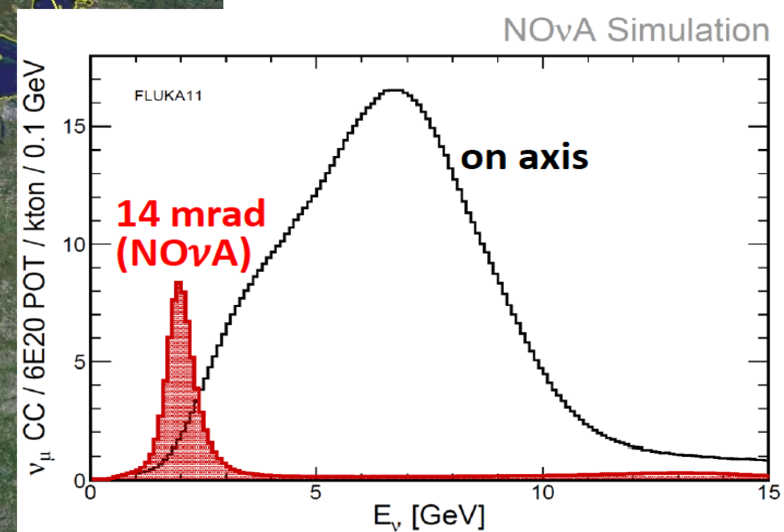
Recent Results of Electron-Neutrino Appearance Measurement at NOvA

Jianming Bian
University of California, Irvine
08-06-2016

ICHEP2016, Chicago

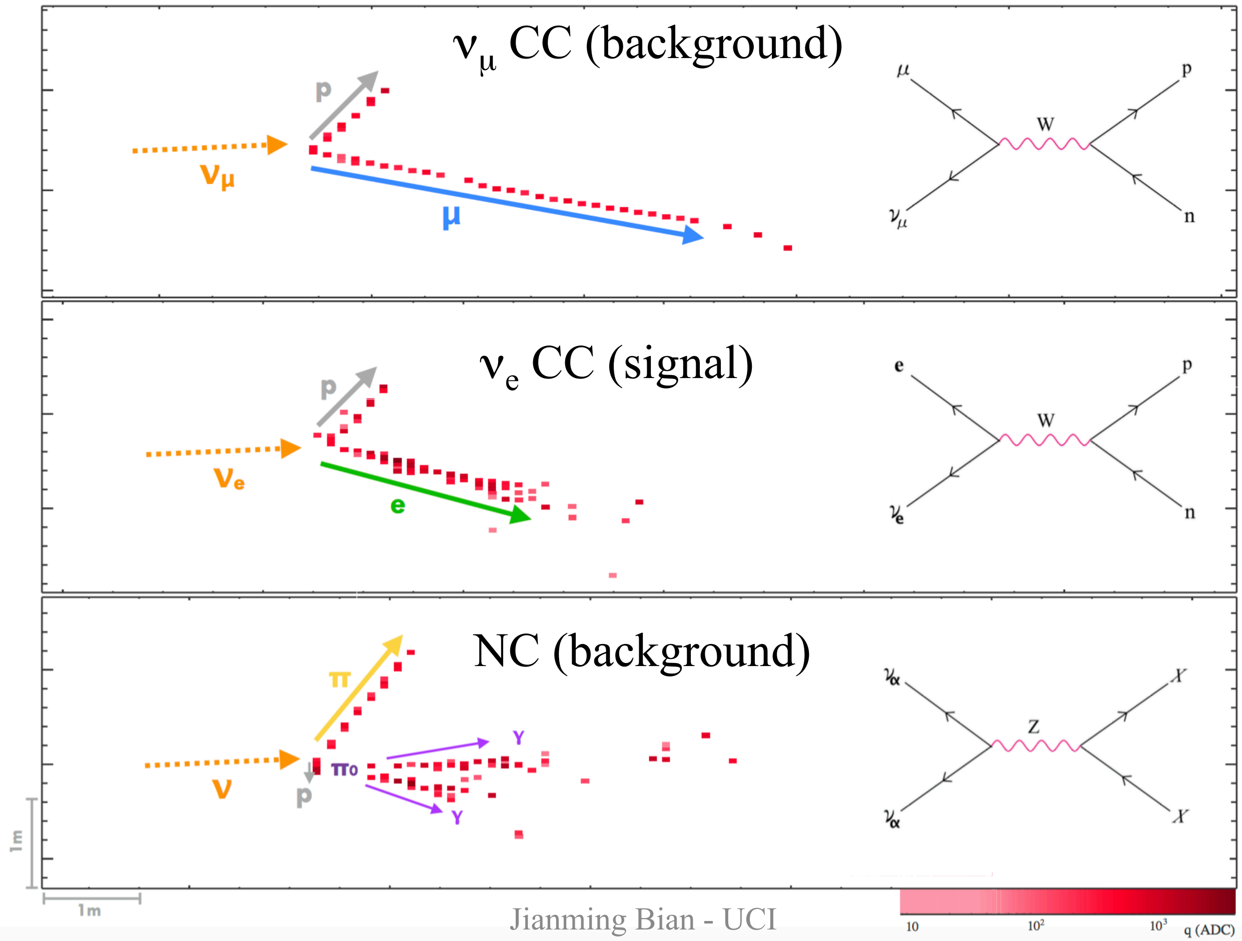
NuMI Off-Axis ν_e Appearance Experiment



- Upgraded NuMI muon neutrino beam at Fermilab (700 kW design)
- Longest baseline in operation (810 km), large matter effect (±30%), sensitive to mass hierarchy
- Far/Near detector is sited 14 mrad off-axis to produce a narrow-band beam around the oscillation maximum region (~2 GeV)

ν_e appearance analysis at NOvA

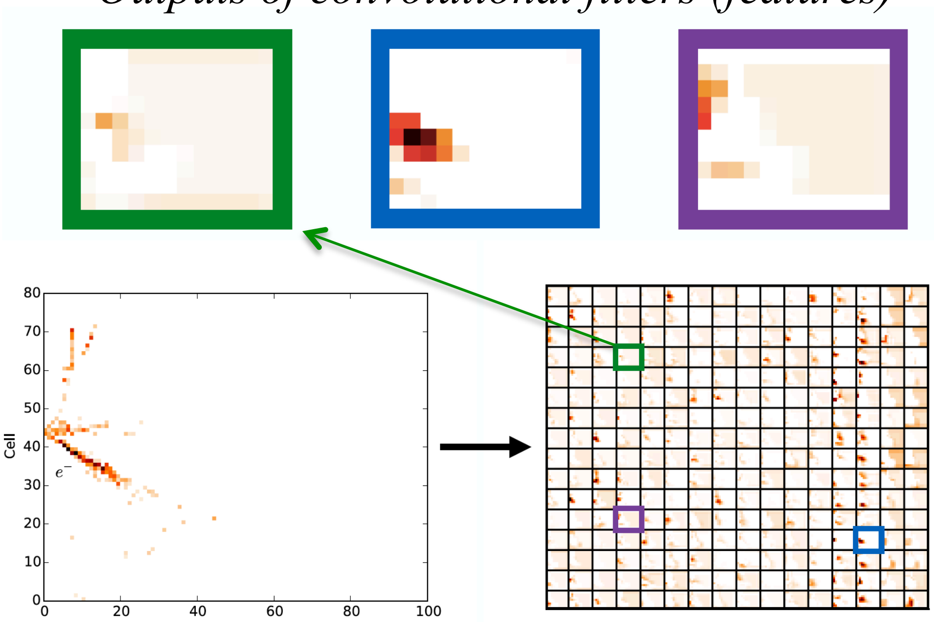
- ν_e (anti-ν_e) appearance: determine neutrino mass hierarchy, constrain CP violation phase (δ_{CP}) and resolve the octant of θ_{23}
- This analysis: use 6.05×10^{20} POT neutrino beam data, >2X exposure of the 2015 analysis.
- New event identifier based on deep learning to identify ν_e CC using direct pixel inputs



Improved Event Identifier - CVN

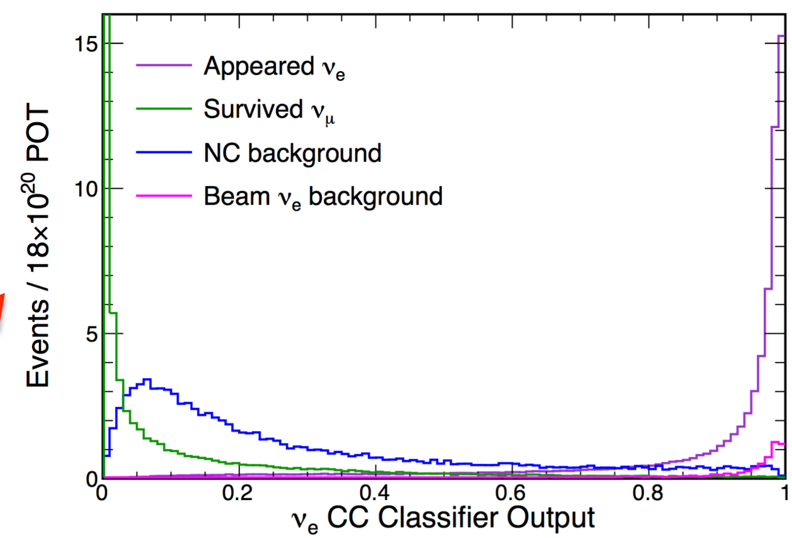
- CVN: a convolutional neural network (CNN), based on modern image recognition technology
- Introduce convolution filters to extract features from the hit map for the training of the neural net
- Statistical power equivalent to 30% more exposure than previous PIDs

Outputs of convolutional filters (features)



Hit map of a ν_e CC event

CVN output in the far detector MC



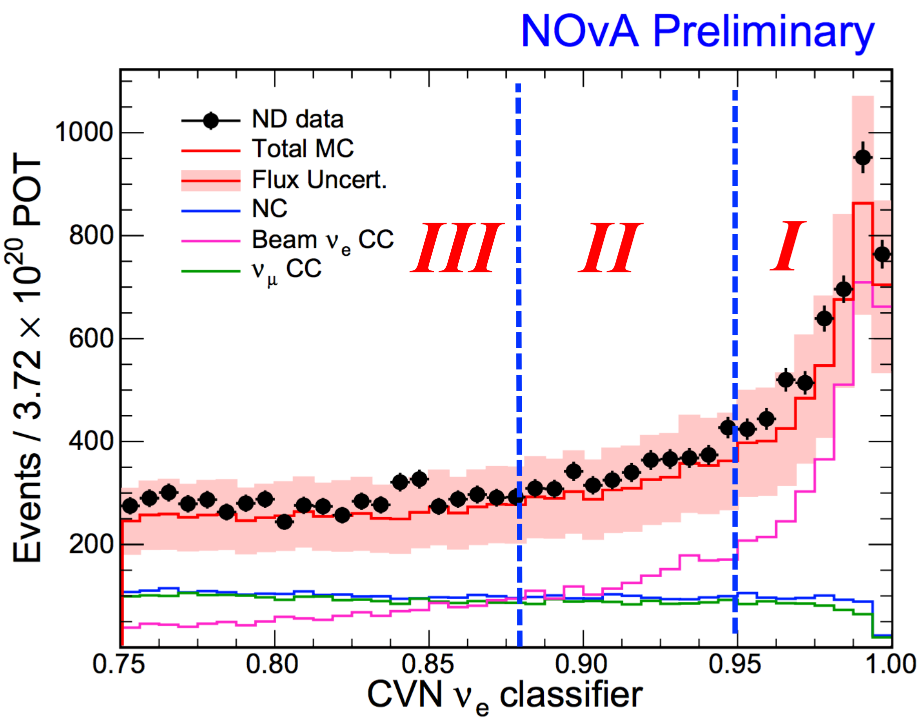
A. Aurisano et al., arXiv:1604.01444, Poster 950 by A. Radovic

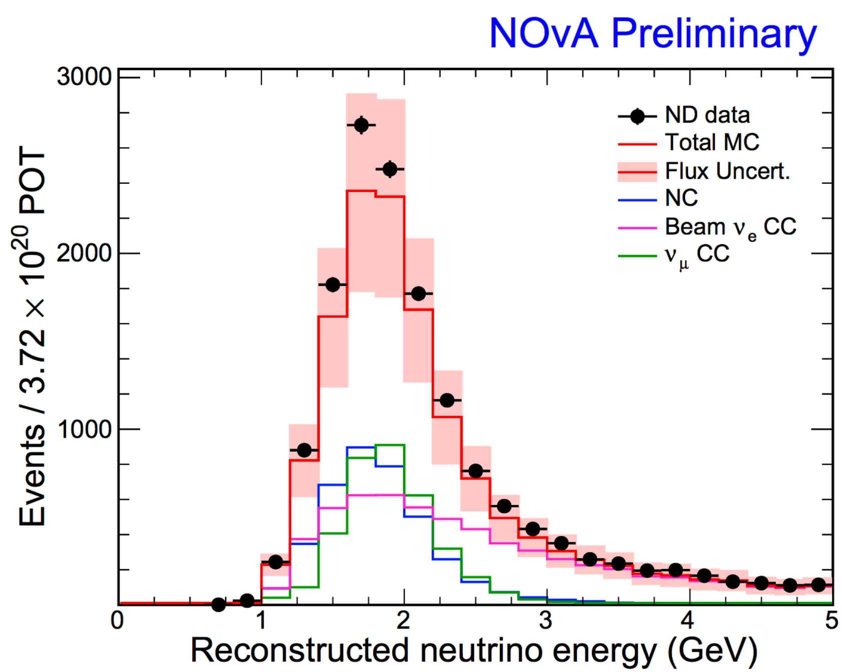
ν_e data in the Near Detector

- Optimize event selection to maximize $FOM = S/\sqrt{S+B}$, including both cosmic rejection and classifier cuts:

73% signal efficiency, 76% purity

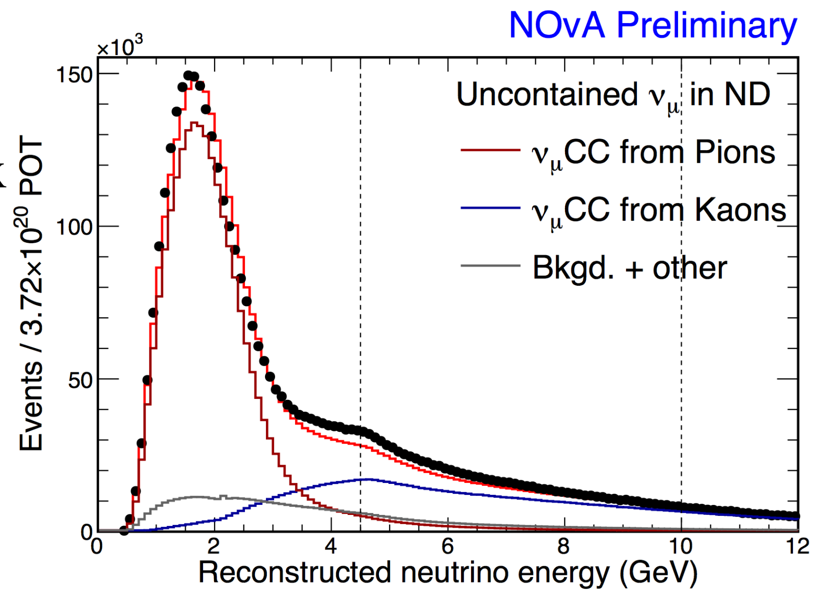
- Reconstruct neutrino energy as a function of the reconstructed electromagnetic and hadronic energy
- Use ND data to predict the energy spectrum in FD in 3 PID regions

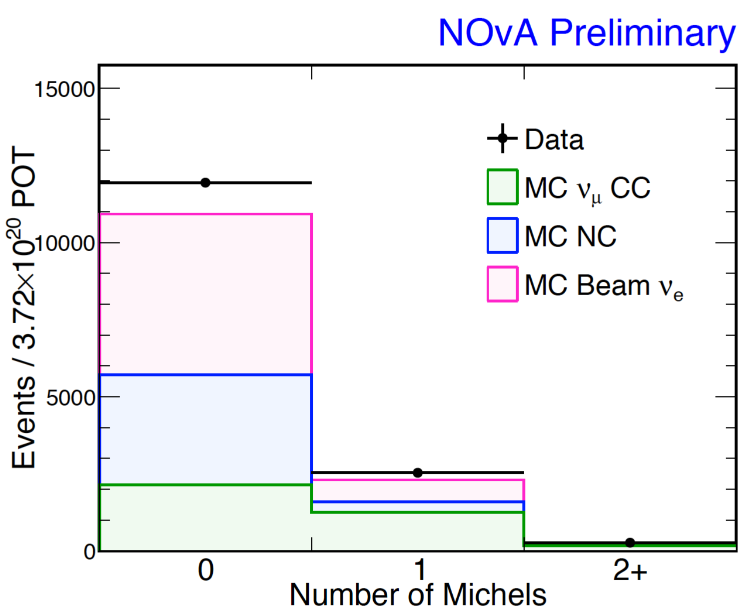




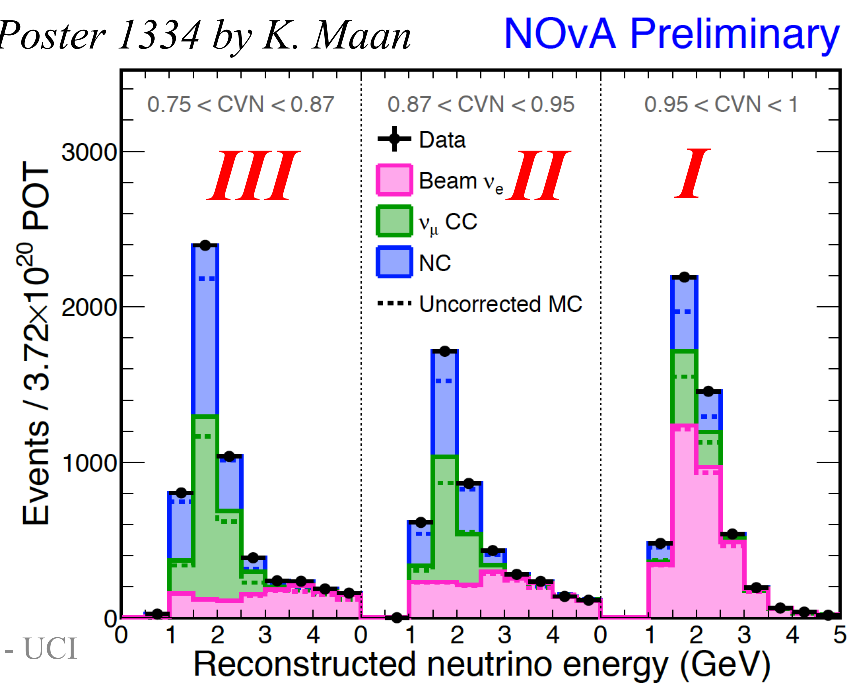
Data-driven background constraint

- ν_e, ν_μ and NC components each extrapolated differently
- Reweight Kaon and Pion components in Flux to match the selected ν_μCC energy spectrum in data
- Fix beam ν_e to the flux-reweighted result in the near detector (up by 4%)
- Constrain ν_μCC (up by 17%) and NC (up by 10%) using Michel Electron distribution



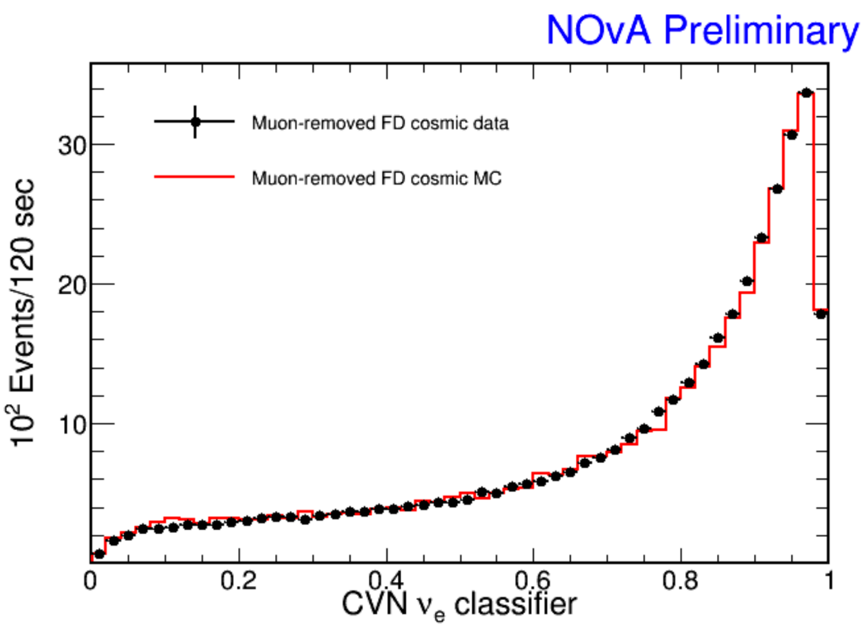


Poster 1334 by K. Maan



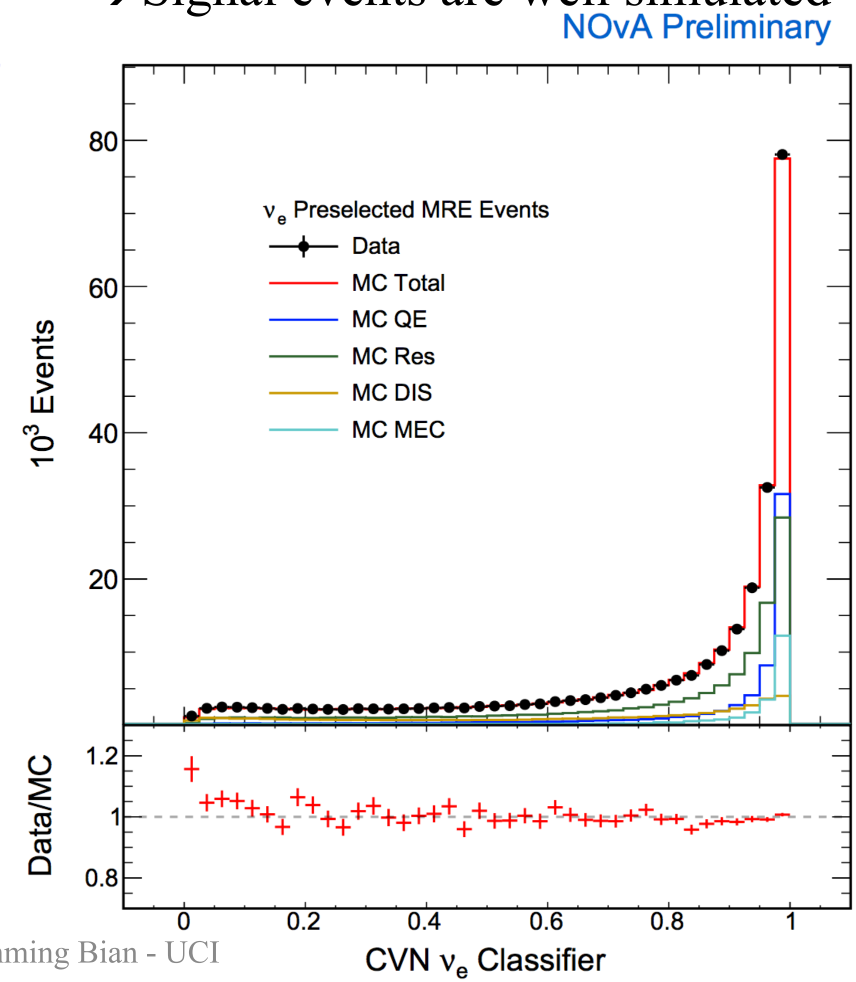
Checking signal selection in Far and Near Detectors

