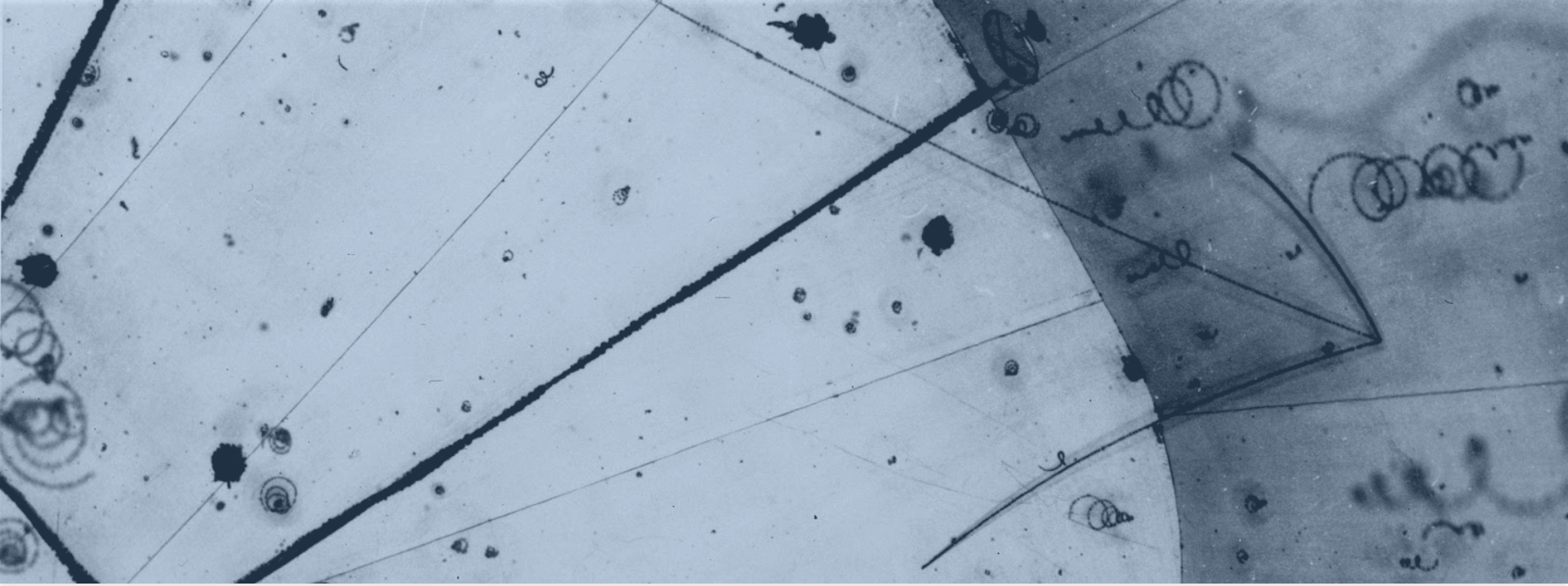

Muon Neutrino Disappearance Analysis in NOvA Improvements

Diana Patricia Méndez Méndez
University of Sussex
For the NOvA Collaboration

DPF Meeting | Fermilab | July 31st 2017

The NOvA Experiment

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Neutrino oscillation experiment

- ν_μ disappearance ($\nu_\mu \rightarrow \nu_\mu$)
- ν_e appearance ($\nu_\mu \rightarrow \nu_e$)

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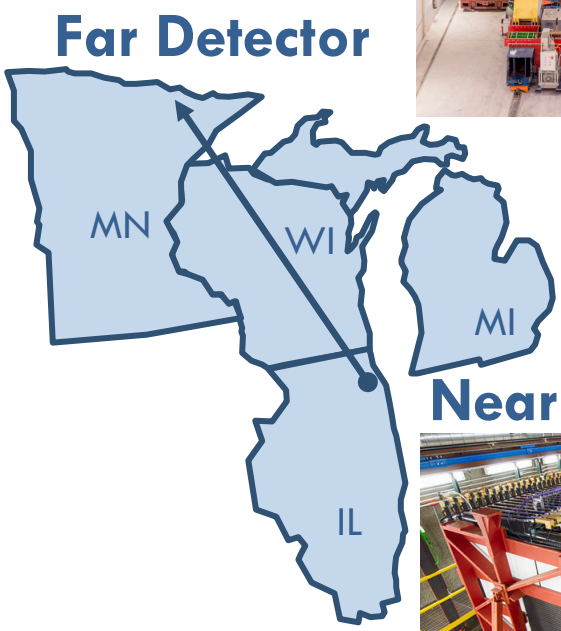
Two detectors separated by 810 km

- Near detector 300 Tons, underground
- Far detector 14 kTons, on the surface



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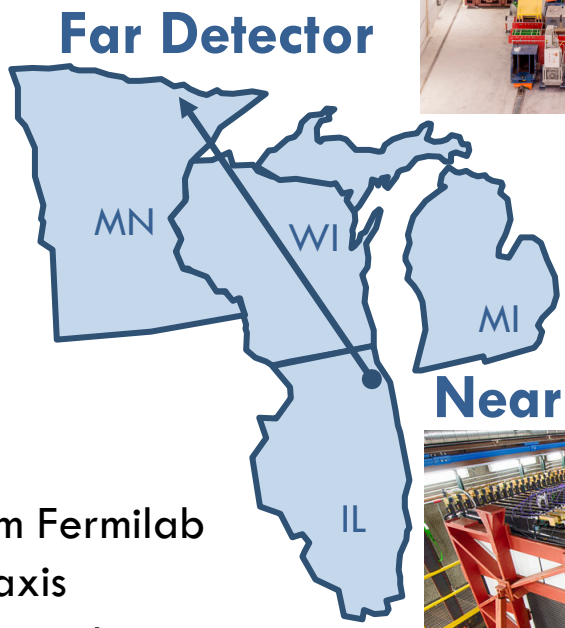

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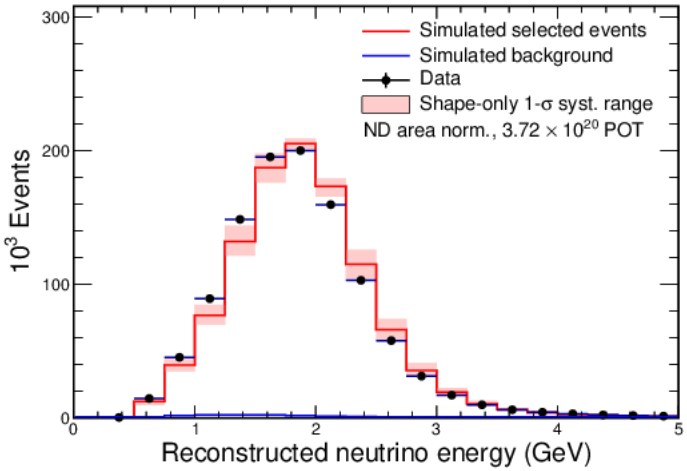

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- NuMI beam from Fermilab
- 14.6 mrad off-axis
- Narrow energy spectrum, peak ~ 2 GeV

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ν_e talks on **Thursday** by Prabhjot S. and Erika C.

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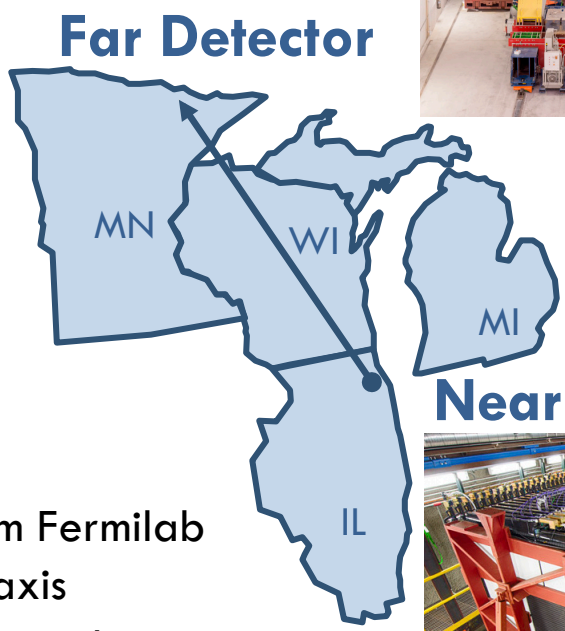

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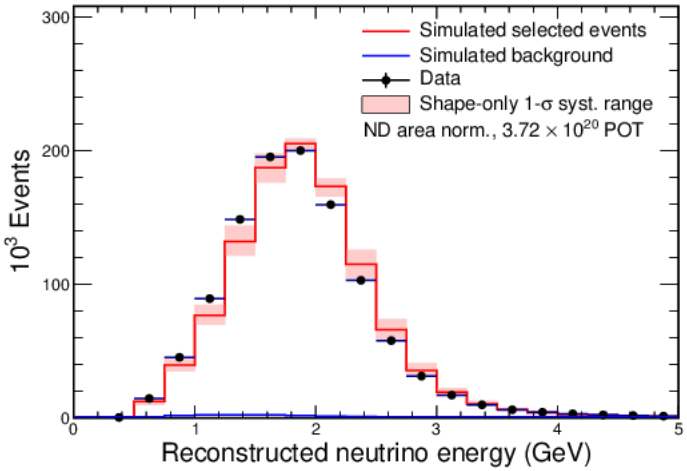

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Muon Neutrino Disappearance

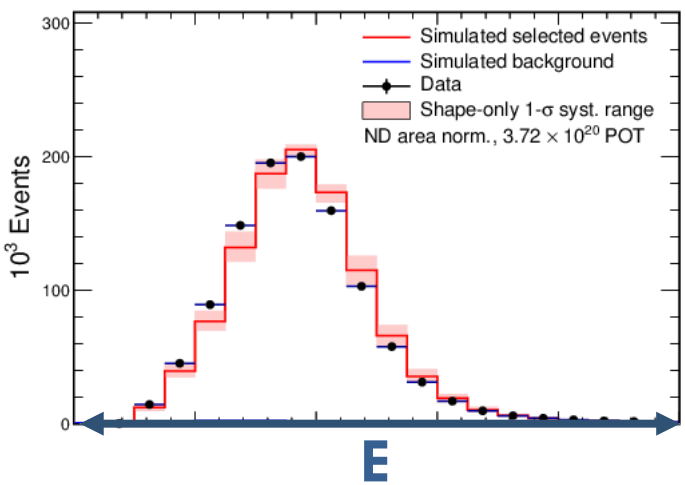
$$P(\nu_\mu \to \nu_\mu) = 1 - \sin^2(2\theta_{23})\sin^2\left(1.27\Delta m^2_{32}\frac{L}{E}\right)$$

2 flavour approximation

Far Detector

L = 810 km

Near Detector



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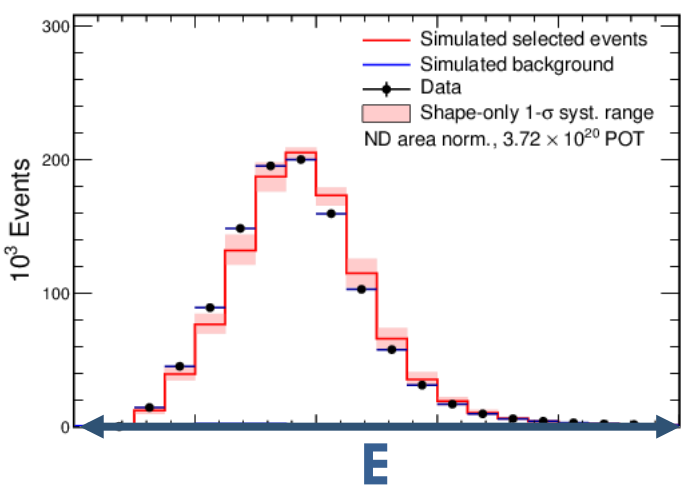
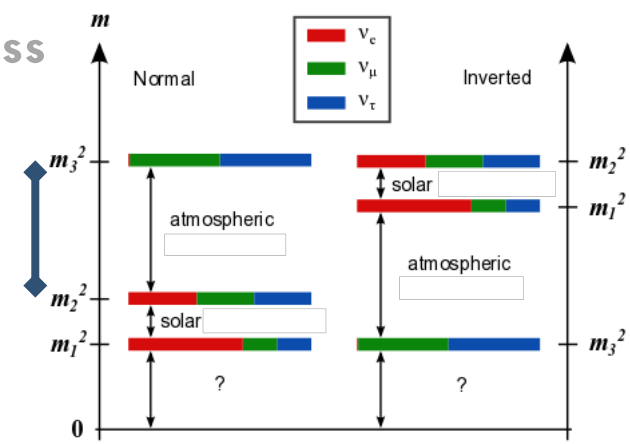


Squared mass difference

Δm^2_{32}



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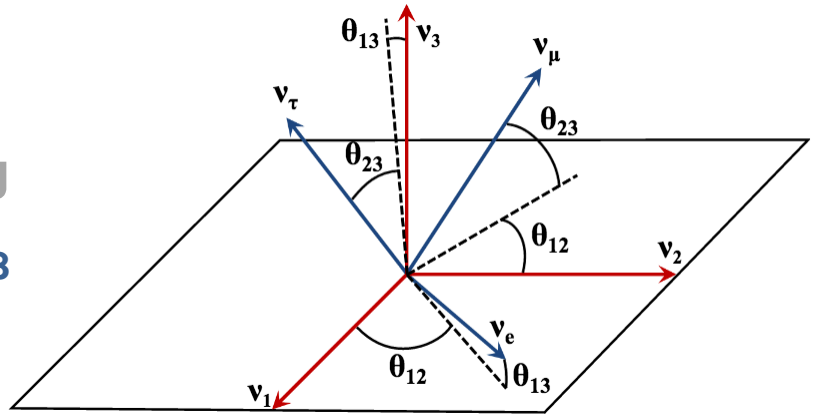
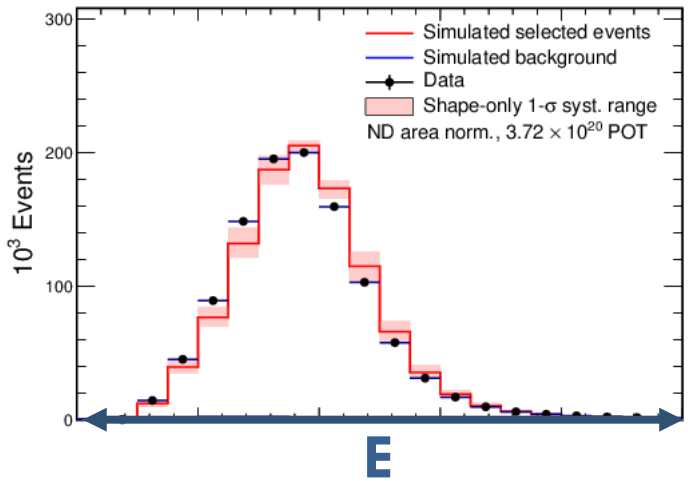
Mixing

