Status of Long Baseline Neutrino Experiments

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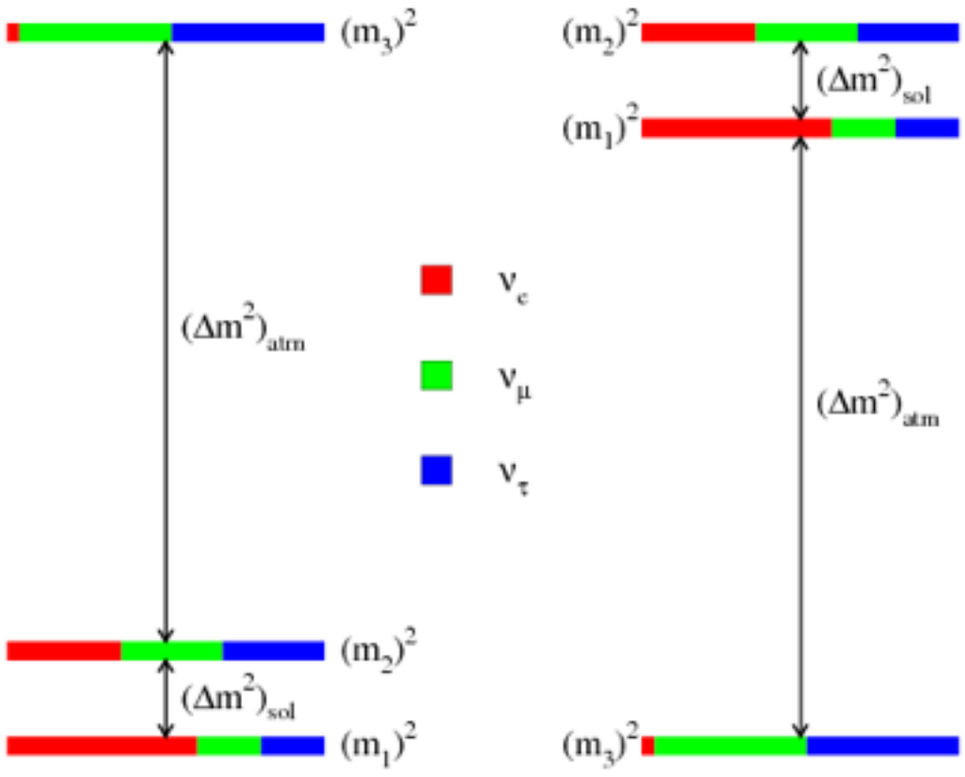
Outline

- Intro
- Current Generation: T2K and NOvA
- Next Generation: HK and DUNE

Neutrino Mixing

Neutrinos have two sets of eigenstates: mass (propagation) and flavor (detection)

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



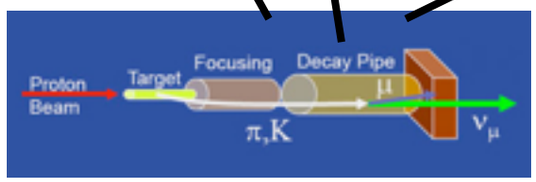
Normal Hierarchy Inverted Hierarchy

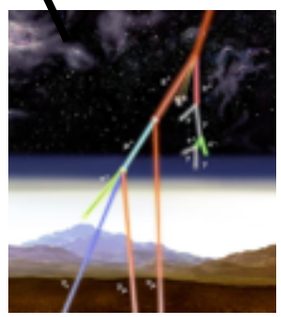
PMNS mixing matrix tells us how mass and flavor eigenstates are related

Neutrino Oscillation

$c_{ij}=\cos\theta_{ij}$ $s_{ij}=\sin\theta_{ij}$

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





Detection also depends on the mass splittings: $\sin^2\left(\frac{\Delta m^2 L}{E}\right)$ $\Delta m^2 = m_i^2 - m_j^2$

$\theta_{23}=45.6\pm2.3°$

$\theta_{12}=33.6\pm0.85°$

$\theta_{13}=8.33\pm0.22°$

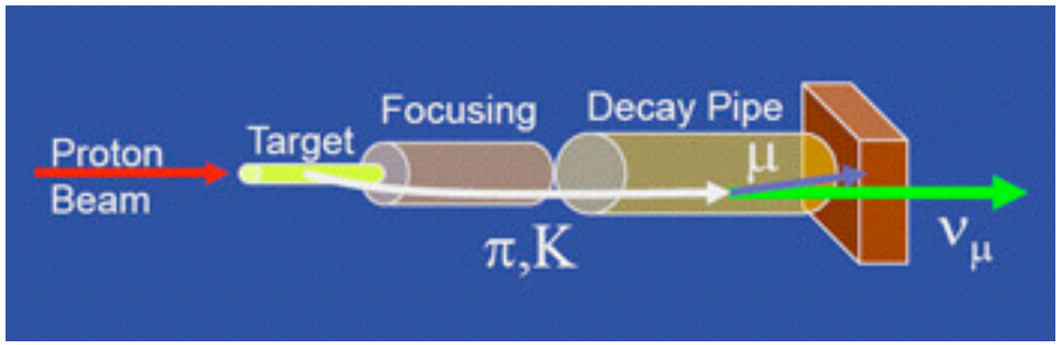
PDG 2016

$\Delta m^2_{21} = 7.53\pm0.18\times10^{-5}$ eV^2

$|\Delta m^2_{32}| = 2.45\pm0.05\times10^{-3}$ eV^2

δ_{CP} = ?

Long Baseline Experiments in a Nutshell



ν beam

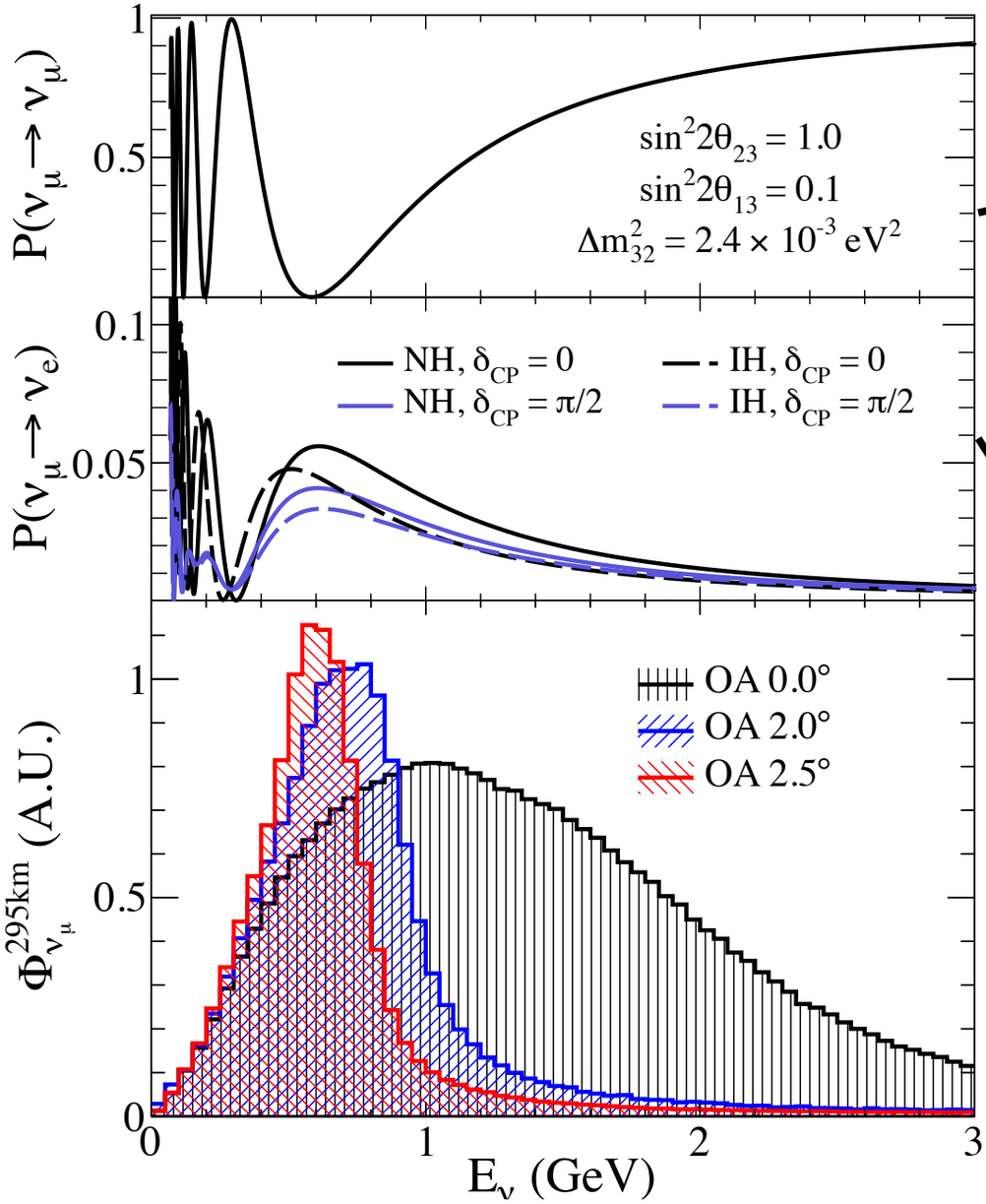
Near Detector

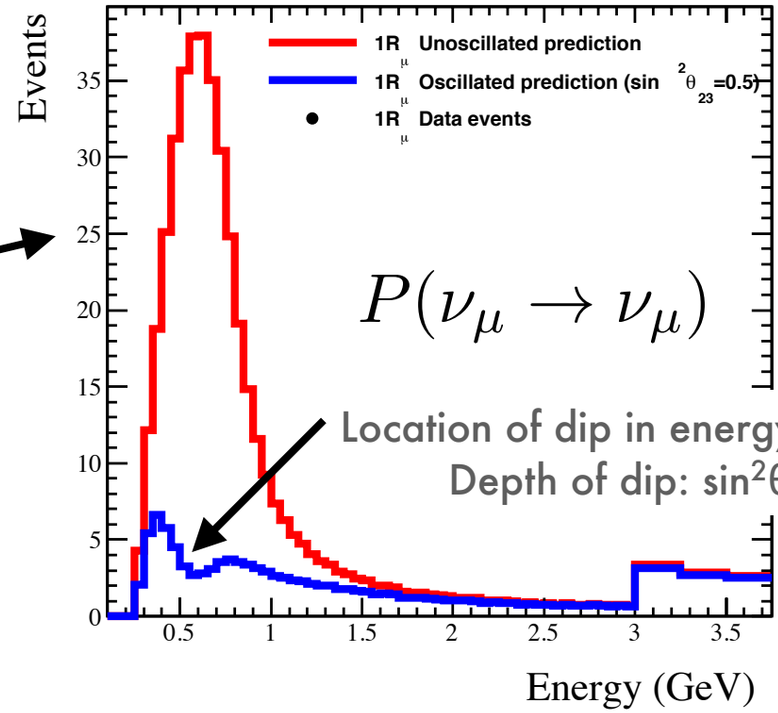
100s of km

How many ν_α here?

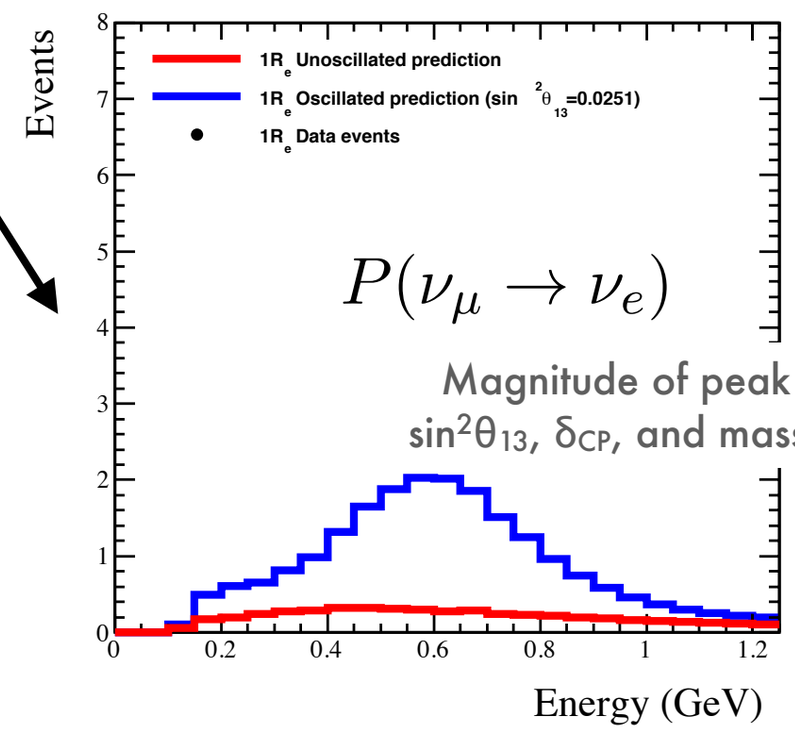
$$N = \Phi \times \sigma \times \varepsilon \times P(\nu_\alpha \rightarrow \nu_\beta)$$

Long Baseline Neutrino Oscillation



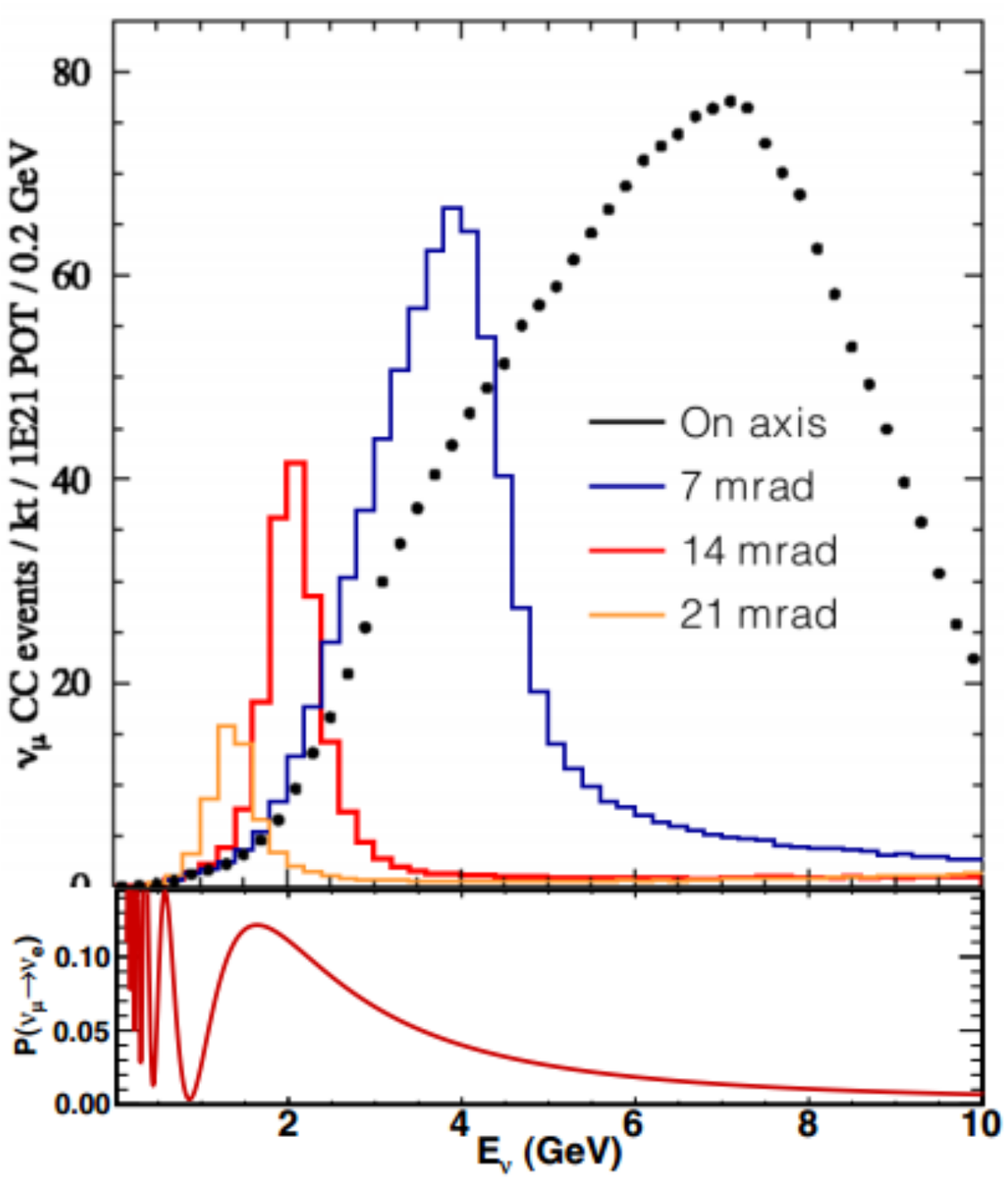


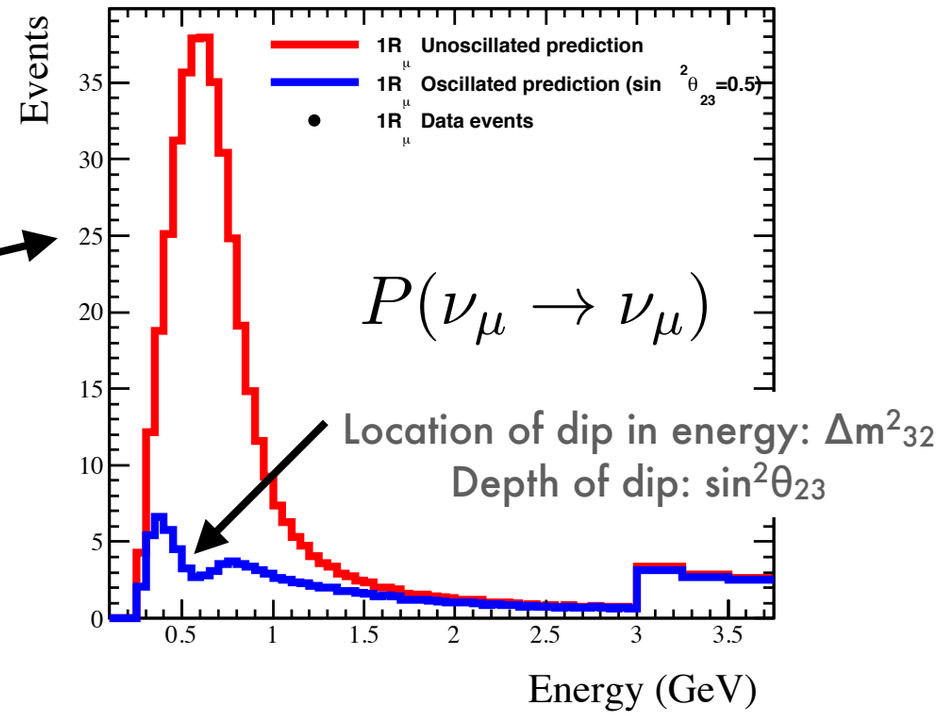
Location of dip in energy: Δm^2_{32}
Depth of dip: $\sin^2\theta_{23}$



Magnitude of peak linked to $\sin^2\theta_{13}$, δ_{CP}, and mass hierarchy

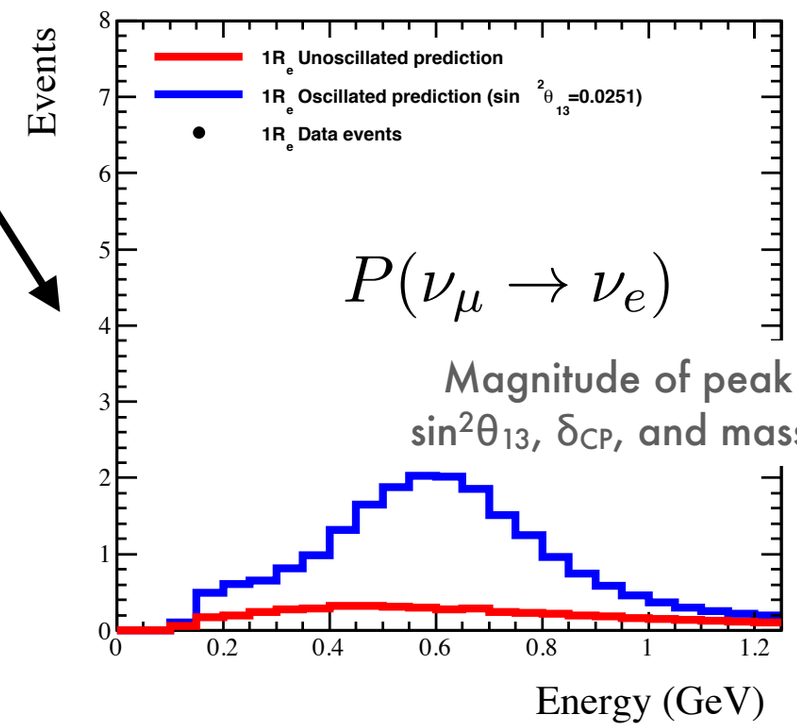
Long Baseline Neutrino Oscillation





$P(\nu_\mu \to \nu_\mu)$

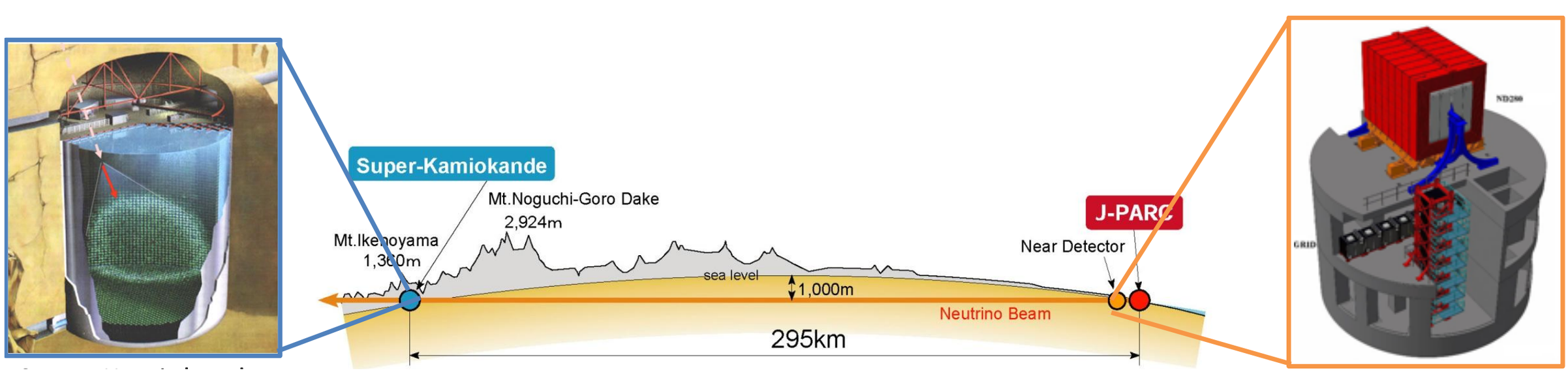
Location of dip in energy: Δm^2_{32}
Depth of dip: $\sin^2\theta_{23}$



