LONG BASELINE NEUTRINO OSCILLATIONS WITH T2K AND DUNE

SEMINÁRIO LIP

JULY 30TH, 2019

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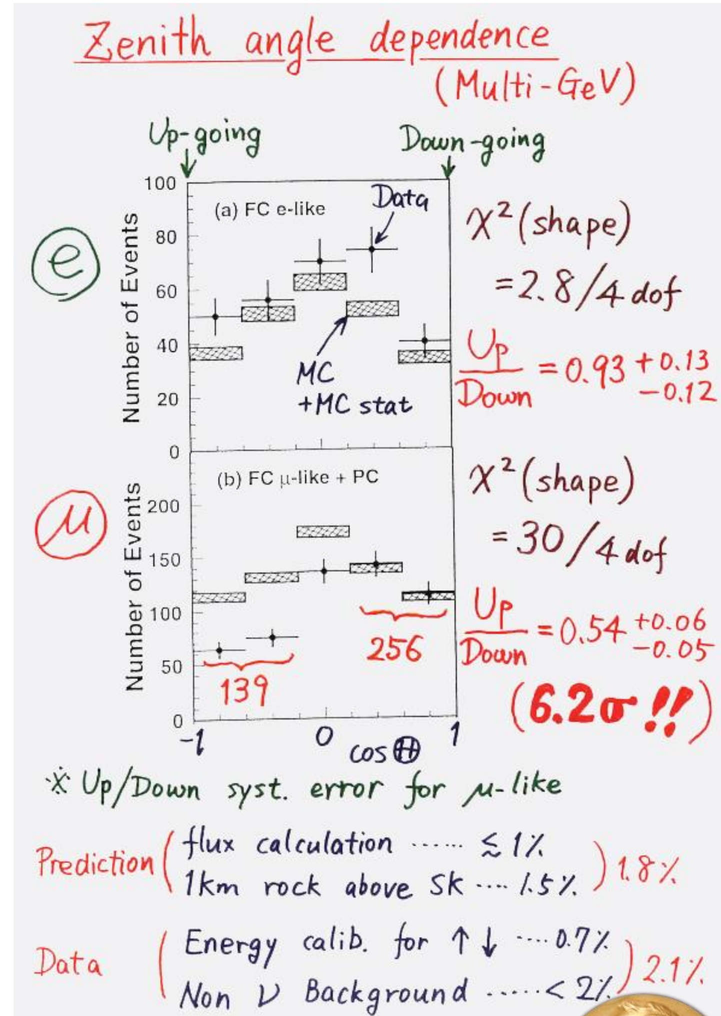
WHY MEASURE NEUTRINO OSCILLATIONS?

- First evidence for neutrino oscillations from Super-Kamiokande and Sudbury Neutrino Observatory ~20 years ago.
- Implication: have finite **mass** states and their mass and flavour states **mix.**
  - Neutrino mass was not foreseen in original formulation of the Standard Model.
- This opens up a set of questions:
  - Are neutrinos their own anti-particles and why is their mass so small?
  - Is there CP violation in the lepton sector?
  - What are the precise values of the neutrino mixing parameters?
  - Does the standard model + neutrino mass and mixing picture describe nature accurately?



T. Kajita, Neutrino 1998

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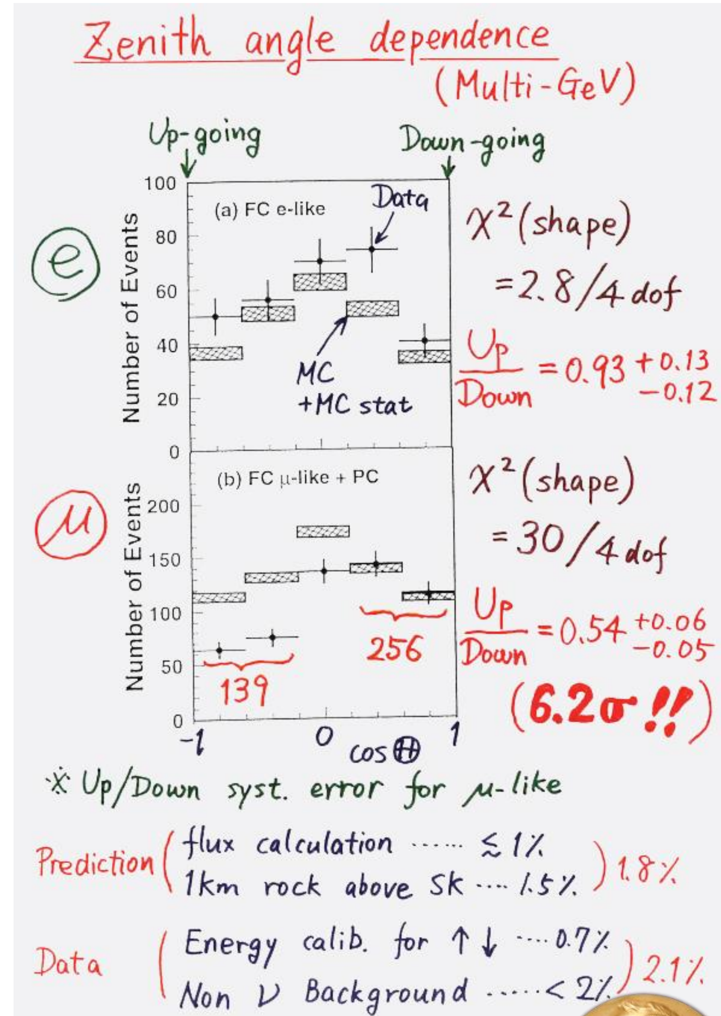
Neutrino oscillations



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NEUTRINO MIXING AND MASS

- The Pontecorvo-Maki-Nakagawa-Sakata (**PMNS**) matrix.

Weak / Flavor states

“Atmospheric” parameters

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1&0&0\\0&\cos\theta_{23}&\sin\theta_{23}\\0&-\sin\theta_{23}&\cos\theta_{23}\end{pmatrix} \begin{pmatrix}\cos\theta_{13}&0&\sin\theta_{13}e^{-i\delta_{CP}}\\0&1&0\\-\sin\theta_{13}e^{+i\delta_{CP}}&0&\cos\theta_{13}\end{pmatrix} \begin{pmatrix}\cos\theta_{12}&\sin\theta_{12}&0\\-\sin\theta_{12}&\cos\theta_{12}&0\\0&0&1\end{pmatrix} \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

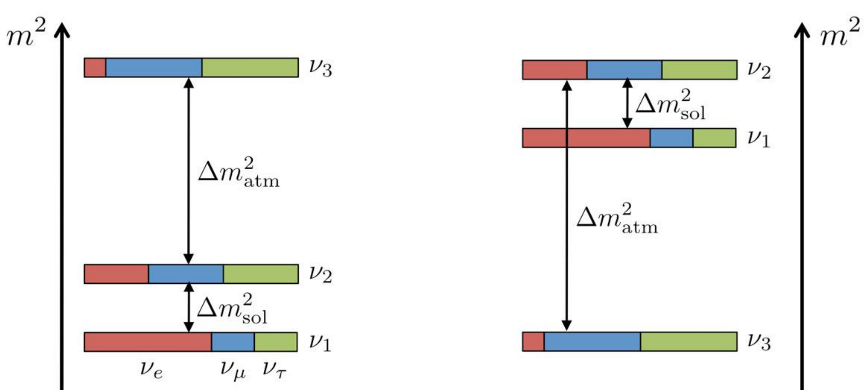
“Reactor” parameters

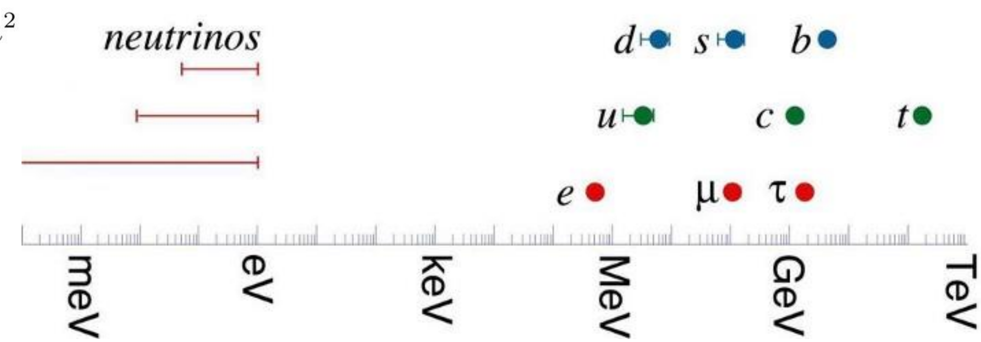
CP violating phase

“Solar” parameters

Mass states

normal hierarchy (NH) **inverted hierarchy (IH)**





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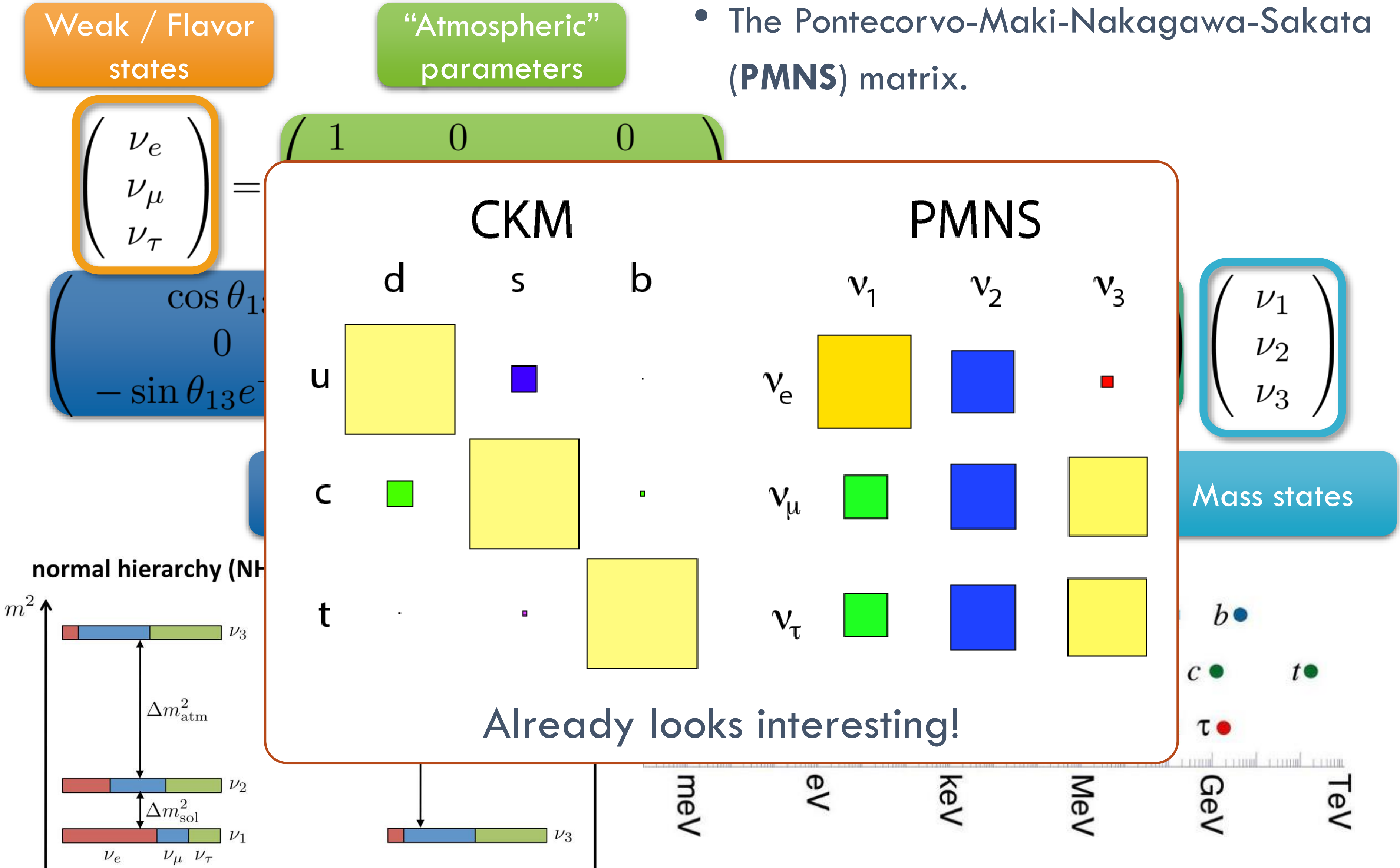


NEUTRINO OSCILLATIONS

$$\left(L/E\right)^{-1} \approx \Delta m^2_{atm}$$

$$P_{\mu\to x} \approx 1 - \left(\cos^4\theta_{13}\cdot\sin^2 2\theta_{23} + \sin^2\theta_{23}\cdot\sin^2 2\theta_{13}\right)\sin^2\left(\frac{\Delta m^2 L}{4E_\nu}\right)$$

Leading-term — Next-to-leading

$$P(\nu_\mu \to \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2\Delta_{31}$$ Leading-term — θ_{13}

$$+8c_{13}^2 s_{12}s_{13}s_{23}(c_{12}c_{23}\cos\delta - s_{12}s_{13}s_{23})\cos\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CPC

$$-8c_{13}^2 c_{12}c_{23}s_{12}s_{13}s_{23}\sin\delta\sin\Delta_{32}\sin\Delta_{31}\sin\Delta_{21}$$ CPV

$$+4s_{12}^2 c_{13}^2(c_{12}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12}c_{23}s_{12}s_{23}s_{13}\cos\delta)\sin^2\Delta_{21}$$ Solar

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

$$\Delta_{ij} = \Delta m^2_{ij}\frac{L}{4E_\nu}$$

Replace δ by –δ for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

Not shown:

Neutrino-matter interaction effect ∝ a:

$$a \equiv 2\sqrt{2}G_F n_e E = 7.56\times10^{-5}\,\mathrm{eV}^2\,\frac{\rho}{\mathrm{gcm}^{-3}}\,\frac{E}{GeV}$$

Replace a by -a for $P(\overline{\nu_\mu} \to \overline{\nu_e})$

NEUTRINO OSCILLATIONS

$$\left(L/_E\right)^{-1} \approx \Delta m^2_{atm}$$

Start with pure ν_μ beam and then look for:

ν_μ Disappearance: $P(\nu_\mu \rightarrow \nu_\mu)$

- Sensitivity to $|\Delta m^2_{32}|$ and θ_{23}.
- Is $\theta_{23} = 45^\circ$? If not, what octant?
  - Maximal mixing might indicate underlying symmetry.
- Test CPT invariance: $P(\nu_\mu \rightarrow \nu_\mu) \neq P(\bar{\nu}_\mu \rightarrow \bar{\nu}_\mu)$?

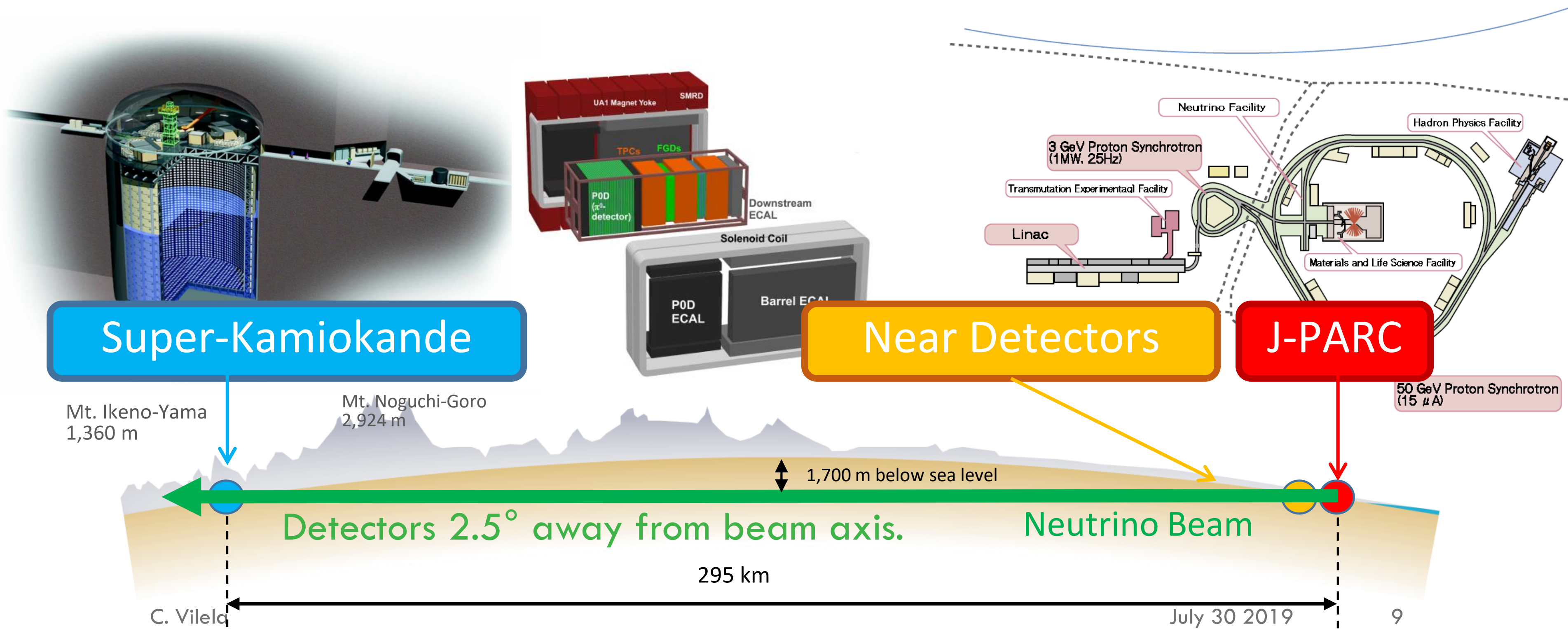
ν_e Appearance $P(\nu_\mu \rightarrow \nu_e)$

- Sensitivity to θ_{13}, δ_{CP}, θ_{23} octant and mass hierarchy through matter effect.
- If δ_{CP} not 0 or π, CP symmetry is **violated** in lepton sector.
- $P(\nu_\mu \rightarrow \nu_e)$ **enhanced** if hierarchy is **normal** or δ_{CP} ~-π/2
- $P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$ **enhanced** if hierarchy is **inverted** or δ_{CP} ~π/2
- **Matter** effect is ∝ E. Better sensitivity with higher E and longer L.

T2K

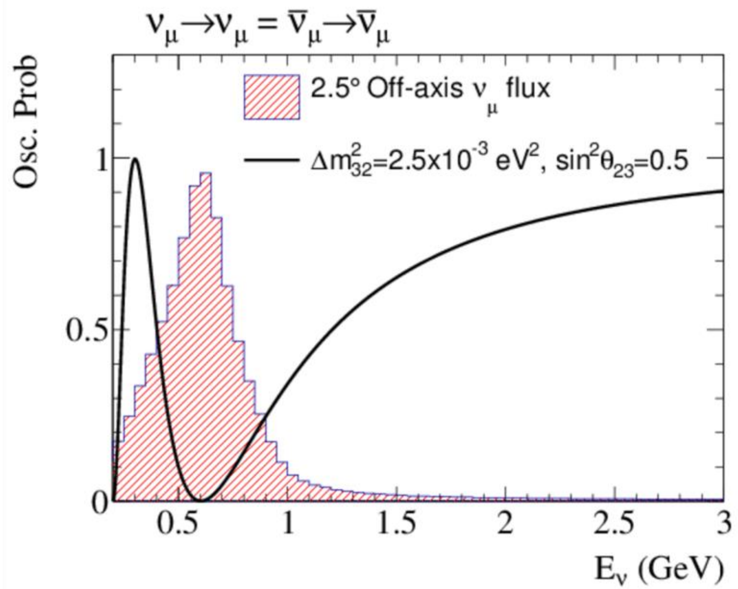
THE TOKAI-TO-KAMIOKA EXPERIMENT

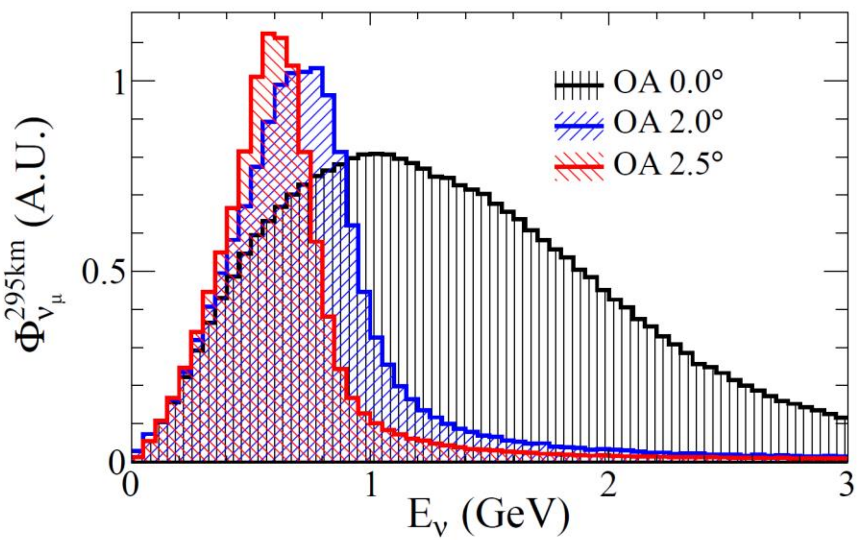
- Long baseline neutrino experiment located in Japan, running since 2010.
- First observation of electron-neutrino appearance in a muon-neutrino beam in 2013
  - Phys. Rev. Lett. 112, 061802 (2014).
- World-leading precision on θ_{23}, Δm^2_{32} and most stringent constraint on leptonic CP violation.

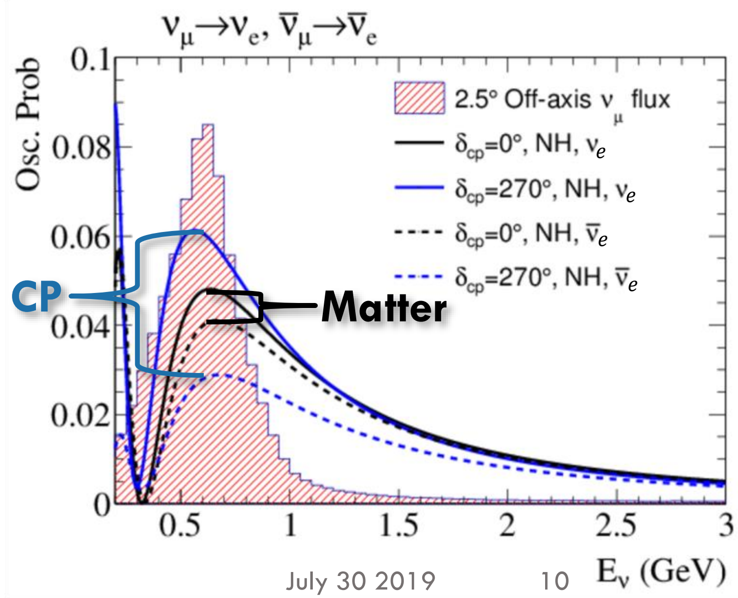


NEUTRINO OSCILLATIONS AT T2K

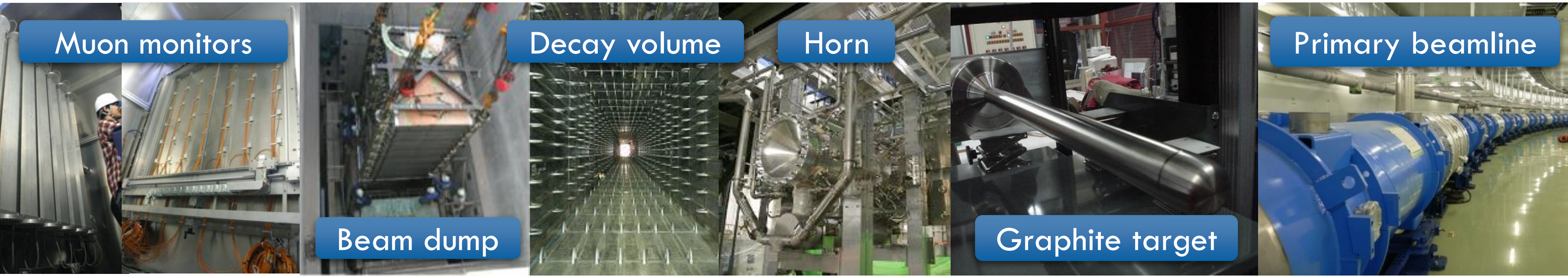
- Relatively short baseline of 295 km enhances effect of CP violation relative to matter effect.
- Detectors are placed 2.5° away from the beam centre.
  - Narrow neutrino flux peaked at oscillation maximum.

