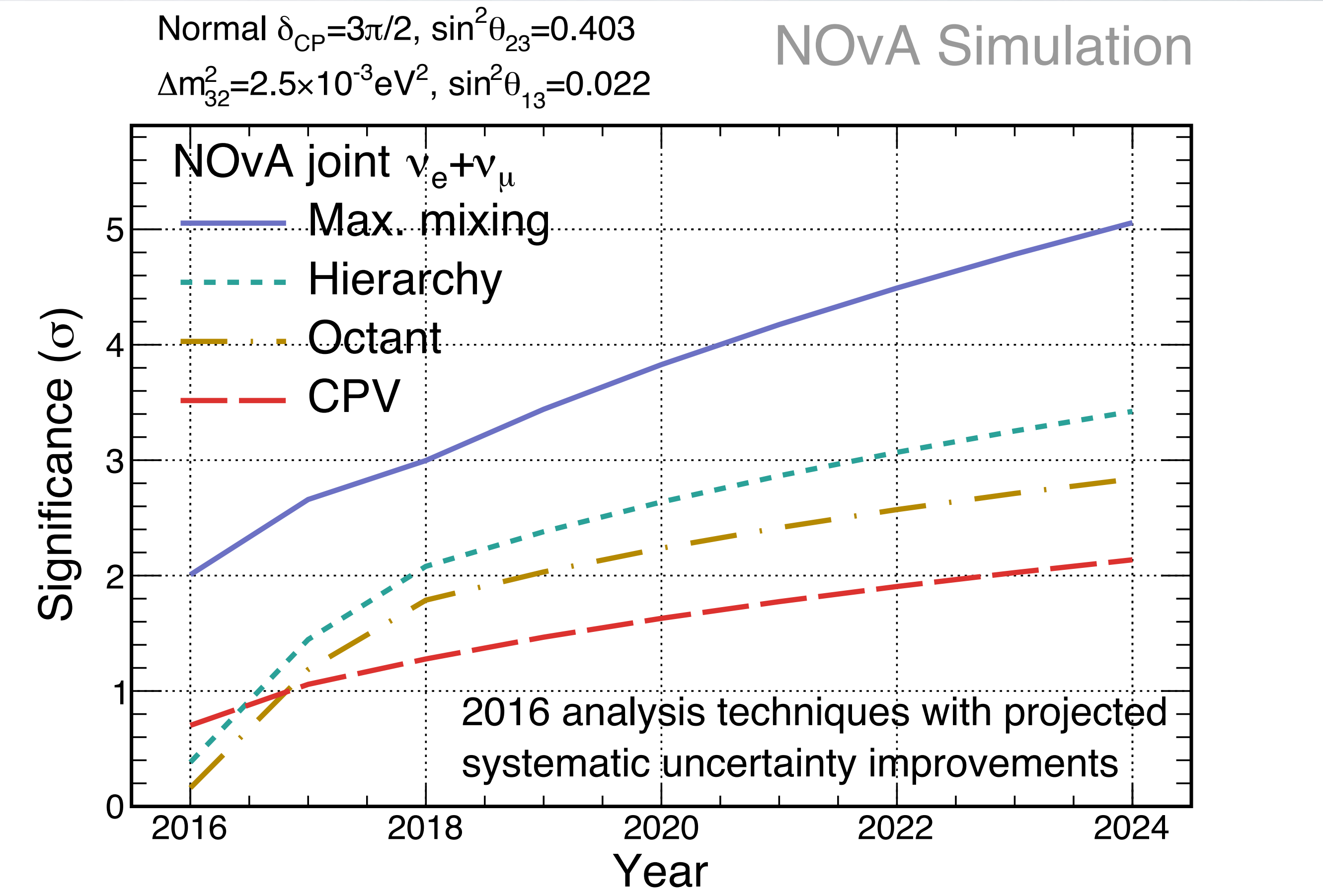




T. Maruyama(ICHEP 2016)

Sensitivity projections





- Running in anti-neutrino mode since February 2017. Planning to accumulate the same exposure in neutrino and anti-neutrino
- 3σ sensitivity to non-maximal mixing in 2018
- 2-3 σ sensitivity to mass hierarchy and 2σ to θ_{23} octant in 2018-2019

THE FUTURE: DUNE IN THE US

2017: Far Site Construction Begins

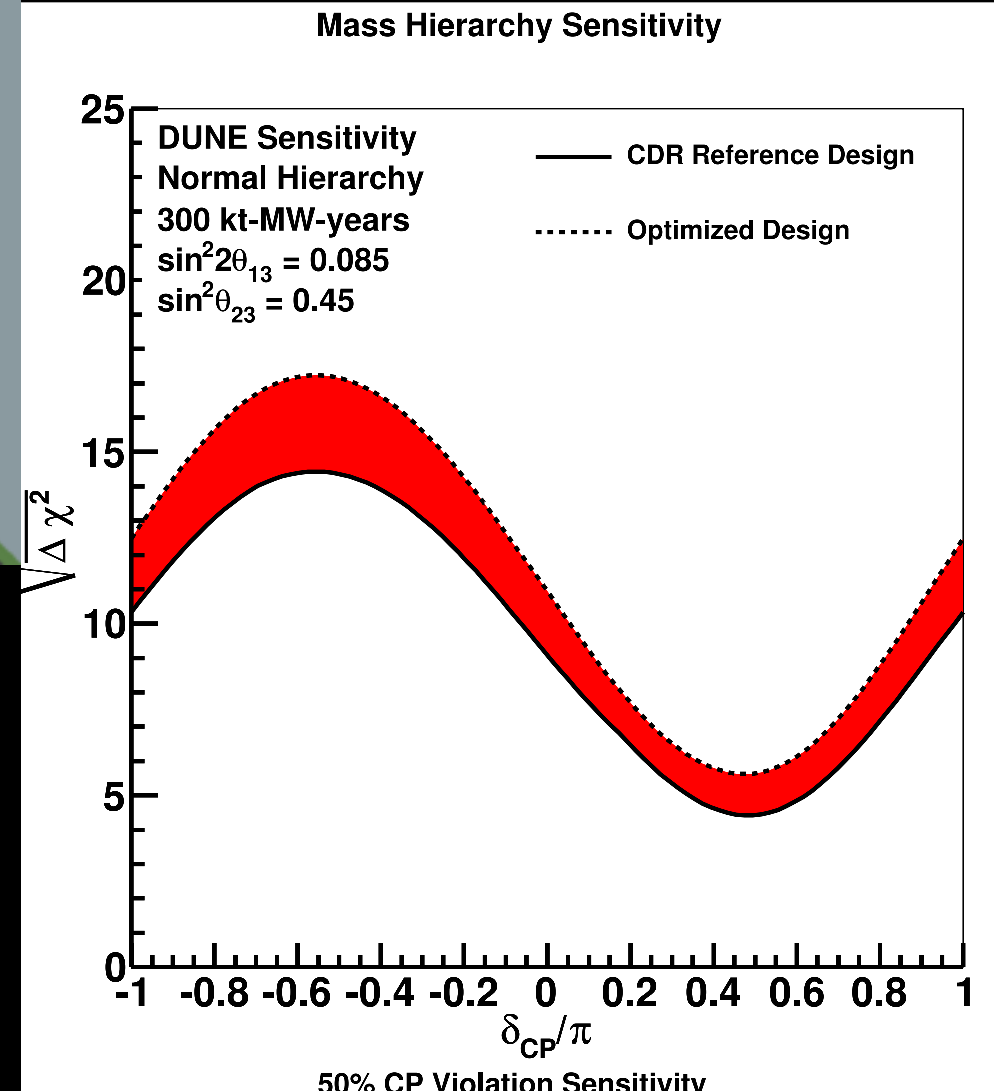
2018: protoDUNEs at CERN

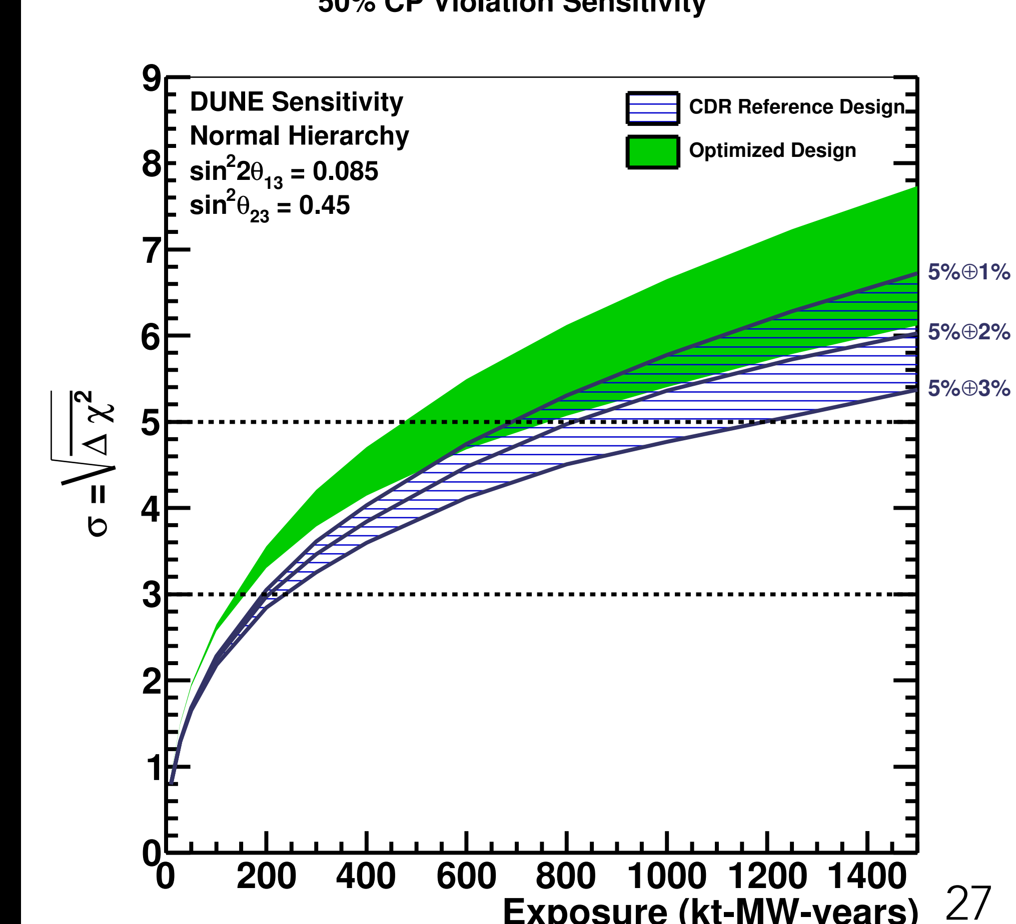
2021: Far Detector Installation Begins

2024: Physics Data Begins (20 kt)

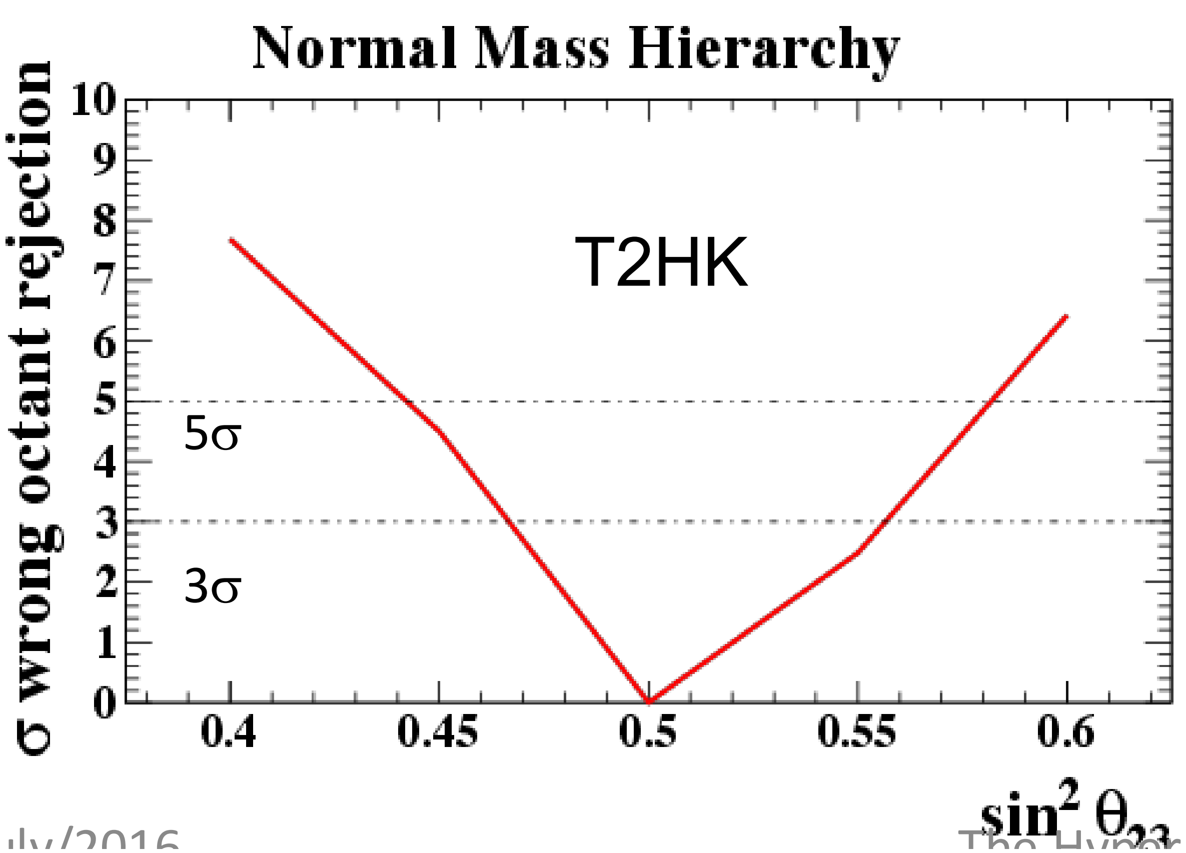
2026: Neutrino Beam Available

- The US program plans to build:
  - 40 kton liquid argon underground detector in four 10-kton (fiducial) modules. Far Site construction begins next year.
  - A wide-band beam from Fermilab (1300km baseline) at 2.3 MW by 2026.
- The mass hierarchy can be determined above 5σ for all values of δ_{CP}.
- CPV at 5σ (δCP = -π/2 or 3π/2) where the uncertainty in the ν_e appearance sample normalization has an impact on reach.

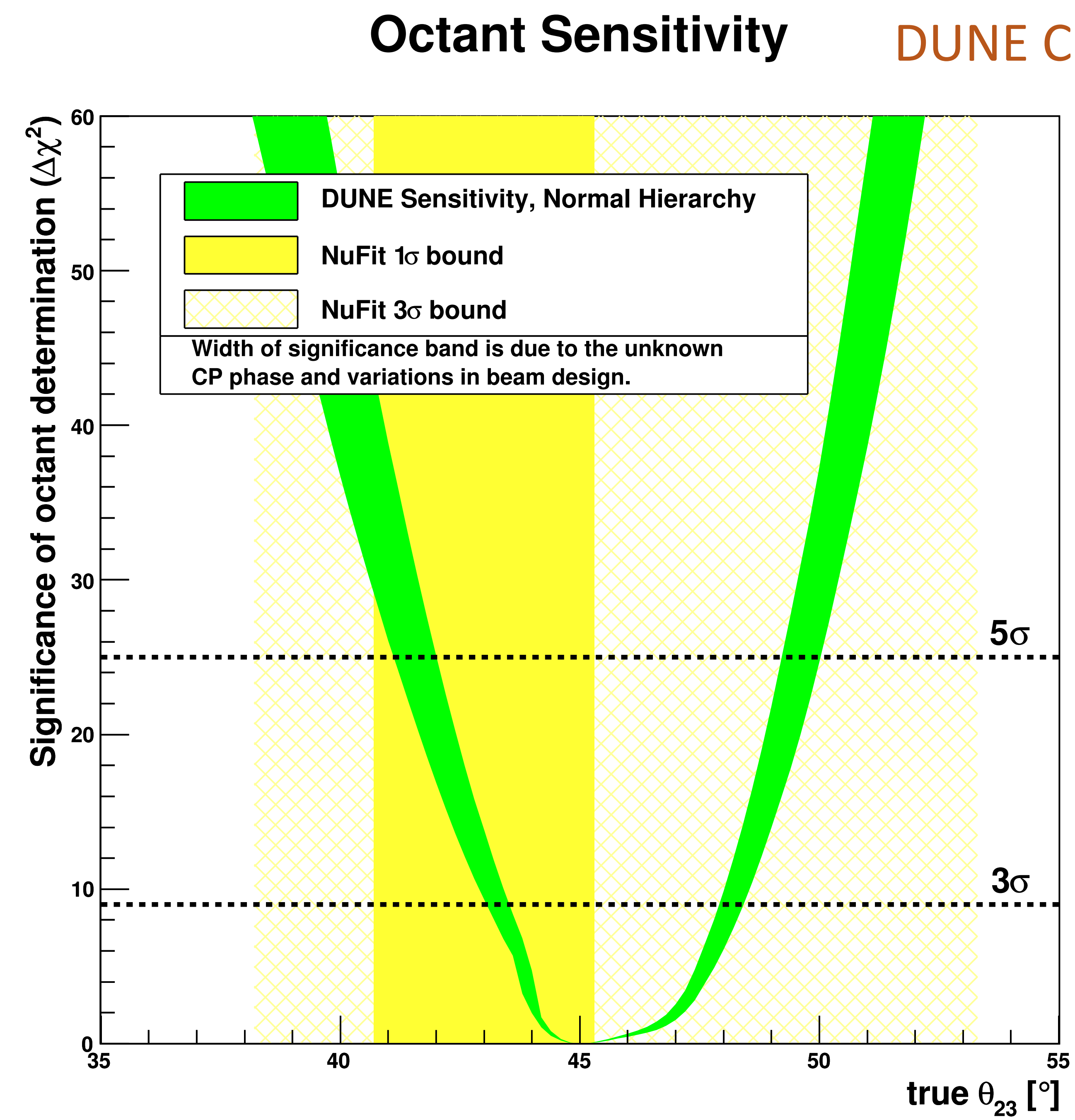




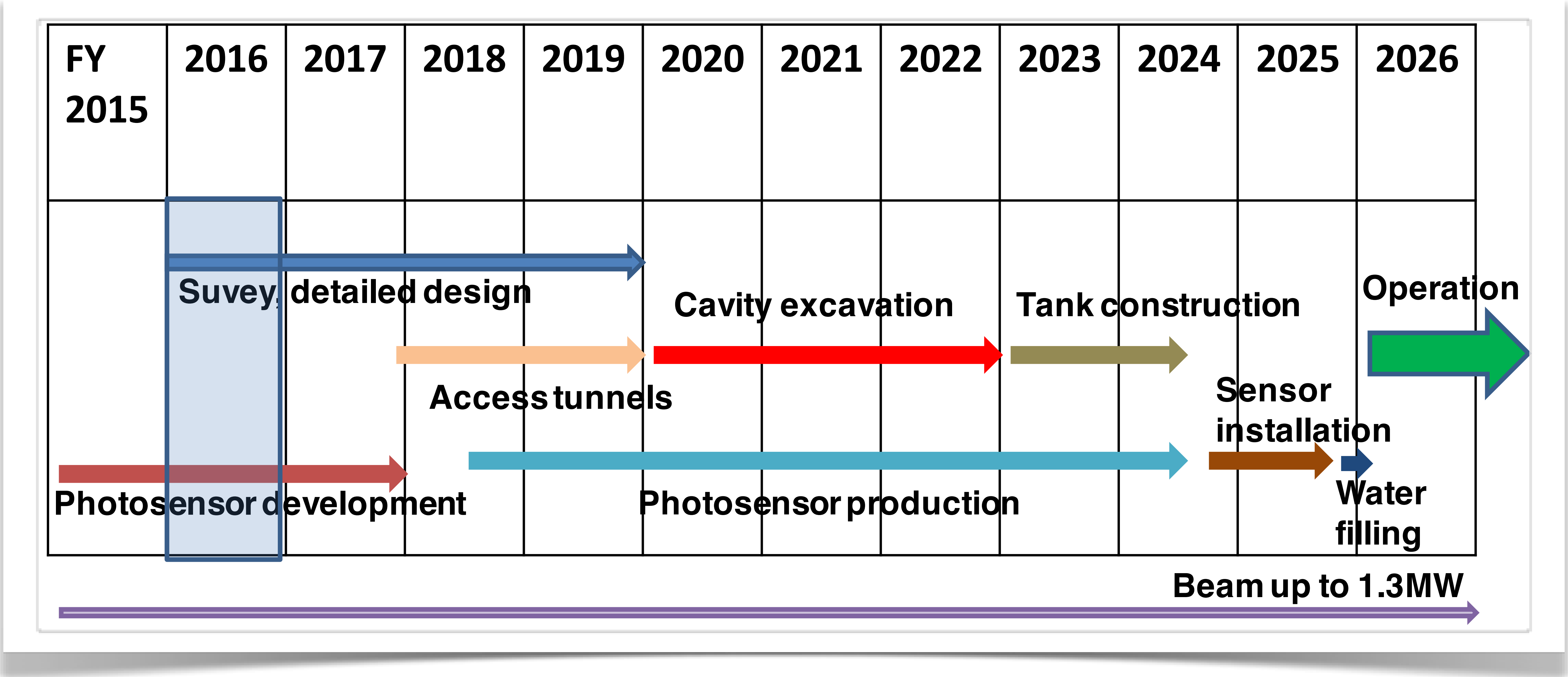
Octant Sensitivity



DUNE CDR



The Hyper-Kamiokande Timeline



- 2018 - 2025 HK construction.
- 2026 onwards CPV study, Atmospherics ν, Solar ν, Supernova ν, Proton decay searches, …
- The 2nd identical tank starts operation 6yrs after the first one.

DUNE event counts

- Physics (MH, θ_{23}, θ_{13}, δ) extracted from combined analysis of 4 samples:

CDR estimates, assuming: CDR optimized beam, 56% LBNF uptime, FastMC detector response

Physics inputs: **δ = 0, θ_{23} = 45º**, others from NuFIT: Gonzalez-Garcia, Maltoni, Schwetz, JHEP 1411 (2014)

ν mode / 150 kt-MW-yr	ν_e appearance	ν_μ disappearance
Signal events (NH / IH)	**945 (521)**	**7929**
Wrong-sign signal (NH /IH)	13 (26)	511
Beam ν_e background	204	–
NC background	17	76
Other background	22	29

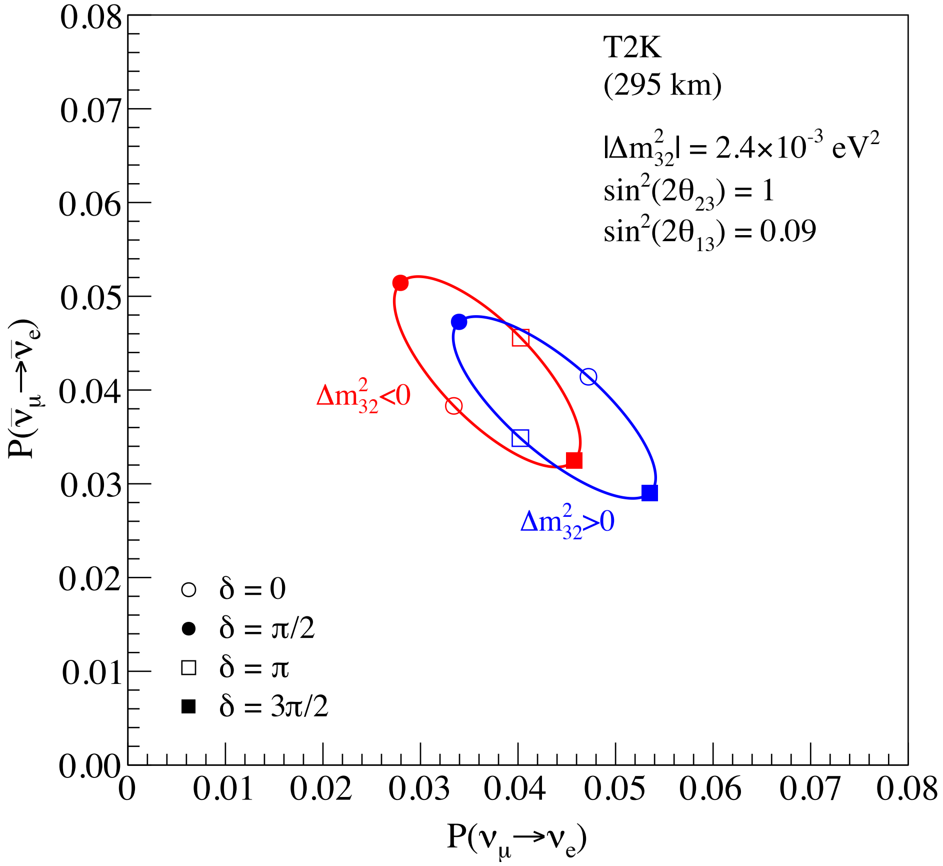
Anti-ν mode / 150 kt-MW-yr	$\bar{\nu}_e$ appearance	$\bar{\nu}_\mu$ disappearance
Signal events (NH / IH)	**168 (438)**	**2639**
Wrong-sign signal (NH /IH)	47 (28)	1525
Beam ν_e background	105	–
NC background	9	41
Other background	13	18

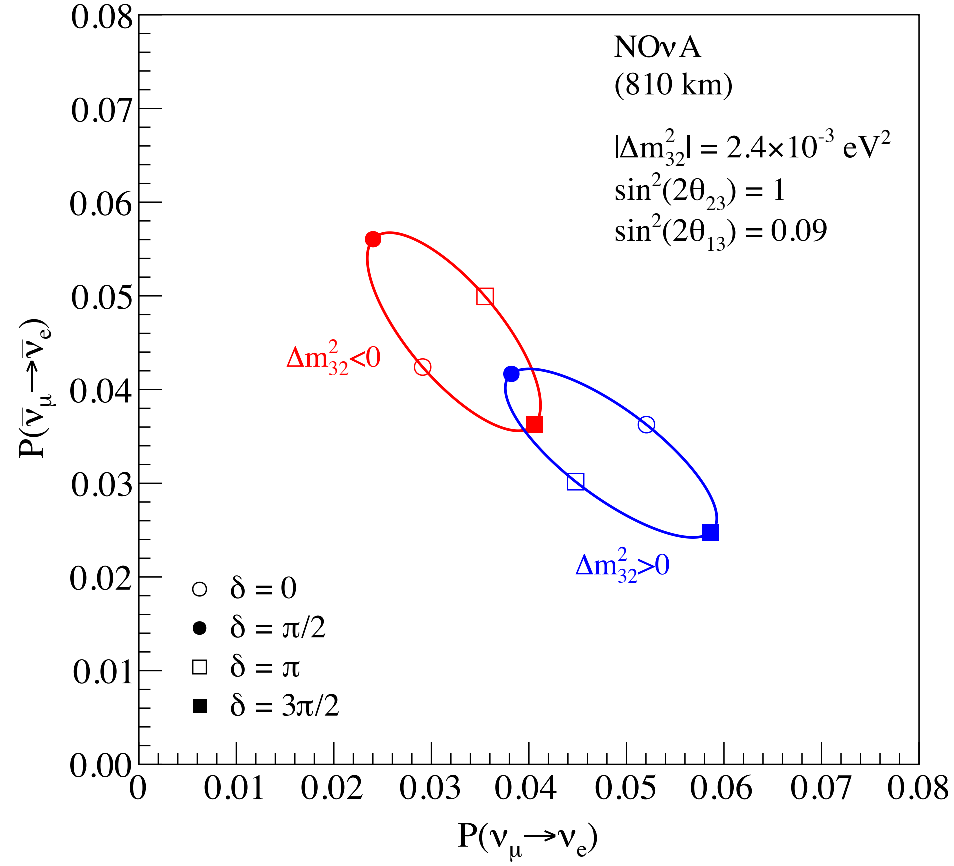
DUNE Collaboration

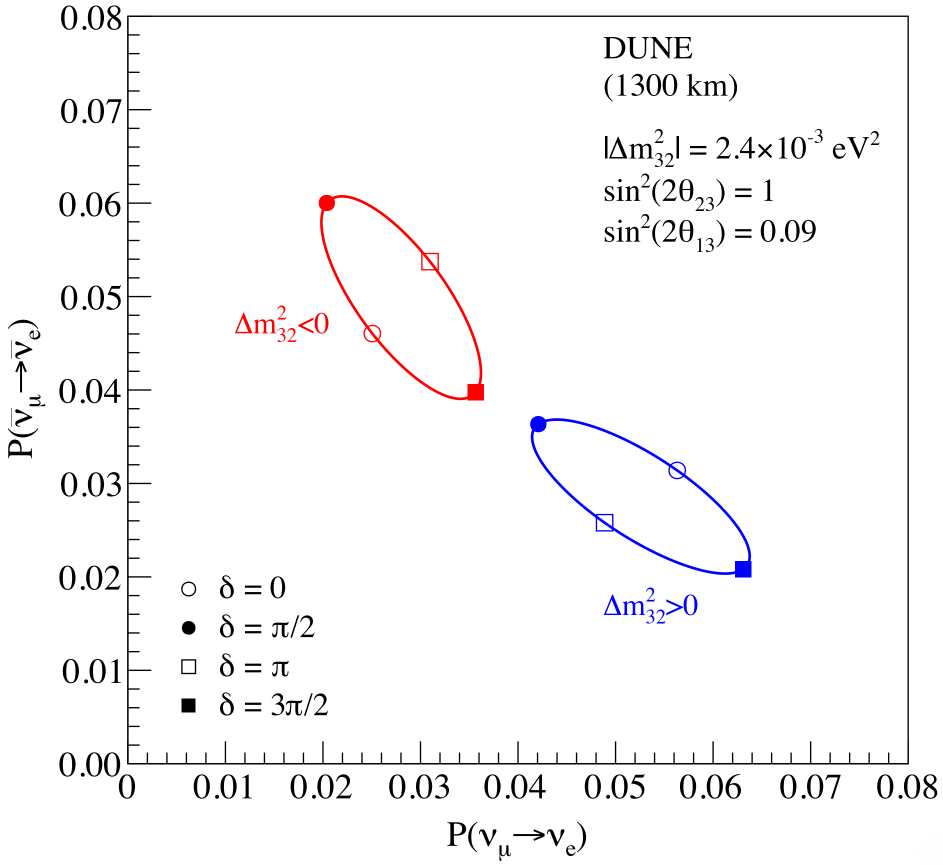
J. Urheim (Neutrino 2016)

Establishment of DUNE as a
fully international scientific collaboration
meant starting from scratch on every organizational aspect

- Now have 856 collaborators…
  …from 149 institutions…in 29 countries
- Strong, inclusive, collaborative spirit driven by ambitious science
- Welcoming to the theory community



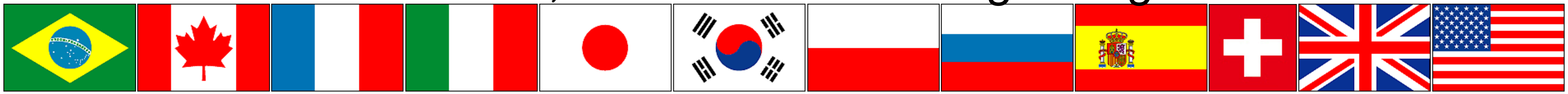




- By increasing the baseline, DUNE provides a much better sensitivity to measuring the MH and CPV simultaneously
- If the MH is determined independently, it provides a very good sensitivity to CPV

Inaugural Symposium of the HK proto-collaboration@Kashiwa, Jan-2015

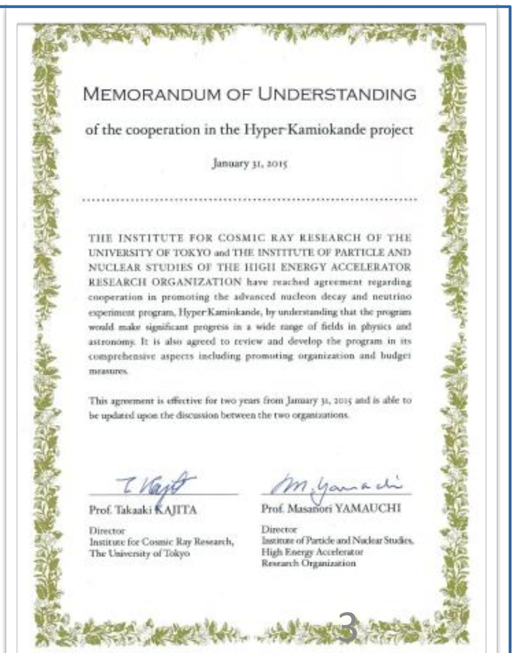
12 countries, ~250 members and growing



- Proto-collaboration formed.
- International steering group
- International conveners
- International chair for international board of representative (IBR)
- International Advisory Committee (HKAC)

F. di Ludovico (Neutrino 2016)

KEK-IPNS and UTokyo-ICRR signed a MoU for cooperation on the Hyper-Kamiokande project.