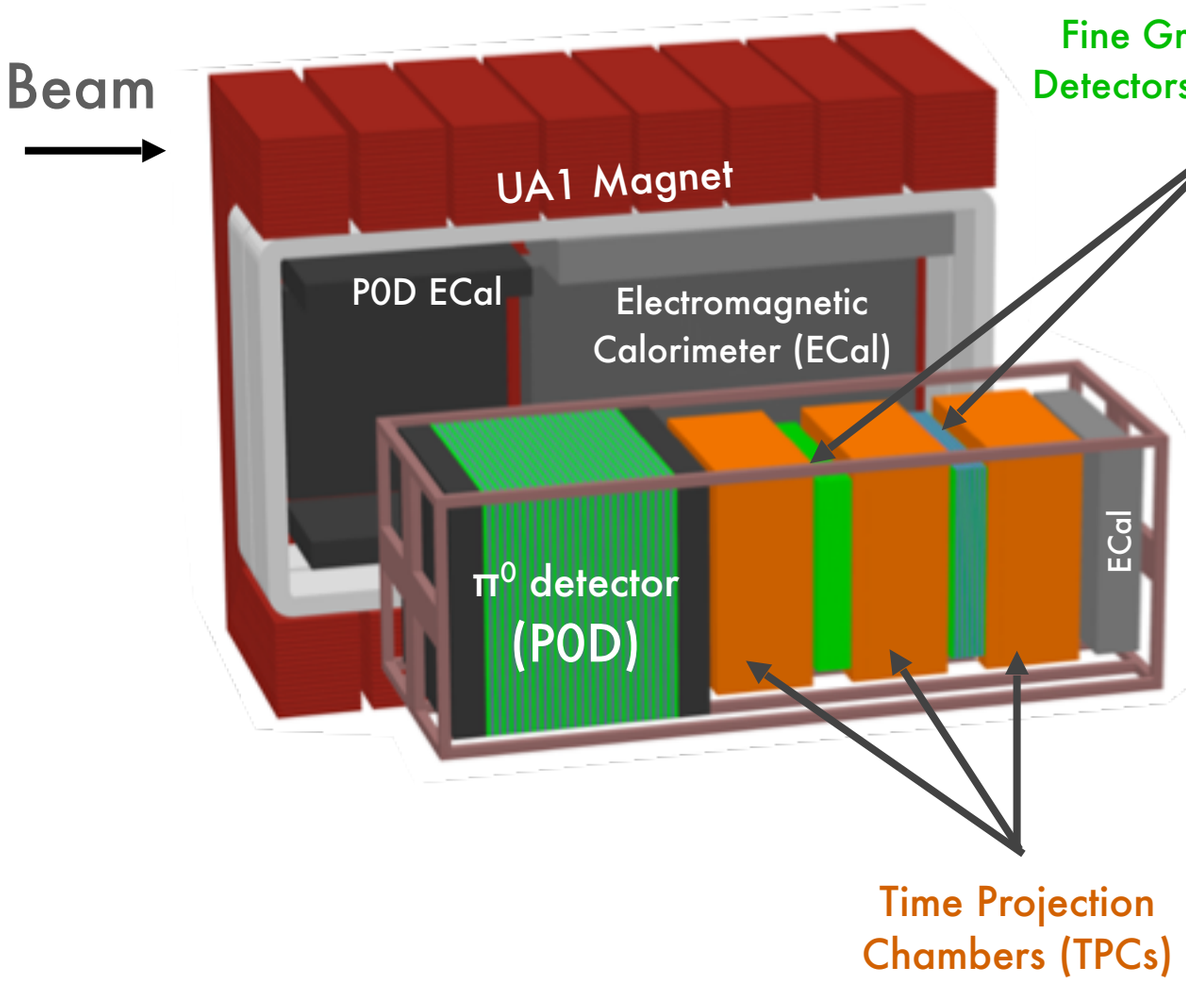
$P(\nu_\mu \to \nu_e)$

Magnitude of peak linked to
$\sin^2\theta_{13}$, δ_{CP}, and mass hierarchy

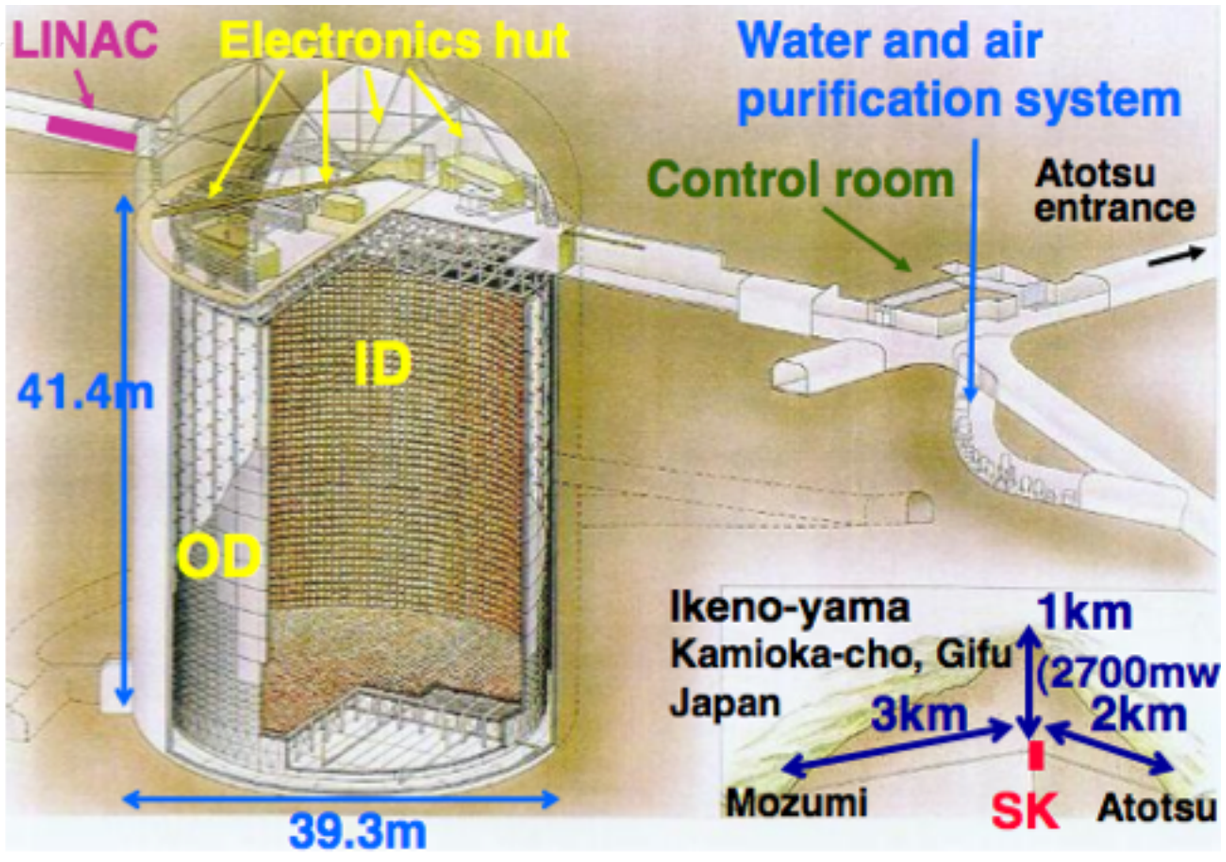
T2K

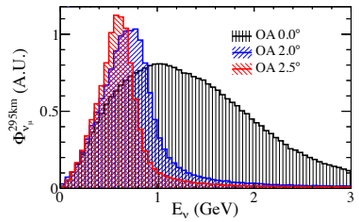

Super-Kamiokande
Mt.Noguchi-Goro Dake
2,924m
Mt.Ikenoyama
1,369m
sea level
1,000m
Neutrino Beam
295km
J-PARC
Near Detector
ND280
GRID

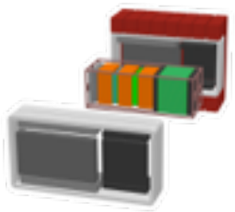
ND280 and SK



Near and Far detectors have very different forms







NA61/SHINE Data

INGRID/Beam Monitor Data

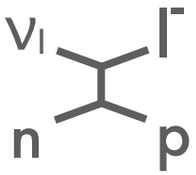
Flux Model

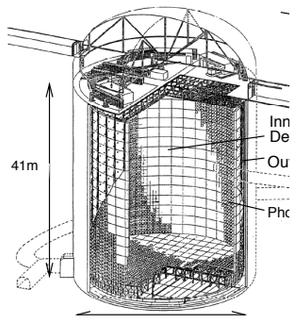
ND280 Detector Model

ND280 Data

External Cross Section Data

Cross Section Model





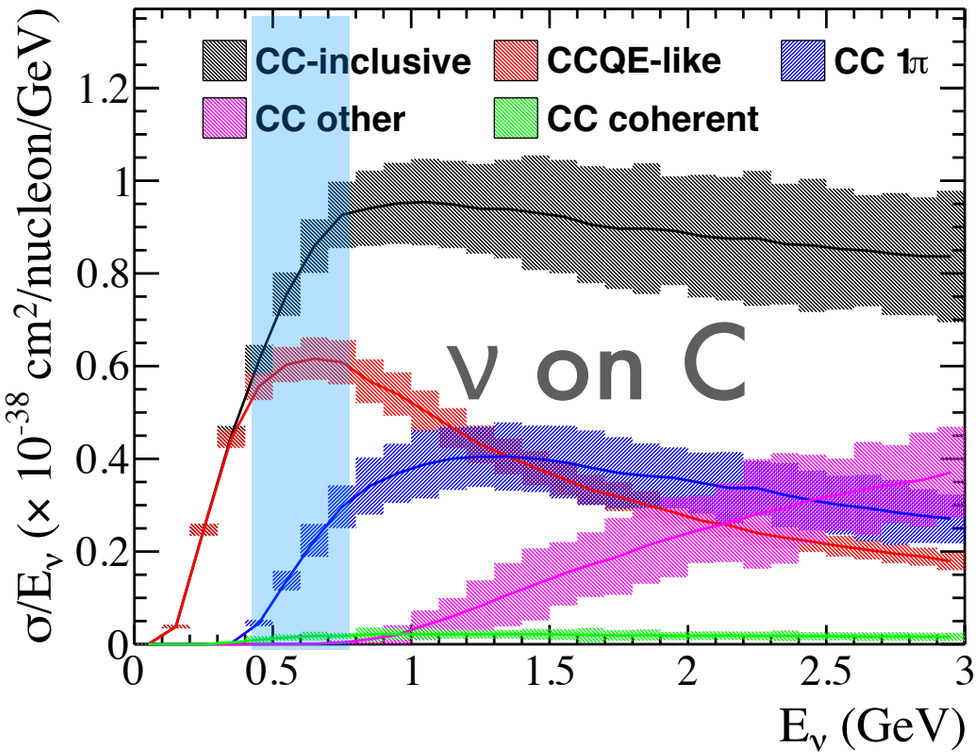
SK Data

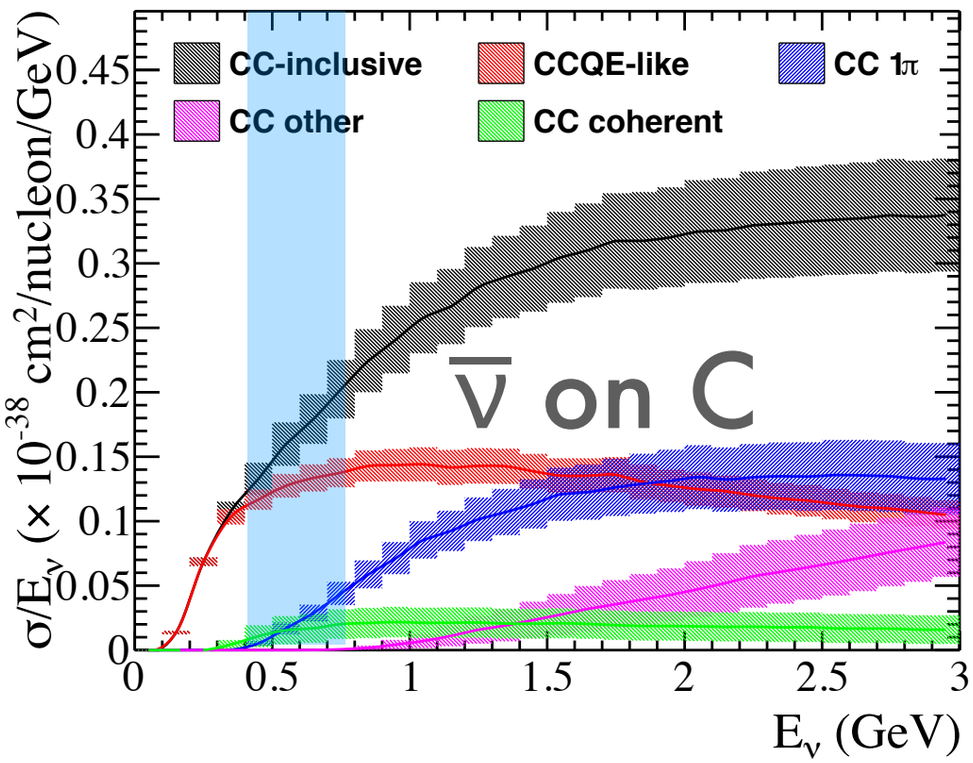
Oscillation Fit

SK Detector Model

Oscillation Parameters

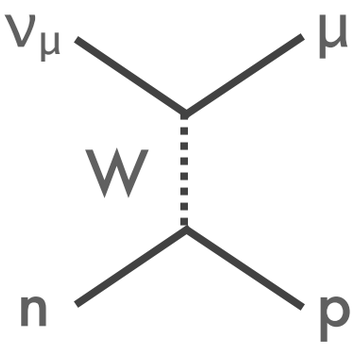
ν-N Cross Section Model





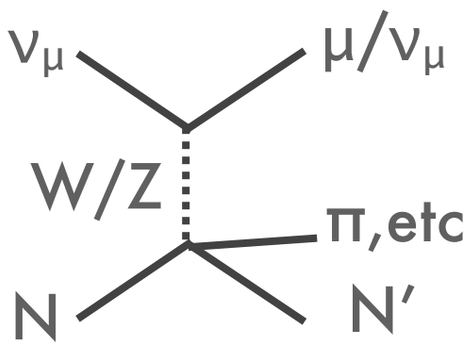
Uncertainties come from underlying model parameters and normalizations