$\sin^2\theta_{23}$





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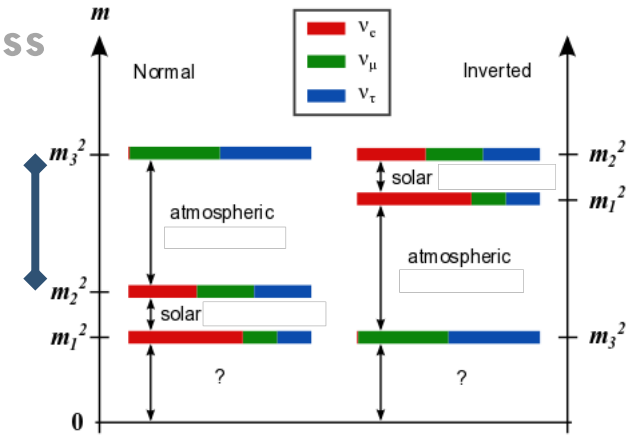
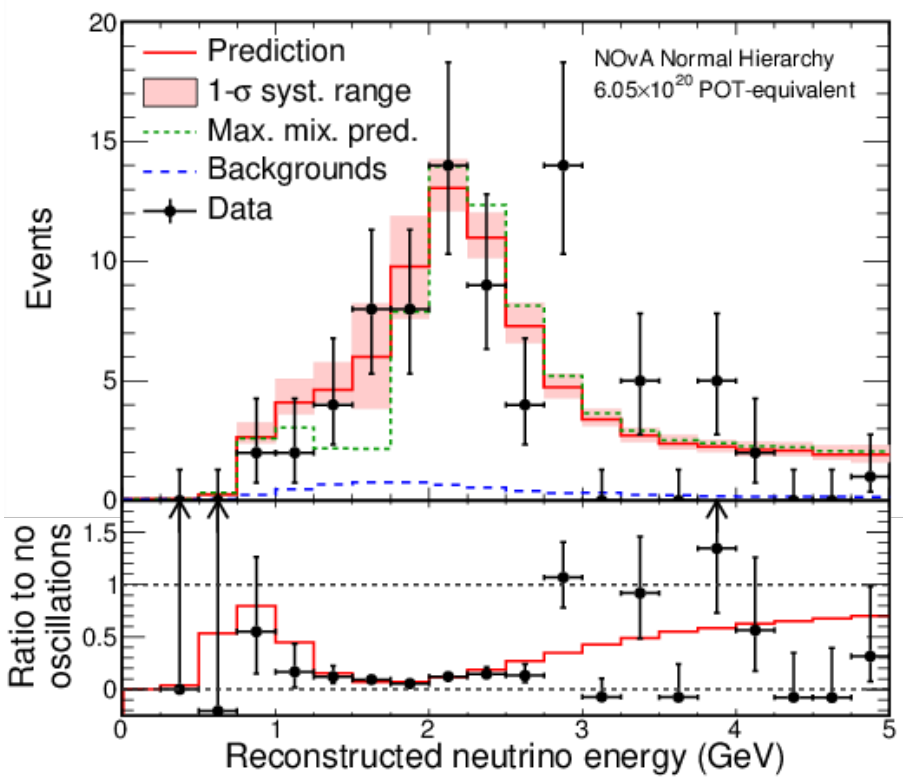
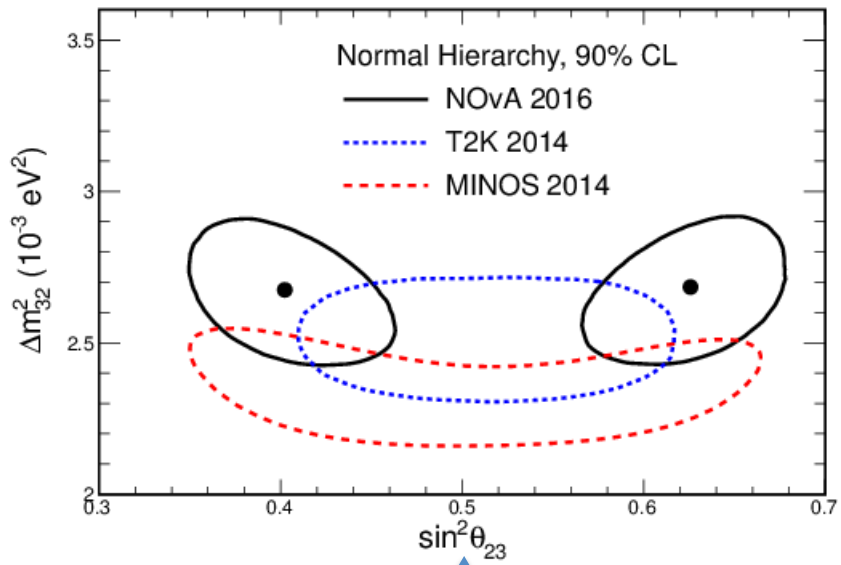


2017 Results

Phys.Rev.Lett. 118, 151802 (2017)





Maximum mixing disfavored by 2.6 σ

Clear ν_μ disappearance

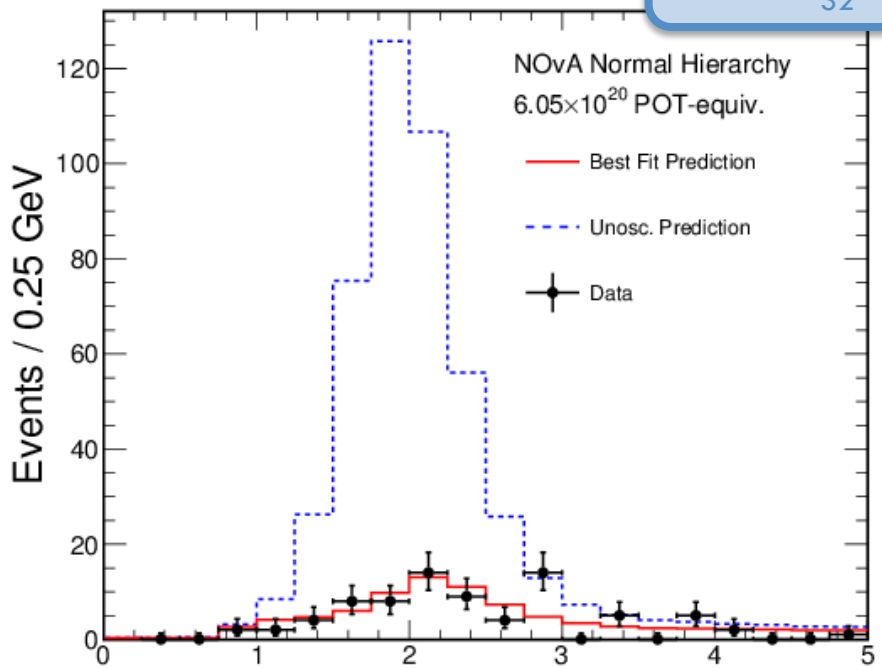
- 473 expected events without oscillations
- 78 observed events in the far detector
- 82 expected events at best fit

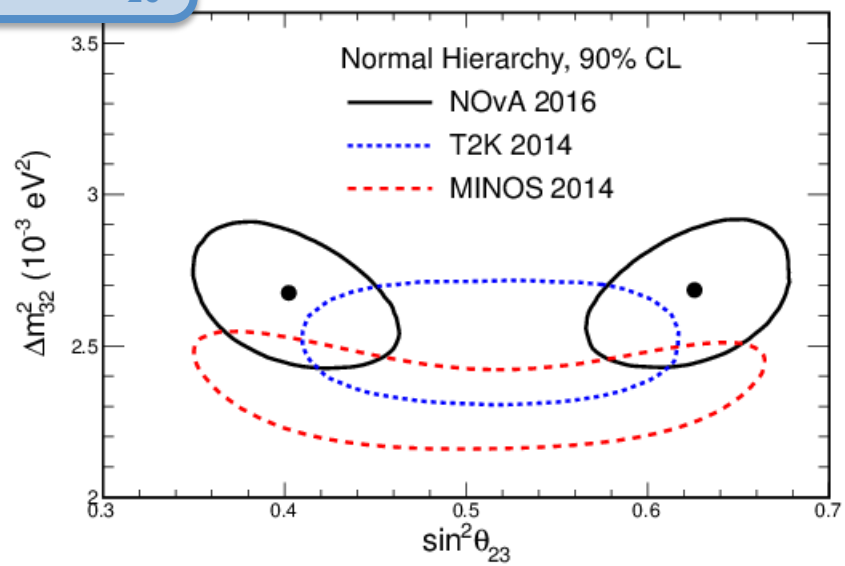
Oscillation parameters

- $\Delta m^2_{32} = (2.67 \pm 0.11) \times 10^{-3}\ eV^2$
- $\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}, 0.624^{+0.022}_{-0.030}$

Improving the Disappearance Analysis

Improve sensitivity to Δm^2_{32} and $\sin^2\theta_{23}$





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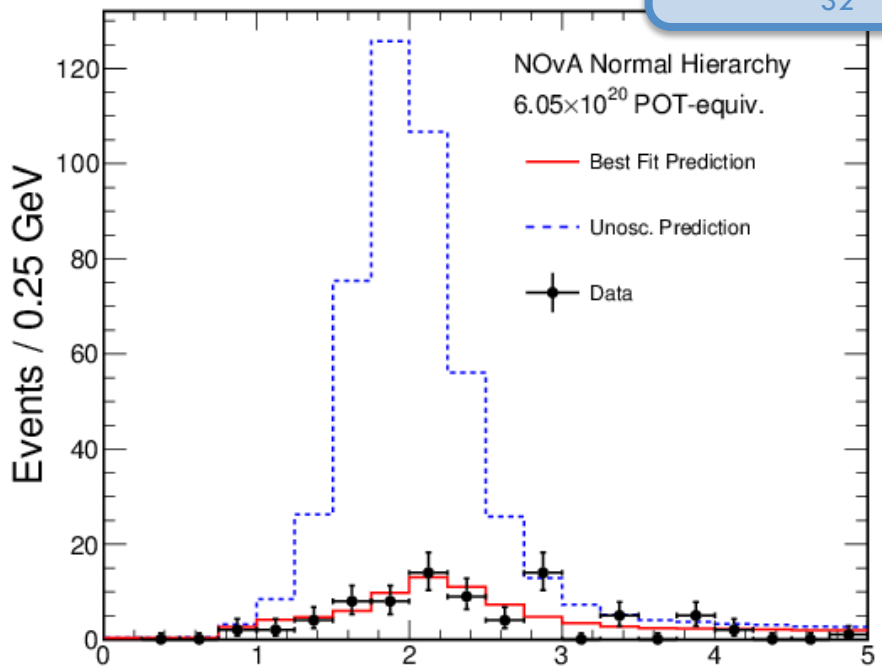

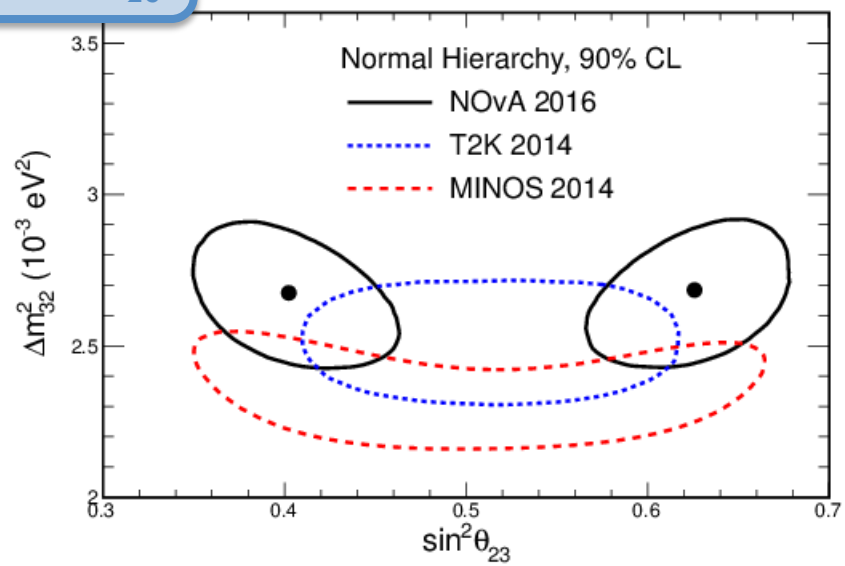

Focus on maximum disappearance region

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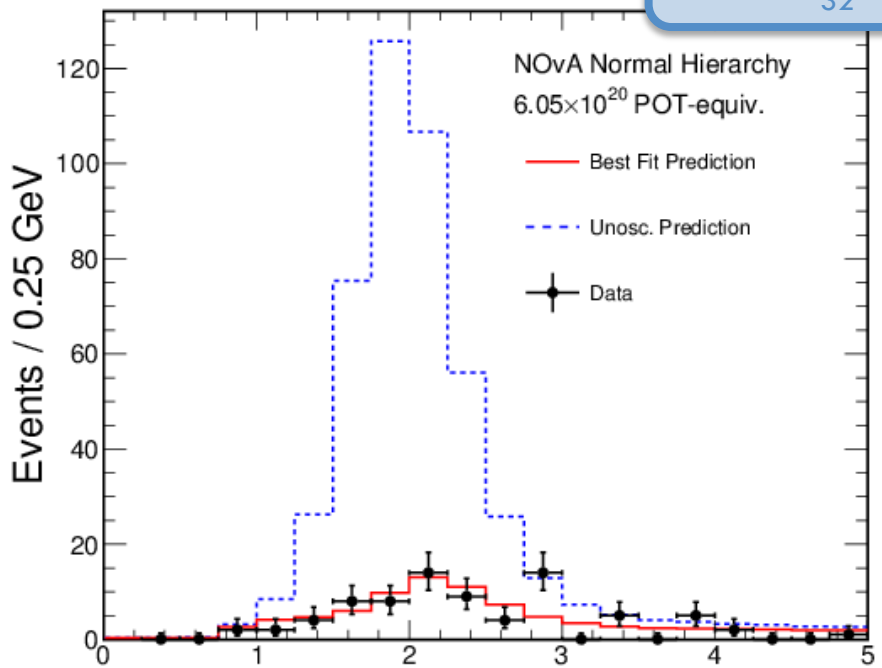

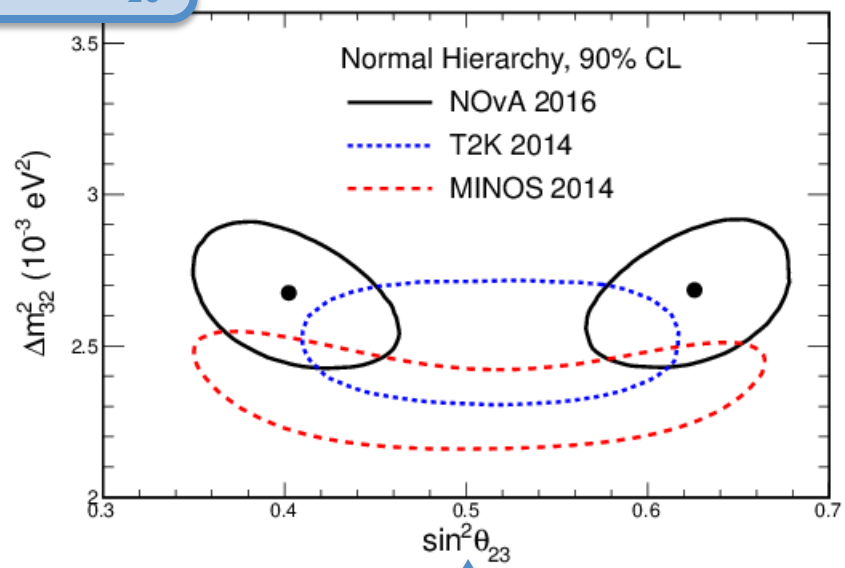

Focus on maximum disappearance region

Increase sensitivity to mixing angle

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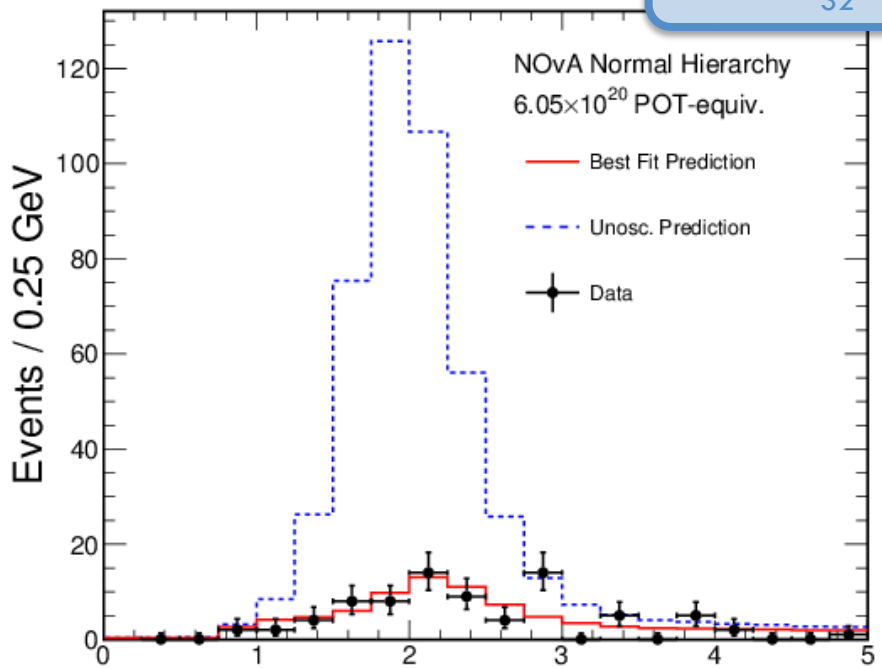