Remove muon tracks in cosmic rays to select Brem. showers in the far detector
→Simulation of EM showers is excellent



Poster 1516 by N. Yadav

Replace muon tracks in ND ν_μCC data with simulated electron showers
→Data/MC difference < 1%
→Signal events are well simulated

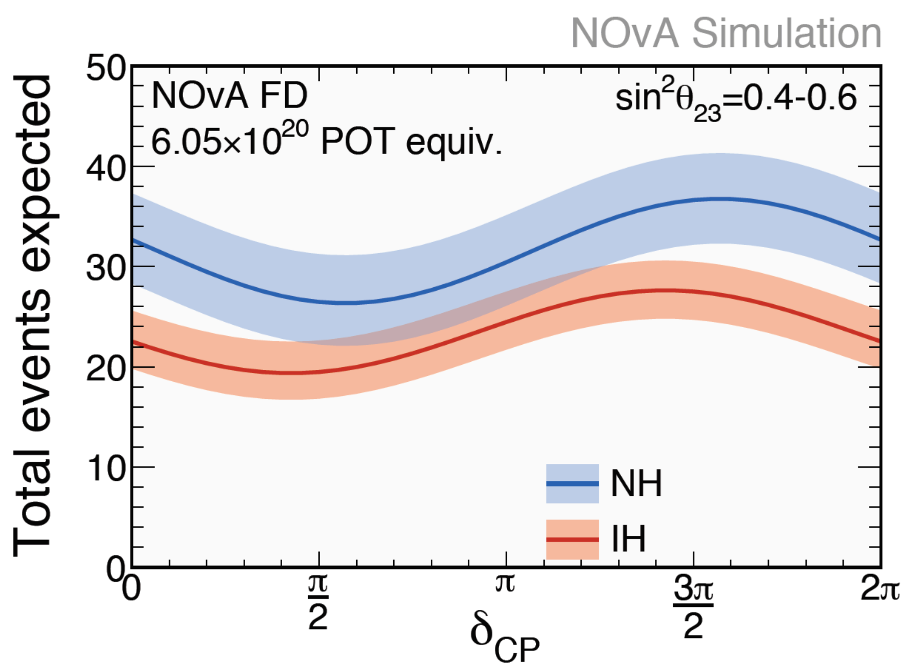


ν_e prediction in the FD

- Extrapolate each component in bins of energy and CVN output
- Expected event counts depend on oscillation parameters

Sig+Bkg (systematic error: 5%)
$\sin^2\theta_{23}=0.5$

NH, 3π/2	IH, π/2
36.4	19.4

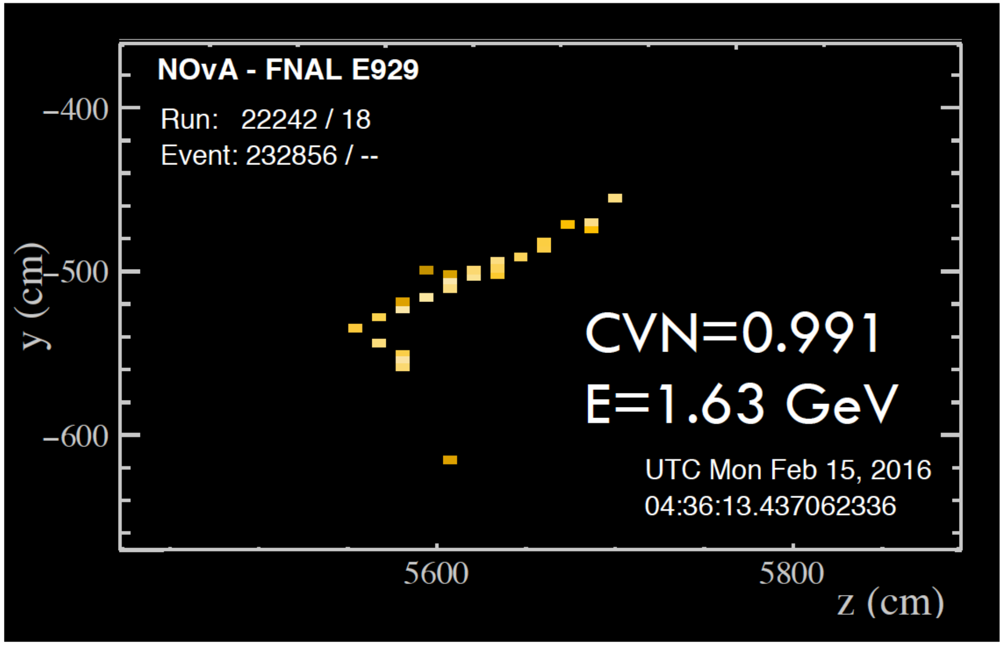


Bkg (systematic error: 10%)

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

ν_e in the FD data

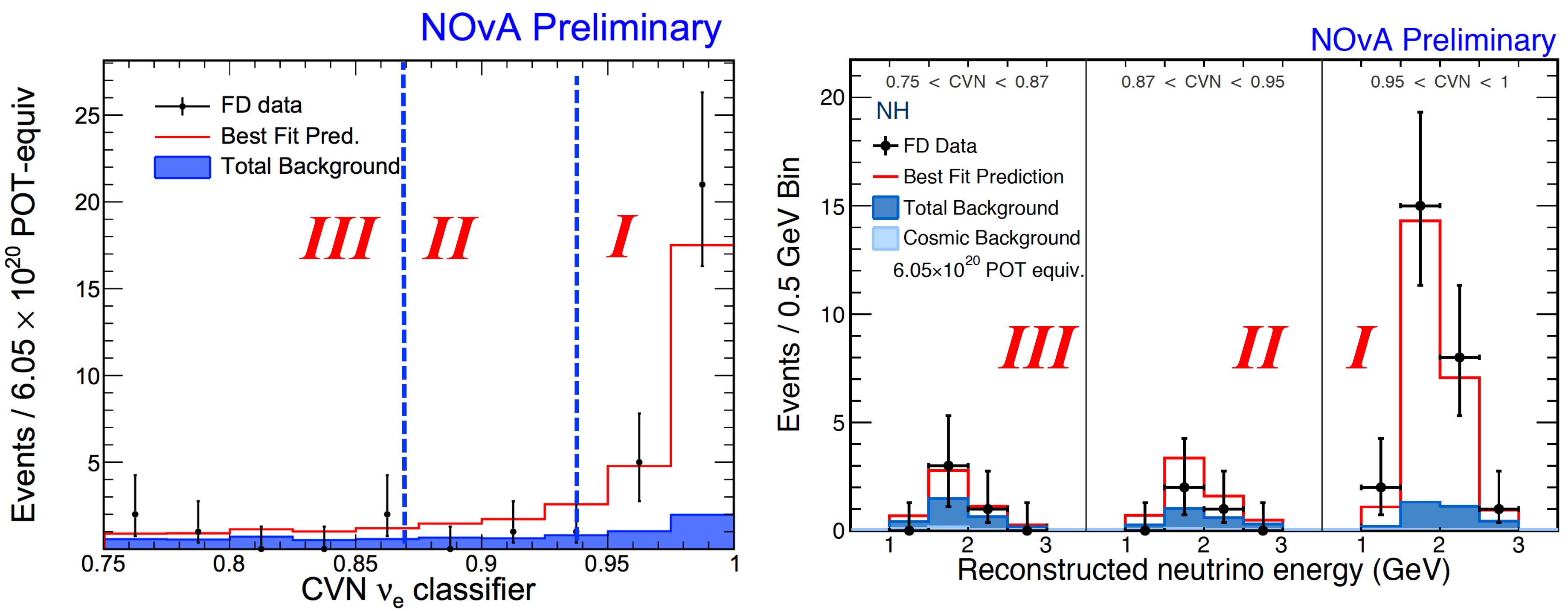
- Before unblinding we check near-PID sideband, high-energy sideband and events outside of the beam spill window in FD
- Observe 33 events in FD
  - background 8.2±0.8



Alternate selectors from 2015 analysis show consistent results
LID: 34 events, 12.2±1.2 BG expected
LEM: 33 events, 10.3±1.0 BG expected

ν_e in the FD data

Fit energy spectra in the 3 PID regions by varying oscillation parameters

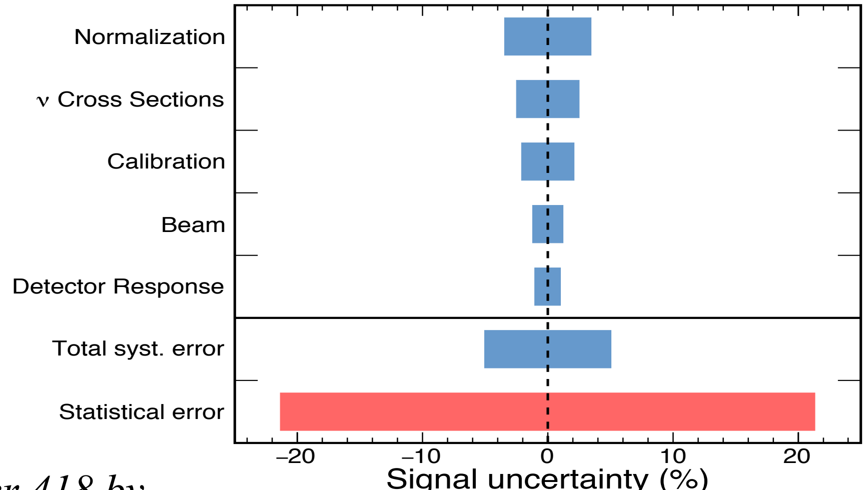


Significance of ν_e appearance > 8 σ

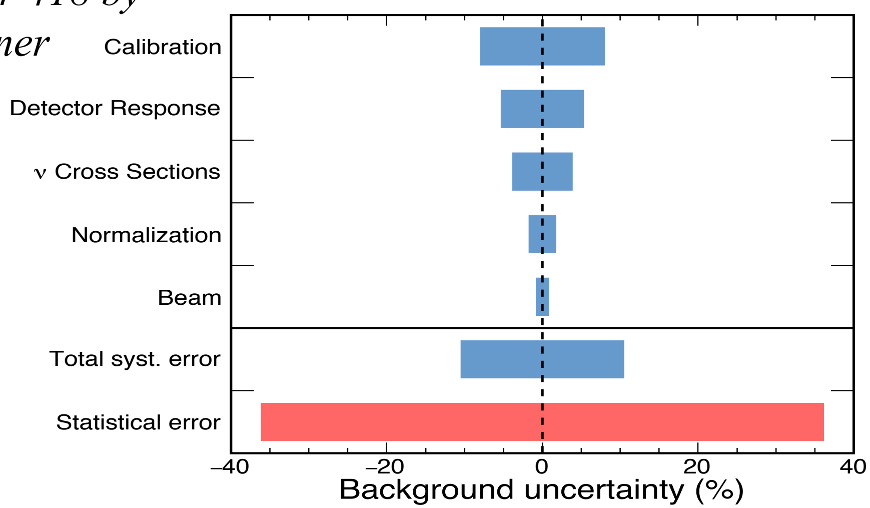
ν_e contours

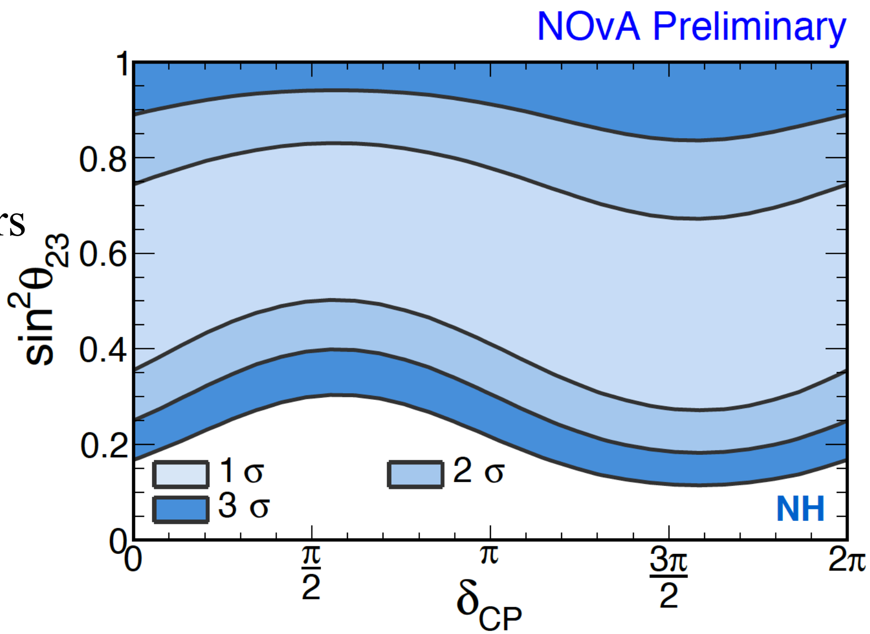
Fit for mass hierarchy, δ_{CP}, $\sin^2\theta_{23}$:

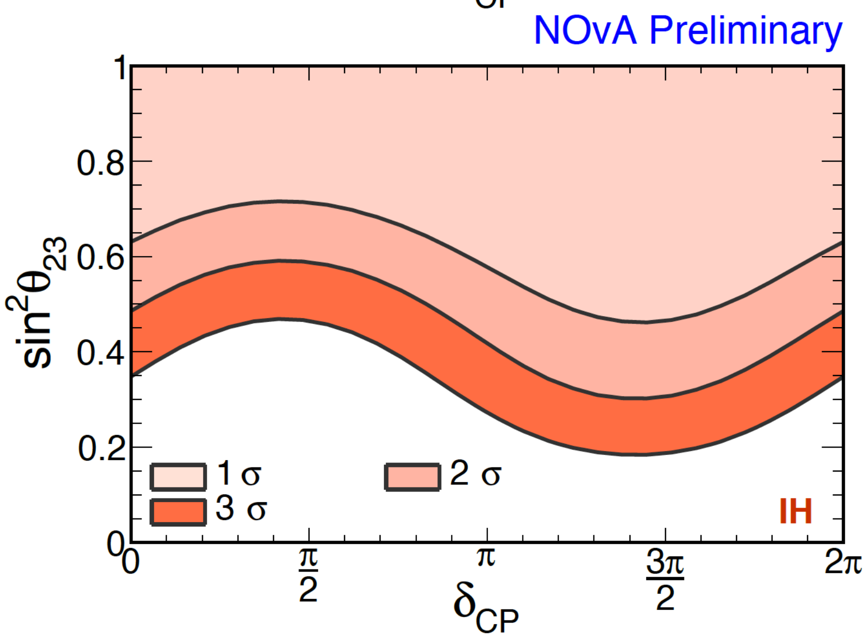
- Applying global reactor constraint of
  $\sin^2 2\theta_{13}=0.086\pm0.05$
- Constrain solar neutrino osc. parameters to PDG
- Systematic errors included as nuisance parameters



Poster 418 by E. Niner

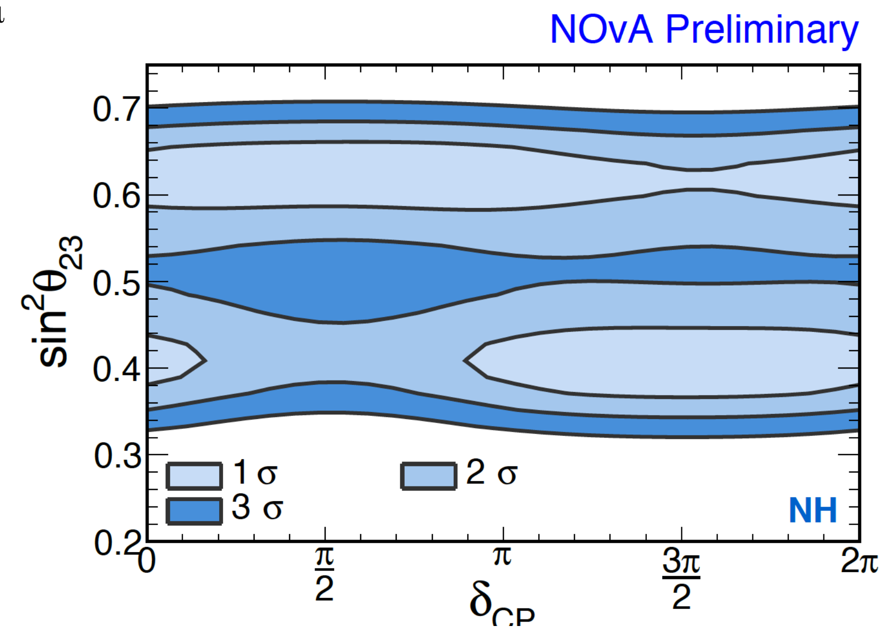




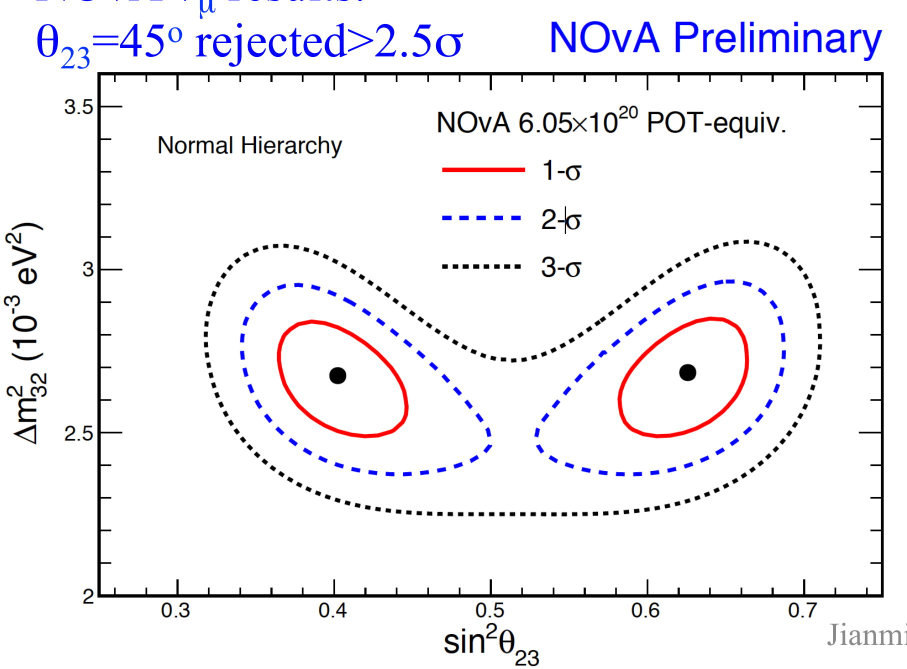


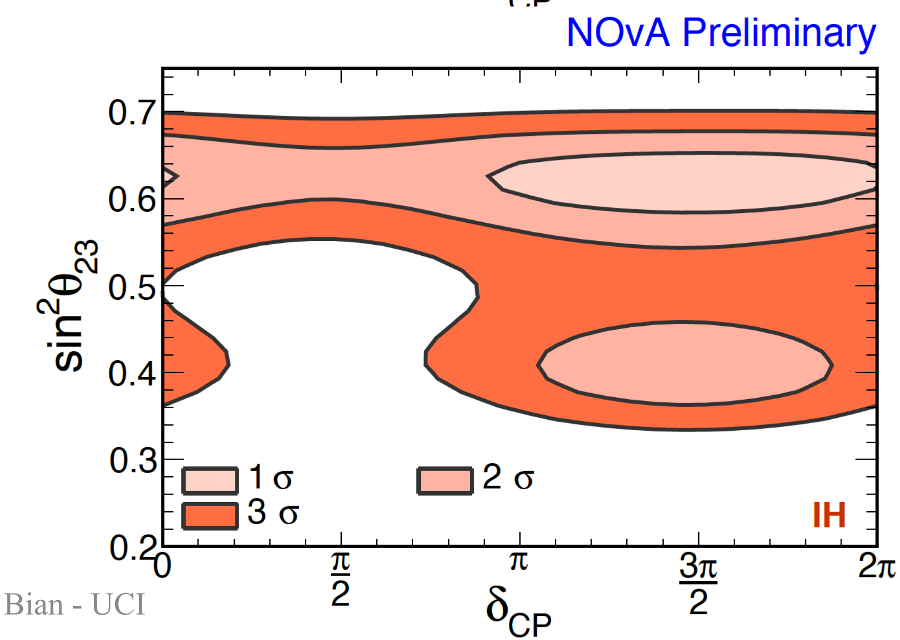
ν_e contours

- Constrain Δm^2 and $\sin^2\theta_{23}$ with NOvA ν_μ disappearance results
- Global best fit: Normal Hierarchy, δ_{CP} = 1.49π, $\sin^2\theta_{23} = 0.4$
- IH, δ_{CP}~π/2 is rejected (3σ) for lower octant
- Both octants and MHs are allowed at 1σ, best fit IH-NH: $\Delta\chi^2$=0.47