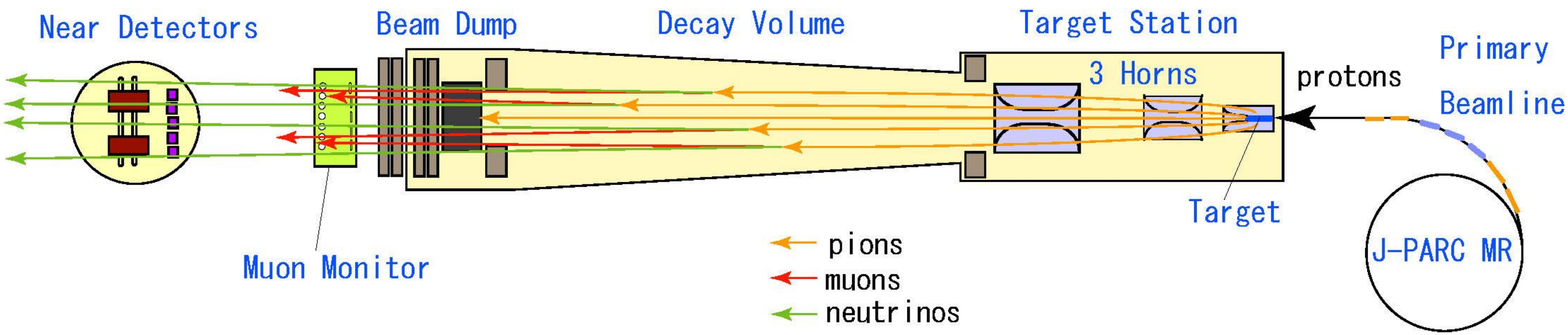






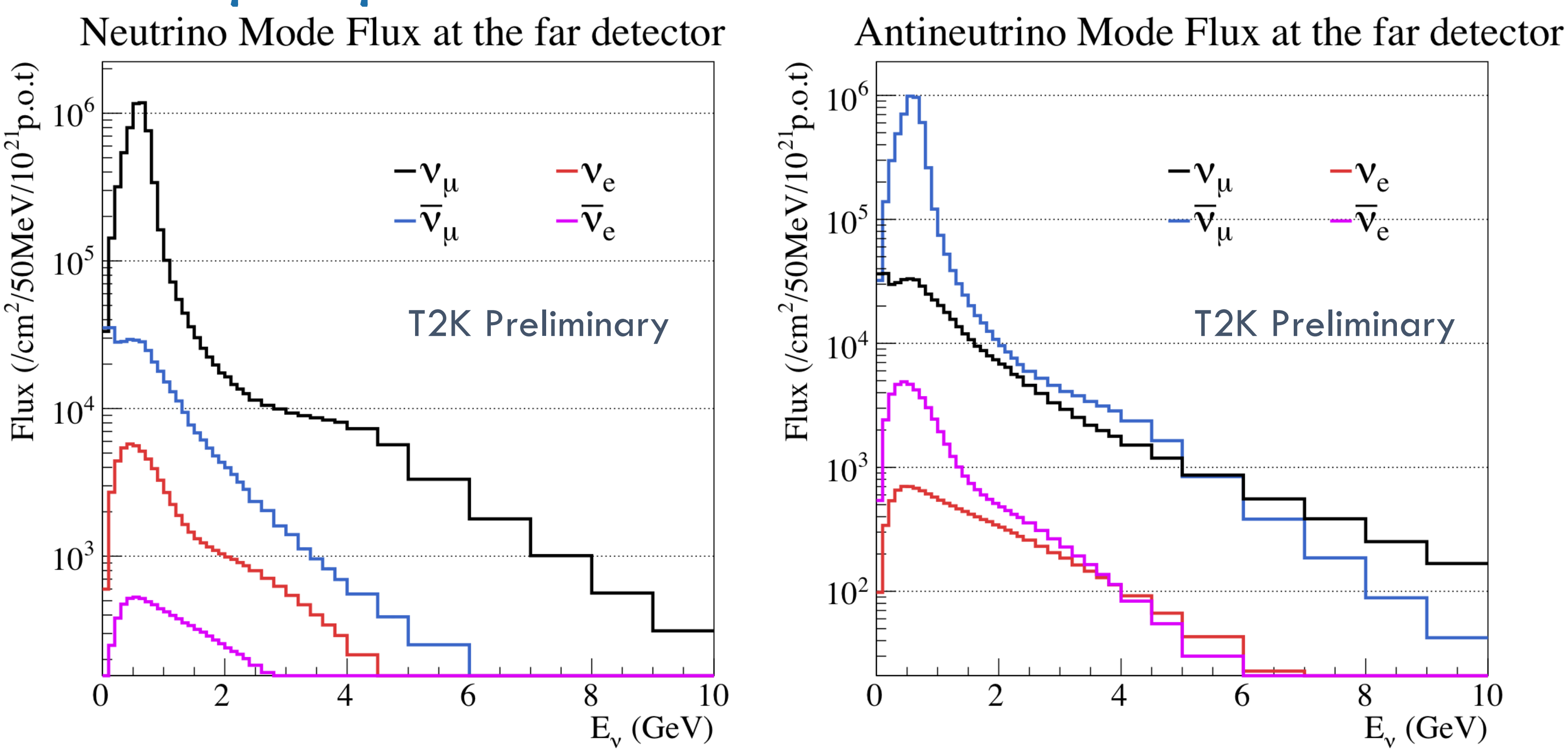
T2K BEAMLINE





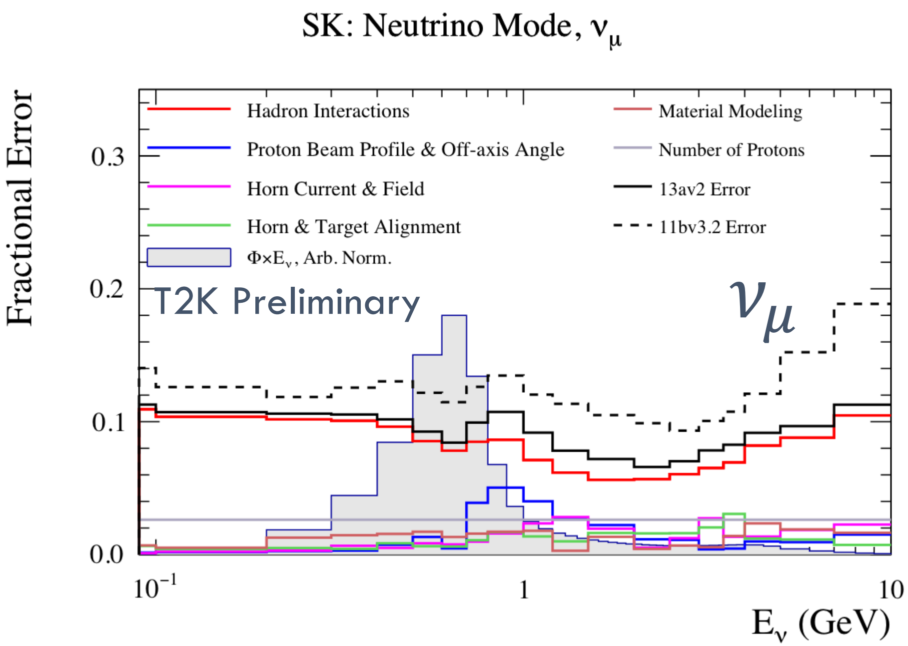
- Protons are extracted from the J-PARC 30 GeV Main Ring onto a graphite target via the superconducting primary beamline.
- $\pi^{\pm}$ focused by three magnetic horns and allowed to decay into $\mu^{\pm}$ and $\nu_{\mu}(\bar{\nu}_{\mu})$
  - Horn polarity determines charge of the focused $\pi^{\pm}$ and helicity of neutrinos in the Earth frame.
- Muon detectors downstream of beam dump monitor beamline stability.

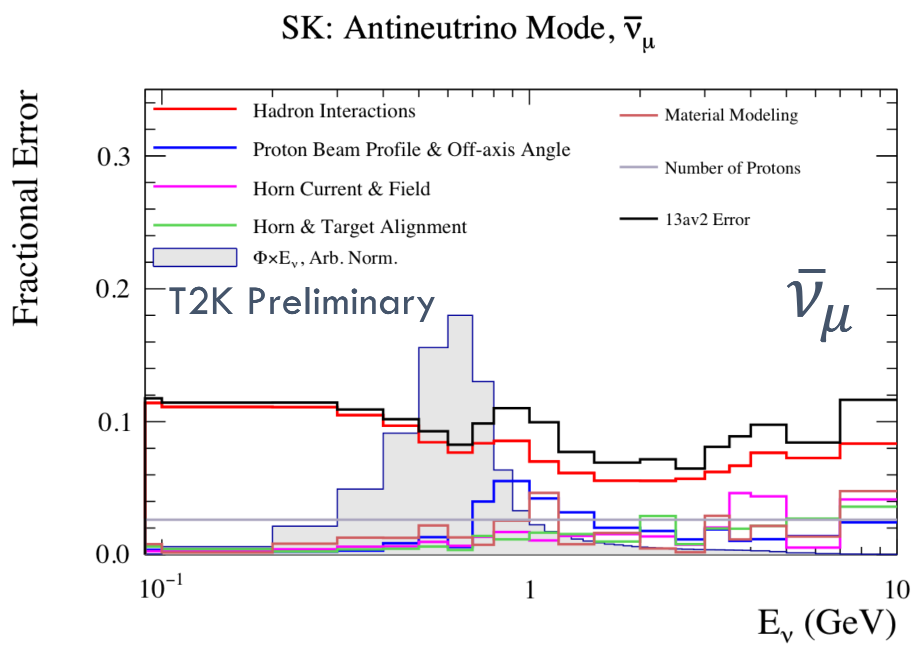
T2K $\nu_\mu(\bar{\nu}_\mu)$ FLUX



- Very low $\nu_e(\bar{\nu}_e)$ contamination. Less than 1% near oscillation maximum.
  - Irreducible background to $\nu_e(\bar{\nu}_e)$ appearance.
- Wrong-sign contamination more significant in antineutrino mode.

FAR DETECTOR $\nu_\mu(\bar{\nu}_\mu)$ FLUX UNCERTAINTIES



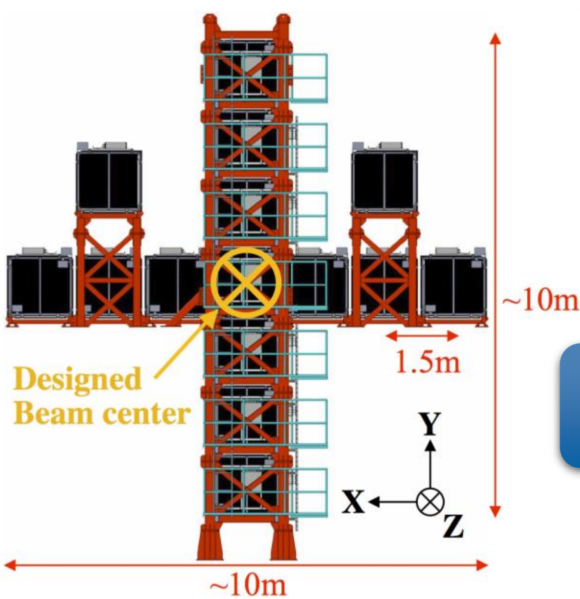


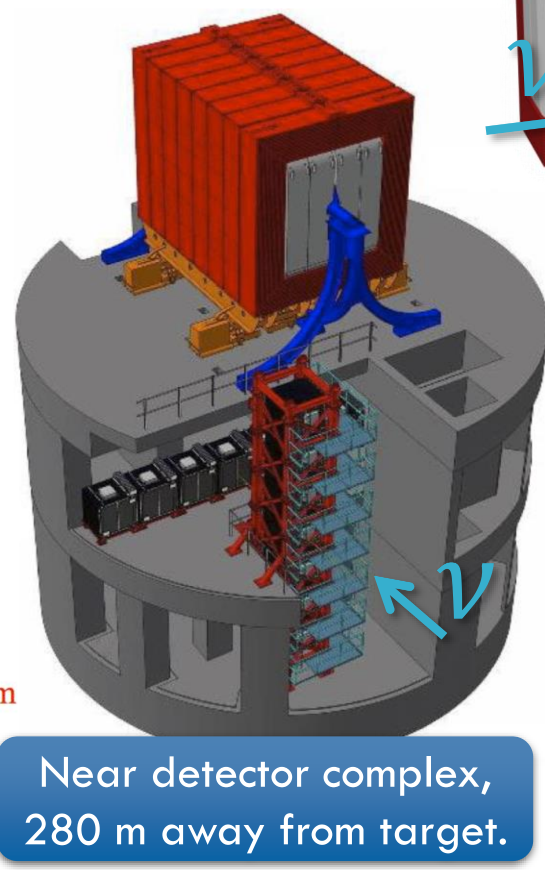
- Flux uncertainties dominated by hadron interaction in the target.
  - Constrained by external measurements at NA61/SHINE.
    - Prior to T2K near detector constraint, absolute flux uncertainties are ~10%.
    - Significant improvements expected from using full replica target at NA61 / SHINE.
      - Currently "thin" target data is used.
  - Significant cancellation in near-to-far oscillation analysis extrapolation.

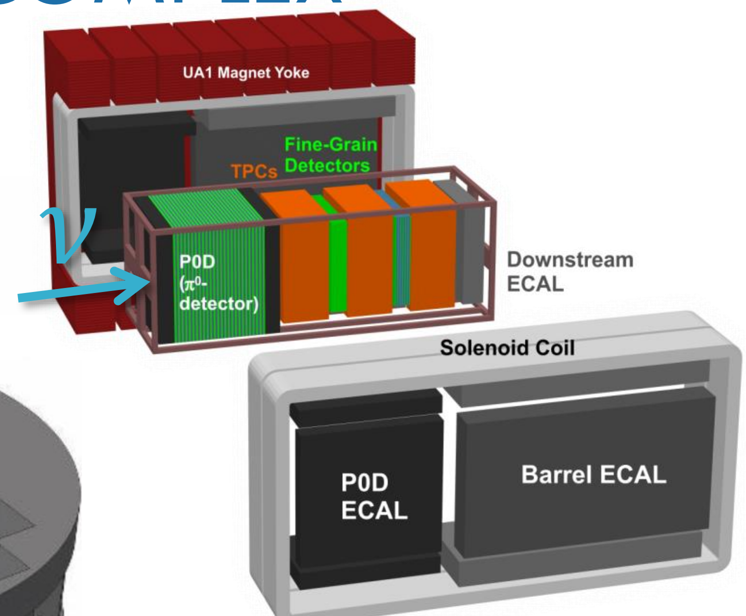
T2K NEAR DETECTOR COMPLEX

INGRID: on axis

- Plastic scintillator and iron neutrino detectors arranged in a grid perpendicular to beam axis.
- Beam stability monitoring with direction and rate measurements.





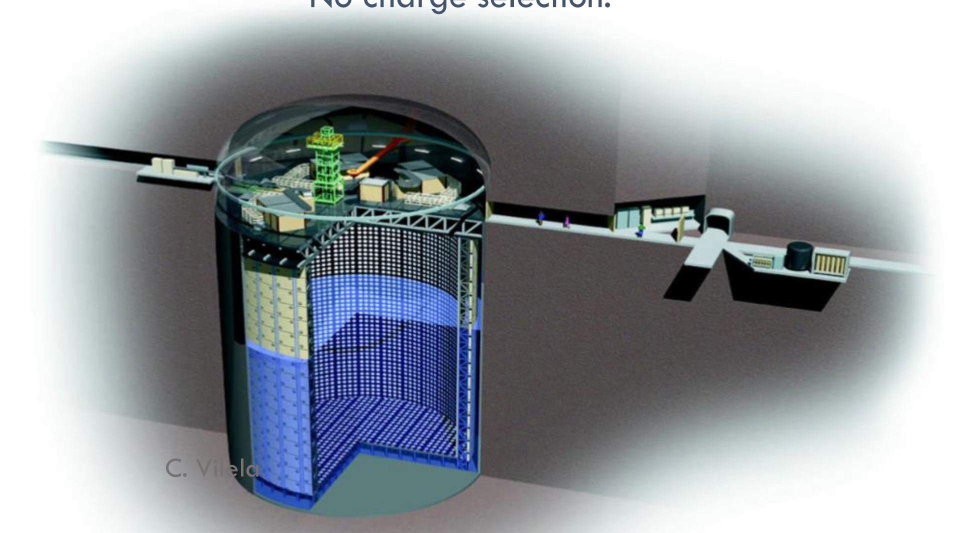


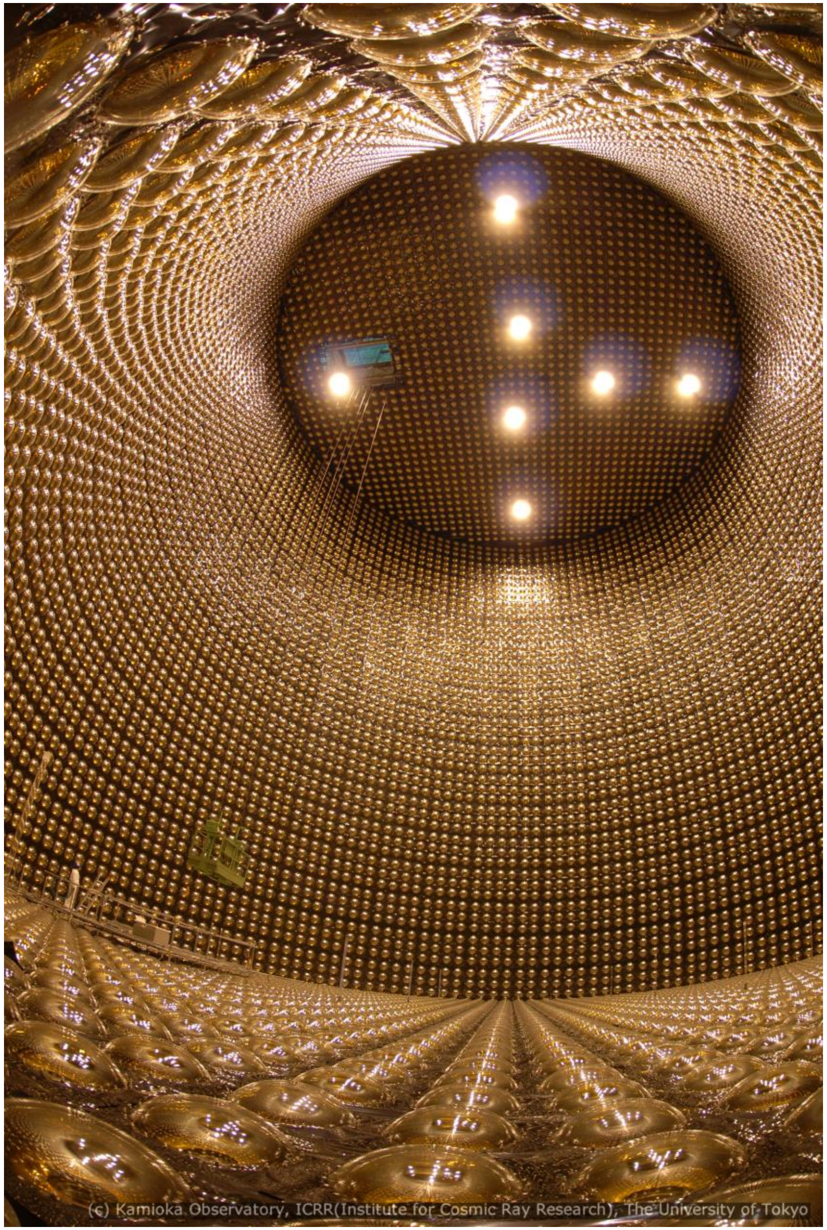
ND280: 2.5° off-axis

- Detectors in 0.2 T field generated by repurposed UA1/NOMAD magnet.
  - Identify μ^-/μ^+ from $\nu/\bar{\nu}$ interactions.
- Dedicated π^0 detector.
- Tracker composed of two plastic scintillator fine-grained detectors (FGDs) and three time projection chambers (TPCs).
- Plastic and **water** targets.

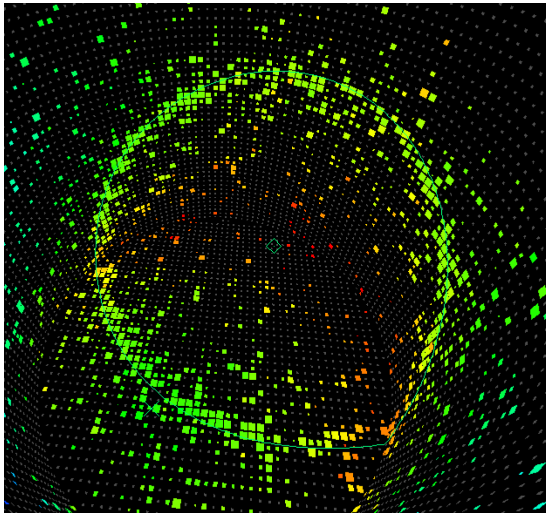
SUPER-KAMIOKANDE

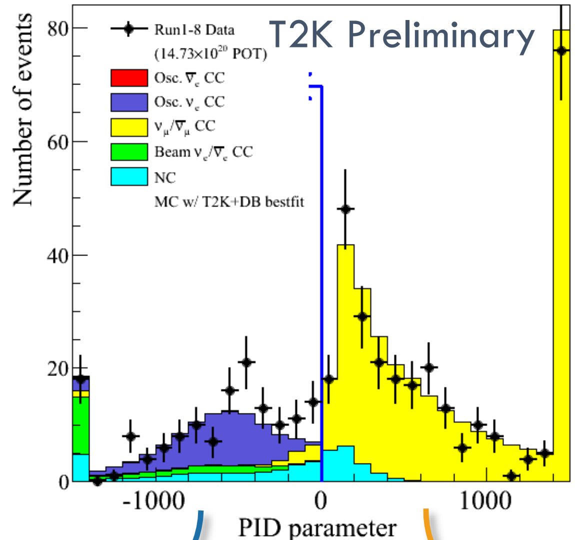
- 50 kiloton water-Cherenkov detector.
- Optically separated outer detector for tagging entering/escaping particles.
- ~11000 20” photomultiplier tubes (PMTs) facing the inner detector giving a photocathode coverage of 40%.
- ~2000 8” PMTs in the outer detector.
- Measure momentum and direction of particles above Cherenkov threshold.
  - Excellent $\mu^{\pm}/e^{\pm}$ separation.
  - No charge selection.

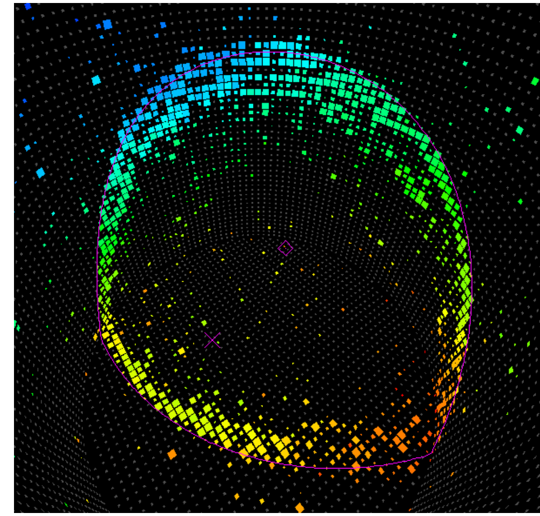




SUPER-KAMIOKANDE SAMPLES



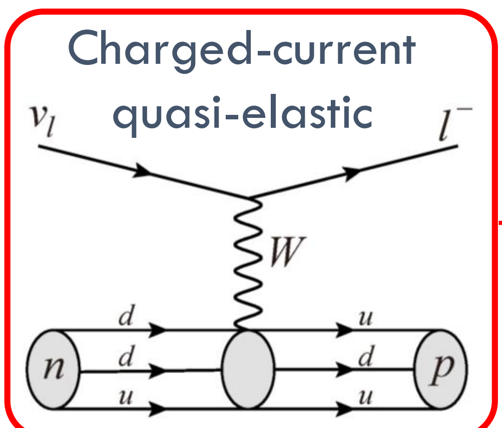


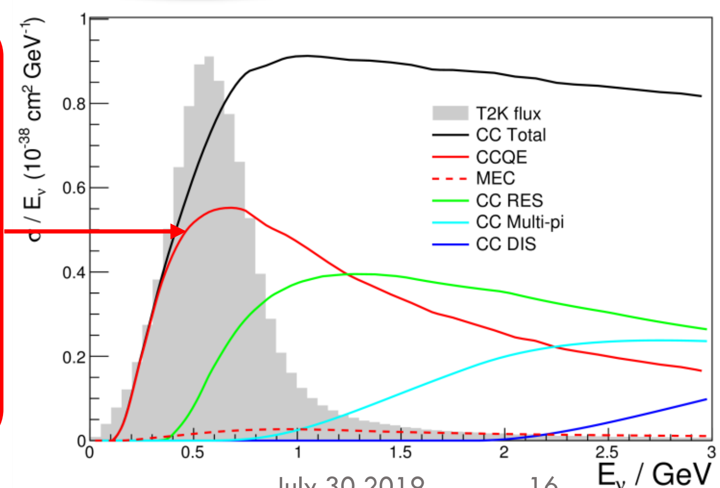


e-like ring

μ-like ring

- Hadronic system typically below Cherenkov threshold.
- Signal samples use single-ring events.
- Infer neutrino energy from lepton p and θ_{beam}.