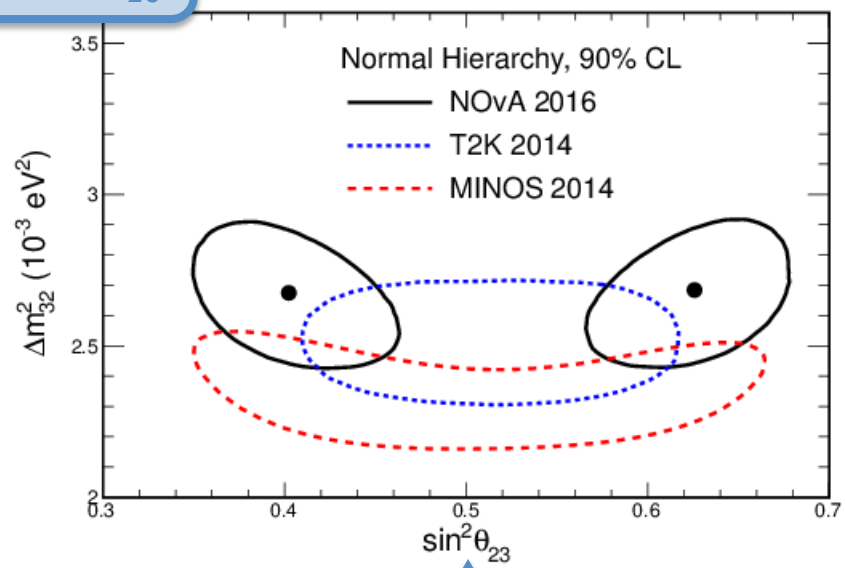

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Increase sensitivity to mixing angle

3 potential improvements:

- Separate neutrino events into bins of resolution
- Inclusion of CVN
- Finer energy binning around maximum oscillation

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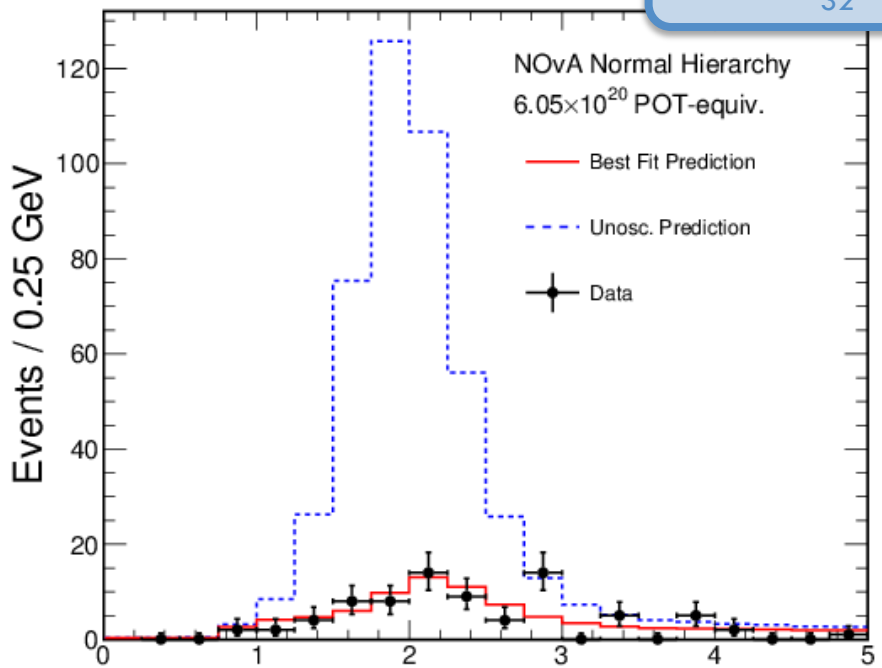

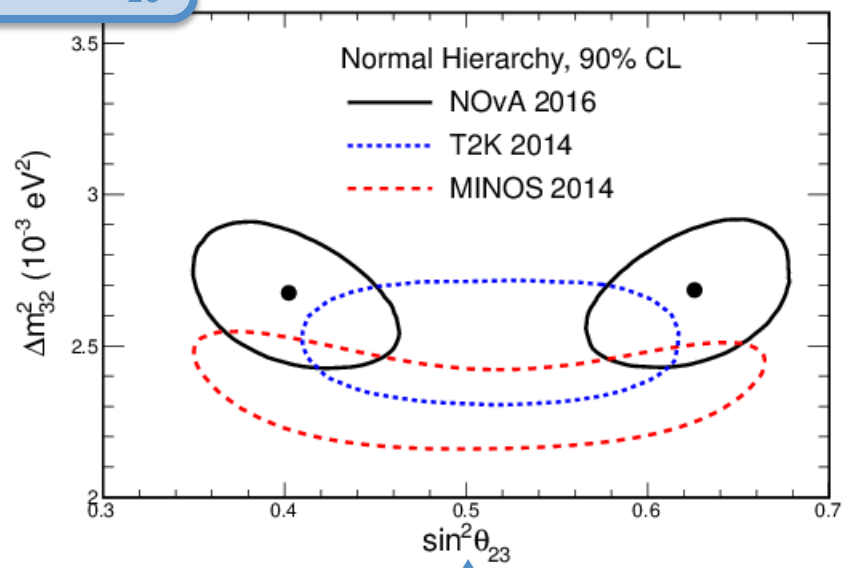

Focus on maximum disappearance region

Increase sensitivity to mixing angle

- **Simulation** with NOvA, MINOS and T2K's best fit points
- 6e20 POT

3 potential improvements:

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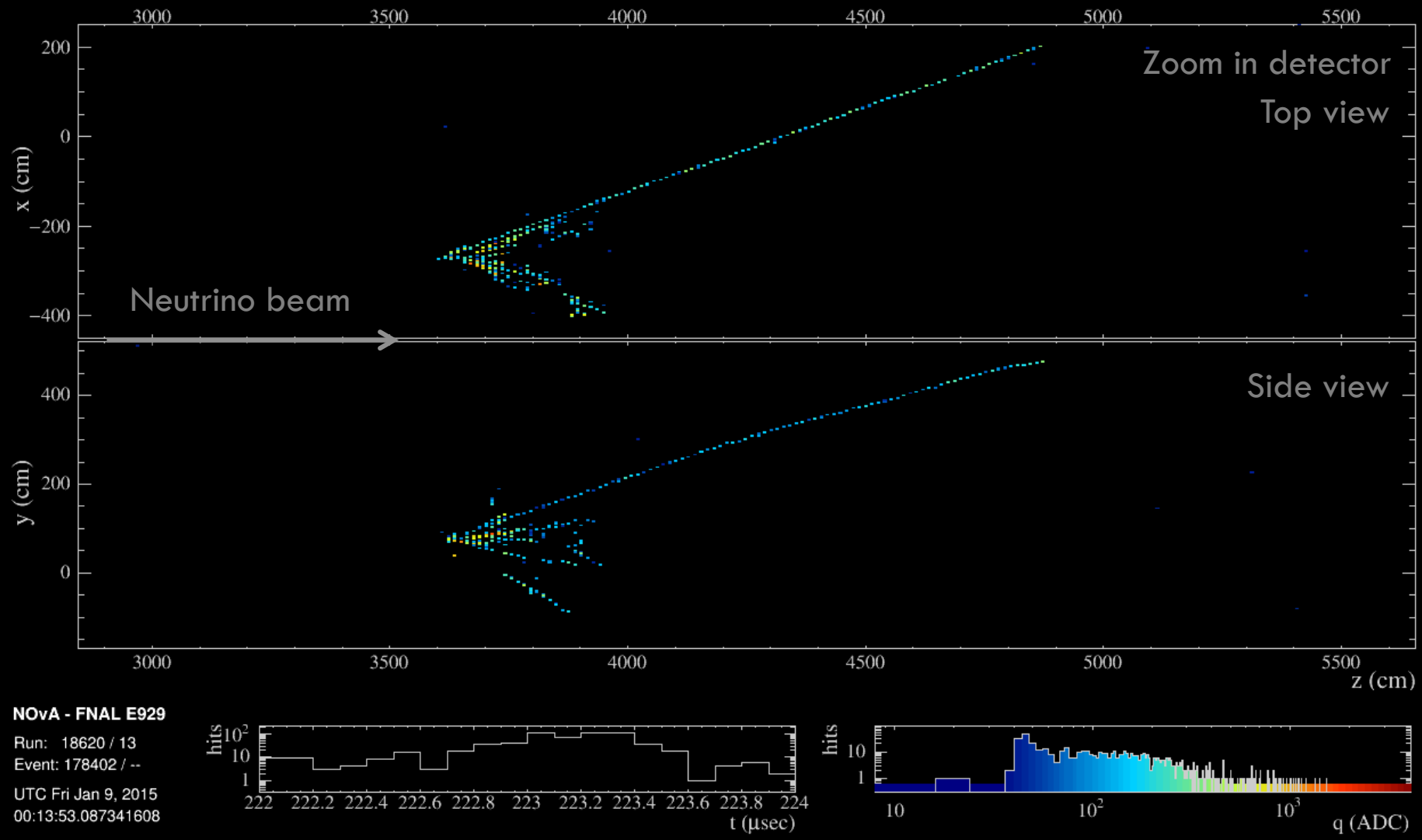
Energy Reconstruction



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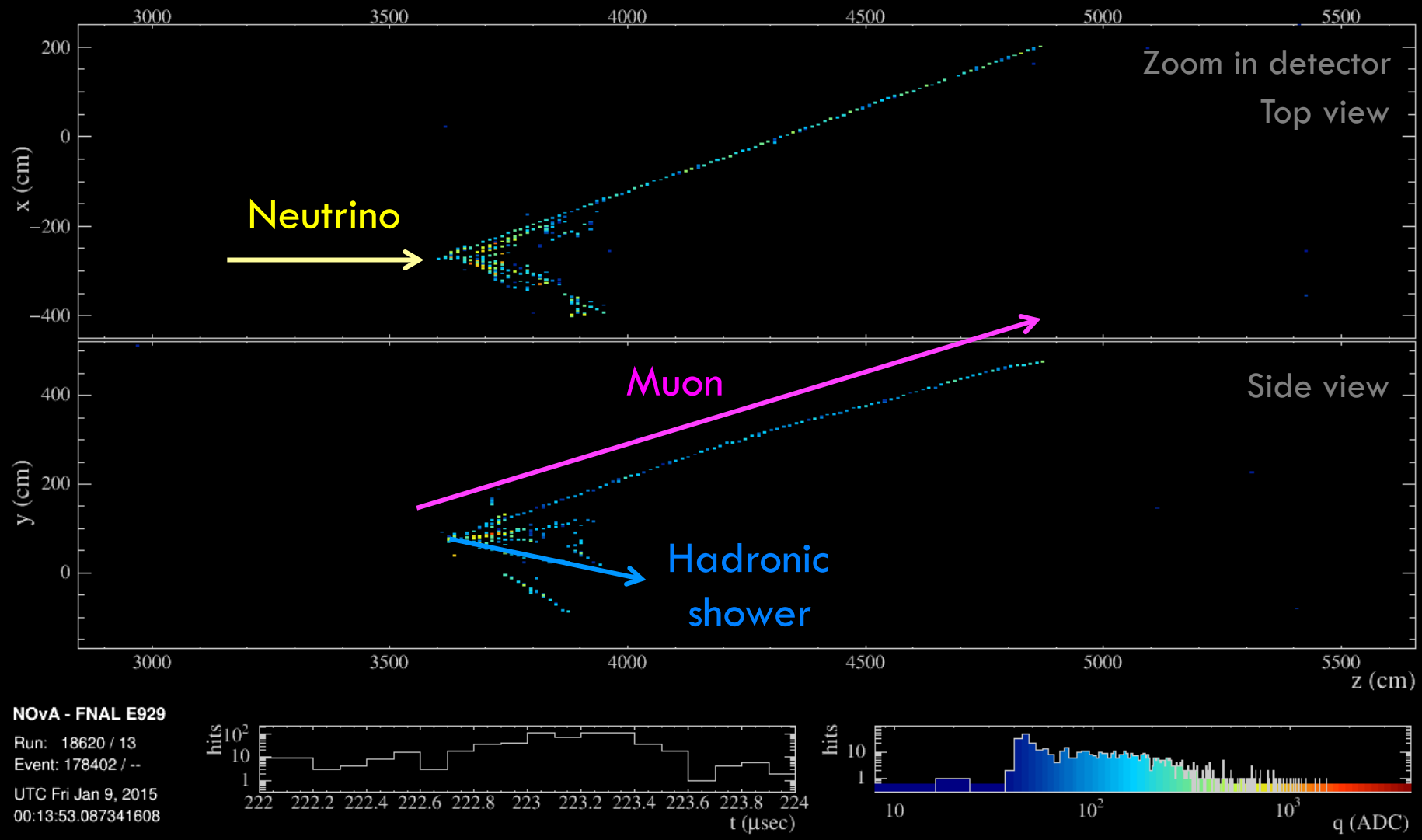

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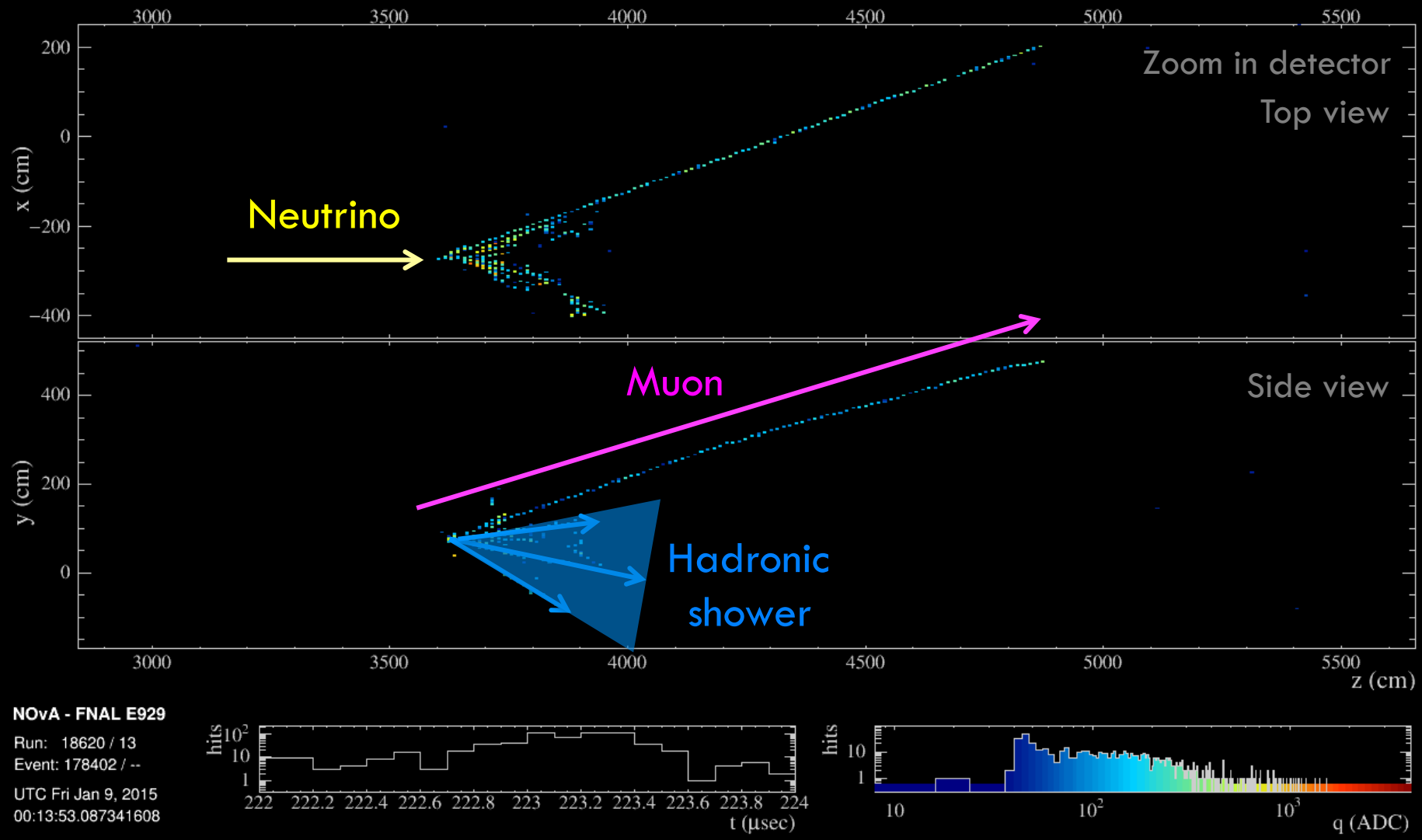