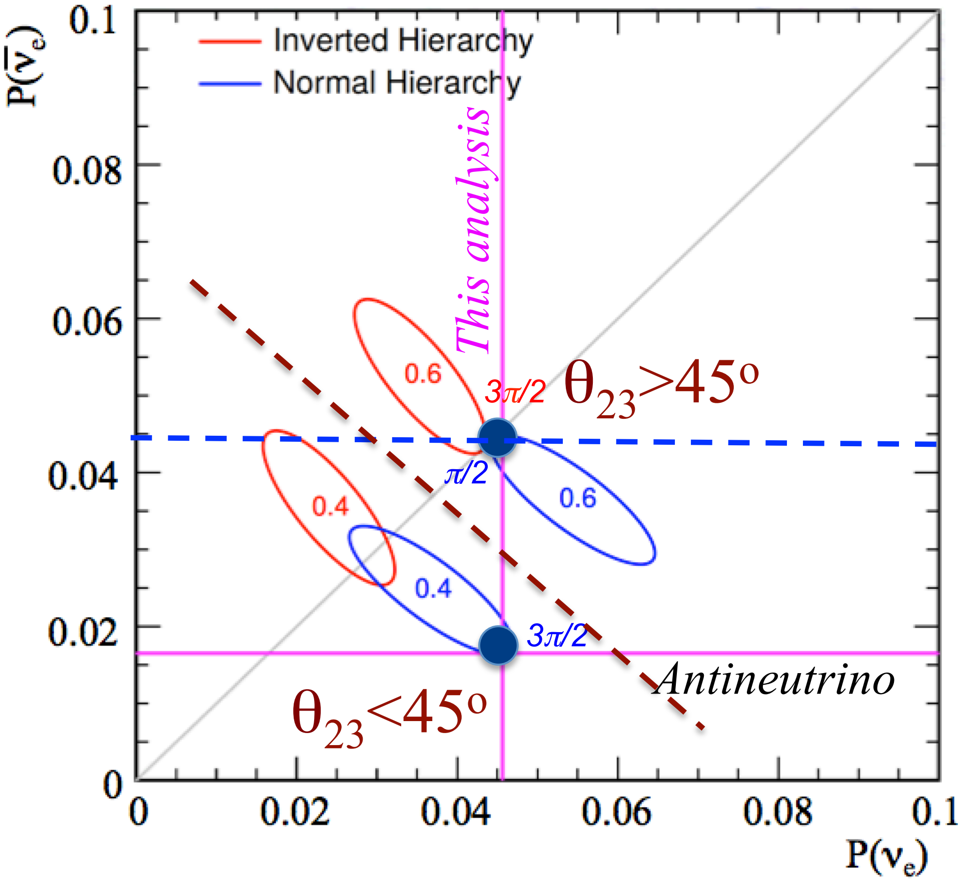


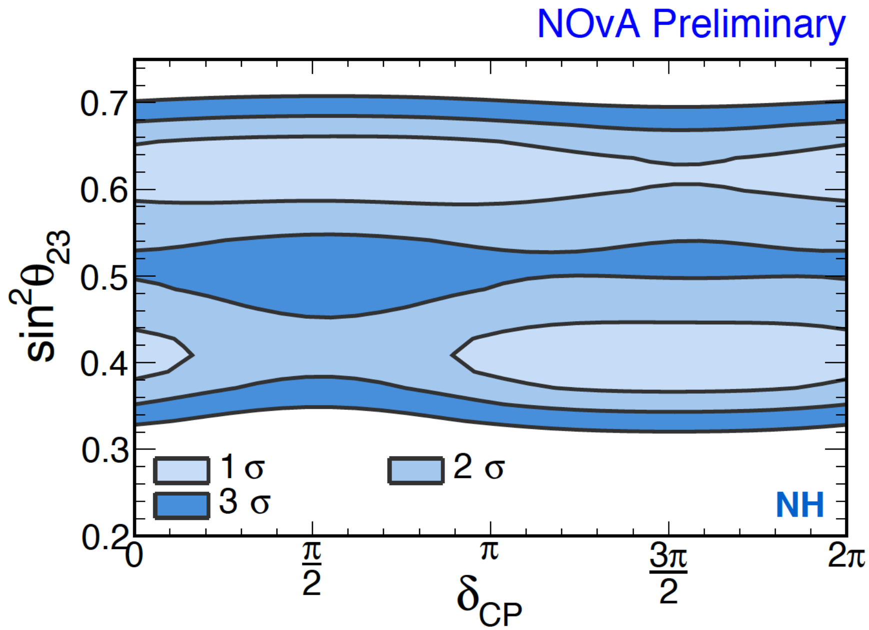
NOvA ν_μ results:
θ_{23}=45° rejected>2.5σ

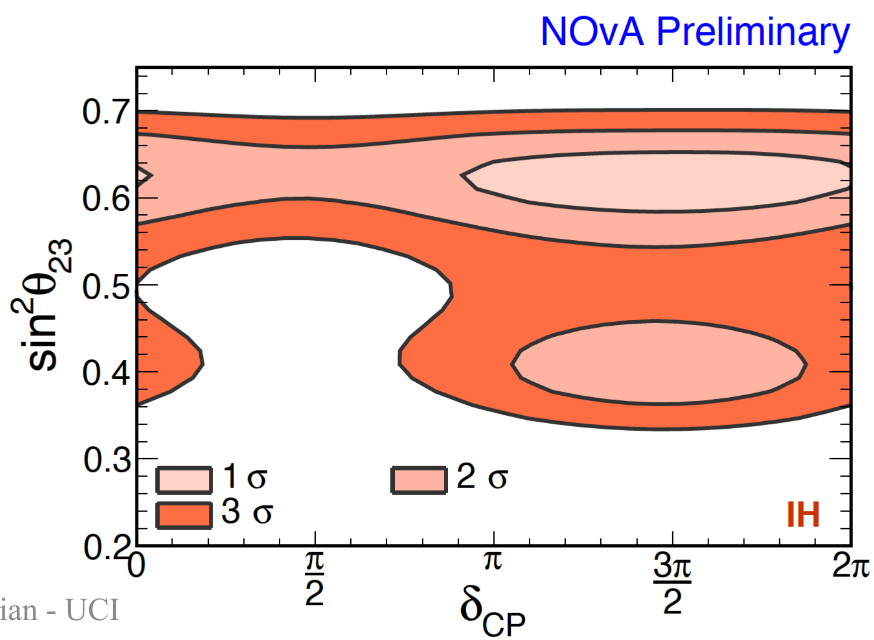




ν_e contours



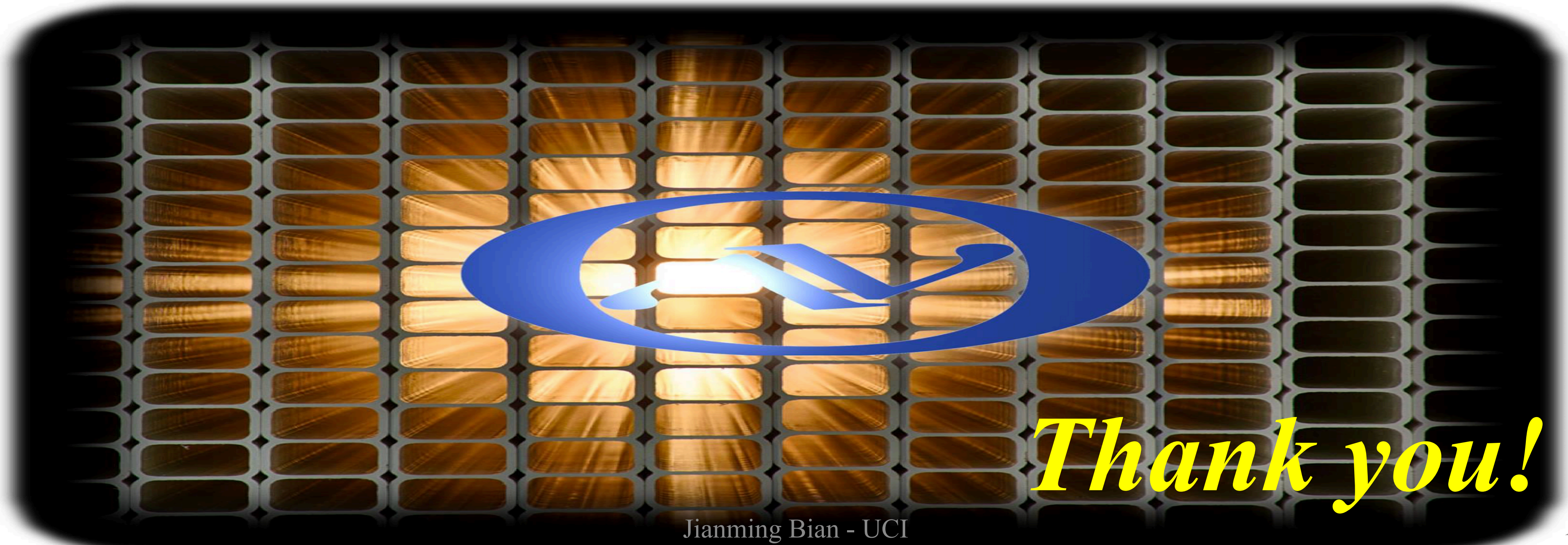




- Ambiguity caused by the octant of θ_{23}, antineutrino is crucial to solve MH
- Anti-ν_e rates for higher octant > 2x lower octant

Summary

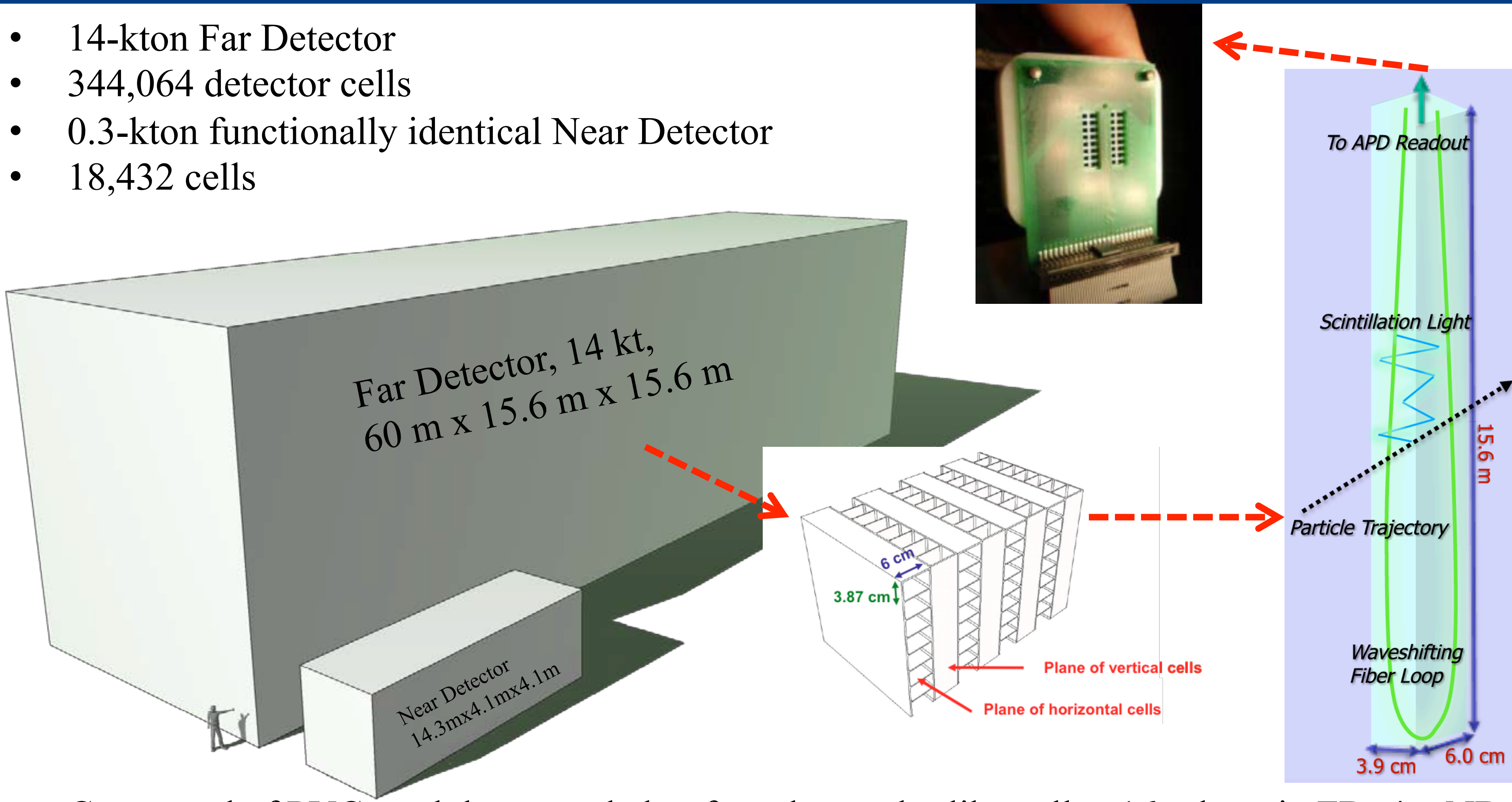
- With 6.05×10^{20} POT NuMI data, we performed the second ν_e appearance measurement
- ν_e appearance significance > 8σ
- Data prefers NH at low significance
- IH, $\delta_{CP} \sim \pi/2$ is rejected for lower octant
- Plan to run antineutrinos in Spring 2017 to solve degeneracies caused by the octant of θ_{23}



Backup

The NOνA Detectors

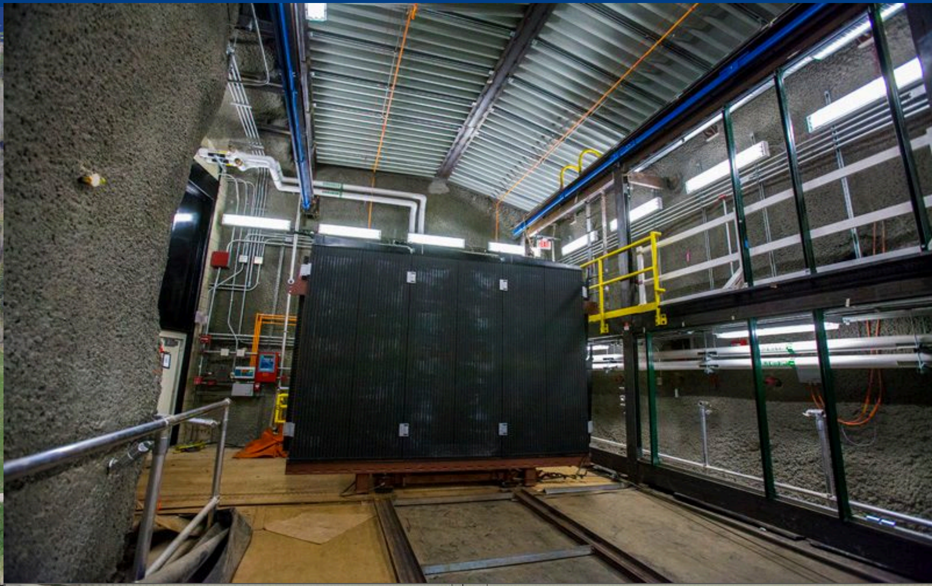
- 14-kton Far Detector
- 344,064 detector cells
- 0.3-kton functionally identical Near Detector
- 18,432 cells

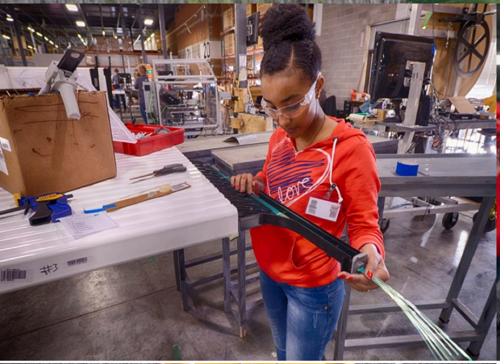


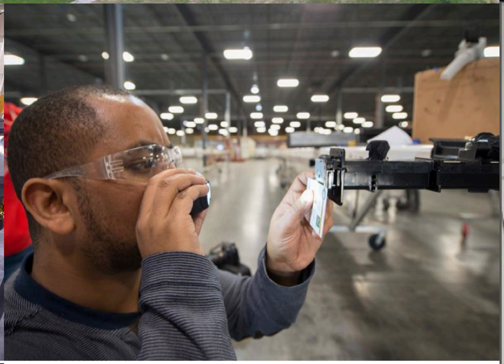
- Composed of PVC modules extruded to form long tube-like cells : 16m long in FD, 4m ND
- Each cell is filled with liquid scintillator and has a loop of wavelength-shifting fiber (WLS) routed to an Avalanche Photodiode (APD)
- Cells arranged in planes, assembled in alternating vertical and horizontal directions
- Low-Z and low-density, each plane just 0.15 X_0. Great for e^- vs π^0

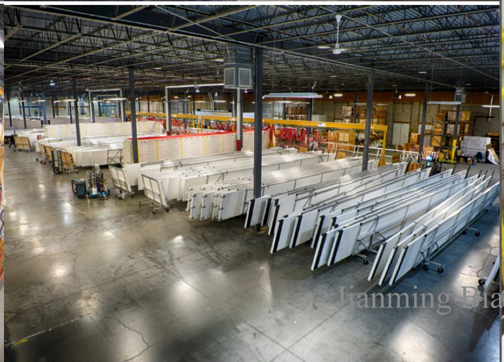
NOvA construction (2009-2014)

As of September 4th 2014, both far and near detectors are fully commissioned.





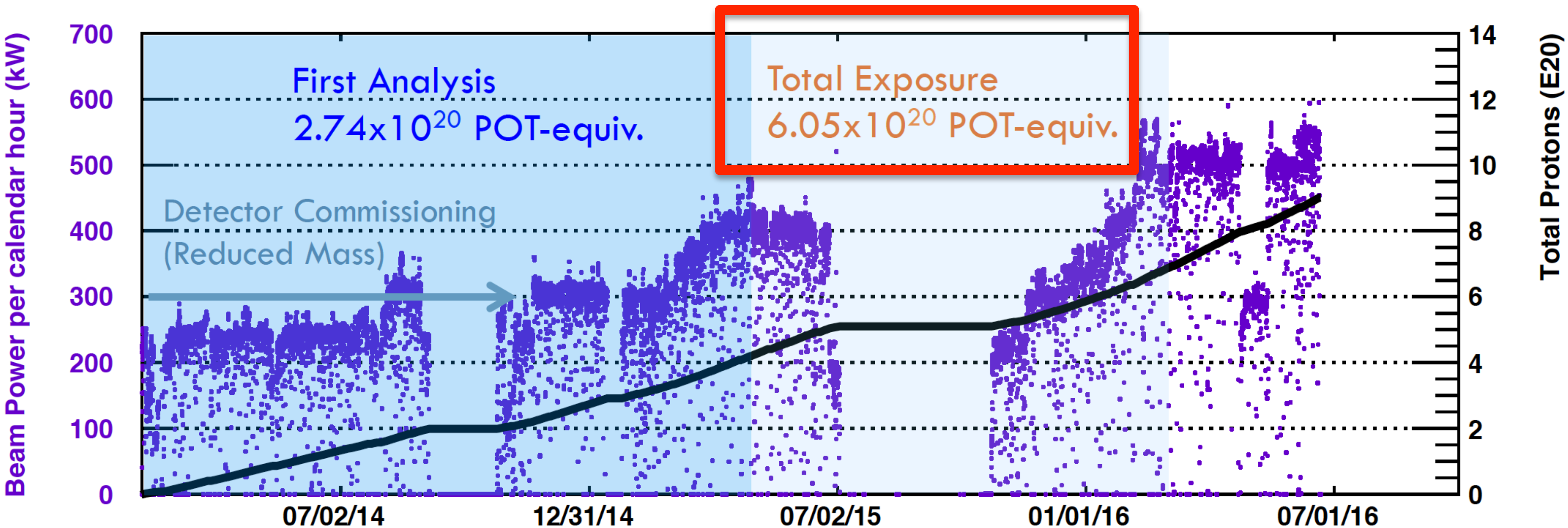




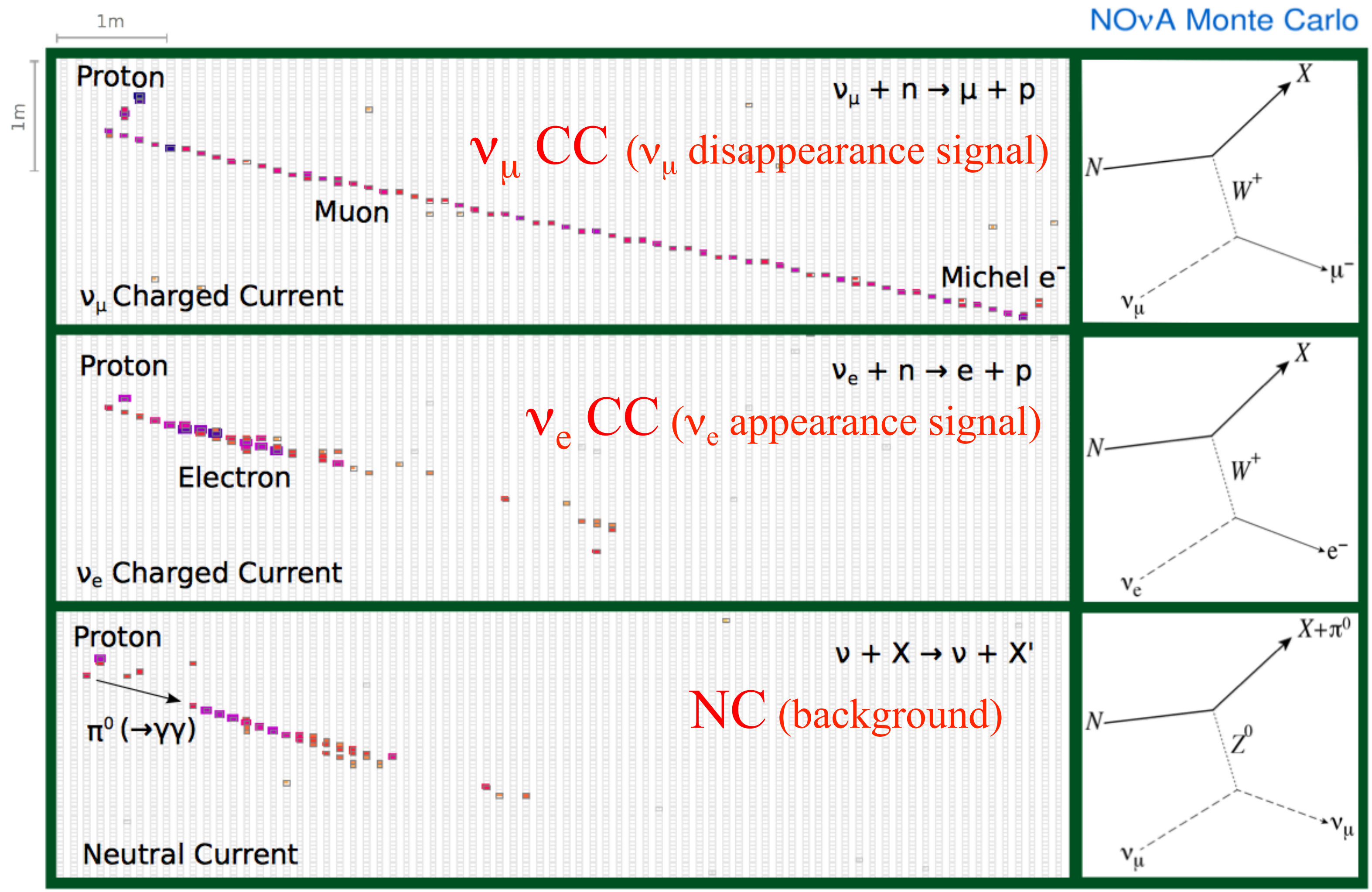
Beam Performance

- NuMI currently running at 560 kW
- Achieved 700 kW in tests on June13, 2016
- 6.05×10^{20} POT FD data has been collected for the second analyses (more than double exposure of 2015 analysis)

