Results and prospects from T2K

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for the T2K Collaboration
NuFact 2018 – Virginia Tech
14th August, 2018

UNIVERSITY OF LIVERPOOL

Outline

- An introduction to the T2K experiment.
    - Increases in our dataset.
- Summer 2018 oscillation results.
    - Improvements in our analysis methods.
- The future of the T2K program.
    - Run scheduling.
    - Current upgrades.
    - Future upgrade plans.
- Conclusions and outlook.

Three-flavour Neutrino Oscillation

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix} \begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{cp}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{cp}} & 0 & c_{13}\end{pmatrix} \begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

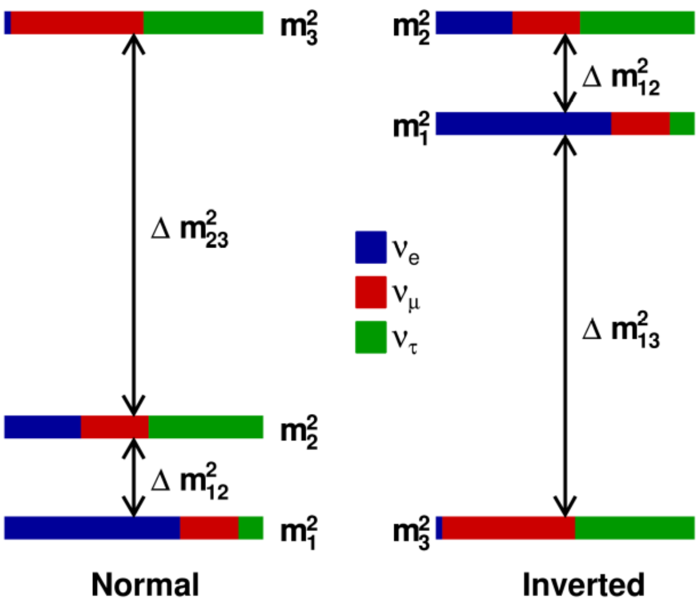
Atmospheric & LBL disappearance

Reactor & LBL appearance

Solar & Reactor

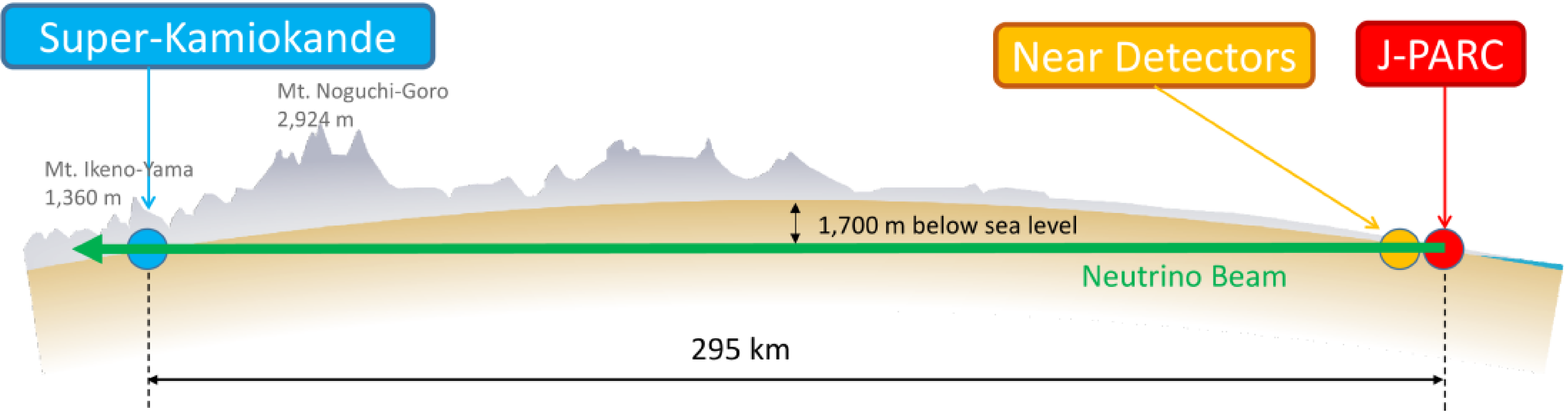
6 parameters: three mixing angles, two mass-squared splittings and a CP-violating phase.

- Long baseline experiments can measure:
  - θ_{23} and $|\Delta m^2_{32}|$ via ν_μ disappearance
  - θ_{13} and δ_{cp} via ν_e appearance.
  - Neutrino mass ordering.



The T2K Experiment

- Long baseline neutrino oscillation experiment in Japan.
  - High intensity muon neutrino beam produced at J-PARC.
  - Super-Kamiokande used as far detector at 295 km.
  - Off-axis technique is used to get beam energy sharply peaked at 0.6 GeV.
- Precision measurements of ν_μ disappearance.
- Originally designed to discover ν_e appearance.
  - Now performing searches for CP violation using ν_e and $\bar{\nu}_e$ appearance.



The T2K Collaboration

~ 500 members, 66 Institutes, 12 countries

Canada
TRIUMF
U. B. Columbia
U. Regina
U. Toronto
U. Victoria
U. Winnipeg
York U.

France
CEA Saclay
LLR E. Poly.
LPNHE Paris

Germany
Aachen

Italy
INFN, U. Bari
INFN, U. Napoli
INFN, U. Padova
INFN, U. Roma

Japan
ICRR Kamioka
ICRR RCCN
Kavli IPMU
KEK
Kobe U.
Kyoto U.
Miyagi U. Edu.
Okayama U.
Osaka City U.
Tokyo Institute Tech
Tokyo Metropolitan U.
U. Tokyo
Tokyo U of Science
Yokohama National U.

Poland
IFJ PAN, Cracow
NCBJ, Warsaw
U. Silesia, Katowice
U. Warsaw
Warsaw U. T.
Wroclaw U.

Russia
INR

Spain
IFAE, Barcelona
IFIC, Valencia
U. Autonoma Madrid

Switzerland
ETH Zurich
U. Bern
U. Geneva

United Kingdom
Imperial C. London
Lancaster U.
Oxford U.
Queen Mary U. L.
Royal Holloway U.L.
STFC/Daresbury
STFC/RAL
U. Glasgow
U. Liverpool
U. Sheffield
U. Warwick

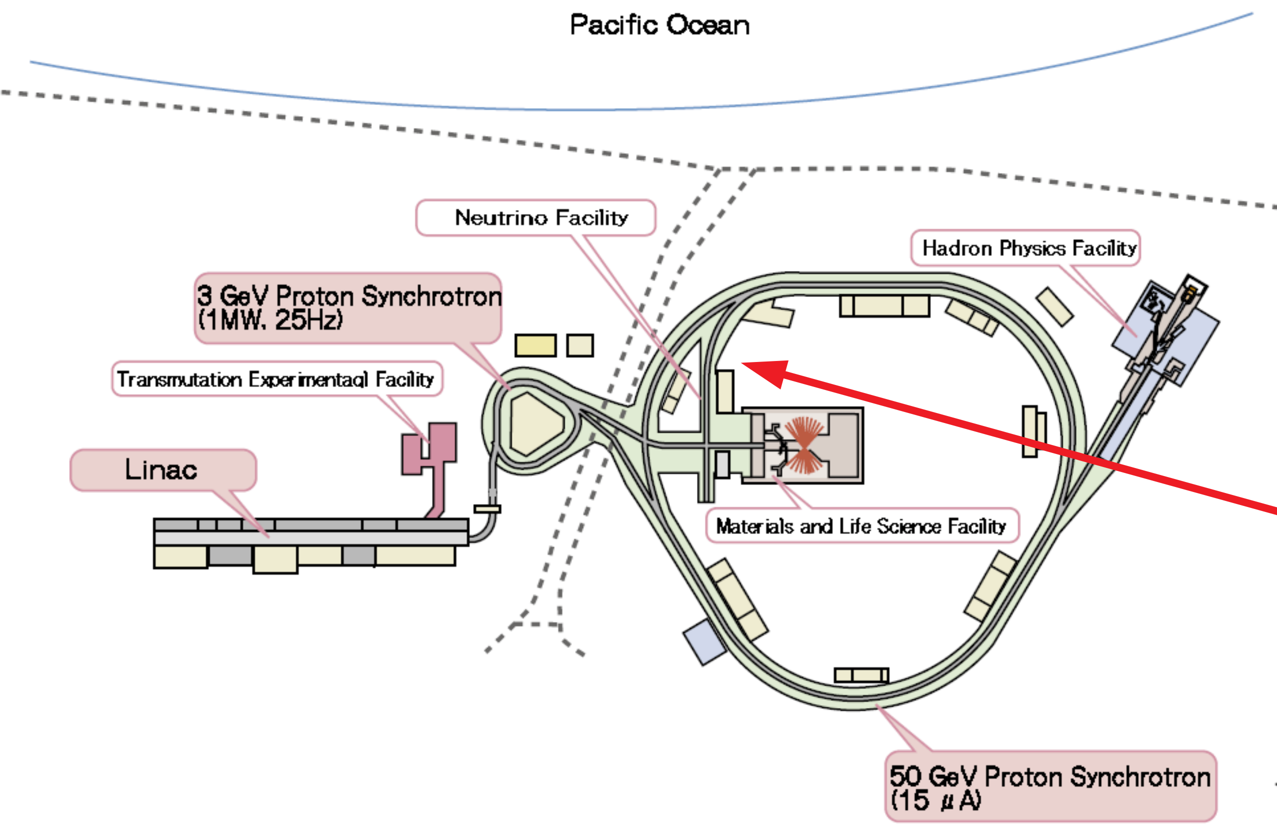
USA
Boston U.
Colorado S. U.
Duke U.
Louisiana State U.
Michigan S.U.
Stony Brook U.
U. C. Irvine
U. Colorado
U. Pittsburgh
U. Rochester
U. Washington

Vietnam
IFIRSE
IOP, VAST

T2K Presentations at NuFACT

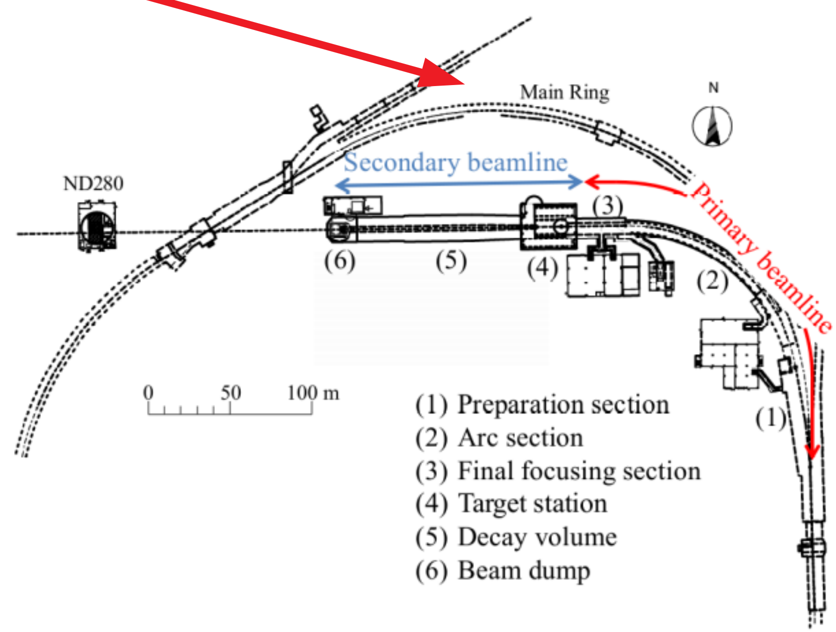
- Clarence Wret: T2K Cross Section Results
  - WG2 Parallel Session, Monday.
- Chris Densham: Upgrades to the J-PARC Target and Beam Window
  - WG3 Parallel Session, Monday
- Xianguo Lu: Recent Results from the T2K Near Detector
  - Plenary VI, Wednesday
- Thorsten Lux: T2K Near Detector Upgrades and Plans for T2HK
  - Plenary VI, Wednesday
- Davide Sgalaberna: Details of the T2K oscillation analyses
  - WG1 Parallel Session, Thursday
- Clarence Wret: T2K Cross-sections for oscillation analysis
  - WG2 Parallel Session, Friday