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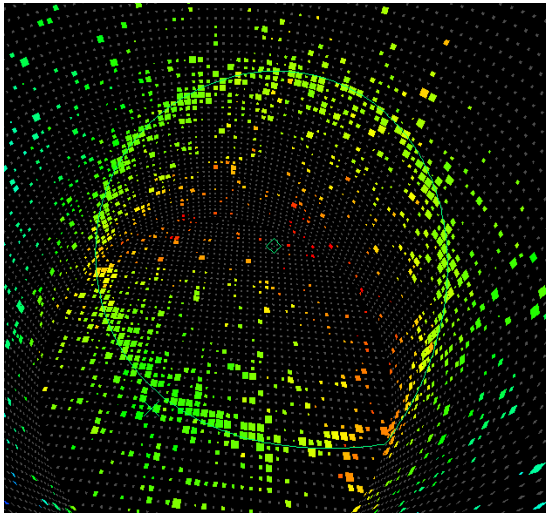
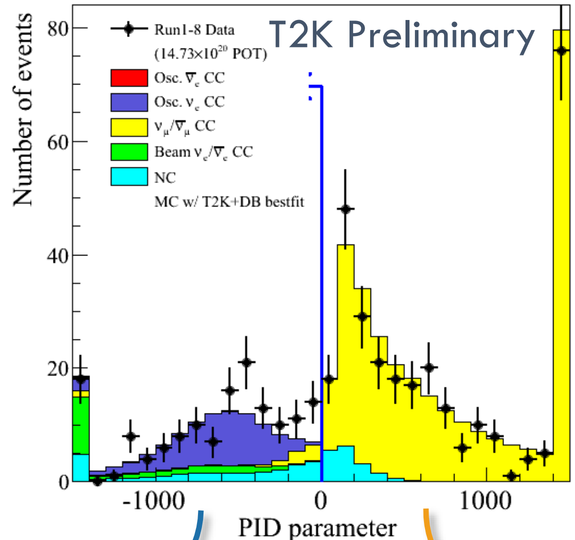
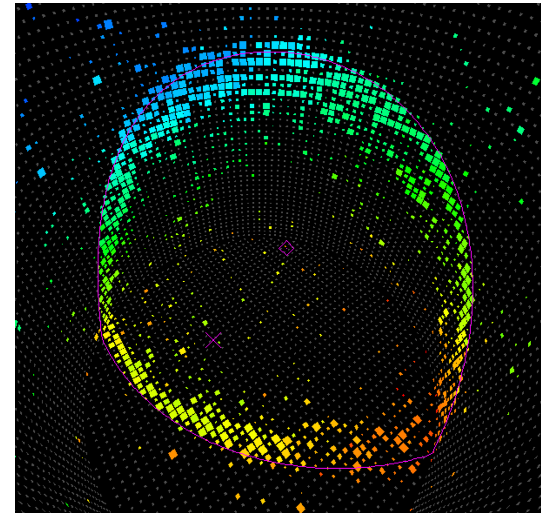


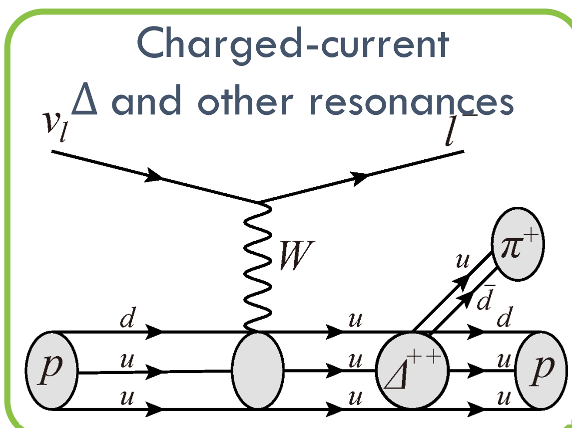


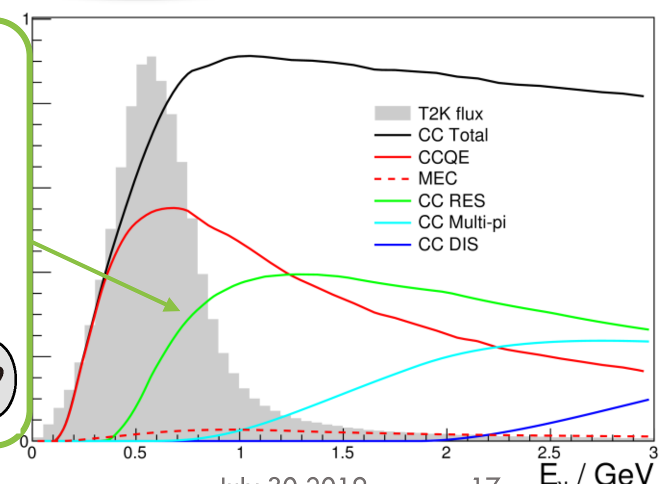


e-like ring

μ-like ring

- New sample since summer 2016.
- π^+ below Cherenkov threshold.
  - Infer from μ^+ decay electron.
- Only neutrino mode e-like.





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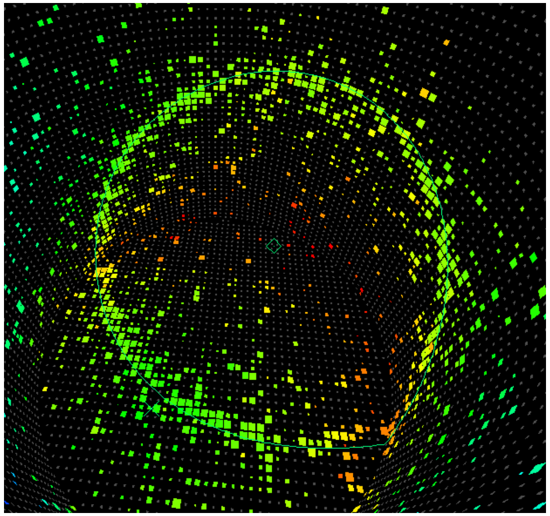
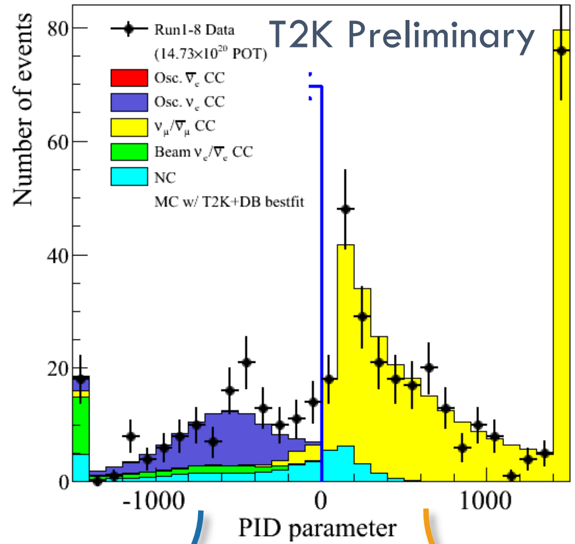
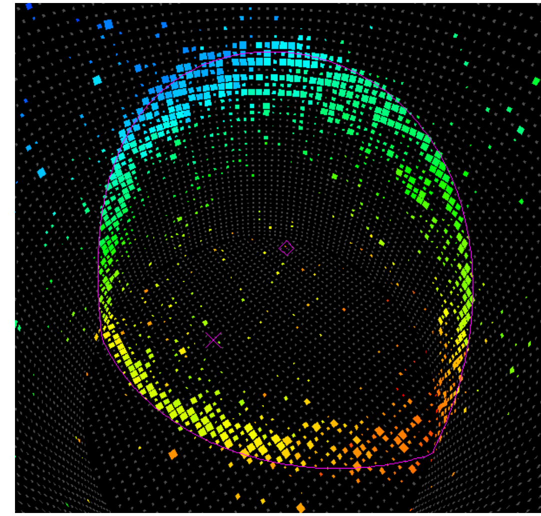






e-like ring

μ-like ring

- Five samples at Super-K, targeting:
  - Charged-current quasi-elastic interactions.
  - Charged-current resonant π production.
- Backgrounds are neutral current π production.
  - $\pi^0 \rightarrow \gamma\gamma$ misidentified as e
  - π^+ misidentified as μ

ν-mode

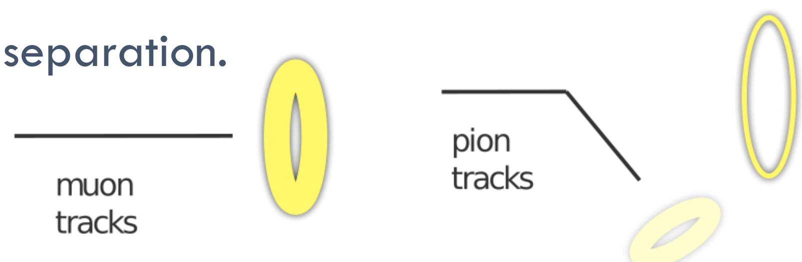
- μ-like, $\leq$1 decay-e
- e-like, 0 decay-e
- e-like, 1 decay-e

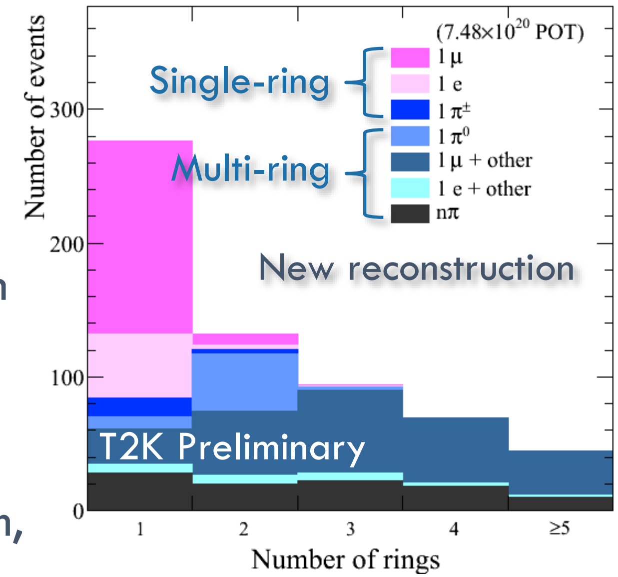
$\bar{\nu}$-mode

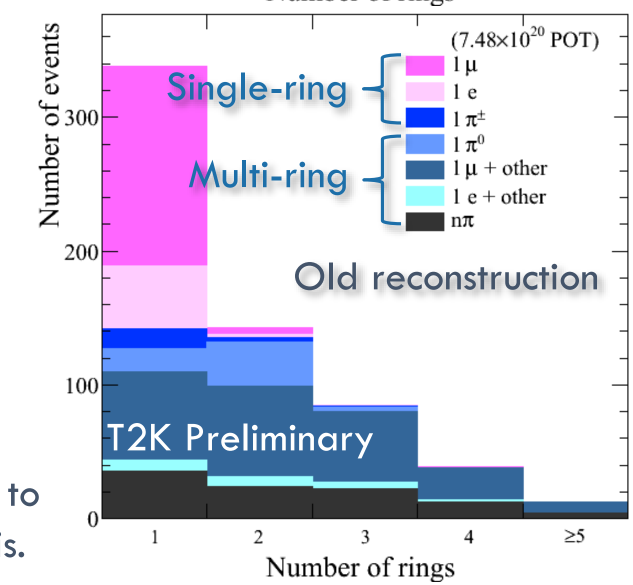
- μ-like, $\leq$1 decay-e
- e-like, 0 decay-e

SUPER-K EVENT RECONSTRUCTION

- New event **reconstruction** algorithm for Super-K.
- Previously used only for neutral current π^0 background rejection.
- Maximum-likelihood estimation using all the information in an event, including **unhit** PMTs.
- Likelihood ratios used to compare event hypotheses.
- Improved particle **identification**, ring-counting, momentum, vertex and direction **resolutions**.
- **New** μ / π^+ separation.



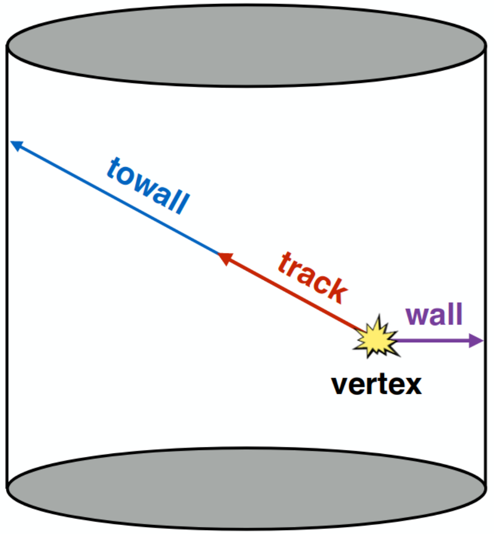


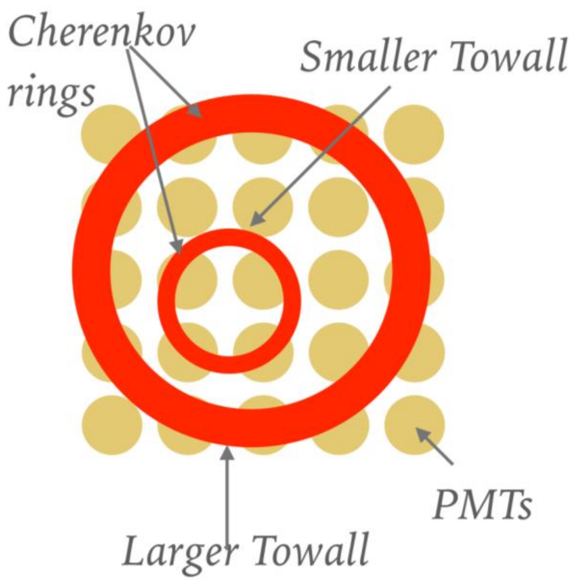


- Optimize **fiducial volume** and **neutral current rejection** criteria for new event reconstruction.
  - Neutral current rejection criteria chosen for optimal sensitivity to oscillation parameters by running simplified oscillation analysis.

FIDUCIAL VOLUME OPTIMIZATION

- In previous T2K results vertices were required to be > 2 m away from the nearest wall.
- For new event selection, fiducial volume defined as a function of:
  - *wall*: reduces background due to particles entering the detector;
  - *towall*: ensures adequate number of PMTs sample the ring, improving reconstruction quality.
- Both *wall* and *towall* are optimized in a fit to Super-K atmospheric neutrino data, taking into account statistical gains and systematic uncertainties.



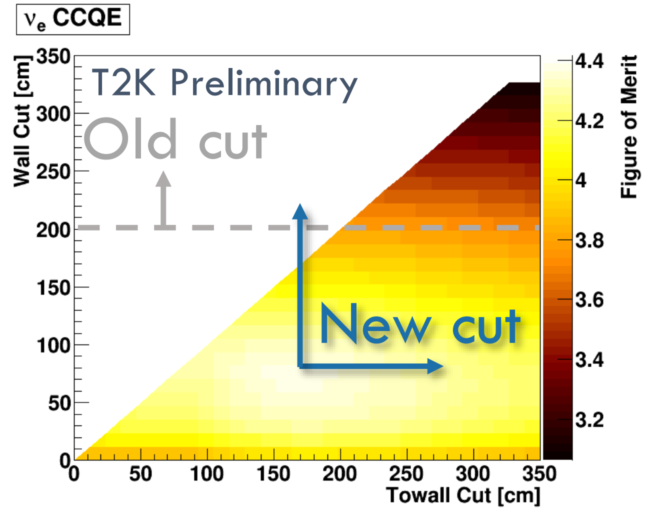


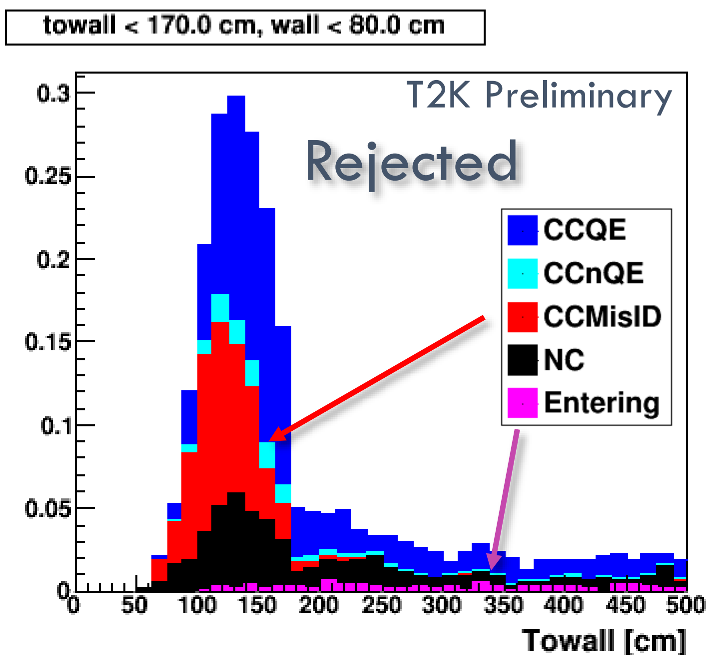
FIDUCIAL VOLUME OPTIMIZATION

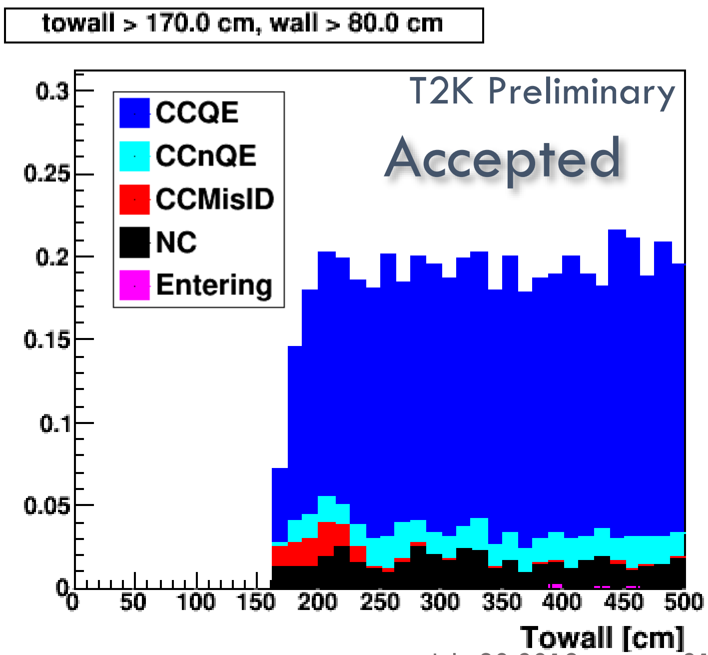
- Optimize figure of merit that enhances events that change significantly under oscillations:

$$FOM = \frac{\left(\frac{\partial \hat{N}}{\partial \theta}\right)^2}{\hat{N}+\sigma_{syst}^2}, \text{ with } \theta = \delta_{CP}, \theta_{23}$$

- Cut points are optimized for each of the five analysis samples separately.







IMPROVEMENTS FROM NEW SELECTION

		New selection		Old selection	
	Sample	Candidates	Purity	Candidates	Purity
ν	μ-like, $\leq$1 decay-e	261.6	**79.7%**	268.7	**68.1%**
	e-like, 0 decay-e	**69.5**	81.2%	**56.5**	81.4%
	e-like, 1 decay-e	**6.9**	**78.8%**	**5.6**	**72.0%**
$\bar{\nu}$	μ-like, $\leq$1 decay-e	62.0	**79.7%**	65.4	**70.5%**
	e-like, 0 decay-e	**7.6**	62.0%	**6.1**	63.7%

- μ-like samples: improved **purity** by reducing neutral current background.

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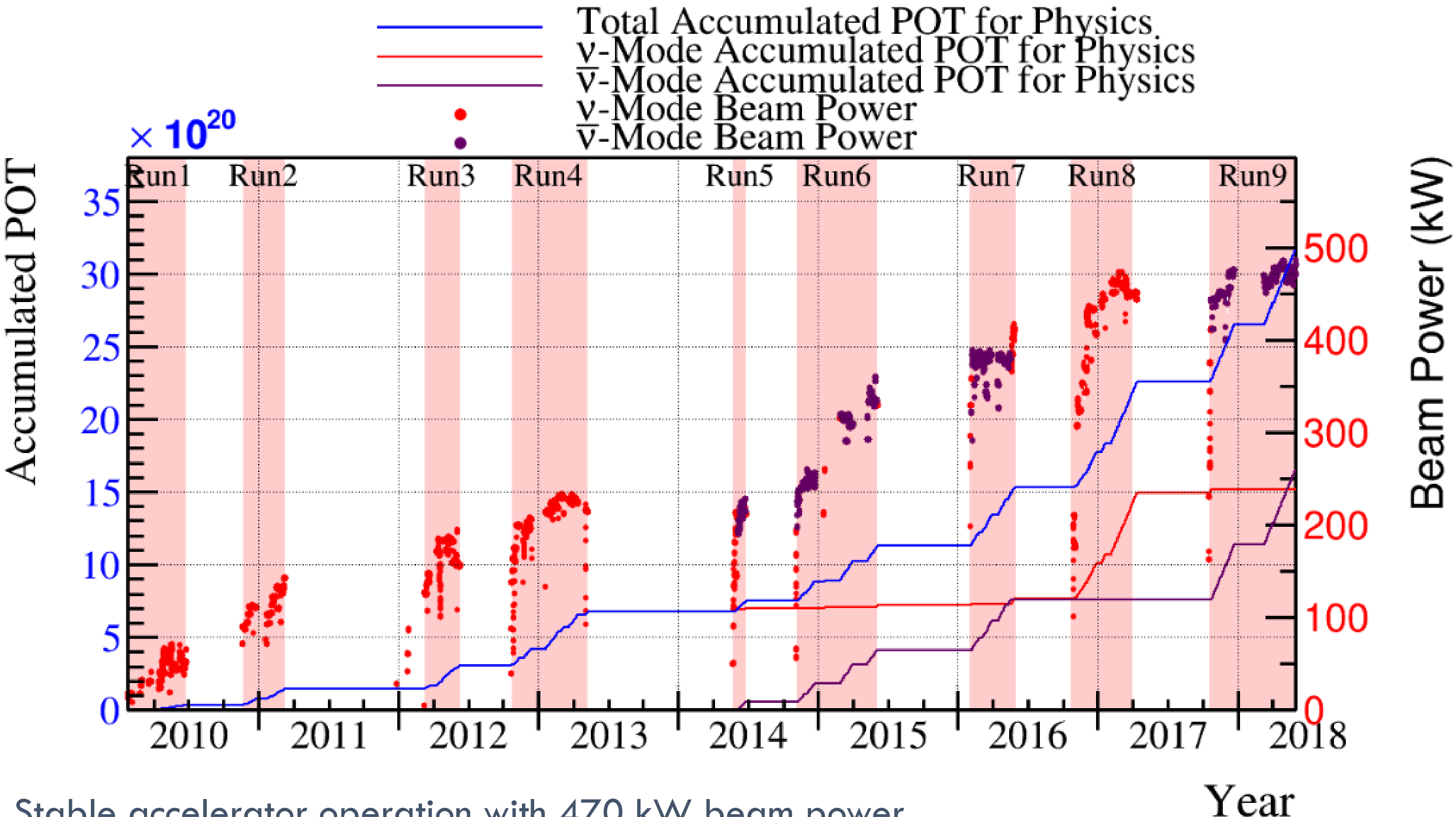
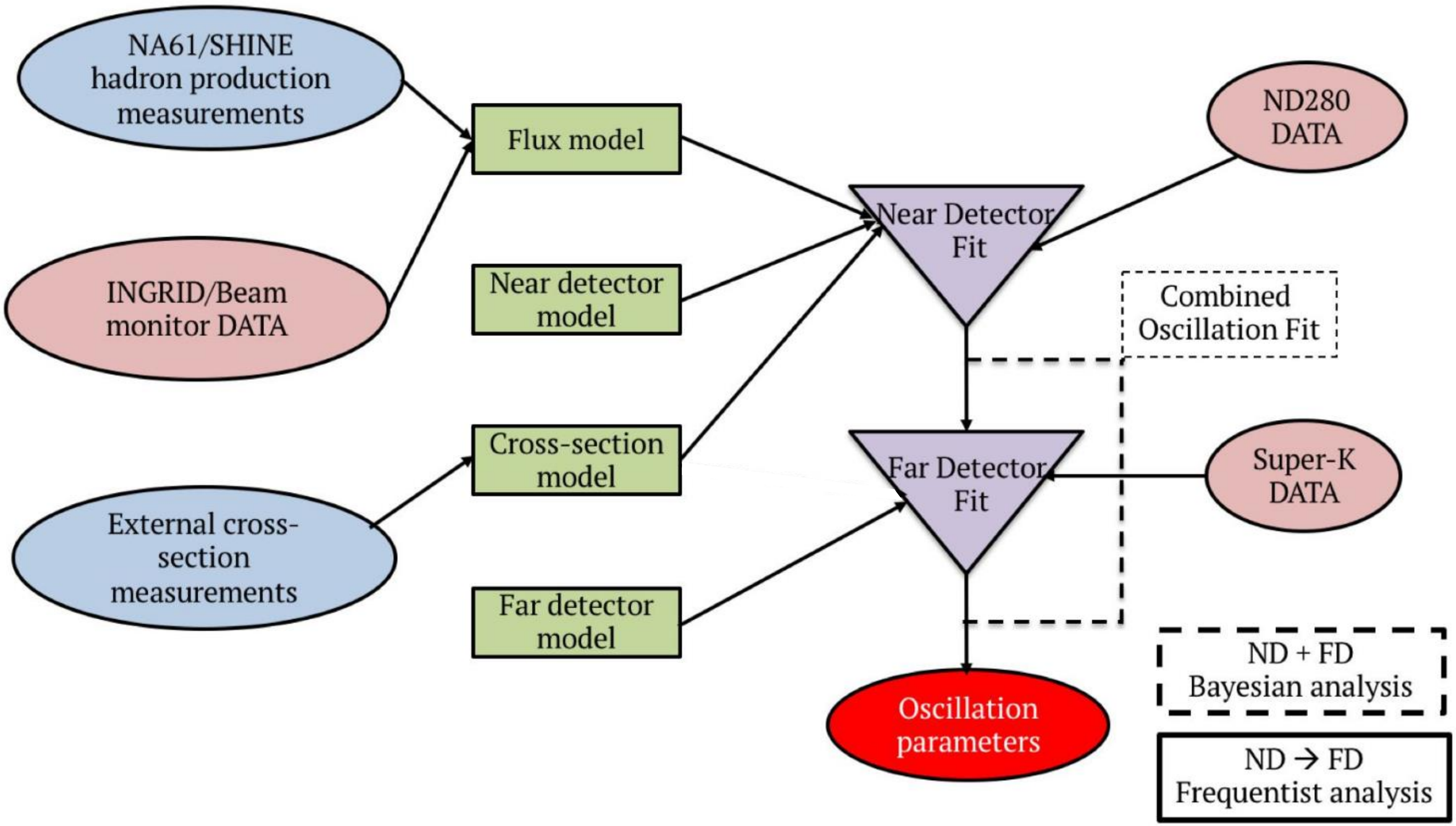
- e-like, 0 decay-e samples: increase **efficiency** by $>$ 20% while keeping previous selection's purity.
- e-like, 1 decay-e sample: improvement in **purity** from better particle identification and increased **efficiency** from fiducial volume expansion.

DATA TAKING



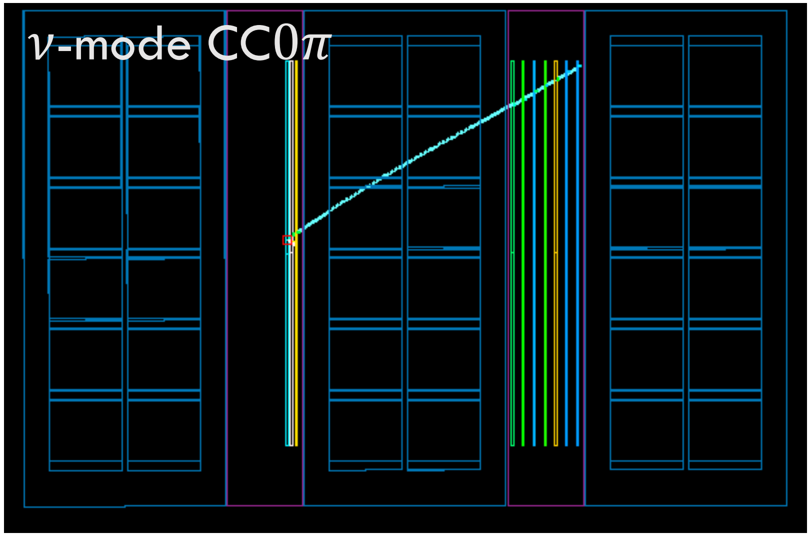
- Stable accelerator operation with 470 kW beam power.
  - Antineutrino mode data set ~doubled in run 9.
  - Neutrino mode data set ~doubled in run 8.
- Up to May 2018 a total of 3.16 x 10^{21} protons on target (POT) have been collected.
  - Split ~equally between neutrino and antineutrino mode.

