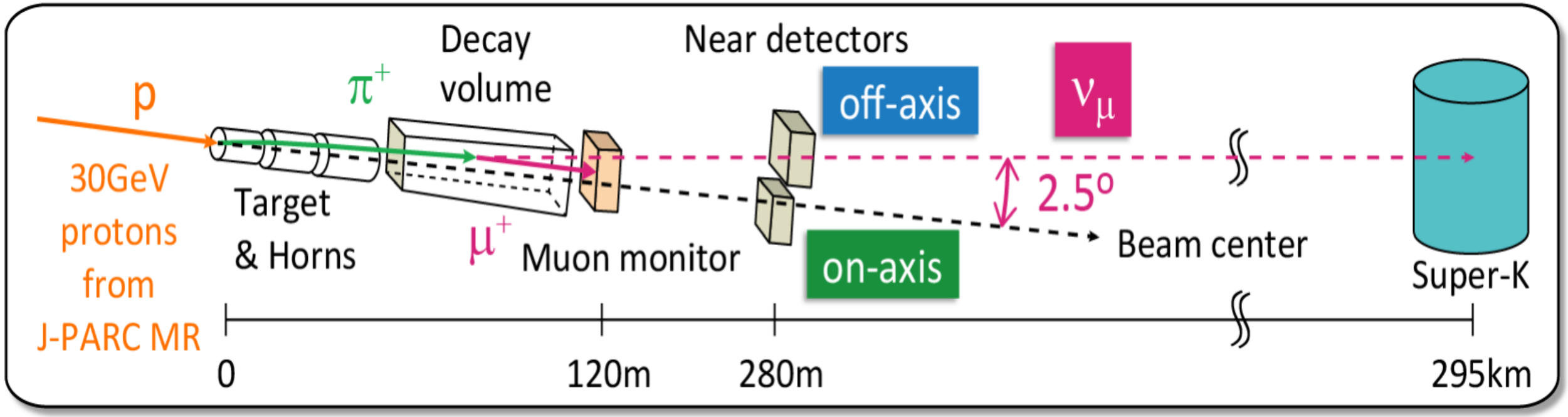
Experimental status of T2K and NOvA

Davide Sgalaberna (CERN)

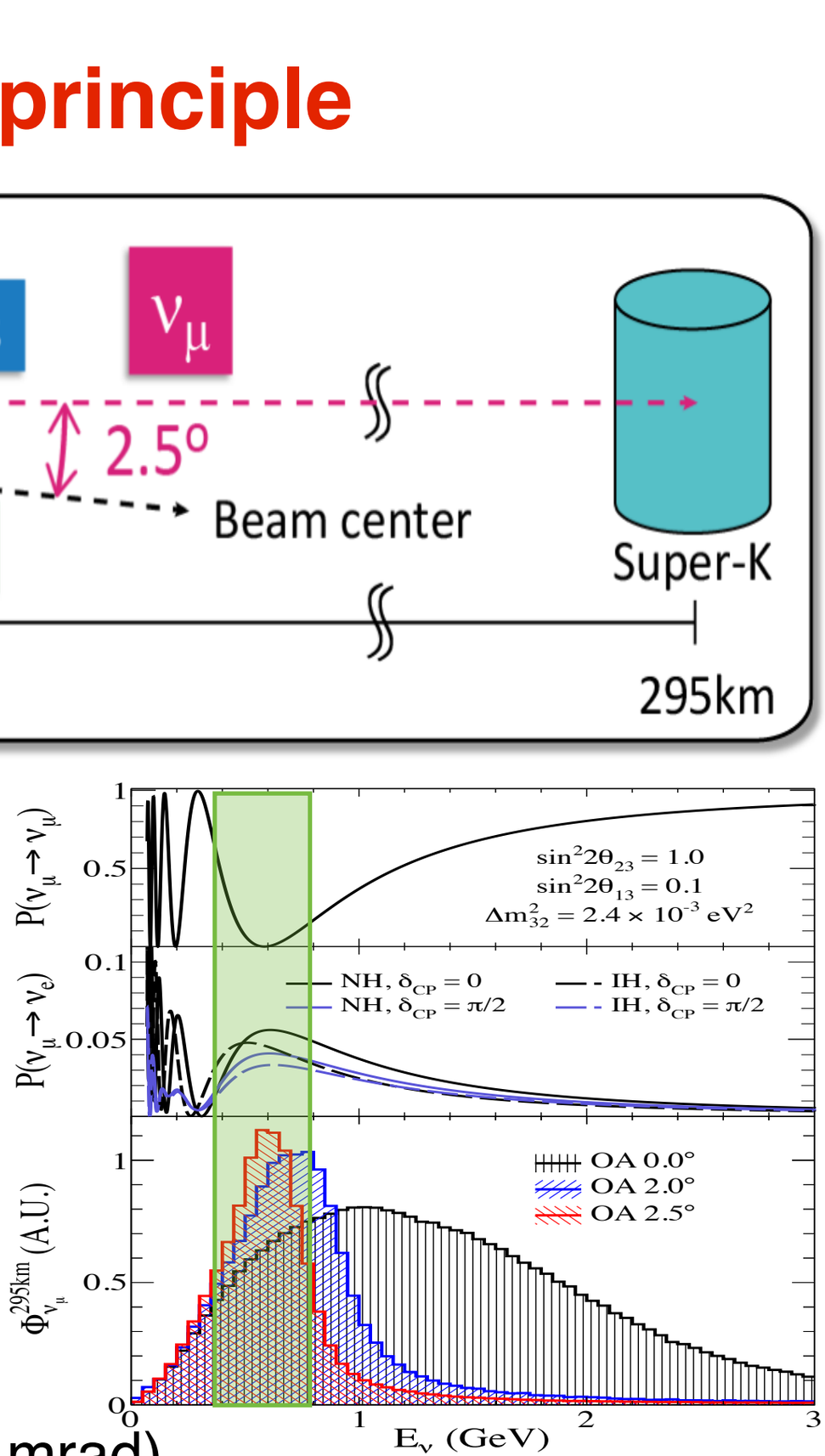
XVth Rencontres du Vietnam

5th August 2019

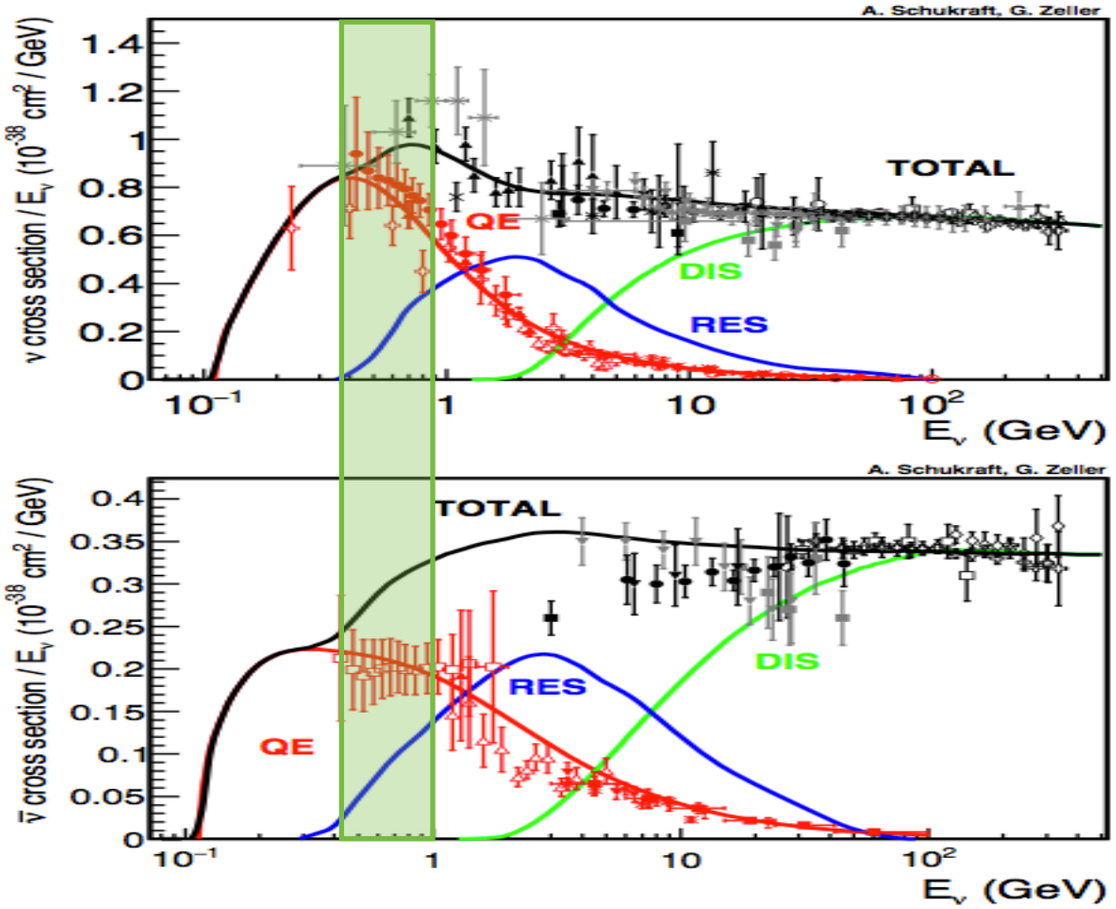
T2K off-axis design principle



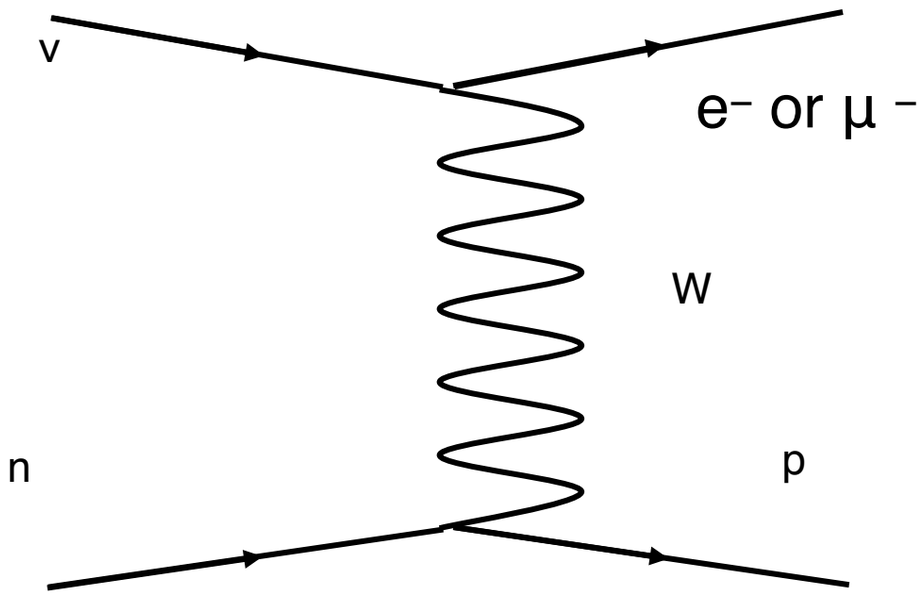
- 30 GeV proton beam on 90 cm long graphite target
- ν_μ and $\bar{\nu}_\mu$ produced by pion and kaon decay:
  - $\pi^+ \rightarrow \mu^+ + \nu_\mu$
  - $\pi^- \rightarrow \mu^- + \bar{\nu}_\mu$
- Invert magnet polarity to produce a $\bar{\nu}_\mu$ beam
- First off-axis neutrino beam experiment 2.5° (44 mrad)
  - narrow spectrum peaked at 0.6 GeV, on the expected oscillation maximum



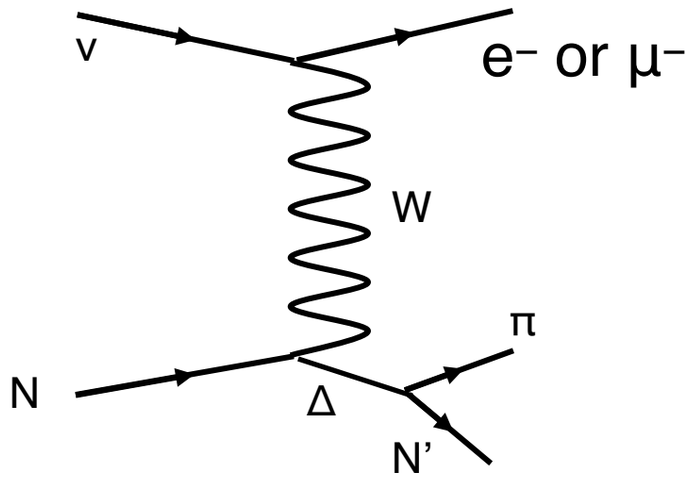
(Anti)Neutrino interactions at T2K



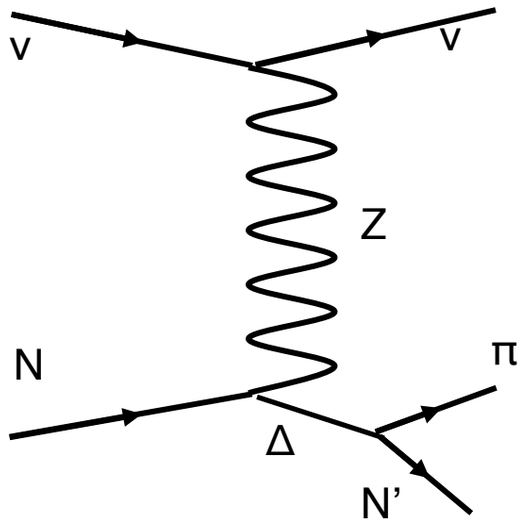
Charged-Current Quasi-Elastic (CCQE)



Charged-Current π

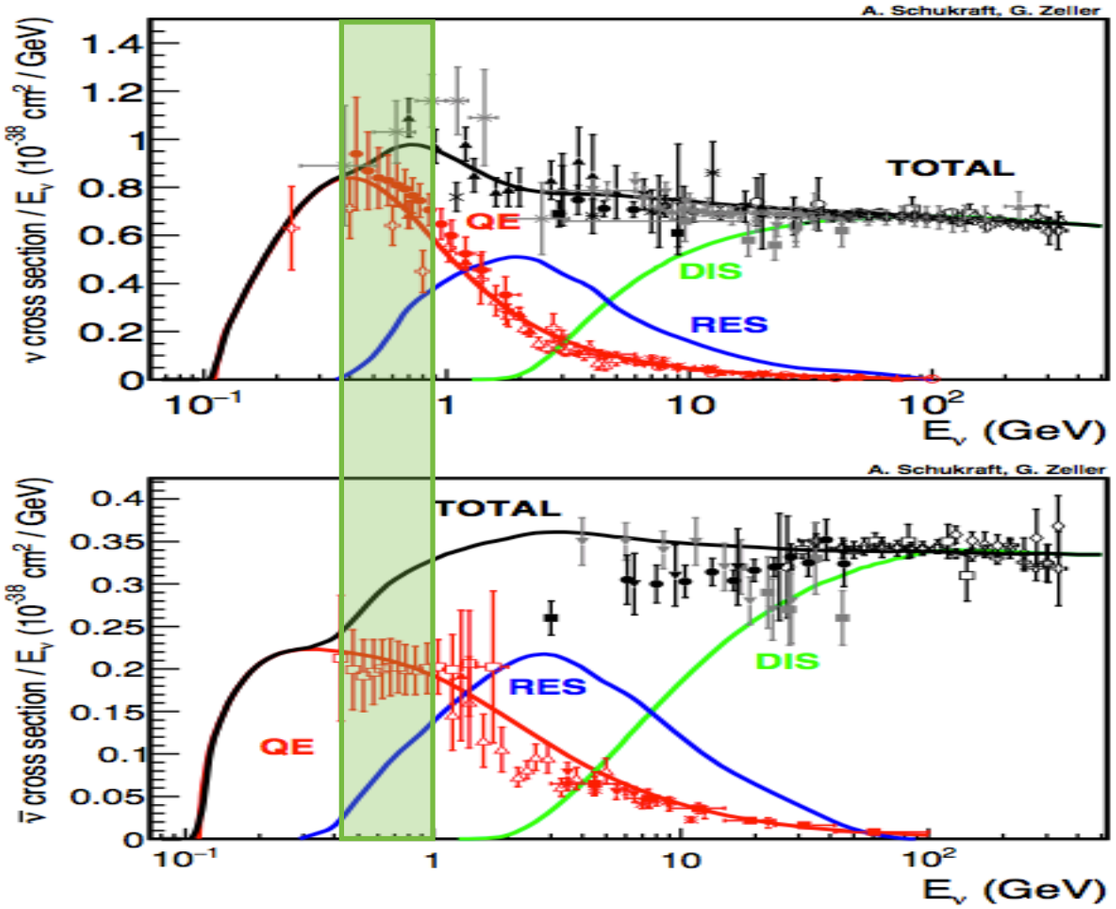


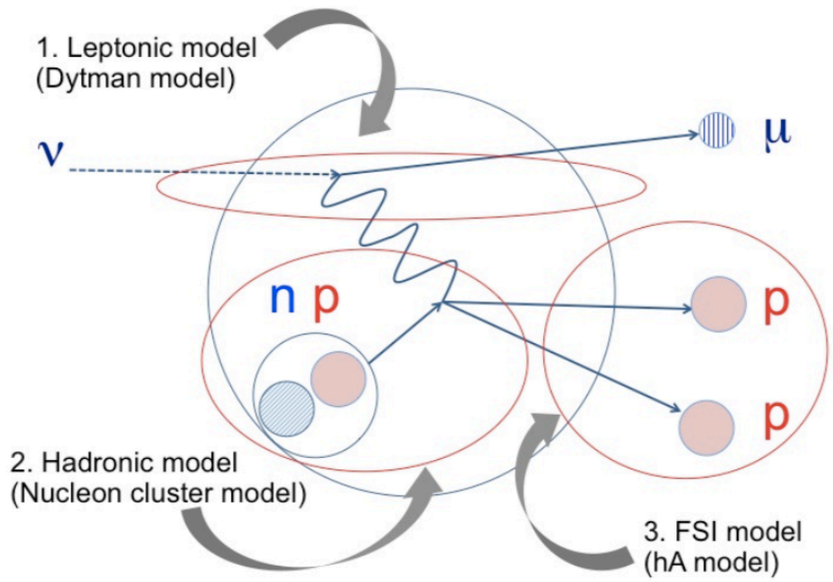
Neutral-Current π



The dominant neutrino interaction mode is Charged-Current Quasi-Elastic (CCQE)

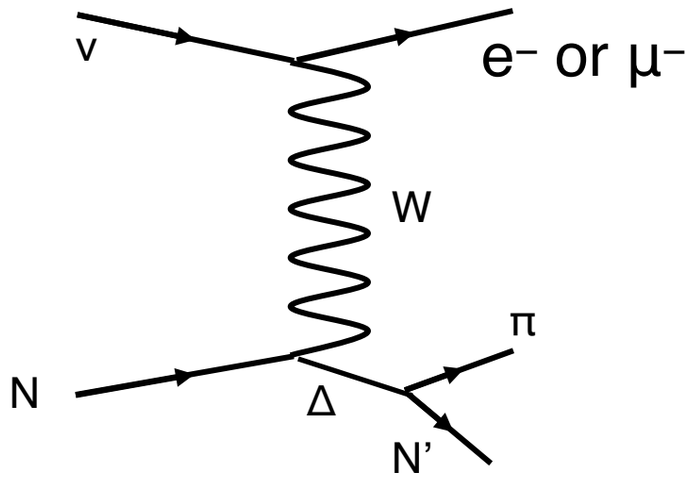
(Anti)Neutrino interactions at T2K



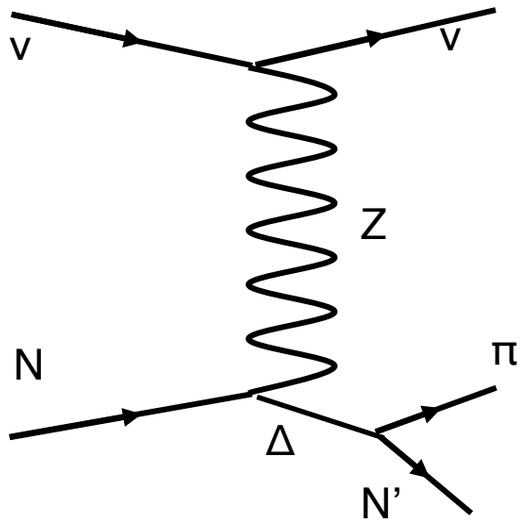


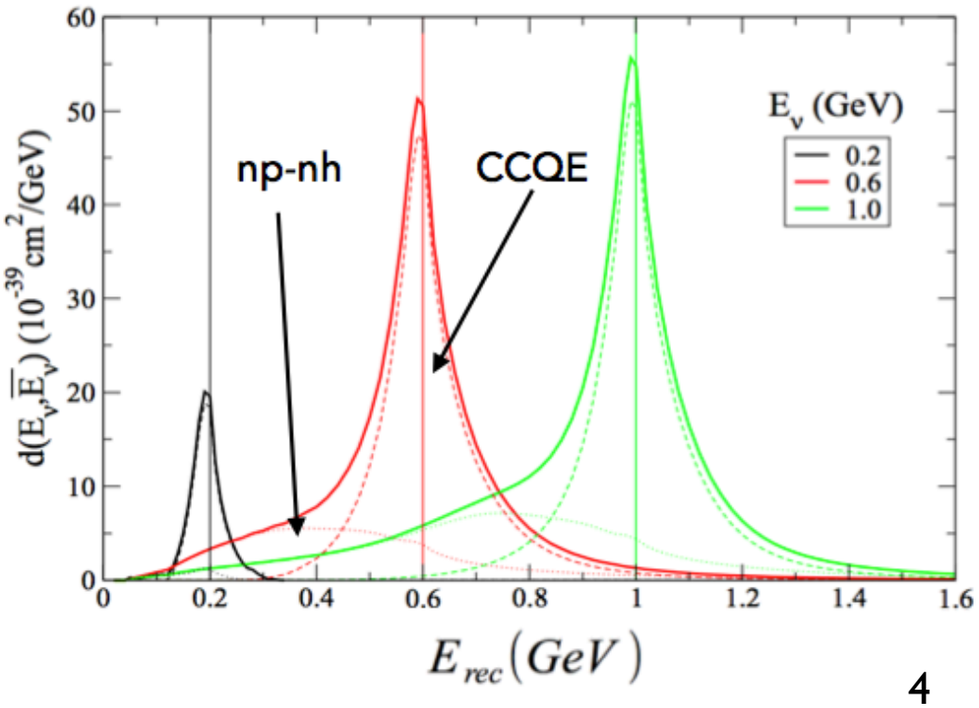
Nieves et al. PRC 83 045501 (2011)
Martini et al. Phys.Rev. D87 (2013) 013009