J-PARC Neutrino Beam



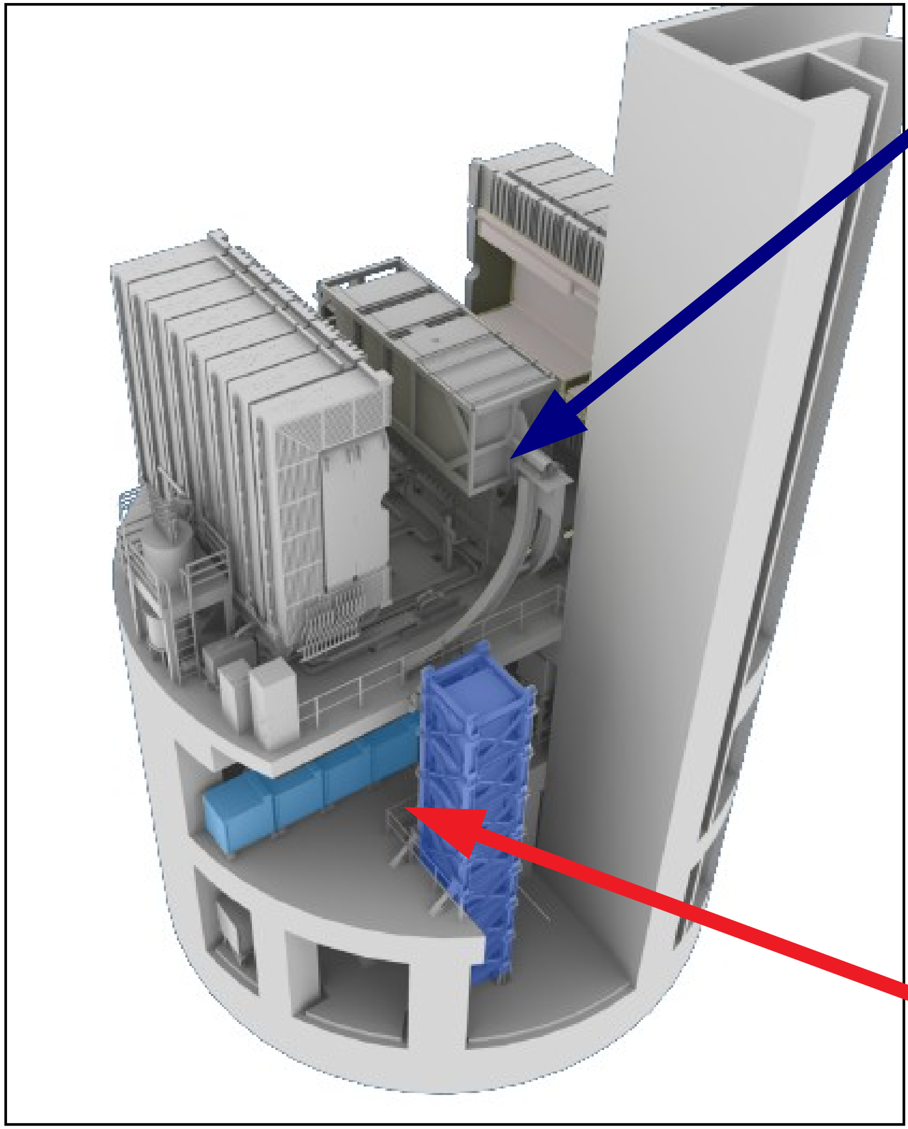
Three-horn design for focusing pions, in two beam modes:

ν-mode	Forward horn current (FHC)
$\bar{\nu}$-mode	Reverse horn current (RHC)

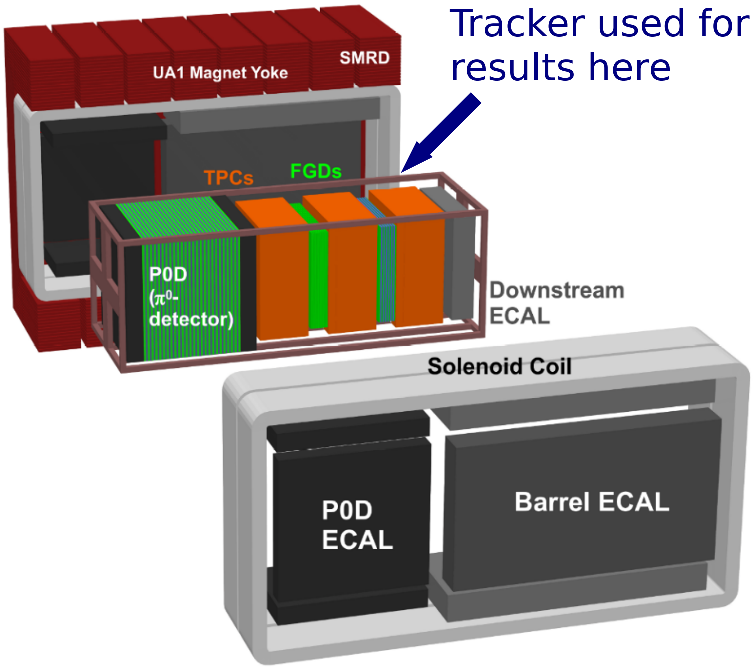


Stable beam running, at ~485 kW.

Near Detectors



Off-axis (2.5°) ND280

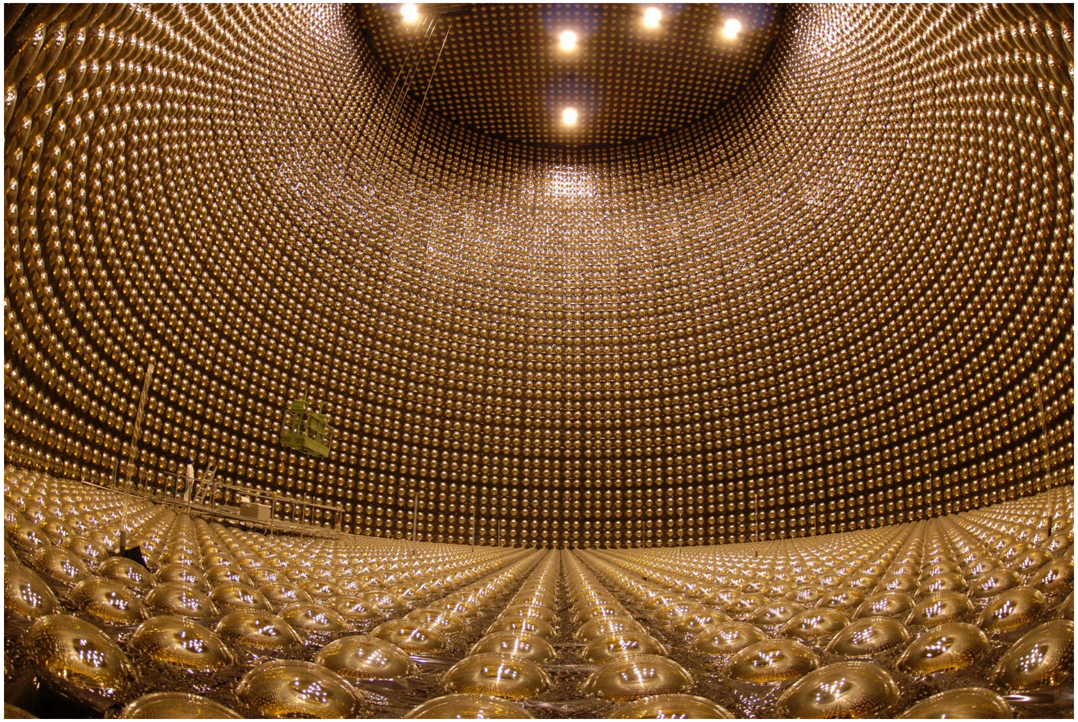


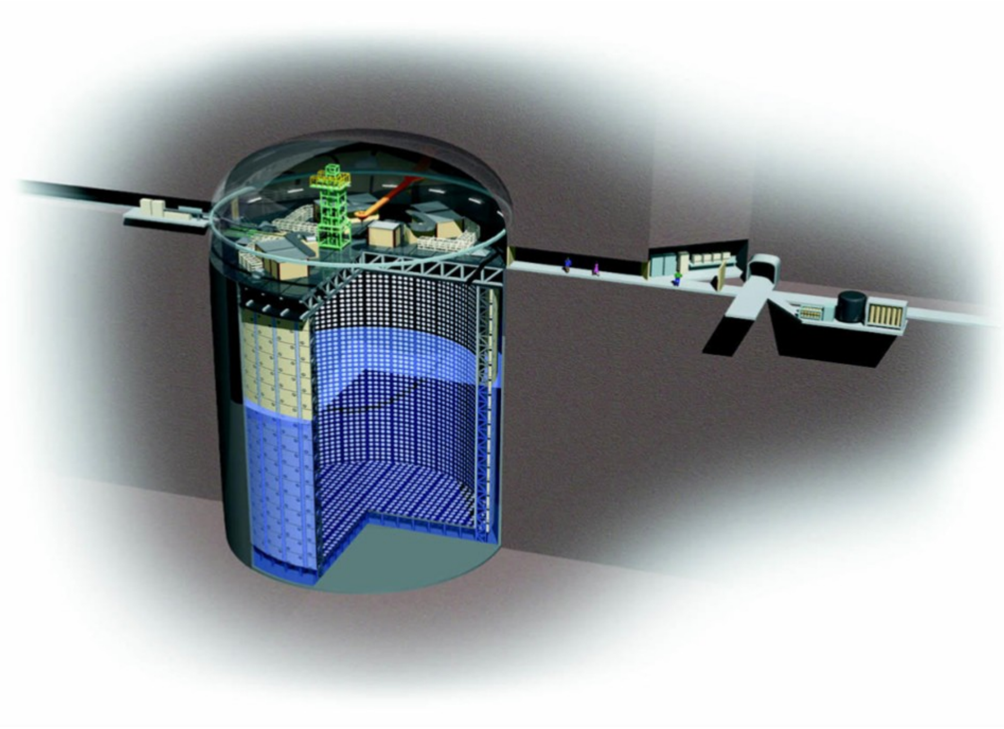
Tracker used for results here

On axis (INGRID)

See Xianguo Lu’s talk for ND280 details

Far Detector: Super-Kamiokande

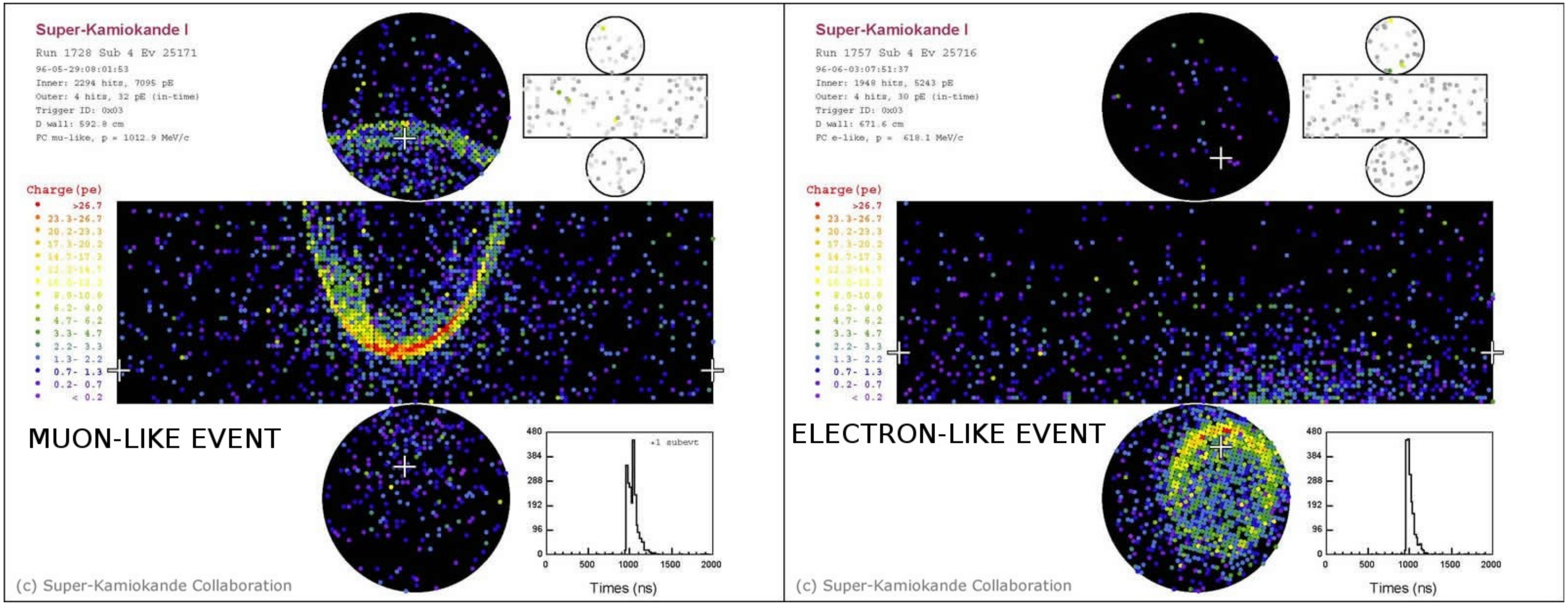




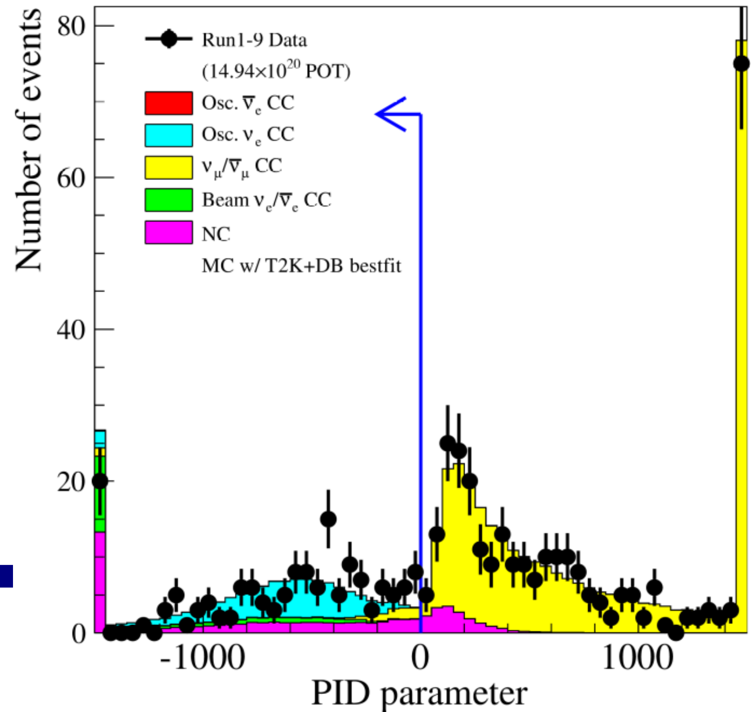
50 kt ultrapure water Cherenkov detector instrumented with 11,000 PMTS in the inner detector for 40% photo-coverage.
1 km underground to reduce background.