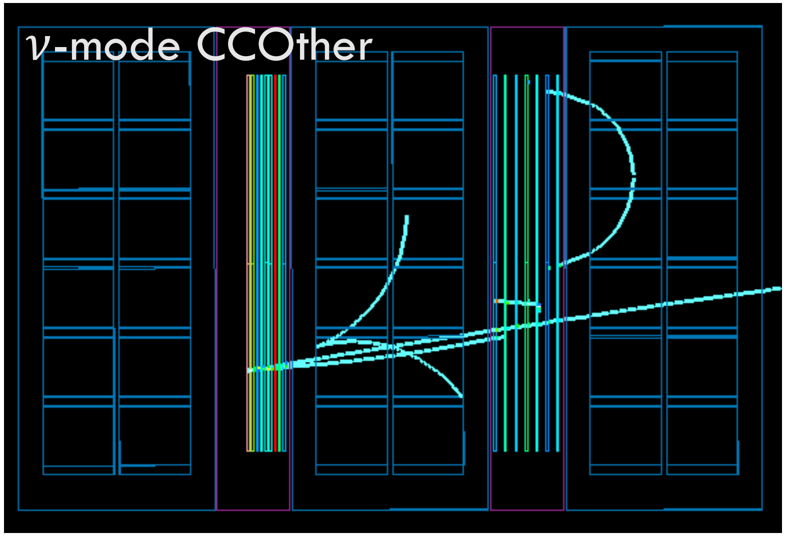
OSCILLATION ANALYSIS STRATEGY

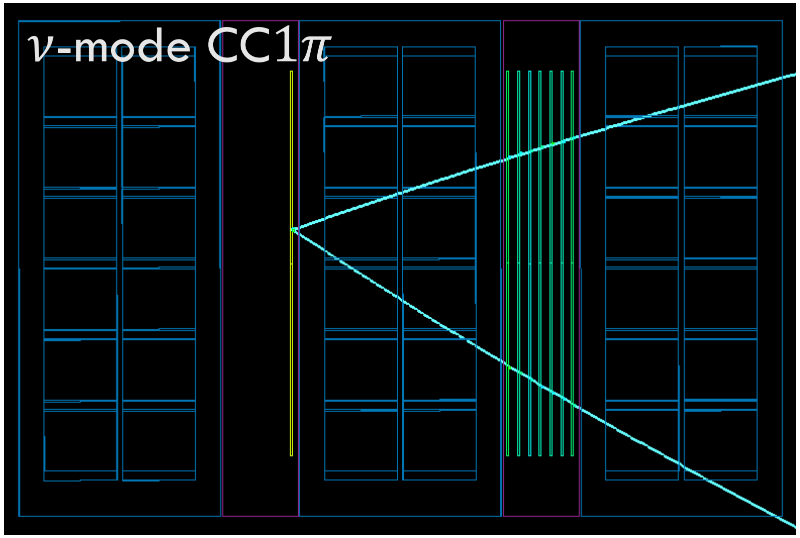


NEAR DETECTOR SAMPLES

- Fourteen near detector samples are used to constrain flux and cross-section model.
    - In ν-mode: charged current with: 0 πs; $1\pi^+$; or other particles.
    - Single-track and multi-track charged current with μ^+ or μ^- for $\bar{\nu}$-mode.
    - Seven samples for each FGD.

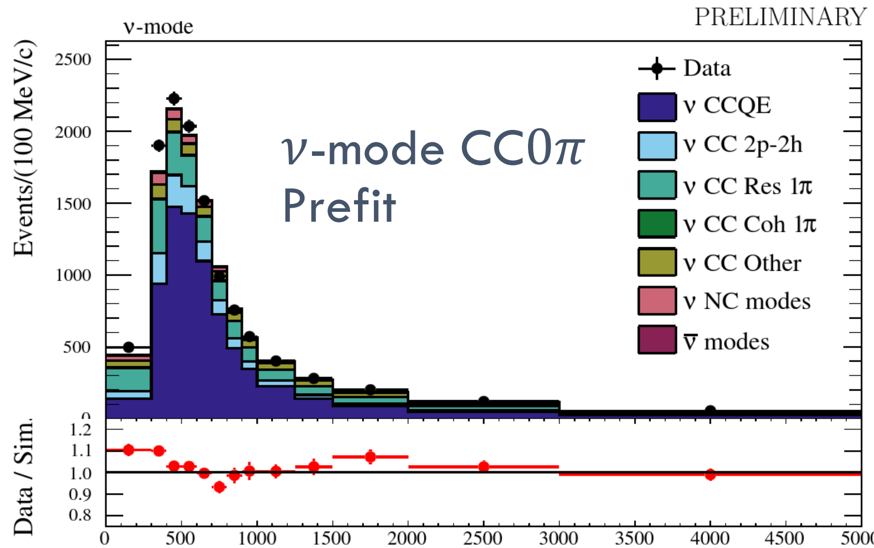


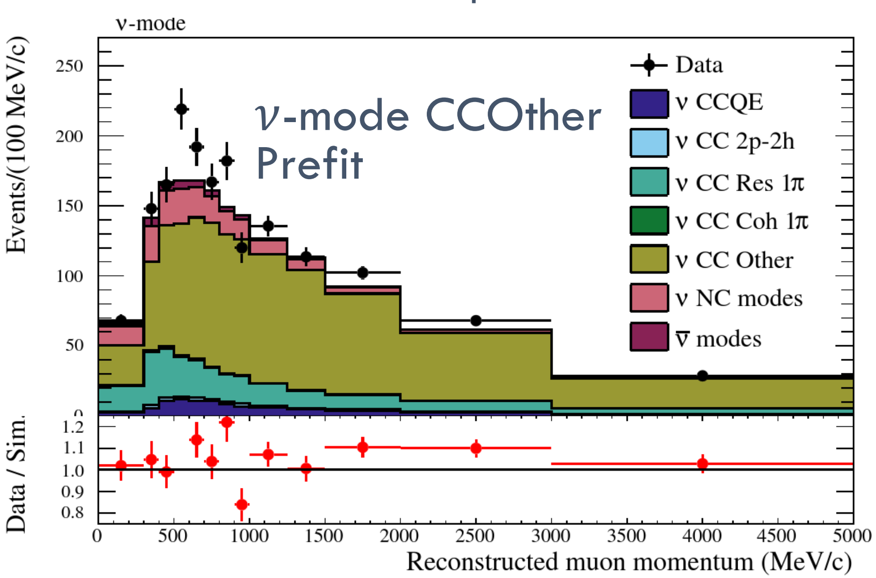


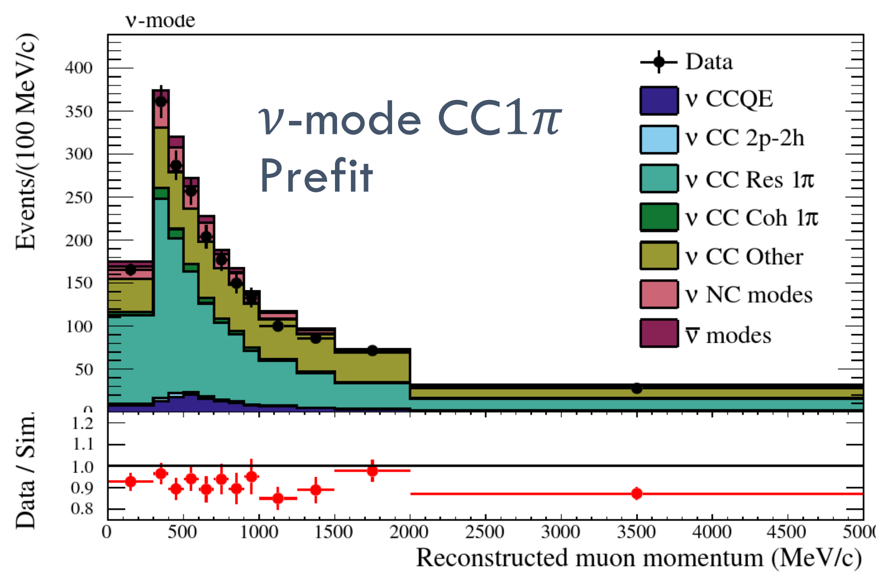


NEAR DETECTOR FIT

- Fourteen near detector samples are used to constrain flux and cross-section model.
  - In ν-mode: charged current with: 0 πs; 1π^+; or other particles.
  - Single-track and multi-track charged current with μ^+ or μ^- for $\bar{\nu}$-mode.
  - Seven samples for each FGD.





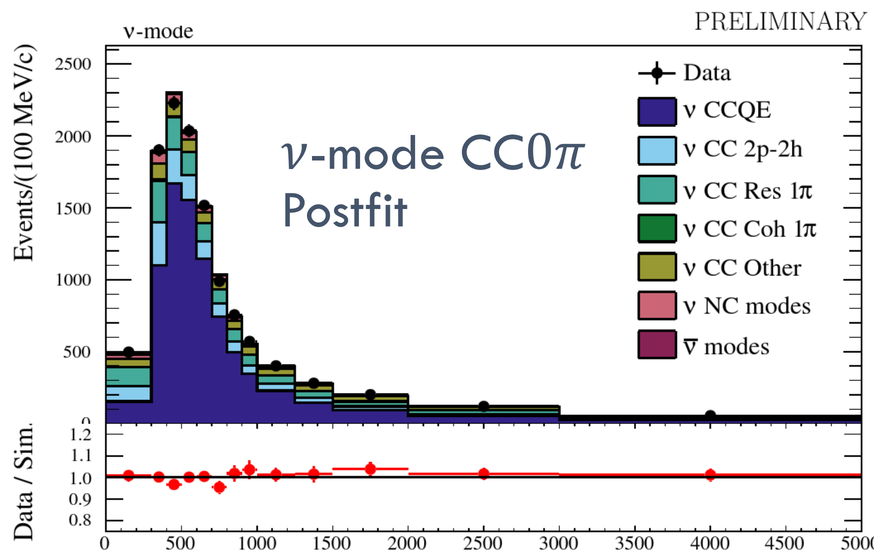


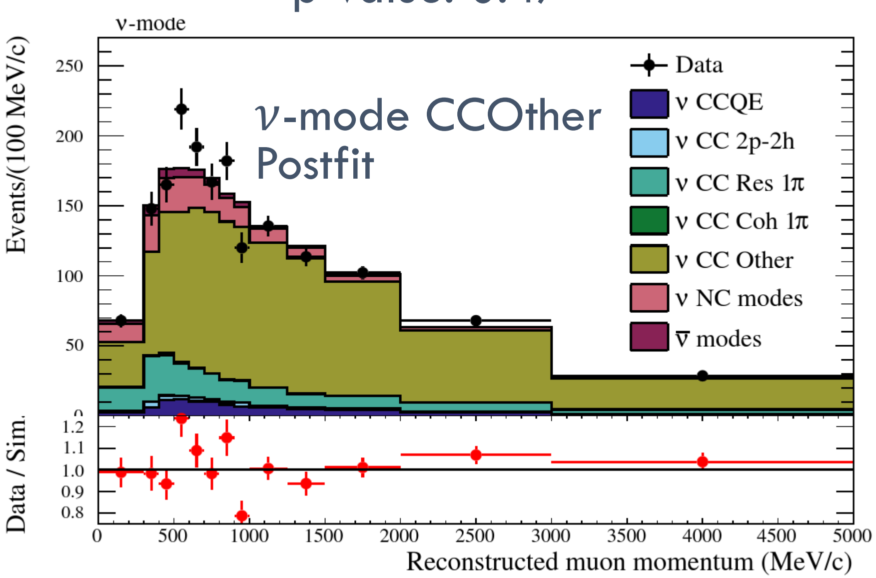
PRELIMINARY

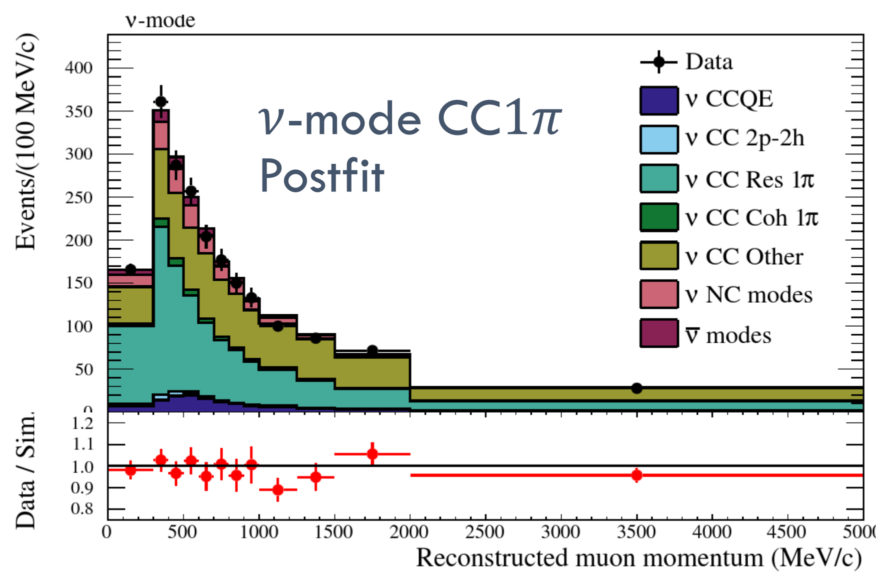
RELIMINARY

NEAR DETECTOR FIT

- After fit to near detector samples, flux and cross-section uncertainties at far detector reduced from ~15% to ~5%.
- Good fit to the data.
  - p-value: 0.47







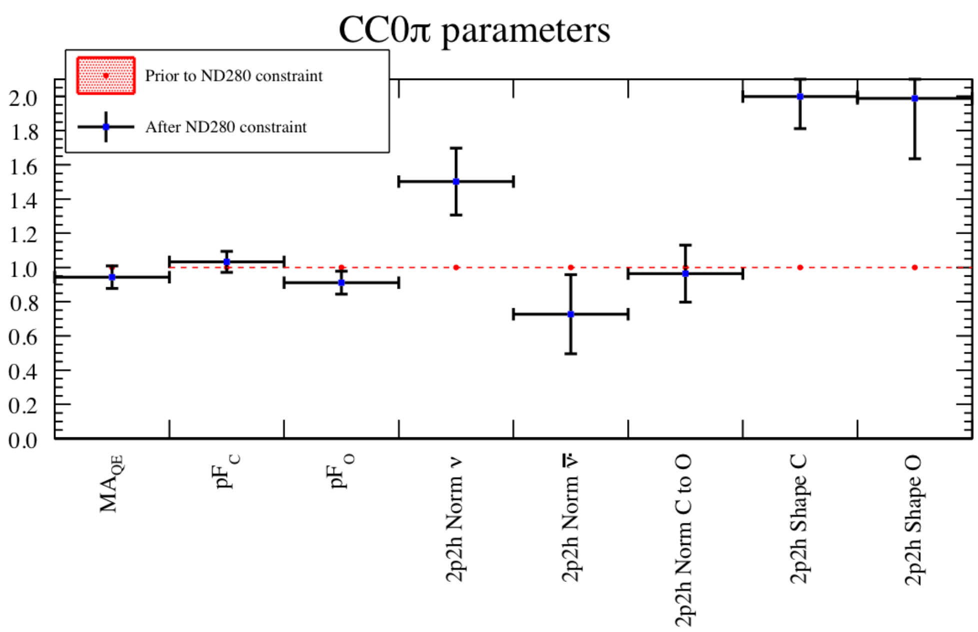
PRELIMINARY

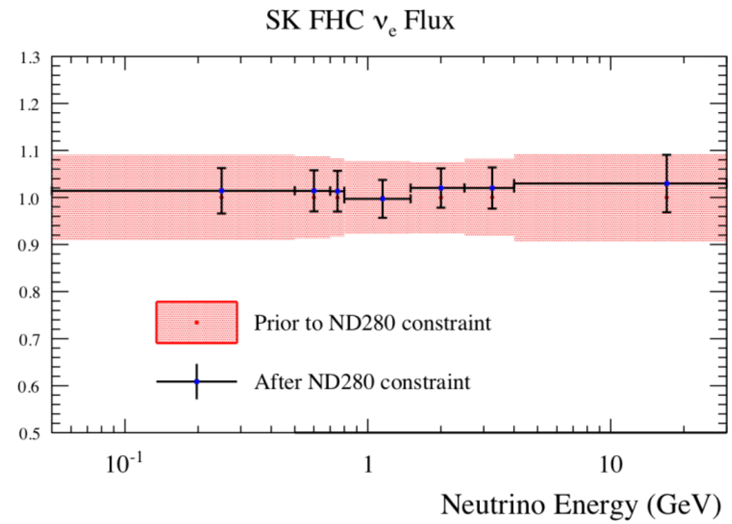
RELIMINARY

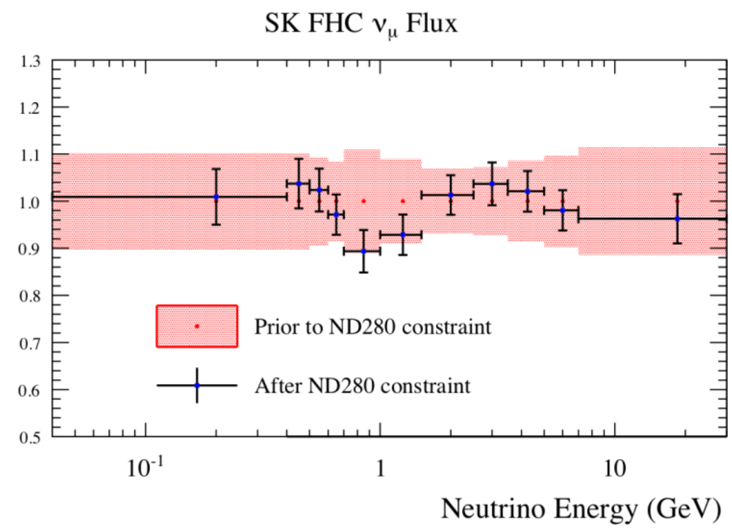
NEAR DETECTOR CONSTRAINTS

- Either propagate to far detector fits with covariance matrix;
- Or fit same model with near and far detector data simultaneously.
- Get nearly identical results.

Many more parameters not shown.

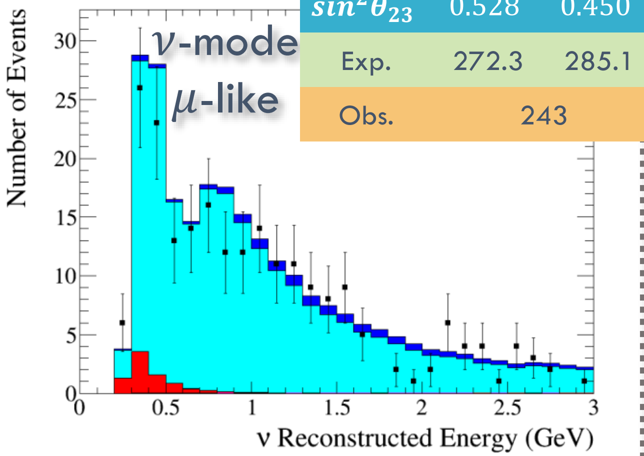






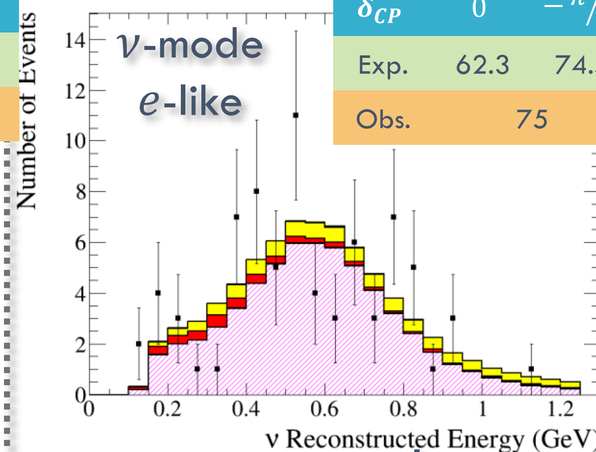
FAR DETECTOR DATA

ν_μ Disappearance

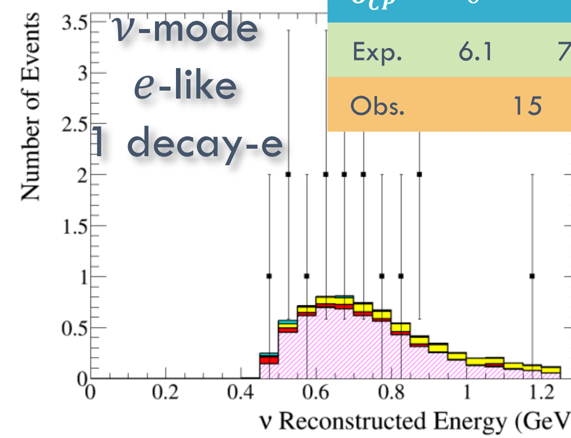


$sin^2\theta_{23}$	0.528	0.450
Exp.	272.3	285.1
Obs.	243	

ν_e Appearance



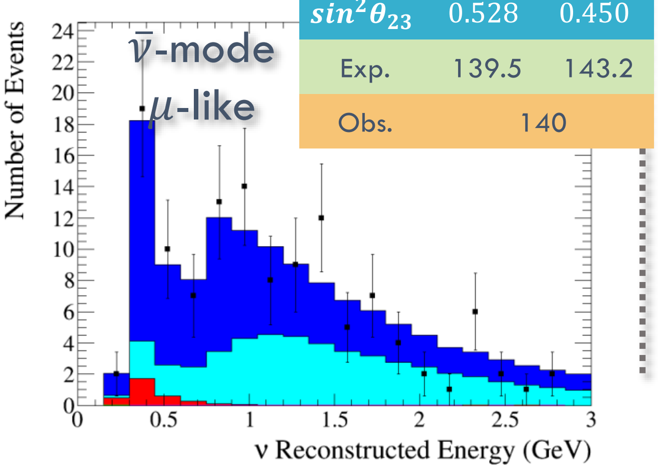
δ_{CP}	0	$-\pi/2$
Exp.	62.3	74.5
Obs.	75	



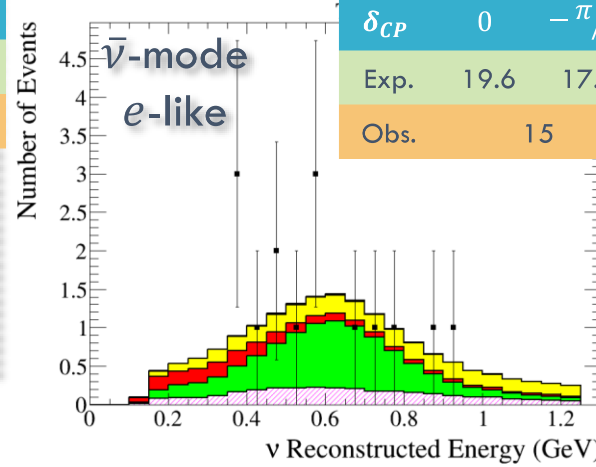
δ_{CP}	0	$-\pi/2$
Exp.	6.1	7.0
Obs.	15	

ν-mode

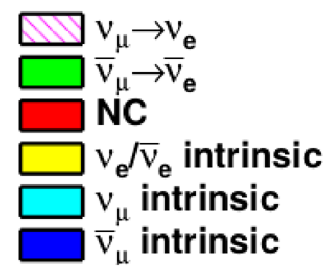
$\bar{\nu}$-mode



$sin^2\theta_{23}$	0.528	0.450
Exp.	139.5	143.2
Obs.	140	



δ_{CP}	0	$-\pi/2$
Exp.	19.6	17.2
Obs.	15	



T2K Preliminary

SYSTEMATIC UNCERTAINTIES

	% Errors on predicted event rate at Super-K					
	μ-like		e-like			
Error Source	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode 1 dcy-e	$\nu/\bar{\nu}$
SK Detector	2.40	2.01	2.83	3.80	13.15	1.47
SK final state and secondary interactions	2.21	1.98	3.00	2.31	11.43	1.57
ND280-constrained flux and cross section	3.27	2.94	3.24	3.10	4.09	2.67
$\sigma(\nu_e)/\sigma(\nu_\mu)$, $\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)$	0.00	0.00	2.63	1.46	2.61	3.03
NC1γ	0.00	0.00	1.09	2.60	0.33	1.50
NC Other	0.25	0.25	0.15	0.33	0.99	0.18
Binding energy	2.38	1.72	7.13	3.66	2.95	3.62
Total Systematic Error	5.12	4.45	8.81	7.13	18.38	5.96

- Largest uncertainties are the Super-K detector modelling and π interaction modelling, both for the e-like events with one decay electron.

SYSTEMATIC UNCERTAINTIES

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- No precise measurement of $\nu_e(\bar{\nu}_e)$ interactions in the near detector.
- Theoretically motivated uncertainty based on Phys.Rev. D86 (2012) 053003.

SYSTEMATIC UNCERTAINTIES

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- No near detector constraint on neutral current modes.
- Uncertainty based on modelling and external data.