Charged current quasi-elastic

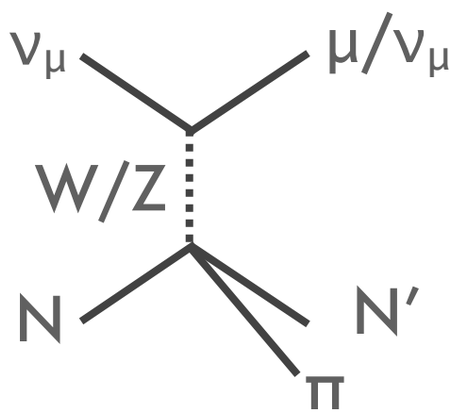


- MAQE
- MARES
- Fermi Mom.
- Binding Energy
- FSI
- 2p2h
- …

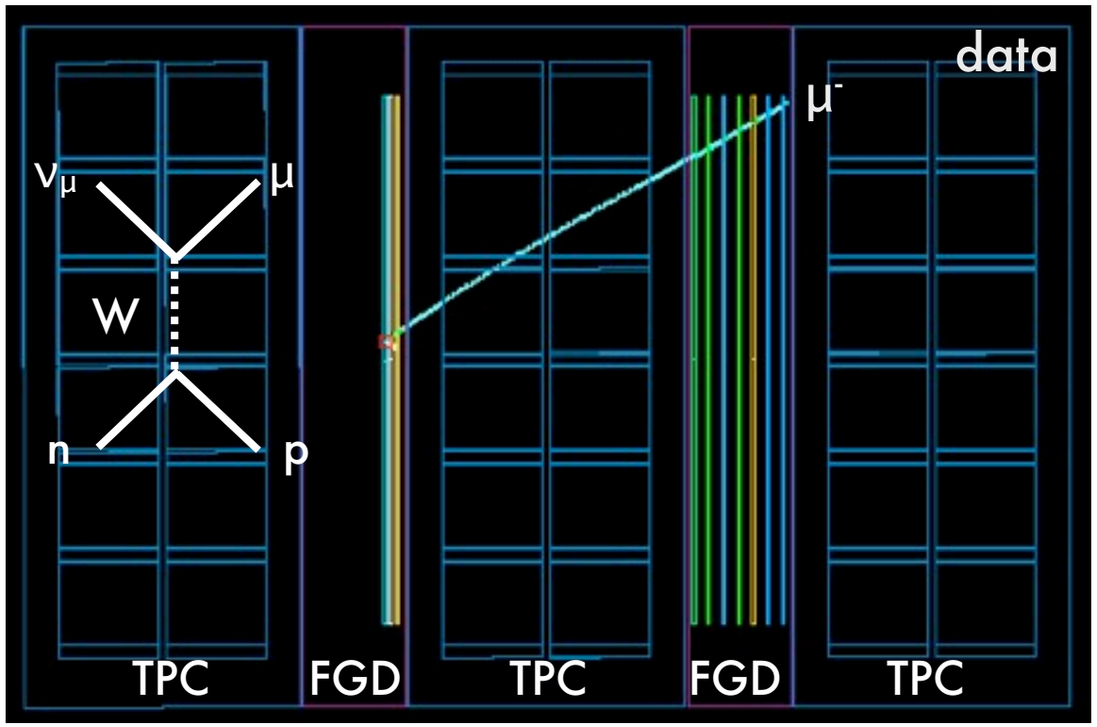
Deep Inelastic Scattering



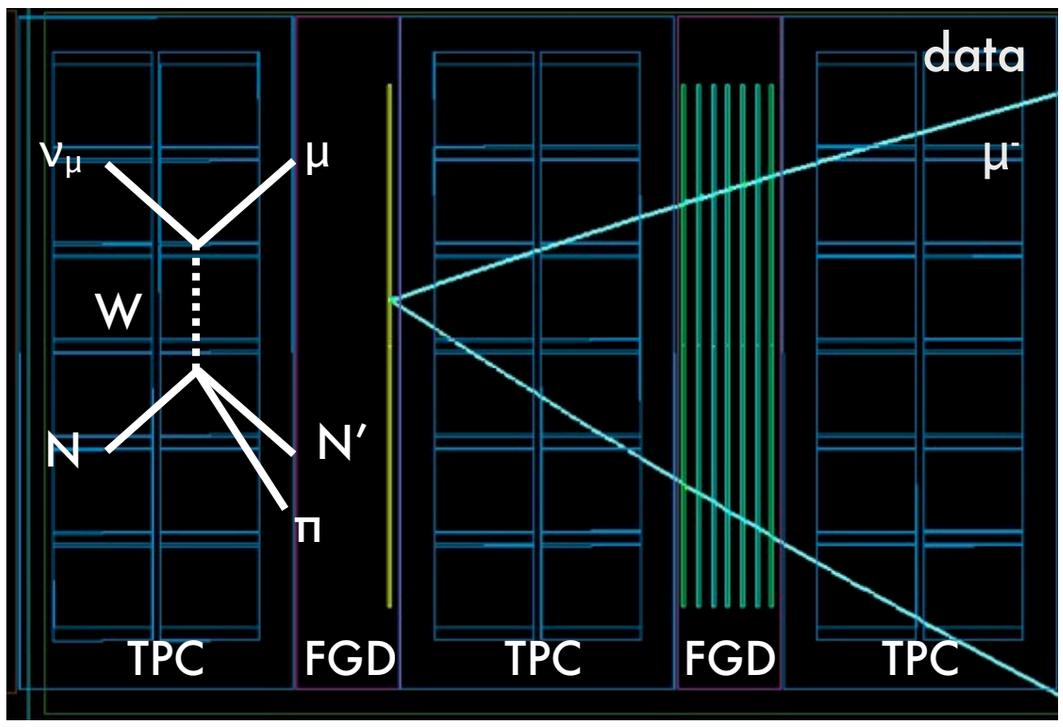
Charged Current 1π



CC0π

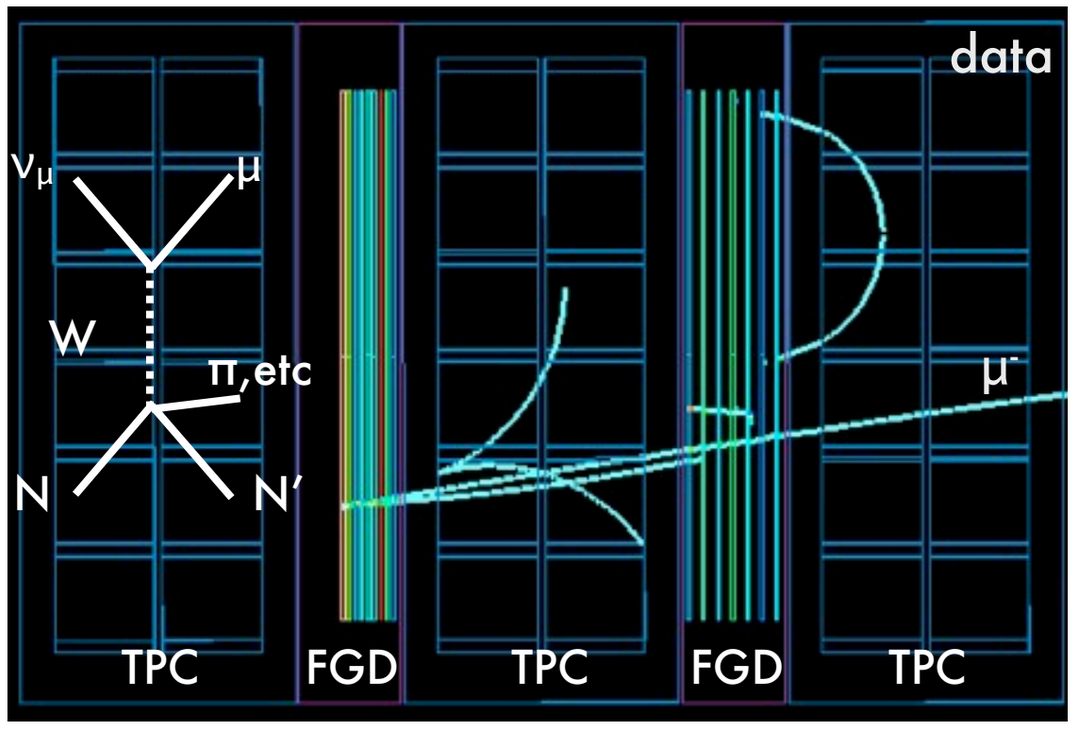


CC1π⁺

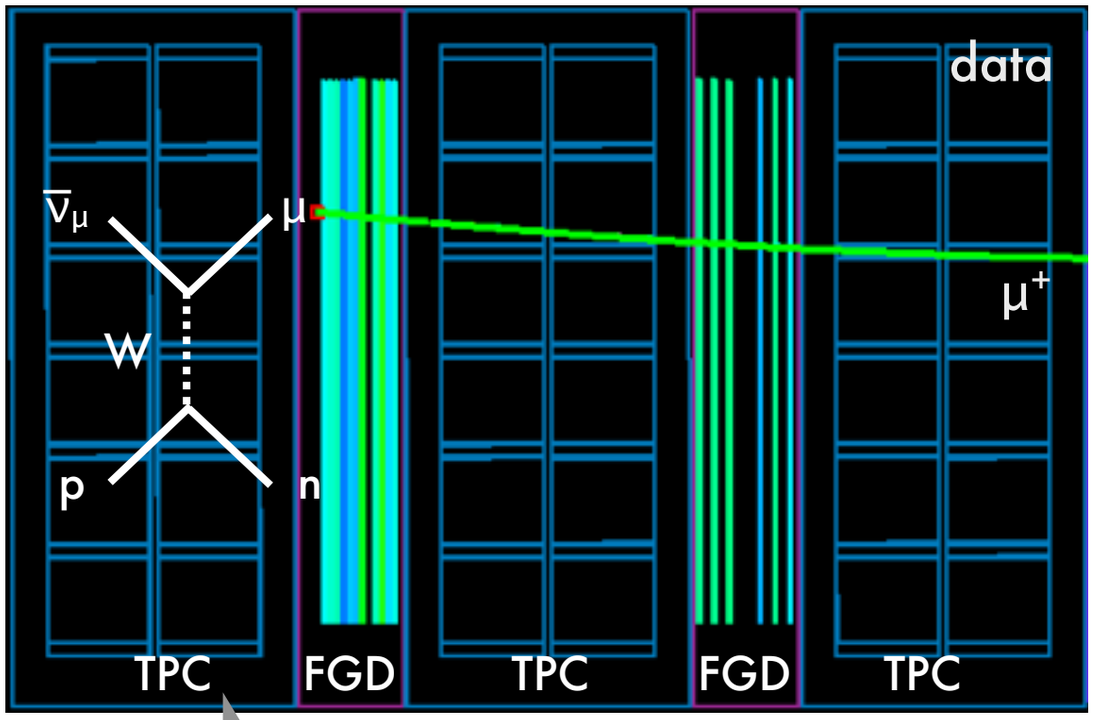


CC other

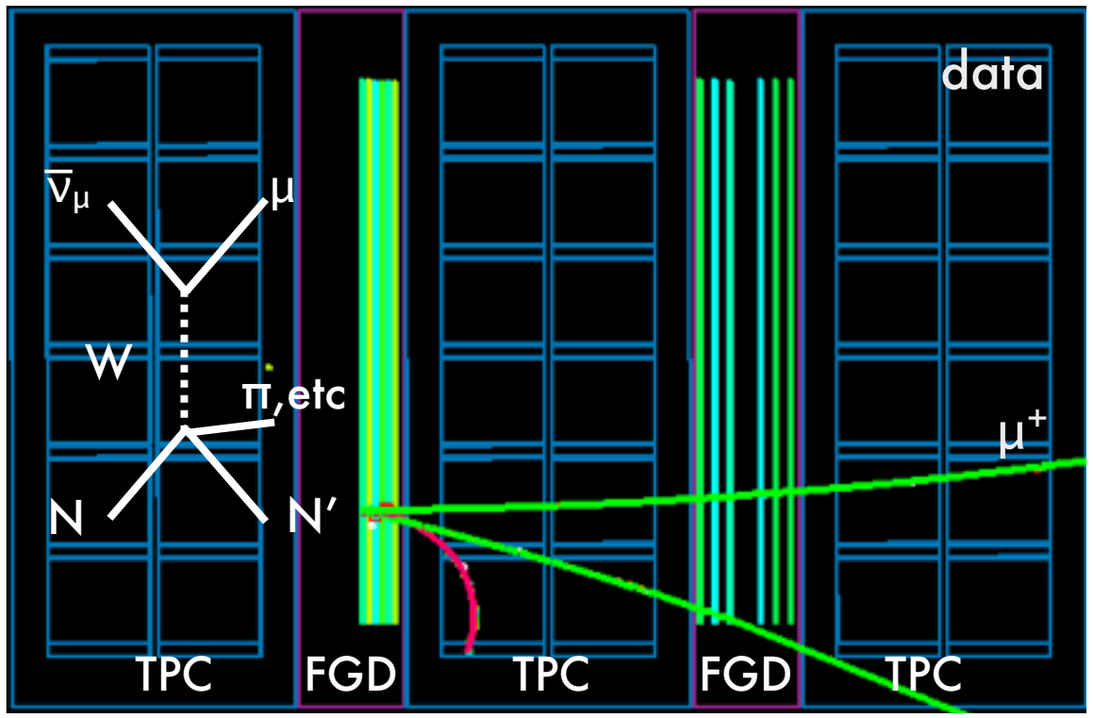
Beam



$\bar{\nu}_\mu$ CC-1Track

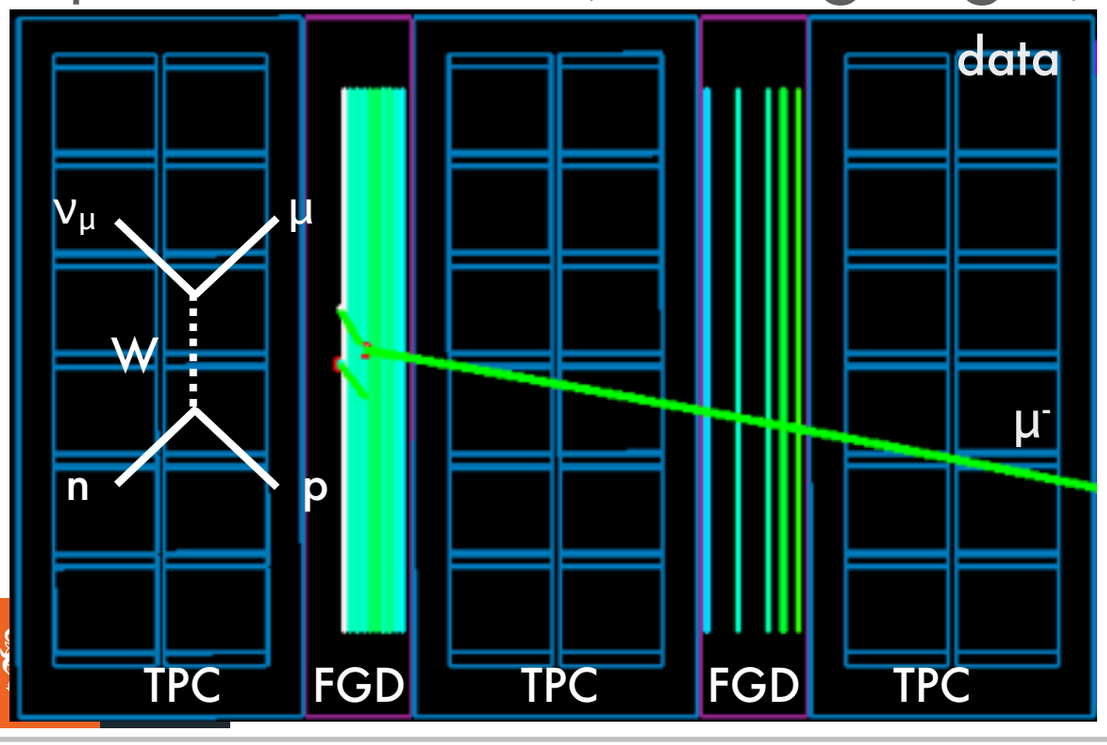


$\bar{\nu}_\mu$ CC-NTrack

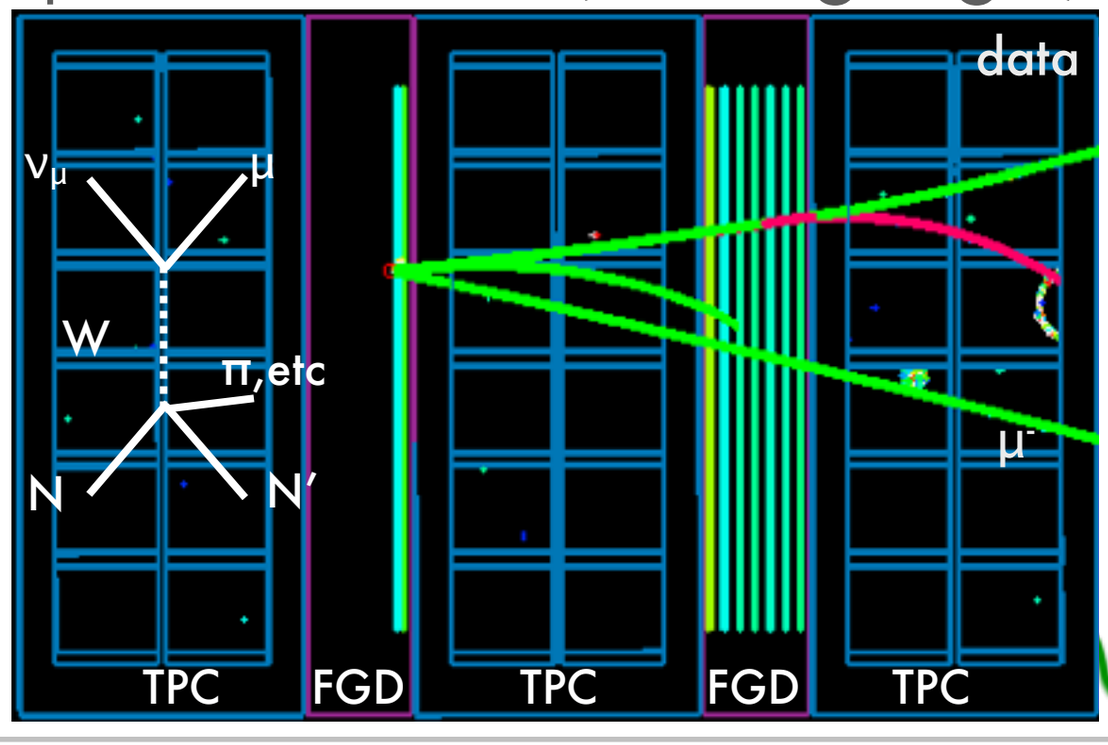


Beam

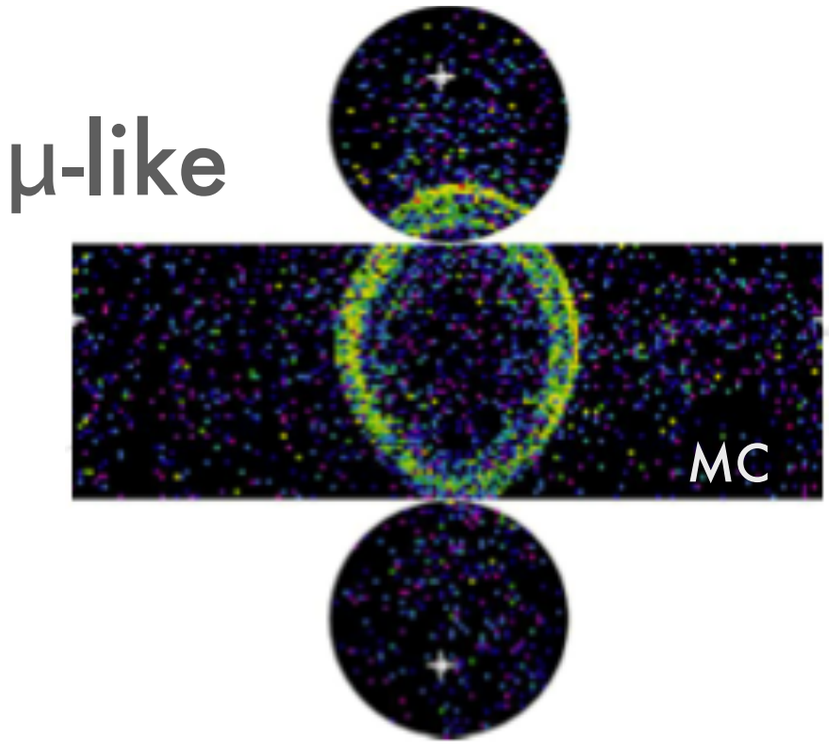
ν_μ CC-1Track (wrong sign)

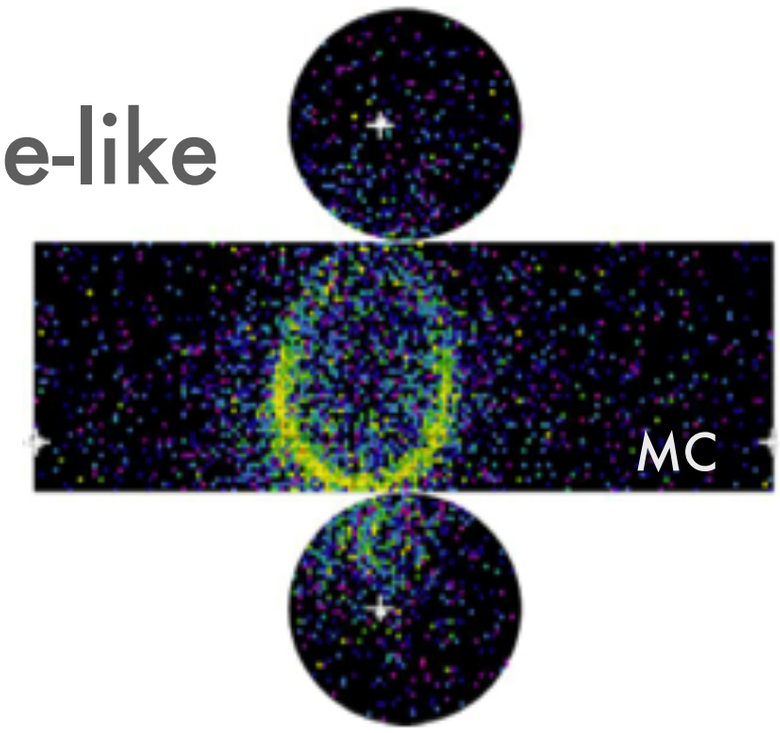


ν_μ CC-NTrack (wrong sign)



SK Data Samples





- New this year: an e-like 1-Michel electron sample in ν-dominated beam—this sample is dominated by resonant pion events
- New this year: A new reconstruction algorithm that improves both efficiency and purity for all samples
- 66% of the data is ν-dominated beam; 34% $\bar{\nu}$-dominated beam