Excellent muon-electron separation
Good at reconstructing T2K energy range neutrinos

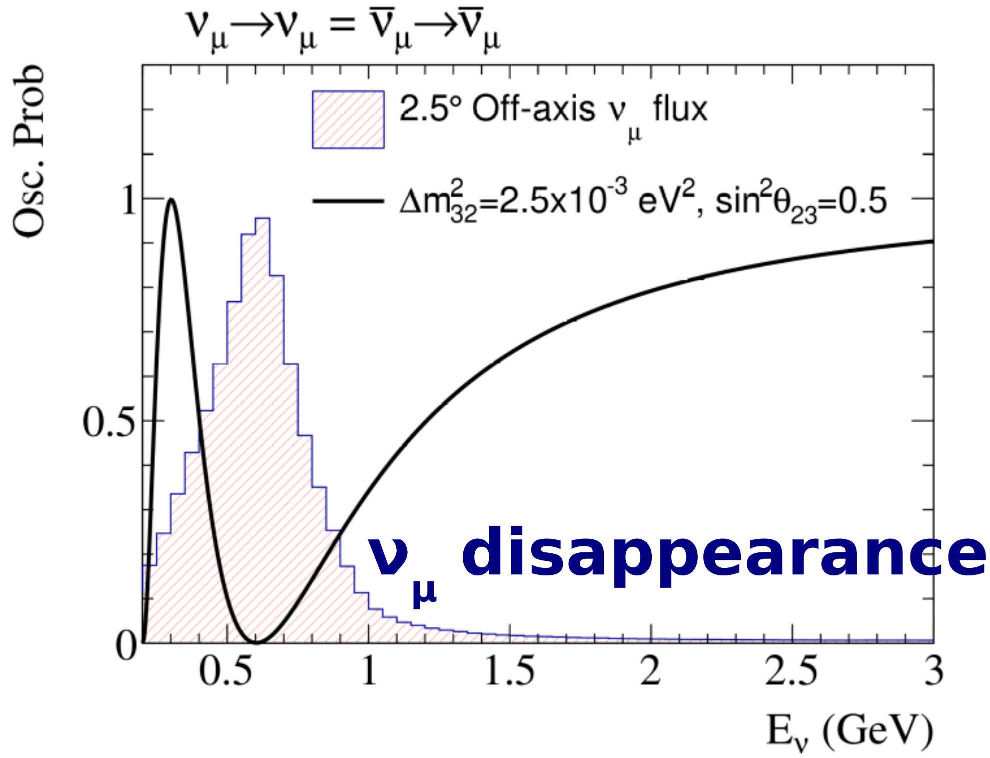
Super-K PID

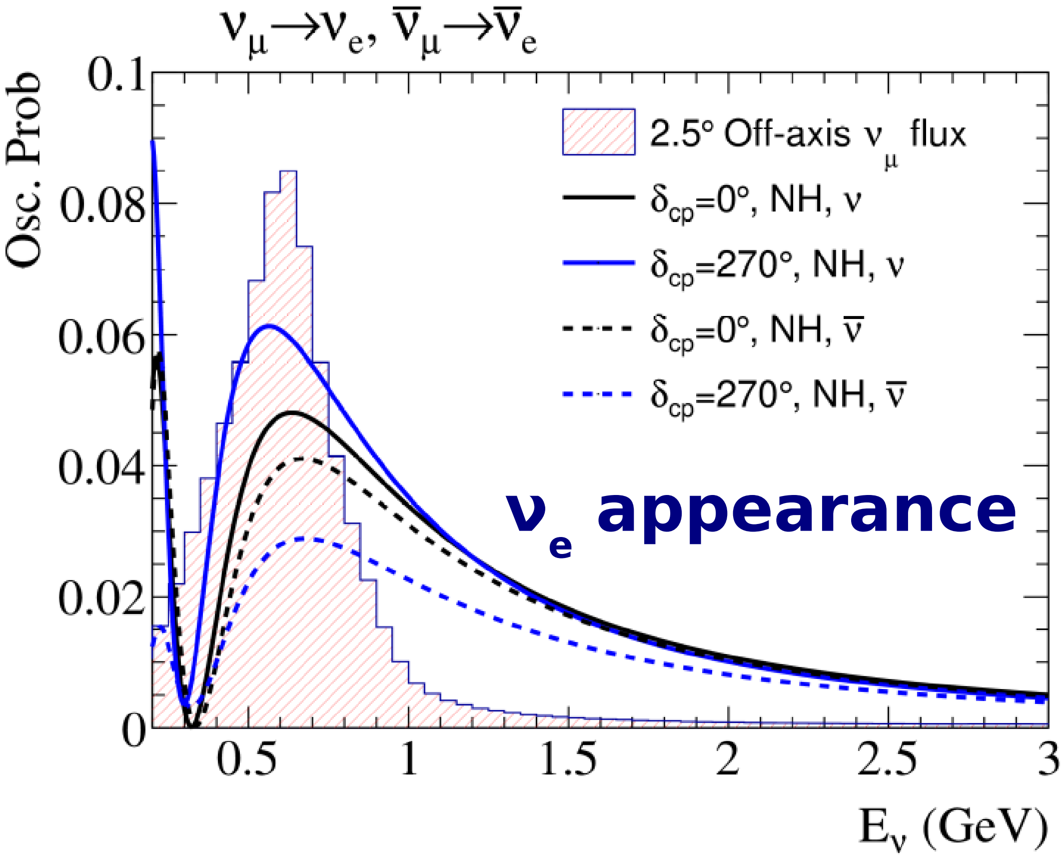


Ring “fuzziness” from scattering: excellent electron-muon separation



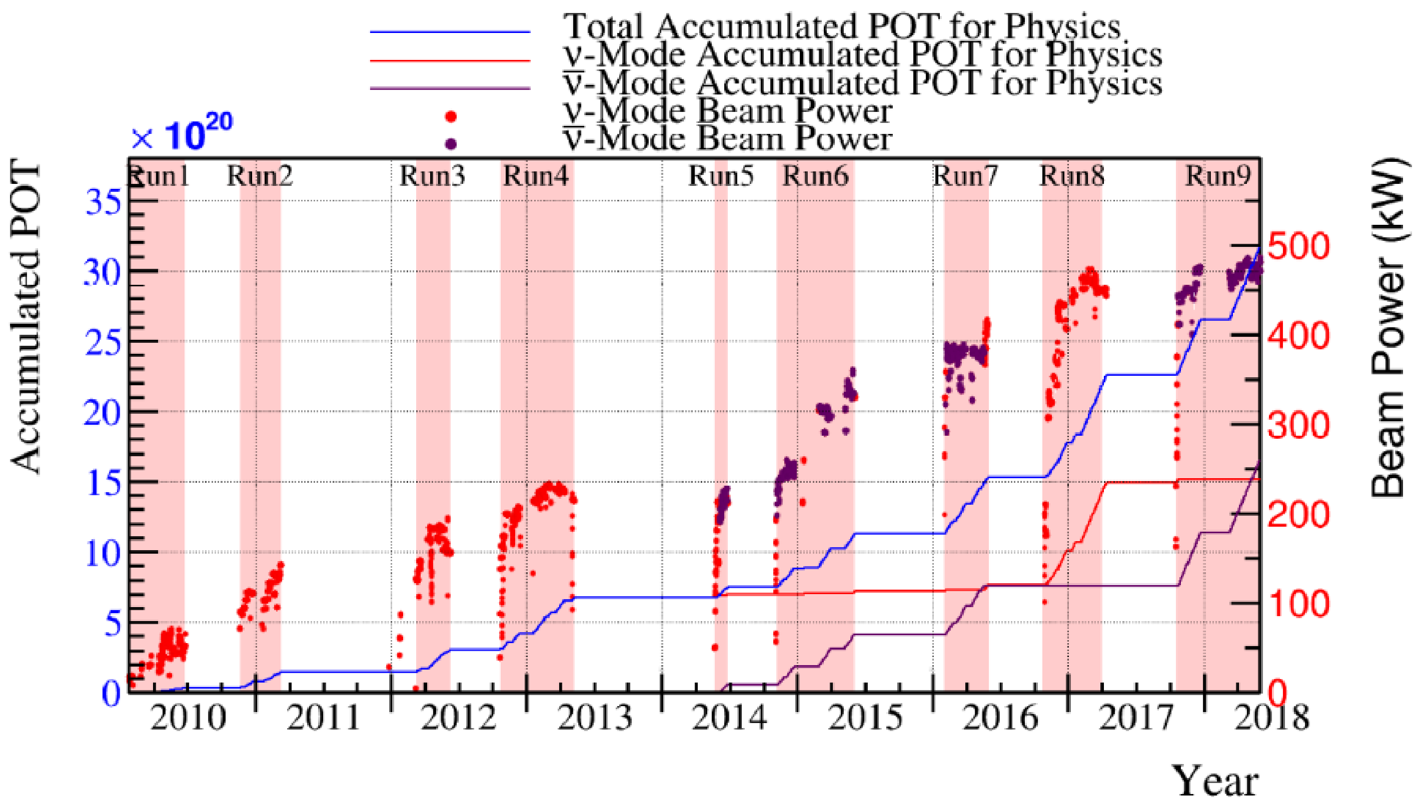
Effects of oscillation at Super-K





Use of the off-axis technique places a sharp flux peak around the first oscillation maximum

Collected Beam to Date



23 Jan. 2010 – 31 May 2018

POT total: 3.16×10^{21}

ν-mode 1.51×10^{21} (47.83%)

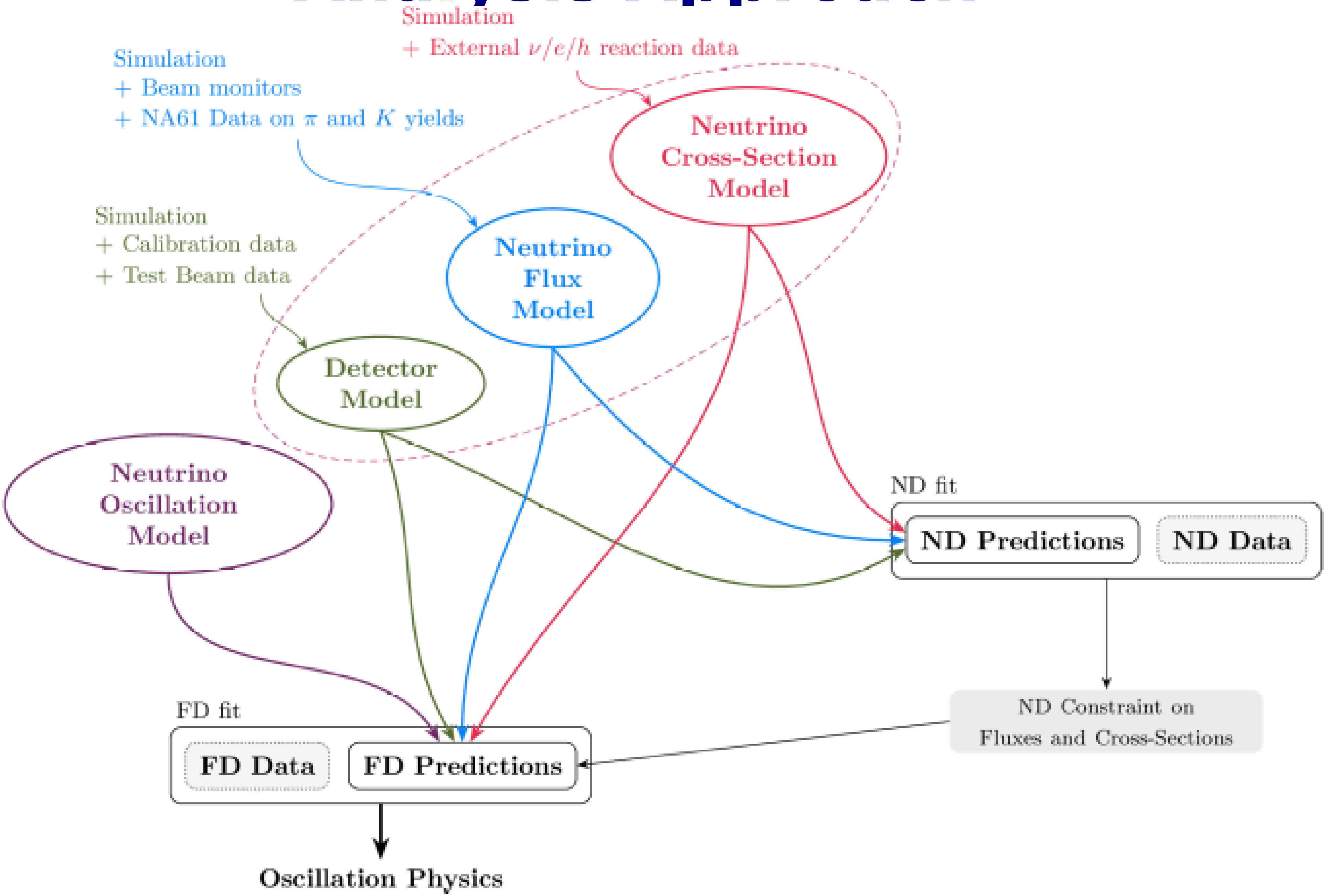
$\bar{\nu}$-mode 1.65×10^{21} (52.17%)

BIG IMPROVEMENT

POT = protons on target
Our measure of exposure.