Charged-Current π



Neutral-Current π

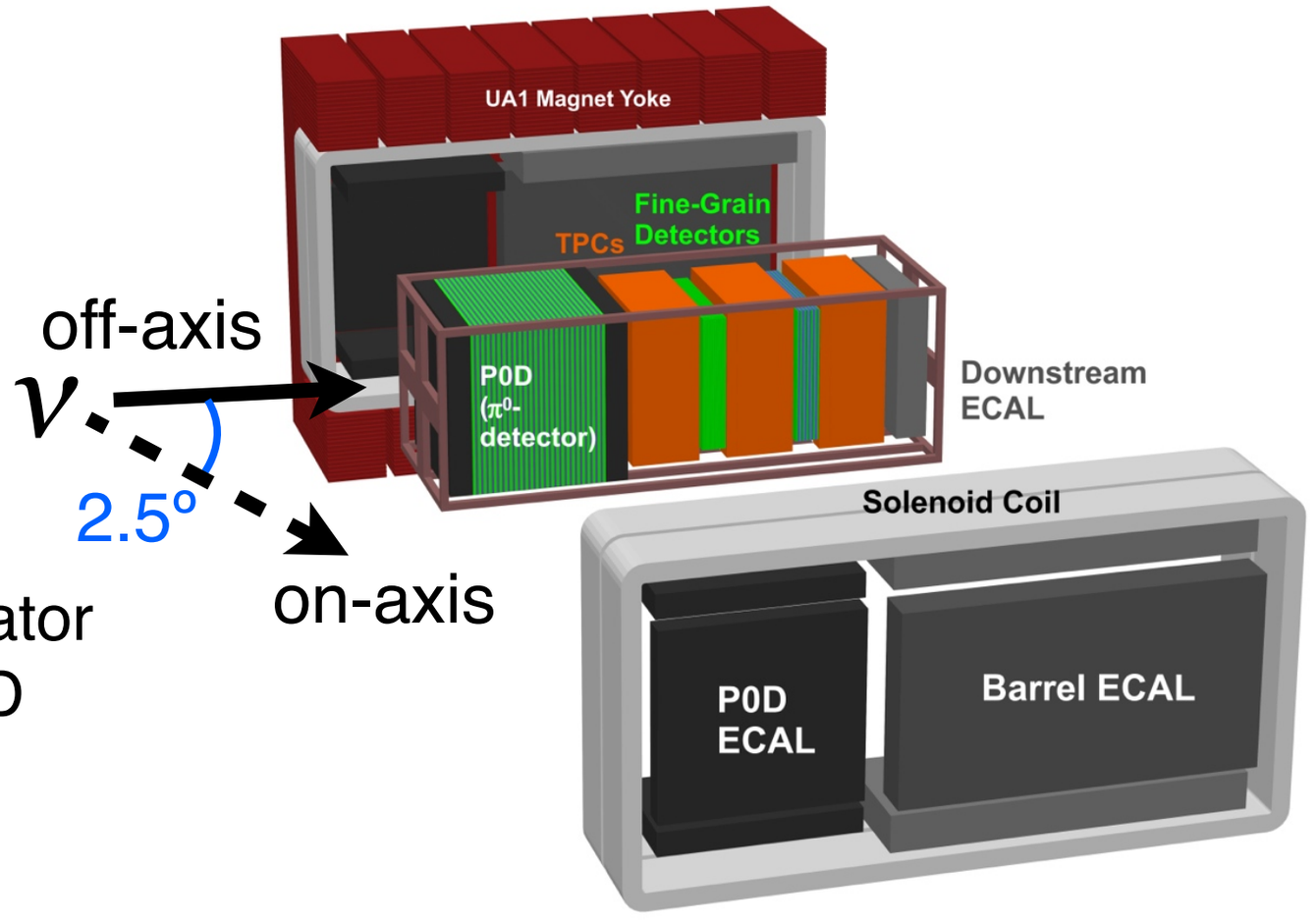


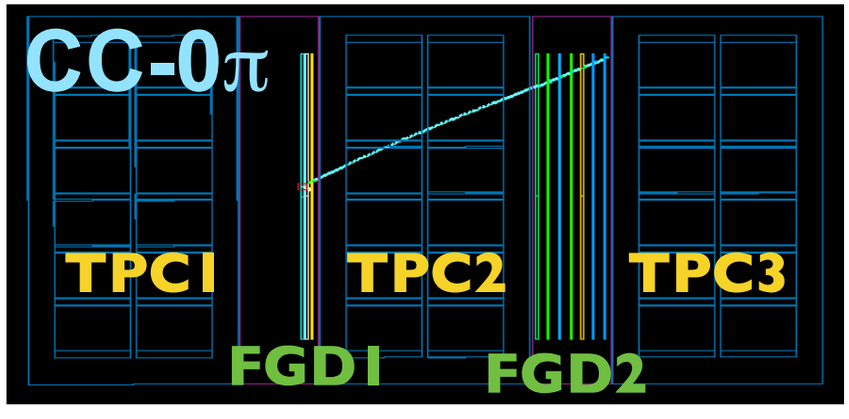


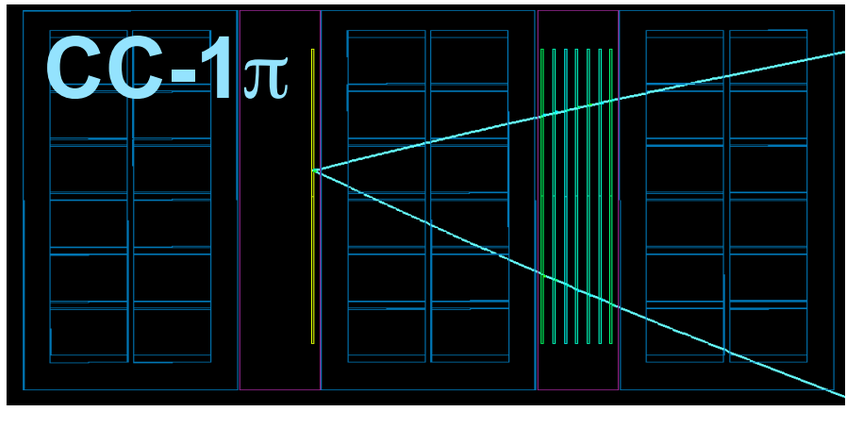
T2K near detector complex

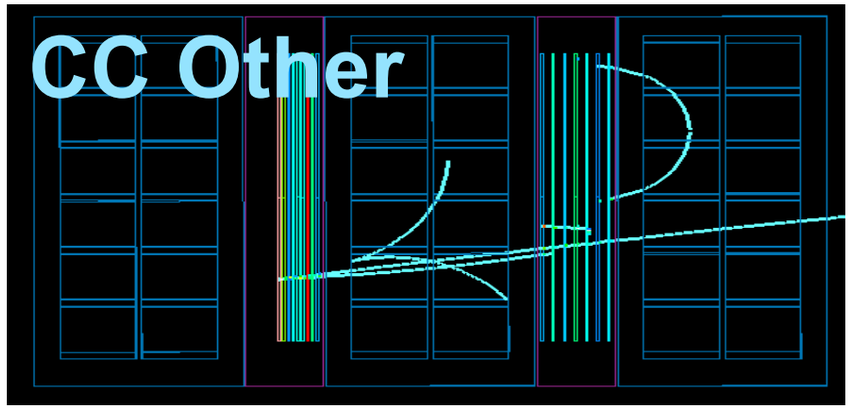
NIM A 659 (2011) 106–135

- **Muon monitor:**
  - ✦ Spill-by-spill monitoring of the beam
- **On-axis detector (INGRID)**
  - ✦ measure beam intensity / direction
- **Off-axis detector (ND280):**
  - ✦ 2.5° off-axis magnetized detector
  - ✦ Fine Grained Detector (plastic scintillator and water), TPCs, ECAL, P0D, SMRD
  - ✦ precise measurement of neutrino flux and cross section
  - ✦ measure wrong-sign background (20-30% ν_μ in $\overline{\nu}_\mu$ beam after interaction)



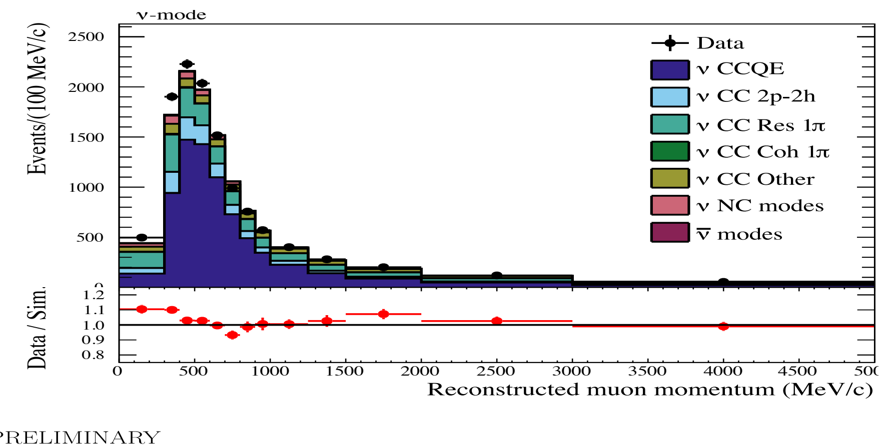


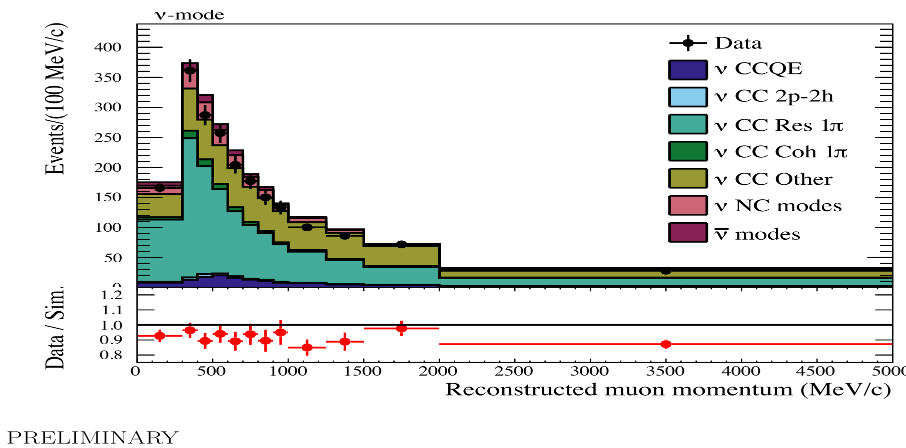


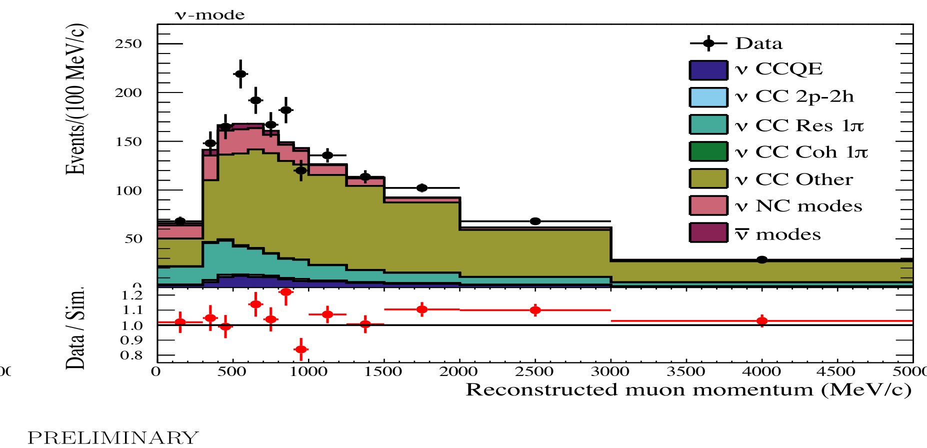


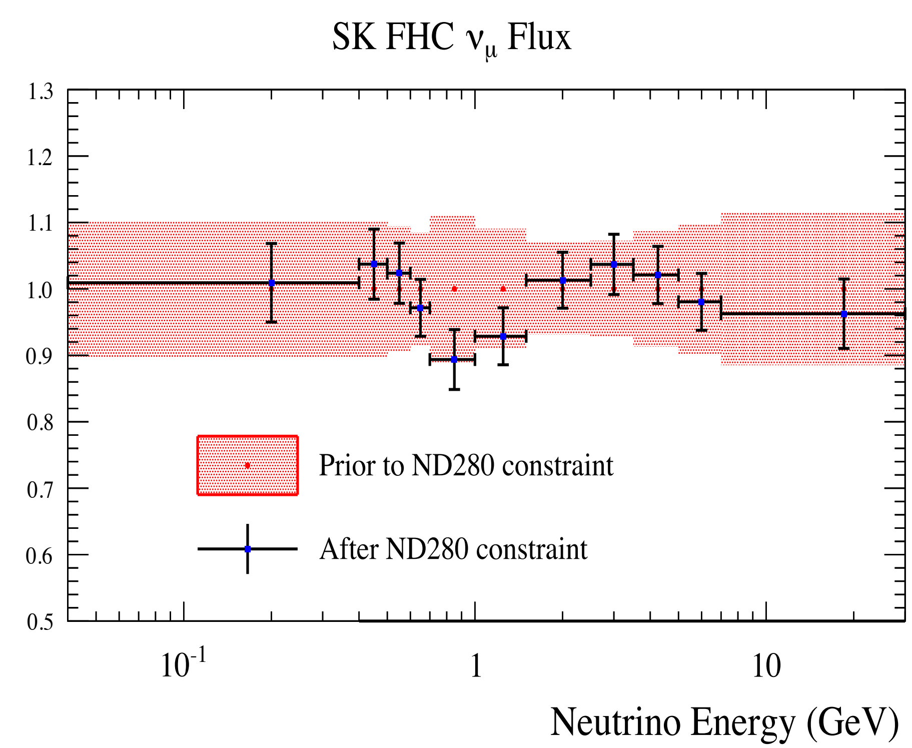
Constraining the systematic uncertainties at ND280

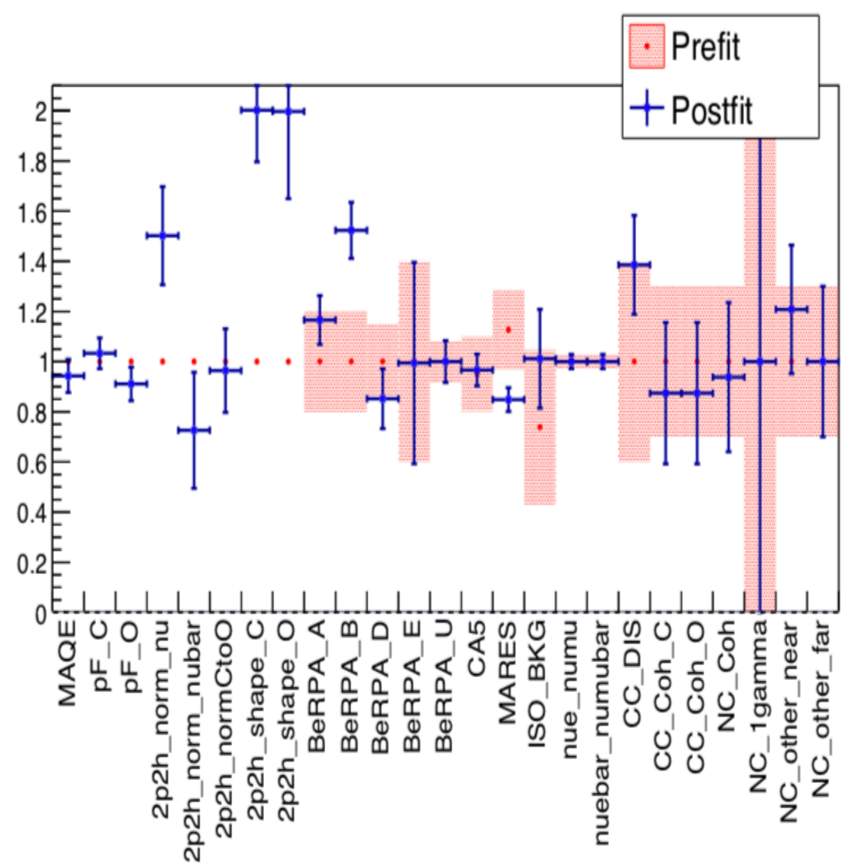
- A joint fit of the following samples is performed: CC-0 pions, CC-1 pion, CC-Other for ν beam, CC-1 track, CC N-tracks for $\overline{\nu}$ beam

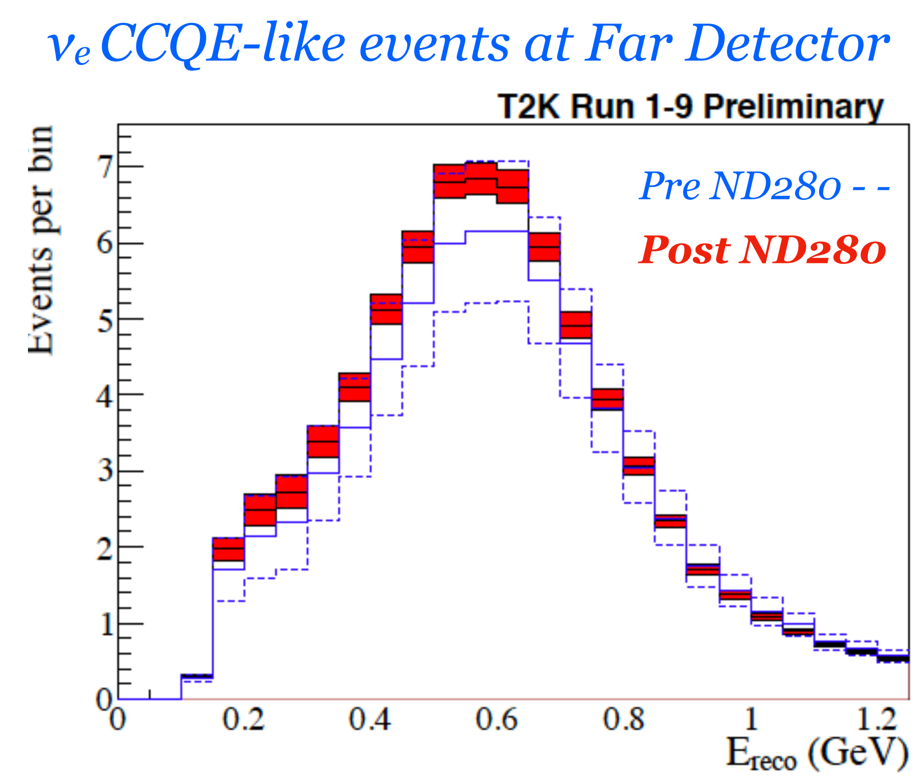








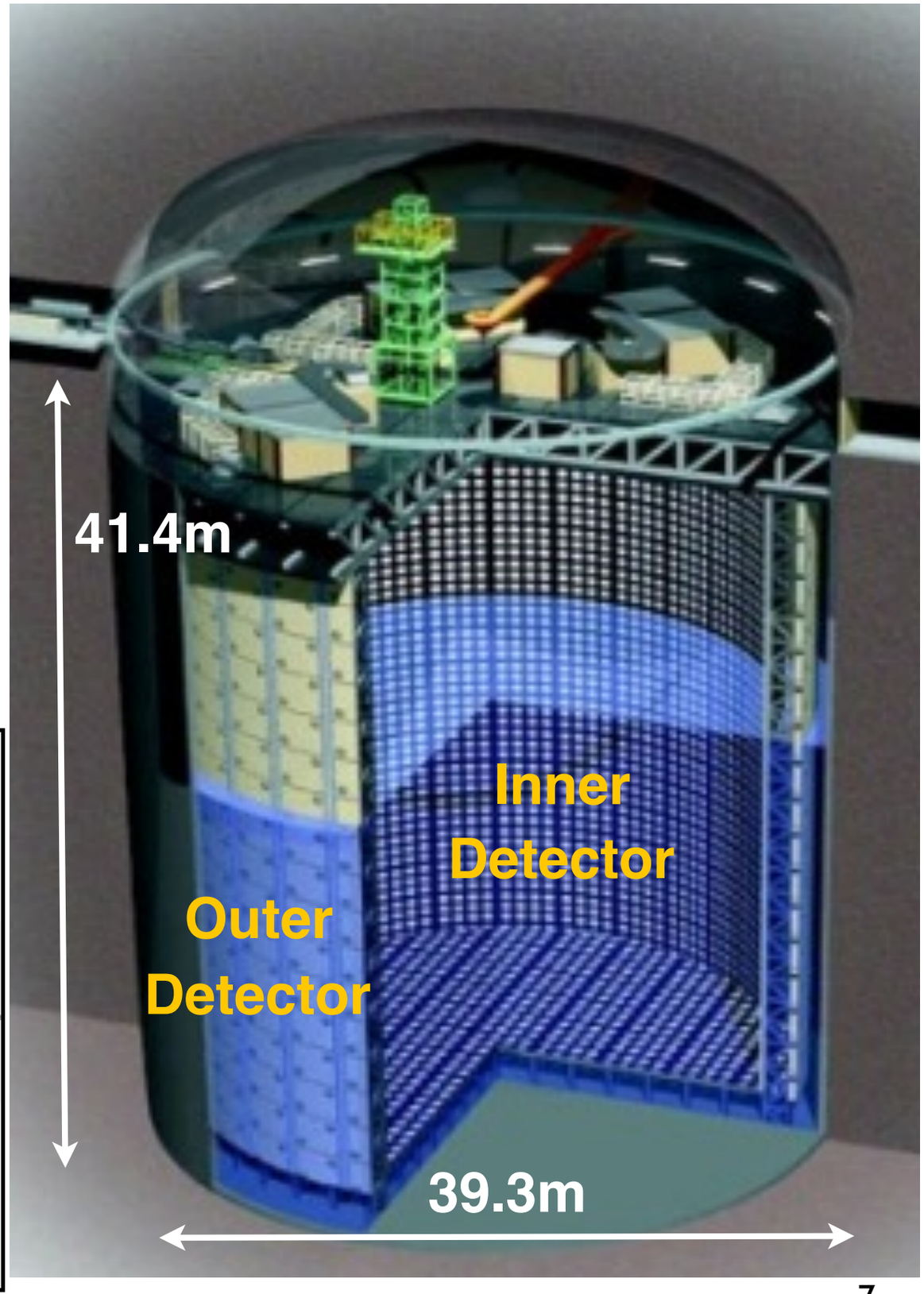


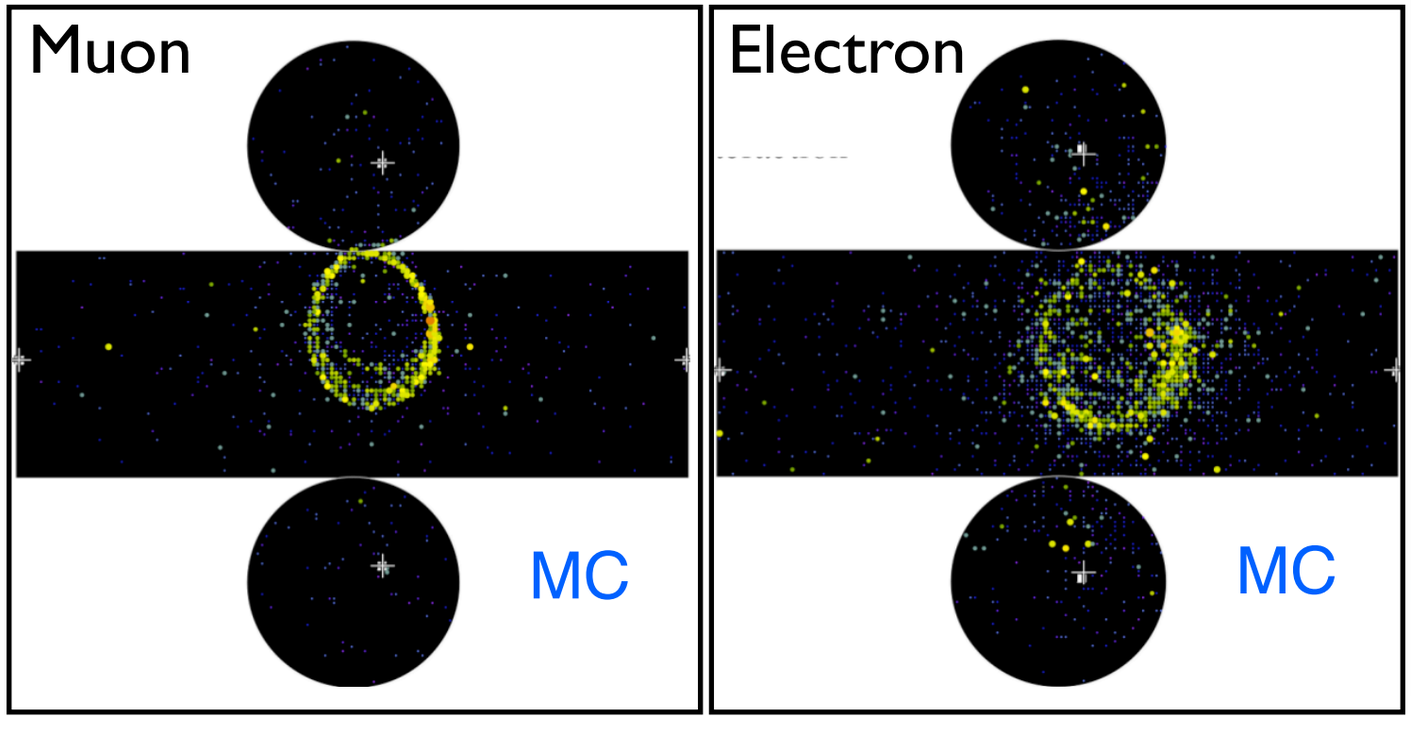


- Most of the parameters fall within 1σ of their assigned prior uncertainty
- The goodness-of-fit test shows a p-value for the model of 0.47