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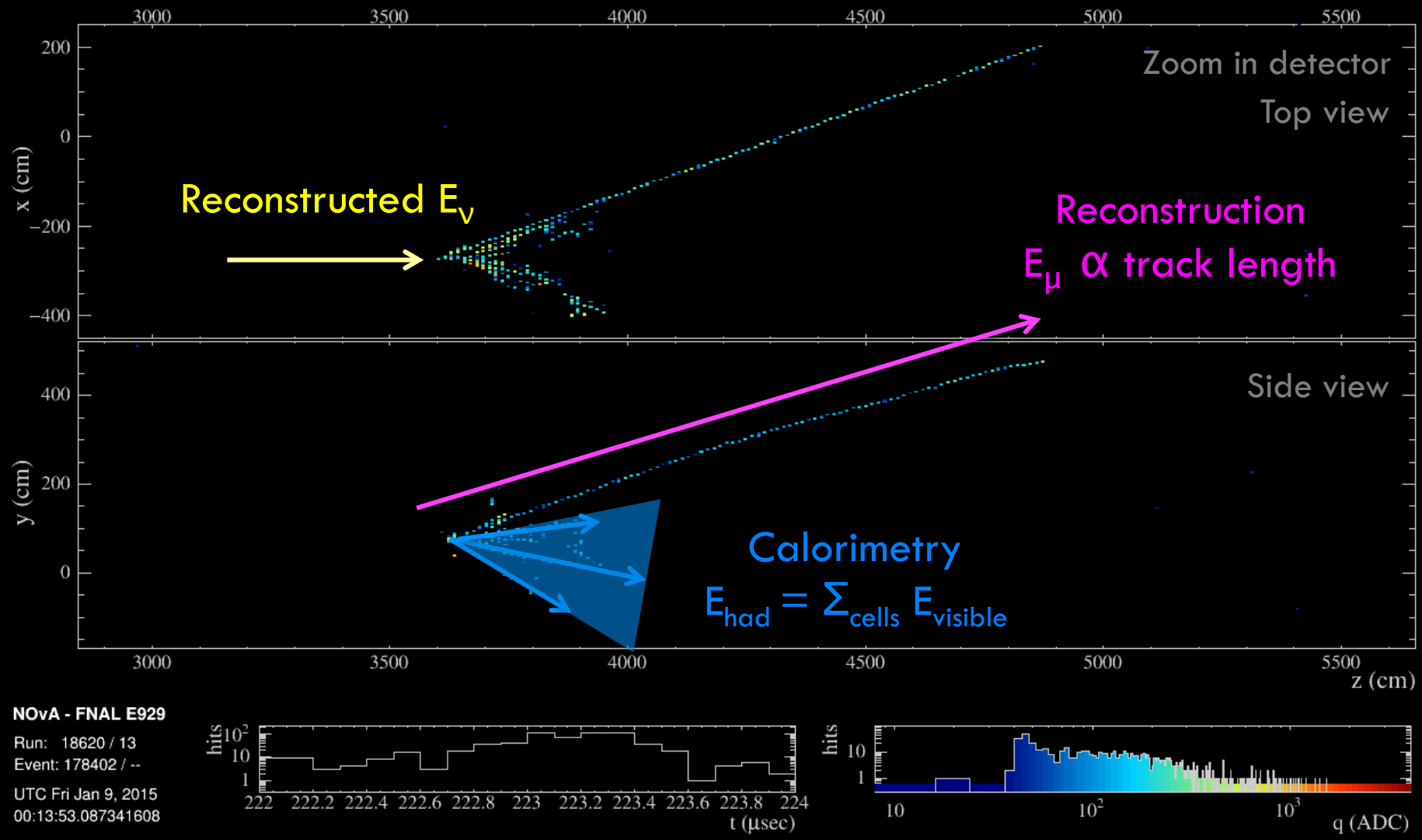

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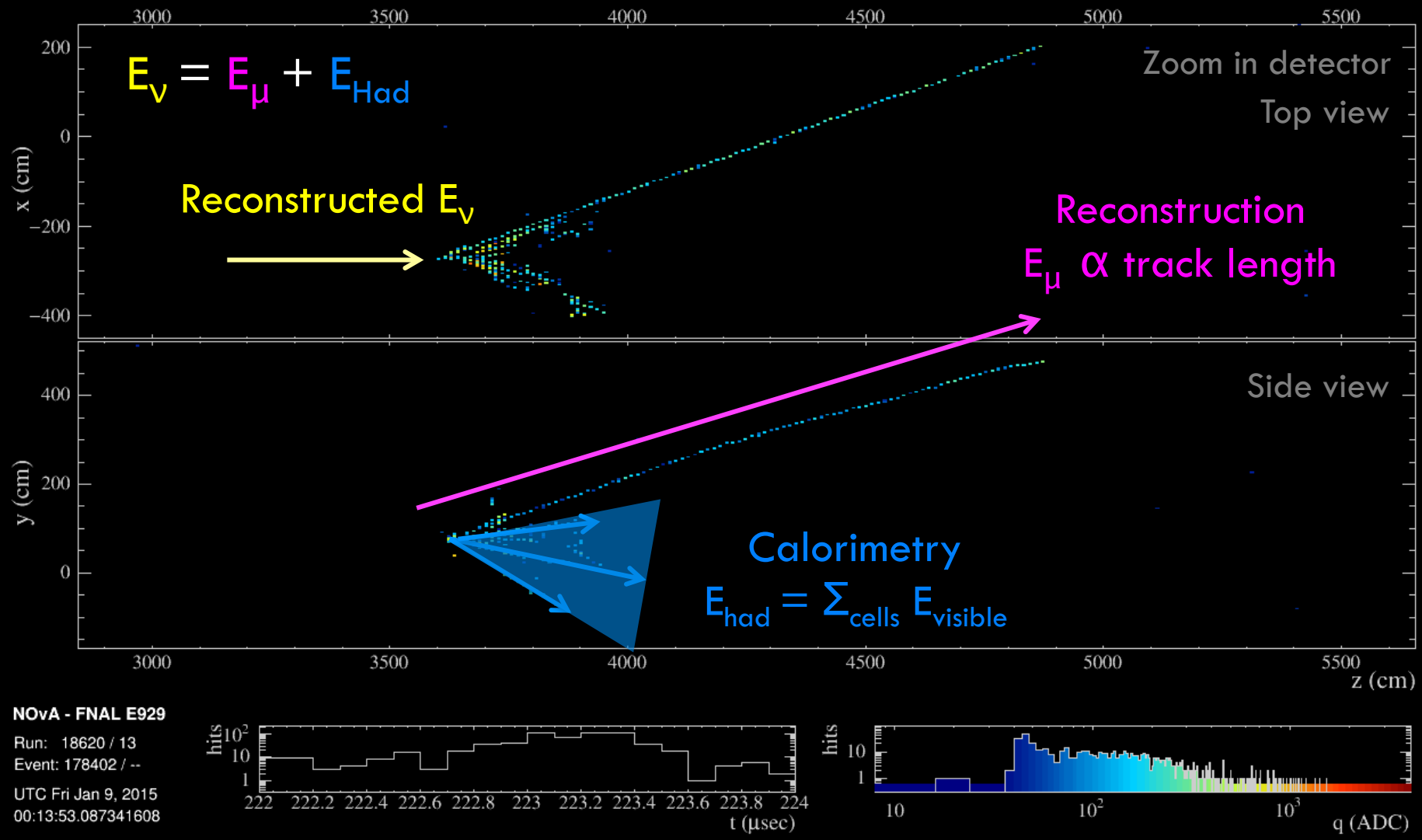

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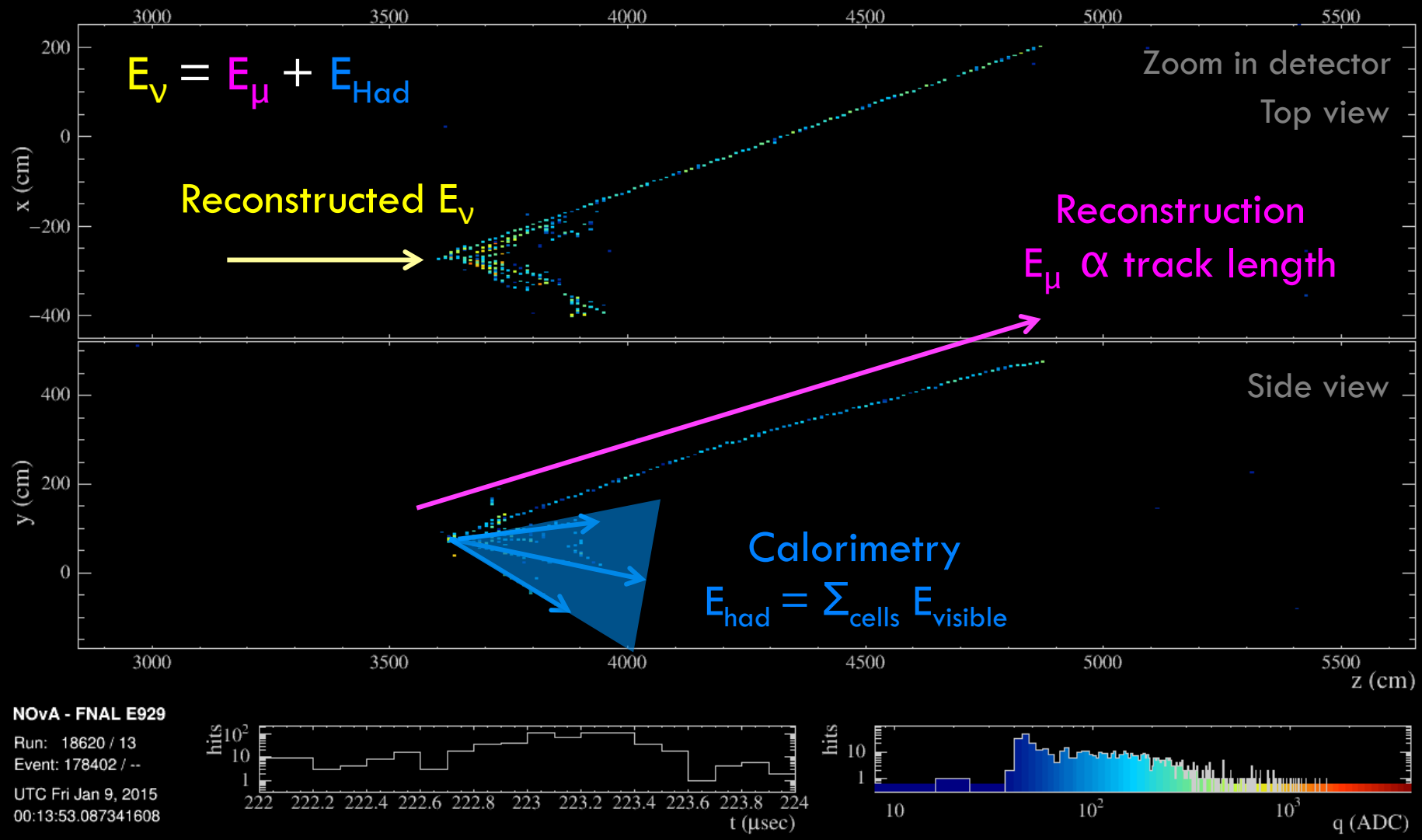

Event and energy reconstruction talks on **Thursday** by Biswanranjan B. and Fernanada P.

Energy Resolution

$E_\nu = E_\mu + E_{had}$ → Neutrino energy resolution = E_{Had}/E_ν

Mean resolution:

- Muon energy = 3.5 %
- Hadronic energy = 25%
- Neutrino energy = 7%

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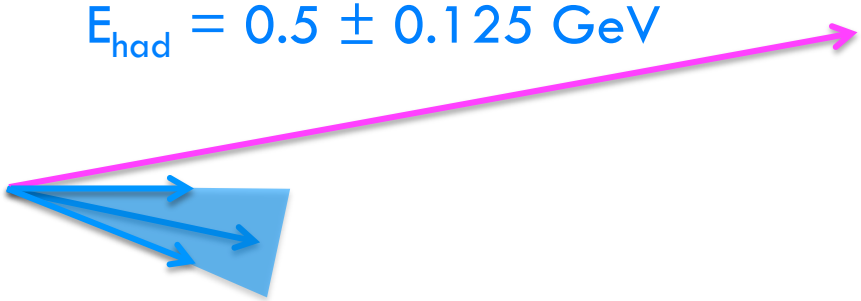
Hadronic fraction = 0.25
→ Uncertainty = 7.0%

$E_\mu = 1.5 \pm 0.06$ GeV

$E_{had} = 0.5 \pm 0.125$ GeV



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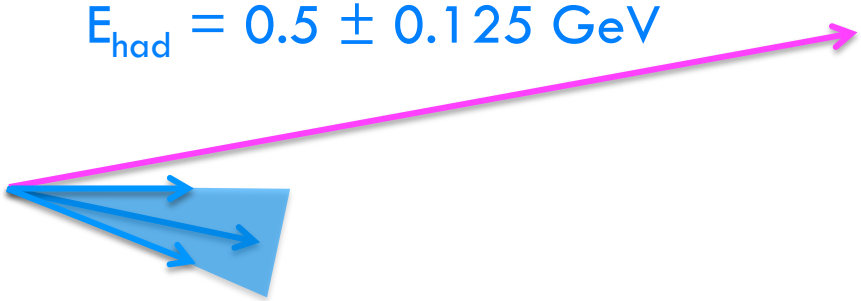
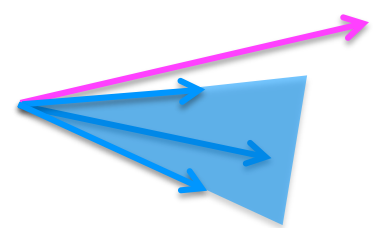


Hadronic fraction = 0.75
→ Uncertainty = 19%

$E_\mu = 0.5 \pm 0.018$ GeV
$E_{had} = 1.5 \pm 0.375$ GeV



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Separate well resolved energies by quantiles of hadronic energy fraction