Results presented today analyse:
FHC: 1.49×10^{21} POT
RHC: 1.12×10^{21} POT

Analysis Approach

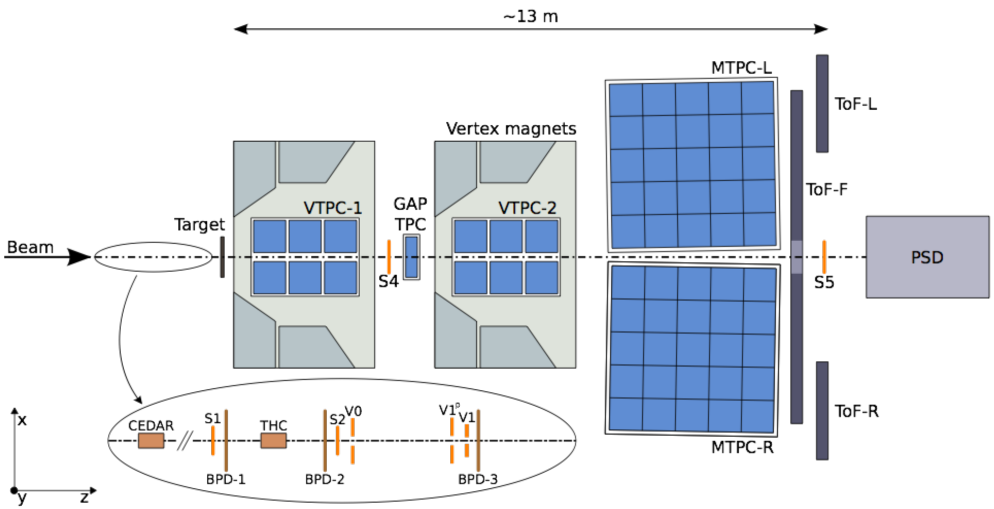


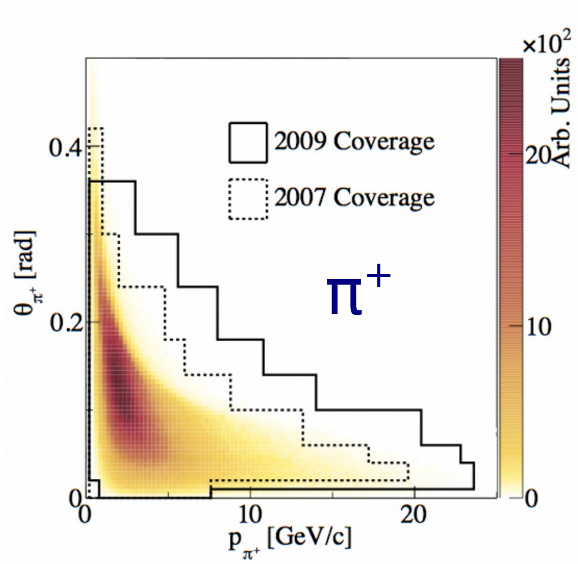
Hadron Yields from NA61/SHINE

- Large-acceptance detector with excellent charge/mass measurement capability.
  - Covers almost the entire T2K p-θ phase space.

See talk by Athula Wickremasinghe

- Measures hadron yields from a 31 GeV/c proton beam.
  - From the SPS at CERN.
- Published using 2cm thin carbon target: Eur. Phys. J. C 76, 84 (2016)
- And using T2K replica target: Eur. Phys. J. C 76, 617 (2016)
  - Total flux uncertainty on signal particle flux reduced from ~10% to ~5% at the T2K beam peak energy.

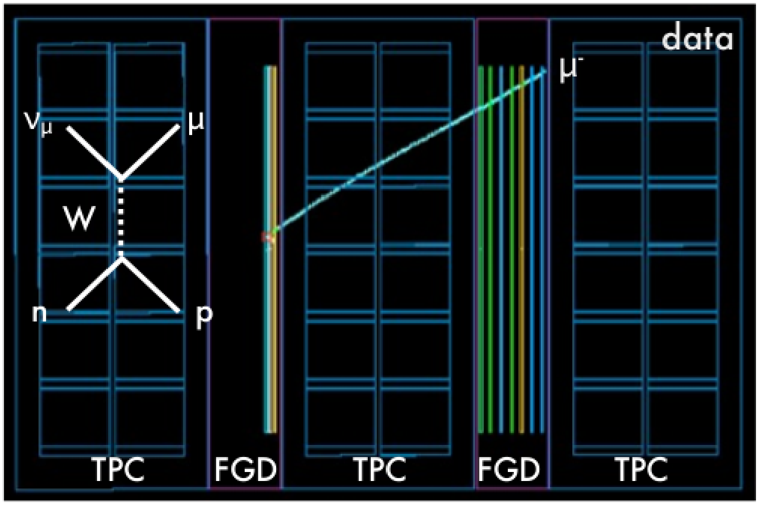


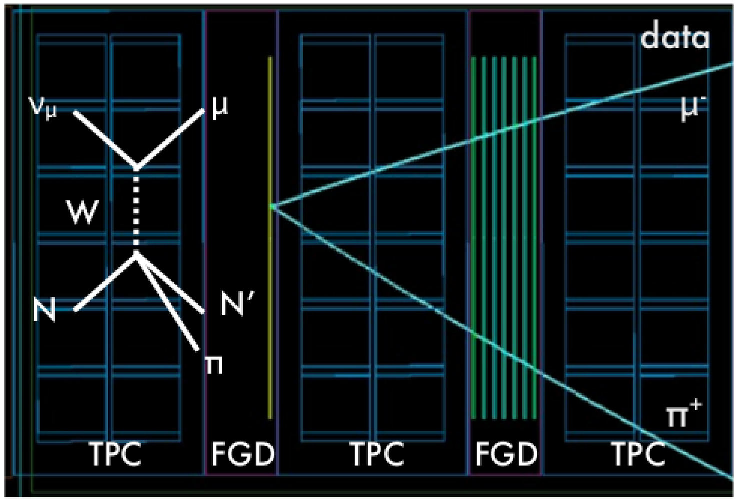


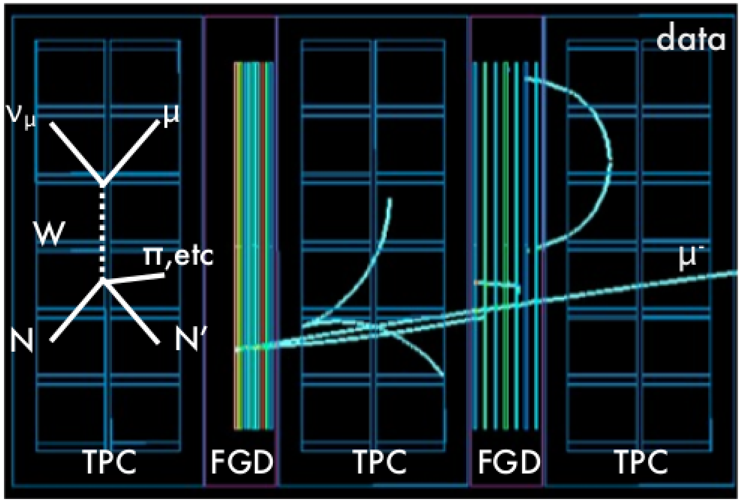
ND280 Data Samples

- To constrain the combination of flux and interaction systematics at Super-K, data samples are fitted at the ND280.
- Uses three topologies in neutrino beam-mode:
  - ν_μ CC0pi, ν_μ CC1π+ and ν_μ CC other
- Four topologies in antineutrino beam-mode:
  - $\bar{\nu}_\mu$ CC 1-track, $\bar{\nu}_\mu$ CC N-track (right-sign)
  - ν_μ CC 1-track, ν_μ CC N-track (wrong-sign)
- Uses data samples interacting on Carbon and Oxygen, binned in muon momentum and angle.
- Fitting multiple samples allows more accurate constraints on interaction physics.

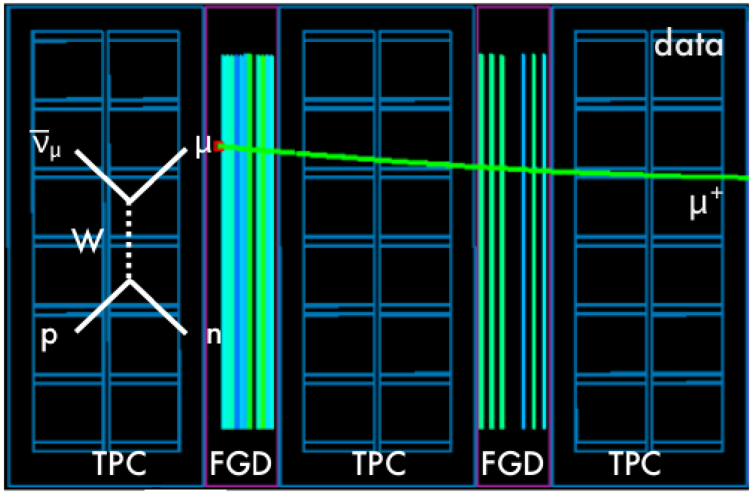
ND280 Topologies
Neutrino Mode (FHC)

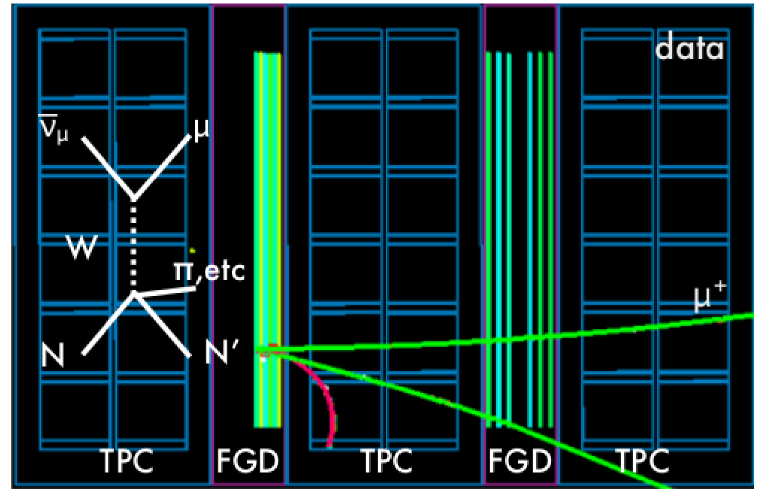


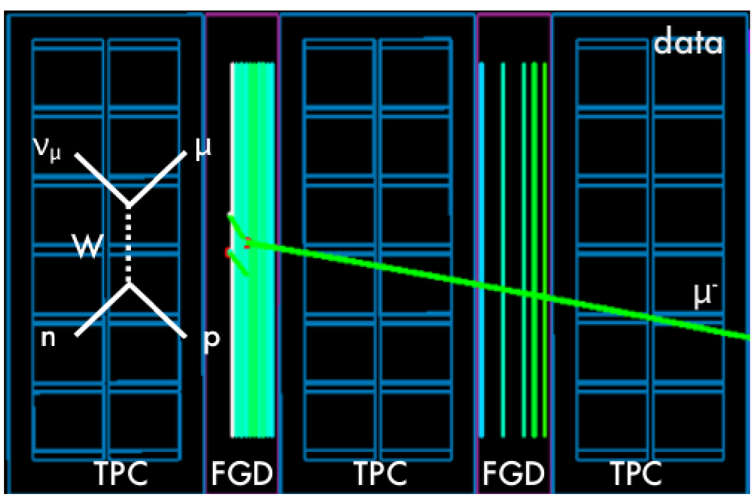




ND280 Topologies
Antineutrino Mode (RHC)







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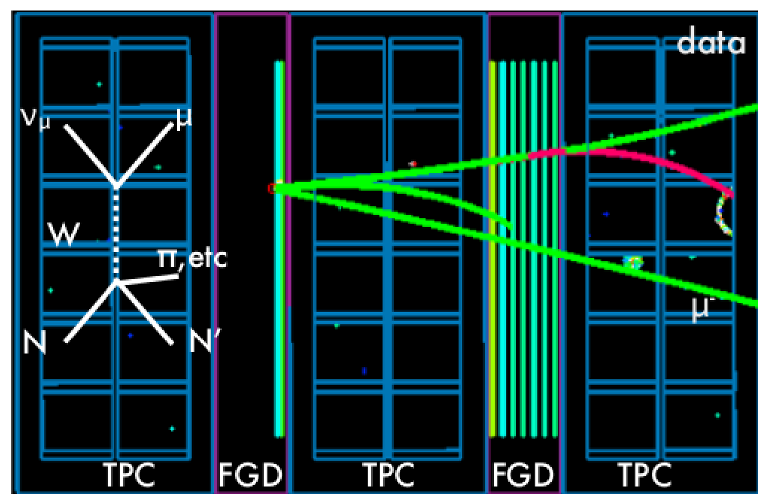
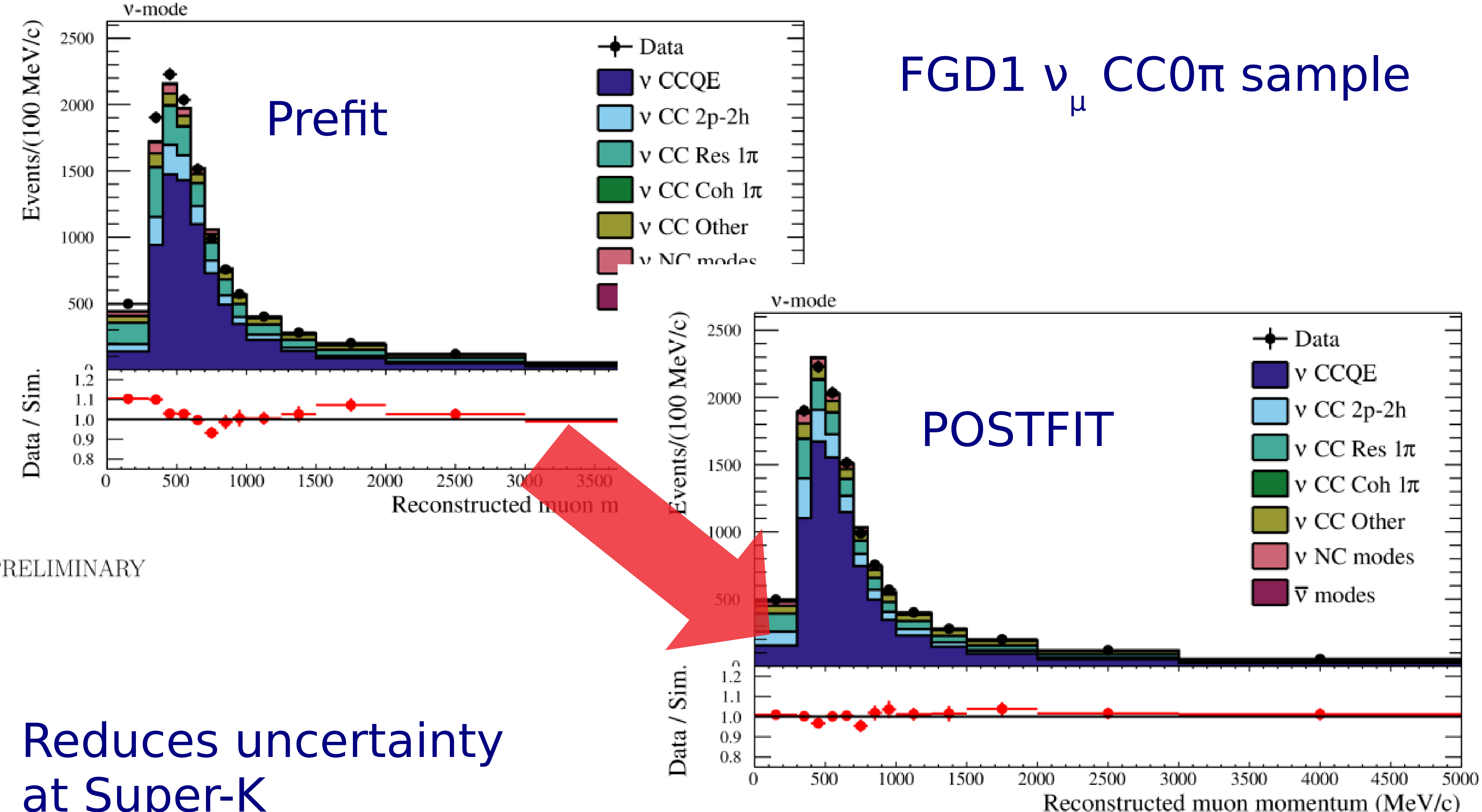