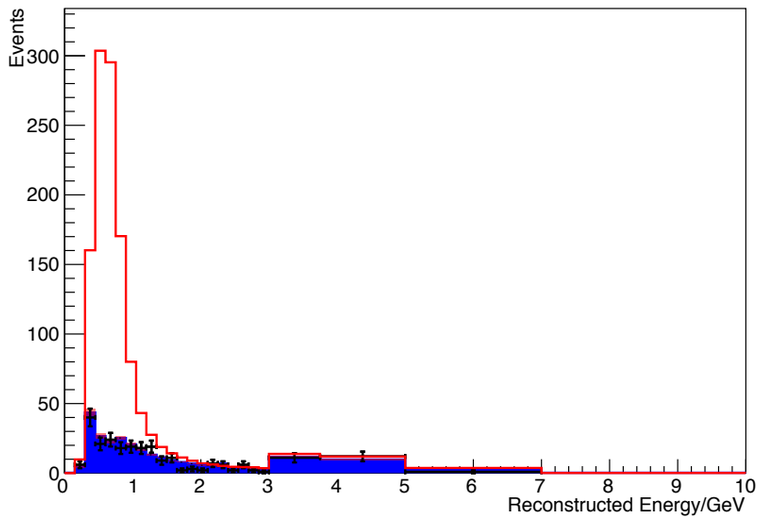
SK Samples

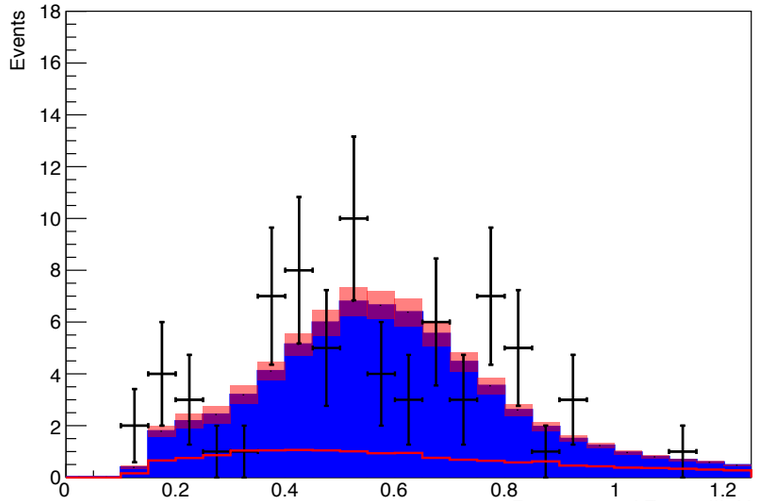
1 ring μ-like

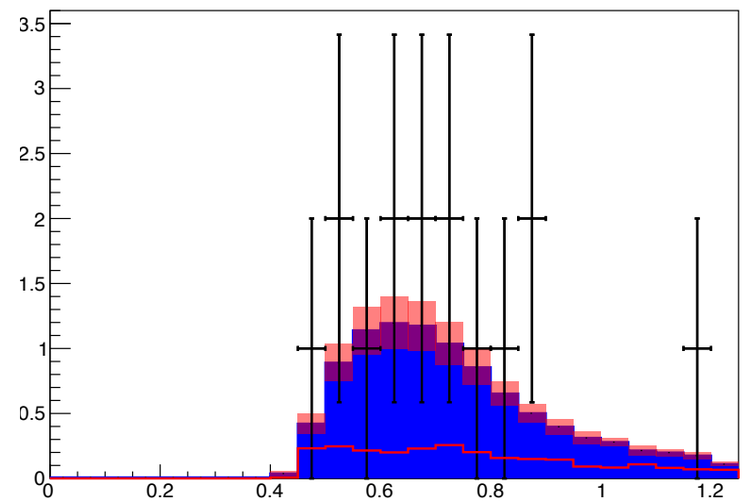
1 ring e-like

e-like+decay e

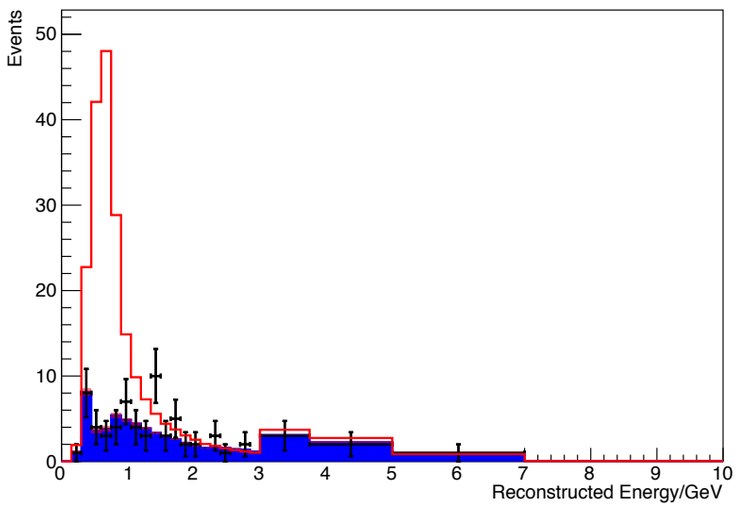
ν beam

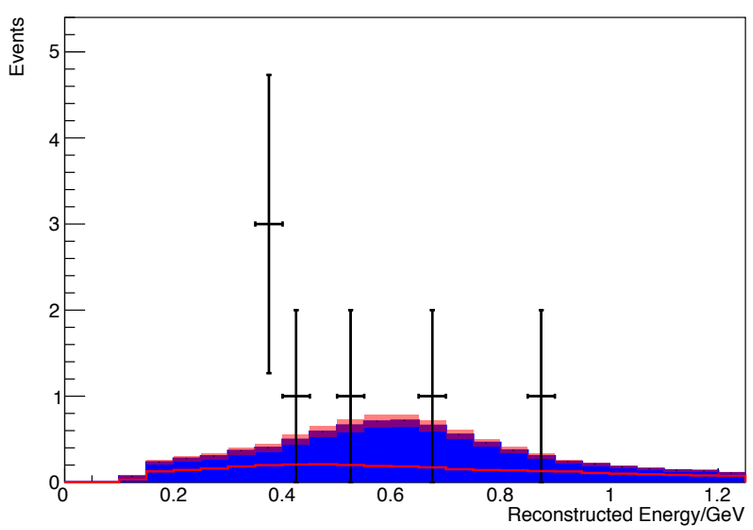






$\bar{\nu}$ beam





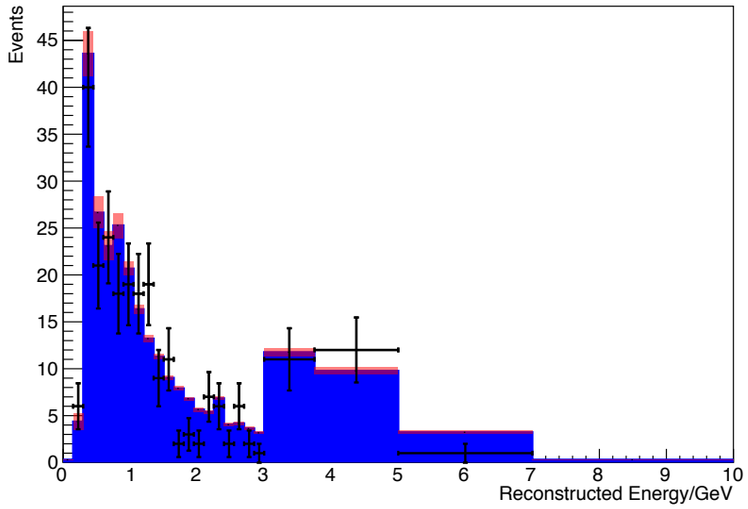
SK Samples

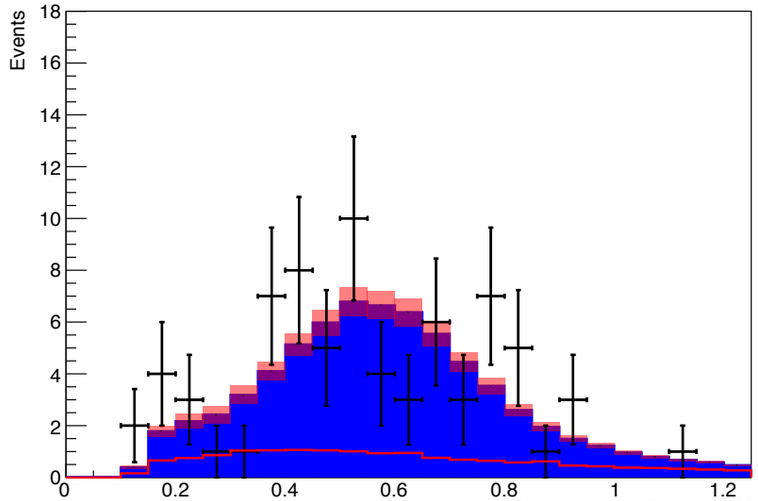
1 ring μ-like

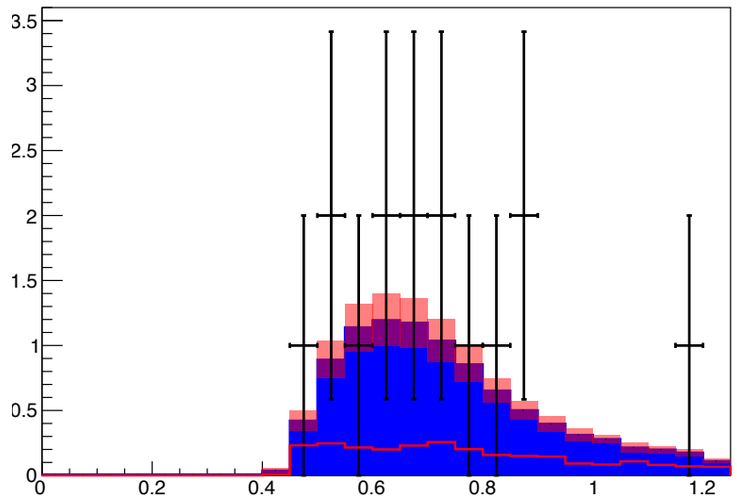
1 ring e-like

e-like+decay e

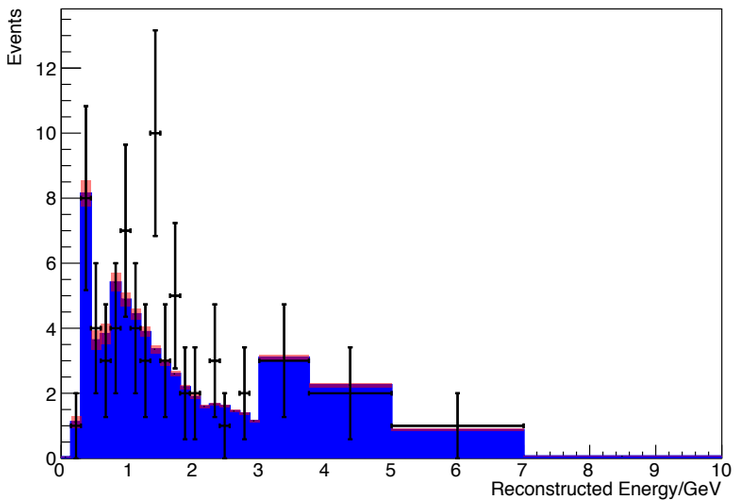
ν beam

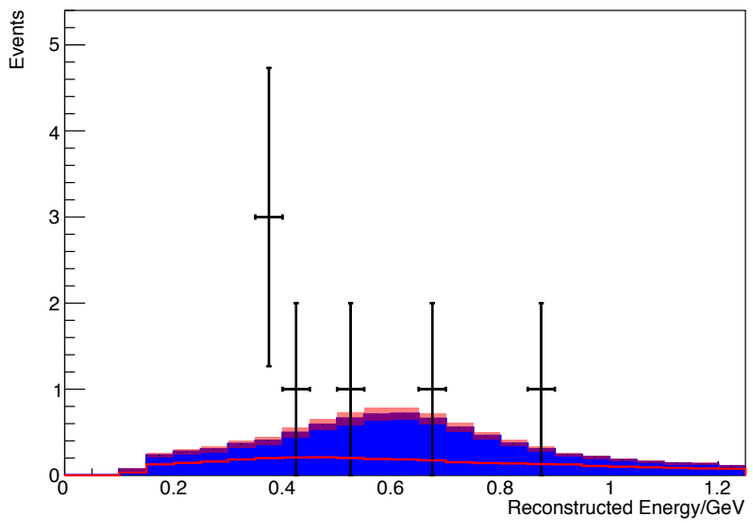






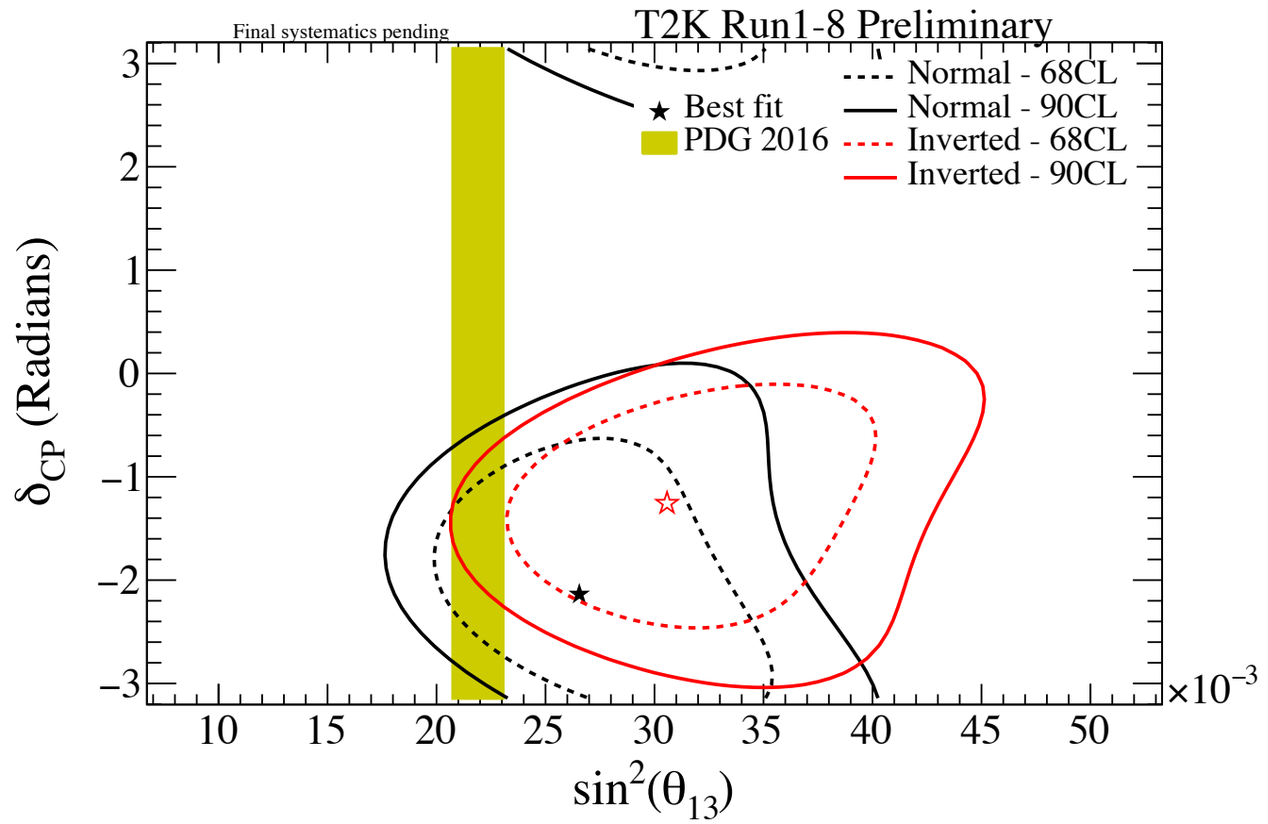
$\bar{\nu}$ beam

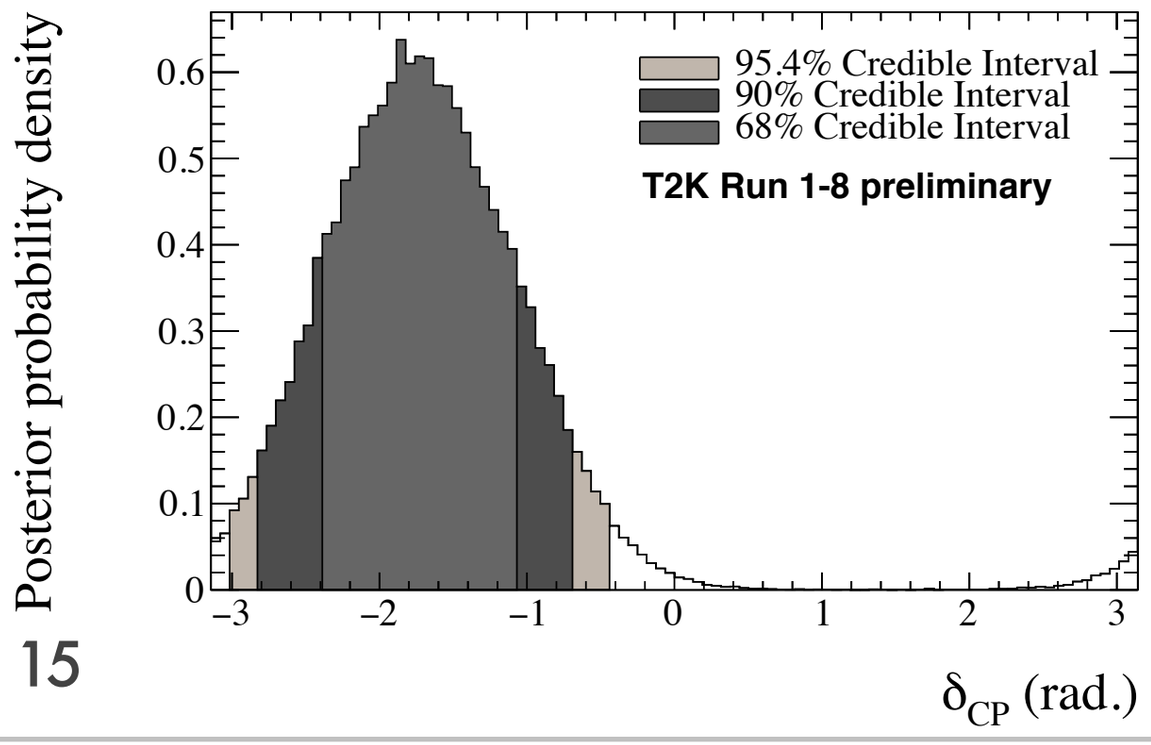




Appearance Results

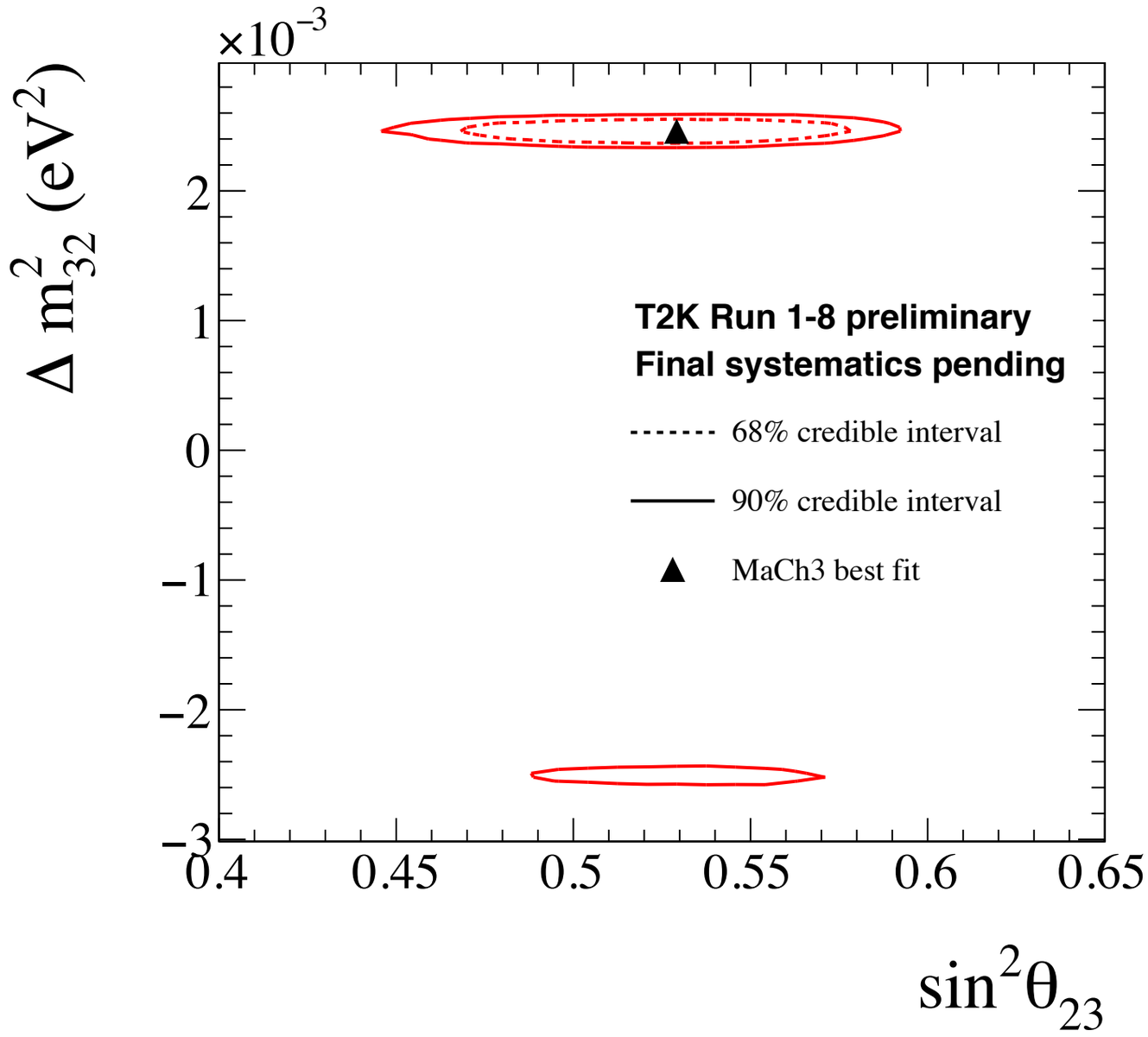
- T2K-only data has closed 90% contours in δ_{CP}
- T2K is consistent with reactor data at 1σ in the NH
- Marginalized over hierarchy, T2K excludes CP conservation at 2σ



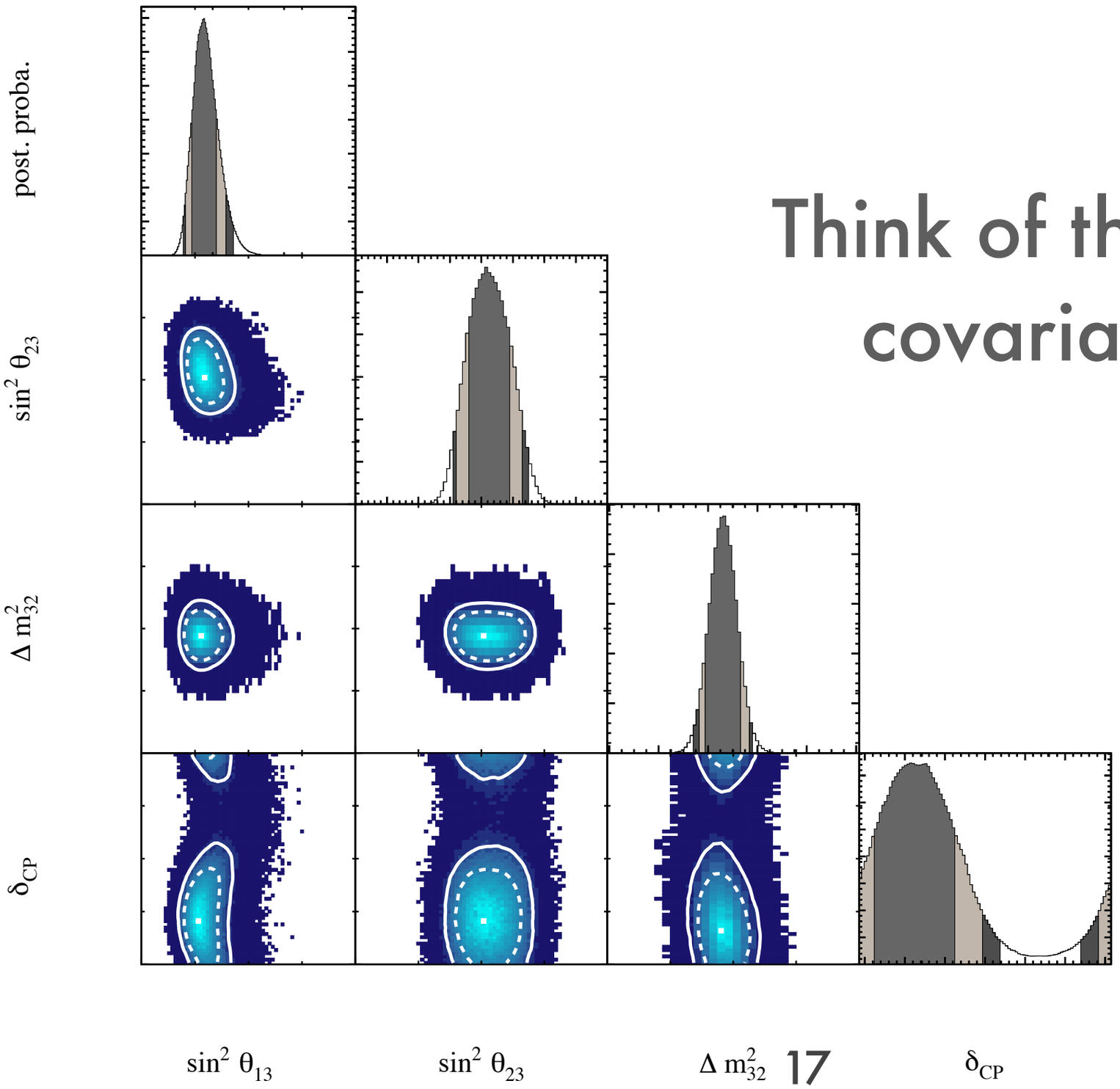


Disappearance Results

- $\Delta m^2_{23} = 2.46 \pm 0.09 \times 10^{-3}$ eV^2
- $\sin^2\theta_{23} = 0.53 \pm 0.03$
- Preference for NH at 87%

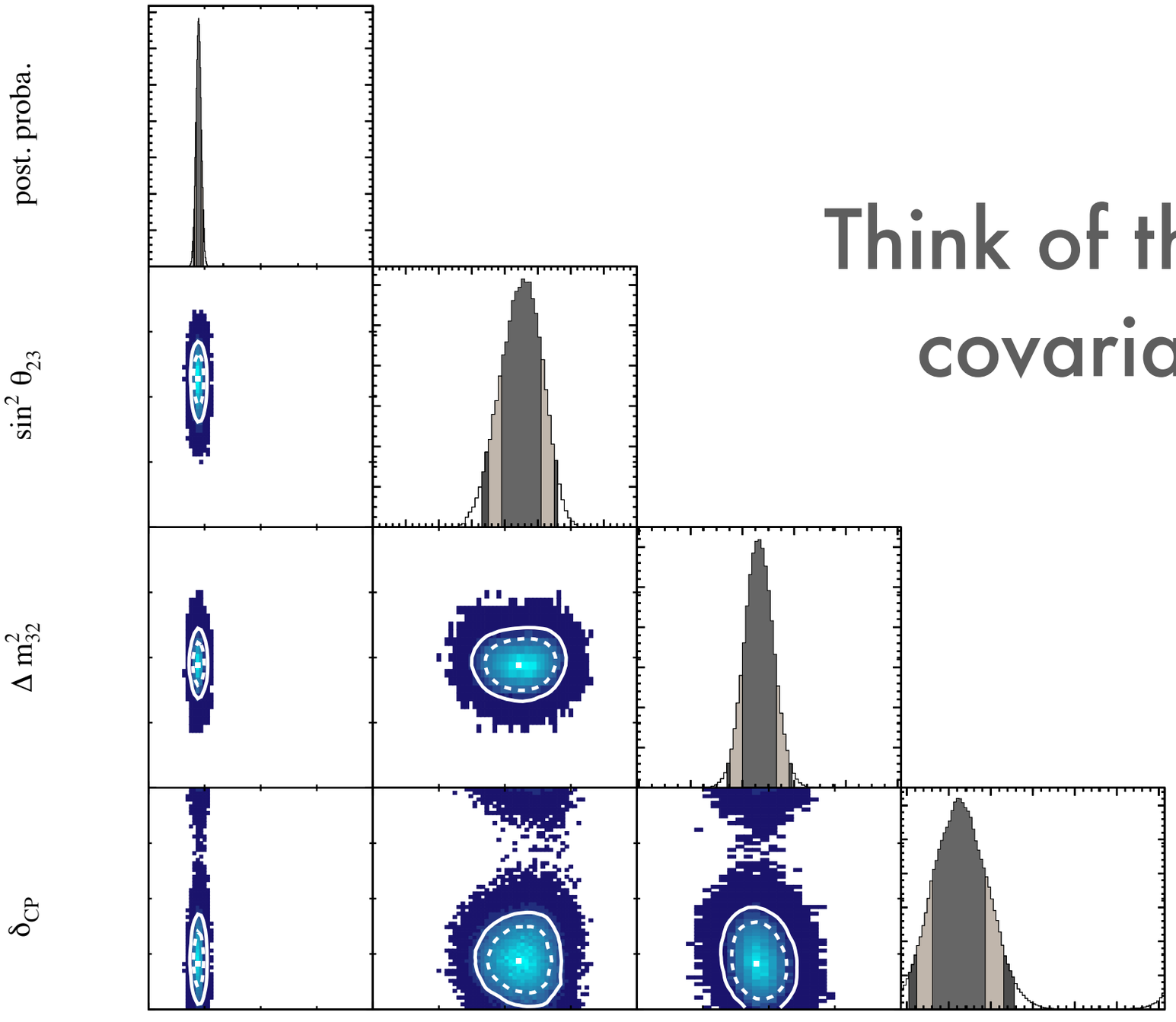


Everything on One Plot!