This analysis

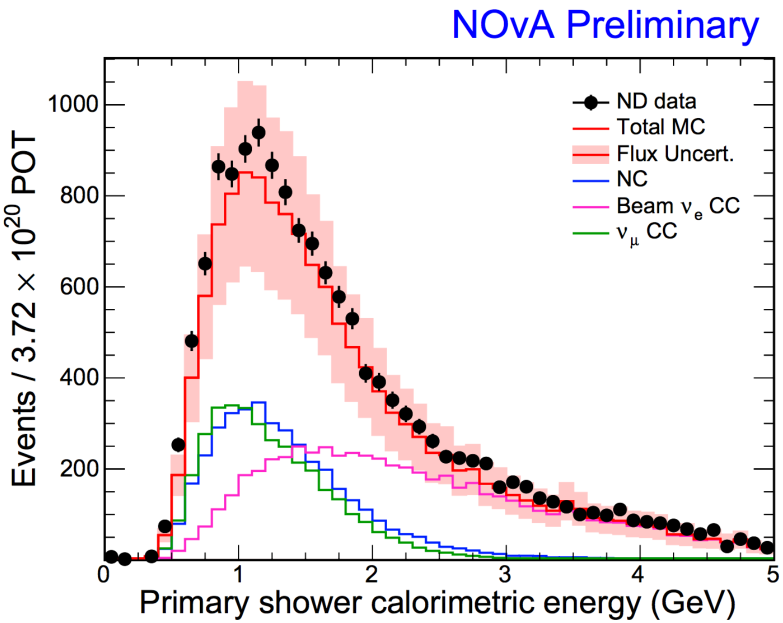


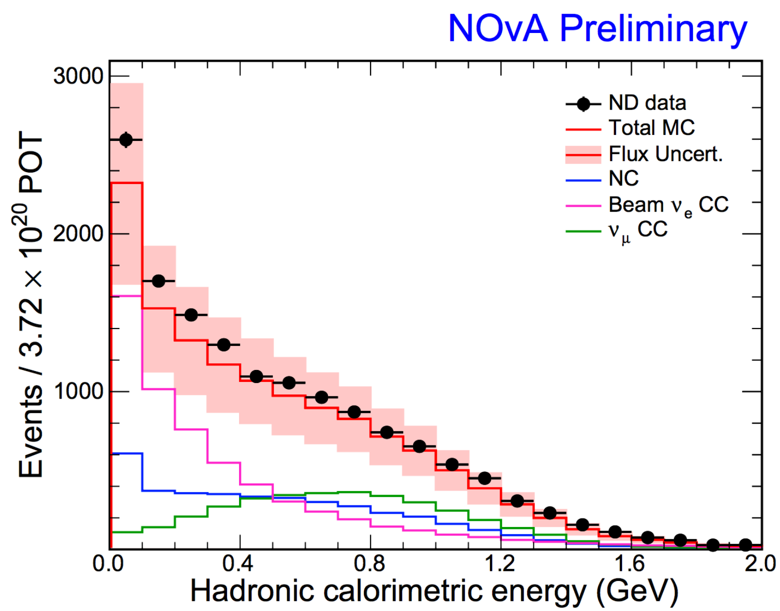
Neutrino Event Topology in NOνA

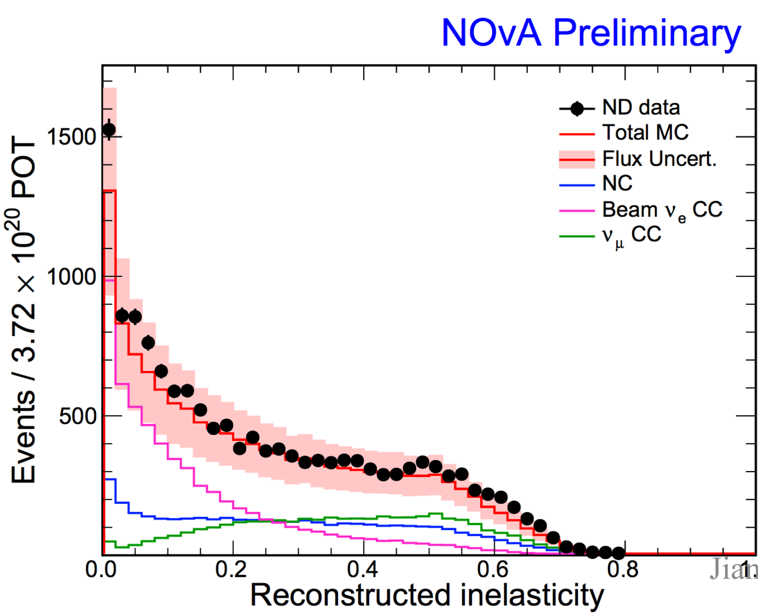


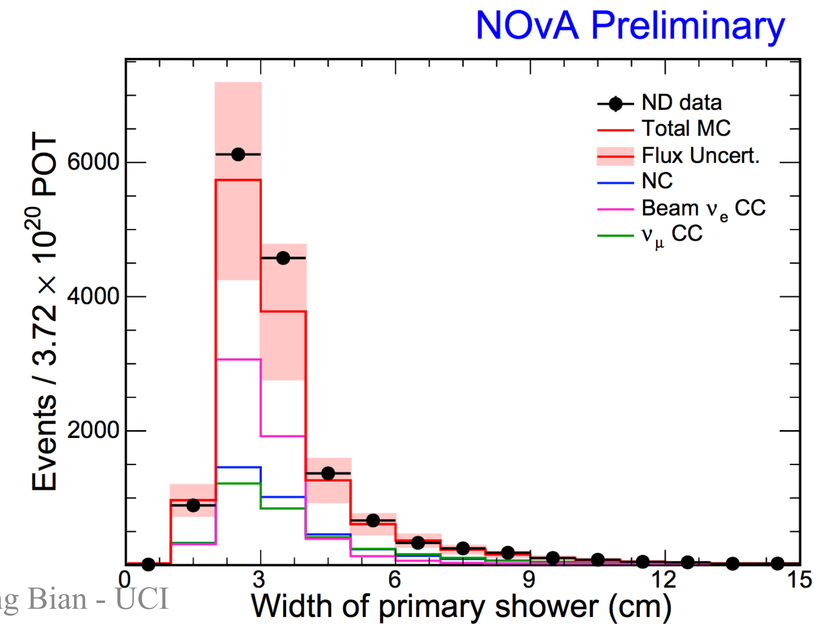
The muon is a long minimum ionizing particle, the electron ionizes in the first few planes then starts to shower and the photon is a shower with a gap in the first few planes.

Data/MC in the ND

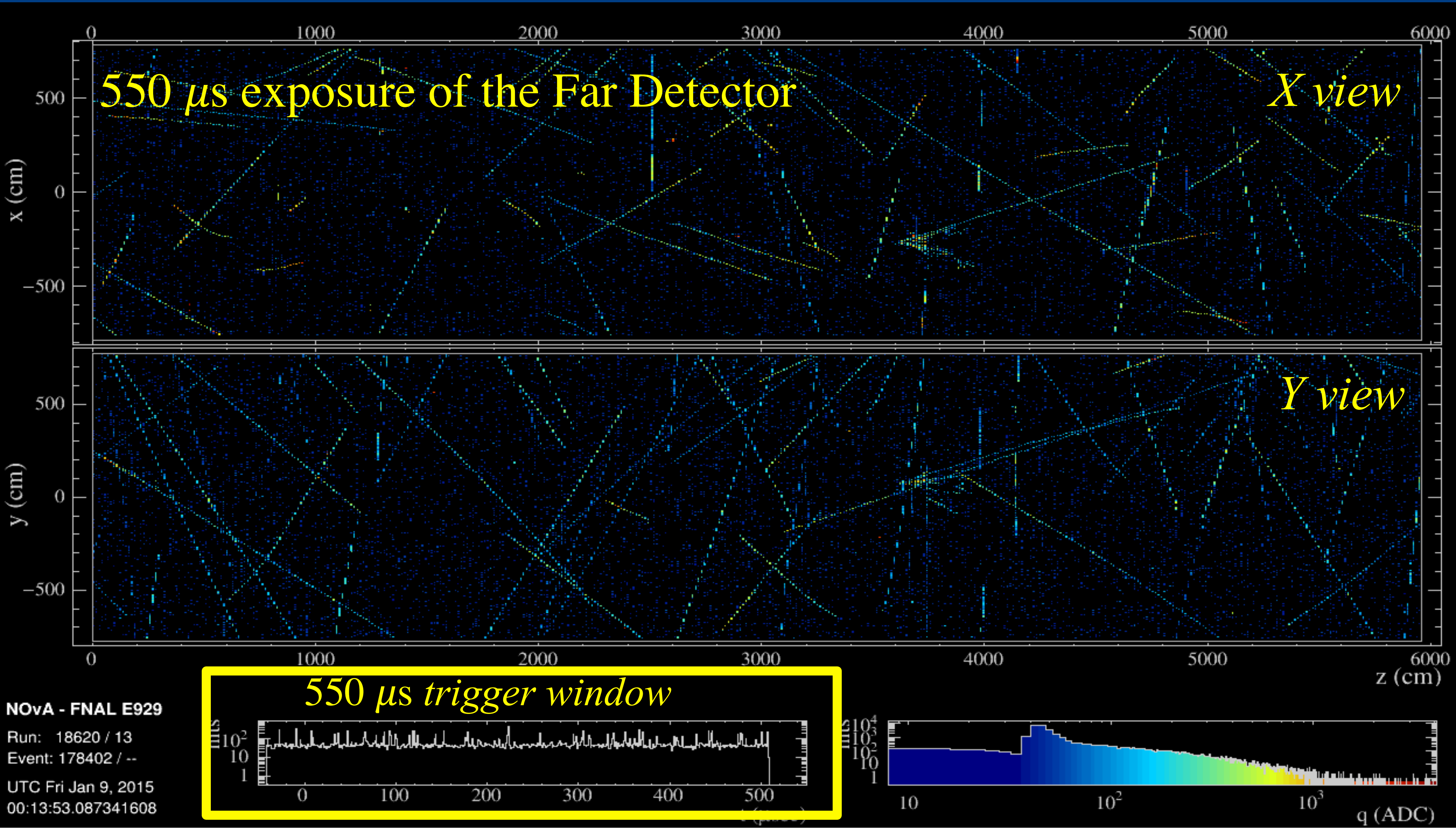






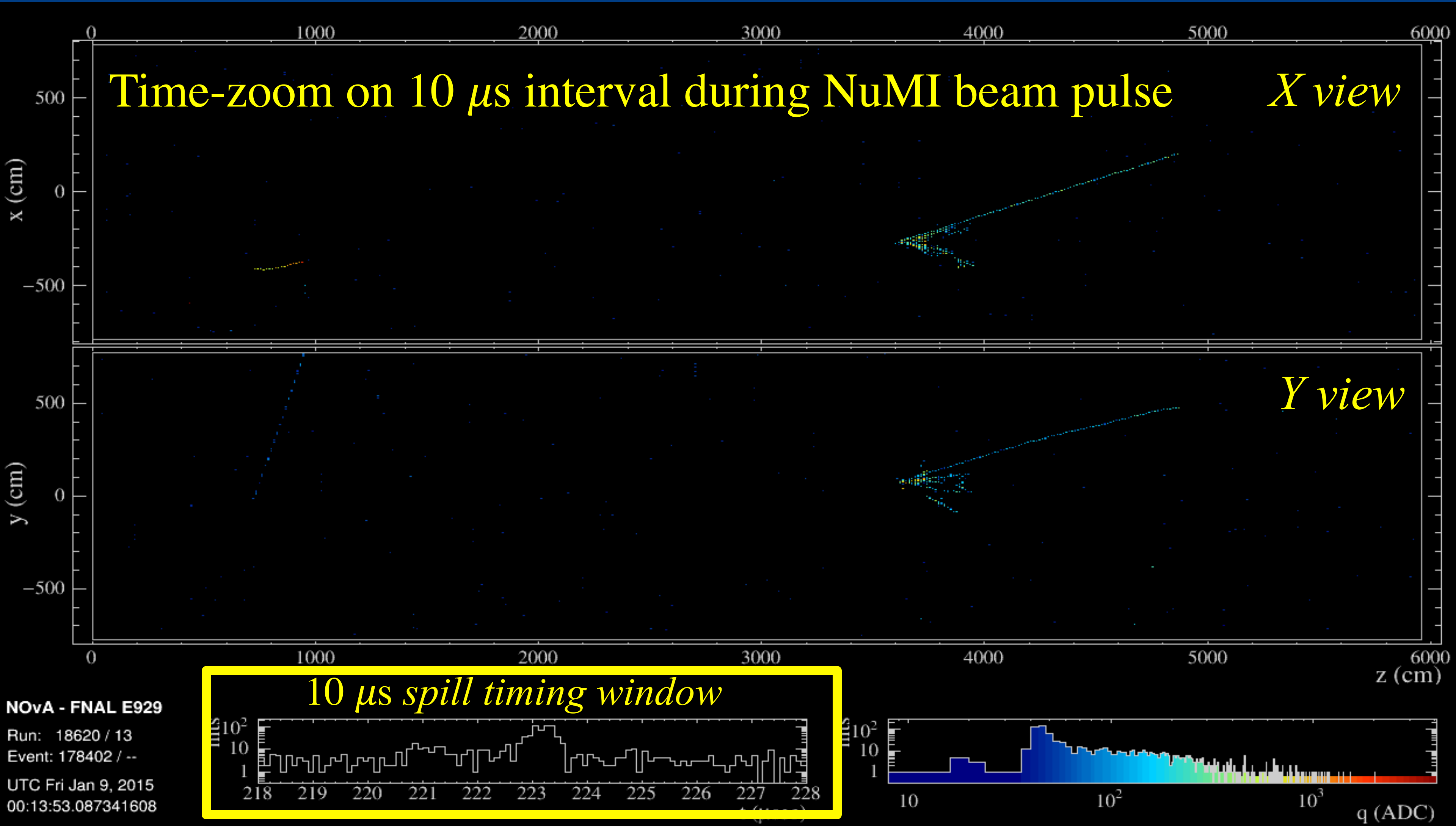


Event clustering



- Because NOvA is on surface, hits in a trigger window are a combination of cosmic and beam events.
- First step in reconstruction is to cluster hits by space-time coincidence to separate neutrino hits and cosmic hits.

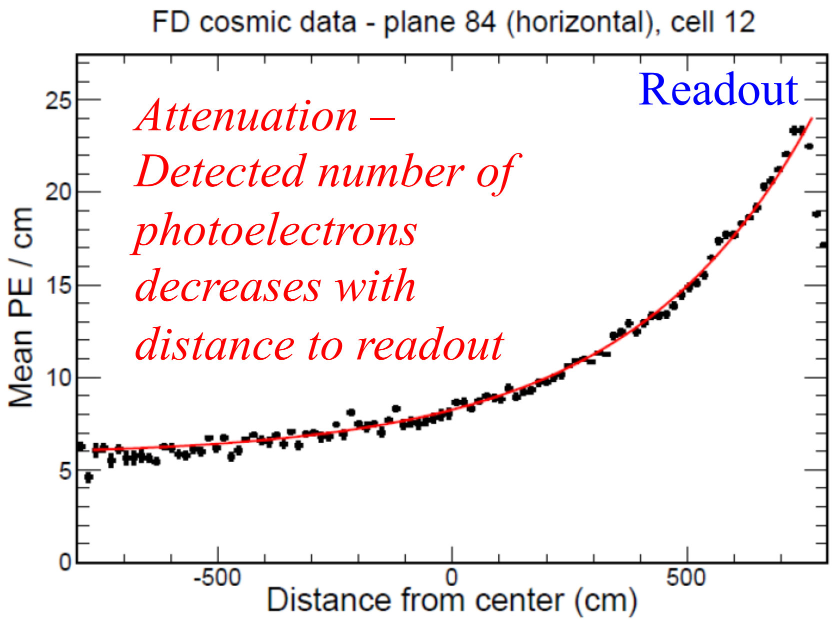
Event clustering

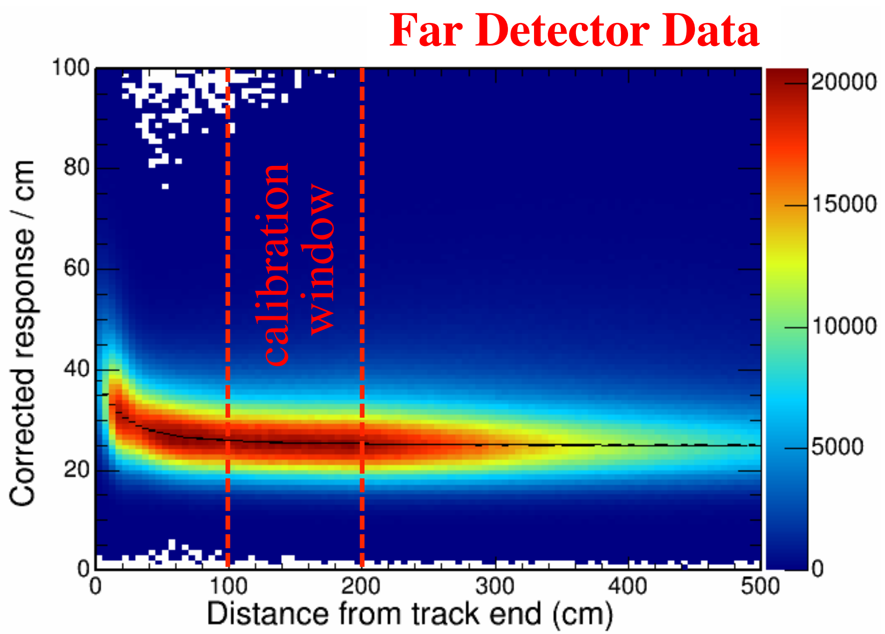


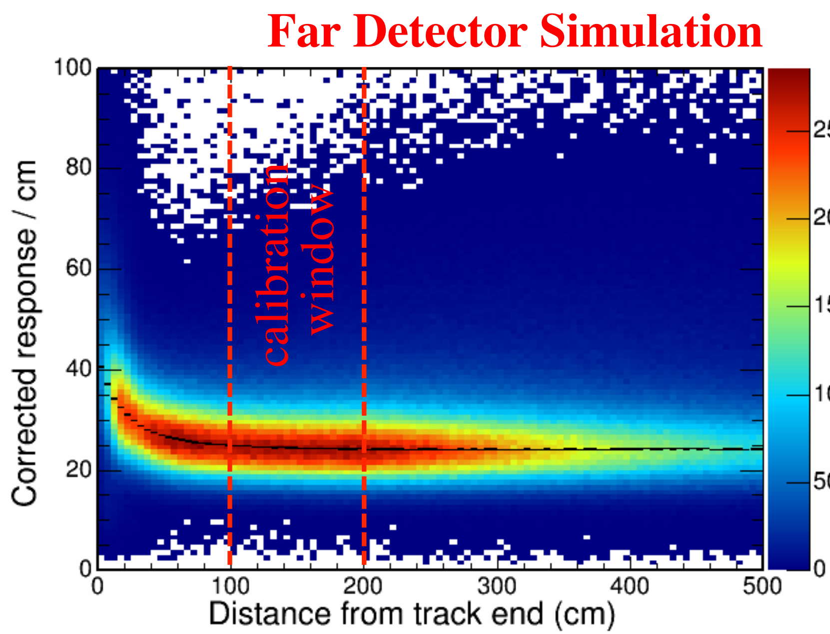
Event clusters that contain neutrino interactions can be correctly selected in the neutrino spill timing window

Calibration

- Use the minimum ionizing peak of cosmic muons to correct the attenuation in the wavelength shifting (WLS) fiber.
- Use stopping muons in cosmic rays to set absolute energy scale.



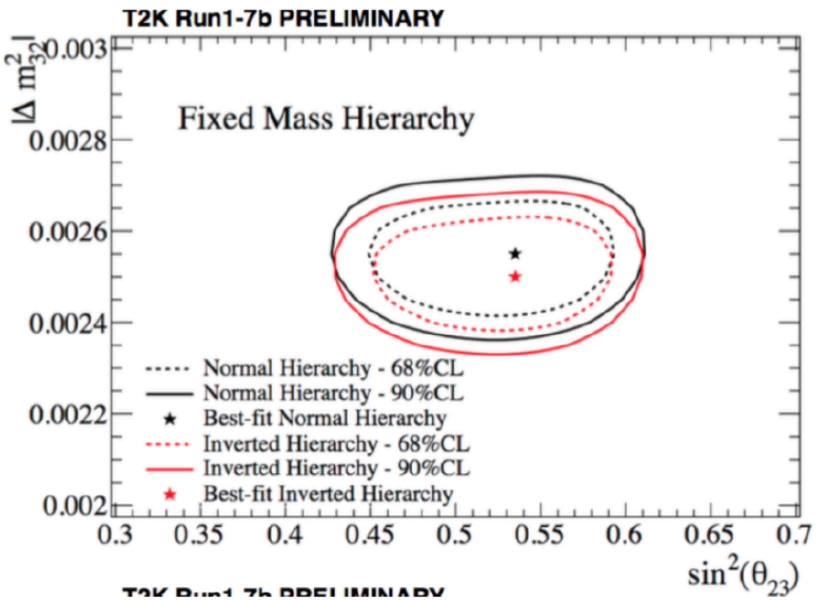


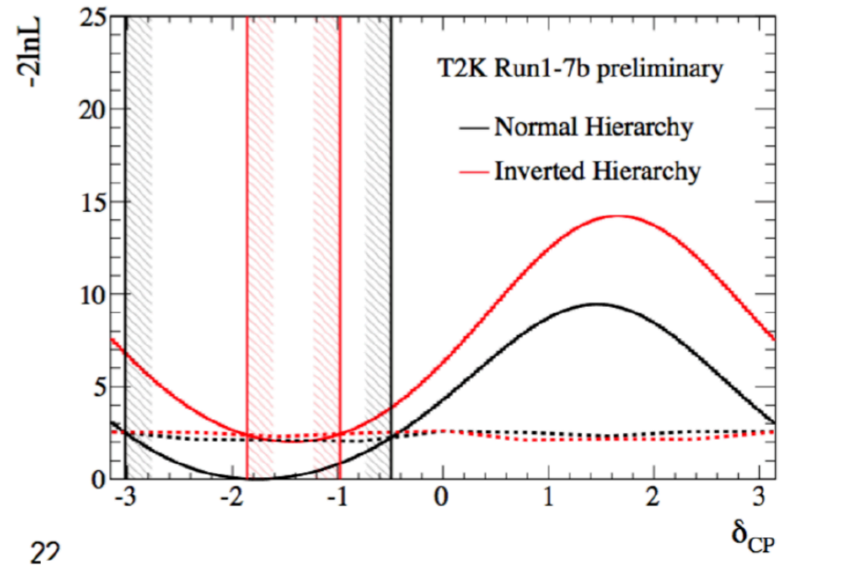


T2K results

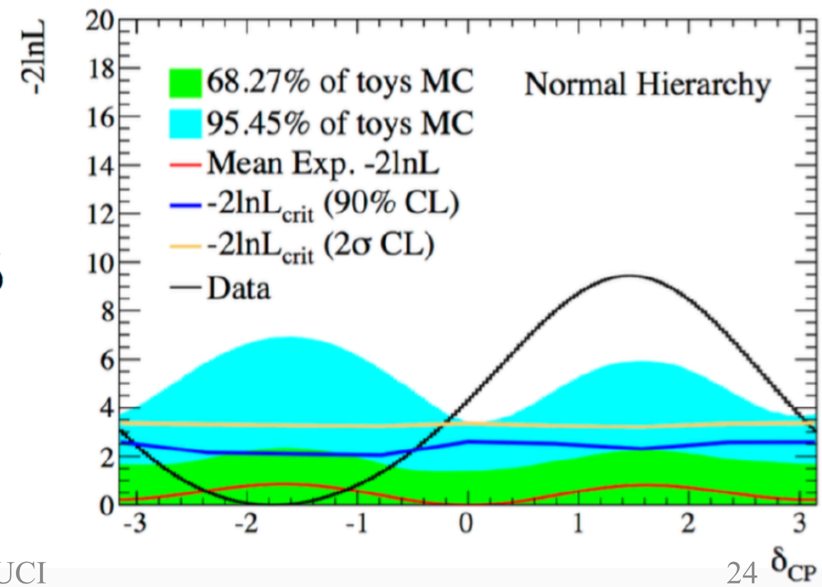
δ_{CP} = [-3.02, -0.49] (NH), [-1.87, -0.98] (IH) @90% CL