ND280 Fitted Data

FGD1 ν_μ CC0π sample



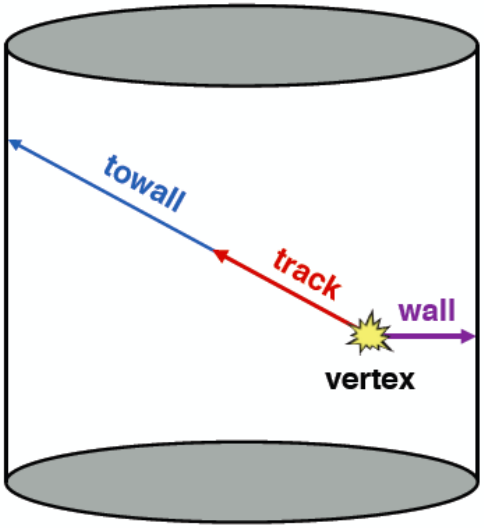
PRELIMINARY

Reduces uncertainty at Super-K

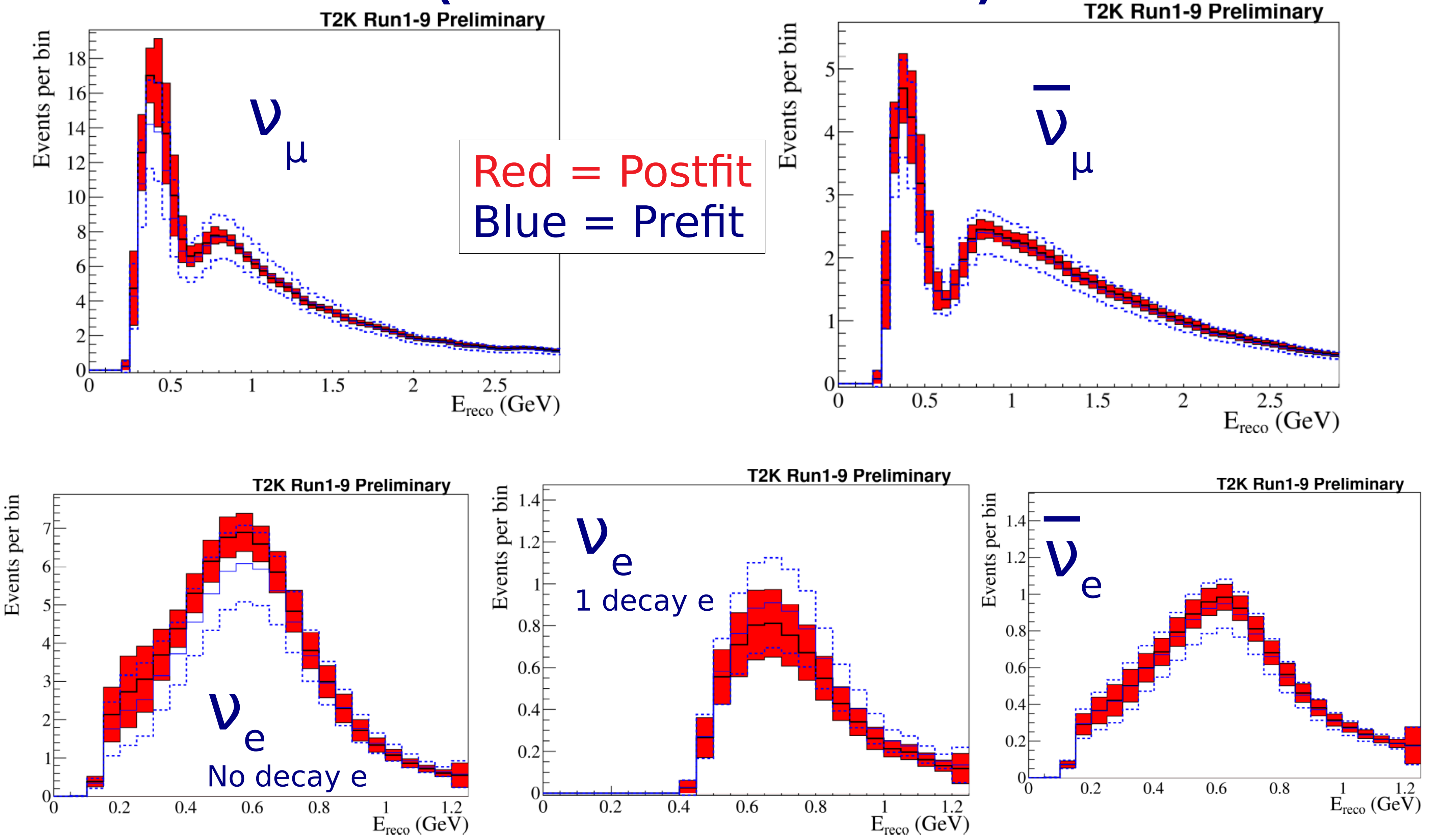
PRELIMINARY

Super-K Analysis Improvements

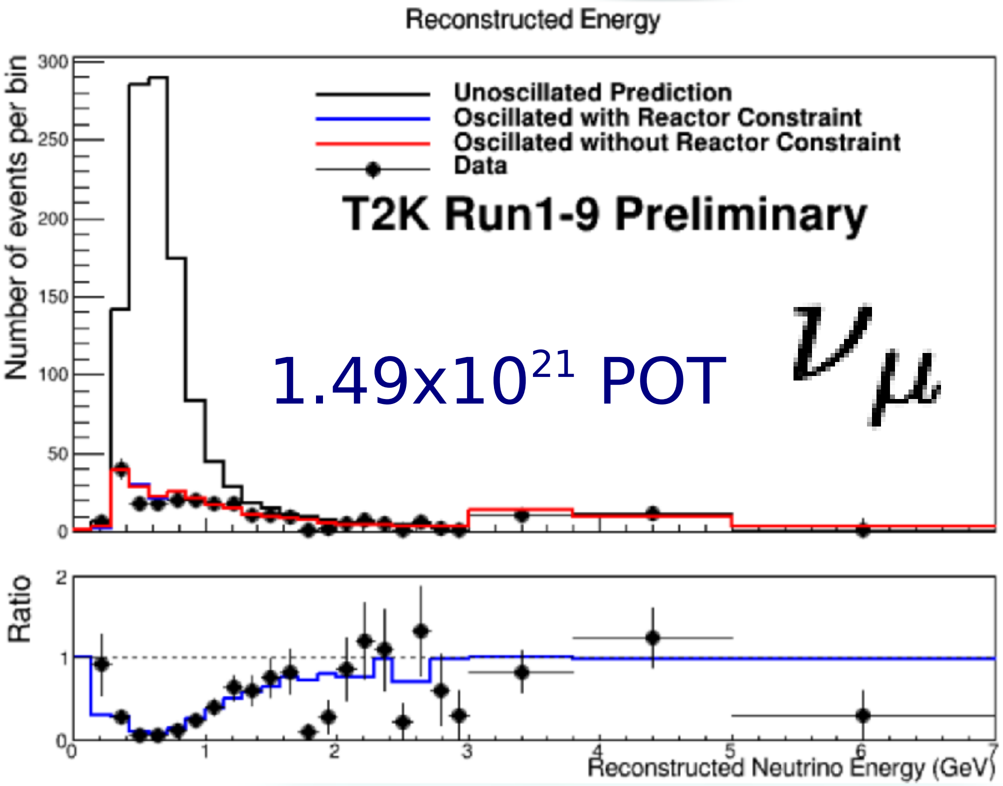
- Two big improvements to Super-K analysis were made for 2017:
- Introduction of ν_e CC1π sample:
  - adds ~10% to ν_e statistics.
- Increase in size of Super-K fiducial volume:
  - Used to cut every event with vertex <2 m from the detector wall
  - Now separate into two cuts:
    - Vertex distance from wall along particle trajectory (aka `towall').
    - Shortest distance vertex to wall (known as `wall').
  - These are tuned per-sample, with wall ~50cm and towall ~2m.
  - This increases fiducial volume, increasing statistics by 15-20%.
- Total improvement of 30% statistics.



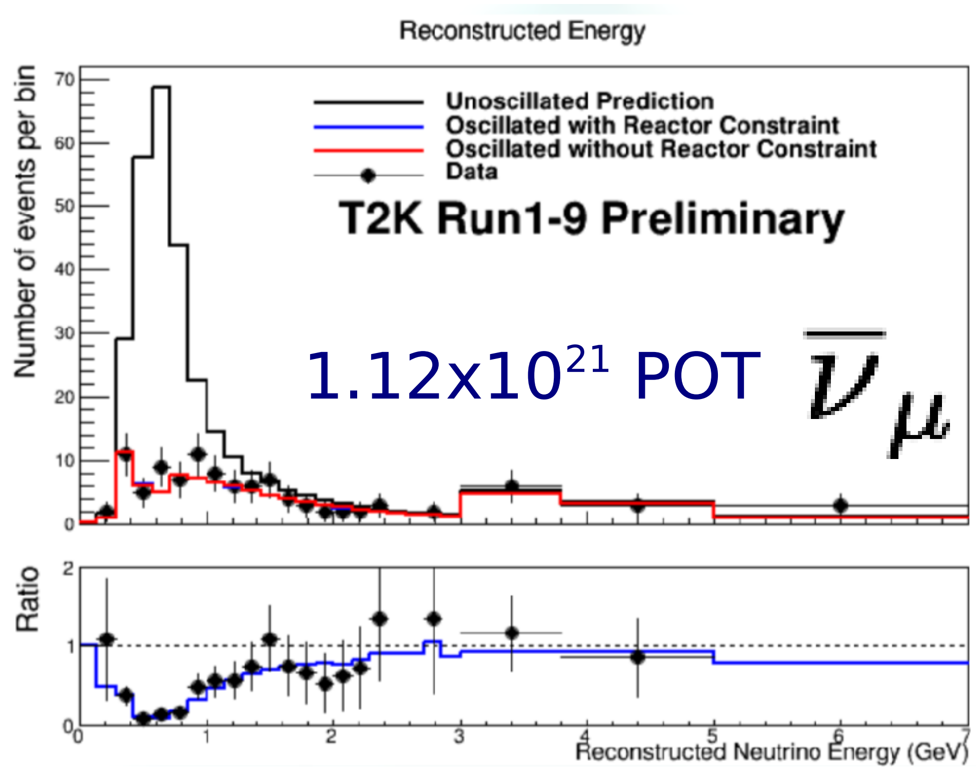
Super-K Predicted Spectra
(PDG2016 Oscillations)