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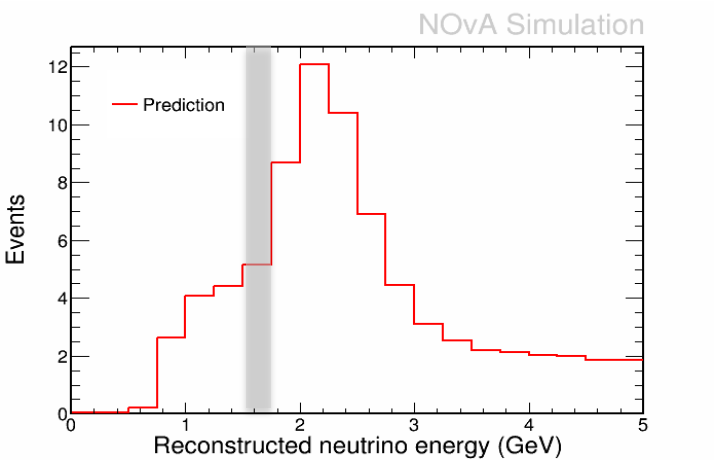

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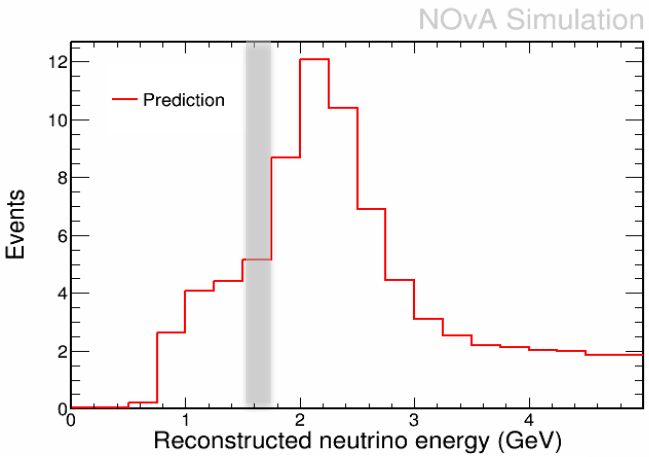

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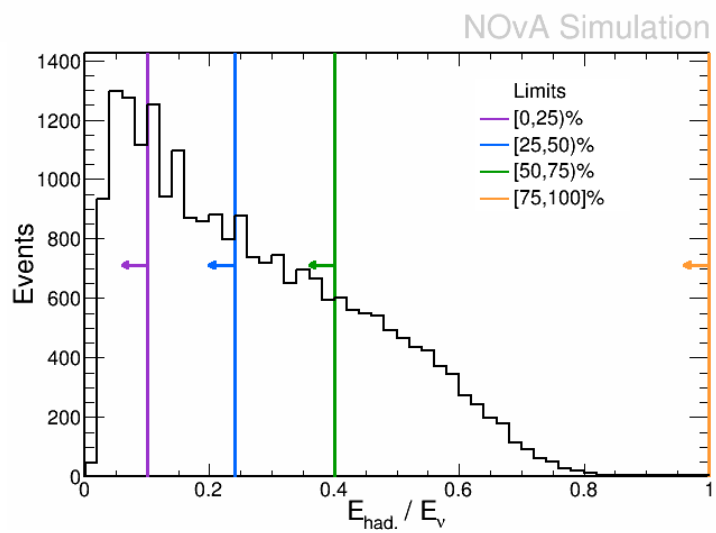
2. Make a distribution of E_{had}/E_ν and divide into quantiles



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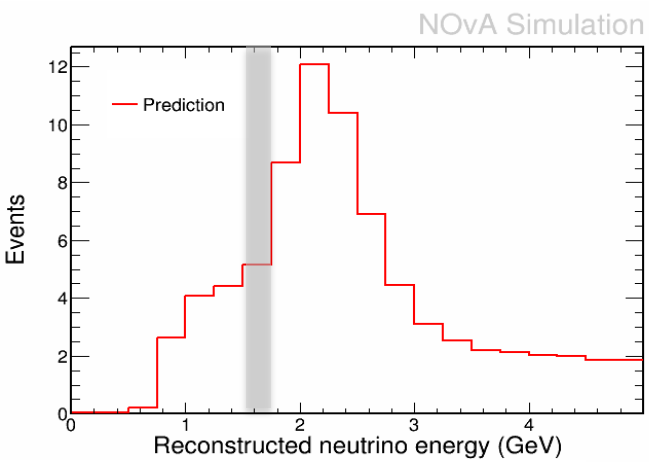

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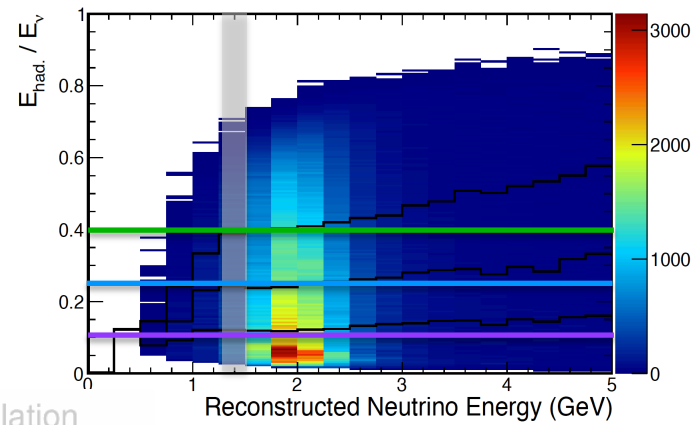
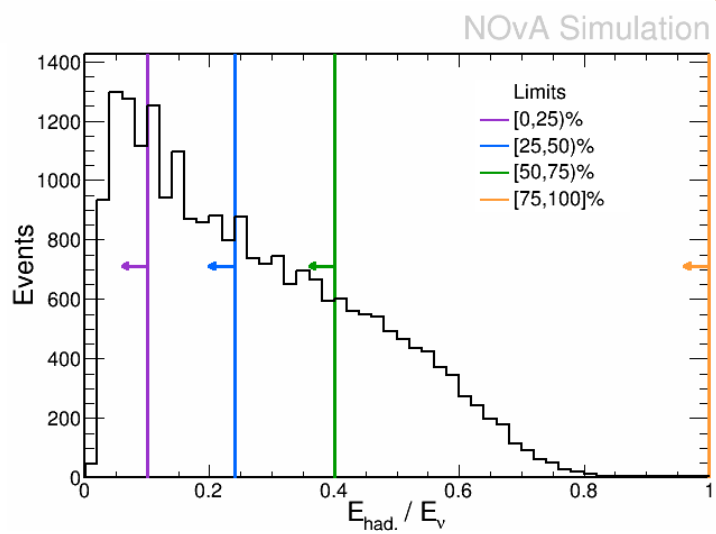
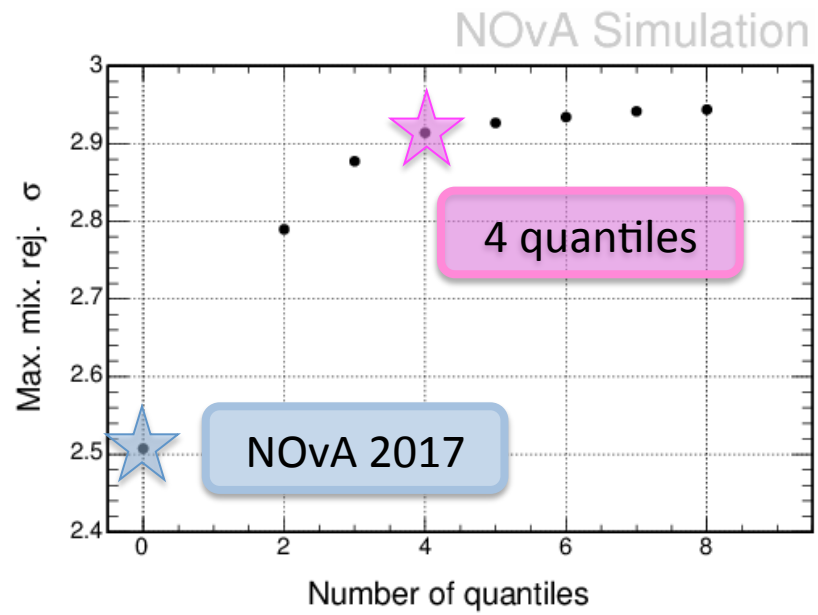
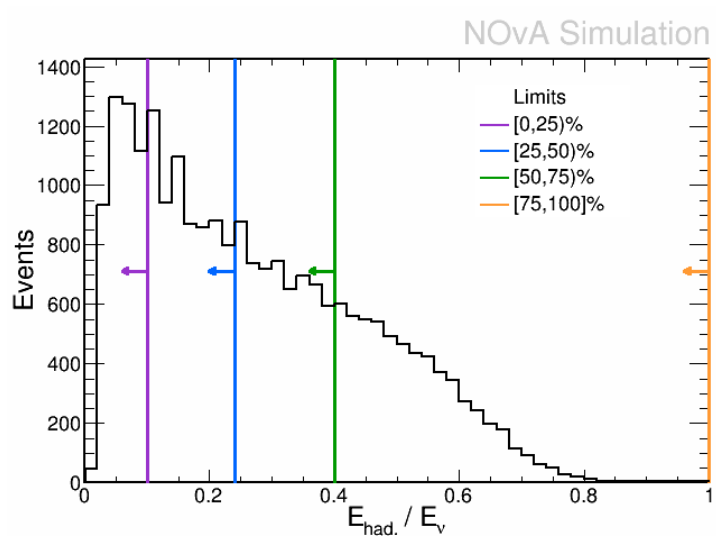




3. Find boundaries to divide the sample evenly

Energy Resolution





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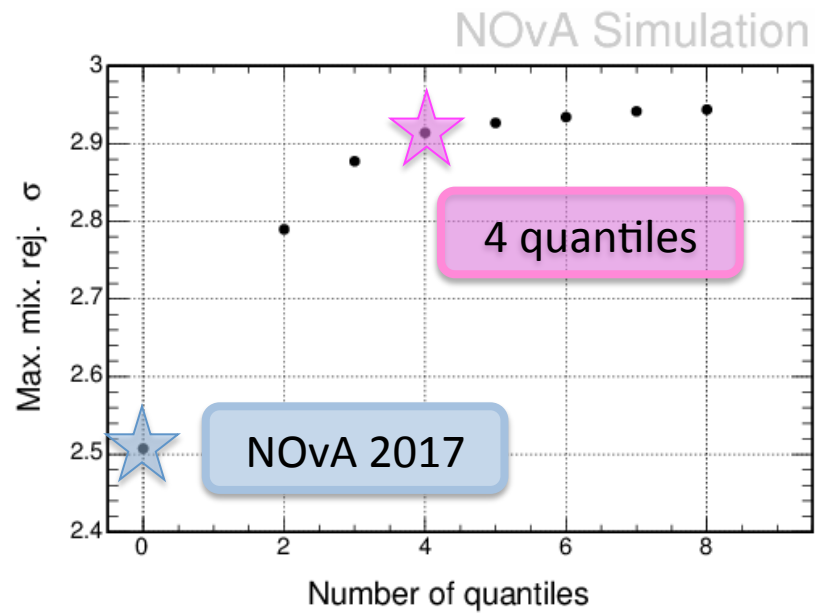
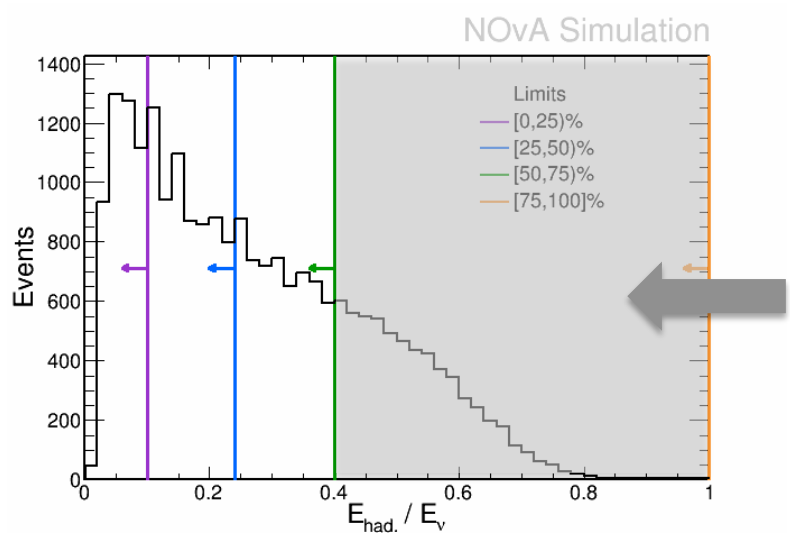


Largest **background** in the **worst energy resolution bin** (highest hadronic energy quantile).



Cosmics

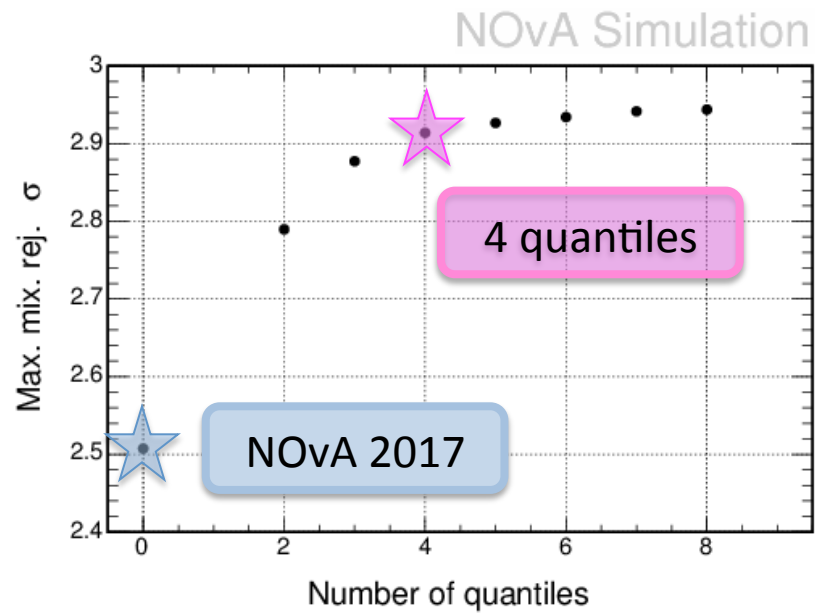
NC

Energy Resolution

1

Neutral current systematic impact improves by a factor of 2-4:

- $\sin^2\theta_{23}$ +3.3/-6.6 → **+1.4/-2.3**
- Δm^2_{32} +9.2/-17 → **+3.3/-4.6**



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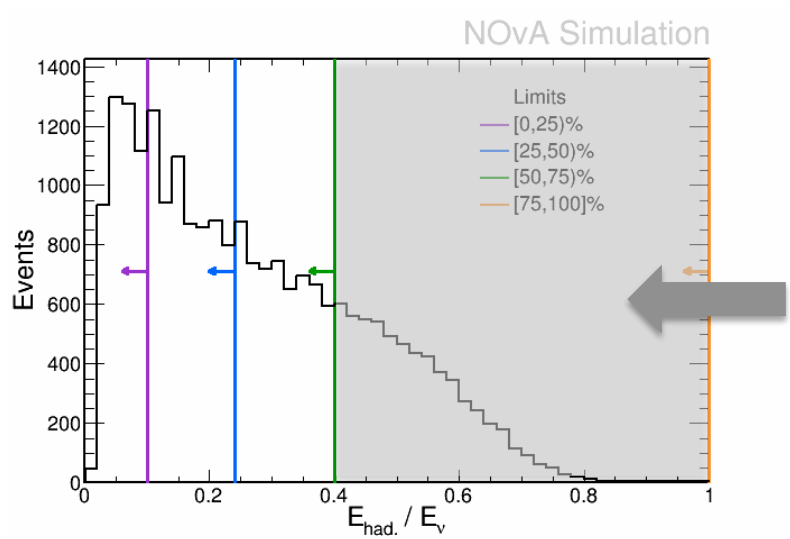