MEMORANDUM OF UNDERSTANDING

of the cooperation in the Hyper-Kamiokande project

January 31, 2015

THE INSTITUTE FOR COSMIC RAY RESEARCH OF THE UNIVERSITY OF TOKYO and THE INSTITUTE OF PARTICLE AND NUCLEAR STUDIES OF THE HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION have reached agreement regarding cooperation in promoting the advanced nucleon decay and neutrino experiment program, Hyper-Kamiokande, by understanding that the program would make significant progress in a wide range of fields in physics and astronomy. It is also agreed to review and develop the program in its comprehensive aspects including promoting organization and budget measures.

This agreement is effective for two years from January 31, 2015 and is able to be updated upon the discussion between the two organizations.

Prof. Takaaki KAJITA
Director
Institute for Cosmic Ray Research,
The University of Tokyo

Prof. Masanori YAMAUCHI
Director
Institute of Particle and Nuclear Studies,
High Energy Accelerator
Research Organization

Pros and cons

DUNE

- Long 1300 km baseline
  - Excellent MH measurement
  - Access to 2nd oscillation maximum with greater CP asymmetry
- Wide band beam
  - See more effects of oscillation
  - Good sensitivity to non-standard effects (e.g., test 3-flavour model)
- Exquisite detector imaging
  - High efficiency and purity
  - Lower statistics

HyperK

- Really huge detector
  - High statistics
  - Excellent early CP-violation sensitivity
  - Limited information on hadronic recoil system
- Short baseline
  - Much smaller matter effects
  - Need to know mass hierarchy
- Narrow band beam
  - Less background to reject
  - Less energy information

Very complementary projects!

Summary

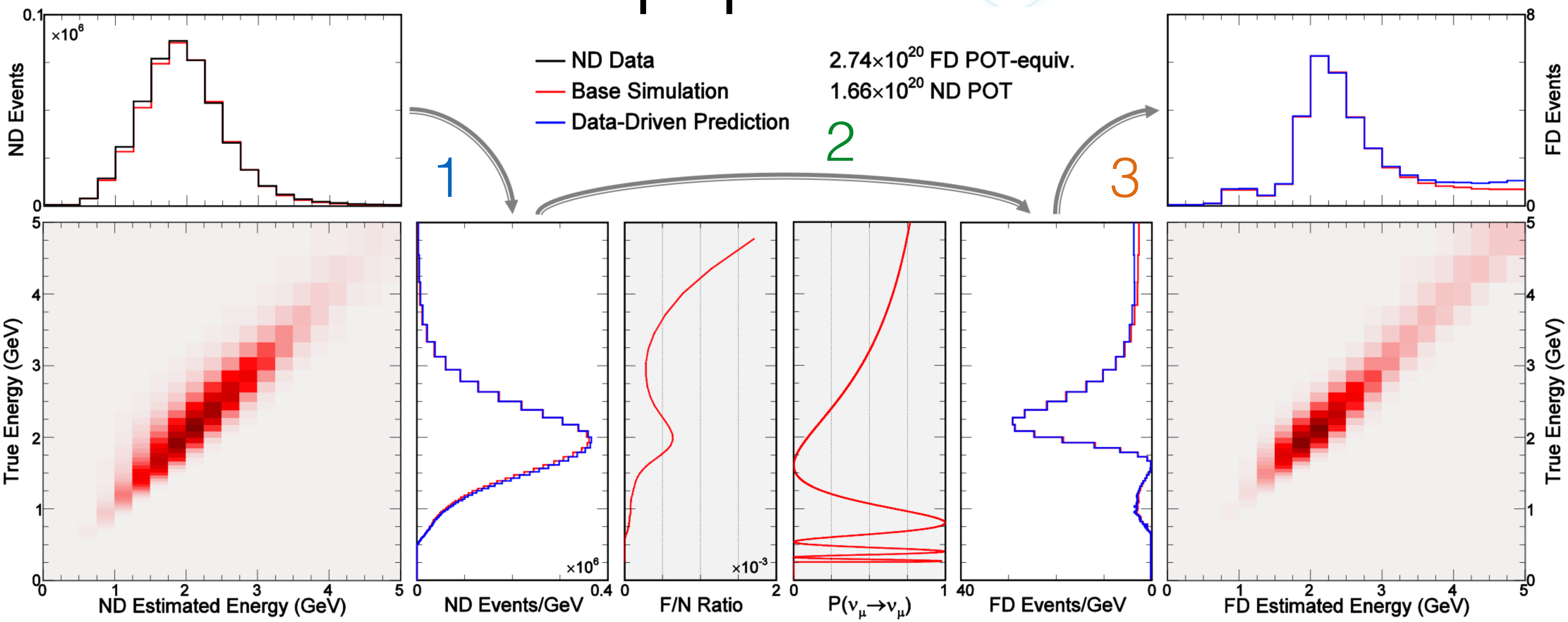
- Discovery of non-zero θ_{13} has opened the door to a 2nd golden age of neutrino oscillation physics
- New NOvA results disfavour maximal mixing at 2.5σ. Also exclude IH, lower octant and $\delta_{CP} \sim \pi/2$ at 3σ
- New techniques, including image recognition, have been pioneered in the field
- T2K excludes CP conservation at 90%
- However, compelling discovery of CP-violation will require new experiments
- Highly precise 3rd generation will allow testing the 3 flavour neutrino oscillation framework

Extremely active and exciting field! Theoretical questions to answer, experiments currently taking data and new projects down the line. Stay tuned!

BACKUP SLIDES

These aren't the slides you're looking for

ND to FD extrapolation is a three step process

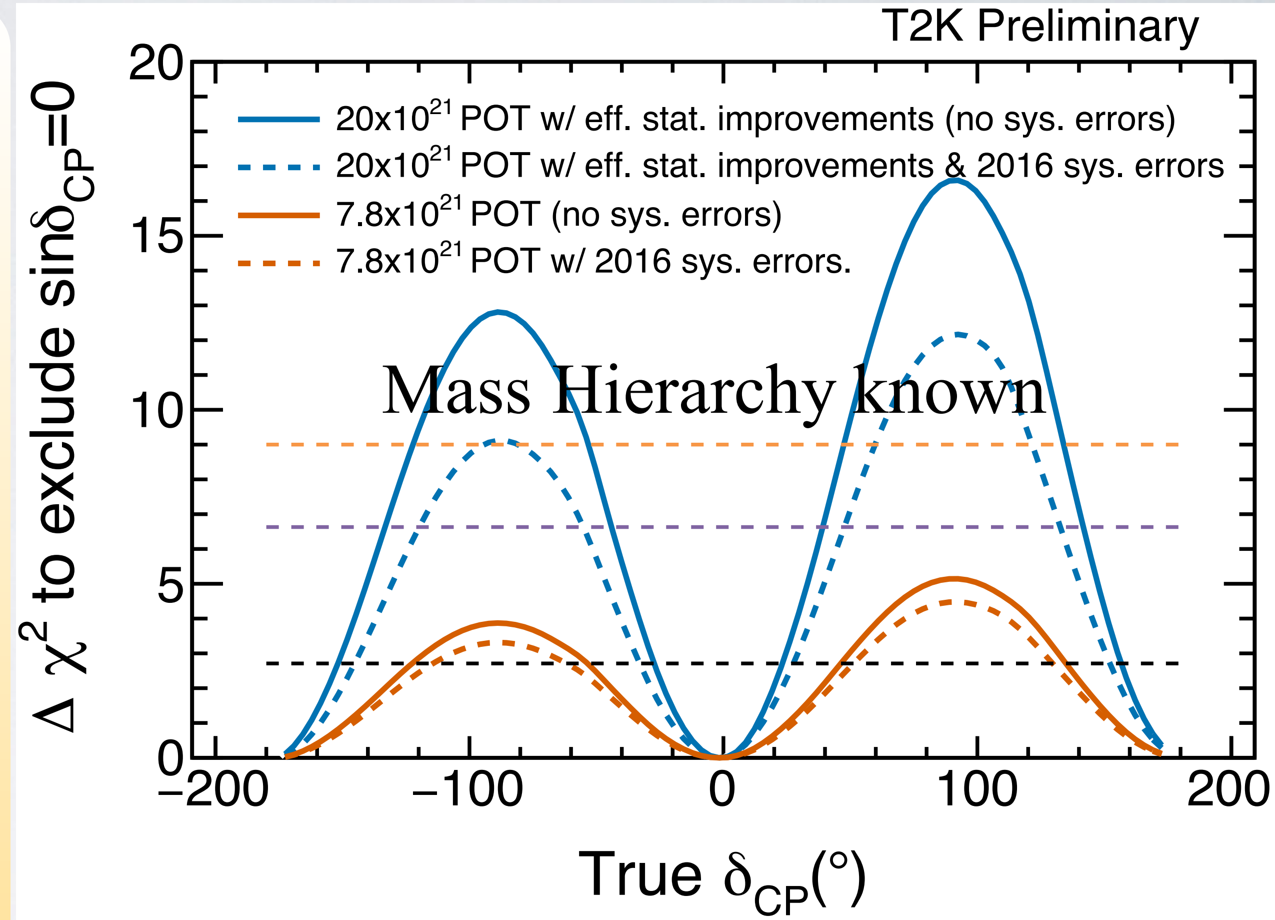


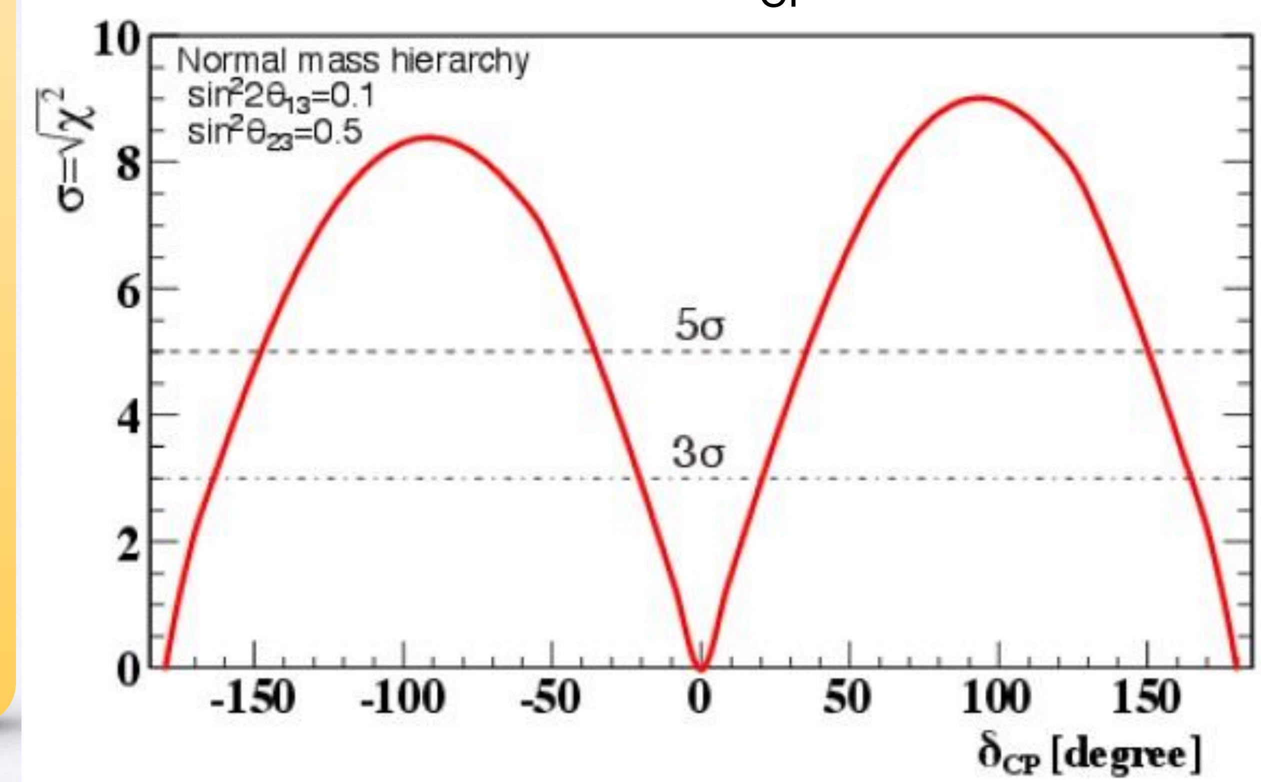
1) Unfold ND reconstructed energy to true energy

2) Use Far/Near ratio to convert to FD true energy spectrum

3) Translate back to reconstructed energy

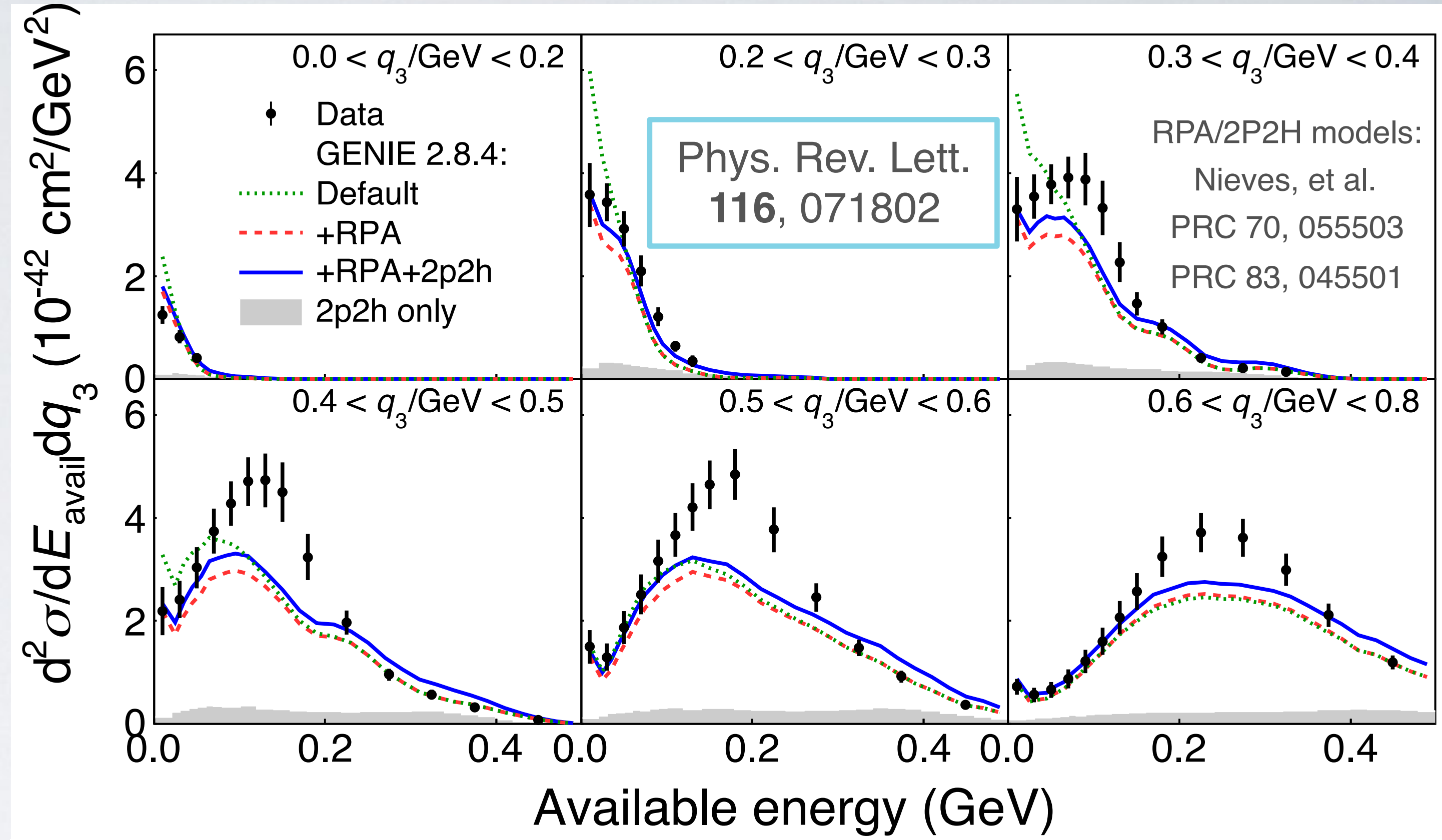
- Current T2K program expects 7.8 × 10^{21} POT by 2020
  - Potential extension (T2K-II) would have 20 × 10^{21} by 2026
  - 3σ sensitivity to δ_{CP}
- Requires accelerator and beam line upgrades to reach 1.3 MW (currently 420 kW)
- While T2K-II is running, construction of the next generation detector (Hyper-kamiokande) begins
  - By 2026, build 2 large water Cherenkov tanks of 260 ton each
  - >5σ sensitivity to δ_{CP}

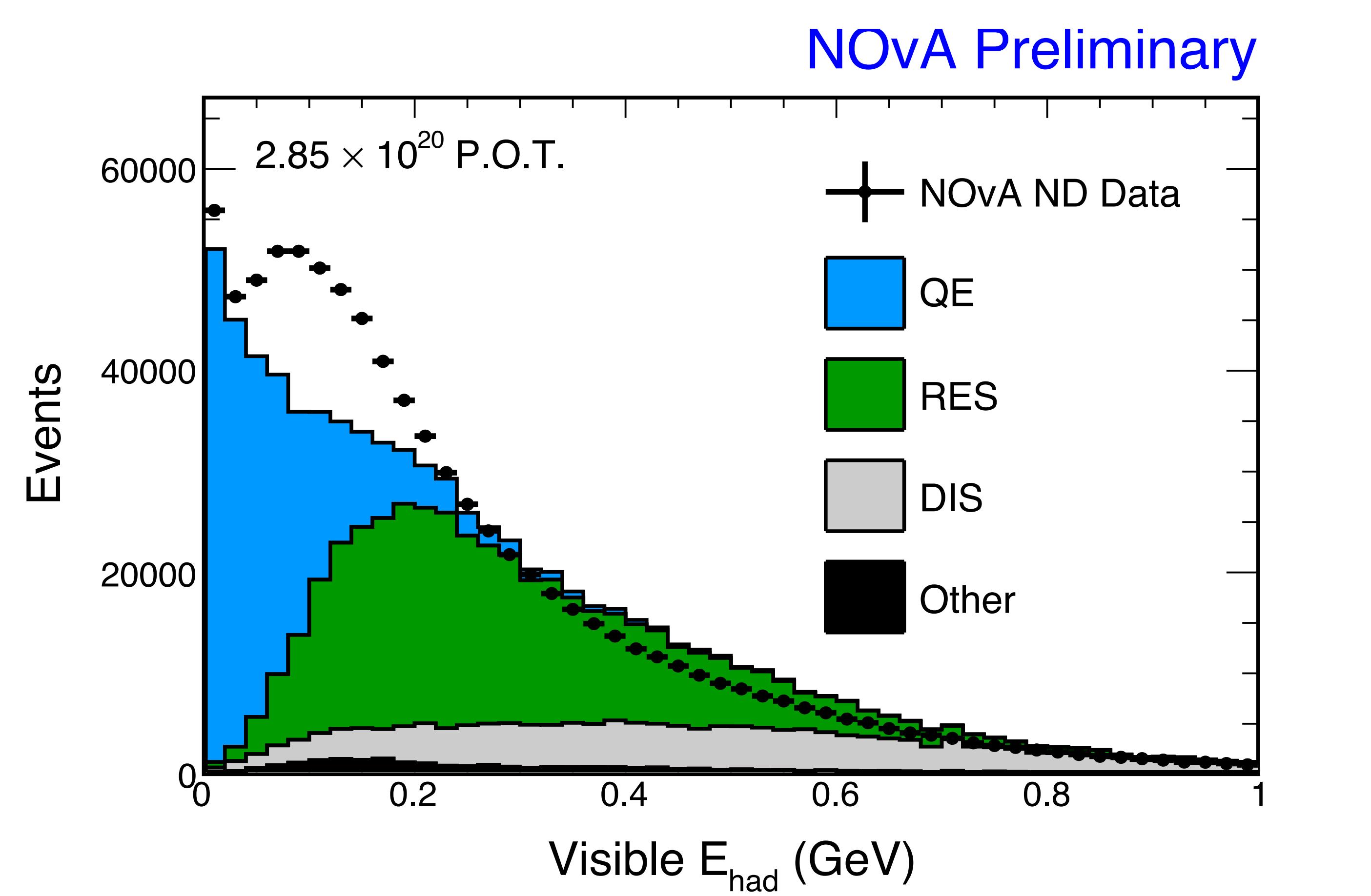




K. Iwamoto & M. Gonin (ICHEP 2016)

- MINERvA runs on the NuMI beam studying neutrino interactions
- Large statistics shows evidence of needs for better models
- Disagreement in selected muon neutrino charged-current events as a function of momentum transfer
- NOvA observes a similar effect
- Partially explained by the absence in models of MEC or 2p2h processes





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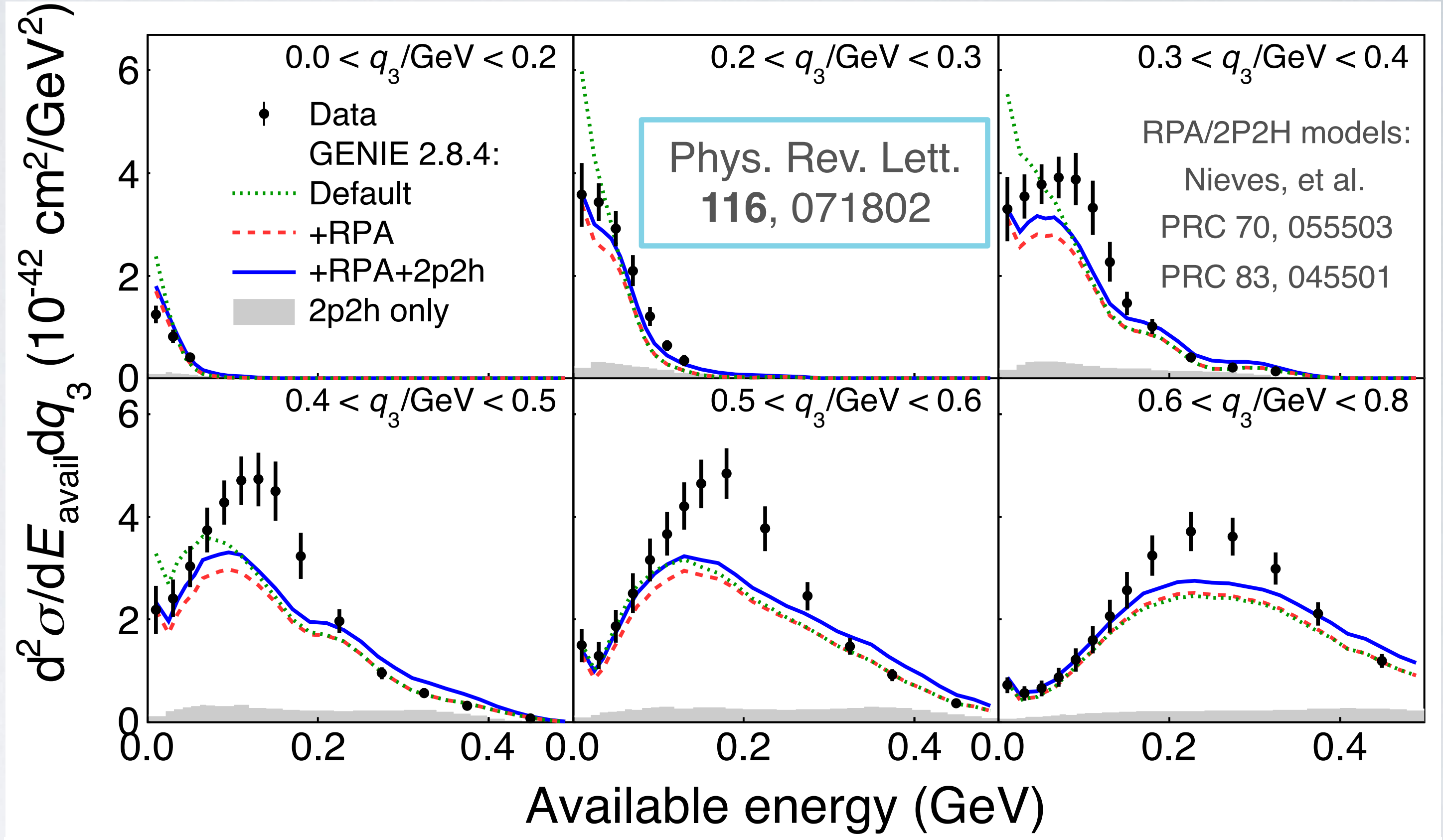
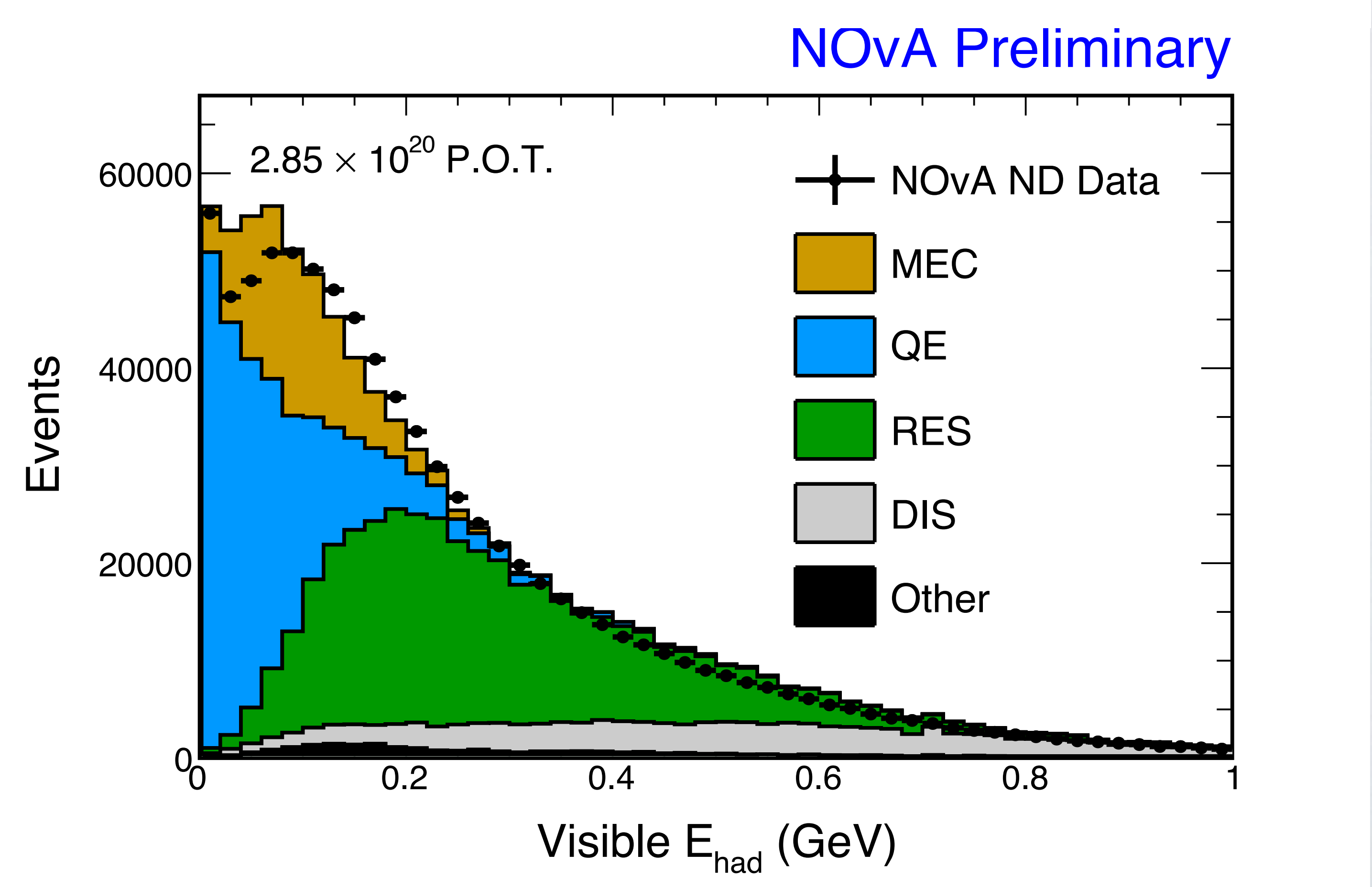
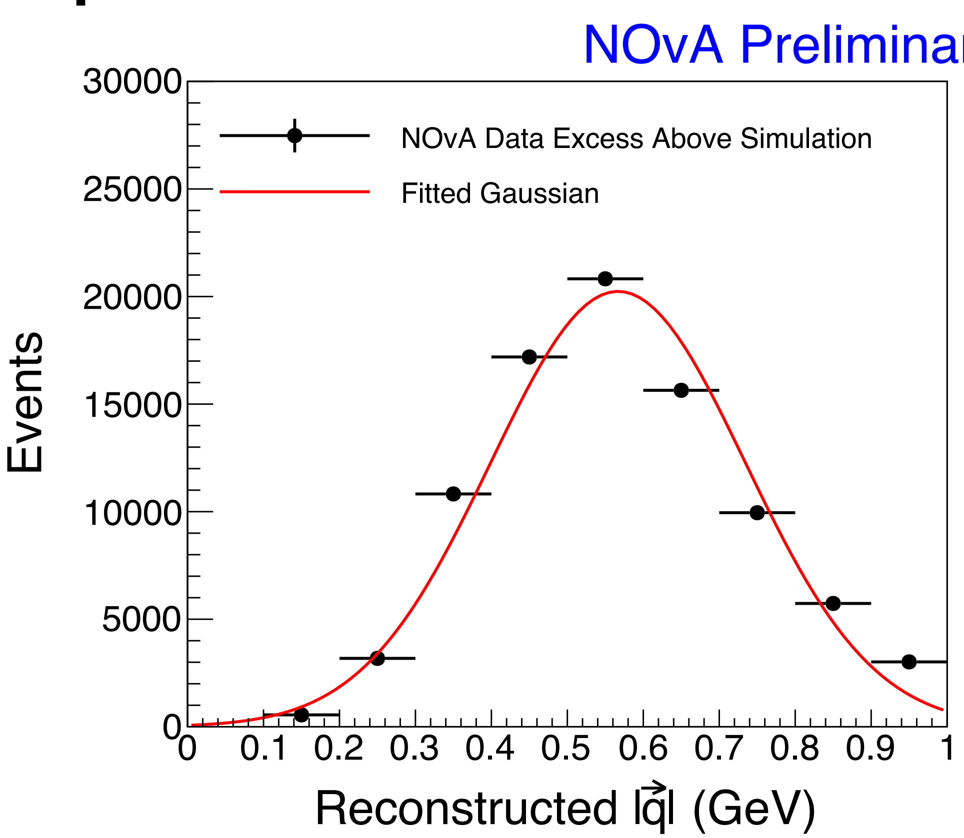
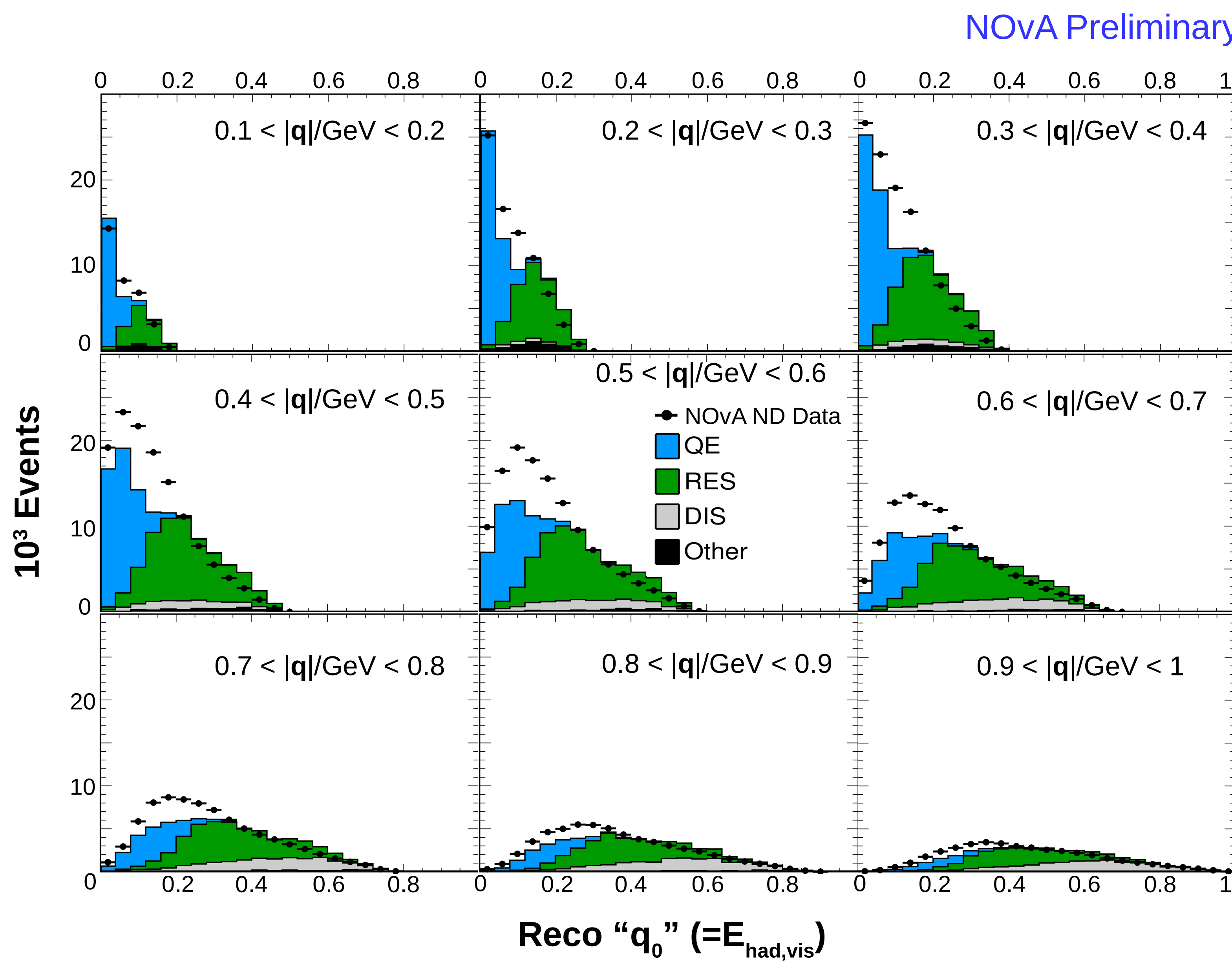
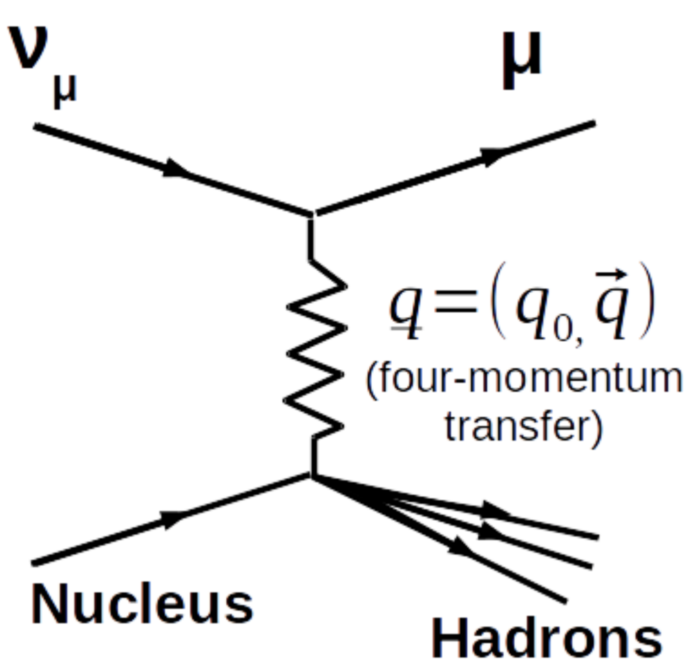