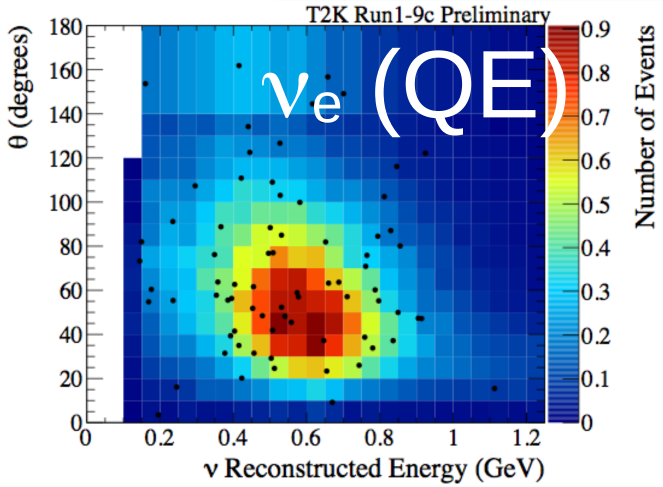
Super-K Data



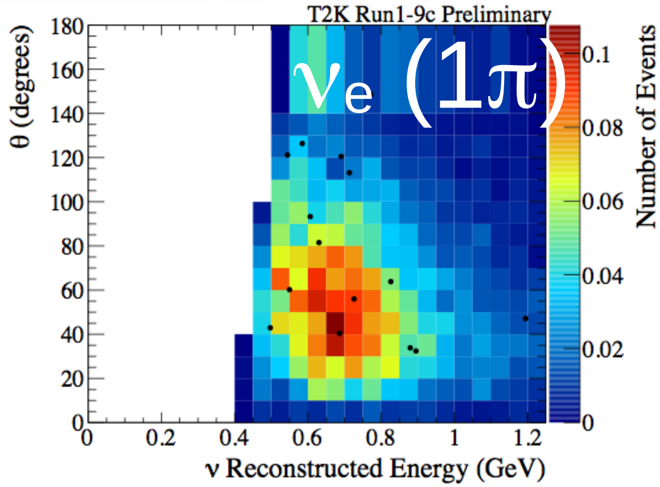
Reconstructed Energy
Unoscillated Prediction
Oscillated with Reactor Constraint
Oscillated without Reactor Constraint
Data
T2K Run1-9 Preliminary
1.49x10^21 POT
ν_μ
Number of events per bin
Ratio
Reconstructed Neutrino Energy (GeV)



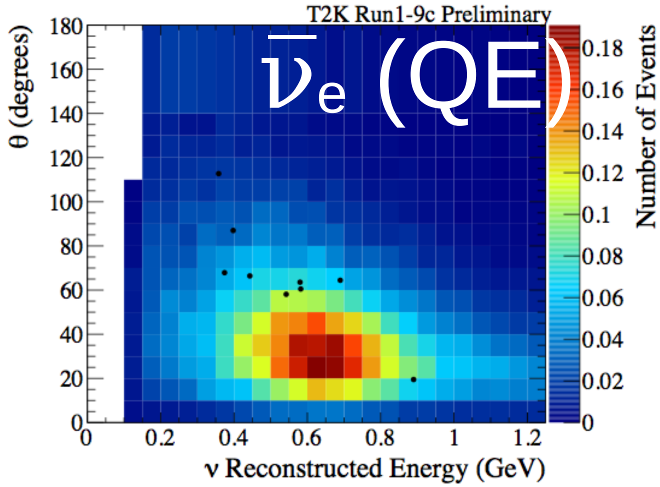
Reconstructed Energy
Unoscillated Prediction
Oscillated with Reactor Constraint
Oscillated without Reactor Constraint
Data
T2K Run1-9 Preliminary
1.12x10^21 POT
ν̄_μ
Number of events per bin
Ratio
Reconstructed Neutrino Energy (GeV)



T2K Run1-9c Preliminary
ν_e (QE)
θ (degrees)
Number of Events
ν Reconstructed Energy (GeV)



T2K Run1-9c Preliminary
ν_e (1π)
θ (degrees)
Number of Events
ν Reconstructed Energy (GeV)



T2K Run1-9c Preliminary
ν̄_e (QE)
θ (degrees)
Number of Events
ν Reconstructed Energy (GeV)

Super-K Event Rates

	Predicted				Observed
δ_{CP} =	-π/2	0	+π/2	π	
FHC 1Rμ	268.5	268.2	268.5	268.9	243
RHC 1Rμ	95.5	95.3	95.5	95.8	102
FHC 1Re No decay e	73.8	61.6	50.0	62.2	75
FHC 1Re 1 decay e	6.9	6.0	4.9	5.8	15
RHC 1Re 0 decay e	11.8	13.4	14.9	13.2	9

HIGH

LOW

Consistent with three-flavour osc, p-value ~0.05

Oscillation Analyses

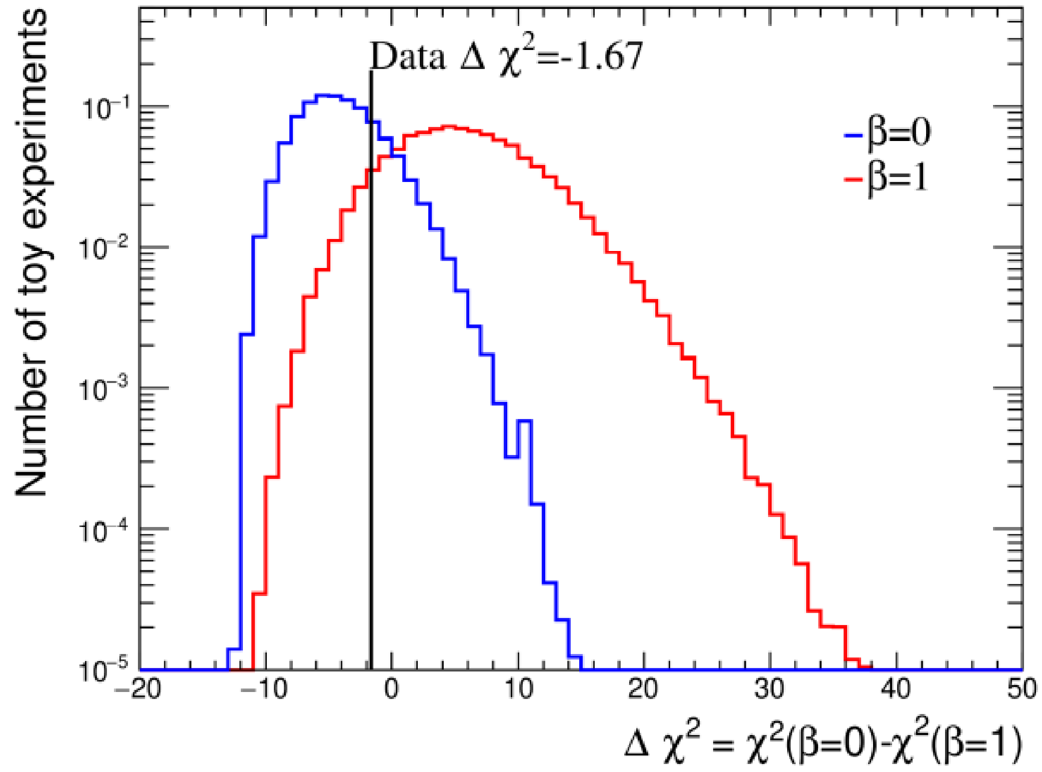
- I'll be presenting several different outputs from the oscillation analysis.
- We search for electron antineutrino appearance, looking for a discovery of this phenomenon.
- We attempt to use full joint-fitting to evaluate $\sin^2\theta_{13}$ and δ_{CP}.
  - We produce δ_{CP} confidence regions both using T2K-only data and by using the precise constraint on $\sin^2\theta_{13}$ from reactors.
- We also perform precision measurements on the atmospheric parameters $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$.
  - Driven by ν_μ / $\bar{\nu}_\mu$ disappearance.
  - This also allows a study of the neutrino mass ordering.

Electron Antineutrino Appearance

Two hypotheses:

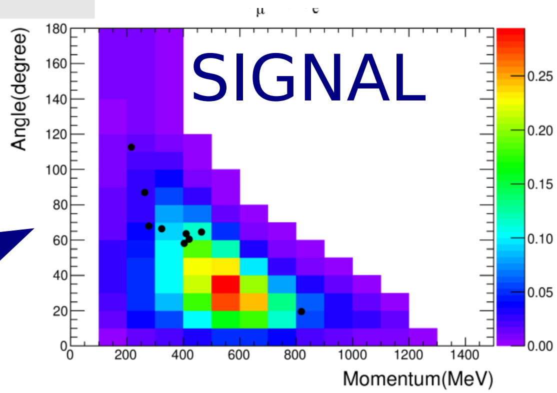
Standard PMNS $\bar{\nu}_e$ appearance (β=1) and no $\bar{\nu}_e$ appearance (β=0)

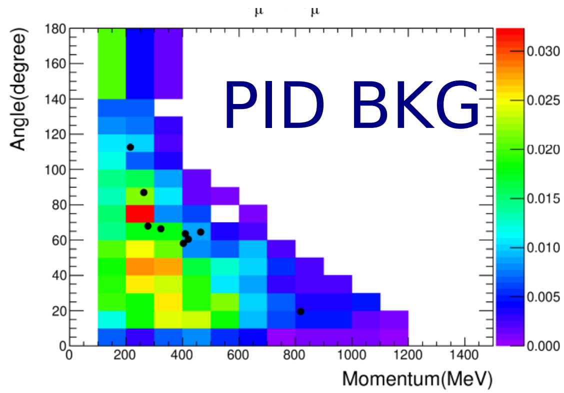
β	Hypothesis	P-Value
β=0	No $\bar{\nu}_e$ Appearance	P=0.233
β=1	PMNS $\bar{\nu}_e$ Appearance	P=0.0867



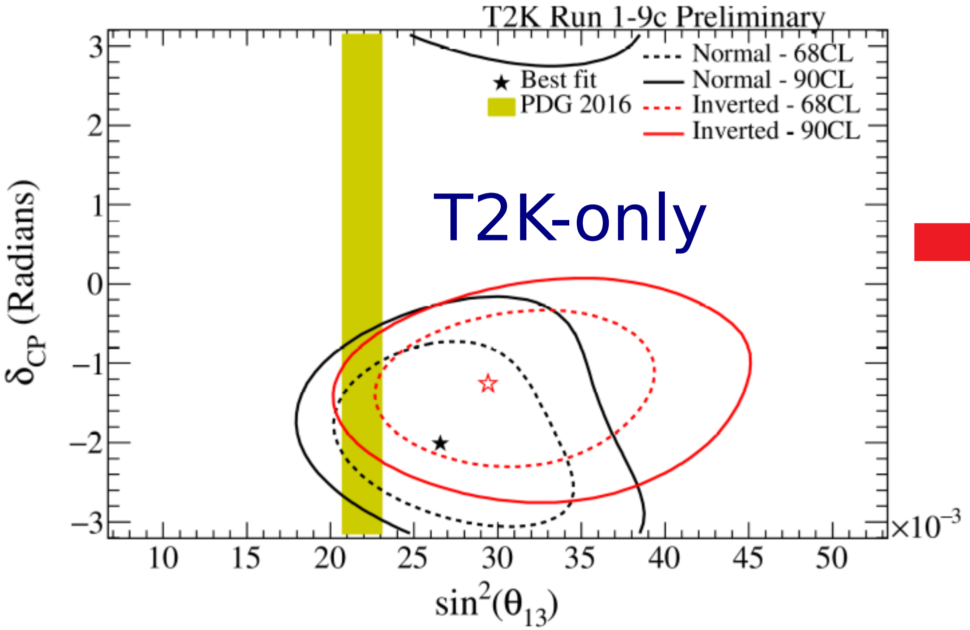
No evidence yet!

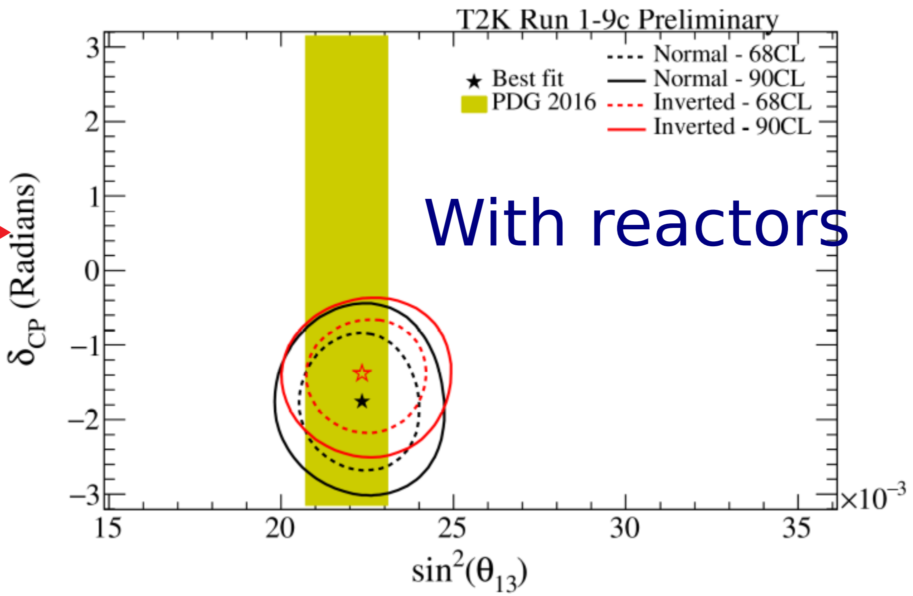
Event distribution is also consistent with background