T2K far detector: Super-Kamiokande

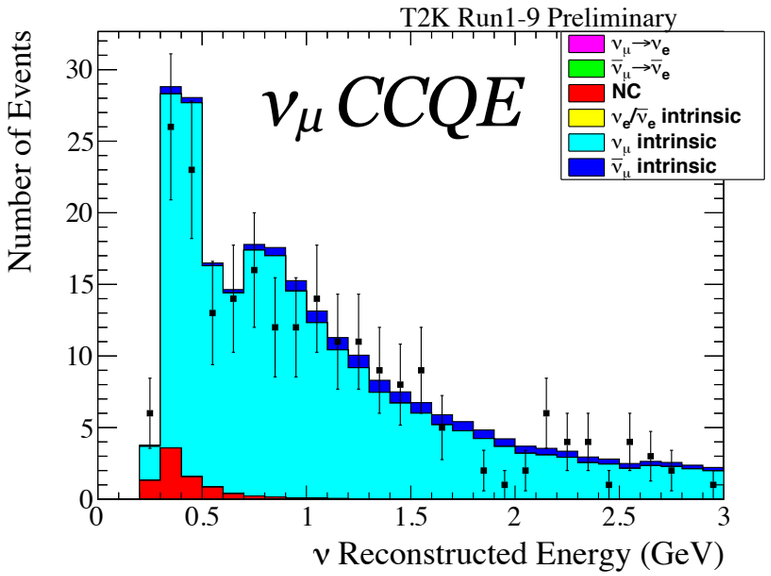
- Located in Mozumi mine
  - 2700 m.w.e overburden
- Water Cherenkov detector (50 kton)
- Fiducial mass 22.5 kton
- Inner detector
  - 11129 20-inch PMTs
- Outer veto detector
  - 1885 8-inch PMTs
  - determine fully-contained events

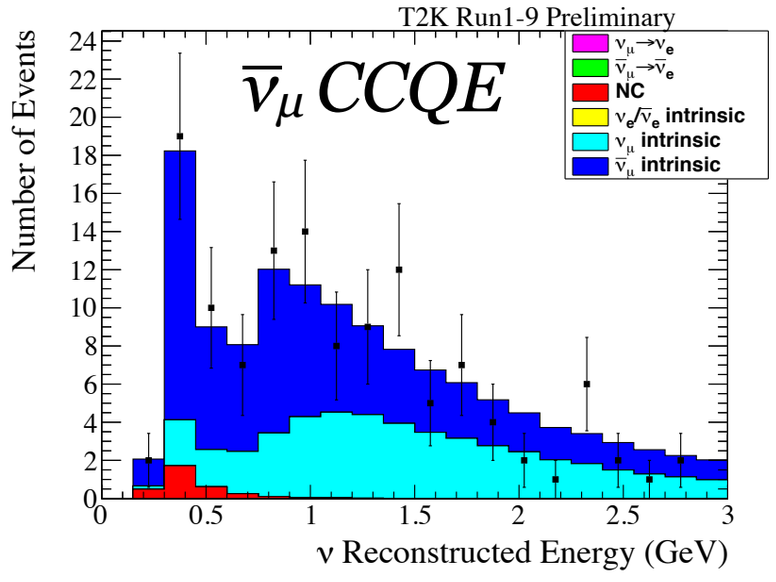


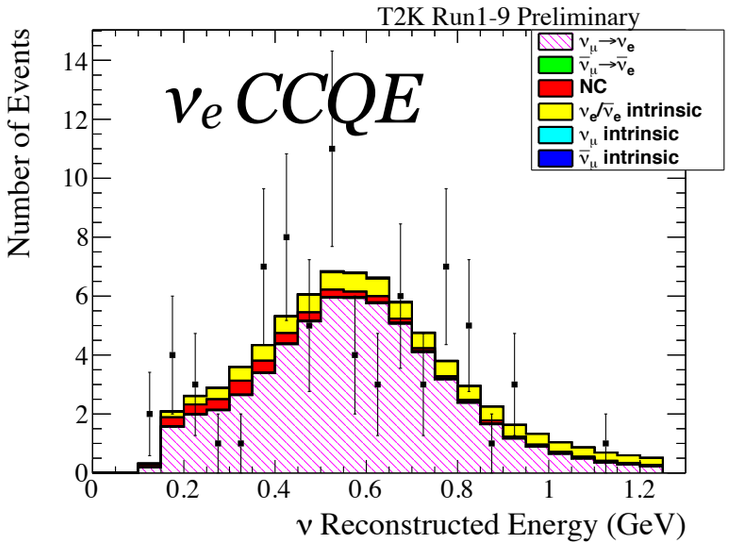


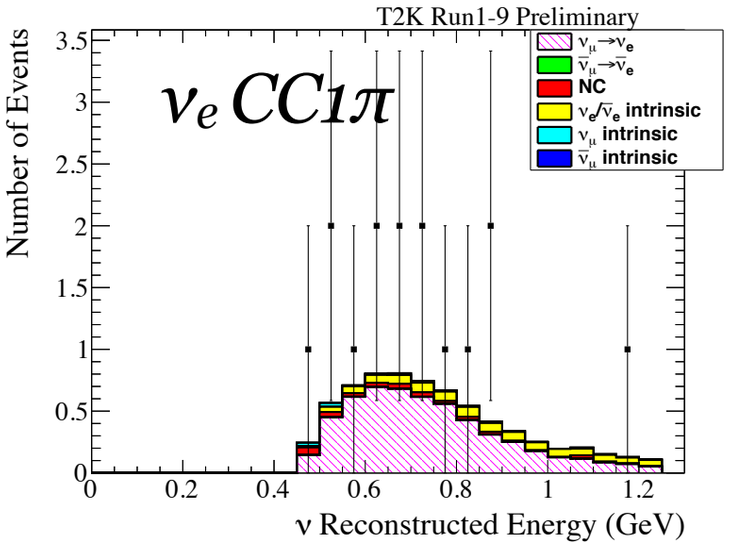
Far Detector ν_μ / $\overline{\nu}_\mu$ event samples

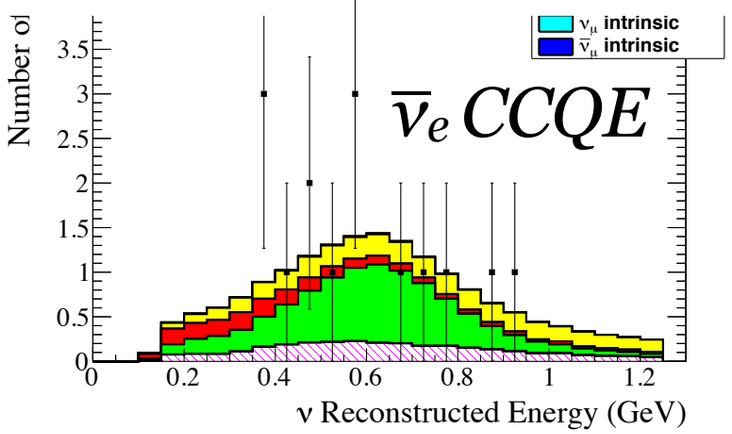
- Data collected: 3.16 x 10^{21} POT (ν - 1.51 x 10^{21} POT, $\overline{\nu}$ - 1.65 x 10^{21} POT)



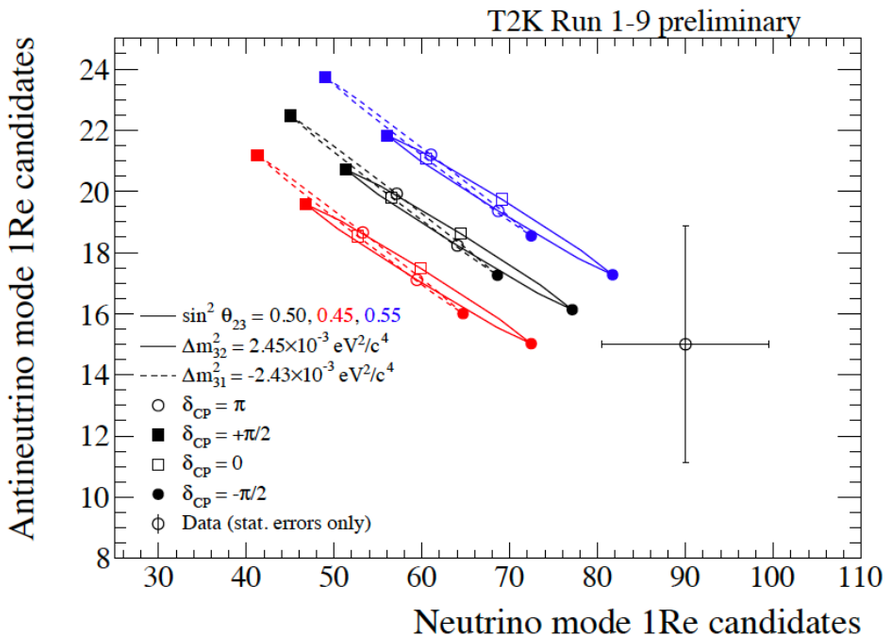






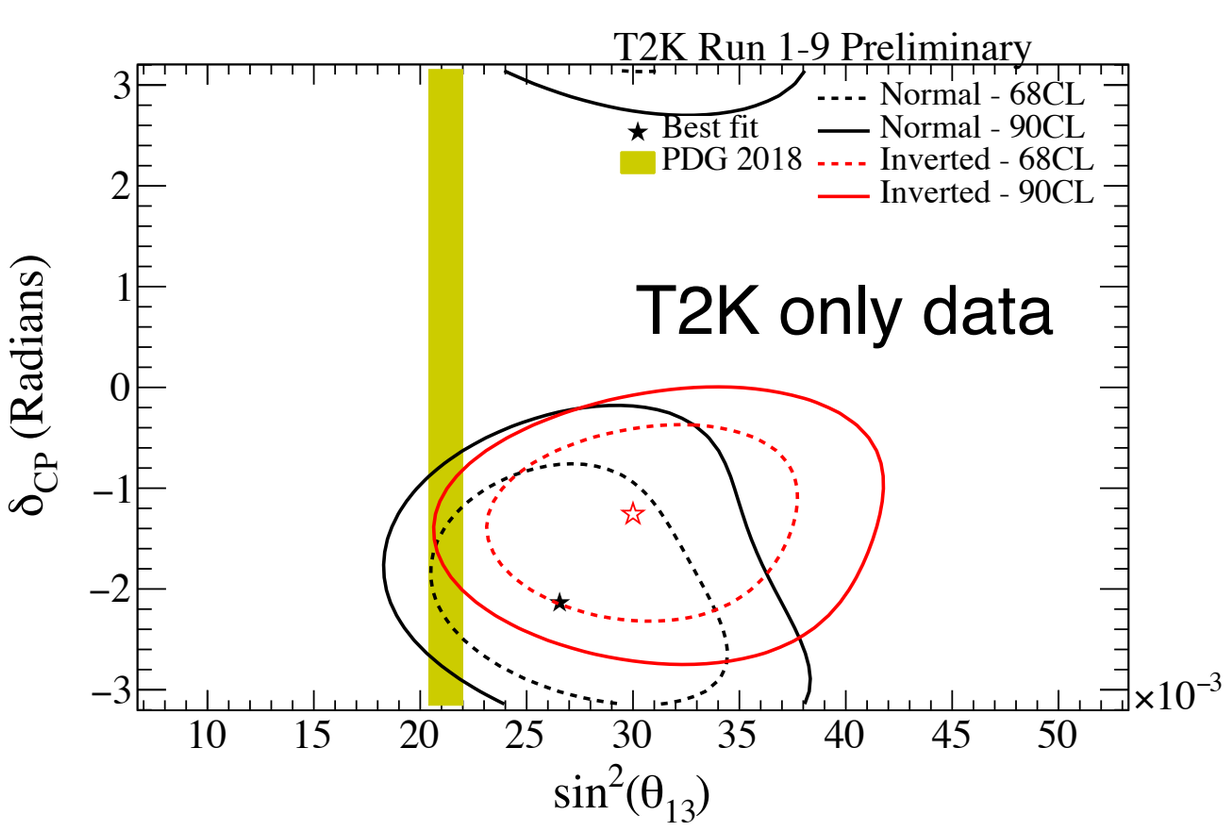


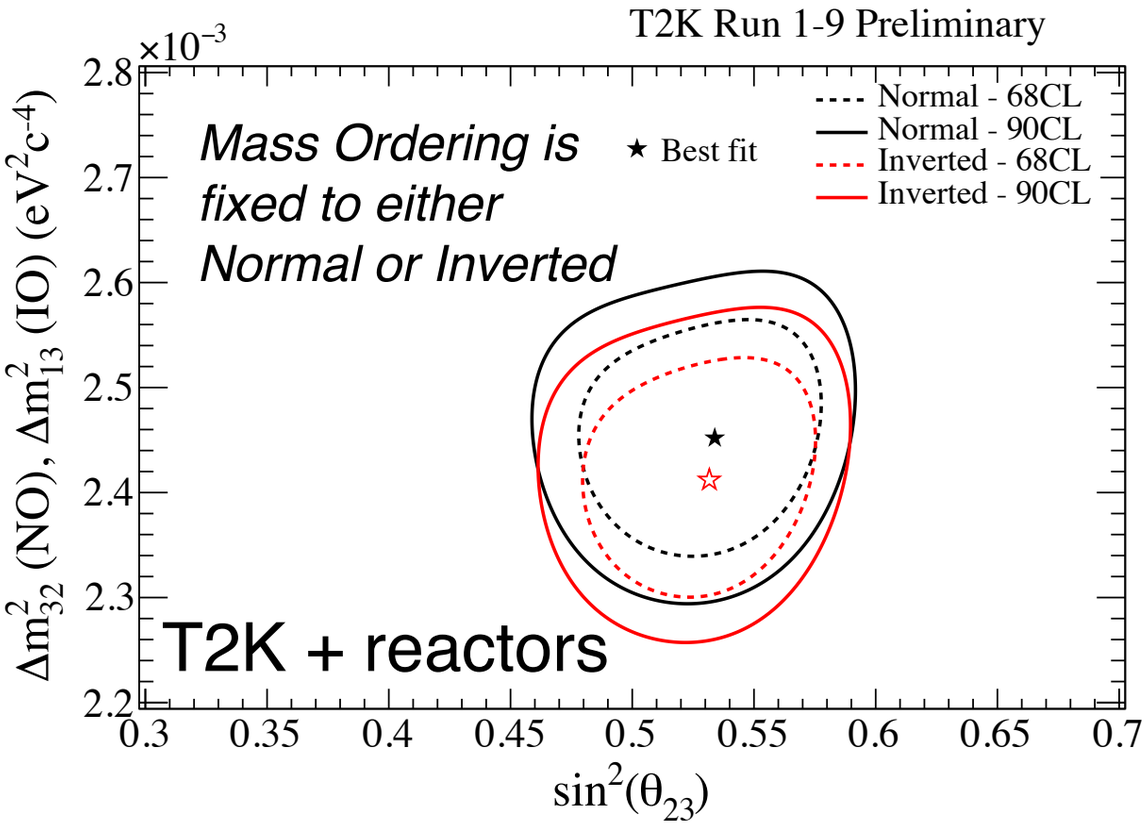
Systematic errors		
Sample	w/o	ND280
ν_e CCQE	14.5%	4.1%
$\overline{\nu}_e$ CCQE	12.2%	4.5%
ν_e CCQE	17.1%	8.8%
$\overline{\nu}_e$ CCQE	14.1%	7.0%
ν_e CC1π	21.6%	18.3%



NO $\overline{\nu}_e$ appearance excluded at 2σ

Oscillation Analysis results



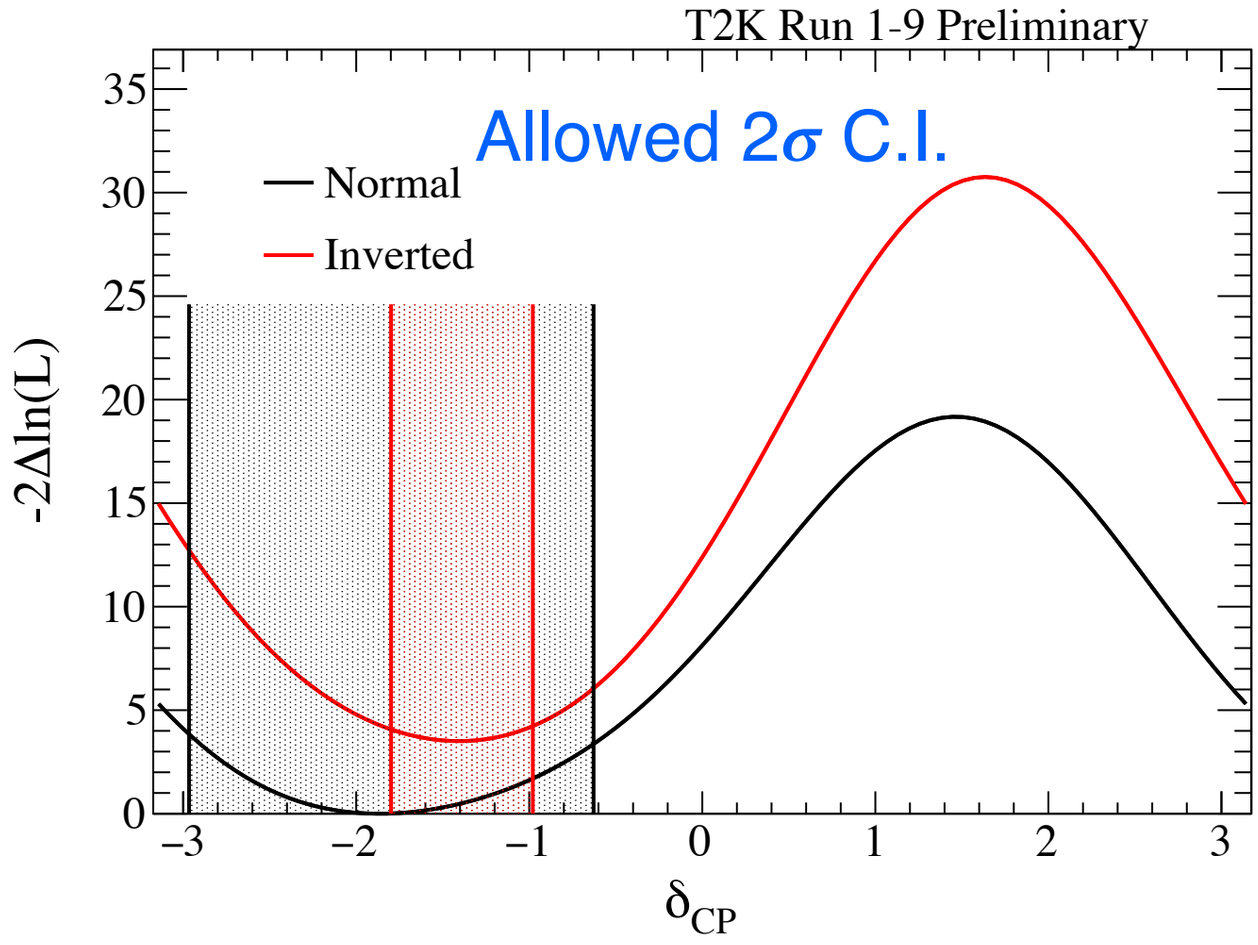


Best-fit	Normal Ordering	Inverted Ordering
$\sin^2\theta_{23}$	0.532	0.532
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.45	2.43

- Consistent with maximal disappearance
- Agreement with reactor measurements
- Preference for $\delta_{CP} \sim -\pi/2$

Confidence intervals of δ_{CP}

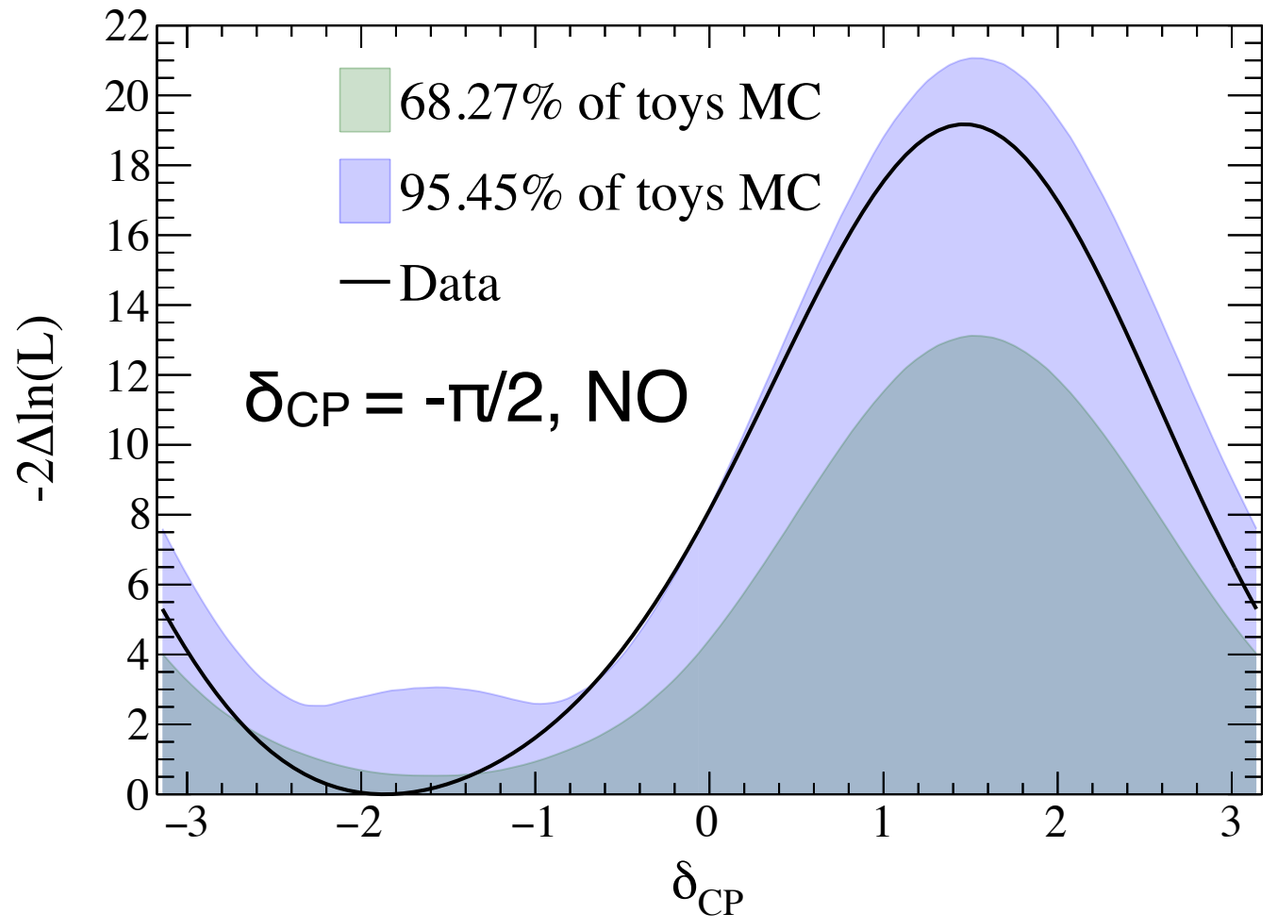
- Confidence intervals were computed with Feldman-Cousins method
- Integrate over θ_{13} using the PDF from reactors' measurement (PDG-2018)