Think of this as a visual covariance matrix

Everything on One Plot!

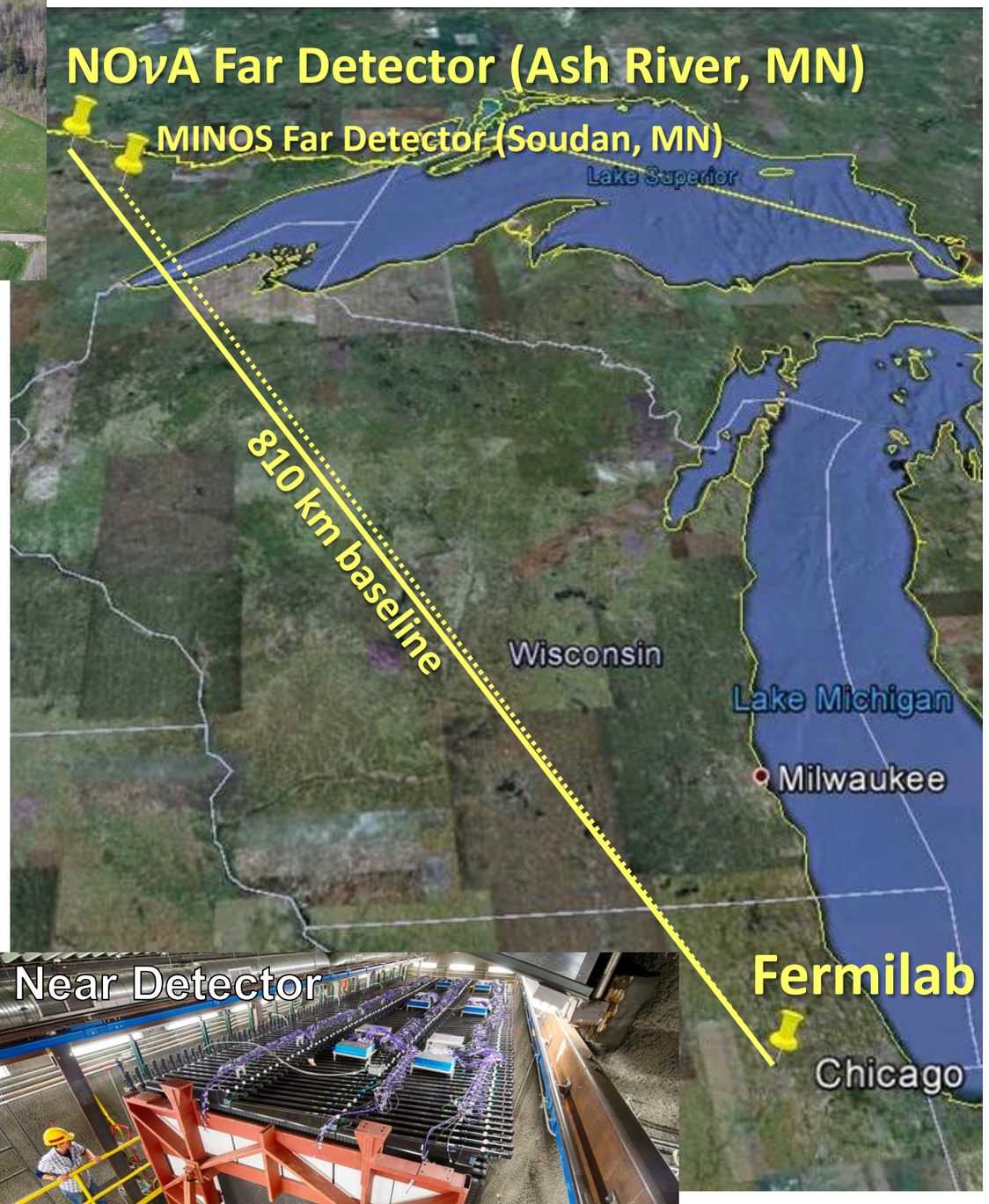


Think of this as a visual covariance matrix

T2K in the Next Year

- $\overline{\nu}$ beam has been operating at 475kW since last autumn and will go until late May
- This will equalize the ν to $\overline{\nu}$ beam ratio
- Look for new results at Neutrino 2018!
- Summer 2018 SK will be opened for PMT repair and leak fixing
- After closing, begin introduction of Gd to SK
- Beam upgrades may happen in late 2018 and 2019

NOvA

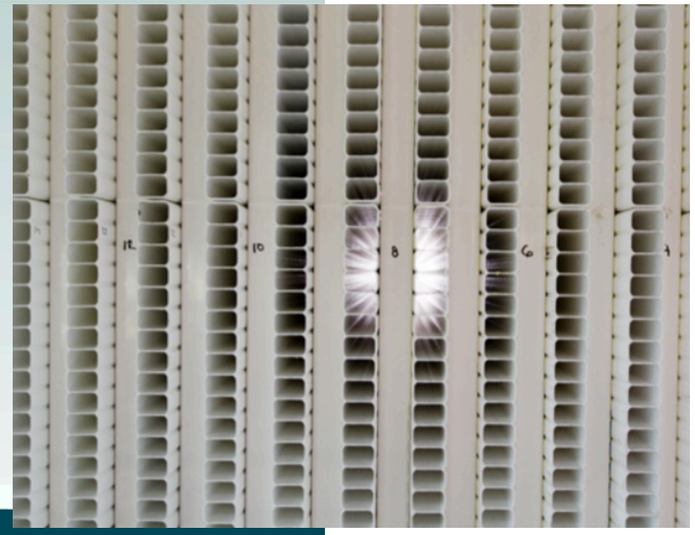

NOνA Far Detector (Ash River, MN)
MINOS Far Detector (Soudan, MN)
Lake Superior
810 km baseline
Wisconsin
Lake Michigan
Milwaukee
Fermilab
Chicago

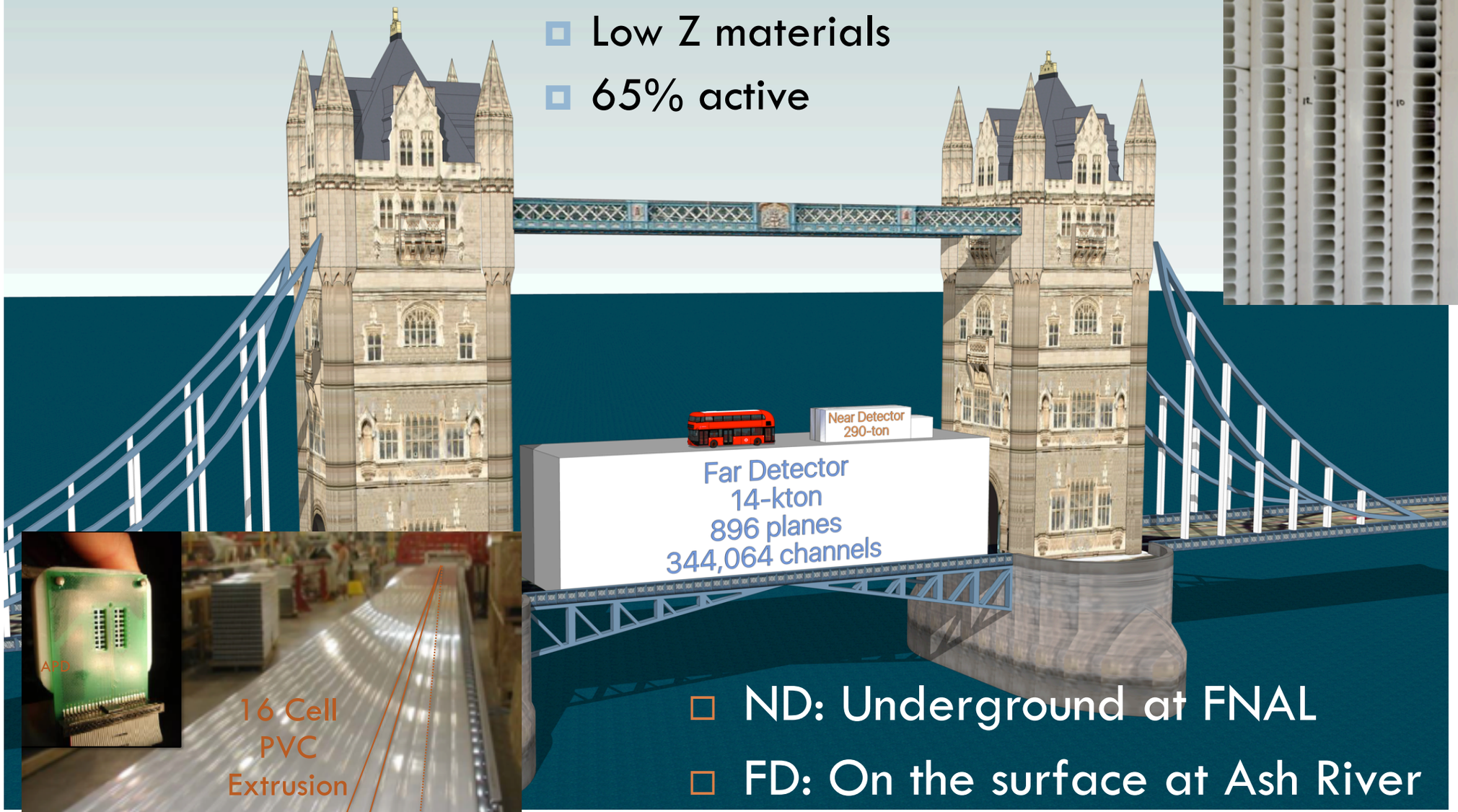
Near Detector

NOvA Detectors

P. Vahle, Neutrino 2016

- Designed for electron ID
  - Low Z materials
  - 65% active

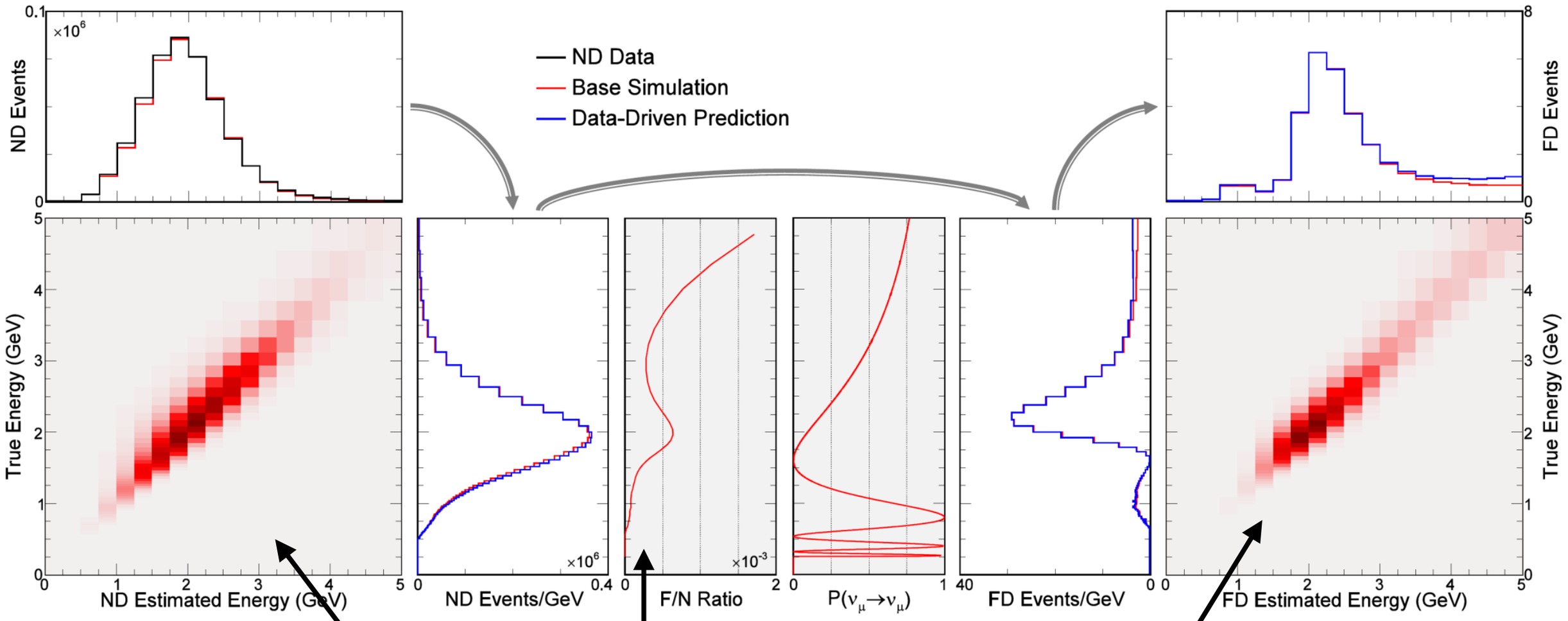




- ND: Underground at FNAL
- FD: On the surface at Ash River

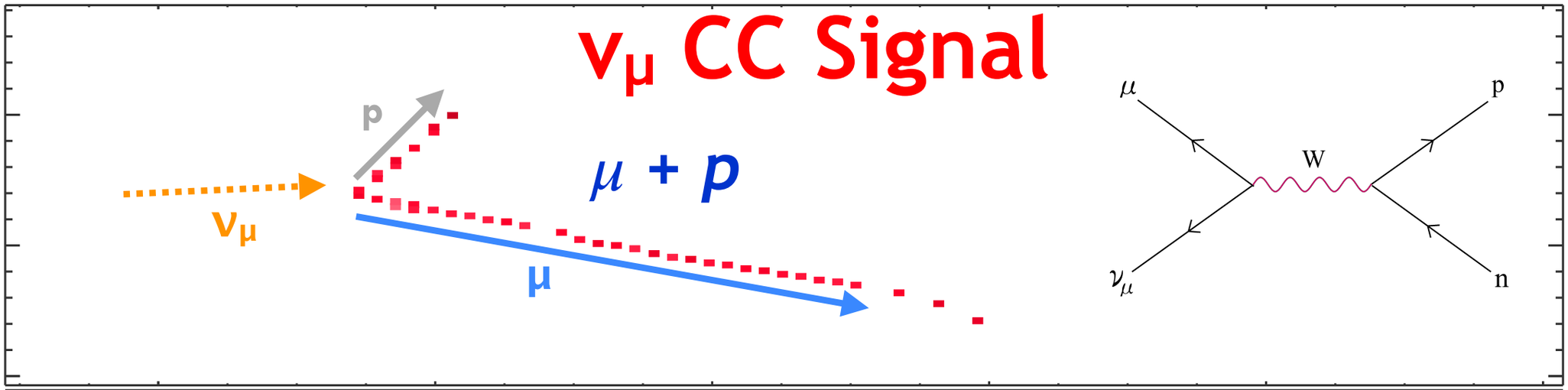
Select CC inclusive

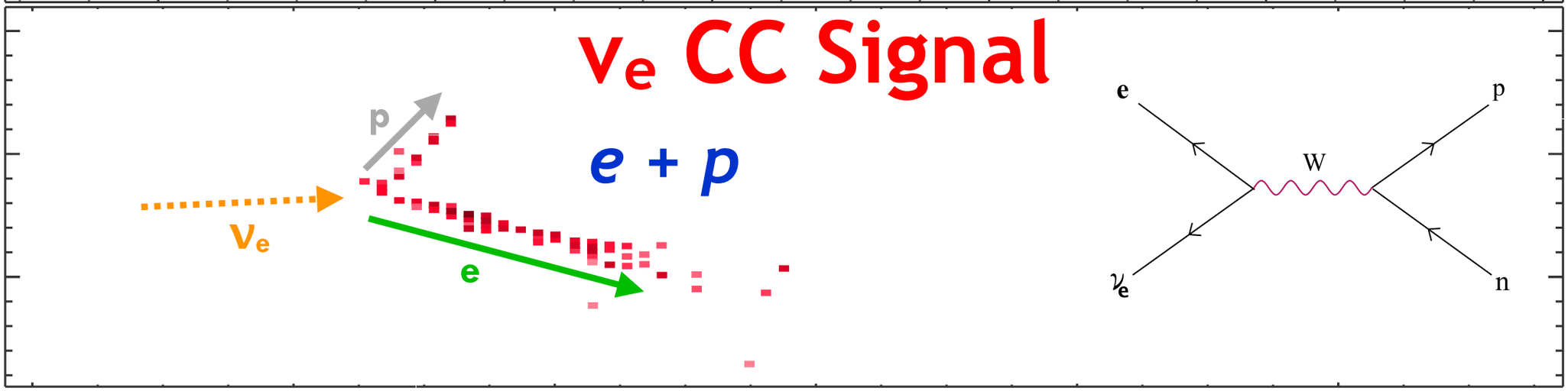
Select CC inclusive

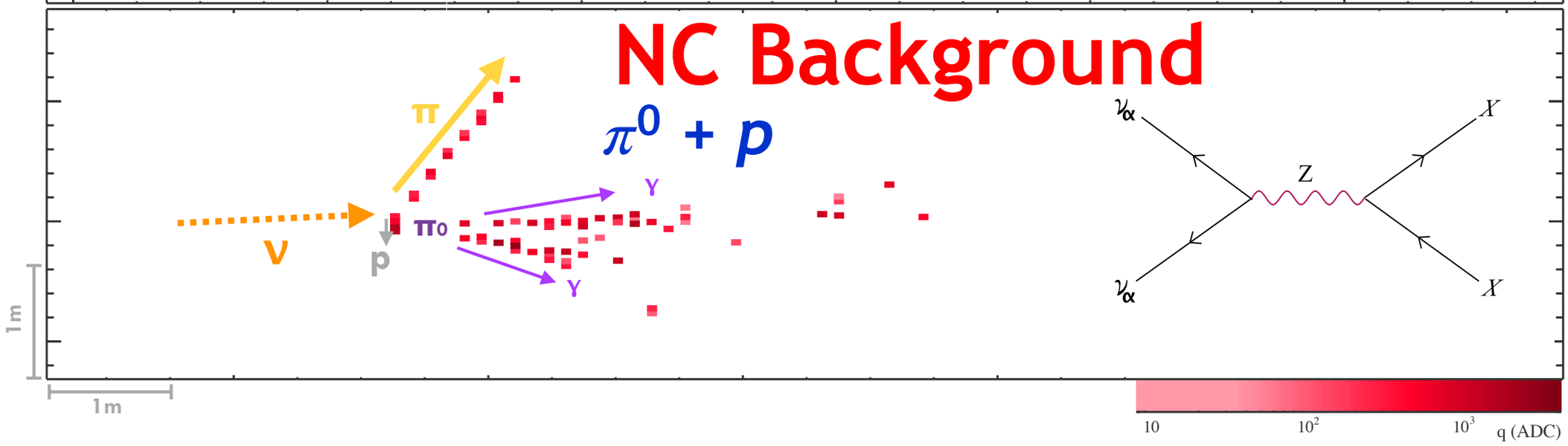


Estimated from simulation

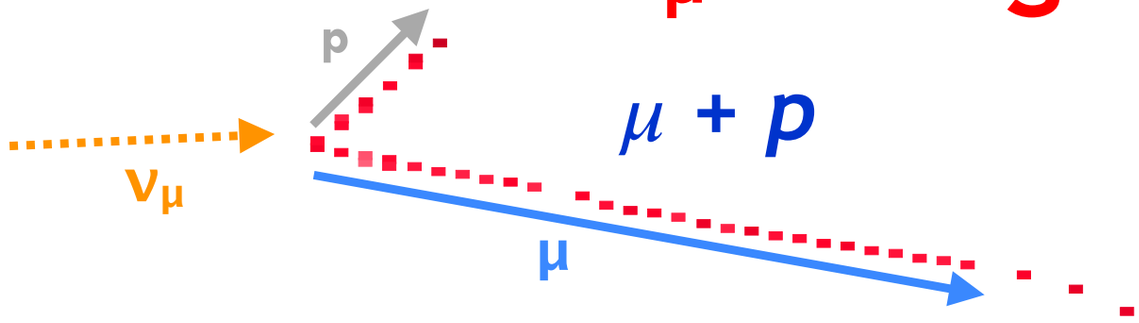
Use a binned ML method


νμ CC Signal
p
μ + p
νμ
μ
μ
W
p
ν_μ
n

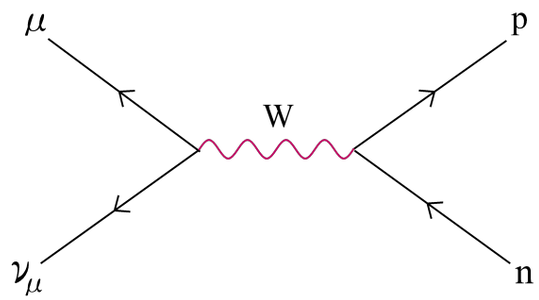

νe CC Signal
p
e + p
νe
e
e
W
p
ν_e
n


NC Background
π
π^0 + p
ν
p
π0
γ
γ
Z
ν_α
ν_α
X
X
1m
1m
10
10^2
10^3
q (ADC)