SYSTEMATIC UNCERTAINTIES

Error Source	% Errors on predicted event rate at Super-K					
	μ-like		e-like			
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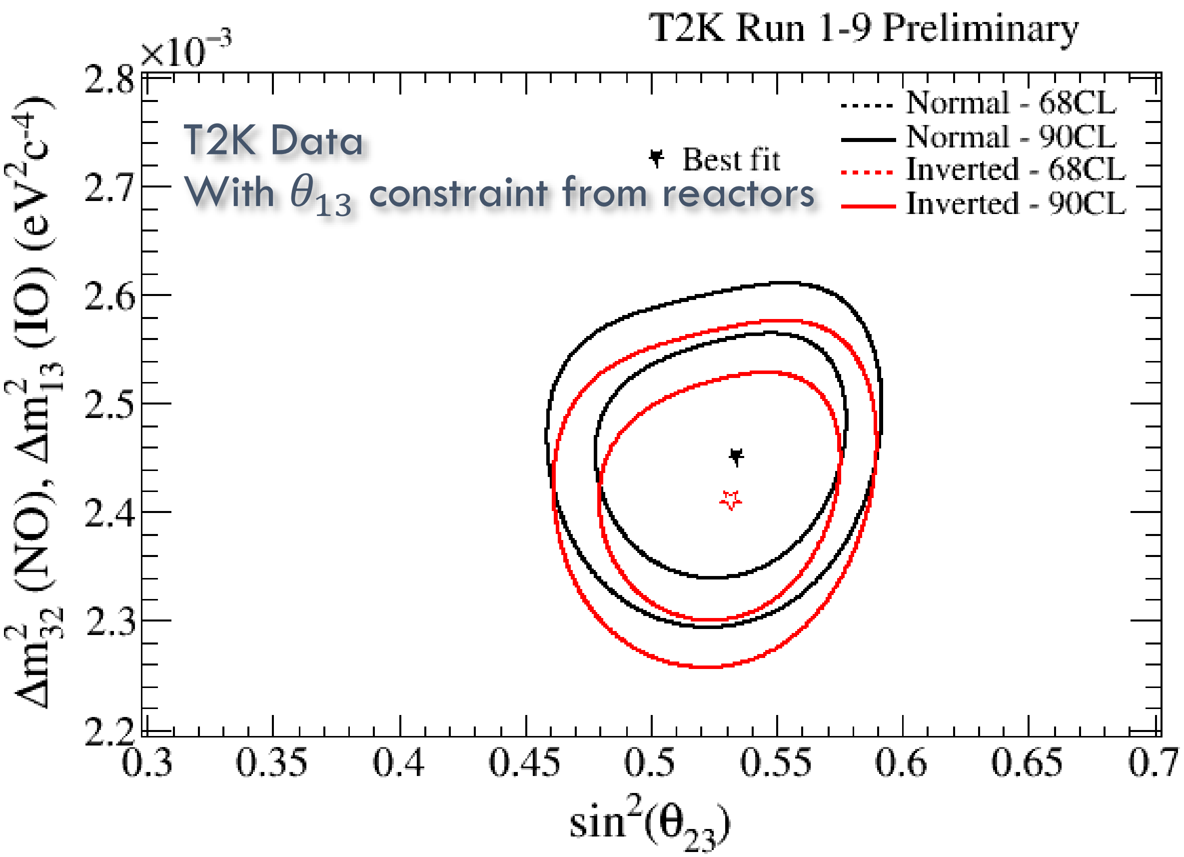
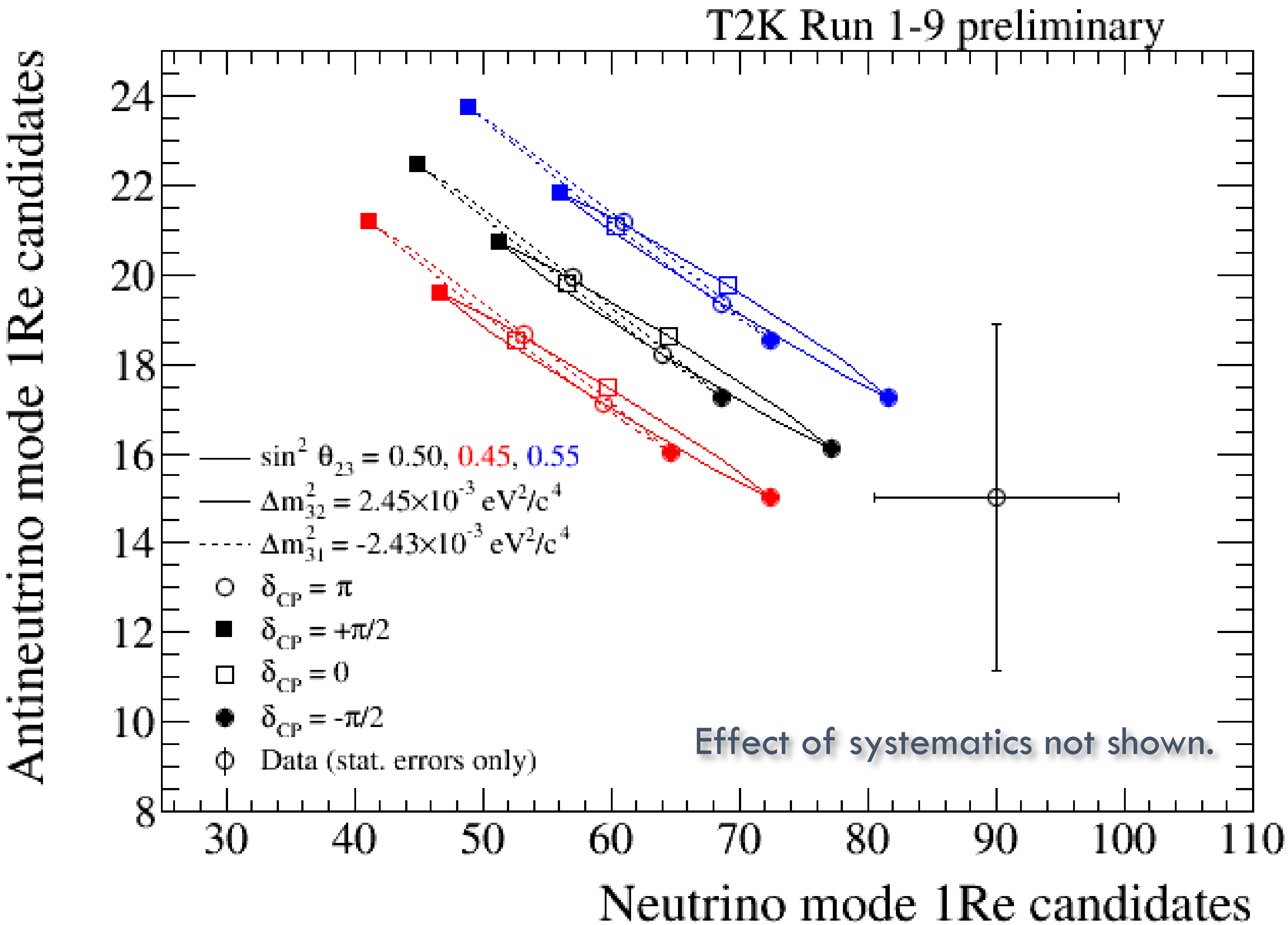
- Binding energy range based on A. Bodek (arXiv:1801.07975), motivated by electron scattering data.
- Size of effect estimated by running oscillation analyses on simulated data.

ATMOSPHERIC PARAMETER CONSTRAINTS

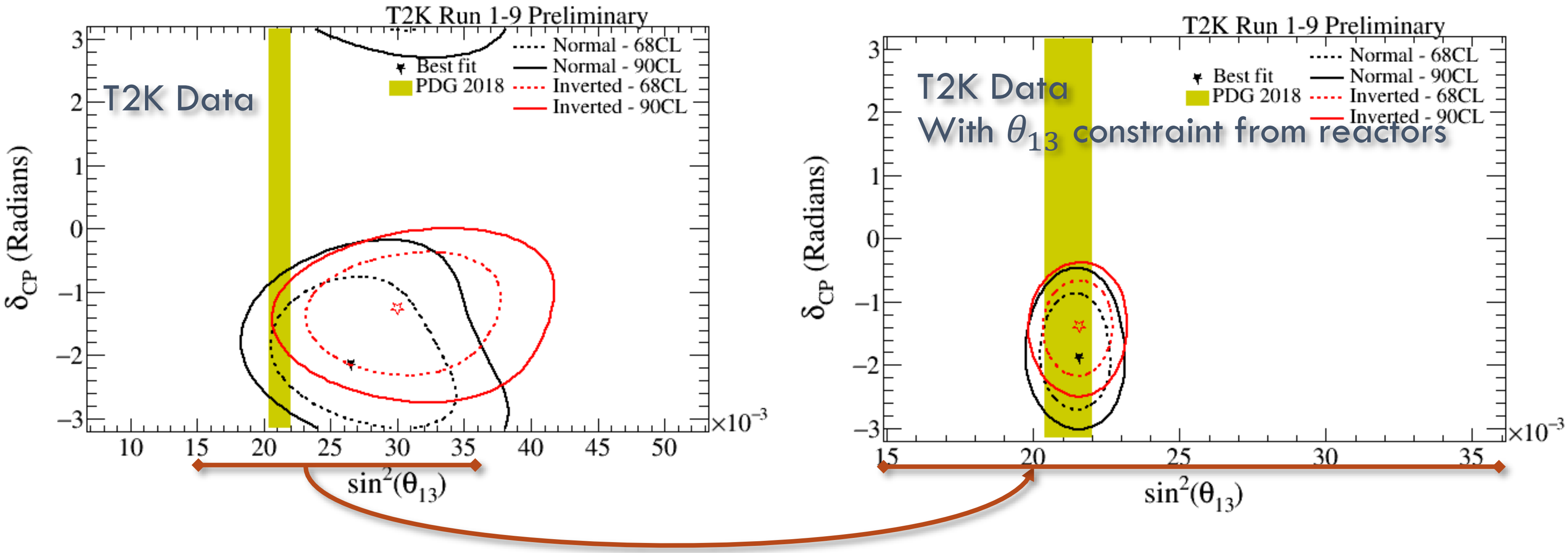


- Fit under normal and inverted hierarchy assumptions separately.
- Apply constraint on θ_{13} from reactor experiments.
- T2K data consistent with maximal mixing.

ν_e AND $\bar{\nu}_e$ APPEARANCE

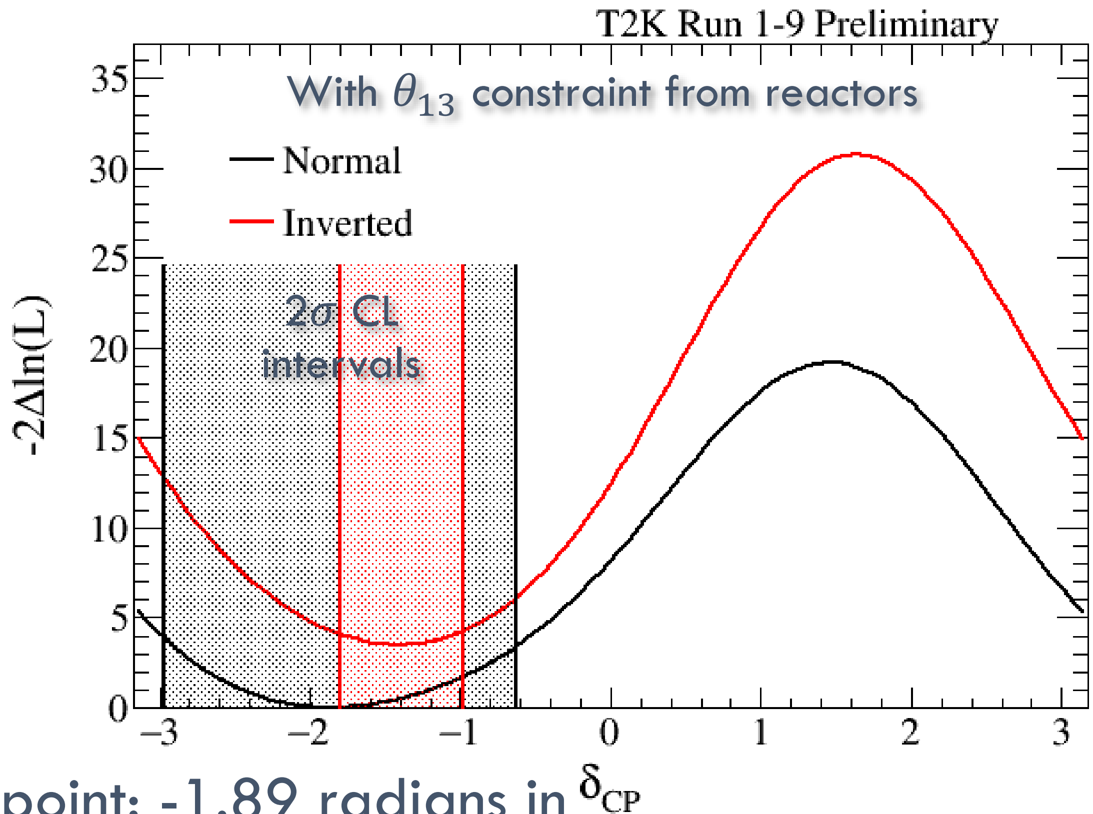


APPEARANCE PARAMETERS



- Closed contours at 90% CL in δ_{CP} for fit without external θ_{13} constraints.
- T2K best fit consistent with PDG 2016.
  - T2K: $\sin^2\theta_{13} = 0.0268^{+0.0055}_{-0.0043}$ (NH)
  - PDG 2018: $\sin^2\theta_{13} = 0.0212 \pm 0.0008$

CONSTRAINT ON δ_{CP}



- Best-fit point: -1.89 radians in Normal Hierarchy
- CP conserving values are outside of the 2σ CL intervals.

	NH	IH
90% CL	[-2.80, -0.84]	∅
2σ CL	[-2.97, -0.63]	[-1.80, -0.98]

θ_{23} OCTANT AND MASS HIERARCHY

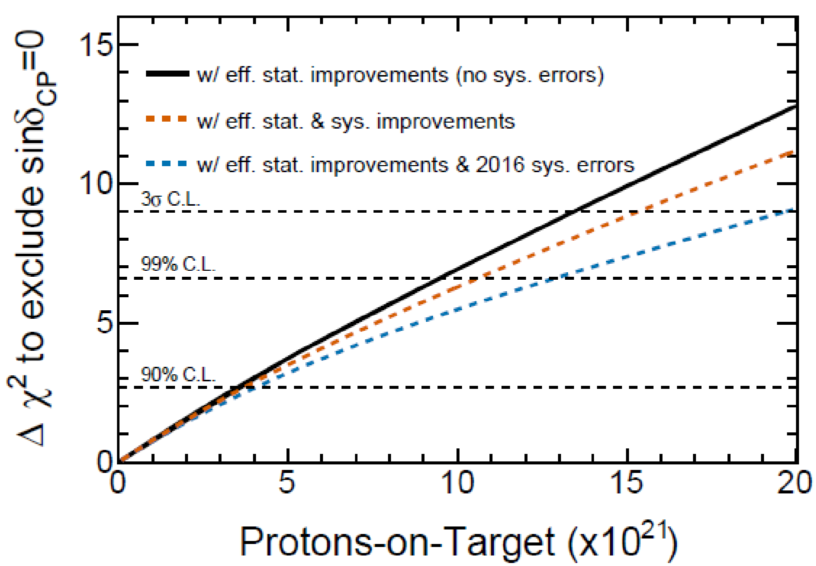
- Look at posterior probability from Bayesian analysis to infer T2K data preference for θ_{23} octant and mass hierarchy.
- Equal prior probability given to all hypotheses.

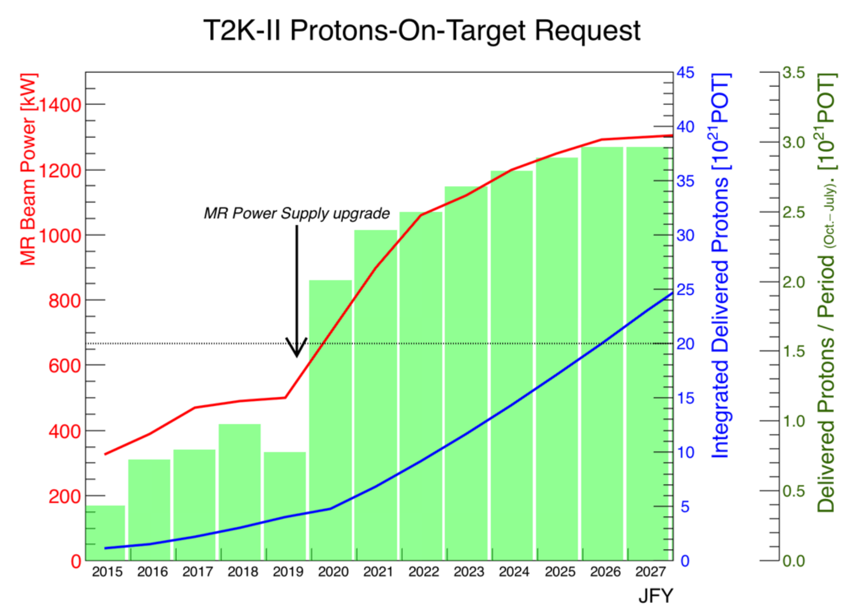
	$sin^2\theta_{23} < 0.5$	$sin^2\theta_{23} > 0.5$	**Sum**
NH ($\Delta m_{32} > 0$)	0.184	0.705	0.889
IH ($\Delta m_{32} < 0$)	0.021	0.090	0.111
Sum	0.205	0.795	

- Data shows weak preference for **normal** hierarchy and **upper** octant.

T2K FUTURE PROSPECTS

- Increase statistics by including multi-ring far detector samples targeting resonant pion production interactions, benefitting from improved reconstruction algorithm.
- Near detector upgrade to replace existing π^0 detector with Super-FGD.
  - Scintillator tracker made of 1 cm^3 cubes with 3 x 2D views will have lower proton tracking threshold and better high-angle acceptance.
- Addition of gadolinium sulphate to Super-K water will greatly increase neutron tagging efficiency.
  - Might help long baseline program with $\nu/\bar{\nu}$ separation and background rejection, but interaction systematics will be challenging!
    - Opportunity to measure neutron multiplicity in neutrino interactions.
- Extend T2K run beyond nominal plan to benefit from J-PARC proton beam upgrade and achieve 3σ sensitivity to maximal CP violation.





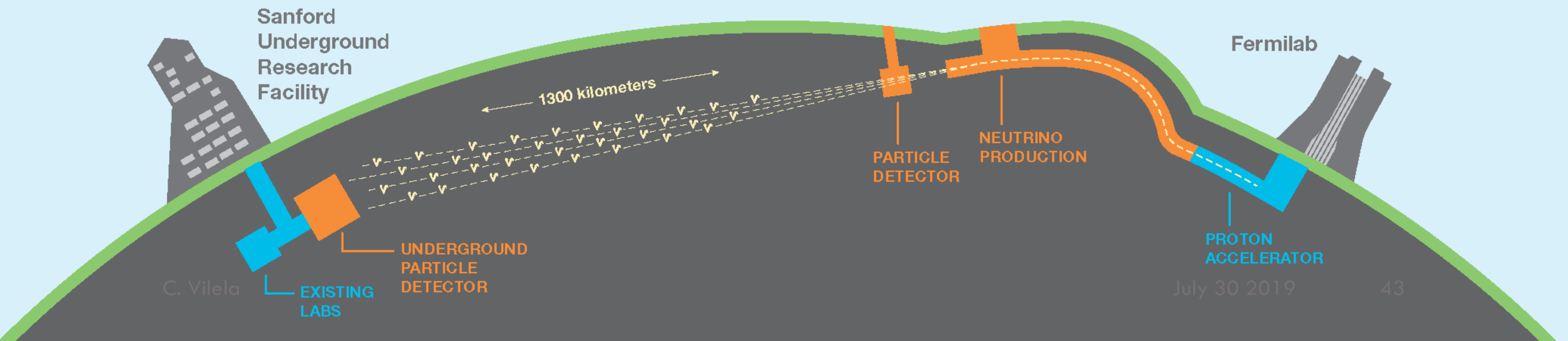
DUNE

DEEP UNDERGROUND

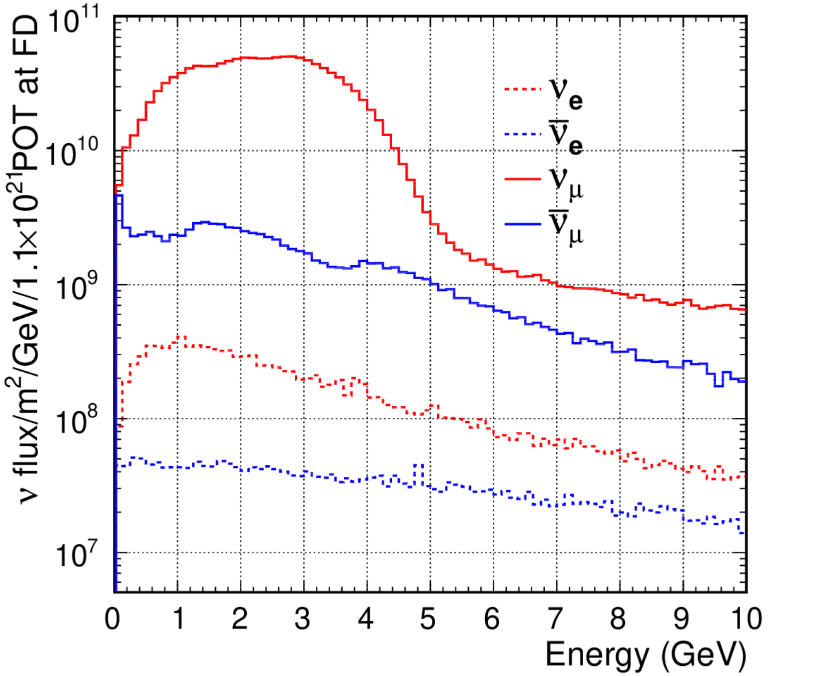
NEUTRINO EXPERIMENT

DEEP UNDERGROUND NEUTRINO EXPERIMENT

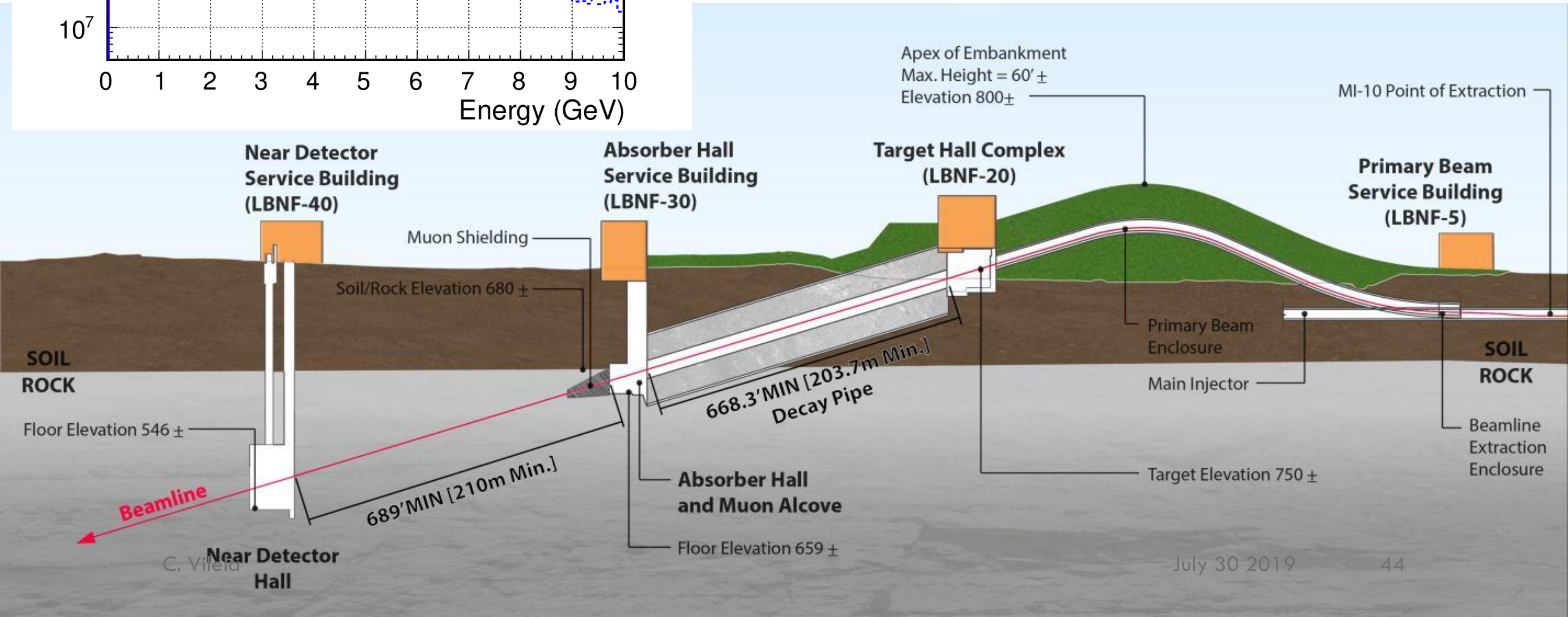
- T2K/Hyper-K use a narrow-band beam tuned to the oscillation maximum and a relatively short baseline.
  - δ_{CP} effect much larger than mass ordering – sensitivity more due to event rate than oscillation shape.
- **DUNE** uses a wide-band beam, longer baseline and higher energy neutrinos.
  - Large effects from both δ_{CP} and mass ordering.
    - Disambiguate using oscillation shape over wide energy range.
  - Benefit from larger neutrino-nucleus cross-section at higher energies
  - More sensitivity to non-standard interactions.
- Unlike T2K, interactions at DUNE are not dominated by CCQE, but rather a mix including resonant pion production and DIS.
  - Kinematic energy reconstruction not so useful.
- Use liquid argon time projection chamber (LArTPC) technology to get both precise tracking and calorimetric energy reconstruction.



