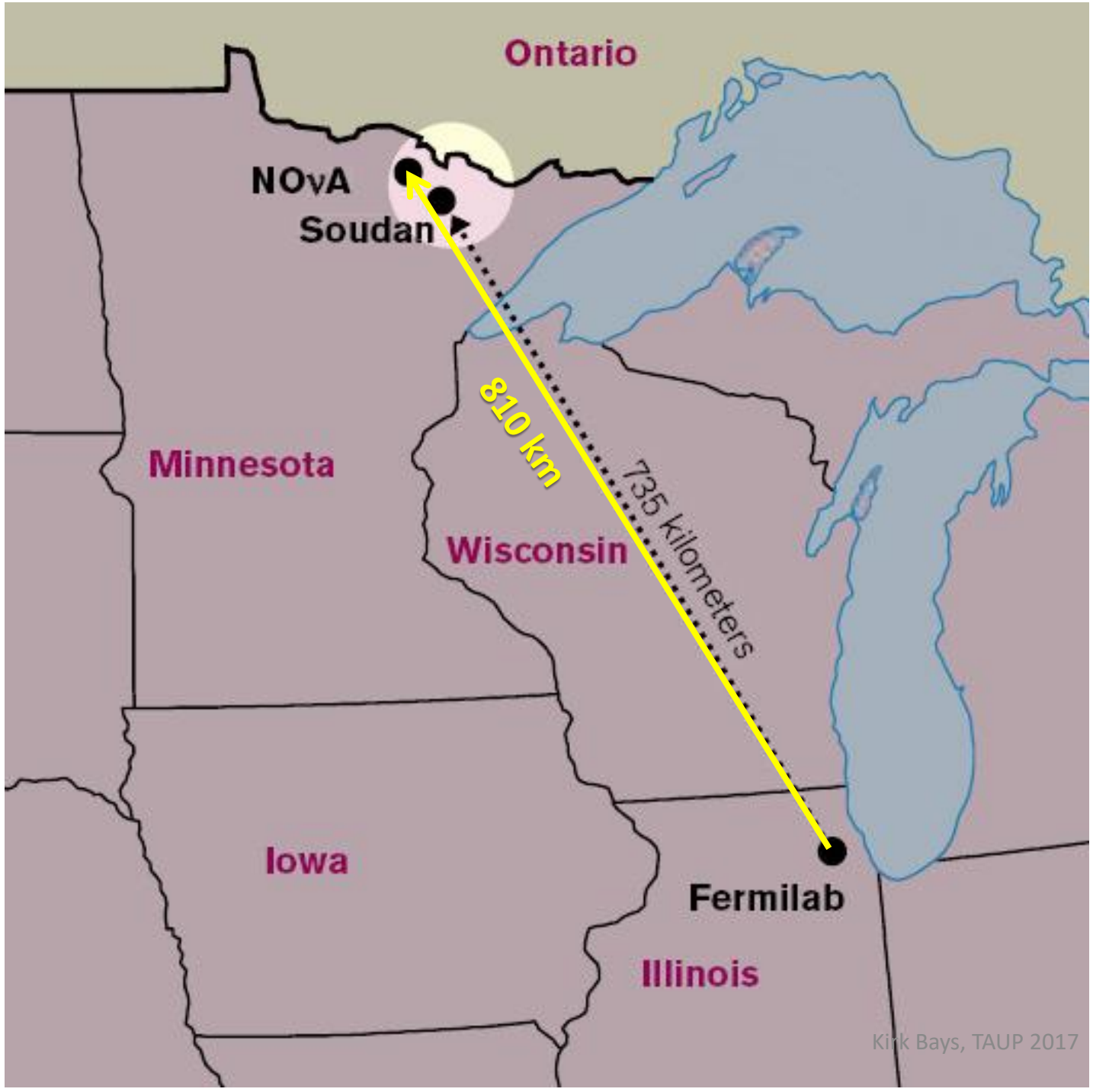
Caltech

The latest from NoVA

Kirk Bays (Caltech)

