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What do the next 10 years have in store?

... For long-baseline neutrino experiments

Mark Scott
UK HEP Forum 2019

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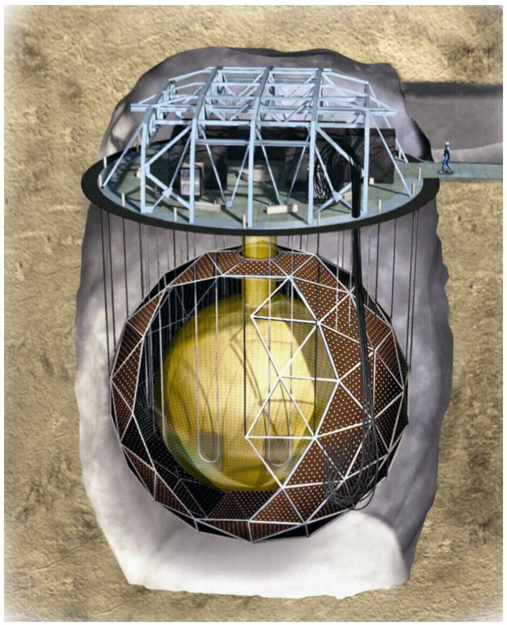
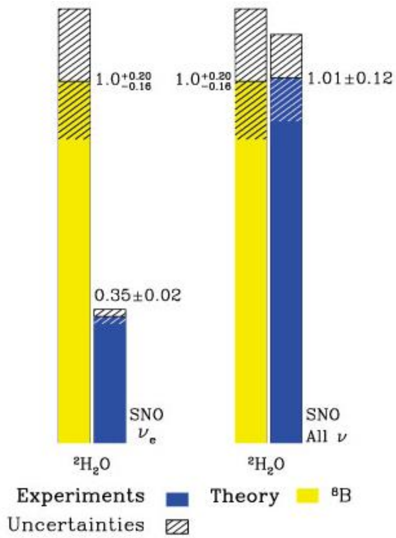
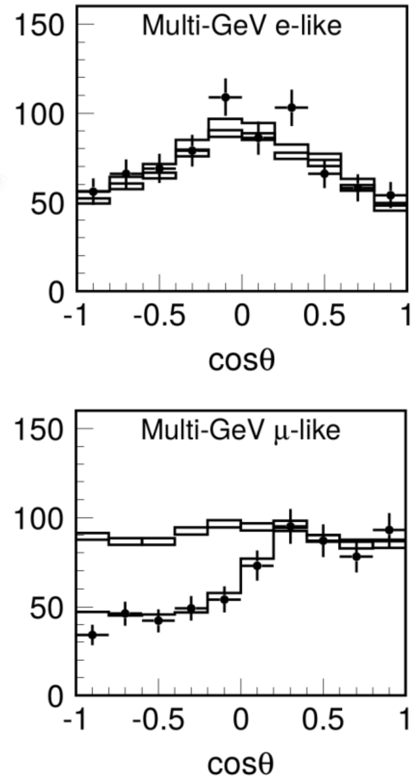
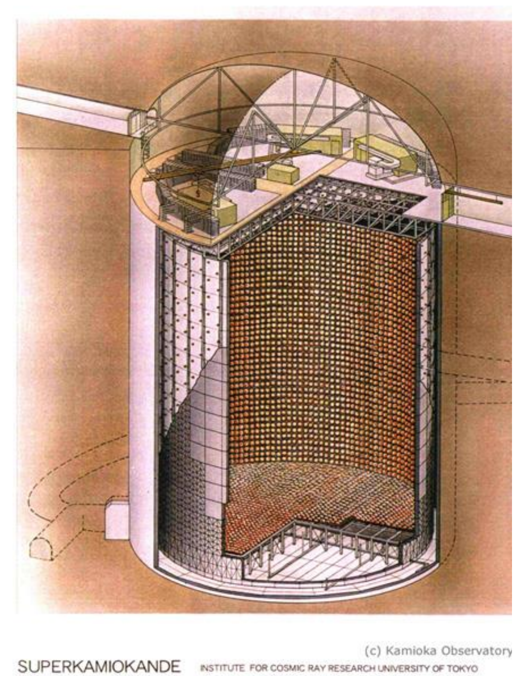
Neutrinos beyond the Standard Model









Neutrinos oscillations

- Flavour and mass eigenstates
- Oscillation probability is function of neutrino energy, E, and propagation distance L
- Measure flavour composition of beam as function of L / E

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

0  1

$$P_{\alpha\to\beta} = \left| \sum_i U^*_{\alpha i} U_{\beta i} e^{-i m_i^2 L/2E} \right|^2$$

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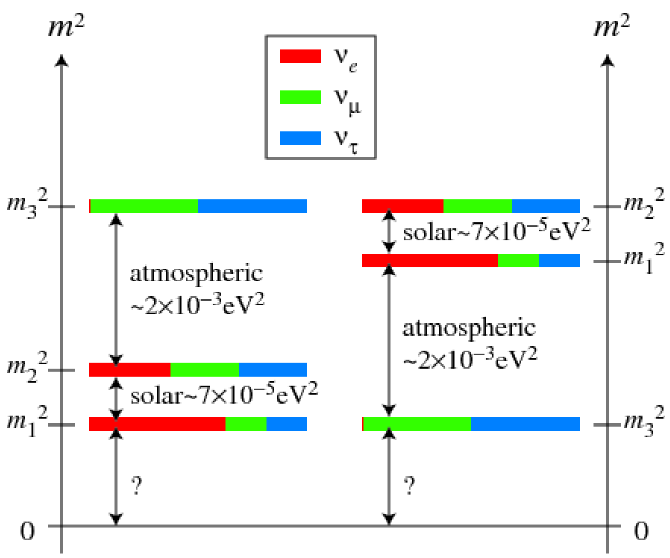
Neutrinos oscillations

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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

- Three mixing angles, θ_{12}, θ_{23} and θ_{13}
- Two mass splittings, Δm^2_{12} and Δm^2_{23}
- One CP-violating phase, δ_{CP}
  - Majorana phases have no effect on oscillations



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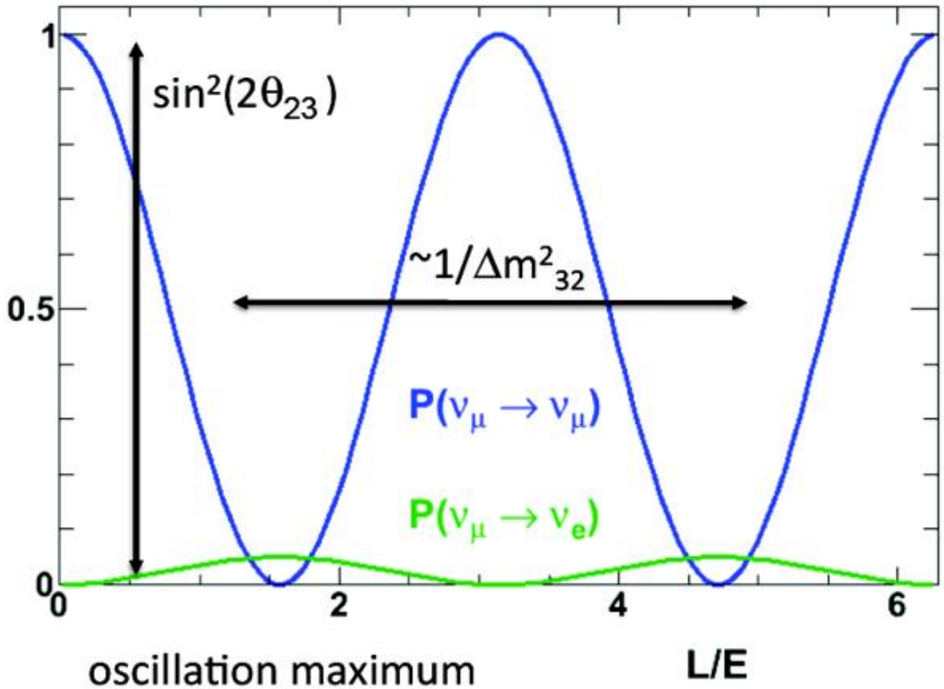
Long-baseline neutrino experiments

- Leading order oscillation probabilities for ν_μ survival and ν_e appearance

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

$$\boxed{P(\nu_\mu \rightarrow \nu_e) \cong \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2\left(\frac{\Delta m^2_{31} L}{4E}\right)}$$



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Long-baseline neutrino experiments

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

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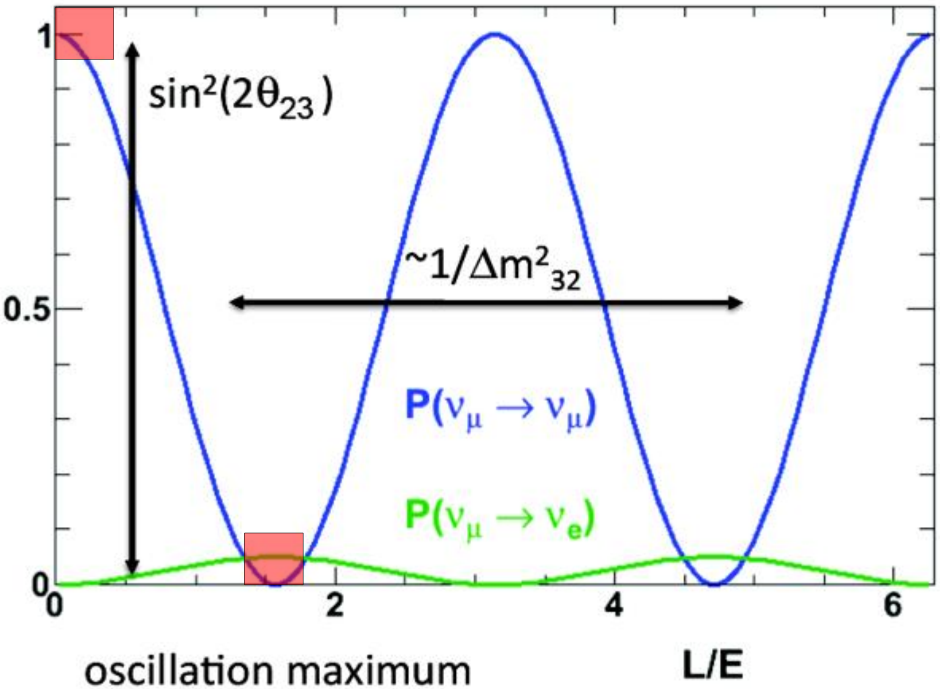

- Need to sample spectrum at different values of L/E
- Build two detectors
- One close to neutrino source
- Other at maximal oscillation

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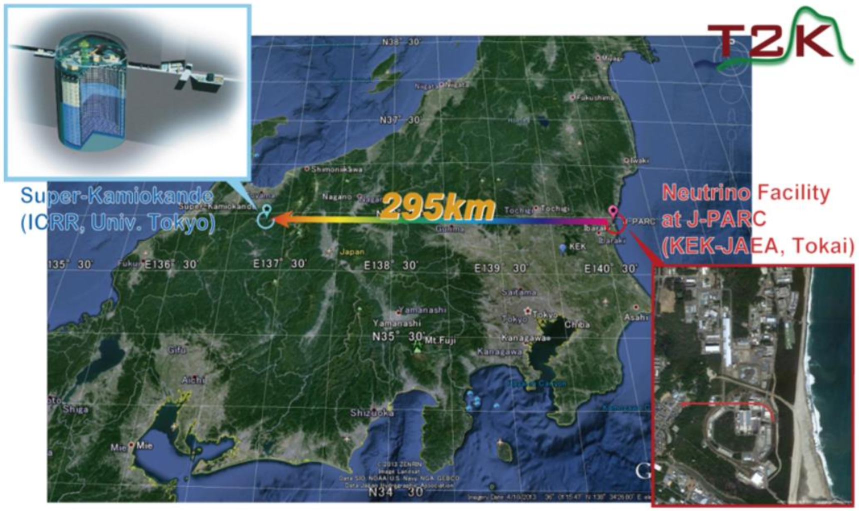
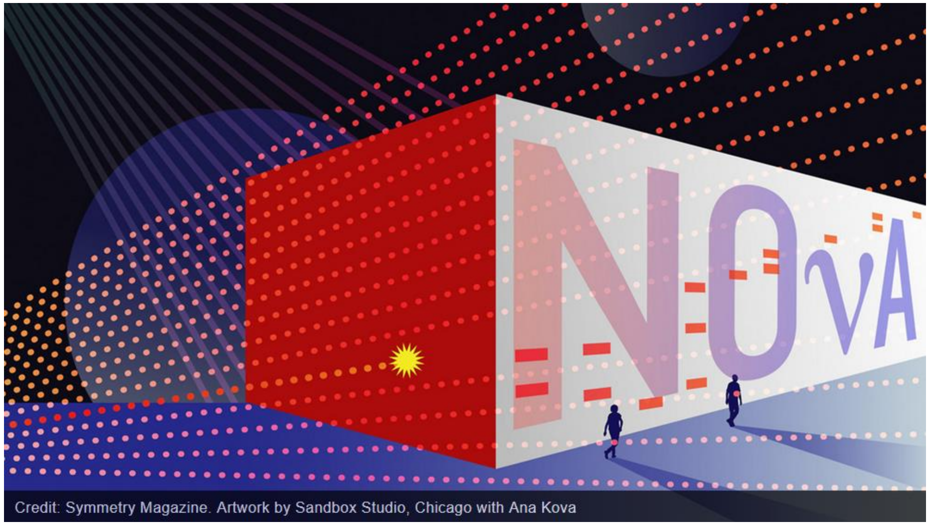
Current experiments





- T2K and NOvA are leading long-baseline neutrino oscillation experiments
- 500 – 700kW beam power
- Far detector masses of 10s of kilotonne

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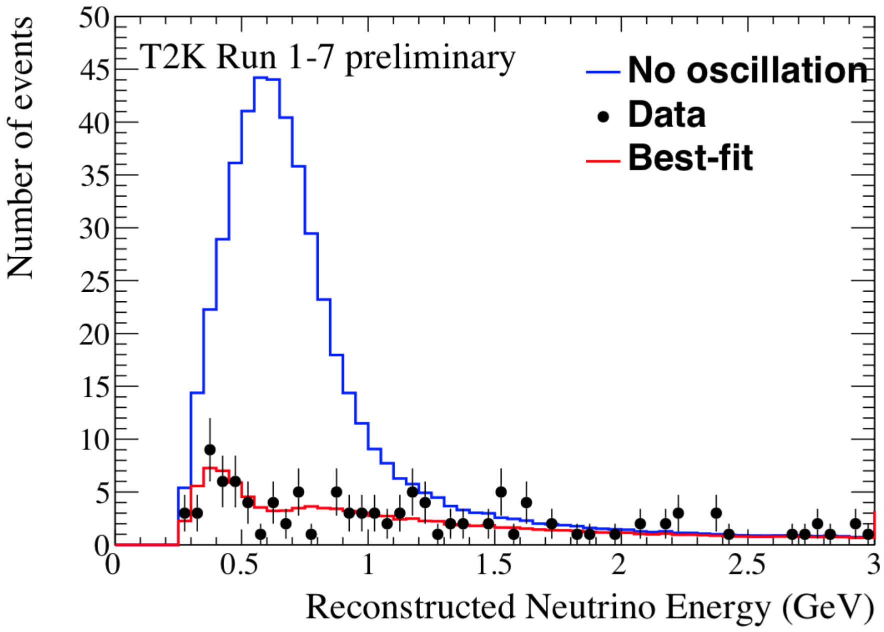
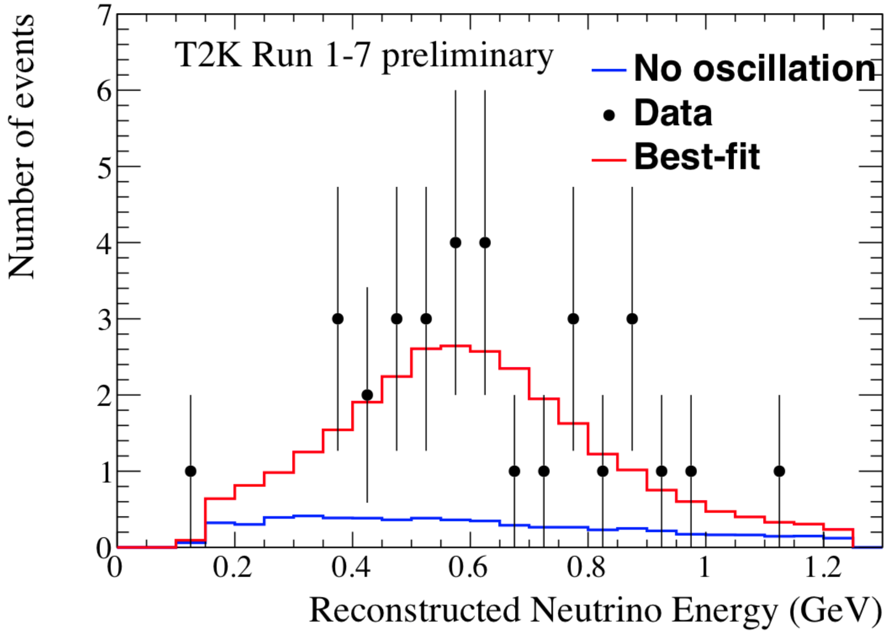
What they measure





- Muon-like neutrino candidates (left), electron-like candidates (right) circa 2017

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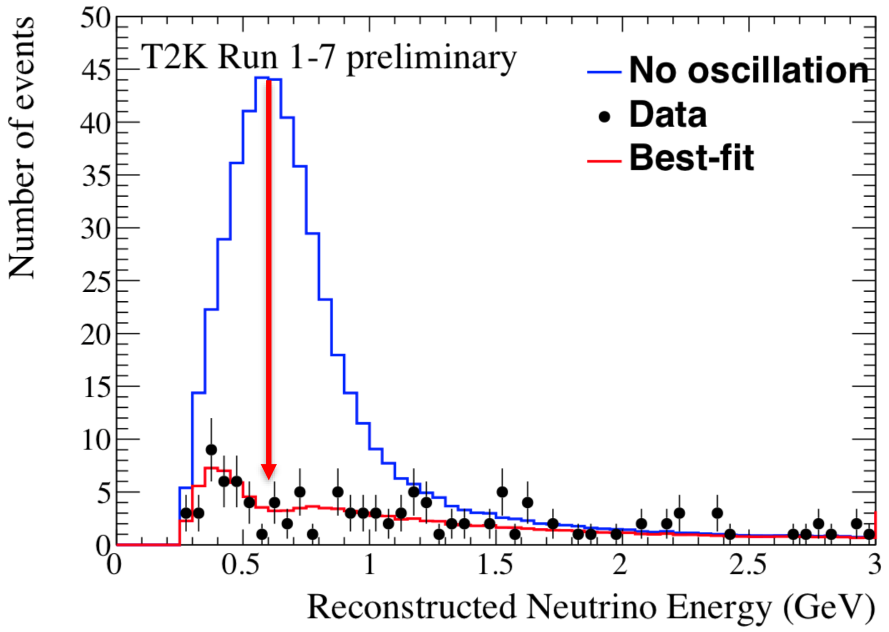
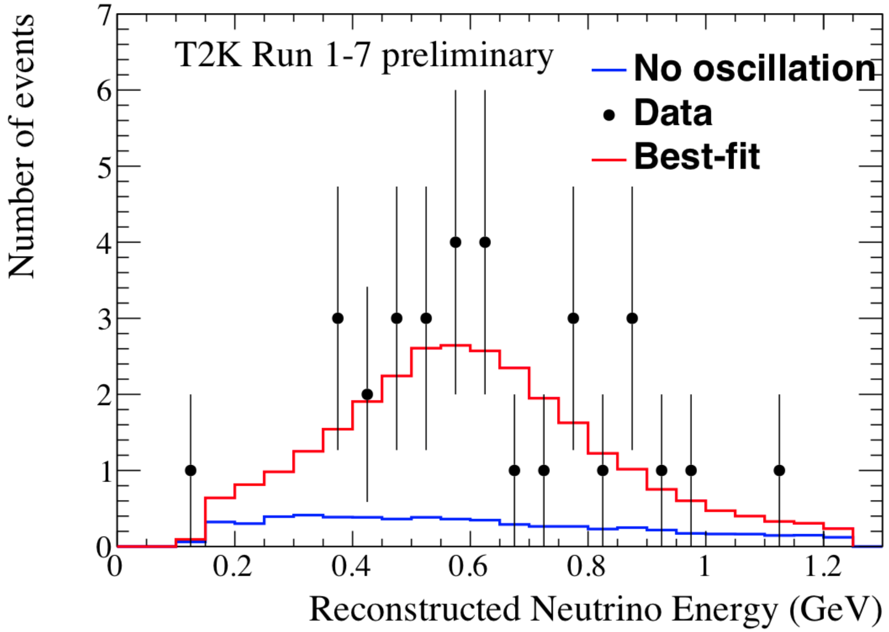
What they measure





- Muon-like neutrino candidates (left), electron-like candidates (right) circa 2017
- Suppression in muon neutrino sample driven by $\sin^2\theta_{23}$, Δm^2_{23}

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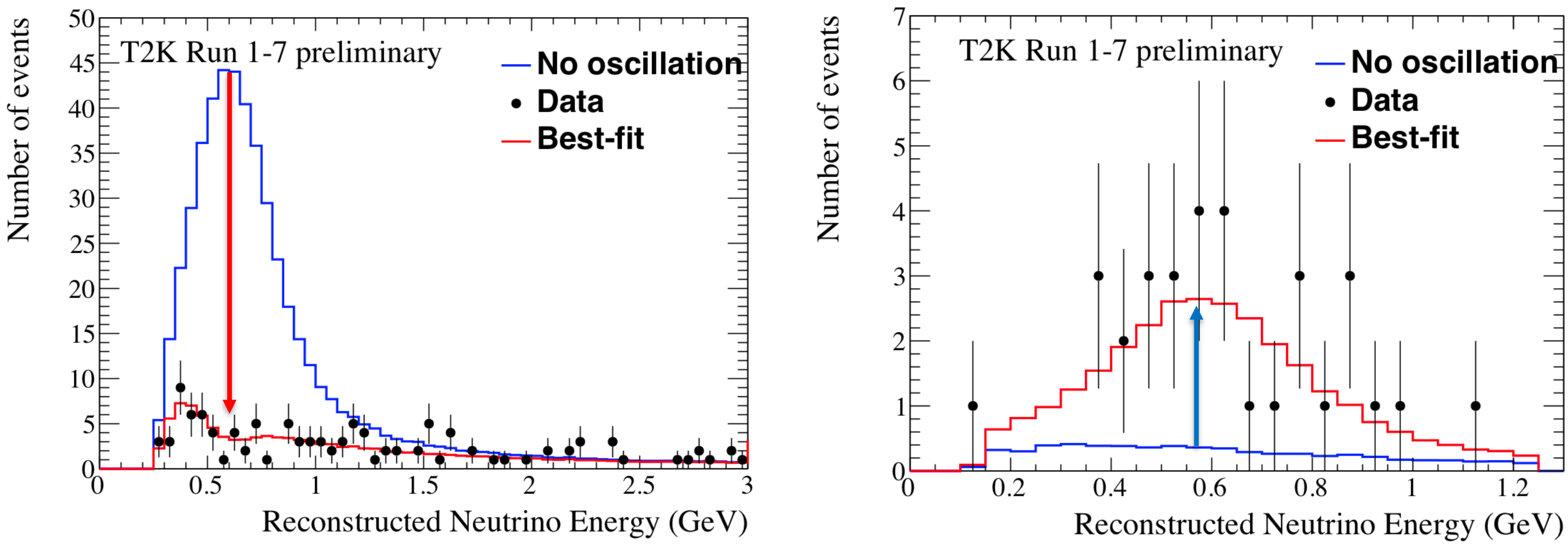
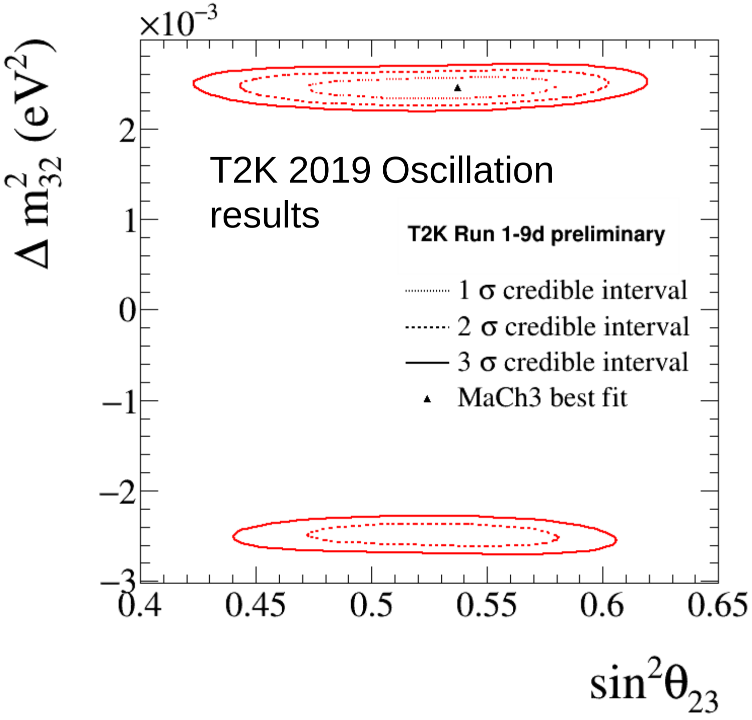
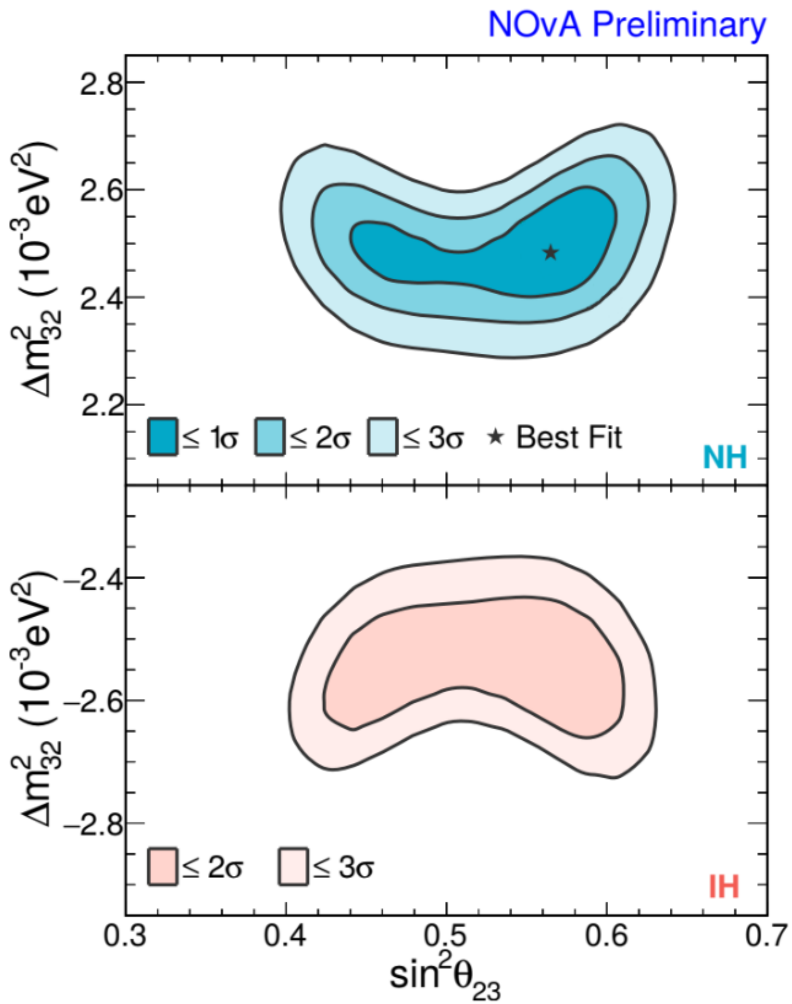
What they measure



- Muon-like neutrino candidates (left), electron-like candidates (right) circa 2017
- Suppression in muon neutrino sample driven by $\sin^2\theta_{23}$, Δm^2_{23}
- Increase in electron neutrino sample driven by $\sin^2\theta_{13}$, δ_{CP} and mass ordering

Current status - ν_μ





- Consistent picture for θ_{23} emerging – hints that it is not maximal?