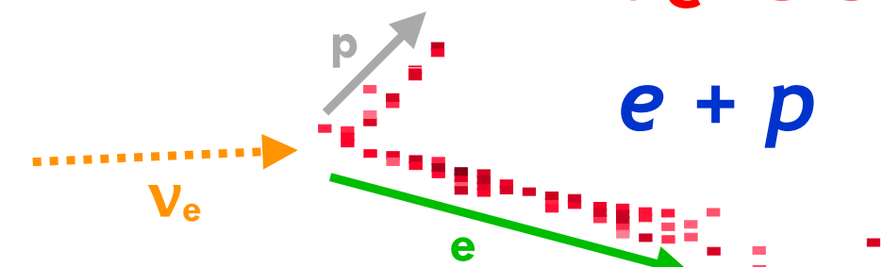
ν_μ CC Signal



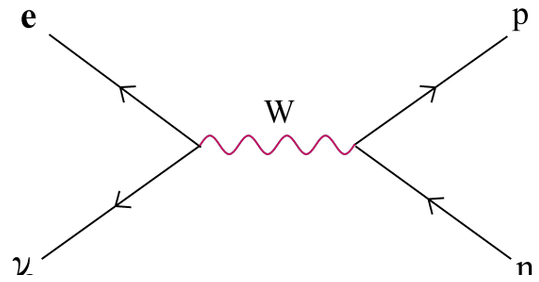
$\mu + p$

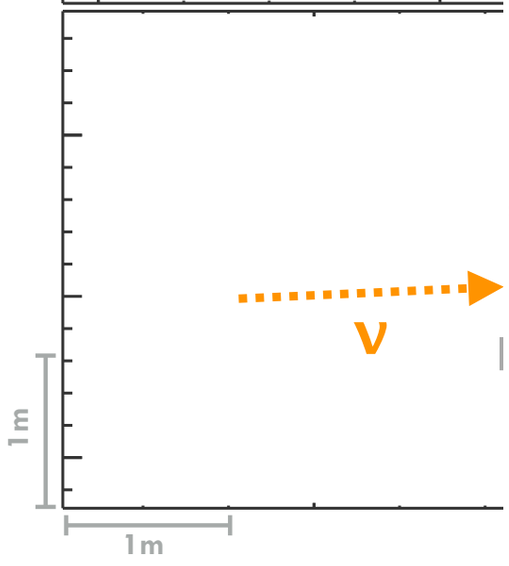


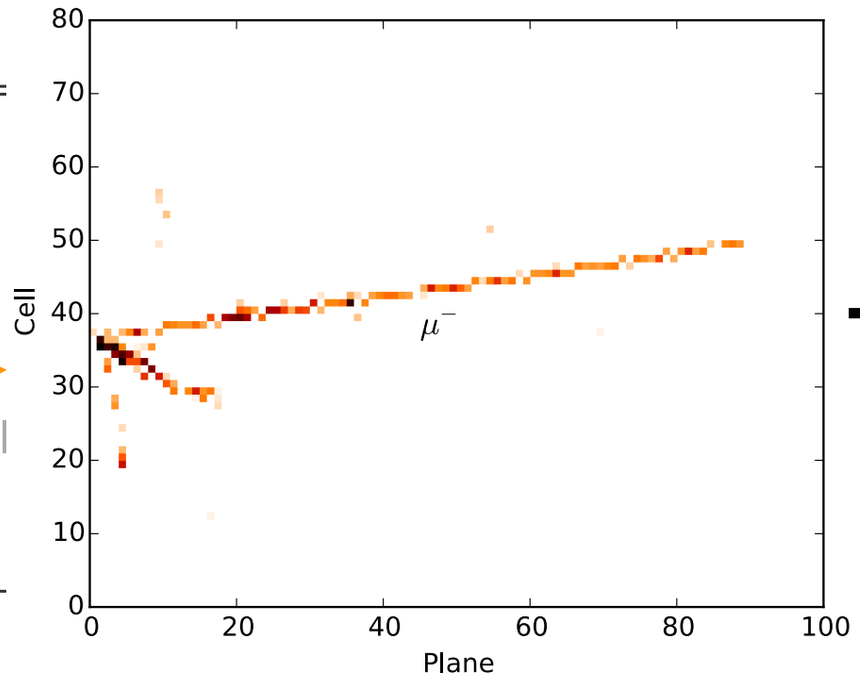
ν_e CC Signal

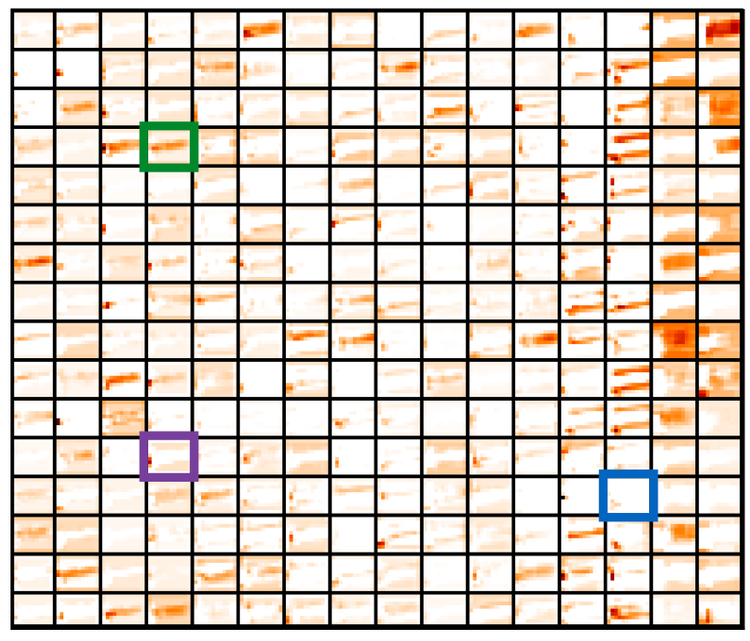


$e + p$



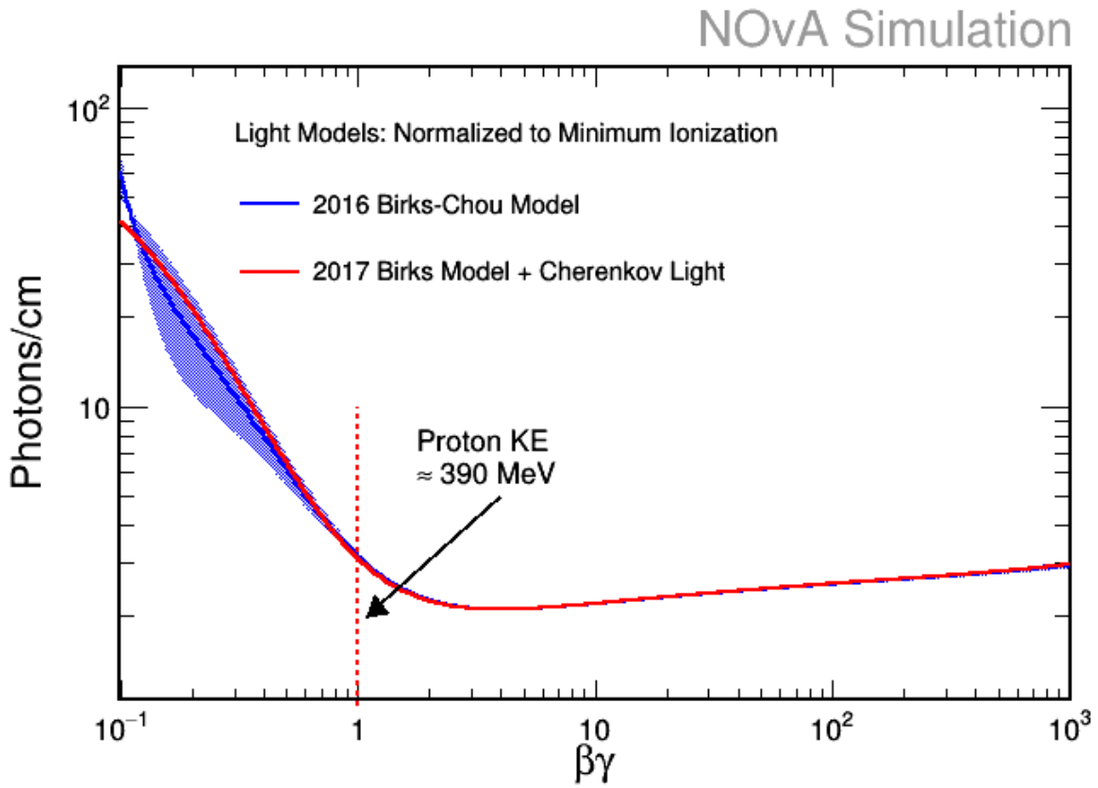


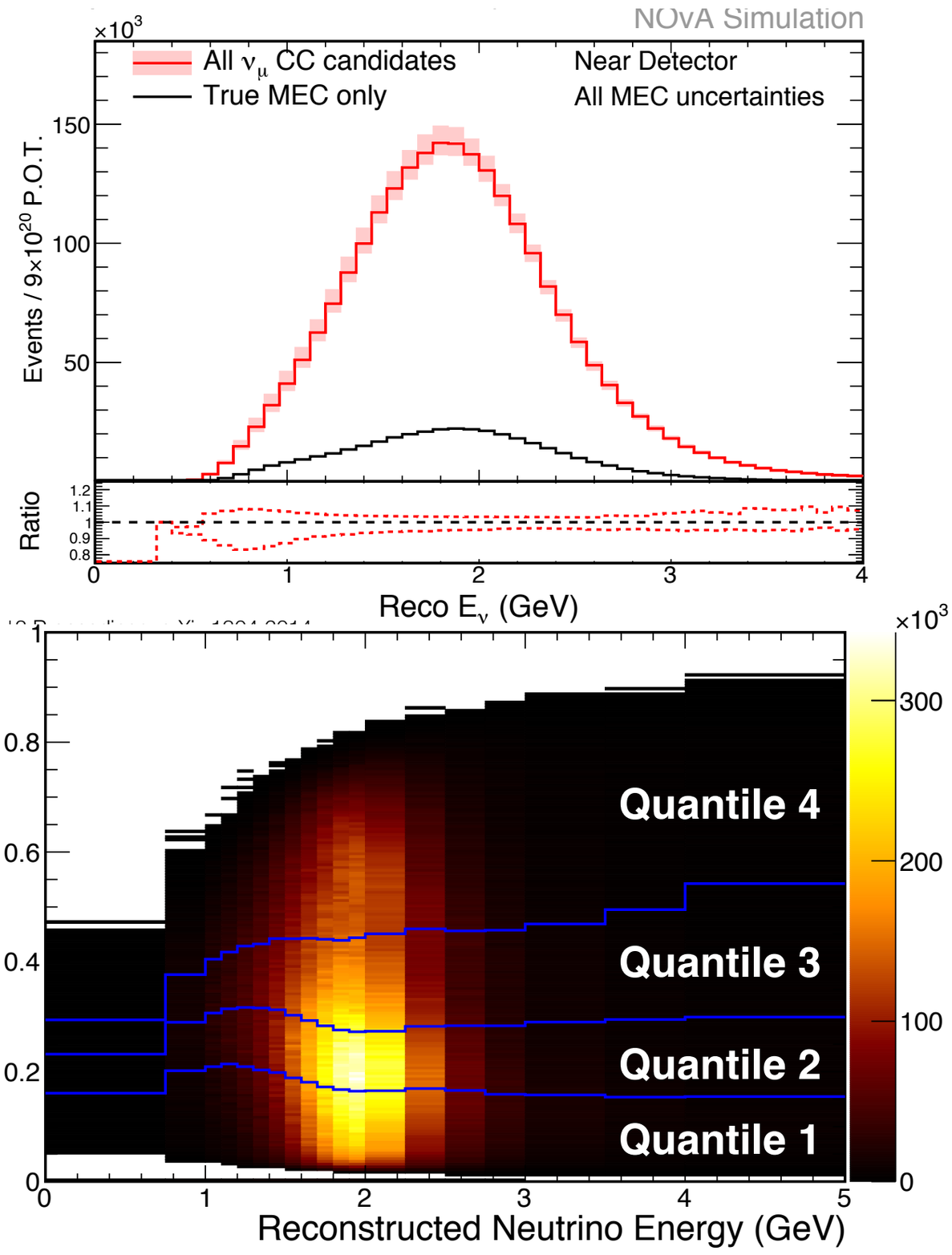




"A Convolutional Neural Network Neutrino Event Classifier"
A. Aurisano, A. Radovic, and D. Rocco et al
Journal of Instrumentation, Volume 11, September 2016

Analysis Updates

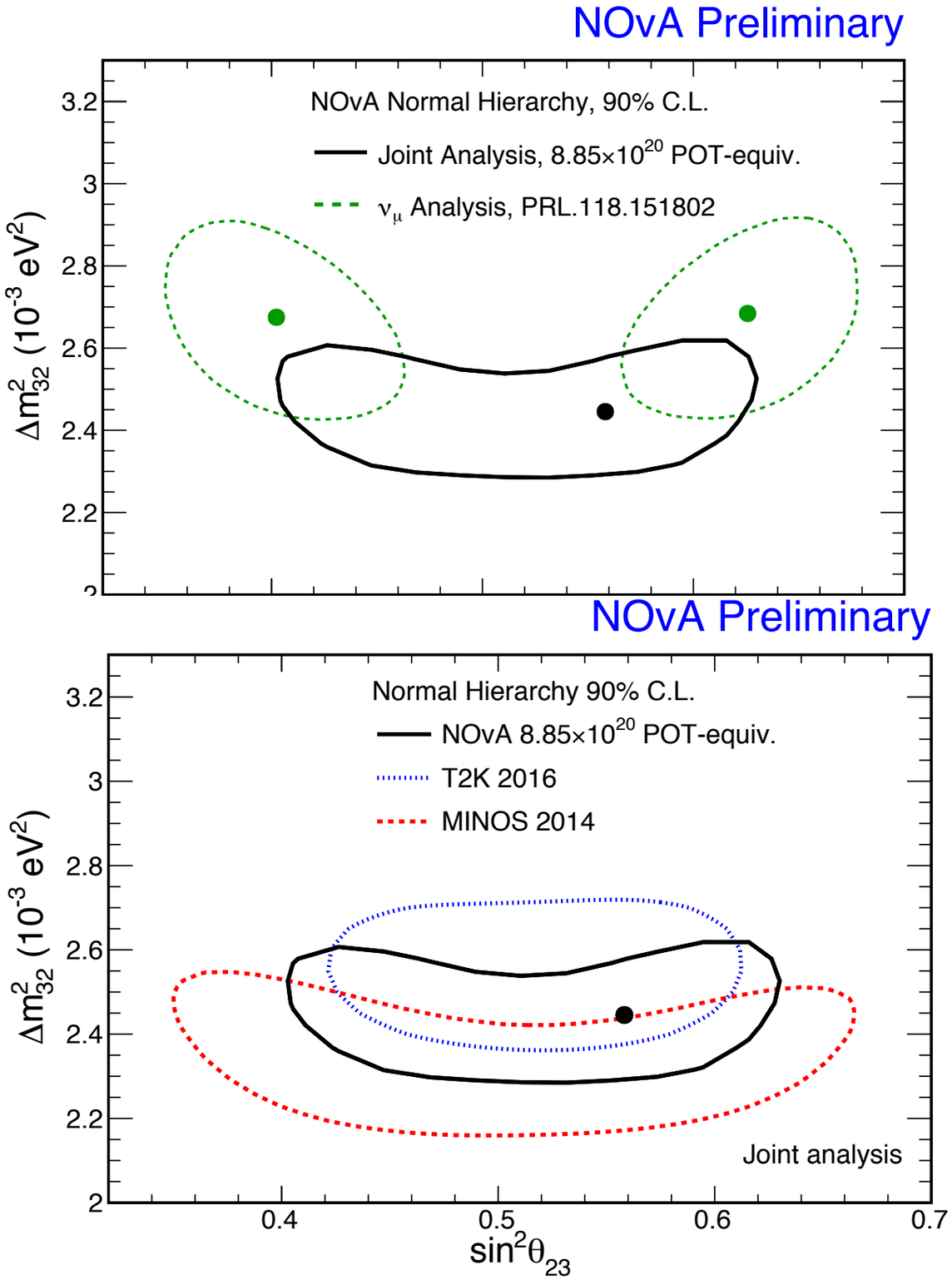




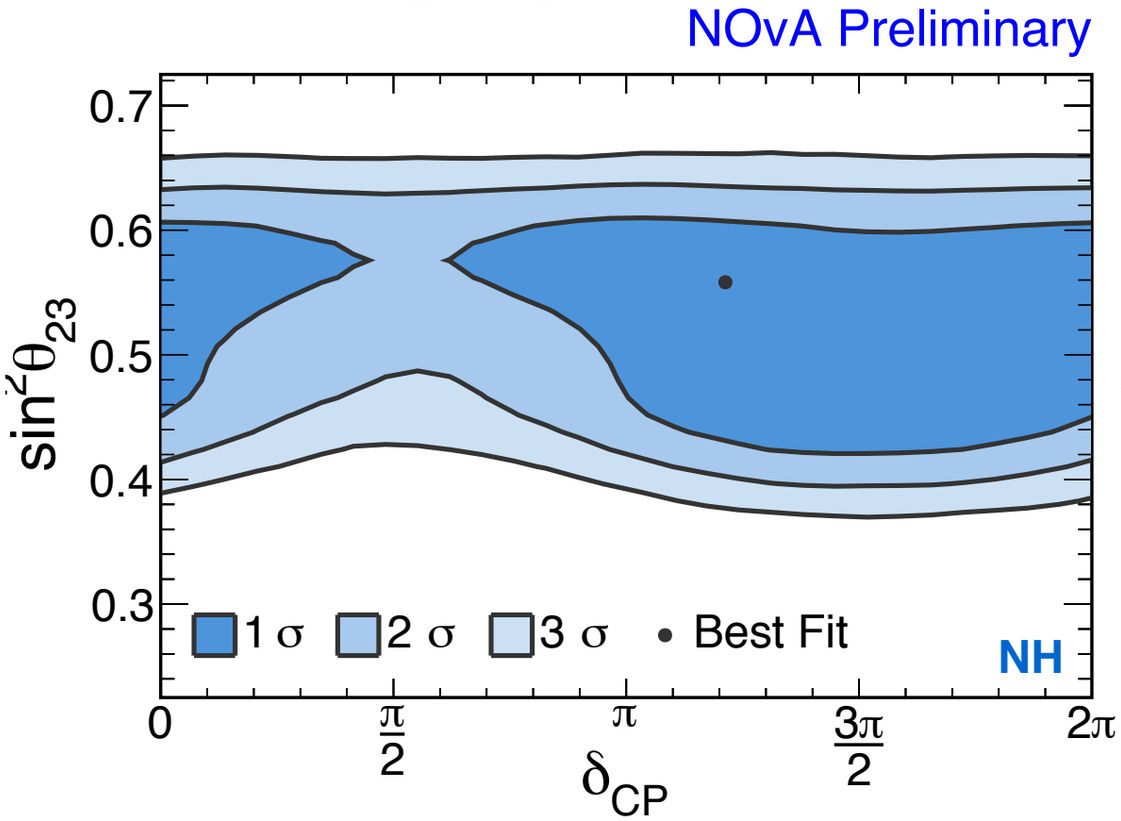
- Detector modeling
- Binning in hadronic energy (dis. only)
- Retuned cross section (especially 2p2h)

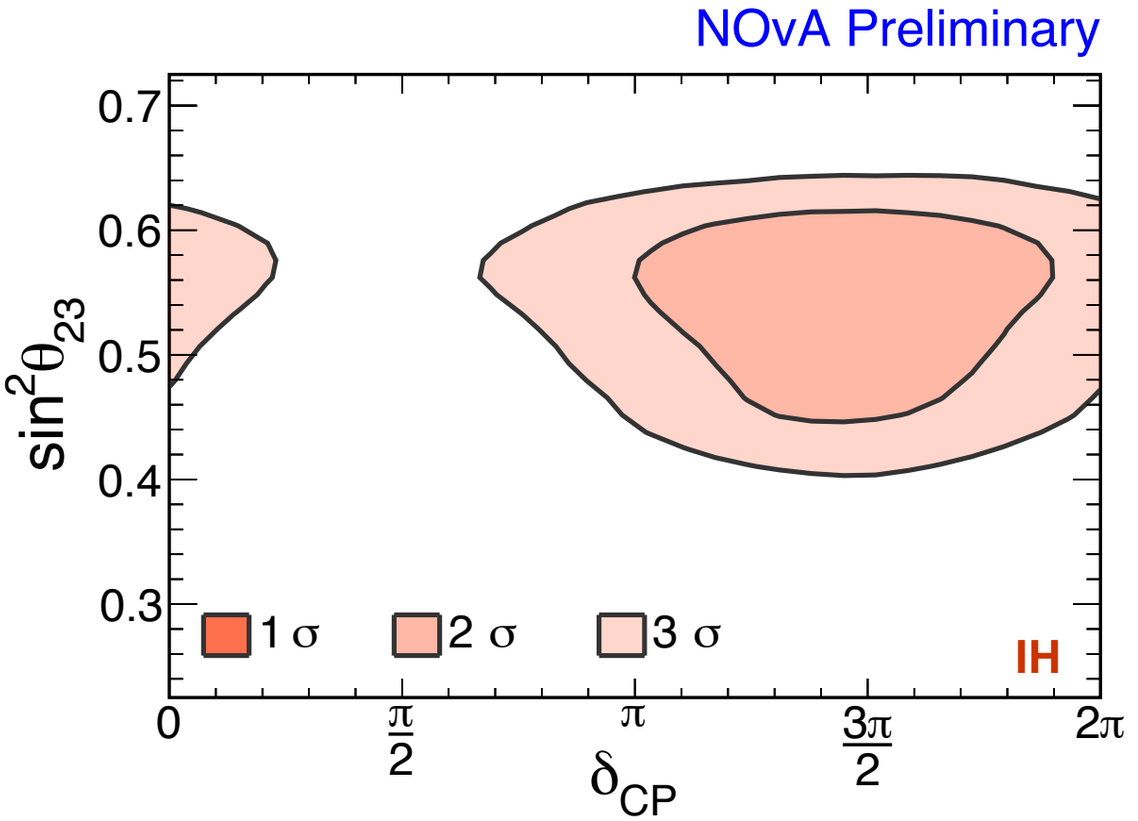
Disappearance Results

- $\Delta m^2_{32} = 2.444^{+0.079}_{-0.077} \times 10^{-3}\ eV^2$
- $\sin^2\theta_{23} = 0.558^{+0.041}_{-0.033}$
- Compatible with 2016 result, but no longer far from maximal mixing
  - Larger energy resolution
  - 70 MeV shift in hadronic energy
  - New selection
  - More data