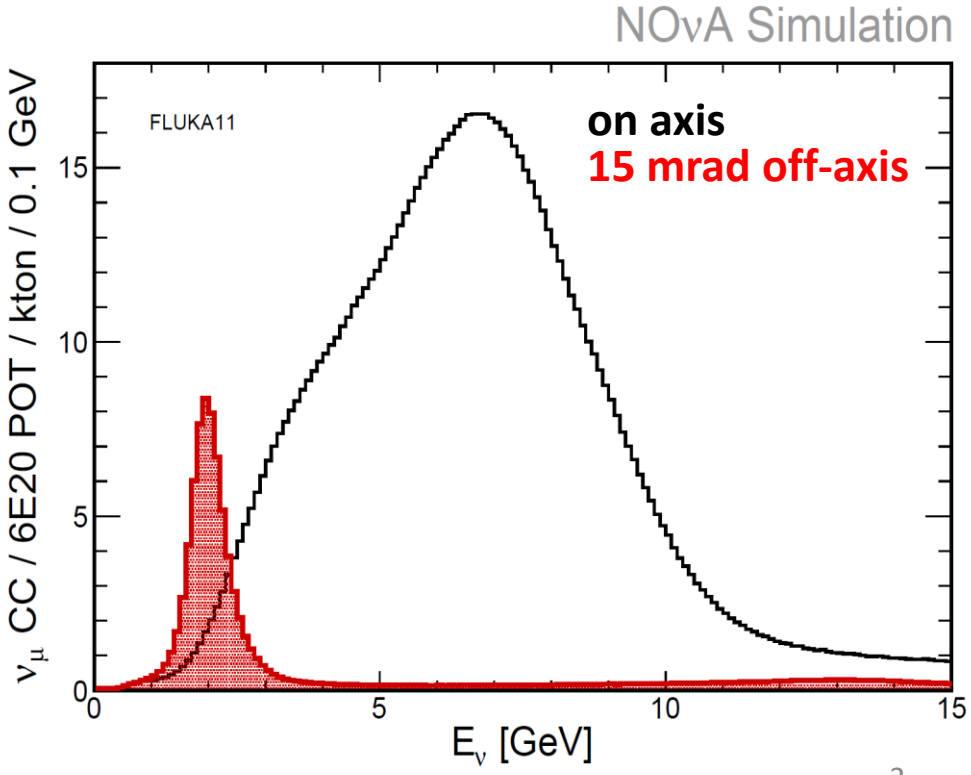
July 26, 2017

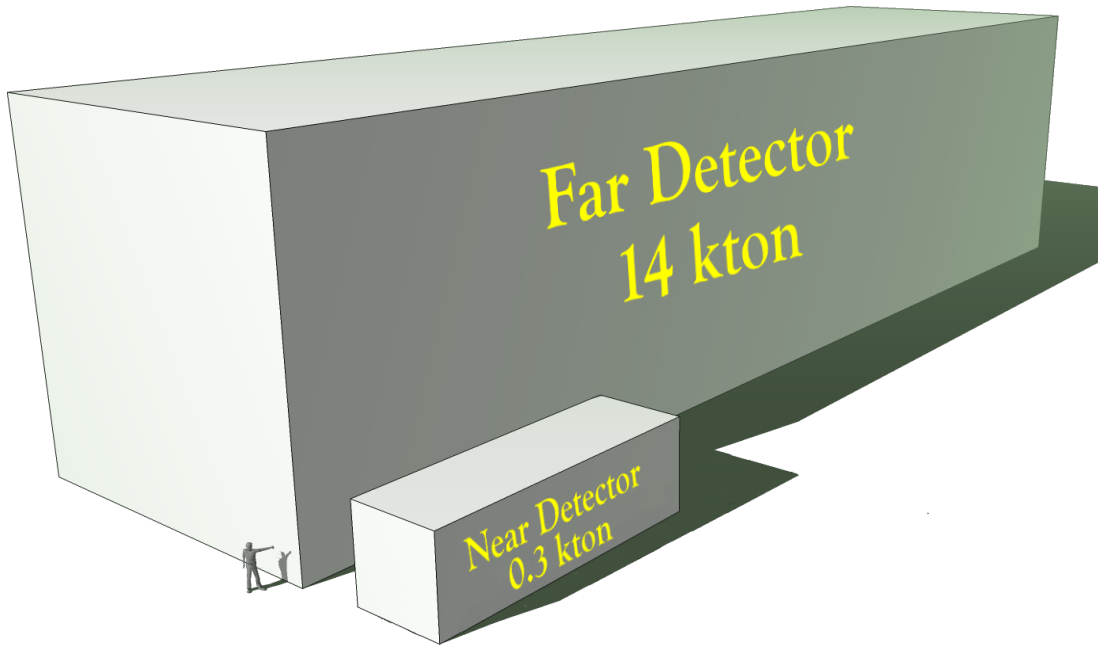
TAUP 2017, Sudbury, Canada

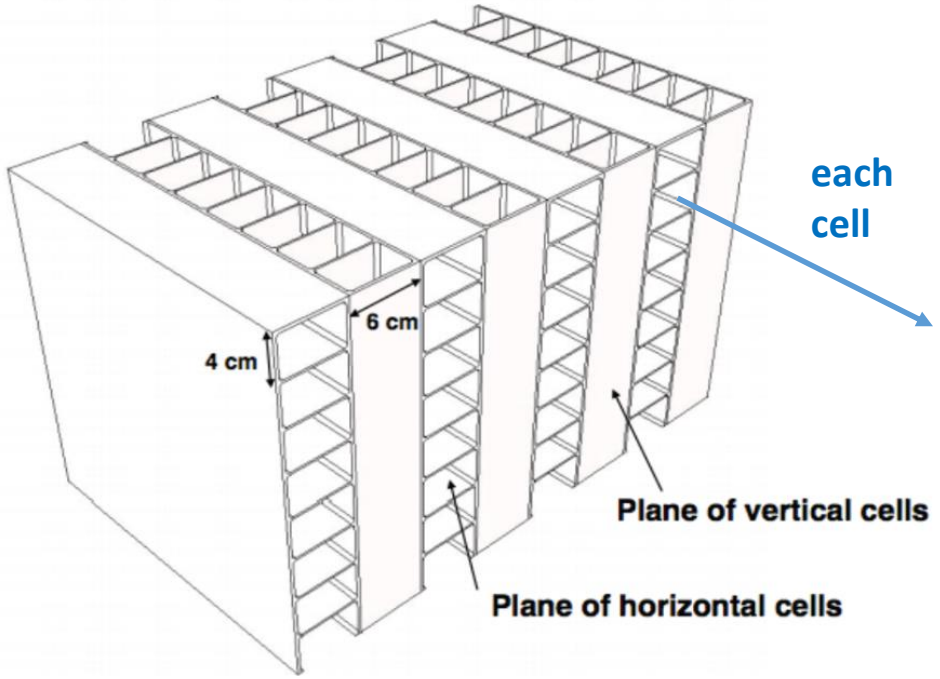


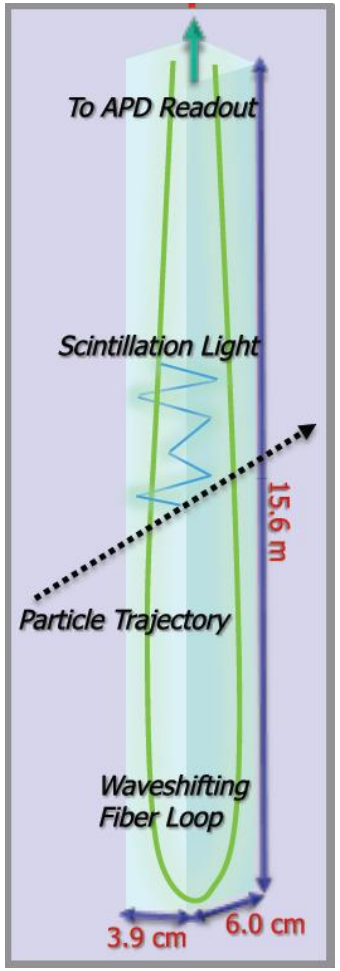
NOvA Overview

- **NOvA (NuMI Off-axis ν Appearance)**
- **Source: NuMI ν_μ beam (FNAL)**
- **Far Det (FD) (810 km @ Ash River, MN)**
- **Near Detector (ND) (1km @ FNAL)**
- **15 mrad off-axis (tight energy peak)**





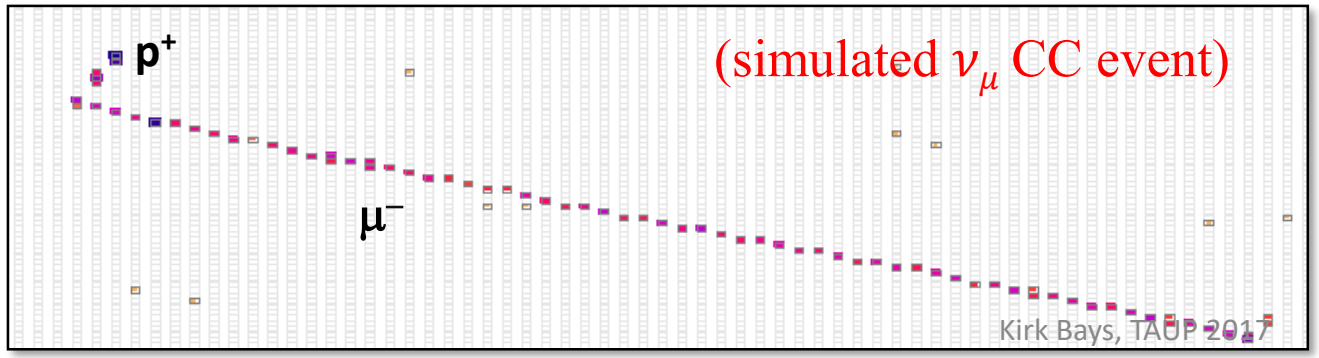


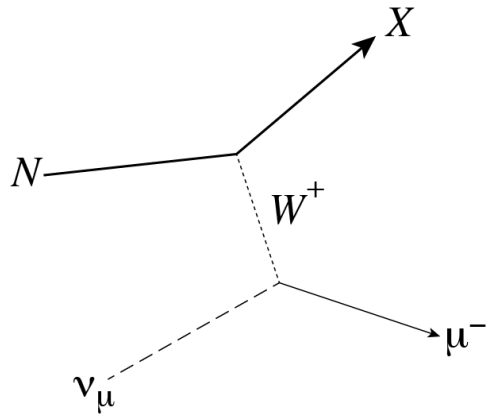


- **FD (at Ash River, MN, 810 km baseline):**
  - 16m x 16m x 60m, 14kton, on surface (some barite overburden)
  - ~2/3 LS by mass, ~344,000 cells, 896 planes (64 planes = 1 kton = 1 diblock)
  - 99.5% of channels operational
- **ND (@ FNAL, 1km from NuMI target):**
  - 4m x 4m x 16m, 0.3kton, underground
  - ~20,000 cells, design similar to FD
  - main differences: size and ND `muon catcher', a range stack at the back end of alternating steel and scintillator planes

ν_μ Disappearance

- **Start with a beam of ν_μs, oscillate to other flavors**
- **$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \sin^2(2\theta_{23})\sin^2(1.27\Delta m^2_{32}L/E)$**
- **Direct measurement of θ_{23} (maximal?), Δm^2_{32}**
- **Backgrounds for disappearance:**
  - **NC neutrino events**
  - **Cosmic ray background**
- **Signature:**
  - **high E muon**
  - **possible vertex hadronic activity**





Second analysis results
published recently (PRL April 2017)
These results shown next
based on 6.05e20 pot
Phys. Rev. Lett. 118 (2017) no. 15, 151802

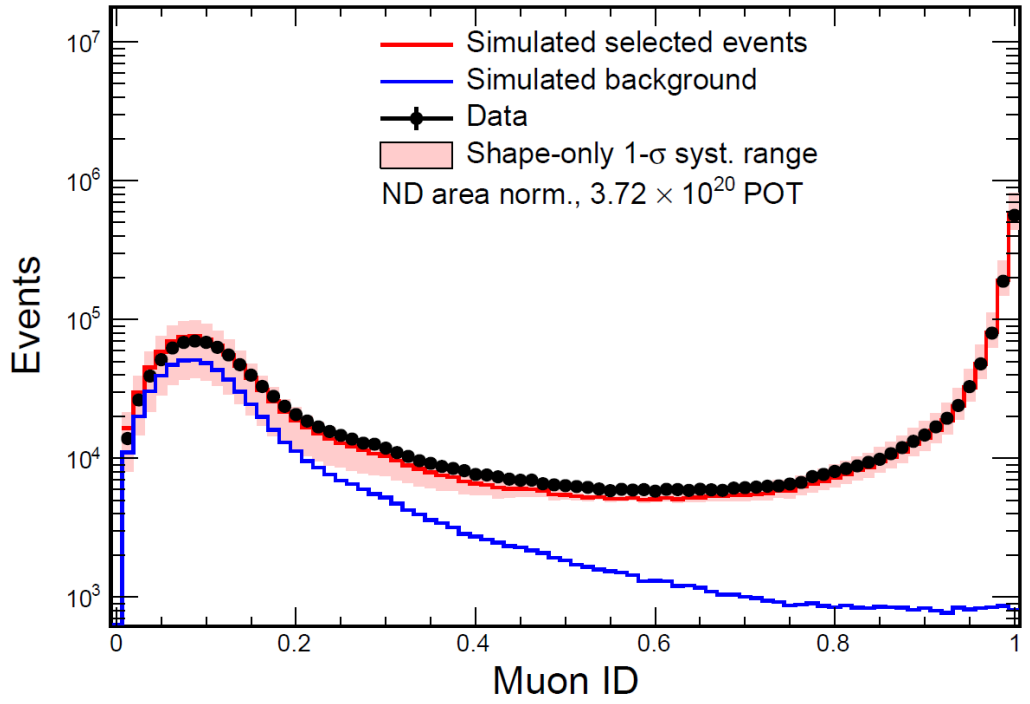
FERMILAB-PUB-17-019-ND

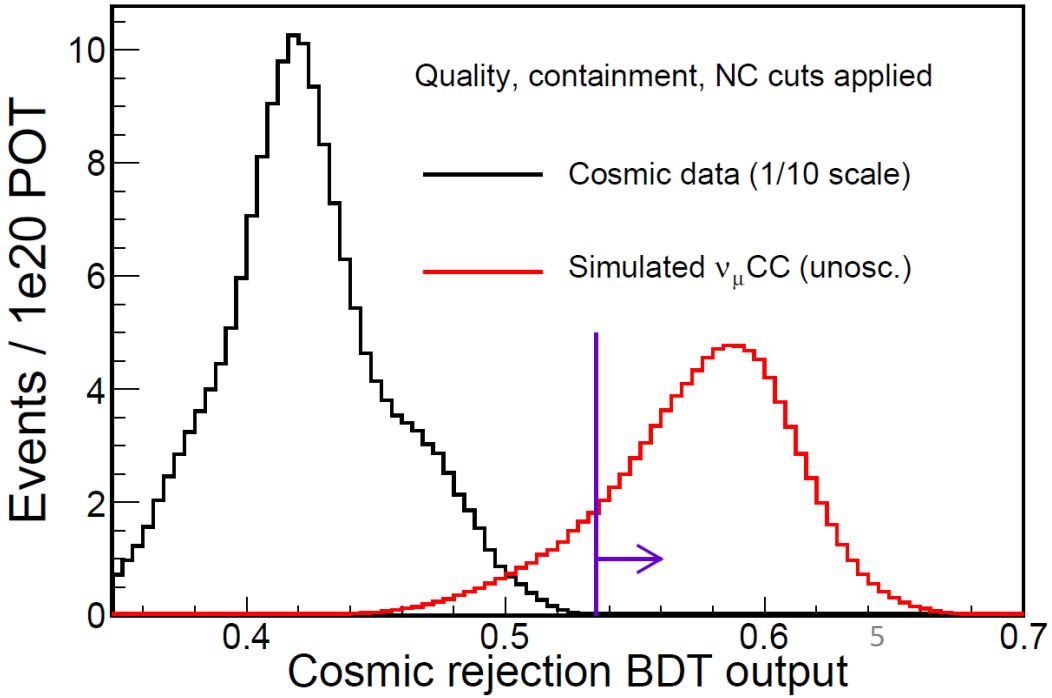
Measurement of the neutrino mixing angle θ_{23} in NOvA