J. Walcott, Fermilab User's Meeting, 2019

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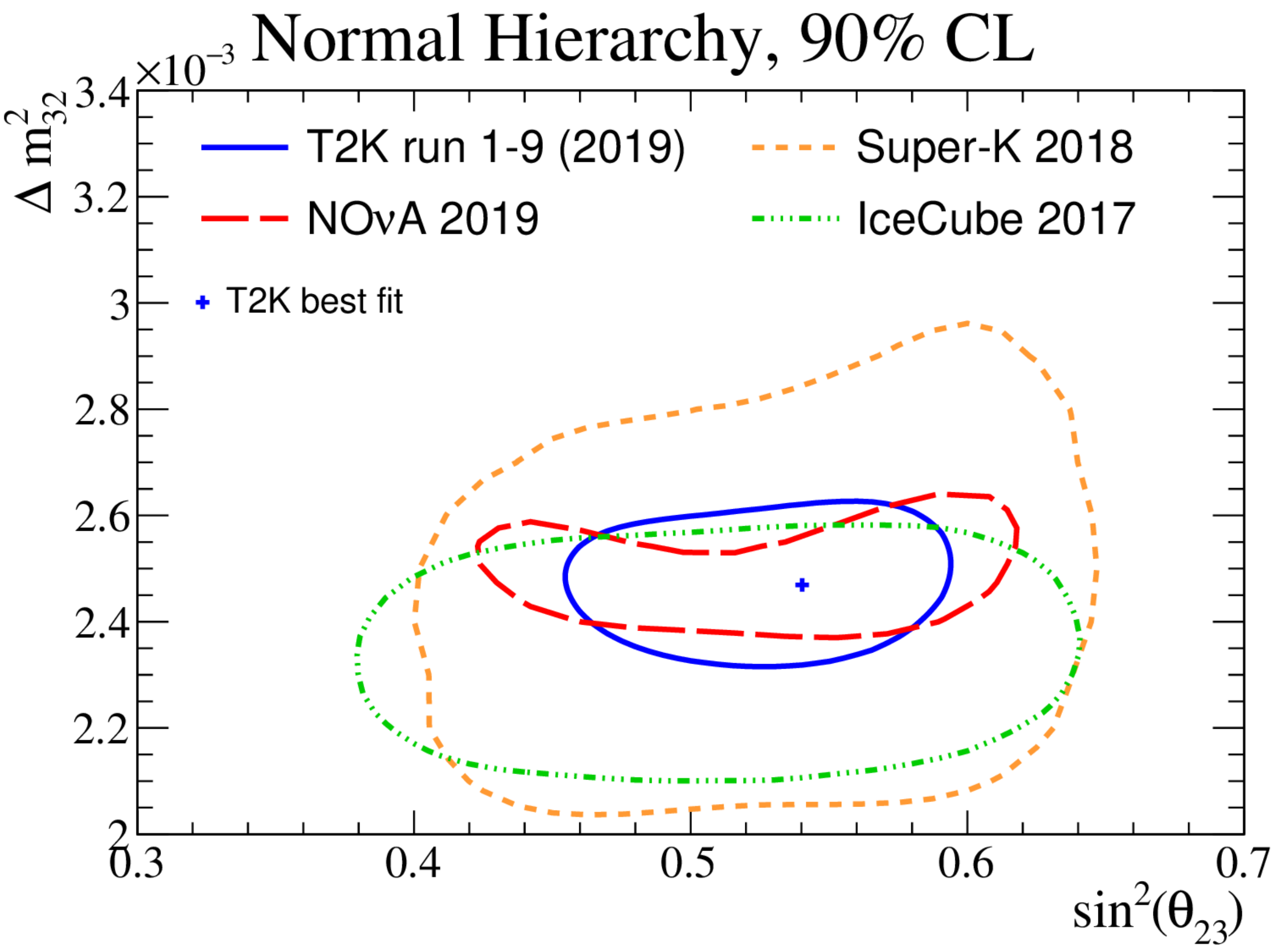
Current status - ν_μ



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Current status - δ_{CP}

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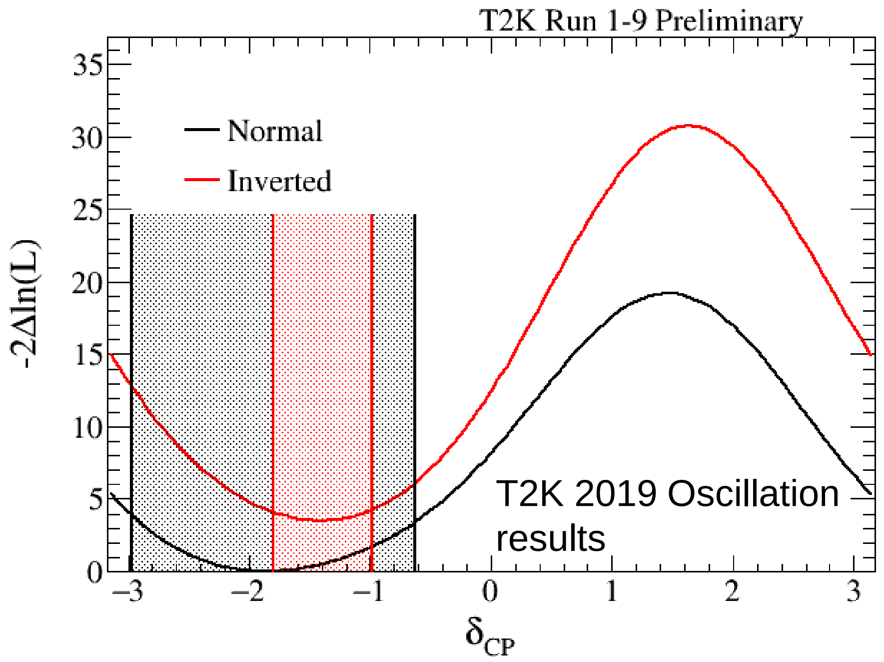
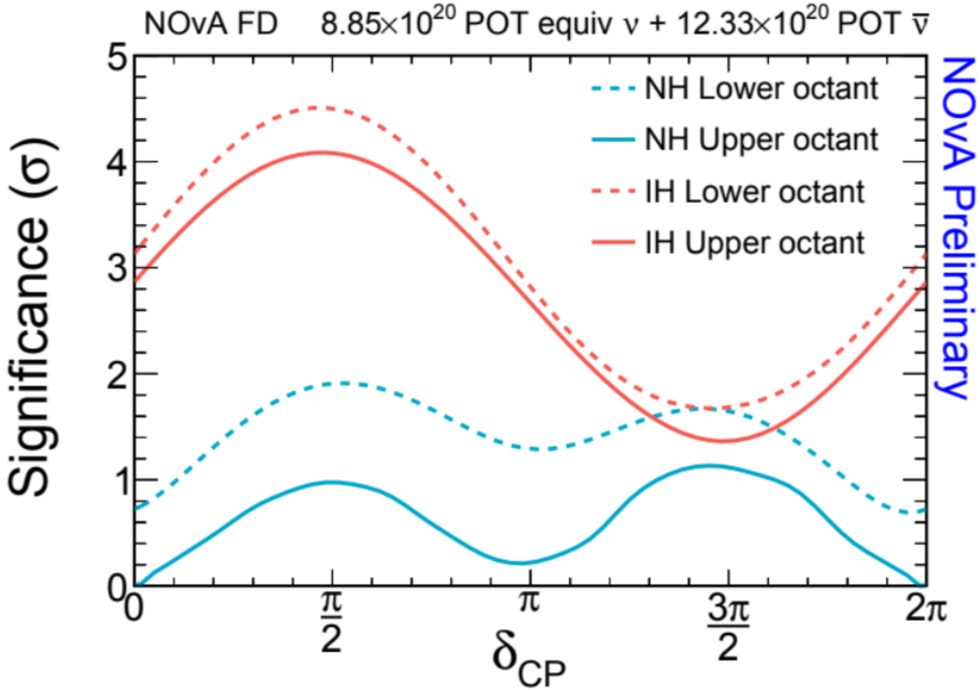
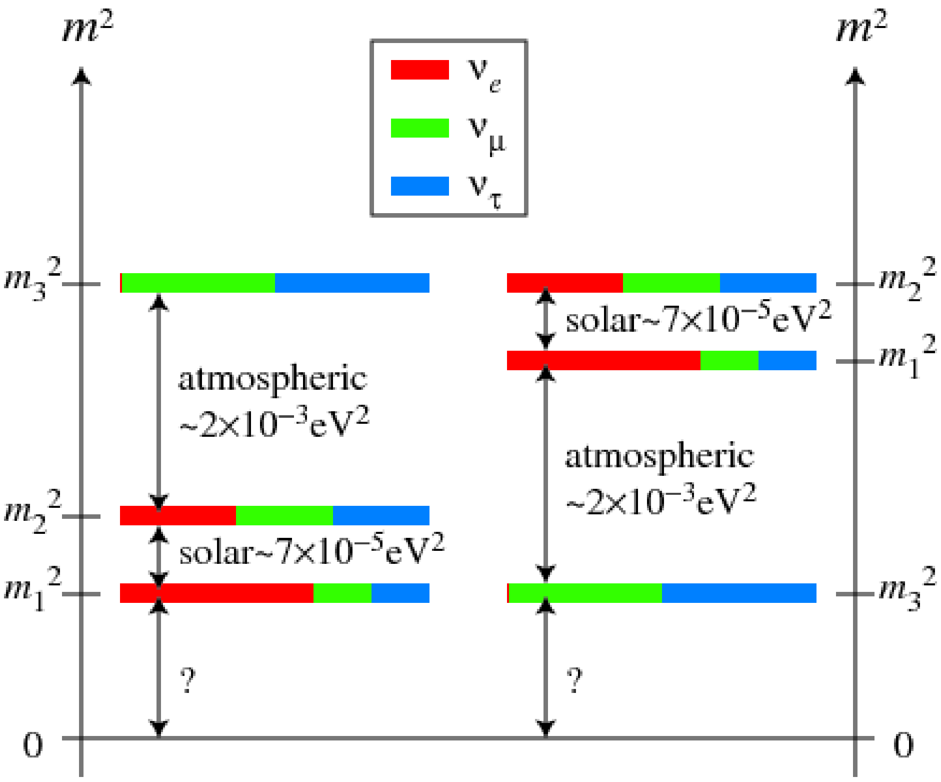




- Some sensitivity to δ_{CP} – plots show significance for excluding given value of δ_{CP}
  - Continuous parameter, $3\pi/2 \equiv -\pi/2$
  - 2σ exclusion of CP conservation at T2K

What don't we know?

- Do neutrinos violate CP?
- Is $m_3 > m_2$? (mass ordering)
- Is $\theta_{23} = 45^o$? (octant)
- What is the value of m_1?
- Are neutrinos Majorana particles?
- New physics?



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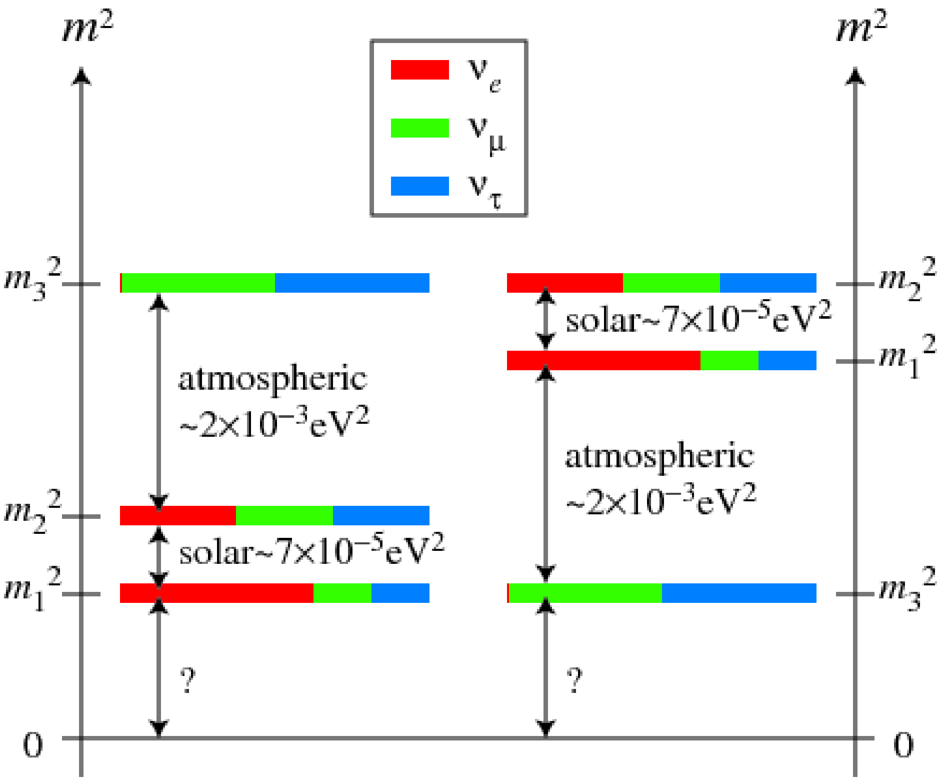

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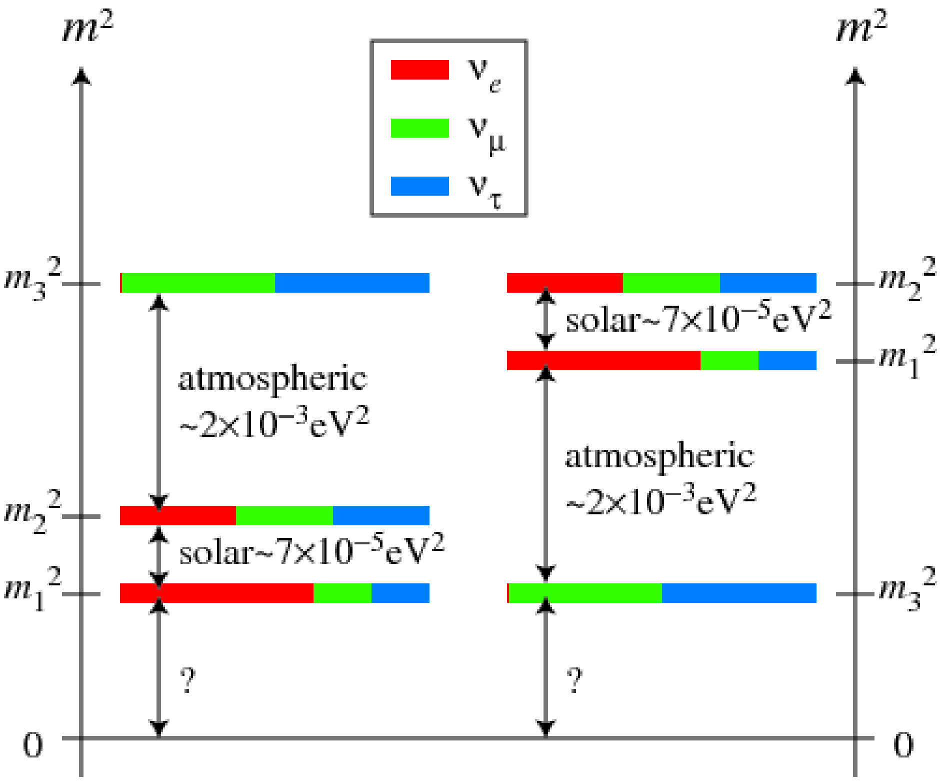
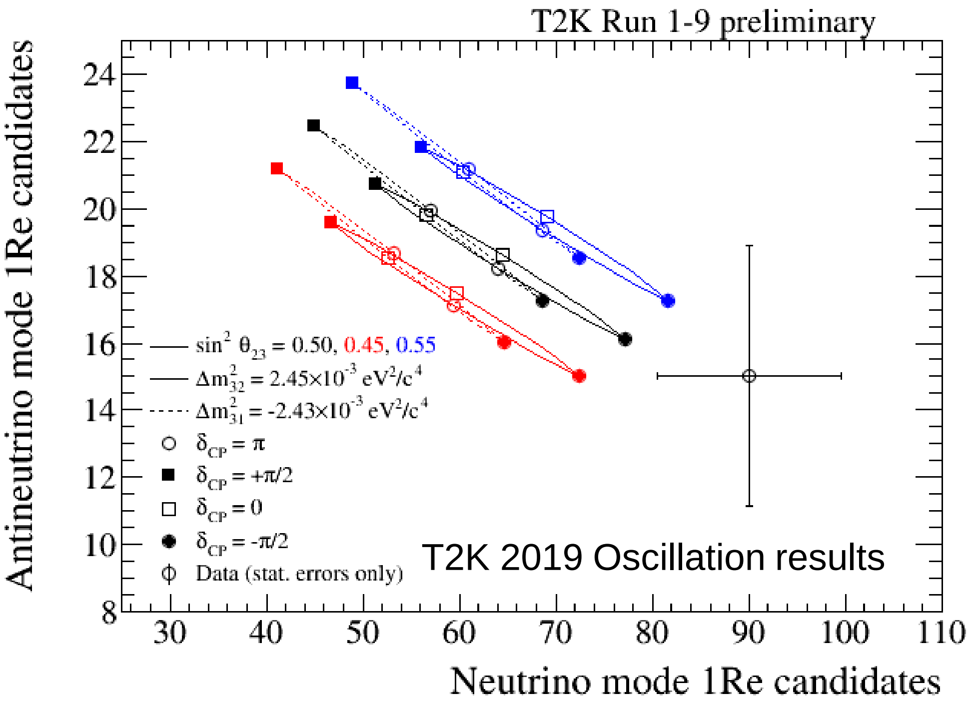
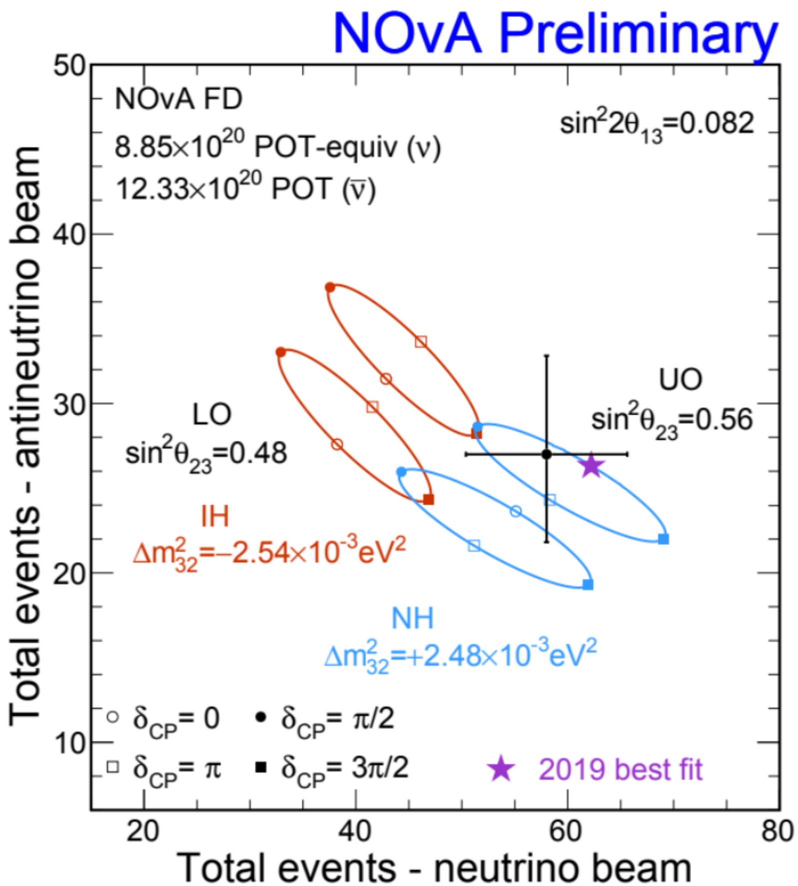


Current status - ν_e





J. Walcott, Fermilab User's Meeting, 2019

- T2K exclusion coming from excess of electron-like neutrino events
- Statistics limited!

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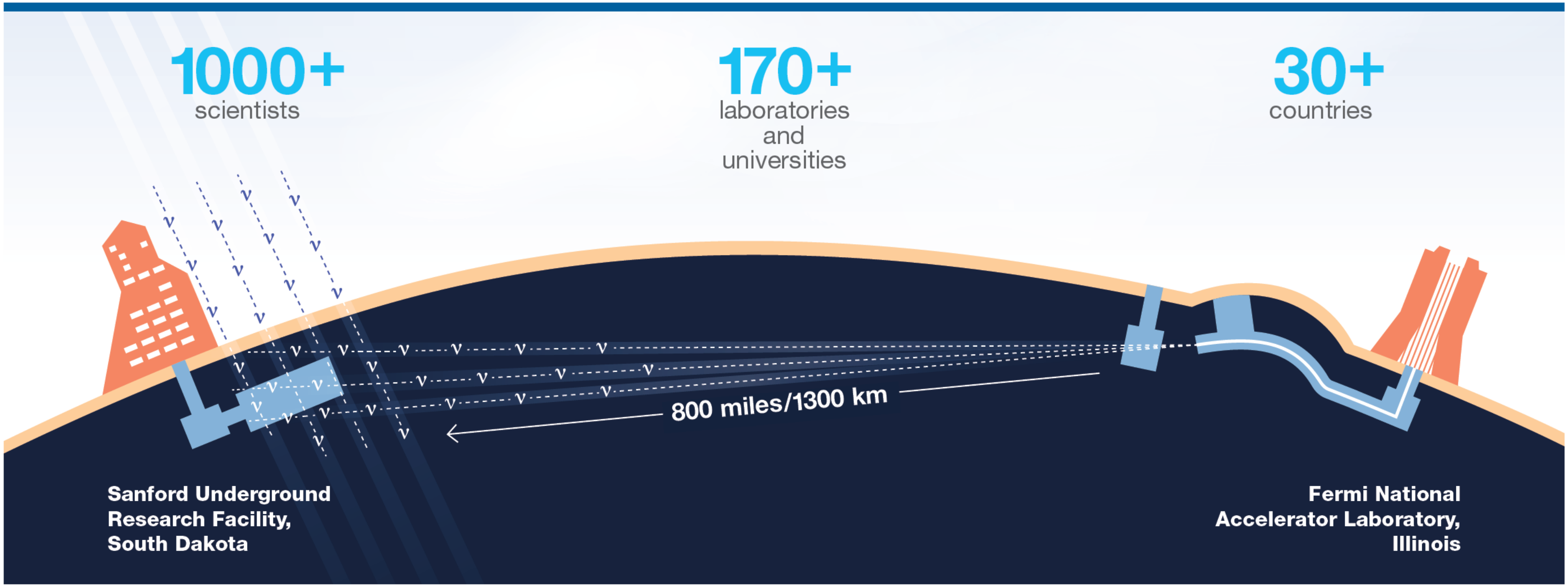
Future long-baseline experiments

- Liquid argon TPCs as far detector (up to 40 kilotonne)
- 1300km baseline
- Few GeV neutrino energy