- The best-fit is $\delta_{CP} = -1.89$ radians and Normal Ordering
- Both $\delta_{CP} = 0$ and π are excluded at 2σ CL
- Allowed 2σ CL region: - Normal Ordering: [–2.97,–0.63]
  - Inverted Ordering: [–1.80,–0.98]
- Preference for maximal CP violation and Normal Ordering

Comparison between sensitivity and data results

- Toy MC study to compare the experiment sensitivity to the observed data set

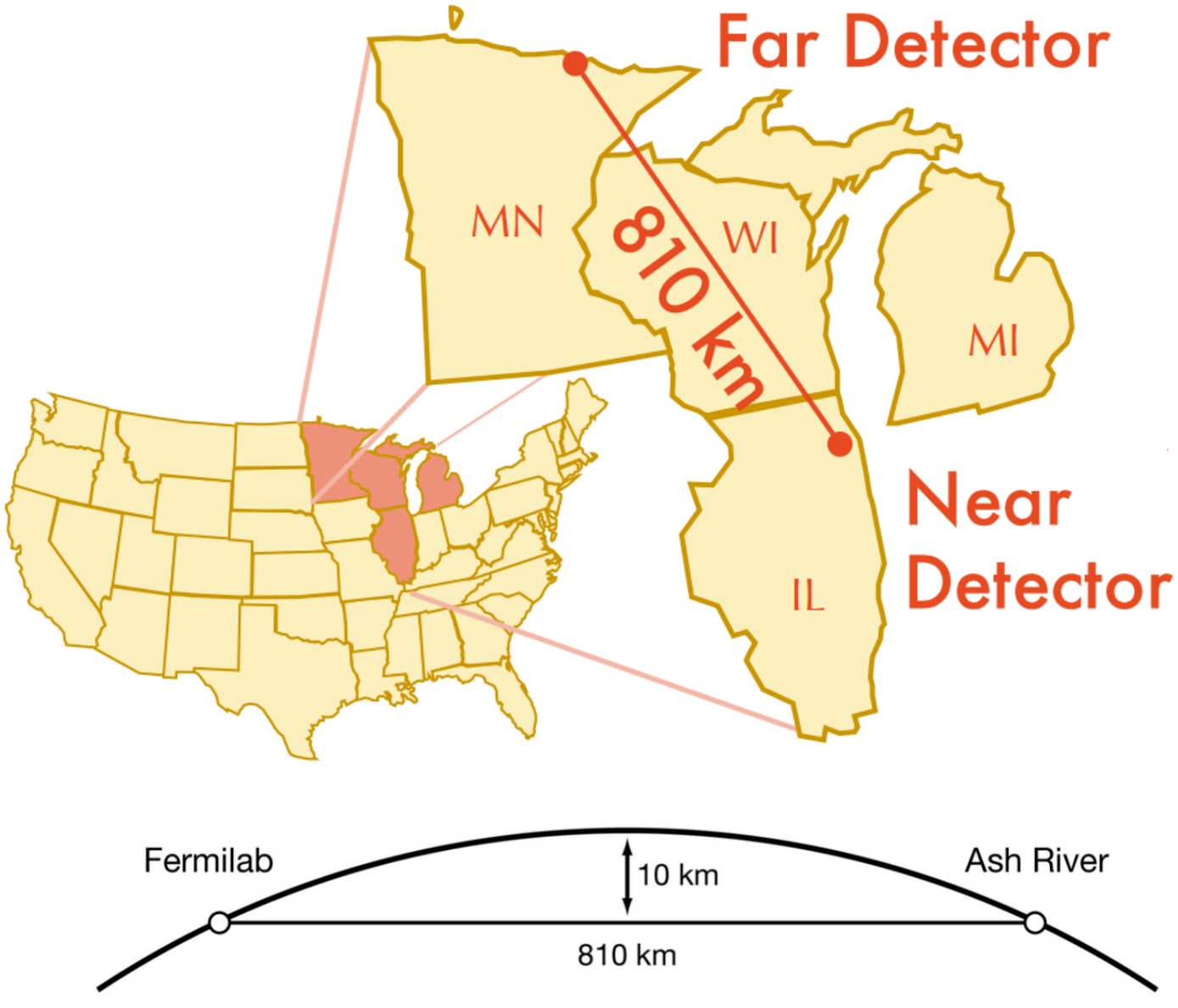


- Less than ~5% of toy MC experiments show stronger exclusion than T2K data
- If Nature is $\delta_{CP} = -\pi/2$ and Normal Ordering:
  - The # of MC experiments that exclude δ_{CP}=0,π (both) at 2σ is 24%

The NOvA experiment

Long-baseline neutrino oscillation experiment based in US

- ✦ Measurement of Mass Hierarchy with significance better than 3σ
- ✦ Hint of CP violation in the leptonic sector



- Intense muon (anti)neutrino beam from NuMI in Fermilab
- Measure muon (anti)neutrino disappearance and electron (anti)neutrino appearance

The NOvA experiment

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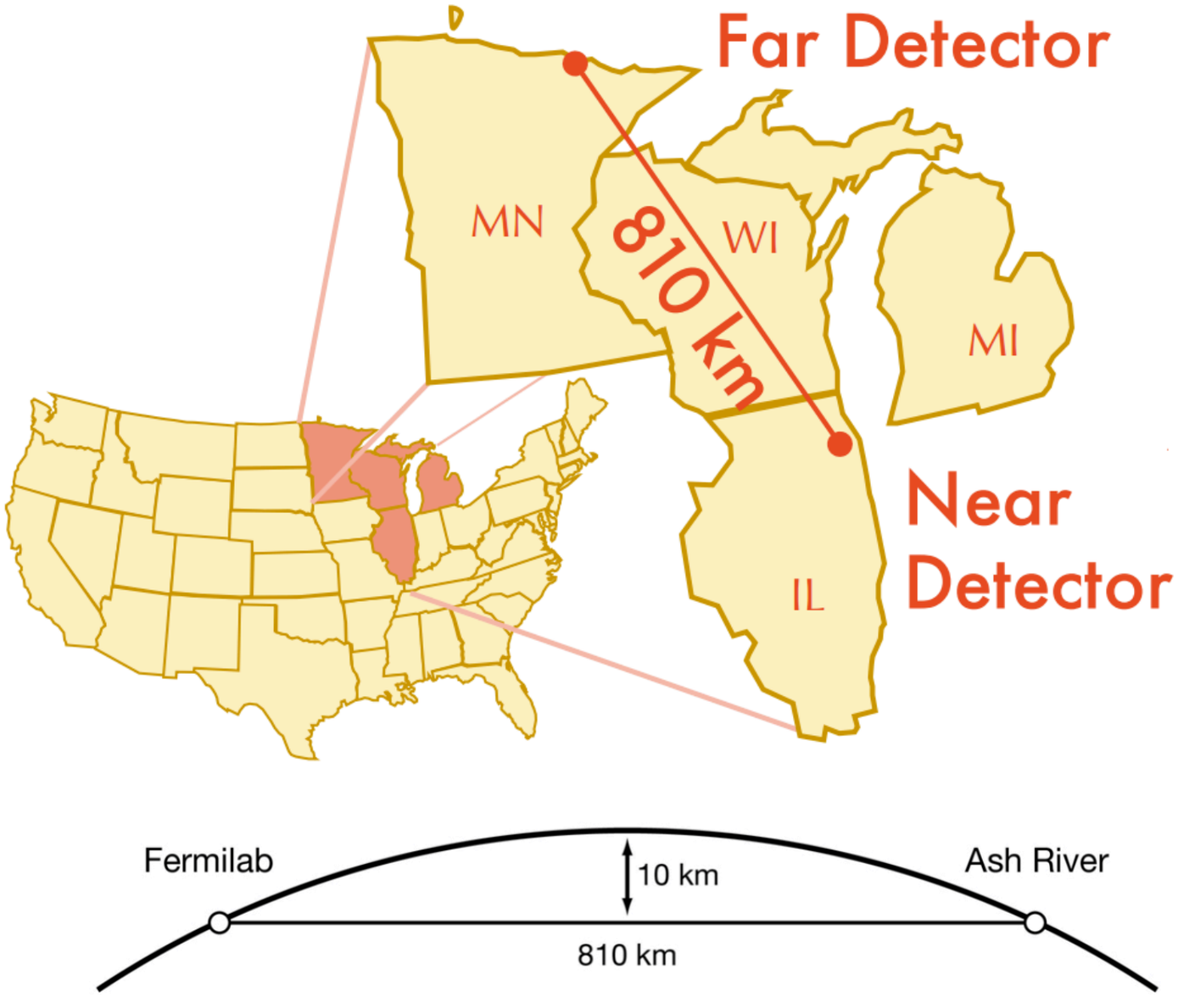

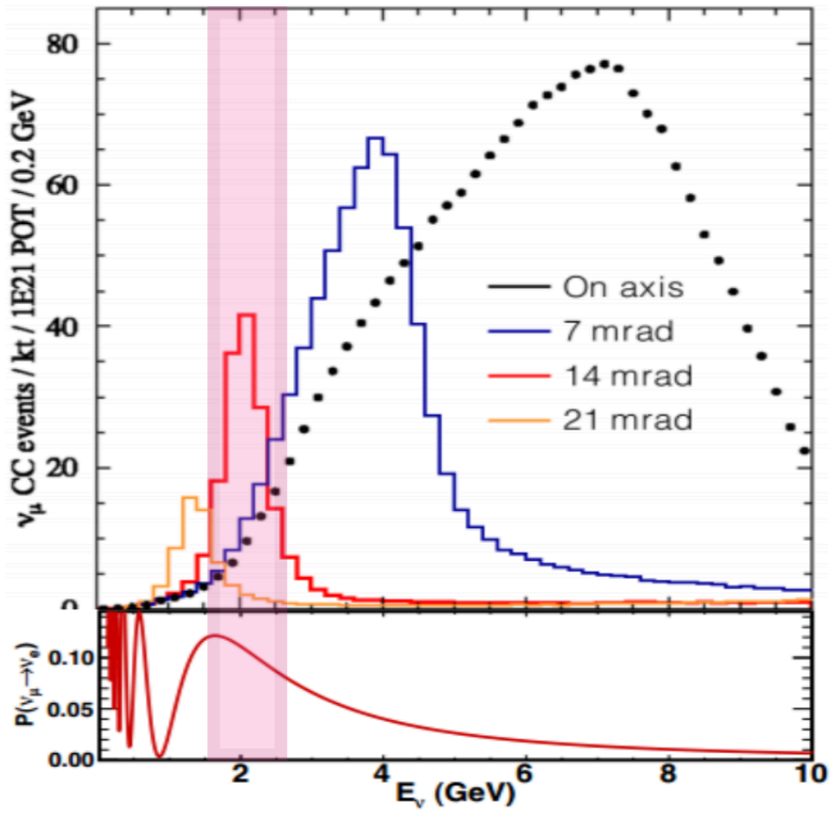

- Off-Axis angle = 14 mrad
- 120 GeV proton beam
- Tuned with NA49 and MIPP experimental data

The NOvA experiment

Long-baseline neutrino oscillation experiment based in US

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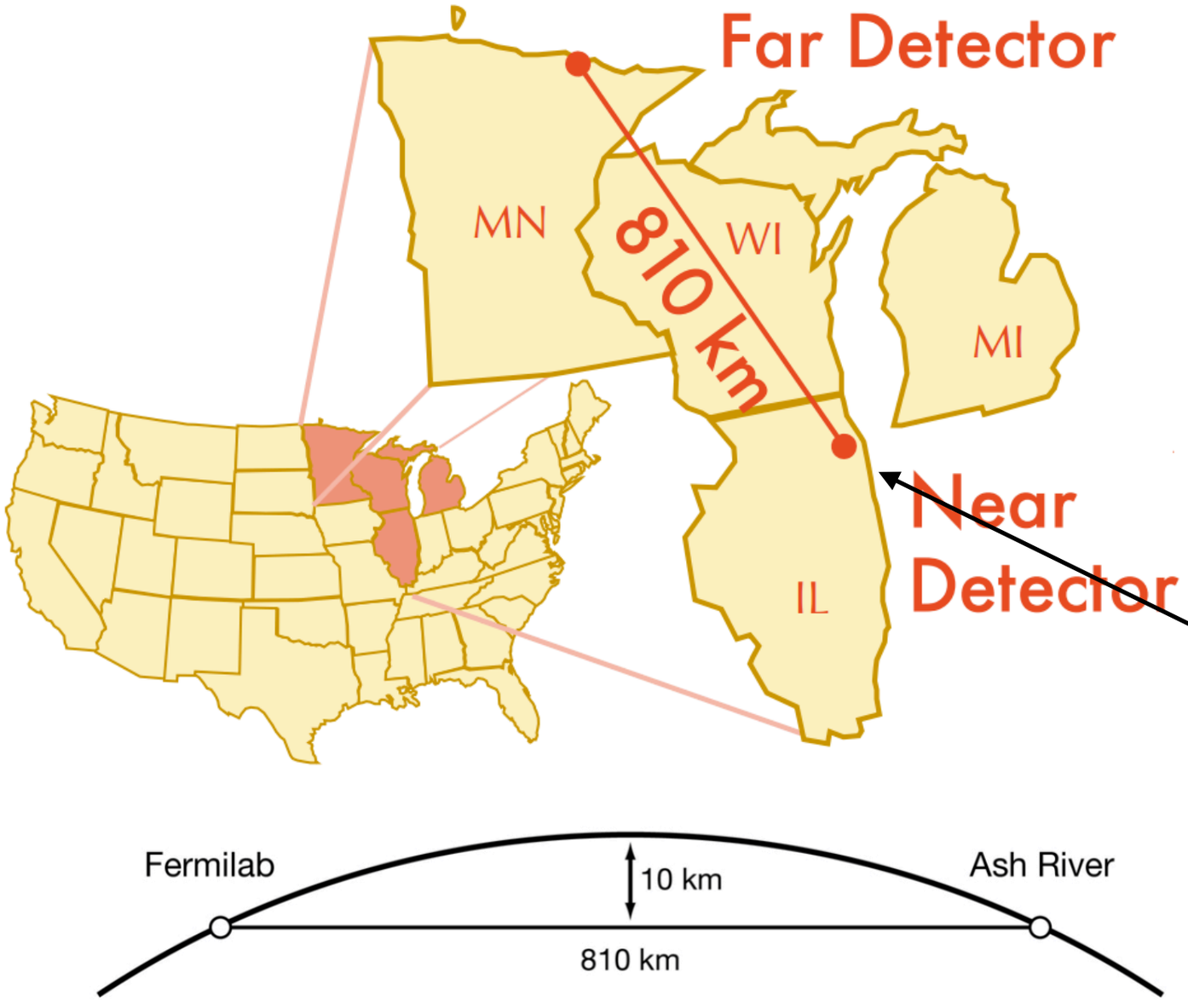
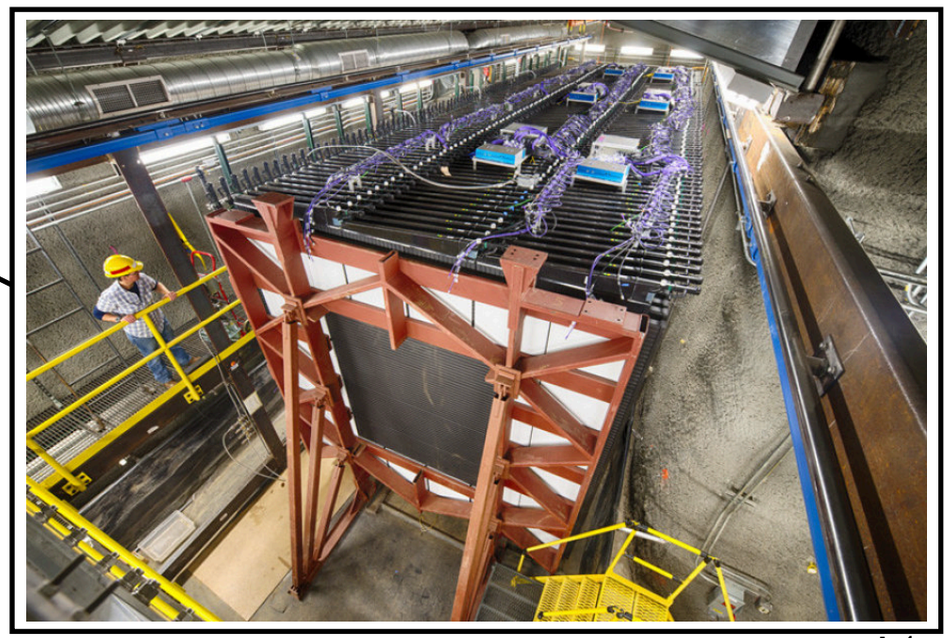


- Near Detector in Fermilab
  - ✦ 330 ton mass
  - ✦ 1 km from source
  - ✦ 300 ft underground



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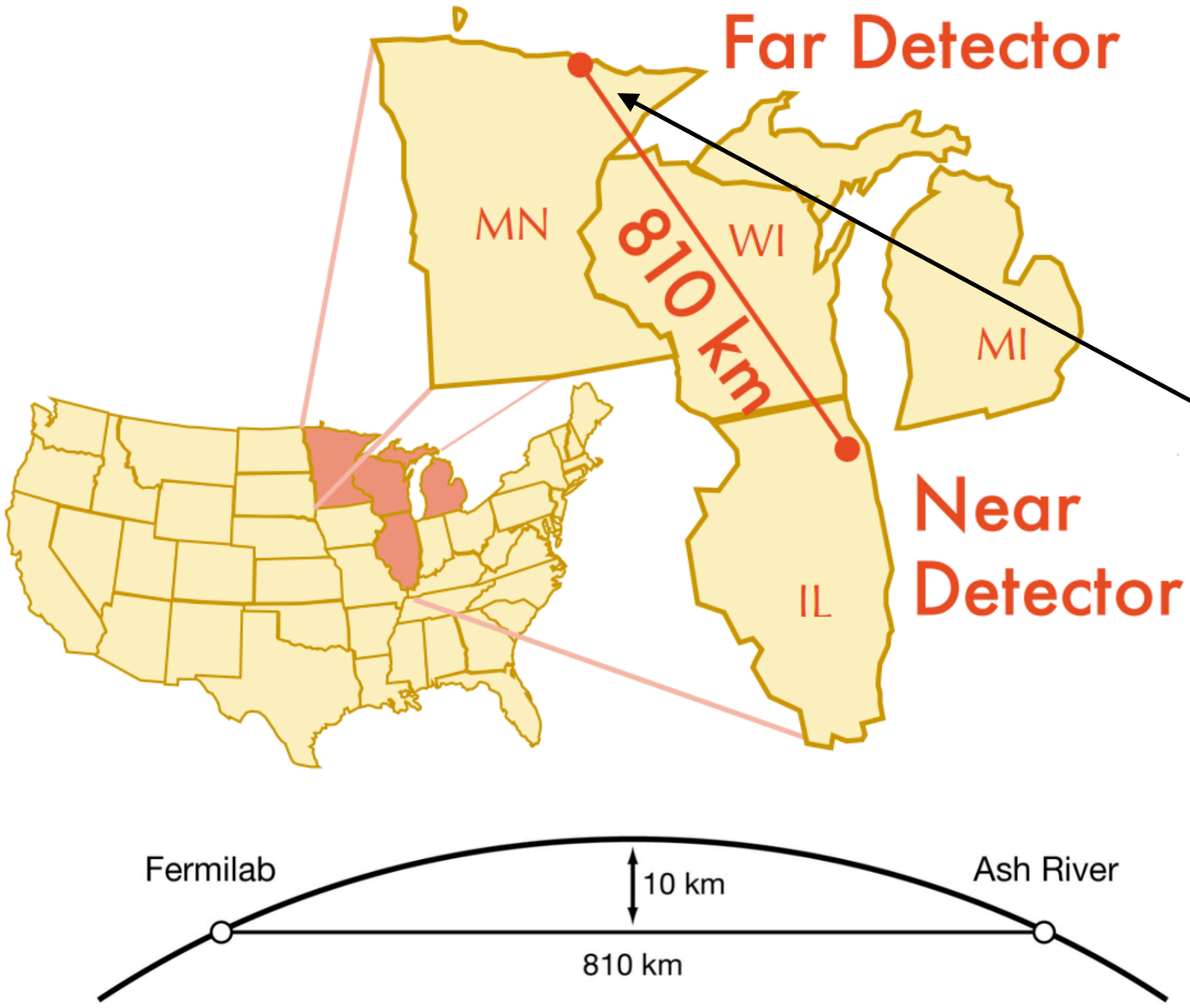
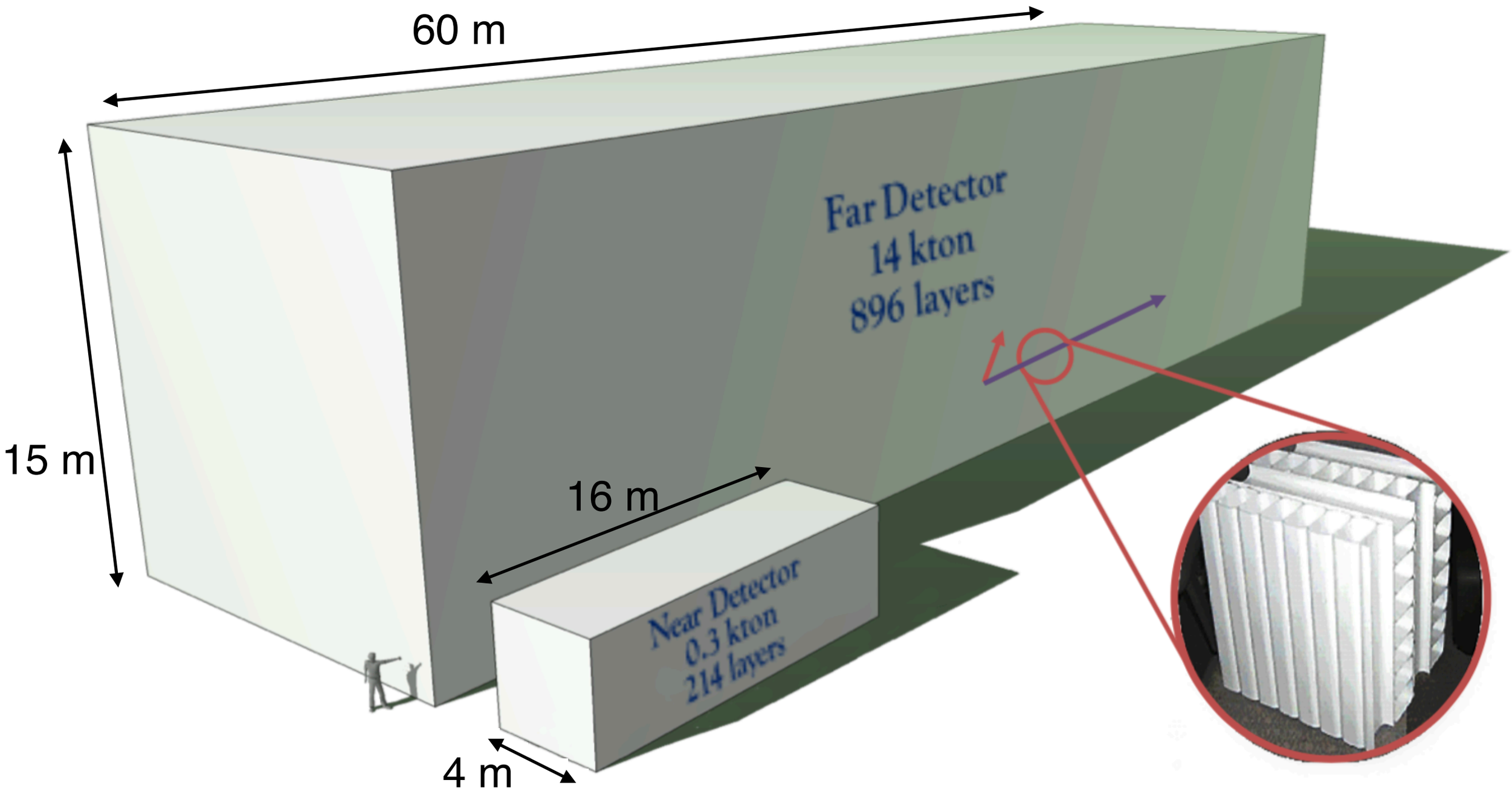