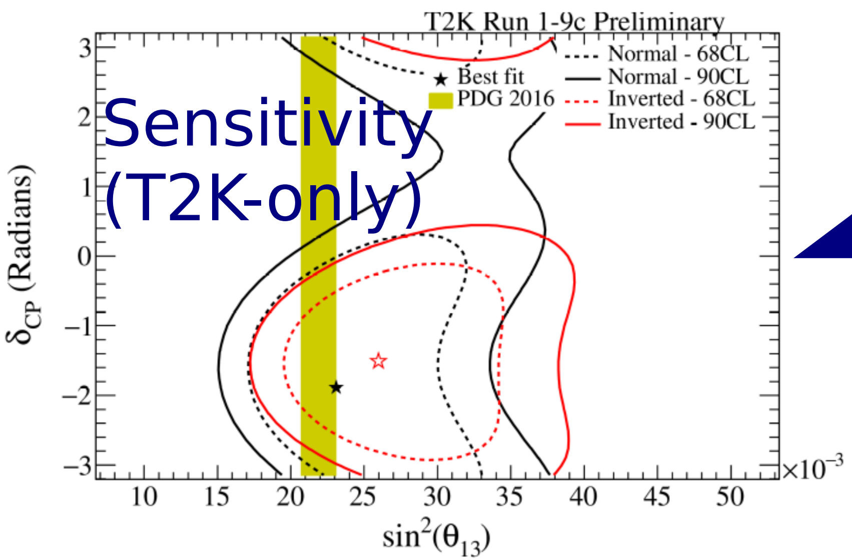




Joint Fits for CP Violation - 2D

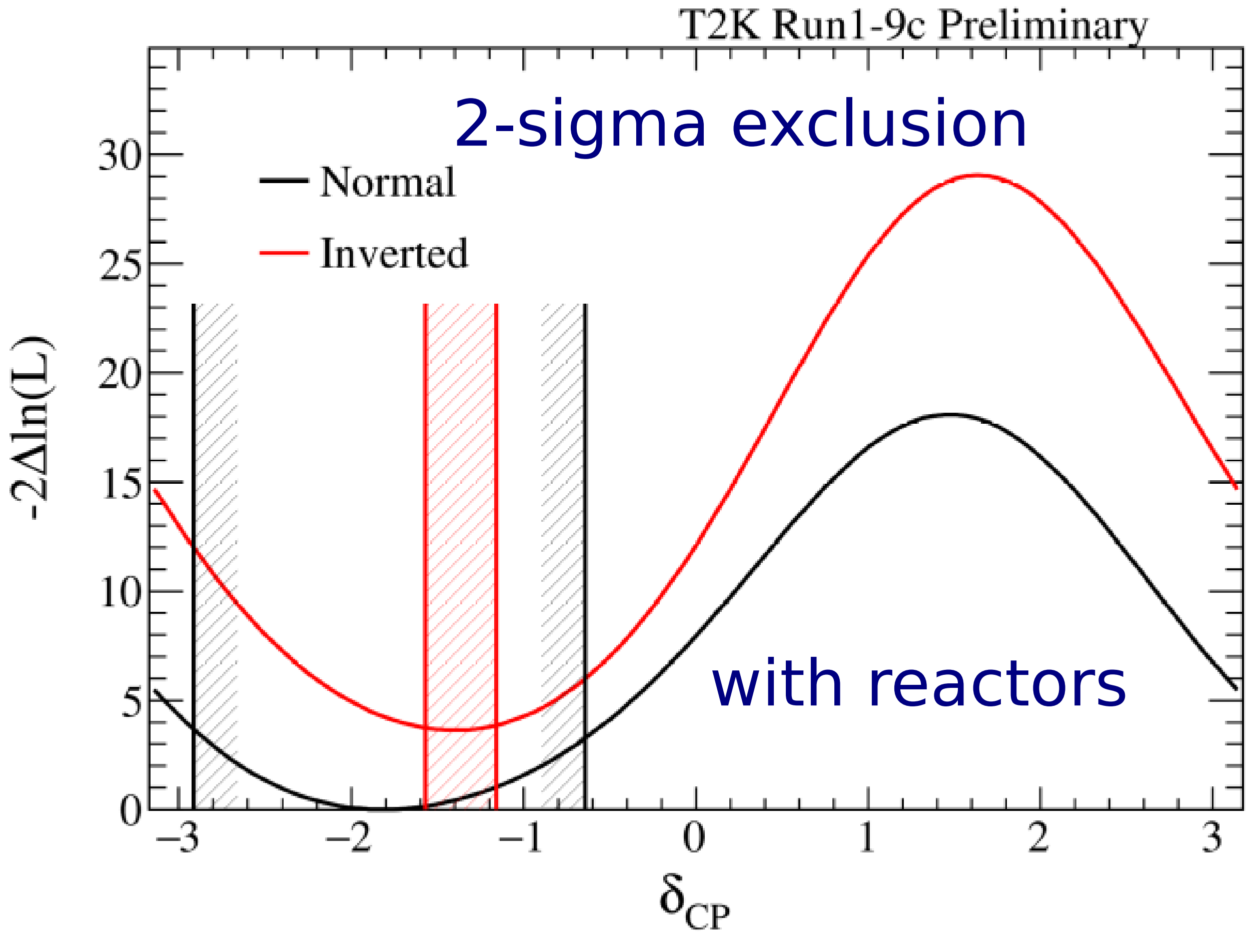






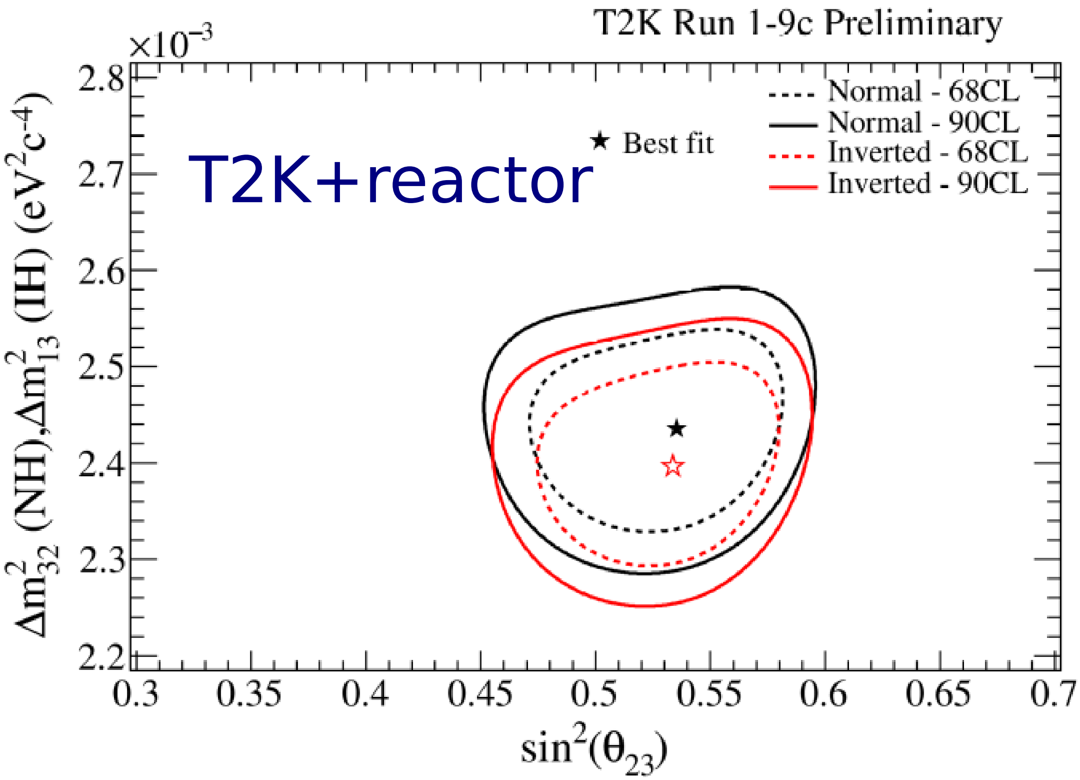
Data fit gives a stronger constraint than the predicted sensitivity given PDG2016 value $\sin^2\theta_{13}$=0.0219

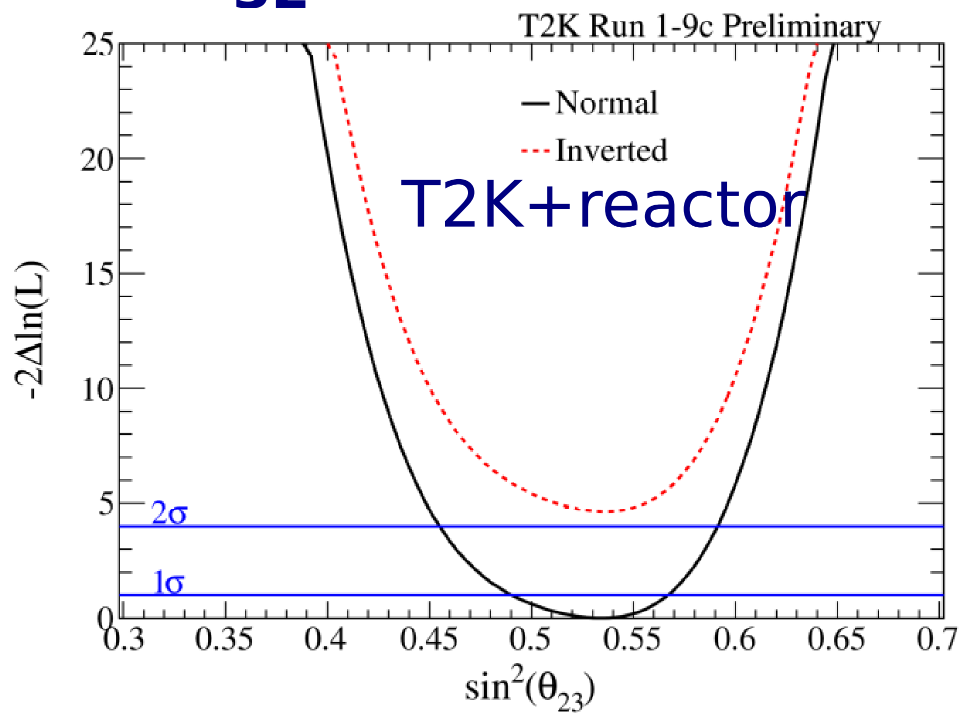
CP Violation - 1D



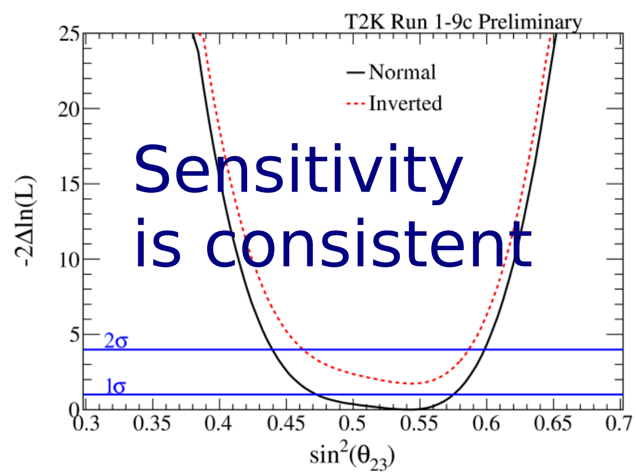
CP conserved values fall outside 2-sigma region for both mass orderings!

$\sin^2\theta_{23}$ vs $|\Delta m^2_{32}|$



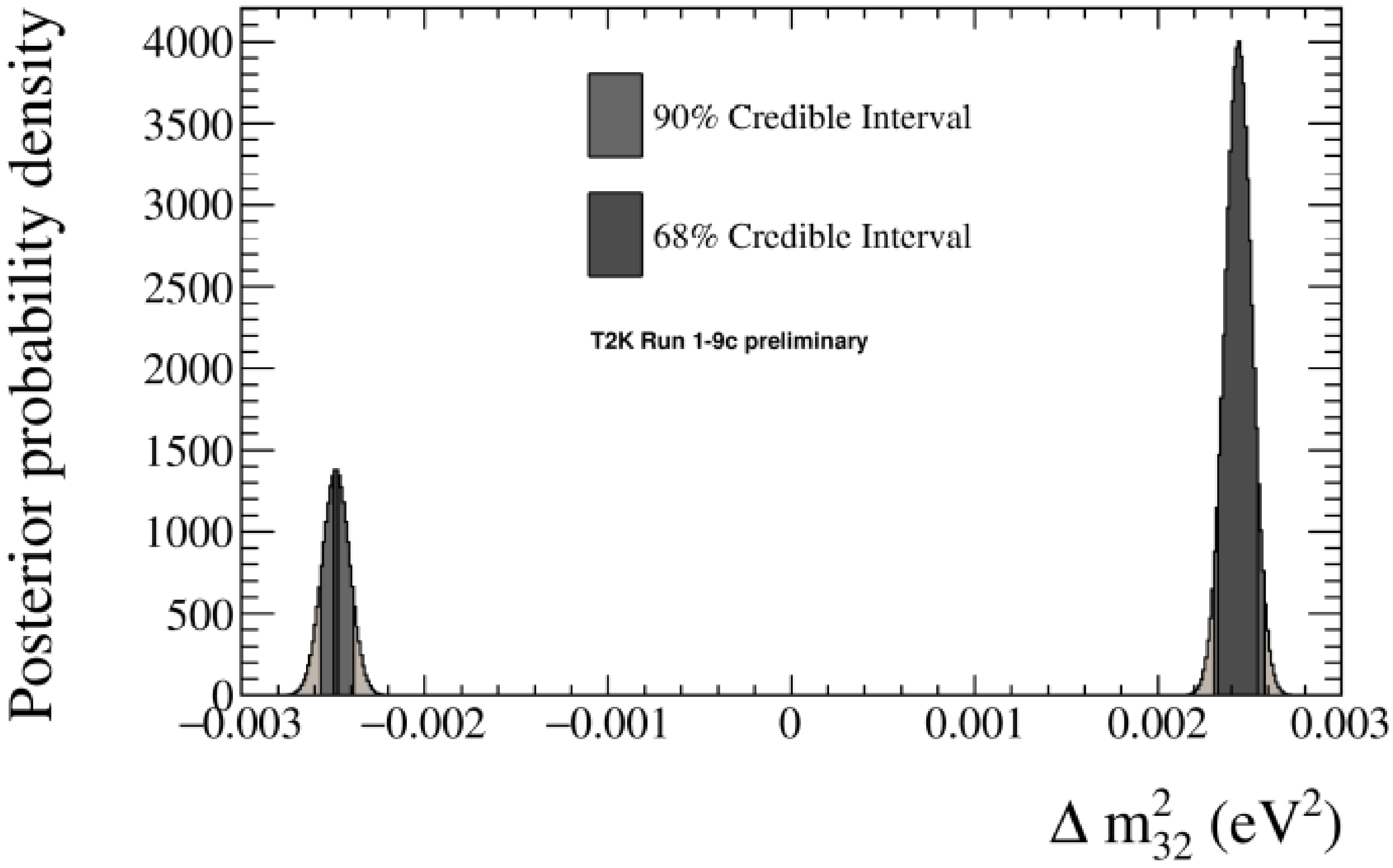


	Normal	Inverted
$\sin^2\theta_{23}$	$0.536^{+0.031}_{-0.046}$	$0.536^{+0.031}_{0.041}$
$\|\Delta m^2\|$ (10^{-3} eV^2)	2.434 ± 0.064	$2.410^{+0.062}_{-0.063}$



Mass Ordering

- We also perform Bayesian analysis, and use this to express our confidence about the mass ordering.
- Currently, we see a Bayes factor of 7.9, preferring normal to inverted ordering.



