Summary of the Latest Neutrino Oscillation Results from the NOvA Experiment

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(for the NOvA Collaboration)

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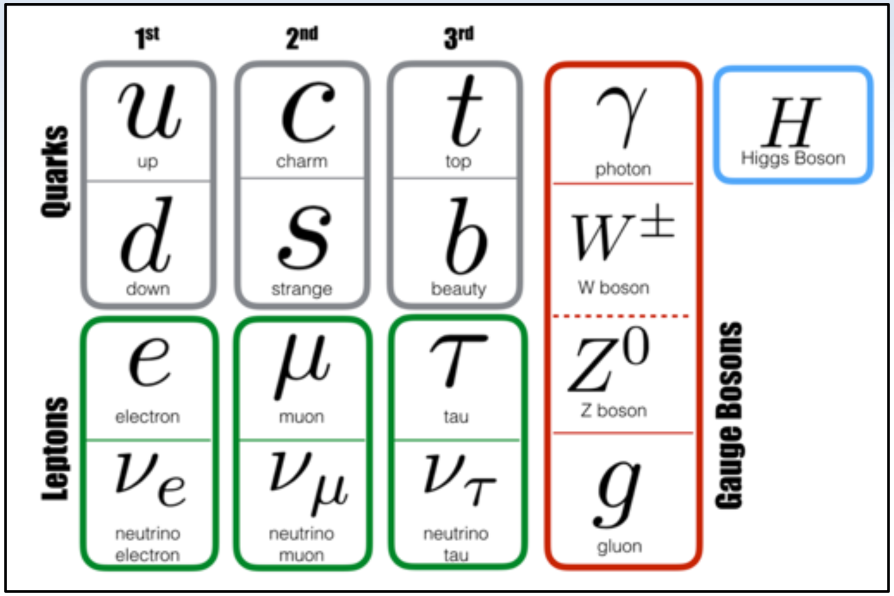
2019 J-PARC Symposium

Neutrinos in General:

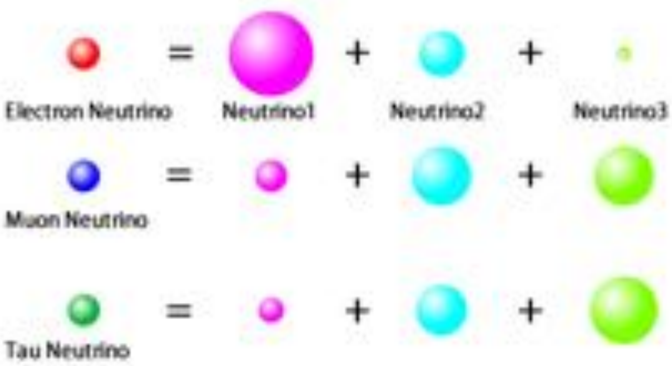
What do we know about neutrinos?

- They are very light (m < a few eV), electrically neutral, and only interact weakly with matter.



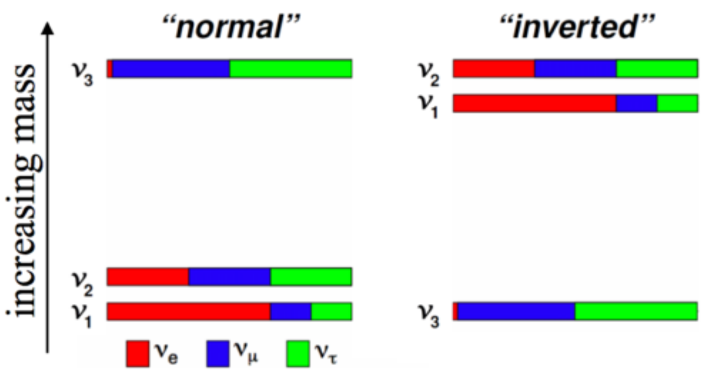
- There are at least 3 types, can be expressed in either the mass of flavor basis.

- These two bases are not the same, rotation from one to the other is described by a mixing matrix (PMNS.)



Unanswered ν Questions:

Hierarchy?



There still are many unanswered questions in neutrino physics today.

Just to list a few:

- Is $m_3 > m_1$ or $m_3 < m_1$?

Unanswered ν Questions:

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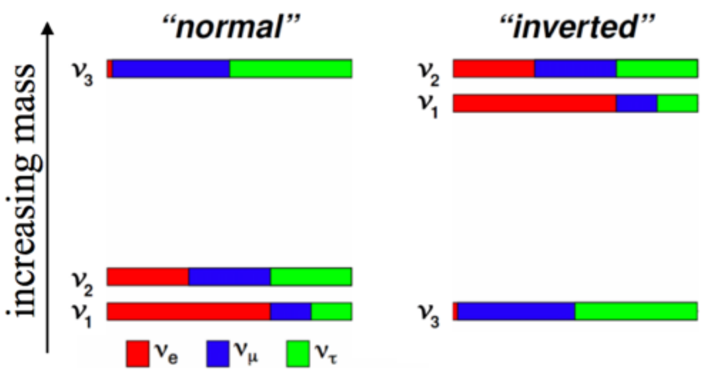
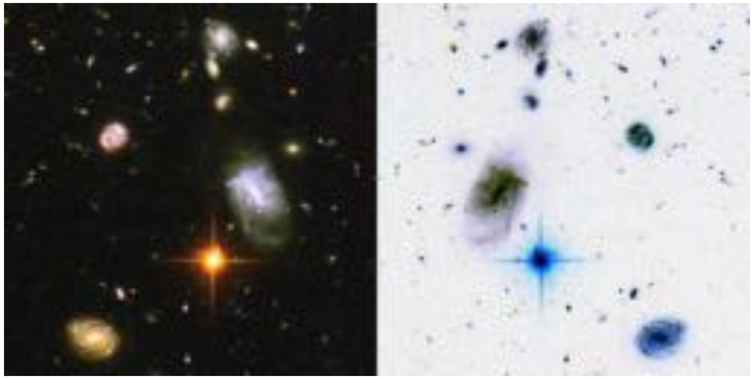


δ_{CP}?



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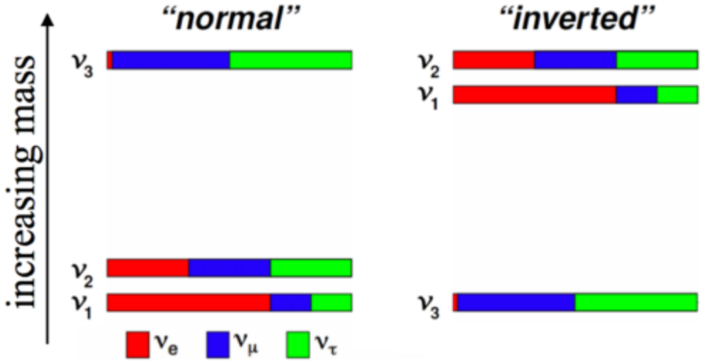
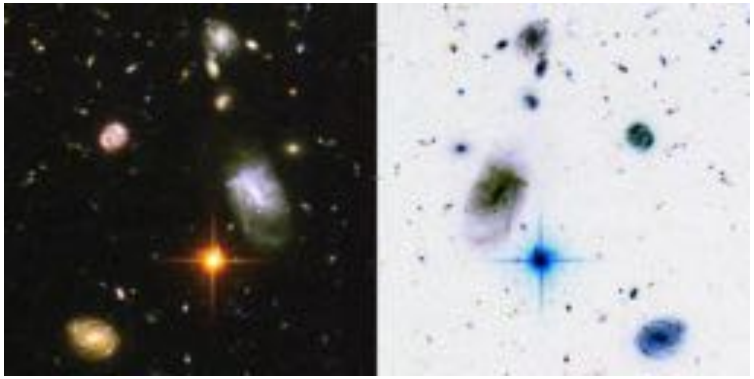


There still are many unanswered questions in neutrino physics today.

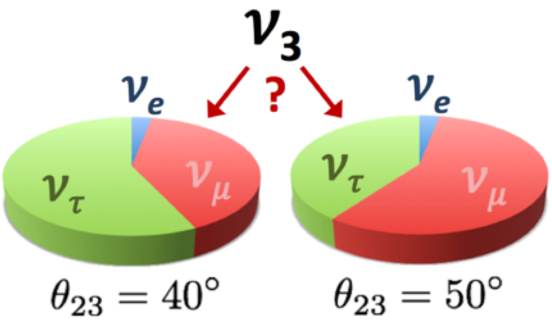
Just to list a few:

- Is $m_3 > m_1$ or $m_3 < m_1$?
- Do neutrinos exhibit CP violation?
- What is the underlying texture of the PMNS mixing matrix?

δ_{CP}?



Octant?



Neutrino Oscillations:

Neutrino Mixing:

$$\begin{pmatrix} \upsilon_e \\ \upsilon_\mu \\ \upsilon_\tau \end{pmatrix} = \begin{bmatrix} C_{12}C_{13} & S_{12}C_{13} & S_{13}e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}S_{13}e^{i\delta} & C_{12}C_{23} - S_{12}S_{23}S_{13}e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}S_{13}e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}S_{13}e^{i\delta} & C_{23}C_{13} \end{bmatrix} \begin{pmatrix} \upsilon_1 \\ \upsilon_2 \\ \upsilon_3 \end{pmatrix}$$

$$S_{ij} \equiv Sin(\theta_{ij}) \;\; C_{ij} \equiv Cos(\theta_{ij})$$

- Neutrinos can be described in one of two different bases: flavor or mass.
- Neutrino mixing is described by 3 real rotation angles and a CP violating phase factor δ, plus 2 squared mass splittings.
- All three rotation angles have been measured, but we don’t yet know (very well) what delta is.

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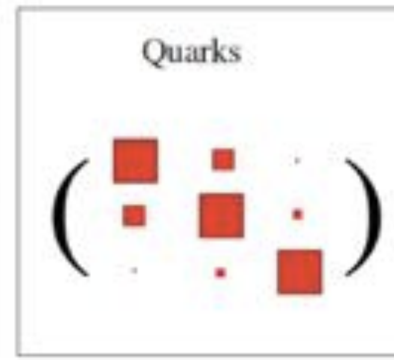
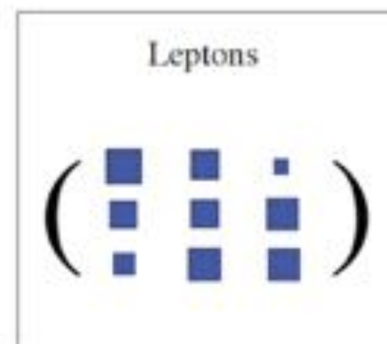
- All three rotation angles have been measured, but we don't yet know (very well) what delta is.
- The mixing is very different in the quark and lepton sectors!





Neutrino Oscillations:

ν_μ **survival probability:**

$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - sin^2(2\theta_{23})sin^2\left(\underbrace{\frac{1.27\Delta m_{32}{}^2 L}{E}}_{\Delta_{23}}\right)$$

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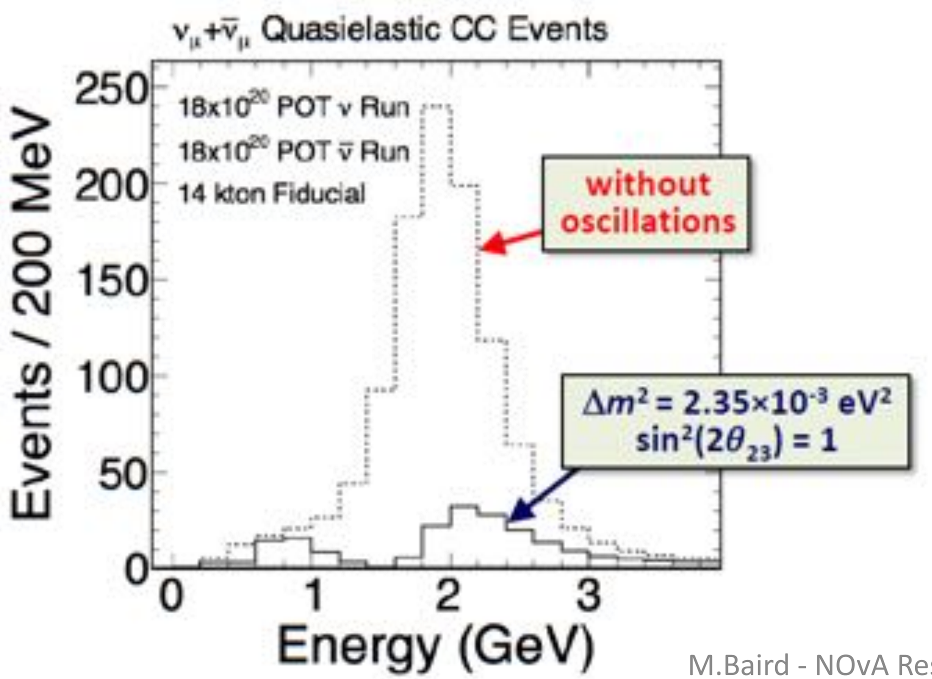

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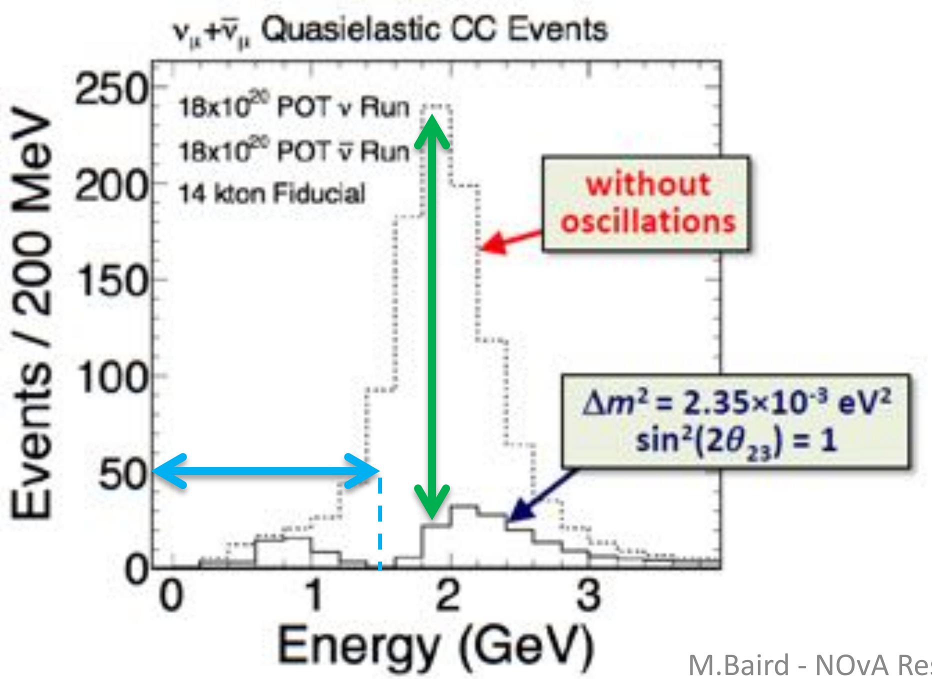

Neutrino Oscillations:

ν_e appearance probability:

$$P(\overset{(-)}{\nu_\mu} \rightarrow \overset{(-)}{\nu_e}) \approx P_{atm} + P_{sol} + 2\sqrt{P_{atm}P_{sol}}[\cos(\Delta_{32})\cos(\delta) \mp \sin(\Delta_{32})\sin(\delta)]$$

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$"-" = neutrinos$

$"+" = anti - neutrinos$

$a \equiv G_F N_e/\sqrt{2}$

$N_e = electron\ density\ in\ Earth$

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matter effect: caused by ν_e scattering off e^- as they travel through the Earth...

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Is $\theta_{23} > 45°$ or $\theta_{23} < 45°$?

hierarchy

Is $m_3 > m_1$ or is $m_3 < m_1$?

CP violation

Is $\delta \neq 0$?

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CP violation

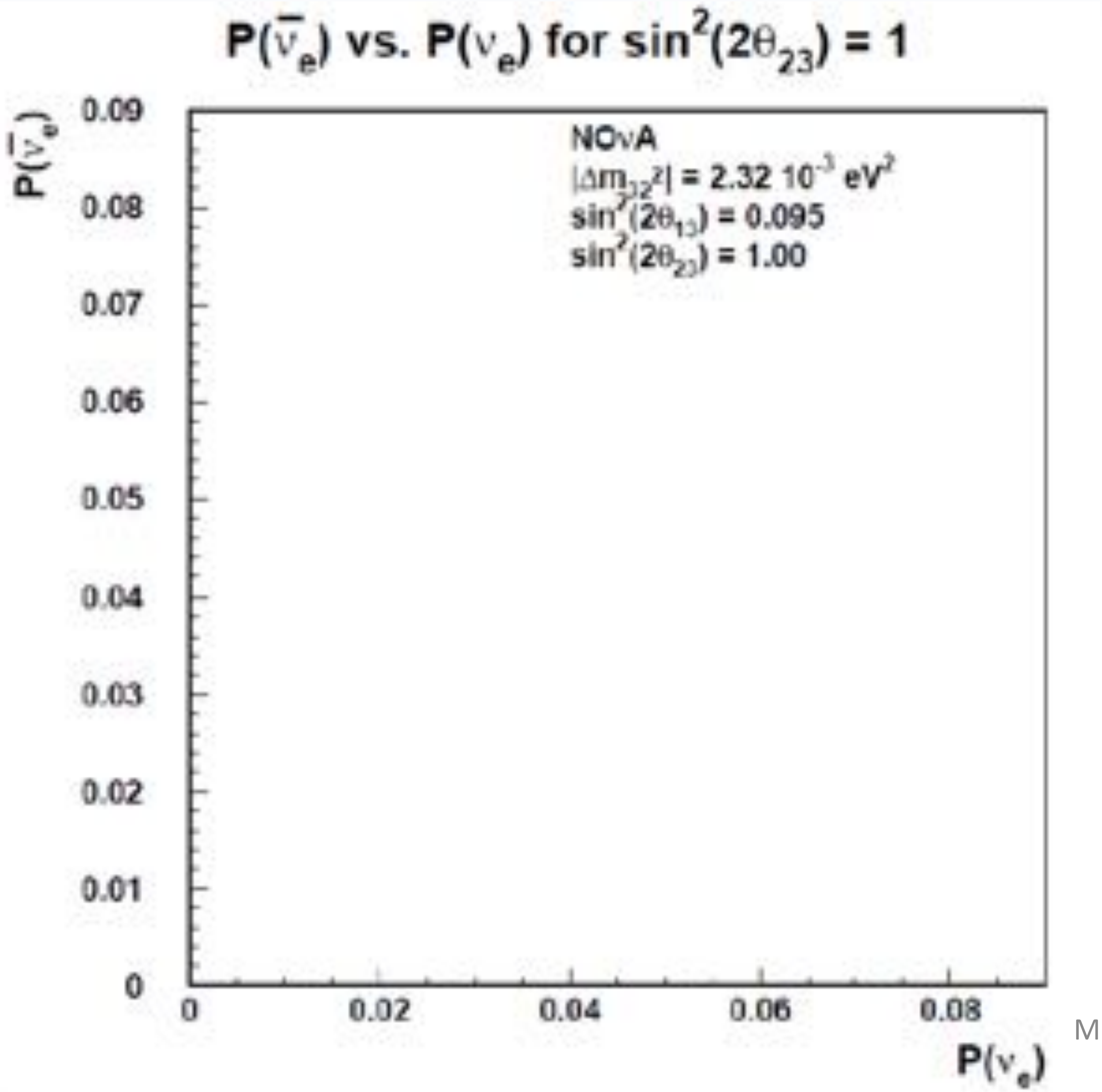
Is $\delta \neq 0$?

From the measurement of ν_μ disappearance, we can constrain θ_{23} and Δm_{32}^2.

From the measurement of ν_e appearance, we can address the above questions.

NOνA performs a simultaneous fit to both the ν_μ and ν_e spectra measured at the far detector.

The "Bi-Probability" Plot:



Measure a single point in $P(\nu_e)$ appearance, $P(\bar{\nu}_e)$ appearance space…

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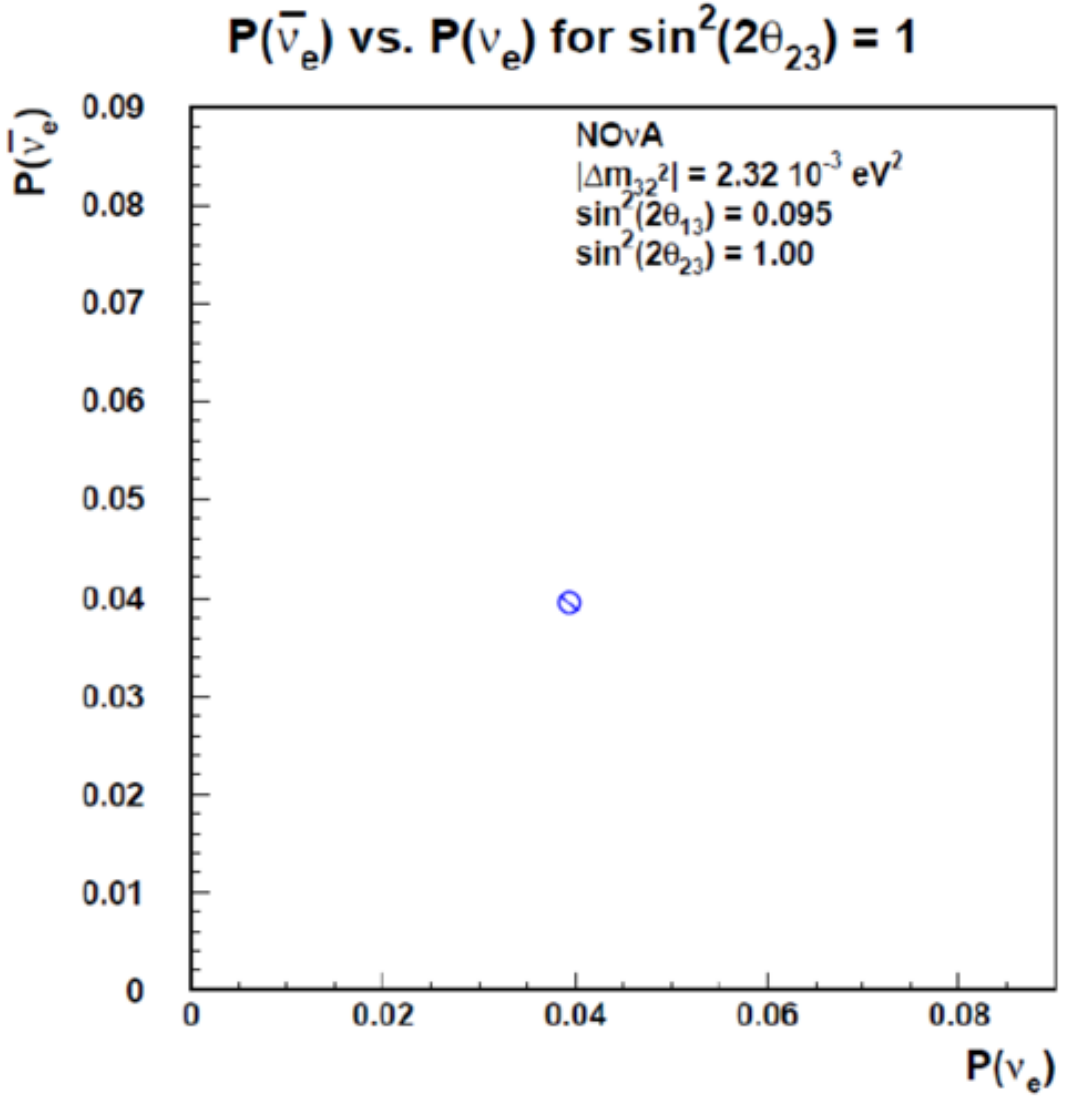

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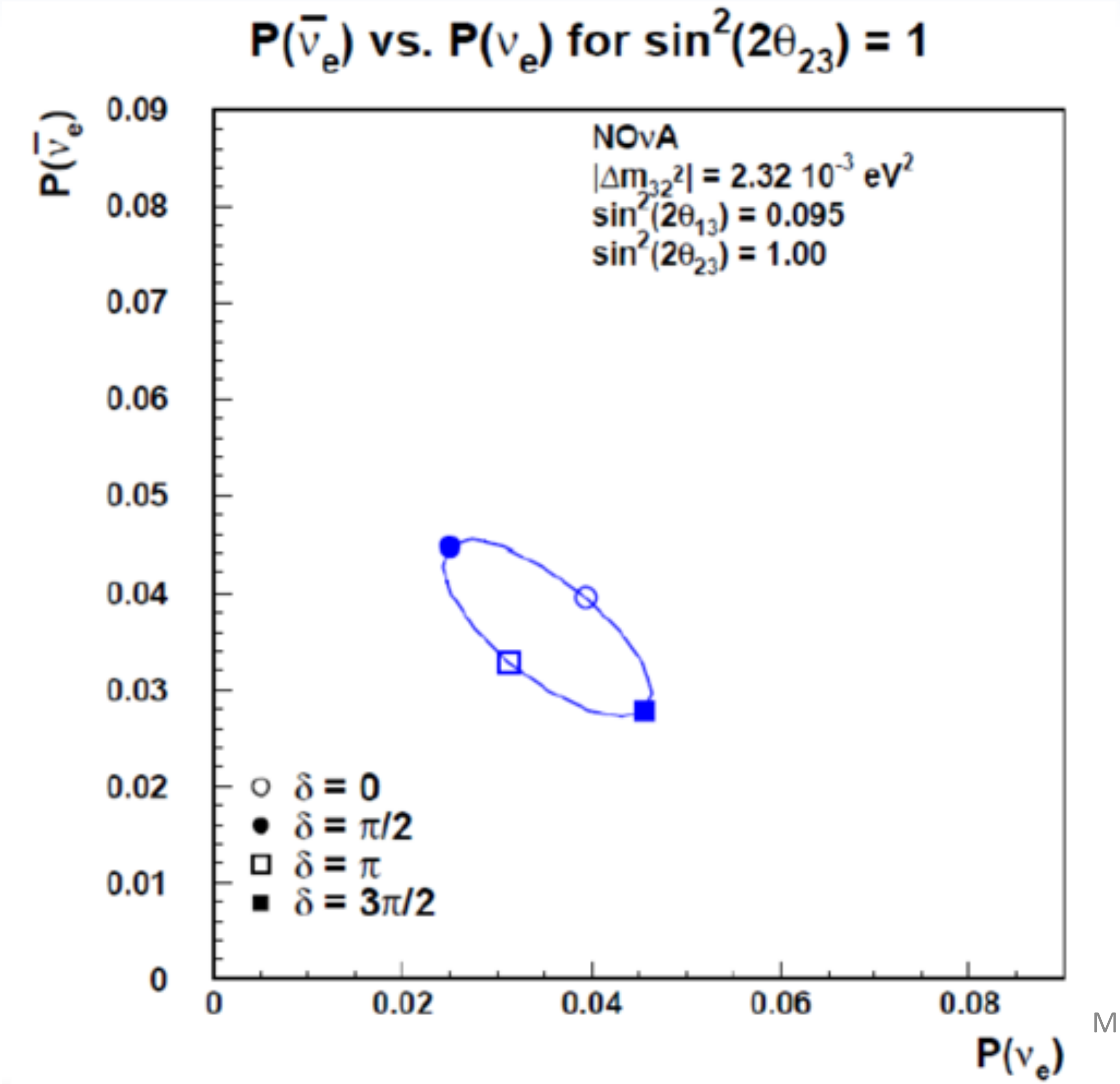

- **Including CP violation**

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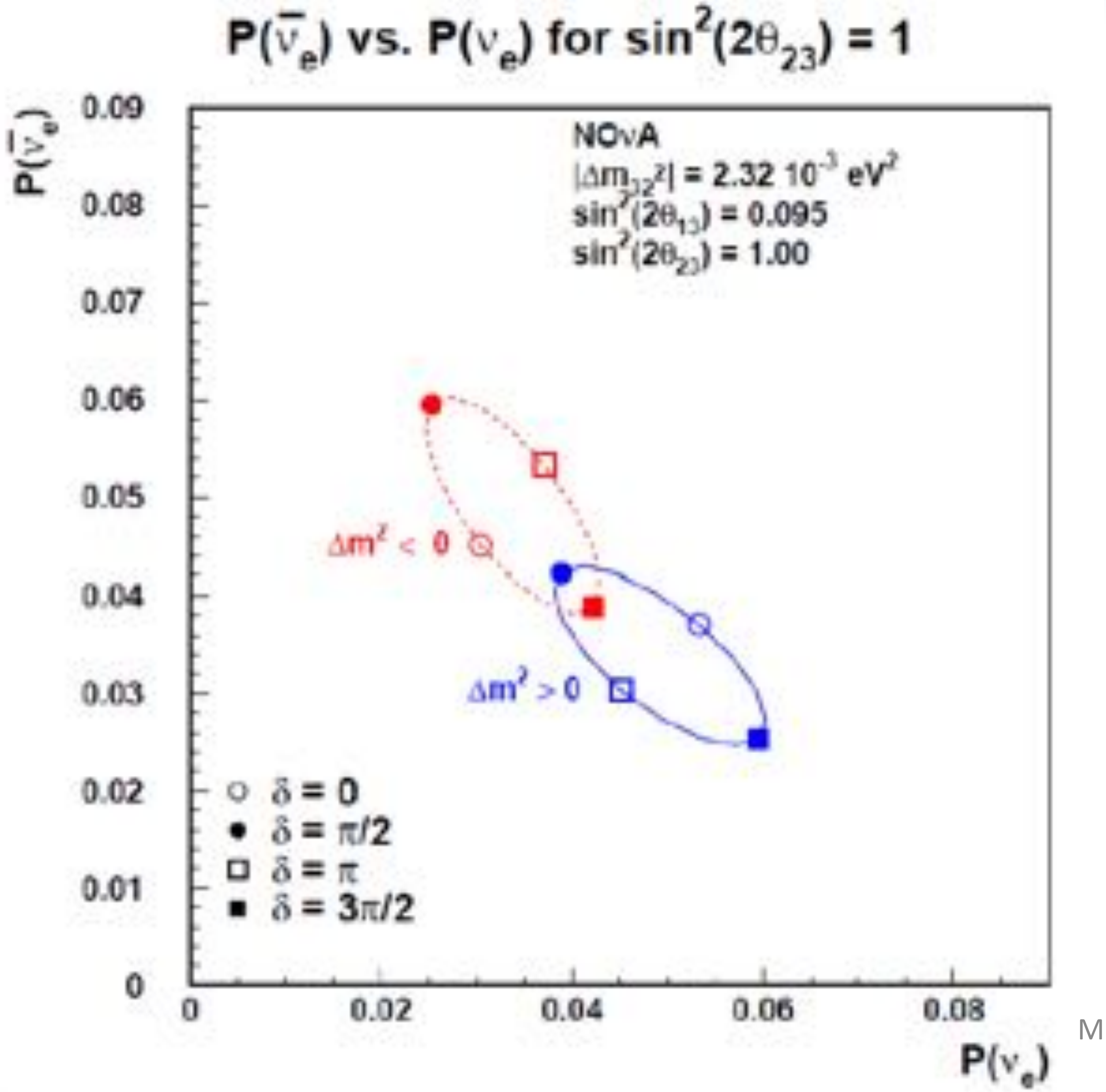