- Far Detector in Ash River
  - ✦ 14 kton mass
  - ✦ 810 km baseline
  - ✦ On surface

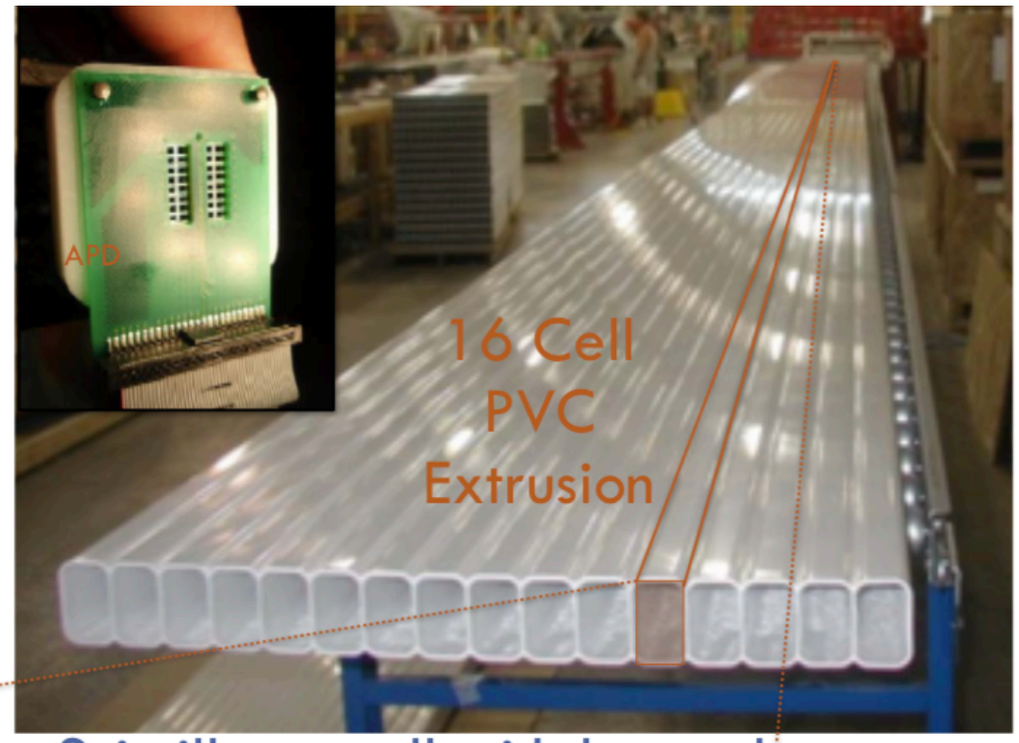
The NOvA Near and Far Detectors



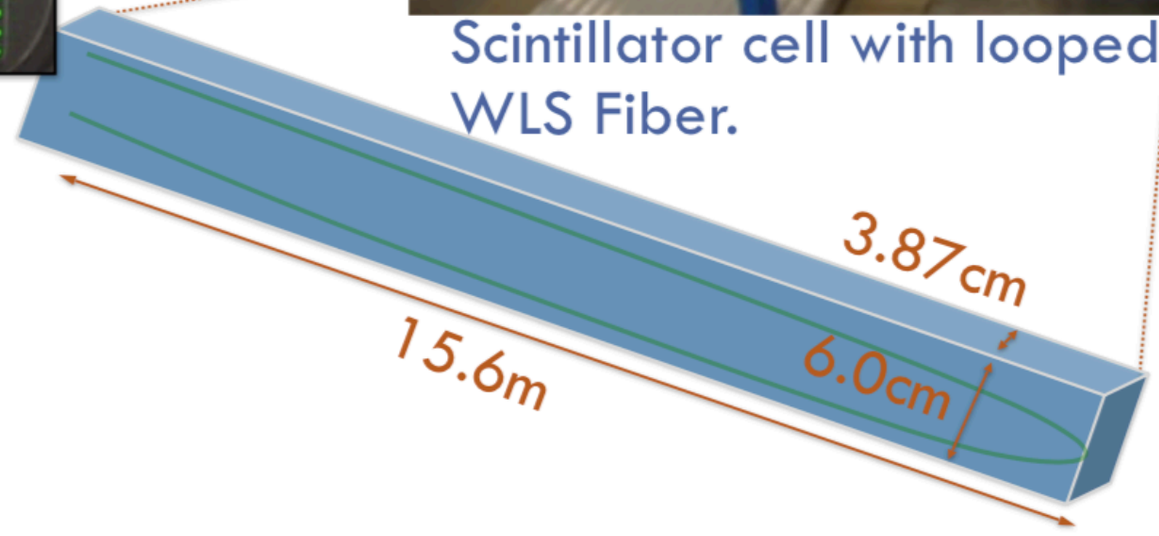
- Same detector technology at Near and Far detectors

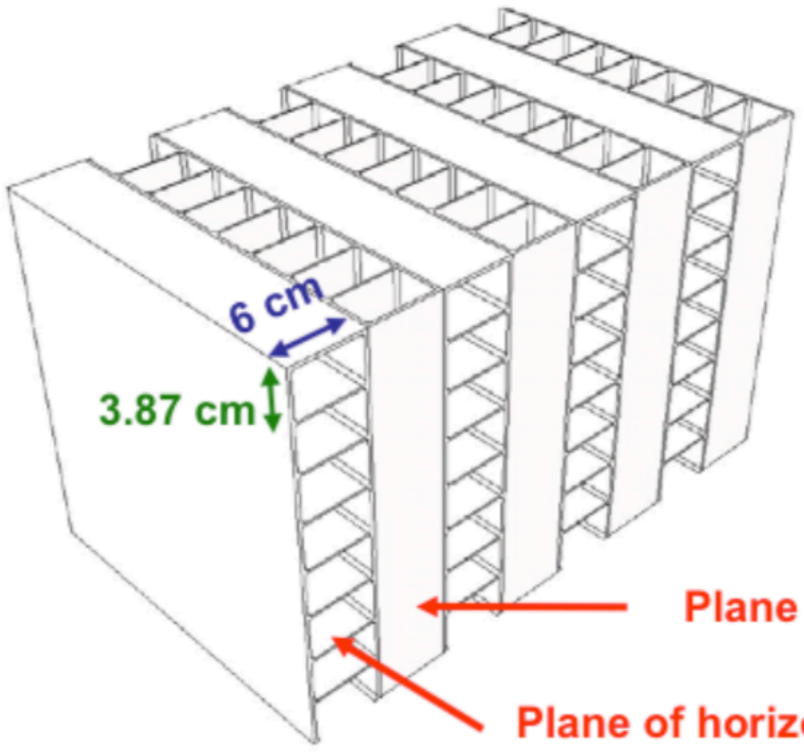
The NOvA Near and Far Detectors

- PVC extrusion + Liquid Scintillator (minerail oil + 5% pseudocumene)
- Read out via wavelength-shifting fiber to Avalanche PhotoDiode (APD)
- ~344k channels at Far Detector



Scintillator cell with looped WLS Fiber.