P. Adamson,[11] L. Aliaga,[11] D. Ambrose,[26] N. Anfimov,[22] A. Antoshkin,[22] E. Arrieta-Diaz,[31] K. Augsten,[9] A. Aurisano,[6] C. Backhouse,[4] M. Baird,[33,17] B. A. Bambah,[15] K. Bays,[4] B. Behera,[16] S. Bending,[37] R. Bernstein,[11] V. Bhatnagar,[27] B. Bhuyan,[13] J. Bian,[20,26] T. Blackburn,[33] A. Bolshakova,[22] C. Bromberg,[24] J. Brown,[26] G. Brunetti,[11] N. Buchanan,[8] A. Butkevich,[18] V. Bychkov,[26] M. Campbell,[37] E. Catano-Mur,[19] S. Childress,[11] B. C. Choudhary,[10] B. Chowdhury,[29] T. E. Coan,[31] J. A. B. Coelho,[36] M. Colo,[40] J. Cooper,[11] L. Corwin,[30] L. Cremonesi,[37] D. Cronin-Hennessy,[26] G. S. Davies,[17] J. P. Davies,[33] P. F. Derwent,[11] S. Desai,[26] R. Dharmapalan,[1] P. Ding,[11] Z. Djurcic,[1] E. C. Dukes,[38] H. Duyang,[29] S. Edayath,[7] R. Ehrlich,[38] G. J. Feldman,[14] M. J. Frank,[28,38] M. Gabrielyan,[26] H. R. Gallagher,[36] S. Germani,[37] T. Ghosh,[12] A. Giri,[16] R. A. Gomes,[12] M. C. Goodman,[1] V. Grichine,[23] R. Group,[38] D. Grover,[3] B. Guo,[29] A. Habig,[25] J. Hartnell,[33] R. Hatcher,[11] A. Hatzikoutelis,[34] K. Heller,[26] A. Himmel,[11] A. Holin,[37] J. Hylen,[11] F. Jediny,[9] M. Judah,[8] G. K. Kafka,[14] D. Kalra,[27] S. M. S. Kasahara,[26] S. Kasetti,[15] R. Keloth,[7] L. Kolupaeva,[22] S. Kotelnikov,[23] I. Kourbanis,[11] A. Kreymer,[11] A. Kumar,[27] S. Kurbanov,[38] K. Lang,[35] W. M. Lee,[11,*] S. Lin,[8] J. Liu,[40] M. Lokajicek,[2] J. Lozier,[4] S. Luchuk,[18] K. Maan,[27] S. Magill,[1] W. A. Mann,[36] M. L. Marshak,[26] K. Matera,[11] V. Matveev,[18] D. P. Méndez,[33] M. D. Messier,[17] H. Meyer,[39] T. Miao,[11] W. H. Miller,[26] S. R. Mishra,[29] R. Mohanta,[15] A. Moren,[25] L. Mualem,[4] M. Muether,[39] S. Mufson,[17] R. Murphy,[17] J. Musser,[17] J. K. Nelson,[40] R. Nichol,[37] E. Niner,[17,11] A. Norman,[11] T. Nosek,[5] Y. Oksuzian,[38] A. Olshevskiy,[22] T. Olson,[36] J. Paley,[11] P. Pandey,[10] R. B. Patterson,[4] G. Pawloski,[26] D. Pershey,[4] O. Petrova,[22] R. Petti,[29] S. Phan-Budd,[41] R. K. Plunkett,[11] R. Poling,[26] B. Potukuchi,[21] C. Principato,[38] F. Psihas,[17] A. Radovic,[40] R. A. Rameika,[11] B. Rebel,[11] B. Reed,[30] D. Rocco,[26] P. Rojas,[8] V. Ryabov,[23] K. Sachdev,[11,26] P. Sail,[35] O. Samoylov,[22] M. C. Sanchez,[19] R. Schroeter,[14] J. Sepulveda-Quiroz,[19] P. Shanahan,[11] A. Sheshukov,[22] J. Singh,[27] J. Singh,[21] P. Singh,[10] V. Singh,[3] J. Smolik,[9] N. Solomey,[39] E. Song,[38] A. Sousa,[6] K. Soustruznik,[5] M. Strait,[26] L. Suter,[1,11] R. L. Talaga,[1] M. C. Tamsett,[33] P. Tas,[5] R. B. Thayyullathil,[7] J. Thomas,[37] X. Tian,[29] S. C. Tognini,[12] J. Tripathi,[27] A. Tsaris,[11] J. Urheim,[17] P. Vahle,[40] J. Vasel,[17] L. Vinton,[33] A. Vold,[26] T. Vrba,[9] B. Wang,[31] M. Wetstein,[19] D. Whittington,[17] S. G. Wojcicki,[32] J. Wolcott,[36] N. Yadav,[13] S. Yang,[6] J. Zalesak,[2] B. Zamorano,[33] and R. Zwaska[11]

ν_μ: Background reduction

- Cut 1: Quality cuts
  - remove junk
- Cut 2: Containment
  - require containment for E reconstruction
- Cut 3: Remove NC events
  - kNN utilizing muon track length, dE/dx, scattering, more
- Cut 4: Remove cosmic ray muons
  - FD is on surface, many cosmic rays
  - use timing for first step: neutrinos only in 10 μs window every 1.3 s
  - still require further ~10^7 reduction
  - use BDT to get remainder of reduction; inputs include track angles, containment, hadronic activity