- **Including CP violation**
- **Including the matter effect**

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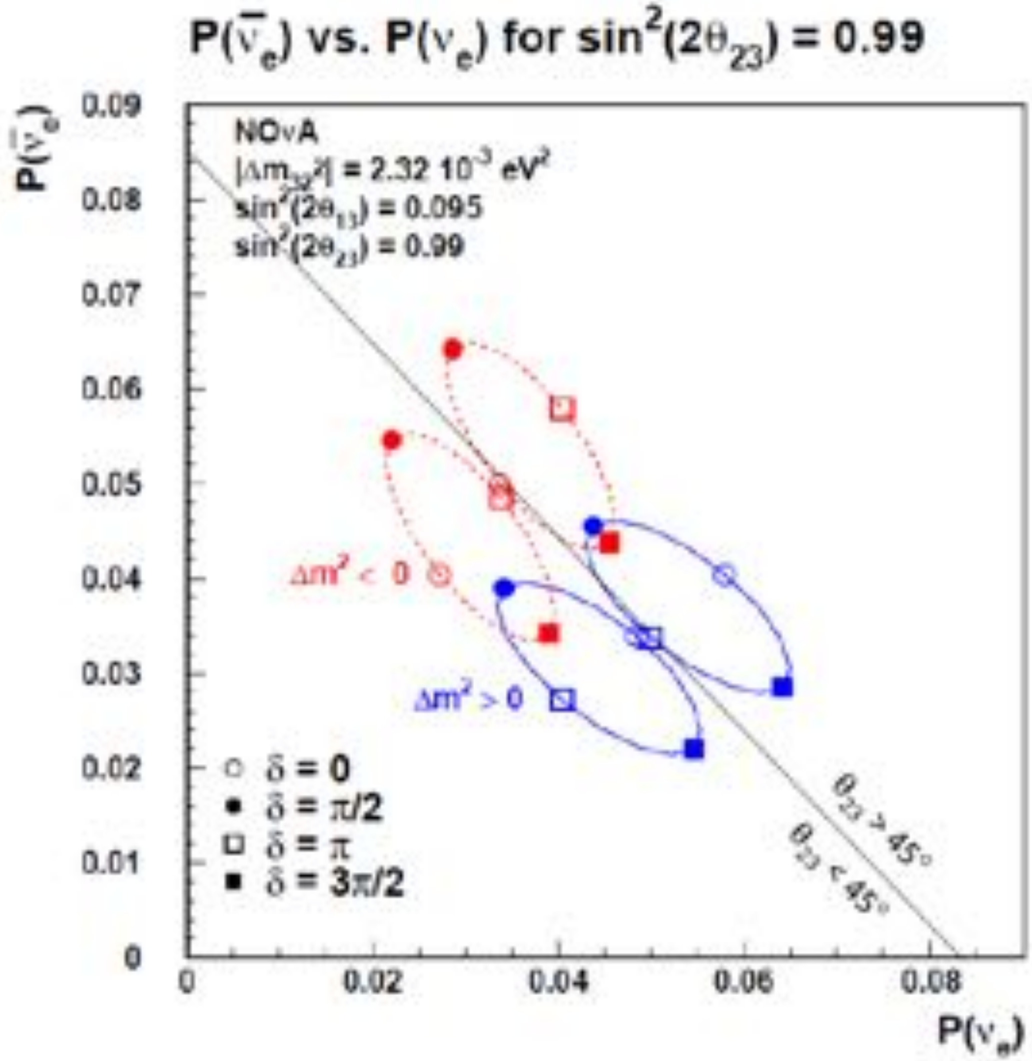
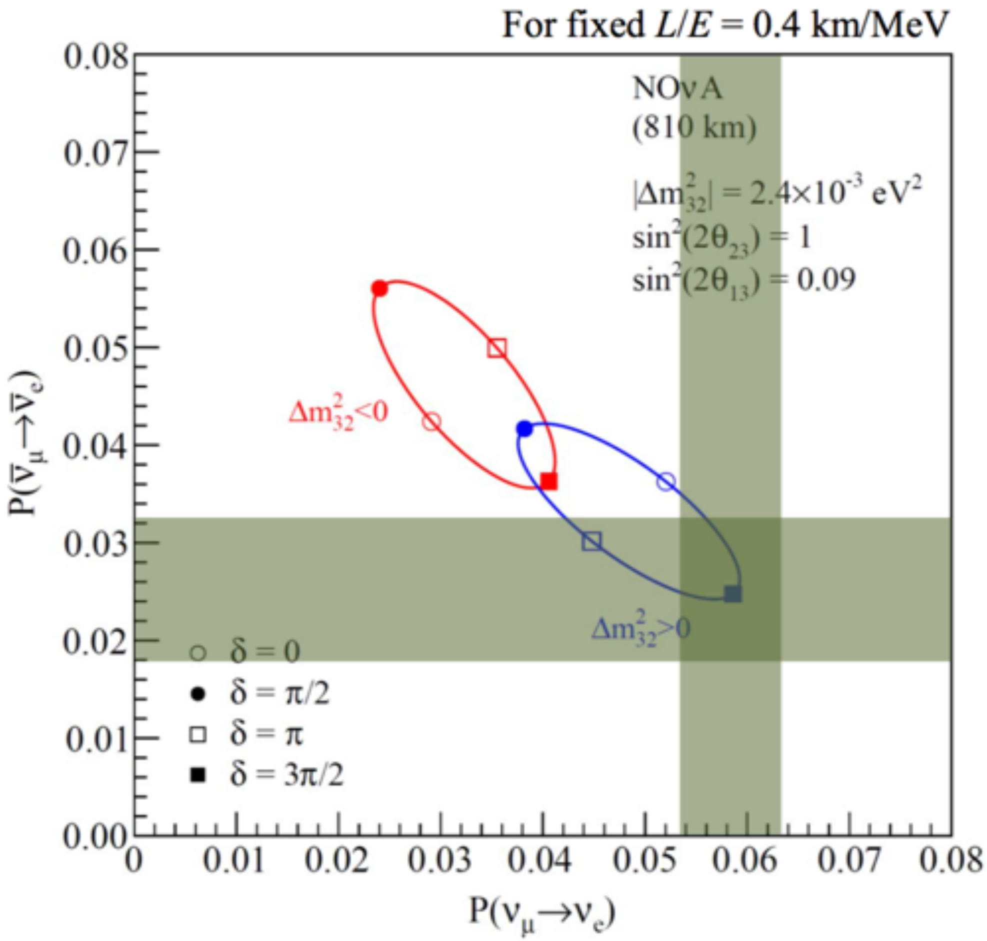


- **Including CP violation**
- **Including the matter effect**
- **Including non-maximal Θ_{23}**

The "Bi-Probability" Plot:

A simultaneous measurement of ν_e appearance and $\overline{\nu_e}$ appearance will help us answer these open questions!



The NOvA Experiment

What is NOvA? (10,000 ft view…)

NOvA is a long-baseline neutrino oscillation experiment based out of Fermilab looking for ν_μ disappearance and ν_e appearance from a (primarily) ν_μ or $\overline{\nu}_\mu$ beam.

Beam Neutrino Physics:

- **ν_μ Disappearance*** } **3-flavor analysis**
- **ν_e Appearance***

- Sterile analysis
- Cross-section physics

"Exotic" Physics

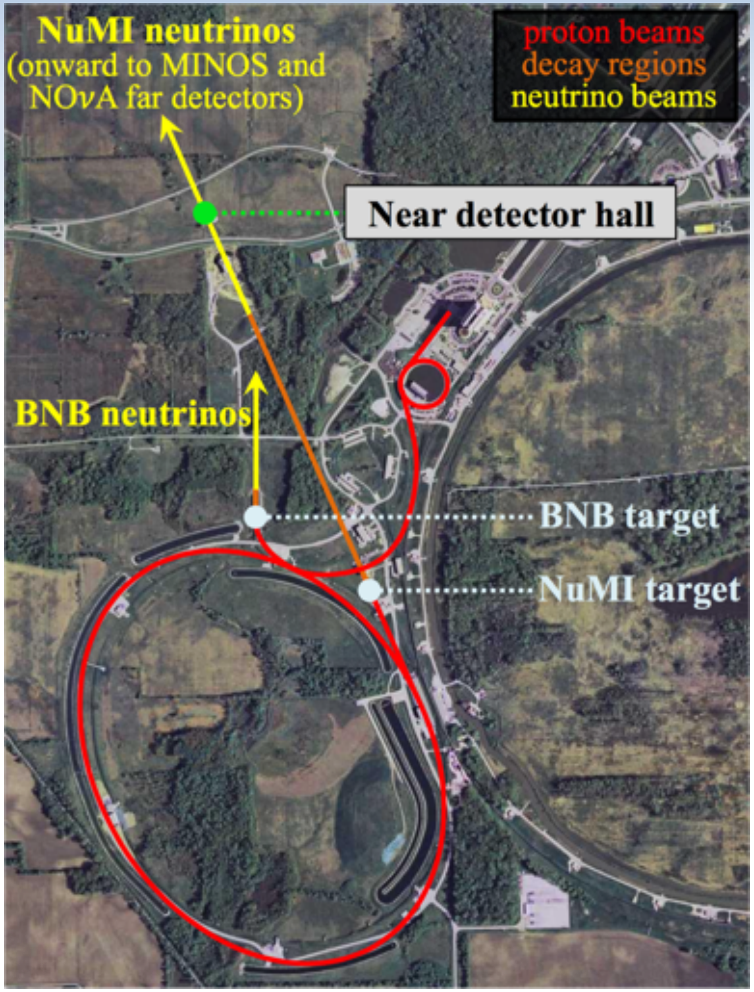
- Supernova neutrinos
- Atmospheric neutrinos
- Magnetic monopoles
- Cosmic ray physics
- Dark matter
- LIGO coincidence
- etc…

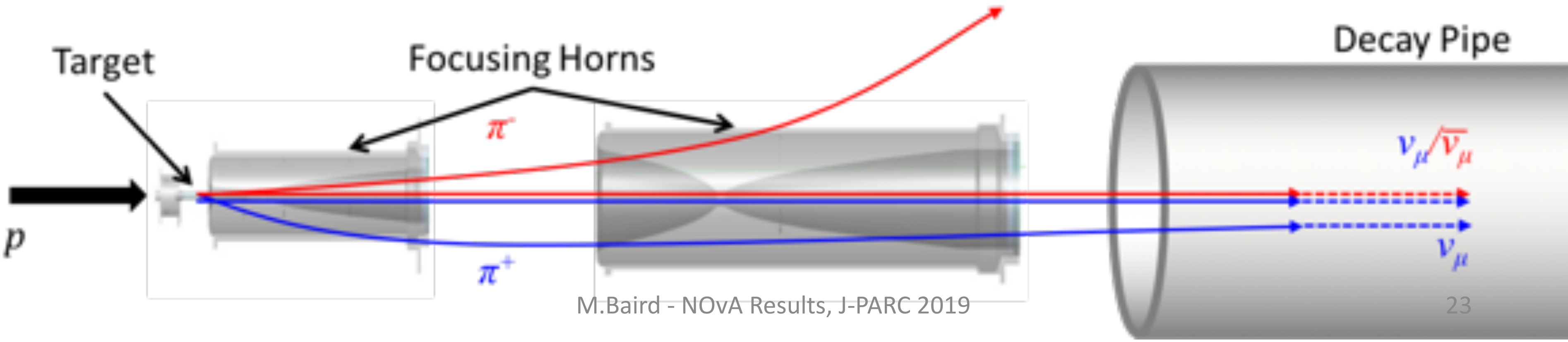
* shown in this talk

The NOvA Experiment:

NuMI - Neutrinos at the Main Injector

- Provides a 10 μsec ν pulse every 1.33 sec
- Beam is roughly 95% ν_μ or 93% $\overline{\nu_\mu}$
- Running at > 700 kW since 2017





The NOvA Experiment:

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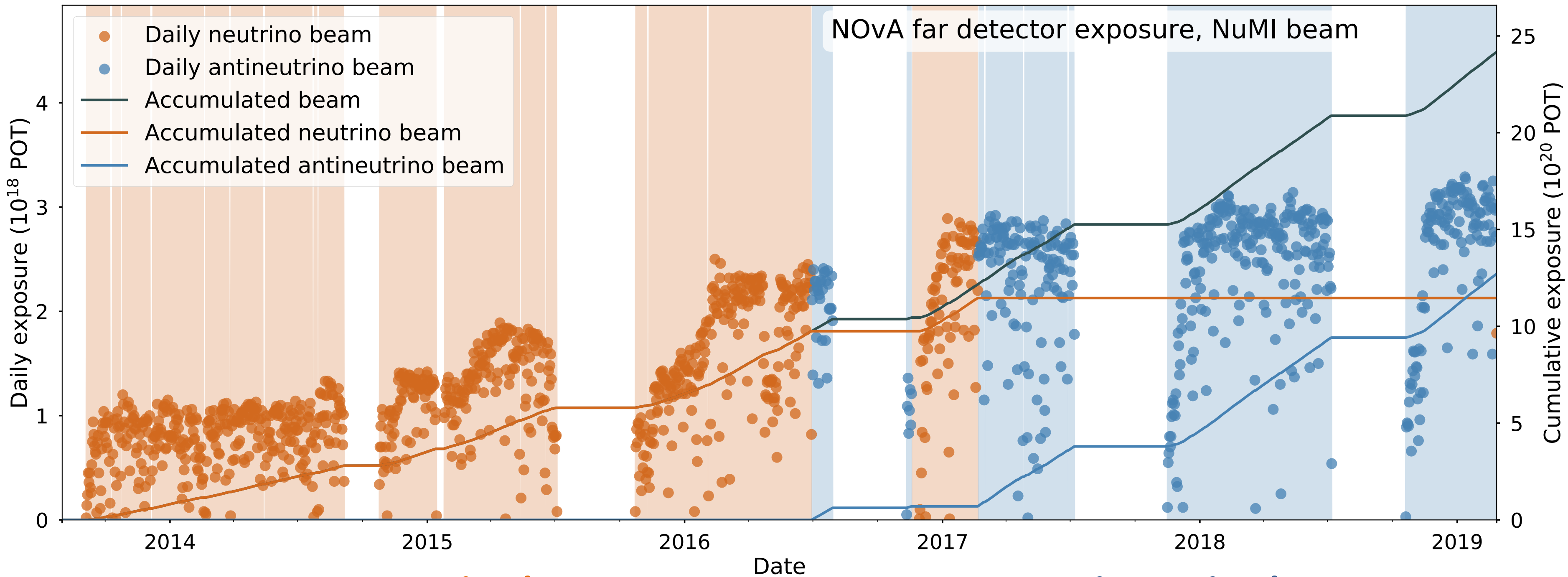


FHC = neutrino beam **RHC = anti-neutrino beam**

This talk:

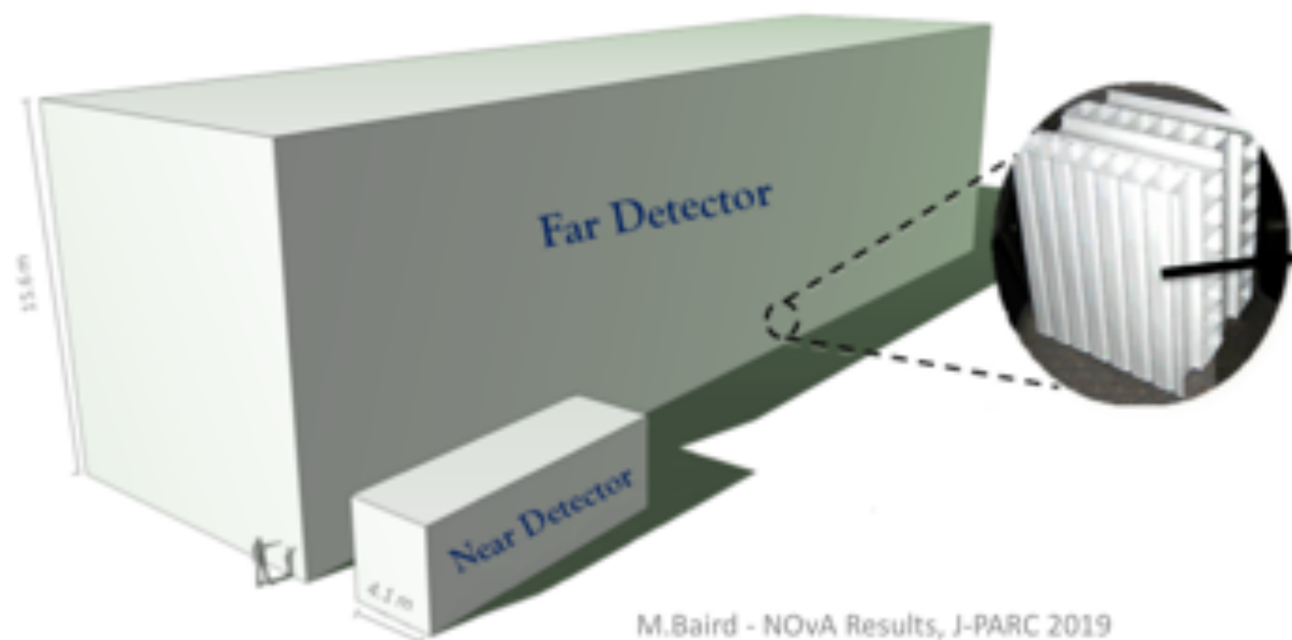
- data taken from Feb. 6, 2014 to Feb. 26, 2019
- recorded 8.85 x 10^{20} POT (14 kton equiv.) in FHC mode
- recorded 12.33 x 10^{20} POT in RHC mode (**adding ~80% more data over 2018 results**)

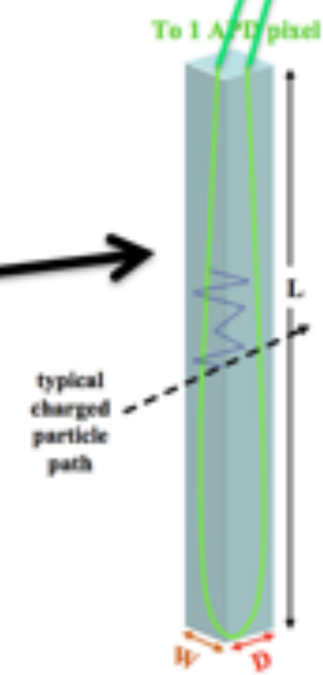
The NOvA Experiment: Detectors

Two functionally identical detectors:

extruded PVC, mineral oil as scintillator, avalanche photo-diodes for light collection

- **Near:** 300 ton, 1 km from source, 105 m underground
- **Far:** 14 kton, 810 km from source, on the surface





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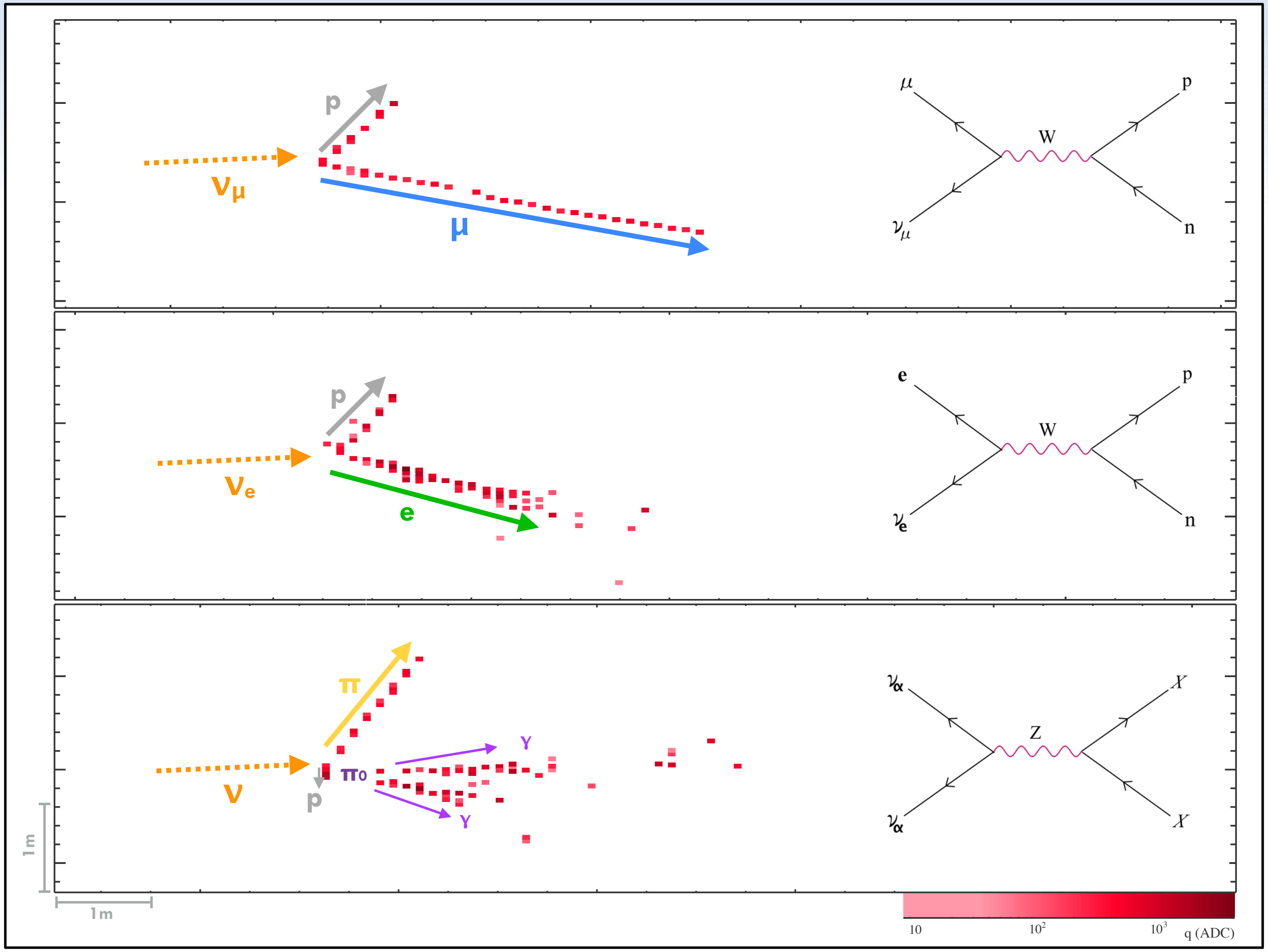
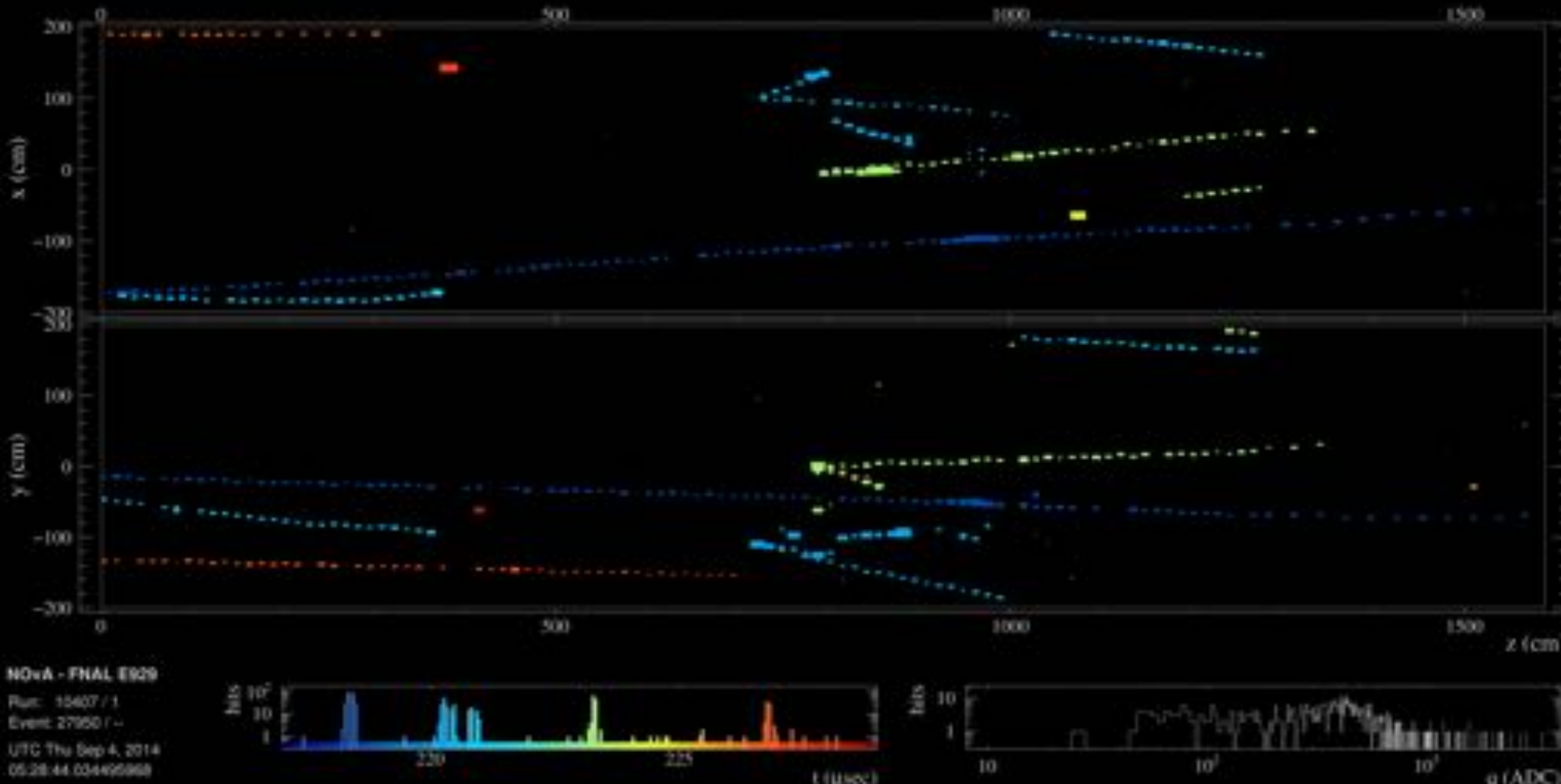


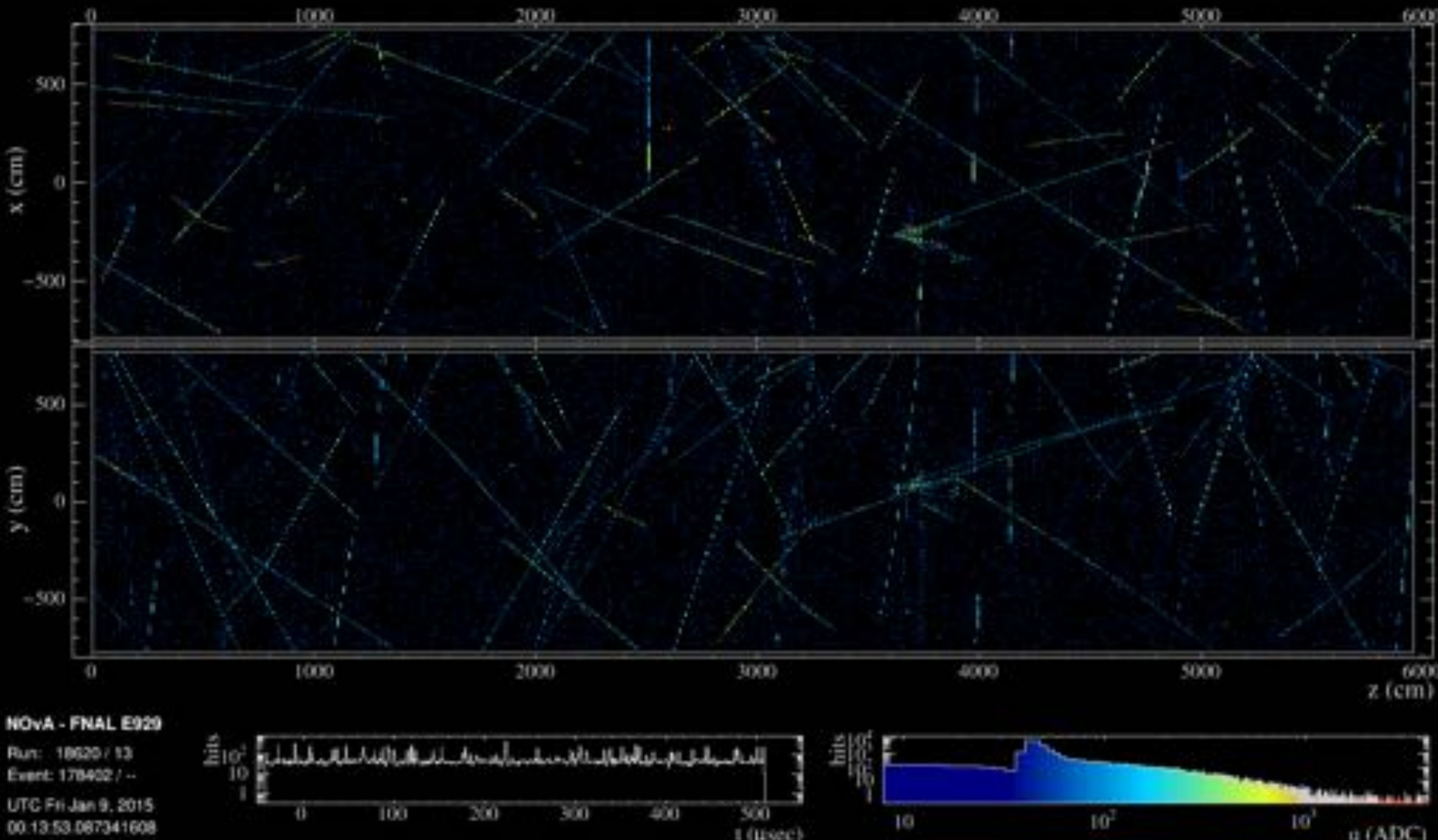
- NOvA is a highly active tracking calorimeter.