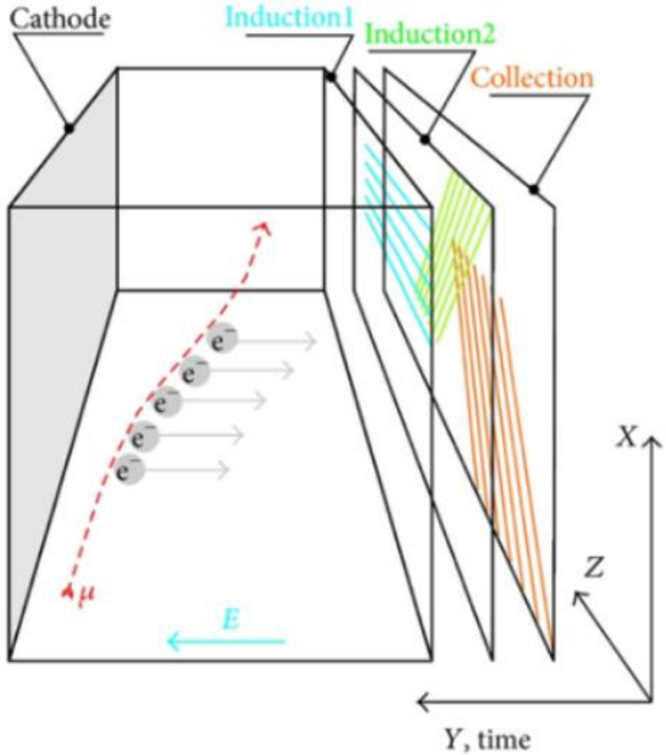
LONG BASELINE NEUTRINO FACILITY

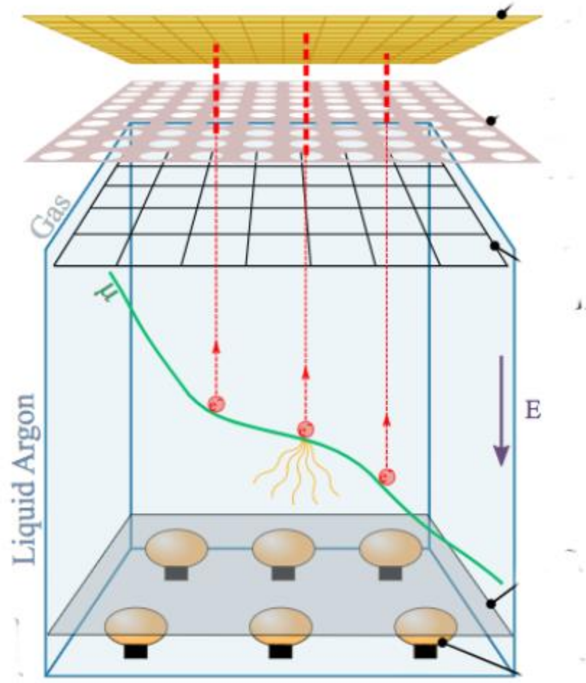


- Fermilab Main Injector 120 GeV proton beam operating initially at 1.2 MW
  - Upgradable to 2.4 MW
- Wide band neutrino beam with beamline design optimized for CP-violation sensitivity.
- Near detector hall 574 m from target.



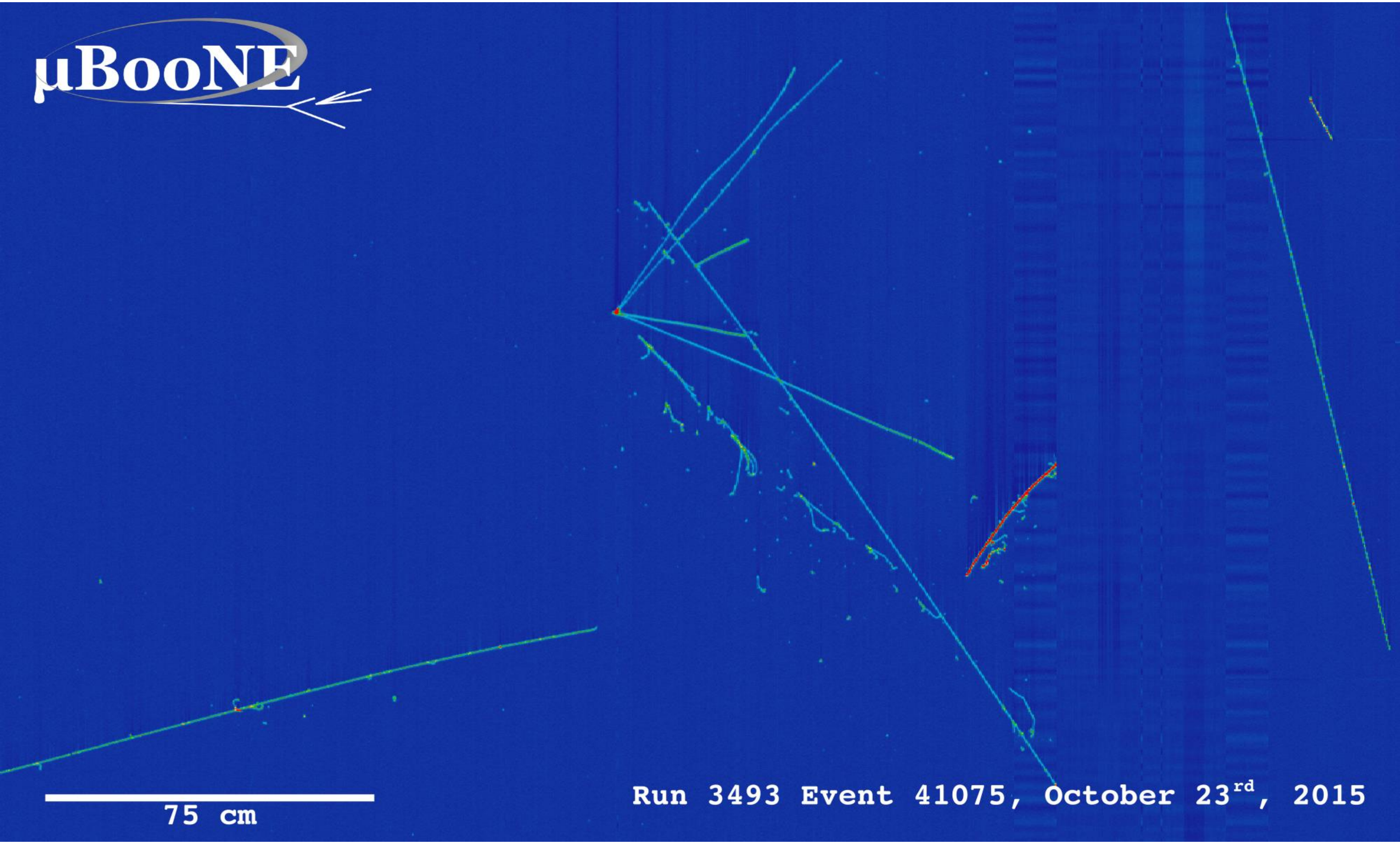
LIQUID ARGON TIME PROJECTION CHAMBERS





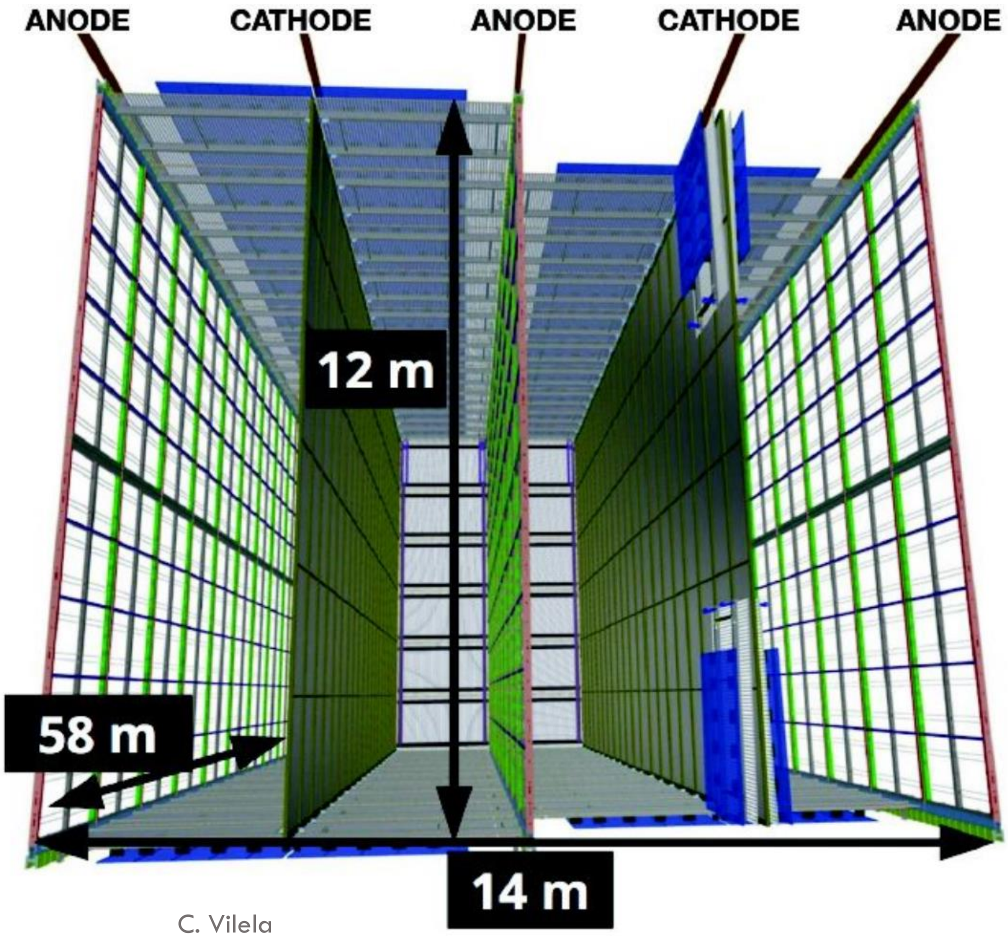
- Dense medium provides massive target for neutrino interactions.
- 3D reconstruction from 2D charge read-out + projection of the drift time.
- Two technologies considered:
  - Single-phase with horizontal drift.
  - Dual phase with vertical drift and charge amplification in the gas phase.
- Very successful single-phase large scale prototype run in CERN charged particle beam last year.

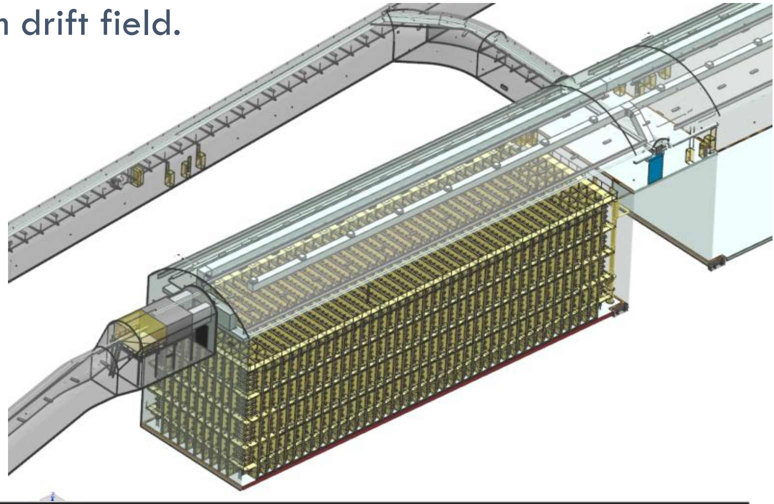
LIQUID ARGON TIME PROJECTION CHAMBERS

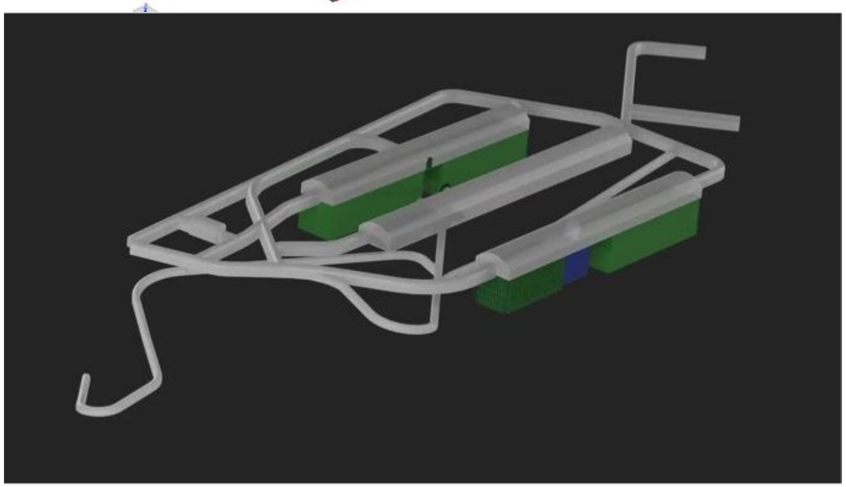


DUNE FAR DETECTOR

- 4 x 10 kton (fiducial) detector modules 1.5 km underground at SURF.
  - Staged construction: first module will be single-phase.
    - 2 cathode planes per module with 500 V/cm drift field.

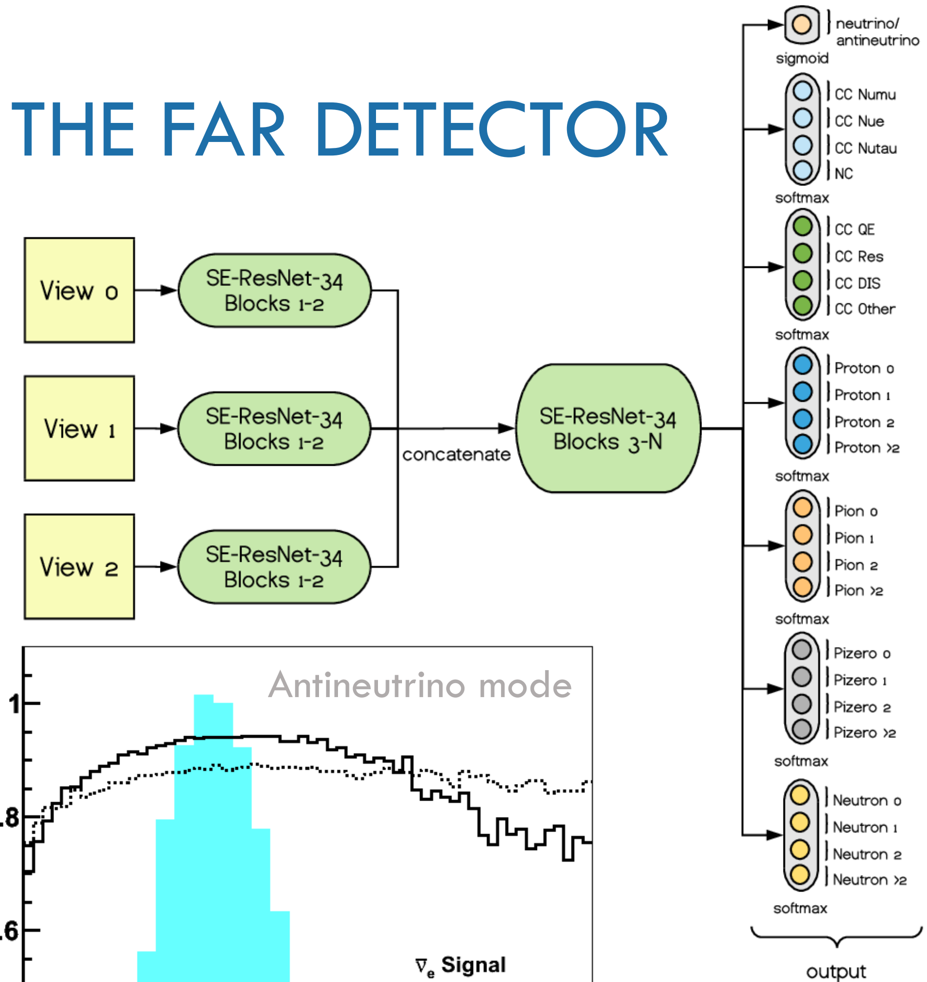


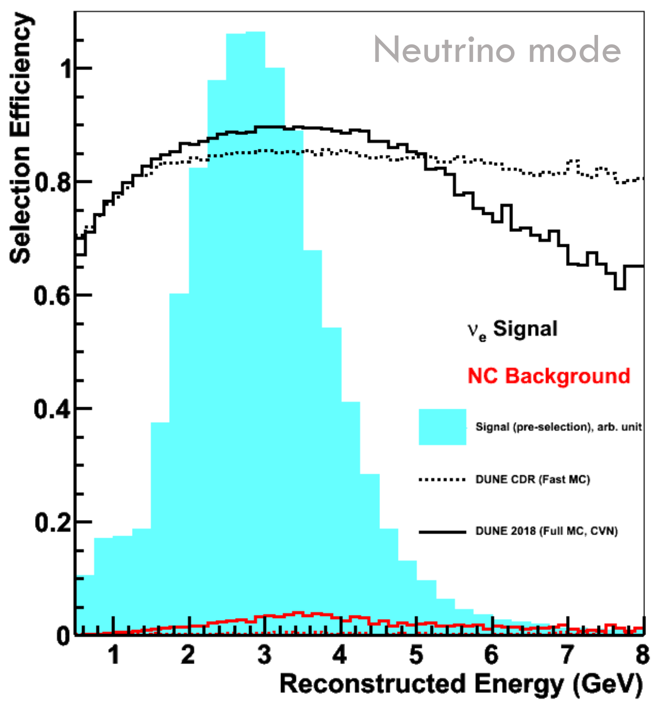


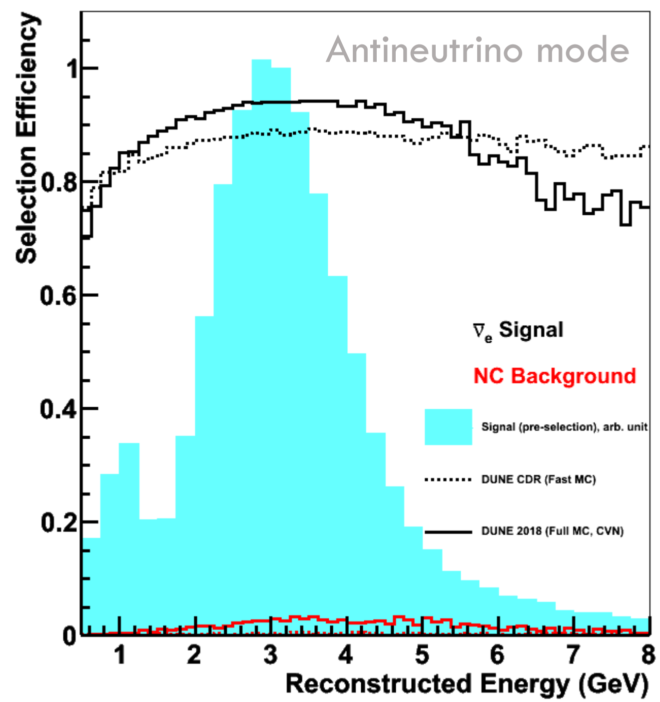


EVENT SELECTION AT THE FAR DETECTOR

- Detailed simulation and reconstruction frameworks in place.
- Deep convolutional neural network used for event classification.

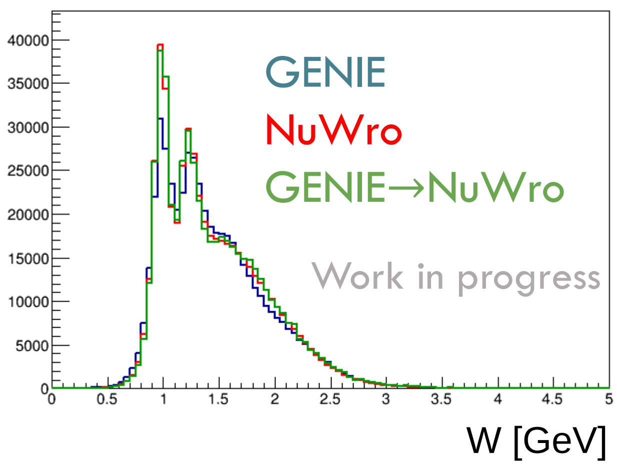


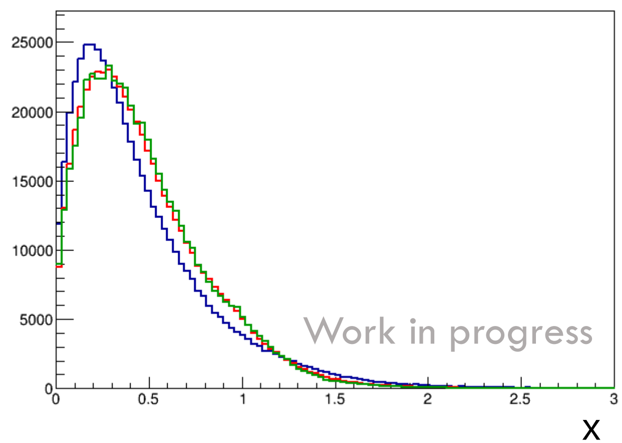


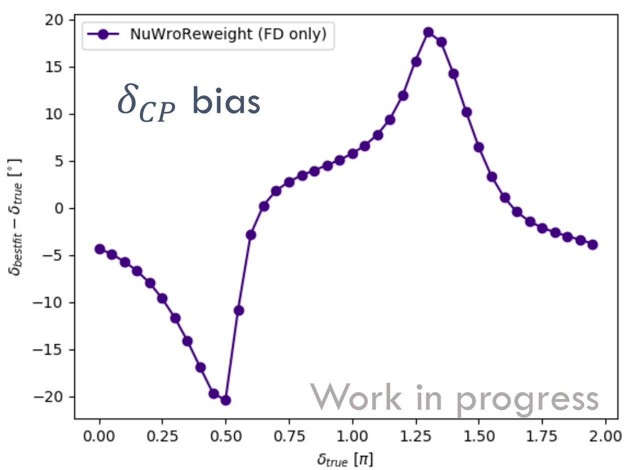


NEAR DETECTOR: AN ESSENTIAL PART OF DUNE

- Demonstrate risk of not having an adequate near detector by running the oscillation analysis using an alternative generator to produce a mock data set.
  - Analysis strategy similar to T2K, using GENIE as the nominal MC generator.
- Reweight existing DUNE MC to an alternative generator, NuWro, which makes predictions that are compatible with current world data.
  - Use multidimensional reweighting technique based on a boosted decision tree algorithm.
  - Nominal MC mimics NuWro in 18-dimensional true kinematics space.
- Near detector fit to mock data is of bad quality (several thousands of χ^2 units) and fit to far detector results in significantly biased measurements!
- Use this technique to assess impact of near detector components on physics output.







A NEAR DETECTOR FOR DUNE

- Precise neutrino oscillation measurements require precise knowledge of both the (unoscillated) flux and the cross-section.
  - Need a high statistics sample of neutrino interactions on argon, ideally taken with a detector with similar response to far detector: **LArTPC**
  - Plenty of opportunities to induce bias by mis-modelling neutrino-nucleus interaction final states. Use **high-pressure gaseous argon TPC** to get "zoomed-in" events on same target as far detector.
  - Resolve flux/cross-section ambiguities by taking data at different **off-axis** angles.
  - Monitor flux with fast highly segmented **plastic scintillator** detector.
    - Prospects of measuring neutron kinematics in neutrino-carbon interactions.

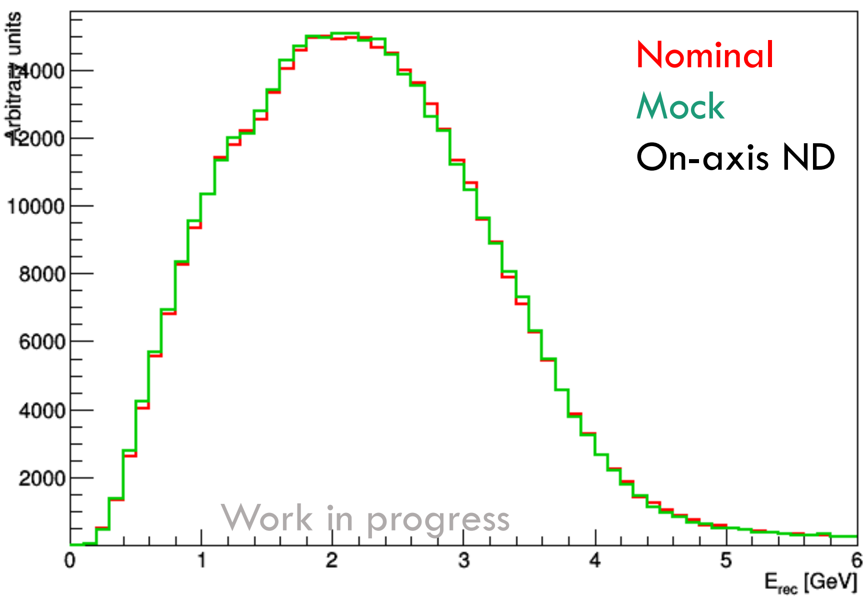
$$E_\nu^{cal} = E_\ell + \epsilon_b + \sum_{i=1}^{n}(E_i - M) + \sum_{j=1}^{m} E_j$$

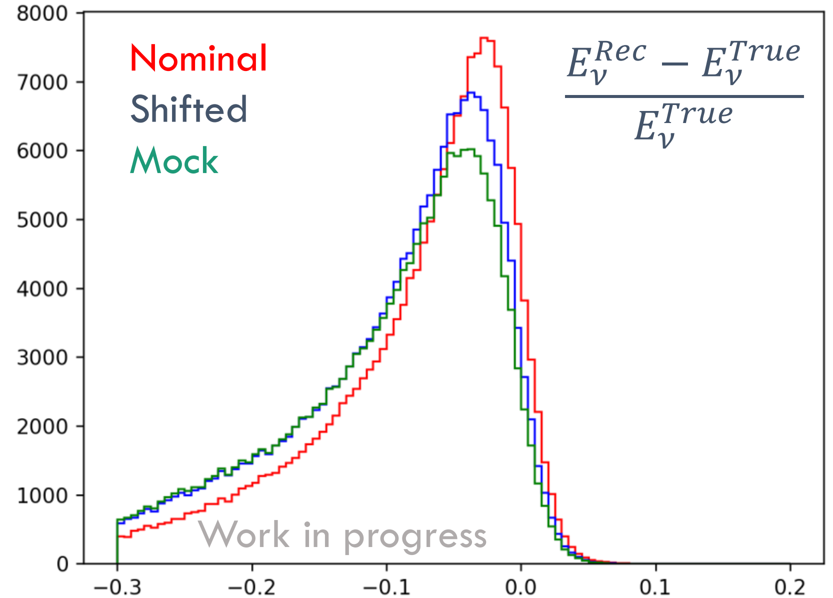
Sum over knock-out nucleons:
- Neutrons!
- How many?
- How is energy shared?