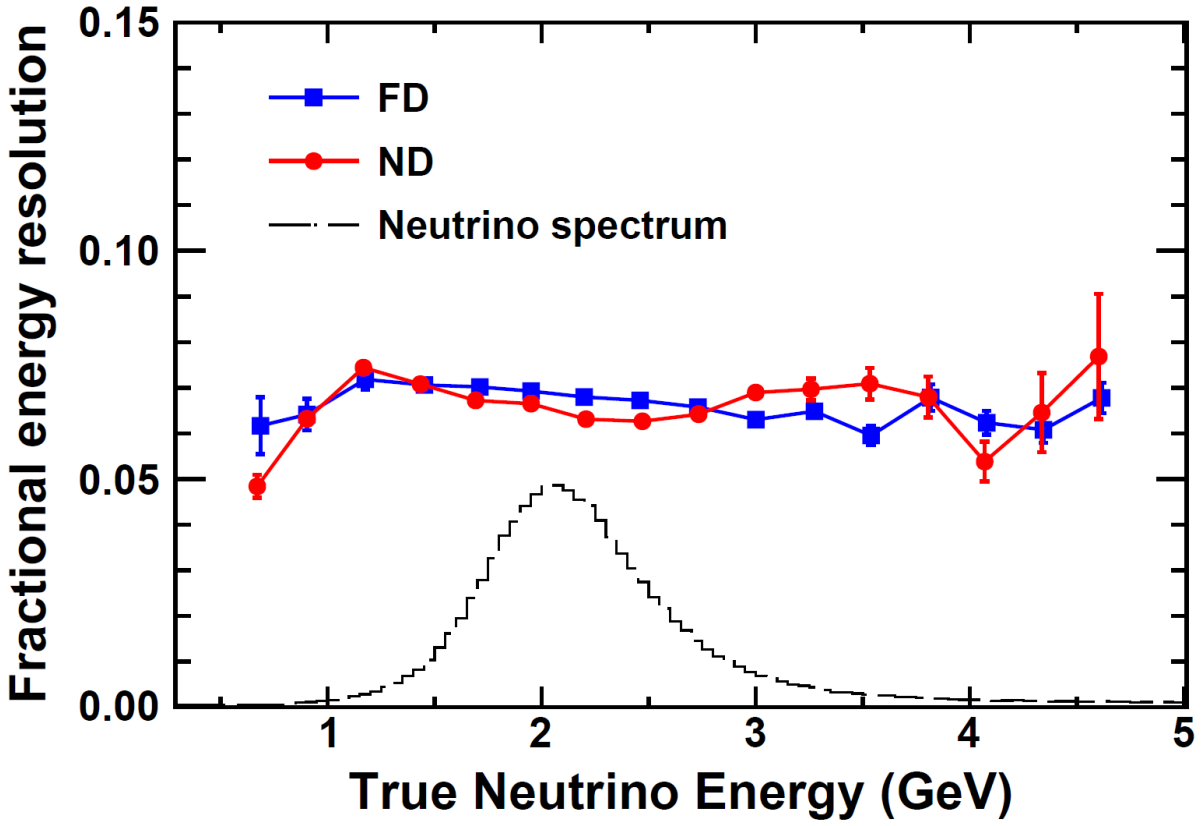


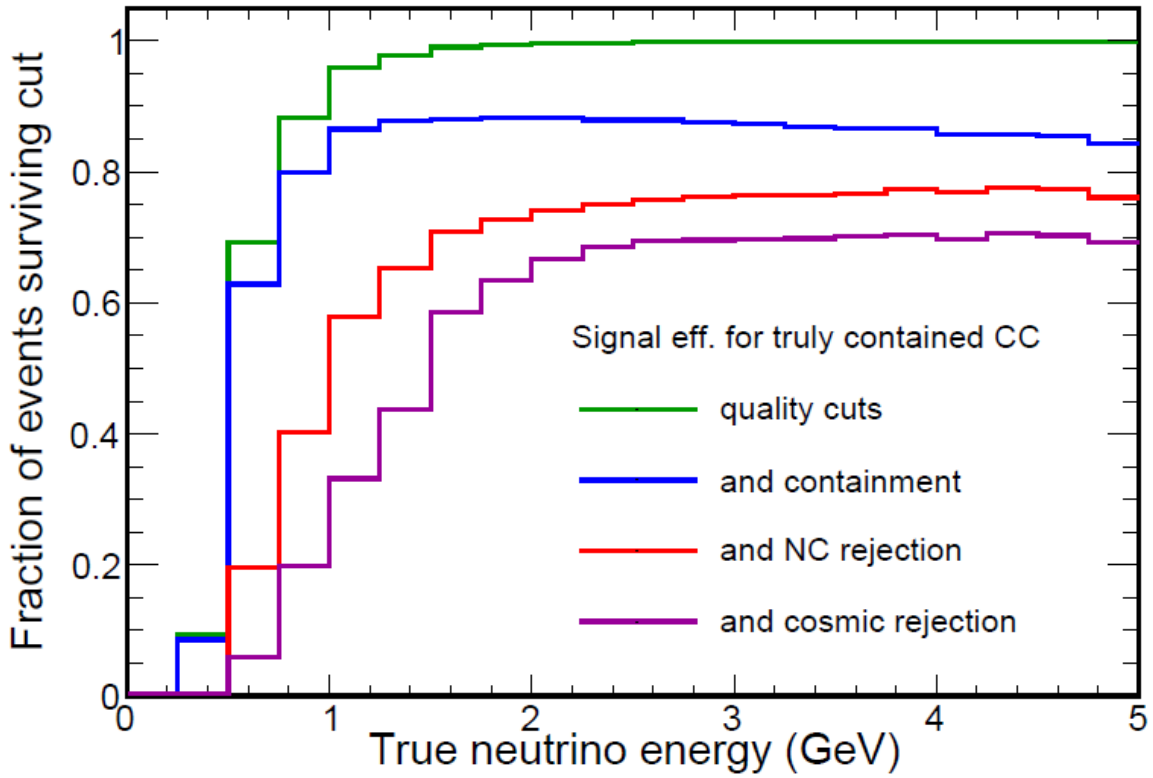


ν_μ: E reco and efficiency

MC estimate at:
$\sin^2\theta_{23}=0.5$
$\Delta m^2_{32}=2.35\times10^{-3}$ eV^2

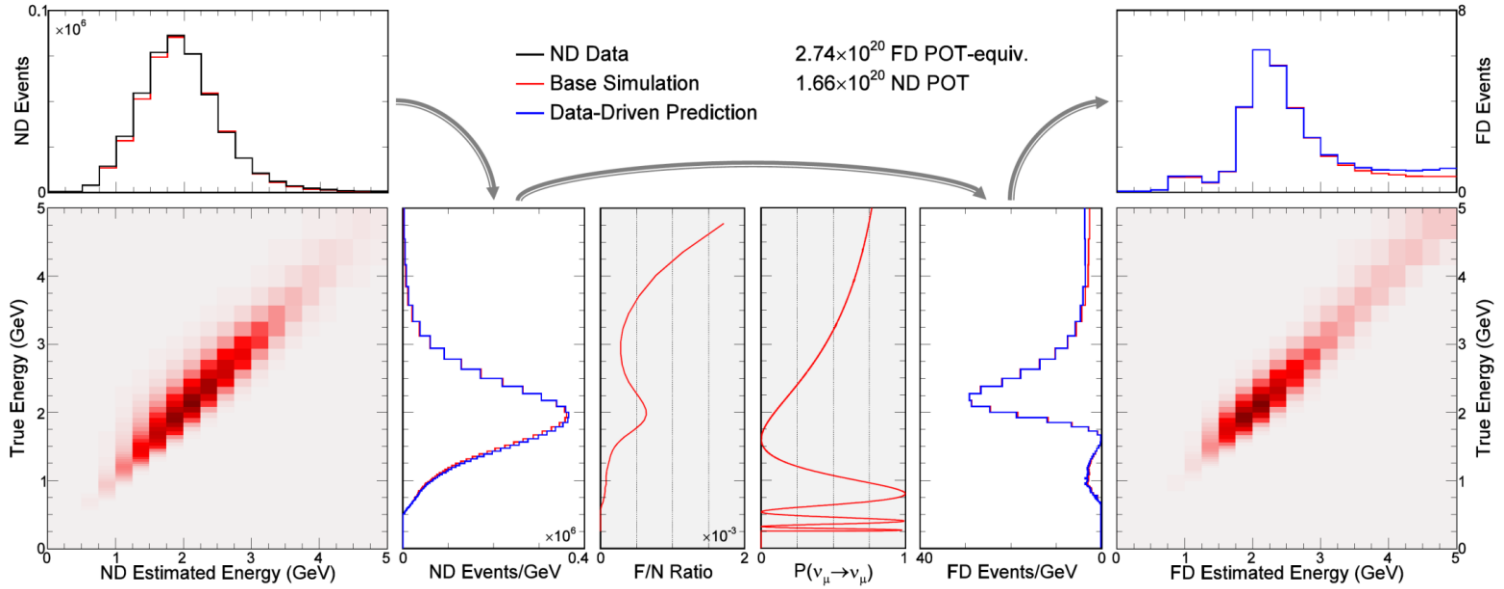
- Neutrino E resolution ~7% FD and ND
- Signal efficiency is function of E





ν_μ: Systematics and extrapolation

- Full 3-flavor far over near extrapolation
- Since ND and FD almost identical many systematics cancel (ie flux)
- Remaining large systematics include energy scales and cross-sections
- 2p2h is included in this analysis, starting with Dytman's empirical MEC model and tuning it to our ND data. Cross-section uncertainties includes 2p2h

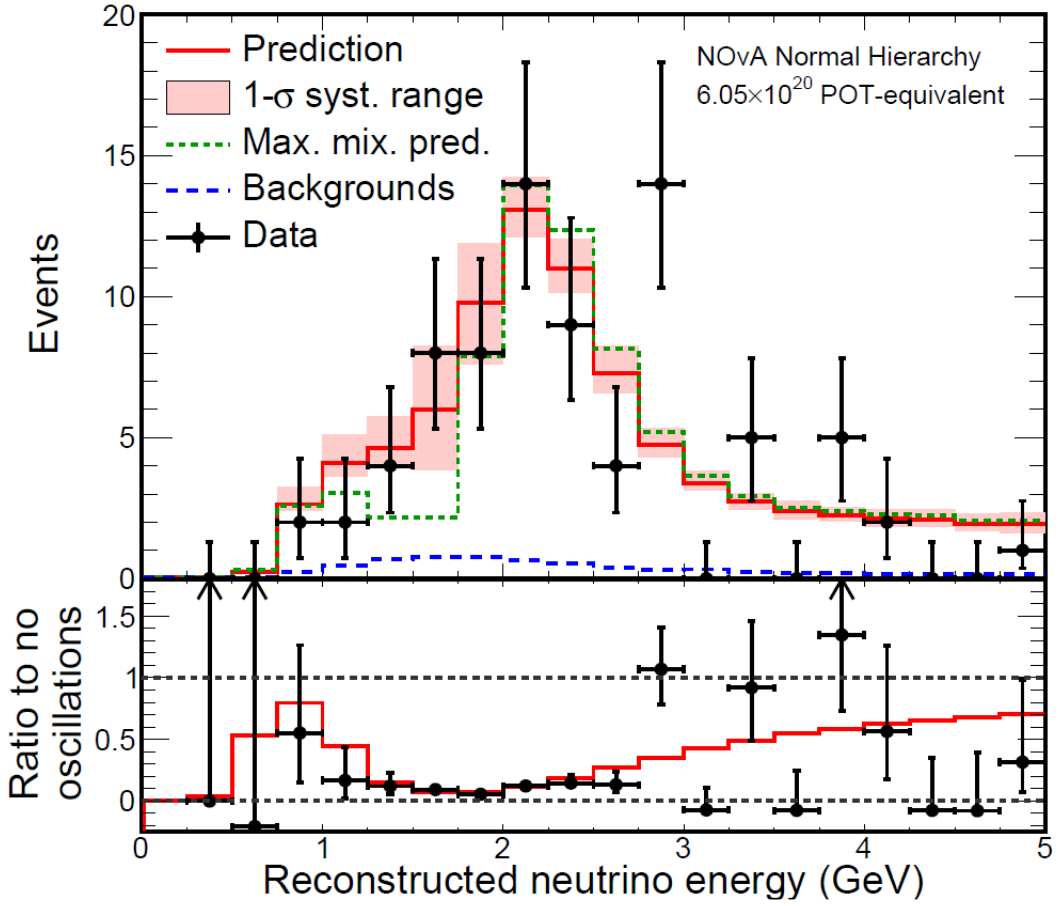


Source of uncertainty	Uncertainty in $\sin^2\theta_{23}(\times10^{-3})$	Uncertainty in Δm^2_{32} $(\times10^{-6}$ eV$^2)$
Absolute muon energy scale [±2%]	+9 / -8	+3 / -10
Relative muon energy scale [±2%]	+9 / -9	+23 / -14
Absolute hadronic energy scale [±5%]	+5 / -5	+7 / -3
Relative hadronic energy scale [±5%]	+10 / -11	+29 / -19
Normalization [±5%]	+5 / -5	+4 / -8
Cross sections and final-state interactions	+3 / -3	+12 / -15
Neutrino flux	+1 / -2	+4 / -7
Beam background normalization [±100%]	+3 / -6	+10 / -16
Scintillation model	+4 / -3	+2 / -5
δ_{CP} $(0-2\pi)$	+0.2 / -0.3	+10 / -9
Total systematic uncertainty	+17 / -19	+50 / -47
Statistical uncertainty	+21 / -23	+93 / -99

