WG1 - Neutrino Oscillations
Summary and Answers to Questions

Alex Sousa
University of Cincinnati

Francesca Di Lodovico
Queen Mary University of London

Mark Hartz
Kavli IPMU (WPI), University of Tokyo/TRIUMF

NuFact 2015
CBPF, Rio de Janeiro, Brasil

August 15, 2015

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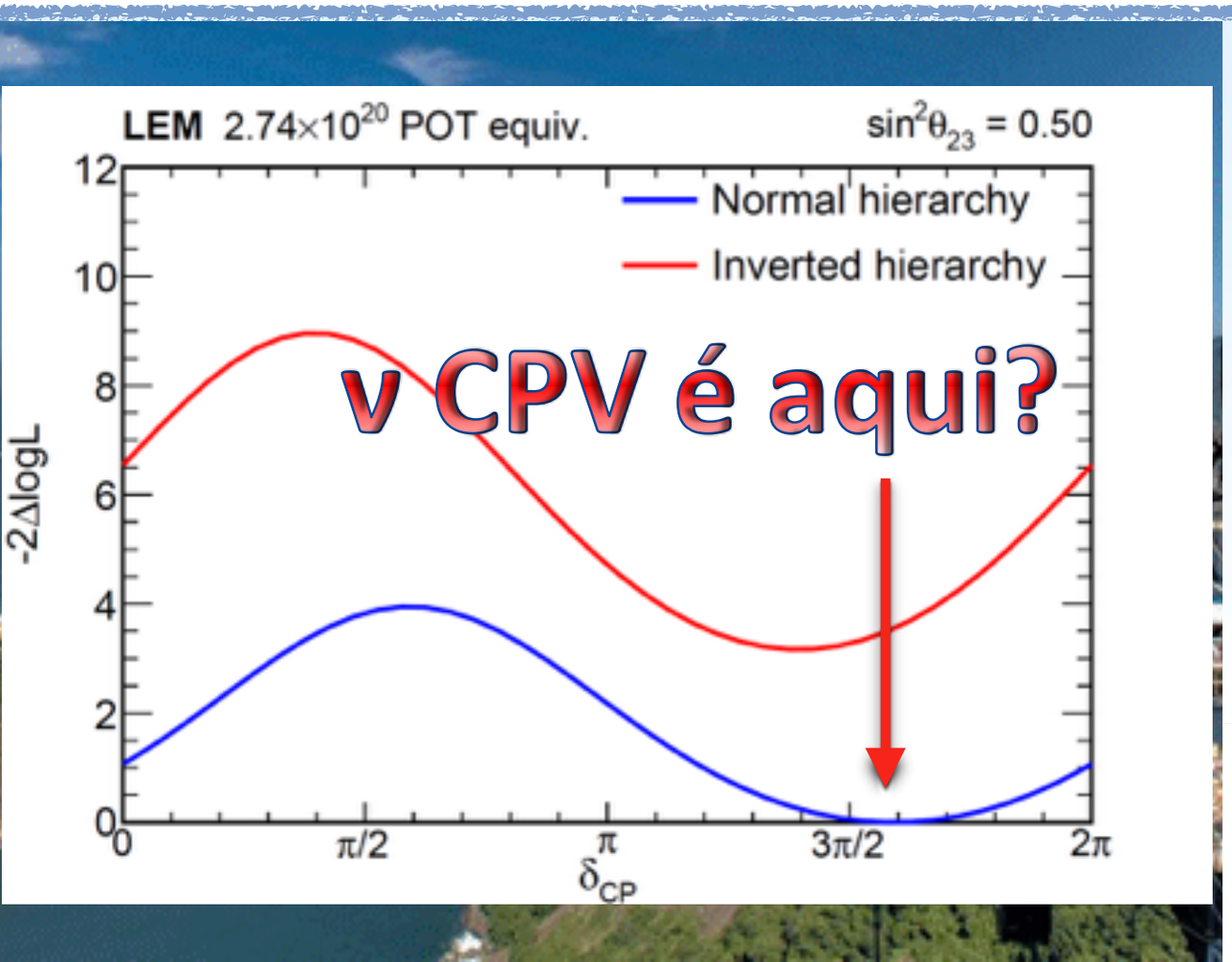