Near Detector Event Display



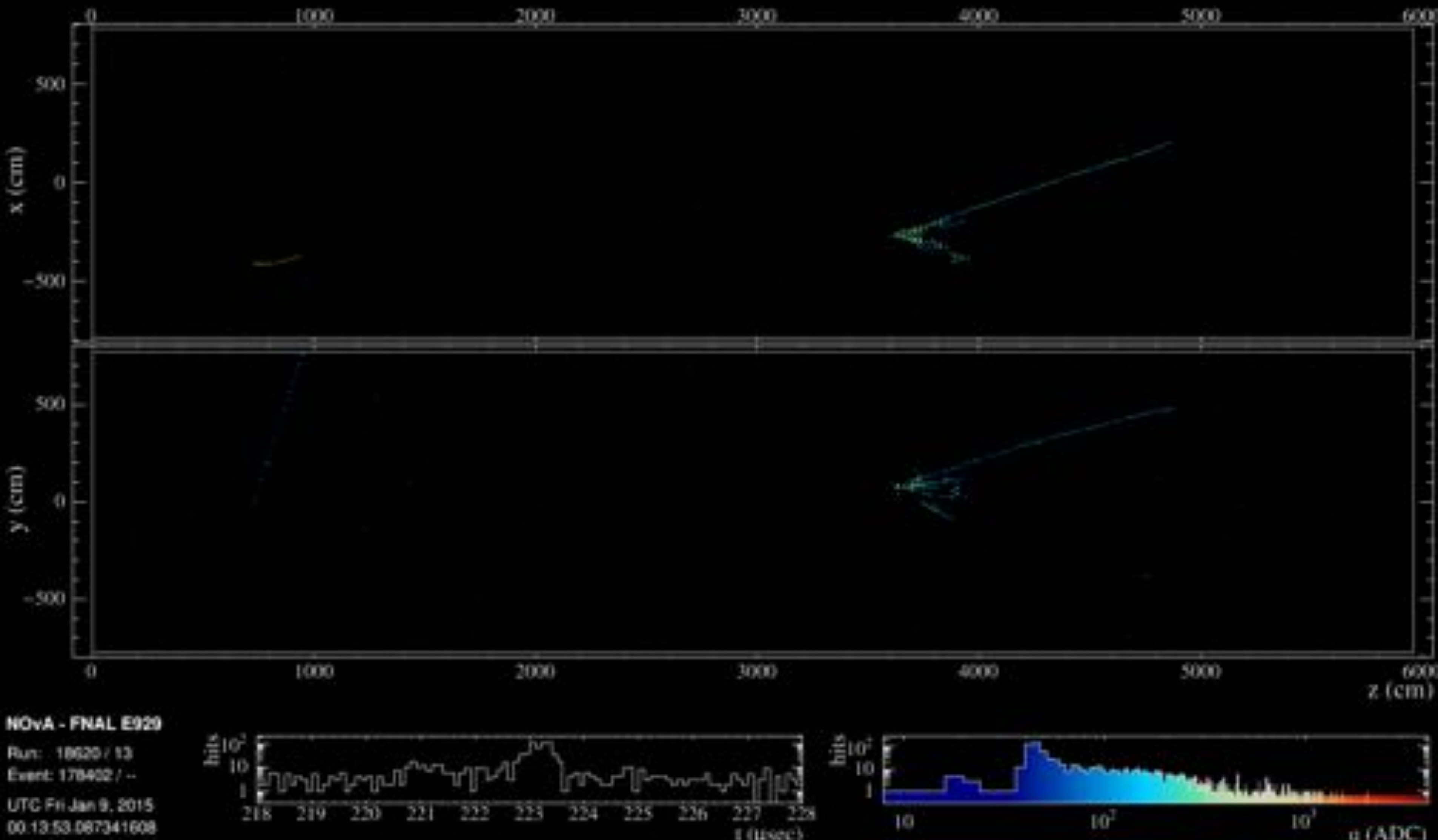
(colors show hit times)

Far Detector Event Display



(colors show charge)

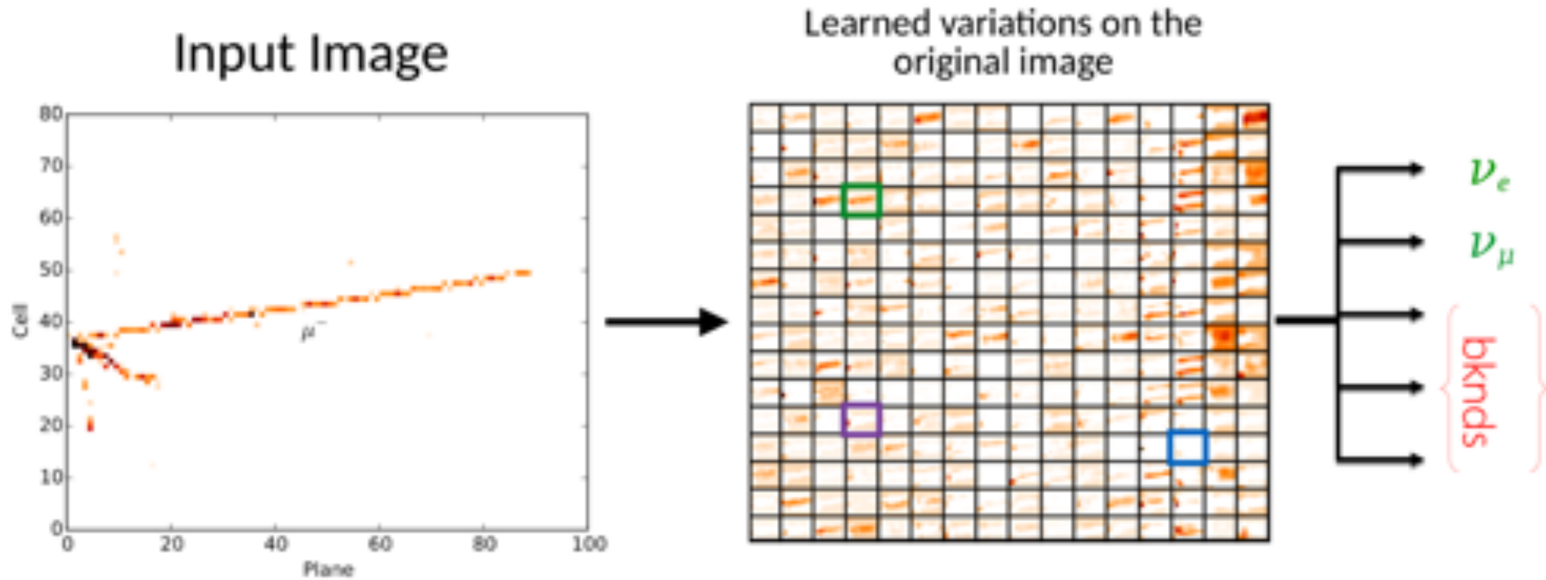
Far Detector Event Display



(colors show charge) zoomed in on beam window

Event Selection (in general):

- We classify events using a convolutional neural network called the Convolutional Visual Network (CVN).
- CVN extracts features from pixel maps and classifies them into 5 output categories.

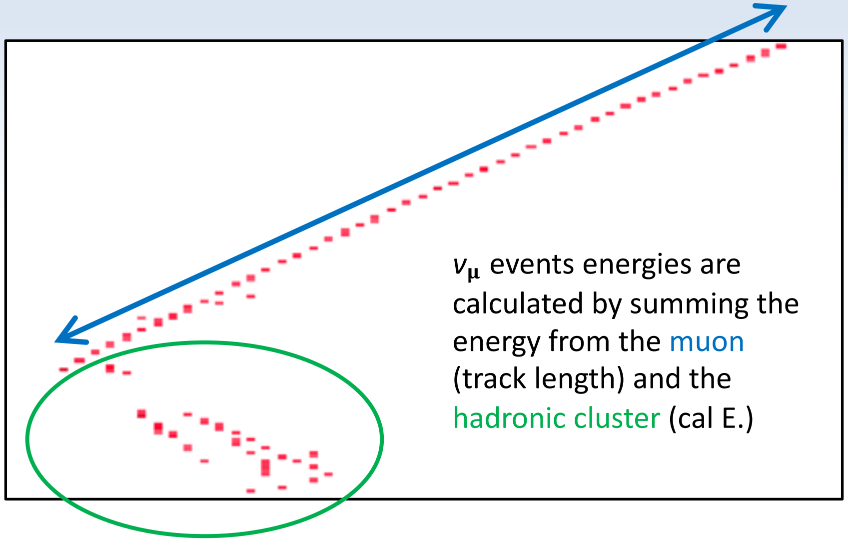


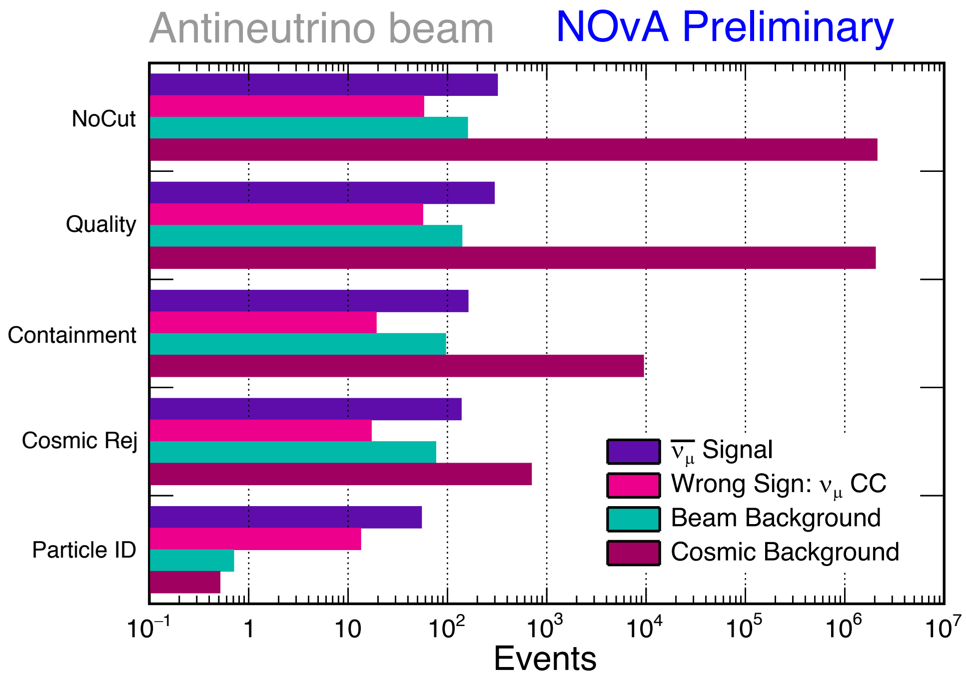
- Effective increase in exposure of 30% over traditional PIDs.
- NOvA was the first to use this technique in a particle physics analysis (JINST 11 P09001 (2016)).
- **See the next talk by Fernanda Psihas for more on NOνAs ML-based efforts!**

ν_μ Selected Event Samples:

- ν_μ candidate events are selected with CVN.

- An additional more "traditional" PID is used to select events with strong muon track candidates (for energy reconstruction.)



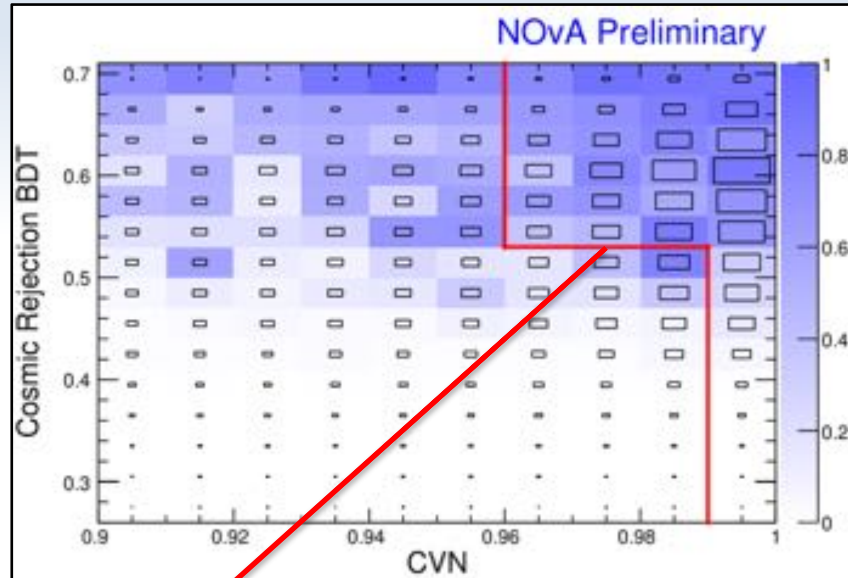


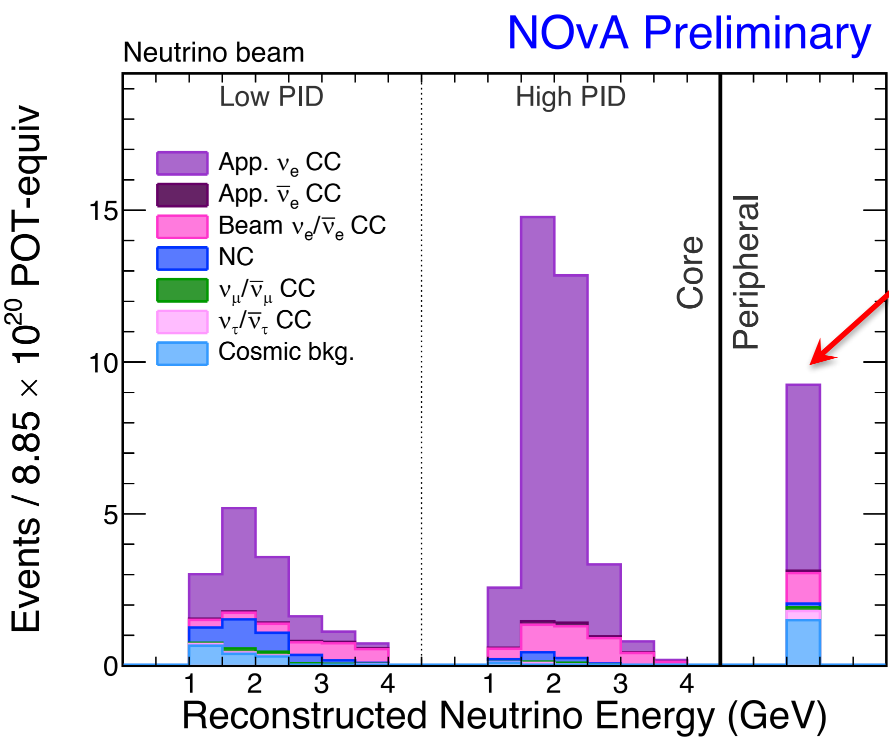
- Cosmic rays are rejected from the FD:
  - quality, containment, and timing cuts
  - event PIDs
  - a BDT trained specifically to reject cosmics, using kinematic info as input

- Cosmics are reduced by ~10^6 yielding Sig:Bak of ~50:1 !

ν_e Selected Event Samples:

- Events passing preselection are selected with CVN PID and separated into low, and high PID spectra.
- Separating spectra by PID helps maintain a high purity subsample of events.

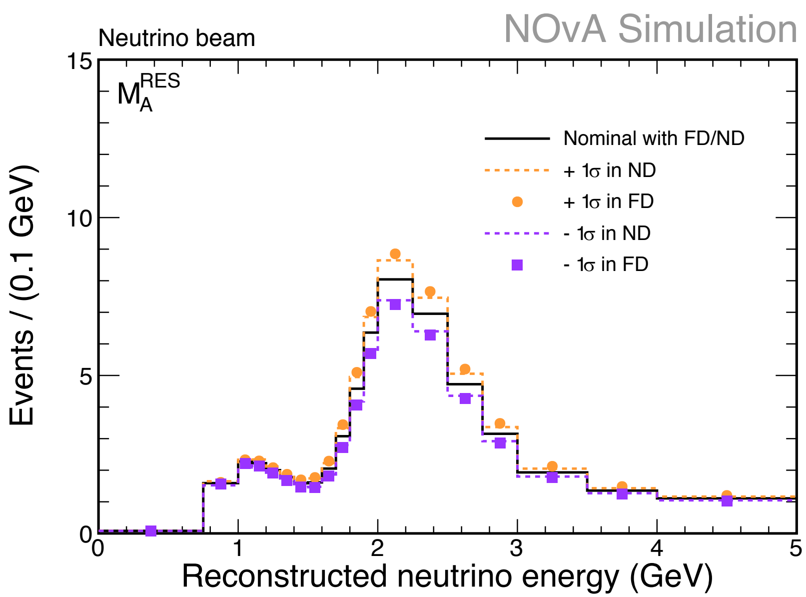


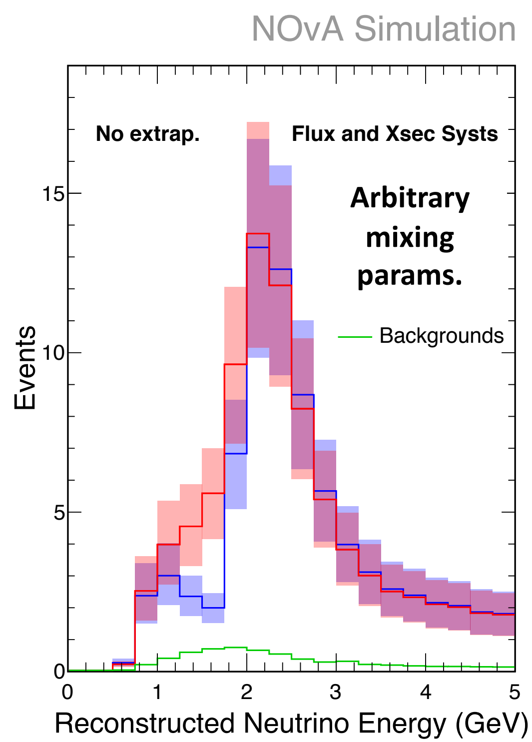


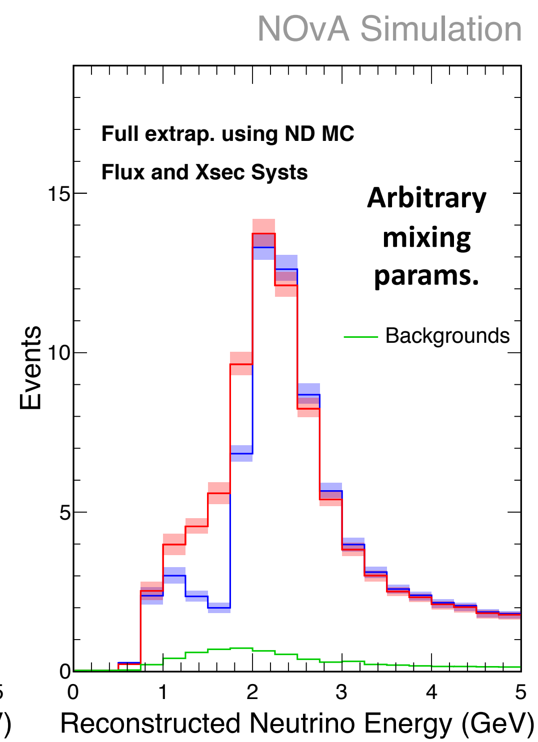
- Events failing preselection & PID that pass a tighter PID & cosmic rejection BDT cut go into "peripheral" sample.
- Using peripheral sample is equivalent to ~15% more exposure!

Far Detector Prediction:

- The near detector data is used to adjust the far detector prediction via an extrapolation procedure. Any shape/normalization differences between the ND data and MC will be translated to the FD.
- This helps reduce some of our major detector-correlated systematics such as flux and cross sections.

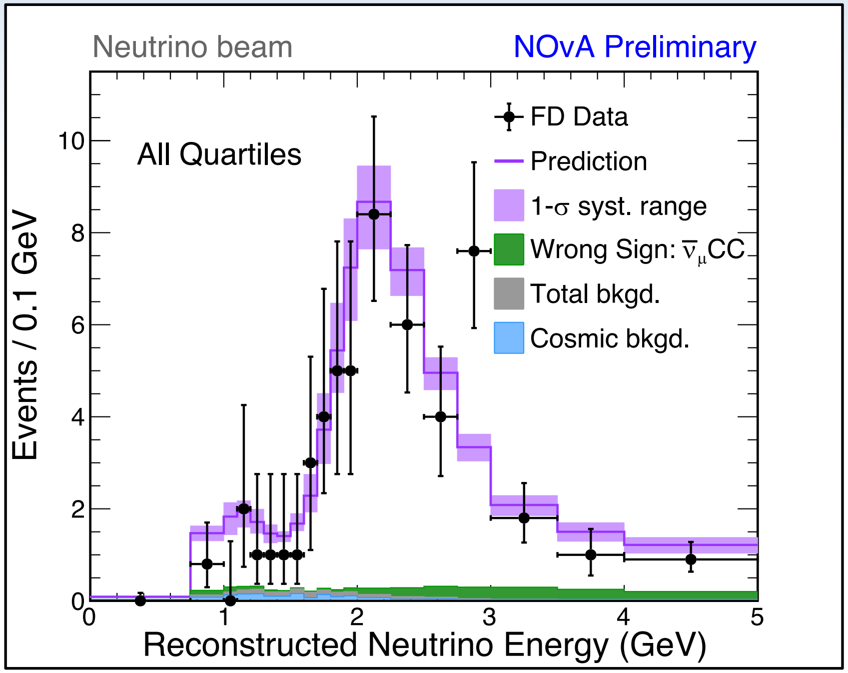


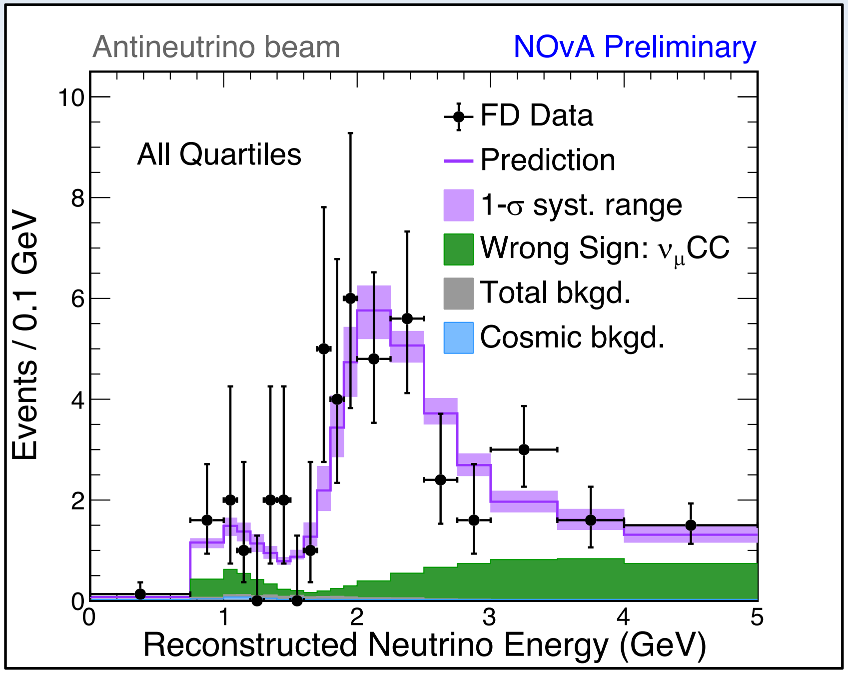




Results:

ν_μ Spectra & Numbers: arXiv:1906.04907 (to appear in PRL)





Data neutrino candidates	113
Best fit total prediction	**124**
total bkgd.:	4.2
↳ cosmic bkgd.	2.1
↳ beam bkgd.	2.1

Data antineutrino candidates	102
Best fit total prediction	**96**
total bkgd.:	2.2
↳ cosmic bkgd.	0.8
↳ beam bkgd.	1.4

ν_e Spectra & Numbers:

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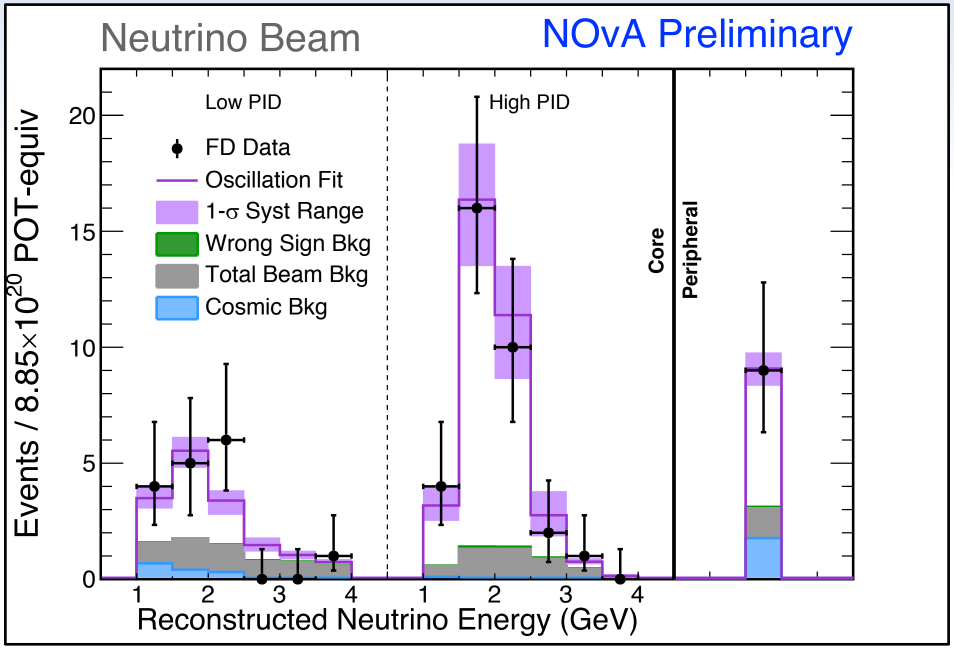
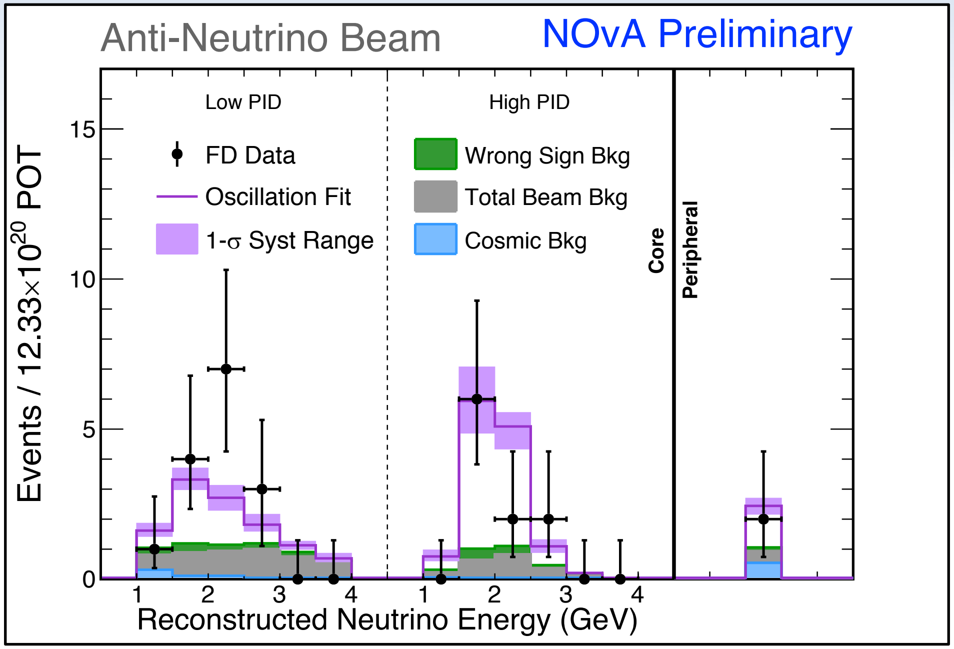


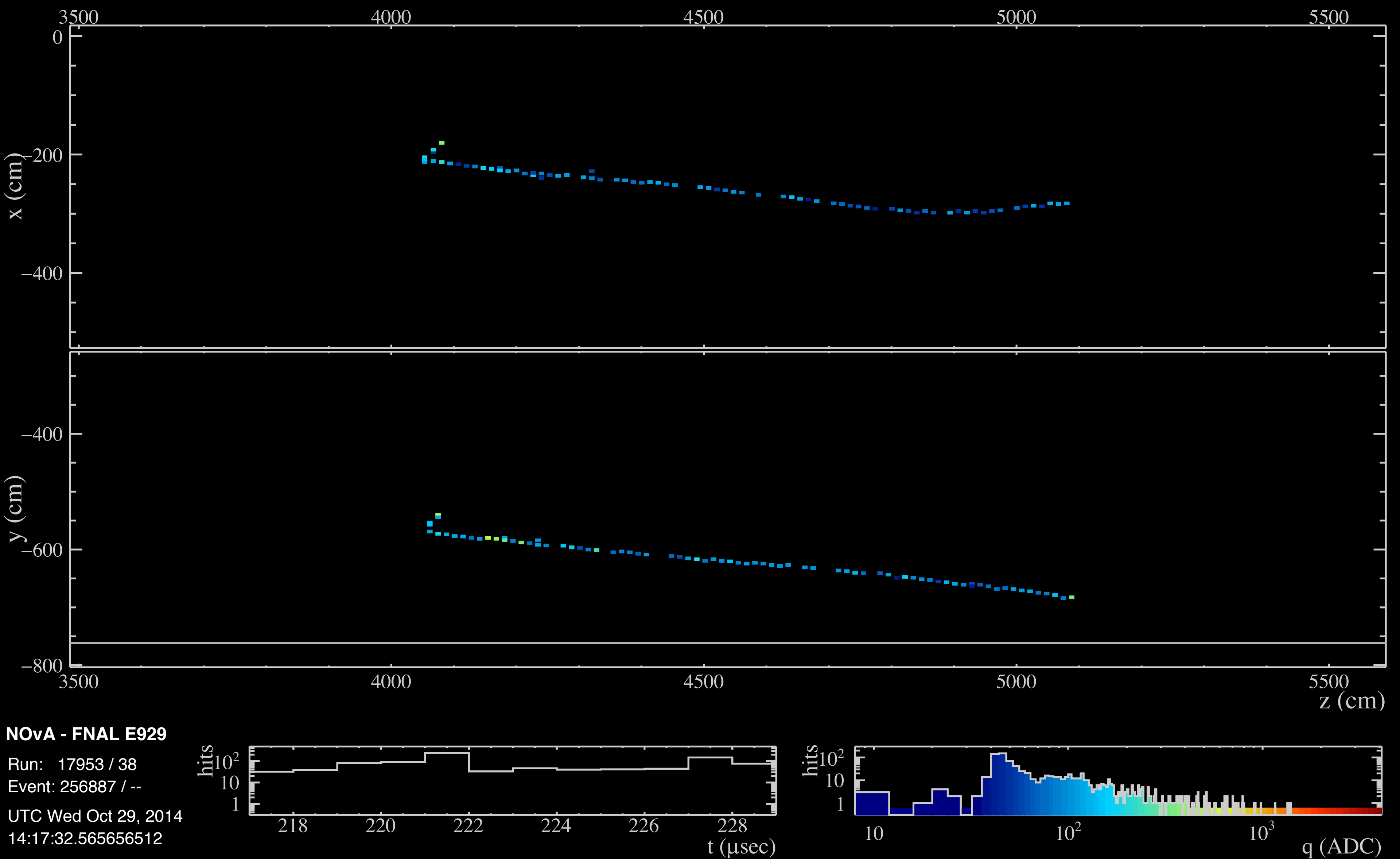


Data neutrino candidates	58
Best fit total prediction	**59**
total bkgd.:	15.0
↳ cosmic bkgd.	3.3
↳ beam bkgd.	11.1
↳ wrong-sign (app. $\bar{\nu}_e$)	0.7

Data antineutrino candidates	27
Best fit total prediction	**27**
total bkgd.:	10.3
↳ cosmic bkgd.	1.1
↳ beam bkgd.	7.0
↳ wrong-sign (app. ν_e)	2.2

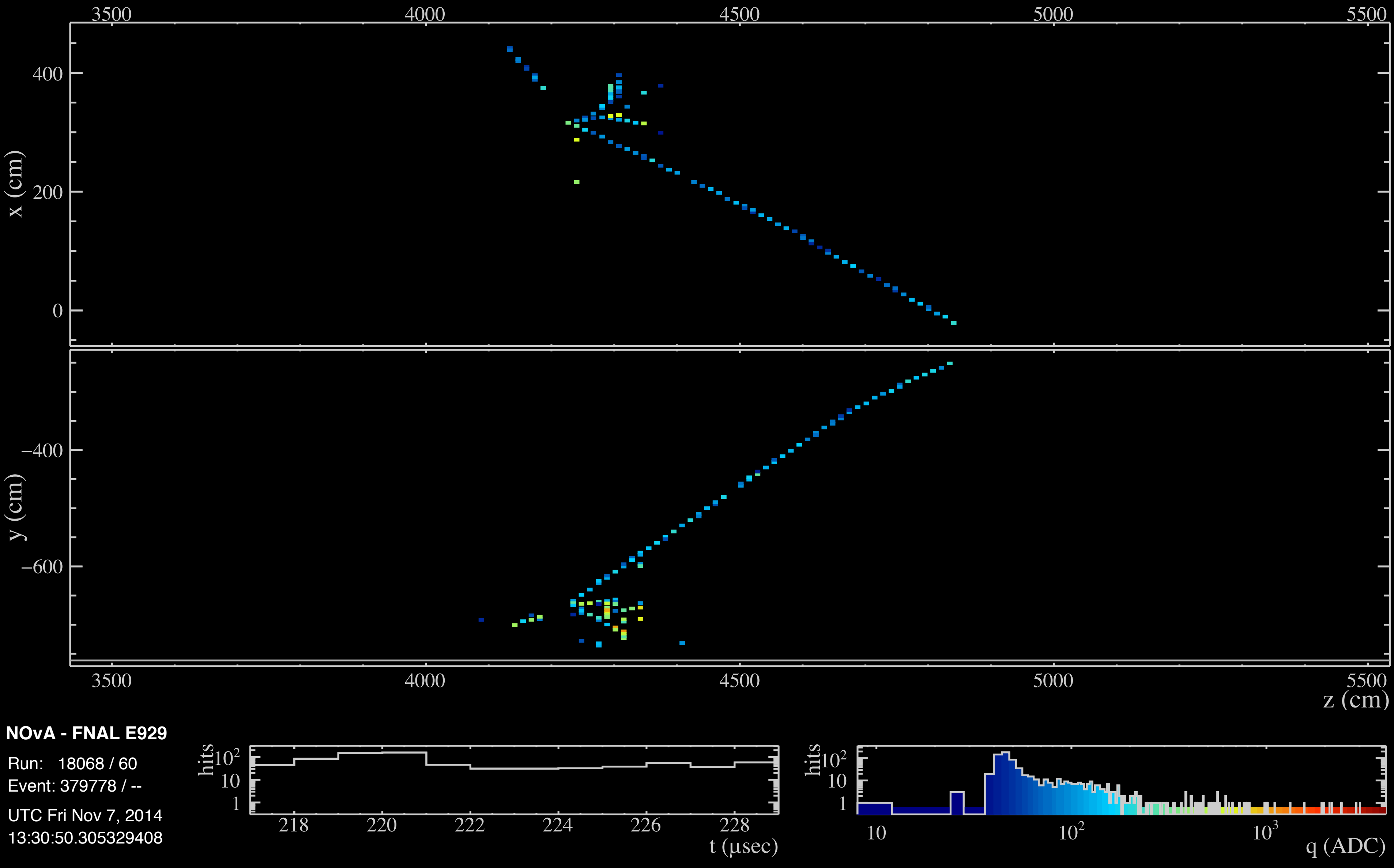
Strong (4.4 σ) evidence for $\bar{\nu}_e$ appearance!