DEEP UNDERGROUND NEUTRINO EXPERIMENT



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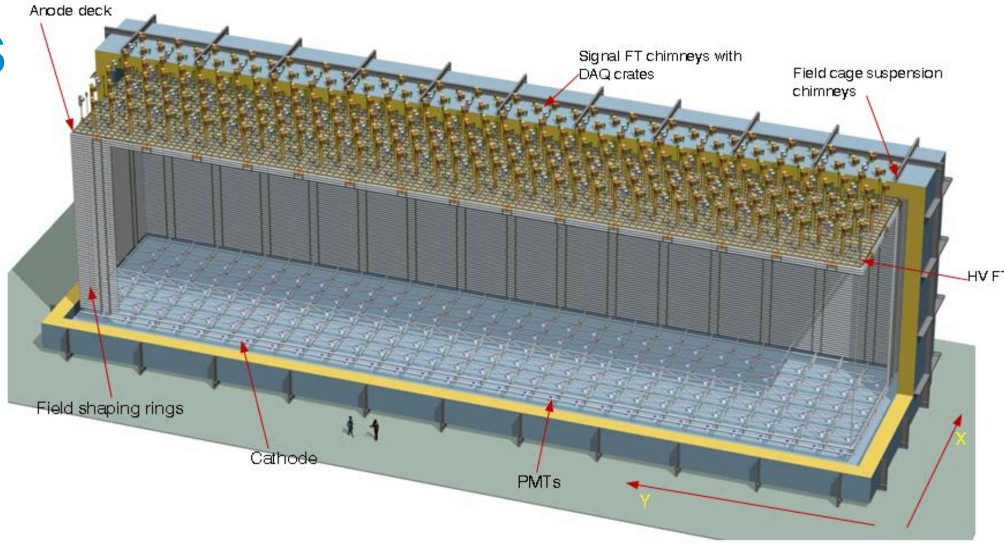
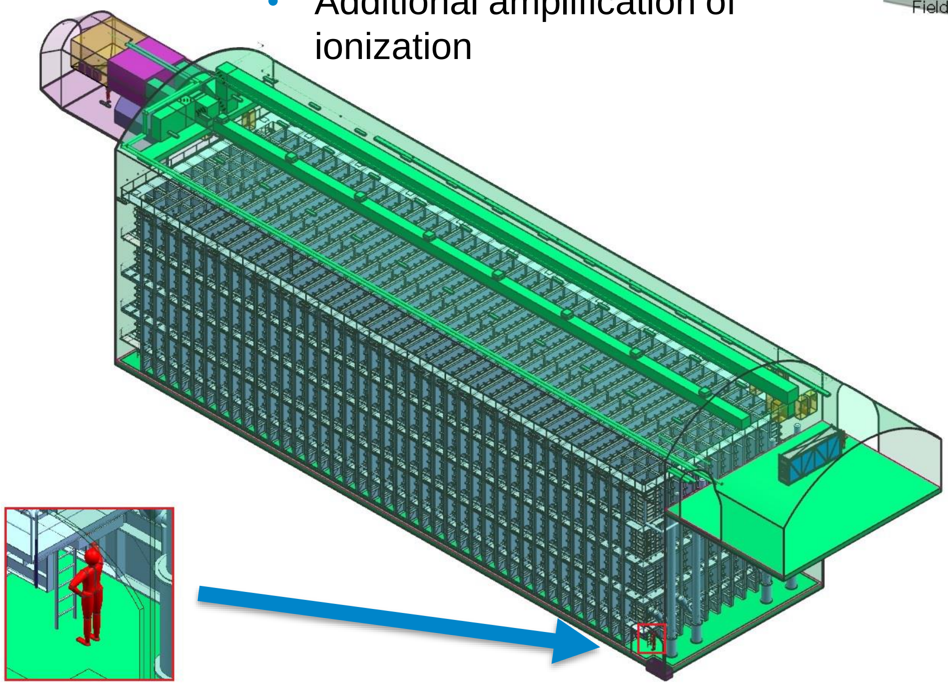
Liquid argon detectors

- Two detector designs
  - Single phase
  - Dual phase
    - Gas region above liquid argon
    - Additional amplification of ionization





- Largest cryogenic LAr detectors in existence
- Prototypes of both detectors at CERN
- Full-scale test of LAr detector components
  - Full drift distance

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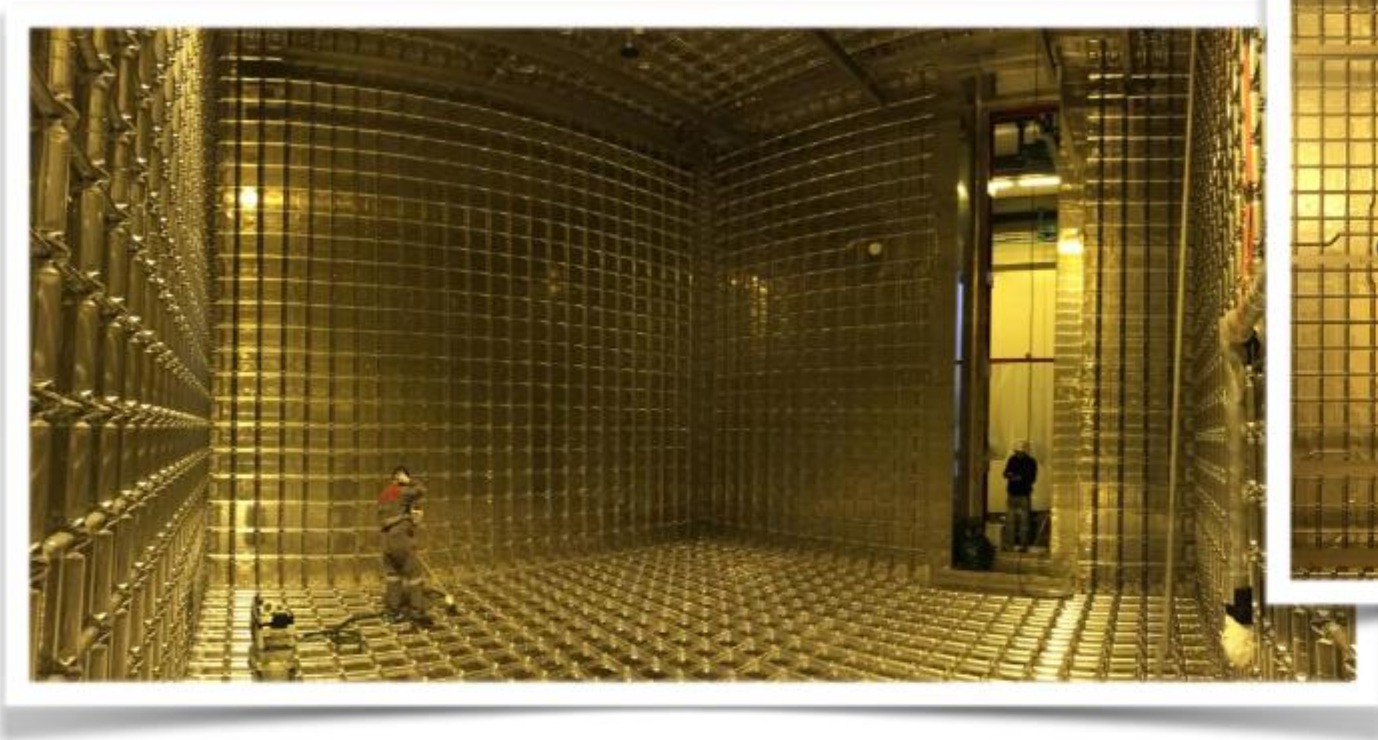
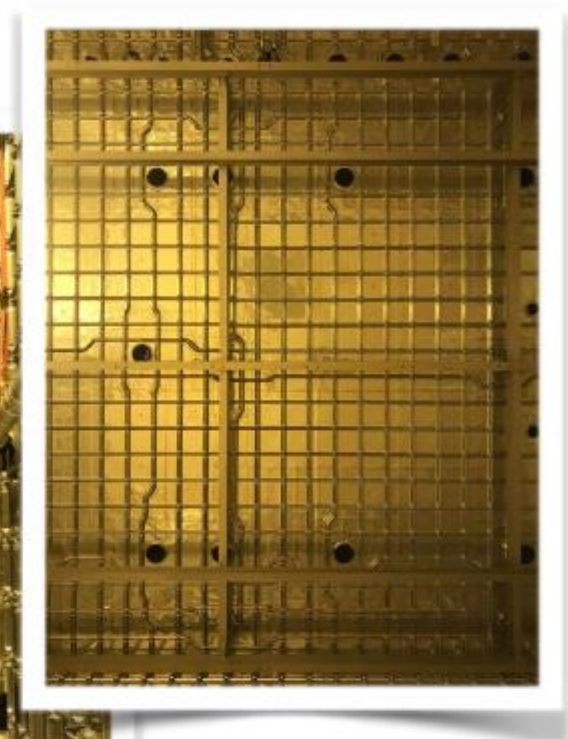
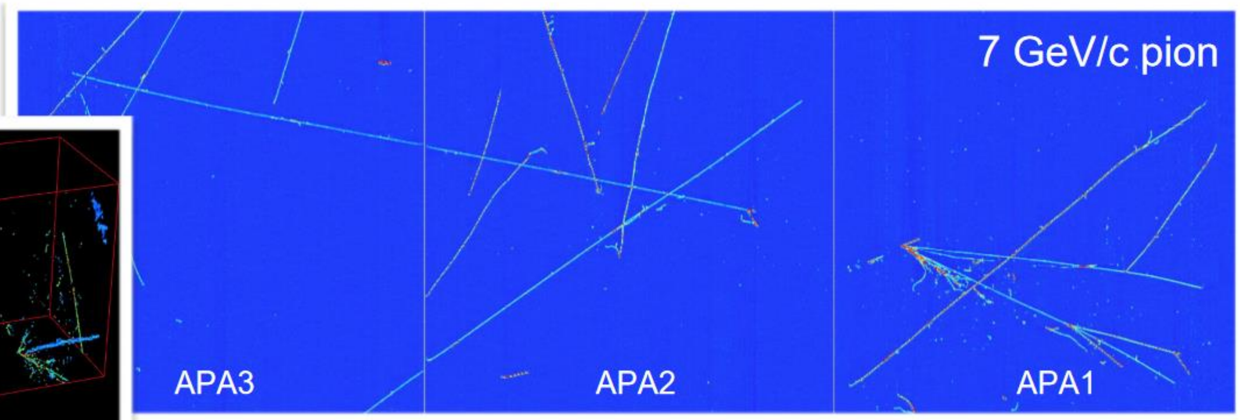
Liquid argon detectors

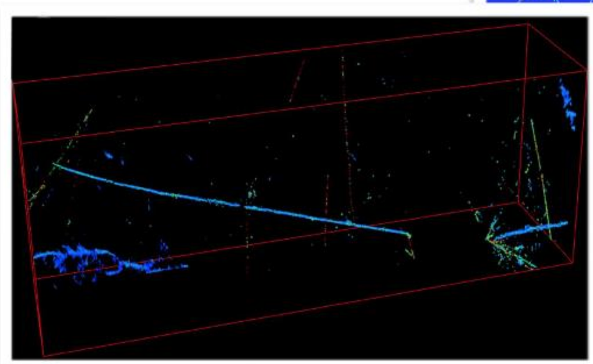
Construction of the inner cryostat

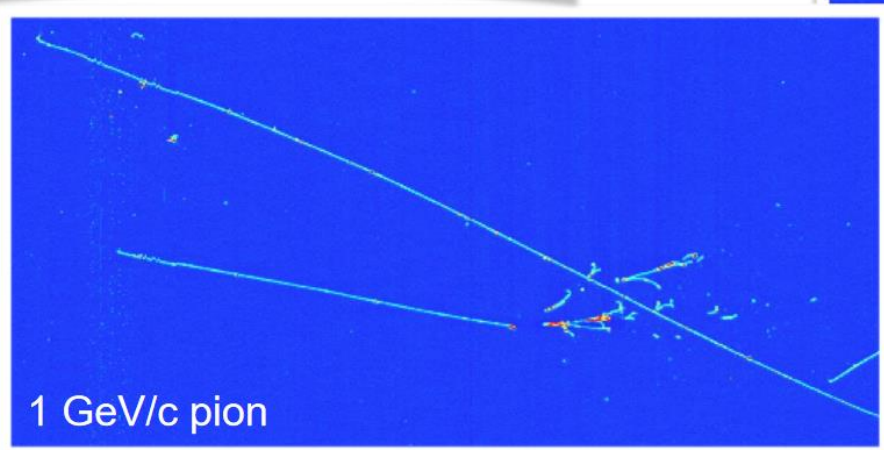


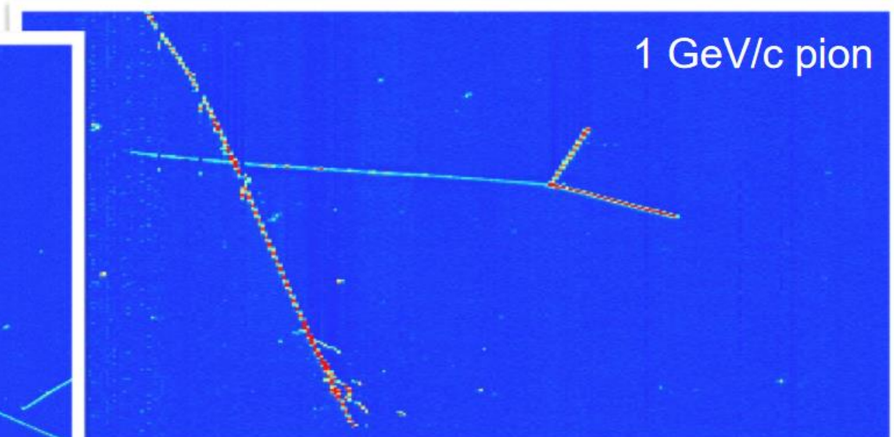


Liquid argon detectors









For more details refer to a recent presentation at NuInt18 by R. Acciarri

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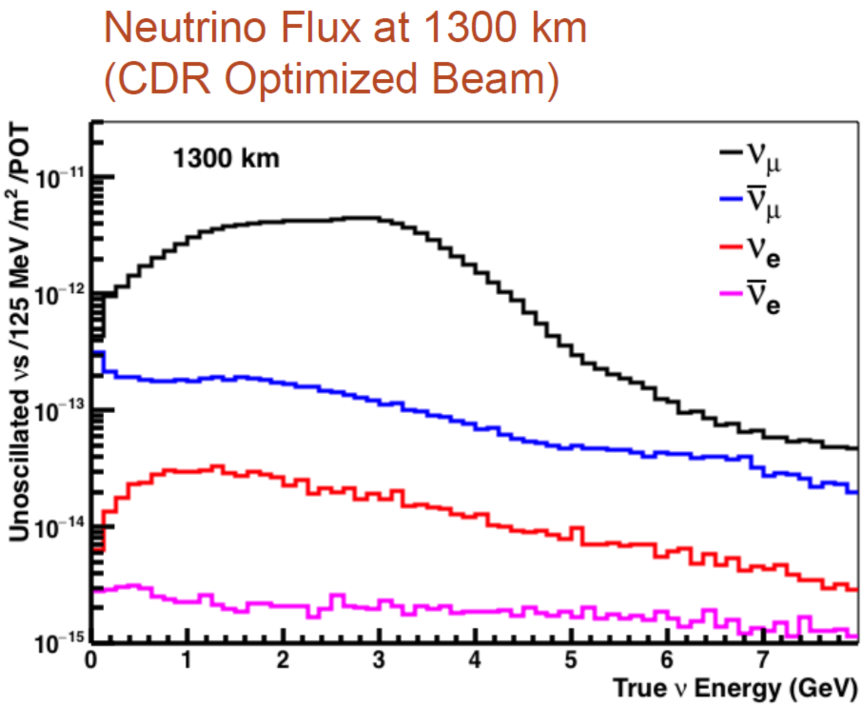
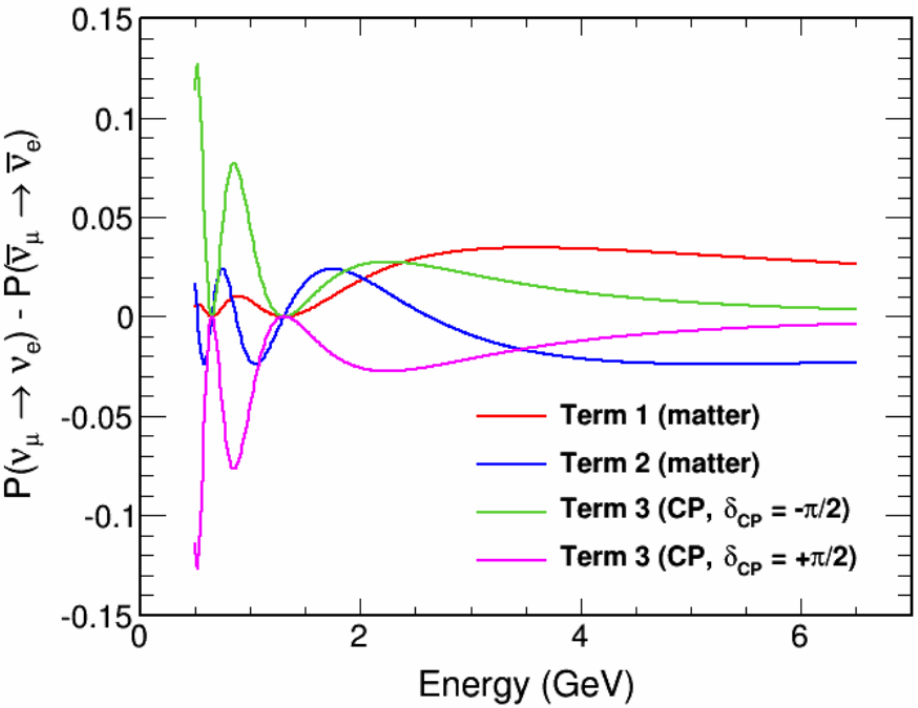
DUNE physics

- Difference between electron neutrino and electron anti-neutrino appearance probability larger at lower energies
  - $\Delta m^2 L/E = 3\pi/2$, second oscillation maximum

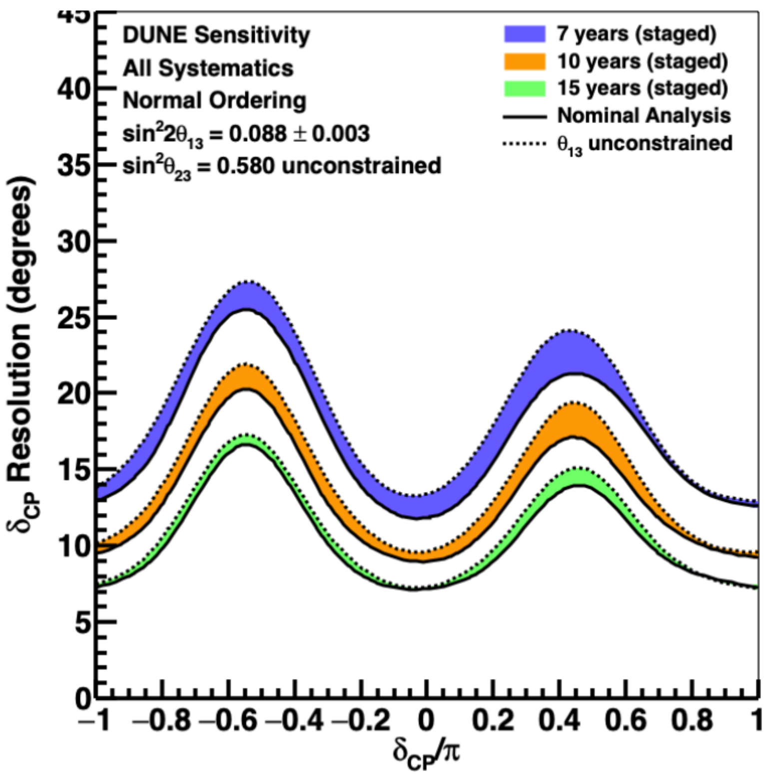


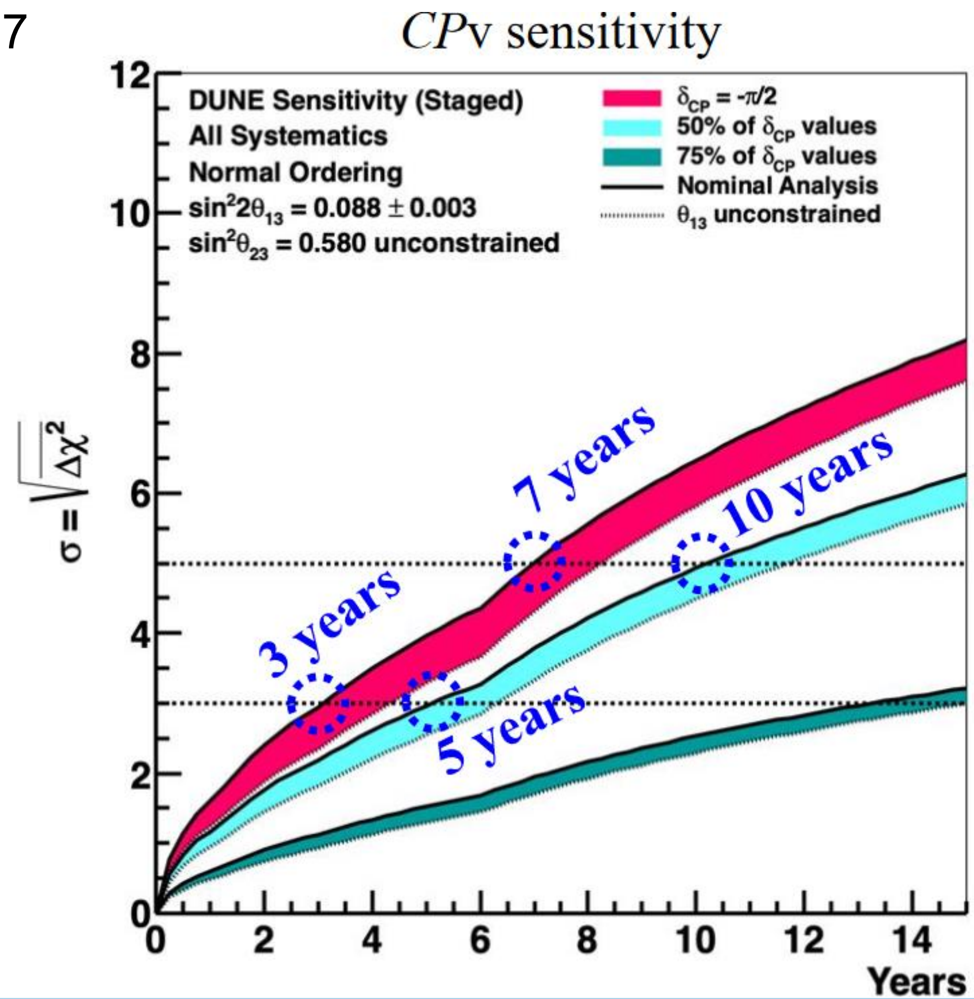


DUNE sensitivities

R. Patterson, Fermilab JETP Seminar, Aug 2nd 2019

- 5σ sensitivity to CP violation after 7 years (best case $\delta_{CP} = -\pi/2$)
- 7° – 17° precision on δ_{CP}





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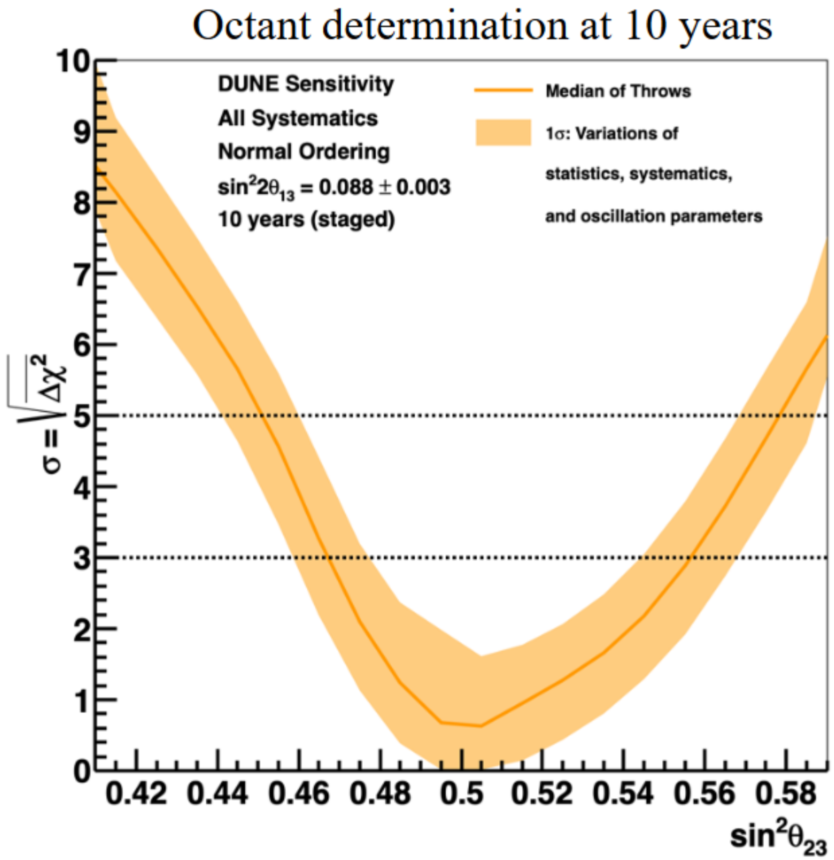
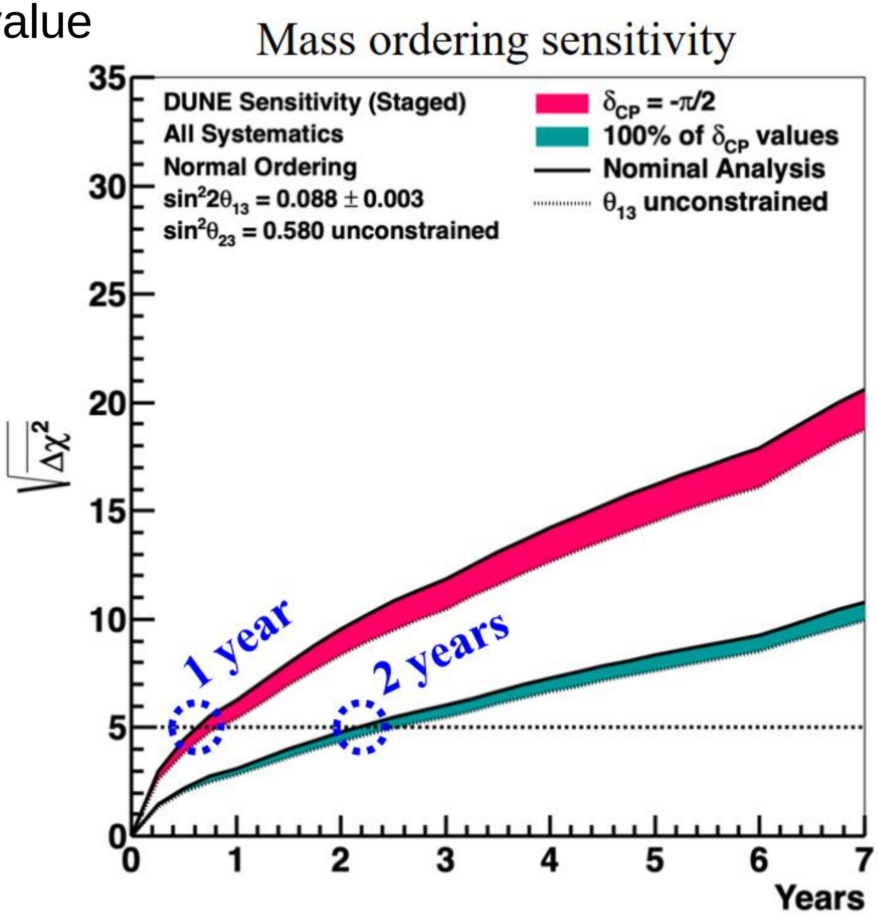
DUNE sensitivities

R. Patterson, Fermilab JETP Seminar, Aug 2nd 2019

- 5σ sensitivity to mass ordering after 1 year (assuming NO)
- 5σ octant possible, depends on true value





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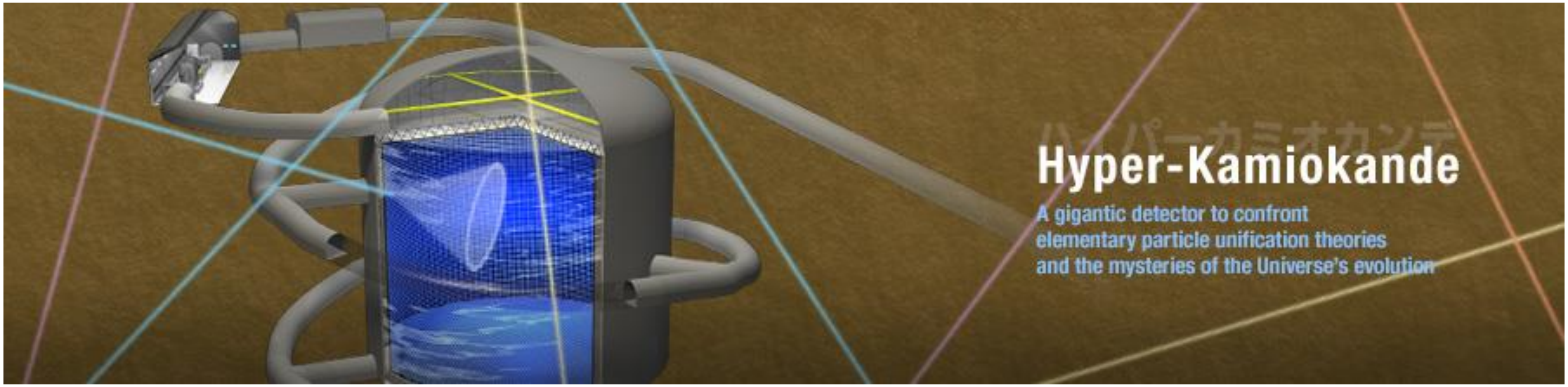
Future long-baseline experiments

- Water Cherenkov far detector (188 kilotonne)
- 295km baseline
- 0.6 GeV neutrino energy

- Included in MEXT budget request September 2019!