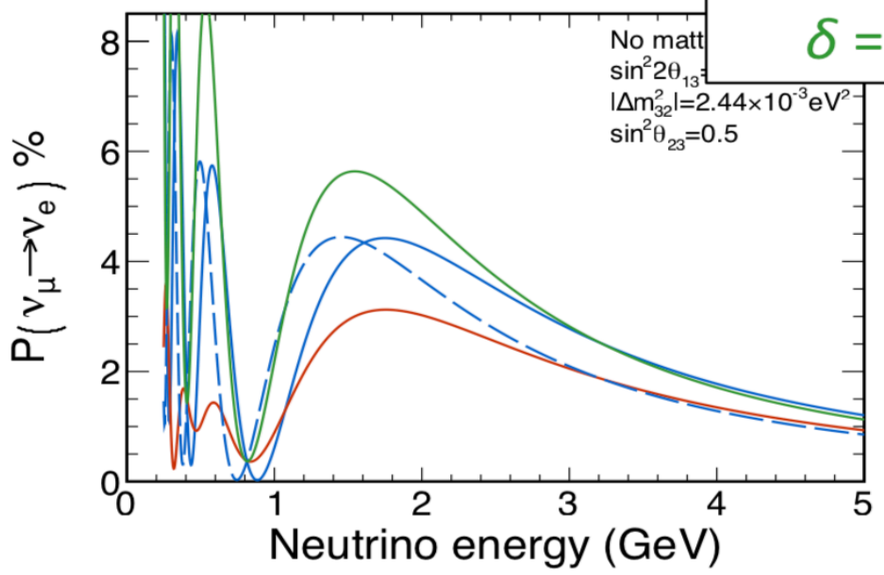


Effect of CP violation and Mass Hierarchy

CP conserved
$\delta = \pi/2$
$\delta = 3\pi/2$

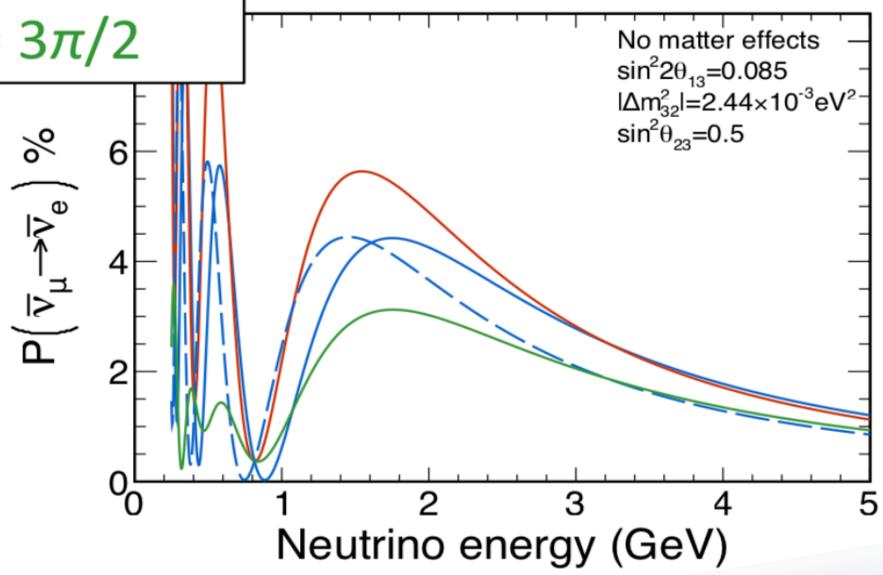
Neutrino

NOvA: L=810 km



Antineutrino

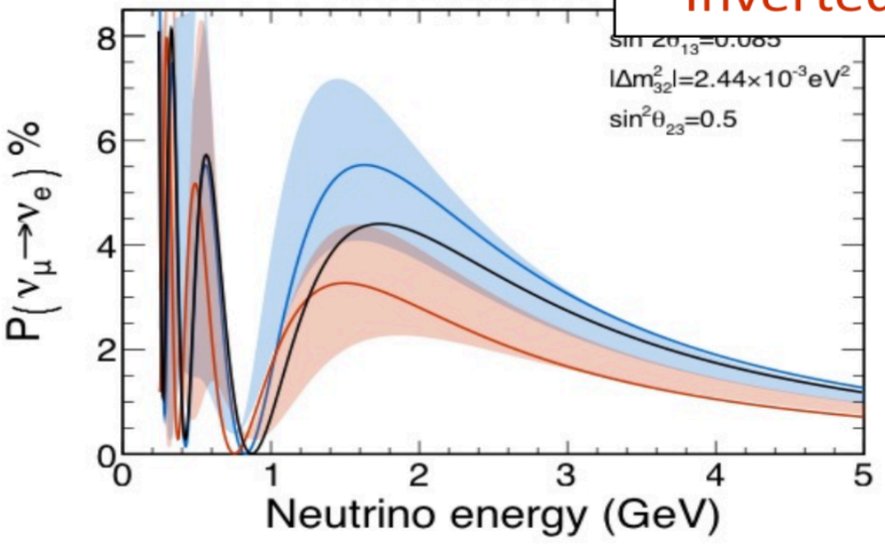
NOvA: L=810 km



Normal Hierarchy
Vacuum
Inverted Hierarchy

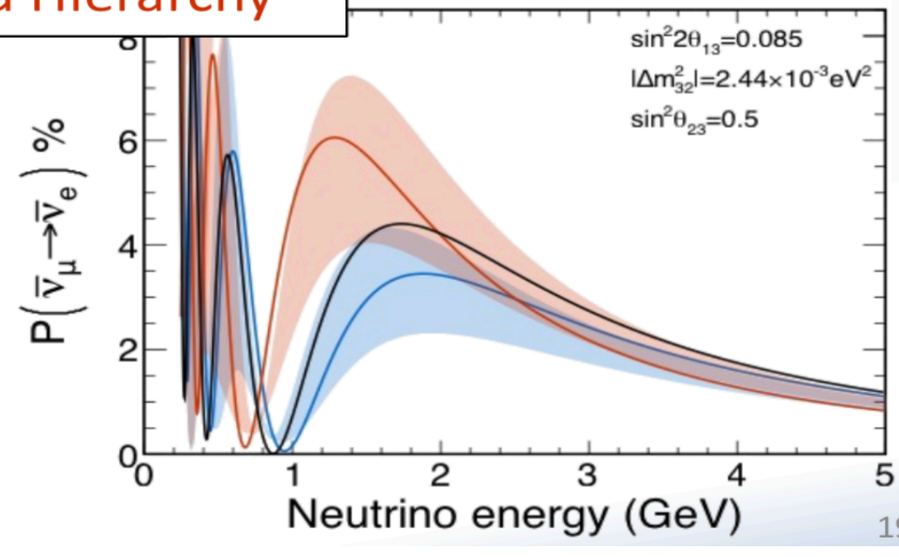
Neutrino

NOvA: L=810 km



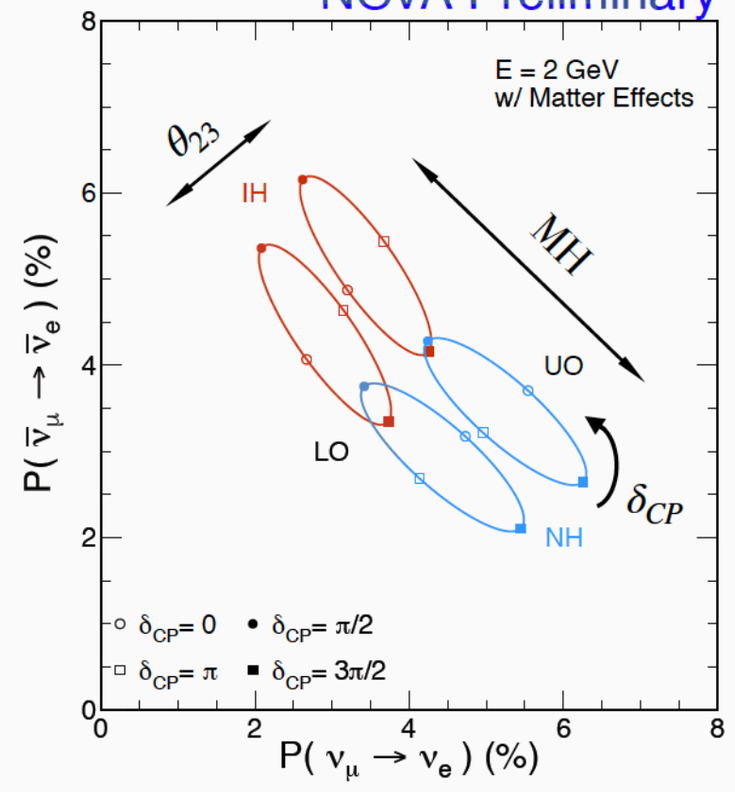
Antineutrino

NOvA: L=810 km



Appearance

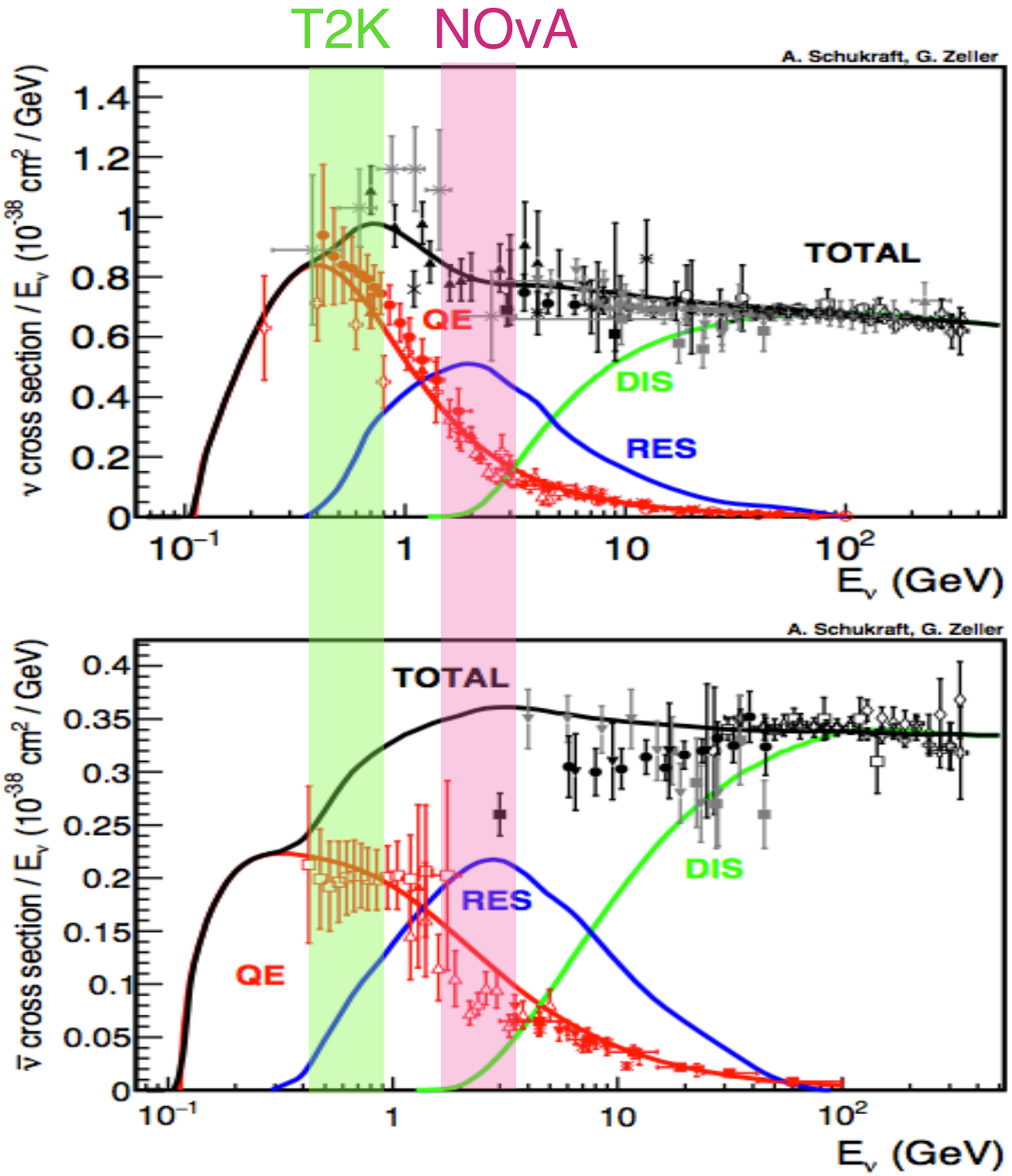
NOvA Preliminary

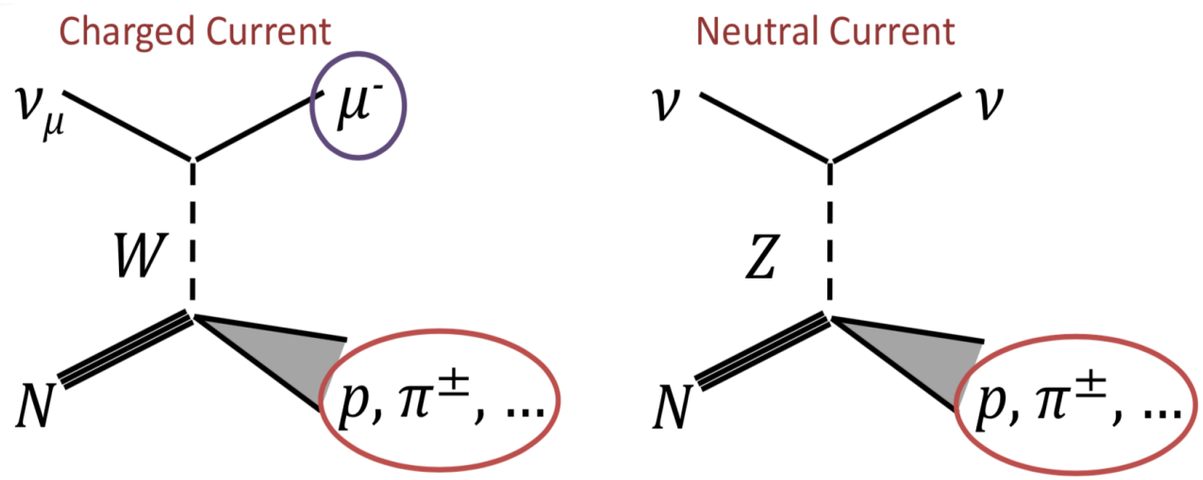


Matter effects enhanced thanks to the longer baseline

- About 30% effect both in δ_{CP} and Mass Hierarchy

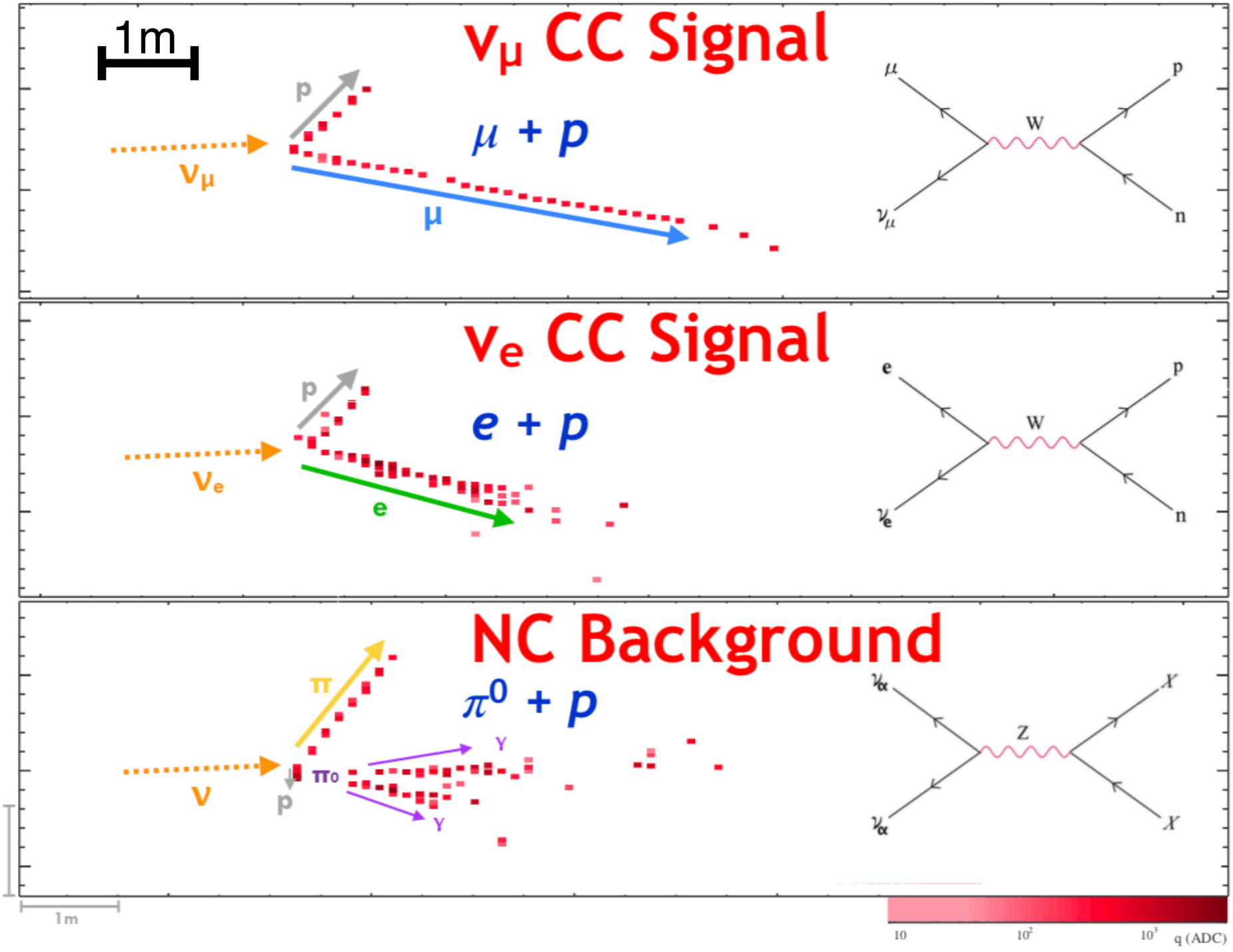
(Anti)Neutrino interactions at NOvA





- Higher energy compared to T2K
- NC background: EM shower from $\pi^0 \rightarrow \gamma\gamma$
- Nuclear effects and 2p-2h are important components

NOvA event topologies



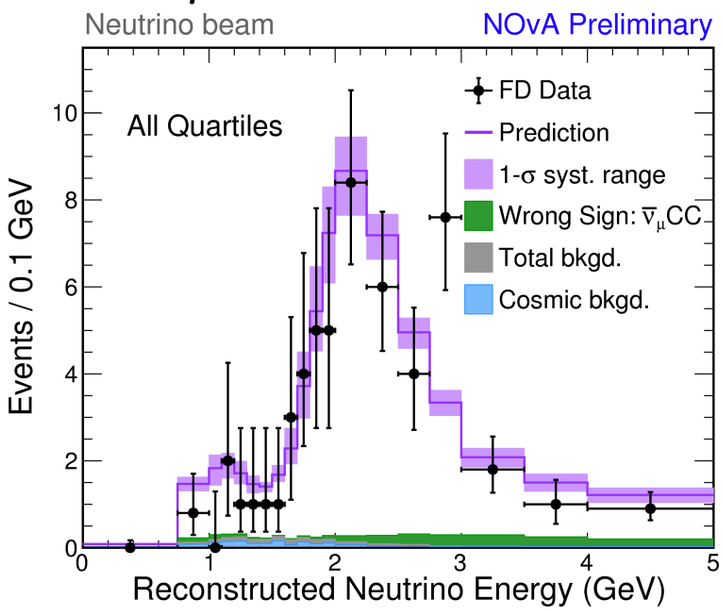
Convolutional Visual Network technique to identify the event topology

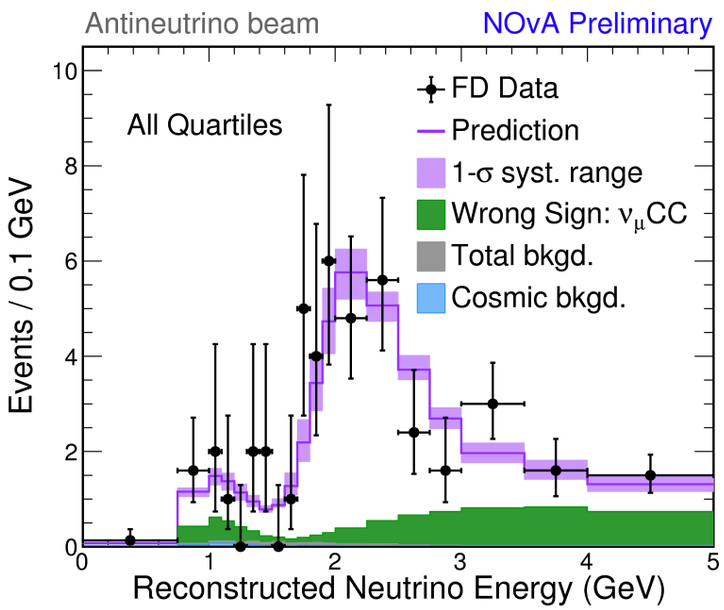
(Aurisano, et al., JINST 11 (2016) no.09, P09001)

Joint Neutrino and Anti-Neutrino analysis

- Data collected: 2.12 x 10^{21} POT (ν - 0.89 x 10^{21} POT, $\overline{\nu}$ - 1.23 x 10^{21} POT)

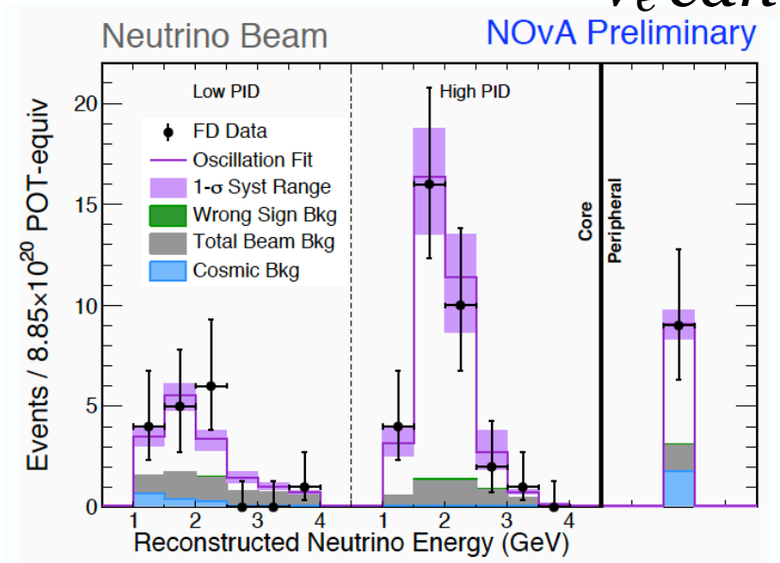
ν_μ candidates

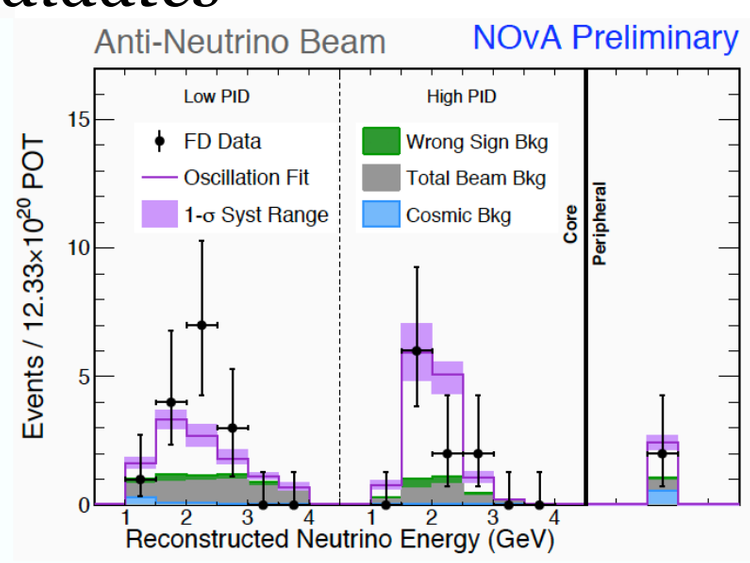




- Observe 113 ν_μ (expect 730) and 102 $\overline{\nu}_\mu$ (expect 476)

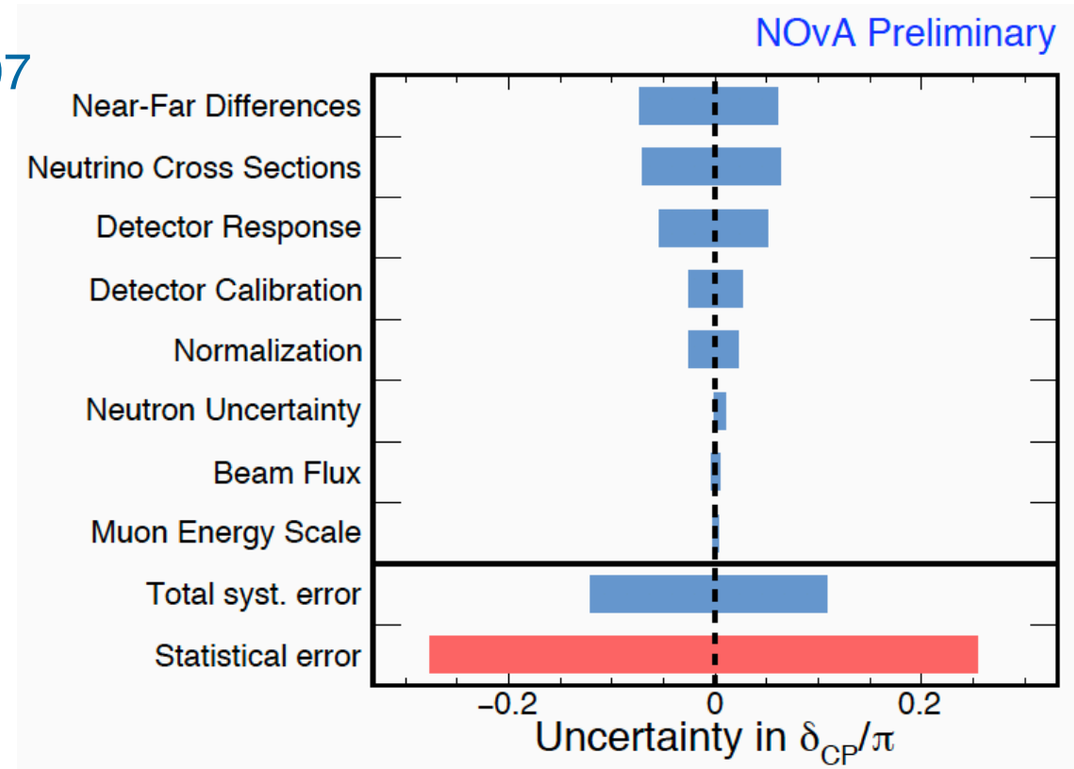
ν_e candidates





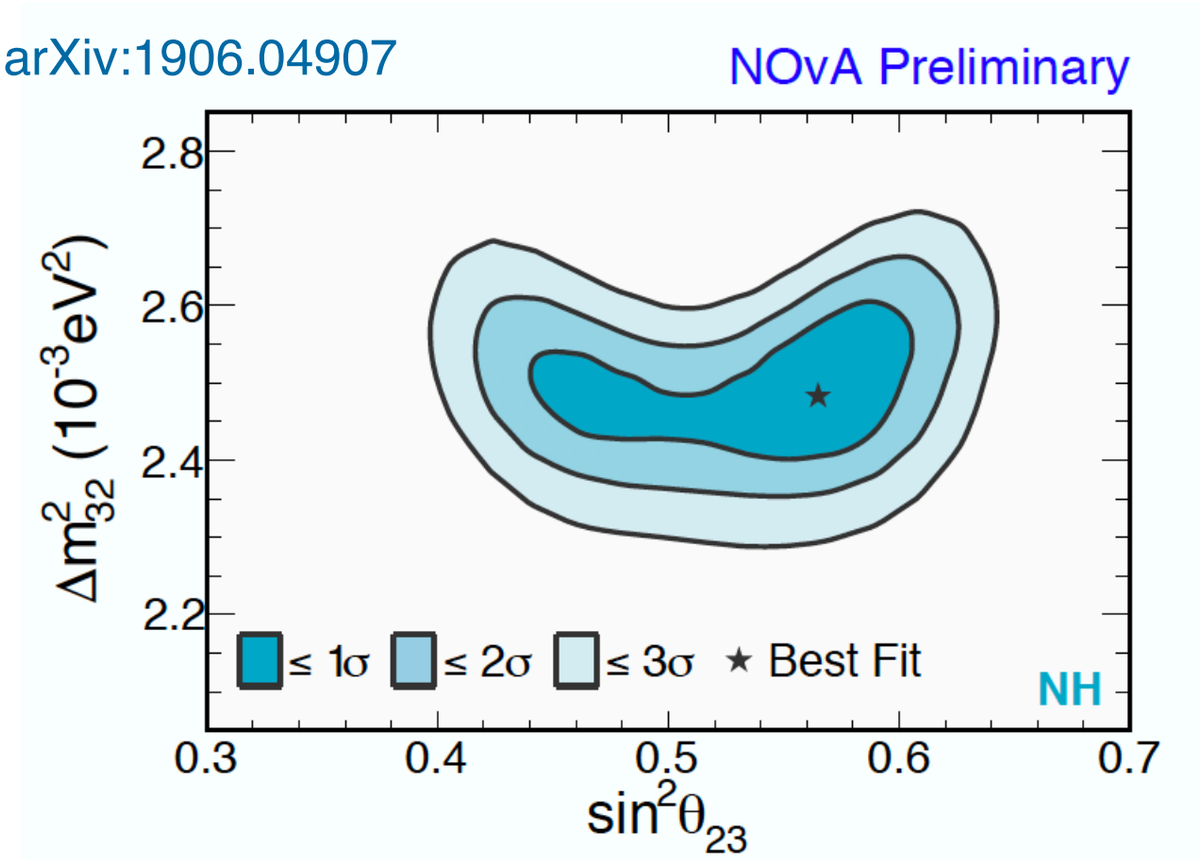
- Observed 58 ν_e (expect 15) and 27 $\overline{\nu}_e$ (expect 10.3)
- Wrong-sign background is ~ 3% in beam and 11% $\overline{\nu}$

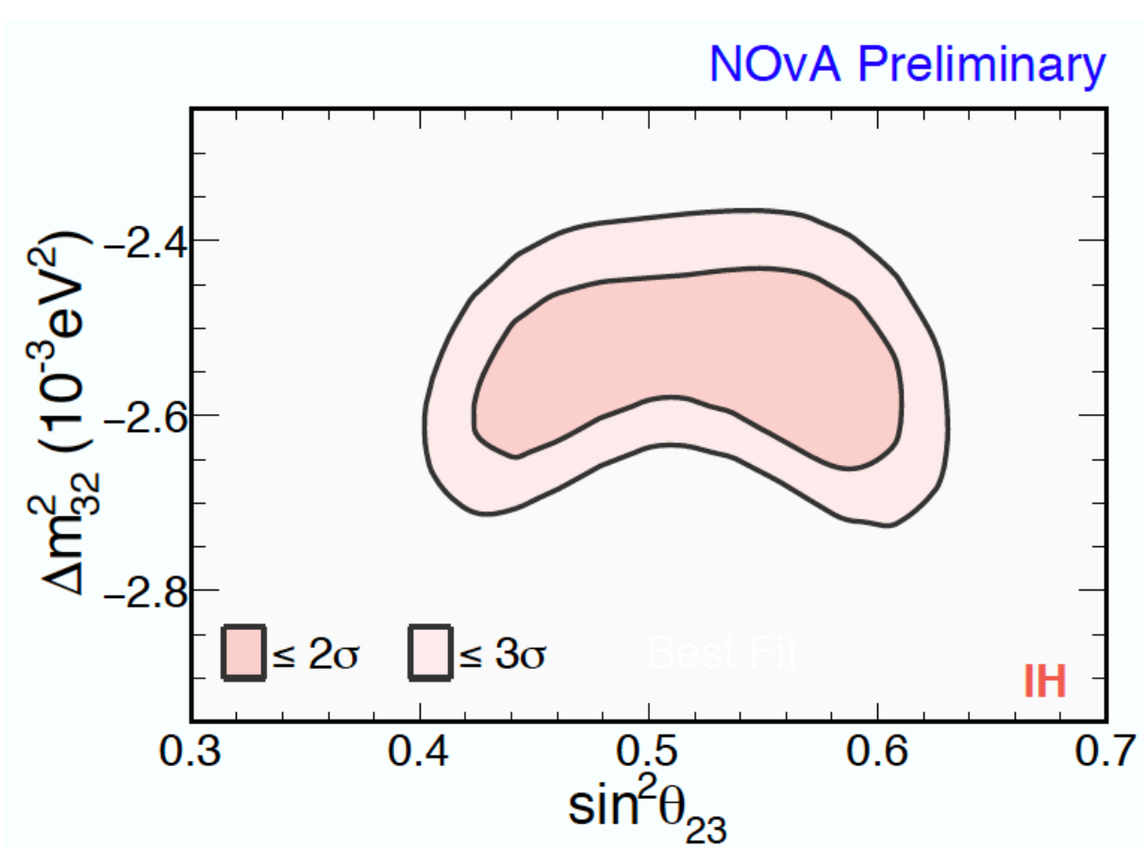
arXiv:1906.04907



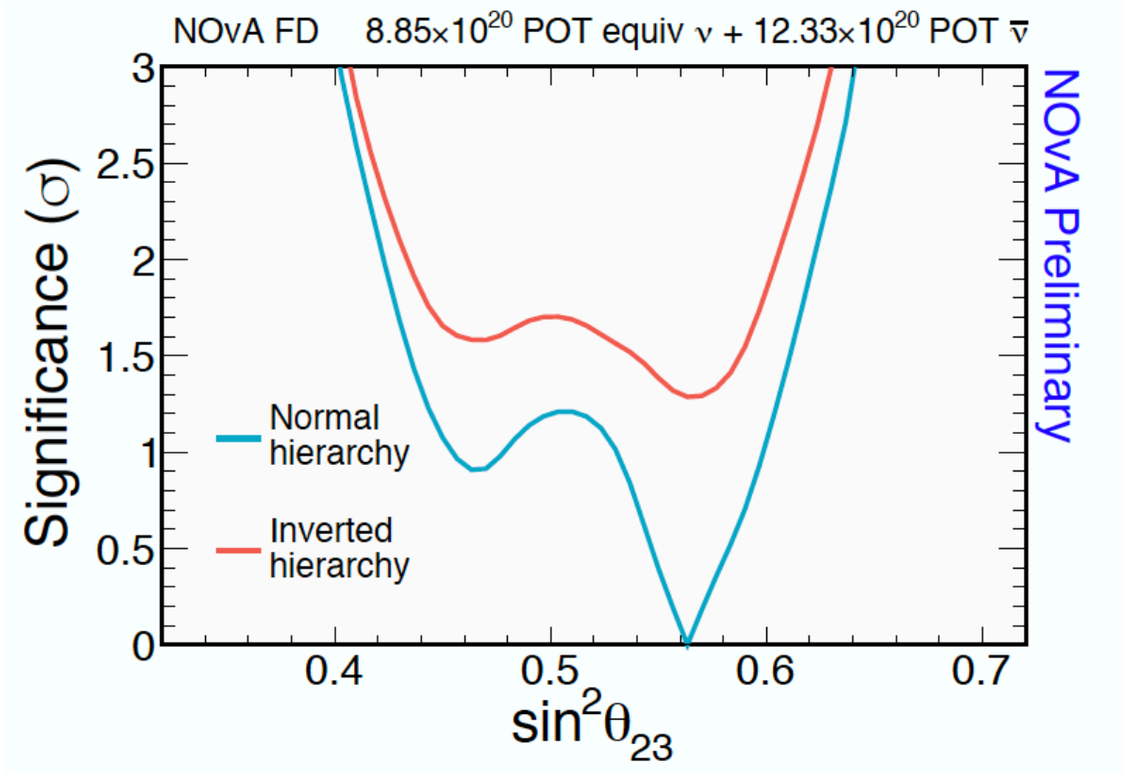
Confidence region $\sin^2\Theta_{23}$ and Δm^2_{32}

arXiv:1906.04907





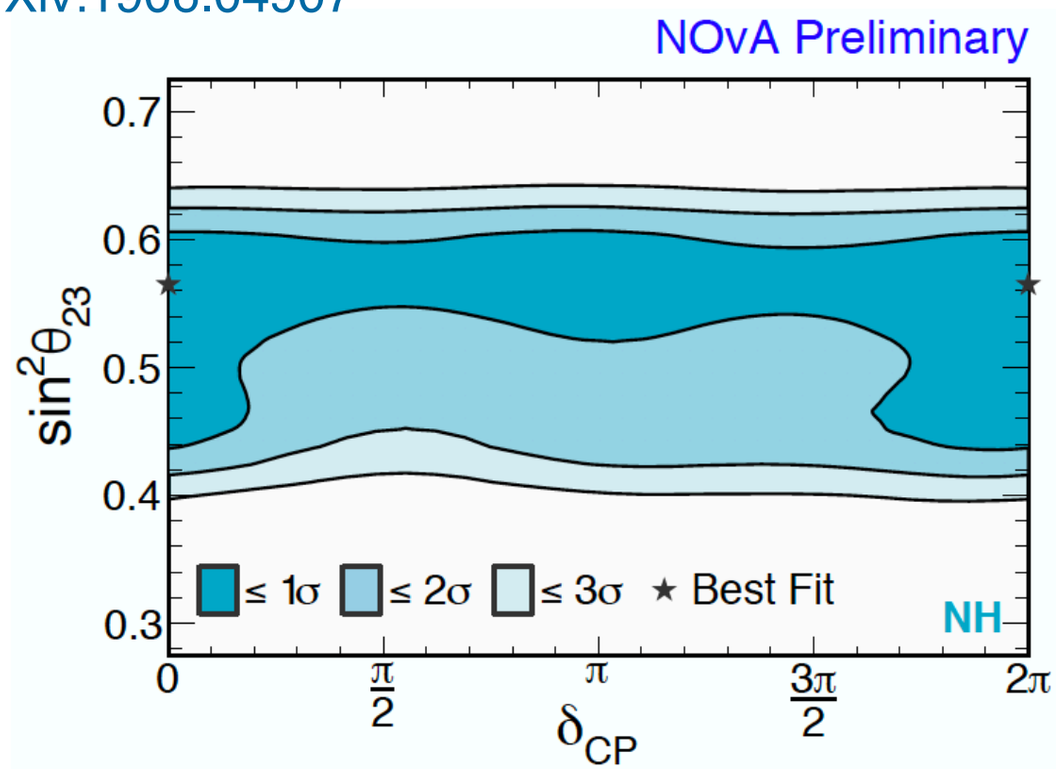
Best-fit	Normal Ordering
$\sin^2\theta_{23}$	0.56
$\lvert\Delta m^2_{32}\rvert$ ($\times 10^{-3}$ eV^2)	2.48