Near Det data suggests an unsimulated process between QE and Δ production



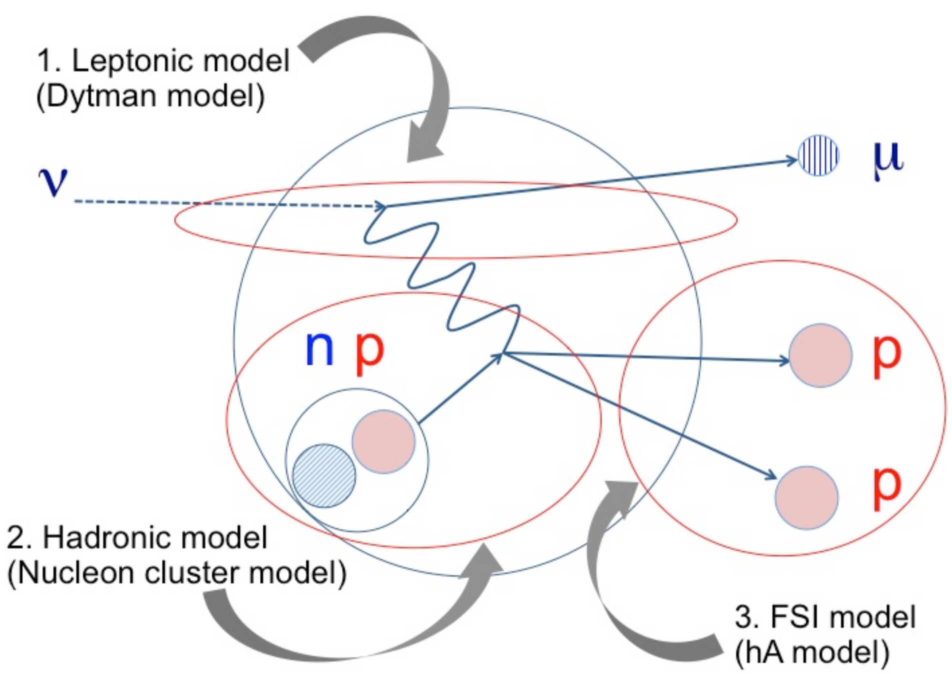




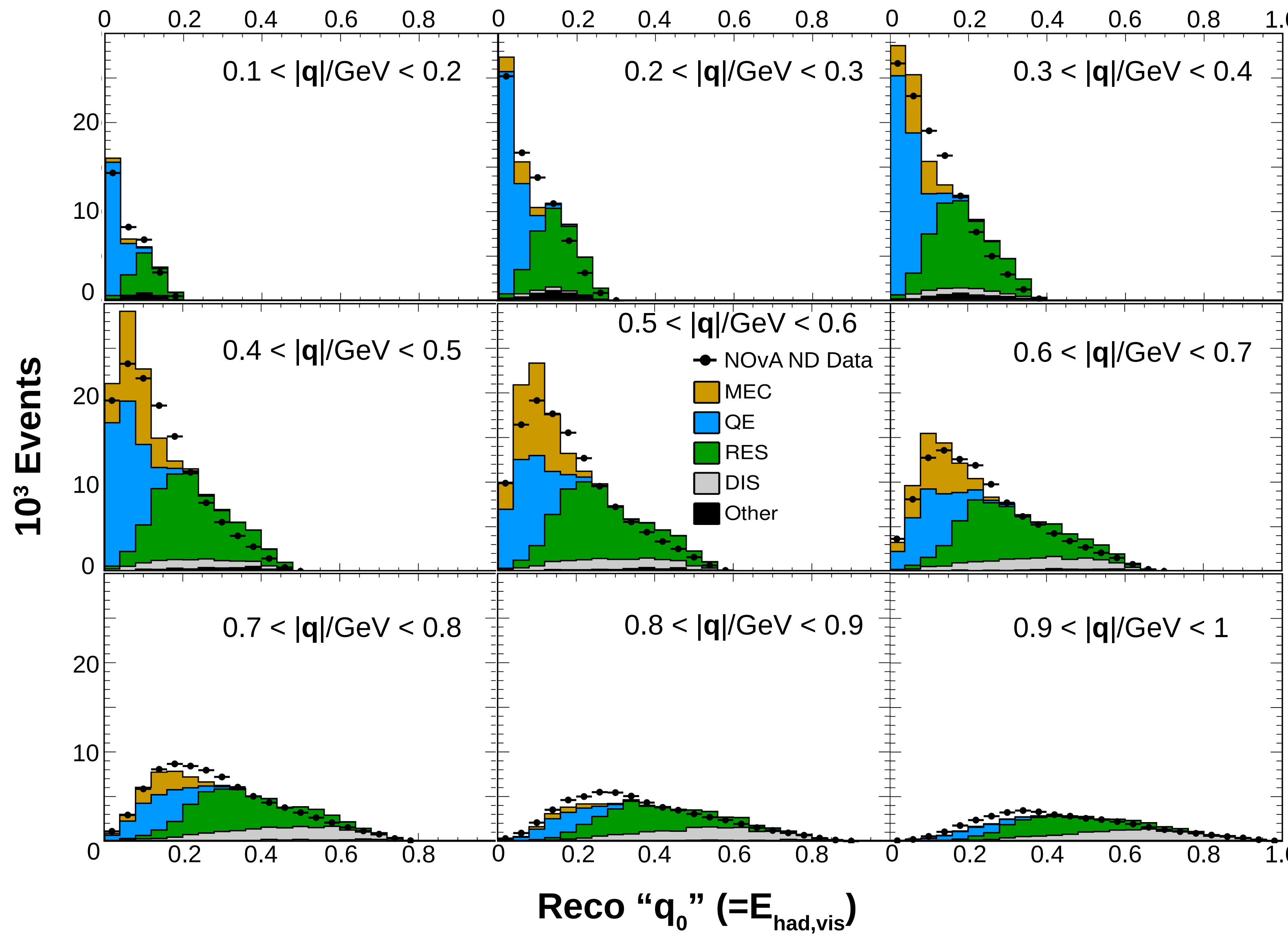
MINERvA reported a similar excess in their data in P.A. Rodrigues et al., PRL 116 (2016) 071802

We enable GENIE's empirical Meson Exchange Current model

We reweight the model to match our observed excess as a function of ***p*** transfer



NOvA Preliminary



Reduce single non-resonant pion production by 50%

(P.A. Rodrigues et al, arXiv: 1601.01888.)

Take 50% systematic uncertainty on MEC component

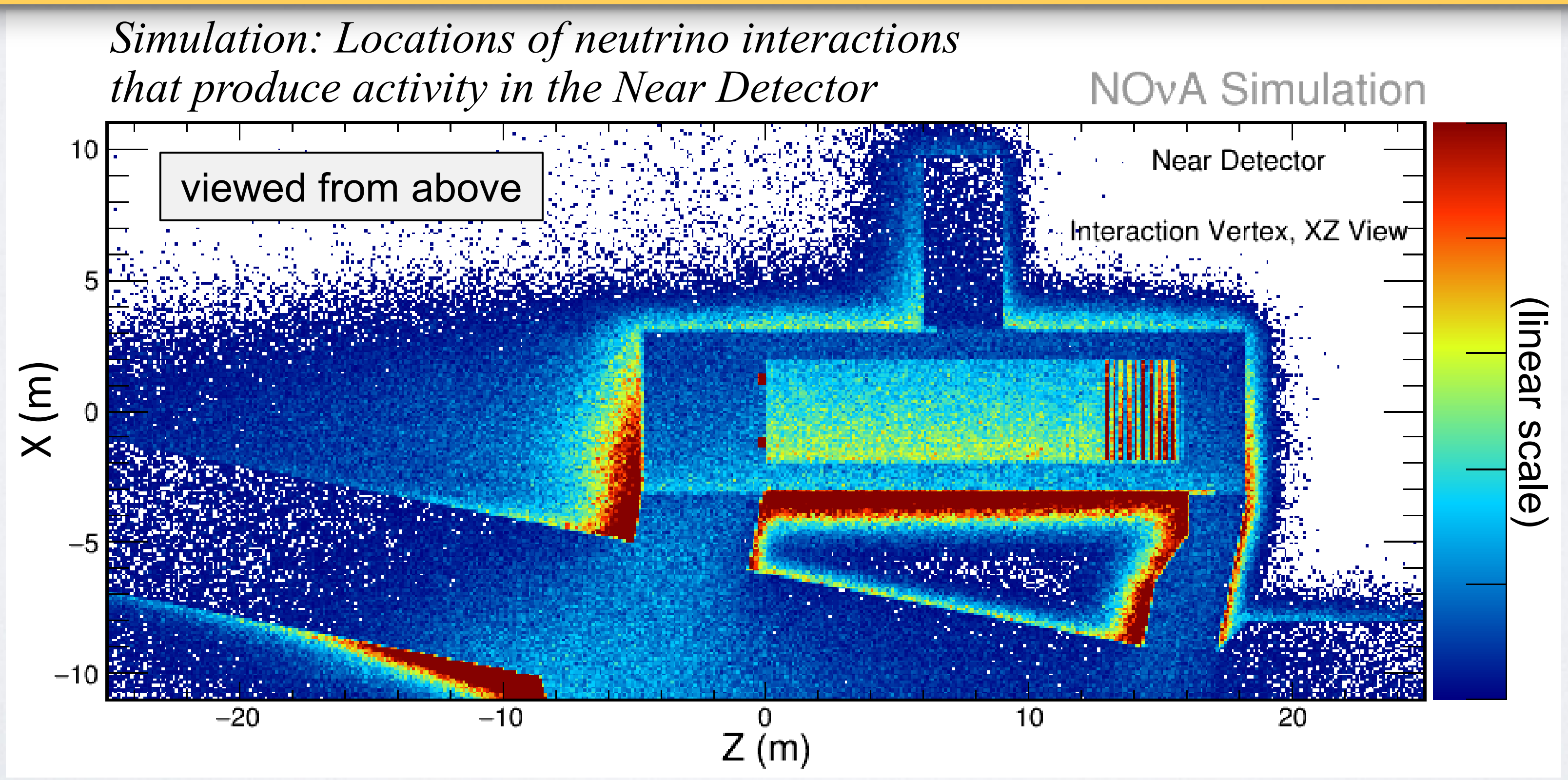
This reduces our largest systematic uncertainties

- Hadronic energy scale
- QE cross-section modeling

Simulation in NOvA

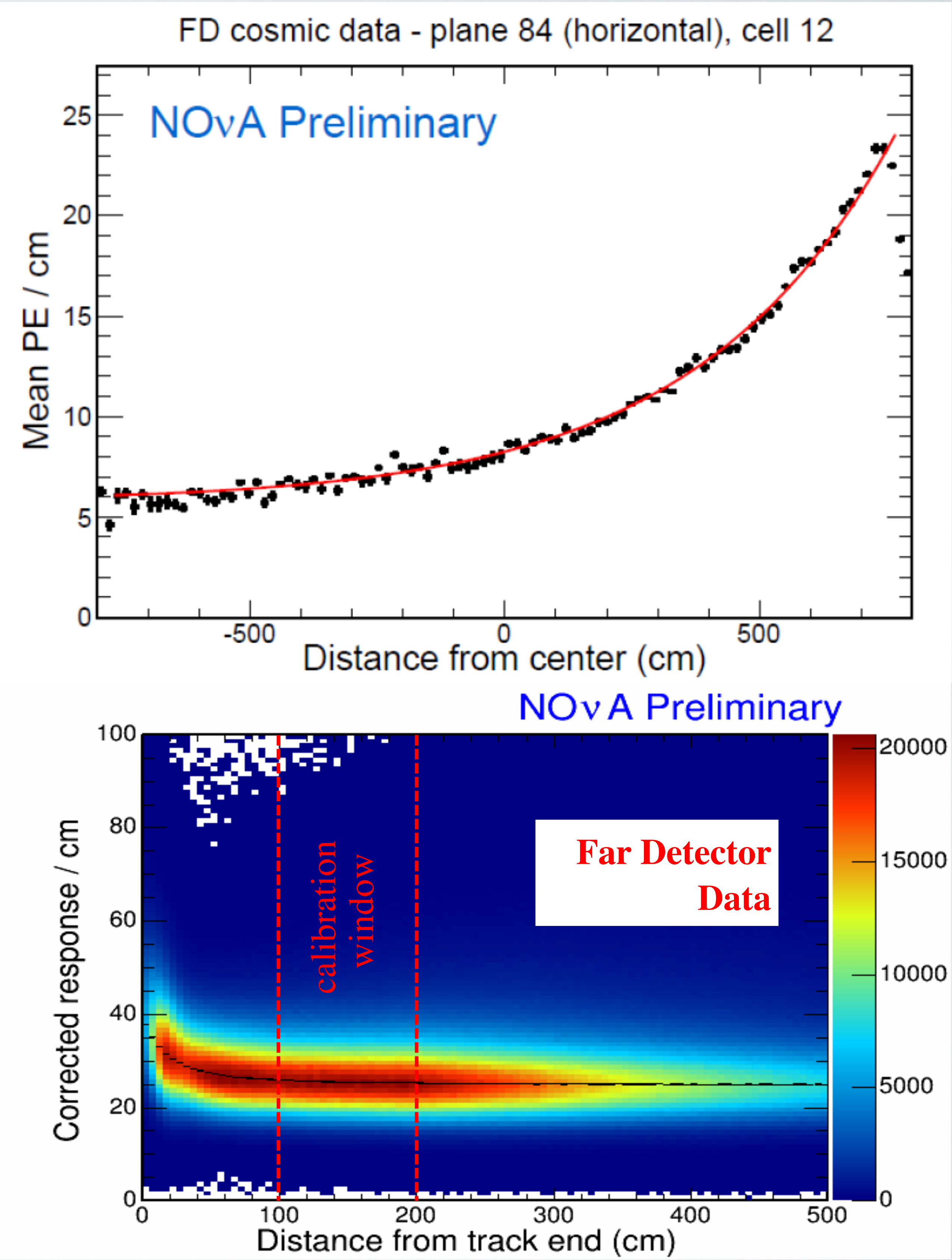
Highly detailed end to end simulation chain

- Beam hadron production, propagation, neutrino flux: **FLUKA/FLUGG**
- Cosmic ray flux: **CRY** (CORSIKA soon)
- Neutrino interactions and FSI modelling: **GENIE**
- Detector simulation: **GEANT4**
- Readout electronics and DAQ: **custom simulation routines**



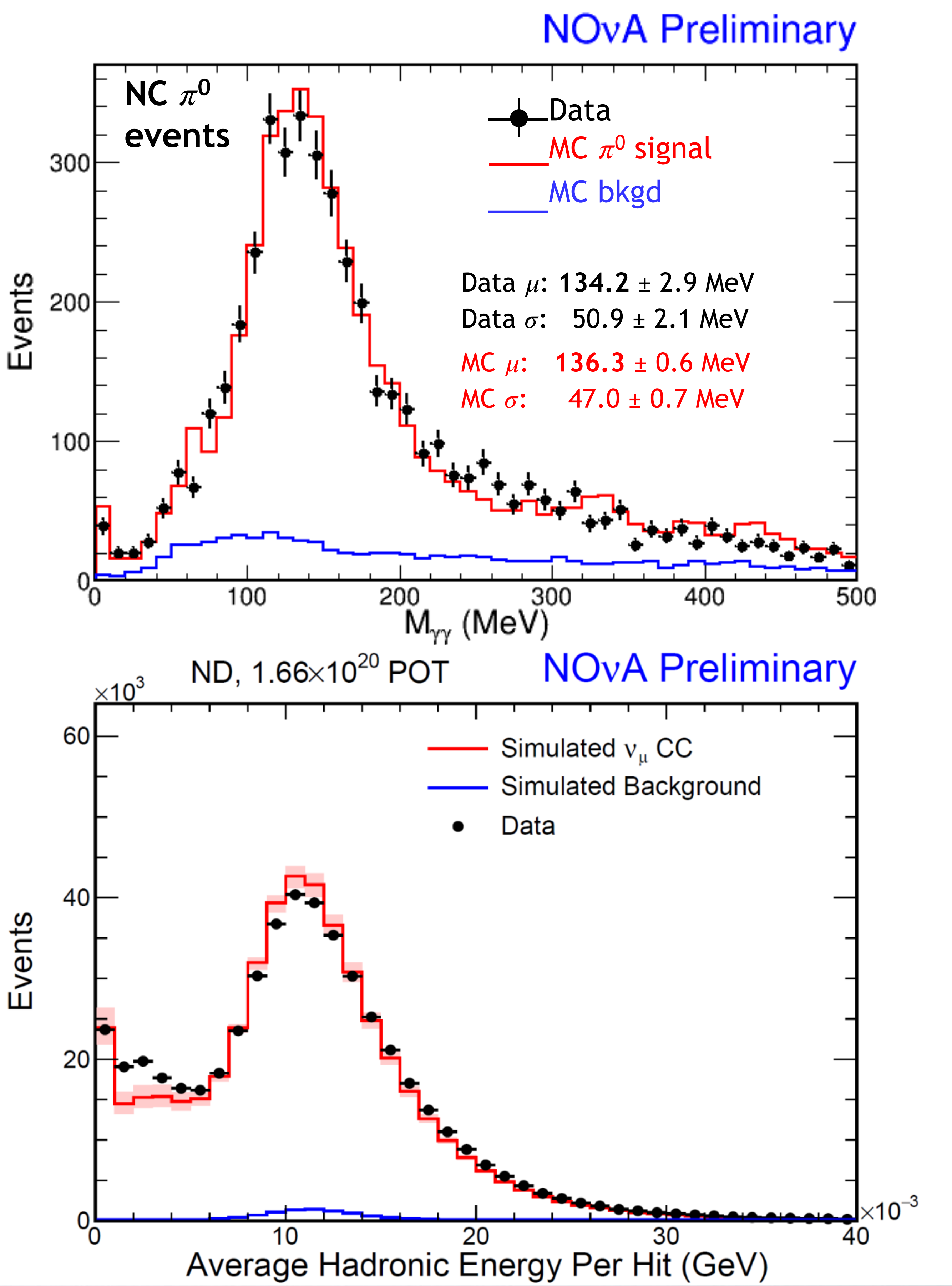
Calibration

- Calibration achieved using cosmic rays
- Light levels drop by a factor of 8 across a FD cell
- Stopping muons provide a standard candle



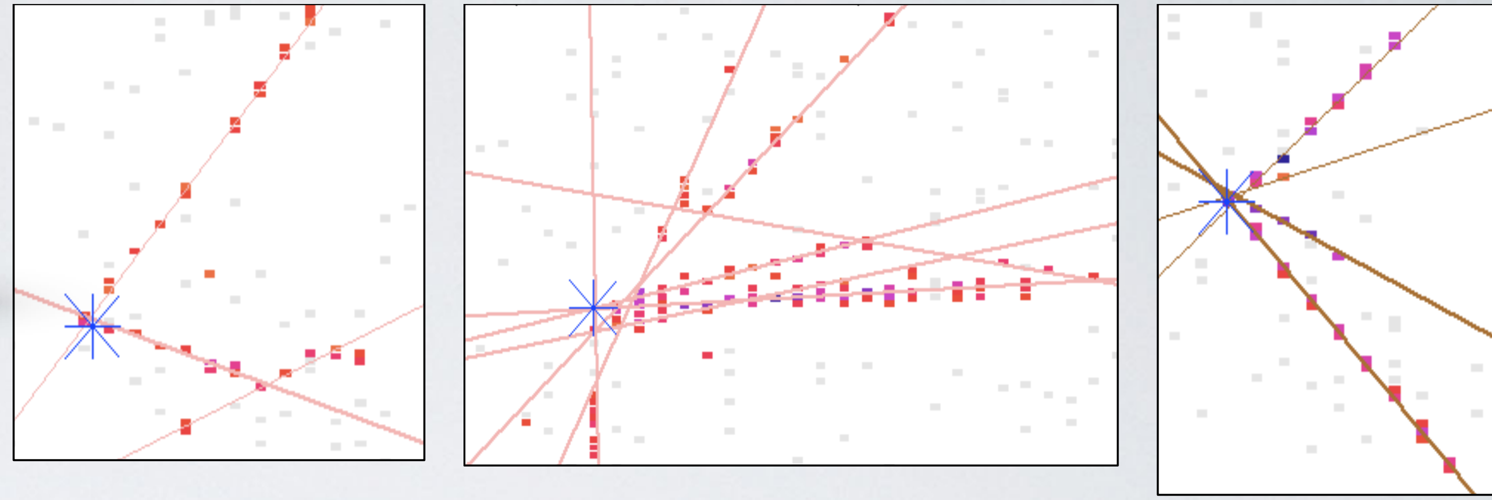
Energy Scale

- Near Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel *e*⁻ spectrum
  - π^0 mass
  - hadronic shower ***E***-per-hit
- Far Detector
  - cosmic μ dE/dx [~vertical]
  - beam μ dE/dx [~horizontal]
  - Michel *e*⁻ spectrum
- All agree to 5%

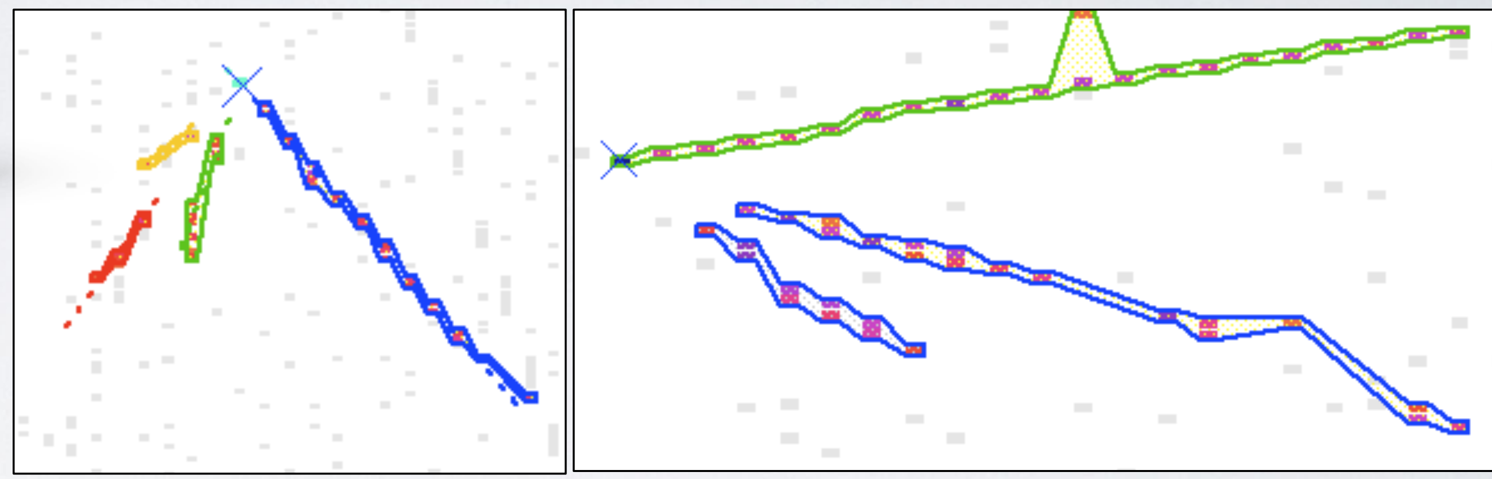


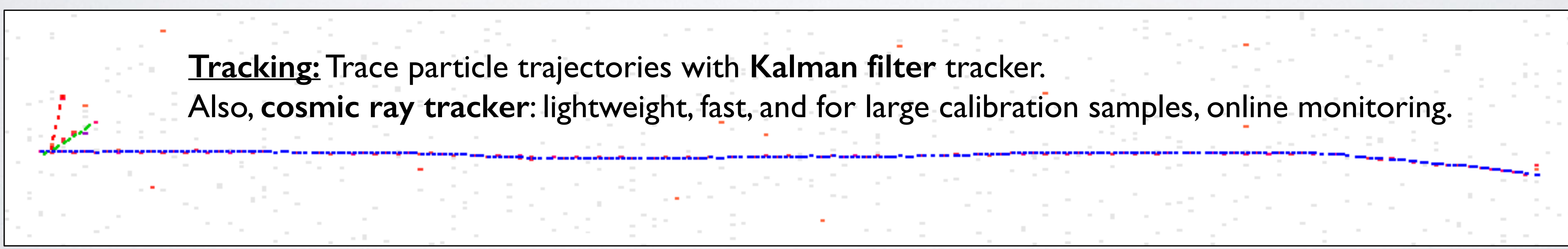
Reconstruction

Vertexing: **Find** lines of energy depositions **w/ Hough transform CC events: 11 cm resolution**



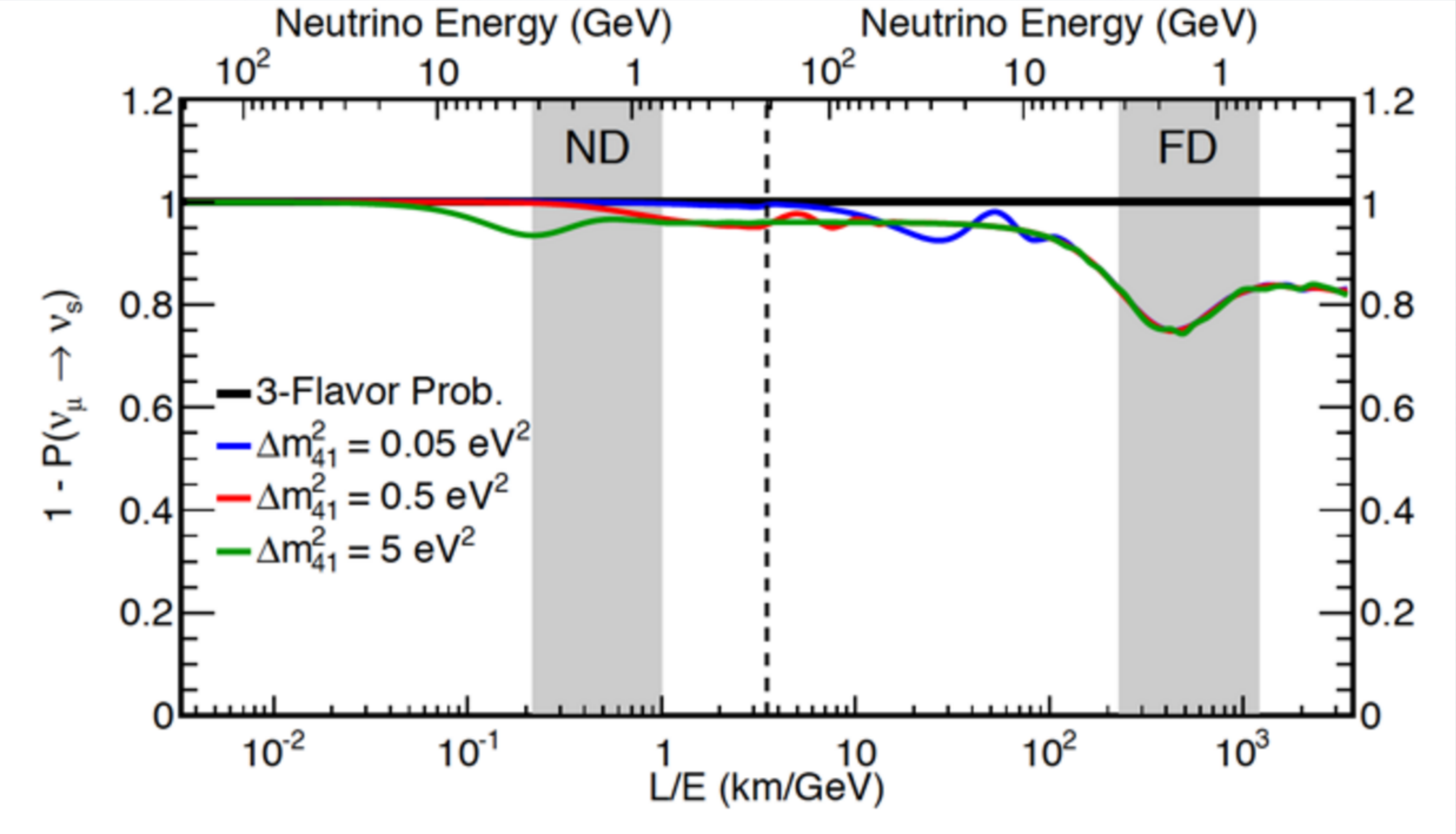
Clustering: **Find** clusters in angular space **around vertex.** Merge views **via topology and prong dE/dx**