Events!!!!



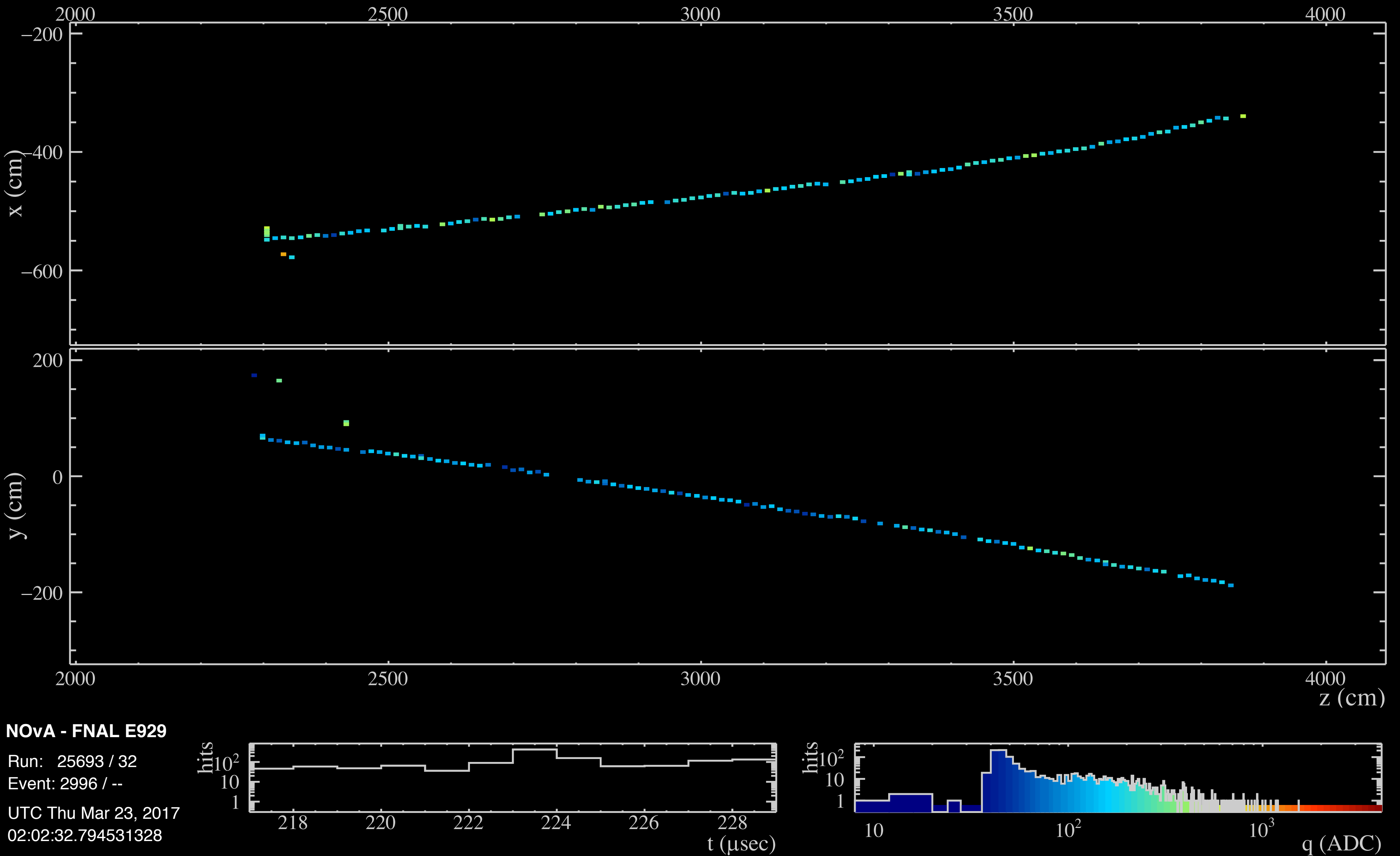
FHC ν_μ CC

Events!!!!



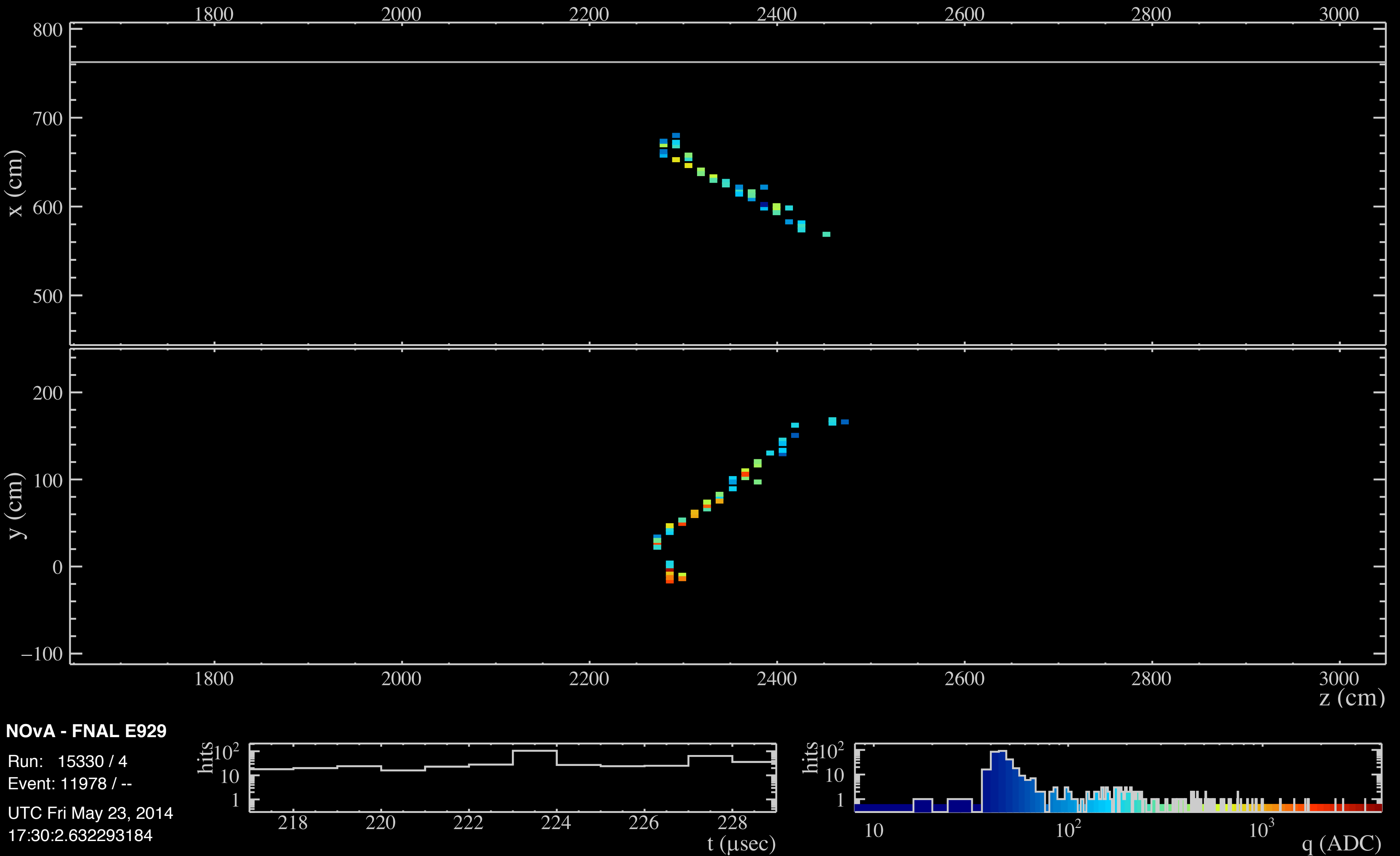
FHC ν_μ CC

Events!!!!



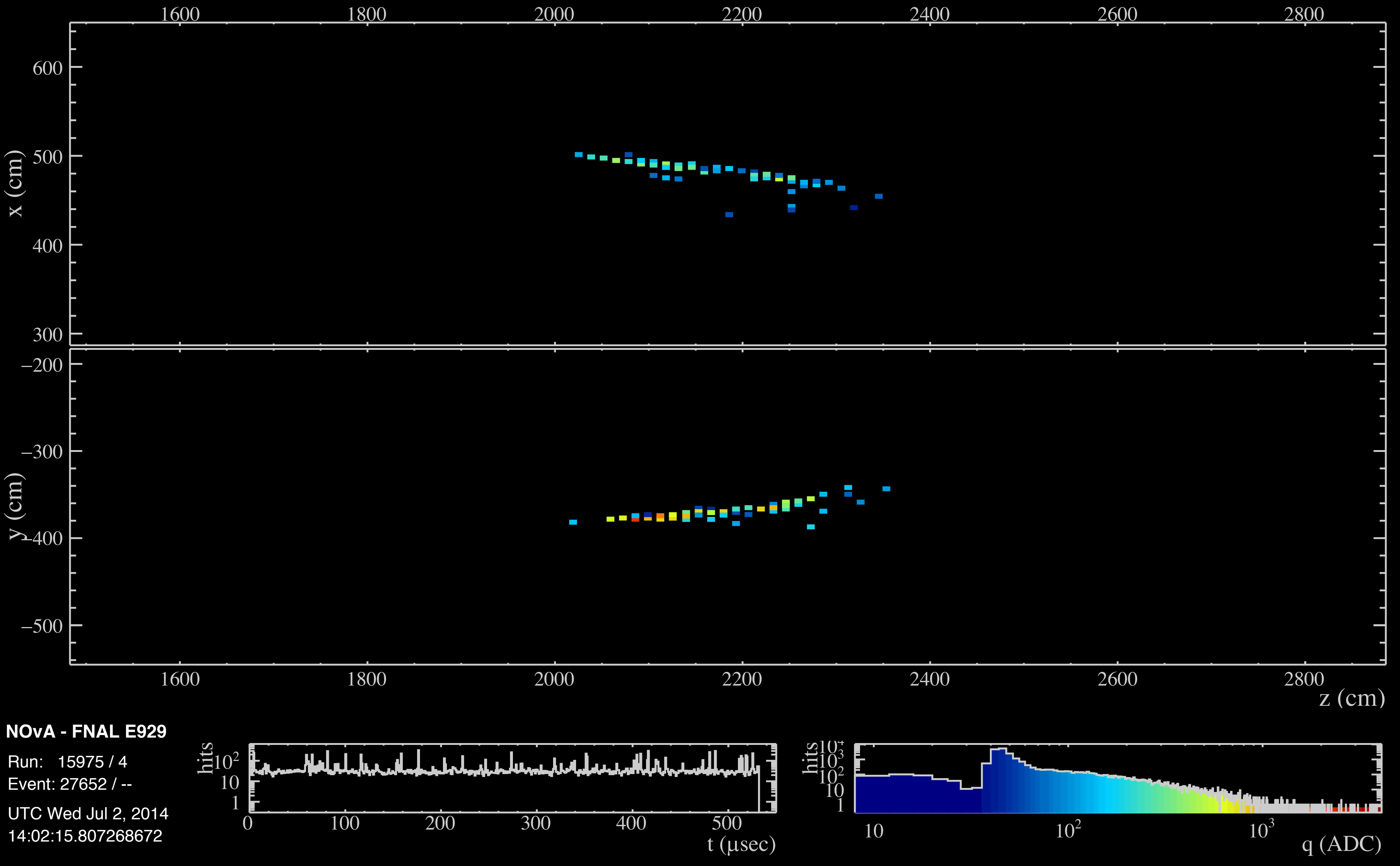
RHC ν_μ CC

Events!!!!



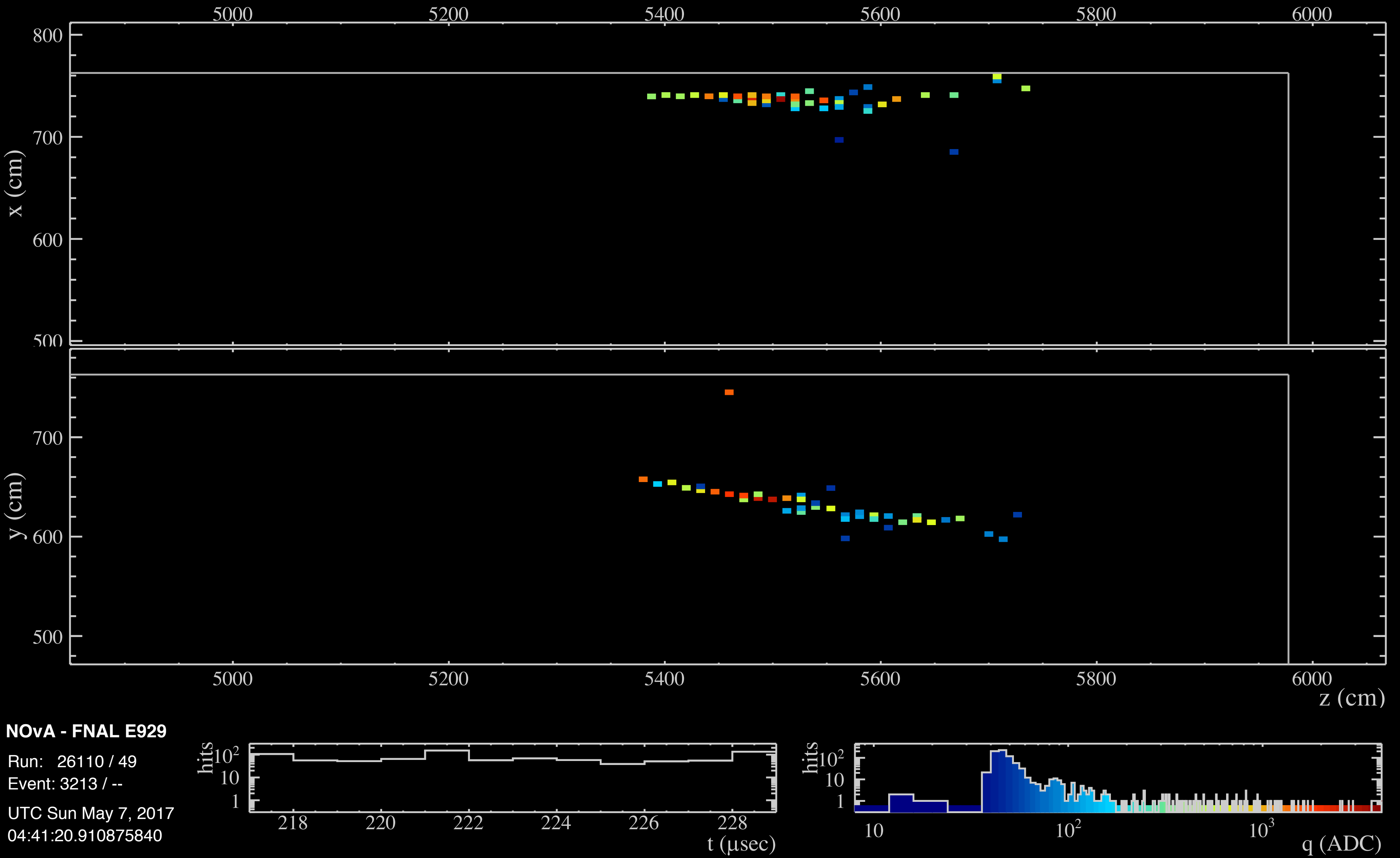
FHC ν_e CC

Events!!!!



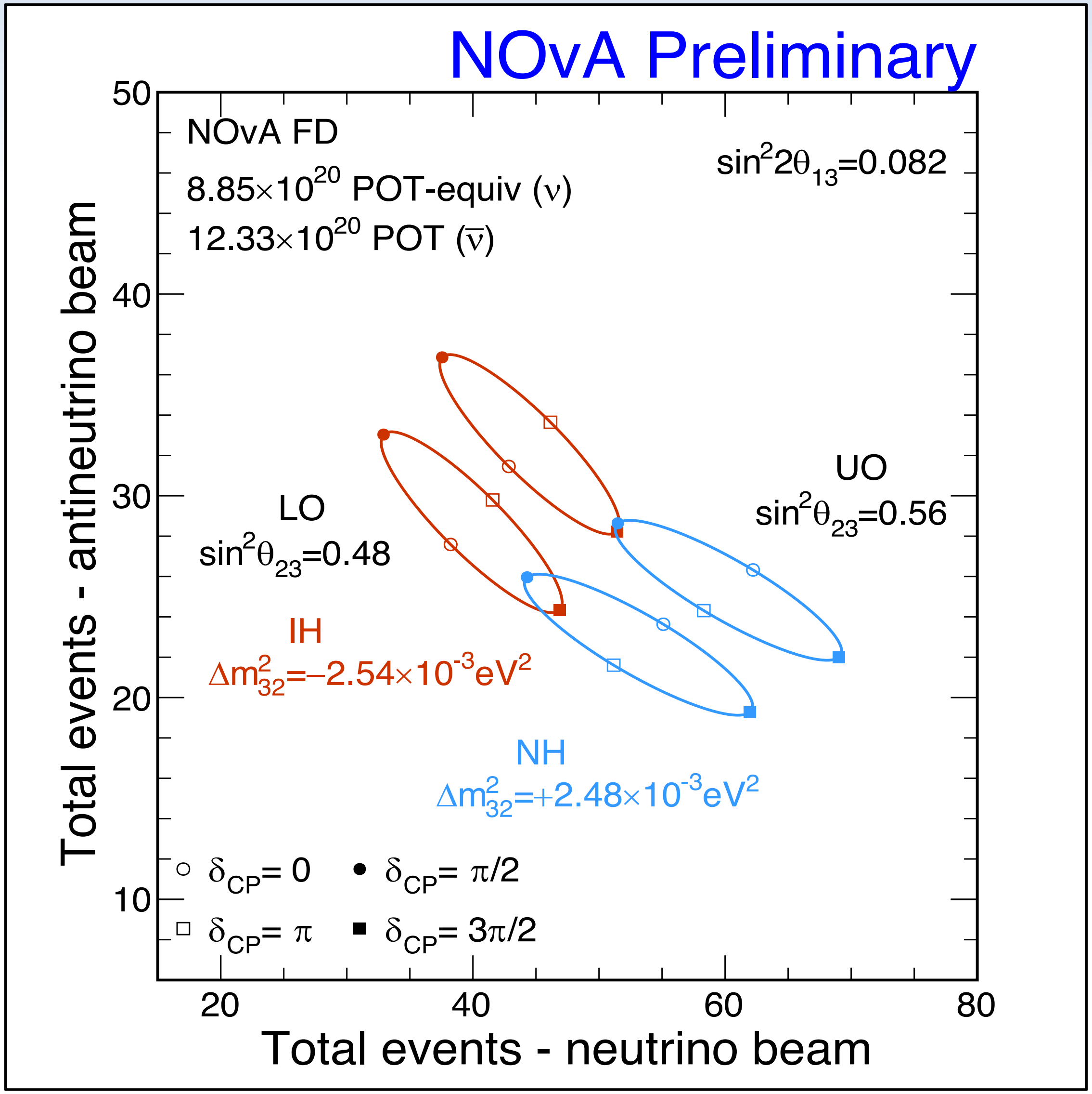
FHC ν_e CC

Events!!!!



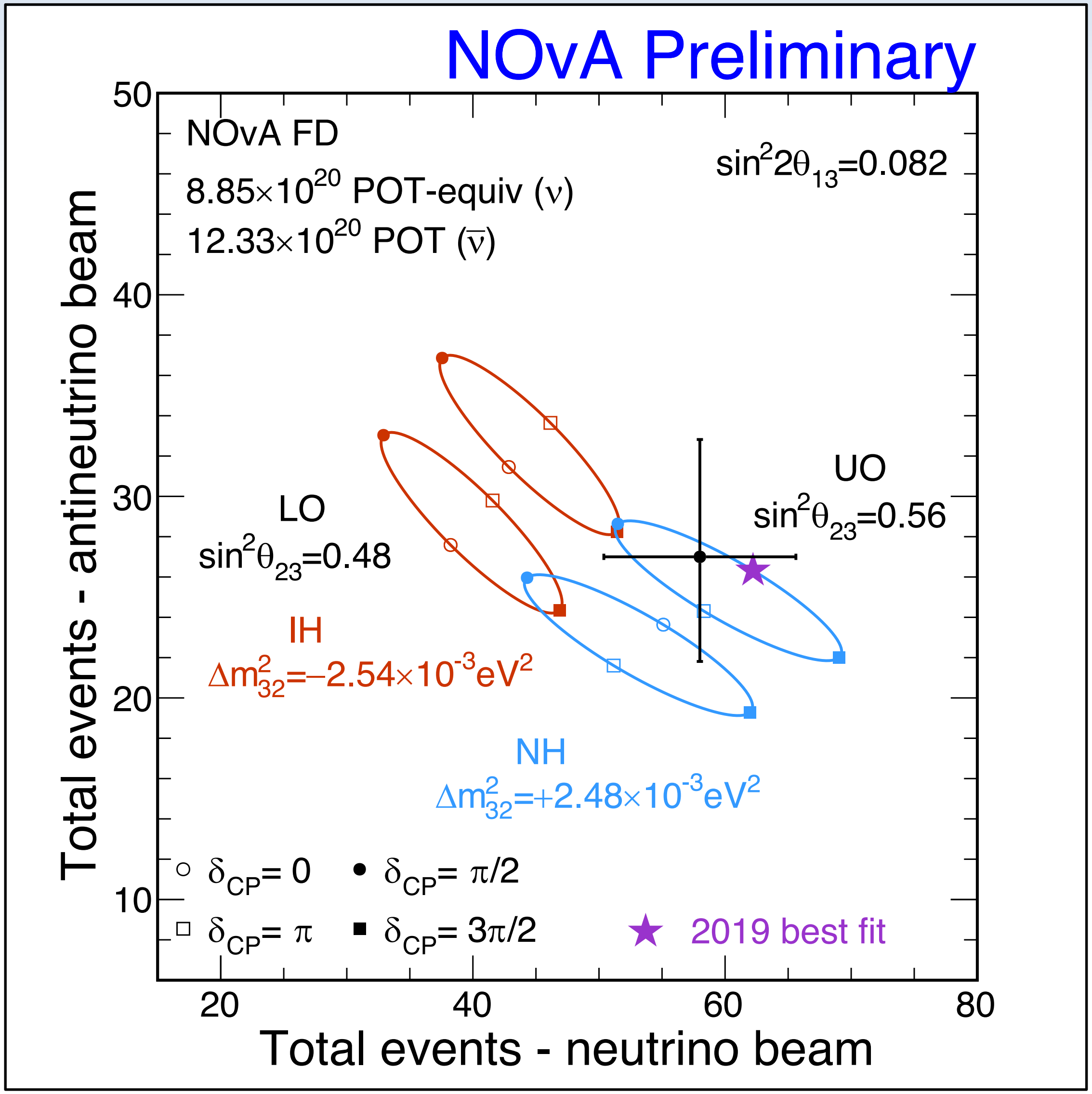
RHC ν_e CC

ν_e Spectra & Numbers:



ν_e Spectra & Numbers:

arXiv:1906.04907 (to appear in PRL)



Observed:

- 58 ν_e candidates
- 27 $\overline{\nu}_e$ candidates

Fit Results:

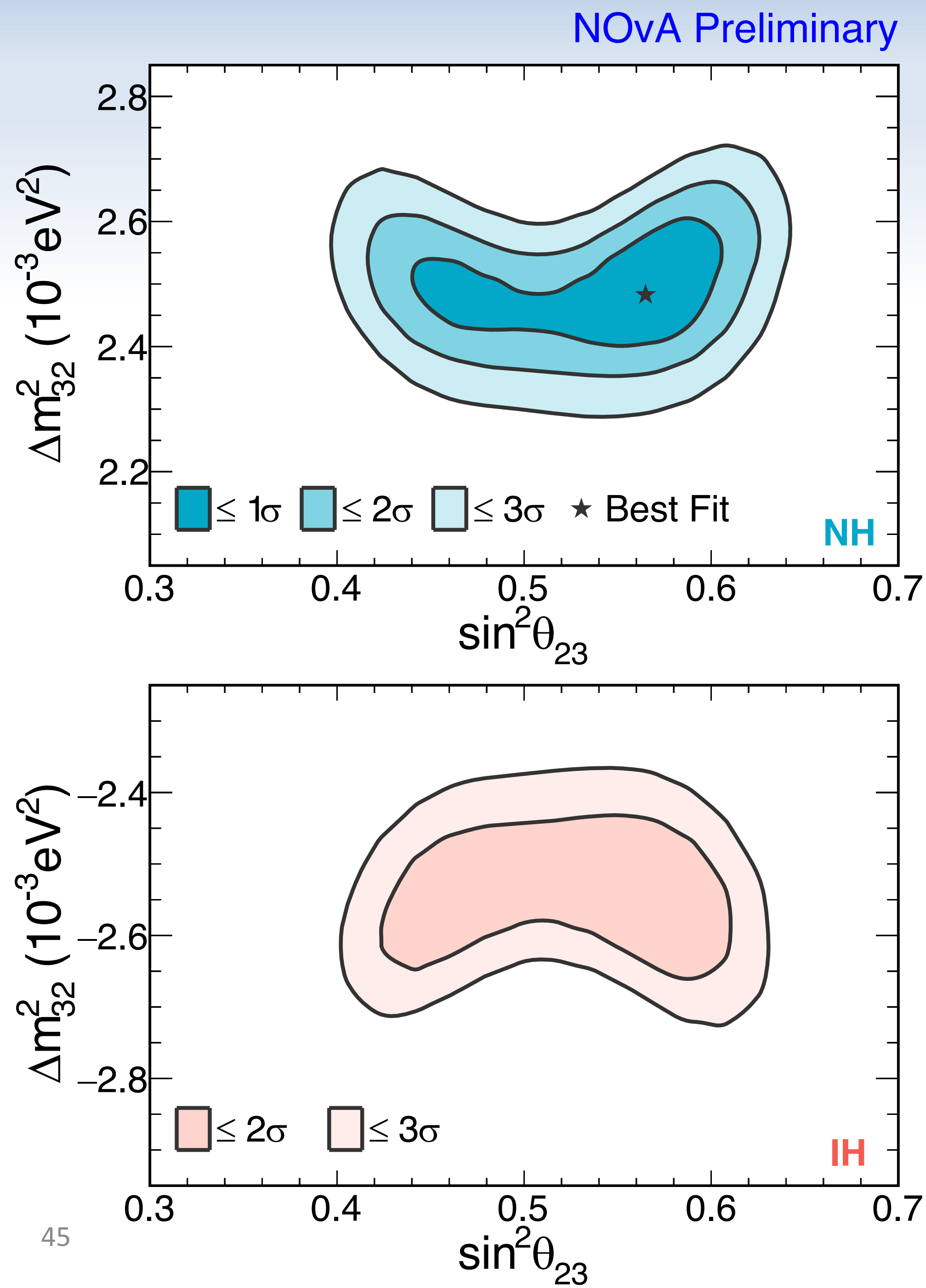
Best Fit:

Normal Hierarchy (1.9 σ)
Upper Octant (1.6 σ)

$\Delta m^2_{32} = 2.48^{+0.11}_{-0.06} \times 10^{-3}\ eV^2$
$\sin^2(\theta_{23}) = 0.56^{+0.04}_{-0.03}$ (48.4°)

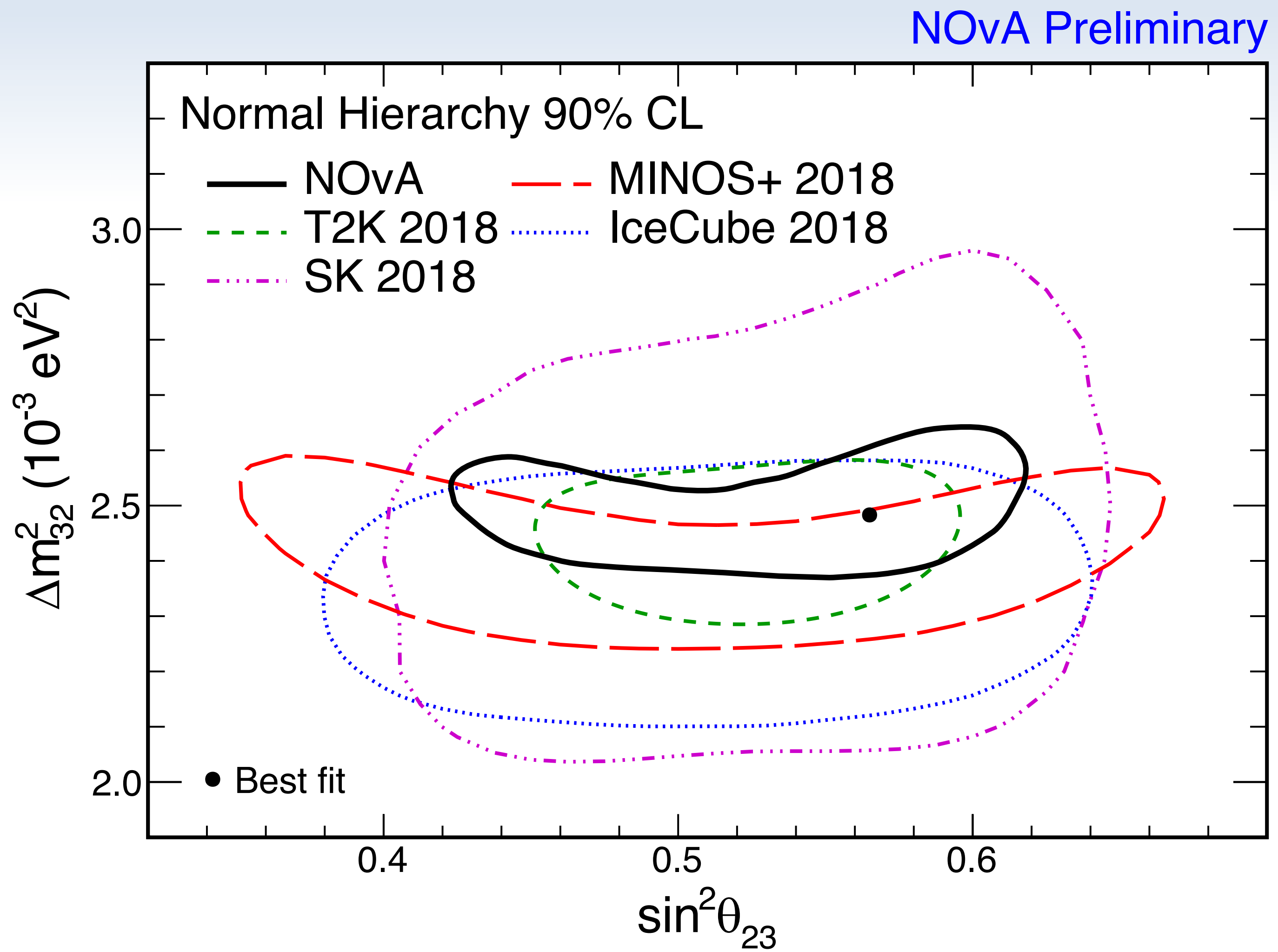
All contours shown have been corrected by the Feldman-Cousins Procedure.

arXiv:1906.04907 (to appear in PRL)



Fit Results:

arXiv:1906.04907 (to appear in PRL)



Our results are consistent with other long-baseline and atmospheric experiments.