assuming upper octant

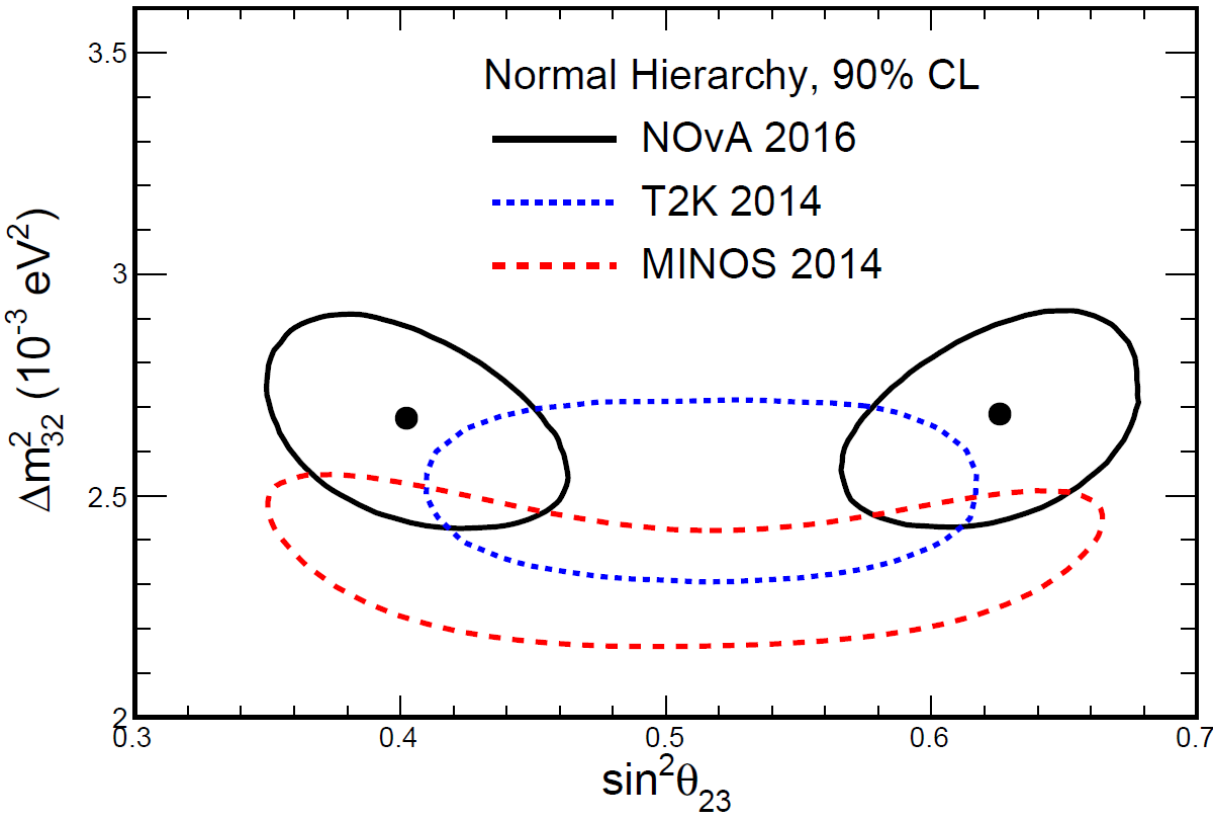
ν_μ: Results

- χ^2 spectrum fit with systematics as nuisance parameters

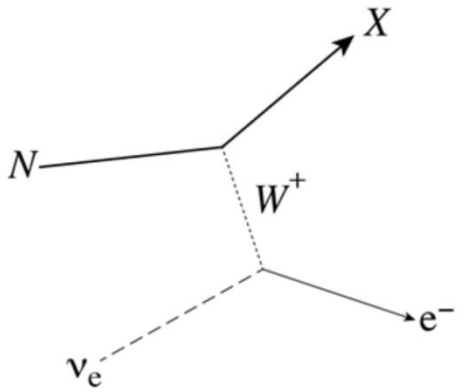


Results:

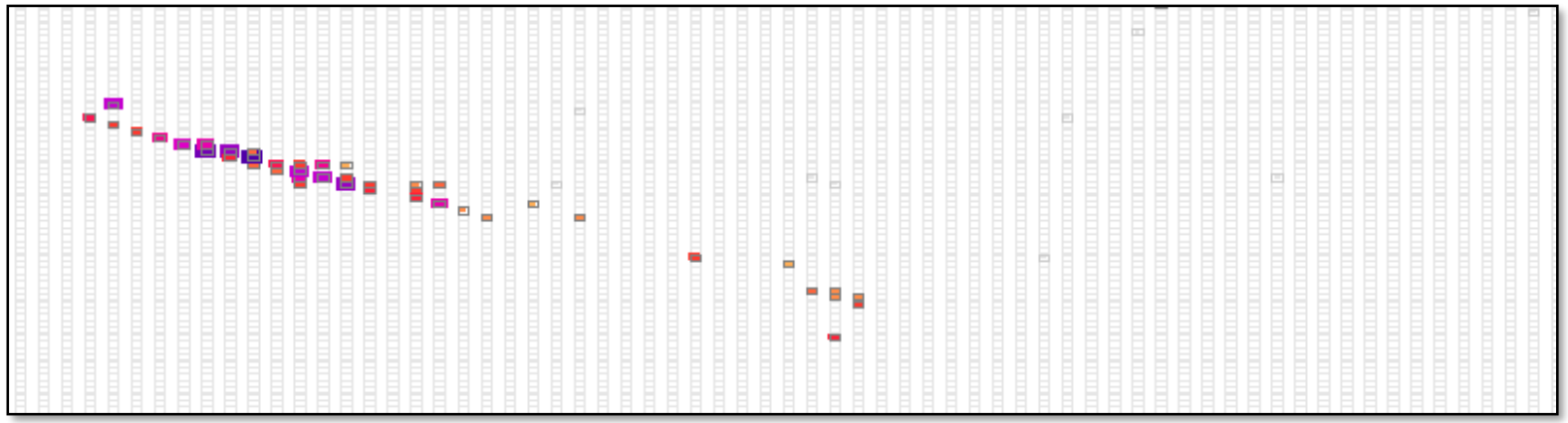
- Δm^2: 2.67 +- .11
- $\sin^2\theta_{23}$: .402 + .03 - 0.22 (.626+.22-.03)
- inconsistent with maximal mixing at 2.6 σ



ν_e Appearance



- ν_μs in beam oscillate to ν_e
  - $P(\nu_\mu \rightarrow \nu_e) \sim \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2(\Delta m^2_{31} L/4E)$
- Measure θ_{13}, possibly hierarchy, constrain δ_{CP}
- Background: beam contamination, NC, cosmics
- Signature is EM shower from electron



$\nu_e + \nu_\mu$ joint analysis
6.05e20 pot data
published PRL May 2017
this result shown next
Phys. Rev. Lett. 118 (2017) no. 23, 231801

FERMILAB-PUB-17-065-ND

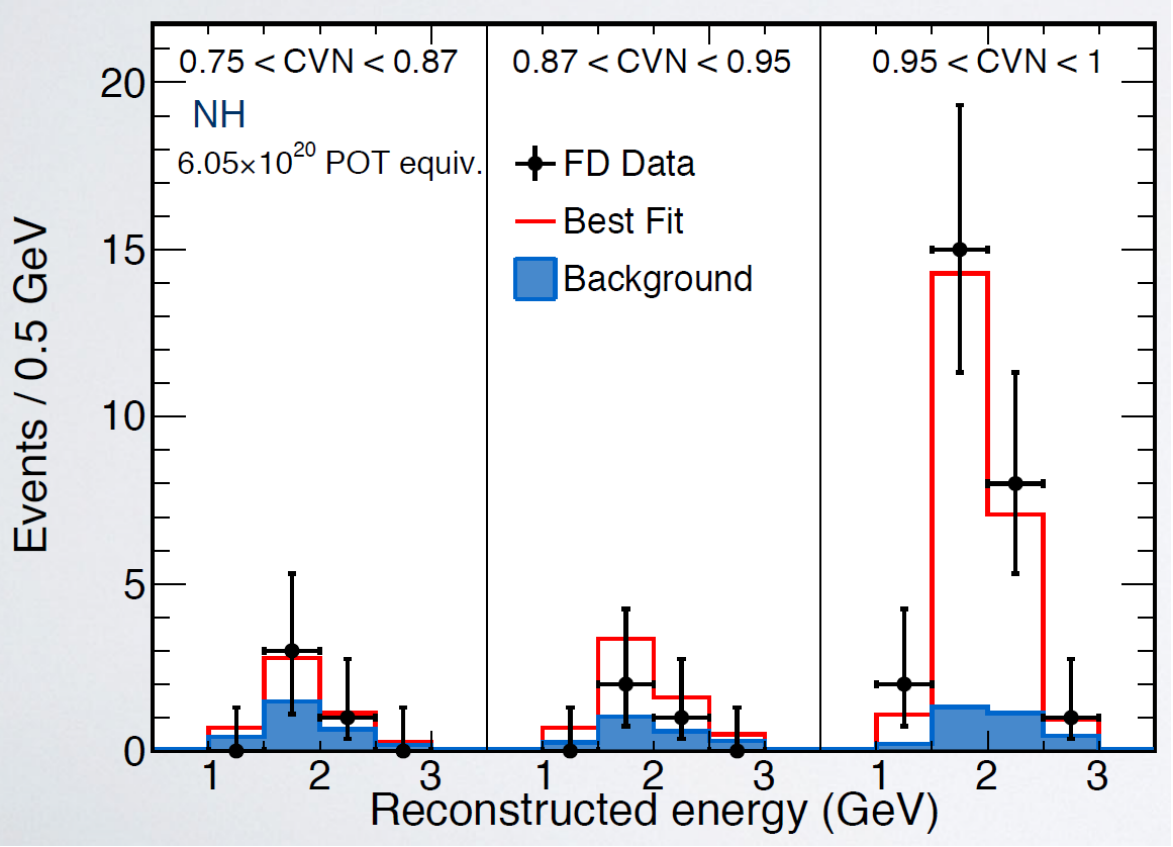
Constraints on Oscillation Parameters from ν_e Appearance and ν_μ Disappearance in NOvA