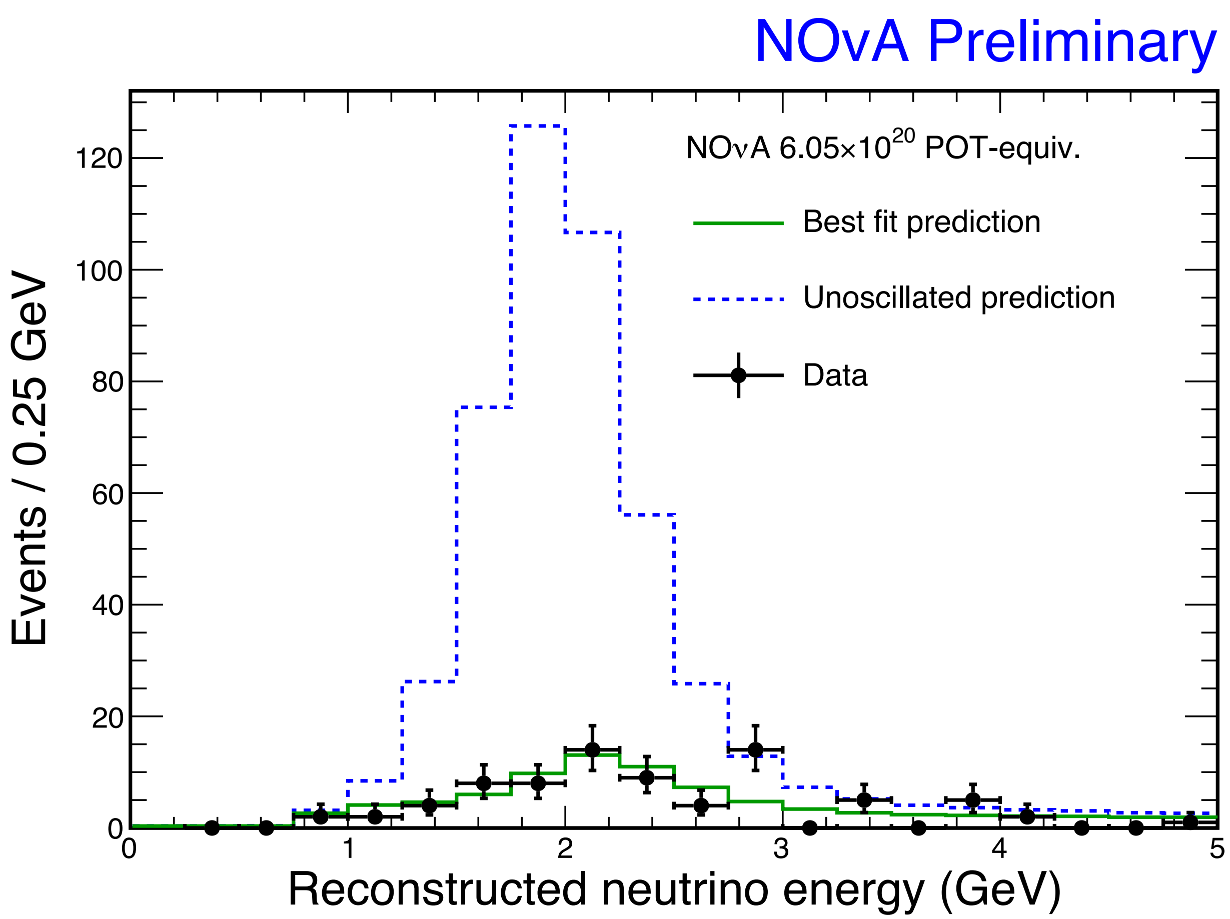


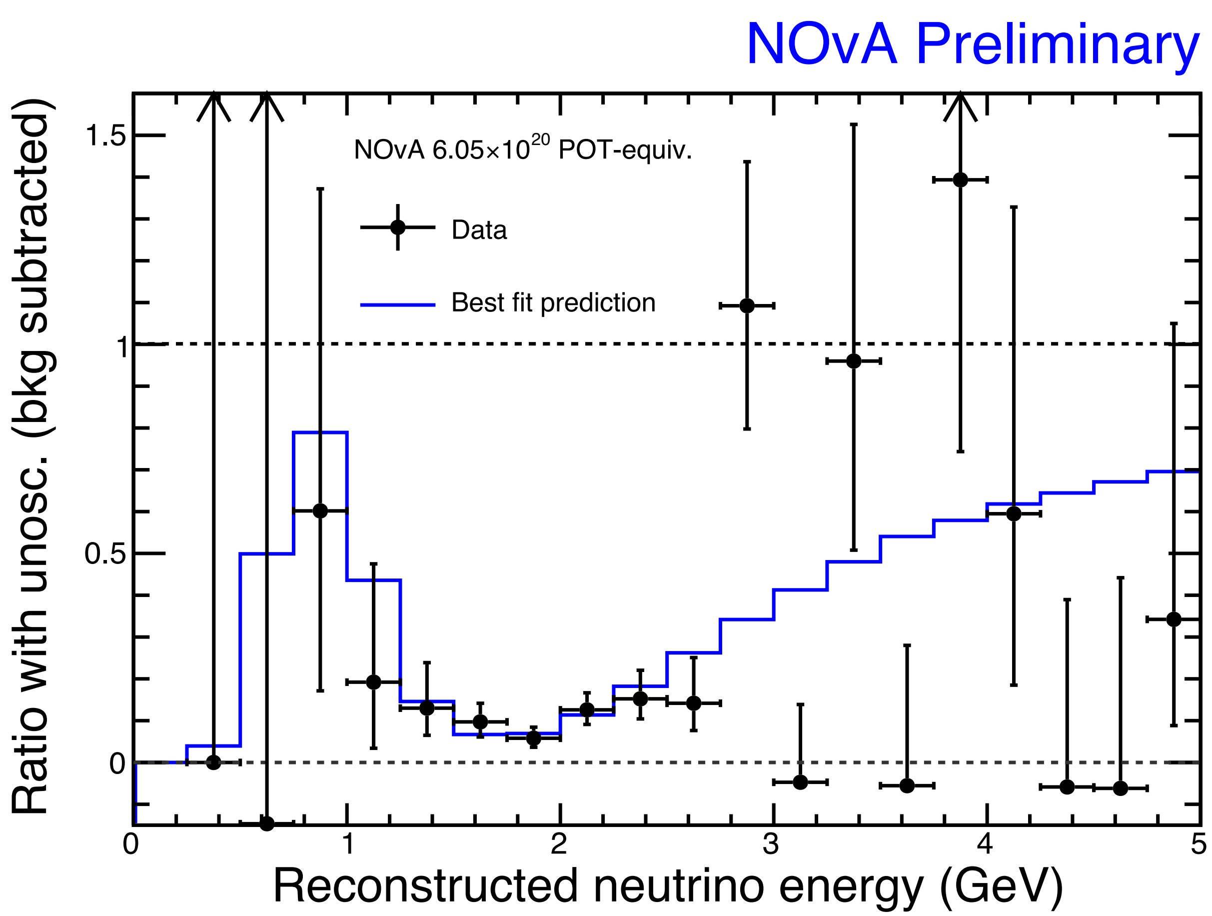
Tracking: Trace particle trajectories with **Kalman filter** tracker.
Also, **cosmic ray tracker**: lightweight, fast, and for large calibration samples, online monitoring.

Sterile oscillations

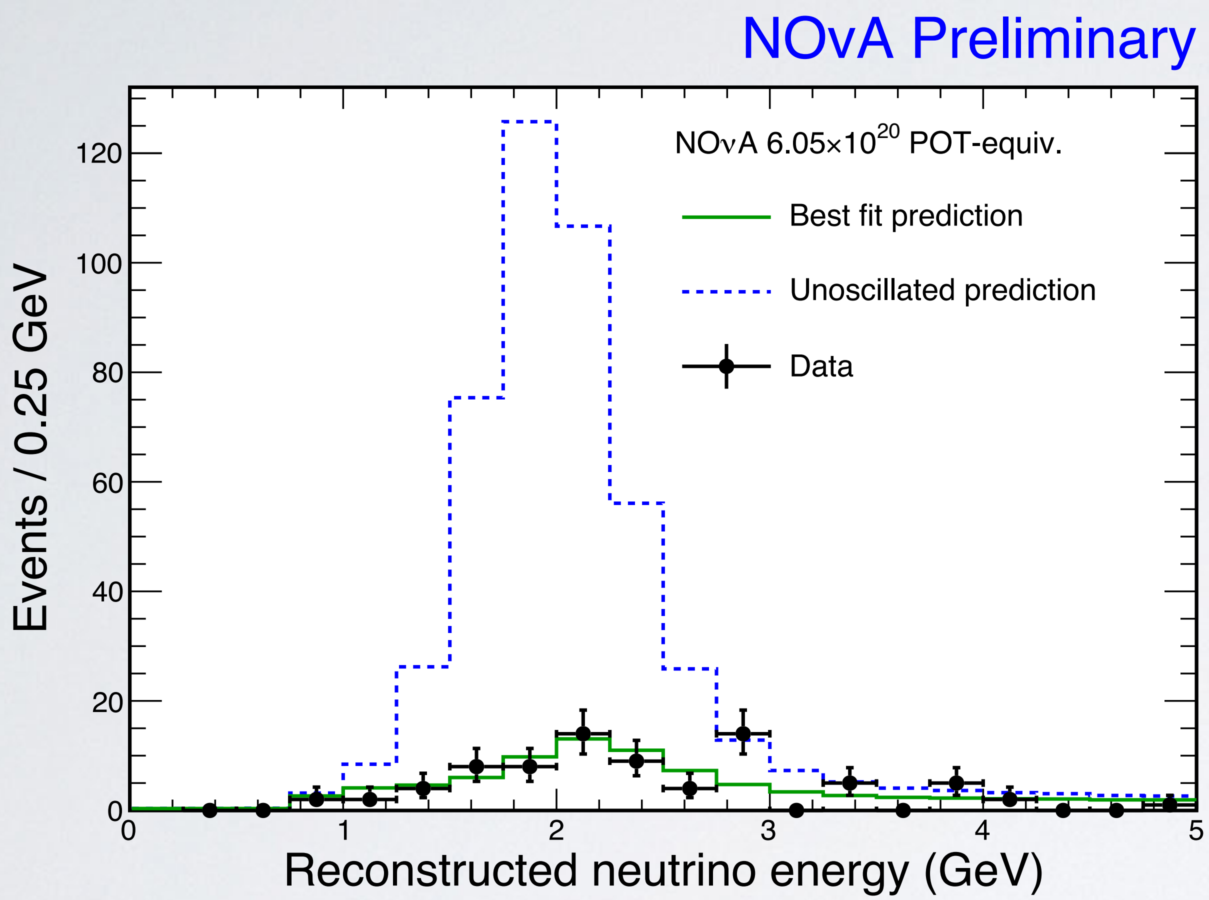


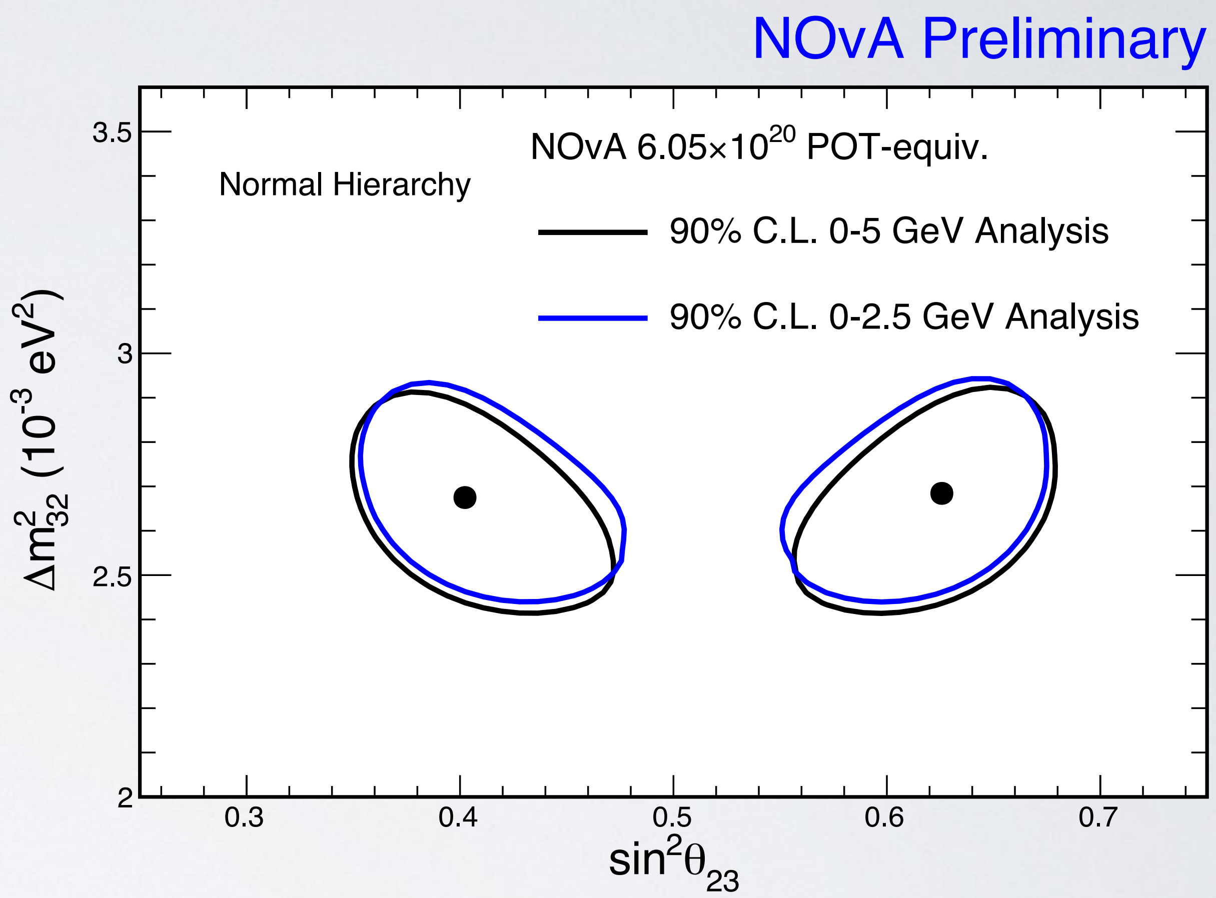
Disappearance


NOvA Preliminary
NOvA 6.05×10^20 POT-equiv.
Best fit prediction
Unoscillated prediction
Data
Events / 0.25 GeV
Reconstructed neutrino energy (GeV)

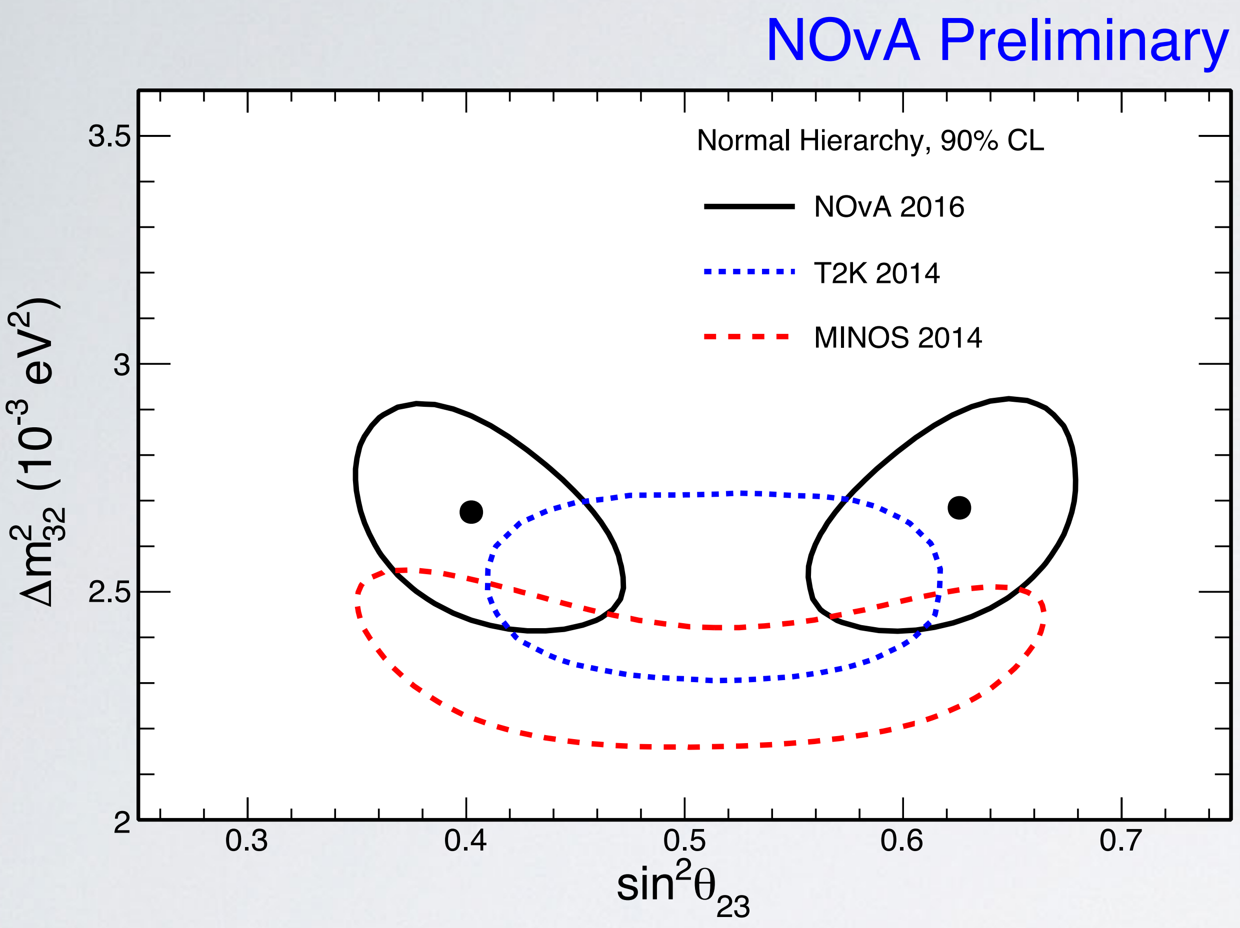

NOvA Preliminary
NOvA 6.05×10^20 POT-equiv.
Data
Best fit prediction
Ratio with unosc. (bkg subtracted)
Reconstructed neutrino energy (GeV)

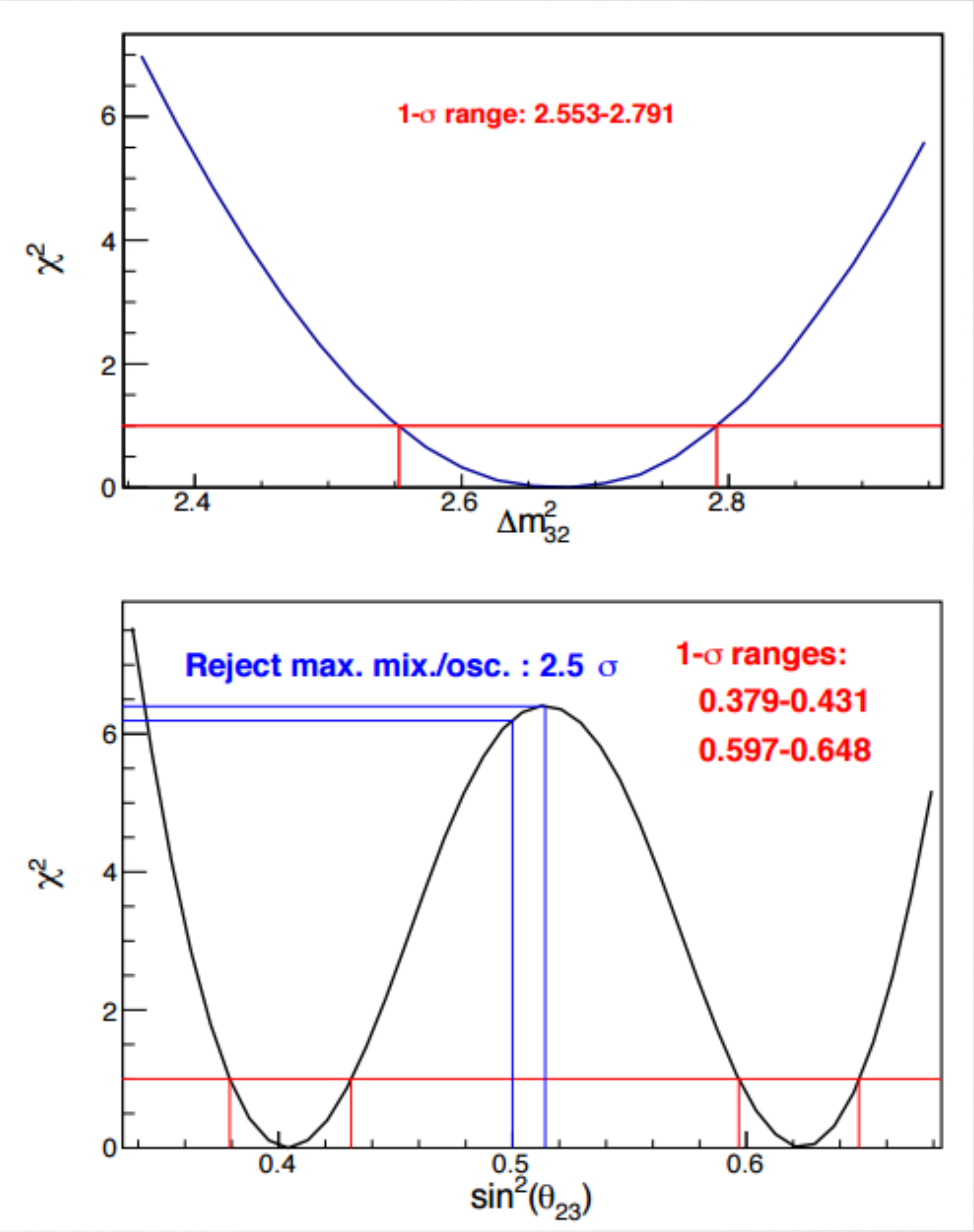
Tail pull on fit





1D bounds



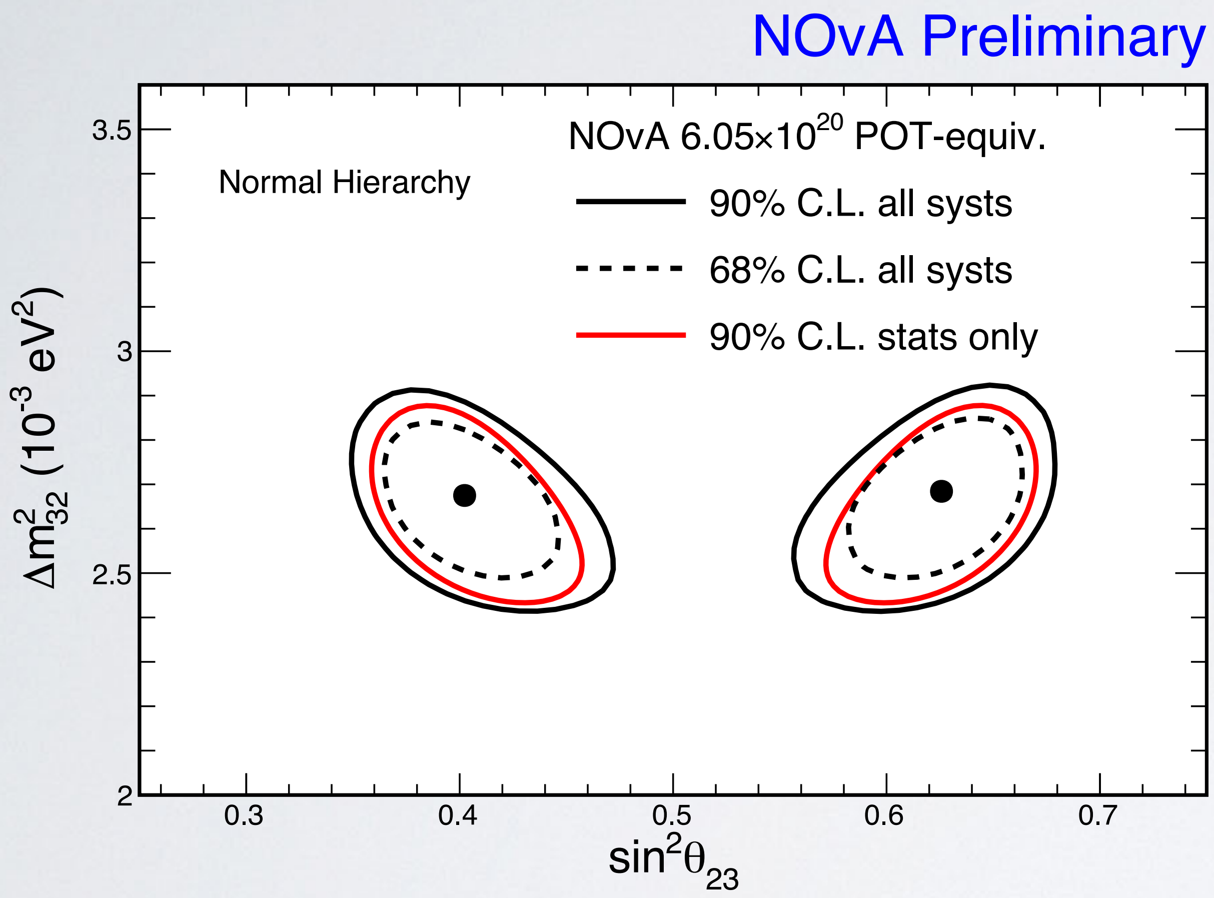


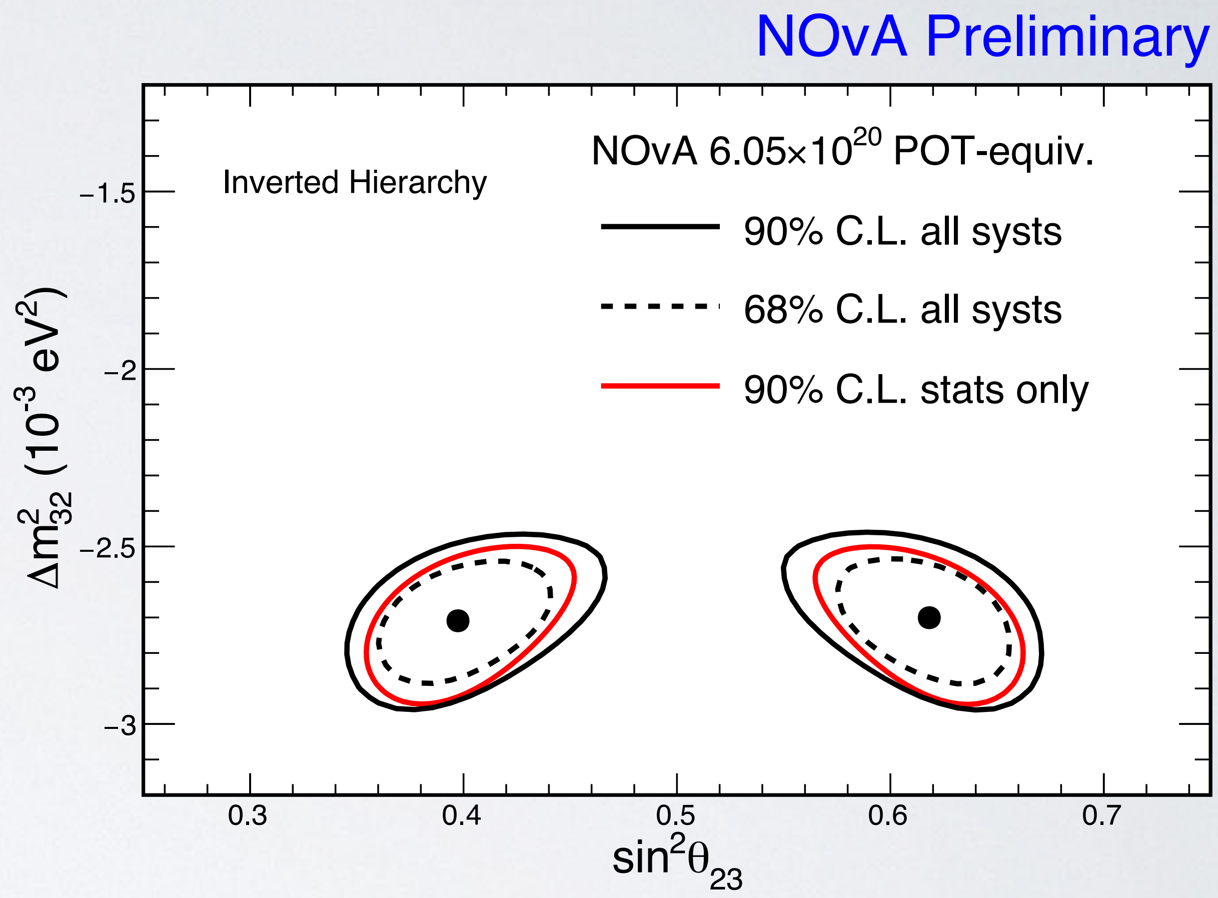
Best Fit:

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3} \mathrm{eV}^2$$

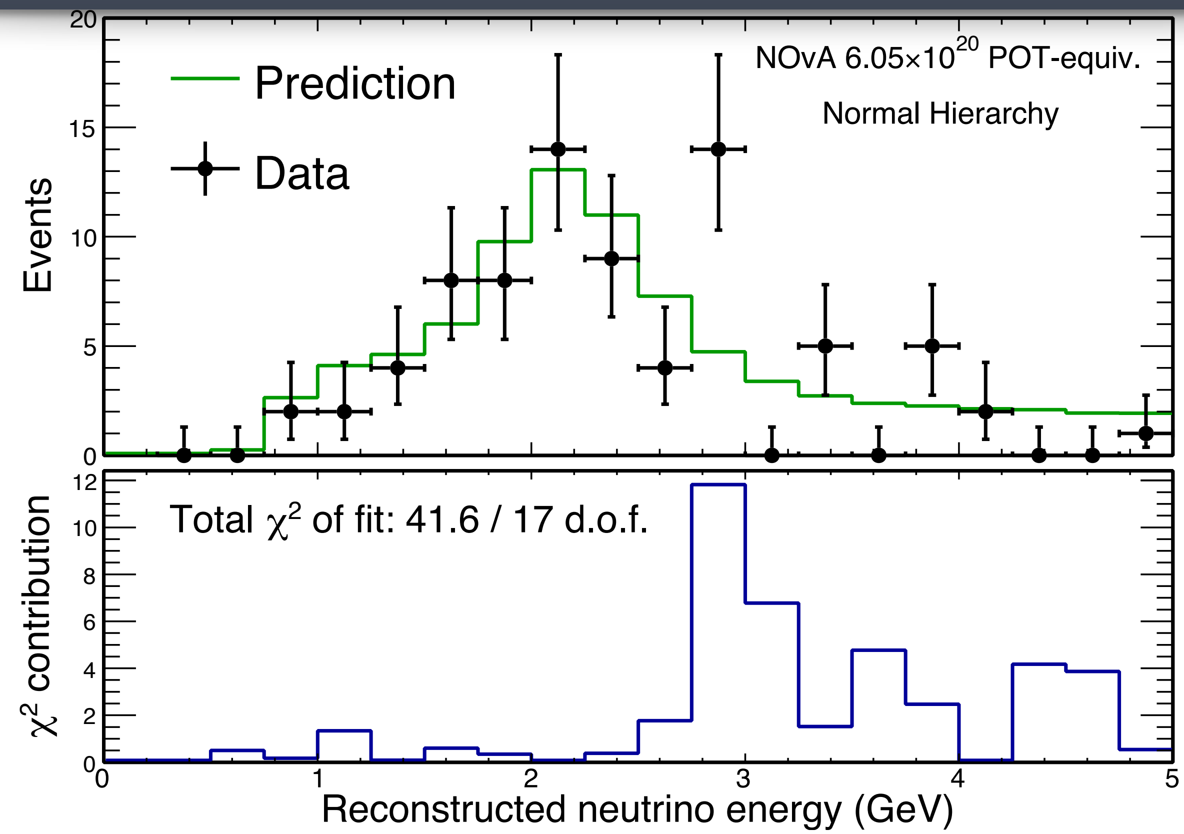
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02} (0.63^{+0.02}_{-0.03})$$