Fit Results:

Best Fit:

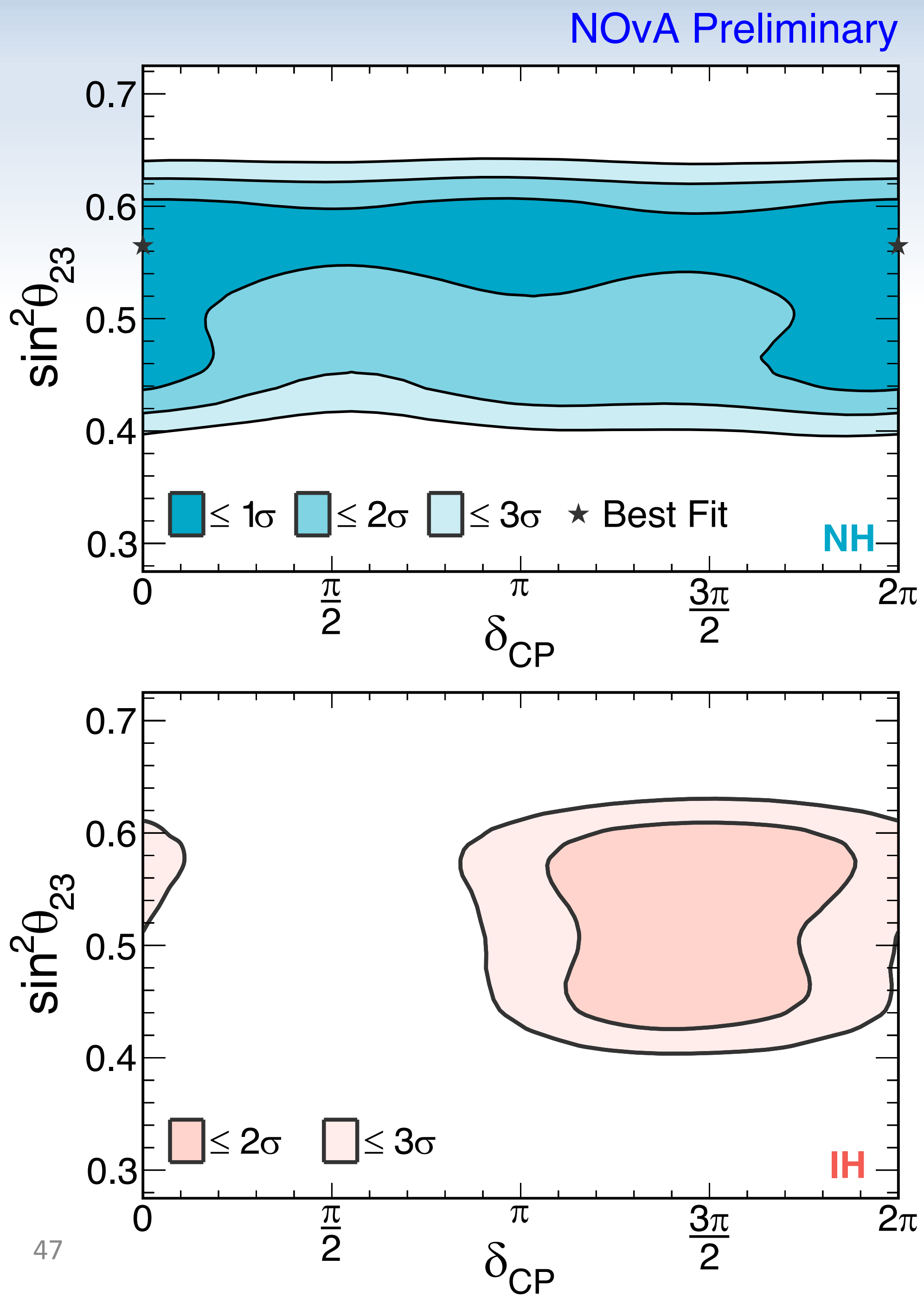
Normal Hierarchy (1.9 σ)
Upper Octant (1.6 σ)

$\Delta m^2_{32} = 2.48\ ^{+0.11}_{-0.06} \times 10^{-3}\ eV^2$
$\sin^2(\theta_{23}) = 0.56\ ^{+0.04}_{-0.03}$ (48.4°)

B.F. for $\delta_{CP} = 0/2\pi$

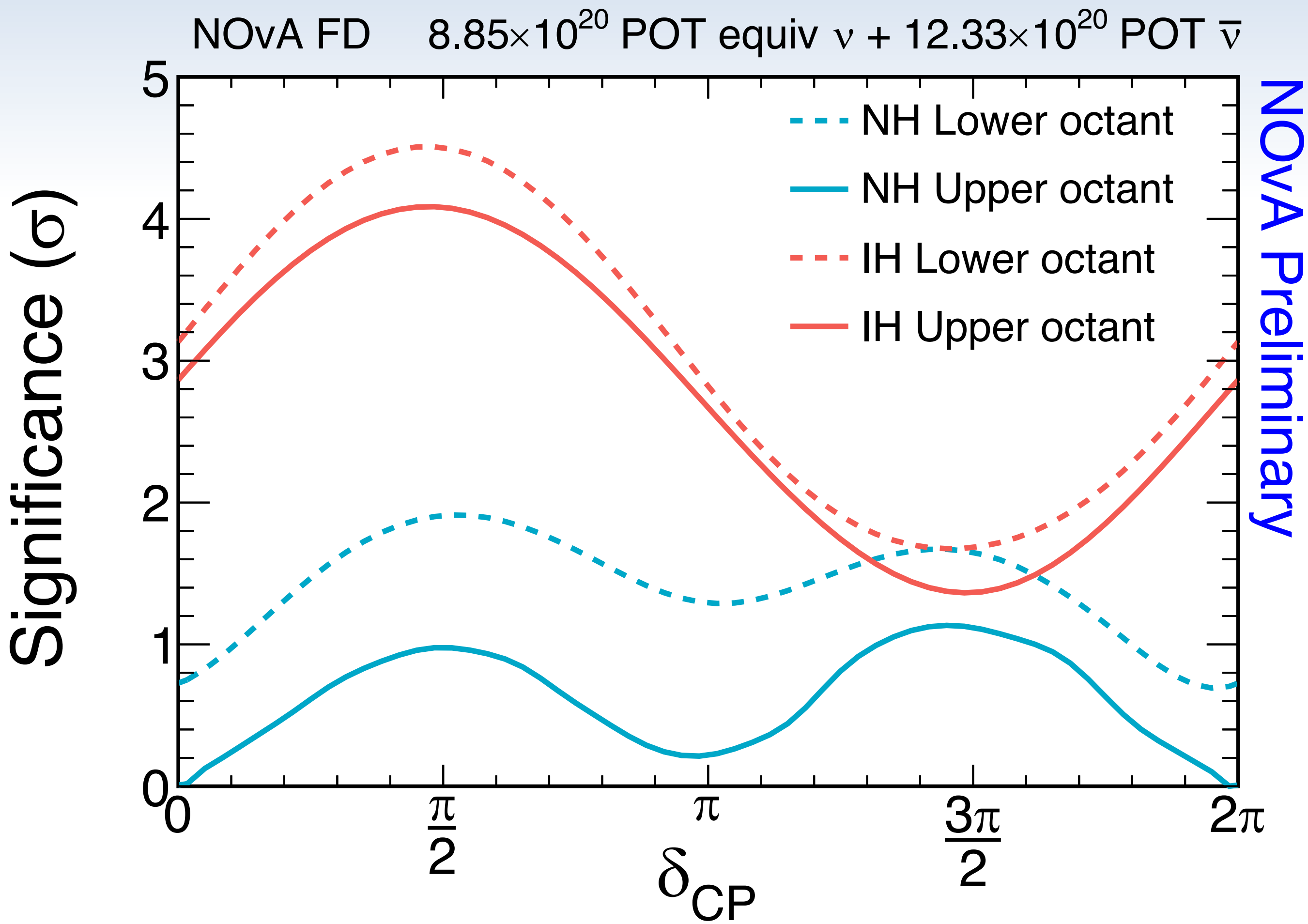
IH $\delta_{CP} = \pi/2$ is excluded at > 3 σ.

arXiv:1906.04907 (to appear in PRL)



Fit Results:

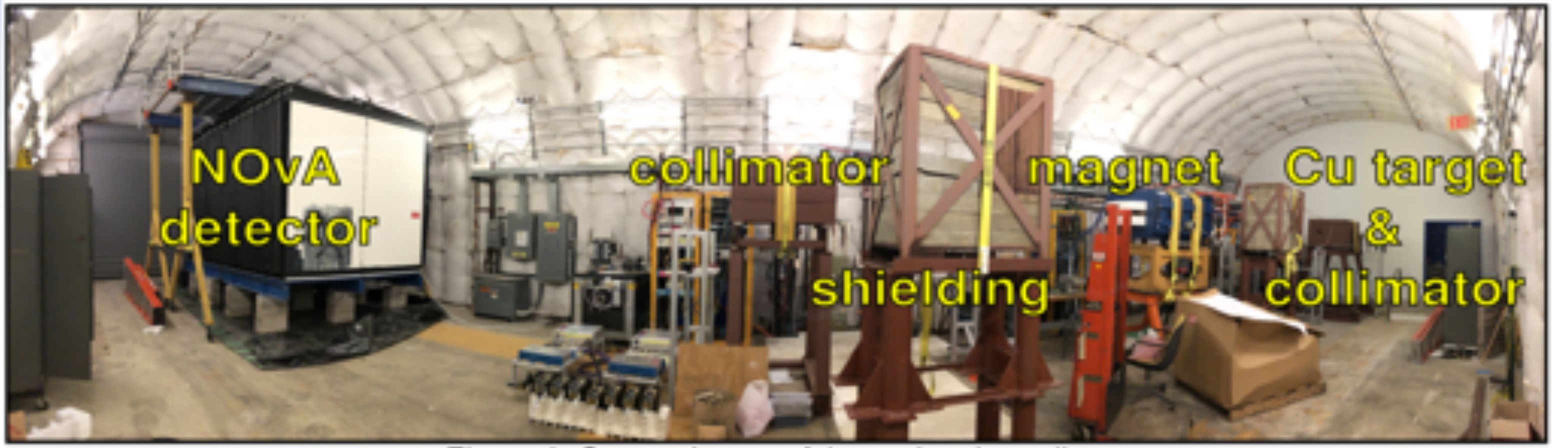
arXiv:1906.04907 (to appear in PRL)



But note: We are ~consistent with all values of **δ** in the NH LO.

What's Next for NOvA?

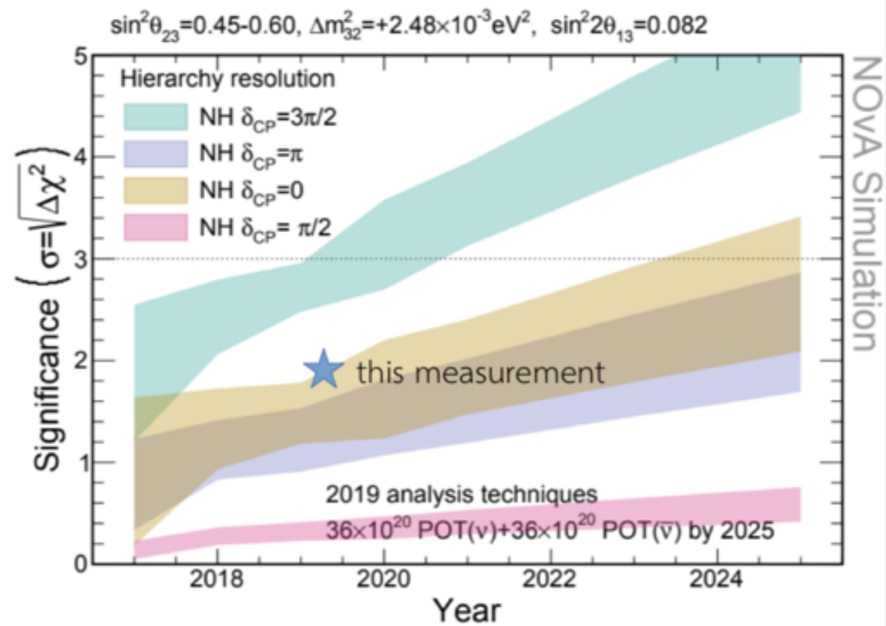
NOvA Test Beam Program:



- Placed in a tunable beam of **π**, p, **μ**.
- Designed to help us address energy-related and detector-response systematics.
- Data taking currently underway!

NOvA future reach:

- Possible 3-5 **σ** sensitivity to the hierarchy with favorable parameters.
- Possible > 2 **σ** sensitivity to CP violation.



Also currently working towards a future joint analysis with T2K!

Conclusions:

- NOvA had made an excellent measurement using < ½ of our expected final POT.

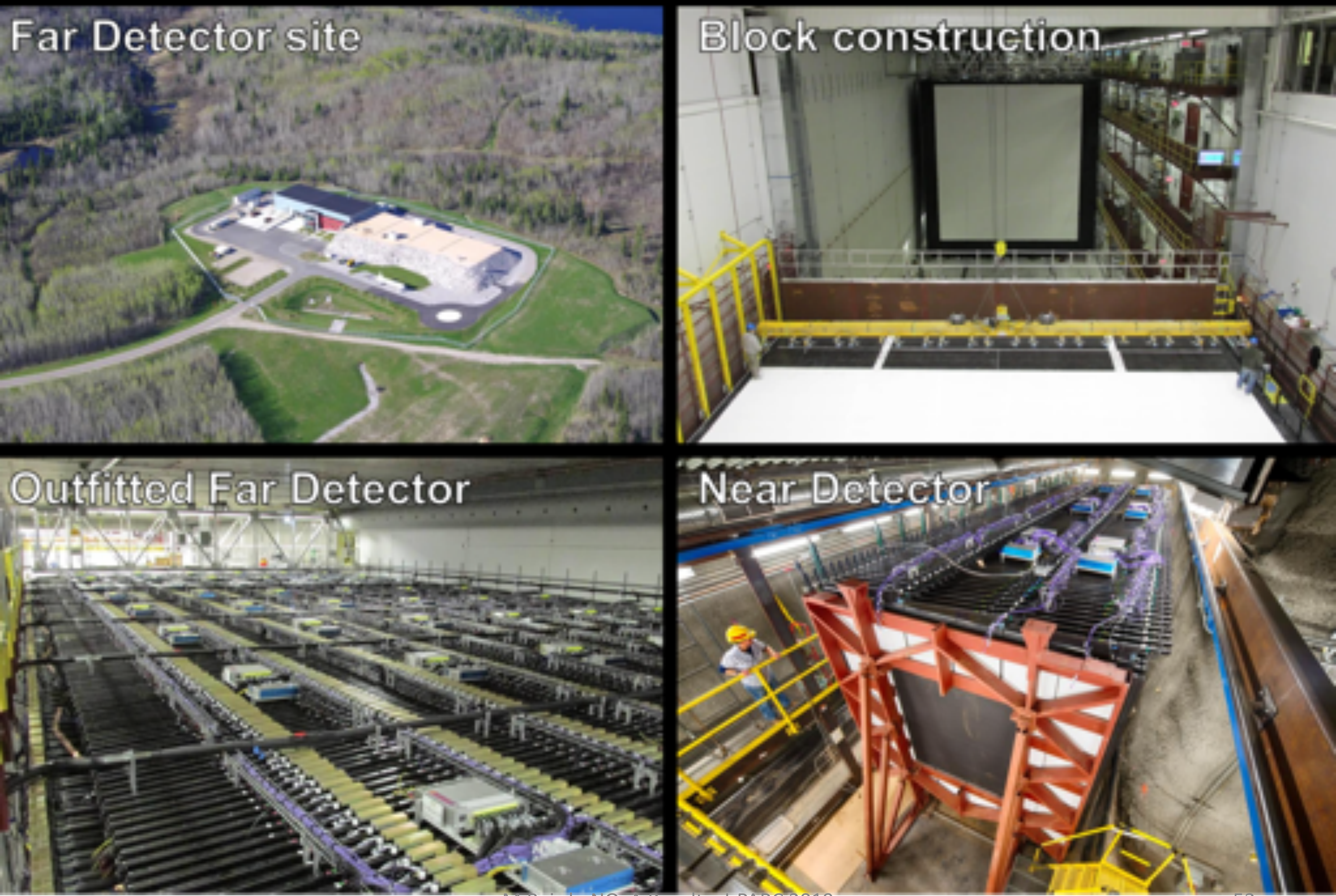
- We have seen strong evidence (4.4 σ) for $\bar{\nu}_e$ appearance at long baseline.

- Our joint analysis combining ν_μ / $\bar{\nu}_\mu$ disappearance and ν_e / $\bar{\nu}_e$ appearance prefers:
  - The NH at 1.9 σ and excludes IH, δ = π/2 at > 3 σ.
  - Non-maximal mixing in the upper octant at 1.6 σ.

- Looking forward to test beam data and a new analysis with new simulation and improved algorithms next summer!

Domo Arigato!

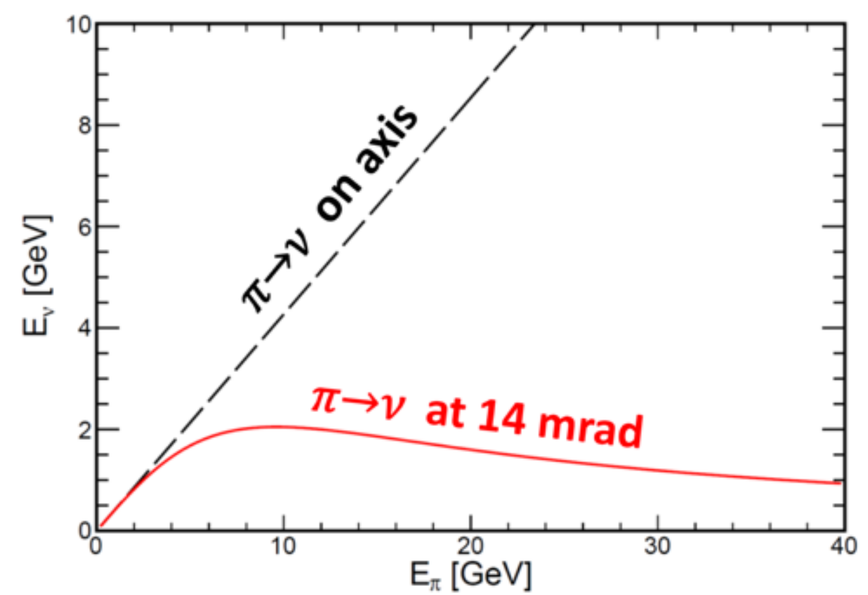
Backups:

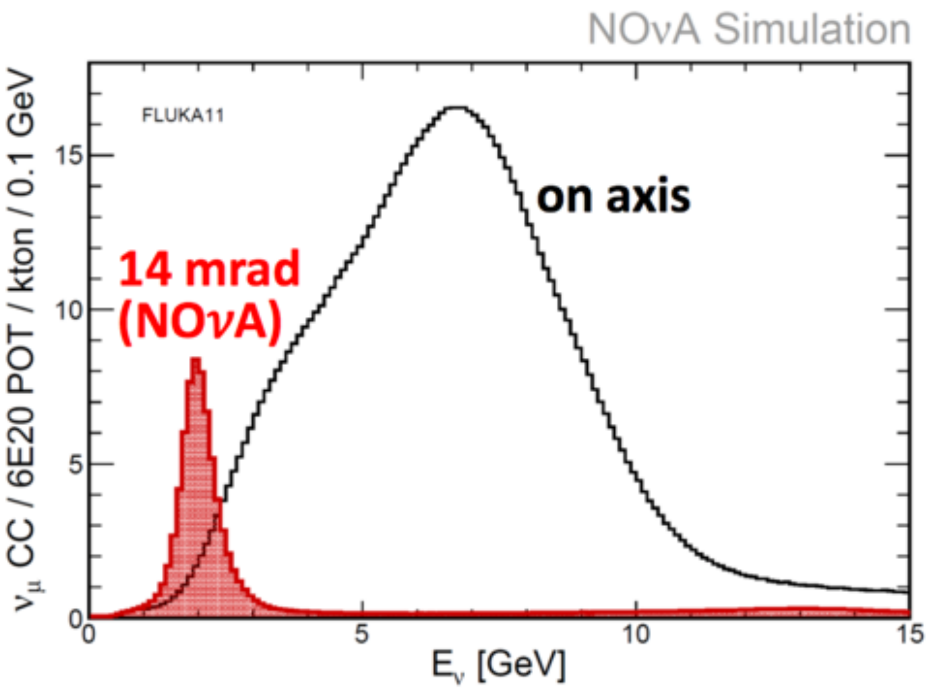

Far Detector site
Block construction
Outfitted Far Detector
Near Detector

The NOvA Experiment: NuMI Beam

The NOvA experiment is 14 mrad off-axis:

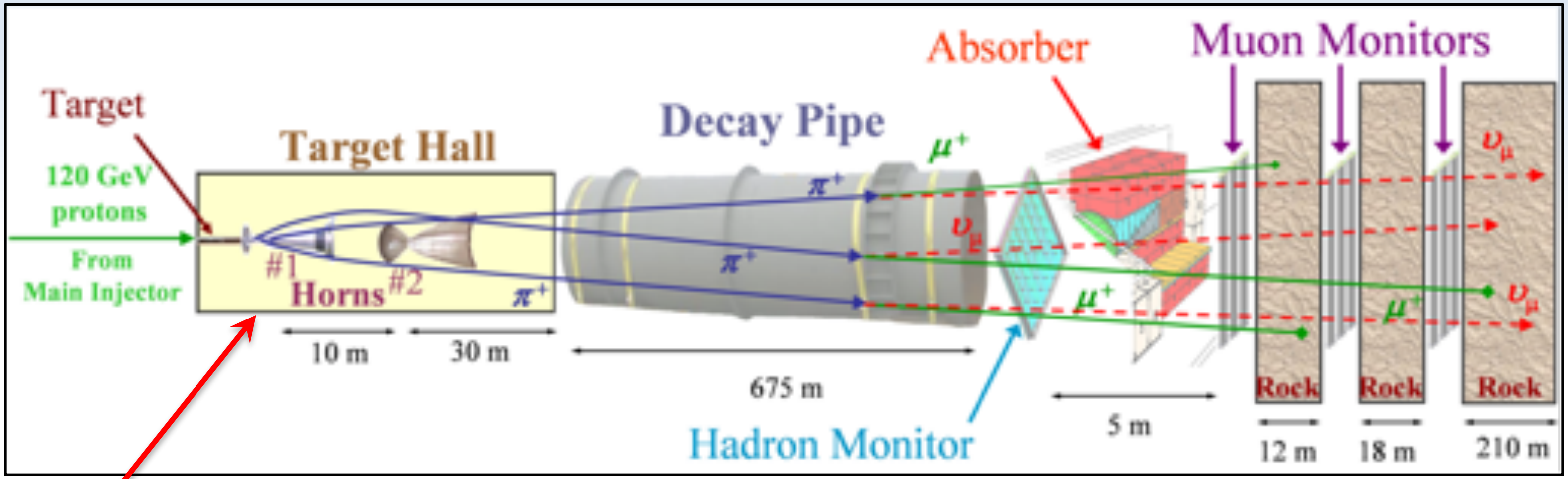
- gives us a narrowly peaked *ν* energy spectrum at 2 GeV
- 2 GeV = oscillation max for 810 km
- helps reduce NC backgrounds





$$E_\nu = \frac{0.43 E_\pi}{1+\gamma^2\theta^2}$$

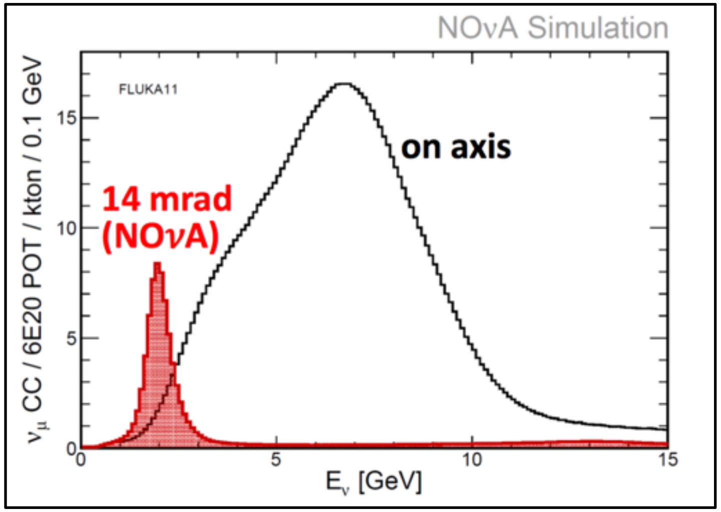
The NOvA Experiment: NuMI Beam



The horns can run in forward current (FHC) or reverse current (RHC) modes to create a neutrino or anti-neutrino beam respectively.

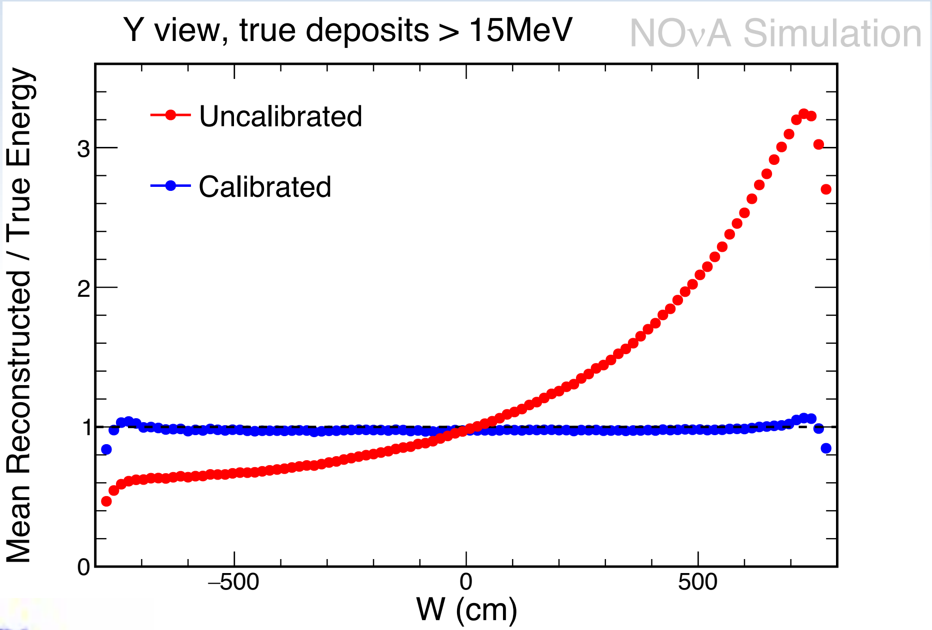
The NOvA experiment is 14 mrad off-axis:

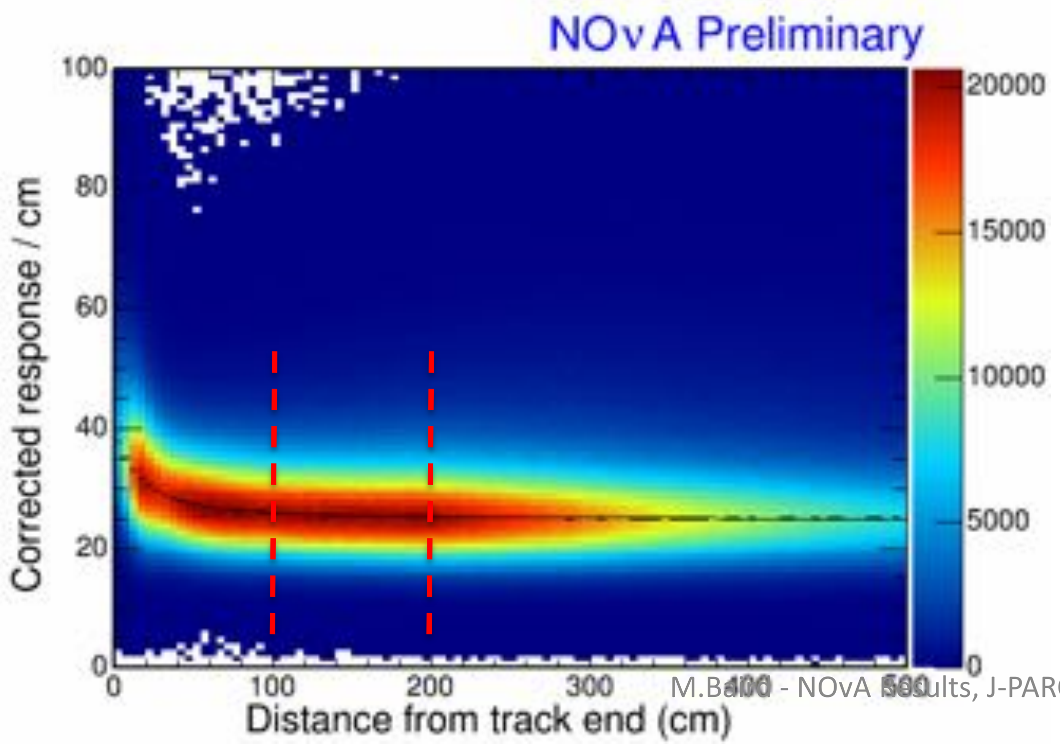
- gives us a narrowly peaked *ν* energy spectrum at 2 GeV
- 2 GeV = oscillation max for 810 km
- helps reduce NC backgrounds



Calibration:

- Compute the attenuation curve for each fiber individually using through-going cosmic muons.
- This puts all fibers and cells on an equal footing.





- Compute the absolute energy scale for the whole detector using stopping cosmic muons.
- Look for “good” hits in the MIP region of the track.