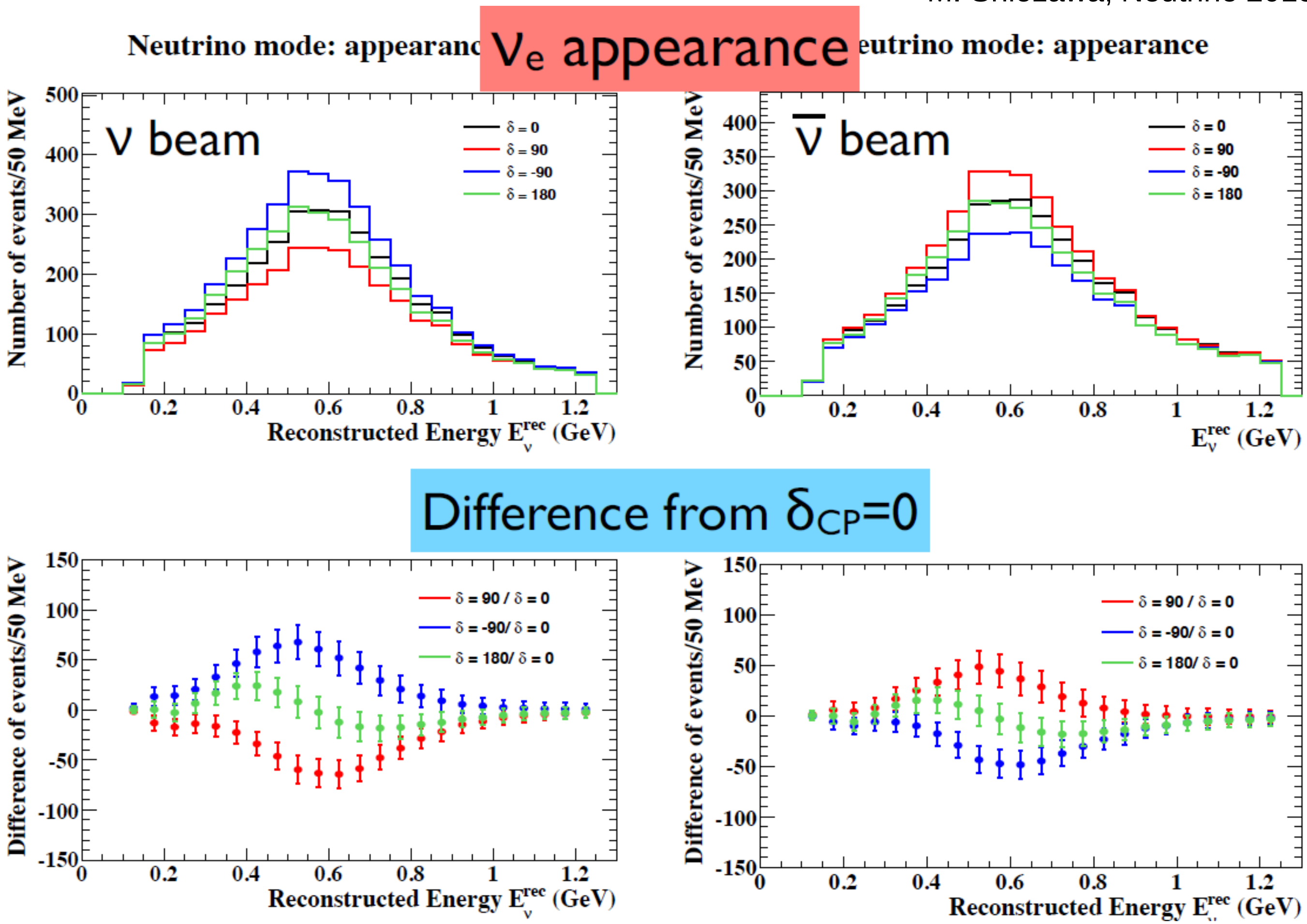
Hyper-Kamiokande

- Upgrade of the T2K far detector and beam
  - Fiducial volume, 22.5kt to 188kt
  - 0.5MW beam power to 1.3MW
  - Improved photosensors with twice the quantum efficiency
- Combined factor ~20 increase in statistics compared to T2K

Hyper-Kamiokande events

M. Shiozawa, Neutrino 2018

- Expect:
  - 2300 ν_e appearance events
  - 1600 $\bar{\nu}_e$ appearance events
- Difference between neutrino and anti-neutrino rates gives δ_{CP}
- About 10,000 muon neutrino events



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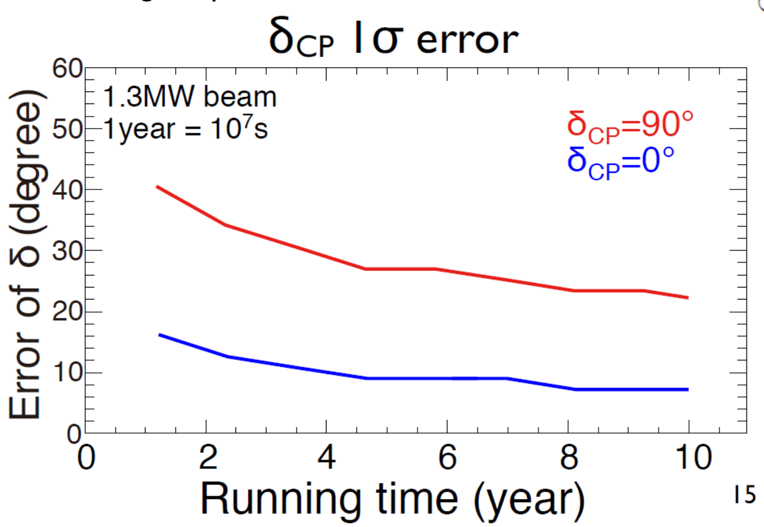
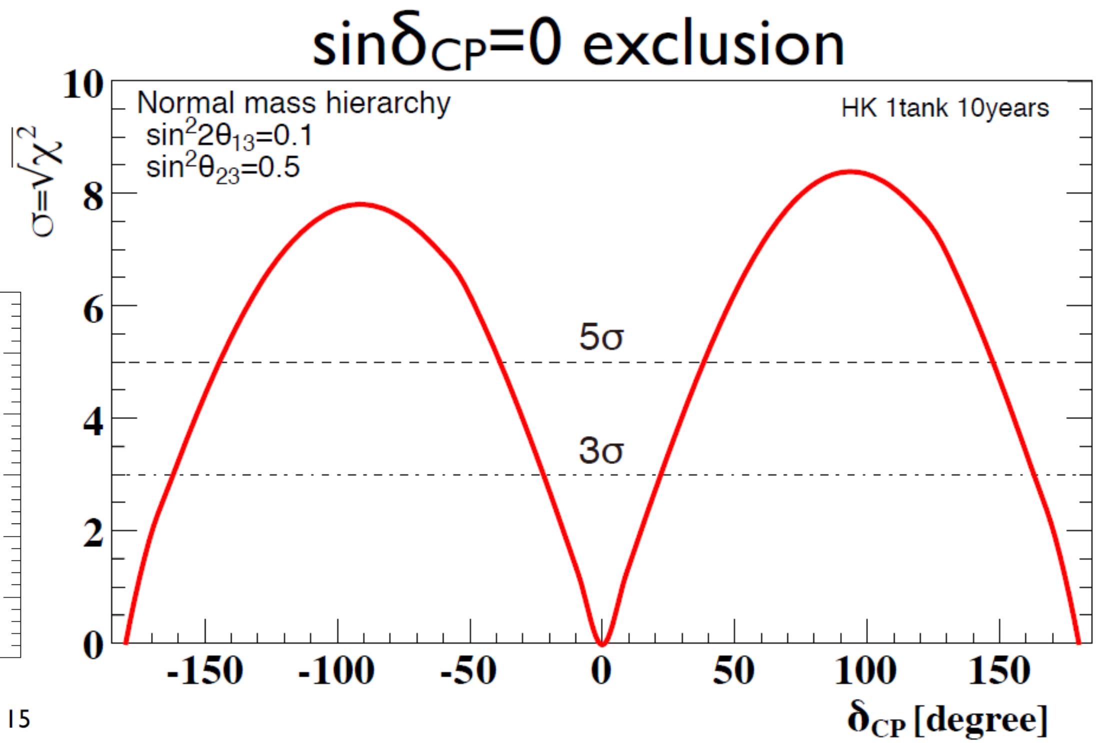
Hyper-Kamiokande physics

- >5σ sensitivity to observe CP violation in lepton sector for >50% of possible values of δ_{CP}
- 22° precision for $\delta_{CP} = -\pi/2$
- 7° precision for $\delta_{CP} = 0$

HK Design report, arxiv:1805.04163





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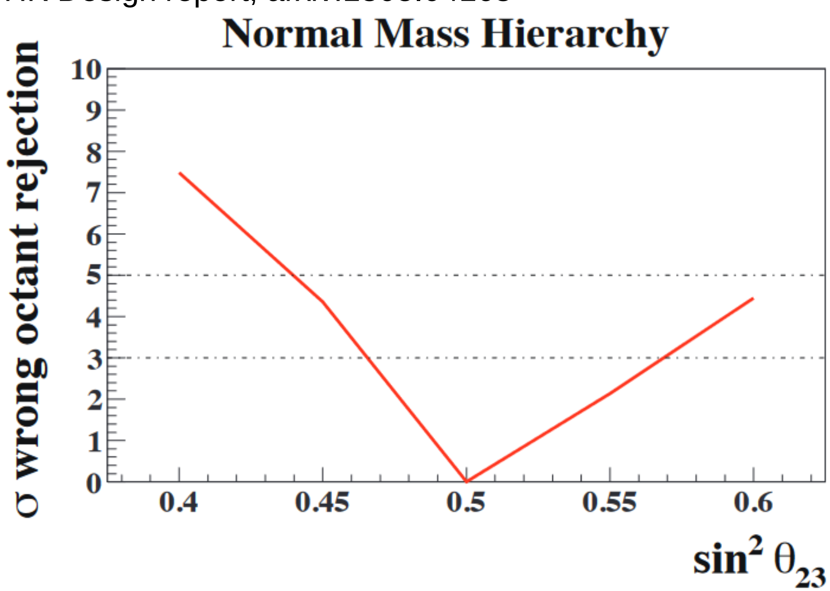
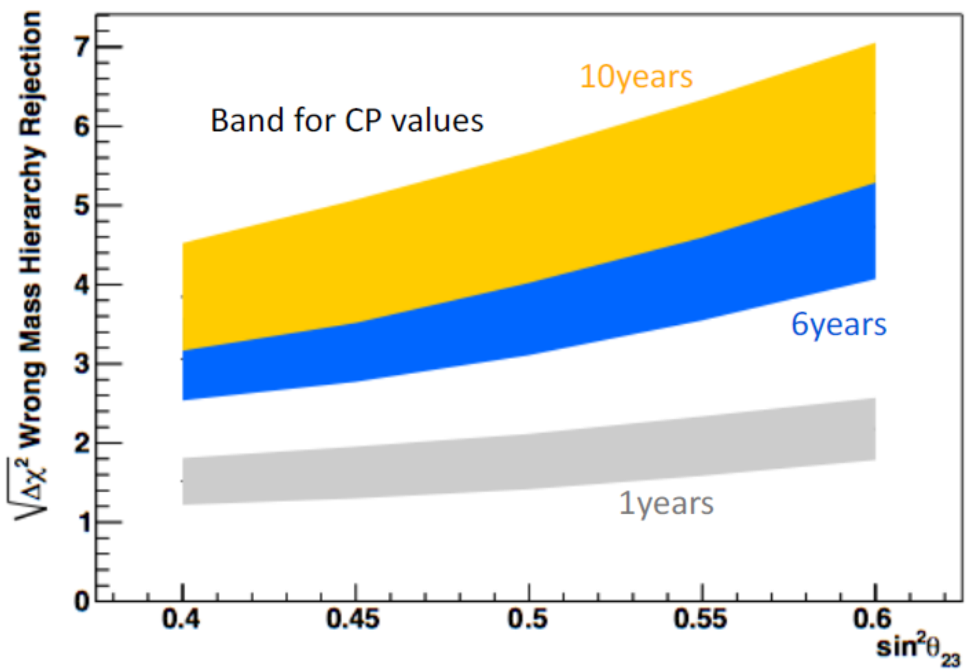
Hyper-Kamiokande physics

- 3 – 7σ to mass ordering, depending upon true values of δ_{CP} and $\sin^2\theta_{23}$ and including atmospheric neutrinos in analysis
- Similar octant sensitivity to DUNE
- 1 – 3% precision on $\sin^2\theta_{23}$

M. Shiozawa, Neutrino 2018

HK Design report, arxiv:1805.04163





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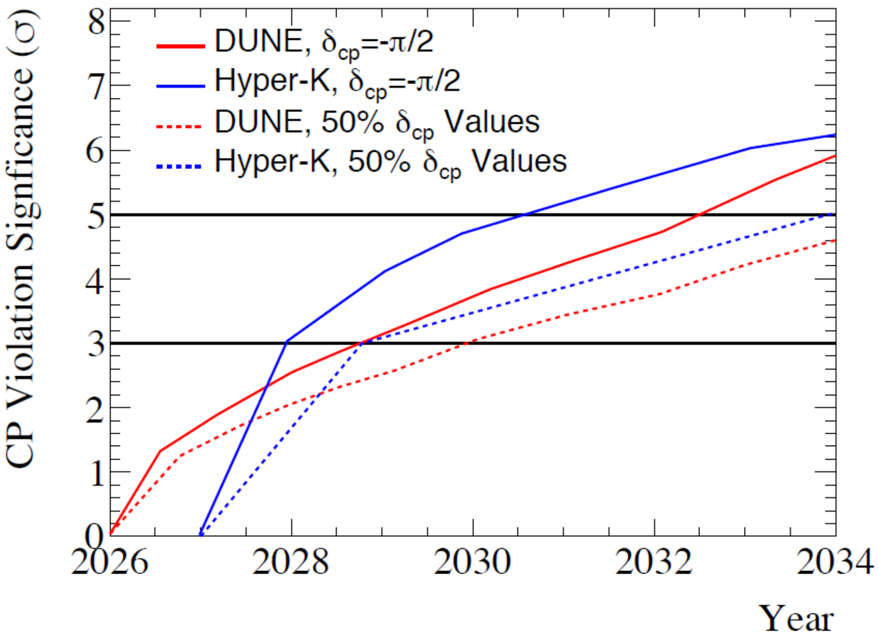
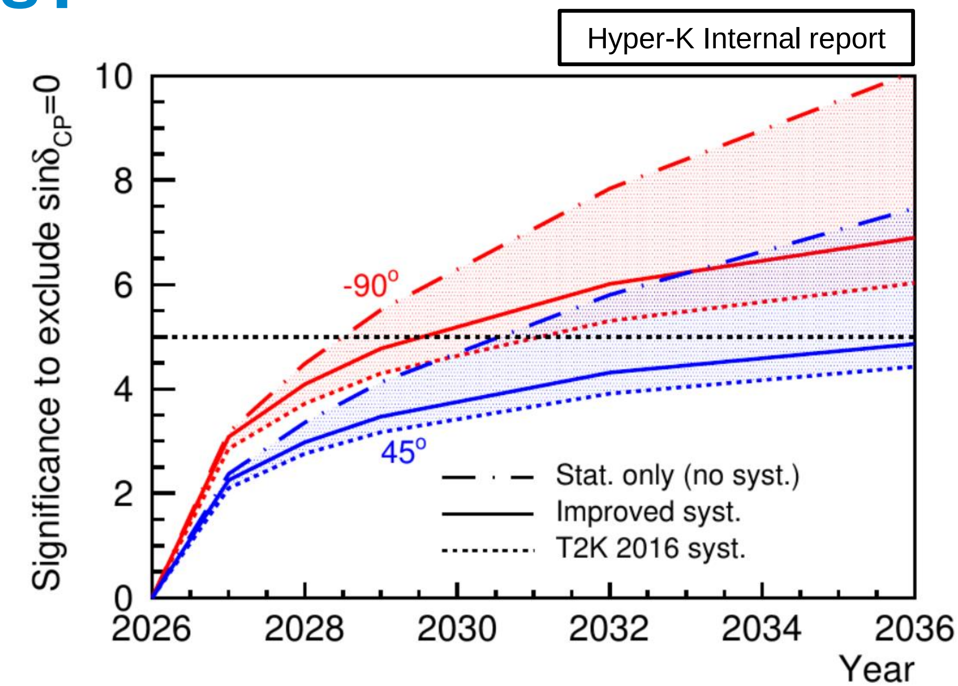
CP violation in ten years?





- DUNE due to switch on in 2026, Hyper-K in 2027
- In most optimistic case, 3σ evidence by 2028 and 5σ observation by 2031

- **Next generation experiments will be limited by systematics, not statistics**

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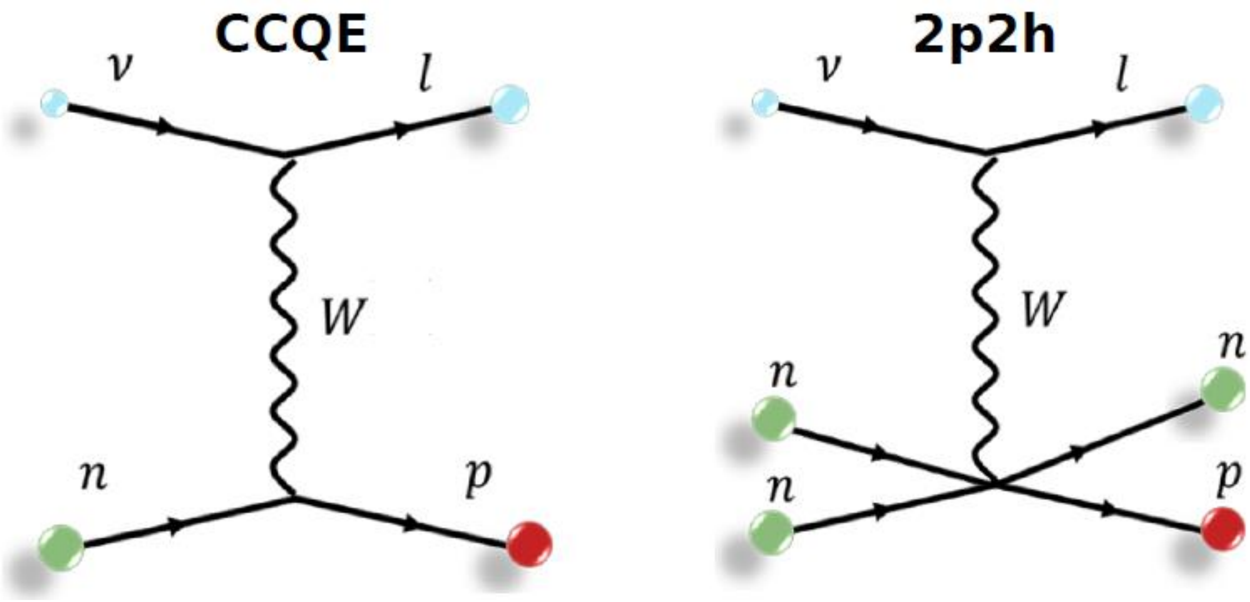
Neutrino oscillation systematics

T2K 2019 Oscillation results

	1-Ring μ		1-Ring e			
Error source	FHC	RHC	FHC	RHC	FHC 1 d.e.	FHC/RHC
SK Detector	2.40	2.01	2.83	3.79	13.16	1.47
SK FSI+SI+PN	2.20	1.98	3.02	2.31	11.44	1.58
Flux + Xsec constrained	2.88	2.68	3.02	2.86	3.82	2.31
E_b	2.43	1.73	7.26	3.66	3.01	3.74
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.07	2.58	0.33	1.49
NC Other	0.25	0.25	0.14	0.33	0.99	0.18
Osc	0.03	0.03	3.86	3.60	3.77	0.79
All Systematics	4.91	4.28	8.81	7.03	18.32	5.87
All with osc	4.91	4.28	9.60	7.87	18.65	5.93

- Uncertainty on ratio of electron appearance to anti-electron appearance ~= uncertainty on δ_{CP}
- Cross-section uncertainties dominate

Example – 2p2h interactions



- Similar to CCQE
- Neutrino interacts with correlated pair of nucleons

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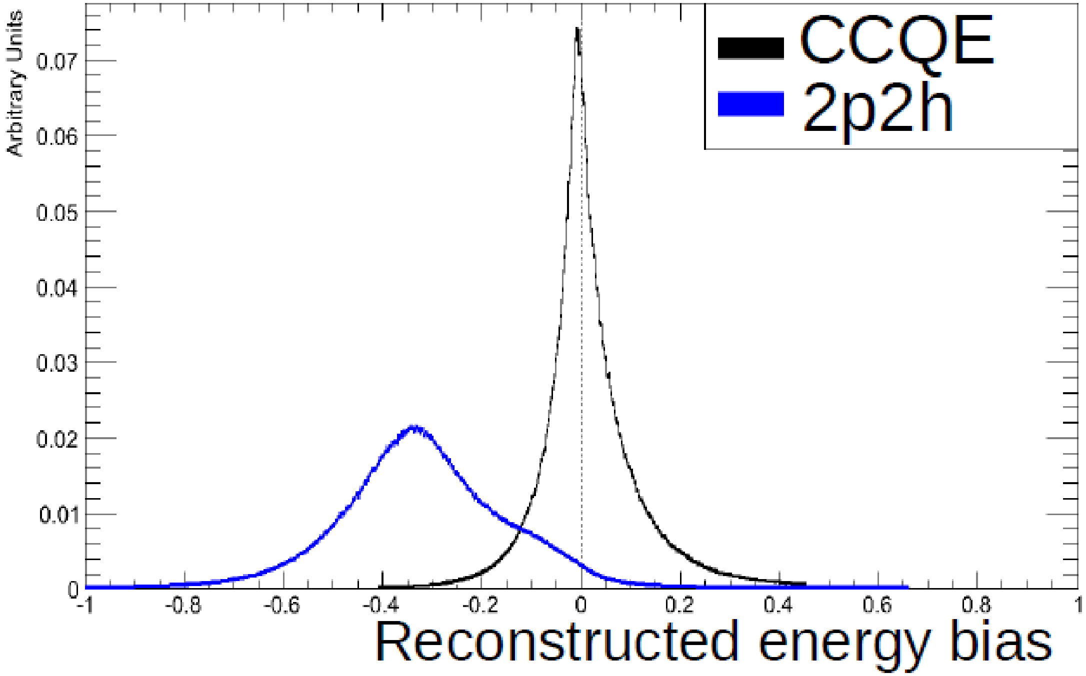

- Similar to CCQE
- Neutrino interacts with correlated pair of nucleons
- Reconstructed neutrino energy is biased, therefore oscillation parameter measurement is biased (or has large uncertainty)