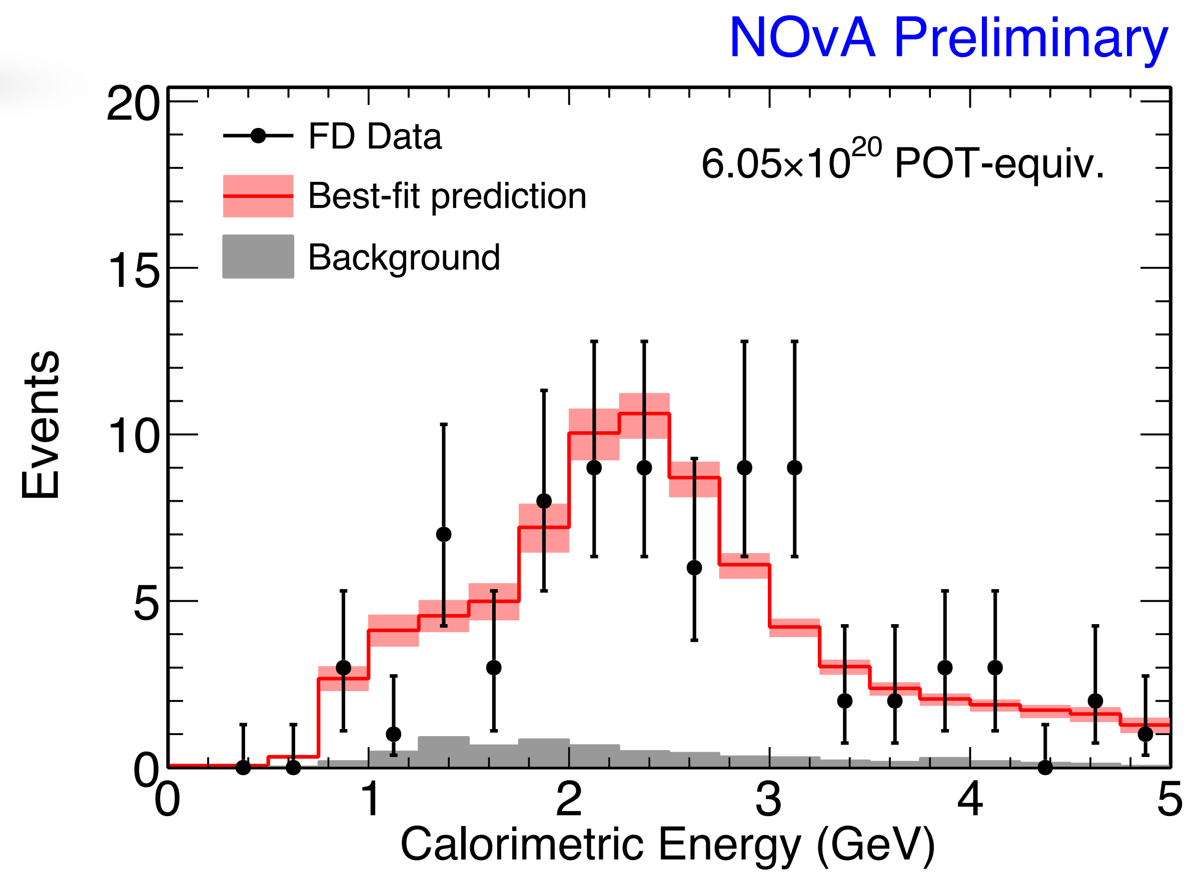
Systematics + IH

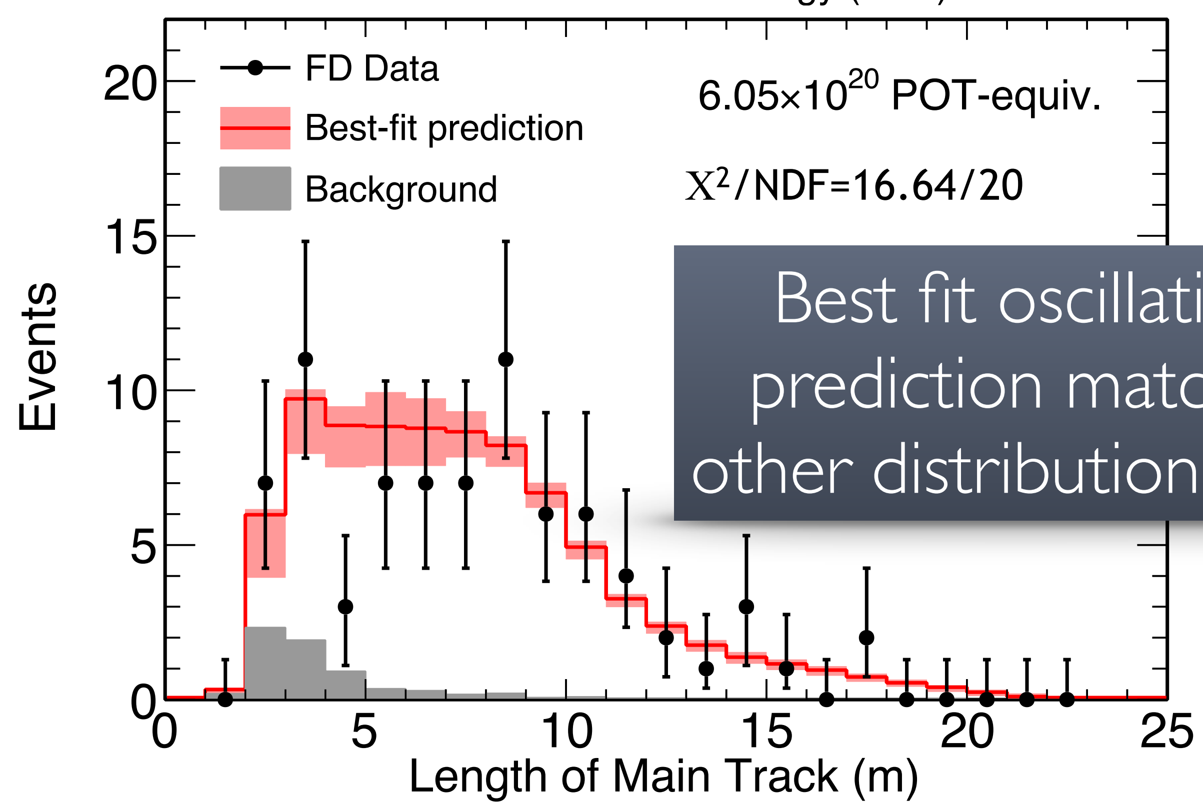




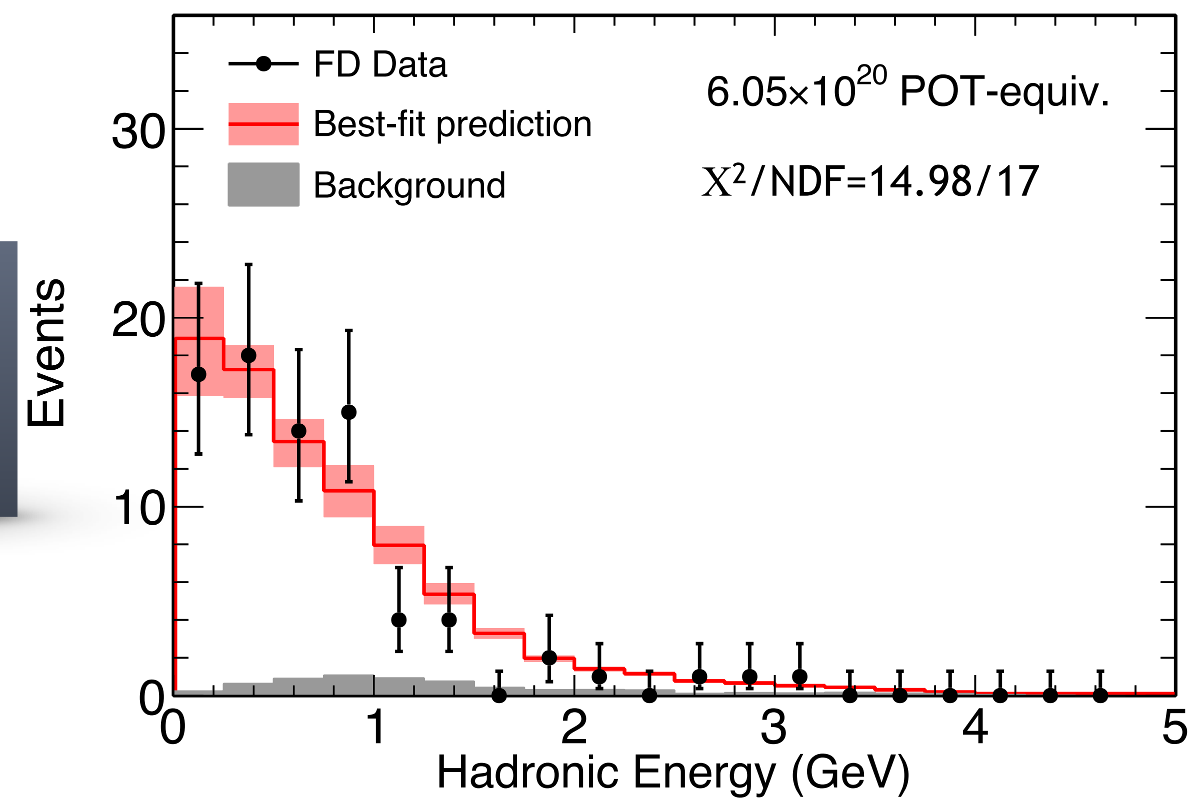
Performing the fit below 2.5 GeV improves X^2 substantially but does not change fit results, sensitivity, or exclusion of maximal mixing



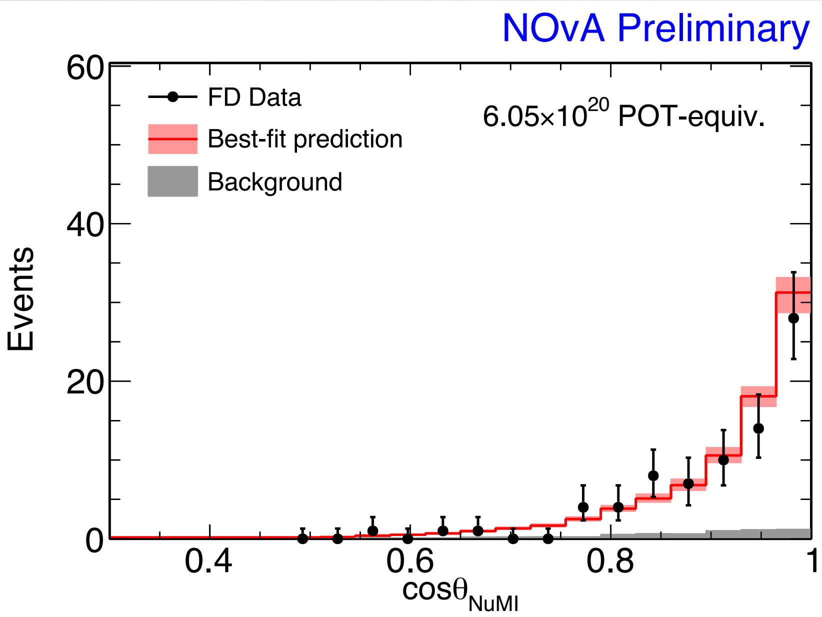


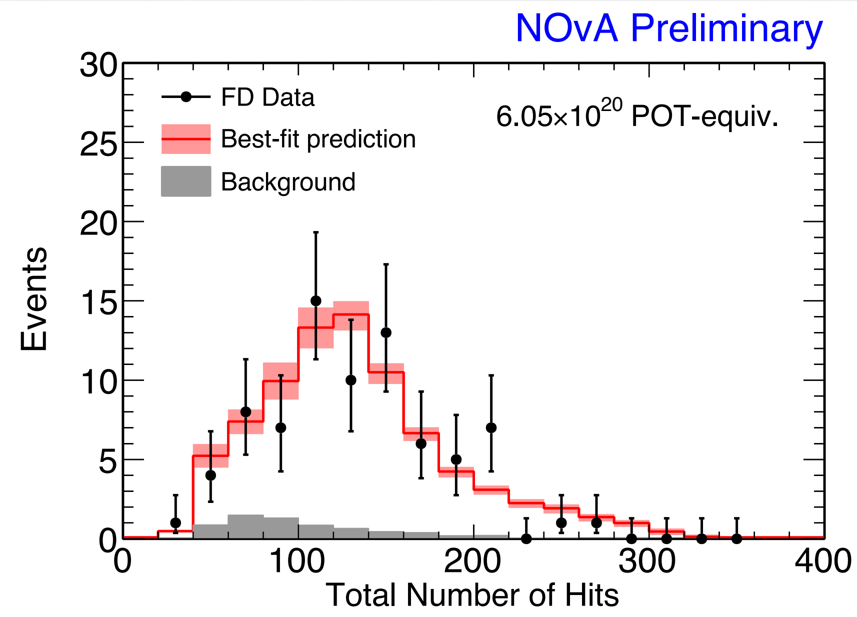


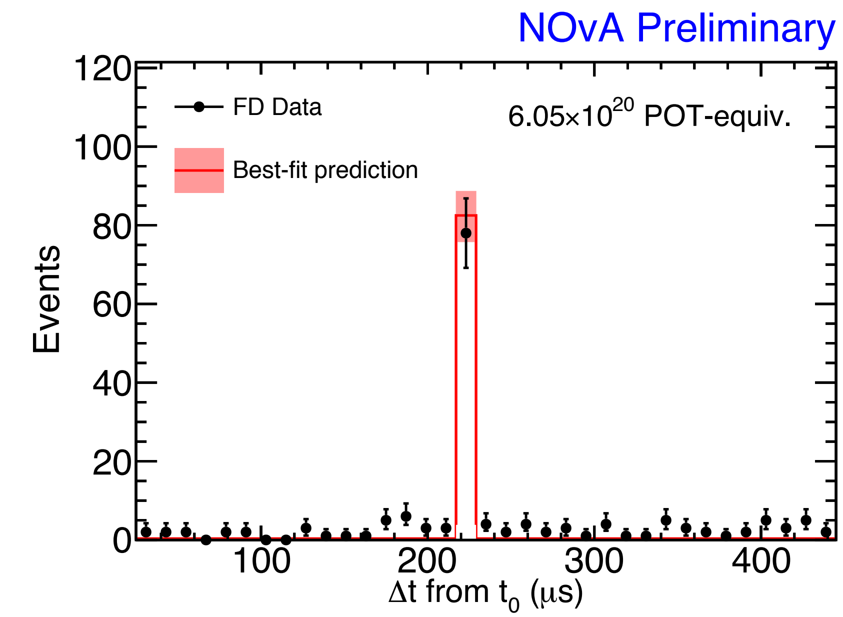
Best fit oscillation prediction matches other distributions well

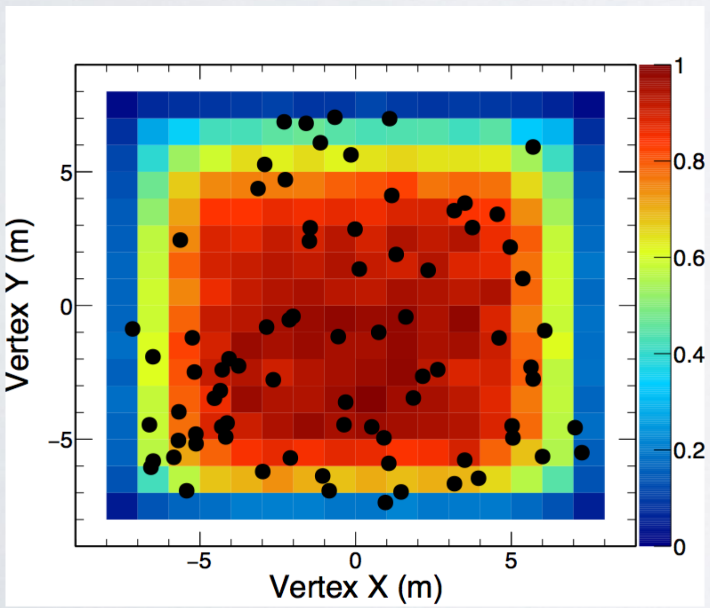


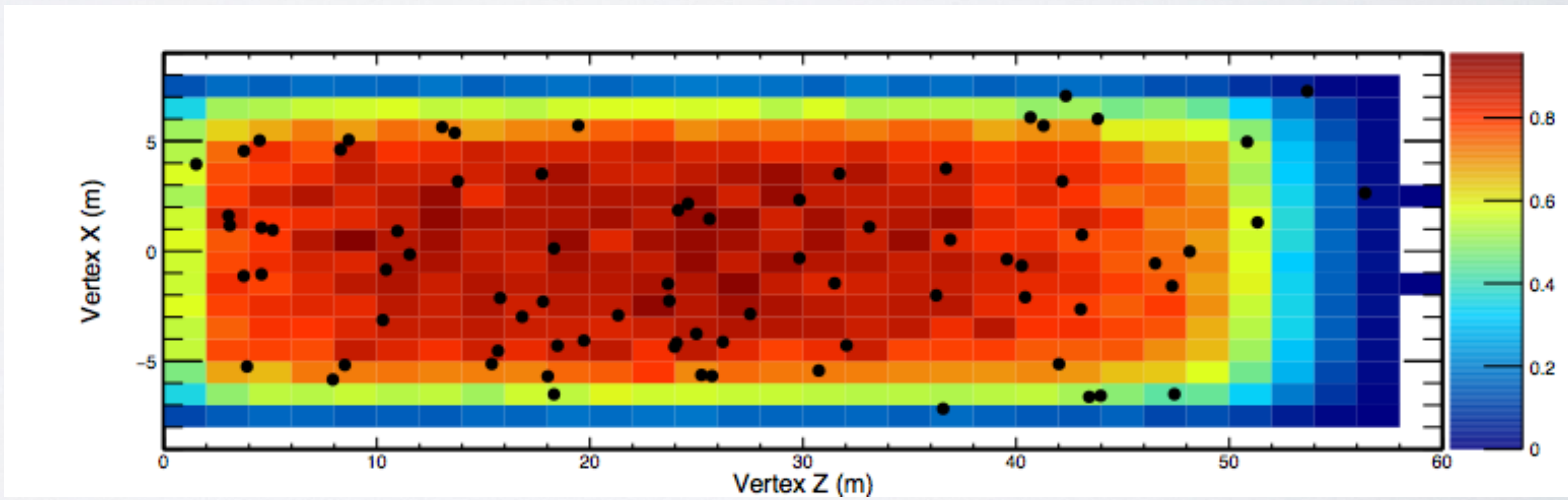
Muon Neutrino FD Data











We consider multiple possible sources of systematic error

Systematic	Effect on $\sin^2(\theta_{23})$	Effect on Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model	± 0.7 %	± 0.1 %
All systematics	**± 3.4 %**	**± 2.4 %**
Stat. Uncertainty	**± 4.1 %**	**± 3.5 %**

In each case:

- The effect is propagated through the extrapolation
- We include those effects as pull terms in the fit
- The increase (in quadrature) of the measurement error is recorded

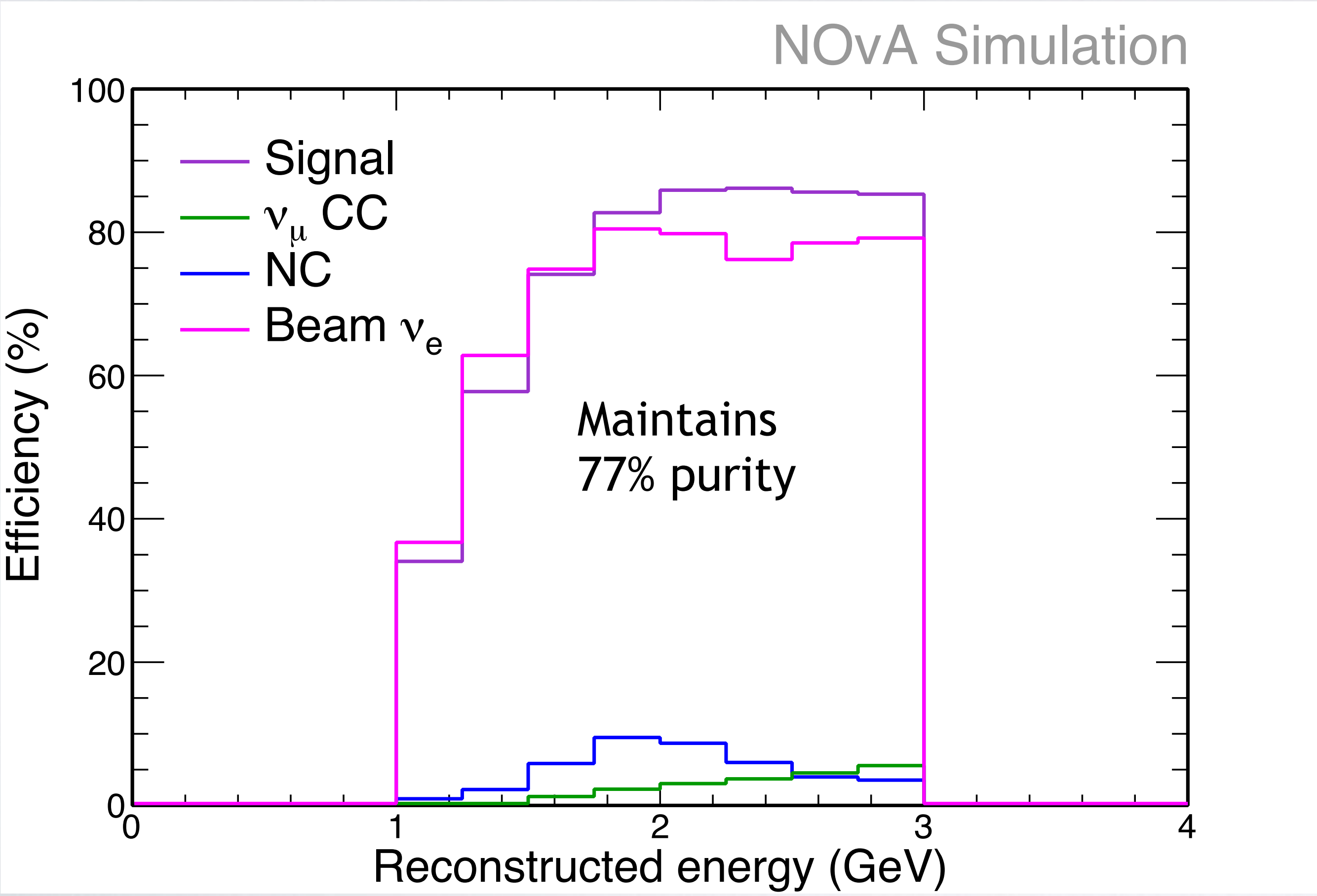
Appearance

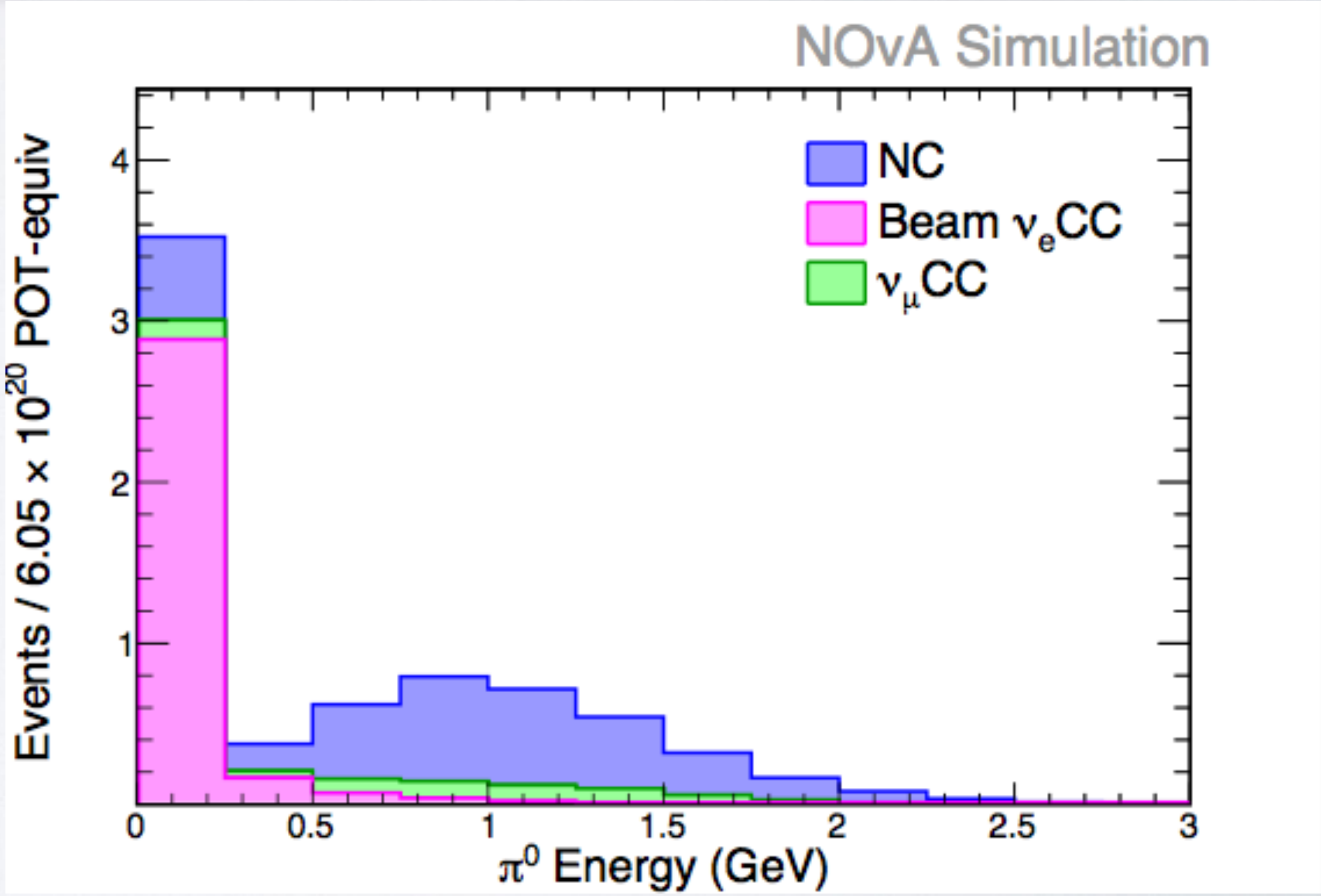
Electron Neutrino Event Selection

- Selection re-optimised to favour parameter measurement (both cosmic rejection and classifier cut)

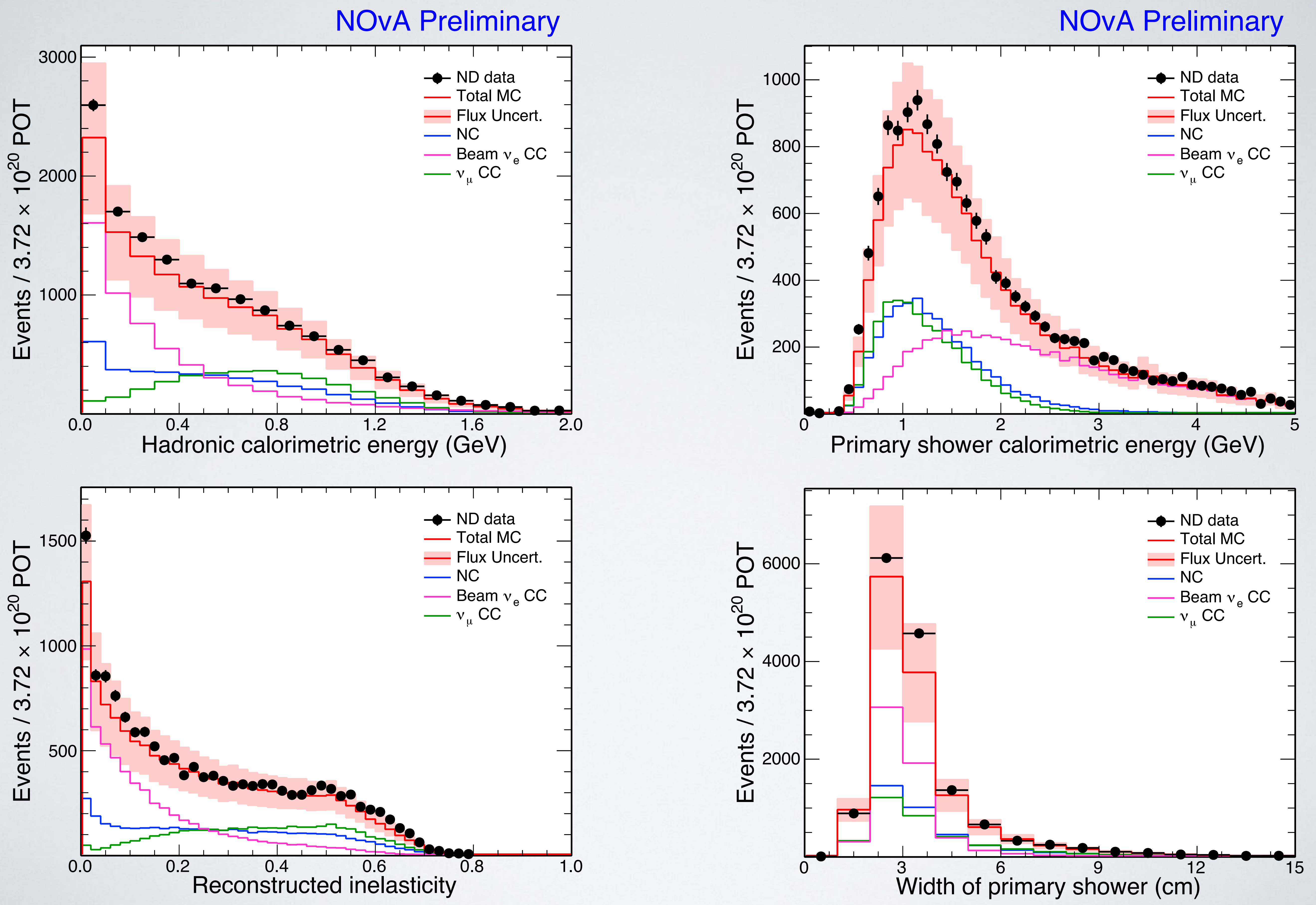
increased signal efficiency, somewhat degraded purity relative to 2015 analysis

91% of selected events have an EM shower

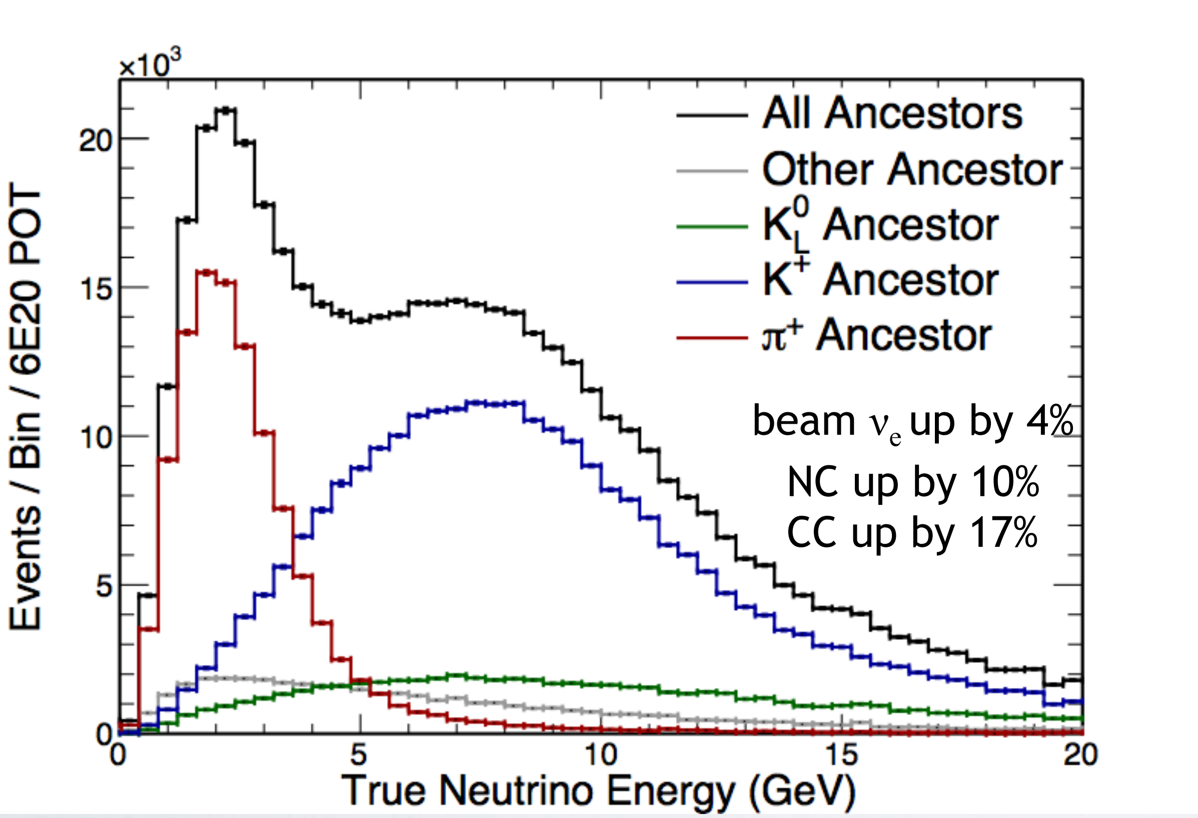




Electron Appearance ND Data/MC



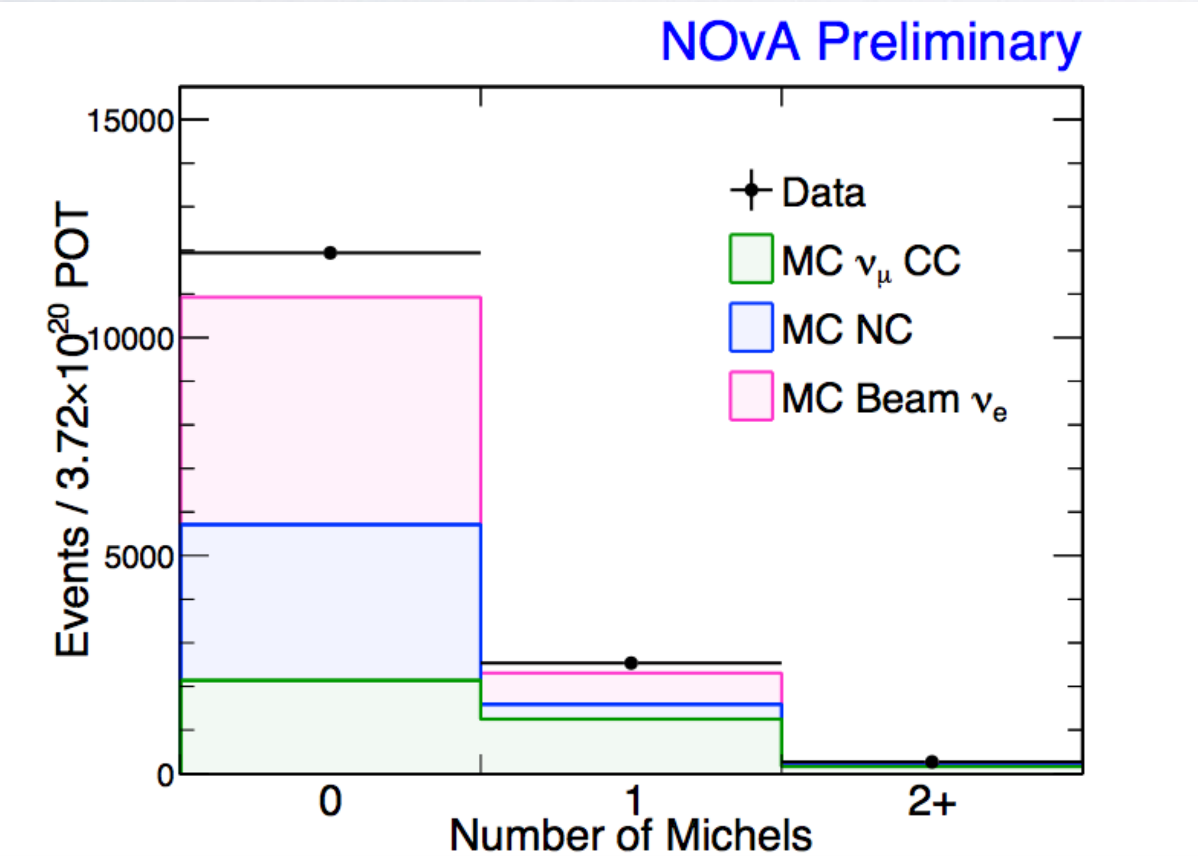
Decomposition

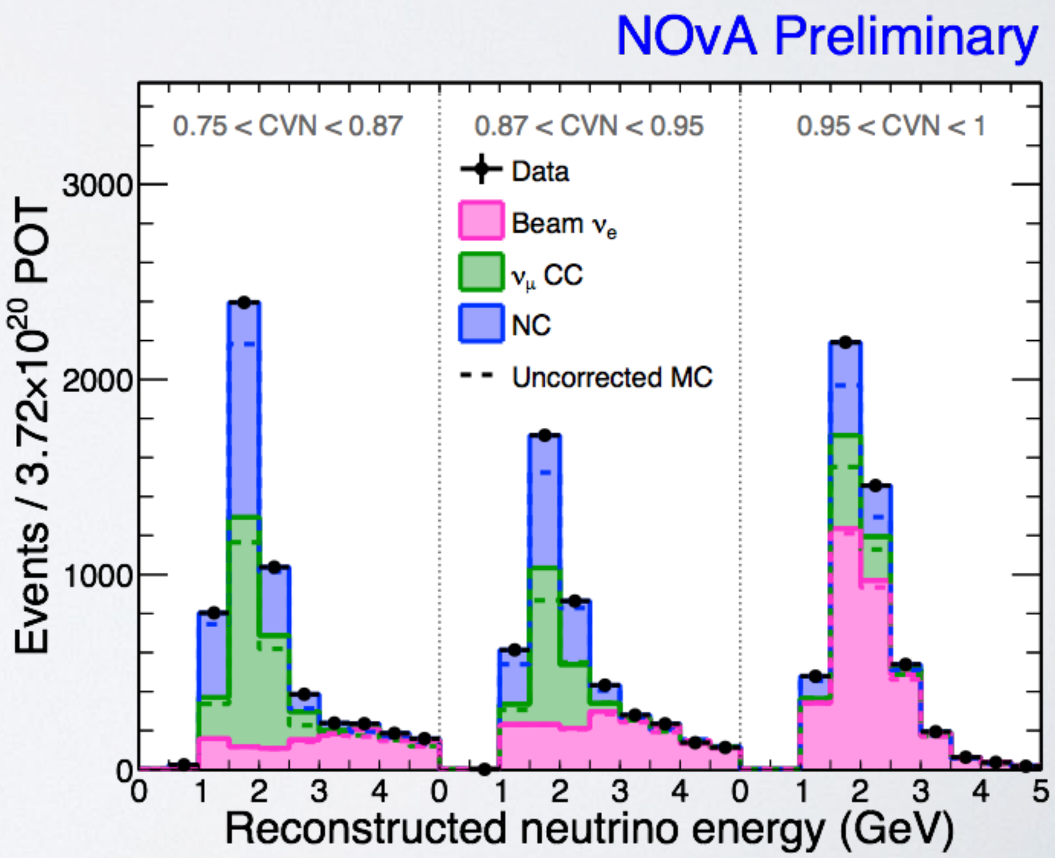


- Use ND data to predict FD background
- NC, CC, beam ν_e extrapolate differently