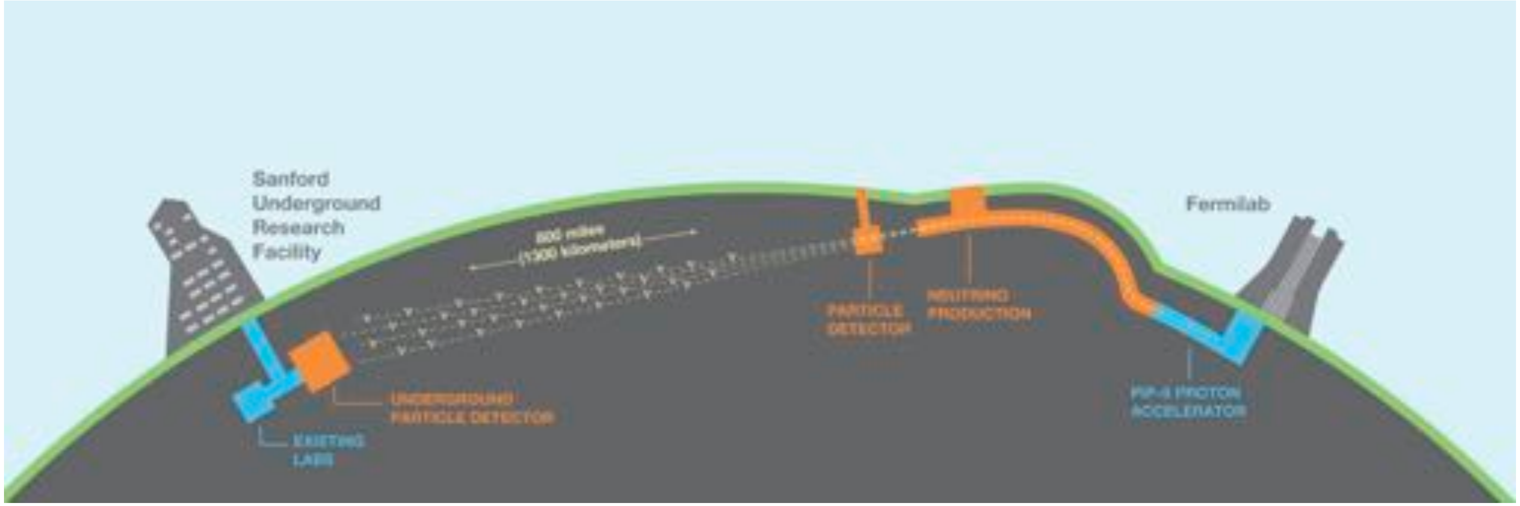
Aspects of a Long-Baseline Neutrino Expt.

General Features and Challenges:

- Main goals include measuring neutrino oscillations and constraining elements of the PMNS mixing matrix. Requires identifying neutrino flavors and estimating their energies.

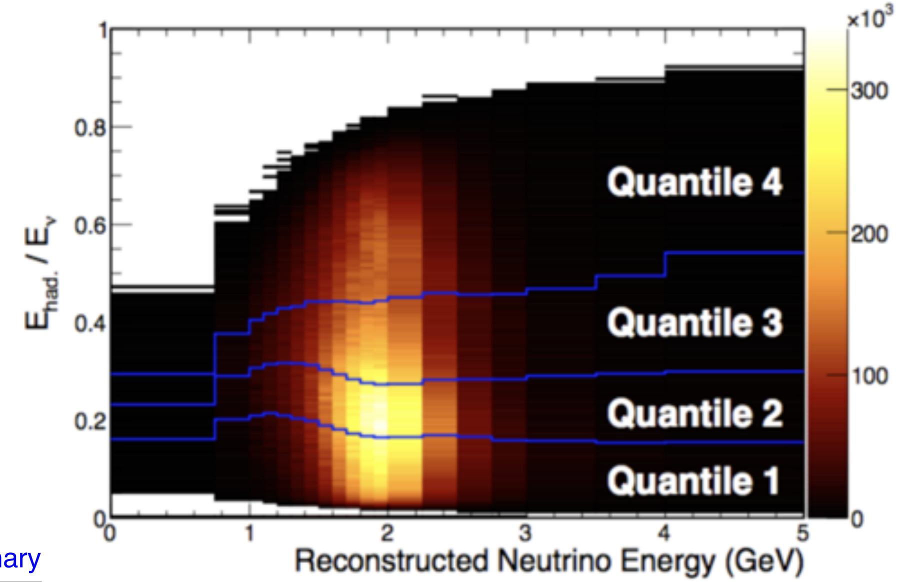
- Typical designs include two detectors (near and far.) The near detector measures the unoscillated beam; and the far, the oscillated beam. Having a near detector helps constrain beam flux, cross section systematics etc.

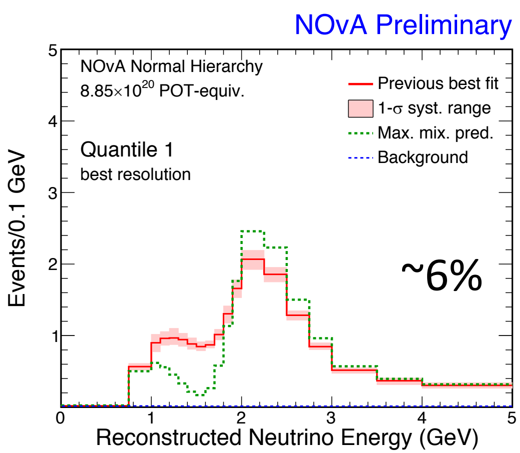
- Beam energies require both detectors to be $O(10^2 - 10^3)$ km apart. Dramatically reduces the far detector flux, but allows for interesting physics measurements via the matter effect.

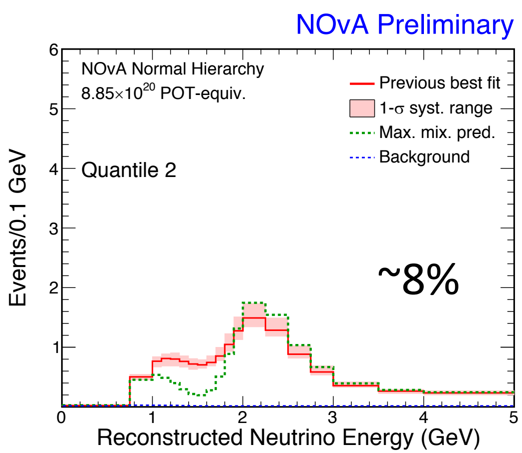


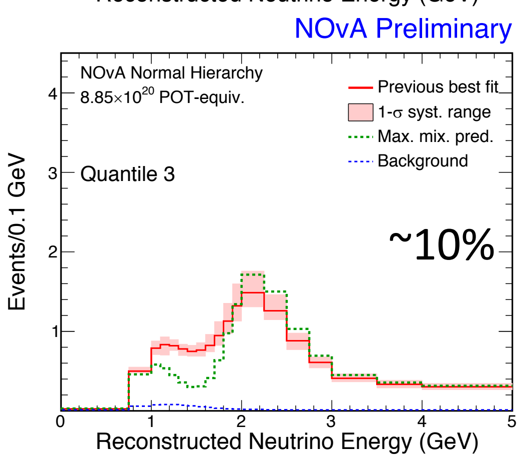
ν_μ Energy:

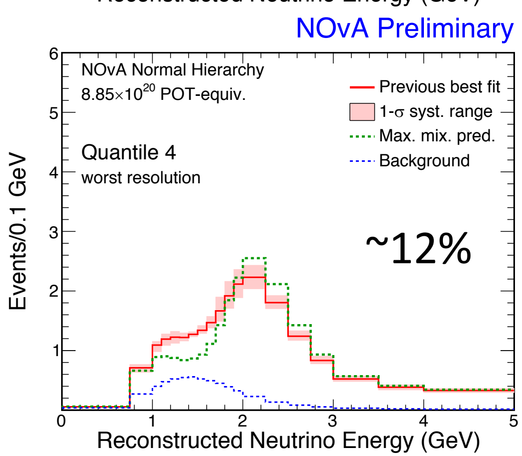
We split the energy spectrum into 4 quantiles by hadronic energy fraction.











Energy resolution for each quantile ranges from 6% in the best one to 12% in the worst.

Most of our background events end up in the 4th (worst) quantile.

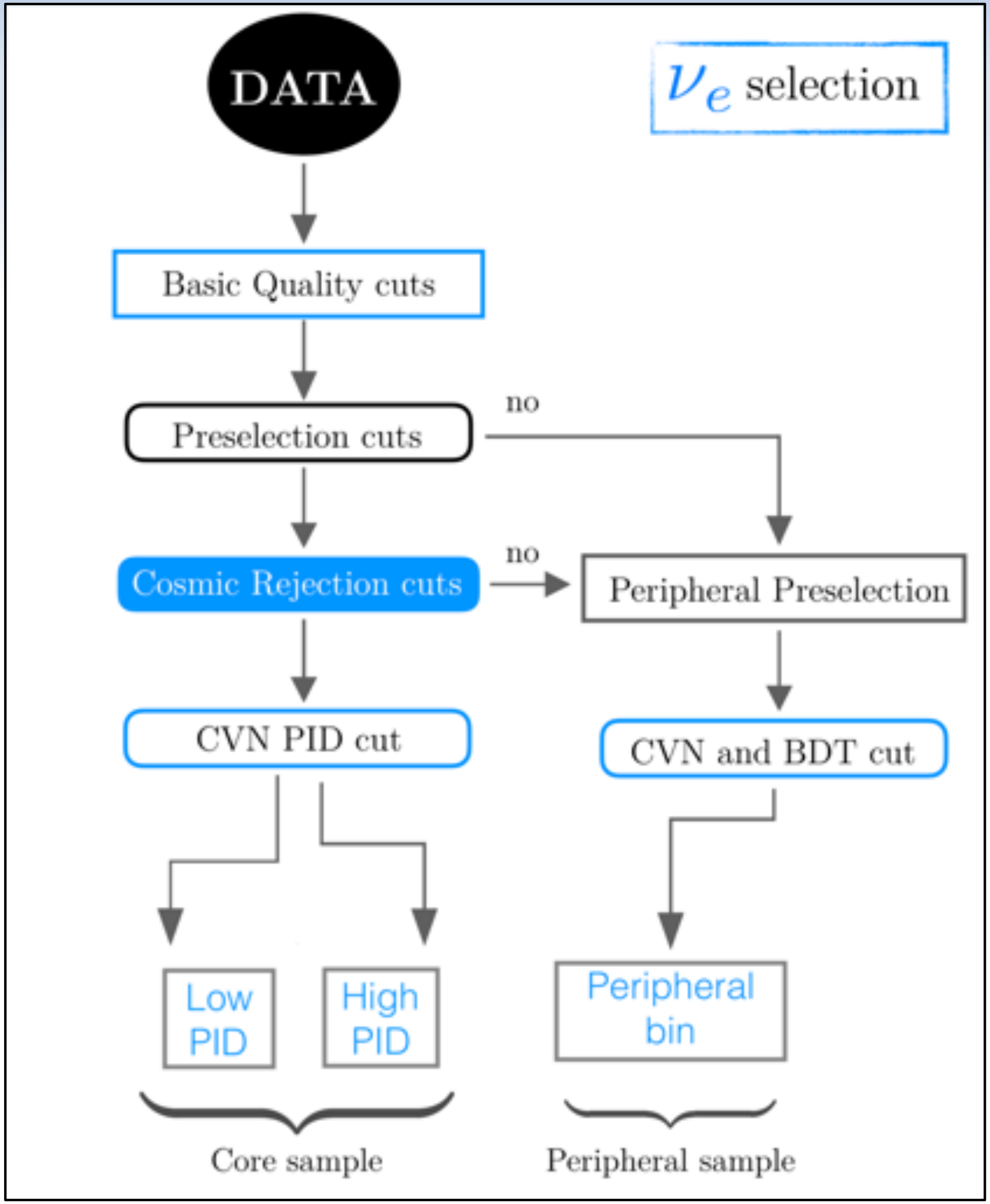
ν_e Summary:

Similar to ν_μ:

- select events (using CVN)
- generate FD prediction
- measure cosmics
- fit for results…

Major differences:

- handle backgrounds differently
- use a “peripheral” event sample
- separate spectra by PID value



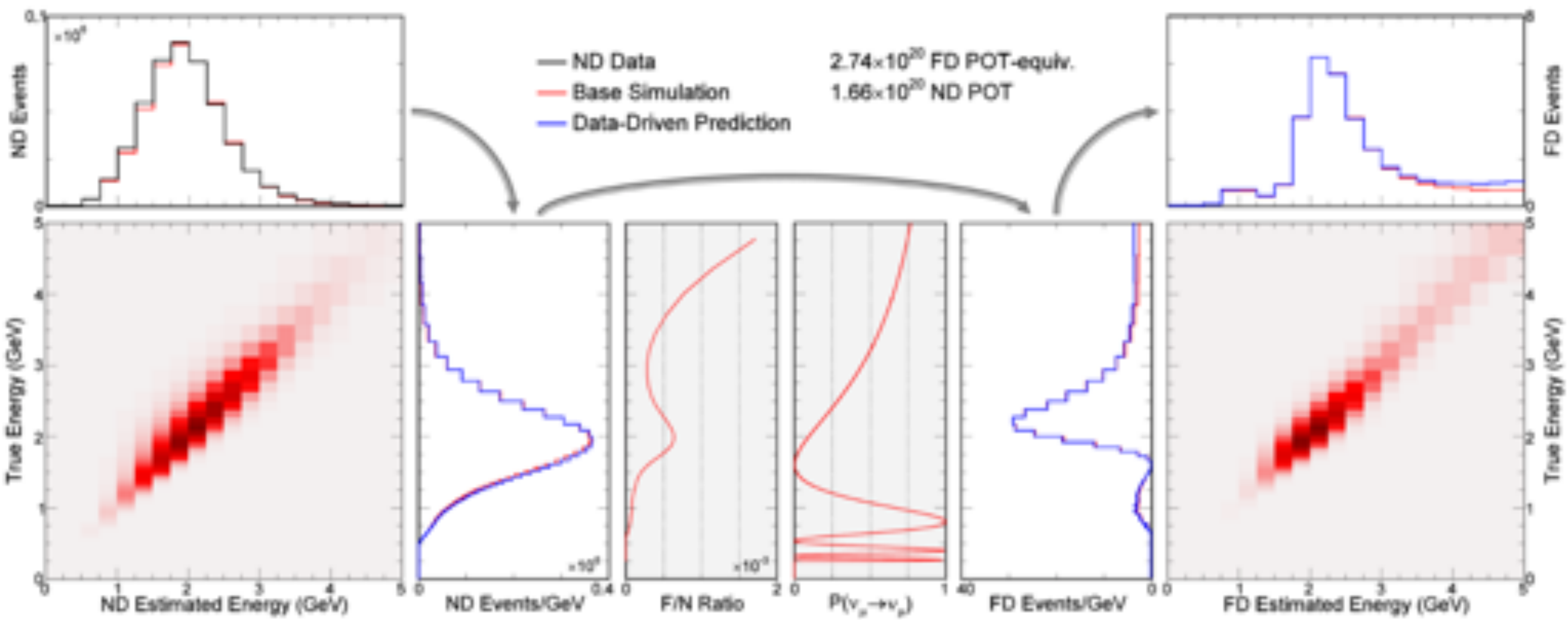
Far Detector Prediction:

The far detector prediction is generated using a near to far extrapolation process.

This extrapolation is repeated separately for each numu quantile.

ND reconstructed E spectra

FD predicted E spectra



Nuclear effects in neutrino cross sections

- Backstory: disagreements are seen in the quasi-elastic cross section as measured on a single nucleons vs. in more complex nuclei.
- Potentially explained by 2 nuclear effects:
- Short-range effects
  - Interactions with nucleon pairs, multi-nucleon ejection
  - Empirical MEC model*, amount tuned to match our ND data.
- Long-range effects
  - Nuclear charge screening
  - RPA from the Valencia group via R. Gran†
- Theory for these effects remains incomplete and the evidence is ambiguous for any particular model.

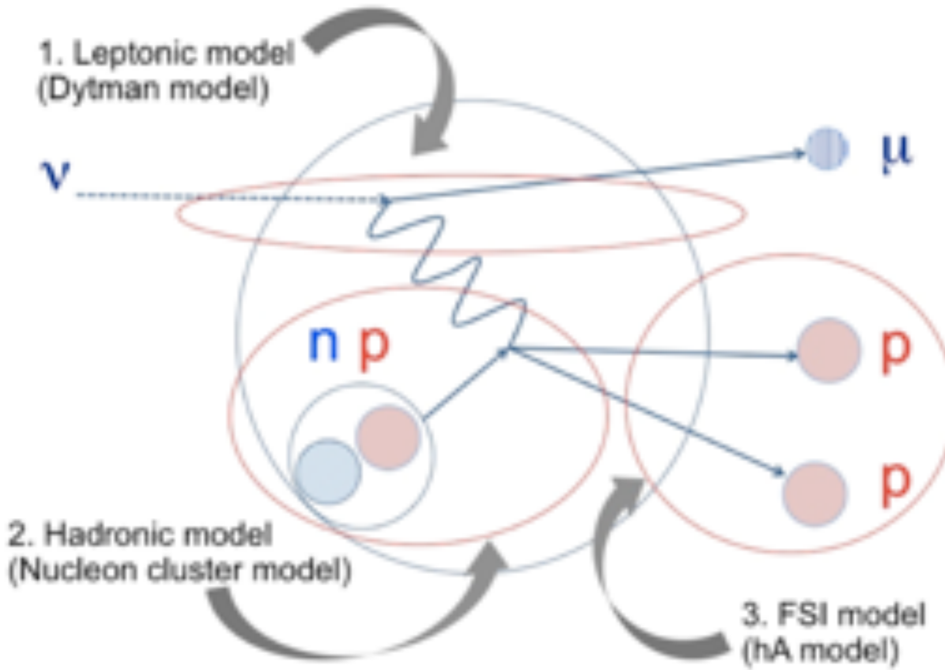


Fig: Teppei Katori, "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators" AIP Conf.Proc. 1663 (2015) 030001

* "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators", Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014

† "Model uncertainties for Valencia RPA effect for MINERvA", Richard Gran, FERMILAB-FN-1030-ND, arXiv:1705.02932

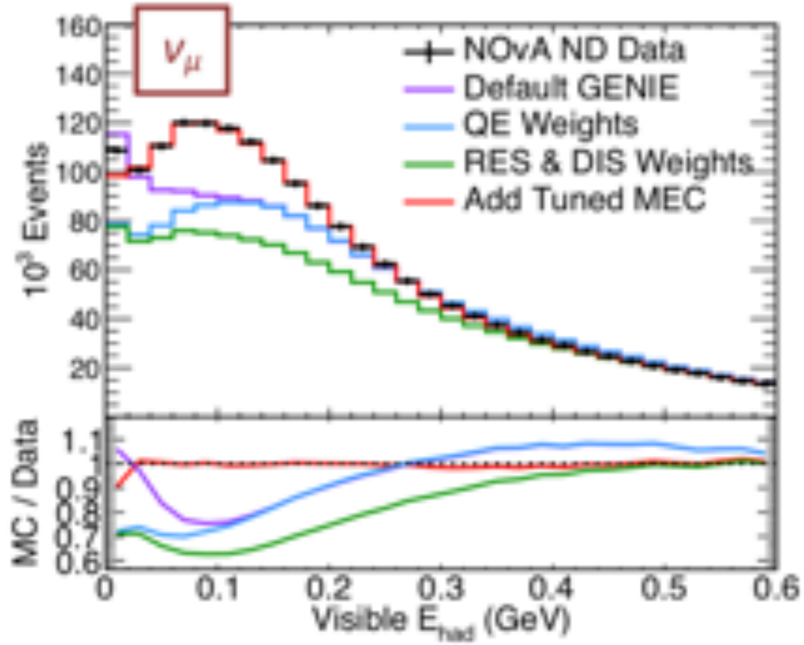
Tuning the Neutrino Interaction Model

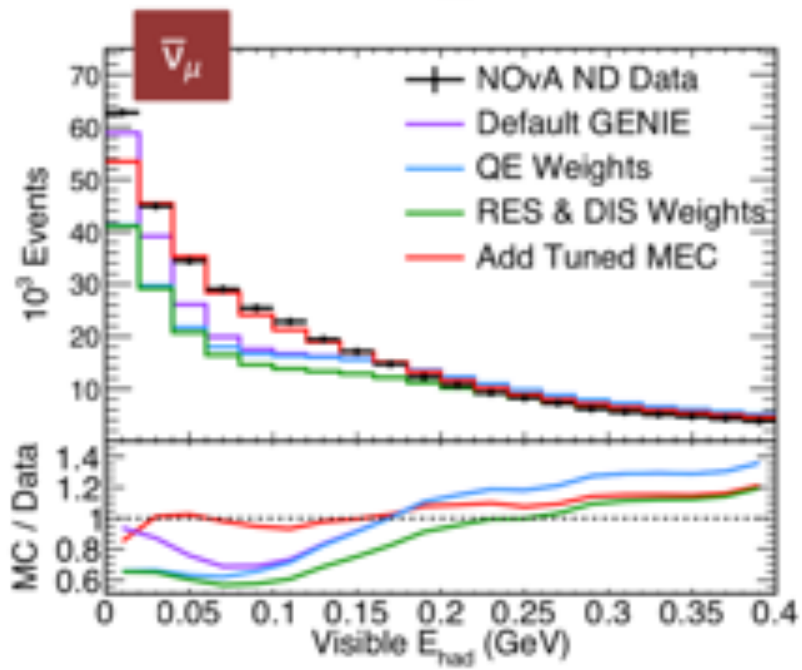
From **external theory**:

- Valencia RPA model† of nuclear charge screening applied to QE.
- Same model applied to resonance.

From **NOvA ND data**:

- 10% increase in non-resonant inelastic scattering (DIS) at high W.
- Add MEC interactions
  - Start from Empirical MEC*
  - Retune in $(q_0, |\boldsymbol{q}|)$ to match ND data
  - Tune separately for $\nu / \bar{\nu}$



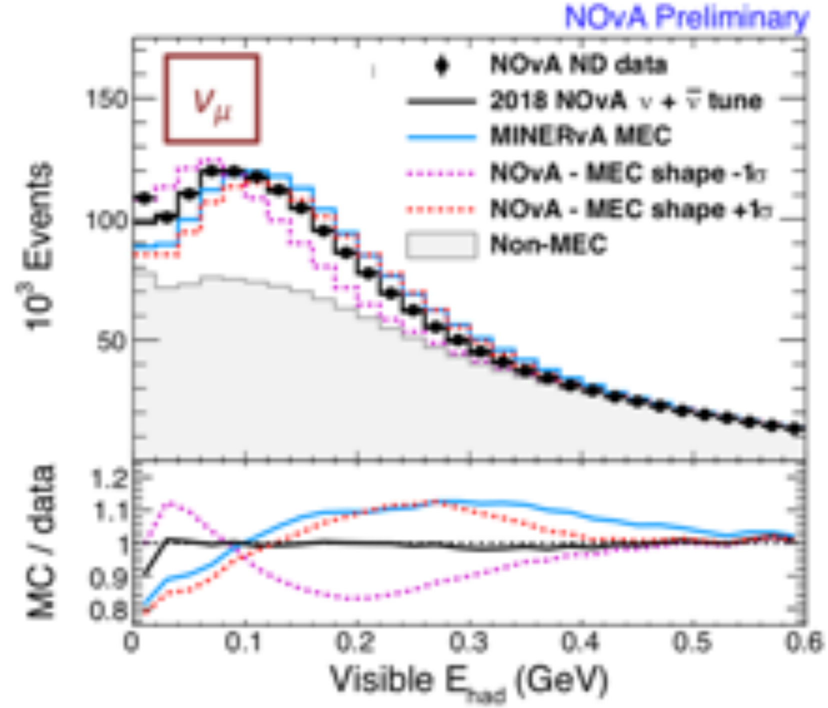


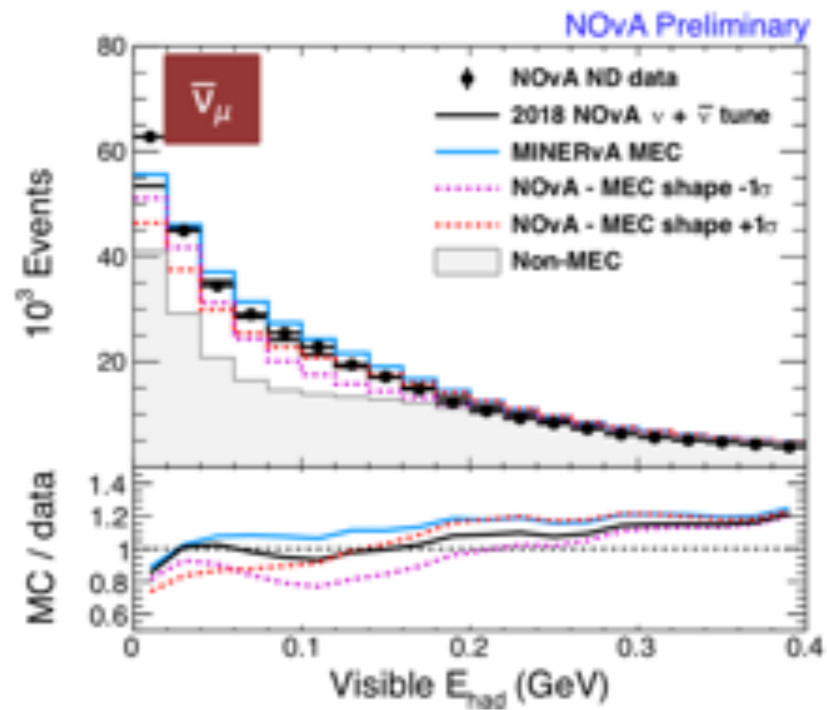
† "Model uncertainties for Valencia RPA effect for MINERvA", Richard Gran, FERMILAB-FN-1030-ND, arXiv:1705.02932

* "Meson Exchange Current (MEC) Models in Neutrino Interaction Generators", Teppei Katori, NuInt12 Proceedings, arXiv:1304.6014

MEC Uncertainties

- We also determine uncertainties on the MEC component we introduce.
  - Both on shape and total rate.
- Repeat the tuning procedure with shifts in the Genie model.
  - Turn Genie systematic knobs coherently to push the non-MEC x-sec more QE-like or more RES-like.
- Independently, **Minerva*** has also tuned a multi-nucleon component to their data.
- The resulting tune is ~1σ away from the NOvA tune.

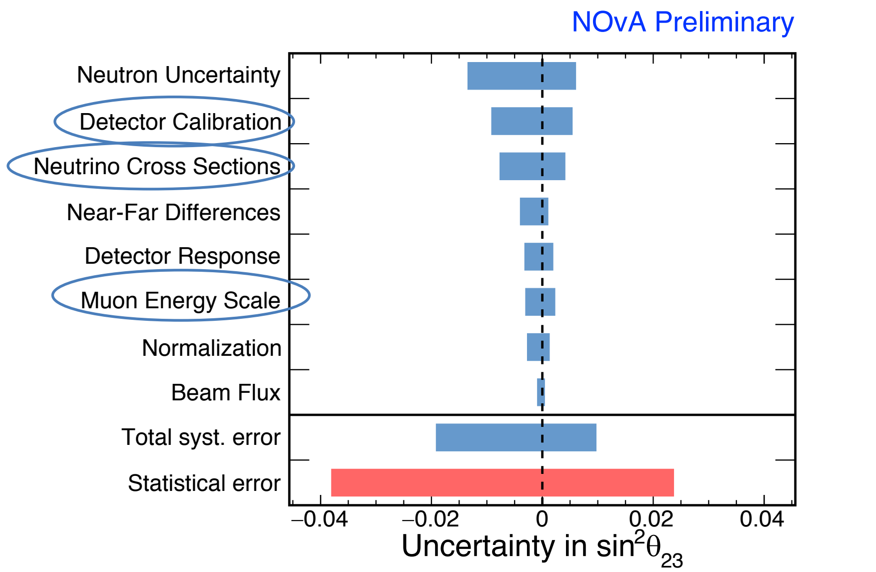


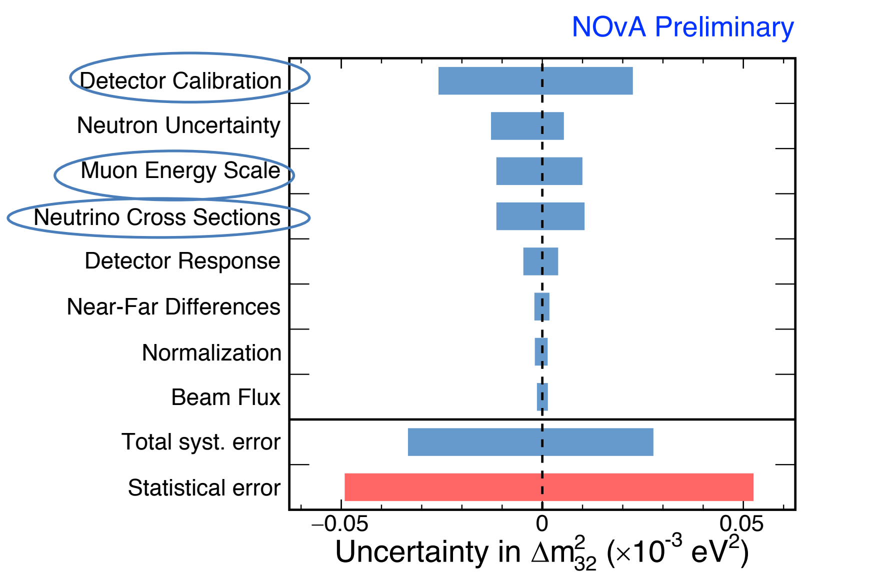


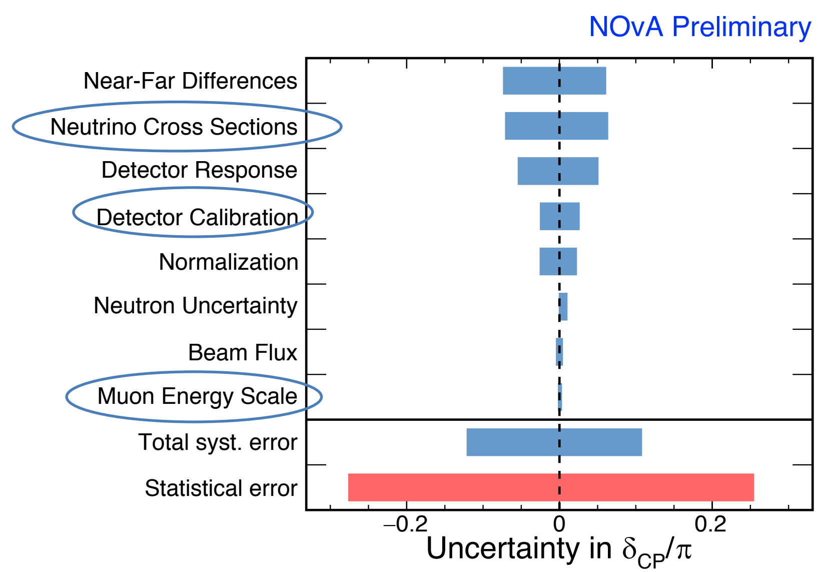
* Minerva, Phys. Rev. Lett. 116, 071802 (2016)
Minerva, Phys. Rev. Lett. 120, 221805 (2018)

Systematics:

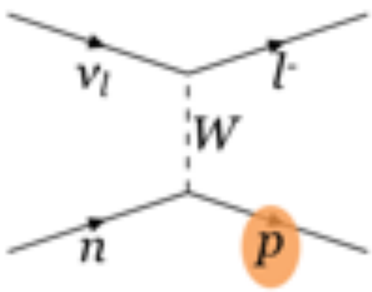
- Systematics are evaluated by shifting individual events at every stage of the extrapolation process, and fit as nuisance parameters.
- Major systematics include:
  - Calibration
  - Cross-sections
  - Muon energy scale
  - Neutrons
- Pulls in the fits are all < 1**σ** and most < 0.5**σ**.