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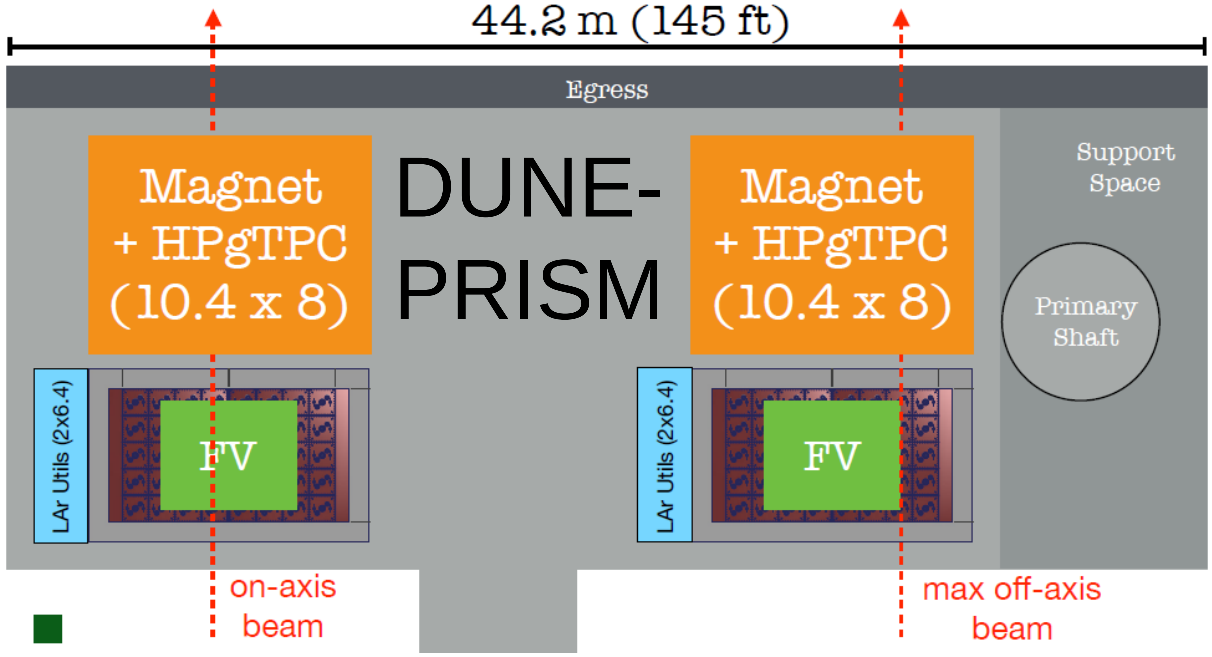
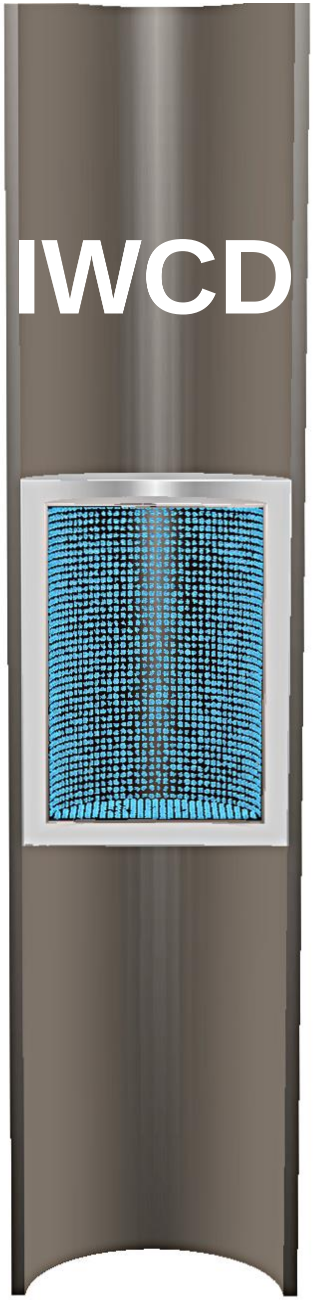
DUNE-PRISM and IWCD





- Near / intermediated detectors for DUNE / HK
- Span a range of angles off the centre of the neutrino beam
  - DUNE-PRISM – horizontal, ~35m
  - IWCD – vertical, ~50m

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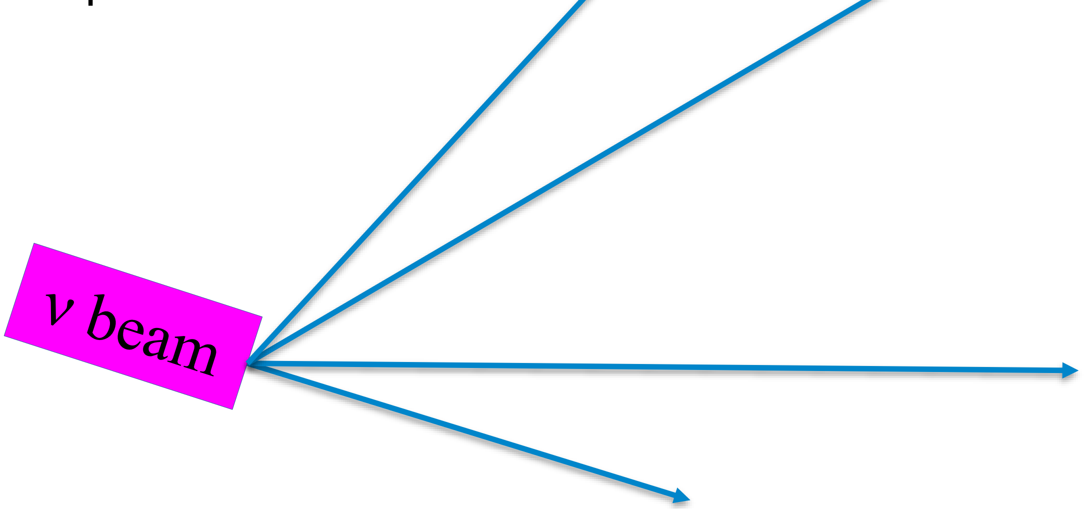
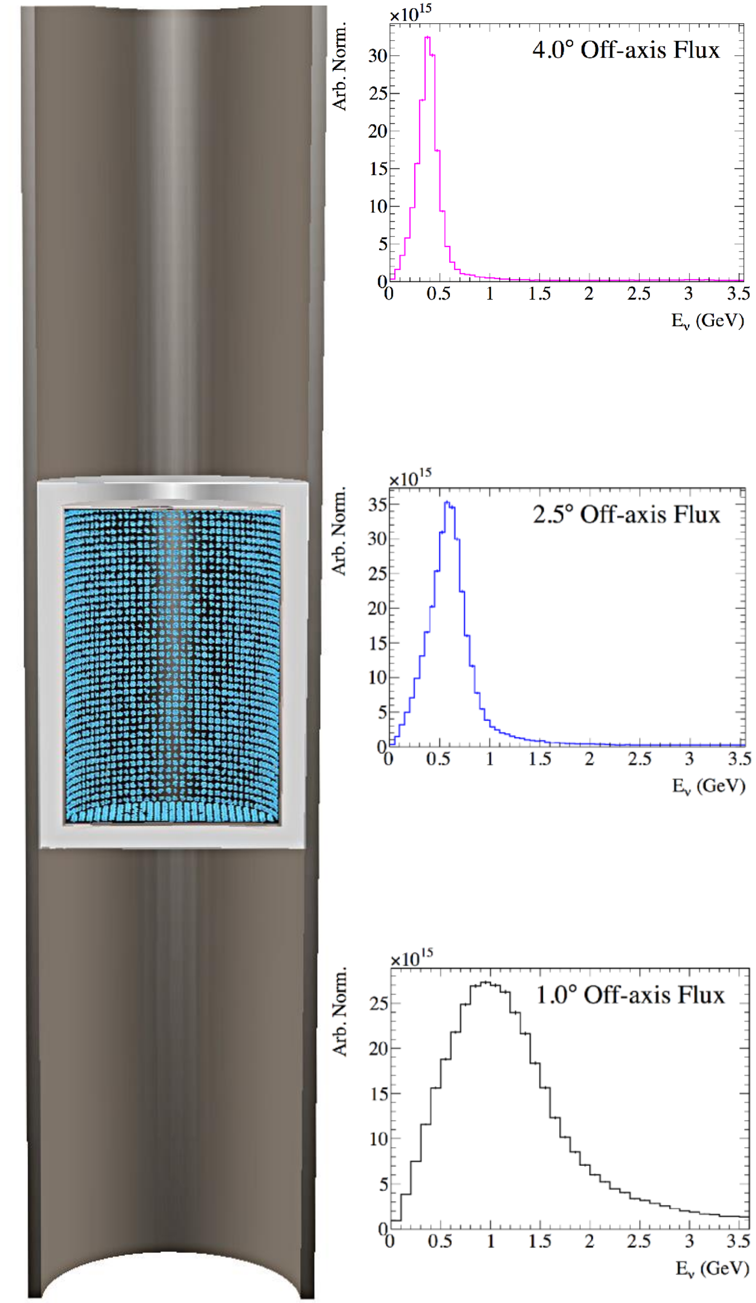
PRISM concept

- Measure neutrino interactions at multiple off-axis positions
- Neutrino flux changes with position





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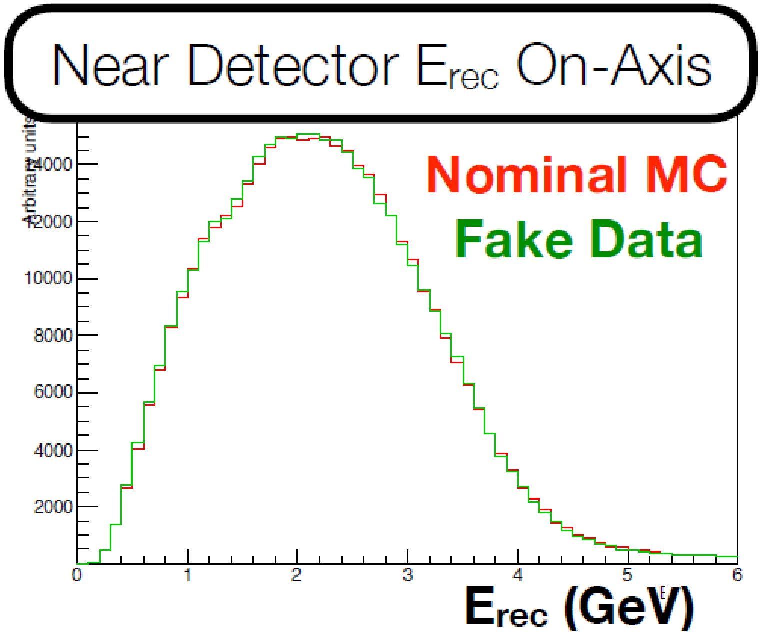
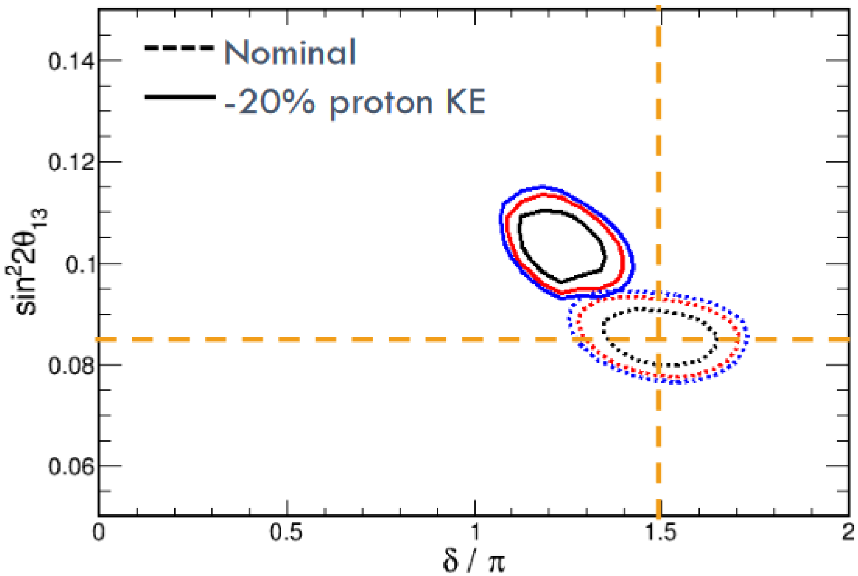
PRISM benefits - 1

DUNE study - C. Vilela, G. Yang





- Near detector along same axis as far detector
  - Standard analysis tunes MC to match data, used to predict far detector rate
  - Incorrect tuning (due to energy mis-reconstruction) bias oscillation result

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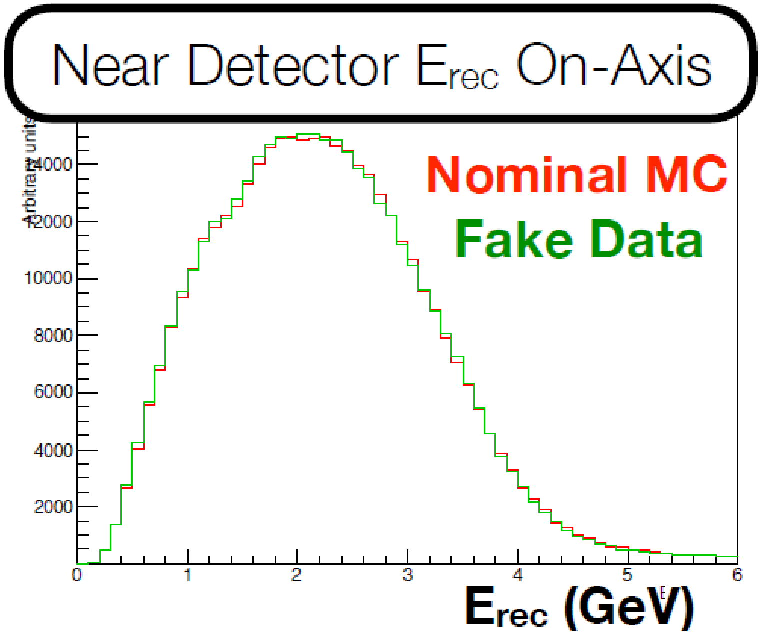
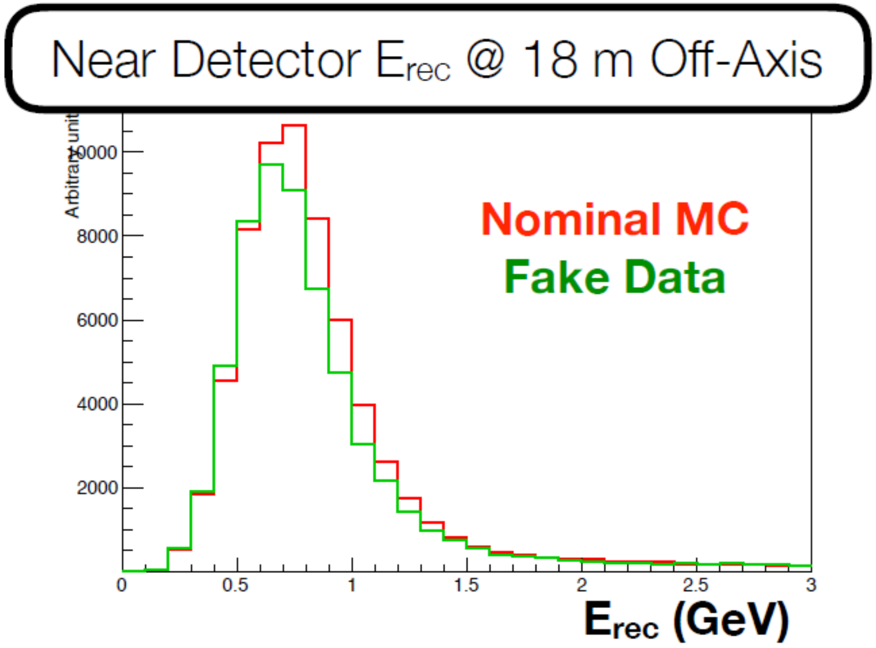
PRISM benefits - 1

DUNE study - C. Vilela, G. Yang





- Can test tune ('Nominal MC' here) by comparing to data at point further off-axis
- Clearly see model does not agree – model tuning wrong / model incomplete
  - Flag that there is something amiss, but doesn't solve it

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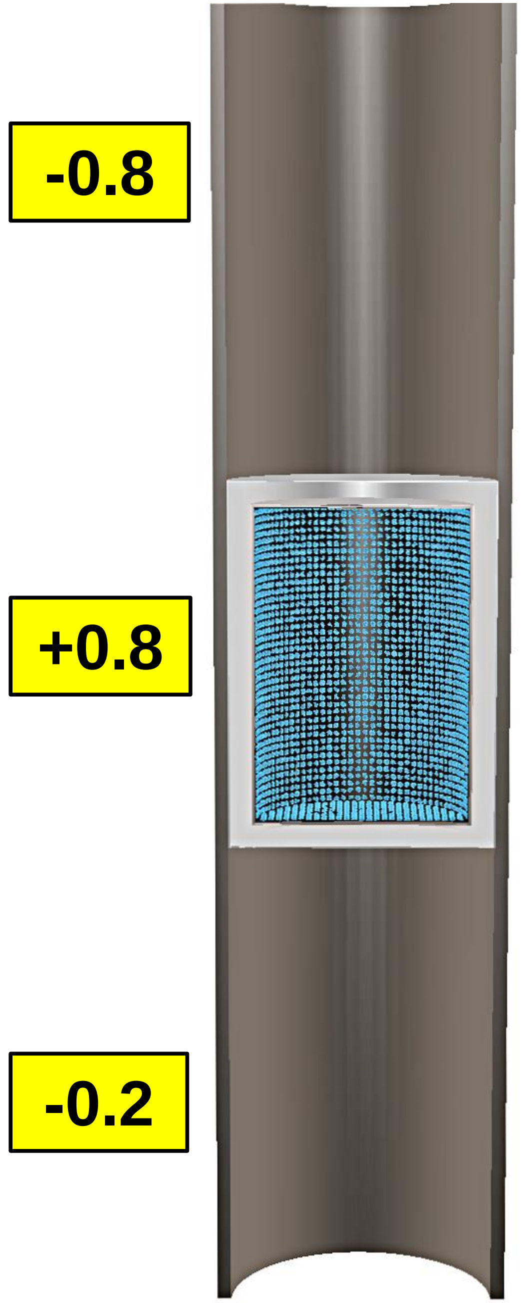
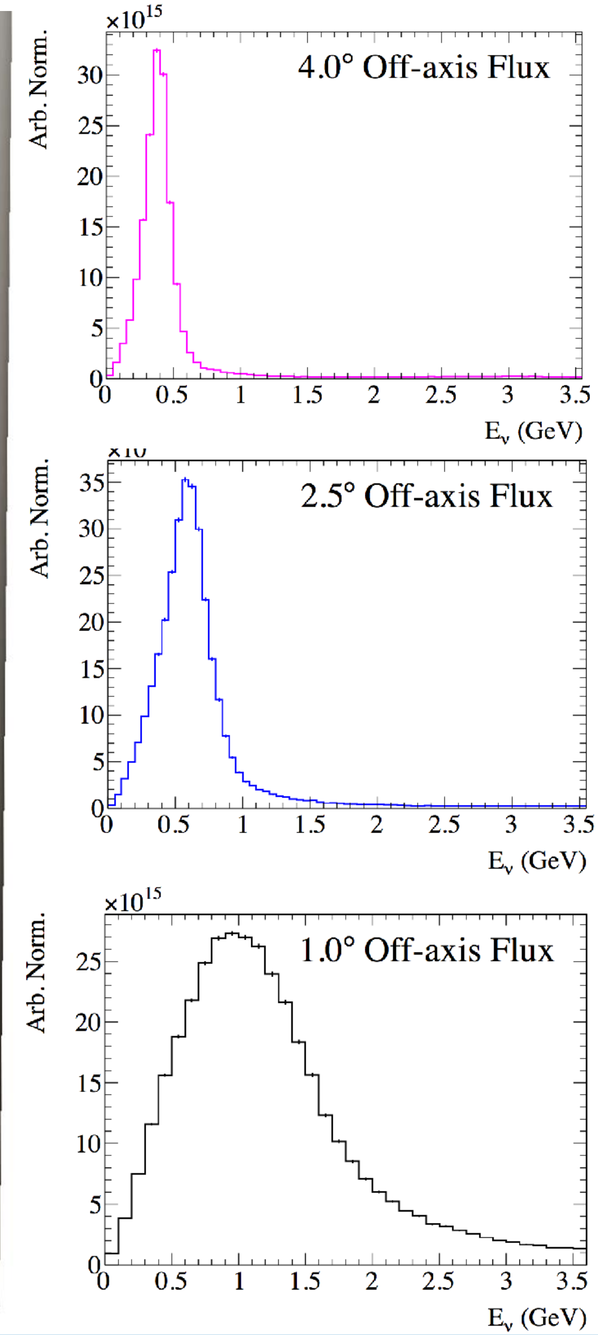
PRISM benefits - 2

- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis 'slices'





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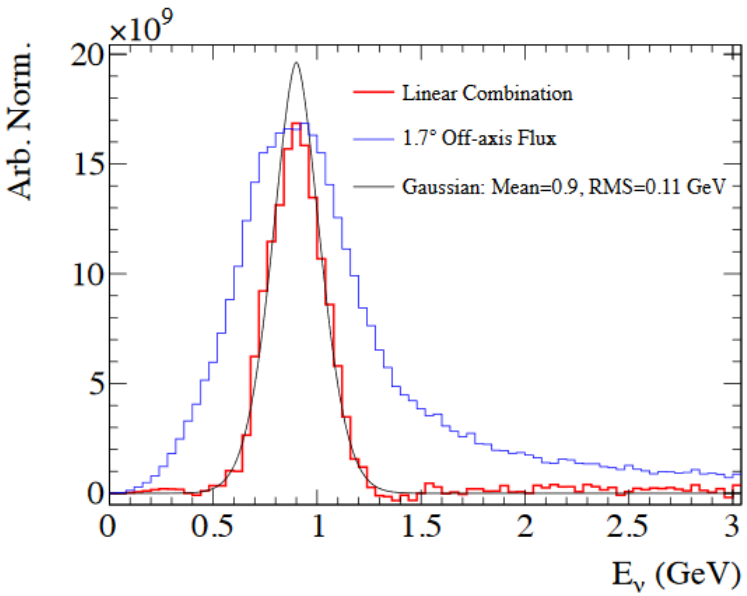
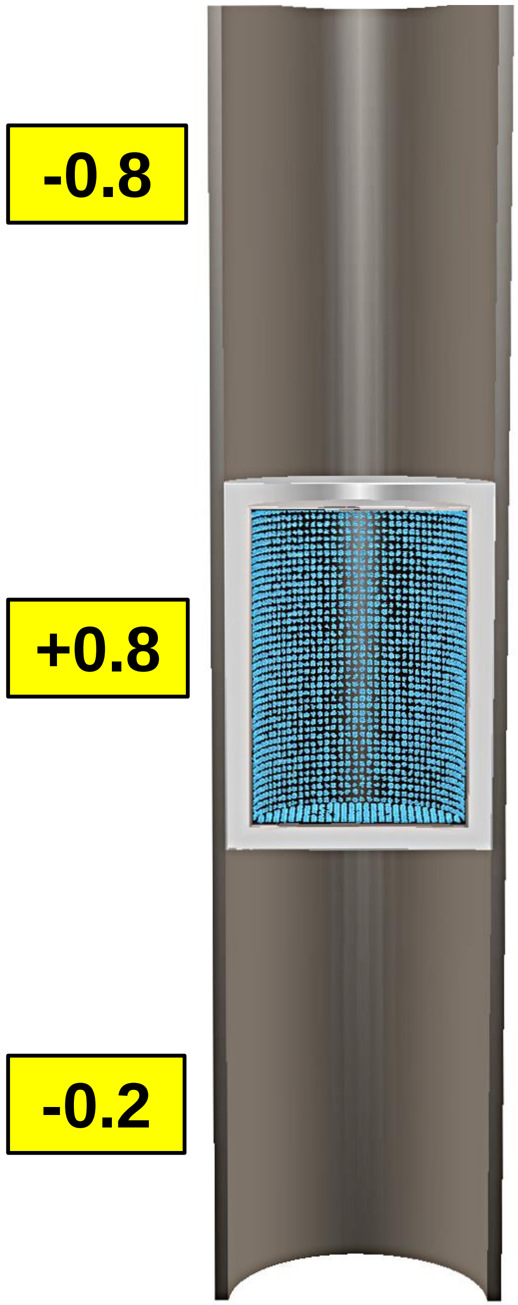
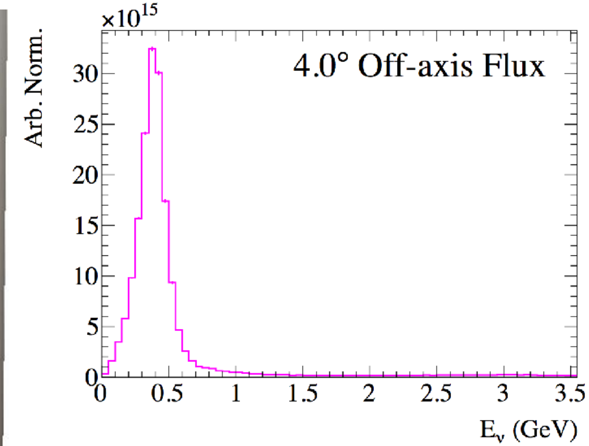
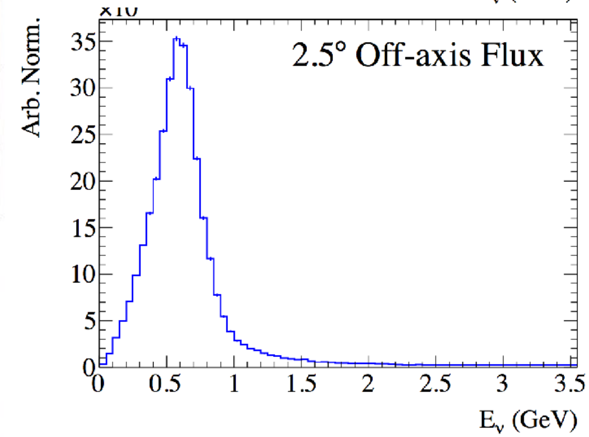
PRISM benefits - 2