constrain beam ν_e using selected ν_μ CC spectrum

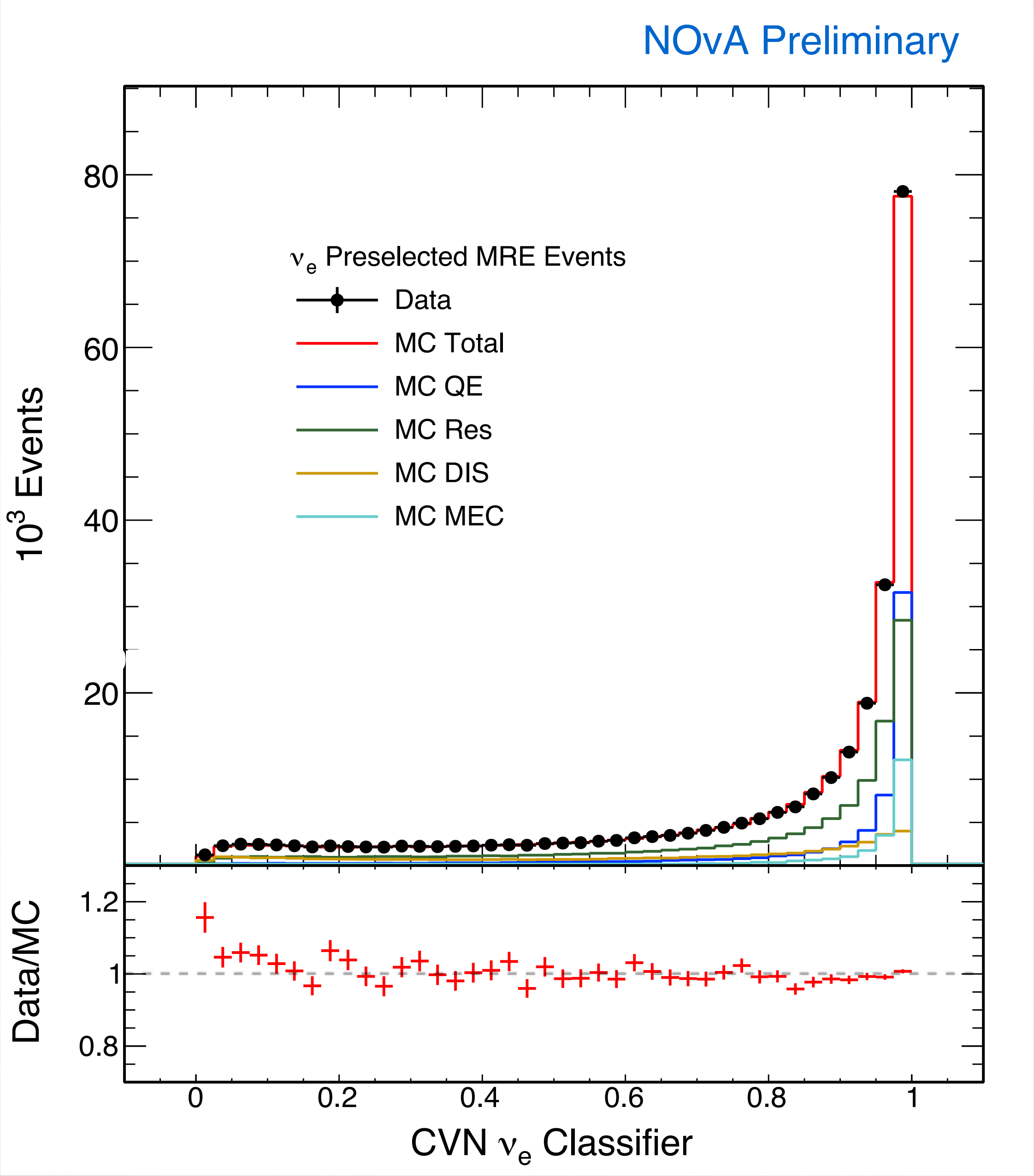
constrain CC with Michel Electron distribution

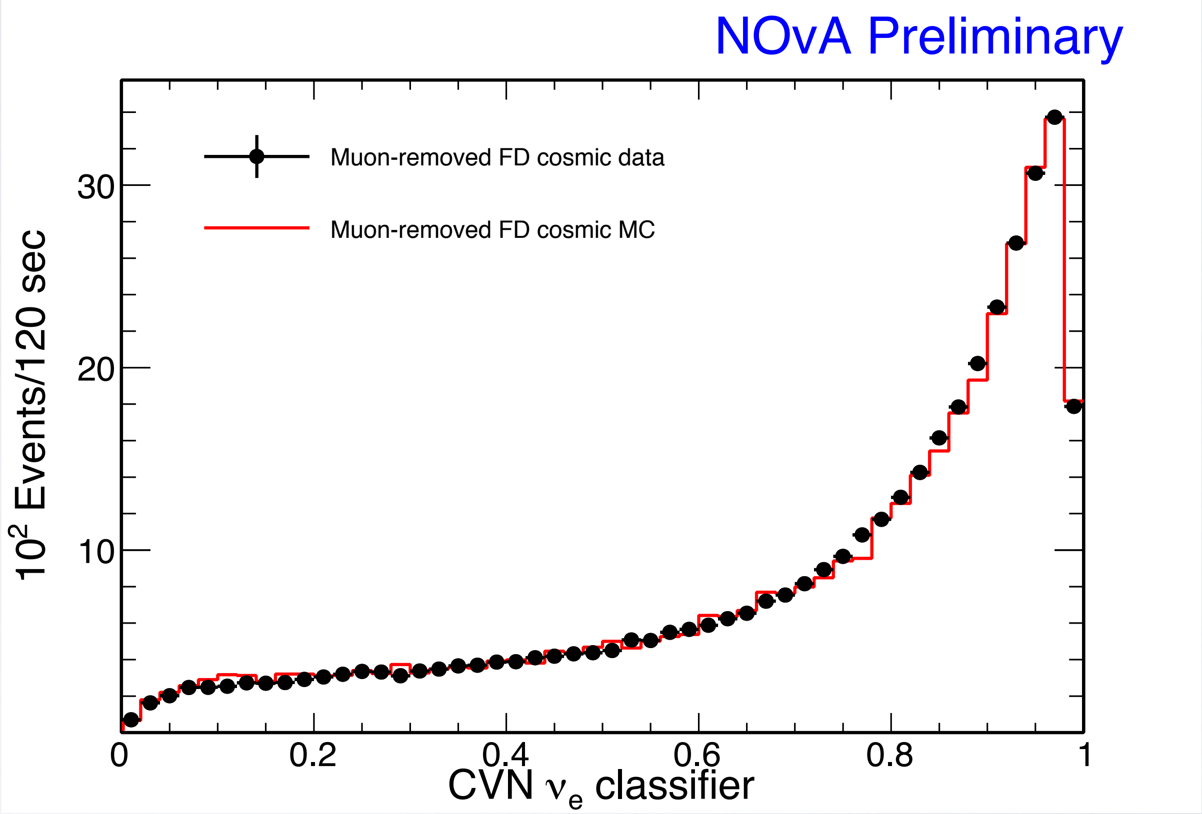




Checking the Signal Efficiency

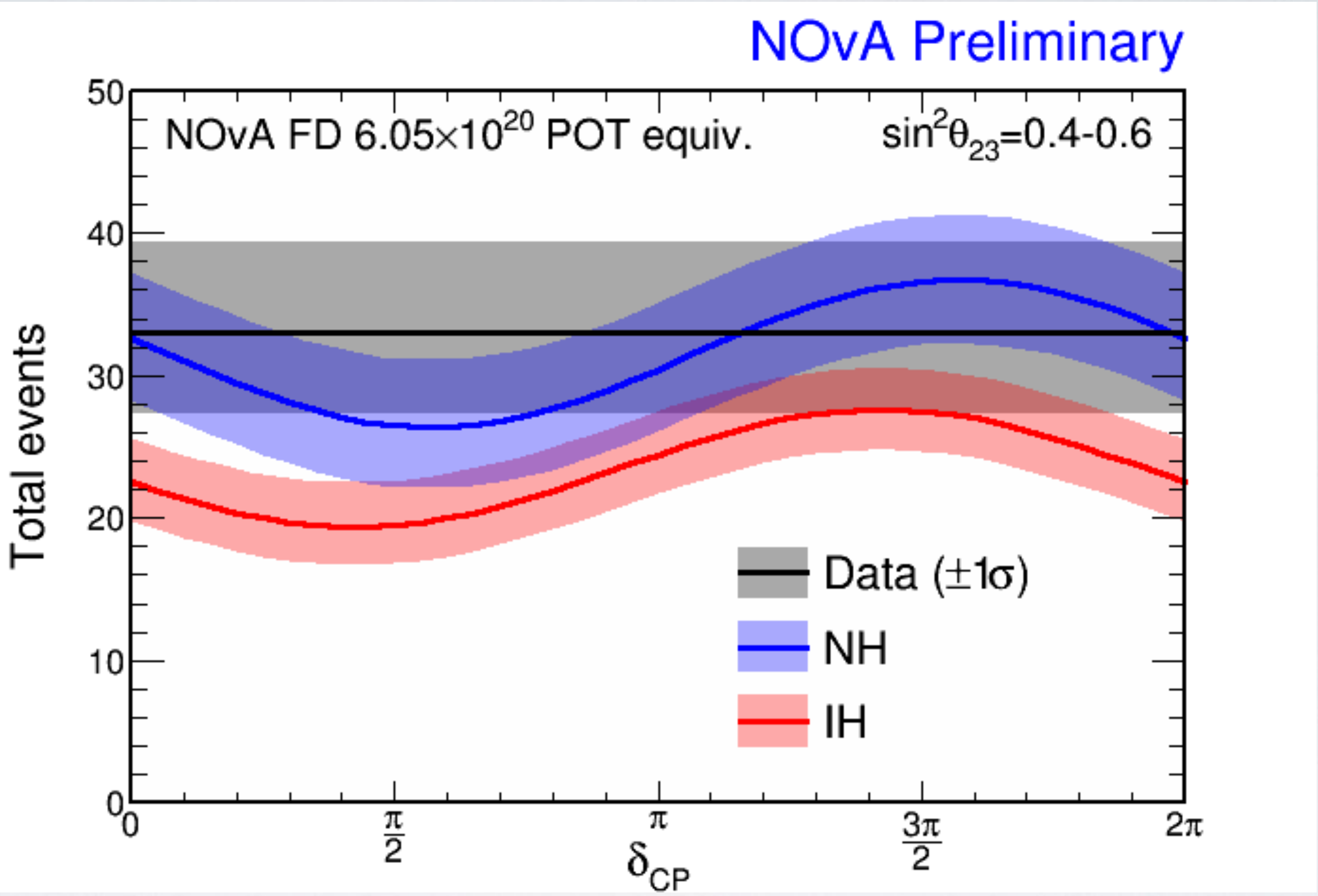
- Use bremsstrahlung from cosmic ray muons to benchmark simulation of electron selection
- Event classifier distributions match well

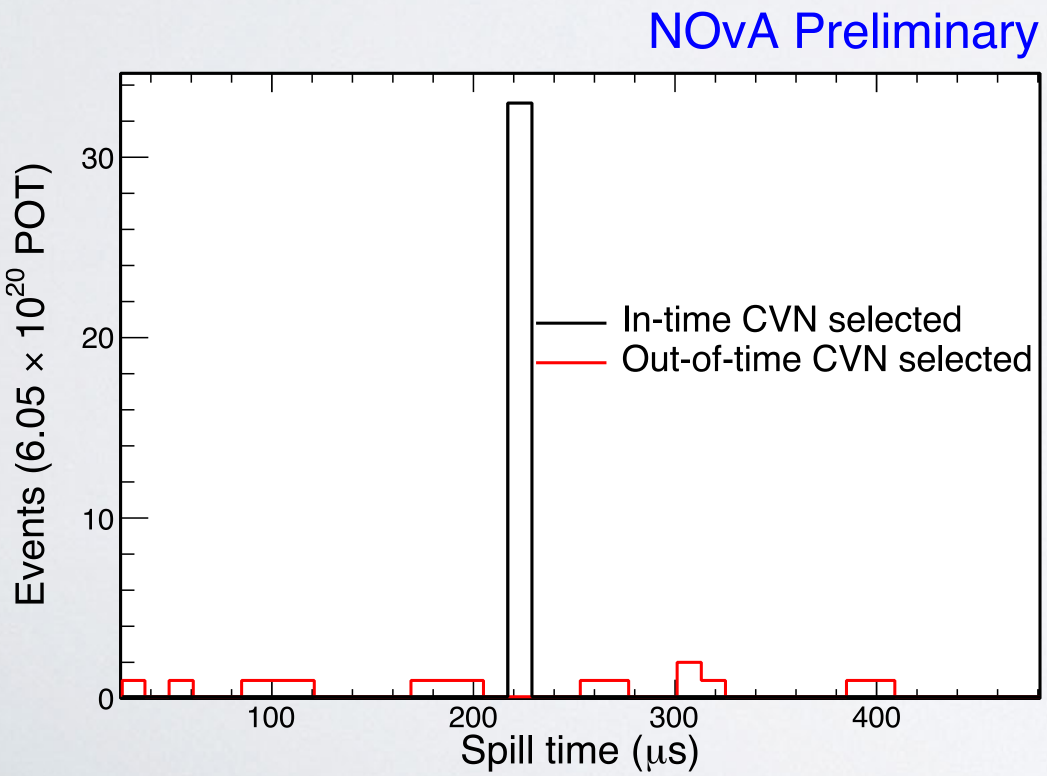


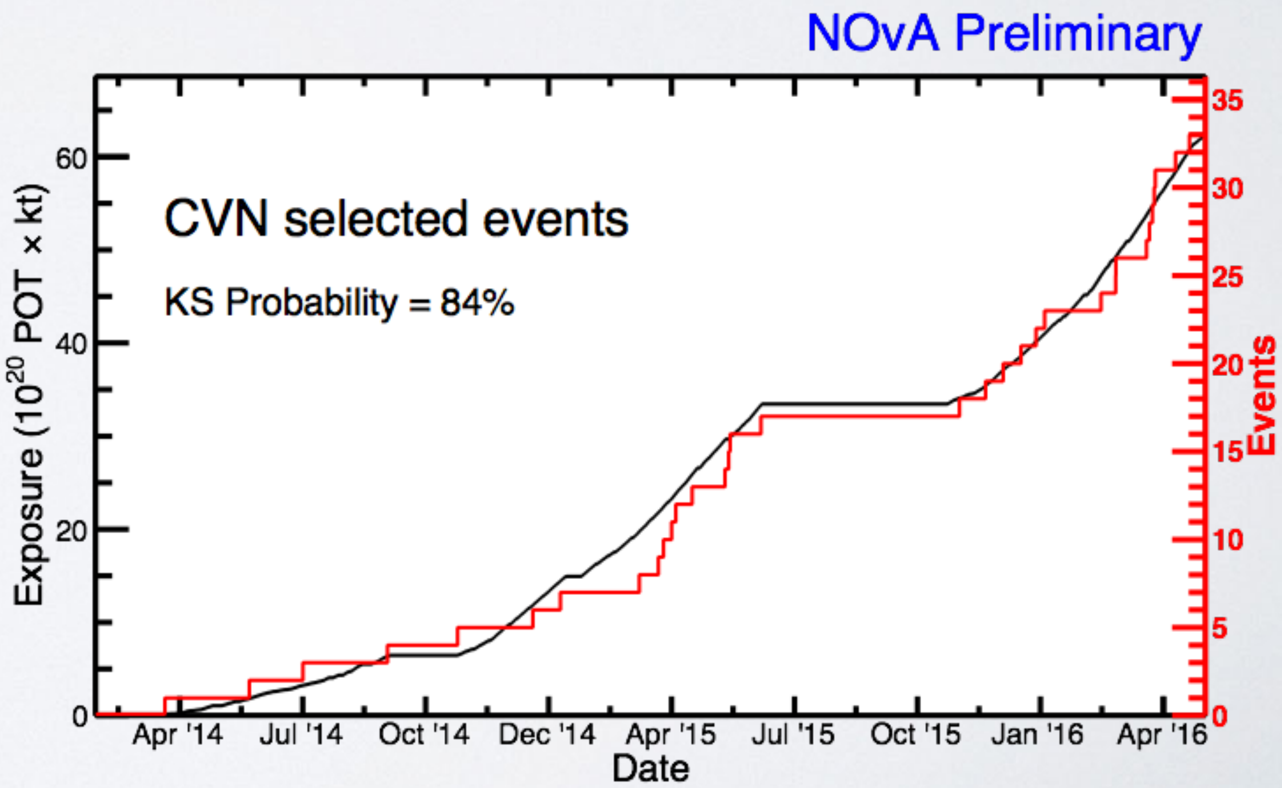


- Remove reconstructed muons from selected ν_μ events, replace with simulated electron (MRE)

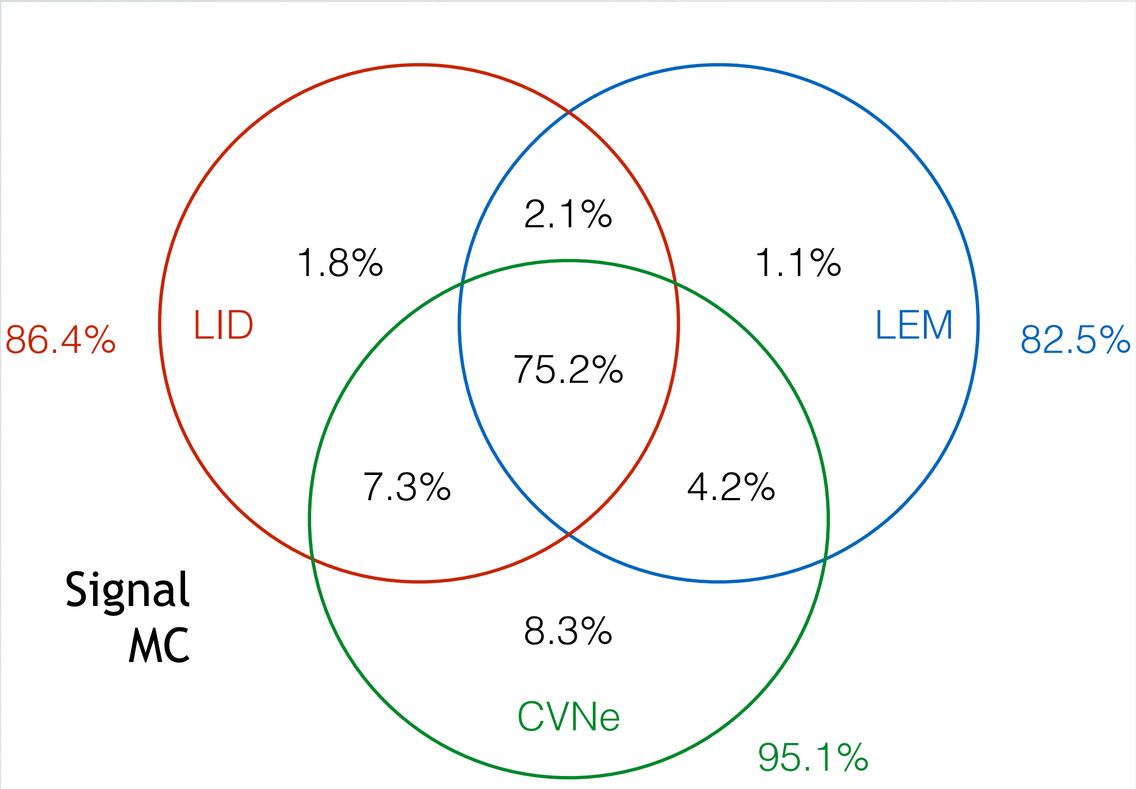
  better than 1% agreement between efficiency for selecting data MRE events and efficiency for selecting MC MRE events

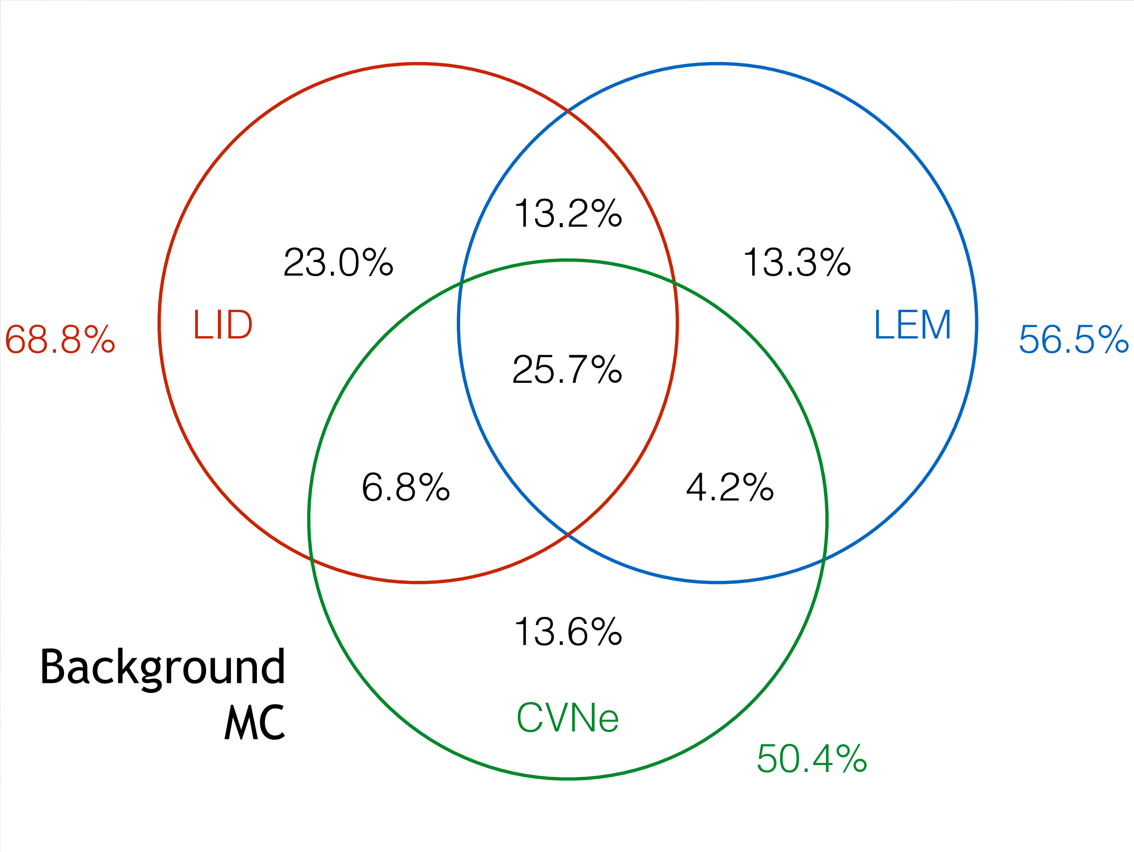

NOvA Preliminary
NOvA FD 6.05×10^20 POT equiv.
sin²θ23=0.4-0.6
Total events
δCP
Data (±1σ)
NH
IH

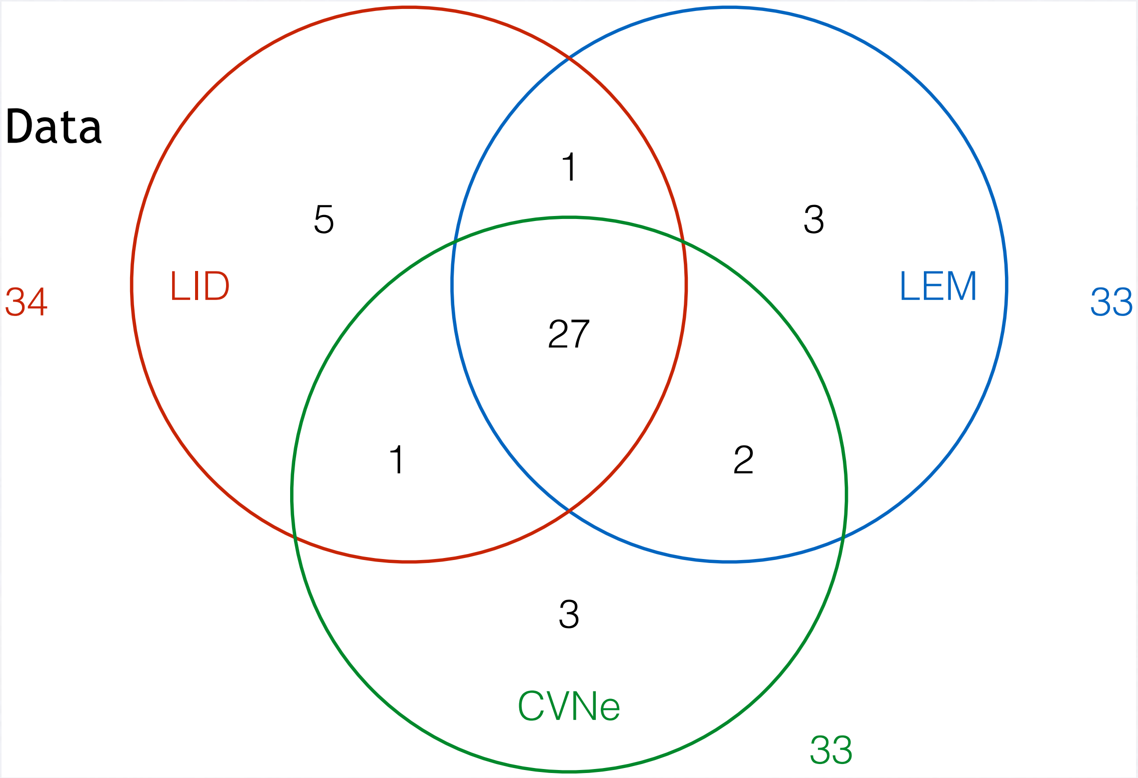

NOvA Preliminary
Events (6.05 × 10^20 POT)
Spill time (μs)
In-time CVN selected
Out-of-time CVN selected


NOvA Preliminary
CVN selected events
KS Probability = 84%
Exposure (10^20 POT × kt)
Events
Date
Apr '14
Jul '14
Oct '14
Dec '14
Apr '15
Jul '15
Oct '15
Jan '16
Apr '16