T2K





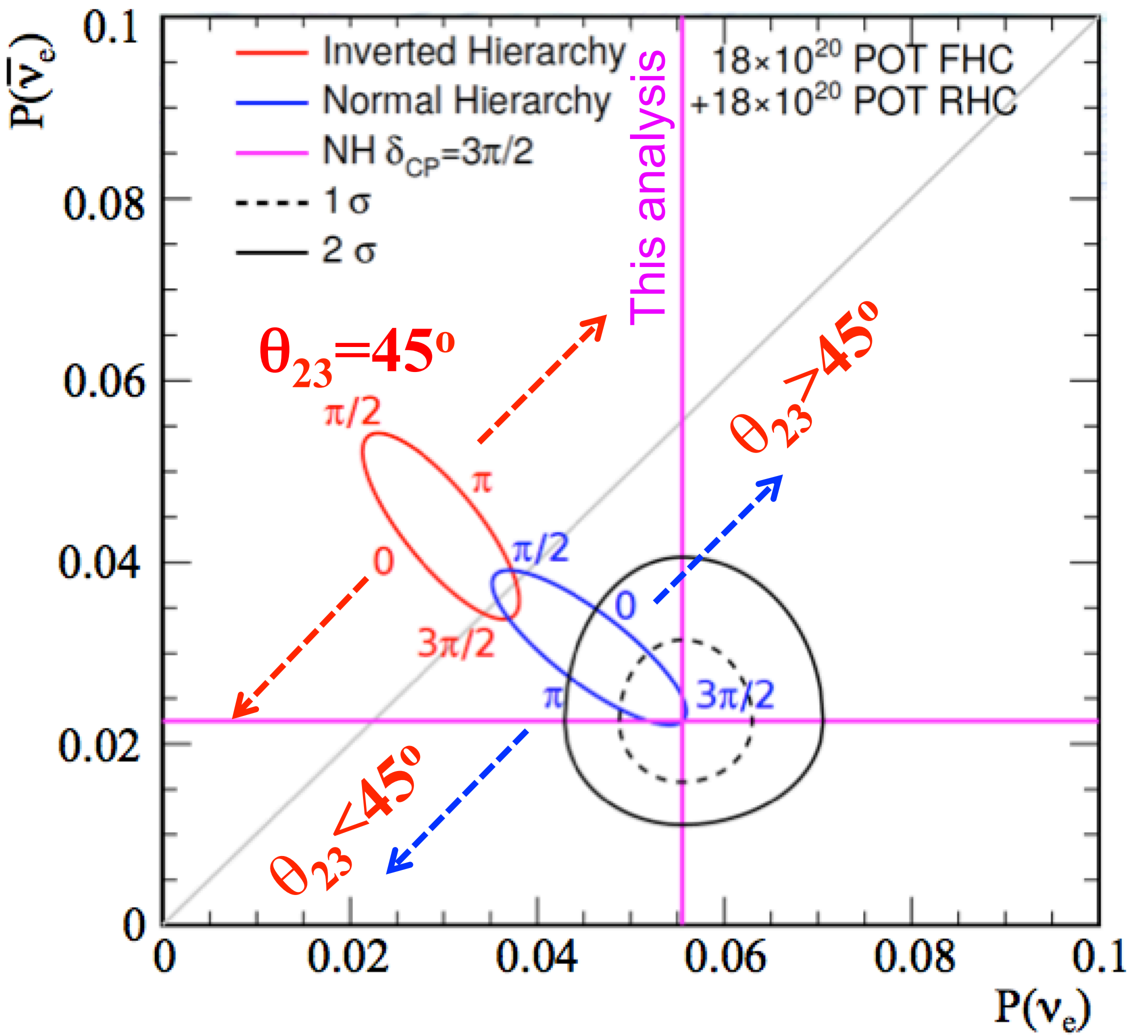
22



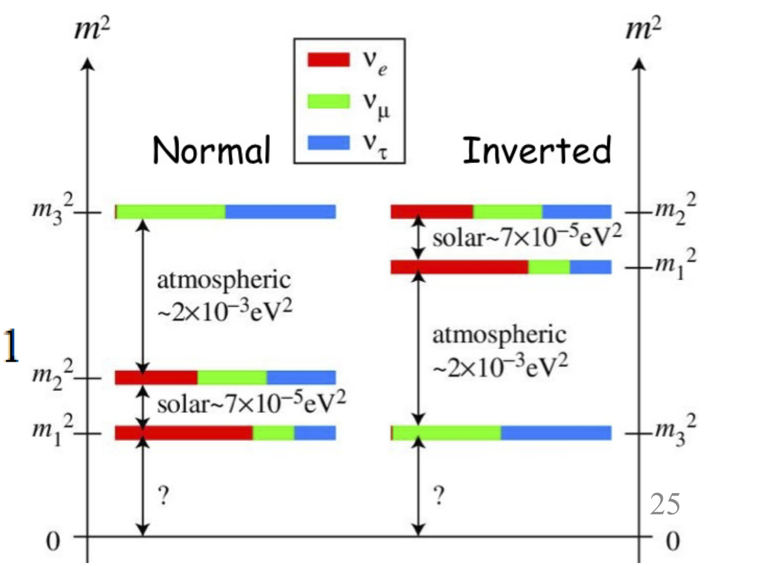
- Prefer maximal mixing
- rule out delta=0,pi at better than 90%
- rule out delta=0 at better than 2 sigma
  - in popular press claim CP violation at 2sigma (?)

http://neutrino2016.iopconfs.org/IOP/media/uploaded/EVIOP/event_948/11.05___1_.pdf

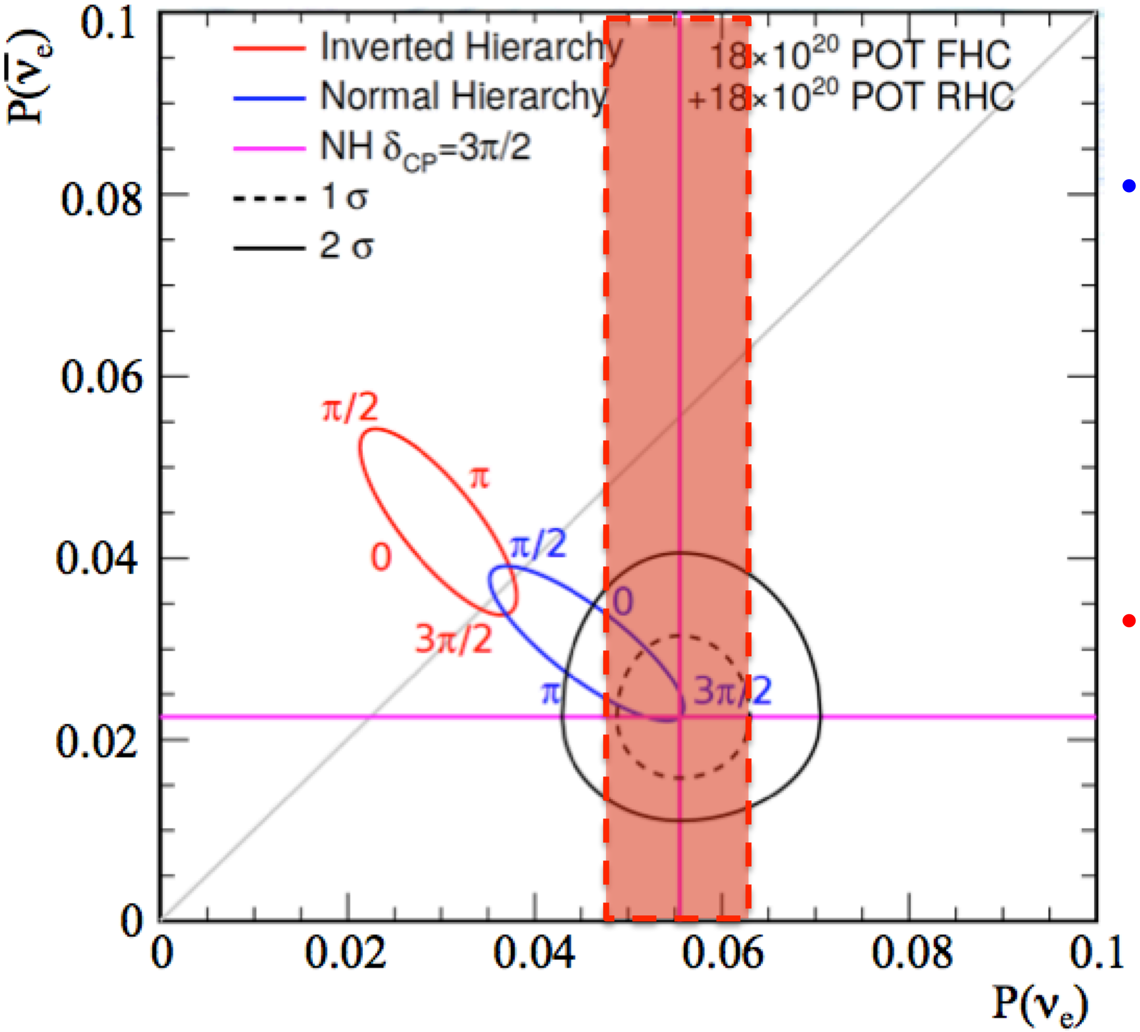
ν_e appearance at NOvA



- Measuring ν_e (anti-ν_e) appearance probability with ν_μ and anti-ν_μ neutrino beam
- ν_e appearance:
  - Determine neutrino mass hierarchy
  - Constrain CP violation phase (δ_{CP})
  - Resolution of the θ_{23} octant



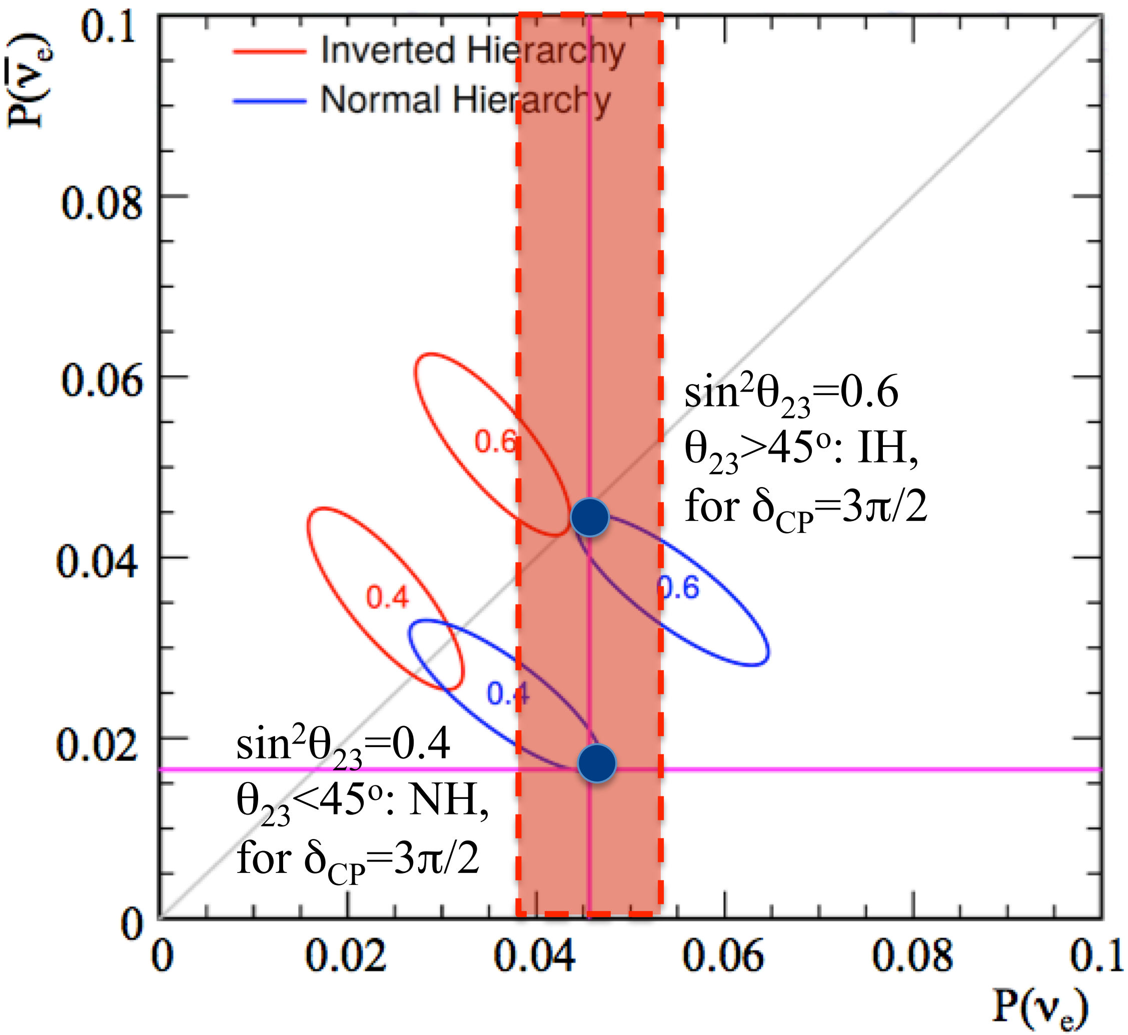
ν_e appearance at NOvA



- Measuring ν_e appearance probability with ν_μ and anti-ν_μ beam.
- ν_e appearance:
  - Determine neutrino mass hierarchy.
  - Constrain CP violation phase (δ_{CP})
  - Resolution of the θ_{23} octant.
- **When θ_{23}=45°, this neutrino run can solve mass hierarchy for δ_{CP}=3π/2**

θ_{23}=45°

ν_e appearance at NOvA



- Measuring ν_e appearance probability with ν_μ and anti-ν_μ beam.

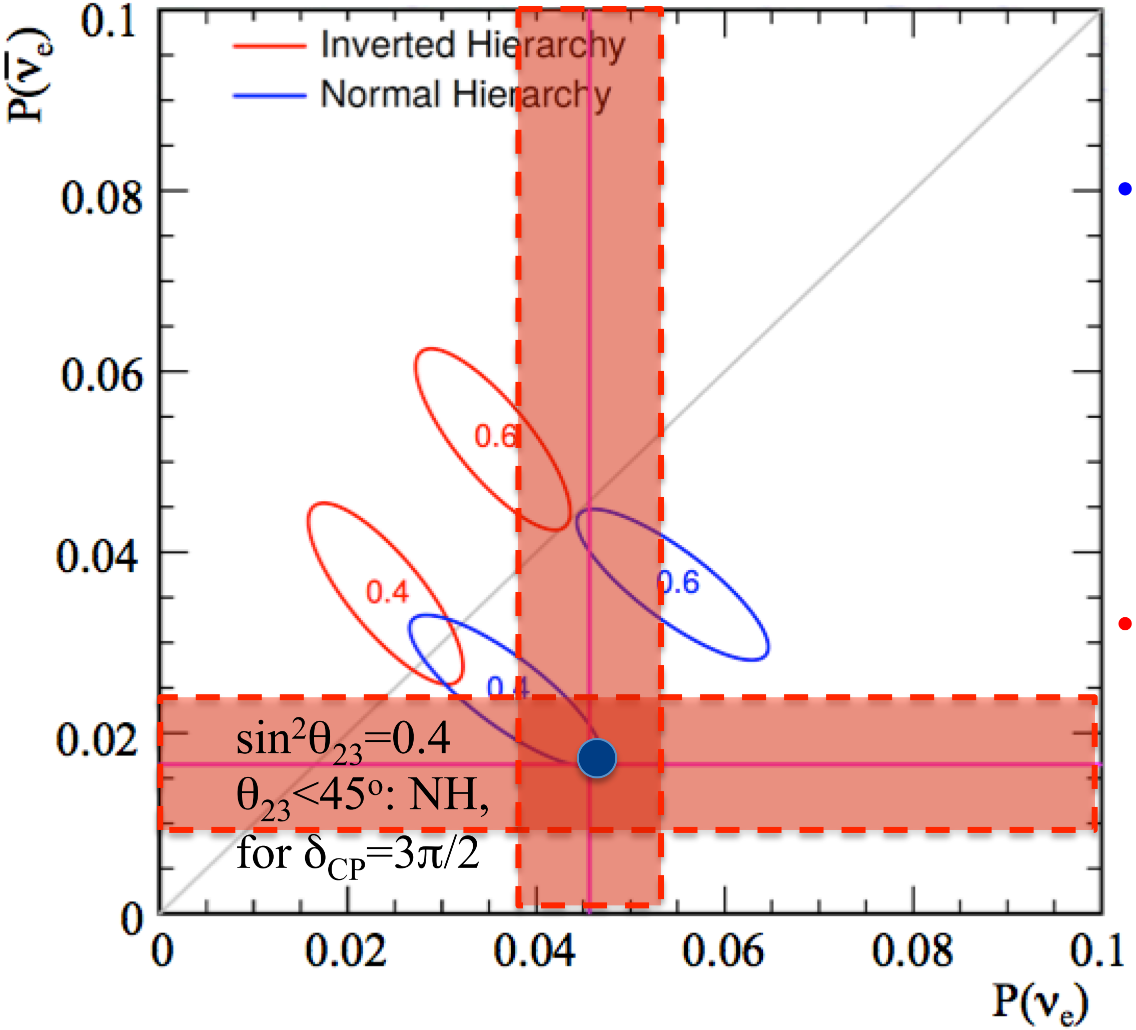
ν_e appearance:

- Determine neutrino mass hierarchy.
- Constrain CP violation phase (δ_{CP})
- Resolution of the θ_{23} octant.

When $\theta_{23} \neq 45^o$, there is an ambiguity caused by the octant of θ_{23} for the neutrino running

$\theta_{23} \neq 45^o$

ν_e appearance at NOvA



- Measuring ν_e appearance probability with ν_μ and anti-ν_μ beam.
- ν_e appearance:
  - Determine neutrino mass hierarchy.
  - Constrain CP violation phase (δ_{CP})
  - Resolution of the θ_{23} octant.
- **When $\theta_{23}\neq45^o$, there is an ambiguity caused by the octant of θ_{23} for the neutrino running, anti-neutrino running is necessary**

$\theta_{23}\neq45^o$

ν_e appearance at NOvA

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$

$$+ \; 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$- \; 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta \mathrm{m}^2_{31} L}{4E} \qquad \mathrm{A} = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

- NOvA measures ν_e appearance probability and ν_μ disappearance probability with ν_u and anti-ν_u beam.
- Measuring mass hierarchy, δ_{CP} and octant of θ_{23} with ν_e appearance

ν_e appearance at NOvA

$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$+ \boxed{2\alpha \sin\theta_{13}} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$- \boxed{2\alpha \sin\theta_{13}} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta \mathrm{m}^2_{31} L}{4E} \qquad \mathrm{A} = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

Depends on θ_{13}

ν_e appearance at NOvA

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2 (A-1)\Delta}{(A-1)^2}$$

$$+ \ 2\alpha \sin\theta_{13} \boxed{\cos\delta_{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$- \ 2\alpha \sin\theta_{13} \boxed{\sin\delta_{CP}} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \qquad \Delta = \frac{\Delta m_{31}^2 L}{4E} \qquad A = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

Depends on θ_{13}

Depends on δ_{CP}

ν_e appearance at NOvA

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \boxed{\sin^2\theta_{23}} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$+ \ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$- \ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \qquad \Delta = \frac{\Delta \mathrm{m}^2_{31} L}{4E} \qquad \mathrm{A} = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

Depends on θ_{13}
Depends on δ_{CP}
Depends on octant of θ_{23}

ν_e appearance at NOvA

$$P(\nu_\mu \to \nu_e) \approx \sin^2 2\theta_{13} \sin^2 \theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$+\ 2\alpha \sin\theta_{13} \cos\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$-\ 2\alpha \sin\theta_{13} \sin\delta_{CP} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}$$

$$\Delta = \frac{\Delta \mathrm{m}^2_{31} L}{4E}$$

$$\mathrm{A} = +G_f N_e \frac{L}{\sqrt{2}\Delta}$$

Matter effect is the correction to neutrino effective masses, when they travel through matter and scatter on electrons

Depends on $\Delta \mathrm{m}^2_{31}$

The difference between normal hierarchy (Δ>0) and inverted hierarchy (Δ<0) is enlarged by matter effect (A)

Matter effect increases with travel distance L

ν_e appearance at NOvA

$$P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e) \approx \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2(A-1)\Delta}{(A-1)^2}$$

$$+ \; 2\alpha \sin\theta_{13} \cos(-\delta_{CP}) \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \cos\Delta$$

$$- \; 2\alpha \sin\theta_{13} \sin(-\delta_{CP}) \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin A\Delta}{A} \frac{\sin(A-1)\Delta}{(A-1)} \sin\Delta$$

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \qquad \Delta = \frac{\Delta \mathrm{m}_{31}^2 L}{4E} \qquad \mathrm{A} = -G_f N_e \frac{L}{\sqrt{2}\Delta}$$

For anti-neutrinos, flip signs on δ_{CP} and matter effect A

ν_μ disappearance at NOvA

The value of θ_{23} is currently the least precisely measured mixing angle

ν_μ disappearance is important to determine $|\theta_{23}|$ and the octant of θ_{23}

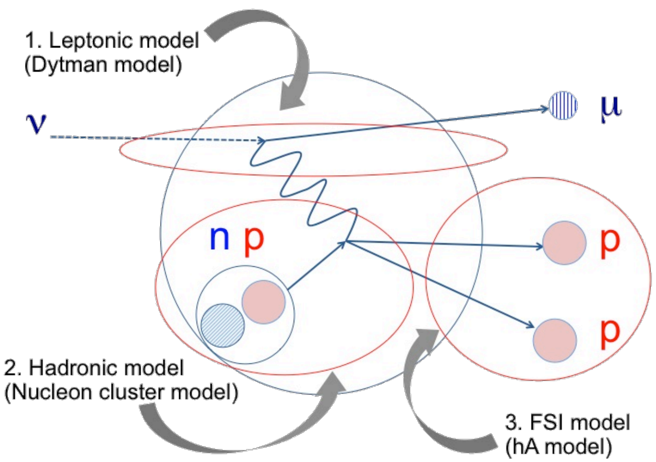
$$P(\nu_\mu \rightarrow \nu_\mu) \approx 1 - \boxed{\sin^2 2\theta_{23}} \sin^2\left(\frac{\boxed{\Delta m^2_{32}} L}{4E}\right)$$

If $\sin^2 2\theta_{23} = 1$ (maximum)
$\theta_{23} = 45^o$
If $\sin^2 2\theta_{23} \neq 1$,
need ν_e appearance to determine $\theta_{23} > 45^o$ or $< 45^o$