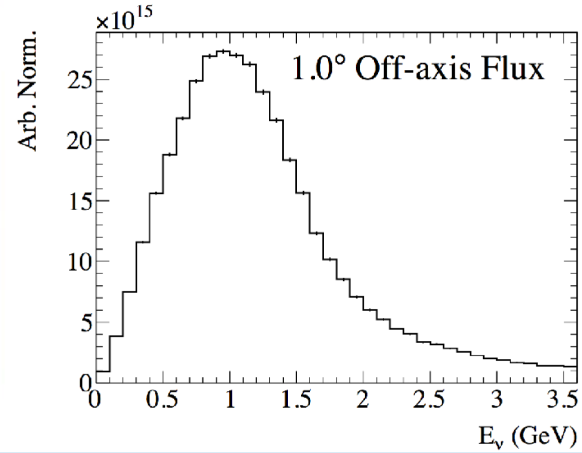
- Same detector measuring all off-axis fluxes
- Can weight and combine different off-axis ‘slices’
- Produce Gaussian energy distribution











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PRISM benefits - 2

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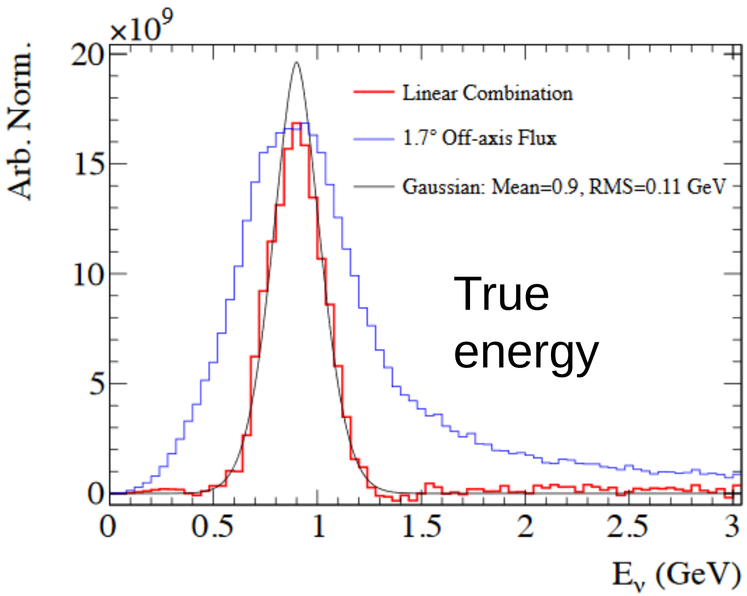
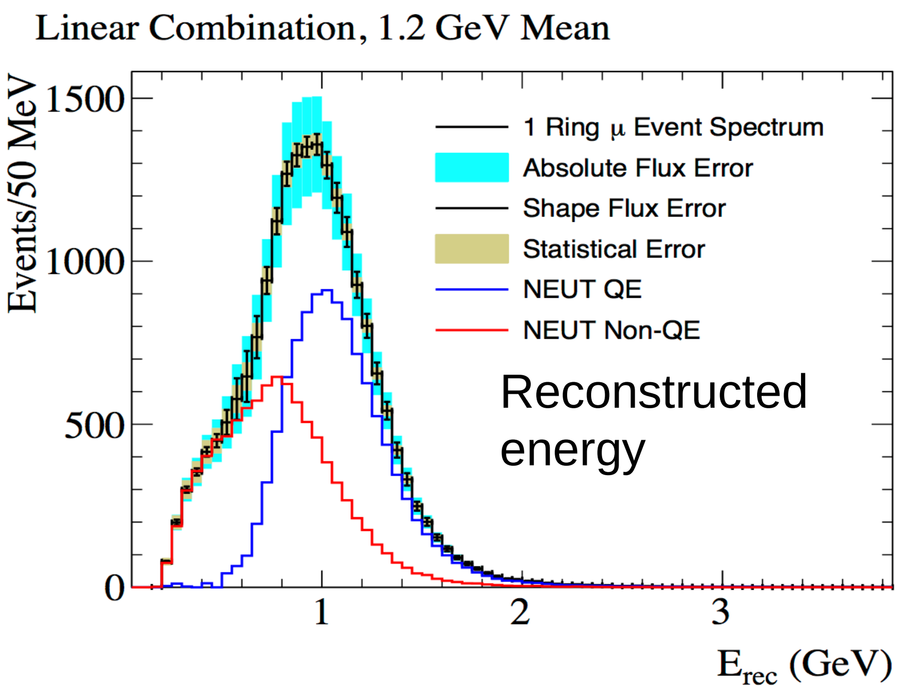


- Measure at a known energy
- Map out true-reco relationship
- Energy range determined by off-axis range



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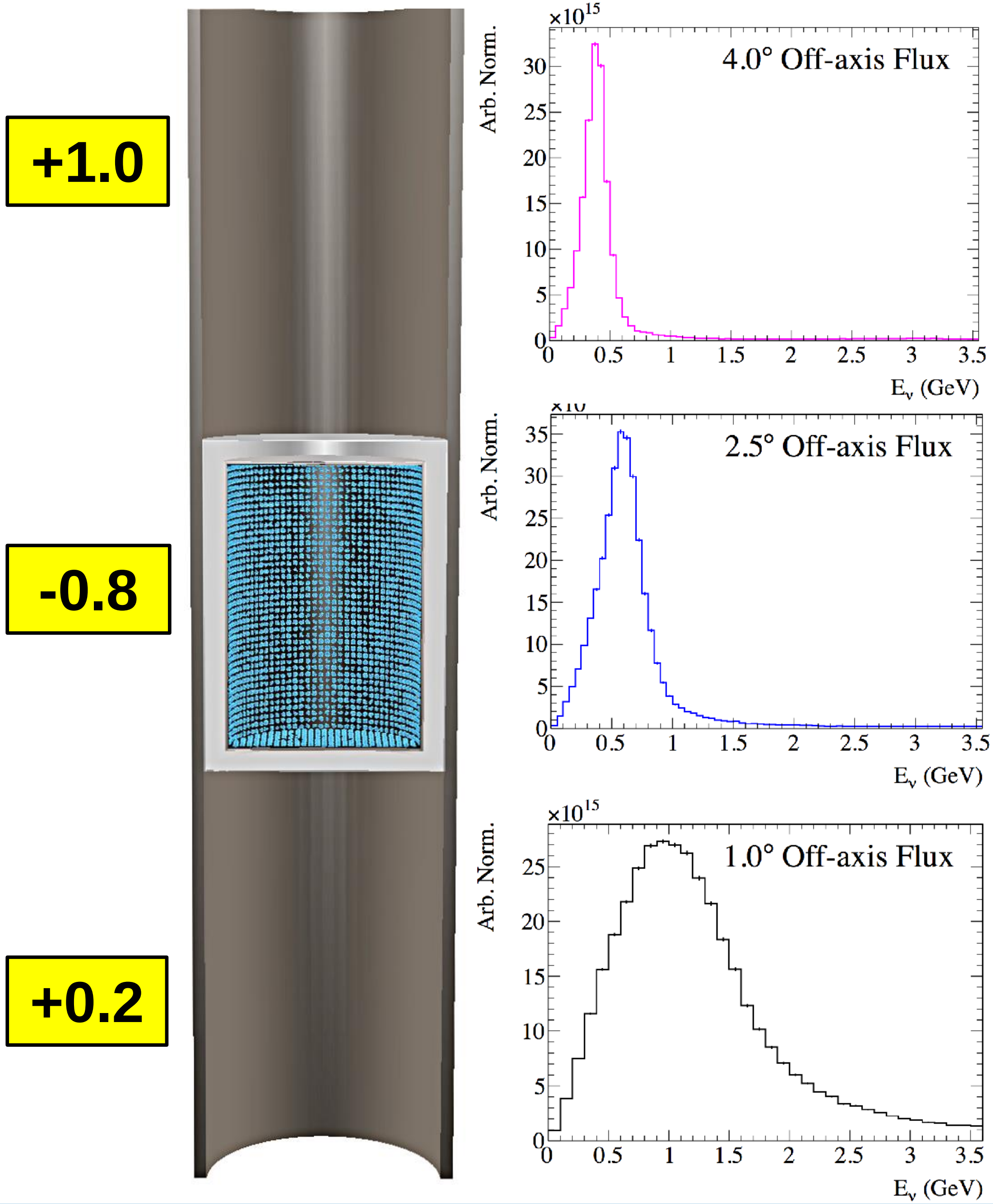
PRISM benefits - 3

- Can have different linear combination



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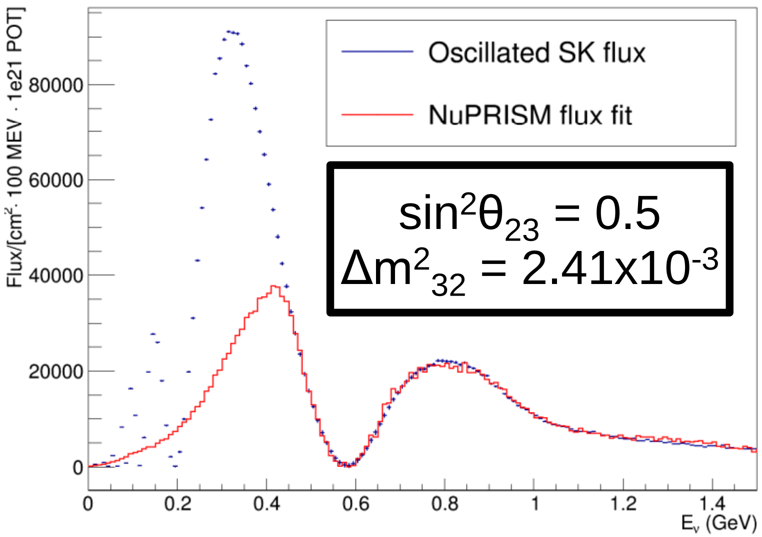
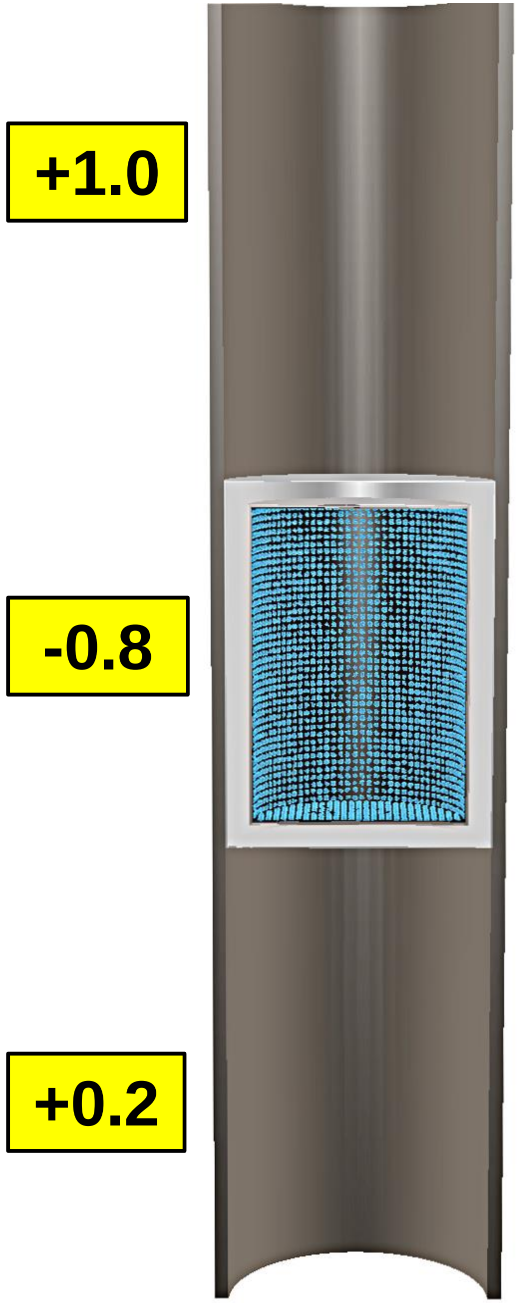
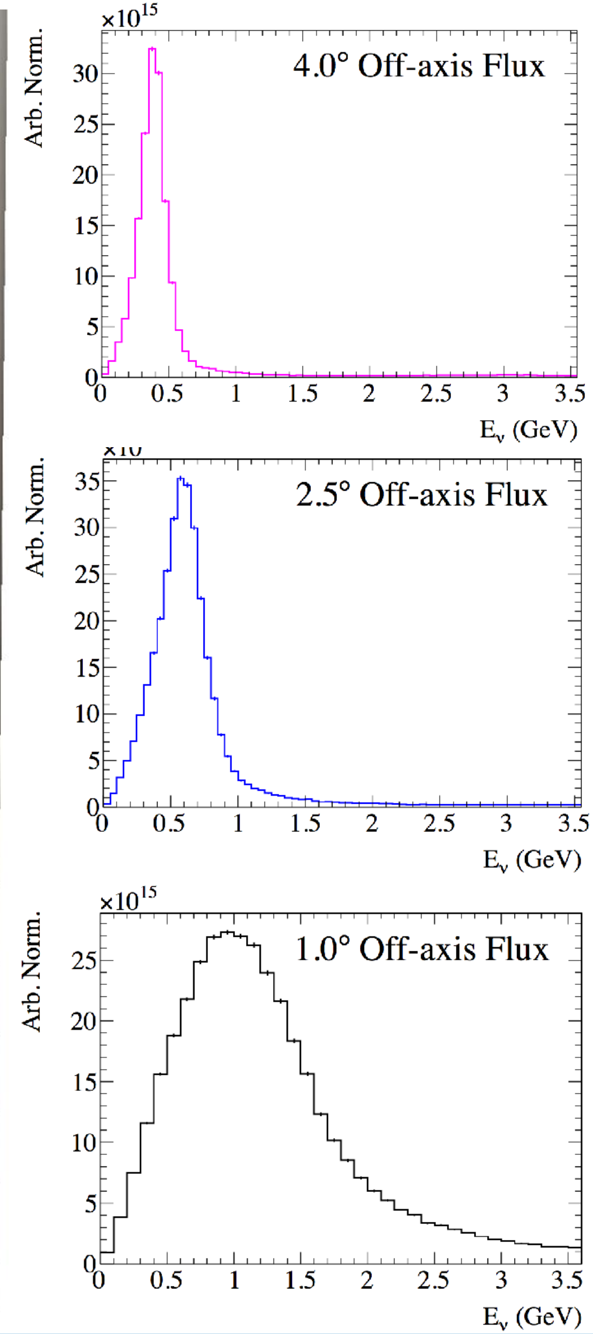
PRISM benefits - 3

- Can have different linear combination
- Recreate oscillated flux using near detector data

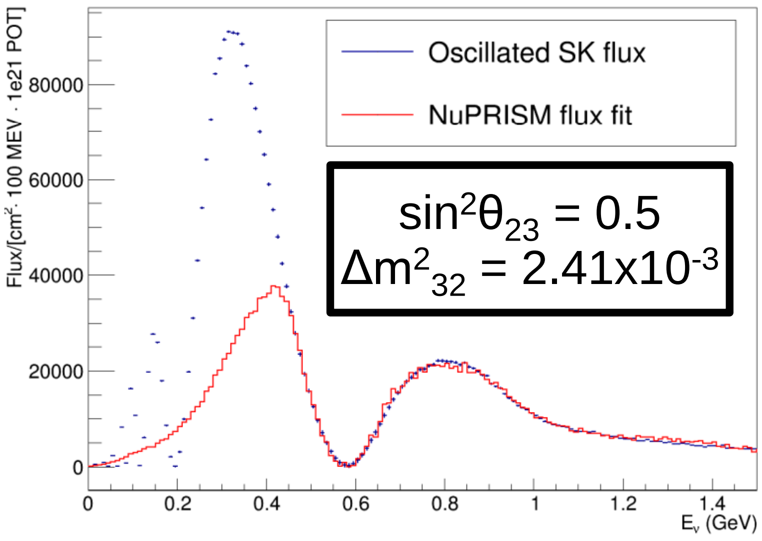


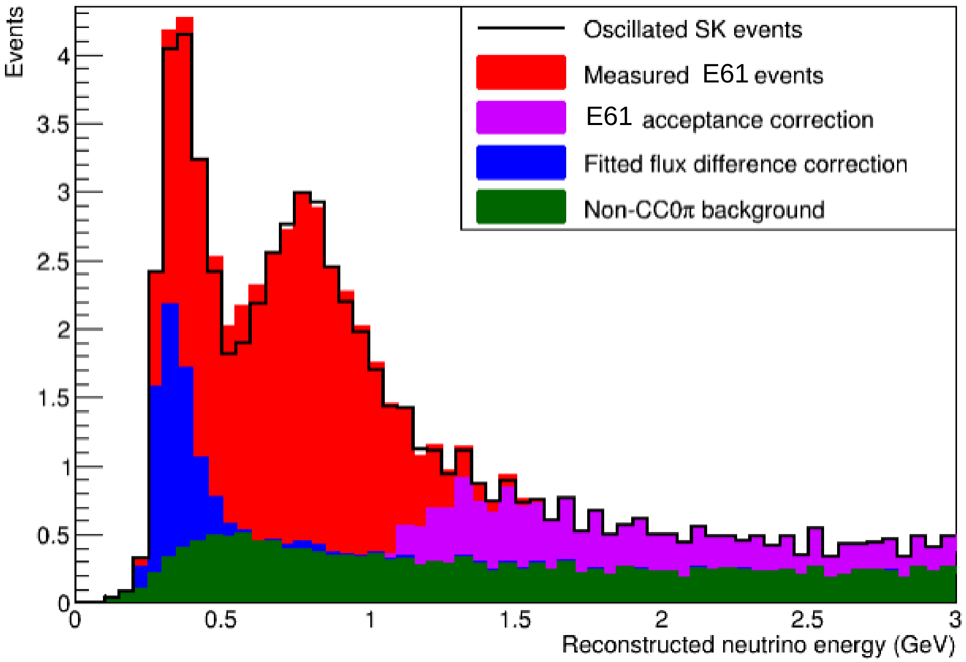




PRISM benefits - 3

- Can have different linear combination
- Recreate oscillated flux using near detector data





- Use data to directly predict oscillated spectrum (red)
- Backgrounds (green) can be measured in-situ
- Oscillation analysis minimally dependent on neutrino interaction model

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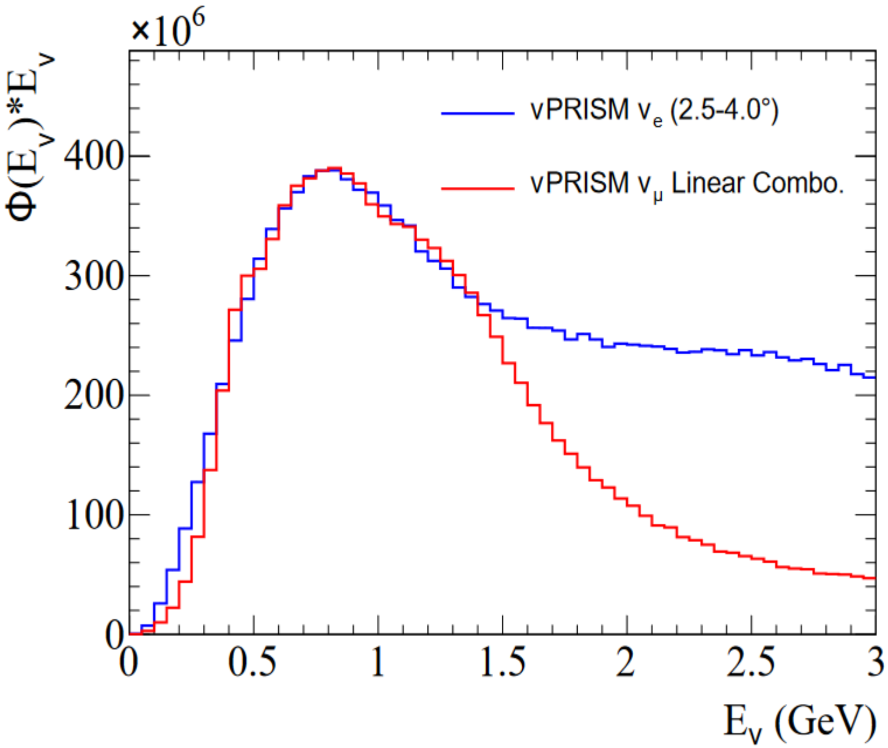
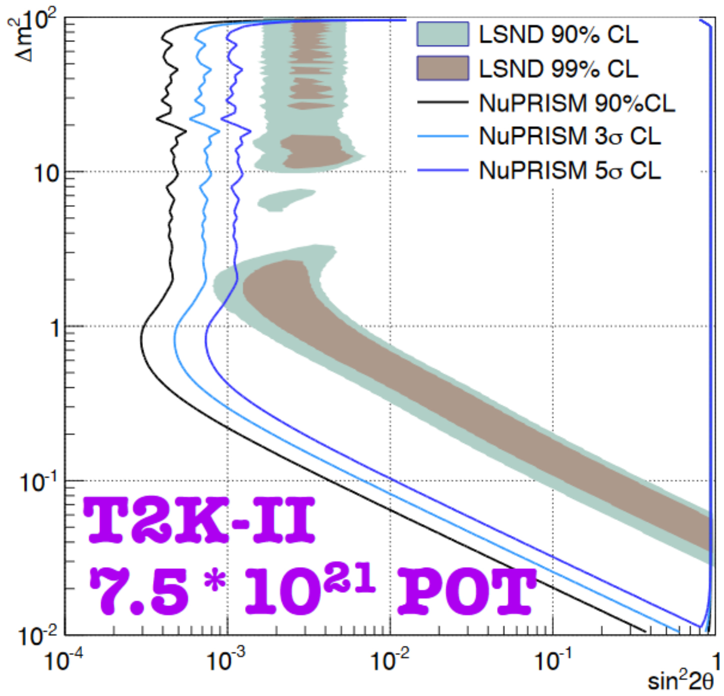
PRISM benefits - 4





- Fit ND ν_e flux
  - Directly measure electron/muon cross-section ratio
- Sterile neutrino searches
  - >5σ exclusion of LSND
  - Oscillation vs off-axis angle

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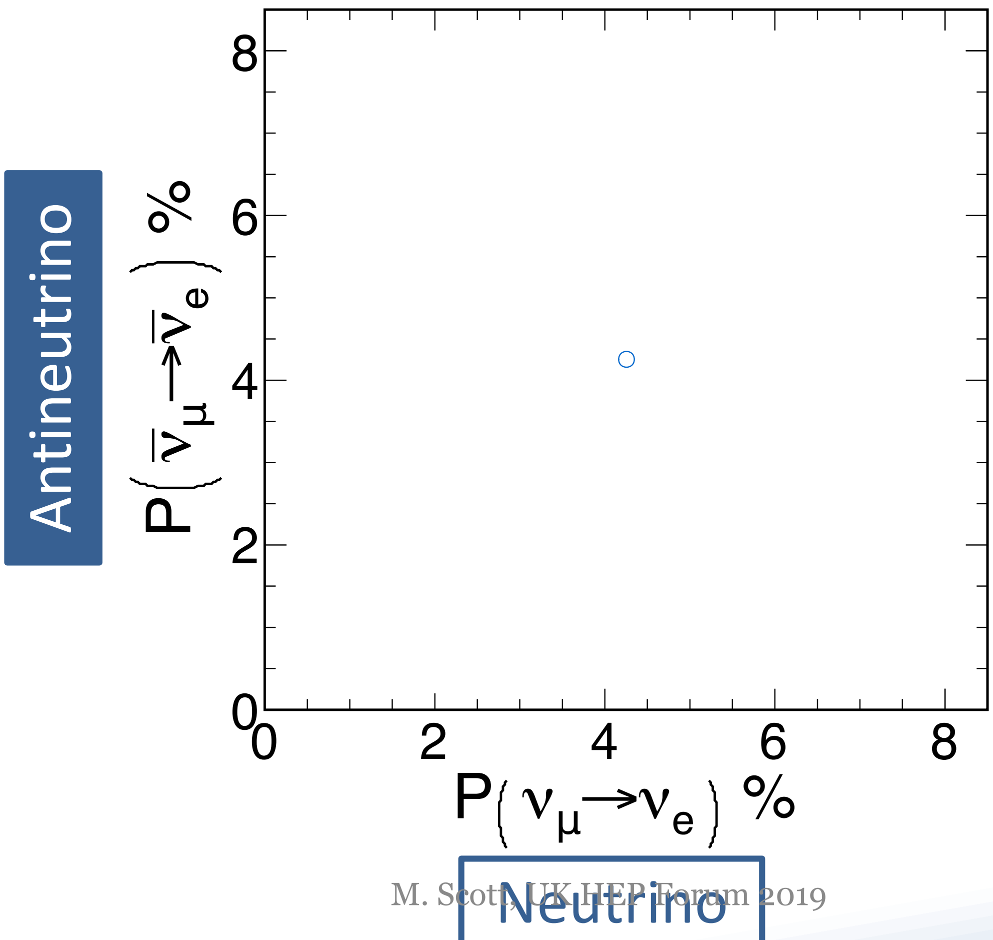
Summary

- Neutrino oscillation physics entering the precision era
- Next generation of long-baseline experiments will measure last unknown parameters in PMNS
  - Experiments will be systematics dominated
  - Major challenge facing community
  - New detector ideas (PRISM etc.) essential to address this
- Ultimate goal is precision neutrino physics
  - Model building / rejection for theory
  - Direct searches for (more) new physics
    - Unitarity measurements in PMNS
    - Non-standard interactions
    - Proton decay
    - Sterile neutrinos, Lorentz violation, etc.