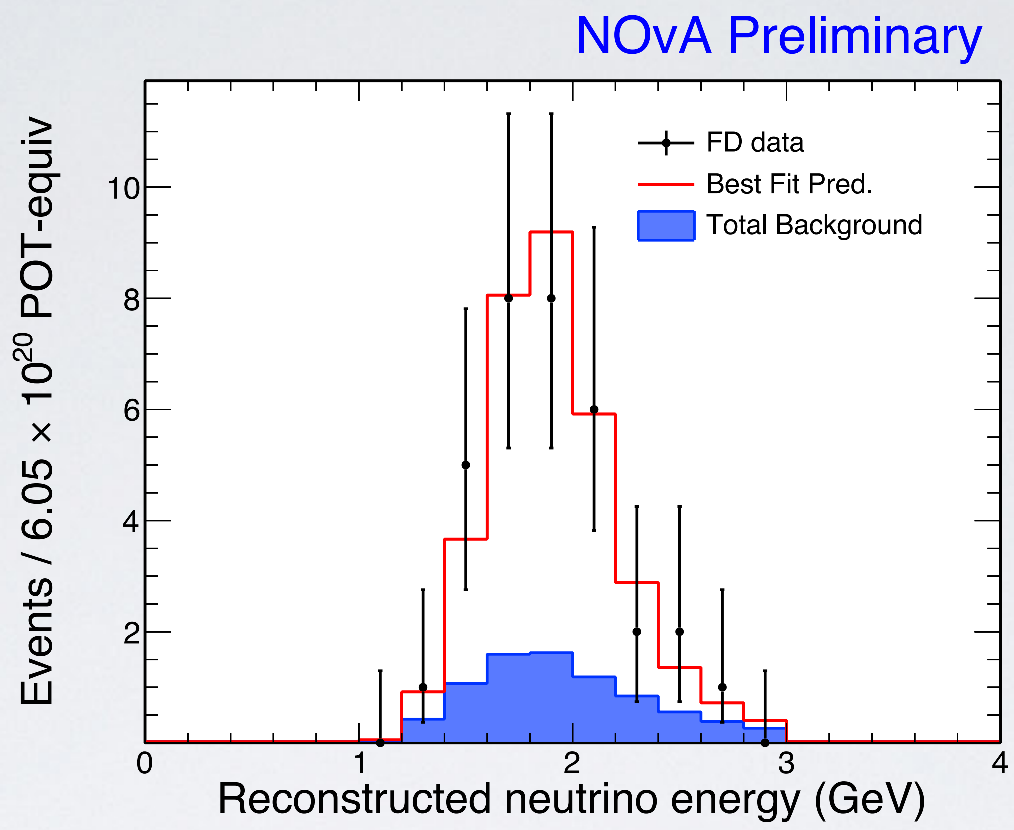
Electron Neutrino Selection Techniques

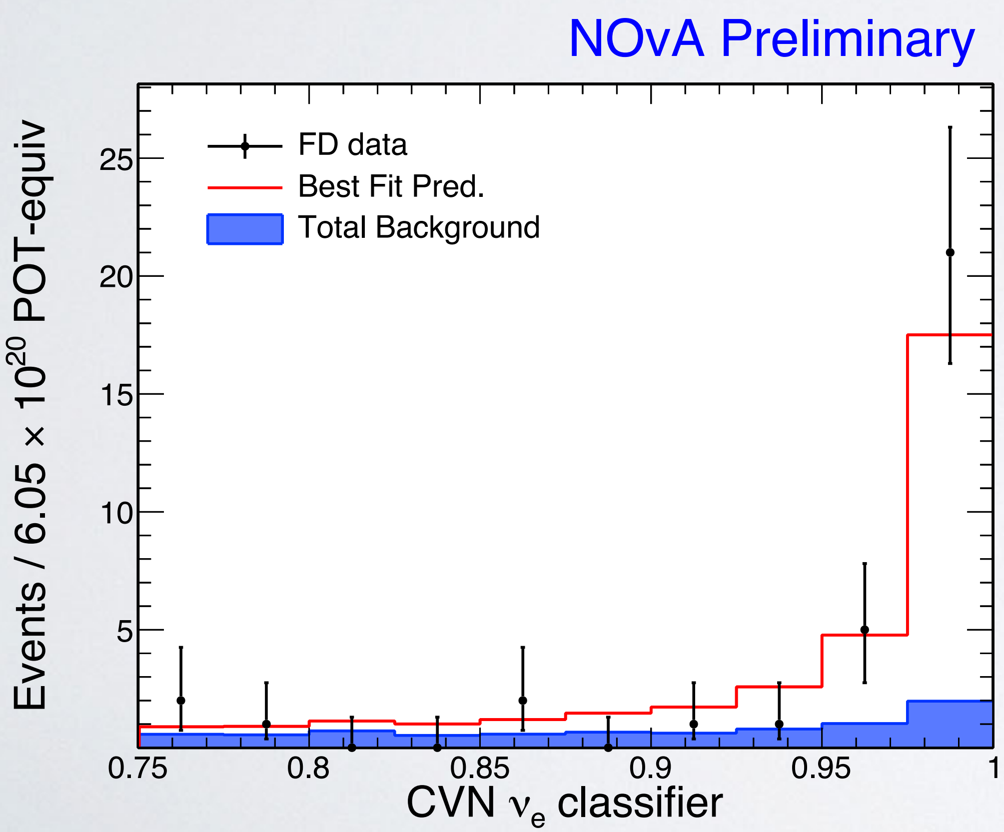


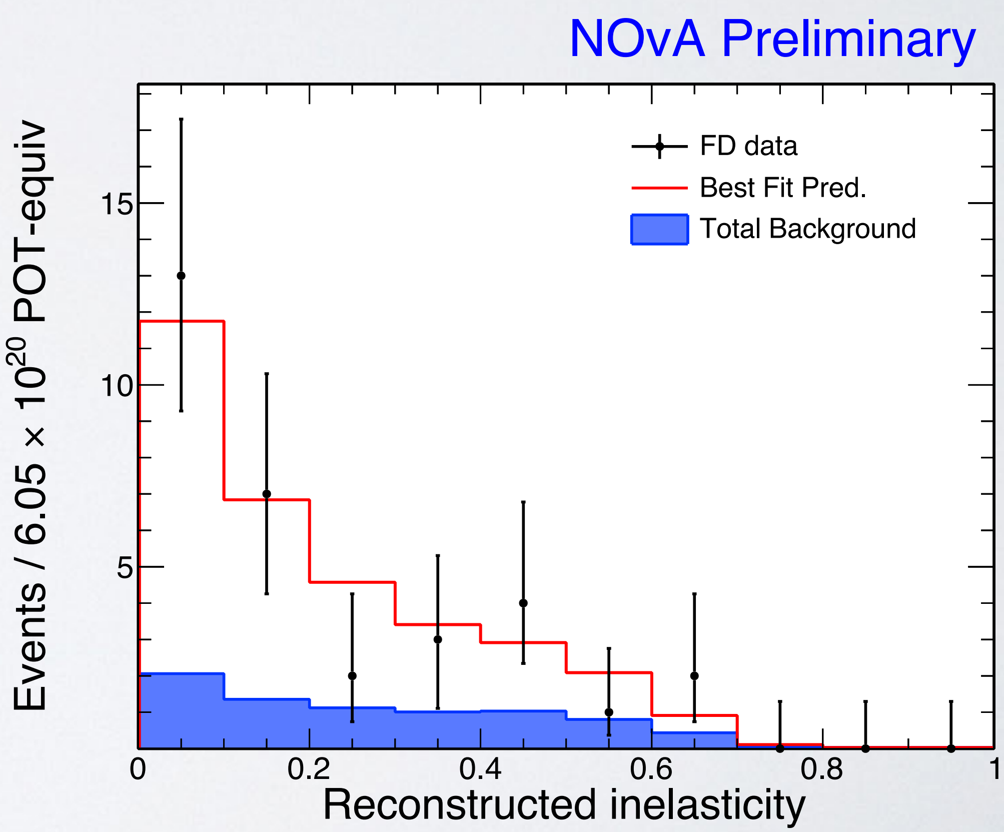




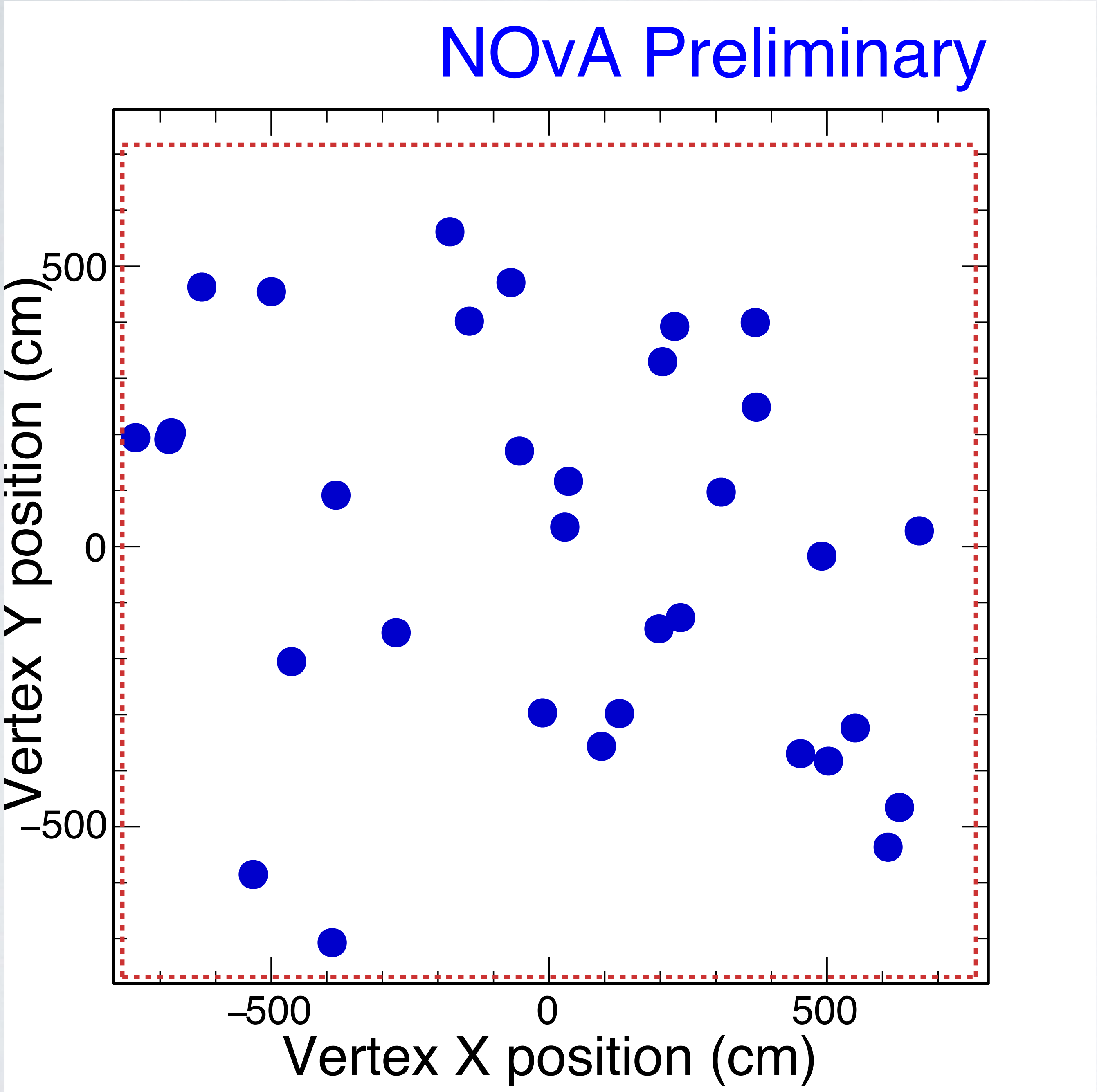
Electron Neutrino FD Data

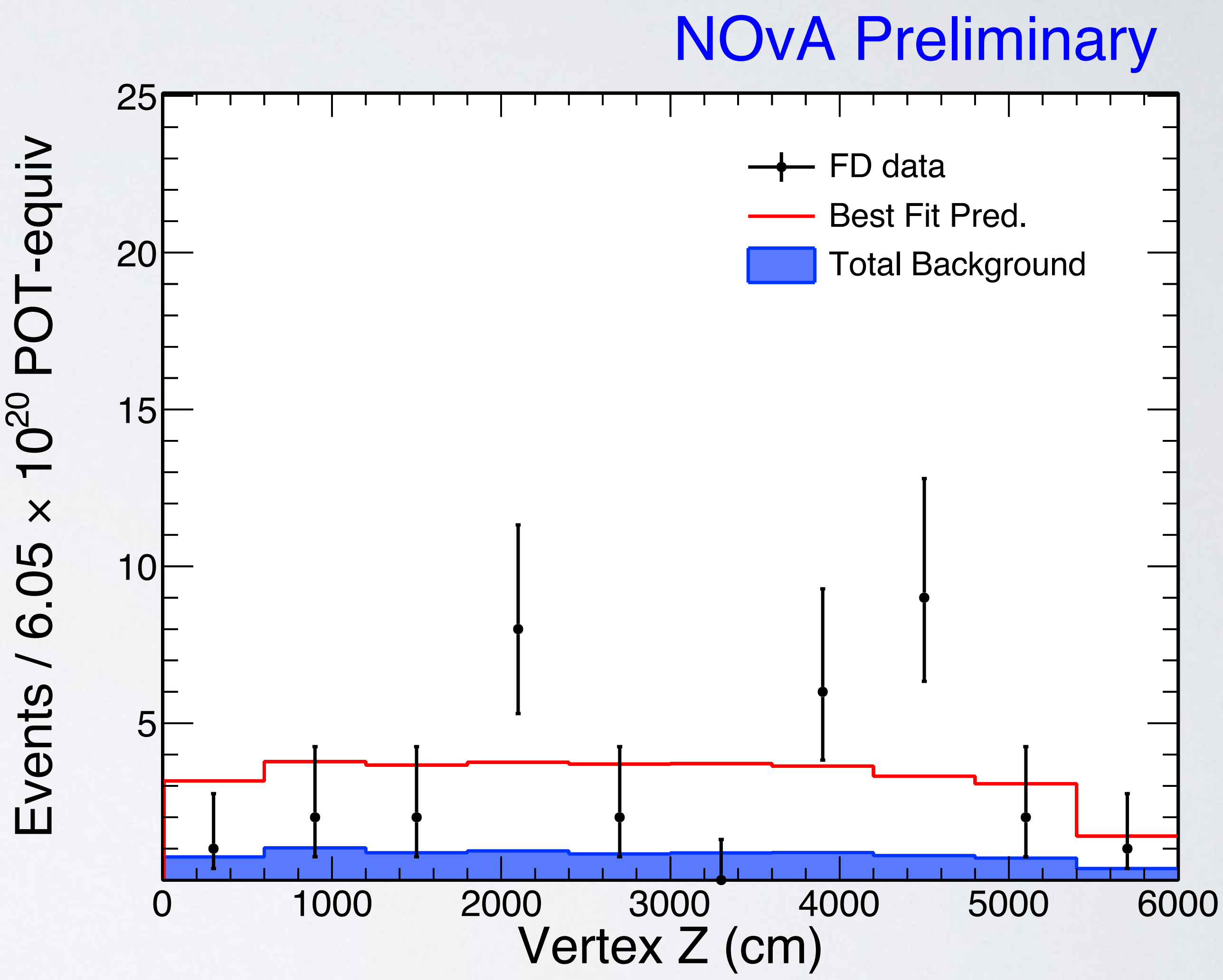




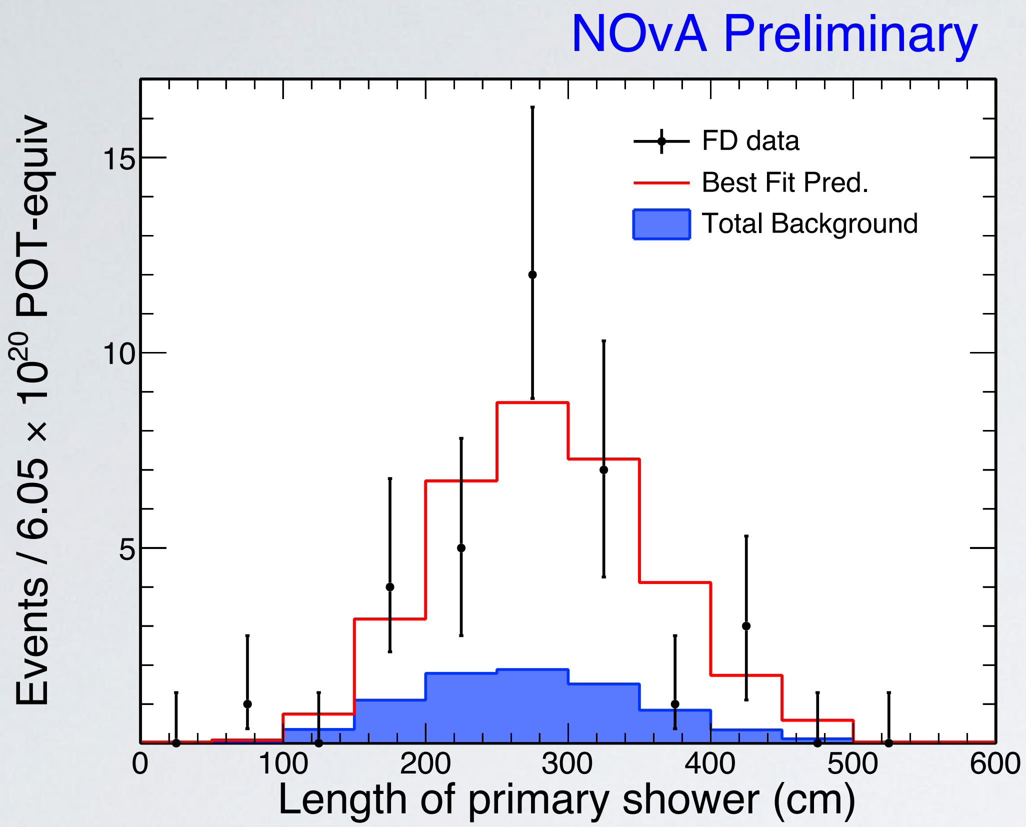


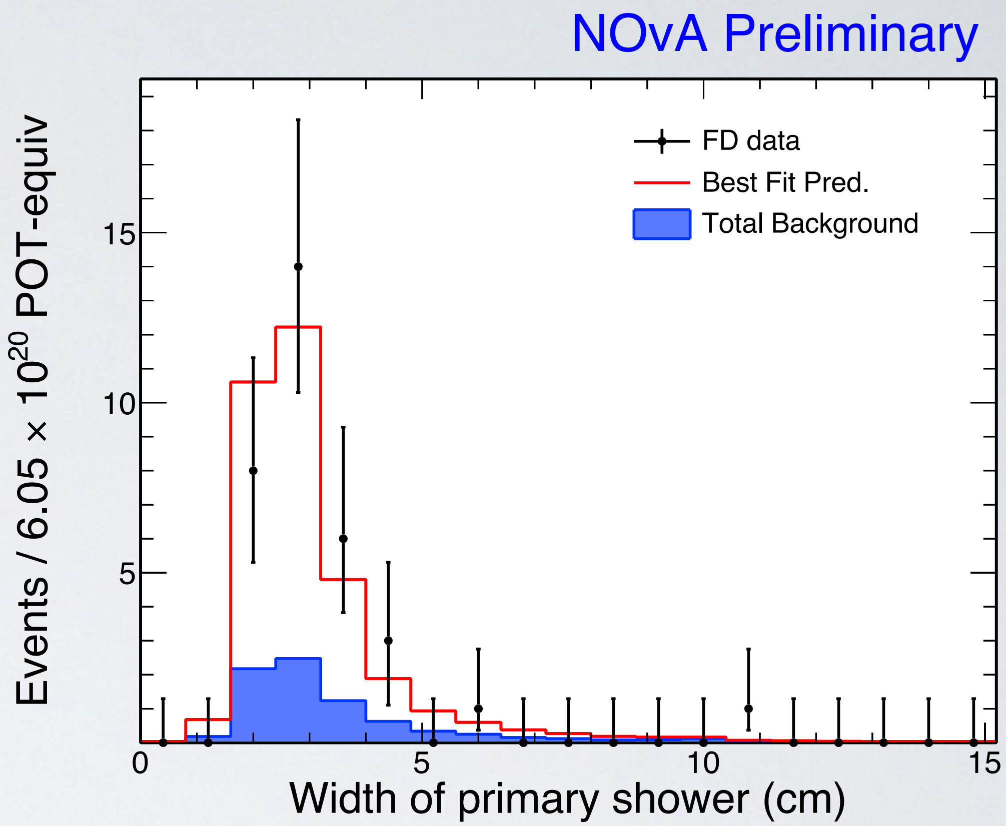
Electron Neutrino FD Data

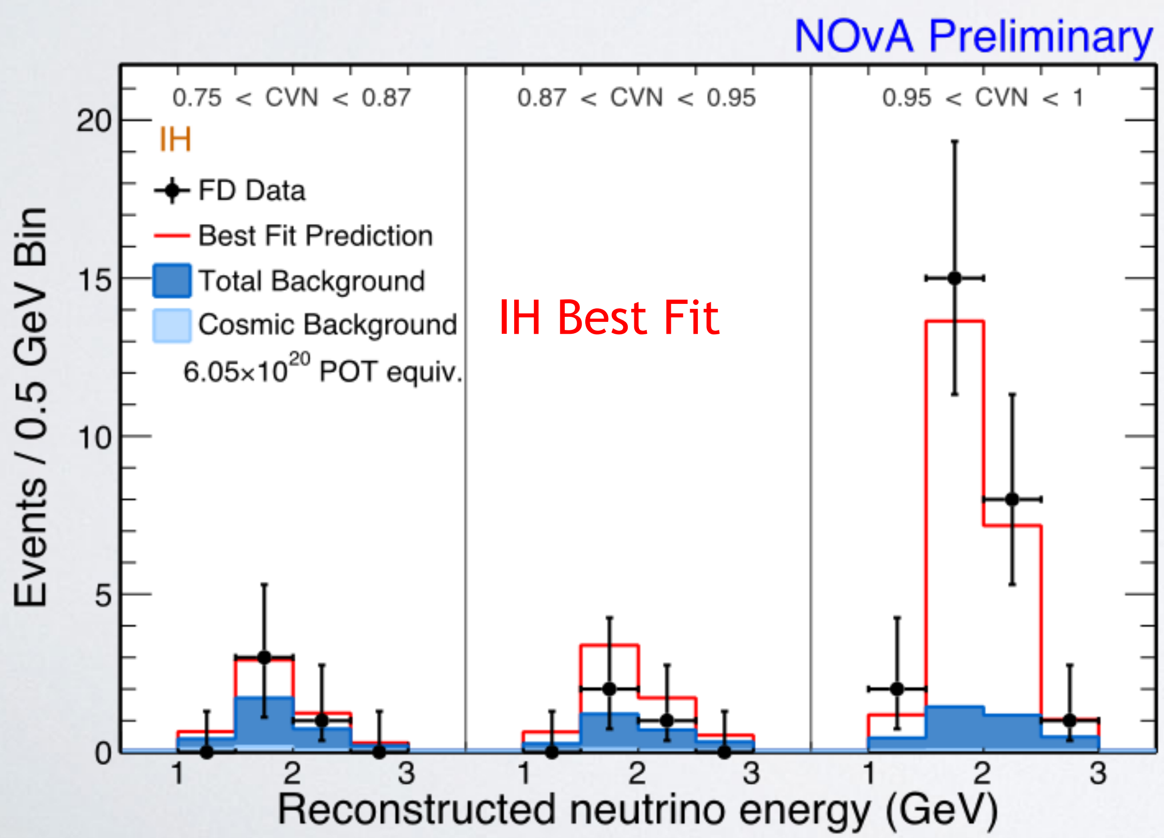




Electron Neutrino FD Data



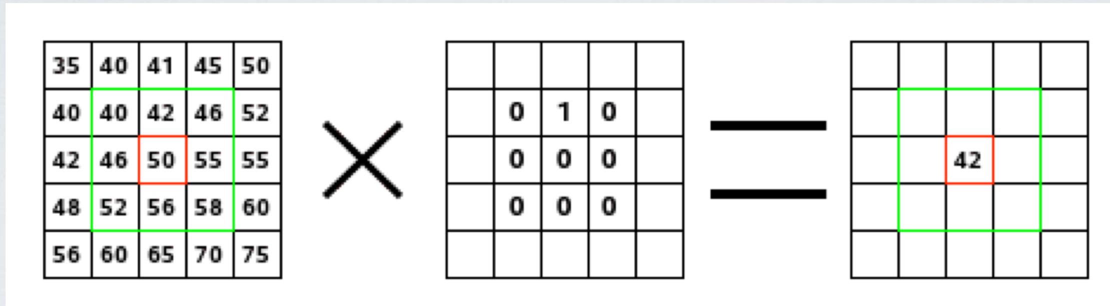




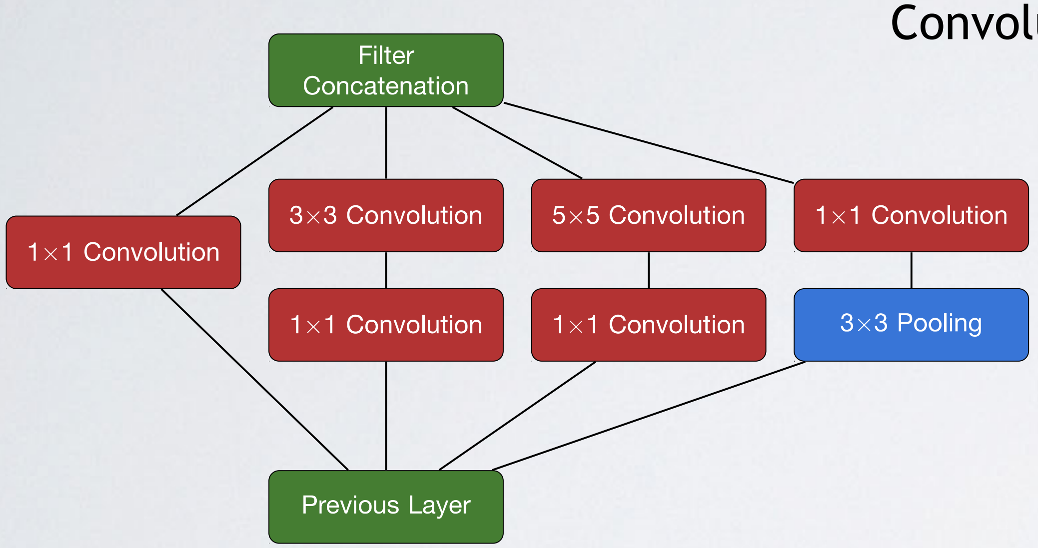
Best fit in Inverted Hierarchy

CVN Architecture

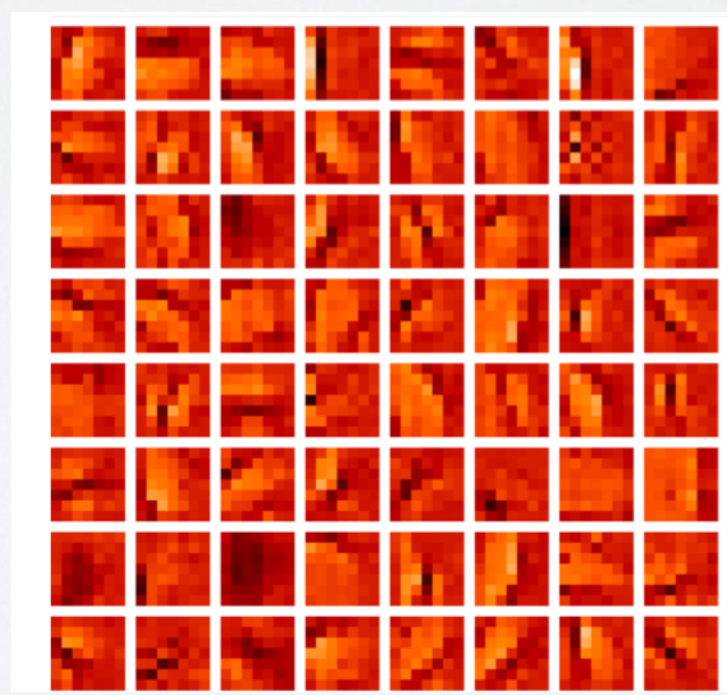
GoogLeNet
Inception Module
C. Szegedy et al.,
arXiv:1409.4842

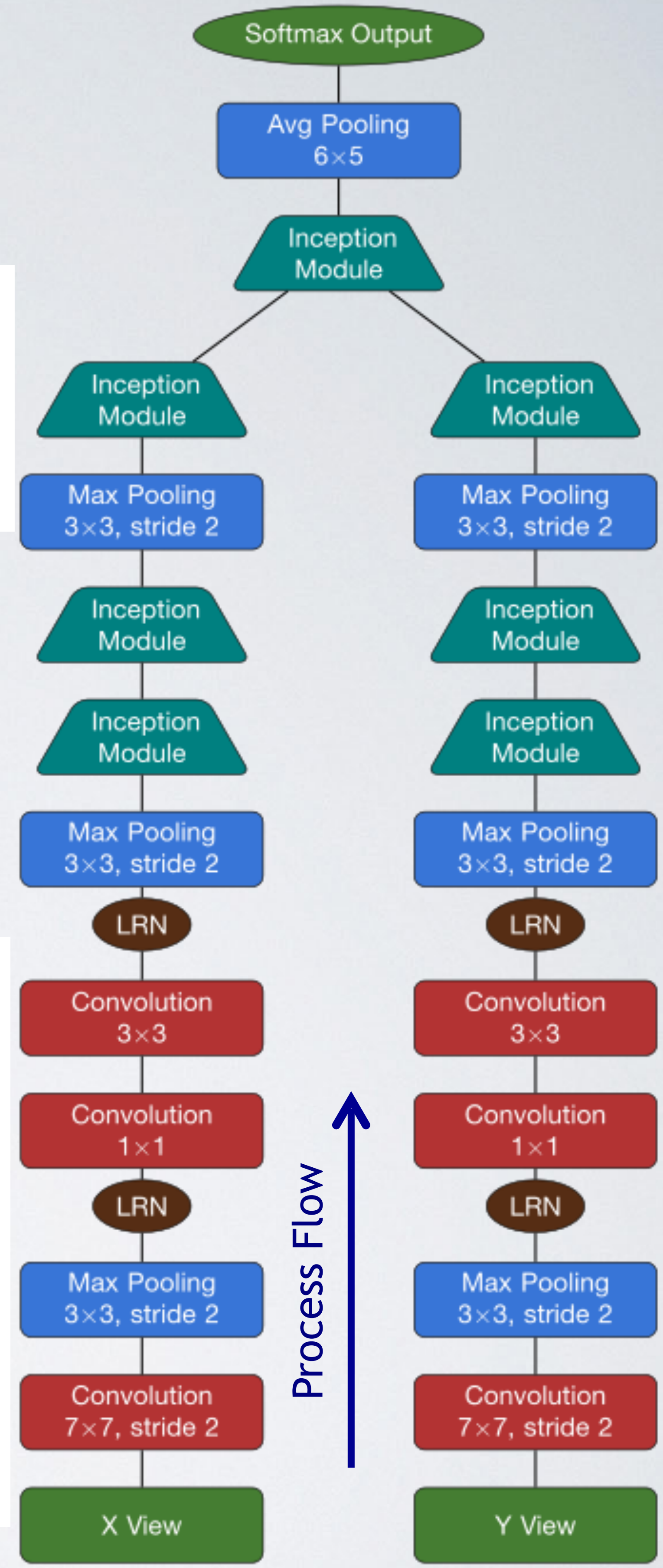


Example image processing transformation
Convolution, or kernel map



Example Convolutional
Filter Layer





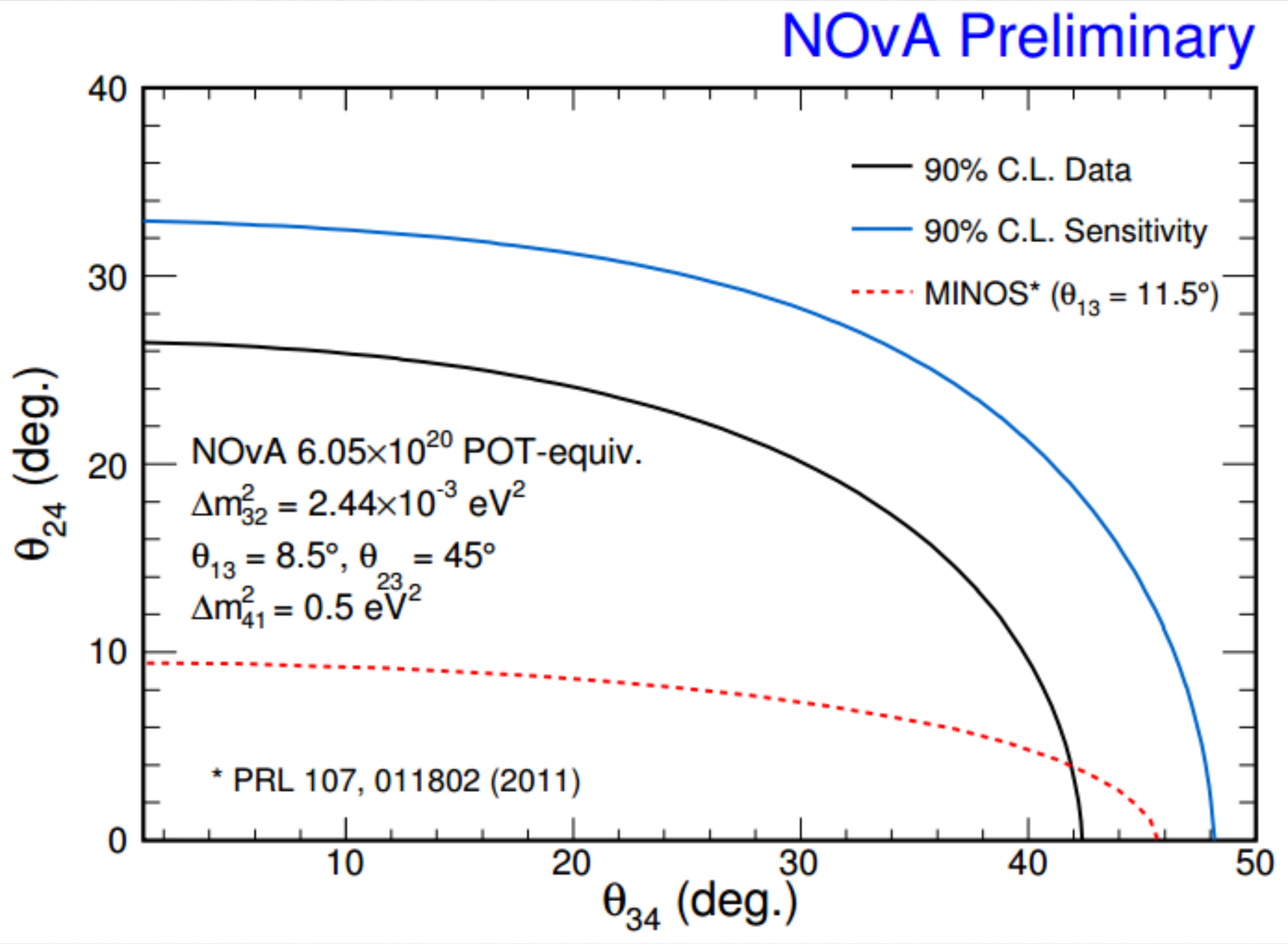
Network implemented and
trained in the Caffe Framework
(Y. Jia et al., arXiv:1408.5093)