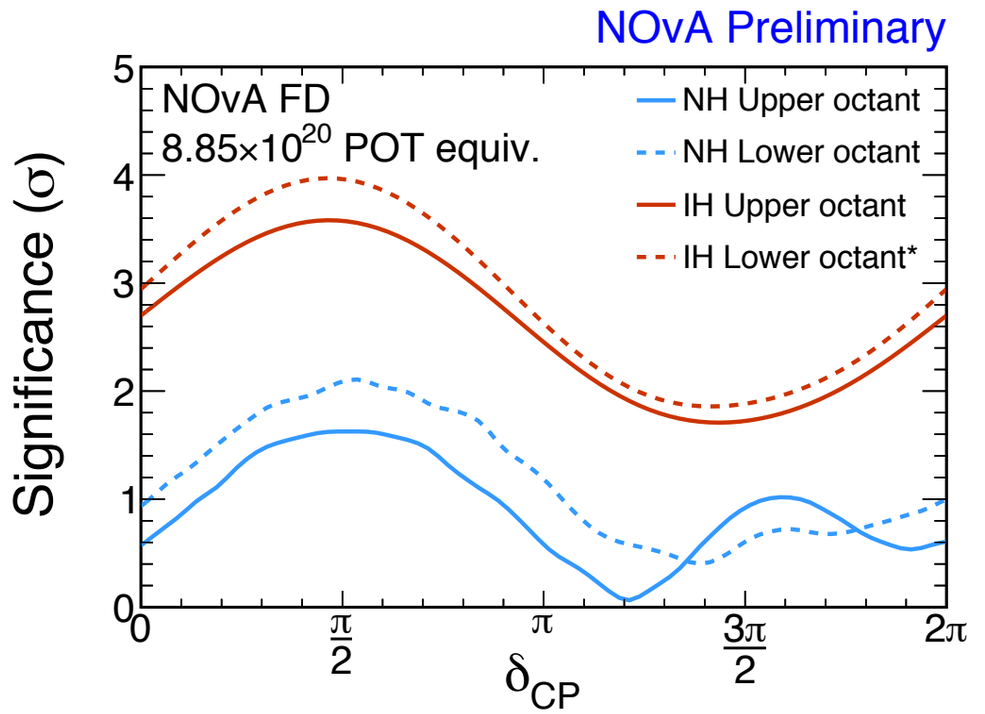


Appearance Results





- Nearly 2σ exclusion of IH
- Disfavor π/2



NOvA in the Next Year

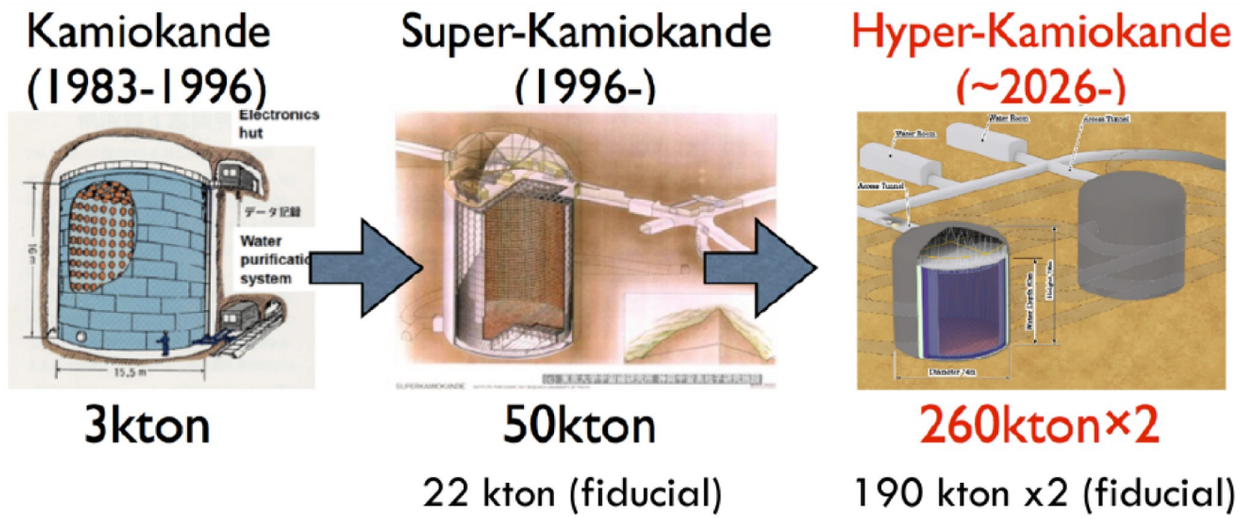
- NOvA is running in $\bar{\nu}$ beam mode now—collected 7×10^{20} POT
- Collecting data at 700kW!!
- New analysis including $\bar{\nu}$ samples to debut at Neutrino 2018

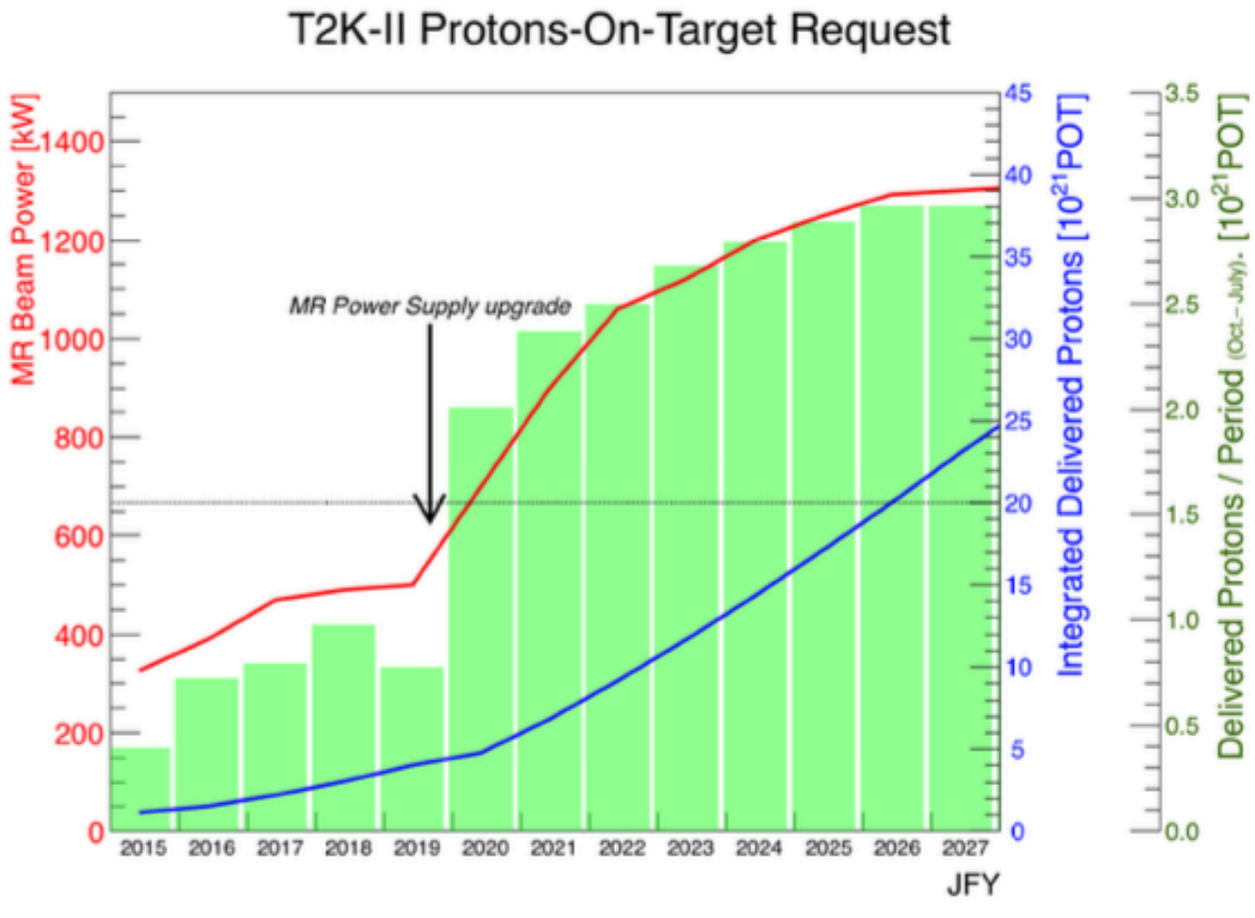
Where We Are Now

- T2K and NOvA largely agree
  - Both prefer NH at around 90%
  - Both are compatible with $\sin^2\theta_{23} = 0.5$
  - Both have compatible $|\Delta m_{32}|$ masses
  - Both disfavor $\delta_{CP} = \pi/2$
- Cross section systematics are becoming an increasing issue for both experiments
- New antineutrino data analysis is expected in early June for both experiments
- A joint T2K-NOvA analysis is coming!

Hyper-Kamiokande

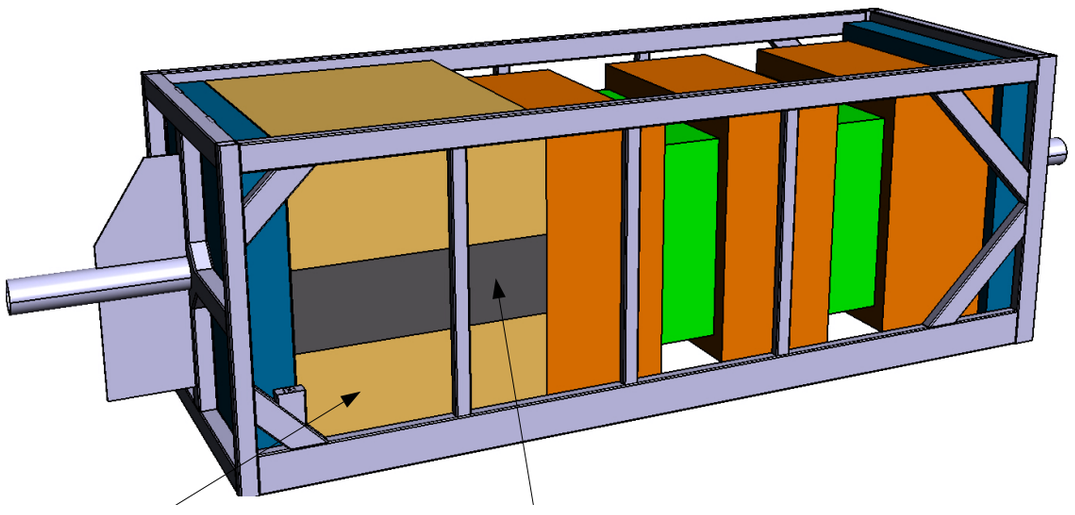
- Scale up from SK and T2K
- Continuous upgrade plan: T2K-II, near detector upgrades, HK
- Requires beam power increase to 1.3MW
- Potential option to put HKD2 in Korea—improves MH sensitivity and reduces δ_{CP} uncertainties
- Experiment has just moved into a formal collaboration with a new structure; new Japanese institute formed to support the work: http://nnso.jp/index.html



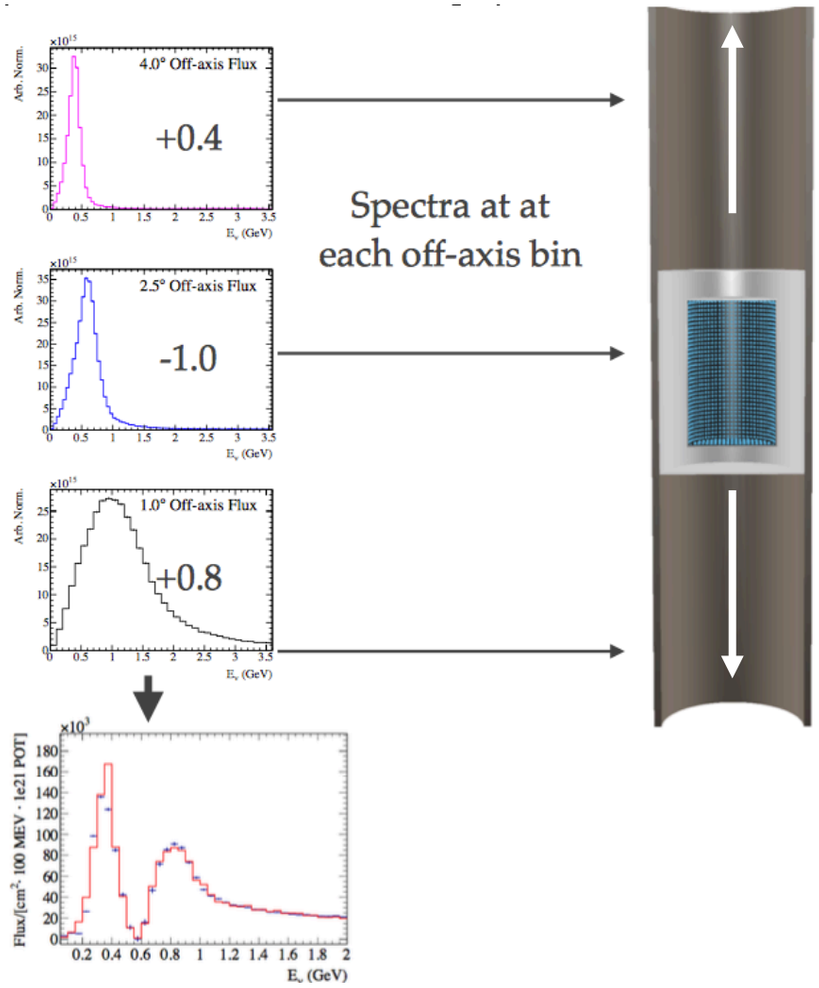


New Near Detectors

ND280 Upgrade

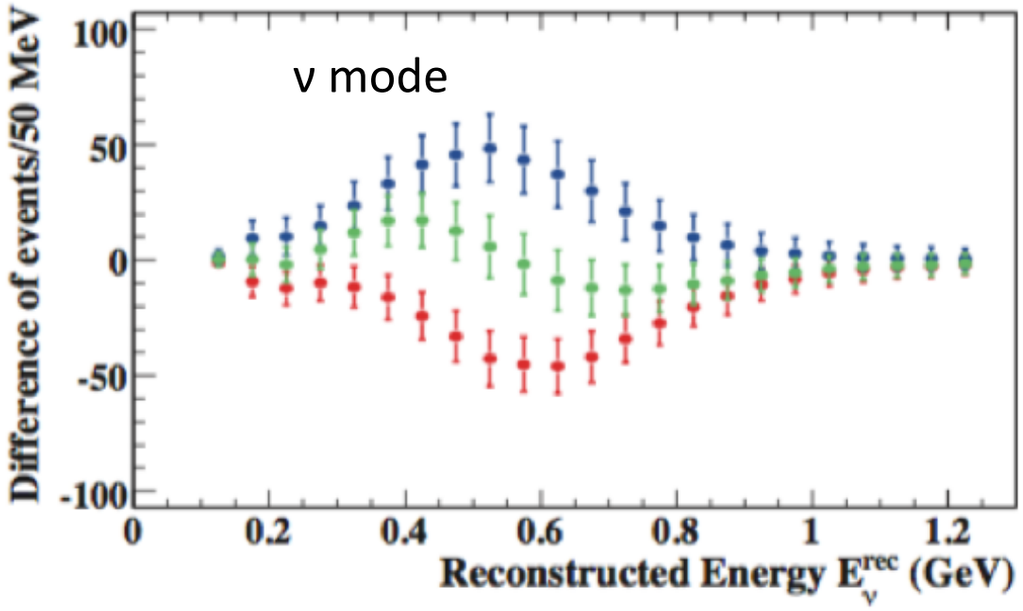


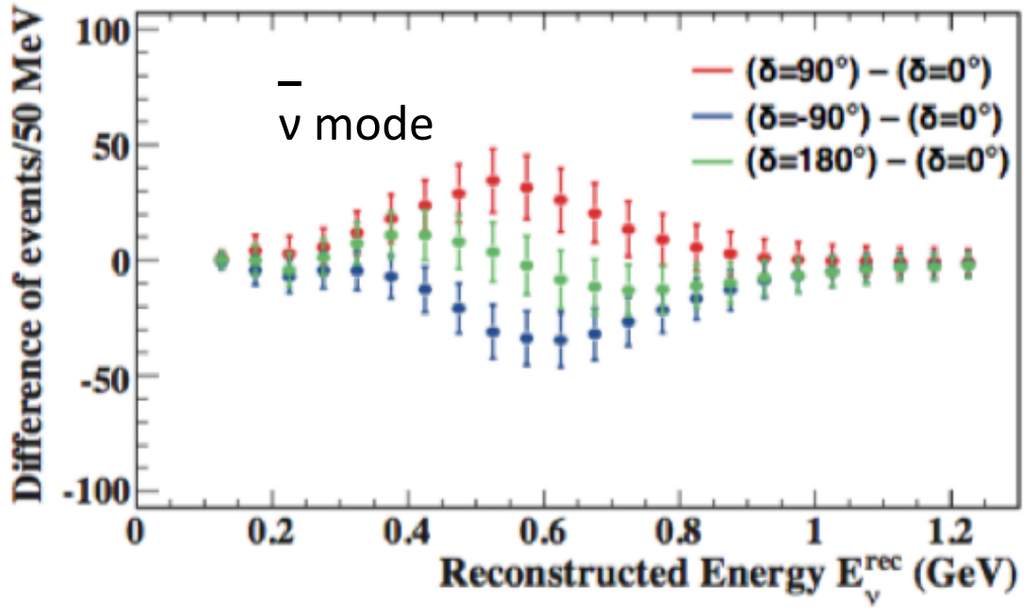
- New `Super-FGD'
- New horizontal TPCs
- Many beam tests this summer!
- Installation during T2K-II

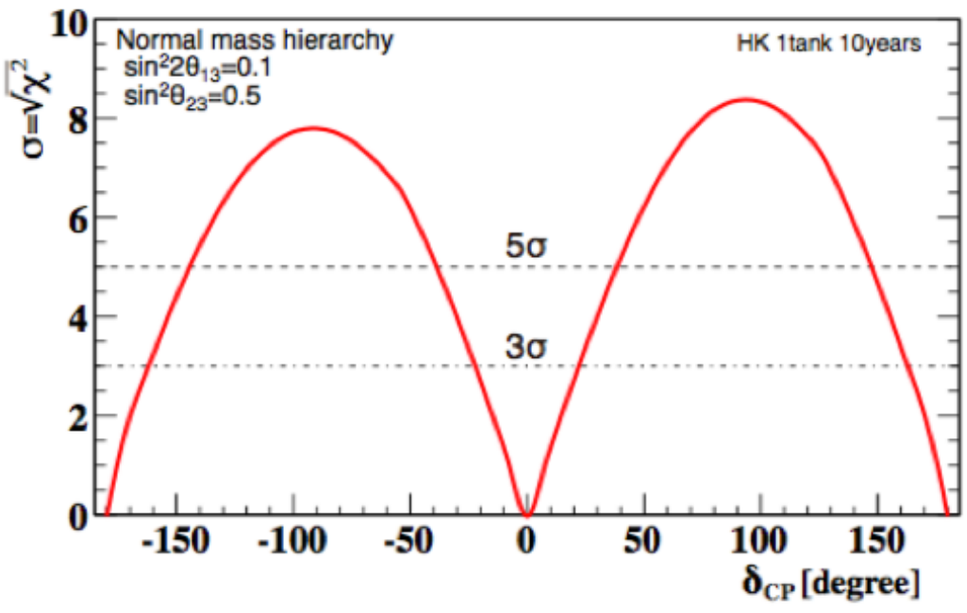


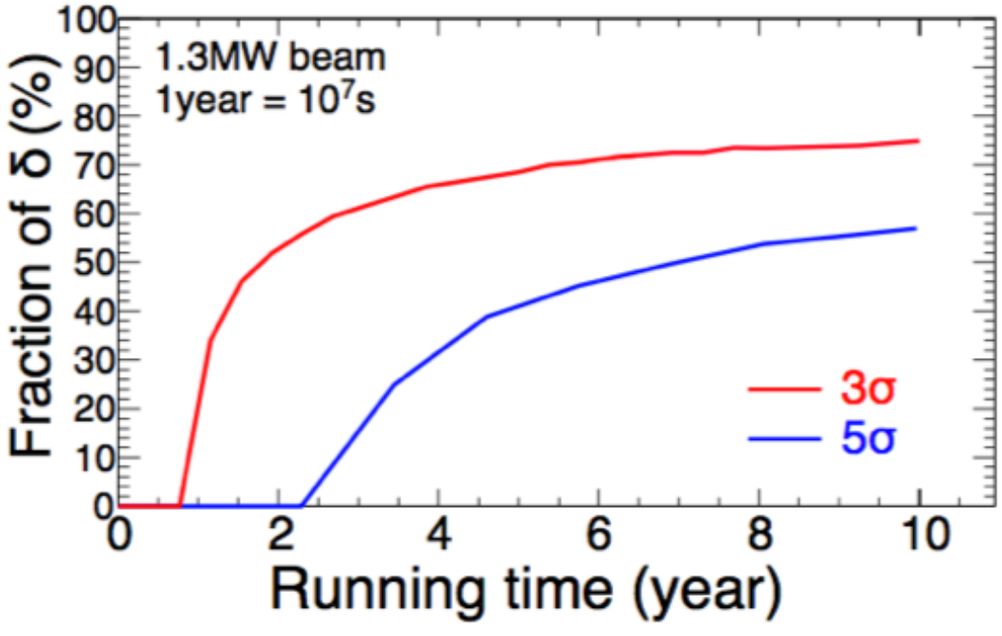
- Intermediate WC detector
- Exploit off-axis behavior for variable energy beams