P. Adamson,[11] L. Aliaga,[11] D. Ambrose,[26] N. Anfimov,[22] A. Antoshkin,[22] E. Arrieta-Diaz,[31] K. Augsten,[9] A. Aurisano,[6] C. Backhouse,[4] M. Baird,[33,17] B. A. Bambah,[15] K. Bays,[4] B. Behera,[16] S. Bending,[37] R. Bernstein,[11] V. Bhatnagar,[27] B. Bhuyan,[13] J. Bian,[20,26] T. Blackburn,[33] A. Bolshakova,[22] C. Bromberg,[24] J. Brown,[26] G. Brunetti,[11] N. Buchanan,[8] A. Butkevich,[18] V. Bychkov,[26] M. Campbell,[37] E. Catano-Mur,[19] S. Childress,[11] B. C. Choudhary,[10] B. Chowdhury,[29] T. E. Coan,[31] J. A. B. Coelho,[36] M. Colo,[40] J. Cooper,[11] L. Corwin,[30] L. Cremonesi,[37] D. Cronin-Hennessy,[26] G. S. Davies,[17] J. P. Davies,[33] P. F. Derwent,[11] R. Dharmapalan,[1] P. Ding,[11] Z. Djurcic,[1] E. C. Dukes,[38] H. Duyang,[29] S. Edayath,[7] R. Ehrlich,[38] G. J. Feldman,[14] M. J. Frank,[28,38] M. Gabrielyan,[26] H. R. Gallagher,[36] S. Germani,[37] T. Ghosh,[12] A. Giri,[16] R. A. Gomes,[12] M. C. Goodman,[1] V. Grichine,[23] R. Group,[38] D. Grover,[3] B. Guo,[29] A. Habig,[25] J. Hartnell,[33] R. Hatcher,[11] A. Hatzikoutelis,[34] K. Heller,[26] A. Himmel,[11] A. Holin,[37] J. Hylen,[11] F. Jediny,[9] M. Judah,[8] G. K. Kafka,[14] D. Kalra,[27] S. M. S. Kasahara,[26] S. Kasetti,[15] R. Keloth,[7] L. Kolupaeva,[22] S. Kotelnikov,[23] I. Kourbanis,[11] A. Kreymer,[11] A. Kumar,[27] S. Kurbanov,[38] K. Lang,[35] W. M. Lee,[11,*] S. Lin,[8] J. Liu,[40] M. Lokajicek,[2] J. Lozier,[4] S. Luchuk,[18] K. Maan,[27] S. Magill,[1] W. A. Mann,[36] M. L. Marshak,[26] K. Matera,[11] V. Matveev,[18] D. P. Méndez,[33] M. D. Messier,[17] H. Meyer,[39] T. Miao,[11] W. H. Miller,[26] S. R. Mishra,[29] R. Mohanta,[15] A. Moren,[25] L. Mualem,[4] M. Muether,[39] S. Mufson,[17] R. Murphy,[17] J. Musser,[17] J. K. Nelson,[40] R. Nichol,[37] E. Niner,[17,11] A. Norman,[11] T. Nosek,[5] Y. Oksuzian,[38] A. Olshevskiy,[22] T. Olson,[36] J. Paley,[11] P. Pandey,[10] R. B. Patterson,[4] G. Pawloski,[26] D. Pershey,[4] O. Petrova,[22] R. Petti,[29] S. Phan-Budd,[41] R. K. Plunkett,[11] R. Poling,[26] B. Potukuchi,[21] C. Principato,[38] F. Psihas,[17] A. Radovic,[40] R. A. Rameika,[11] B. Rebel,[11] B. Reed,[30] D. Rocco,[26] P. Rojas,[8] V. Ryabov,[23] K. Sachdev,[11,26] P. Sail,[35] O. Samoylov,[22] M. C. Sanchez,[19] R. Schroeter,[14] J. Sepulveda-Quiroz,[19] P. Shanahan,[11] A. Sheshukov,[22] J. Singh,[27] J. Singh,[21] P. Singh,[10] V. Singh,[3] J. Smolik,[9] N. Solomey,[39] E. Song,[38] A. Sousa,[6] K. Soustruznik,[5] M. Strait,[26] L. Suter,[1,11] R. L. Talaga,[1] M. C. Tamsett,[33] P. Tas,[5] R. B. Thayyullathil,[7] J. Thomas,[37] X. Tian,[29] S. C. Tognini,[12] J. Tripathi,[27] A. Tsaris,[11] J. Urheim,[17] P. Vahle,[40] J. Vasel,[17] L. Vinton,[33] A. Vold,[26] T. Vrba,[9] B. Wang,[31] M. Wetstein,[19] D. Whittington,[17] S. G. Wojcicki,[32] J. Wolcott,[36] N. Yadav,[13] S. Yang,[6] J. Zalesak,[2] B. Zamorano,[33] and R. Zwaska[11]

(The NOvA Collaboration)

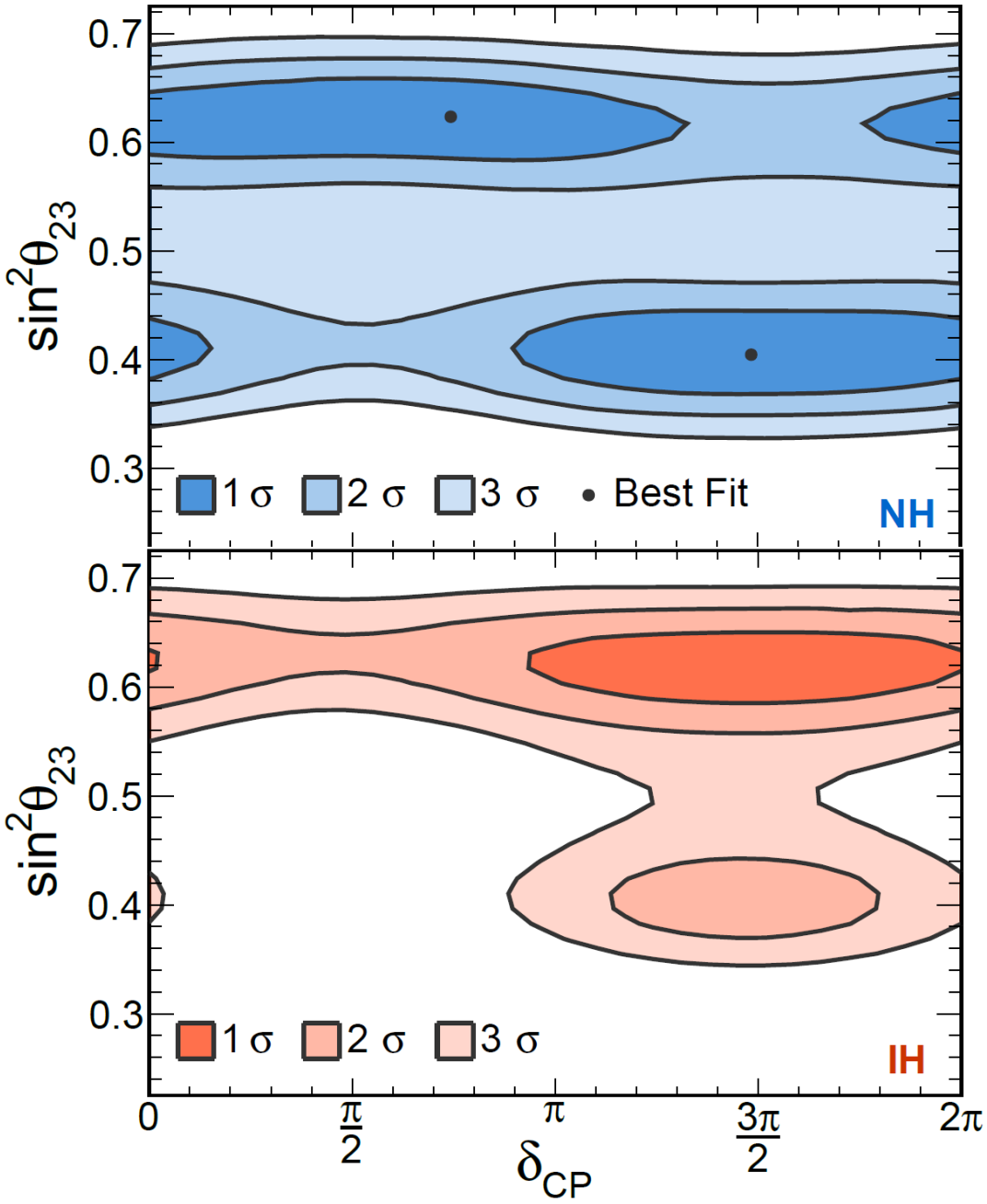
ν_e: Selection

- Cosmic rays are an easier problem since the signal signature isn't a muon; a cut eliminates these
- Then signal is isolated by use of a **C**onvolutional **V**isual **N**etwork
- This advanced deep-learning technique uses the raw pixel maps, which are transformed to pull out abstract features, which are fed into a neural network
- 30% signal efficiency increase over our first analysis
- Data divided into 3 CVN bins x 4 energy bins

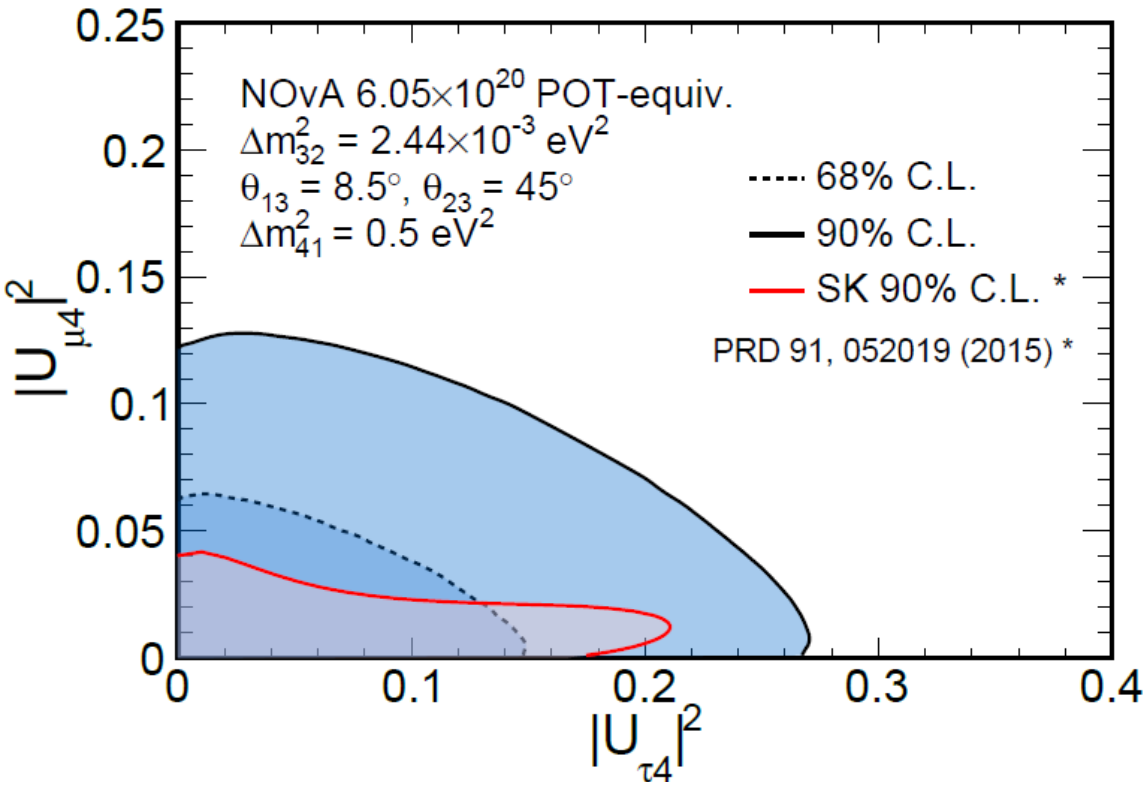


ν_e: Results

- 33 final ν_e events pass selection
  - background 8.2+-0.8
- The data is combined with the ν_μ data and fit simultaneously to extract δ_{CP} information
- Because the number of selection events is high, IH hierarchy with δ_{CP} values between 0 and π are largely excluded