Trained over 4.7M simulated events,
Trained on FNAL GPU farm

A. Aurisano et al., arXiv 1604.01444

Sensitivities

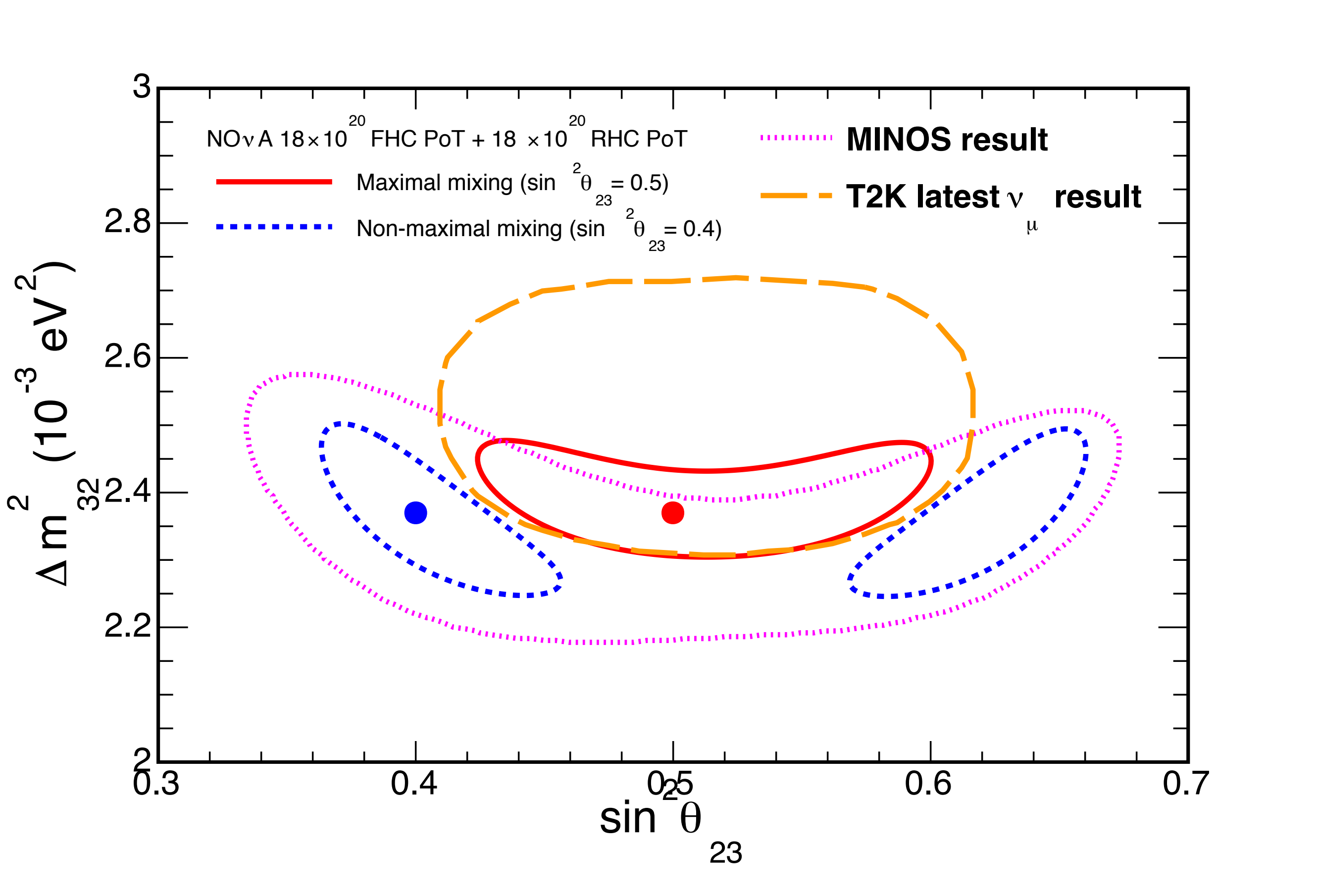
NC Disappearance 2D limits



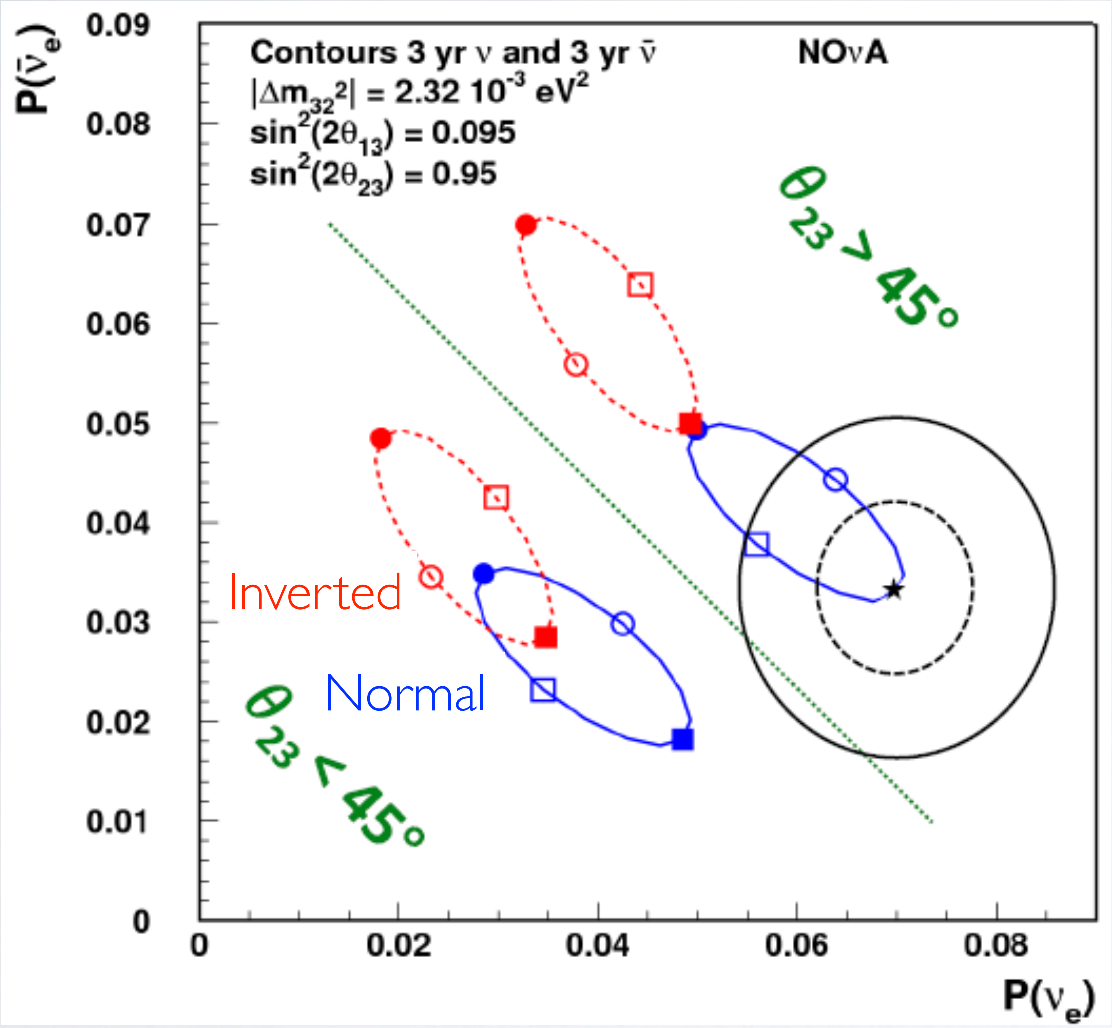
90% C.L. curves obtained by fitting a 3+1 flavour hypothesis with the predicted FD NC spectrum in data.

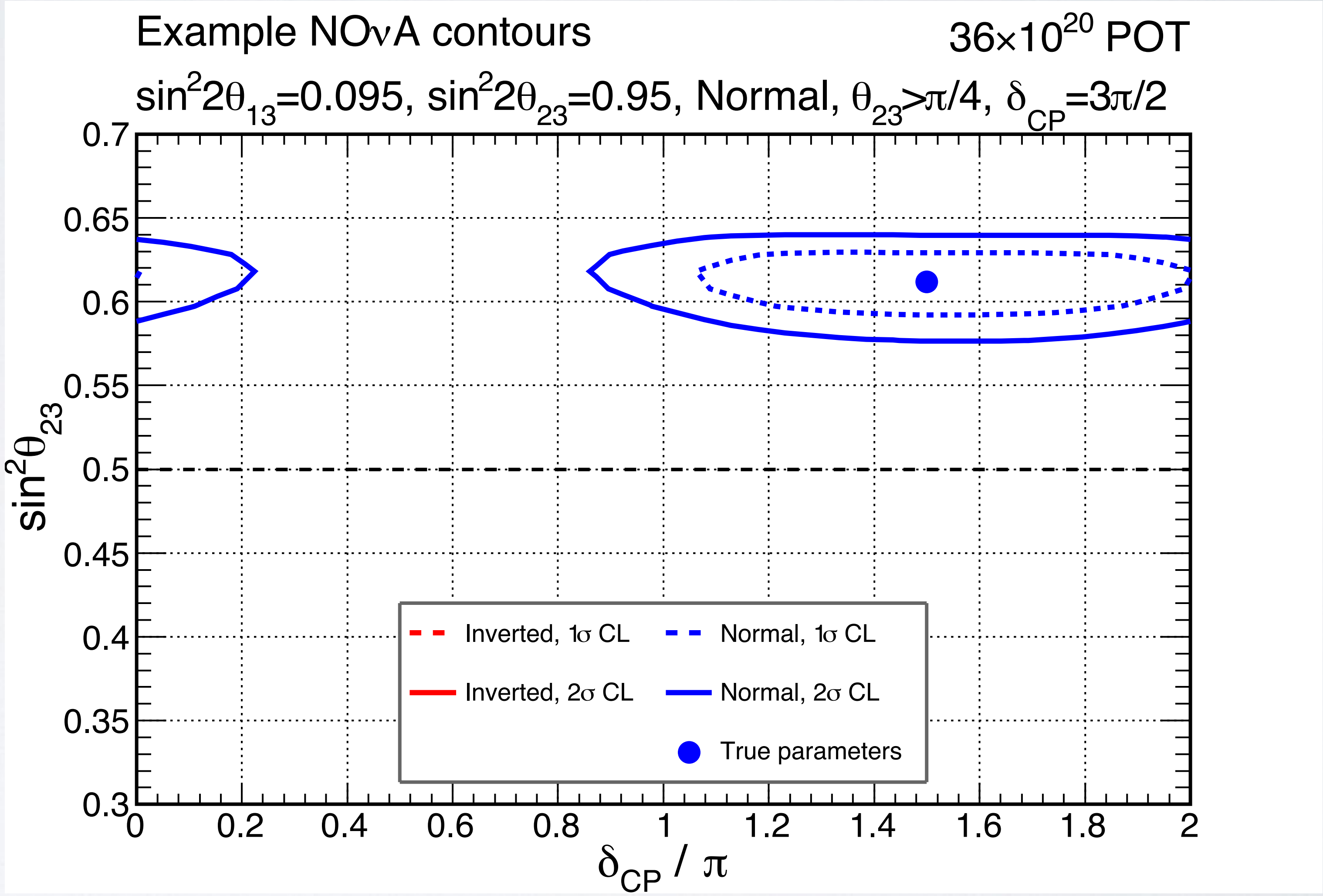
These sensitivities are valid in the range 0.05 eV^2 < Δm^2_{41} < 0.5 eV^2

- 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



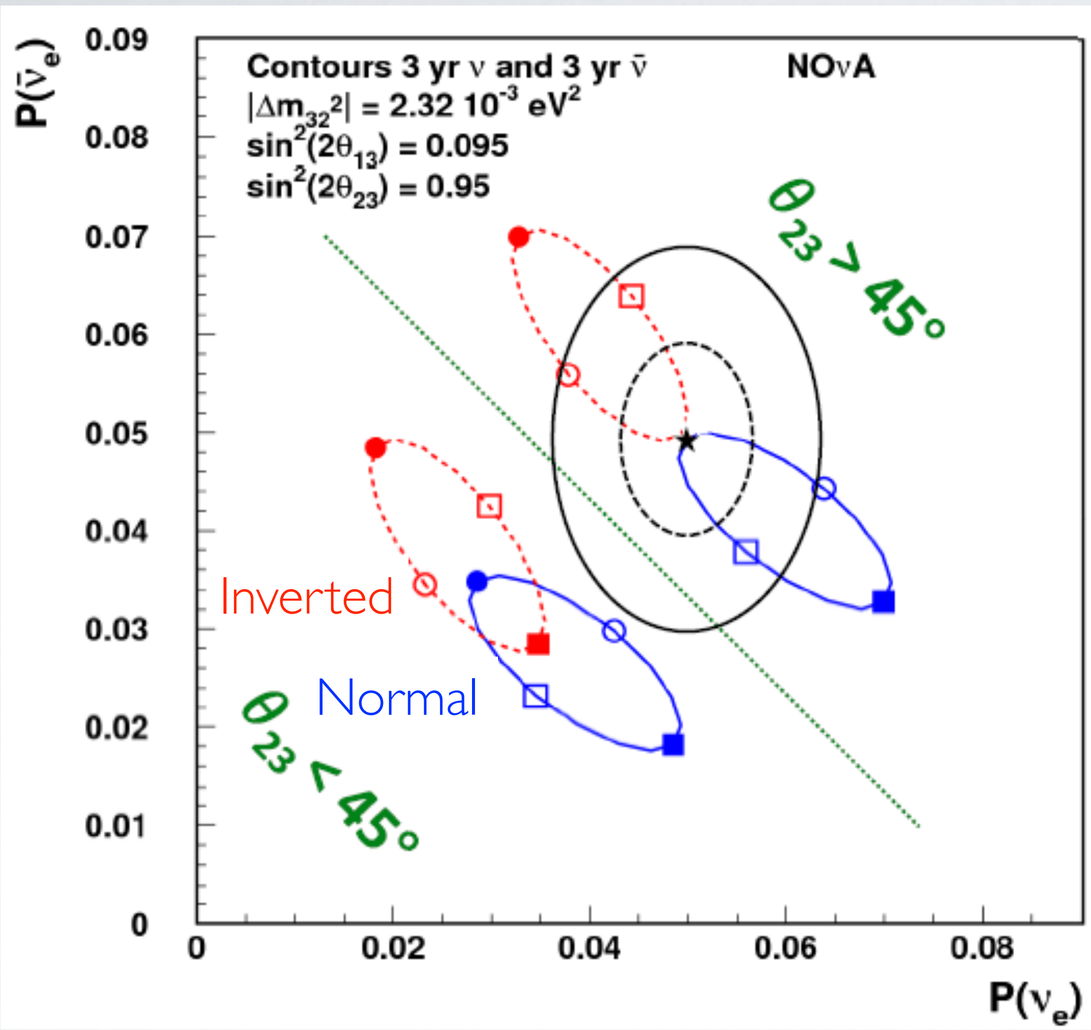
COMBINING MUON AND ELECTRON NEUTRINO ANALYSES

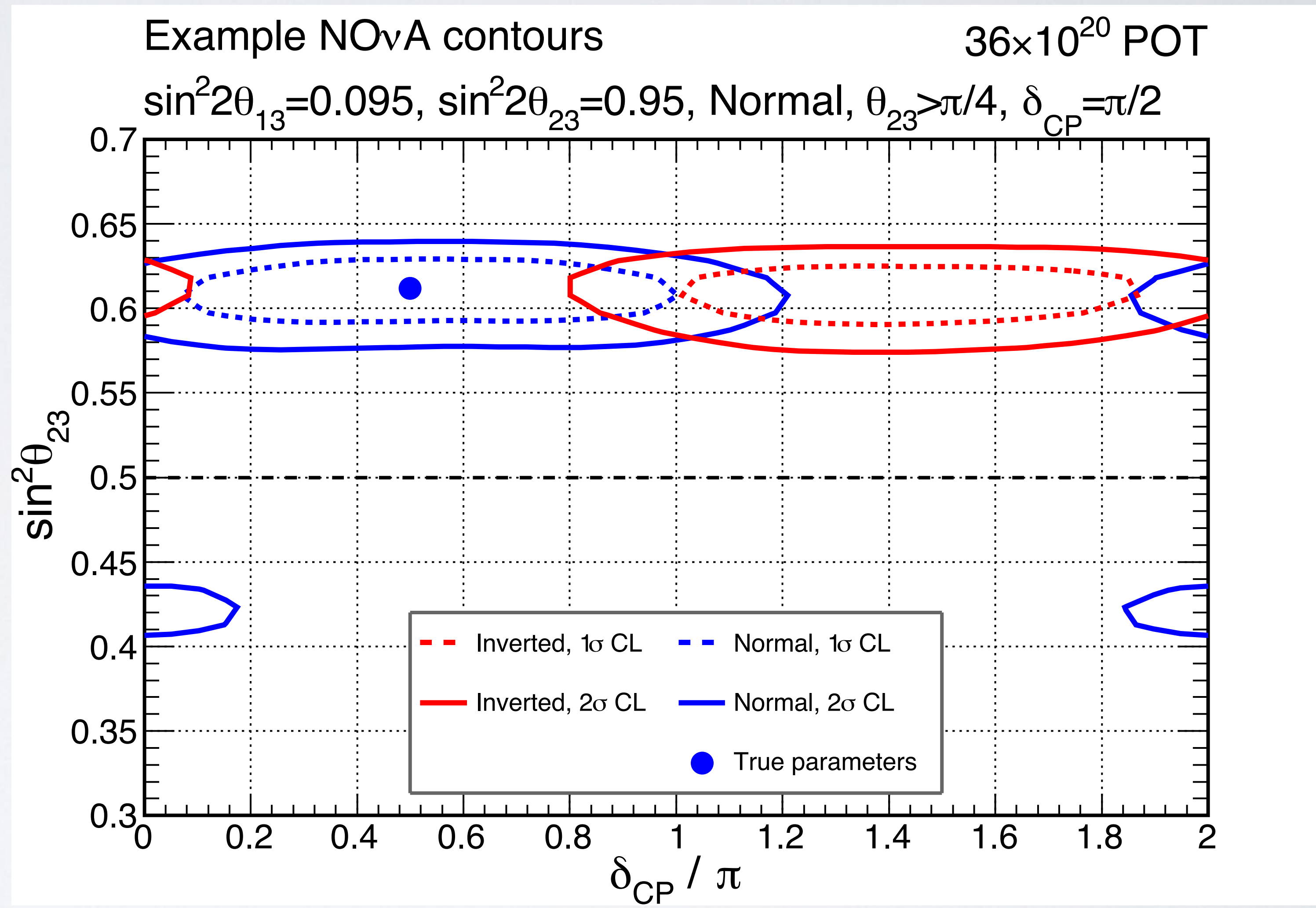




Best case scenario: NOvA simultaneously measures the mass ordering, CP violation and octant information!

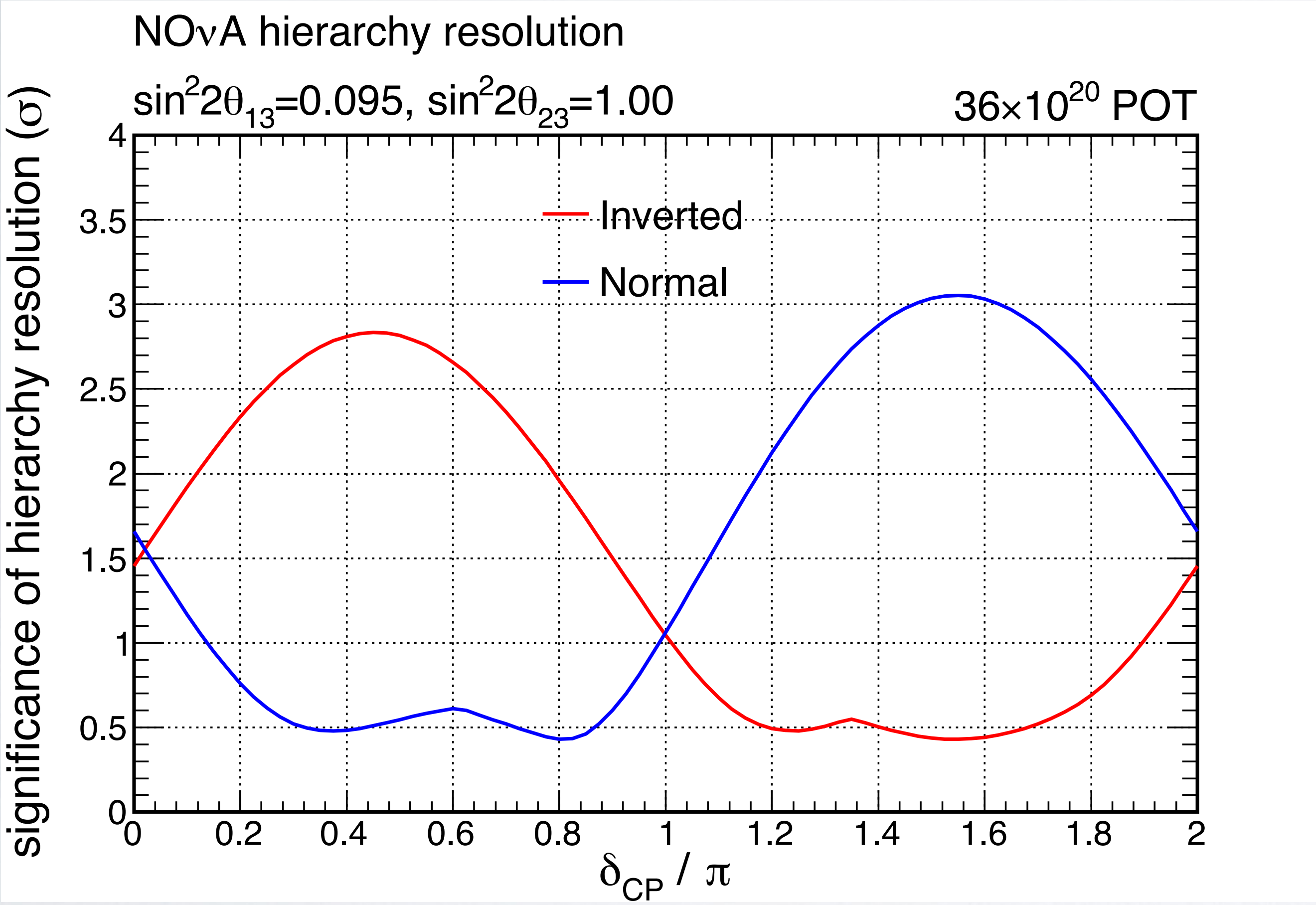
COMBINING MUON AND ELECTRON NEUTRINO ANALYSES

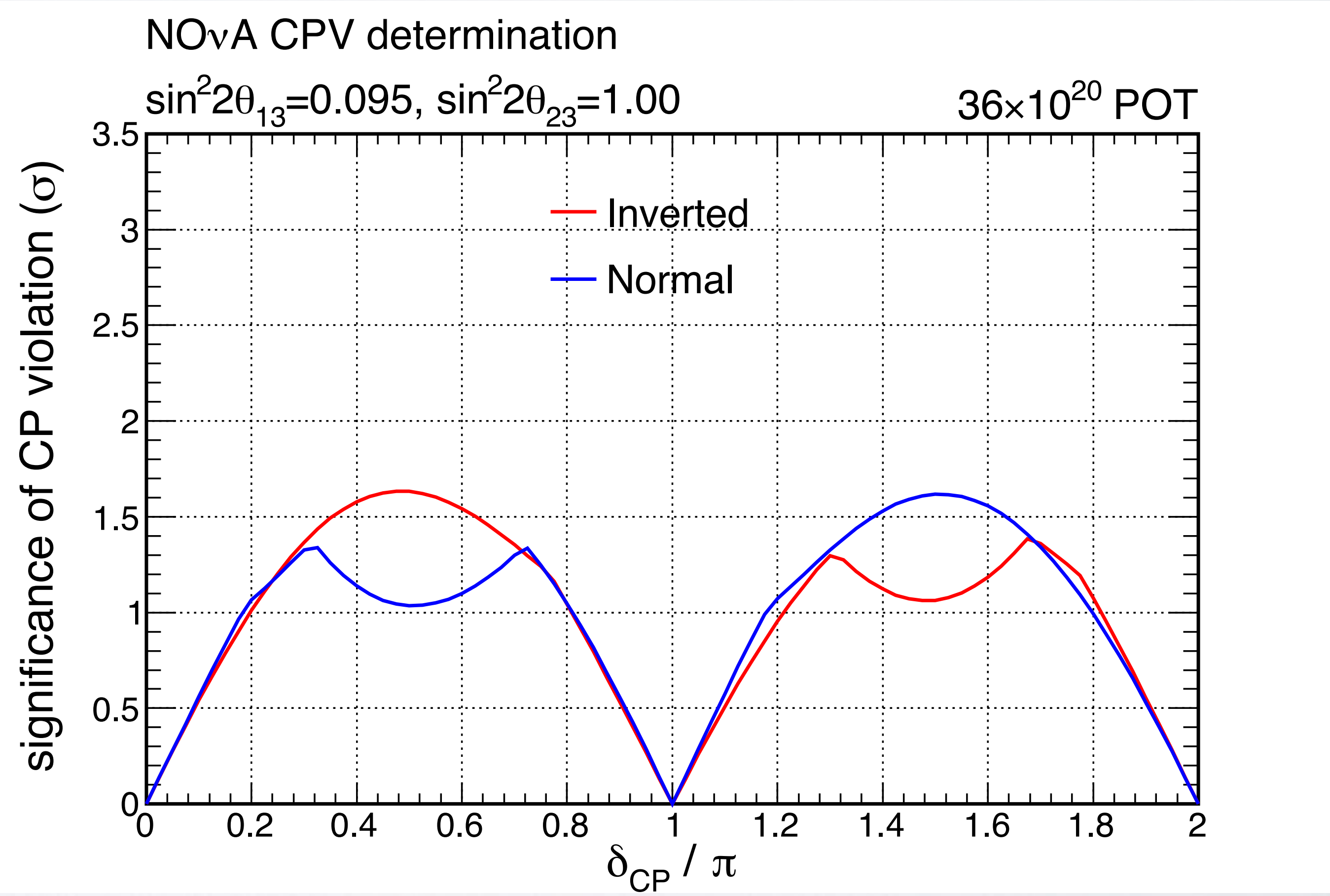




Degenerate case: mass ordering and CP violation are coupled, but the octant information is not

MASS HIERARCHY AND CP-VIOLATION

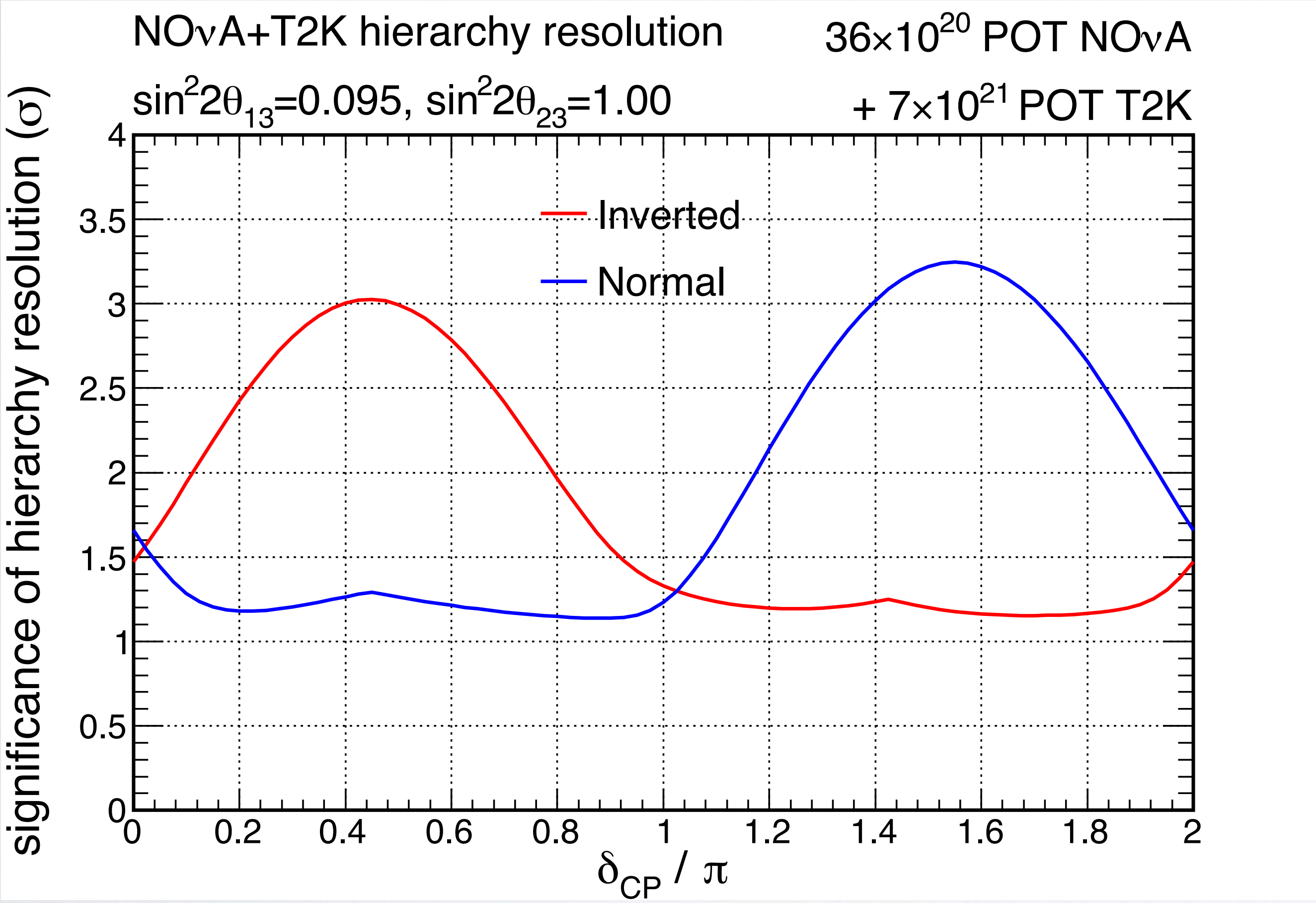


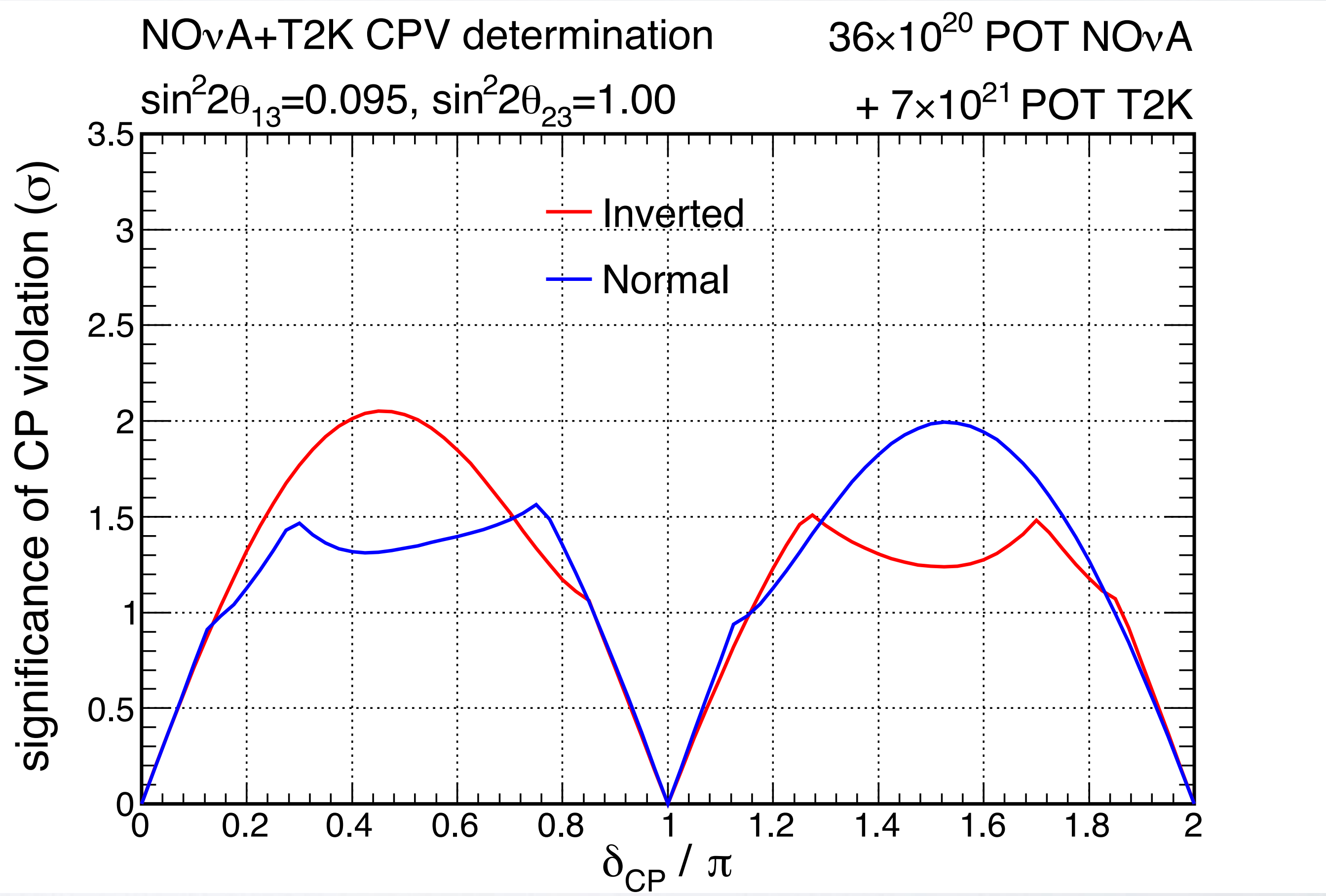


3+3 years (ν_μ +anti-ν_μ): 2 sigma in about 30% of the δ_{CP} range

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%