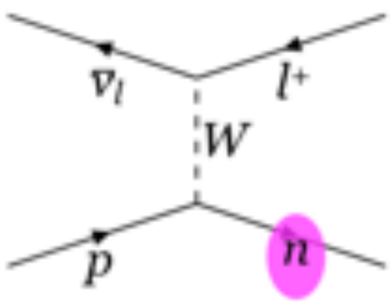




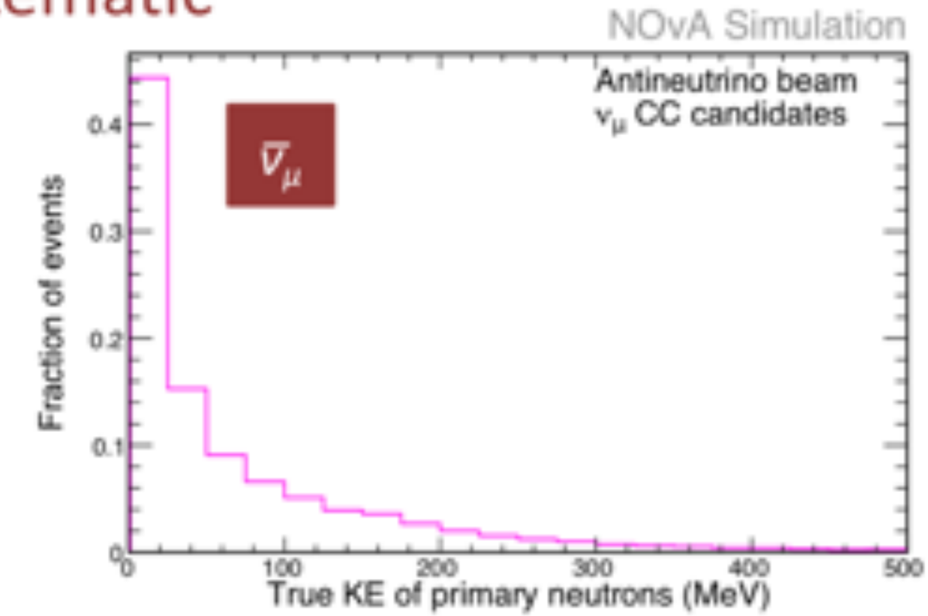


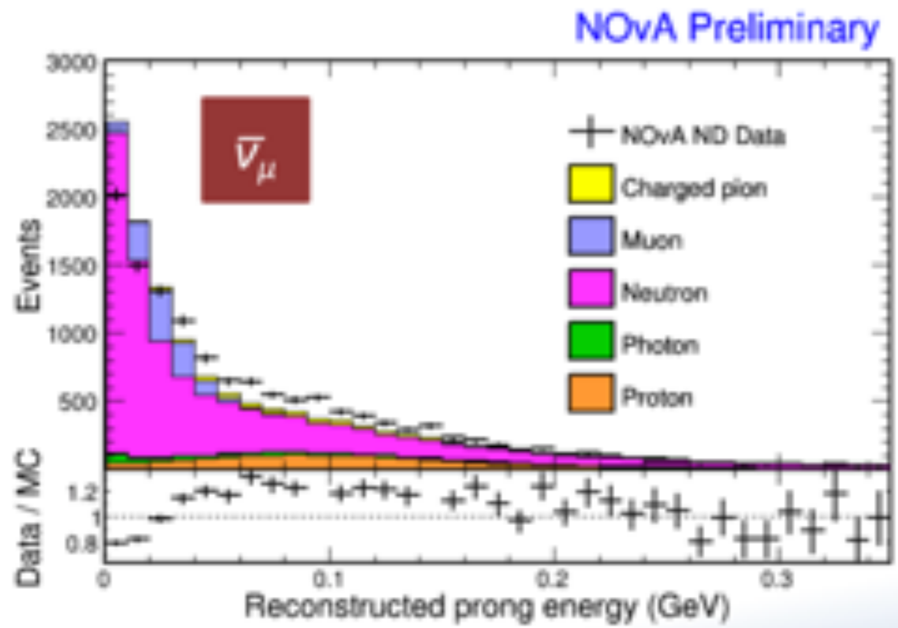
New neutron response systematic



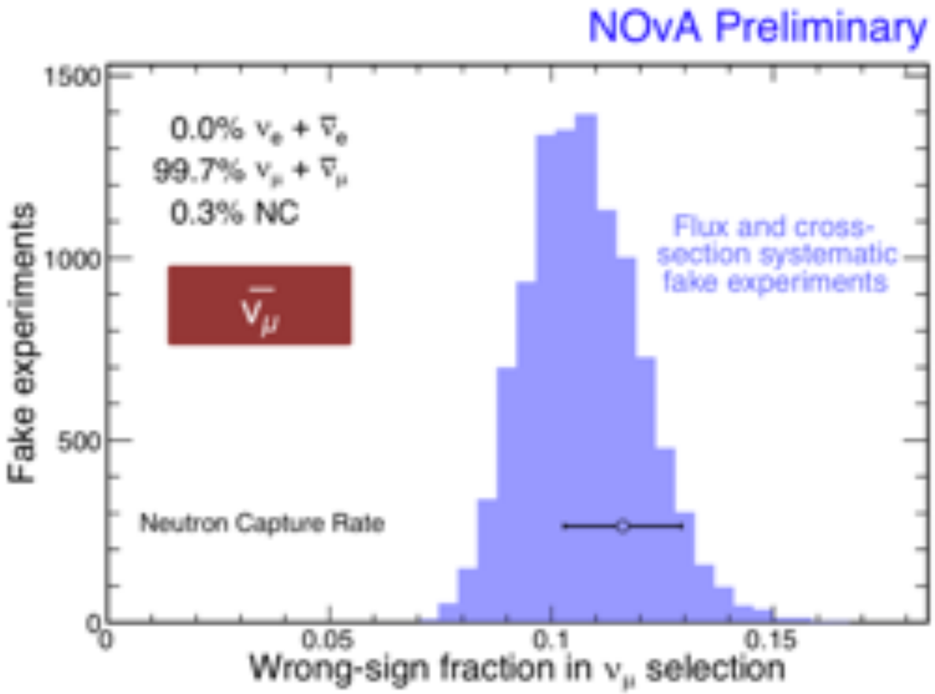


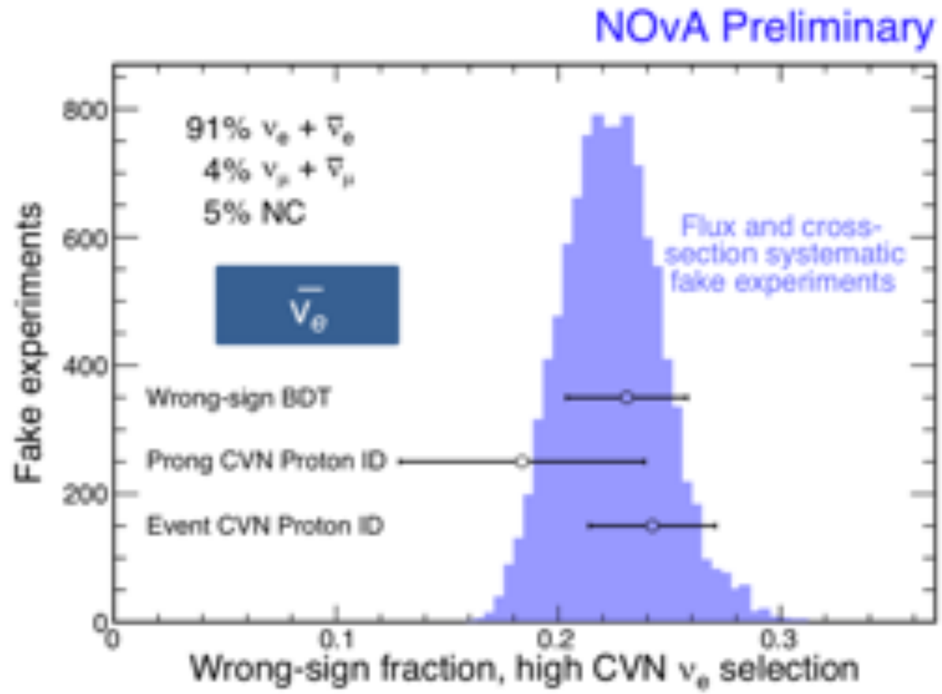
- $\bar{\nu}$'s have neutrons where ν's have protons.
  - Often several hundred MeV of energy.
  - Modeling these fast neutrons is known to be challenging.
- See some discrepancies in an enriched sample of neutron-like prongs.
- New systematic introduced:
  - Scales the amount of deposited energy of some neutrons to cover the low-energy discrepancy.
- Shifts the mean ν_μ energy by 1% in the antineutrino beam and 0.5% in the neutrino beam.
  - Negligible impact was seen on selection efficiencies.





What's new with $\bar{\nu}$'s? Wrong-sign contamination

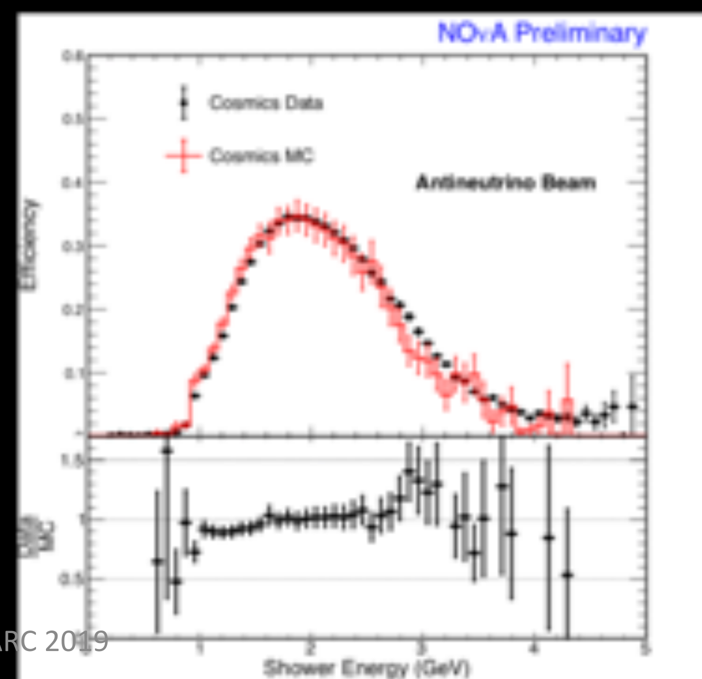




- ~10% systematic uncertainty on wrong-sign from flux and cross section
  - Both in ν_μ-like and ν_e-like events.
  - Does not include uncertainties from detector effects.
- Confirm using data-driven cross-checks of the wrong-sign contamination
  - 11% wrong-sign in the ν_μ sample checked using neutron captures.
  - 22% wrong-sign in beam ν_e checked using identified protons and event kinematics.

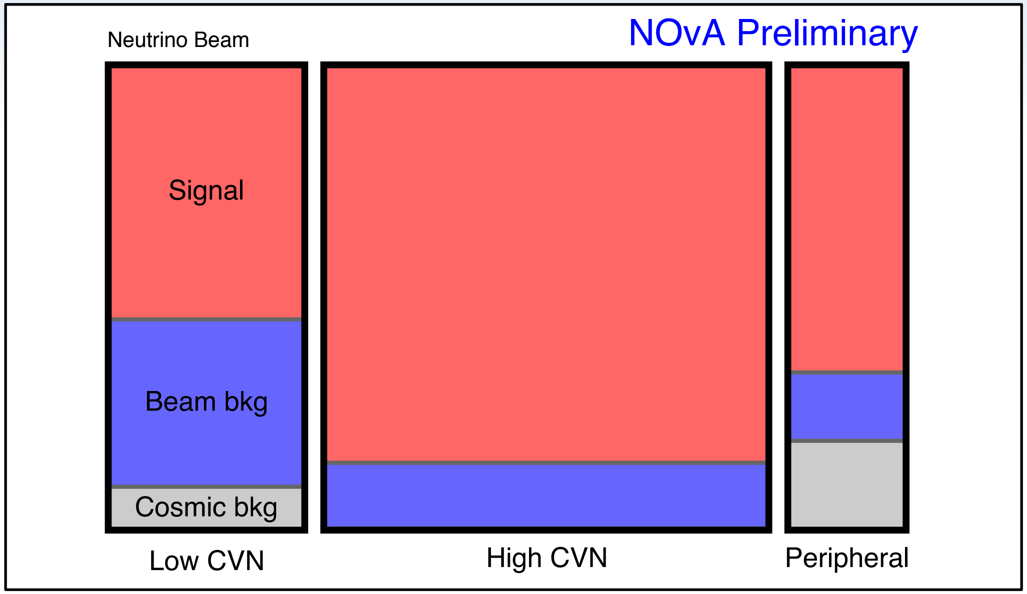
CROSS-CHECKS: MUON-REMOVED FROM BREMSSTRAHLUNG

- Bremsstrahlung showers in cosmic ray muons provide a sample of known electron showers in data at the Far Detector.
- Compare efficiency between data and simulated brem showers.
  - Look at both the neutrino and antineutrino tunes of CVN, but the underlying brem showers are of course the same.



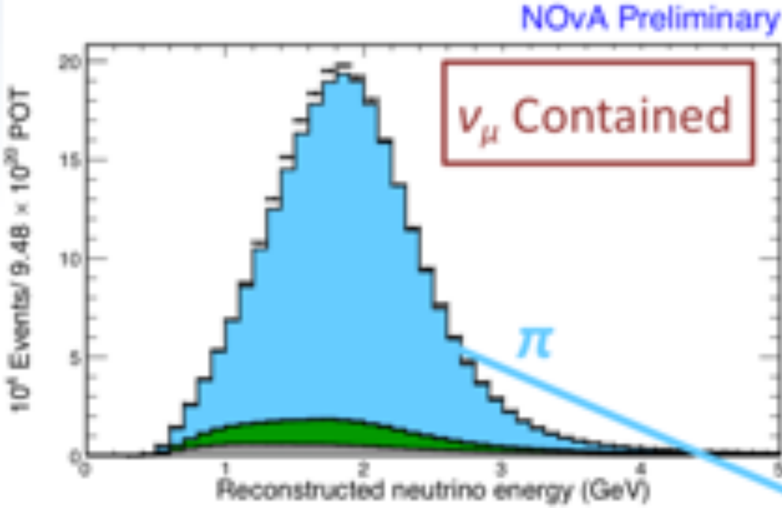
ν_e Background Decomposition:

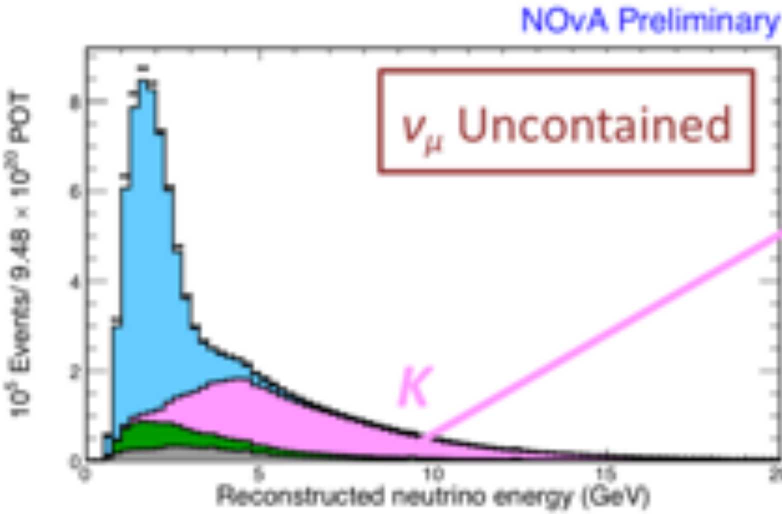
We expect more backgrounds in the ν_e event sample, and each component extrapolates differently to the FD.

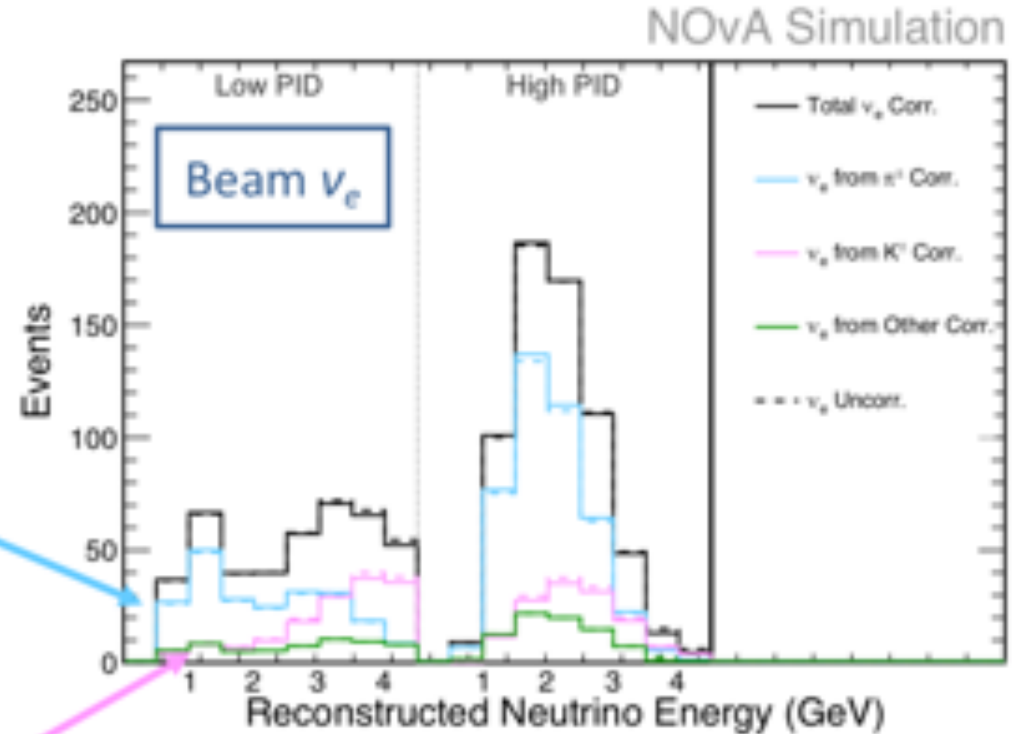


- We can improve our background estimates using statistical techniques (tracking ν_e events to parent pions, michele e^- tagging) by comparing ND data and MC.
- Results in adjustments to expected ND background components (beam ν_e +3%, NC -4%, ν_μ CC +7%) for FHC data
- Stats are too low in RHC data, so we fall back on a proportional decomposition method.

ν_e Decomposition



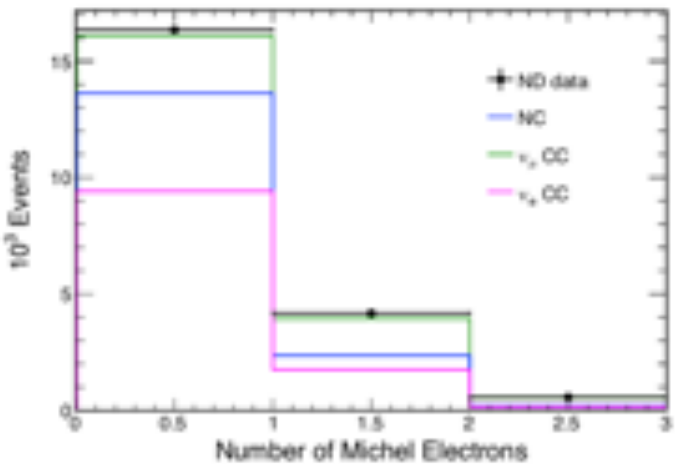




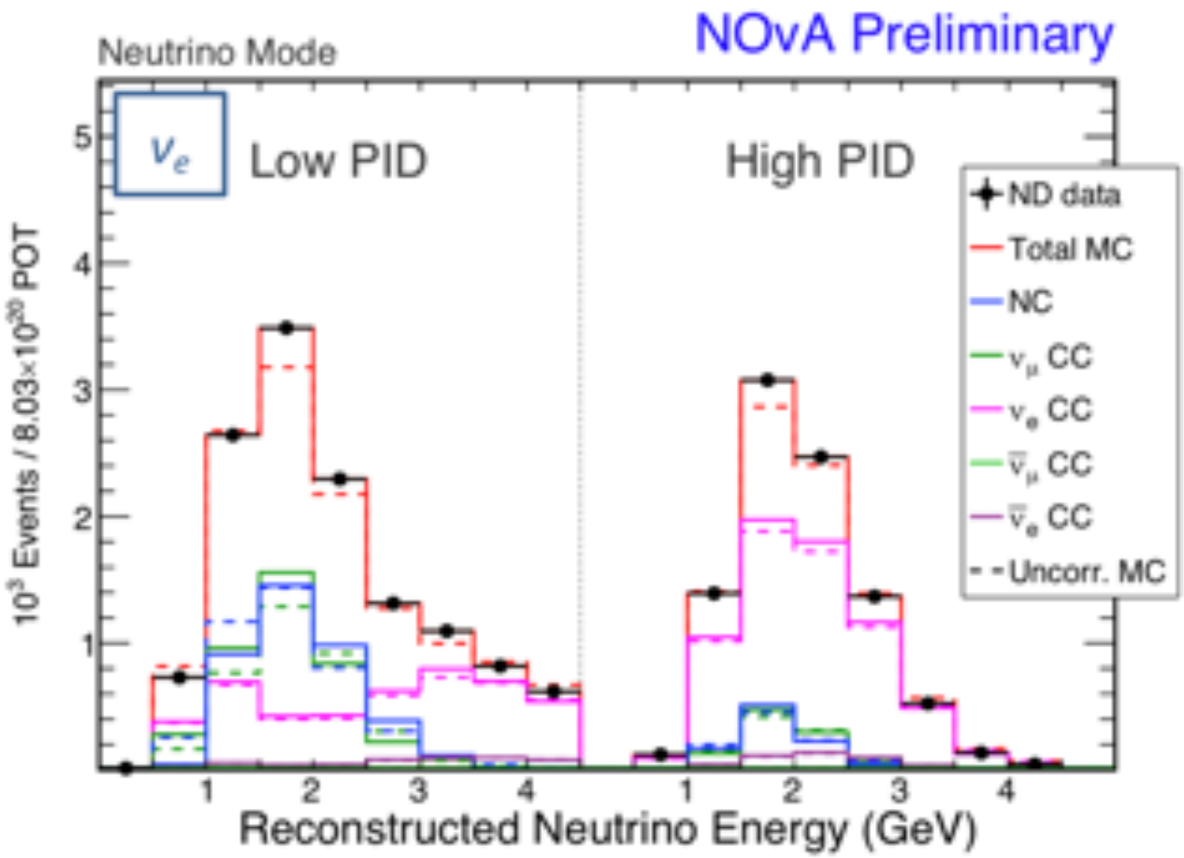
- ν_e and ν_μ events come from the same parents:
  - Lower energy neutrinos come primarily from π decay.
  - Higher energy neutrinos come primarily from K decay.
- Use contained ν_μ data to constrain the π flux
- Use higher energy uncontained events to constraint the K flux.

ν_e Decomposition

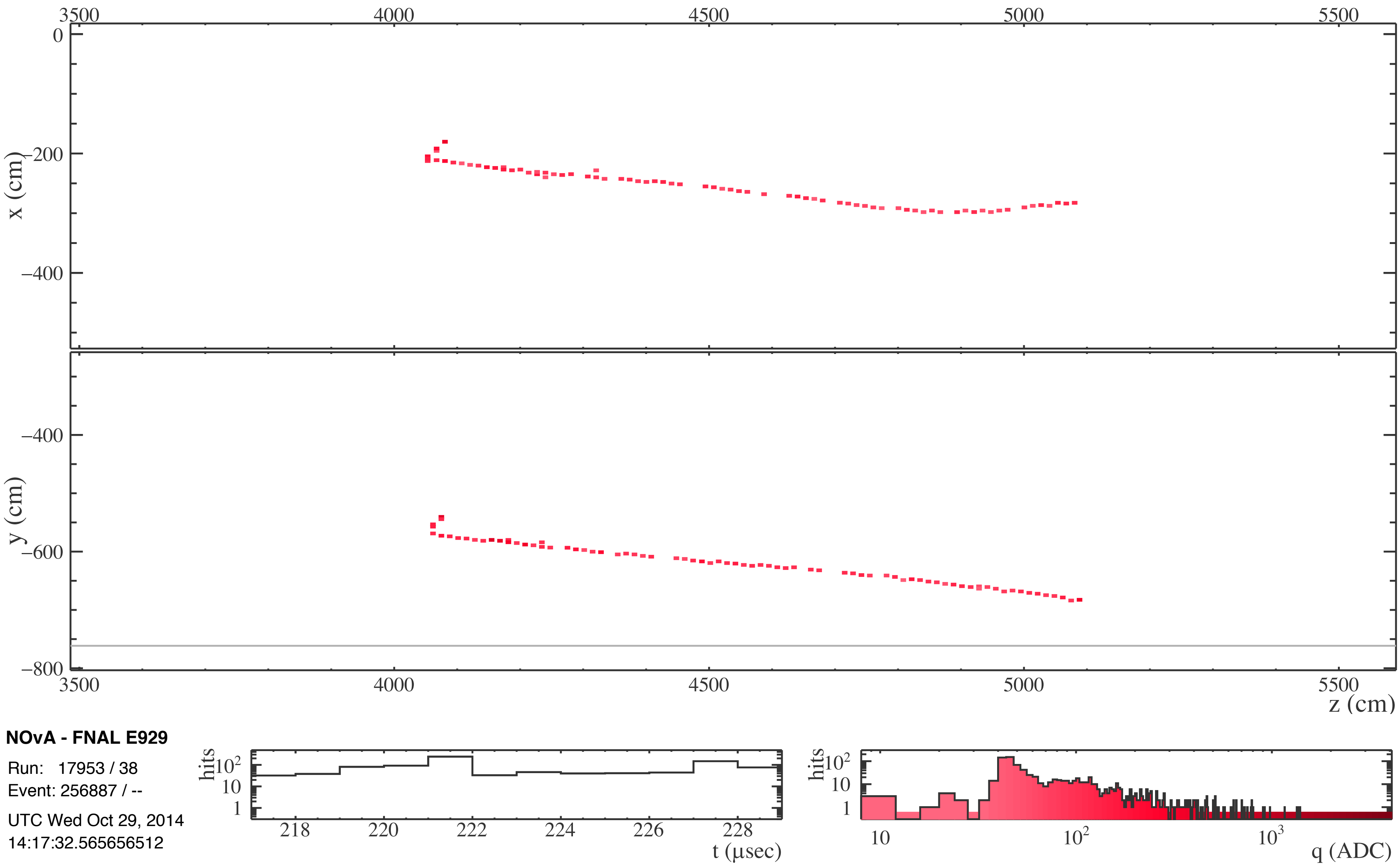
- The CC/NC constrained using the number of observed Michel electrons.
  - Determine the fraction of the two components in each analysis bin.



Change in Total	
ν_e CC	+3%
ν_μ CC	+7%
NC	-4%

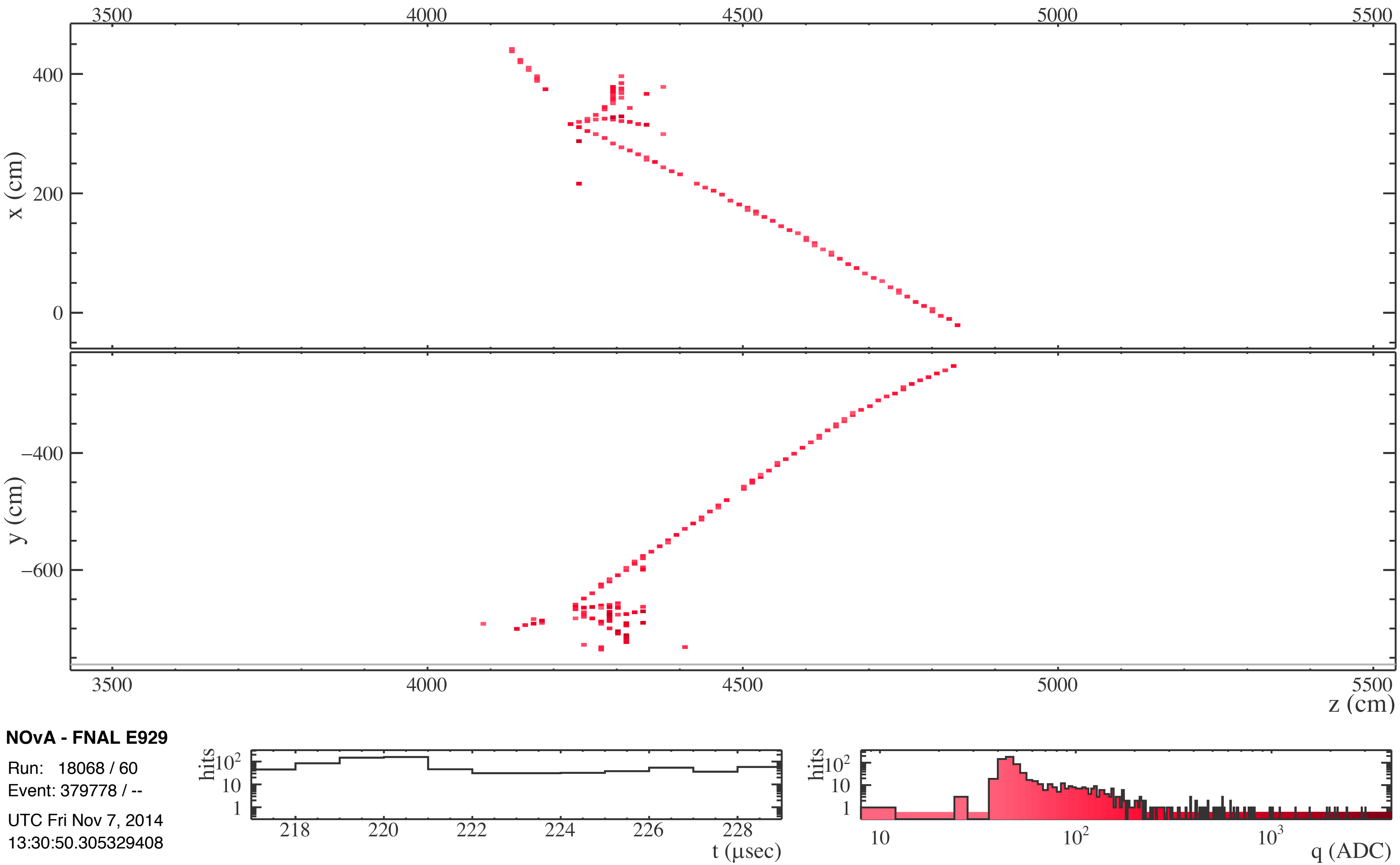


Events!!!!