Physics Reach



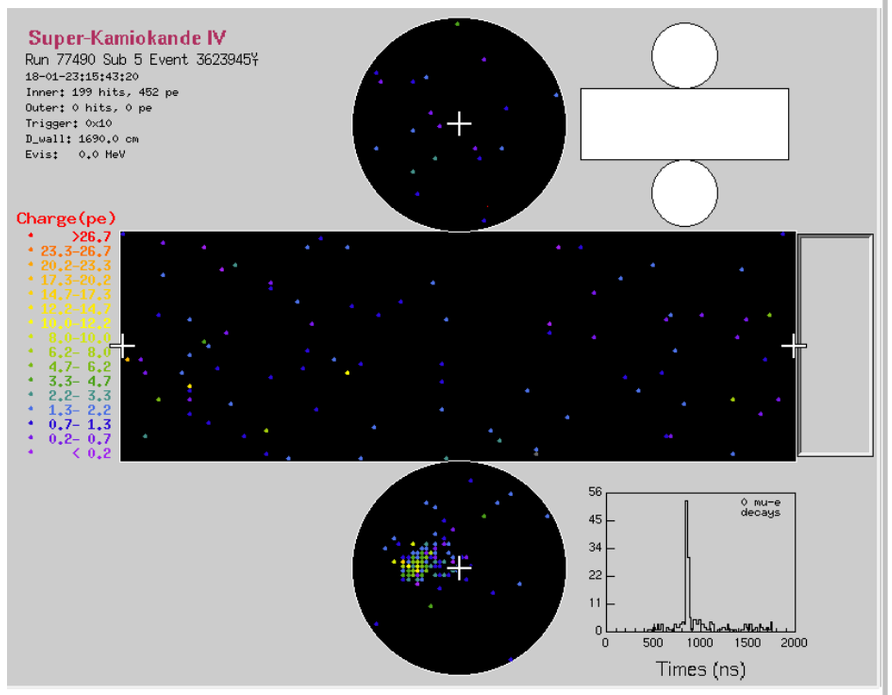


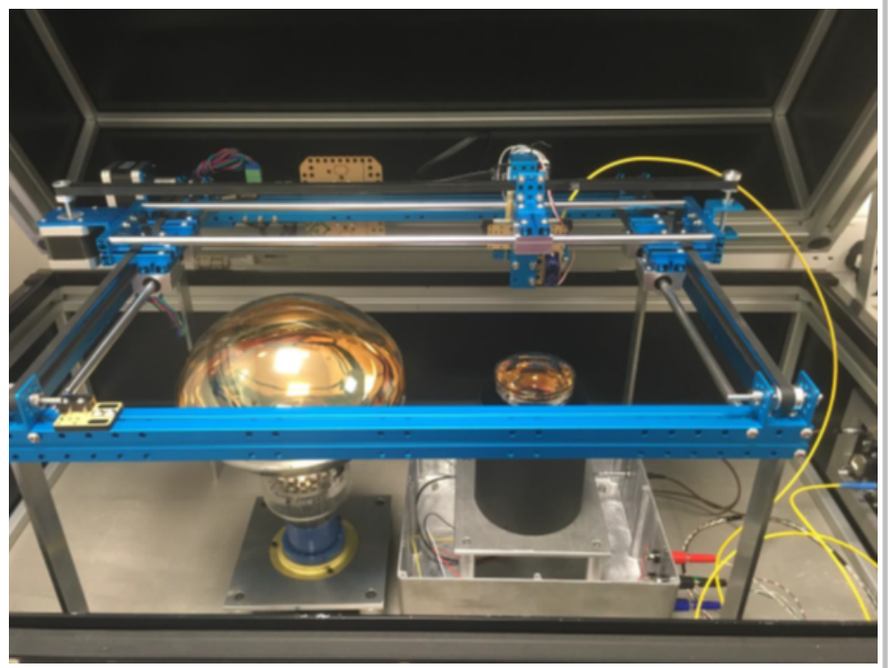




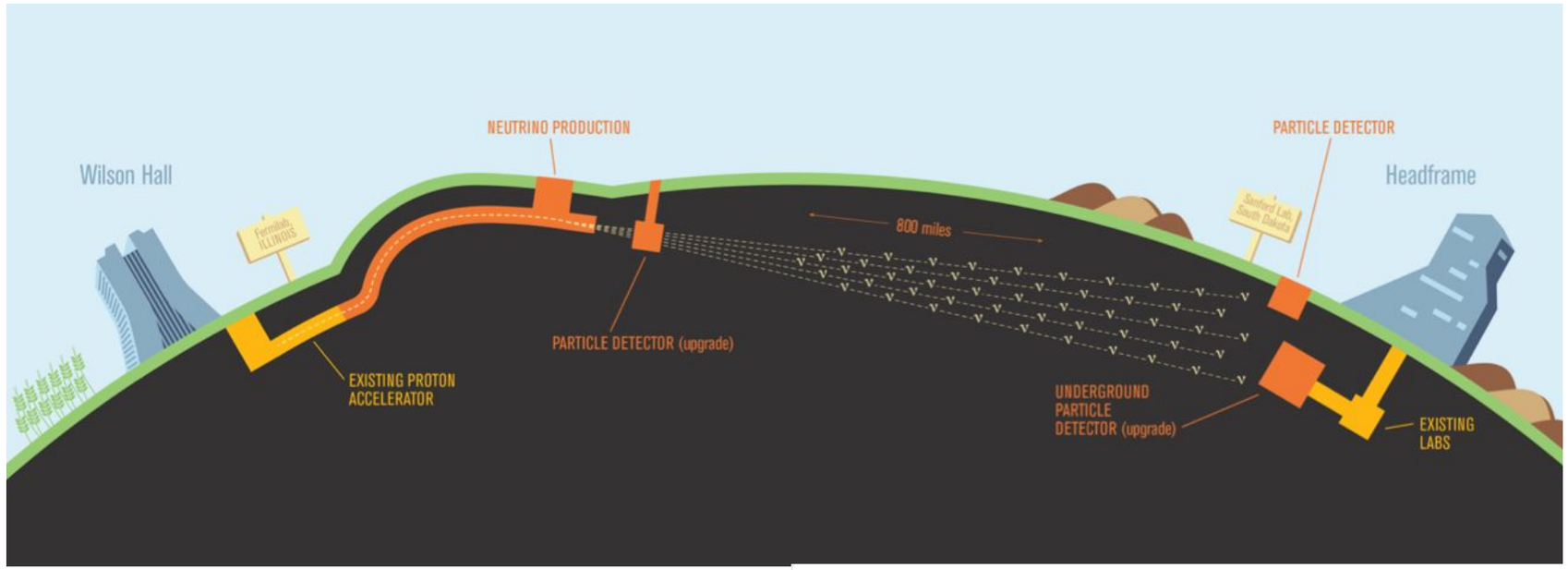
UK Activities

- Intermediate WC detector: design, calibration, DAQ
- DAQ: IWCD and HK; triggering methods
- Calibration: New light injection methods (L. Anthony, S. Valder, S. Jenkins)
- Beam: Upgrades for 1.3 MW operation
- Outer Detector: optimization (S. Zsoldas)
- Physics Sensitivity Studies: broad range of physics (J. Migenda)

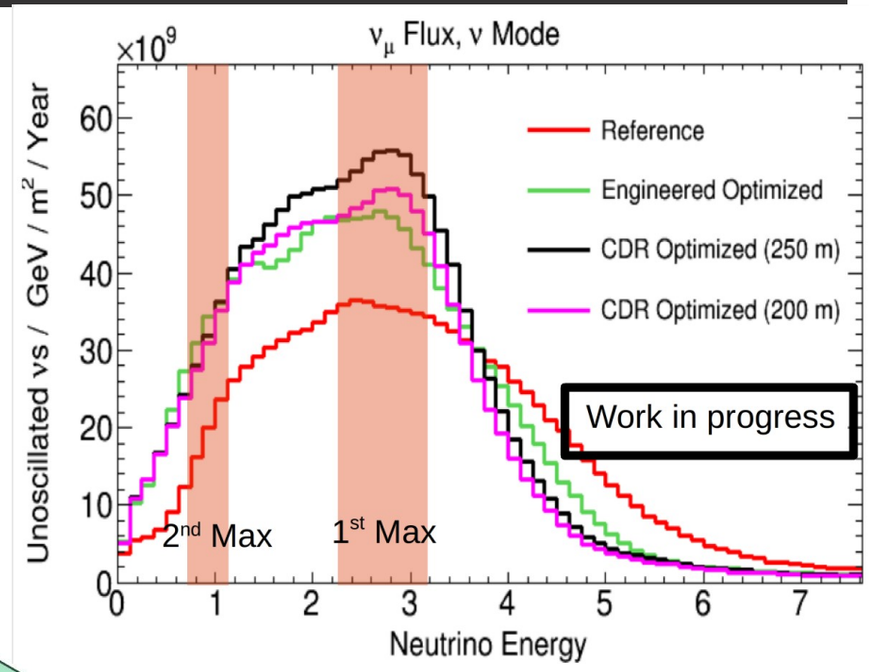


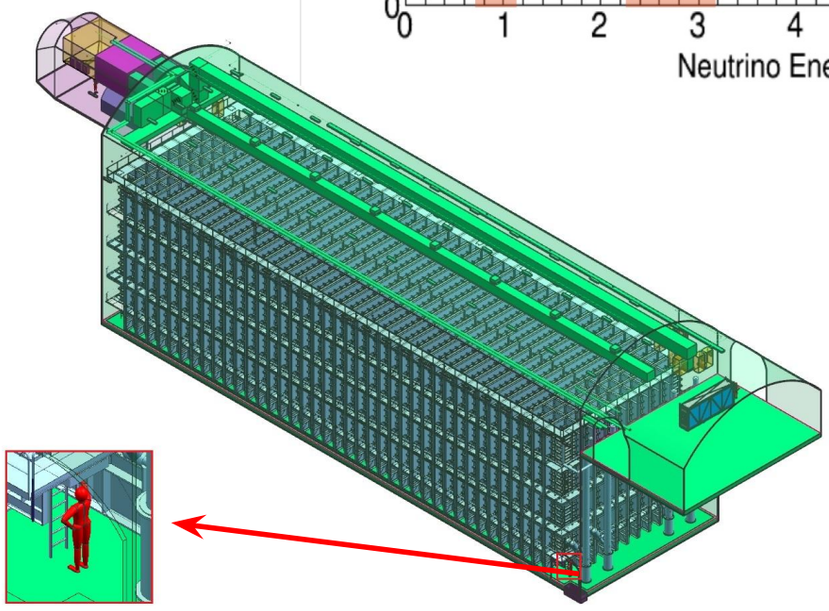


DUNE



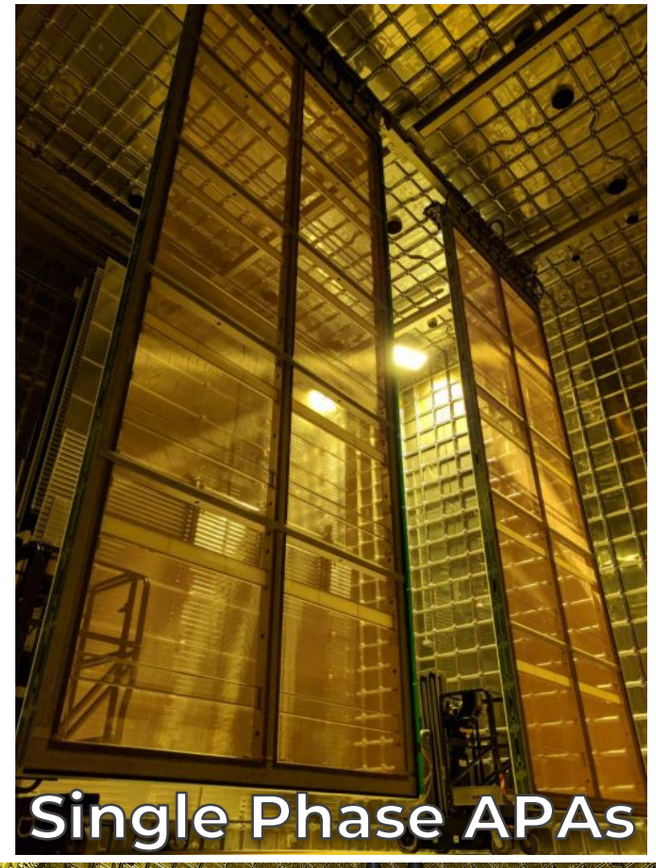
- LAr based far detector with a staged approach
  - First module will be single phase
  - Additional modules may be dual phase
- Beam is broad band: potential access two oscillation maxima
- Near detector design still under consideration

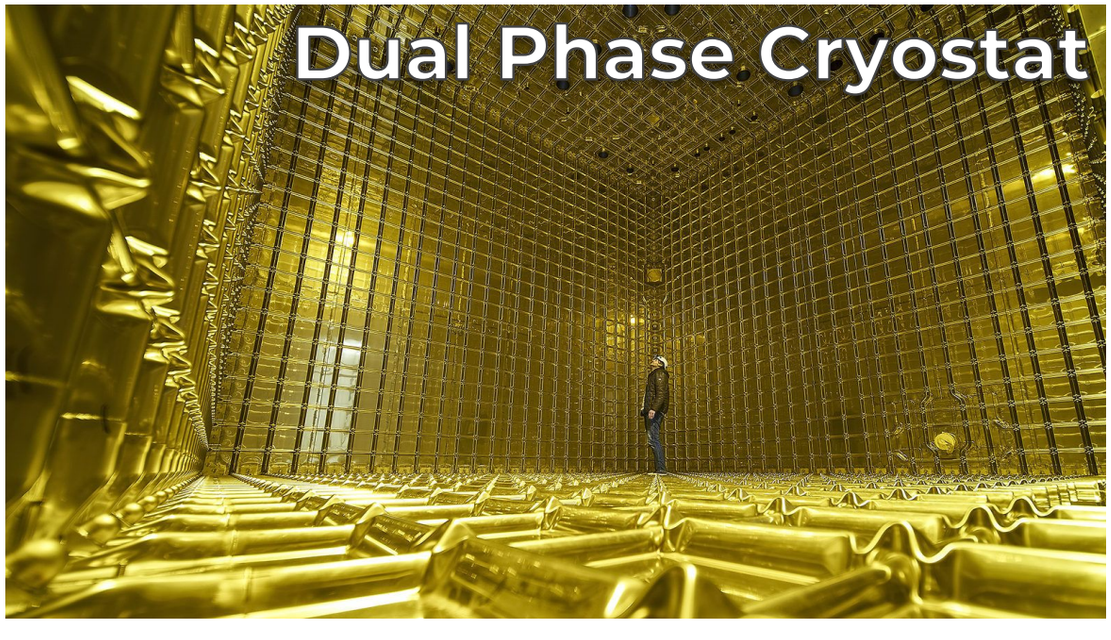




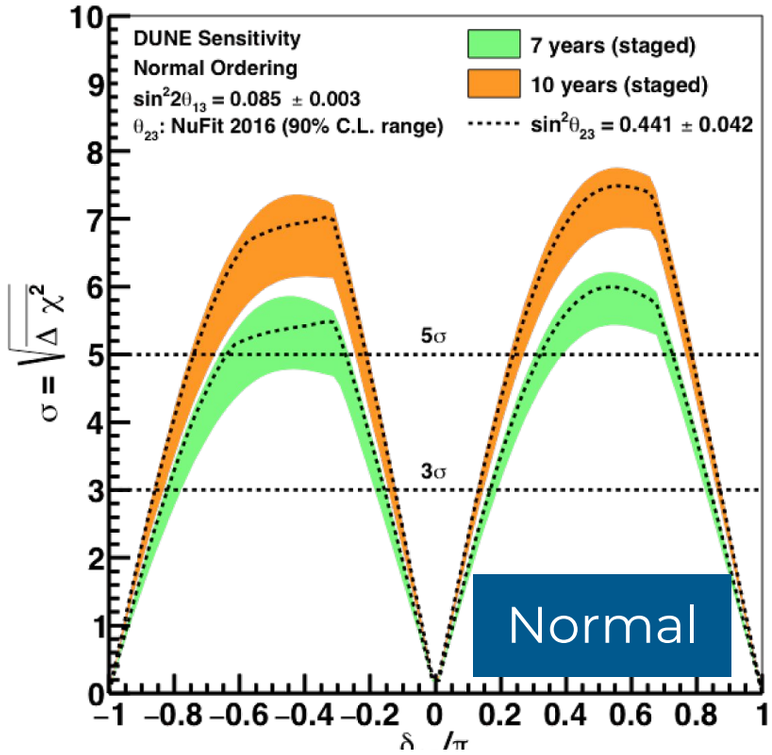
ProtoDUNEs

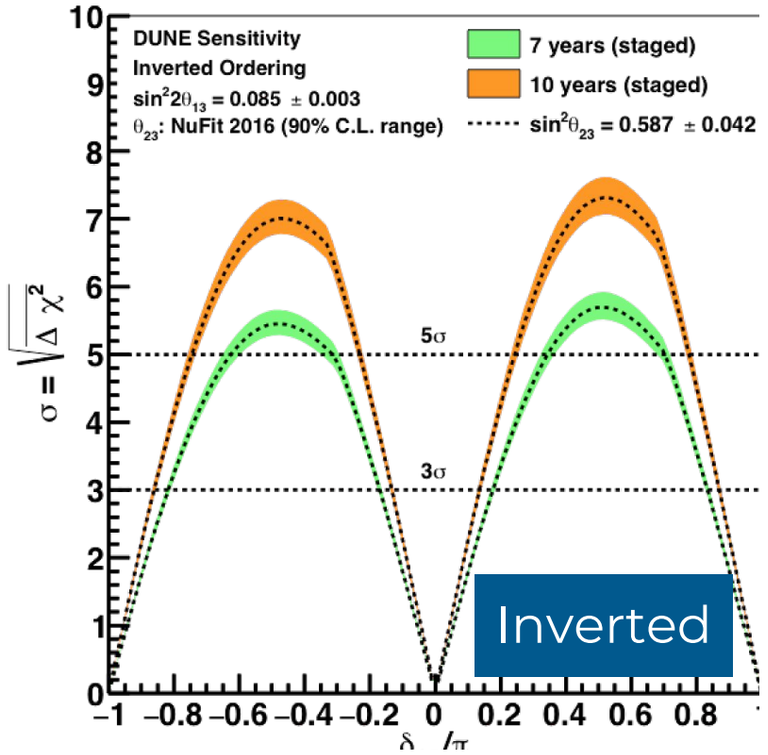
- Single and Dual Phase prototypes constructed at CERN as part of the Neutrino Platform
- Will take test beam in late 2018
- Exciting test of technology and will get important hadron-Ar data (J. Thompson)

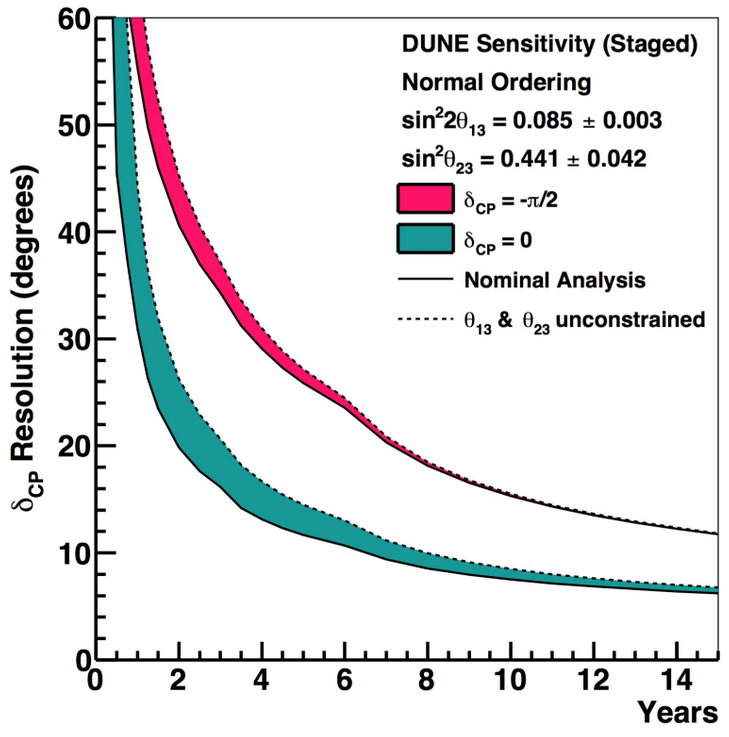

Single Phase APAs

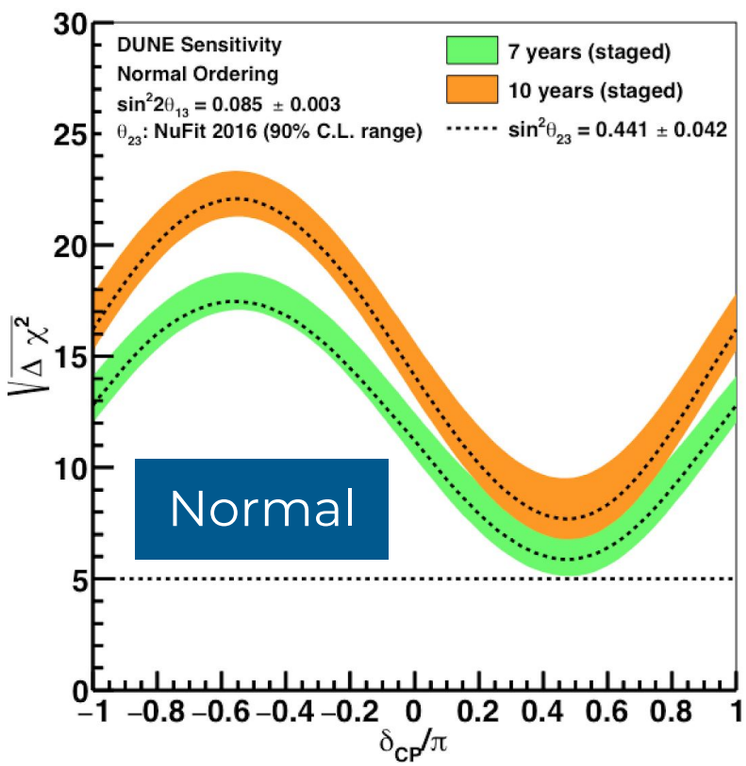

Dual Phase Cryostat

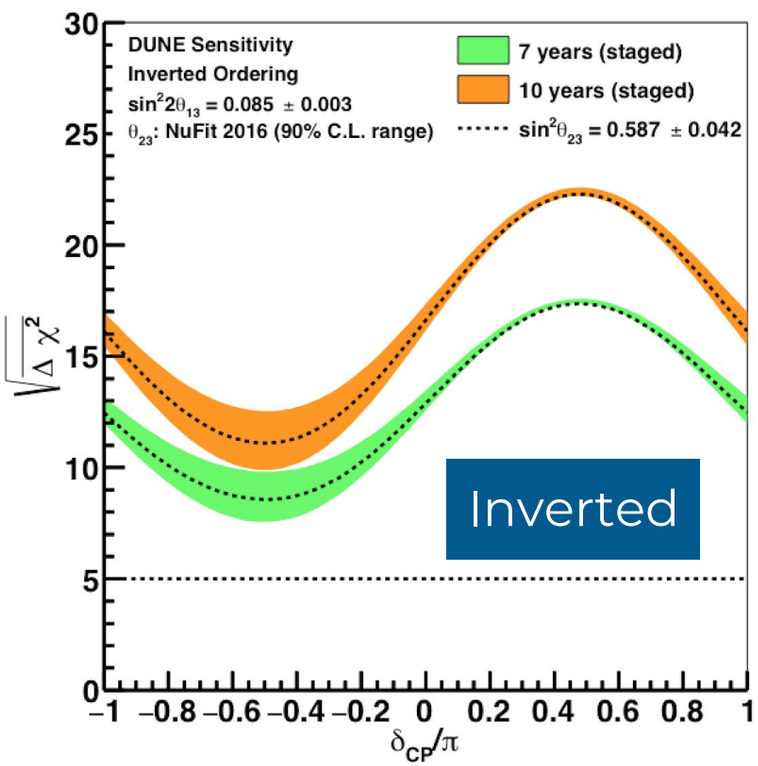
Physics Reach











UK Activities

- DAQ: hardware, firmware, and online computing
- Beam target: optimization for high power operation
- Anode plane construction: Delivery of APAs to proto-DUNEs as preparation for FD construction
- Reconstruction software: pattern recognition in complex events
- Physics sensitivity studies

Summary

- T2K and NOvA are racing ahead with new data and exciting results!
- We have a hint of CP-violation
  - Need new data from both
  - Combined analysis is coming
- DUNE and HK are an exciting future for CPV discovery!