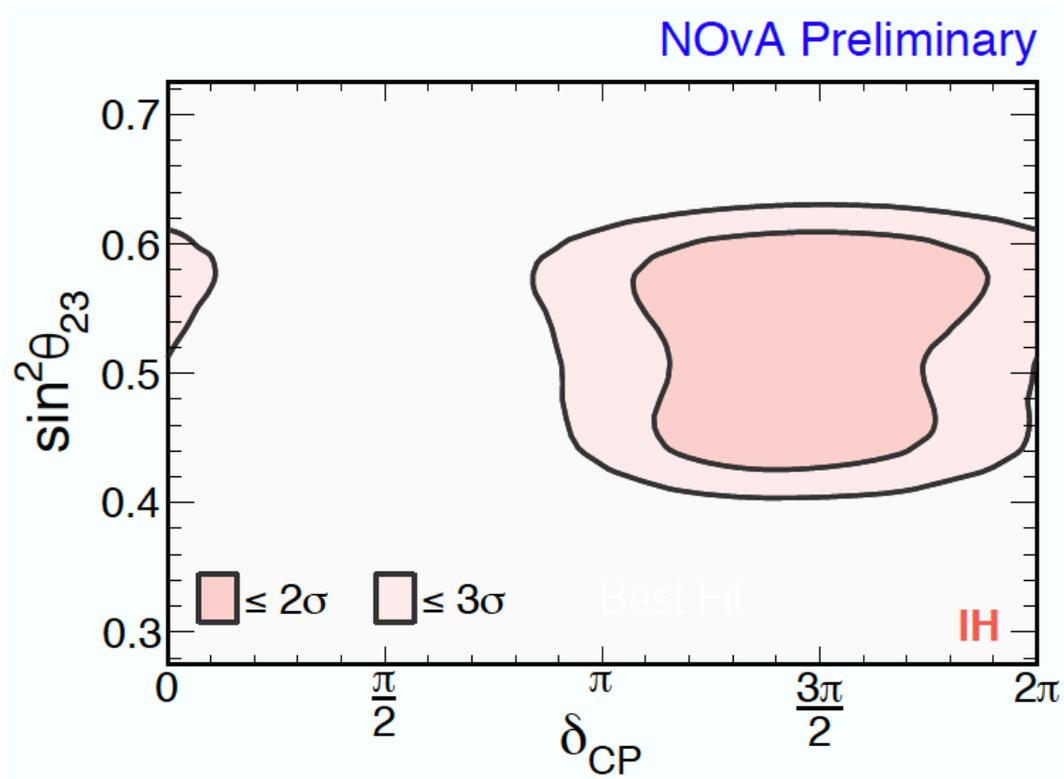


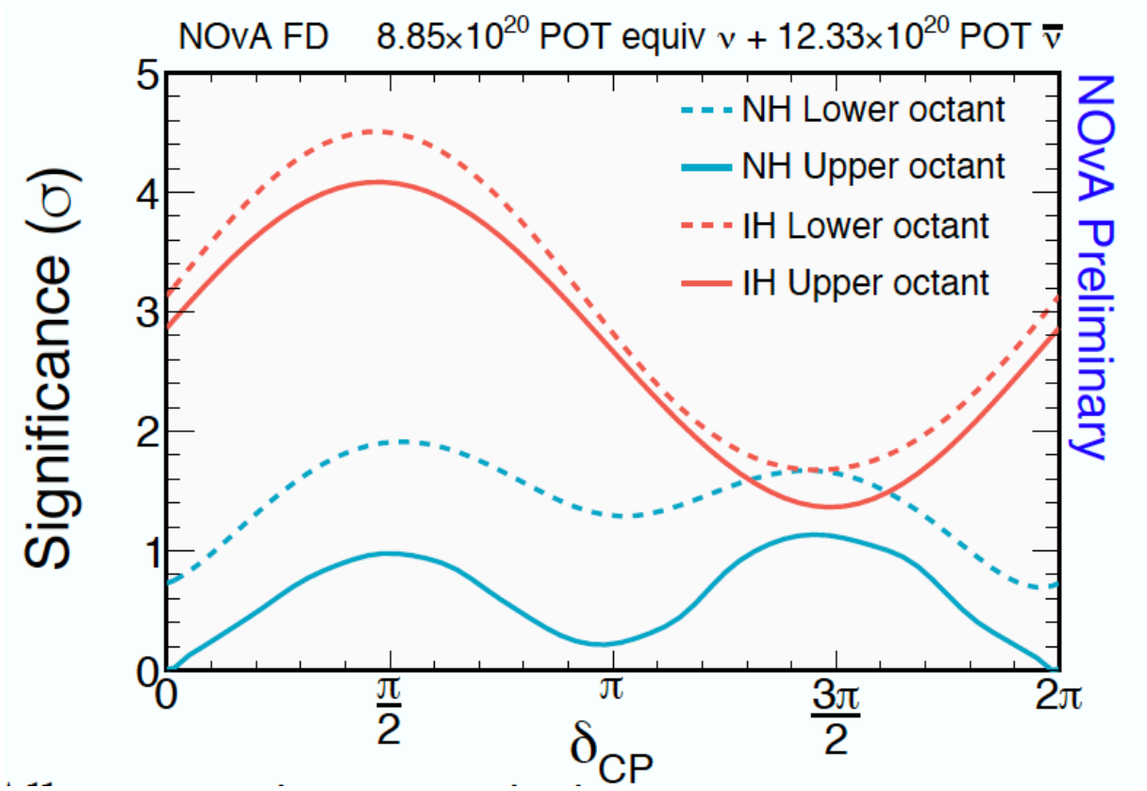
$\sin^2\theta_{23} < 0.5$ (lower octant) is disfavored at 1.5 σ

Confidence interval of δ_{CP}

arXiv:1906.04907

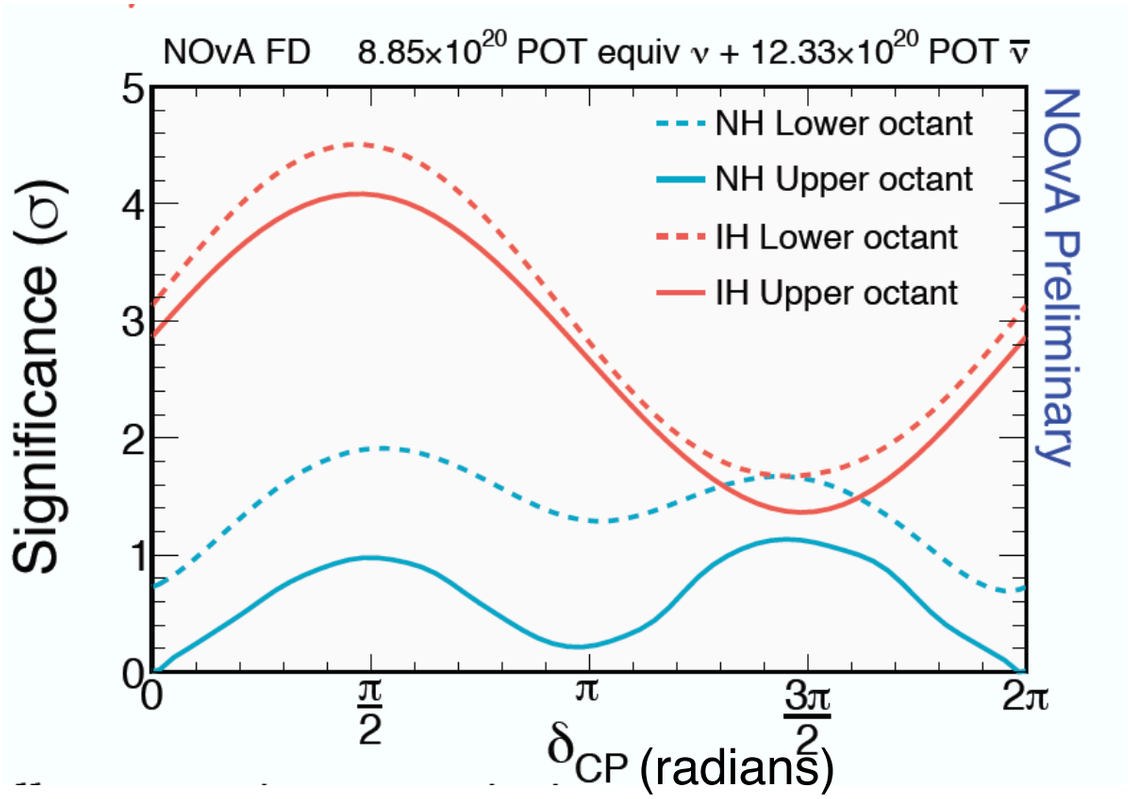


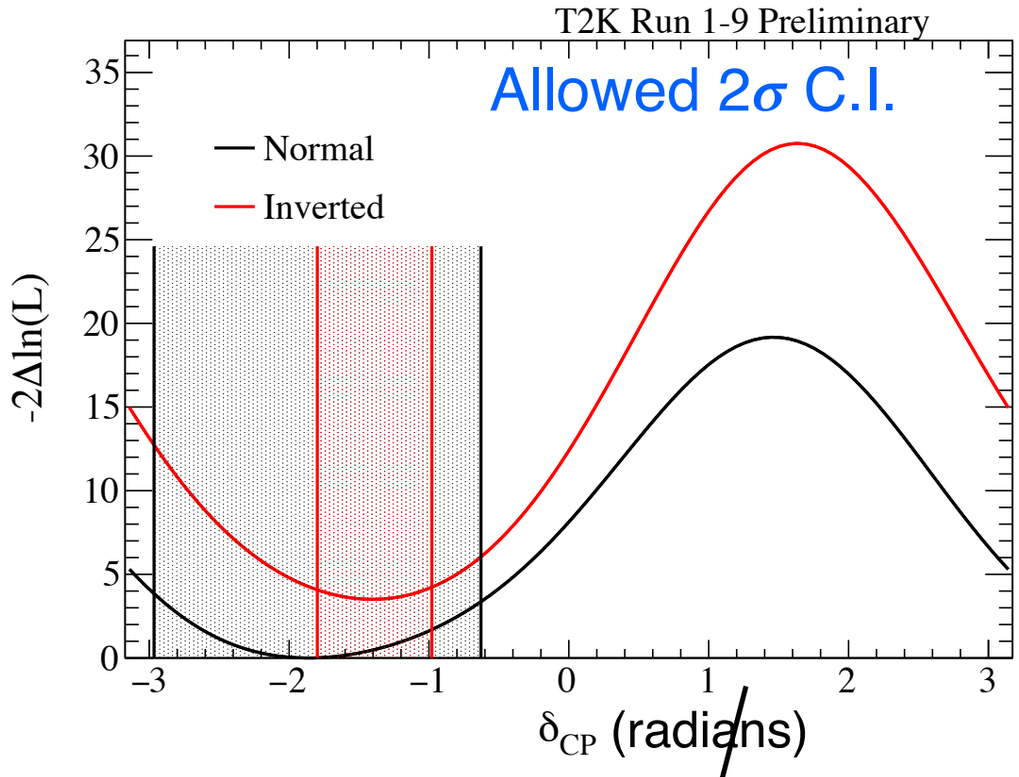


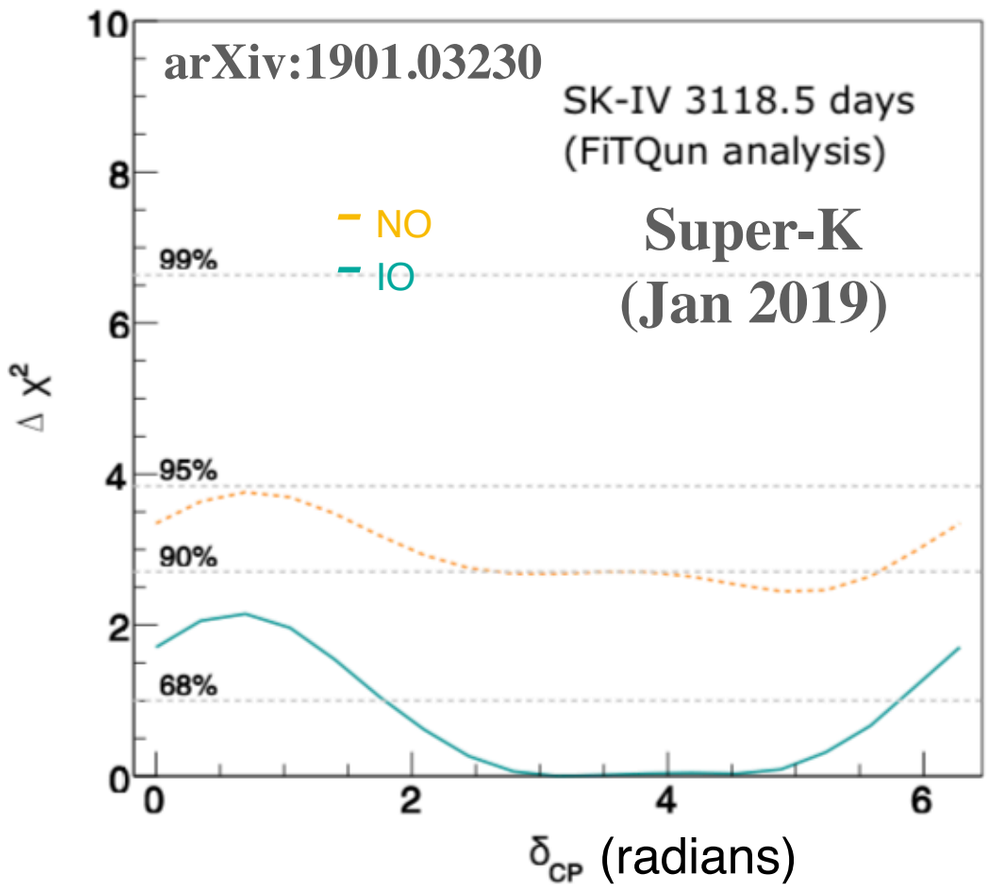


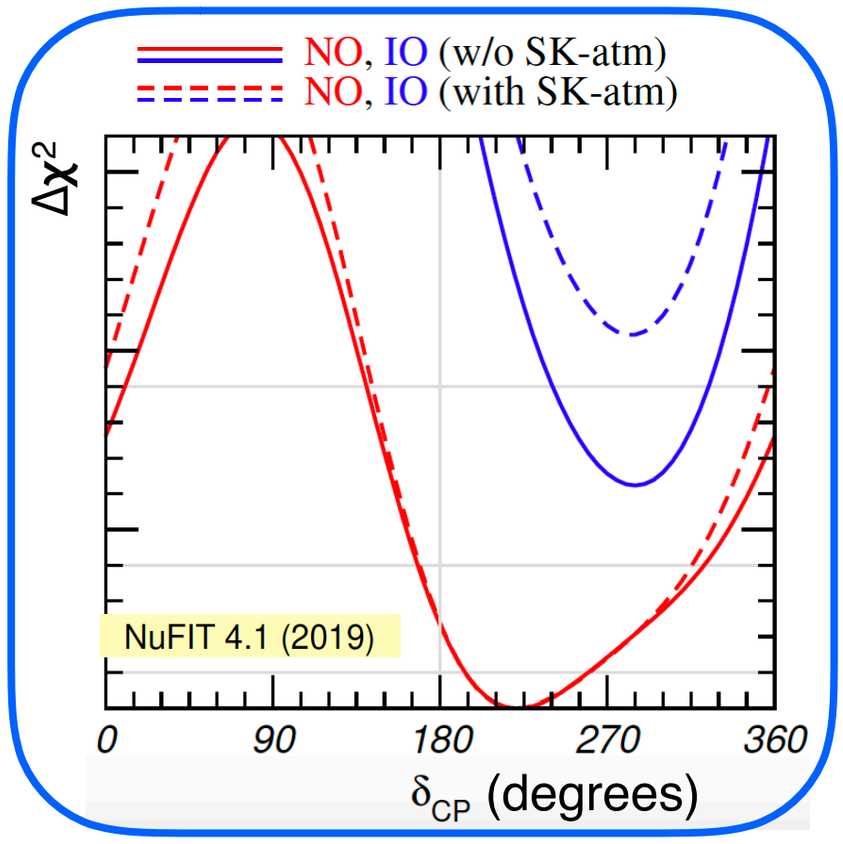
- Preference for Normal Hierarchy, Inverted Hierarchy excluded 1.9σ
- All values for Normal Hierarchy are allowed at 1.1σ (NH, upper octant)
- Region around $\delta_{CP} \sim +\pi/2$ and Inverted Hierarchy is excluded at >4σ
- Results are in agreement with T2K

Comparison of different experimental results



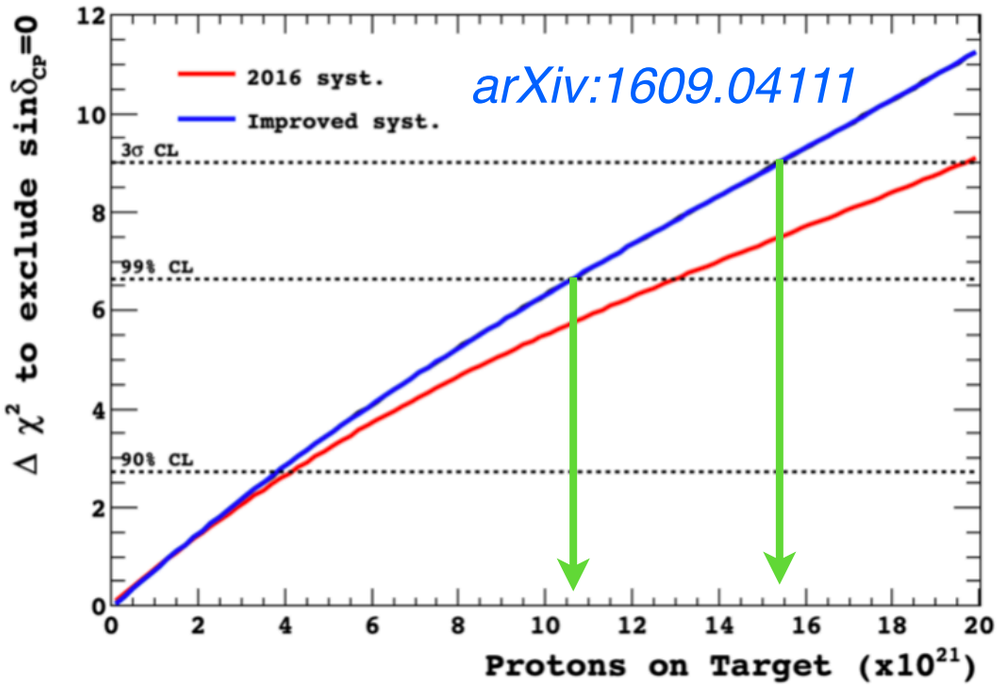


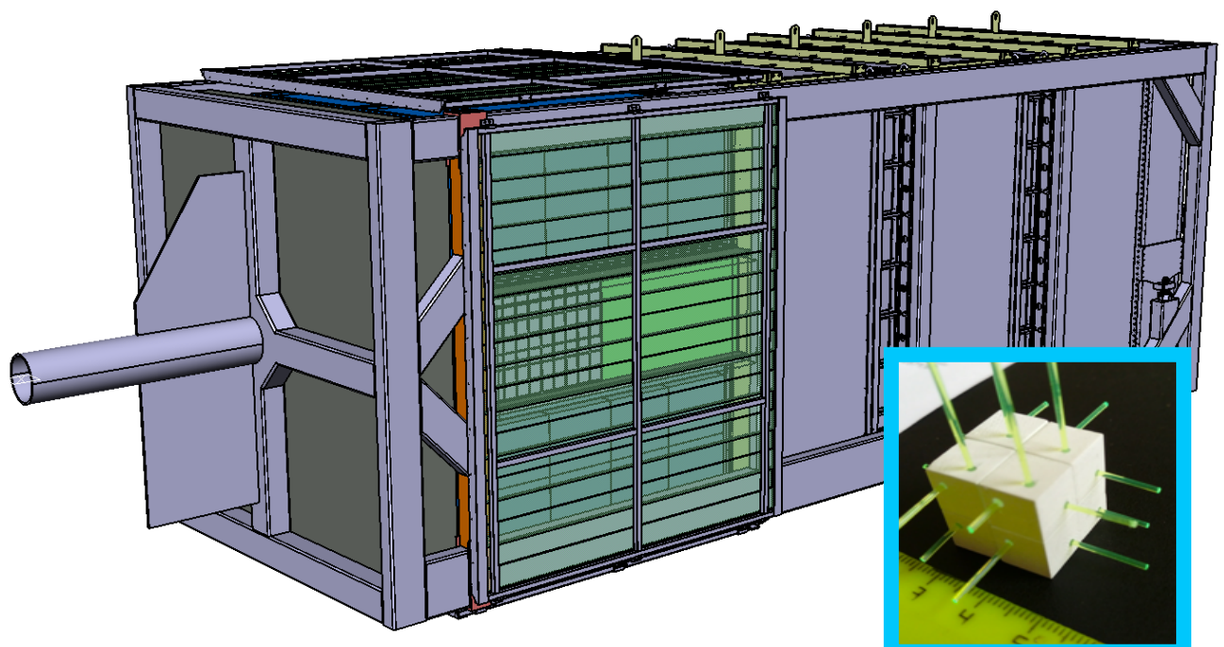




Prospects for the future

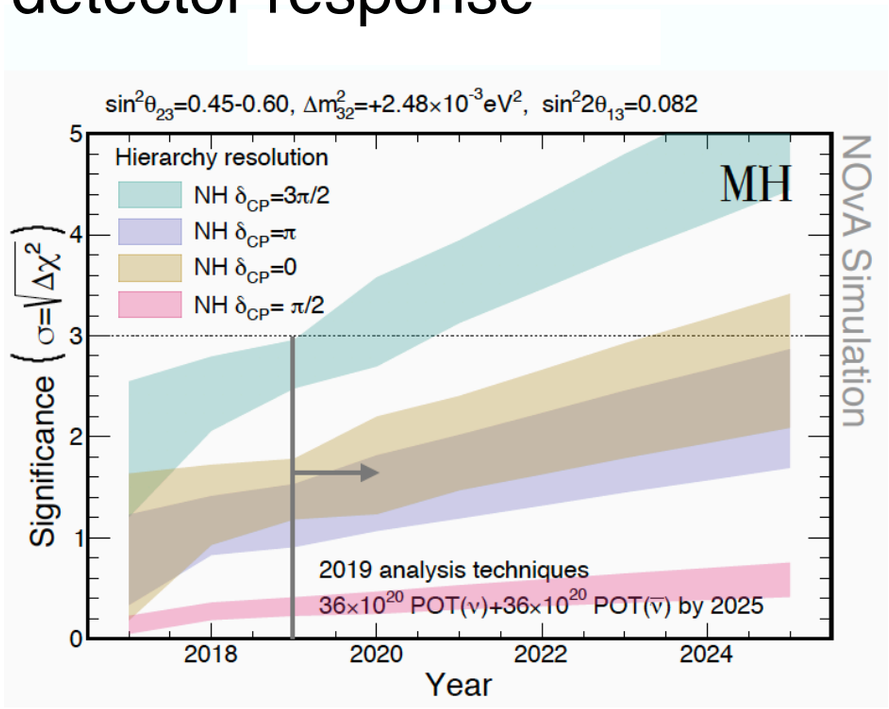
T2K data taking will be extended to phase II up to 2025 Increased beam intensity up to ~1 MW in 2021