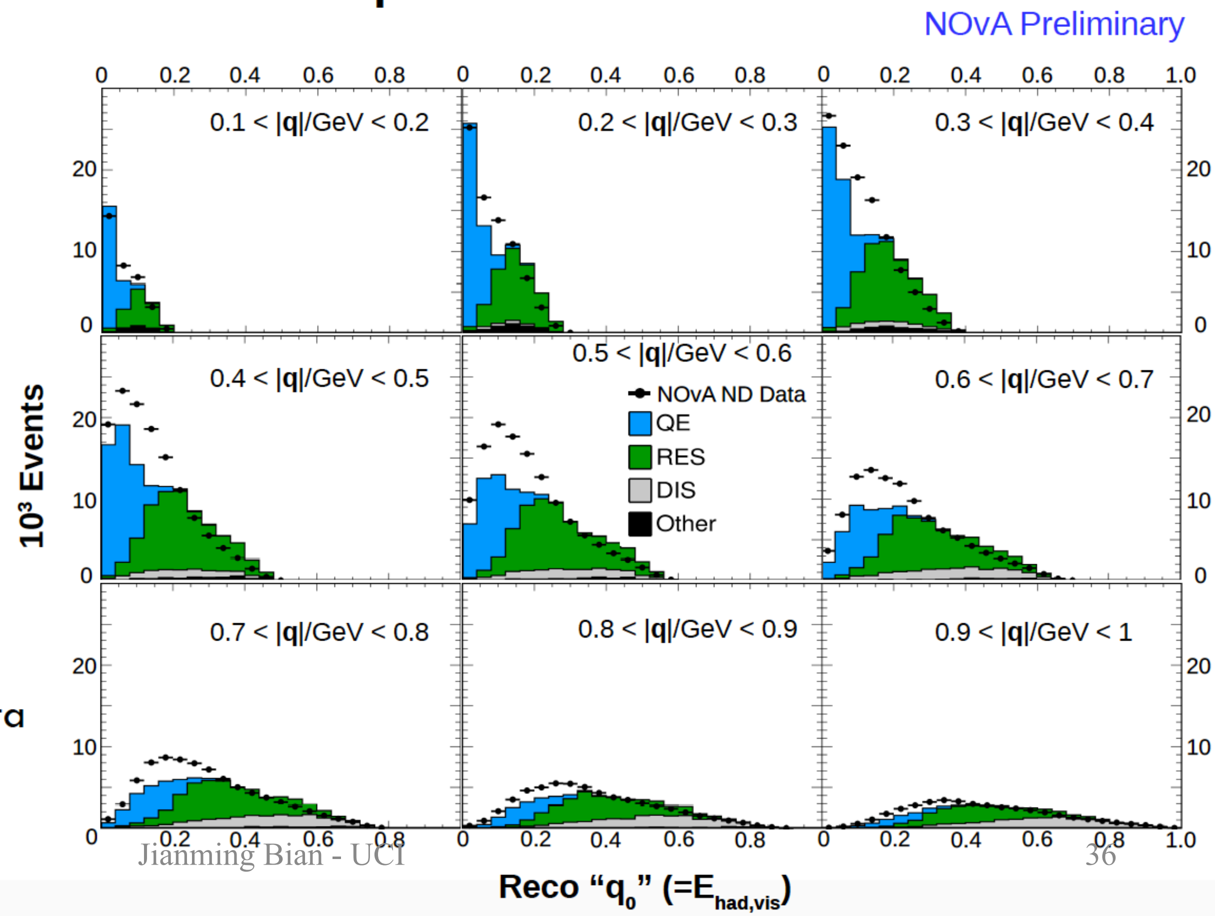
- Measuring ν_e appearance probability with ν_μ and anti-ν_μ beam.
- ν_e appearance:
  - Determine neutrino mass hierarchy.
  - Constrain CP violation phase (δ_{CP})
  - Resolution of the θ_{23} octant.
- **When $\theta_{23} \neq 45^o$, there is an ambiguity caused by the octant of θ_{23} for the neutrino running, anti-neutrino running is necessary**

Scattering in a Nuclear Environment

- Near detector hadronic energy distribution suggests unsimulated process between quasi-elastic and delta production



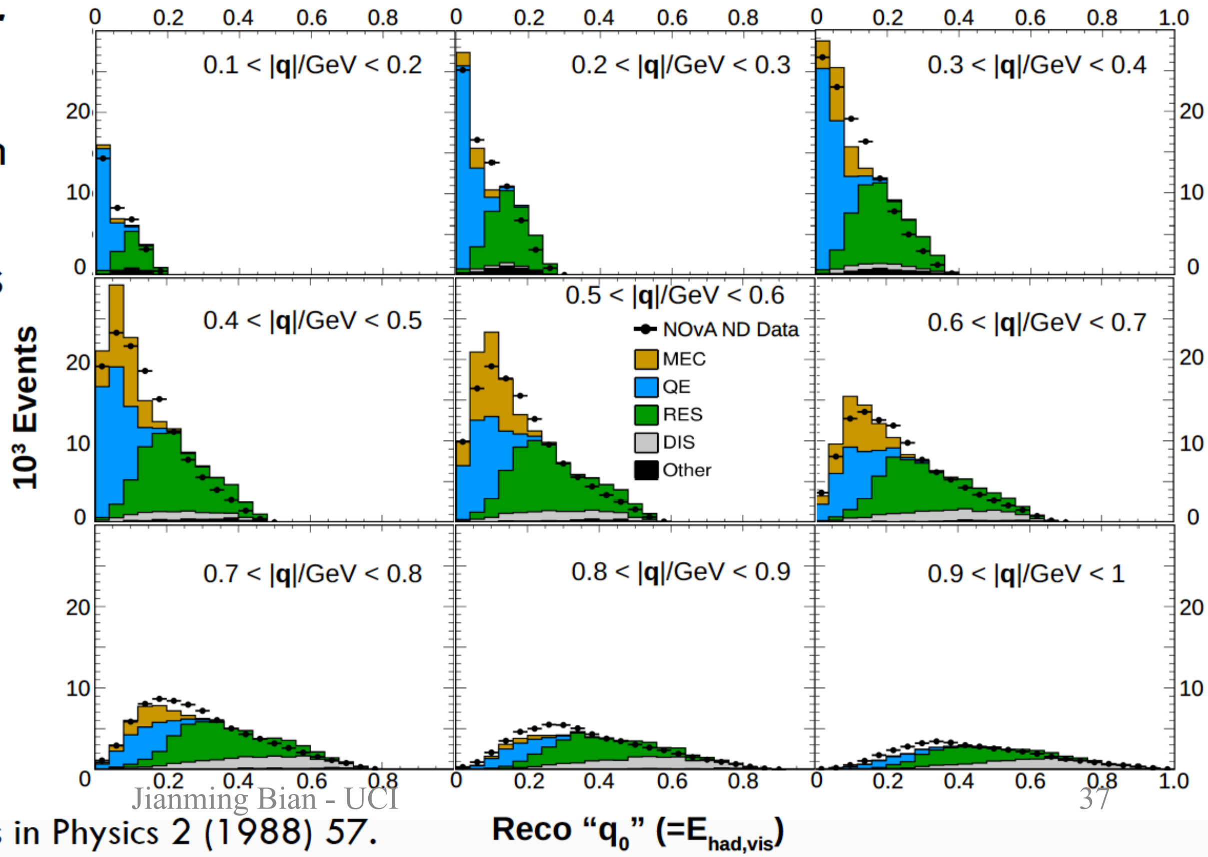
Similar conclusions from MINERvA data reported in P.A. Rodrigues et al., PRL 116 (2016) 071802



Scattering in a Nuclear Environment

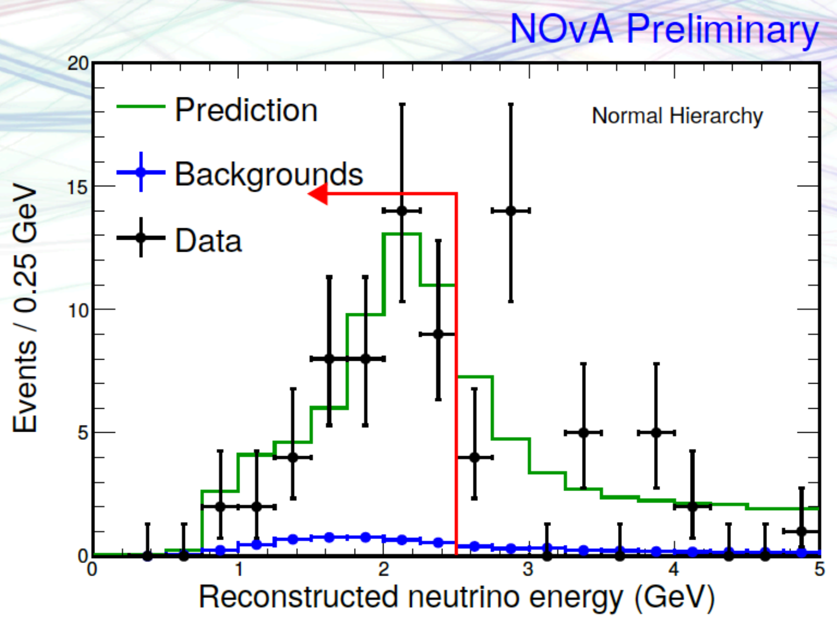
- Enable GENIE empirical Meson Exchange Current Model
- Reweight to match NOvA excess as a function of 3-momentum transfer

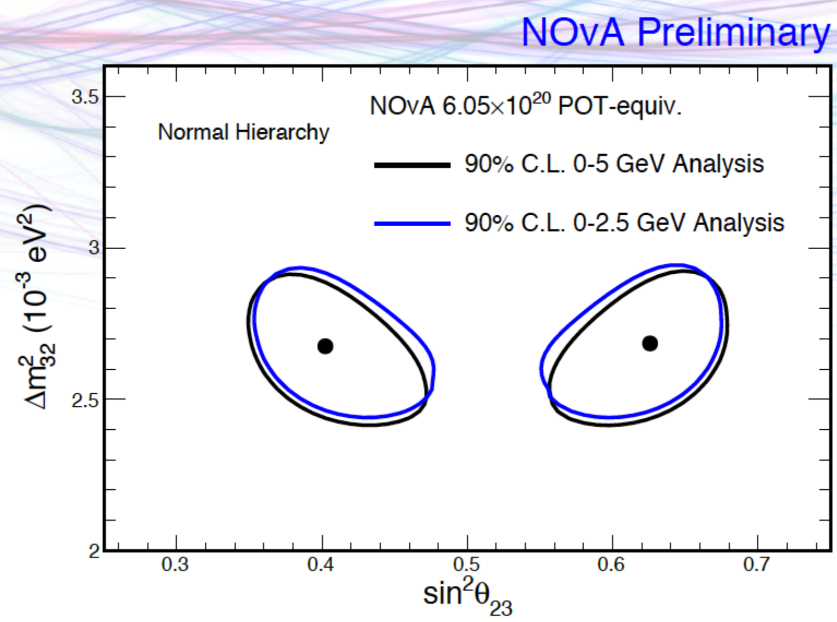
- 50% systematic uncertainty on MEC component
- Reduces largest systematics
  - hadronic energy scale
  - QE cross section modeling
- Reduce single non-resonant pion production by 50%
  (P.A. Rodrigues et al, arXiv:1601.01888.)



MEC model by S. Dytman, inspired by J. W. Lightbody, J. S. O'Connell, Computers in Physics 2 (1988) 57.

ν_μ results with different energy cuts

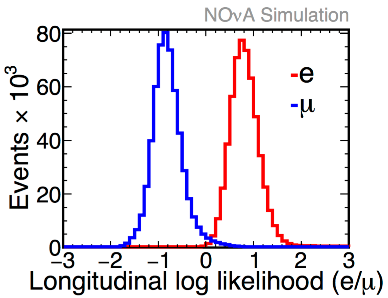




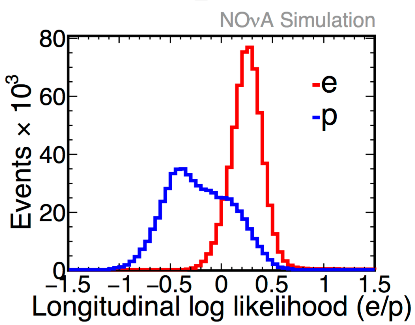
- $\chi^2/\text{dof} = 41.5/17$, driven by fluctuations in the tail
- No significant pull on oscillation fit from these bins

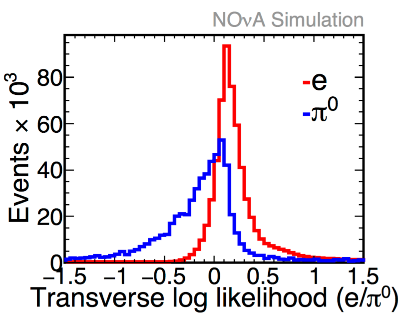
LID

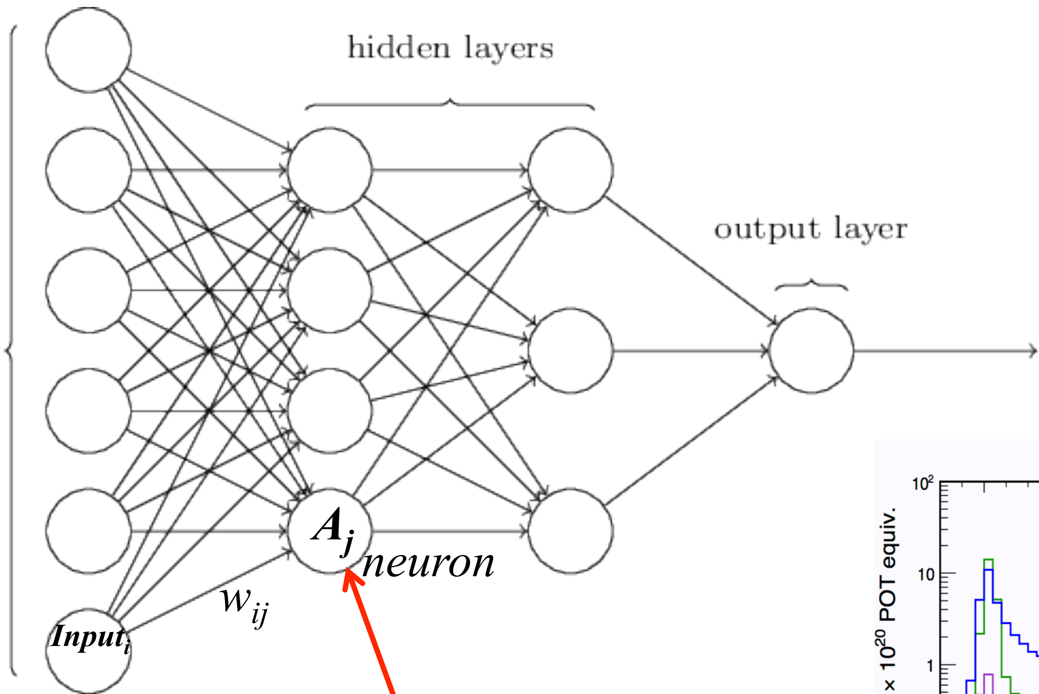
Reconstruct dE/dx based particle likelihoods as the inputs of an ANN, extracting features based on physics knowledge from the raw data (pixel).



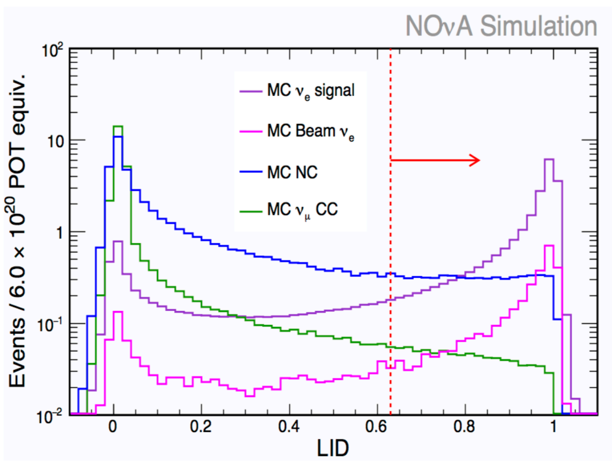
⋮ Inputs







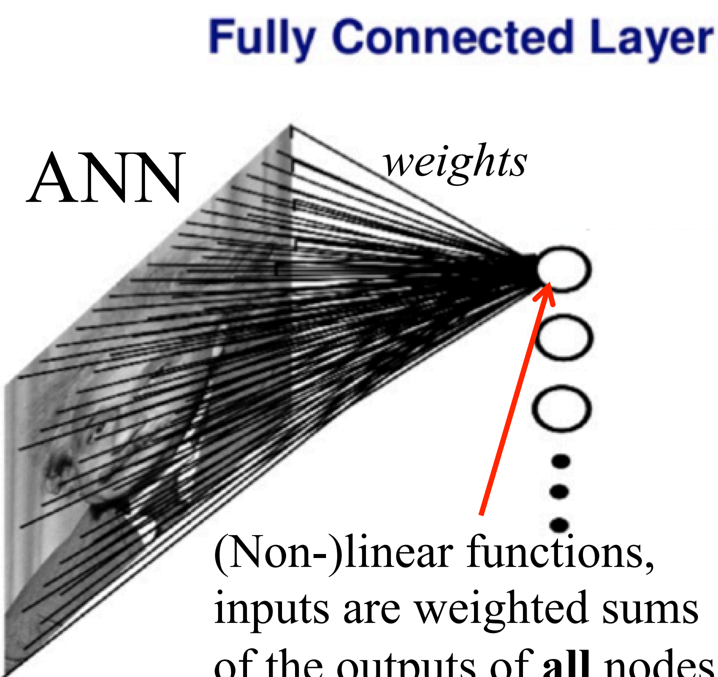
Output of the ANN is the identity of a event



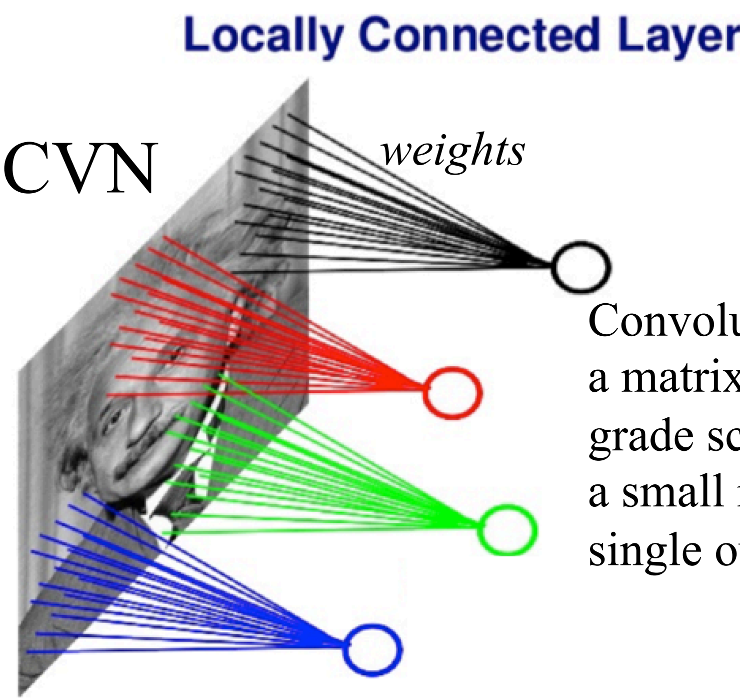
(Non-)linear functions, inputs are weighted sums of the outputs of **all** nodes in the previous layers
(fully connected layer)

Improved Event Identifier - CVN

- Artificial neuron network (ANN) uses reconstructed variables as inputs, but there are tasks such as vertex energy decomposition need direct pixel level inputs
- CVN: a convolutional neural network (CNN) using raw pixels as inputs
- Introduces convolutional layers to reduce free parameters, in which neurons are only connected to a small region of the layer before it
- Statistical power equivalent to 30% more exposure than previous PIDs



(Non-)linear functions, inputs are weighted sums of the outputs of **all** nodes in the previous layers



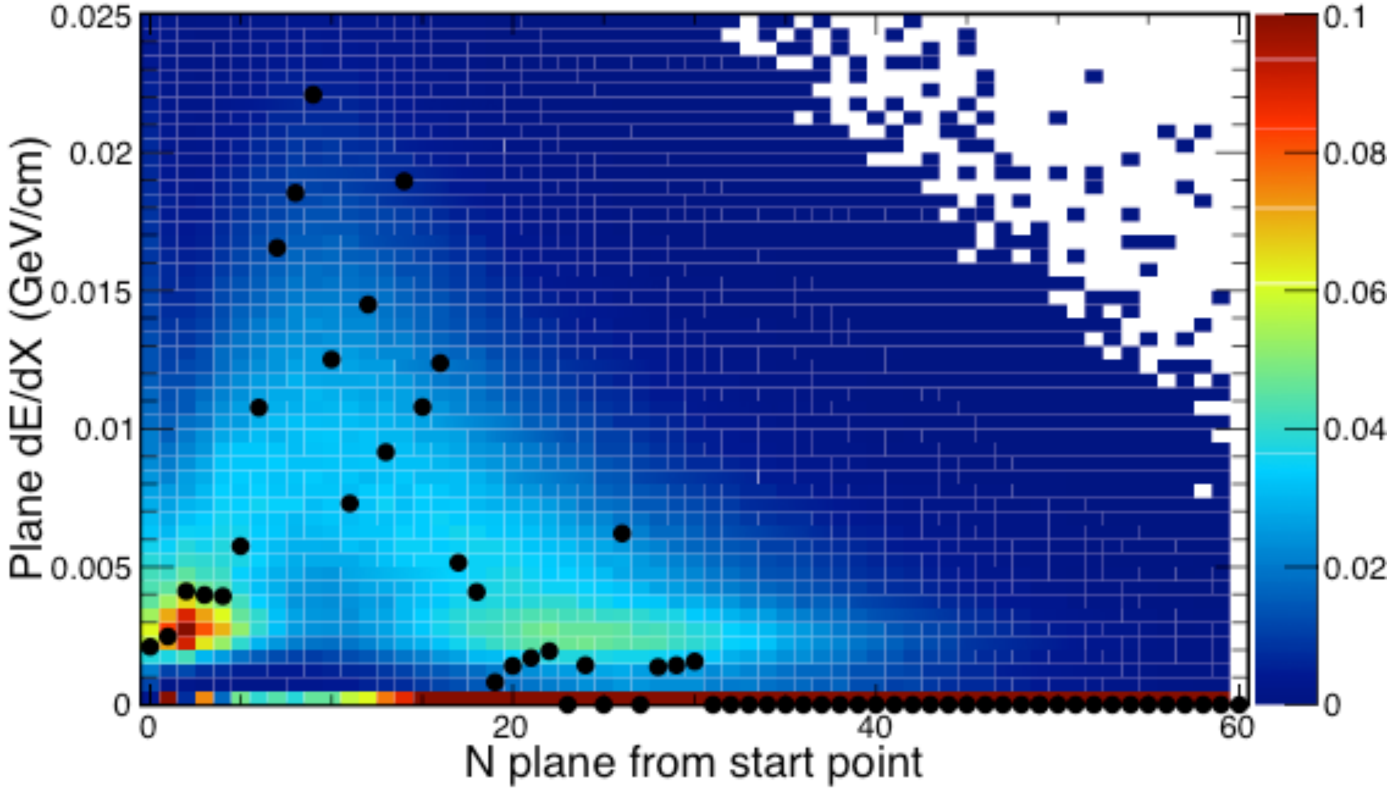
Convolutional Filter: a matrix that convert grade scales of pixels in a small region into a single output