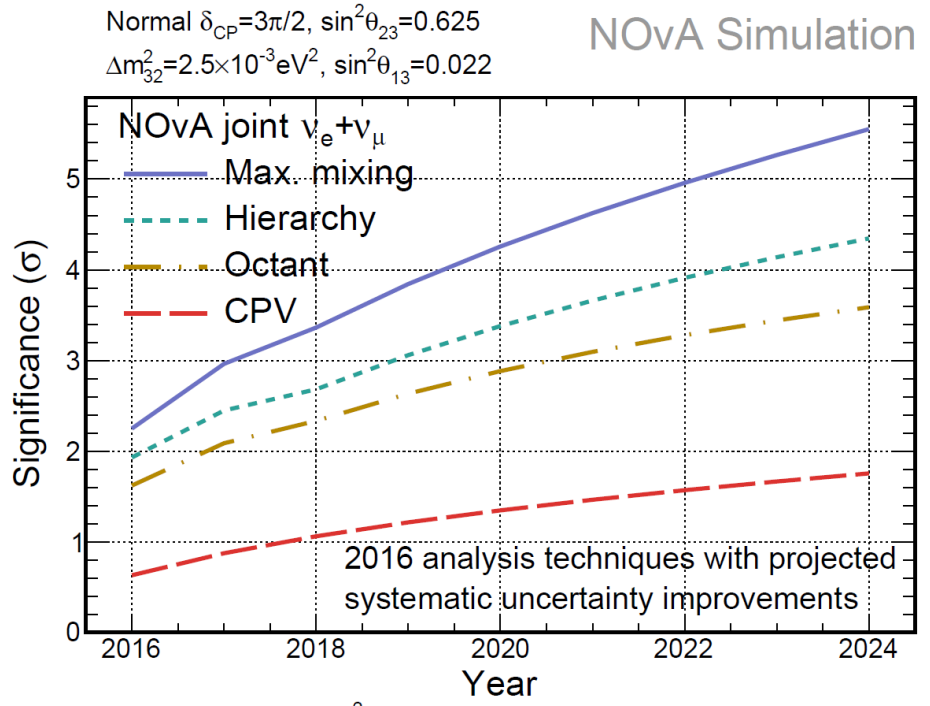
Sterile analysis

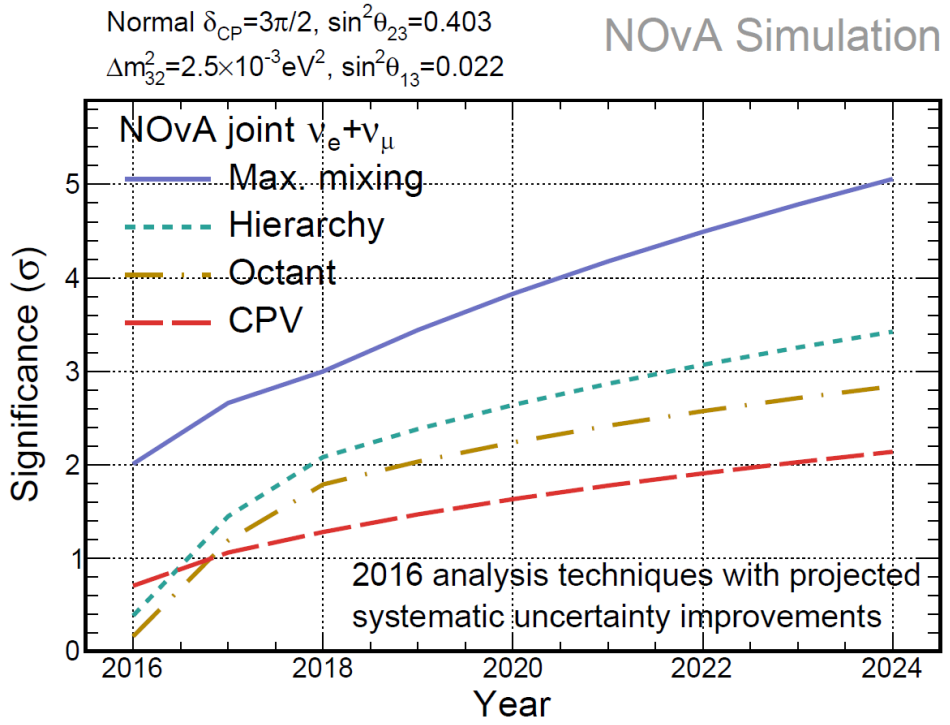


- A recent search for sterile neutrinos by looking for NC oscillations
- No evidence for sterile oscillations, constraints set
- Paper submitted, arXiv version:
  - arXiv:1706.04592
- Check it out!

Next for NOvA

- Preparing for next data release: 9e20 data neutrino mode (50% increase)
- Also analysis improvements:
  - better systematics
  - using CVN for ν_μ
  - improved cuts
  - revised 2p2h and x-section handling
- Timescale for 9e20: by end of year
- Just finished taking anti-neutrino mode data (~3.5e20 pot), currently on shutdown, will take more after
- Anti-neutrino and joint neutrino/anti-neutrino analyses in the works