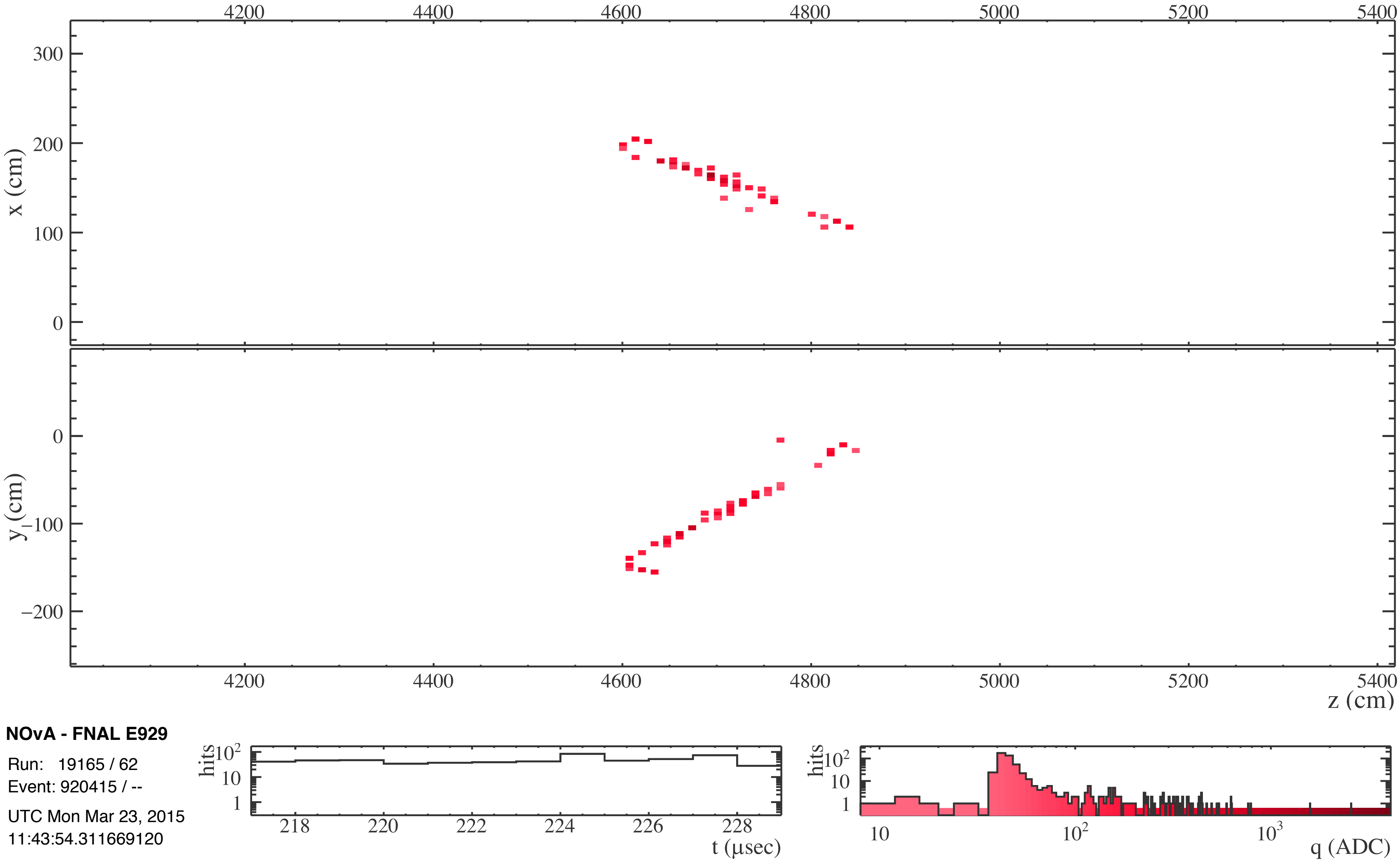
FHC ν_μ CC

Events!!!!



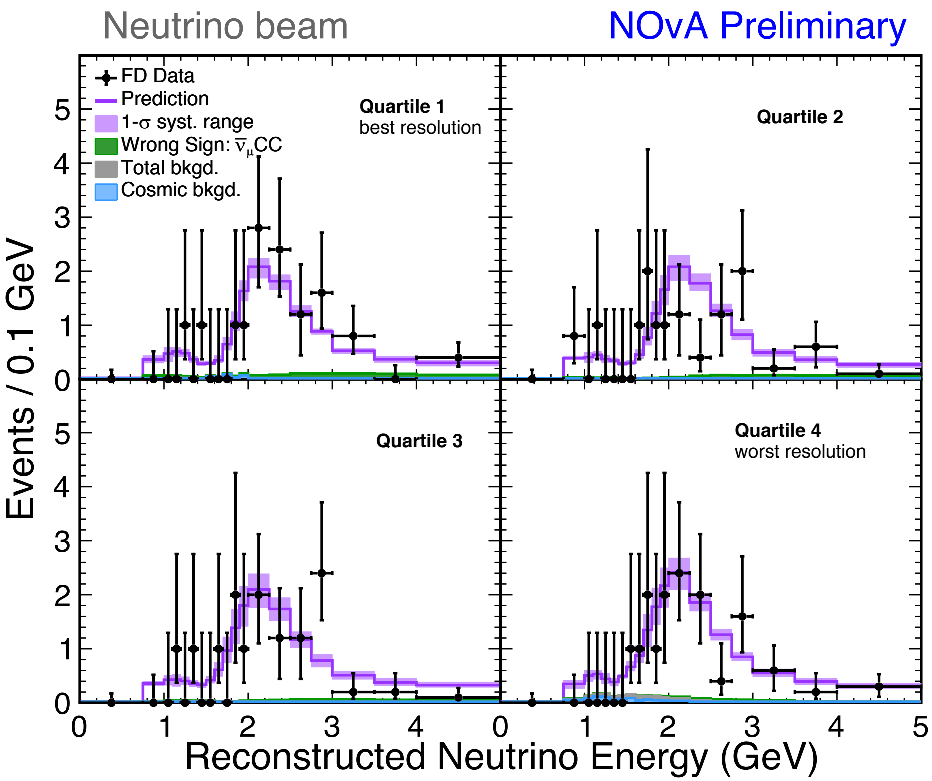
FHC ν_μ CC

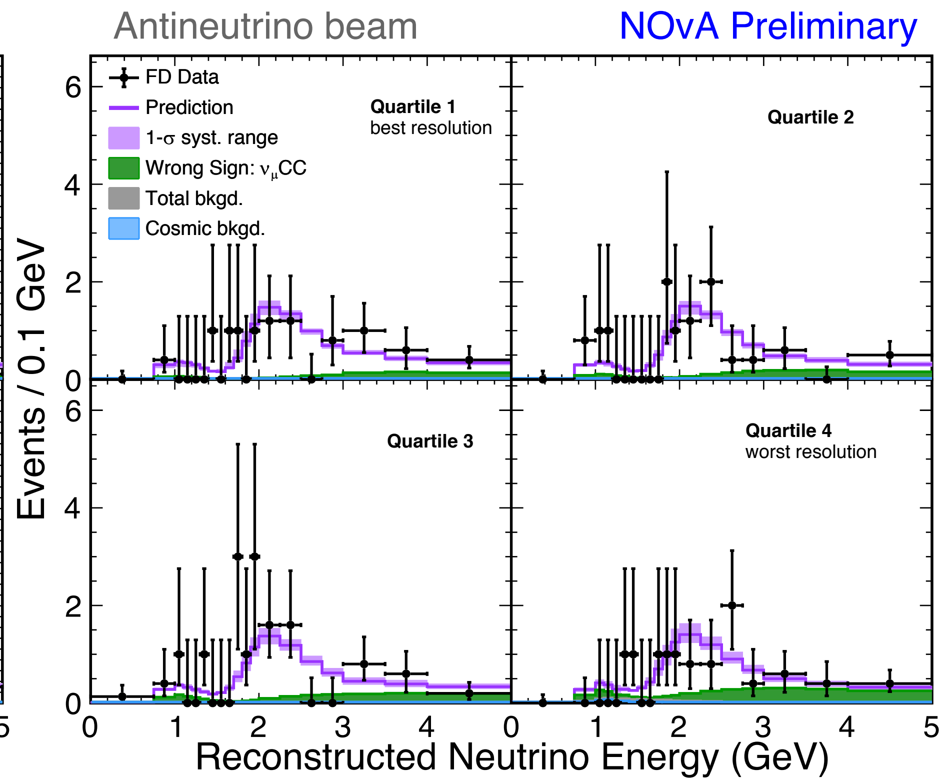
Events!!!!



FHC ν_e CC

ν_μ Spectra & Numbers:

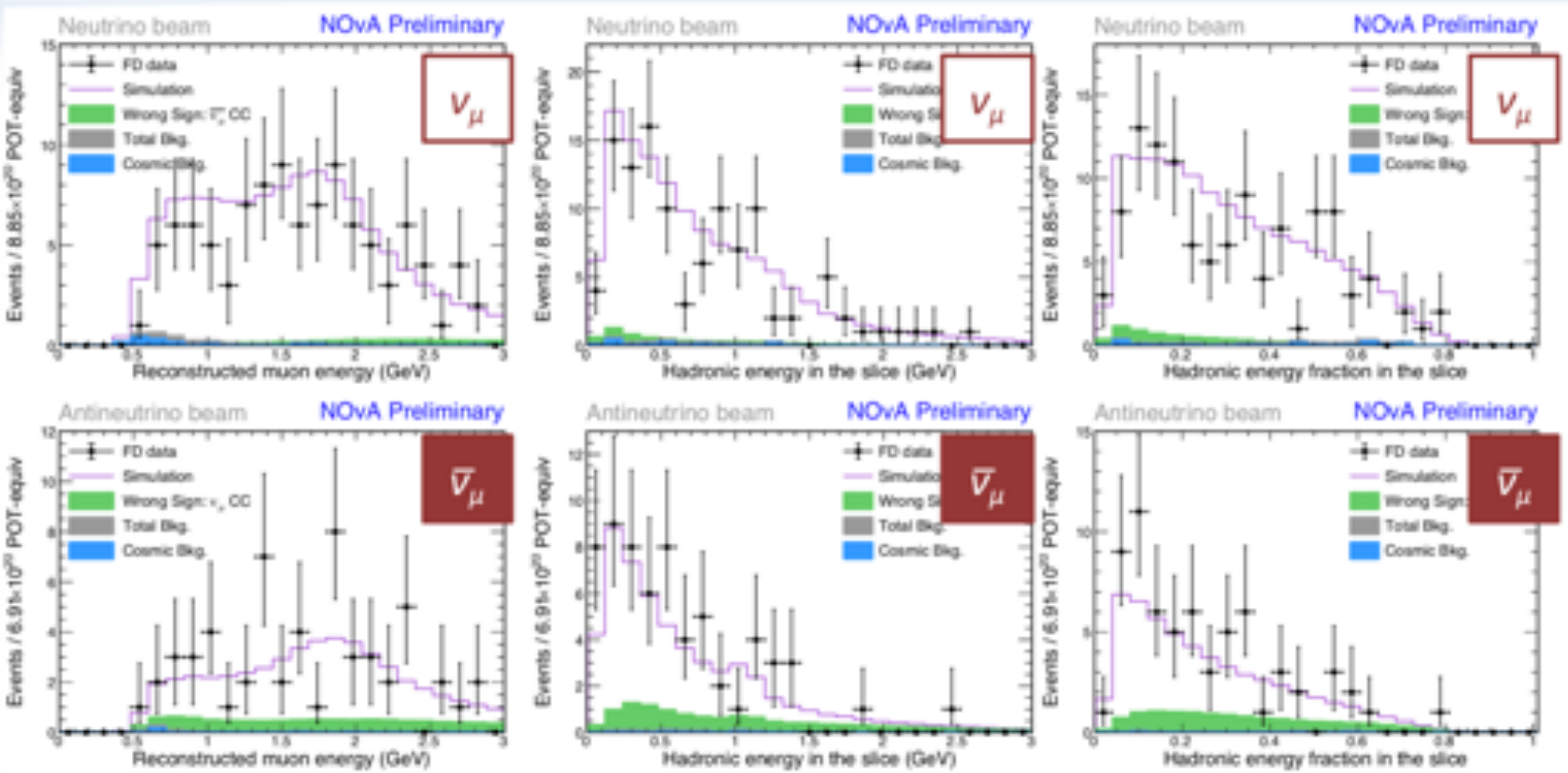




Data neutrino candidates	113
Best fit total prediction	**124**
total bkgd.:	4.2
↳ cosmic bkgd.	2.1
↳ beam bkgd.	2.1

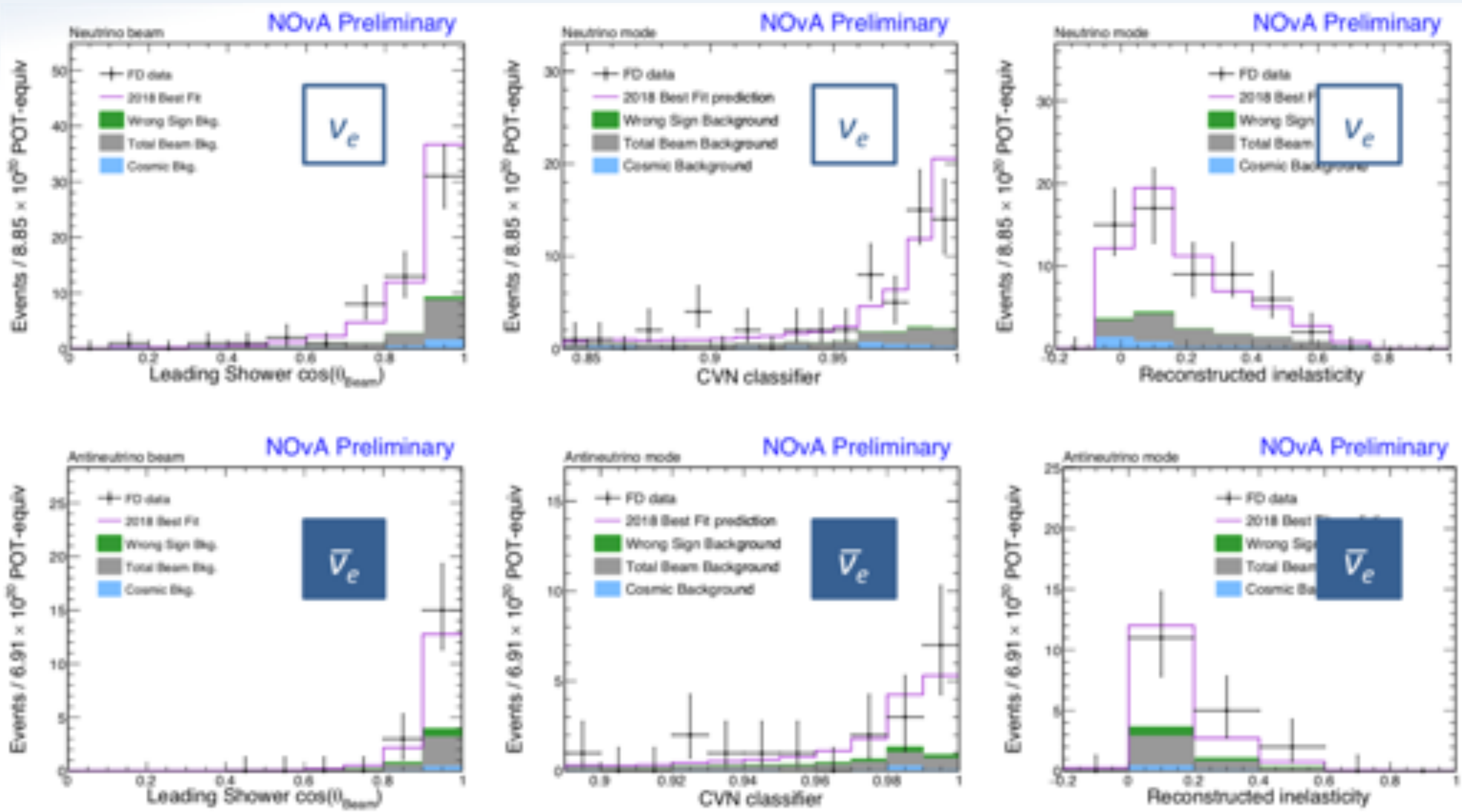
Data antineutrino candidates	102
Best fit total prediction	**96**
total bkgd.:	2.2
↳ cosmic bkgd.	0.8
↳ beam bkgd.	1.4

FD Data/MC Agreement



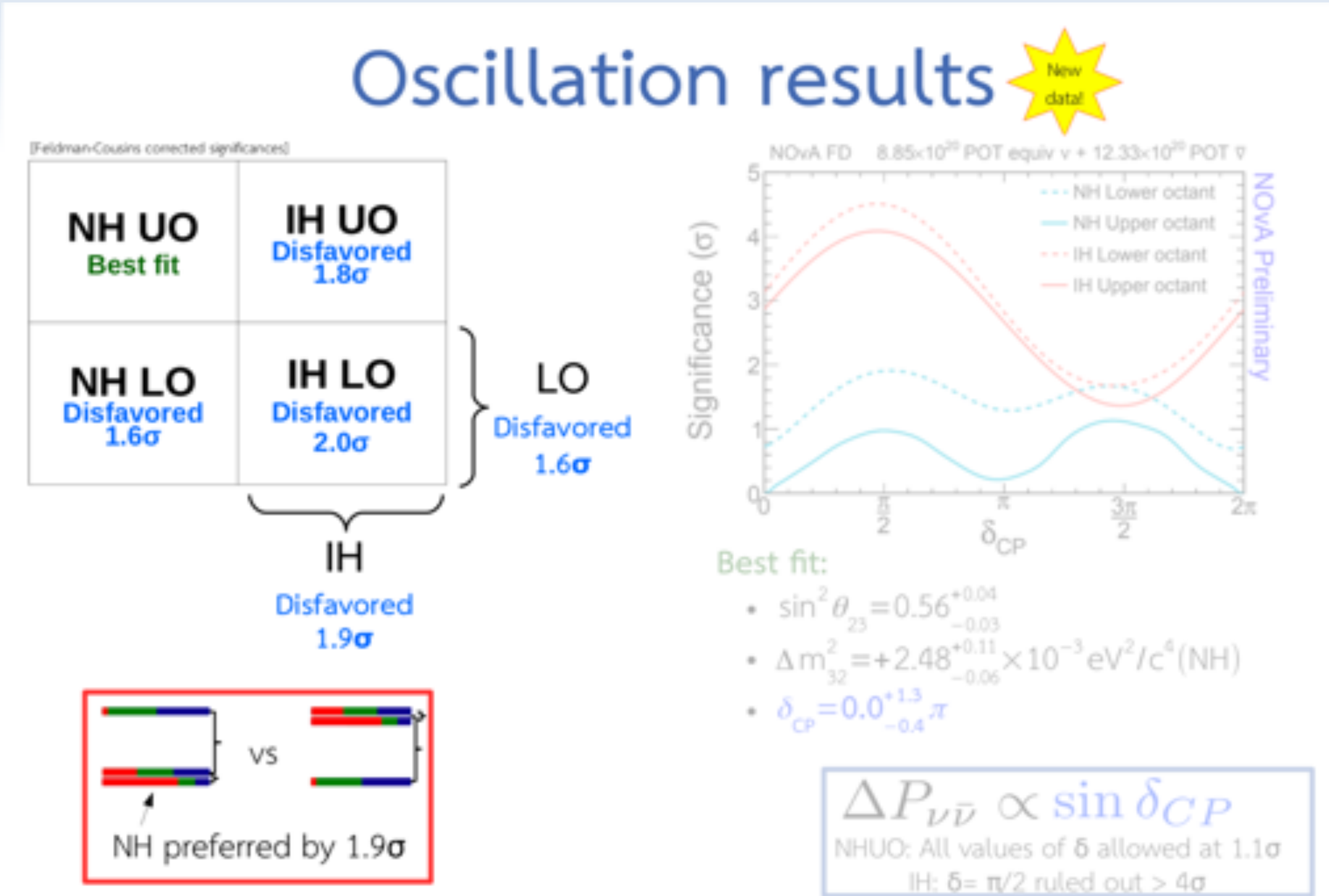
- Good agreement in FD data distributions of muon and hadronic energy and inelasticity.

FD Data/MC Agreement

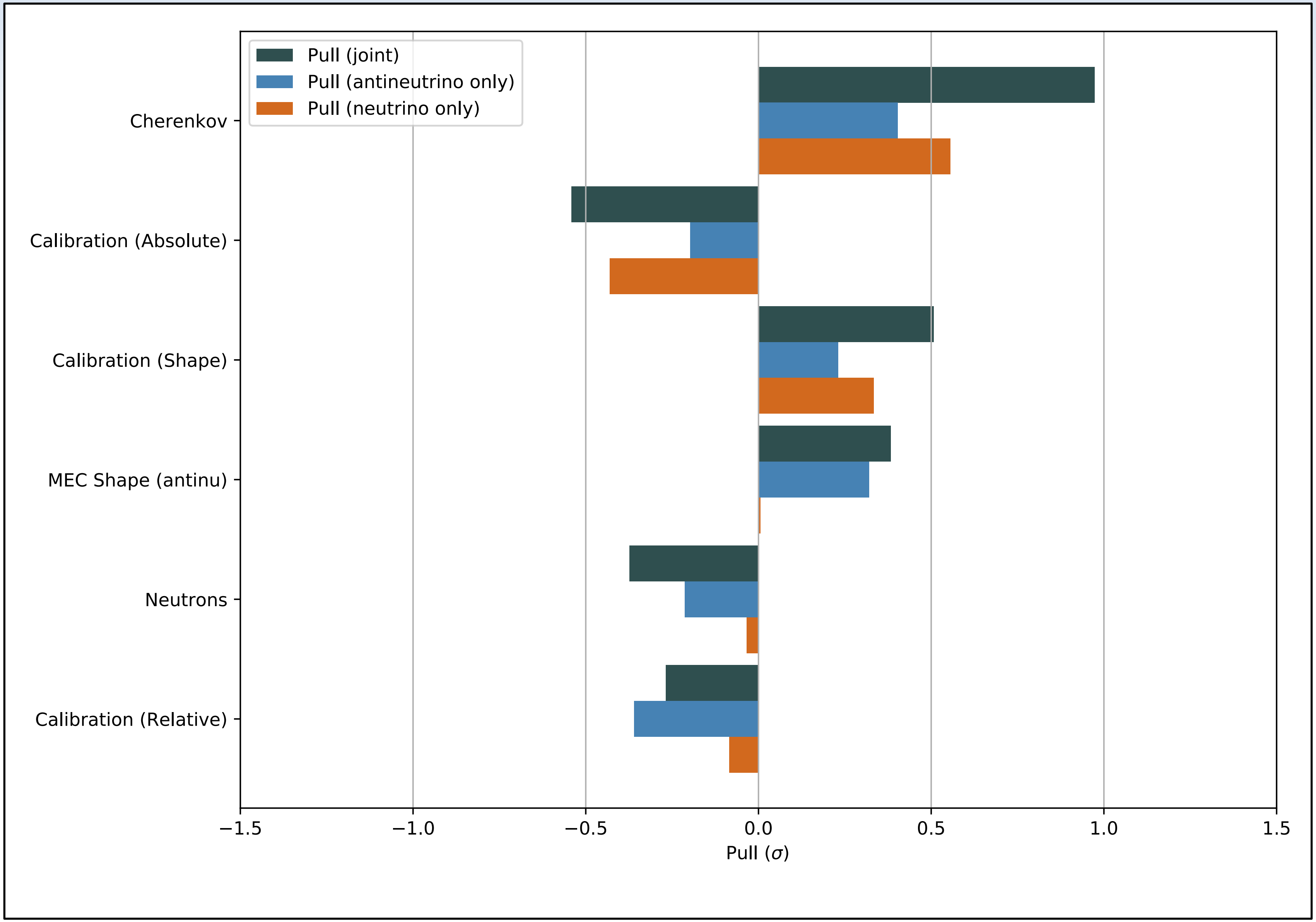


- Good agreement in FD data distributions of lepton angle, CVN, and inelasticity.

Results:


Oscillation results
New data!
[Feldman-Cousins corrected significances]
NH UO
Best fit
IH UO
Disfavored
1.8σ
NH LO
Disfavored
1.6σ
IH LO
Disfavored
2.0σ
LO
Disfavored
1.6σ
IH
Disfavored
1.9σ
vs
NH preferred by 1.9σ
NOvA FD 8.85×10^20 POT equiv ν + 12.33×10^20 POT ν̄
NH Lower octant
NH Upper octant
IH Lower octant
IH Upper octant
NOvA Preliminary
Significance (σ)
δCP
Best fit:
sin²θ23=0.56 +0.04 −0.03
Δm²32=+2.48 +0.11 −0.06 ×10⁻³eV²/c⁴(NH)
δCP=0.0 +1.3 −0.4 π
ΔPνν̄ ∝ sin δCP
NHUO: All values of δ allowed at 1.1σ
IH: δ= π/2 ruled out > 4σ

Systematic Pulls in the Final Fit:



Systematic Pulls in the Final Fit:

Table 1: Top ten systematic pulls in the joint fit with neutrino and antineutrino beam data, ordered by absolute size of the pull. The systematic pulls are produced by running a one point fit with oscillation parameters fixed at the following values: $\delta_{CP} = 2.00\pi$, $\sin^2(\theta_{23}) = 0.565$, $\sin^2(2\theta_{13}) = 0.082$, $\Delta m^2_{32} = 2.48 \times 10^{-3}$, which correspond to the best-fit point in the fit to neutrino beam data, with all systematics included.

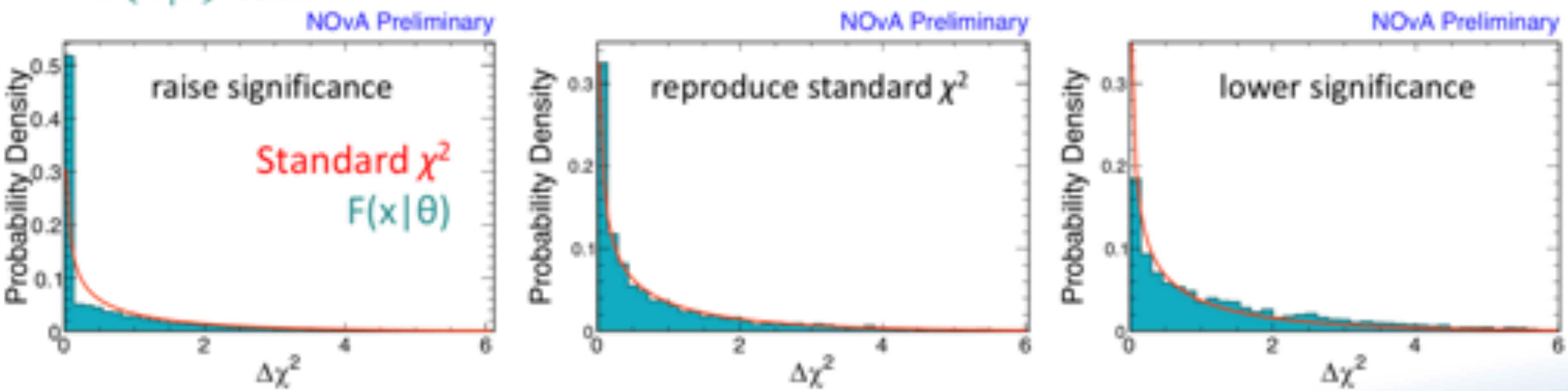
Systematic	Pull	Pull (neutrino only)	Pull (antineutrino only)
Cherenkov	0.973	0.556	0.403
Calibration	-0.541	-0.431	-0.198
CalibShape	0.508	0.333	0.231
MECShape2018AntiNu	0.383	0.005	0.320
NeutronEvisPrimariesSyst2018	-0.374	-0.035	-0.214
RPAShapeRES2018	0.280	0.349	-0.049
RelativeCalib	-0.268	-0.085	-0.360
ppfx_hadp_beam_pc02	-0.241	-0.152	-0.083
MaCCRES	0.196	0.053	0.284
AbsMuEScale2017	0.170	-0.184	0.427

Statistical Approach: Feldman-Cousins

- Replace the standard χ^2 with an empirical distribution, $F(x|\theta)$:

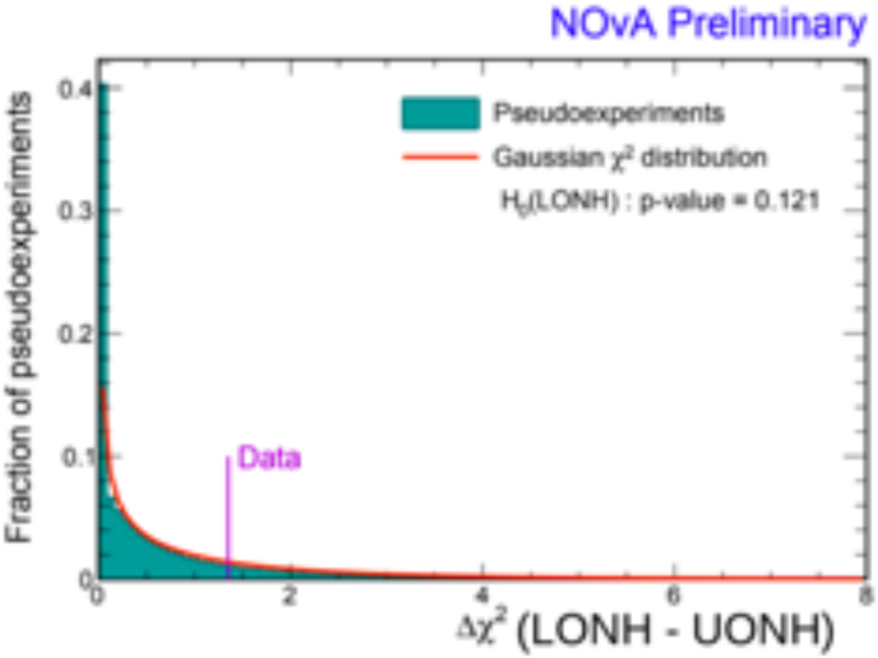
$$F(x|\theta) = \text{Fraction of } N \text{ experiments where } [\ \chi^2(\text{fixed } \theta) - \chi^2(\text{best fit}) = x\ ]$$

- Pseudo-experiments are generated from the data profile at θ.
  - i.e. fit all other parameters to data holding θ fixed at a particular value.
  - This procedure gives proper coverage while minimizing over-coverage.*
- A point θ is inside the (1-α) confidence interval if less than (1-α) experiments are more extreme than the data.
  - i.e. if the integral of $F(x|\theta)$ up to the observed $\Delta\chi^2$ at θ is < (1-α).
- $F(x|\theta)$ can...



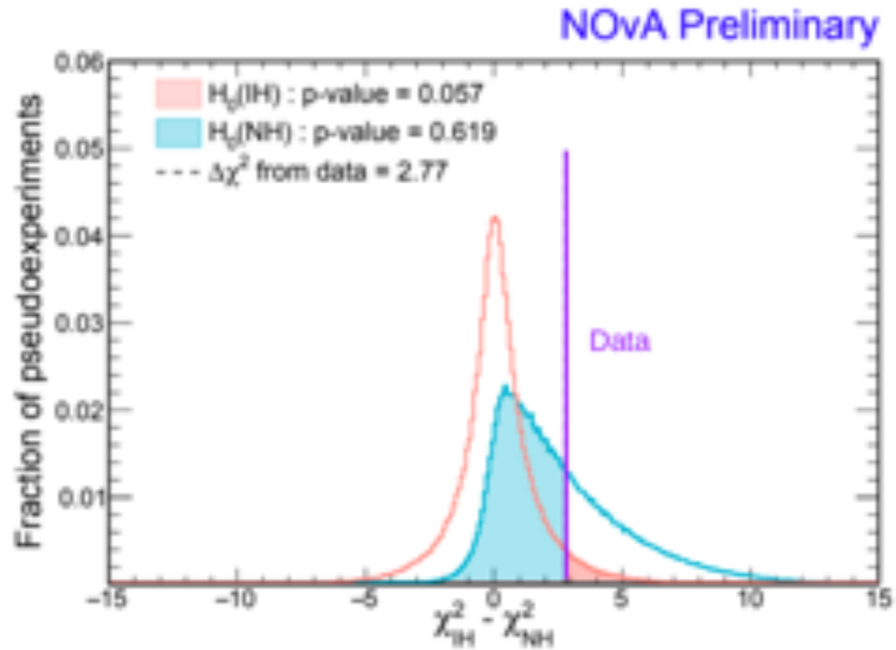
* Test coverage using method from: R. L. Berger and D. D. Boos, J. Amer. Statist. Assoc., 89, 1012 (1994)

Calculating significances



Feldman-Cousins method

Generate many pseudoexperiments w/ null hypothesis: measure *p*-value of data exclusion of null "empirically"



CL_s:

Compute *p*-values of *both* hypotheses; if p_{null}/p_{alt} is large, exclusion of null is suspicious.

$CL_S = 0.094$