See Alexander Radovic's poster

LID

Color: p.d.f. for dE/dx in each plane (e^- assumption)

Points: measured dE/dx in each plane (example event)

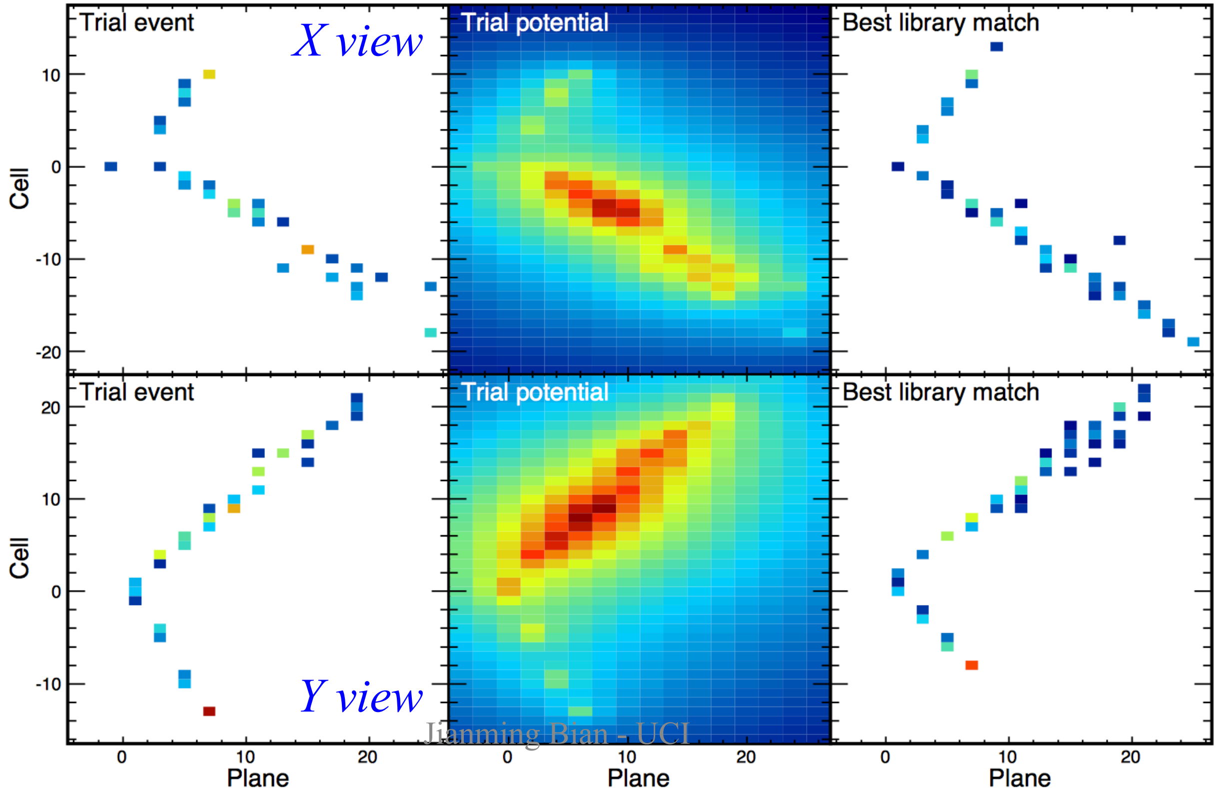


- Adding up log-likelihoods in all longitudinal/transverse slices we have overall longitudinal/transverse log-likelihoods for each type of particle
- The difference of log-likelihoods indicates the identity of the particle, for example: LL(e/μ)=LL(e)-LL(μ)

LEM

- Compare an unknown trial event to an enormous **MC library**, using individual cell hits rather than high-level reconstructed variables
- Extract **the pattern function (potential)** for the **trail event** by cell, including both position and charge information
- Loop over all events in the library, place each event on the pattern function to calculate match value and record the **1000 best matching library events**
- **Five matching goodness variables** based on the 1000 best matching events, along with the **energy** of the trial event are trained in a Boosted Decision Tree (BDT) to form the PID (LEM)

Both PIDs have very similar efficiency and background rejection

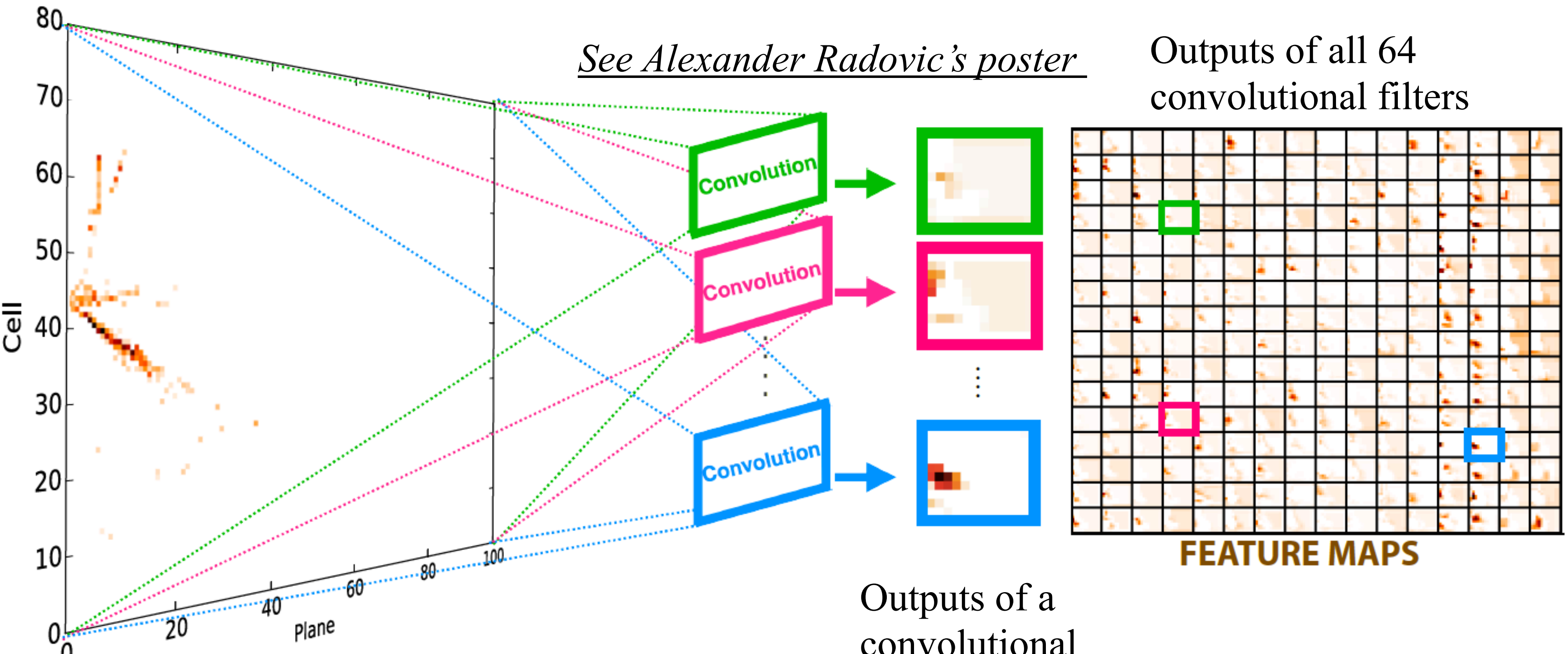


Convolutional Visual Network (CVN)

- Calibrated hit maps are inputs to Convolutional Visual Network (CVN)
- Early layers perform convolutions to pick out abstract features
- 64 7x7 filters, each filter convolves the entire hit map. Outputs (features) are used as inputs of next layer
- Statistical power equivalent to 30% more exposure than LID and LEM

See Alexander Radovic's poster

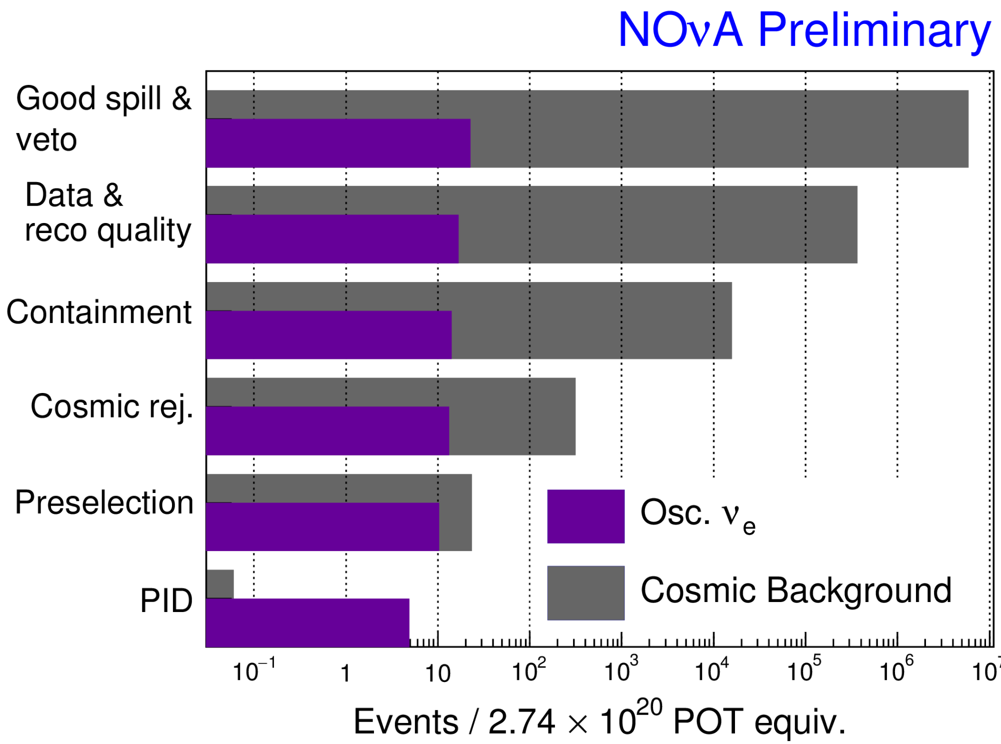
Outputs of all 64 convolutional filters



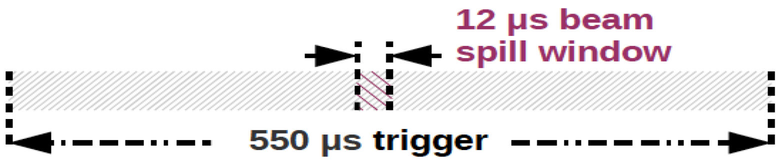
Outputs of a convolutional filters

Hit map of an ν_e CC event

Cosmic Ray Background Prediction



	Cosmic ray background
Good spill	21.9e6
Containment & data & reco quality	1.56e4
Cosmic rejection	312.16
ν_e Selection	0.06 (2)



Because the NOvA FD is on surface, the rejection of cosmic rays is extremely important.

Three cuts are used to reject the cosmic induced backgrounds prior to PID

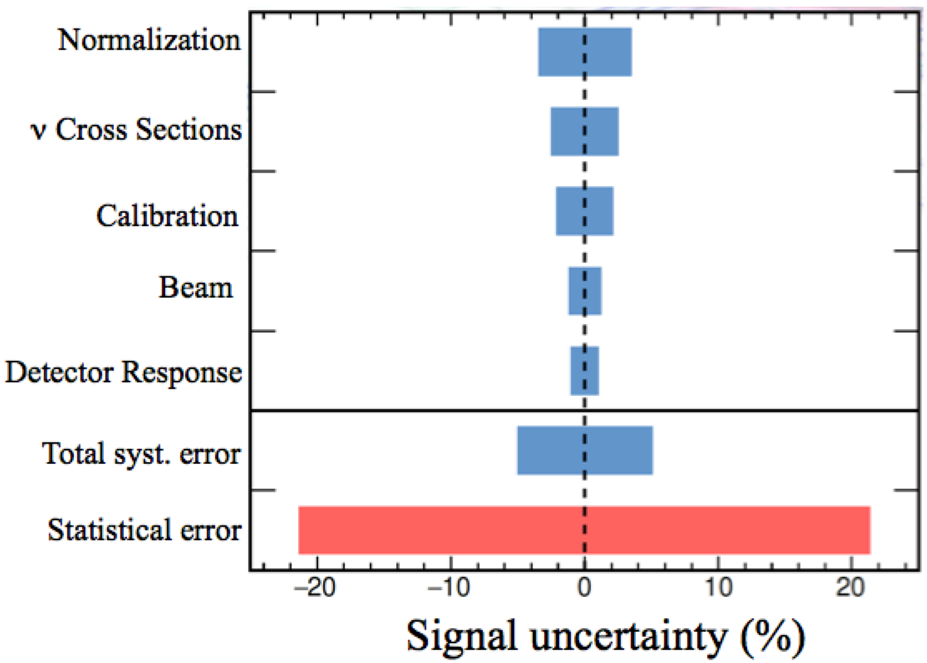
- P_t/P - require the event direction is consistent with the beam direction
- *Max Y hit position* – remove particles entering from the top of the detector
- Vertex Gap – assure reconstruction quality

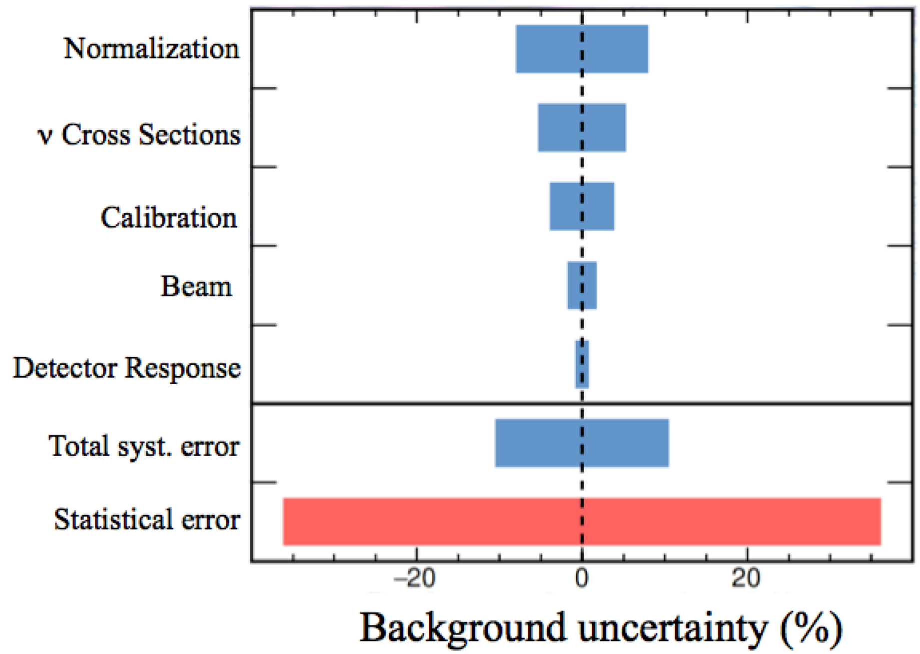
Achieves 350 million to 1 cosmic rejection

Systematic Errors

- A two detector experiment allows for the canceling or reduction of many systematic uncertainties such as beam flux and neutrino interaction modeling.
- The residual systematic uncertainties are evaluated by extrapolating our ND data with our nominal simulation and a systematically modified simulation
- For the appearance measurement, we consider a number of systematic effects

See Kuldeep Maan, Evan Niner and Nitin Yadav's posters

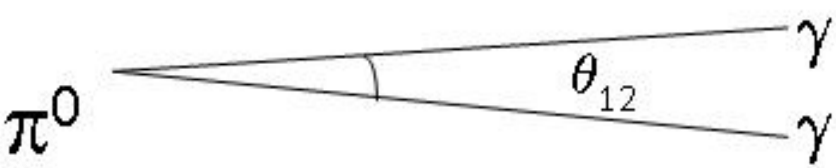




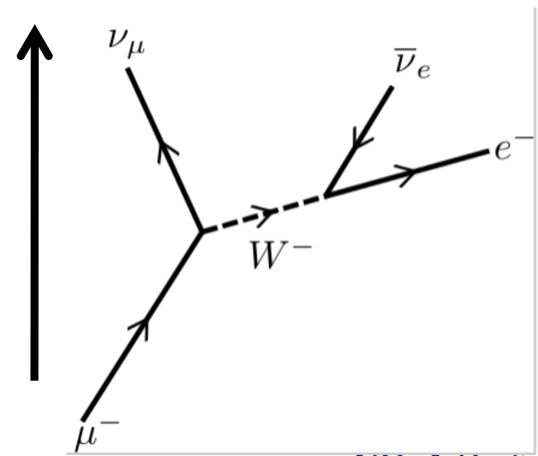
Systematic Error in Calibration

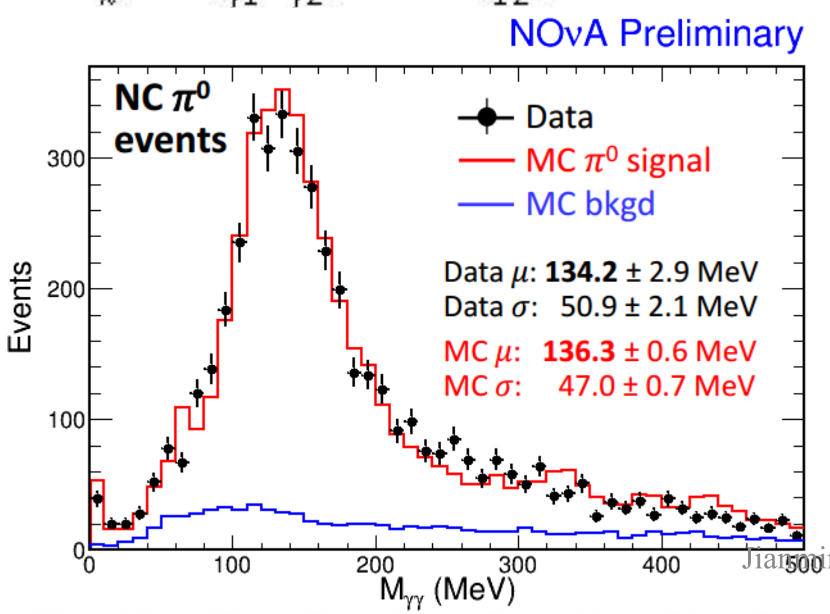
- Our calibration is built on dE/dx from stopping cosmic muons.
- Control samples for calibration uncertainty
  - π^0 mass peak in ND
  - Michel electrons in ND and FD

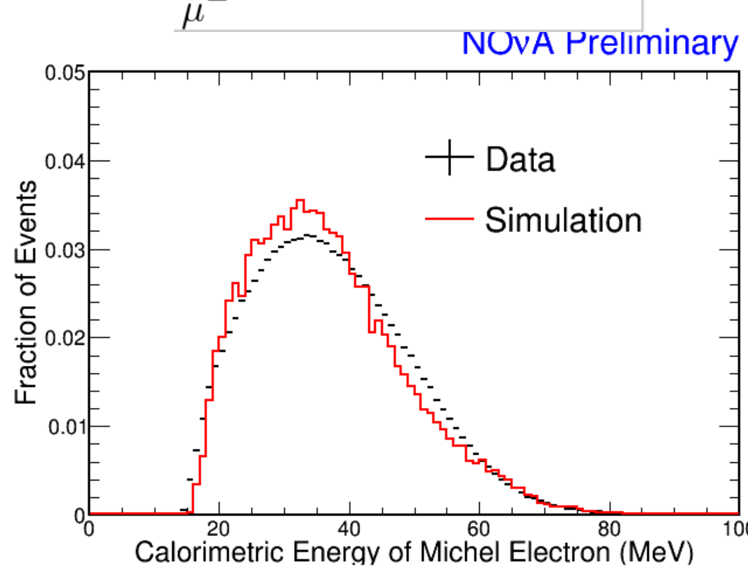
Michel electrons from muon decays



$$m^2_{\pi^0} = 2E_{\gamma 1}E_{\gamma 2}(1-\cos\theta_{12})$$

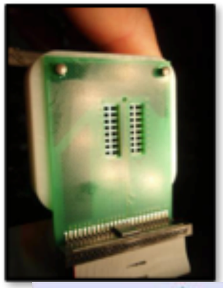






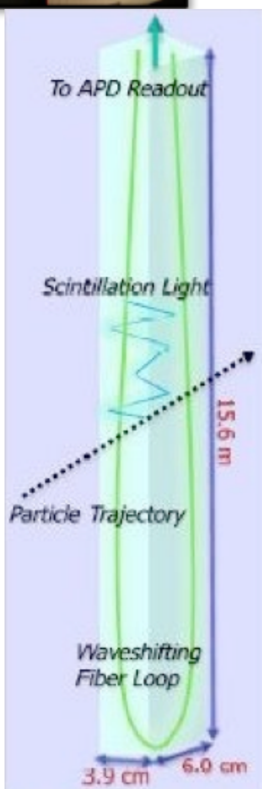
Detectors readout

32-pixel APD

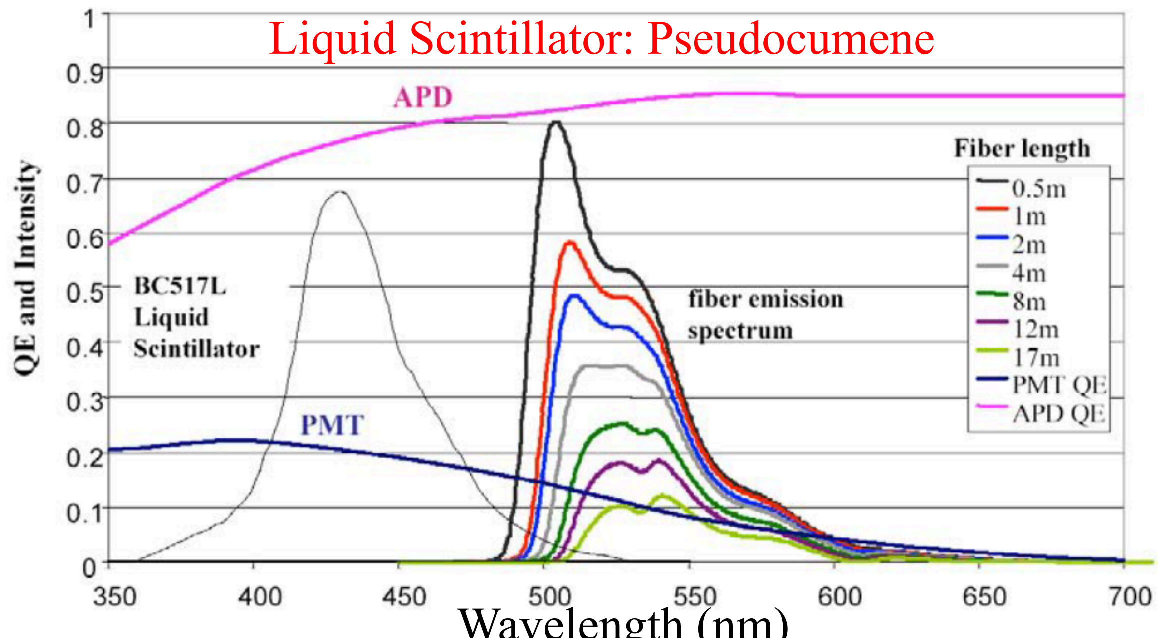


Fiber pairs from 32 cells

Each cell has a wavelength-shifting fiber routed an Avalanche Photodiode (APD). Scintillation light emitted isotropically and captured in wavelength -shifting fibers that convert wavelength to APD's sensitive region.