Sum over mesons:
- If undetected, $\sim m_\pi$ bias!
- How many?
- How is energy shared?

CROSS-SECTION AMBIGUITIES

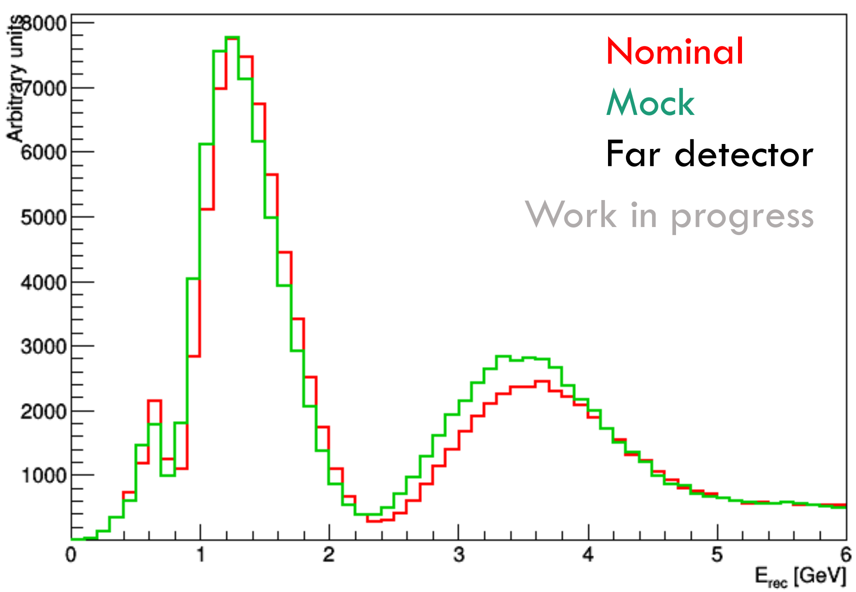
- Neutrino flux is different in far detector compared to near detector: neutrinos oscillate!
- This presents an additional difficulty in constraining neutrino interaction models as we only ever measure a combination of flux and cross-section.
- Demonstrate this effect with mock data bias study:
  - Move 20% of final-state proton energies to neutrons.
  - Use the same multi-dimensional reweighting technique to leave distributions of observables at the near detector unchanged.
    - Bias in reconstructed energy persists, leading to biased oscillation parameters.

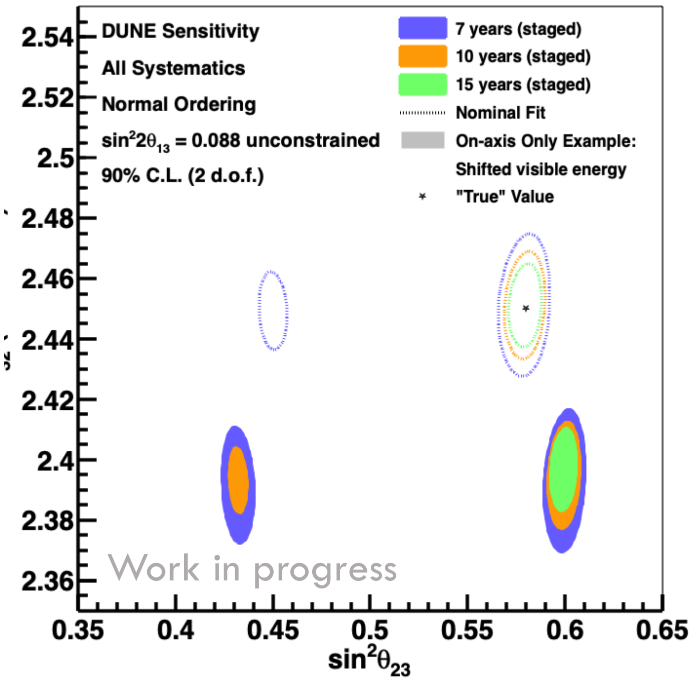




CROSS-SECTION AMBIGUITIES

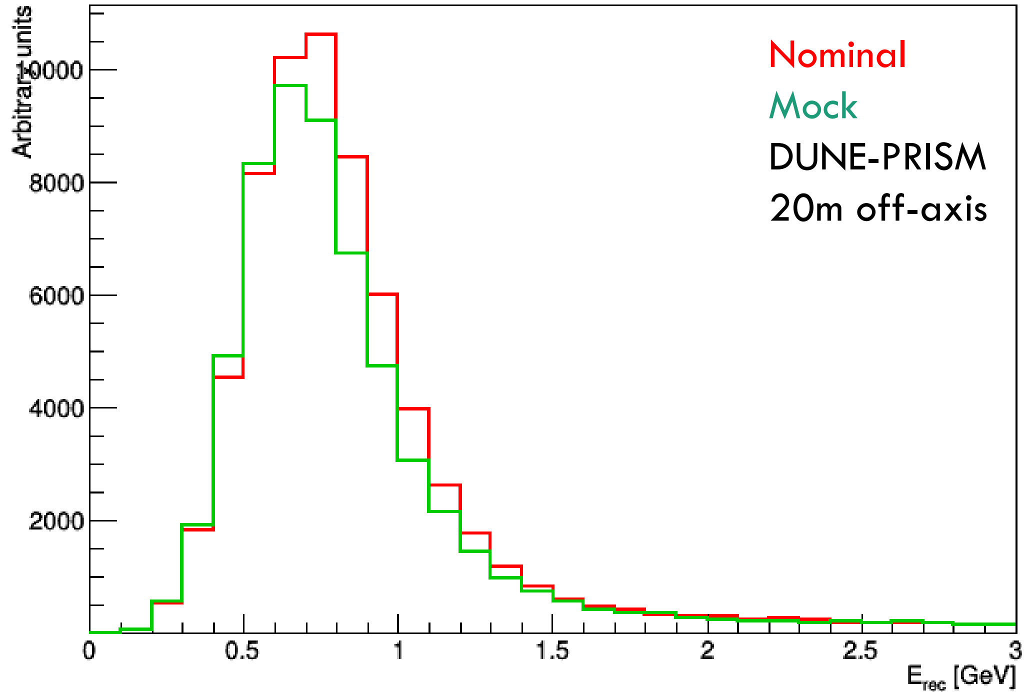
- Neutrino flux is different in far detector compared to near detector: neutrinos oscillate!
- This presents an additional difficulty in constraining neutrino interaction models as we only ever measure a combination of flux and cross-section.
- Demonstrate this effect with mock data bias study:
  - Move 20% of final-state proton energies to neutrons.
  - Use the same multi-dimensional reweighting technique to leave distributions of observables at the near detector unchanged.
    - Bias in reconstructed energy persists, leading to biased oscillation parameters.



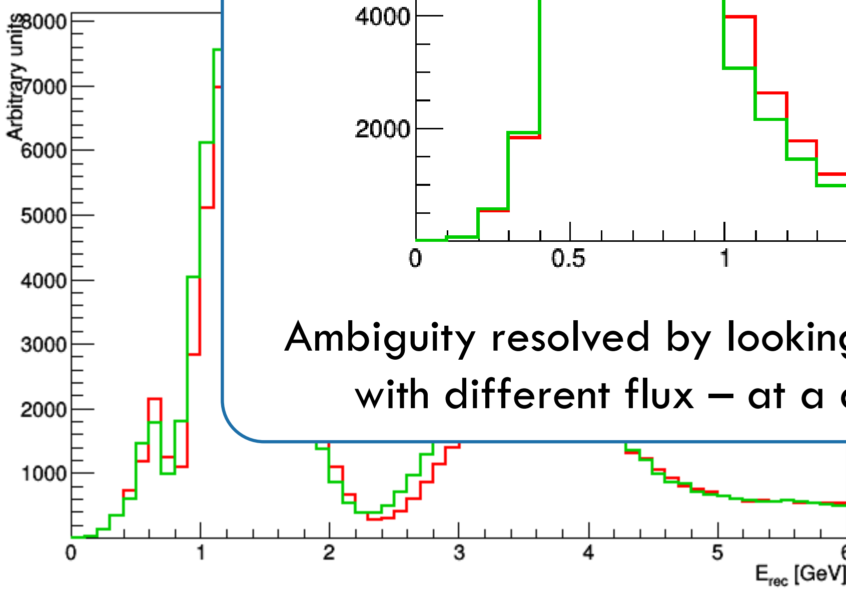


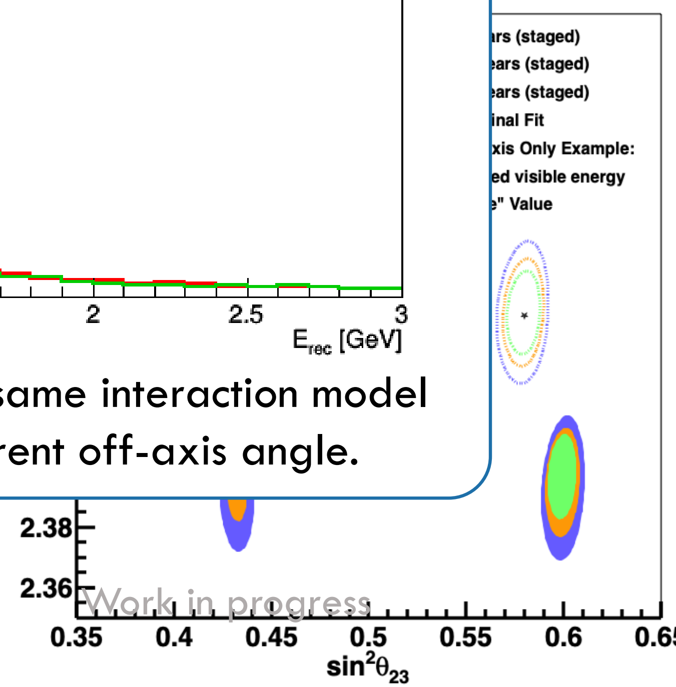
CROSS-SECTION AMBIGUITIES

- Neutrino flux is different in far detector compared to near detector: neutrinos oscillate!
- This presents … as we only ever measure a c…
- Demonstrate…
  - Move 20…
  - Use the s… at the near detector
    - Bi…



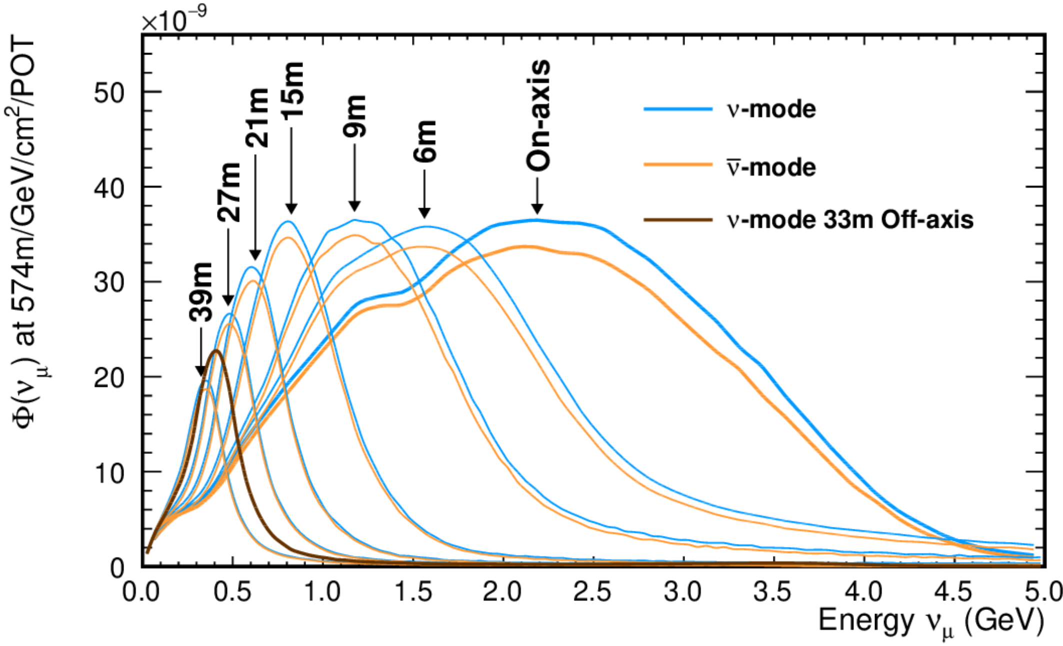
Ambiguity resolved by looking at same interaction model with different flux – at a different off-axis angle.

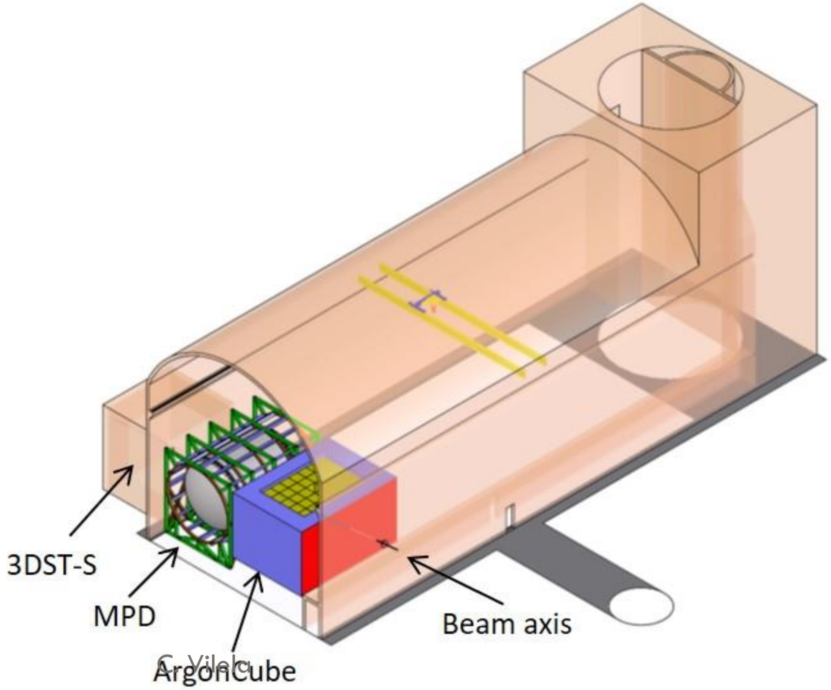


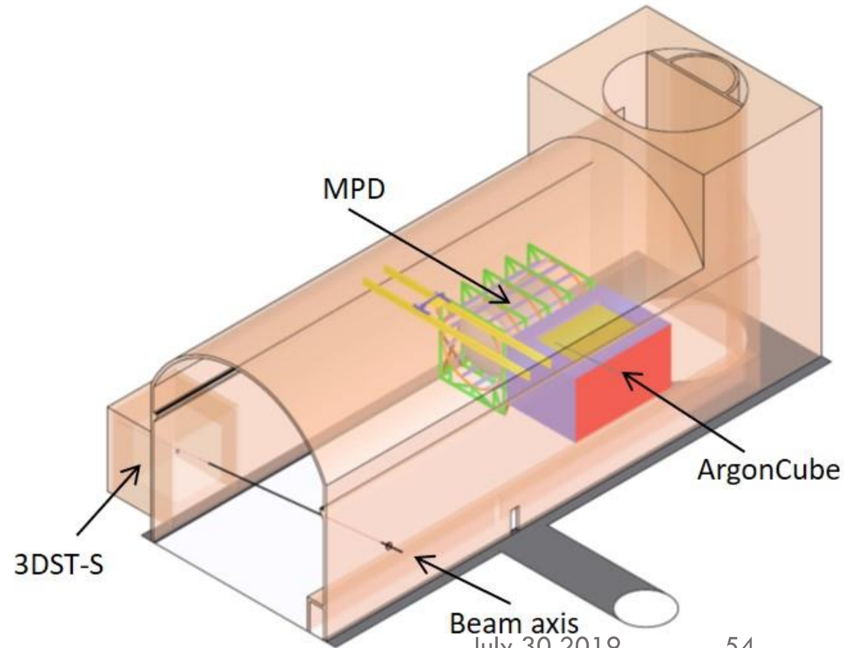


DUNE-PRISM

- Sample different fluxes with the near detector by **moving** the detector in a direction transverse to the beam axis, changing the off-axis angle.
- Data-driven oscillation analysis possible, largely bypassing interaction model.







NEAR DETECTOR CONCEPT

3DST-S

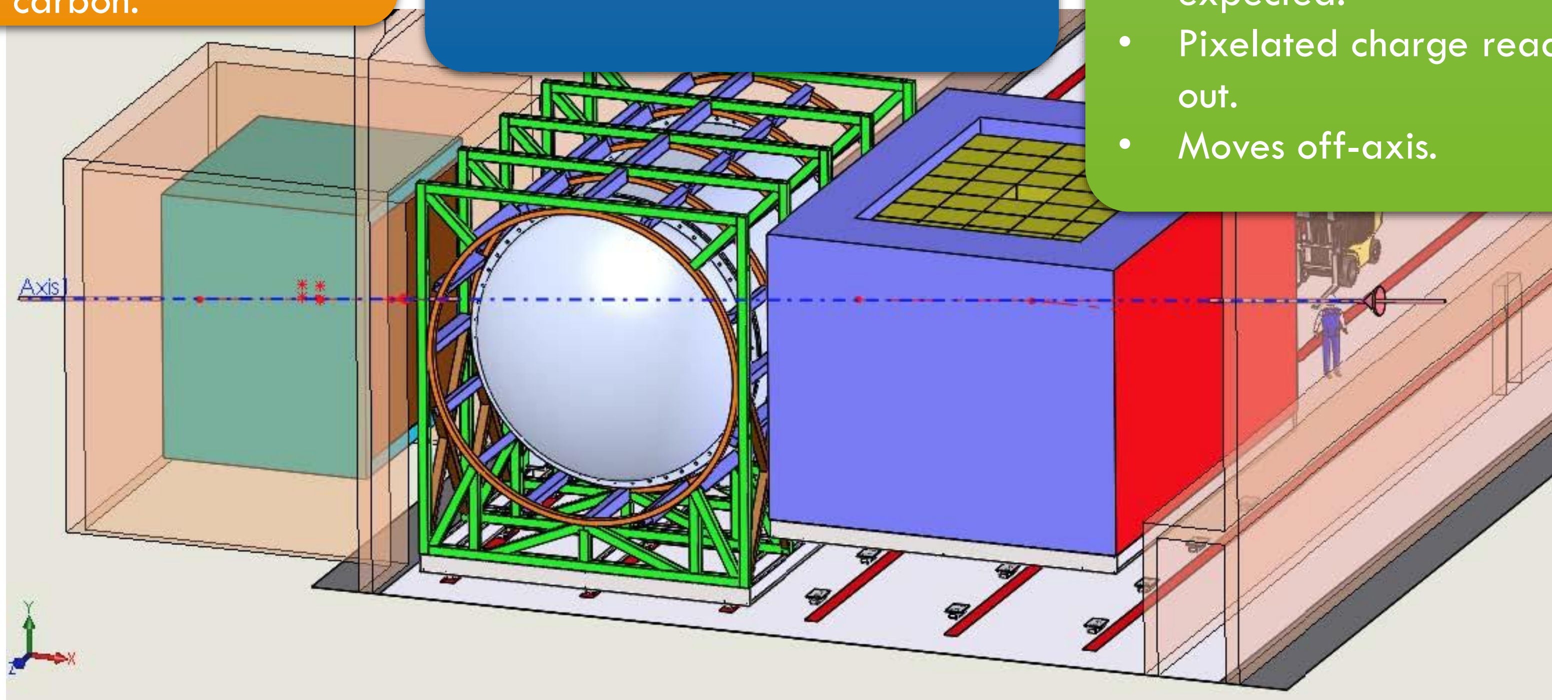
- Finely segmented plastic scintillator.
- Permanently on-axis for flux monitoring.
- Help validate interaction models with neutron measurements on carbon.

HPGArTPC

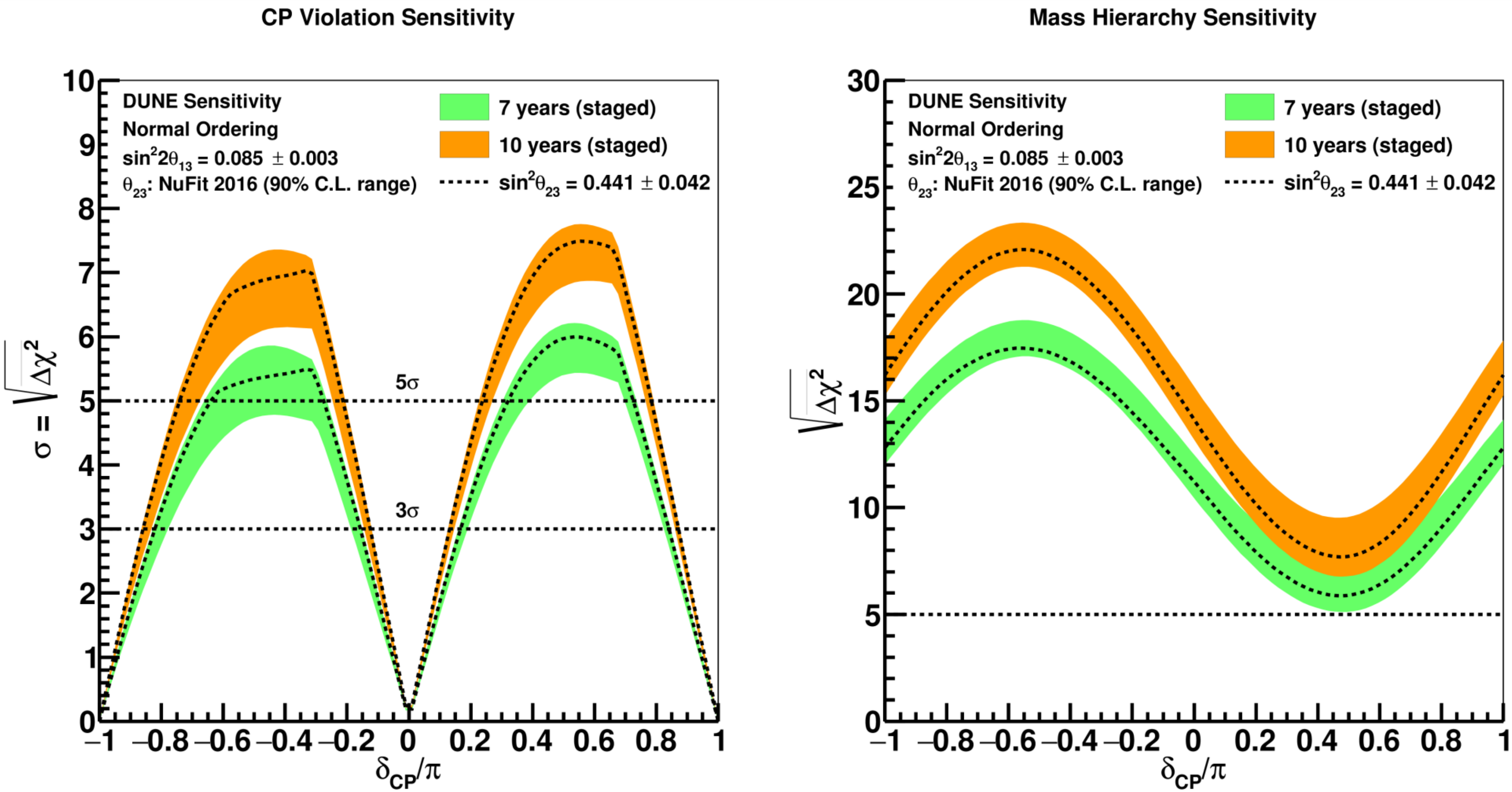
- High pressure gaseous argon TPC in magnetic field.
- Constrain neutrino-argon interaction model with low tracking threshold.
- Muon spectrometer for ArgonCube.
- Moves off-axis.

ArgonCube

- Modular LAr TPC with optically separated volumes to disambiguate pile up with scintillation light read out.
- Detector response very close to that of far detector.
- Very high statistics expected.
- Pixelated charge read out.
- Moves off-axis.



δ_{CP} AND MASS ORDERING SENSITIVITY



- DUNE will unambiguously measure the mass ordering and has 5σ CP violation discovery potential for a large fraction of the true parameter space.
- Updated sensitivities with complete far detector simulation, reconstruction and sophisticated oscillation analysis including detailed interaction model systematics will be released August 2nd.

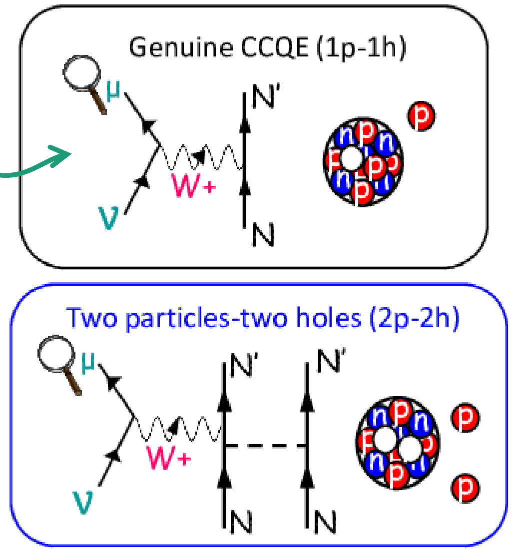
SUMMARY

- Long baseline neutrino oscillation measurements address some of the key questions in neutrino physics.
- Measurements of electron neutrino appearance in a muon neutrino beam at T2K are now starting to constrain the leptonic CP violating phase.
  - This might be an indication that leptonic CP violation is large!
- DUNE will determine the neutrino mass ordering and discover CP violation, as long as it's not too close to 0 or π.
  - Maybe there will be some (good) surprises along the way…
- Systematic uncertainties from interaction modelling and other sources present a significant challenge that is mitigated with sophisticated near detector designs.