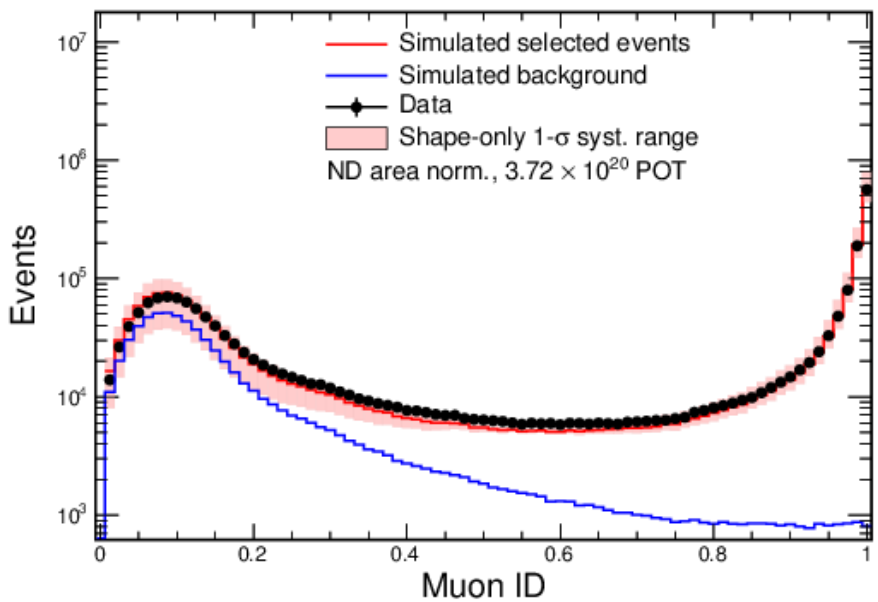
Cosmics

NC

Event identification

ReMId (Reconstructed Muon Identification) good at identifying muon tracks. kNN (k-Nearest Neighbor) with

- Track length
- dE/dx
- Scattering
- Plane fraction



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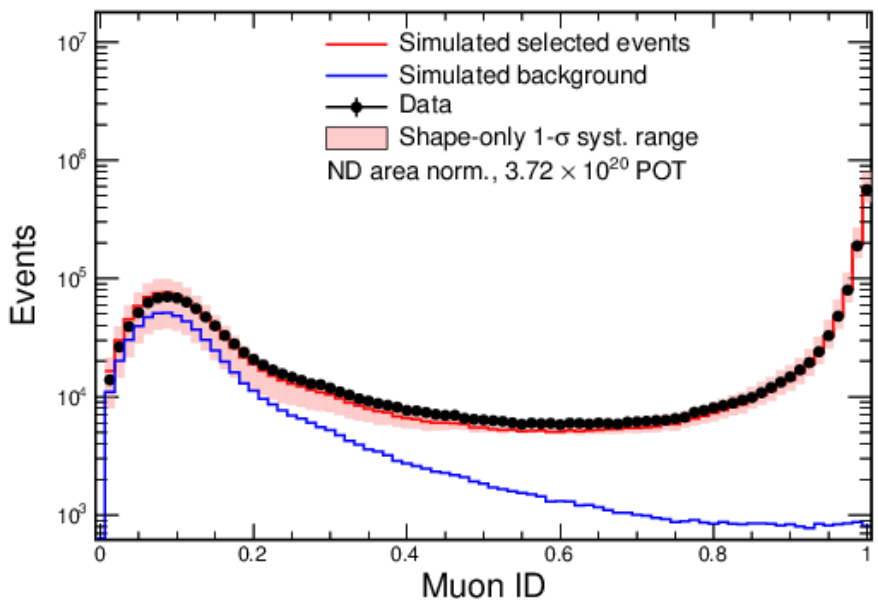
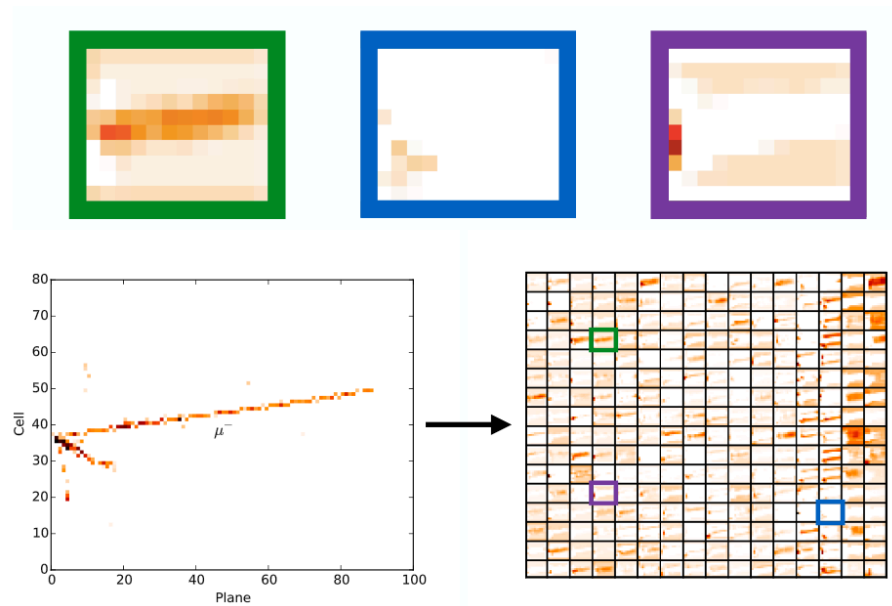
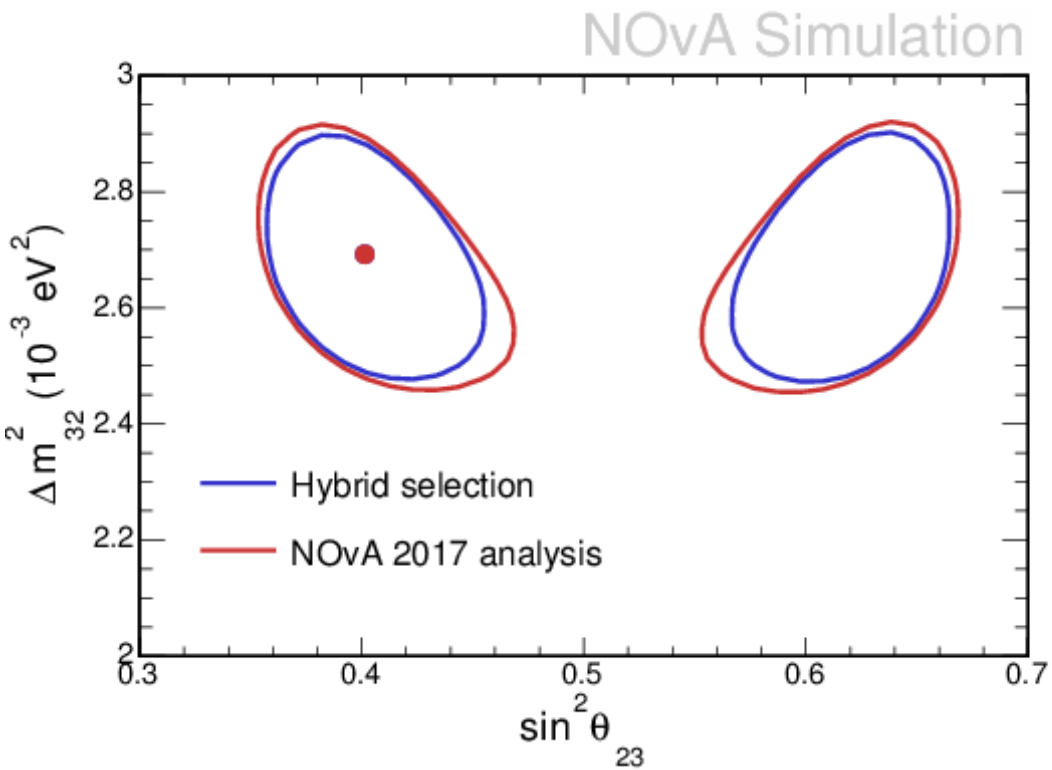
CVN (Convolutional Visual Network) More advanced algorithm to separate ν_e-CC and NC

- Based on CNN (Convolutional Neural Networks)
- Treats events as images
- Extracts features





Event identification



Proposed new selection requires values of

- **ReMId > 0.5**
- **CVN > 0.5**

Including CVN in our selections improves efficiency by ~10% while reducing background by nearly 50%

NOvA 2017 selection required ReMId > 0.75 (only)

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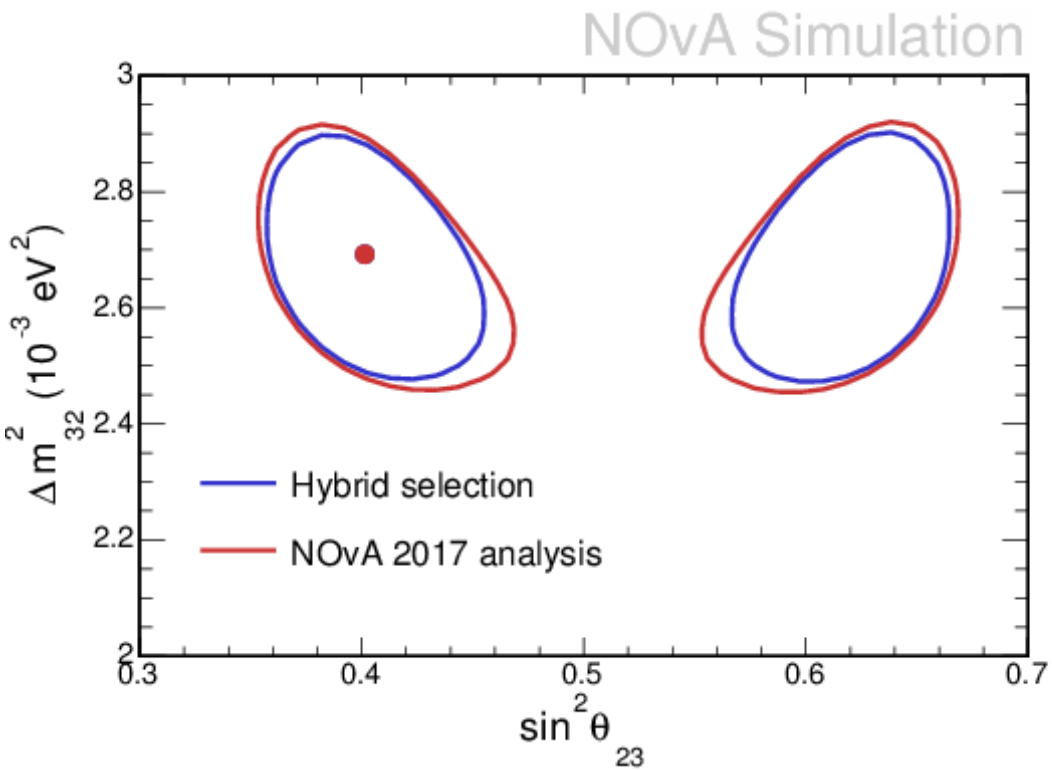

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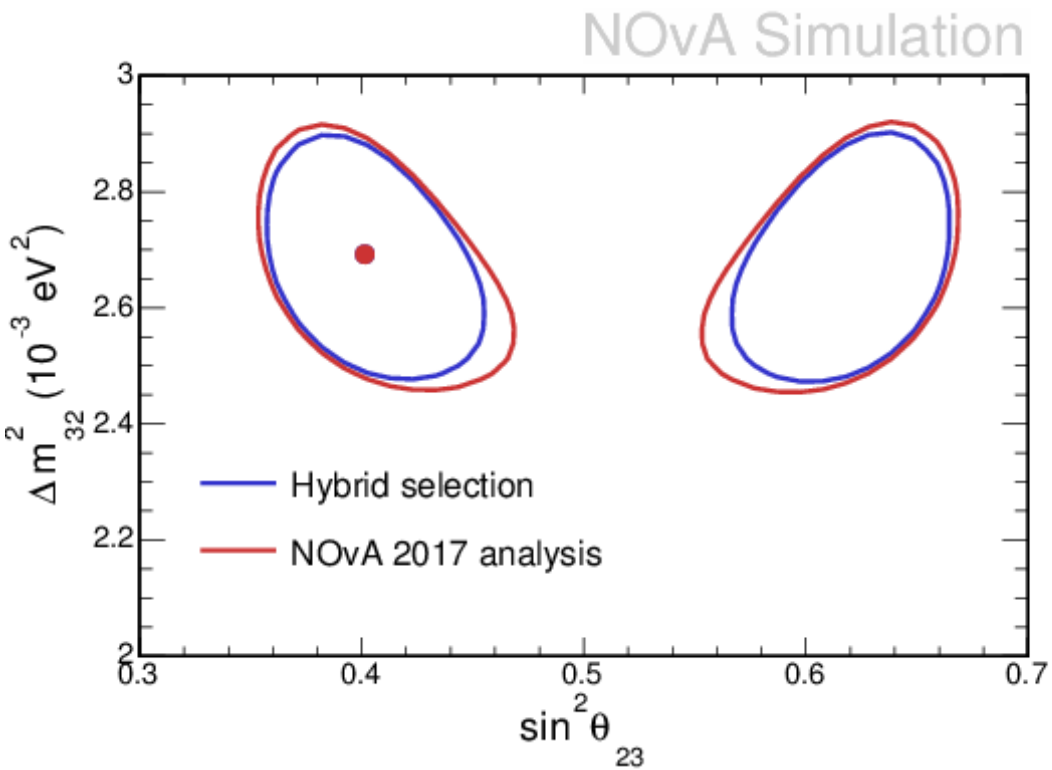

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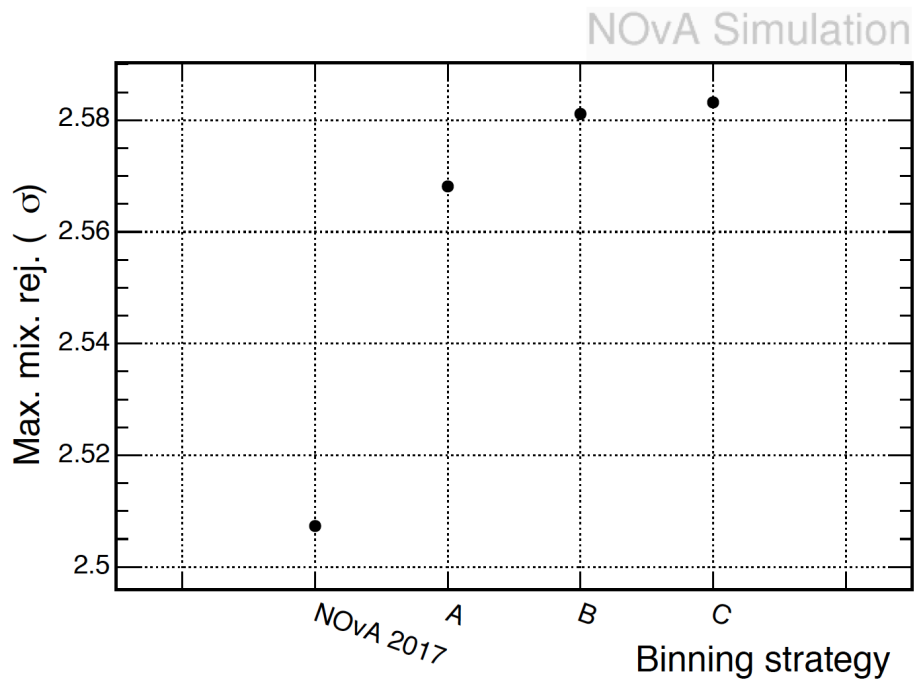
Deep Convolutional Networks talk on **Wednesday** by Fernanada P.