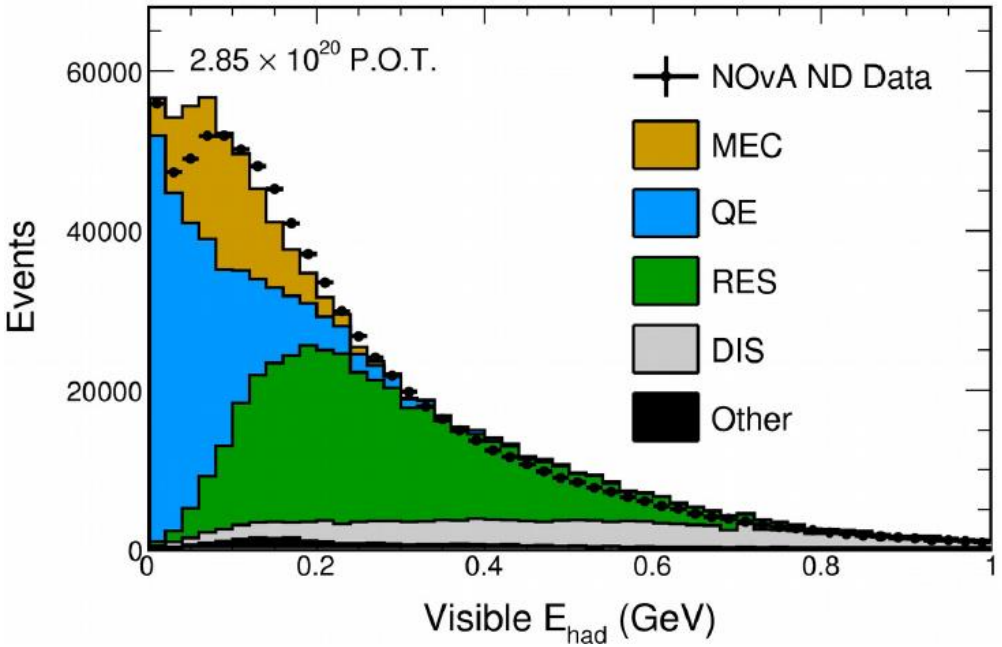


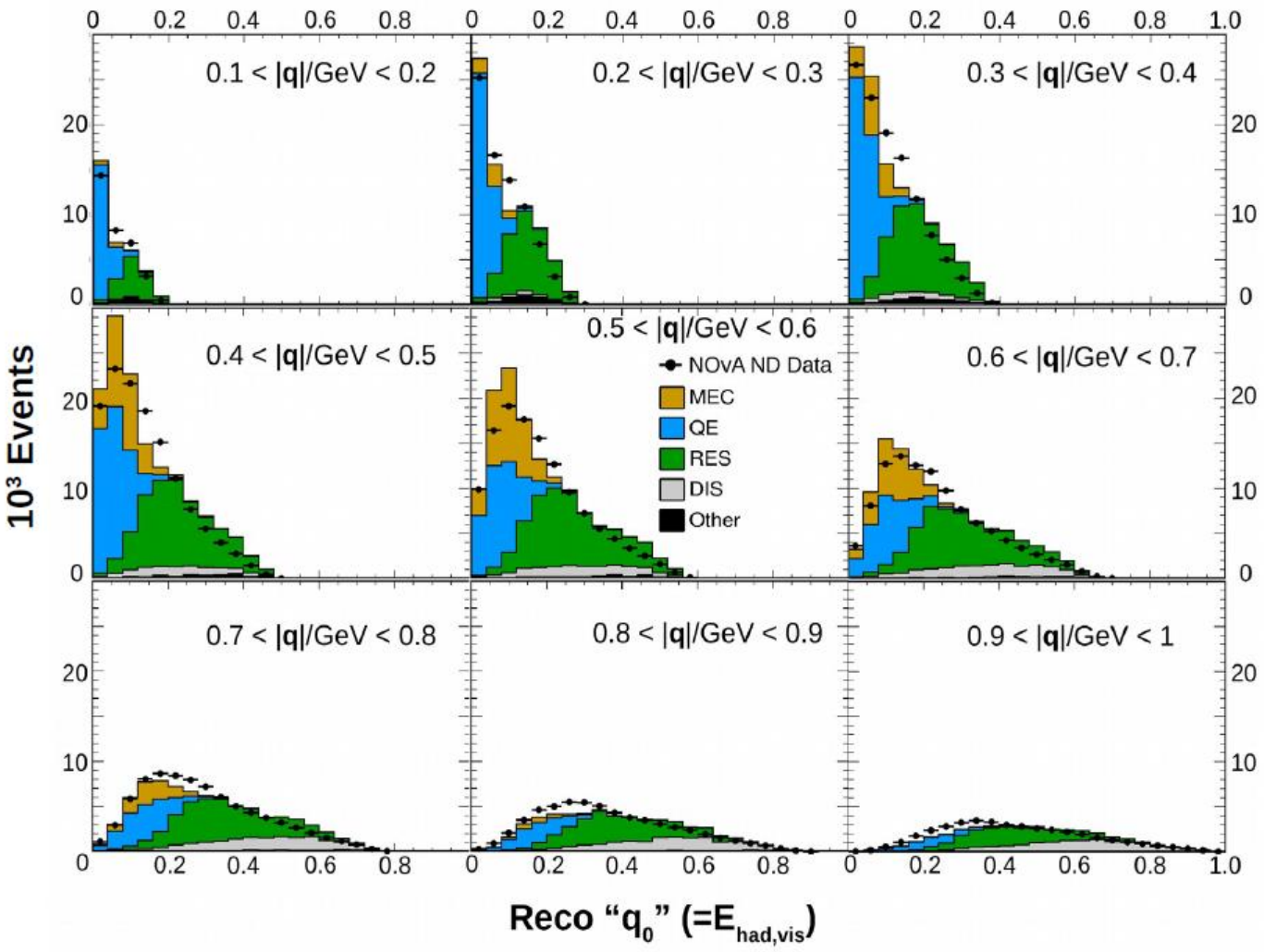



Thanks!
Fermilab

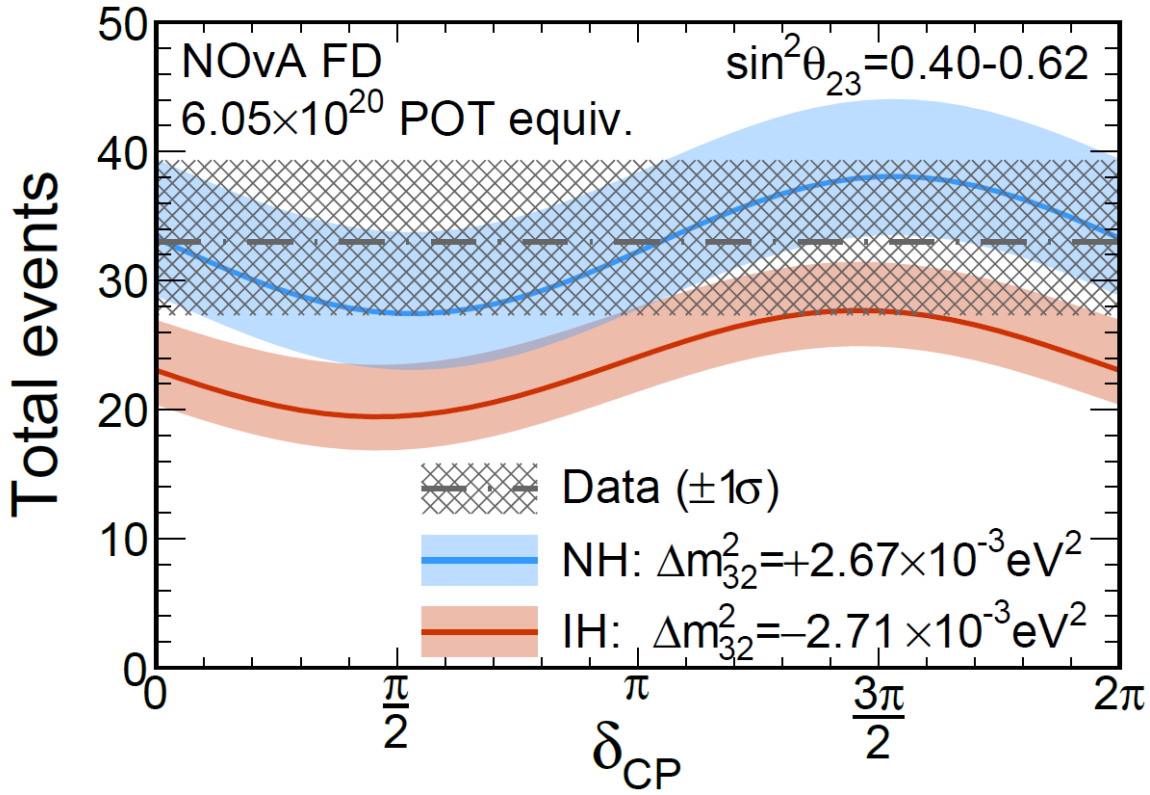
Backups

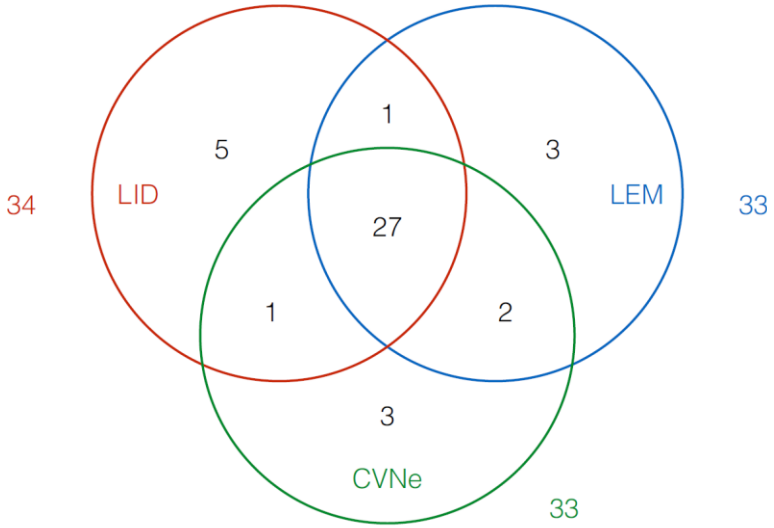
2p2h





2 functional parameters: q0 and |q|
q0 taken to match QE
|q| tuned to our ND data





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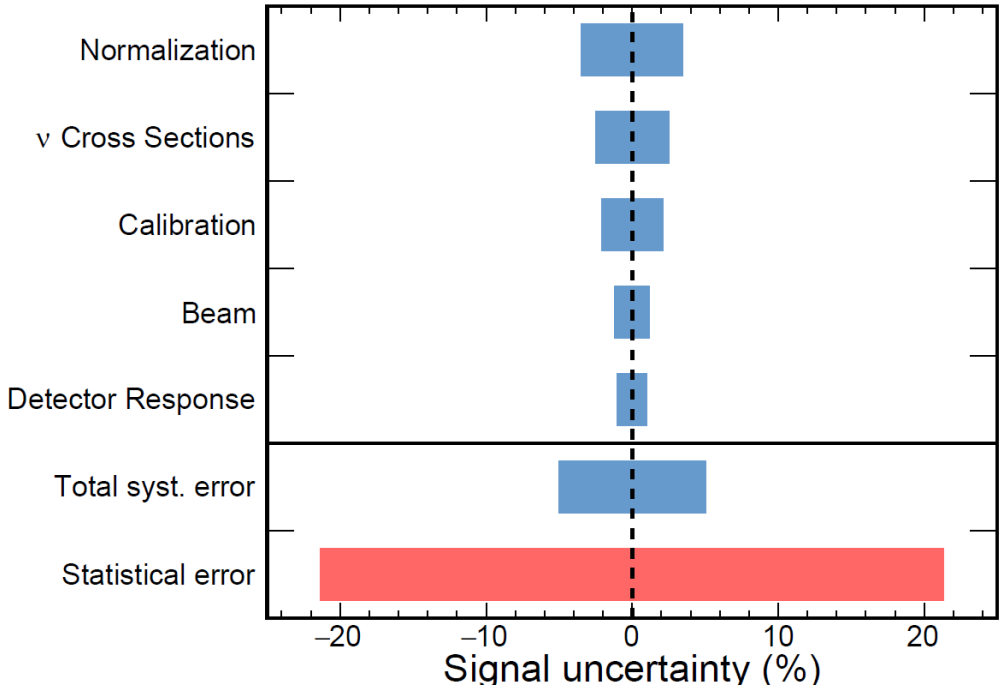
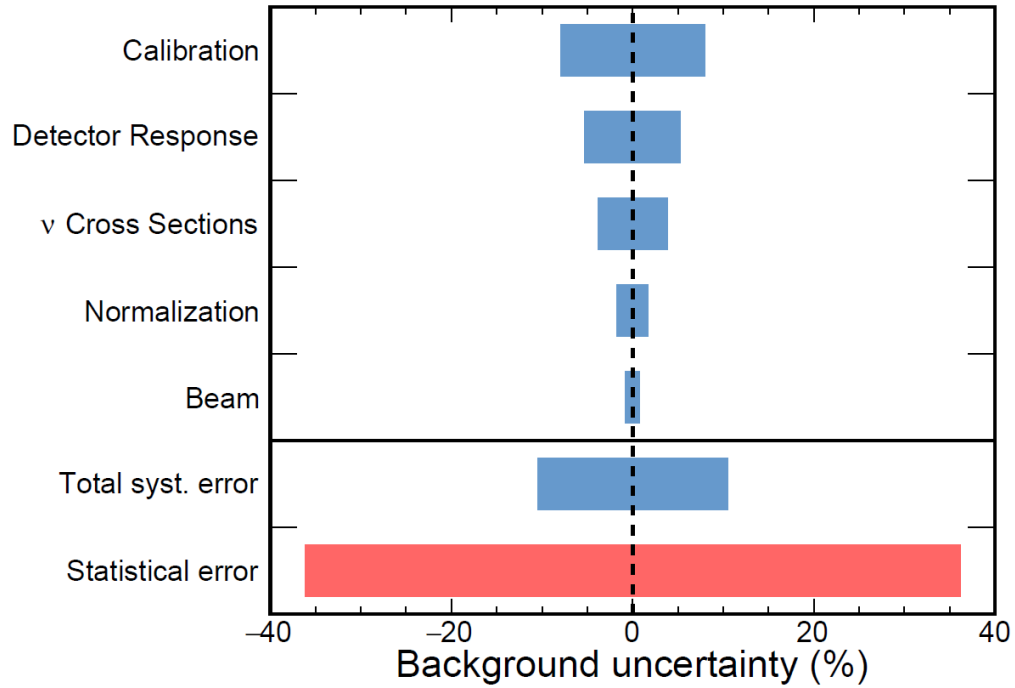
extra





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