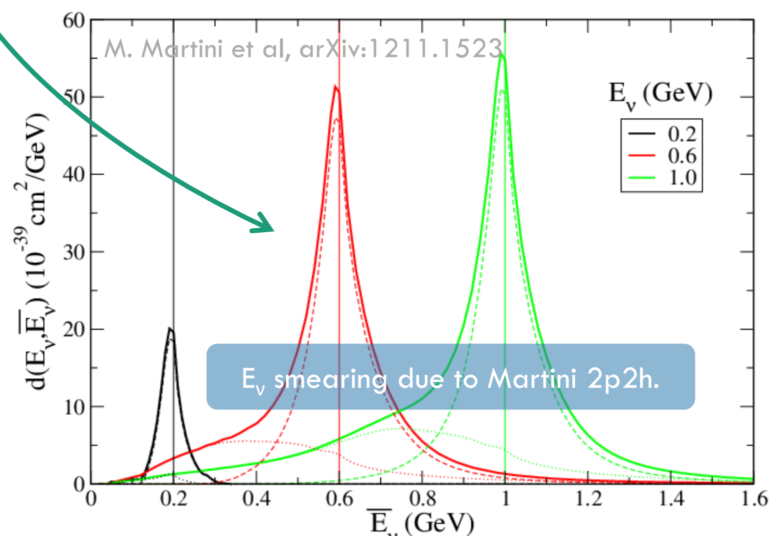
SUPPLEMENTARY

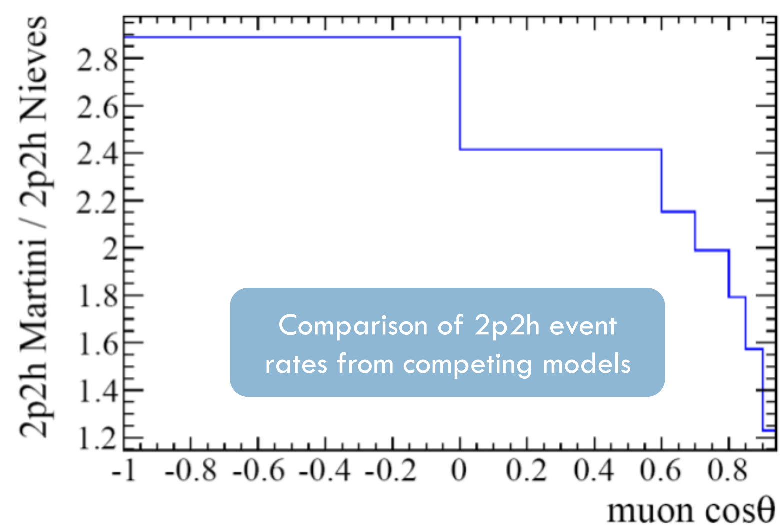
MEASURING NEUTRINO ENERGY
USING LEPTON KINEMATICS ONLY

- Model assumptions play important role in inferring neutrino energy from detected neutrino-nucleus interaction products.
- For example, in Super-K charged lepton kinematics are measured and CCQE dynamics are assumed.
  - Multi-nucleon contributions to CCQE cross-section can bias E_ν significantly.
  - Large uncertainties from final state and secondary interaction models.
- Calorimetric measurements suffer from similar model dependence.
  - For example, through uncertainties in the multiplicity of (undetected) neutrons.



T. Katori, M. Martini, arXiv:1611.07770

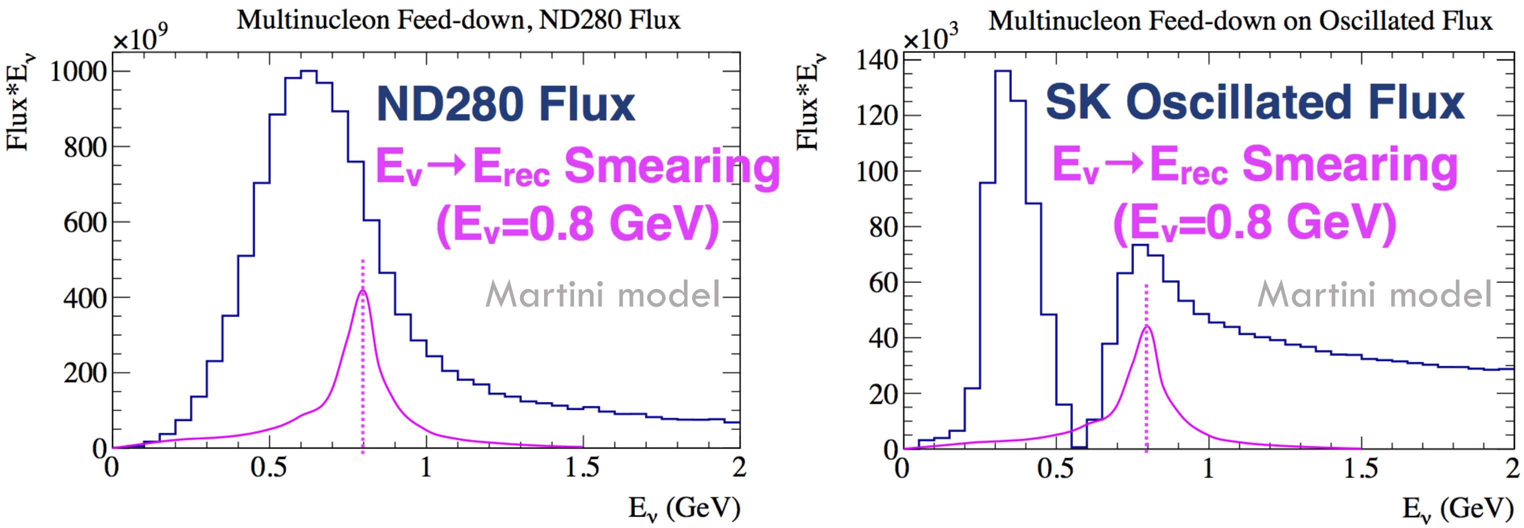




FLUX/CROSS-SECTION AMBIGUITY

AN EXAMPLE FROM WATER-CHERENKOV

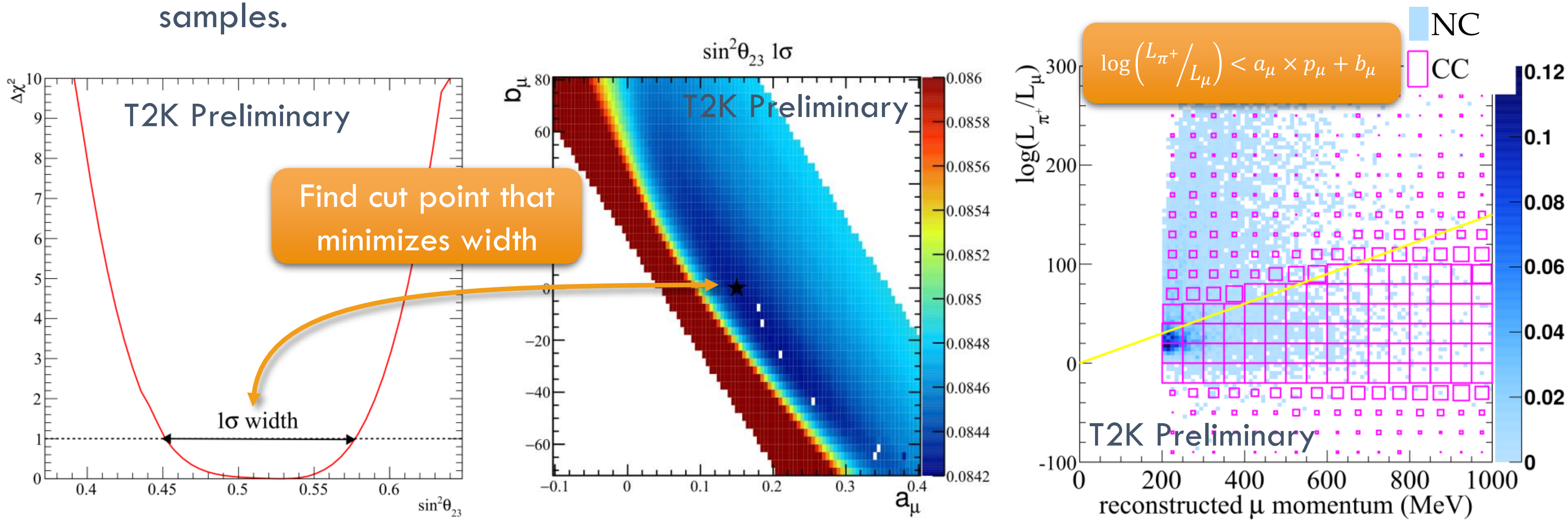
- Neutrino flux is different in far detector compared to near detector: neutrinos oscillate!



- This presents an additional difficulty in constraining neutrino interaction models.
- We only ever measure a combination of flux and cross-section.
- Multi-nucleon effects can smear reconstructed neutrino energy into oscillation **dip** at far detector, biasing the measurement.
  - But this is obscured by the flux **peak** at the near detector!
- Similar effects in calorimetric energy reconstruction, for example, due to modelling of final state neutrons.

NEUTRAL CURRENT REJECTION

- Optimize selection criterium to reject neutral current π^+events in $\nu_\mu(\bar{\nu}_\mu)$ samples.
  - Large uncertainty on cross section degrades precision on disappearance measurements.
- Run simplified oscillation analysis framework, including systematic uncertainties.
- Choose cut point in $\log\left({}^{L_{\pi^+}}/_{L_\mu}\right)$ vs p_μ that maximizes precision on $\sin^2\theta_{23}$ measurement.
  - Optimal cut point is different for equivalent study with statistical uncertainty only.
- Same procedure for neutral current π^0 rejection cut optimization for appearance samples.

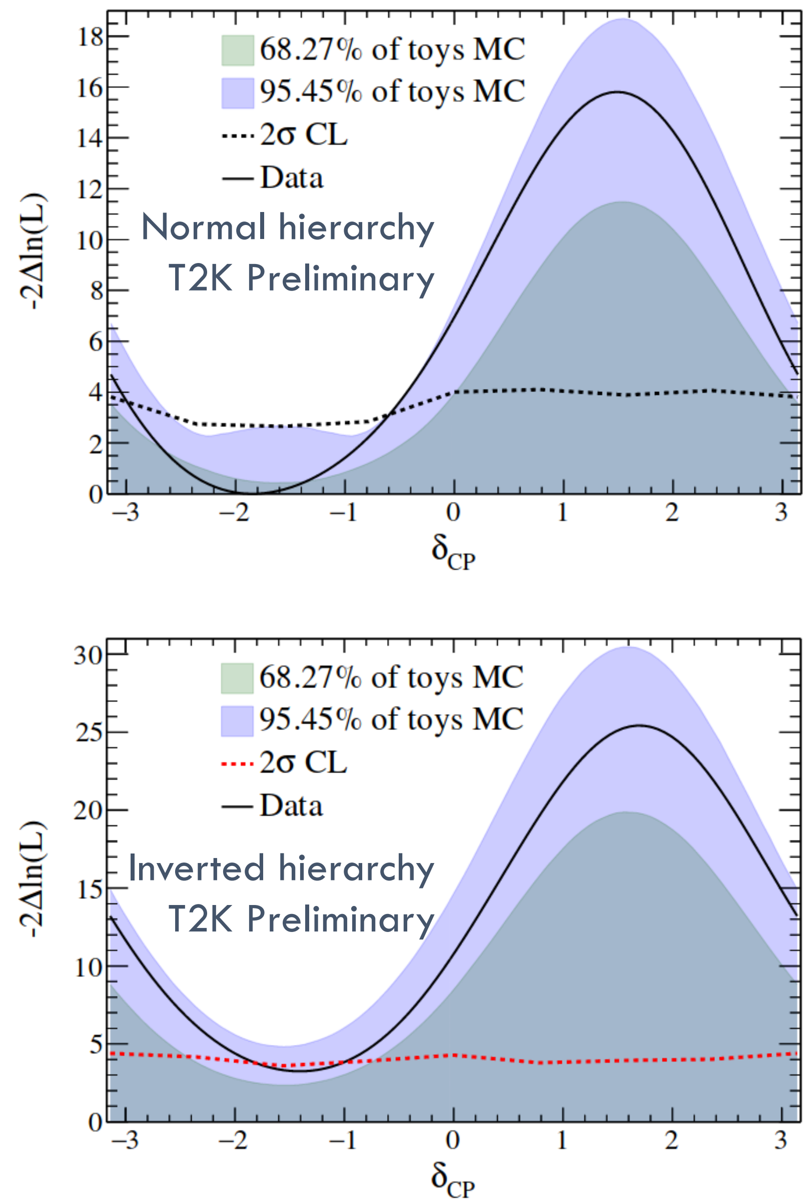


SIMULATED DATA STUDIES FOR E_B

- Generate 2D templates of μ momentum shifts in E_ν vs θ_μ.
  - For each ν species and for carbon and oxygen targets.
    - Carbon: 25^{+18}_{-9} MeV
    - Oxygen: 27^{+18}_{-9} MeV
  - Shifts are applied to 1p1h events.
- Produce simulated data sets using E_B templates and run oscillation analysis fit.
- Setting both C and O E_B to the maximum value considered gives:
  - At the near detector: slight decrease in CCQE cross-section parameters; increased 2p2h contribution.
  - At far detector: significant bias in Δm^2_{32} estimation; small impact on θ_{13}, δ_{CP}.
- Setting E_B to maximum for ν and minimum for $\bar{\nu}$ gives similar results.

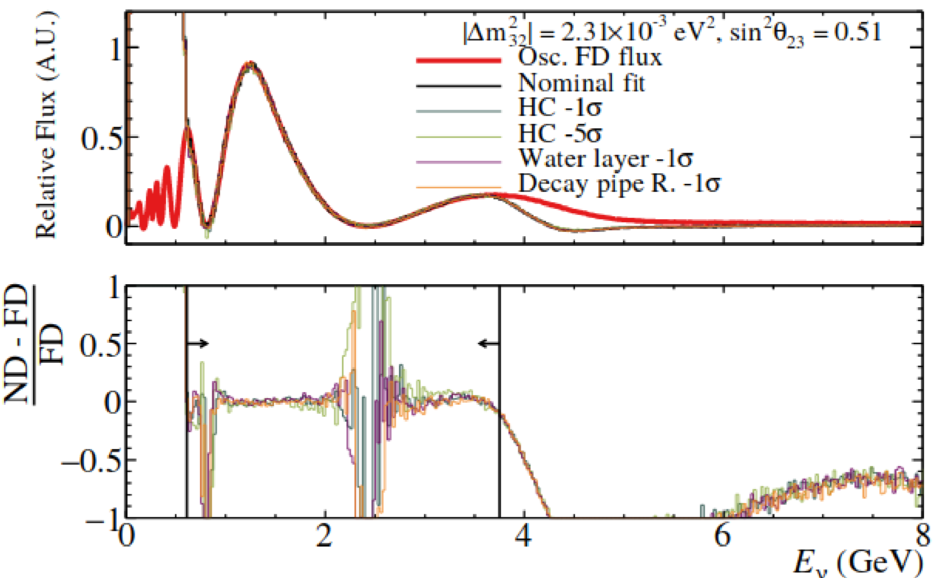
δ_{CP} SENSITIVITY

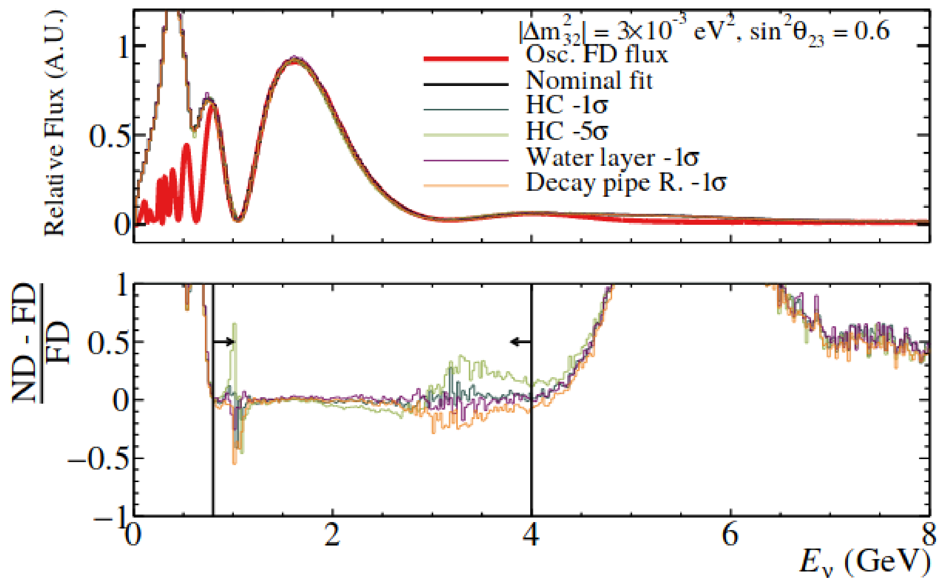
- Data constraint on δ_{CP} is stronger than the average sensitivity.
- Run toy experiments with normal hierarchy and $\delta_{CP} = -\pi/2$.
- Data constraint falls within range for 95.54% of experiments for most δ_{CP} points.
- 30% of experiments exclude $\delta_{CP} = 0$ at 2σ.
- 25% of experiments exclude $\delta_{CP} = \pi$ at 2σ.



FLUX FITS FOR DUNE

- Can reproduce both dips with linear combinations.
  - Even without access to fluxes peaking at higher energies than unoscillated FD flux.
- Beam uncertainties have a small effect on the linear combinations.
- Linear combinations tend to diverge at the low energy end of the spectrum.
  - Solvable by improving fitting method and regularization – work in progress.
- Difficult to fit high energy bump completely.
  - Region close to the dip is well reproduced – most important to control feed-down effects.

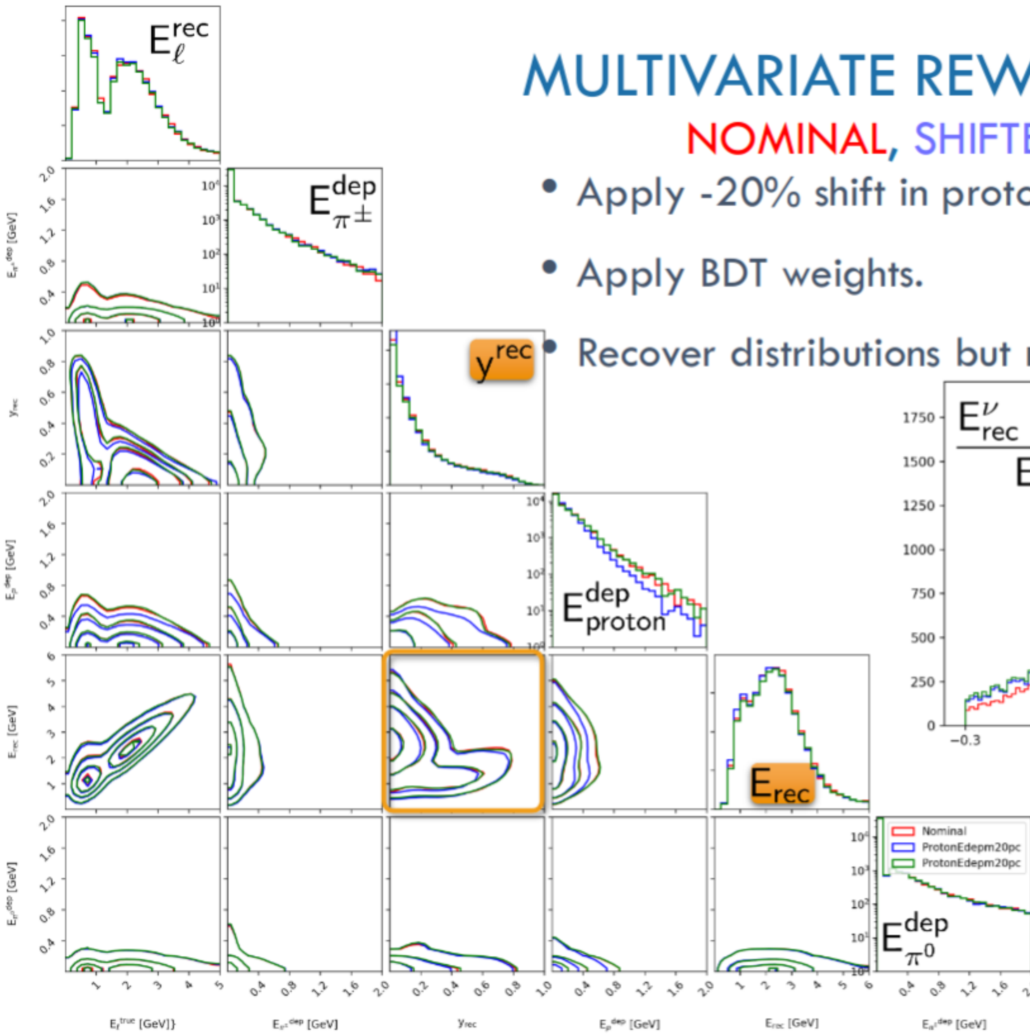


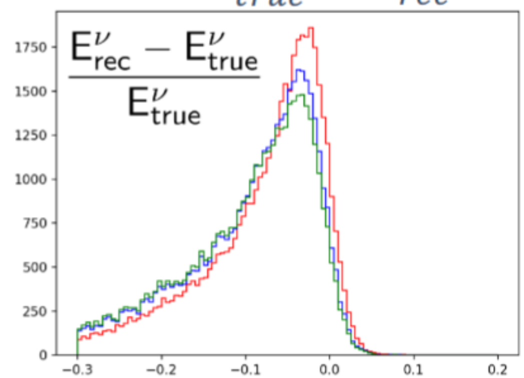


MULTIVARIATE REWEIGHTING

NOMINAL, SHIFTED, FAKE DATA

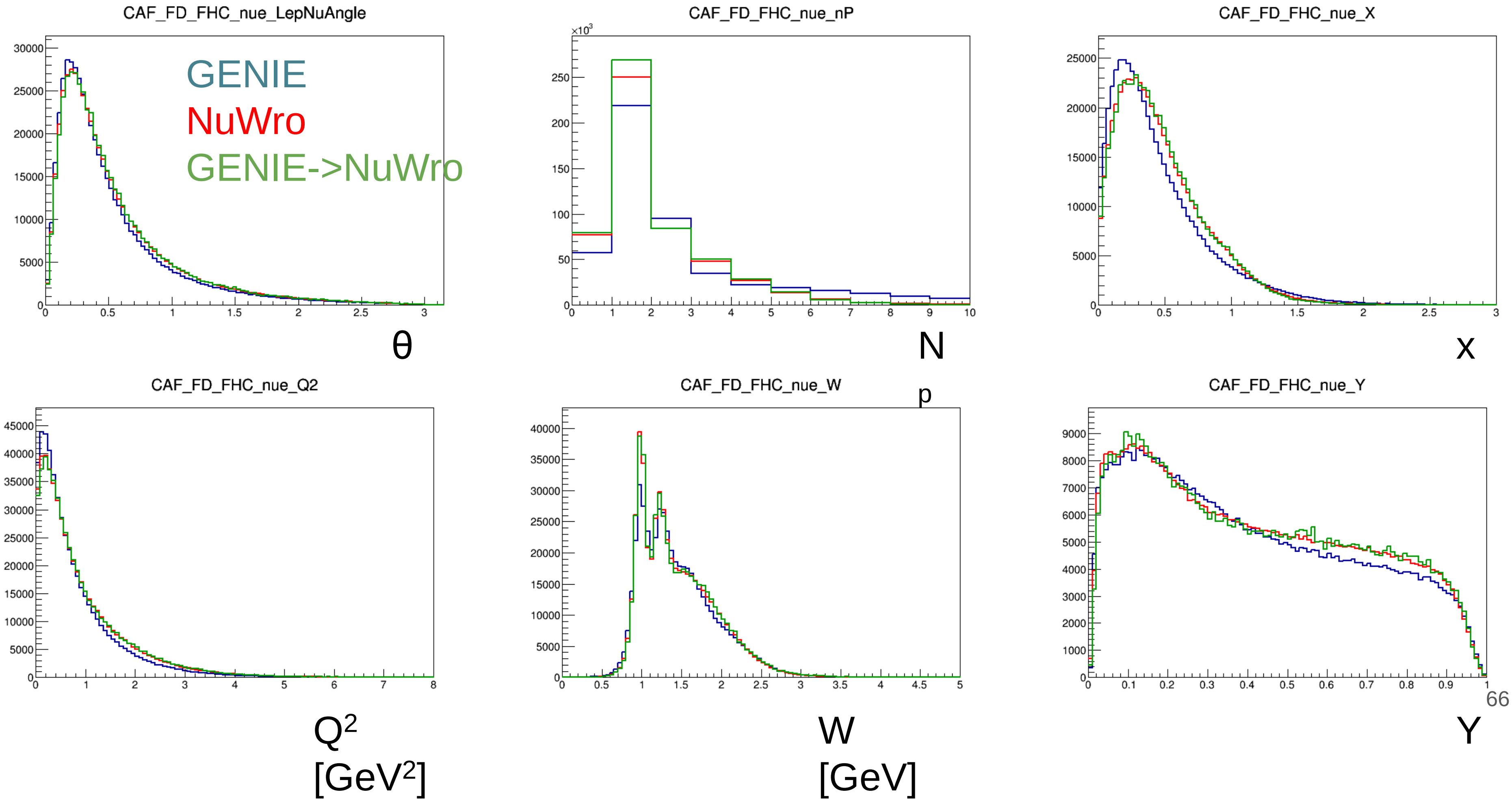
- Apply -20% shift in proton deposited energy.
- Apply BDT weights.
- Recover distributions but **not** $E^{\nu}_{true} \rightarrow E^{\nu}_{rec}$.





More details in, e.g.:
https://indico.fnal.gov/event/16764/session/14/contribution/51/material/slides/0.pdf

FD FHC nue


CAF_FD_FHC_nue_LepNuAngle
GENIE
NuWro
GENIE->NuWro
θ
CAF_FD_FHC_nue_nP
×10^3
N
p
CAF_FD_FHC_nue_X
x
CAF_FD_FHC_nue_Q2
Q^2 [GeV^2]
CAF_FD_FHC_nue_W
W [GeV]
CAF_FD_FHC_nue_Y
Y

FD RHC nuebar