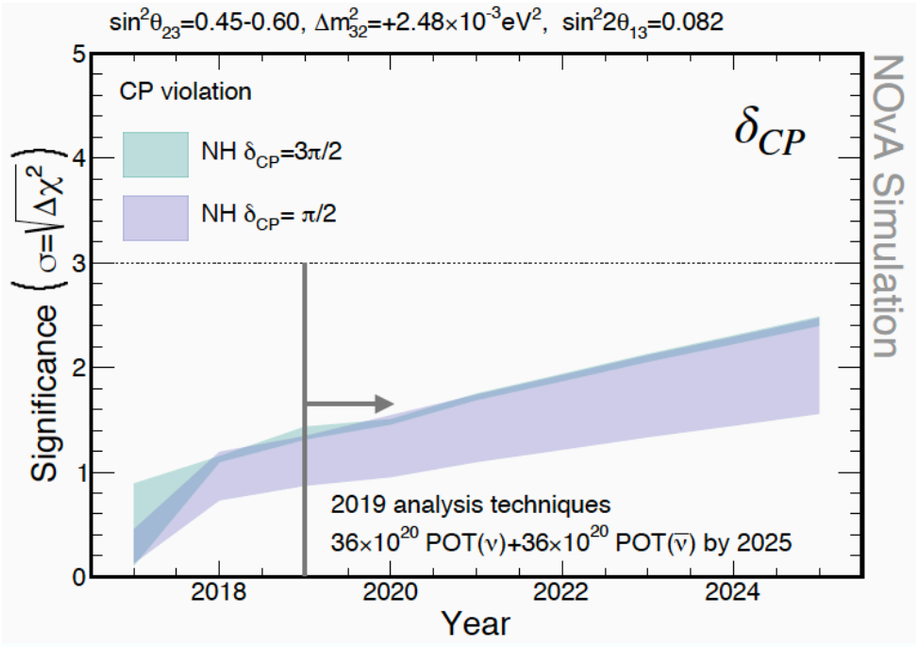




CERN-SPSC-2018-001 / SPSC-P-357

NOvA expected improvements: beam intensity, test beam for detector response





NOvA+T2K joint data fit foreseen for 2021

Conclusions

- T2K and NOvA are currently the most sensitive experiments for the measurement of the neutrino CP violating phase and mass ordering

- Similar in the concept but the different configurations (water Cherenkov vs plastic scintillator, different vs identical ND-FD technologies, different energies) make any comparison of the oscillation comparison more robust

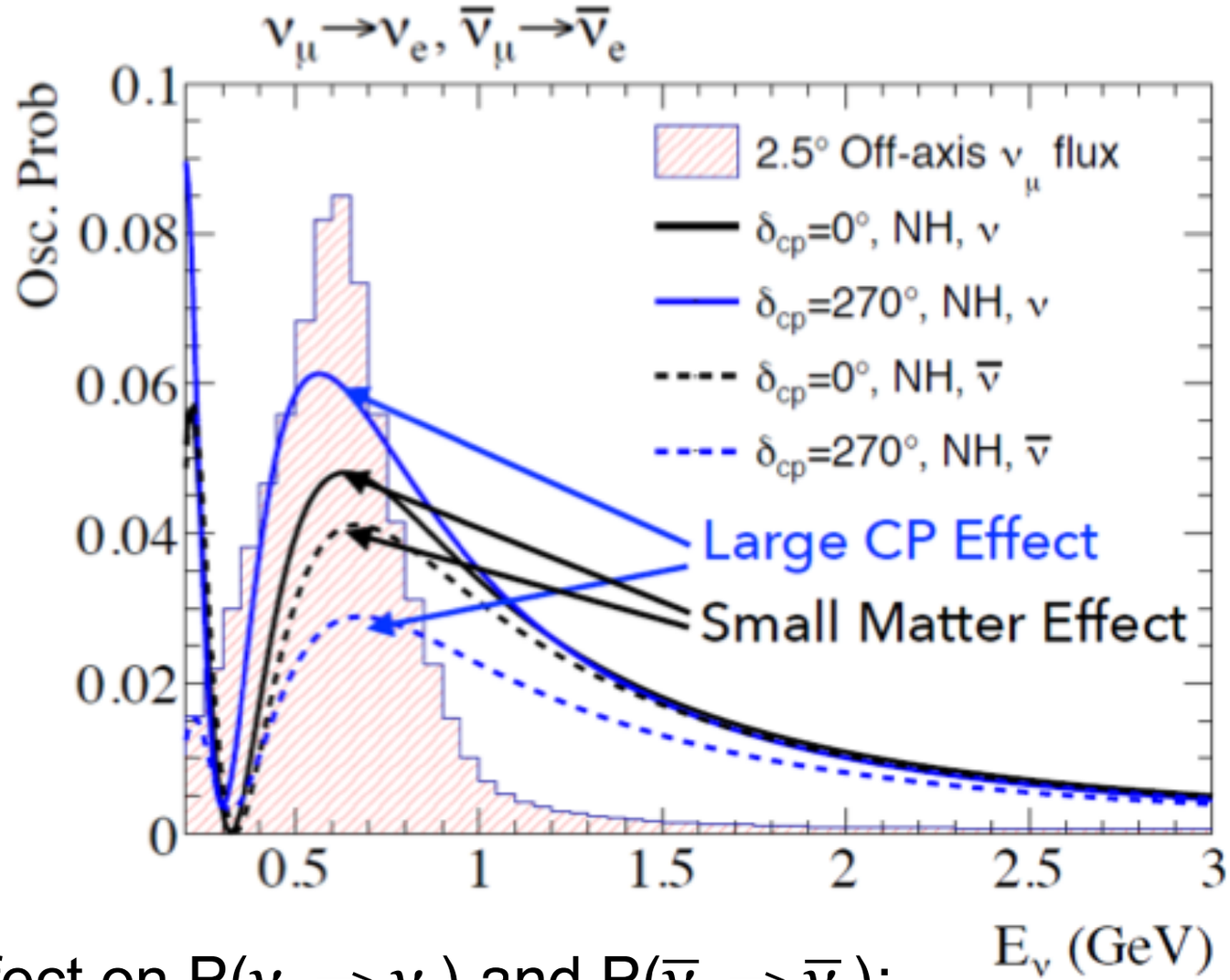
- Latest results are in good agreement

- Future improvements are foreseen, i.e. T2K Near Detector upgrade and NOvA test beam data analysis to characterize the detector response

- Plan for combined NOvA+T2K data analysis

BACKUP

Effect of CP violation and Mass Hierarchy at T2K



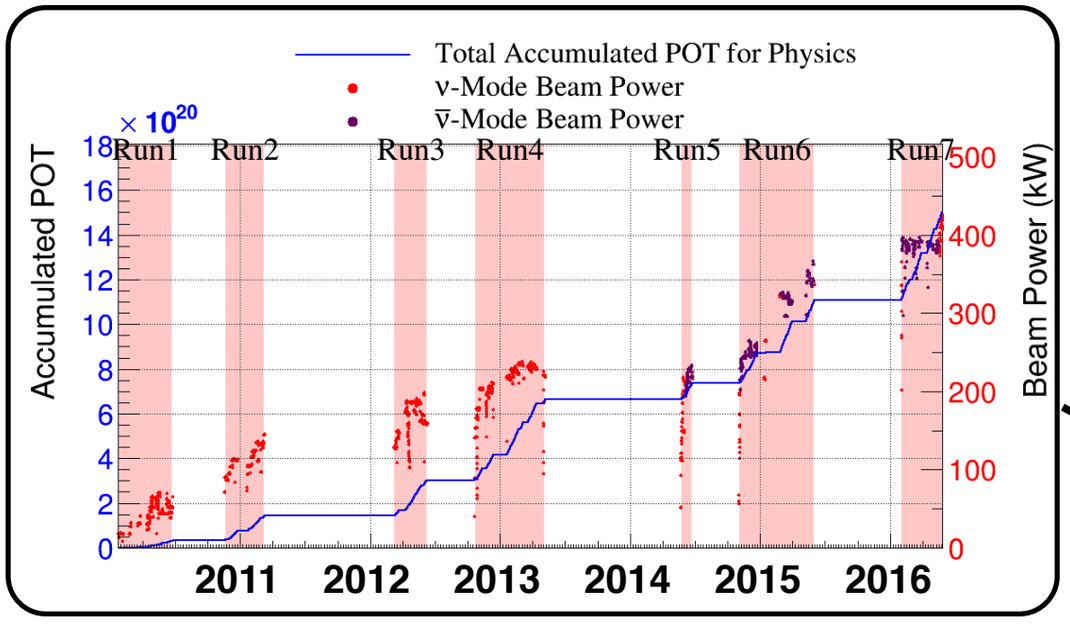
- Asymmetric effect on P($\nu_\mu \rightarrow \nu_e$) and P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$):
  - $\delta_{CP} = -\pi/2$ → maximizes P($\nu_\mu \rightarrow \nu_e$) and minimizes P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
  - $\delta_{CP} = +\pi/2$ → minimizes P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) and maximizes P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$)
- Effect of δ_{CP} on $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_e$ is about ±20-30%
- Effect of Mass Hierarchy is about ±10% —> 295 km baseline not long enough

Prospects for the future: T2K-II

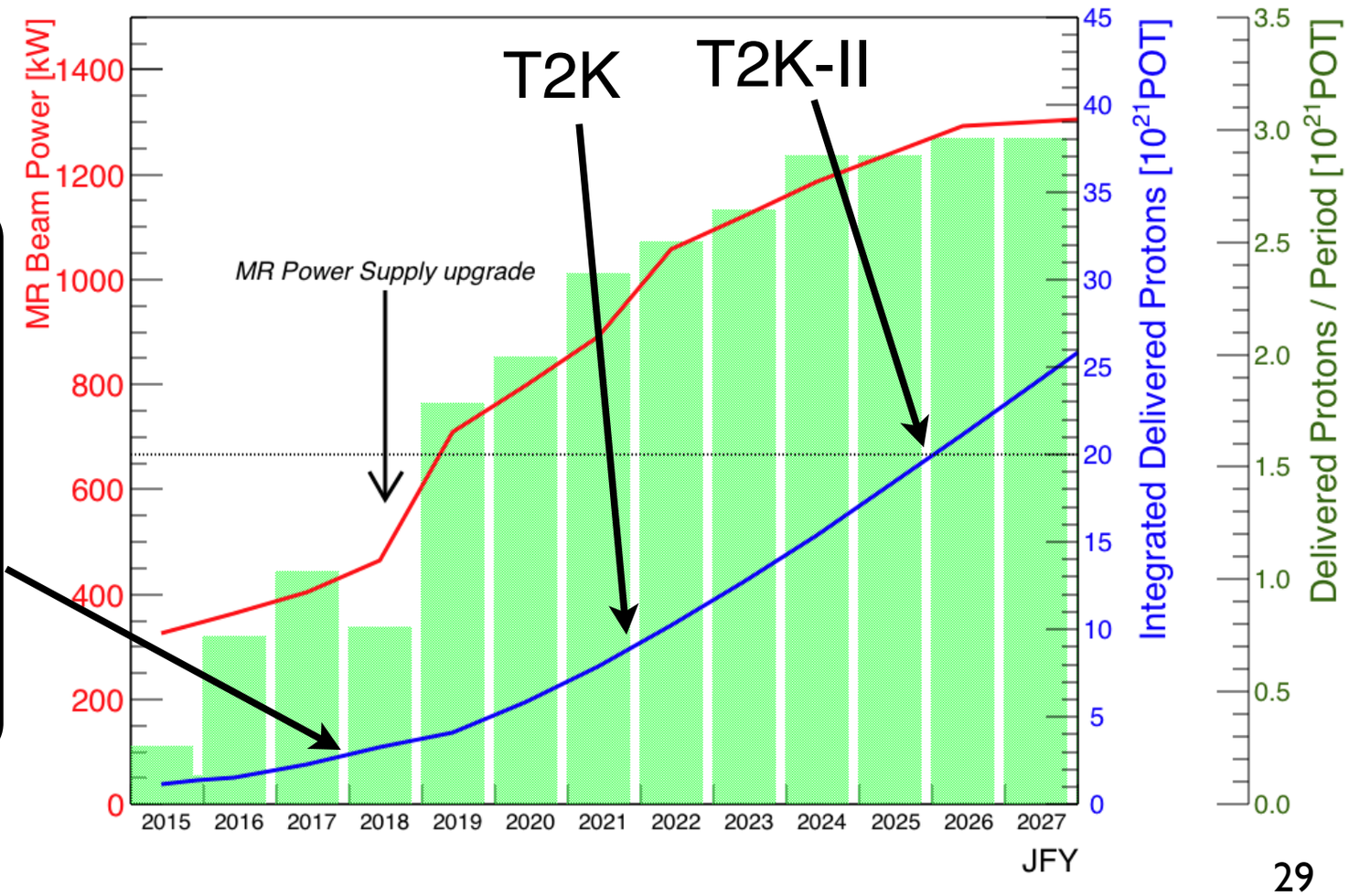
- Expect to reach the approved T2K statistics (7.8×10^{21} POT) around 2021
- **T2K-II phase**: proposed to extend T2K run to 20×10^{21} POT by 2025 (Stage-I status at summer JPARC PAC)
- Plan to gradually increase the beam intensity up to ~1 MW in 2021
- Aiming for >1 MW intensity for 2021 and 1.3 MW in ~2026: accelerator and beam-line upgrade is needed
- Demonstrated 3.41×10^{13} protons per beam operation → 1MW equivalent

arXiv:1609.04111

TODAY

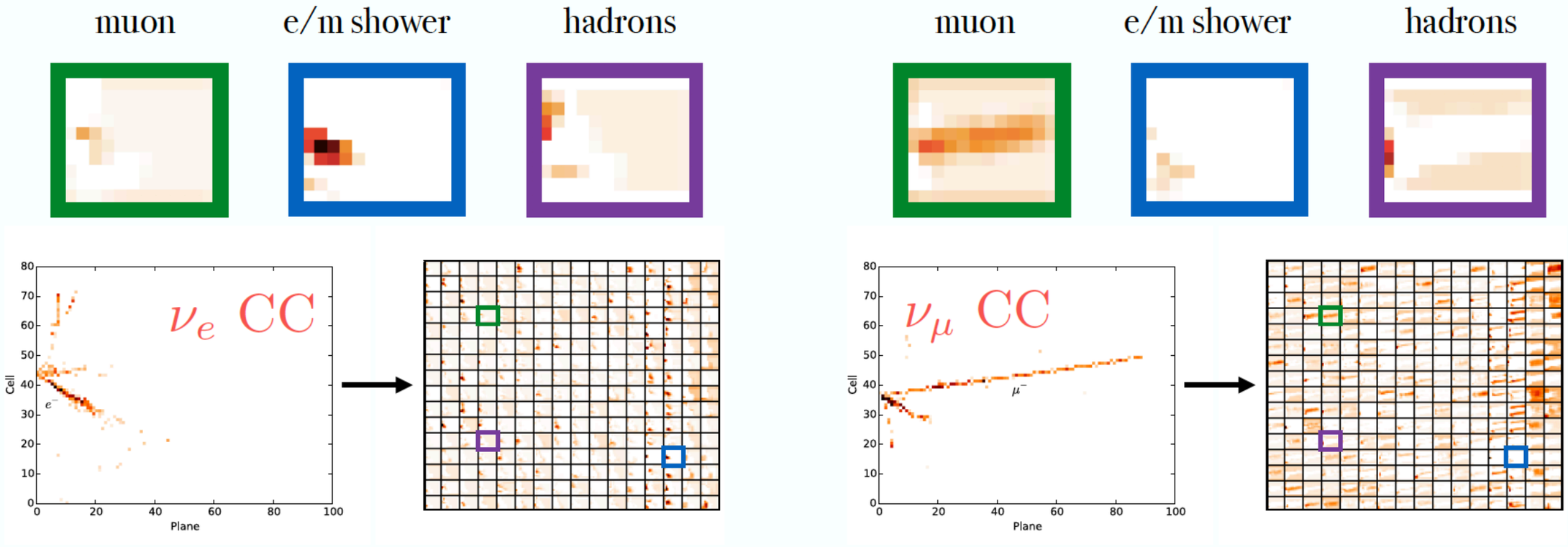


Will reach 500 kW soon



ν_e/ν_μ event selection with CVN

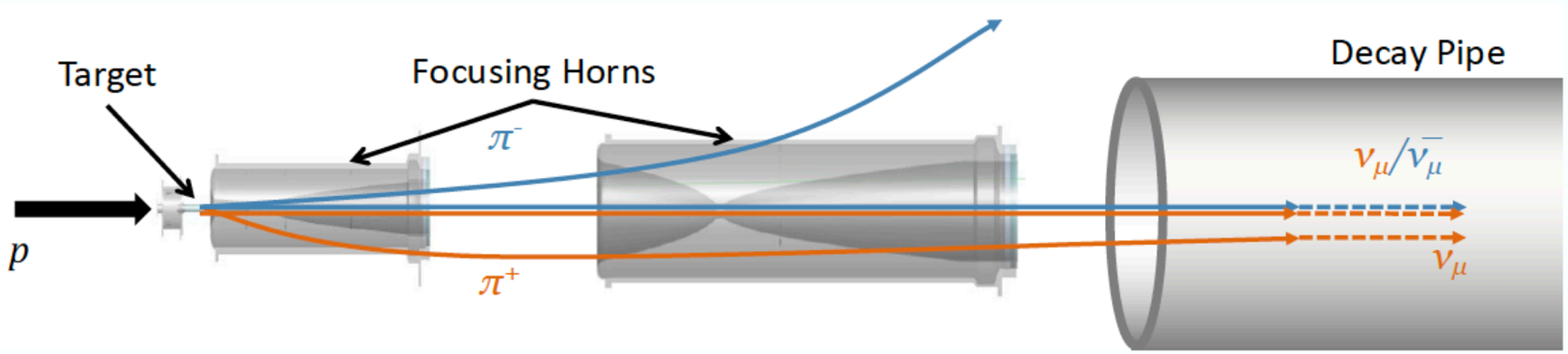
L. Kolupaeva @EPS 2019



- We use convolutional neural network called CVN (Convolutional Visual Network).
- Particle identification technique based on ideas from GoogLeNet (computer vision and deep learning).
- Multi-label classifier – the same network used in multiple analyses: can classify ν_e, ν_μ, ν_τ, NC and cosmic.

A. Aurisano et. al, JINST 11, P09001 (2016)

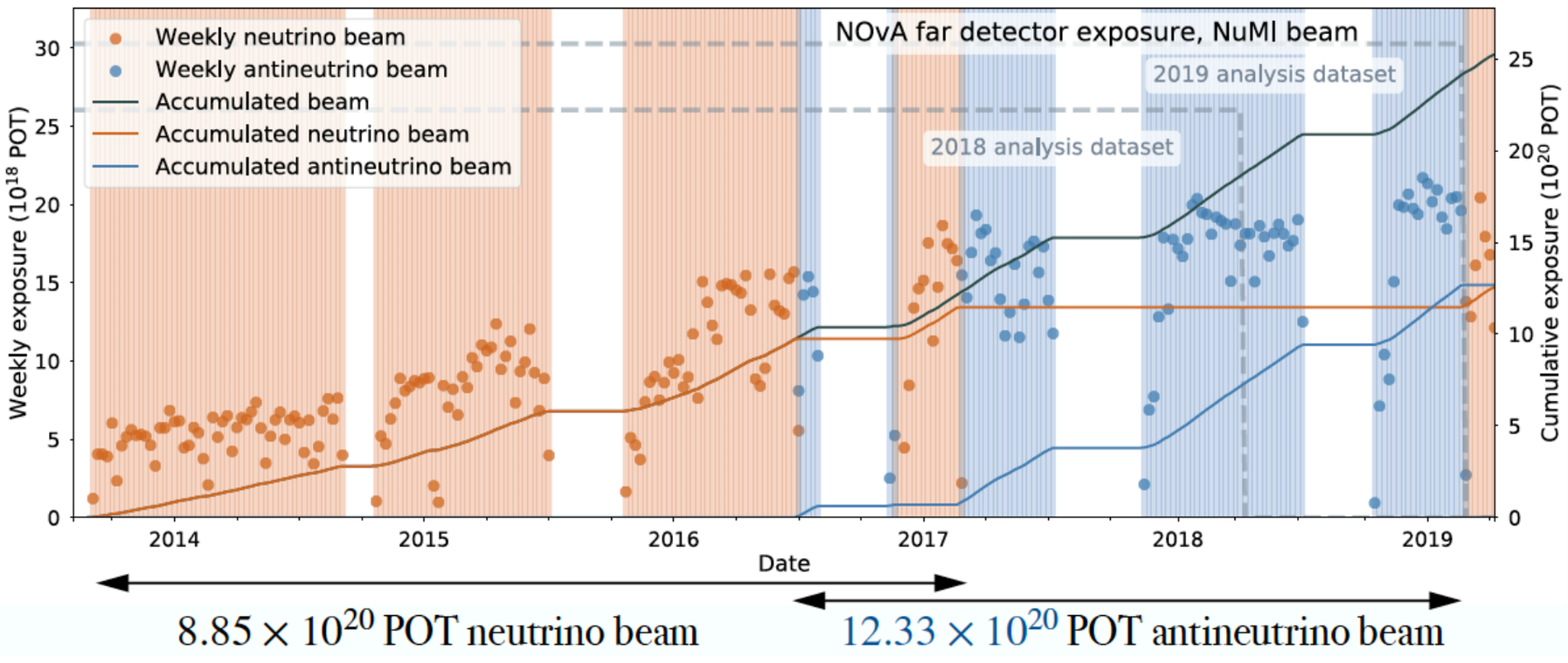
Neutrino beam



✶ 120 GeV protons on a carbon target, produce mesons which yield neutrinos.
Beam purity with $\nu(\bar{\nu})$: 95% ν_μ, 4% $\bar{\nu}_\mu$, 1% ν_e (93% $\bar{\nu}_\mu$, 6% ν_μ, 1% ν_e).

✶ NOvA is designed for the 700 kW NuMI beam, with 6×10^{20} POT/year
(POT = Protons On Target).

✶ Running at 700 kW since January 2017.



78% increase in $\bar{\nu}$ exposure:
$6.91 \times 10^{20} \rightarrow 12.33 \times 10^{20}$
(2018 → 2019)