NOvA basic cell



APDs have high quantum efficiency and uniform spectral quantum efficiency. This enables the use of very long scintillator modules, thus significantly reducing the electronics channel count.

Liquid Scintillator and Wavelength shifting fibers

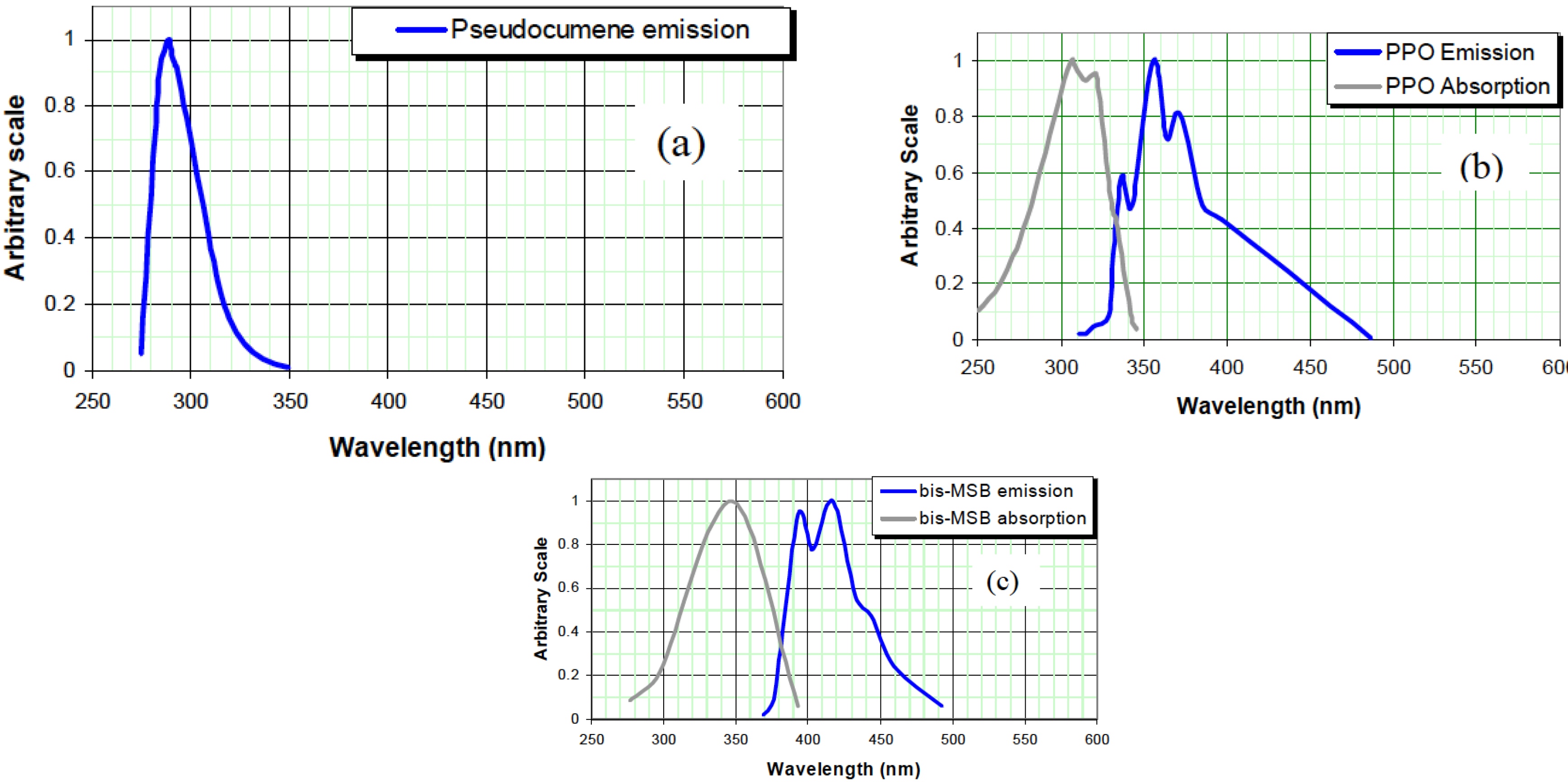
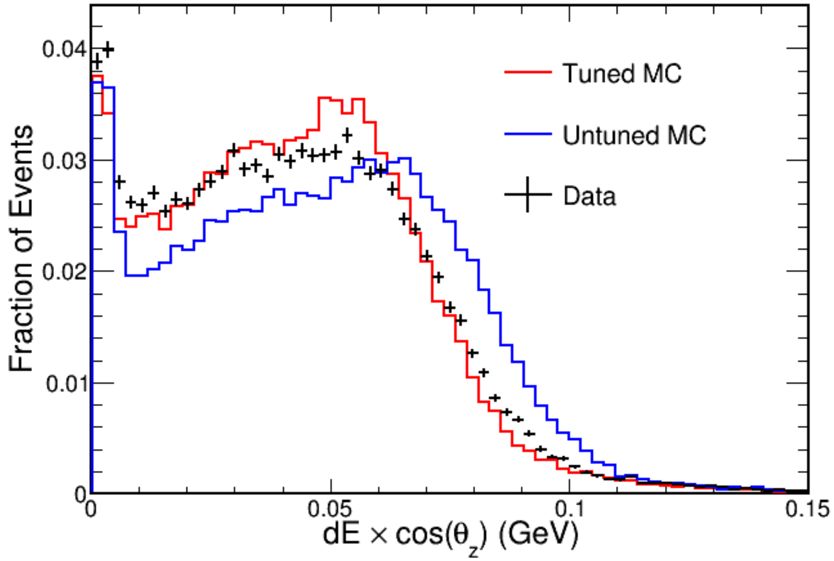


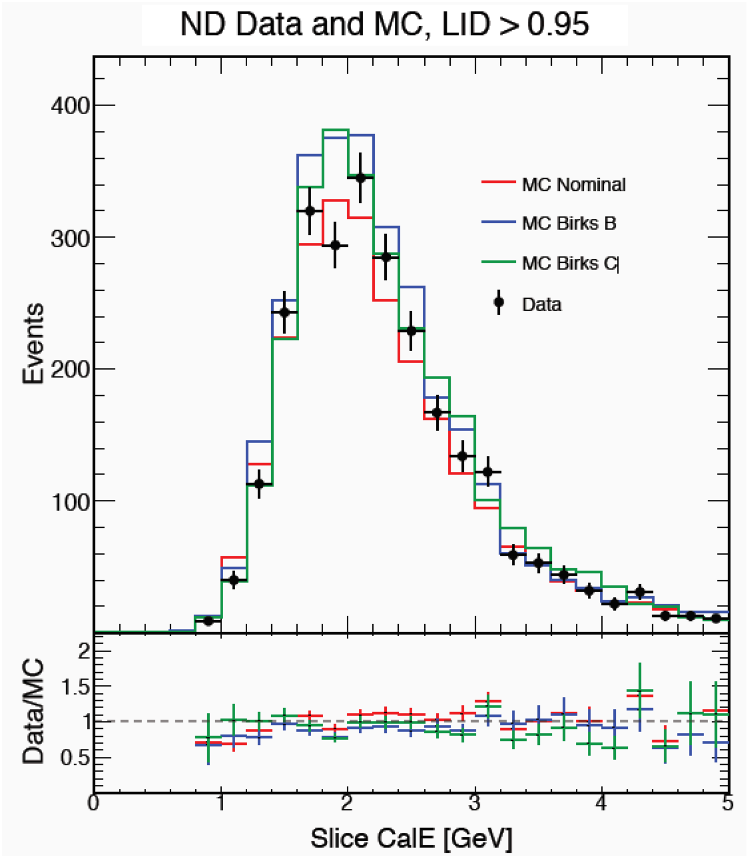
Fig. 10.1: Light production by liquid scintillator. The emission spectrum of the primary scintillant psueudocmene when traversed by an ionizing particle is shown in (a); the absorption and emission spectrum of the first waveshifter PPO is shown in (b); the absorption and emission spectrum of the second waveshifter bis-MSB is shown in (c).

Non-linearity in scintillator Detector Response

- The Birks-Chou Law gives an empirical description of non-linearity for scintillator detector response.
- We extract effective Birks-Chou constants in Data using ND ν_μCC QE sample.
- We treat the difference between the tuned parameter and typical values as a systematic error.

$$Light\ yield = A \frac{\frac{dE}{dx}}{1 + k_B \frac{dE}{dx} + k_C \left(\frac{dE}{dx}\right)^2}$$





Neutrino interactions

- GENIE is the Monte Carlo generator at NOvA that is used to simulate neutrino interactions.
- Reweight parameters in GENIE for uncertainty due to neutrino interaction simulation:
  - cross-section (11 par.)
    - Example: Adjust rate of two-pion production in CC and NC for non-resonant inelastic events by ±50%
  - hadronization model uncertainties (5 par.)
    - Example: Adjust the transverse momentum distribution for low multiplicity DIS events by ±3%
  - final state interactions (13 par.)
    - Example: Adjust the elastic scattering probability for pions by ±10%

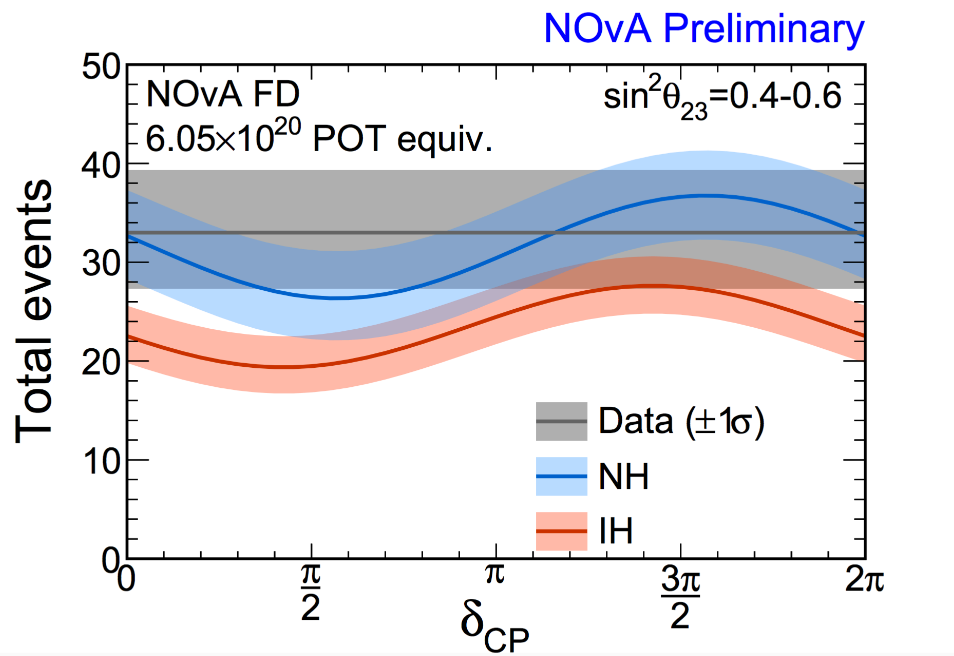
ν_e prediction vs. data in the FD

- Extrapolate each component in bins of energy and CVN output
- Expected event counts depend on oscillation parameters

Sig+Bkg (systematic error: 5%)

$\sin^2\theta_{23}$=0.5

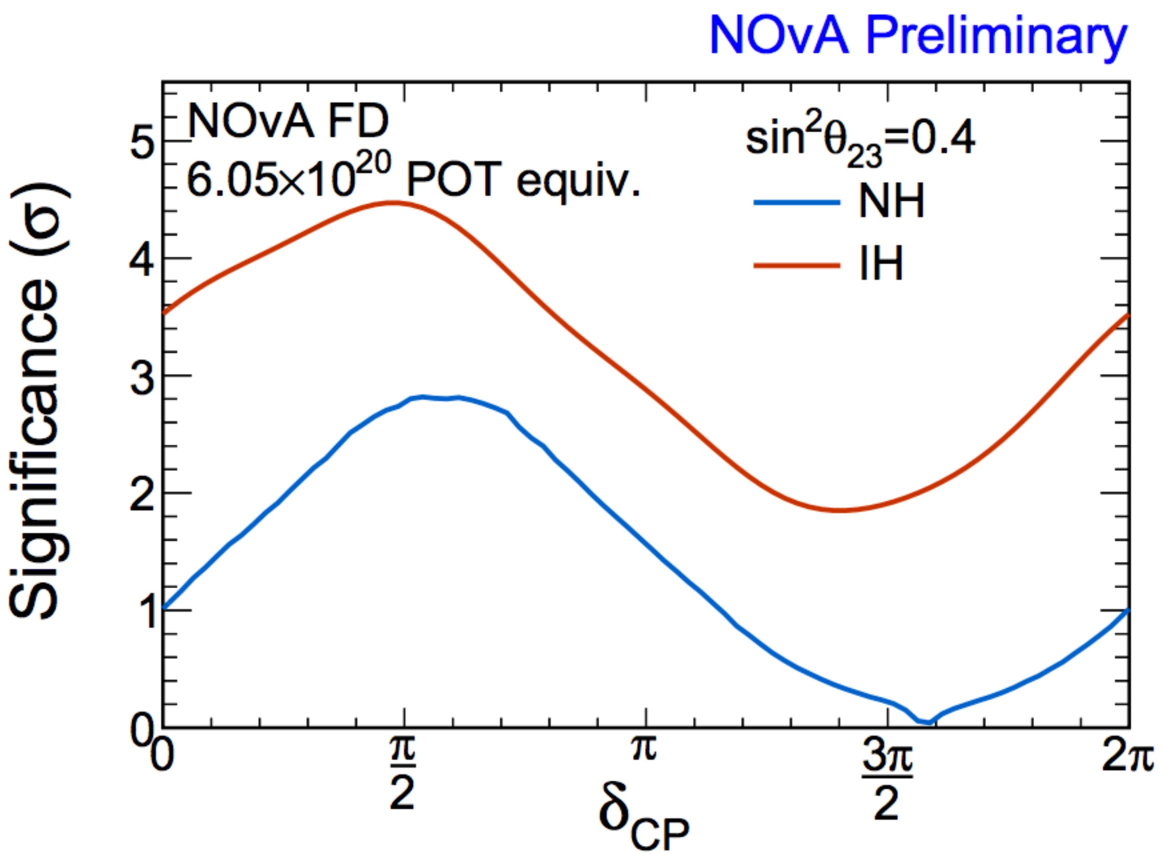
NH, $3\pi/2$	IH, $\pi/2$
36.4	19.4



Bkg (systematic error: 10%)

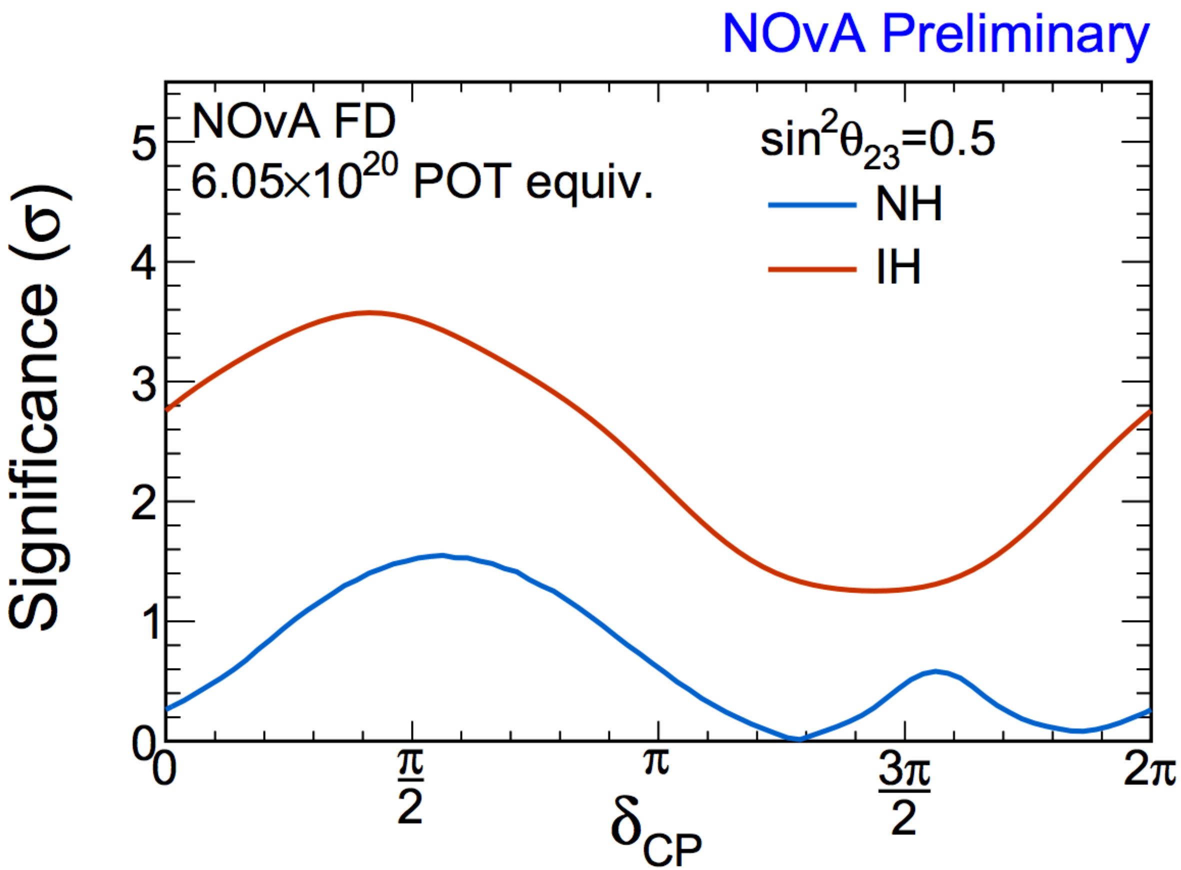
Total BG	NC	Beam ν_e	ν_μ CC	ν_τ CC	Cosmics
8.2	3.7	3.1	0.7	0.1	0.5

ν_e slices for $\sin^2\theta_{23}$=0.4



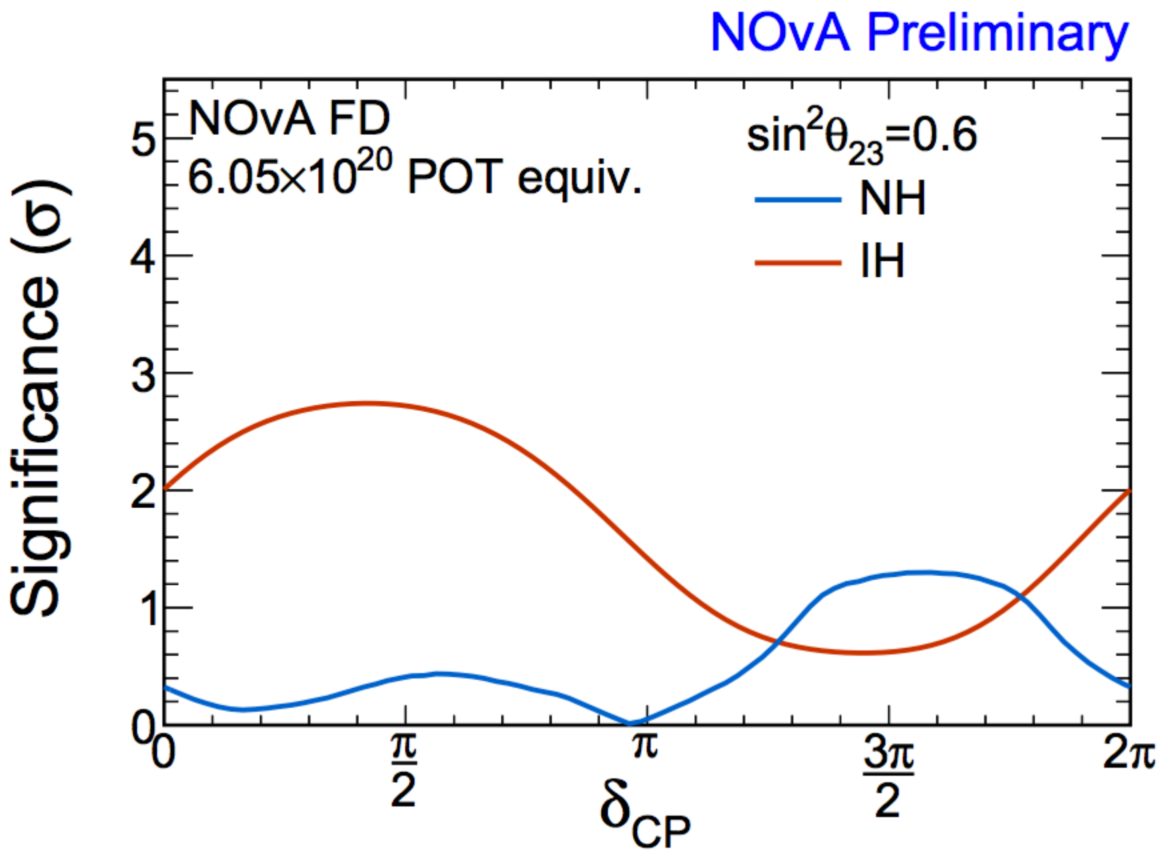
Significance as a function of δ_{CP} for NH (blue) and IH (red), with fixed $\sin^2\theta_{23} = 0.4$. Feldman-Cousins corrections are applied. Signal and background systematics are taken into account. Δm^2_{32} and $\sin^2 2\theta_{13}$ are held within global uncertainties.

ν_e slices for $\sin^2\theta_{23}$=0.5



Significance as a function of δ_{CP} for NH (blue) and IH (red), with fixed $\sin^2\theta_{23} = 0.5$. Feldman-Cousins corrections are applied. Signal and background systematics are taken into account. Δm^2_{32} and $\sin^2 2\theta_{13}$ are held within global uncertainties.

ν_e slices for $\sin^2\theta_{23}$=0.6



Significance as a function of δ_{CP} for NH (blue) and IH (red), with fixed $\sin^2\theta_{23} = 0.6$. Feldman-Cousins corrections are applied. Signal and background systematics are taken into account. Δm^2_{32} and $\sin^2 2\theta_{13}$ are held within global uncertainties.

$\nu_e + \nu_\mu$ combined analysis