Energy Binning

Finer binning around the maximum oscillation region could enhance the sensitivity of the analysis



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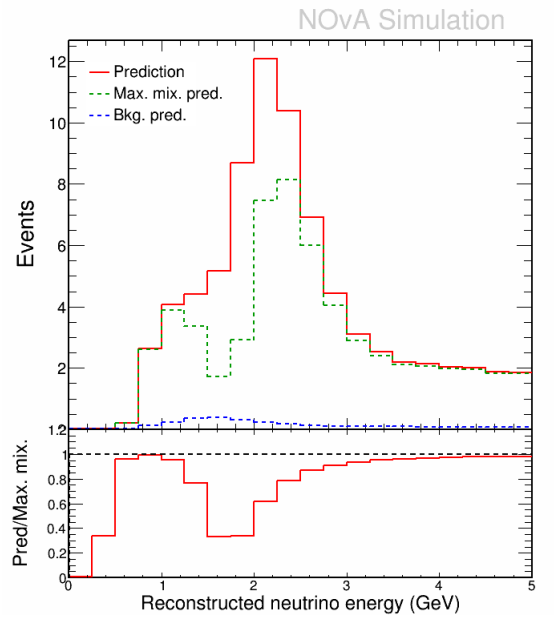

NOvA 2017

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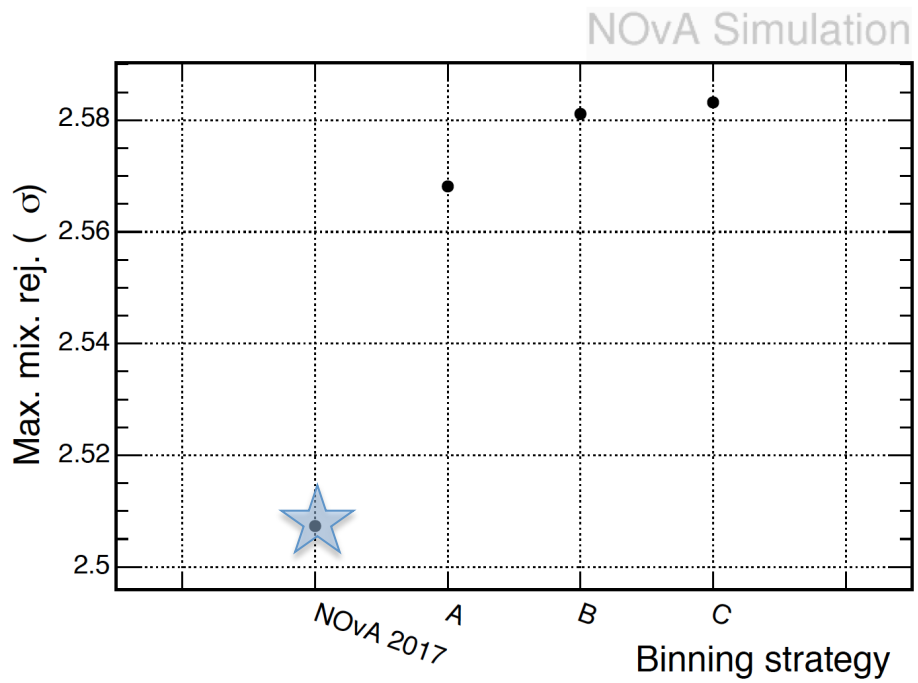
- NOvA' standard energy binning: 20 bins of 0.25 GeV each



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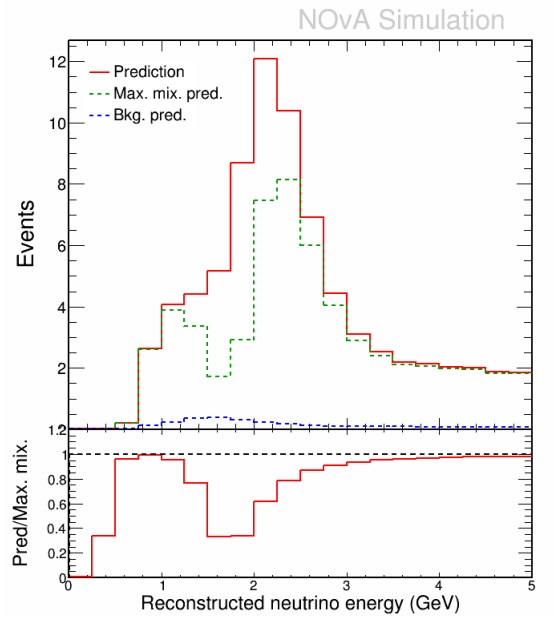

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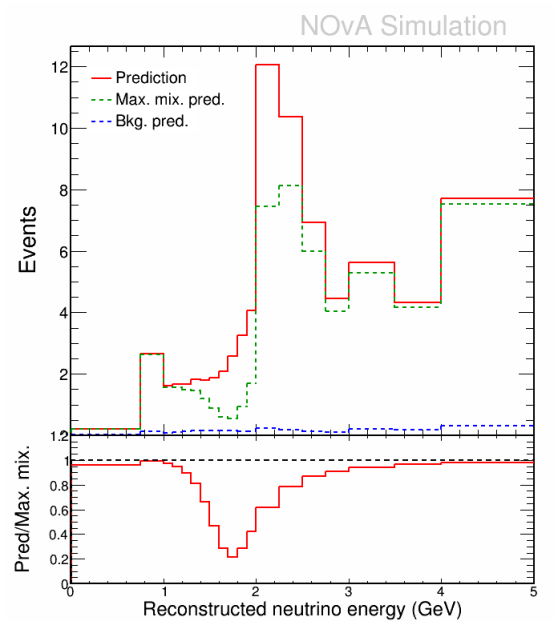

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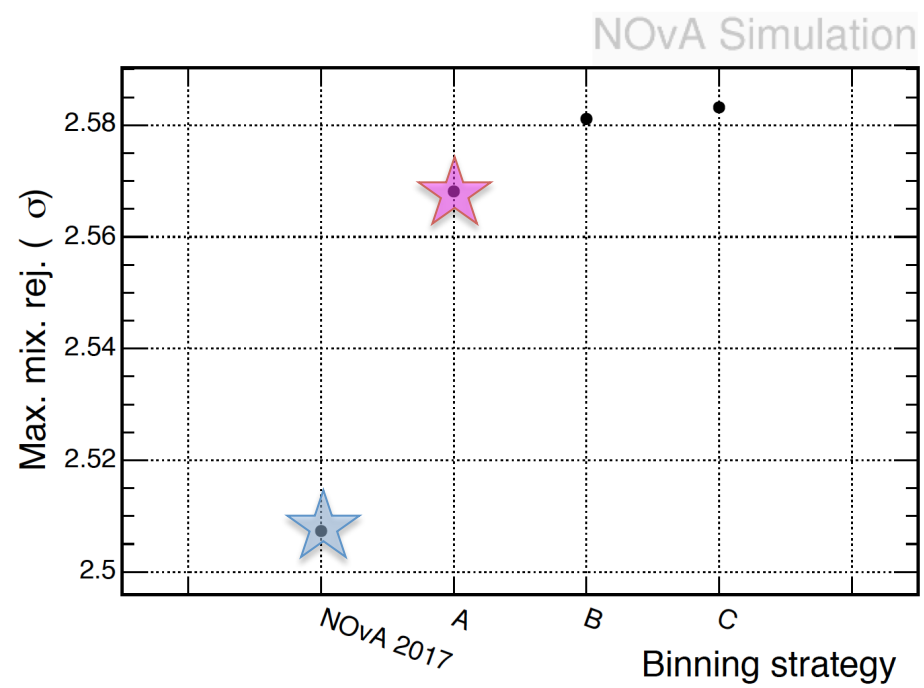
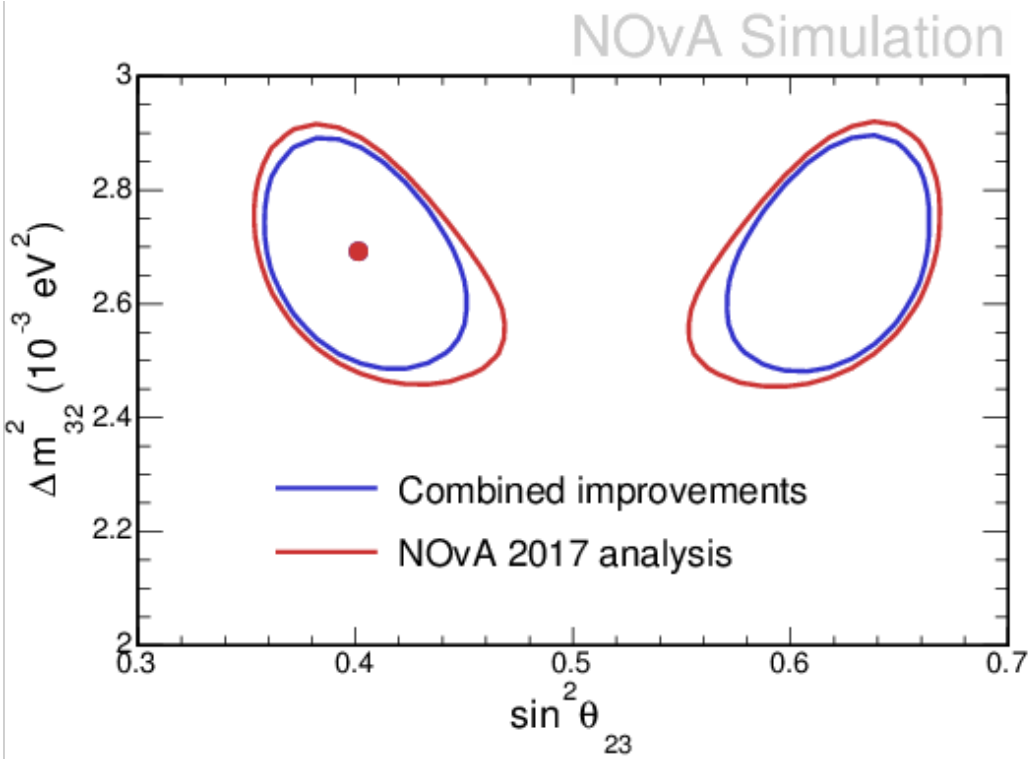


Combined Improvements



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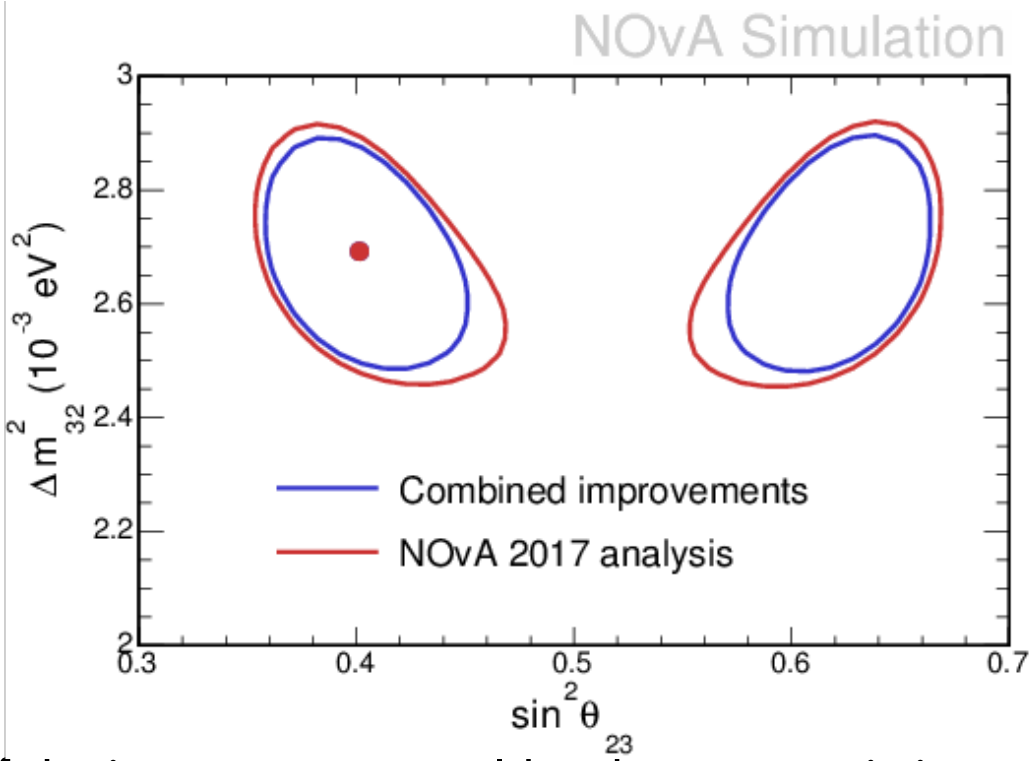
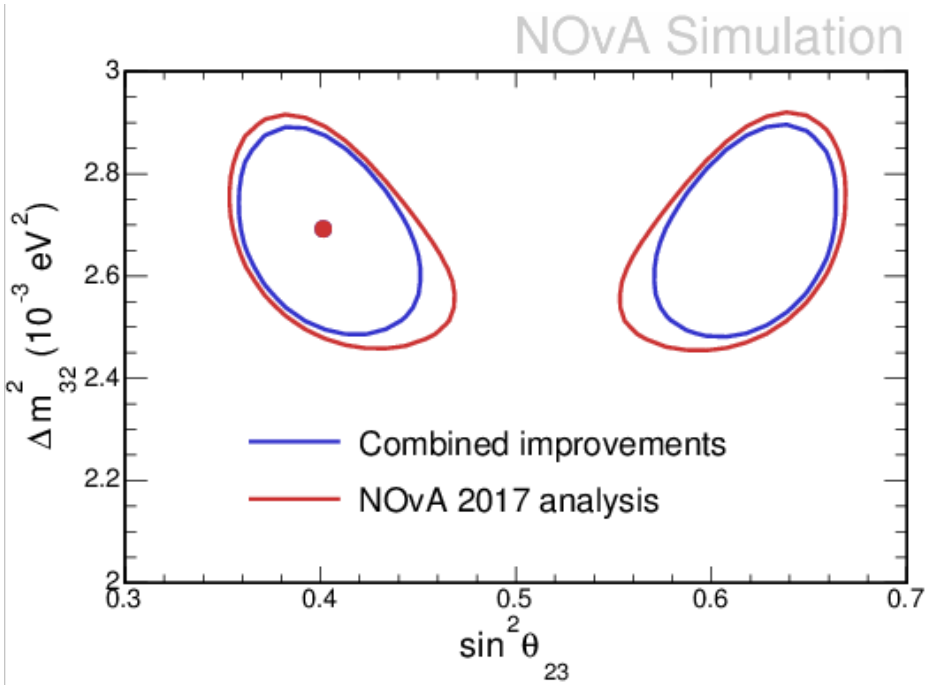


Combination of the improvements would reduce uncertainties and would significantly increase NOvA's sensitivity:

- **Systematic uncertainties** expected to **reduce** from 2.2% to 2.0% on Δm^2_{32} and from a 2.1% to 1.5% on $\sin^2\theta_{23}$
- Simulated maximal mixing rejection increases from **2.51** to **3.25** σ equivalent to **75% more data**