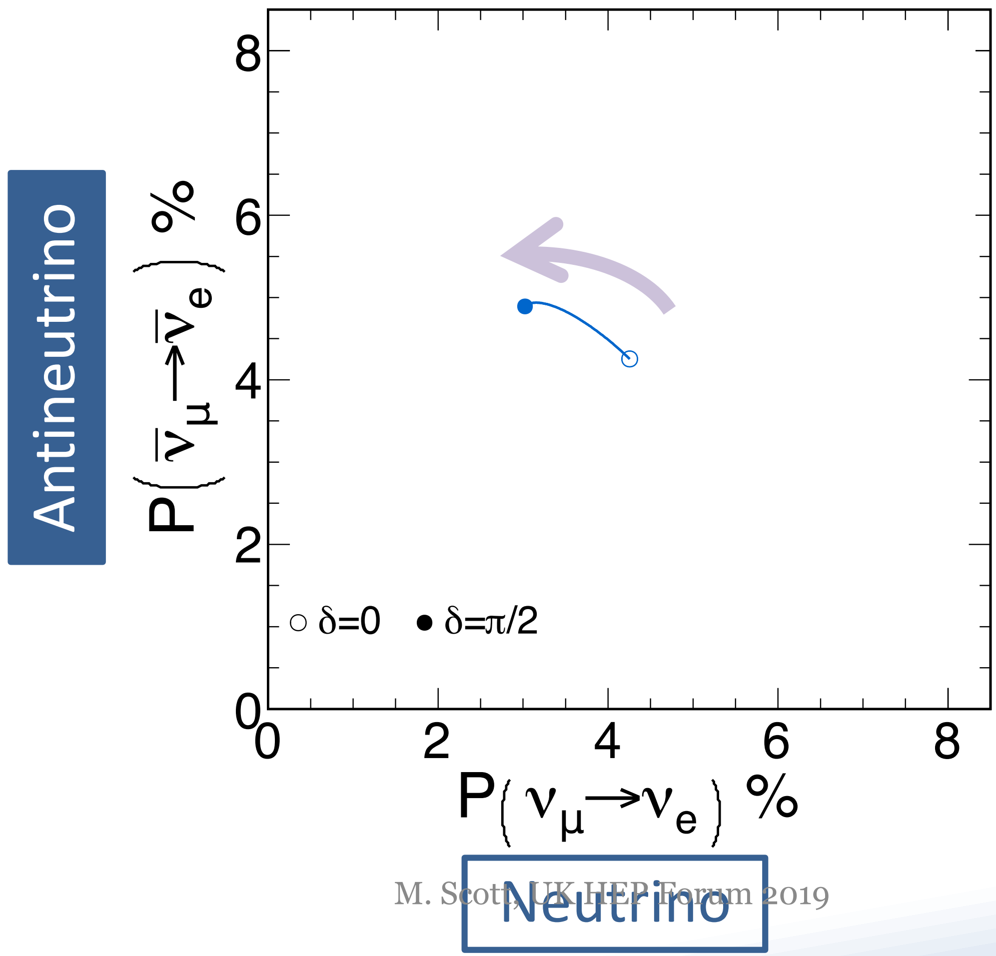
1. Is the mass hierarchy "normal" or "inverted?
2. Do neutrino oscillations violate *CP* symmetry?
3. What is the "octant" of θ_{23}?



Vacuum and no CP violation: neutrinos and antineutrinos are the same

Slides by A. Himmel

1. Is the mass hierarchy "normal" or "inverted?
2. Do neutrino oscillations violate *CP* symmetry?
3. What is the "octant" of θ_{23}?



CP-violation through δ creates opposite effects in neutrinos and antineutrinos

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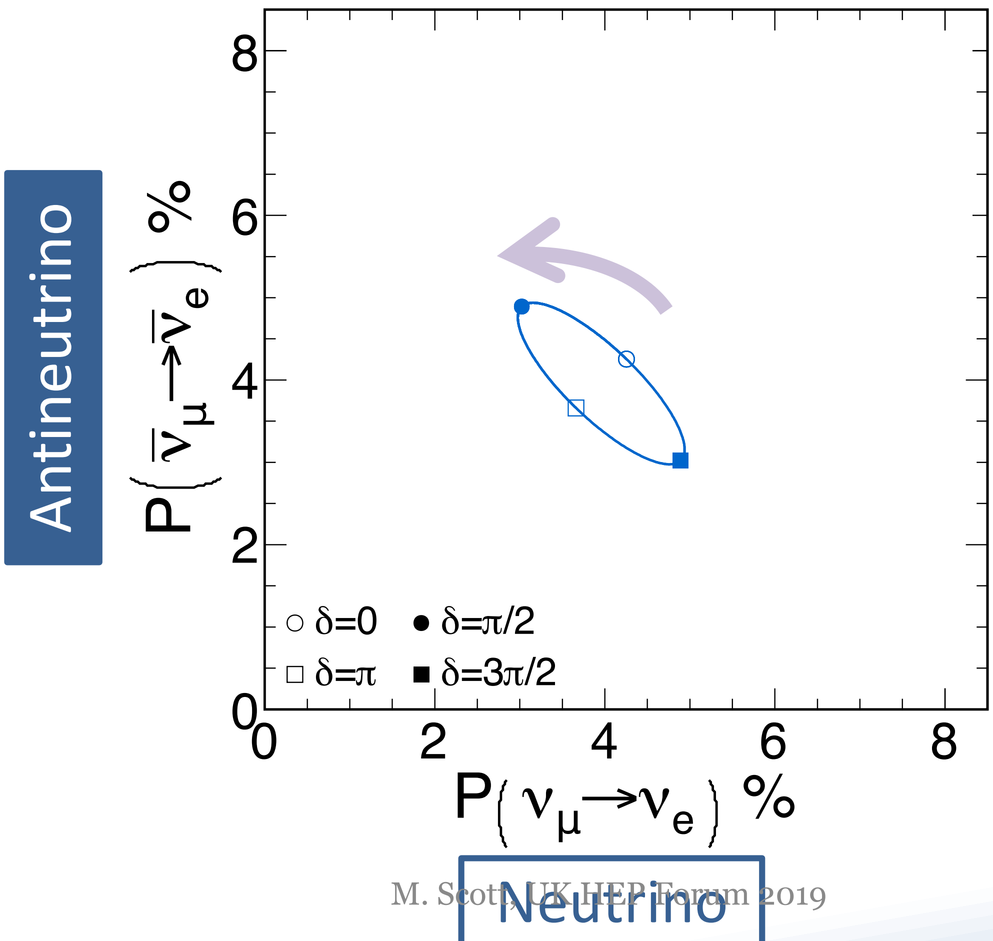

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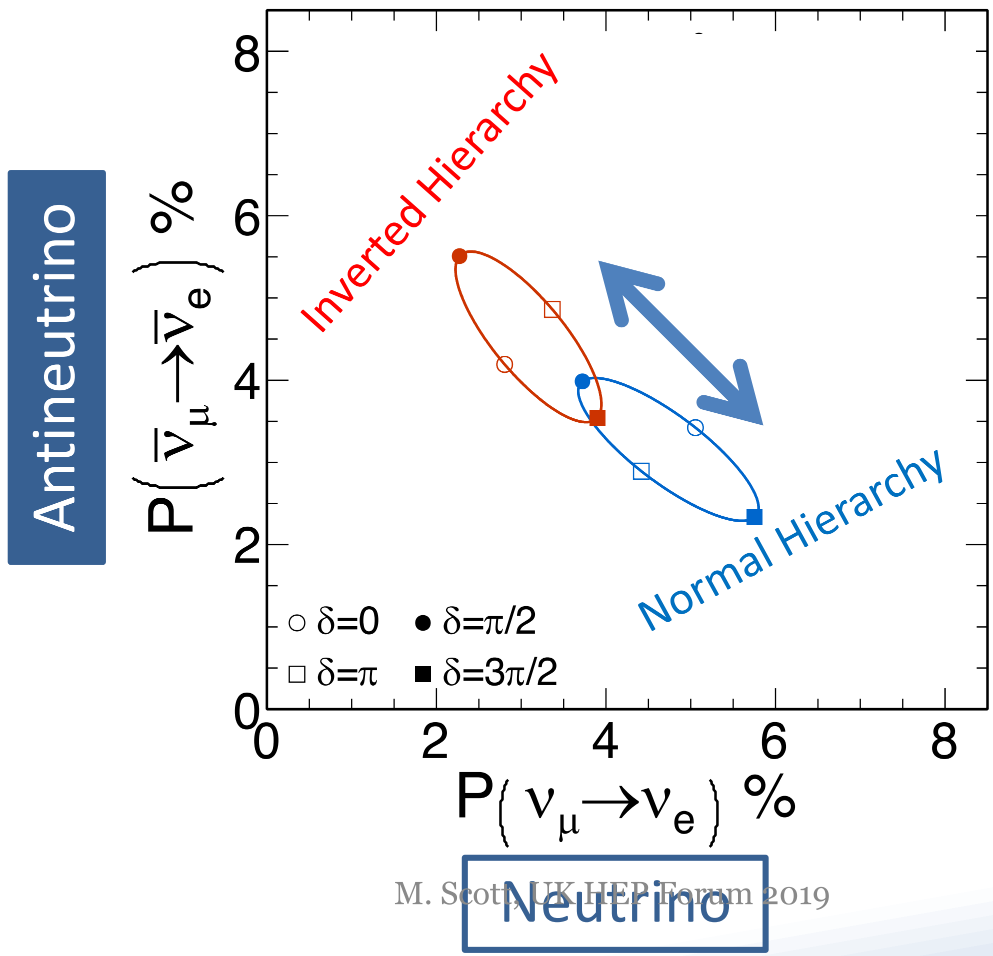
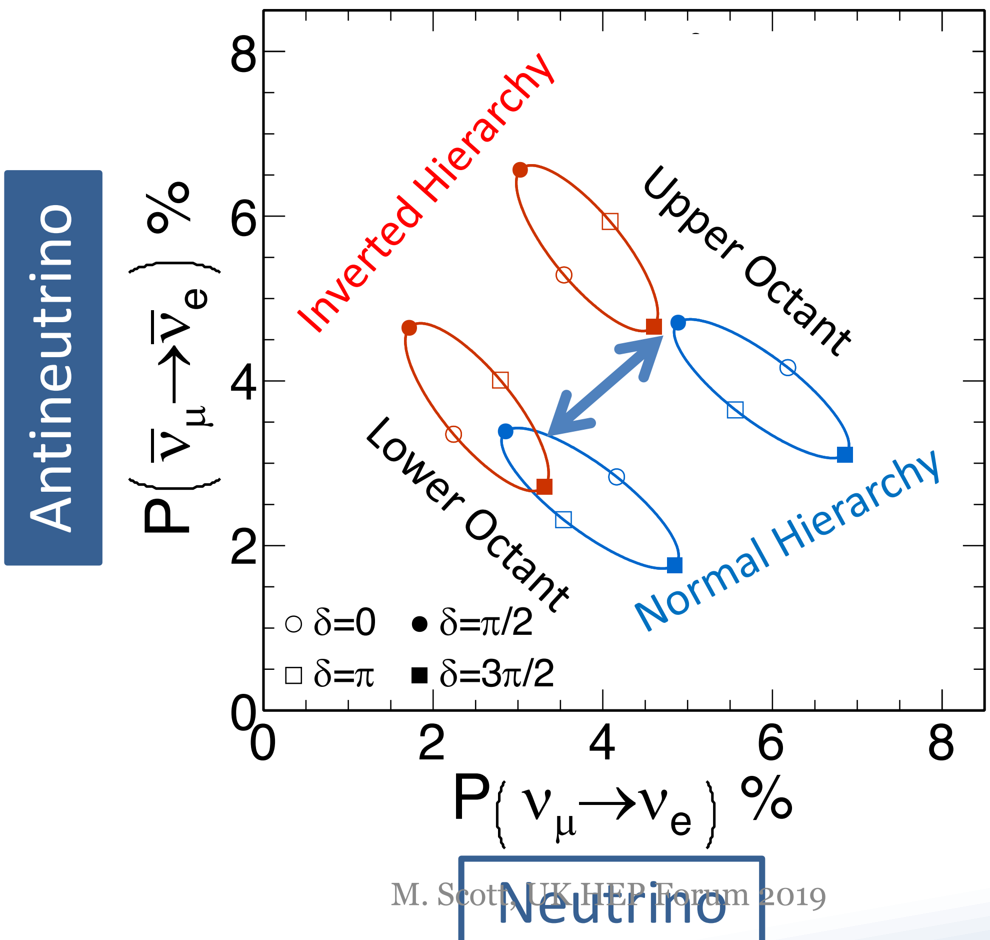


Matter effects also introduce opposite neutrino-antineutrino effects.

Slides by A. Himmel

1. Is the mass hierarchy "normal" or "inverted?
2. Do neutrino oscillations violate *CP* symmetry?
3. What is the "octant" of θ_{23}?

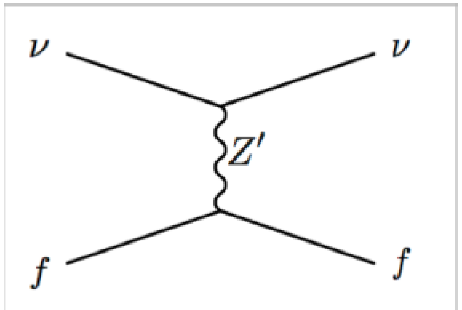


The octant creates the *same* effect in neutrinos and antineutrinos.

Slides by A. Himmel

Searches for new Physics: NSI's

NSI's ←→ new physics at high scales
Which are integrated out
Z', new scalars, … ➔ ε_{ij}



$$\mathcal{L}_{NSI} \simeq \epsilon_{\alpha\beta} 2\sqrt{2} G_F (\bar{\nu}_{L\beta}\, \gamma^\rho\, \nu_{L\alpha})(\bar{f}_L \gamma_\rho f_L)$$

$$\frac{d\sigma}{dT}(E_\nu, T) = \frac{G_F^2 M}{\pi}\left(1 - \frac{MT}{2E_\nu^2}\right) \times \left\{ \left[Z(g_V^p + 2\varepsilon_{ee}^{uV} + \varepsilon_{ee}^{dV}) + N(g_V^n + \varepsilon_{ee}^{uV} + 2\varepsilon_{ee}^{dV}) \right]^2 + \sum_{\alpha=\mu,\tau} \left[Z(2\varepsilon_{\alpha e}^{uV} + \varepsilon_{\alpha e}^{dV}) + N(\varepsilon_{\alpha e}^{uV} + 2\varepsilon_{\alpha e}^{dV}) \right]^2 \right\}$$

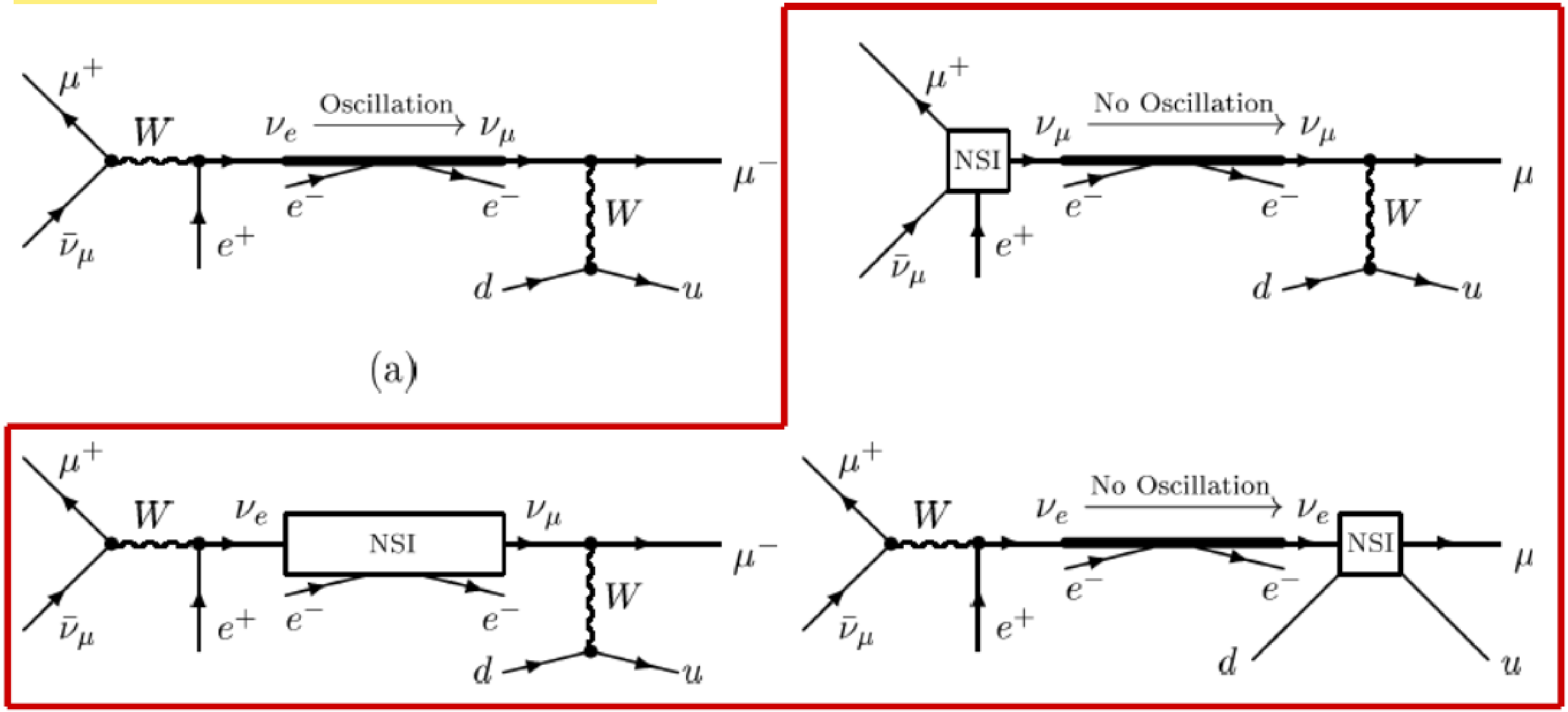
Barranco et al. 2005

$$|\epsilon| \simeq \frac{M_W^2}{M_{NSI}^2}$$

➔ **Competitive method to test TeV scales**
$\varepsilon = 0.01$ ←→ TeV scales

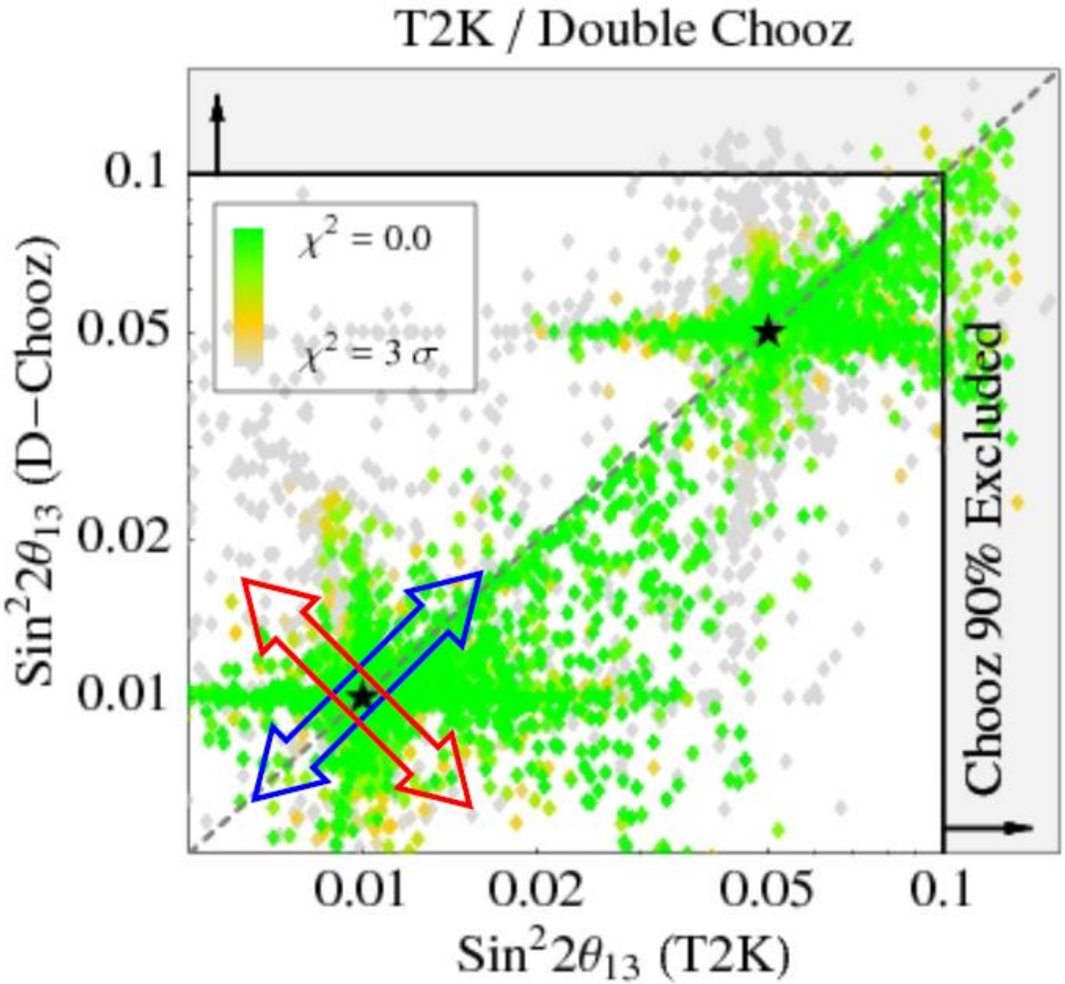
NSIs interfere with Oscillations

the "golden" oscillation channel | **NSI contributions to the "golden" channel**



interference in oscillations ~ε ⟷ FCNC effects ~ε²

NSI: Offset and Mismatch in θ_{13}



Redundant measurements:

Double Chooz + T2K

***=assumed 'true' values of θ_{13}**

scatter-plot: ε values random
- **below existing bounds**
- **random phases**

NSIs can lead to:

- **offset**
- **mismatch**

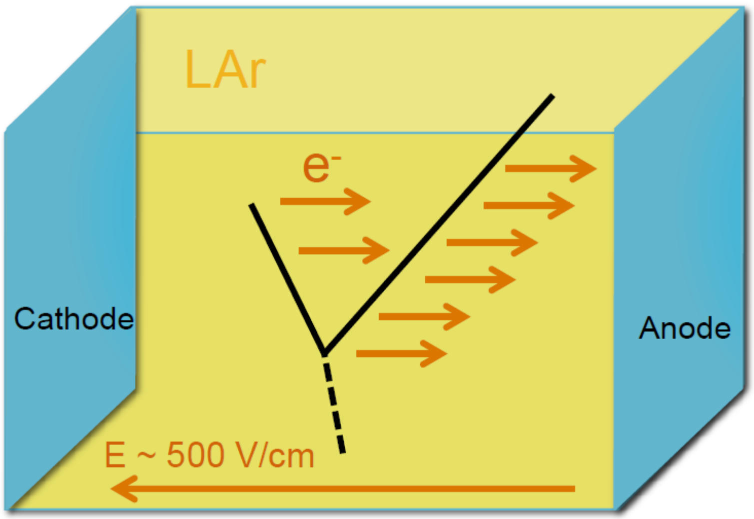
➔ **redundancy**

➔ **interesting potential**

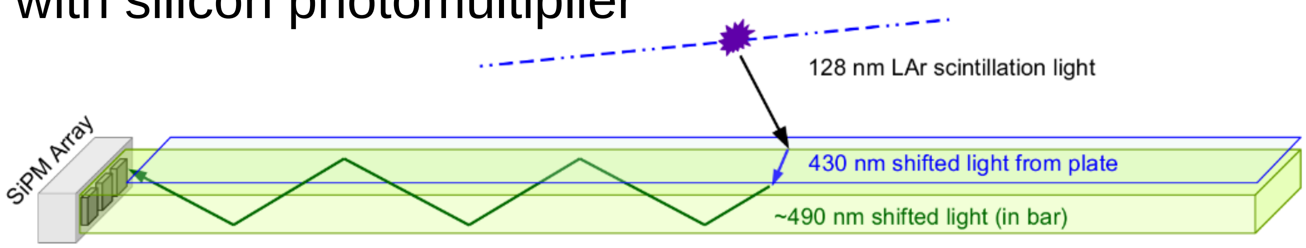
Kopp, ML, Ota

Liquid argon neutrino detectors

- Ionization readout planes
  - Wire planes on anode – 2 induction, 1 collection
  - 180kV potential
  - High resolution 2D reconstruction



- Light collection for 3rd dimension
  - Measures time of interaction
  - Scintillator bar with silicon photomultiplier readout



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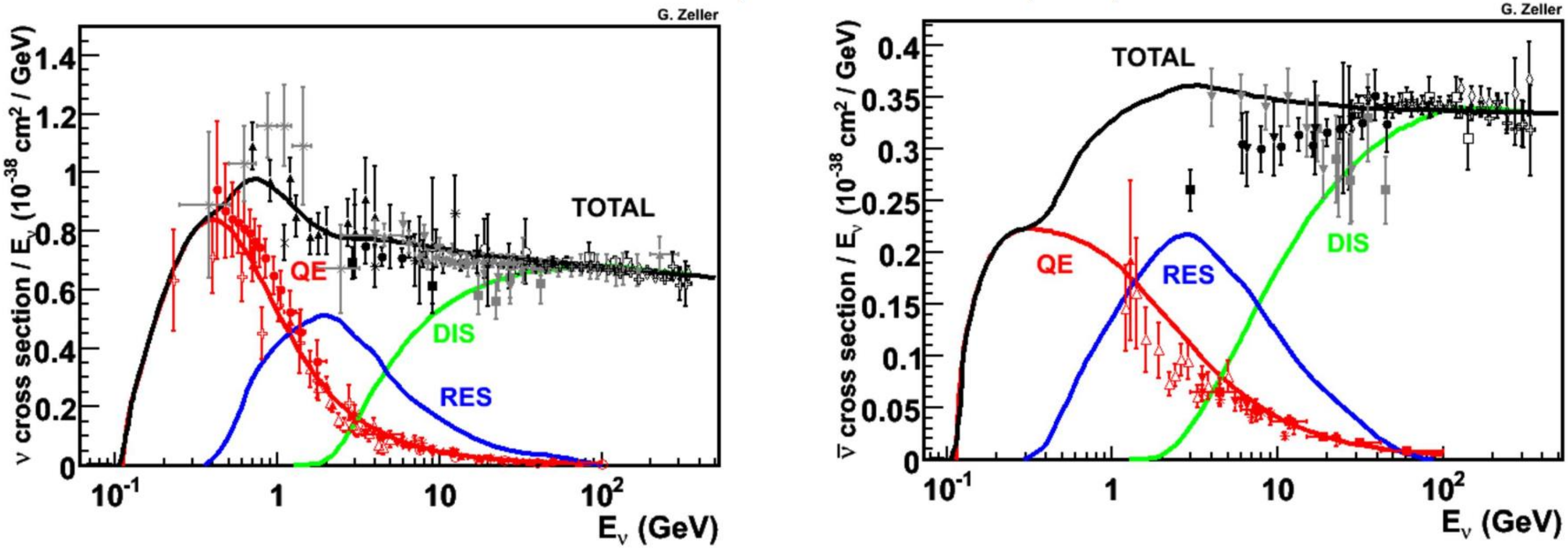
Neutrino cross-section measurements