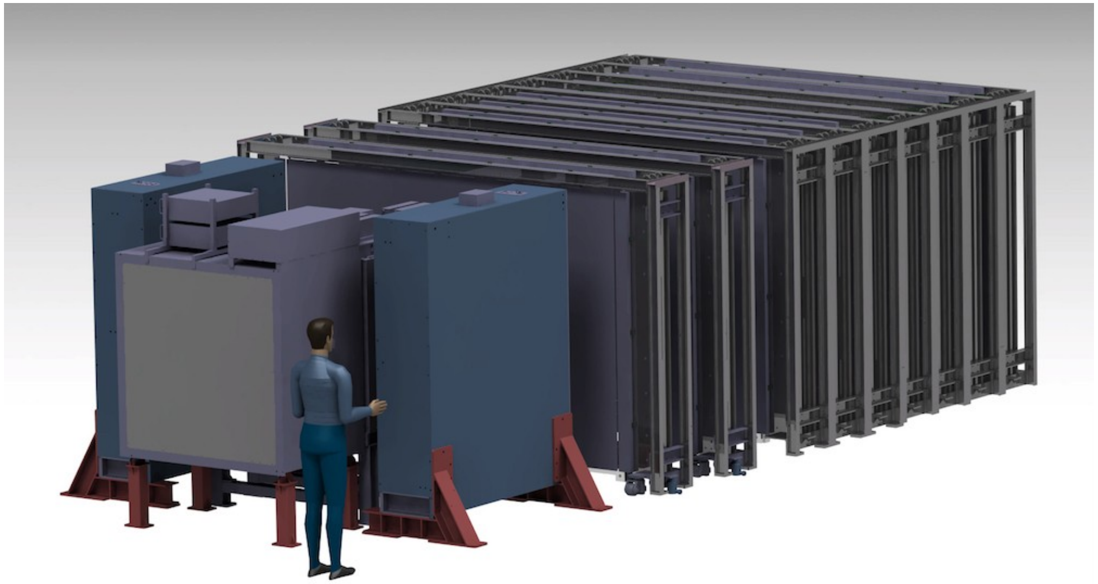
The Future of T2K

- New near-detectors constructed at J-PARC.
  - WAGASCI (Water Grid and Scintillator) modules installed both on and off-axis.
  - Baby MIND (Magnetised Iron Neutrino Detector) installed as spectrometer for WAGASCI.
- Super-K being upgraded with Gadolinium doping to allow neutrino/antineutrino separation via neutron capture.
- Extension to T2K running period (“T2K-II”).
  - “Stage 1” approval from KEK/J-PARC.
  - Upgrade to Main Ring power.
  - Allows 3-sigma median CP violation sensitivity.
- Upgrade to the ND280 near detector has been proposed

WAGASCI and BabyMIND

- WAGASCI (Water Grid and Scintillator) modules installed in both on-axis and off-axis locations.
  - Measures neutrino interaction cross-sections on water and carbon.

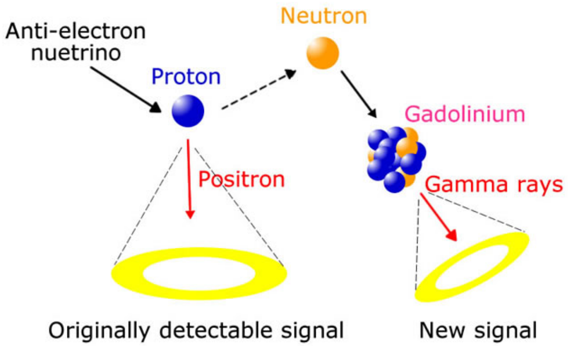
- BabyMIND:
  - Magnetised Iron Neutrino Detector
  - Constructed at CERN
  - Installed in ND280 complex this year.
  - Serves as a spectrometer and charge-ID for WAGASCI.



WAGASCI and BabyMIND

Super-K Gadolinium Upgrade

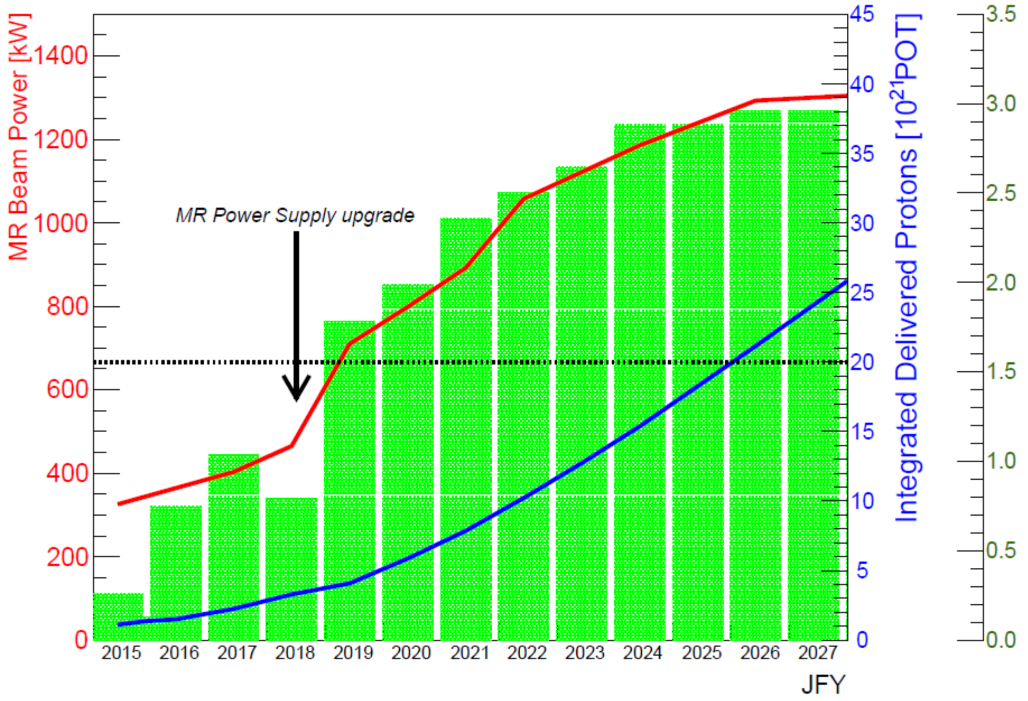
- For the first time in a decade, the Super-K tank is open.
- There are ongoing repairs and maintenance to the tank.
- This will be followed by two phases of gadolinum-doping for the water target.
  - First 0.02% Gd, offering 50% neutron capture rate.
  - Later 0.2% Gd, offering 90% neutron capture rate.
- ^{157}Gd has a very high neutron capture cross-section.
- Delayed coincidence emission of 8 MeV photons can be used to tag antineutrinos.
- Allows charge discrimination:
  - Greater CP-violation sensitivity.
  - And inprovements to many other SK targets.

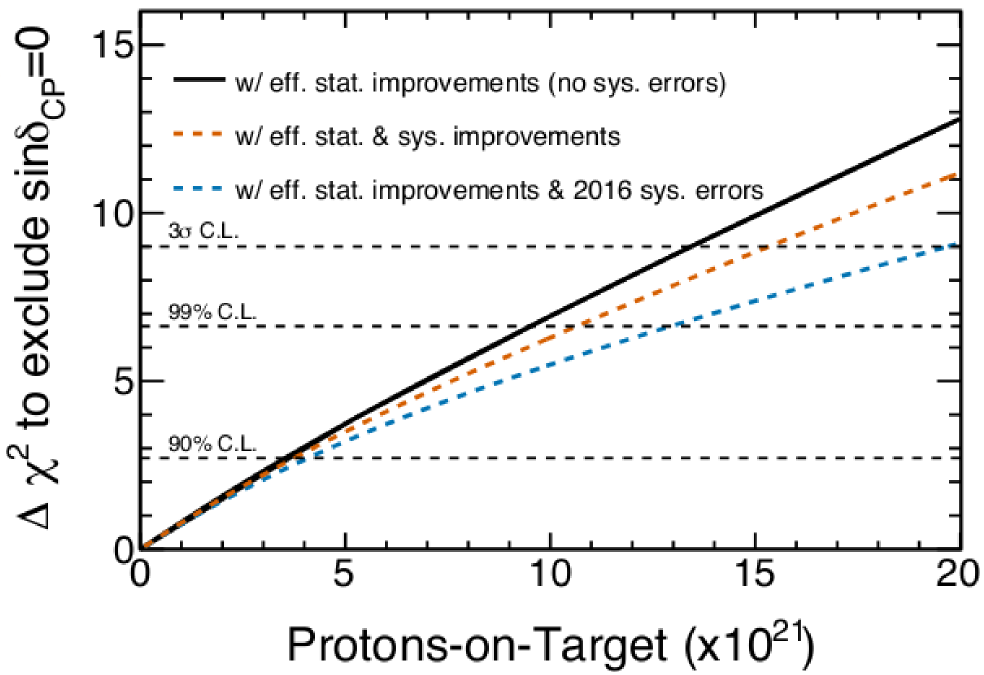


T2K-II Motivation

- T2K's primary goal is now observation of CP violation in the neutrino sector.
- With the large value of $\sin^2\theta_{13}$ observed, it is now worth extending the T2K-run period:
  - See arXiv:1609.04111
  - T2K's original POT target was 7.8×10^{21} POT.
  - We propose extending this to 20×10^{21} POT.
  - This allows up to 3σ median CPV sensitivity.

arxiv:1609.04111



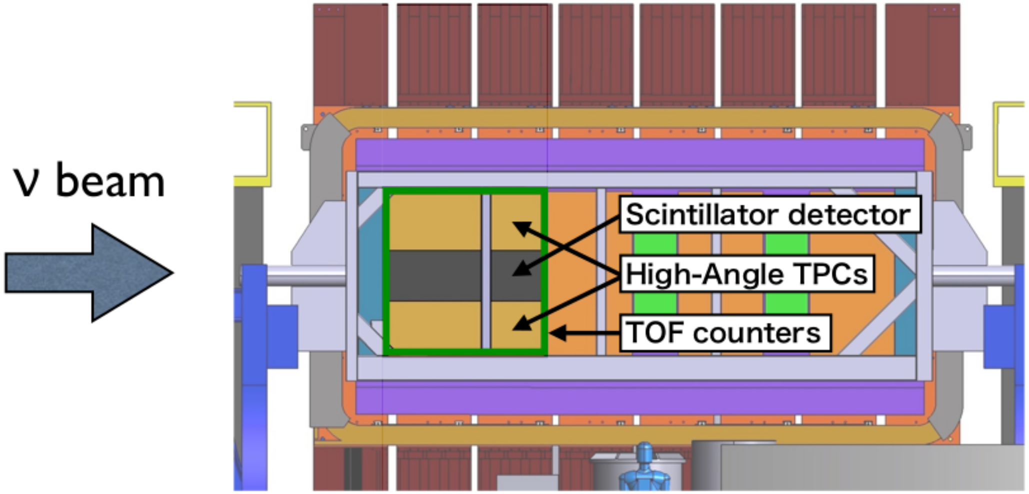


ND280 Upgrade

- Next generation upgrade for ND280.
  - Want complete polar angular coverage for muons.
  - Fiducial mass of a few tonnes.
  - High efficiency 4π tracking of pions and protons in the active volume.
  - Reduce systematic uncertainties at SK to 3-4%.
- Submitted to CERN SPSC as part of the CERN neutrino platform.
  - TDR by end of the year.
  - Installing in 2021.

- Replace P0D with scintillator detector.
- Add high angle TPCs and TOF measurement.
- Keep old tracker and ECal.

ND280 upgrade configuration



Conclusions

- T2K has significantly increased the size of its dataset this year, up to 3.16×10^{21} protons-on-target.
- With an analysis of 2.61×10^{21} POT split between FHC and RHC, we exclude CP-conservation at 2-sigma.
  - Expect full 3.16×10^{21} dataset analysis this year.
- T2K dataset shows a preference for the normal mass ordering.
  - Bayes factor of 7.9
- Many sets of upgrades on the way and we expect continued stable beam running.
  - Potential to see evidence for CP-violation in the lepton sector with the current generation of experiments!

Thanks for listening

Backup

Mass Ordering

- We also perform Bayesian analysis, and use this to express our confidence about the mass ordering.
- Currently, we see a Bayes factor of 7.9, preferring normal to inverted ordering:
  - eg $K=10^{-0.9}$ against the inverted mass ordering.
- Rule of thumb for interpreting these, from The Theory of Probability (Jeffreys, 1961):

Grade 0. $K > 1$. Null hypothesis supported.

Grade 1. $1 > K > 10^{-1/2}$. Evidence against q, but not worth more than a bare mention.

Grade 2. $10^{-1/2} > K > 10^{-1}$. Evidence against q substantial.

Grade 3. $10^{-1} > K > 10^{-3/2}$. Evidence against q strong.

Grade 4. $10^{-3/2} > K > 10^{-2}$. Evidence against q very strong.

Grade 5. $10^{-2} > K$. Evidence against q decisive.

Then again, most fields have less strict standards for statistical significance than us...