Conclusions



1. **Separation by energy resolution**

   Improves neutral current impact in our systematics

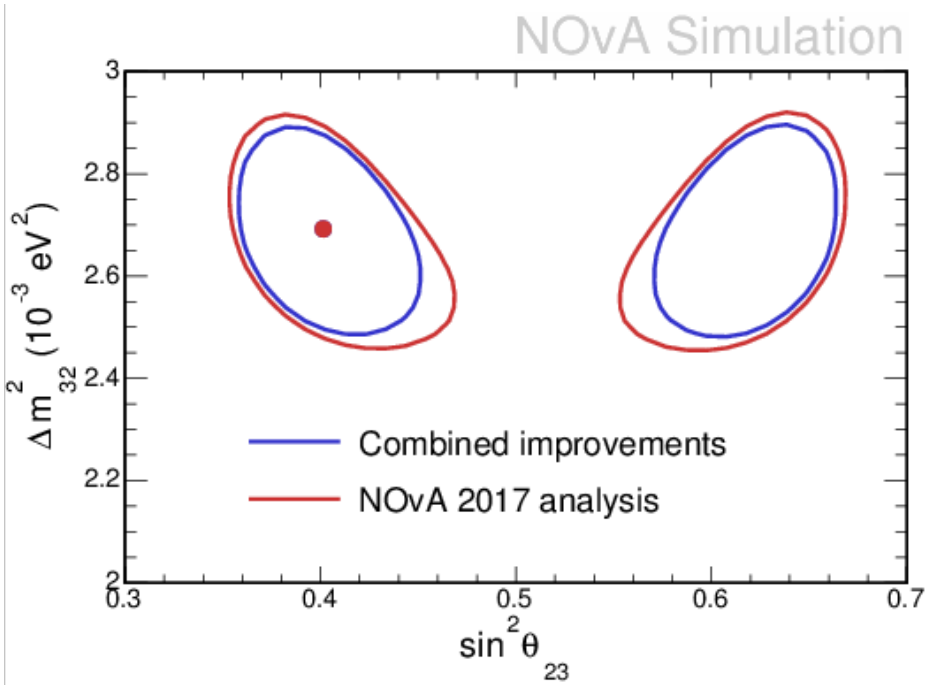
2. **Inclusion of CVN**

   Increases efficiency
   Reduces background

3. **Fine energy binning**

   Enhances the sensitivity to disappearance

Conclusions



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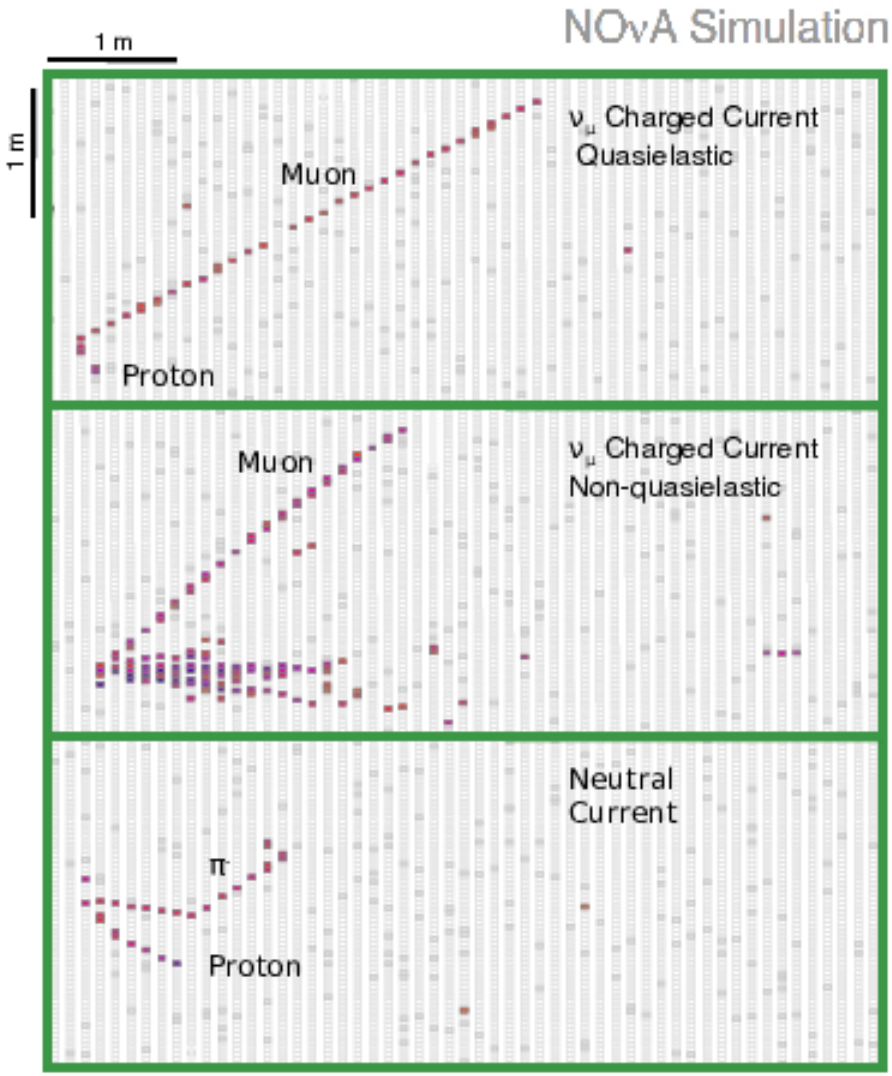
Combination of improvements to the ν_μ disappearance analysis would **reduce systematic uncertainties** on Δm^2_{32} and $\sin^2\theta_{23}$ and **increase** our **rejection to maximal mixing**.

BACKUP

Event topology



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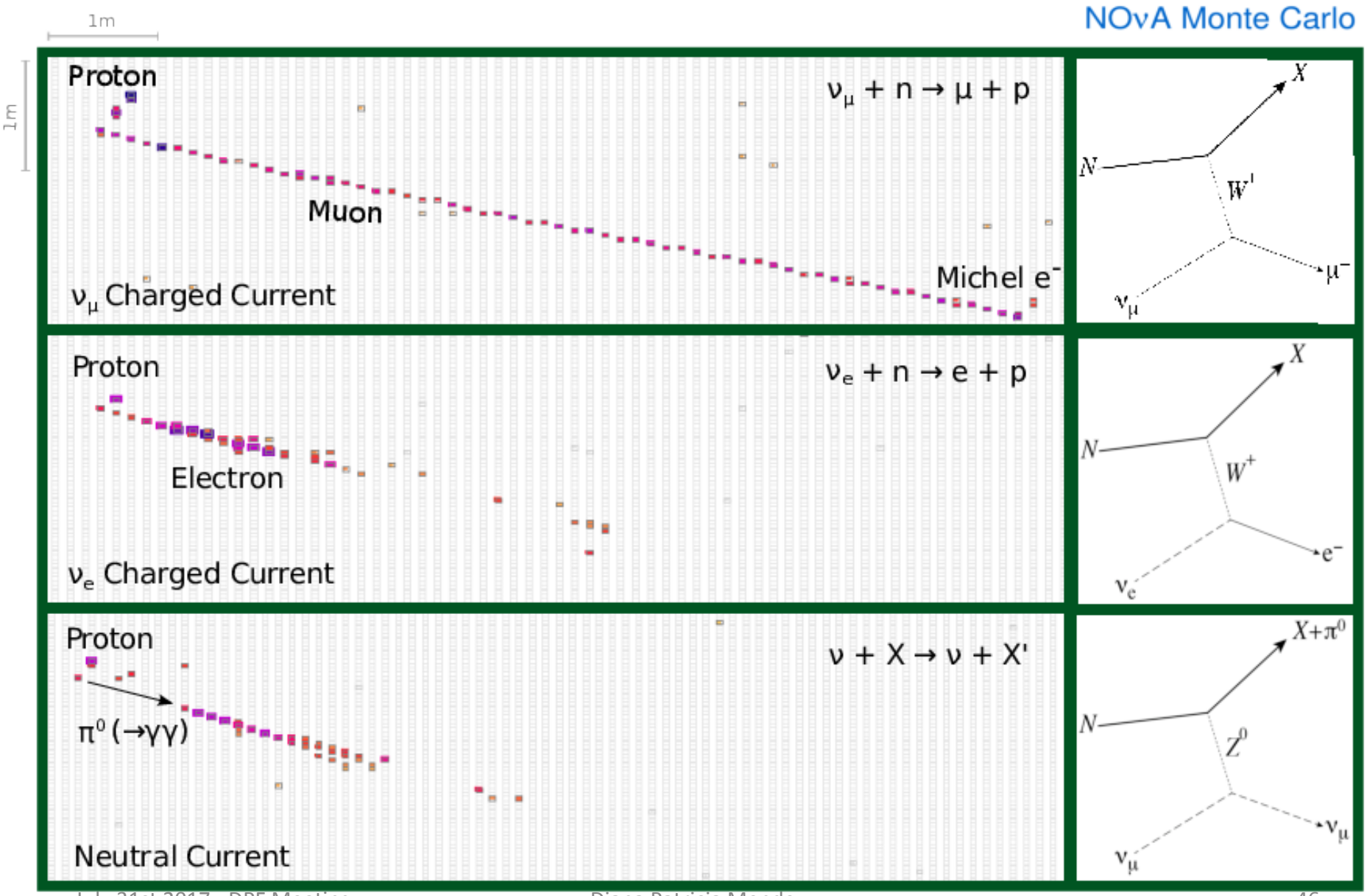

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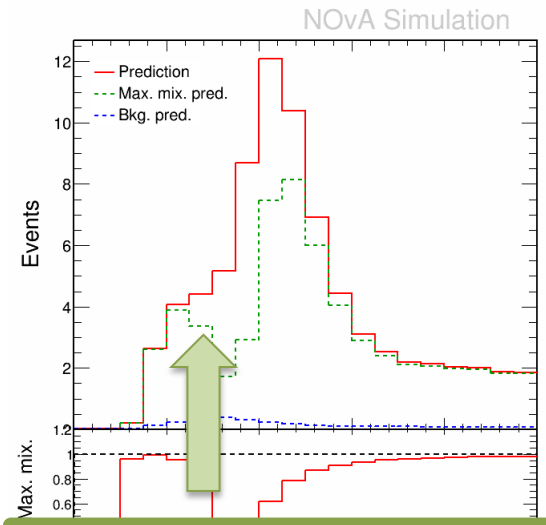
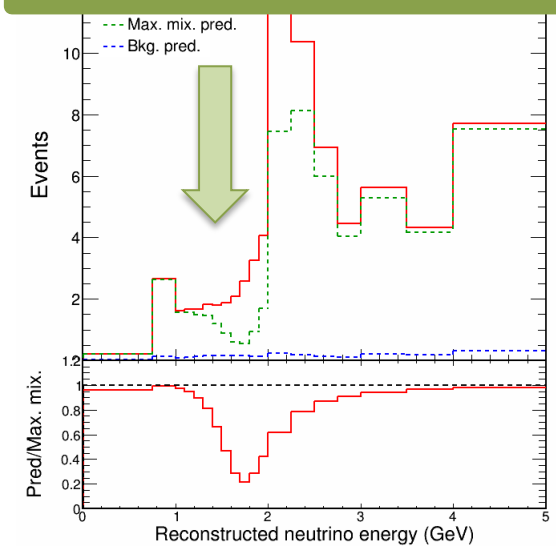


NOvA 2017

The oscillation maximum moves up by about 0.065 GeV per 0.1e^{-3} eV^2 at the NOvA baseline.



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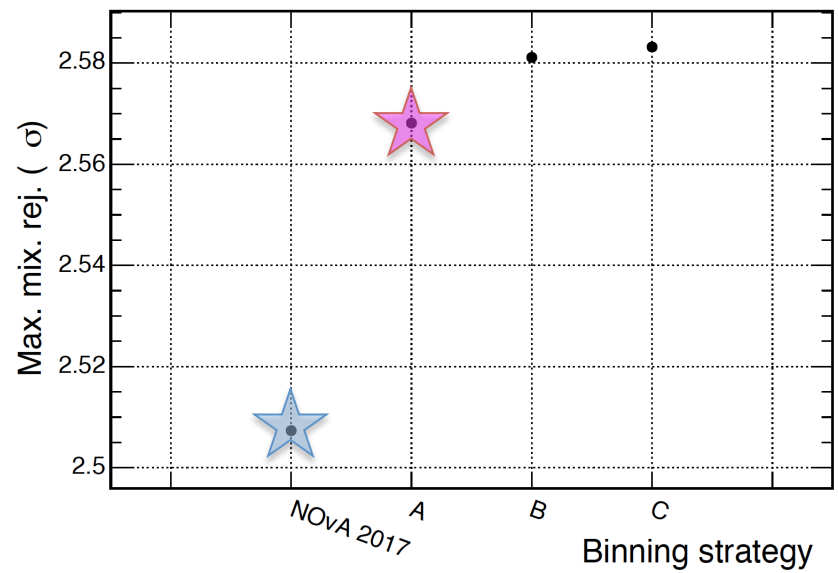
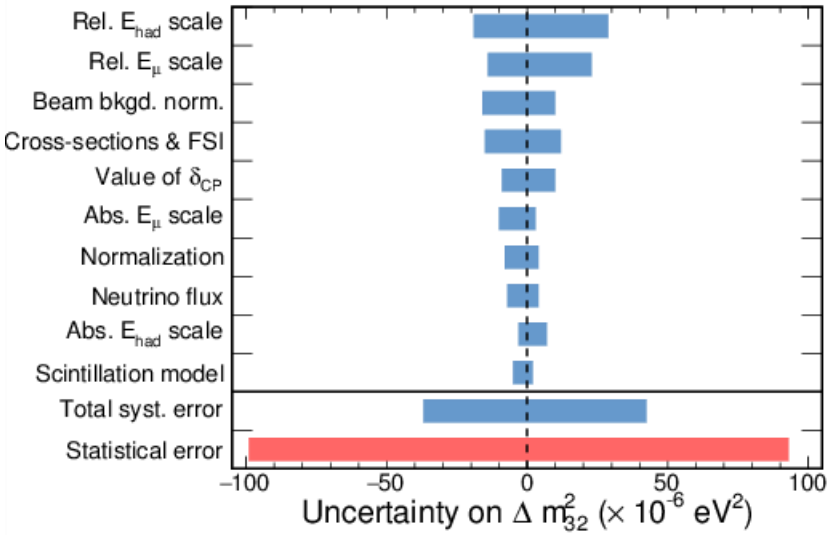
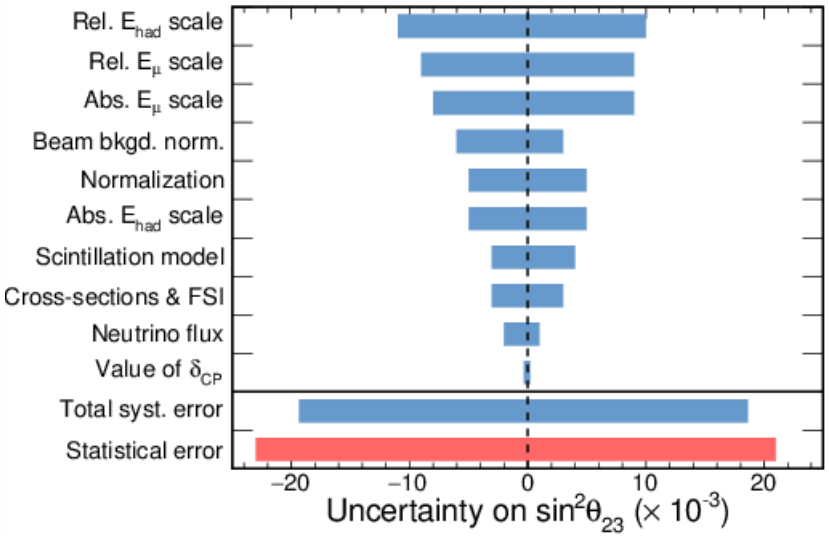


Uncertainties





Source of uncertainty	Uncertainty in $\sin^2\theta_{23}(\times 10^{-3})$		Uncertainty in $\Delta m^2_{32}\left(\times 10^{-6}\ \mathrm{eV}^2\right)$	
	NOvA '17	New analysis	NOvA '17	New analysis
Normalisations	+5.4 / -4.7	+5.2 / -5.1	+5.1 / -11	+1.0 / -9.2
Absolute muon energy	+3.7 / -2.6	+2.4 / -1.8	+14 / -20	+16 / -23
Relative muon energy	+4.4 / -4.7	+3.1 / -3.3	+11 / -9.3	+7.7 / -4.4
Relative hadronic energy	+5.0 / -5.5	+3.0 / -3.2	+14 / -11	+8.2 / -5.2
Comb. GENIE+MEC+RPA	+1.8 / -1.9	+1.6 / -1.8	+18 / -21	+15 / -18
NC background	+3.3 / -6.6	+1.4 / -2.3	+9.2 / -17	+3.3 / -4.6