Rev. Mod. Phys. 84, 1307–1341 (2012)



- High energy (>10 GeV region) – data and theory agree quite well
- Lower energy (~1 GeV region) – a lot more variation
  - Very hard to calculate and (very) hard to measure directly

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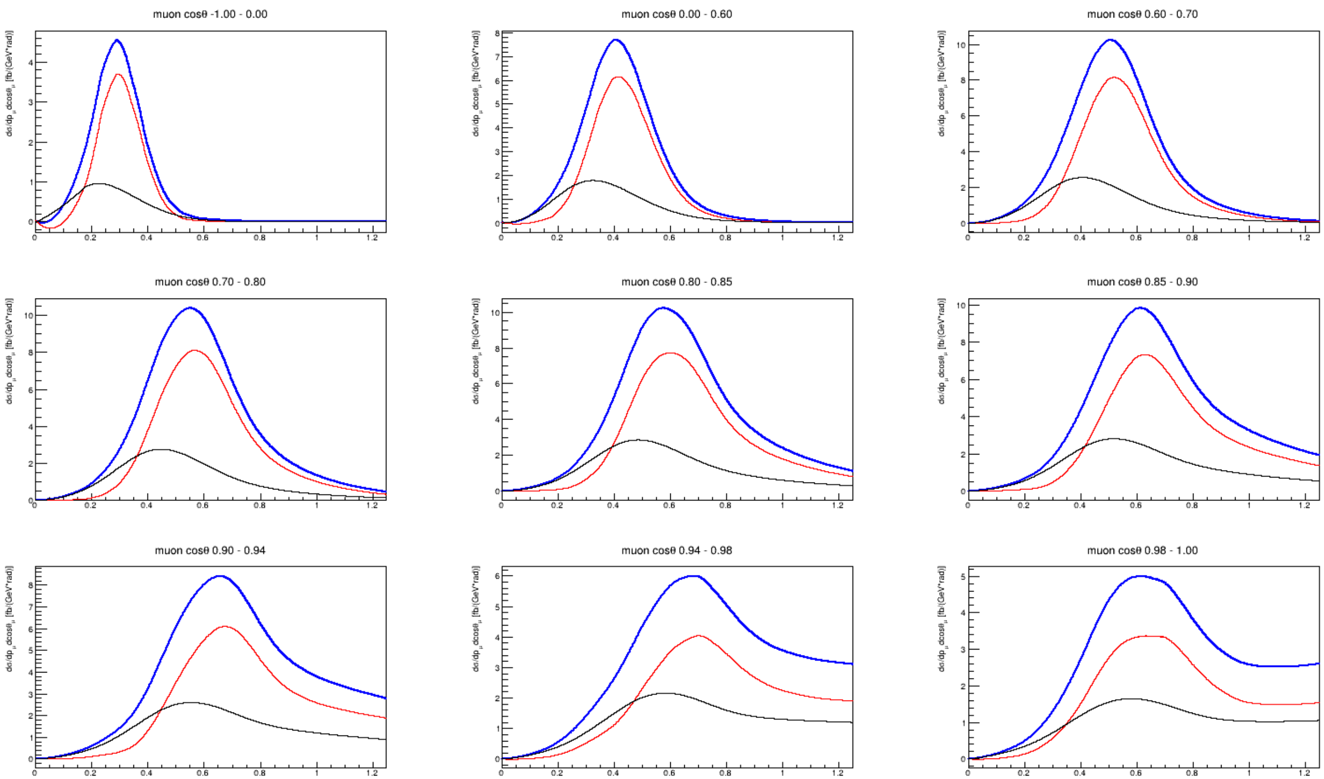
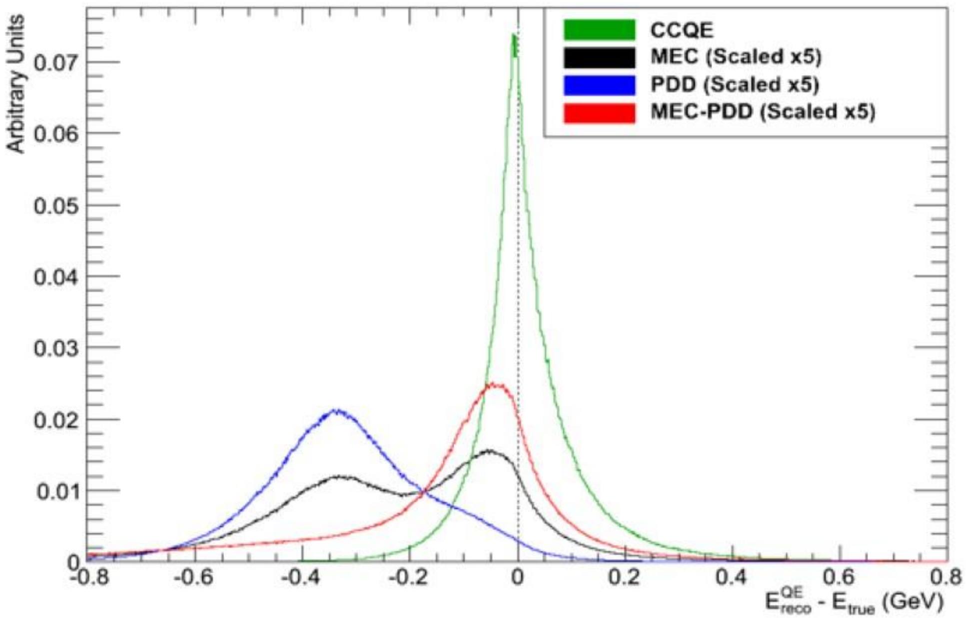
Why can't we just measure it?



- Red – CCQE events
- Black – 2p2h events
- Very hard to differentiate between them
- Can confuse oscillation analysis – attribute 2p2h events to CCQE model

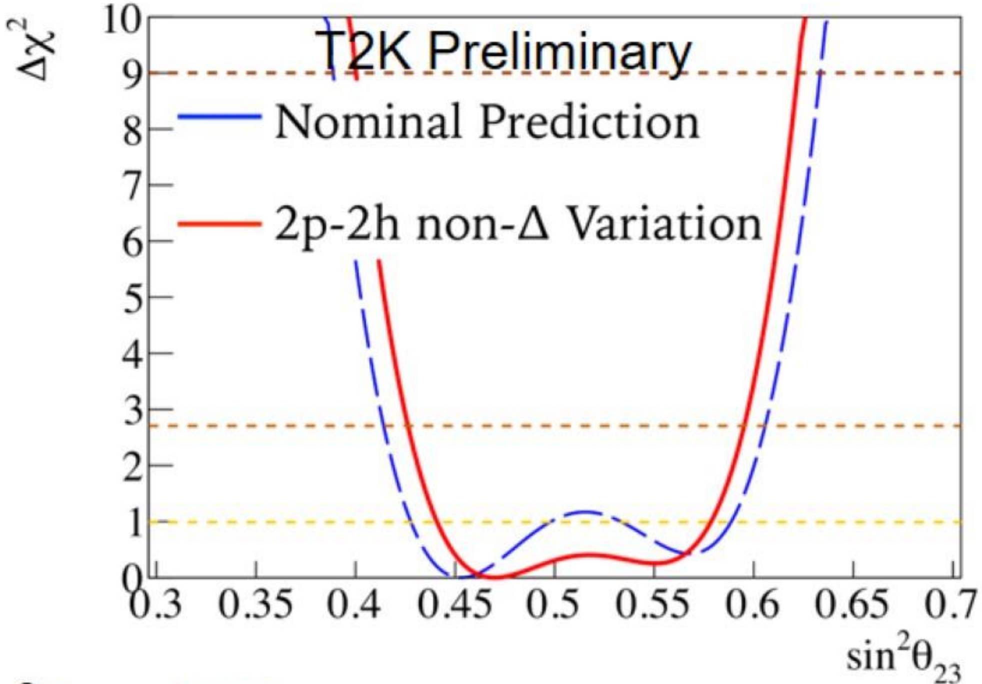
Simulated data studies

- Choice of interaction model changes mapping between true and reconstructed energy
- Near detector fit attributes data – MC difference to wrong interaction
- Predicted true energy spectrum is incorrect
- Measured oscillation parameters are biased
- At T2K I study these biases using simulated data
- Generate simulated ND280 and SK data samples using a different cross-section model
- Fit ND280 simulated data with nominal MC
- Fit SK simulated data using ND280 fit result
- Compare oscillation parameter contours to expectation from nominal fits



Oscillation contours

- Results from oscillation fit – likelihood contour for $\sin^2\theta_{23}$
- Assume normal mass ordering and apply reactor constraint on $\sin^2\theta_{13}$
- Blue – expected nominal contour
- Red – simulated data contour



- True value of $\sin^2\theta_{23} = 0.45$
- Bias towards more maximal mixing

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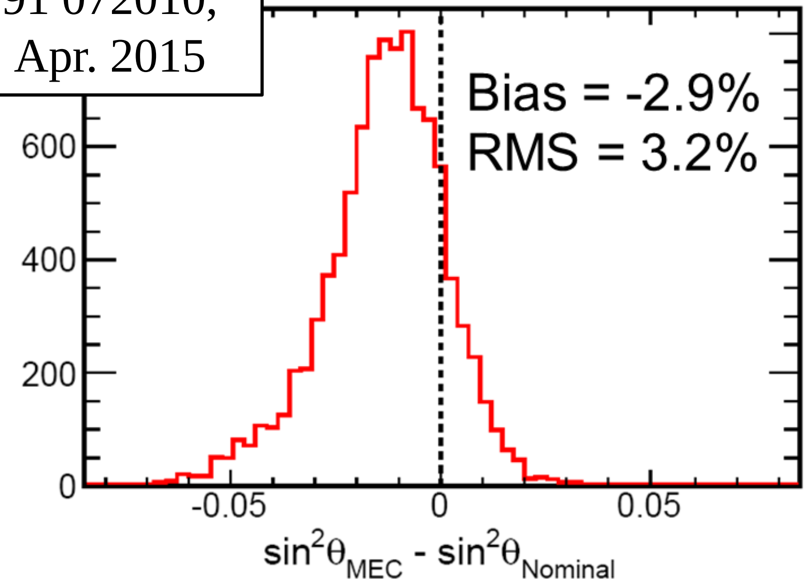
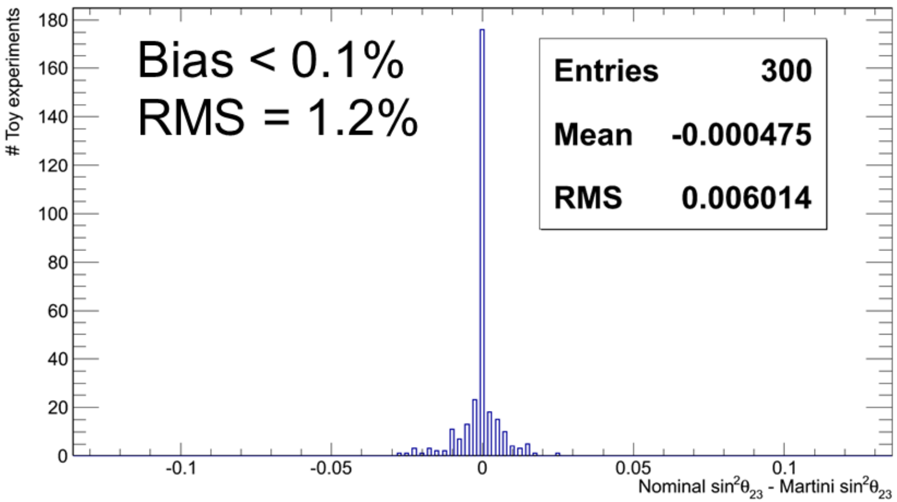
PRISM benefits - 3

- Mock data analysis at T2K
  - Addition of multi-nucleon events to mock data
  - Analysis MC without multi-nucleon events
  - Biased values of θ_{23} measured

K. Abe *et al*, *Phys. Rev. D*, 91 072010, Apr. 2015

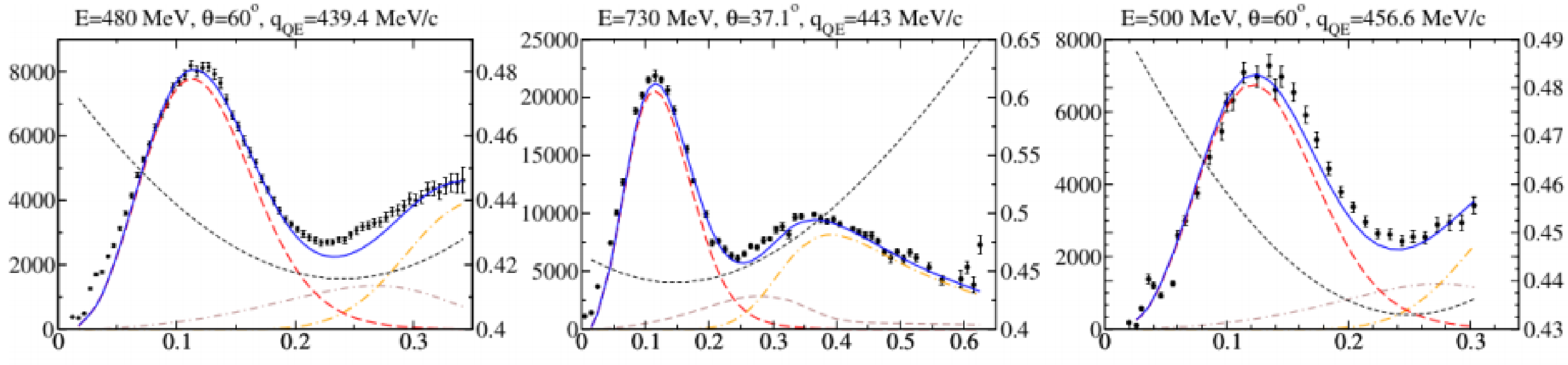




- Identical analysis with E61
  - Multi-nucleon events added to mock data
    - Not MC
  - Linear combination applied
  - Measured θ_{23} unbiased

Improved models

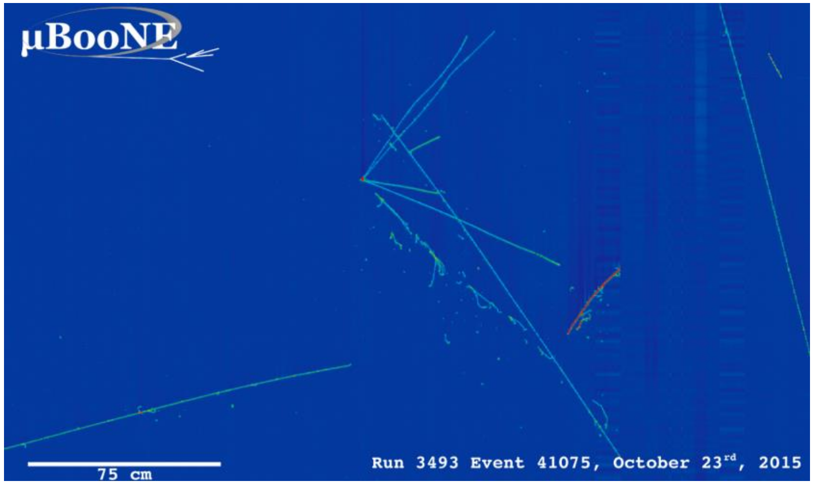
- Theory and experimental community working to produce better models
- e.g. SuperScaling v2 + MEC model – Amaro et al. (arXiv:1603.08396)



- Tune to electron scattering data, ongoing comparison to neutrino scattering

New experiments + techniques

- Liquid argon (right)
- Transverse variables
- Momentum-Energy transfer
- Will improve situation in future – is it enough?



2p-2h events

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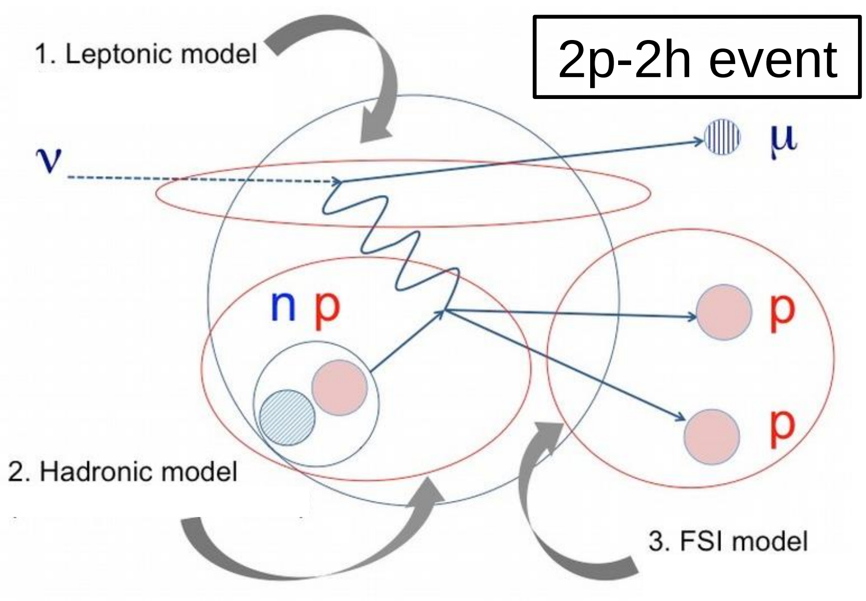
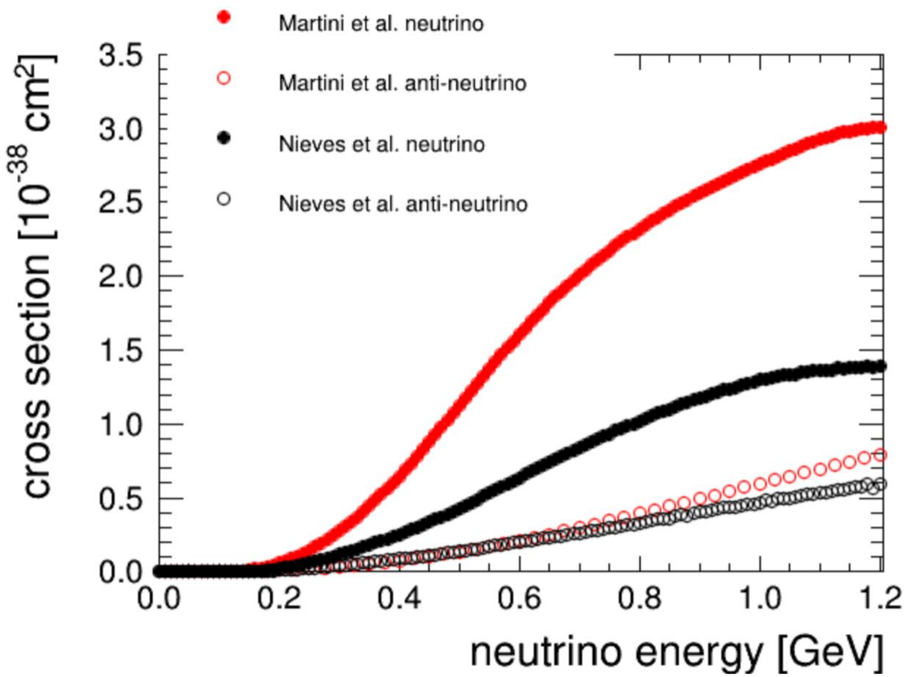
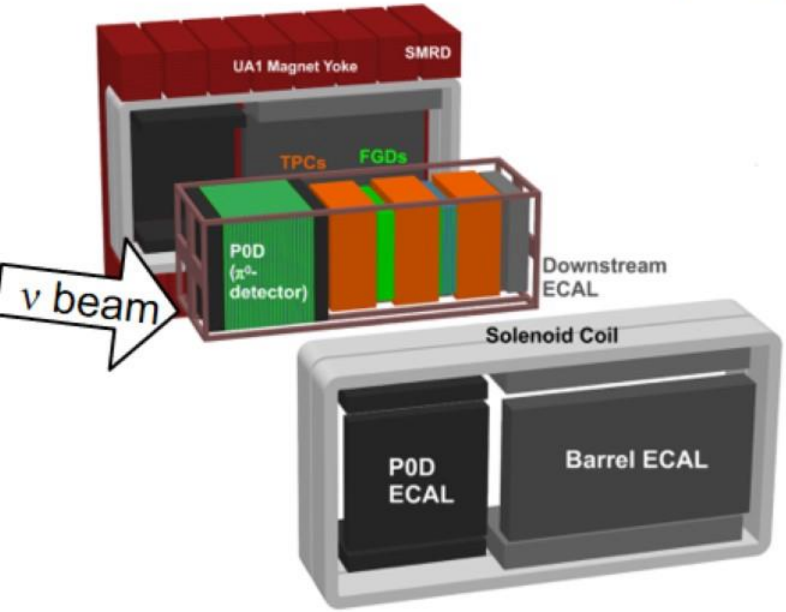


Image from T. Katori



- Many different theoretical models
- Two shown on right
- ~15% of CCQE-like cross-section
- Predict different rates for neutrinos vs anti-neutrinos
- Direct 'CP-violating' systematic

T2K detectors



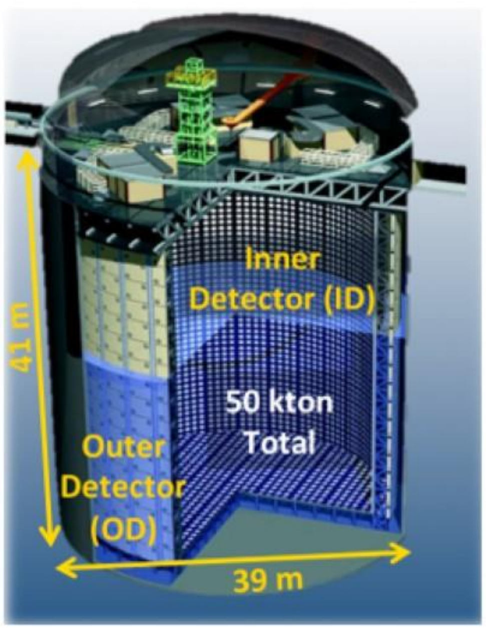
Near, Off-axis detector (ND280)

Two fine-grained detectors (FGDs)

- FGD1 – Fully active carbon target
- FGD2 – Active carbon and passive water layers

Magnet + three TPCs

- Particle charge + momentum via curvature
- Particle ID from dE/dx - 0.2% mis-ID rate



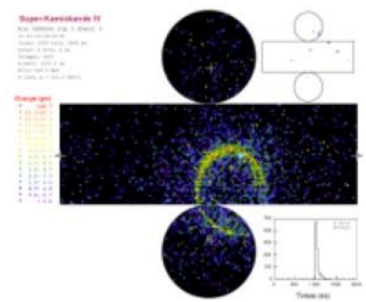
Super-Kamiokande (SK)

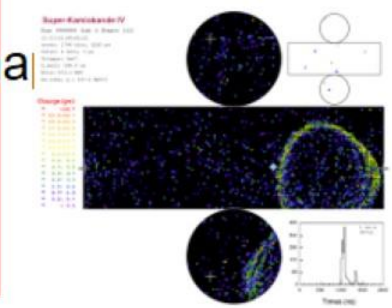
Large water-Cherenkov detector

- ~11,000 20” PMTs in inner detector
- 22.5 kT fiducial volume

Separate electrons and muons by ring sha

- Mis-ID <1%
- No sign selection

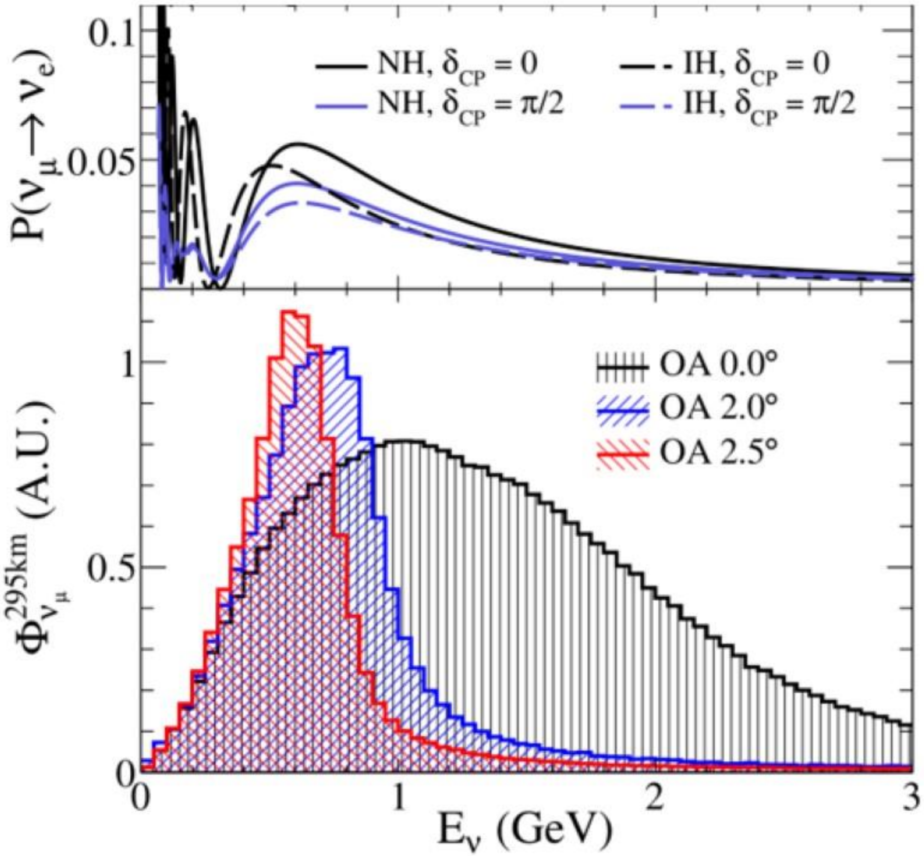




Off-axis beam and detector TRIUMF

Moving off axis:

- Lower peak energy
- Smaller high energy tail
- Less energy spread



ND280 Off-axis detector (ND280):

- Fine-grained target (FGD)
- Magnet + TPC
- Characterise neutrino beam