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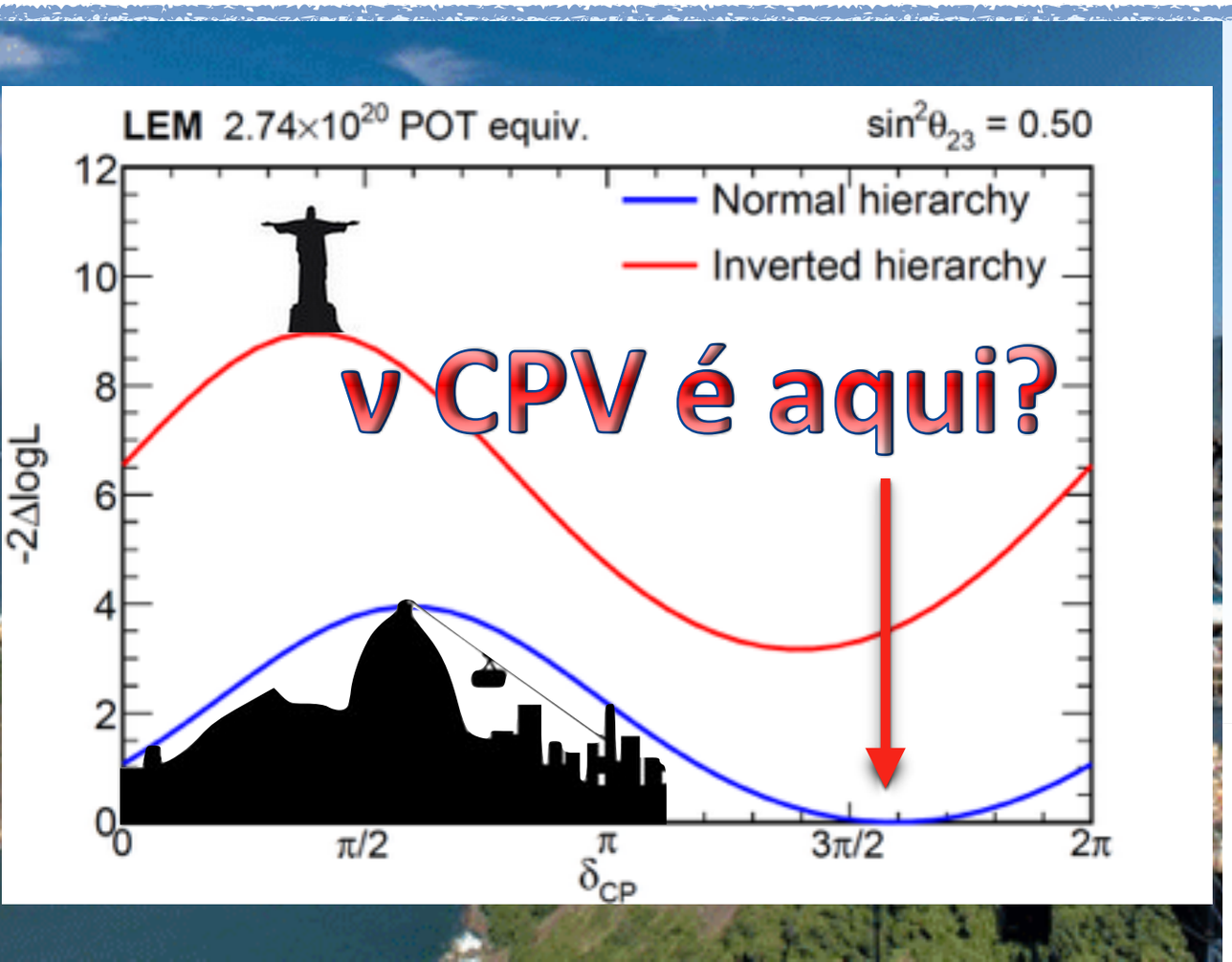

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Q1: ν Mass and Flavor Models

Question from NuFact '14: What are the new developments and predictions from flavor models on neutrino oscillation parameters? What precision do we need to achieve to probe them? Which parameters (or combinations of them) are more powerful to test them?

ν Mass and Flavor Models

- **Mu-Chun Chen - Neutrino Mass and Flavor Models**

- Simple "Tribimaximal" (TBM) mixing and "golden ratio" models are ruled out by non-zero θ_{13}
  - Try to construct models from TBM + higher order corrections using continuous or discrete family symmetries
  - Leads to sum rules connecting mixing angles and CP phase

- A_4 (tetrahedron)
- T′ (double tetrahedron)
- S_3 (equilateral triangle)
- S_4 (octahedron, cube)
- A_5 (icosahedron, dodecahedron)
- Δ_{27}
- Q_4

- Tri-bimaximal Mixing Pattern

$$U_{TBM} = \begin{pmatrix} \sqrt{2/3} & \sqrt{1/3} & 0 \\ -\sqrt{1/6} & \sqrt{1/3} & -\sqrt{1/2} \\ -\sqrt{1/6} & \sqrt{1/3} & \sqrt{1/2} \end{pmatrix}$$

"Golden Ratio"

$$U_{\rm GR} \equiv \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\frac{\sin\theta_{12}}{\sqrt{2}} & \frac{\cos\theta_{12}}{\sqrt{2}} & \frac{1}{\sqrt{2}} \\ -\frac{\sin\theta_{12}}{\sqrt{2}} & \frac{\cos\theta_{12}}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \end{pmatrix}$$

Double Tetrahedral Group T′: double covering of A4

$$\tan^2\theta_\odot \simeq \tan^2\theta_{\odot,TBM} + \frac{1}{2}\theta_c\cos\delta$$

M.-C.C, K.T. Mahanthappa (2007, 2009)

A_5 P. Ballett, S. Pascoli, J. Turner (2015)

G_e	θ_{12}	θ_{23}	$\sin\alpha_{ji}$	δ
$\mathbb{Z}_3$	$35.27^\circ + 10.13^\circ\, r^2$	45°	0	90°
				270°
$\mathbb{Z}_5$	$31.72^\circ + 8.85^\circ\, r^2$	$45^\circ \pm 25.04^\circ\, r$	0	0°
				180°
		45°	0	90°
				270°
$\mathbb{Z}_2 \times \mathbb{Z}_2$	$36.00^\circ - 34.78^\circ\, r^2$	$31.72^\circ + 55.76^\circ\, r$	0	0°
				180°
		$58.28^\circ - 55.76^\circ\, r$	0	0°
				180°

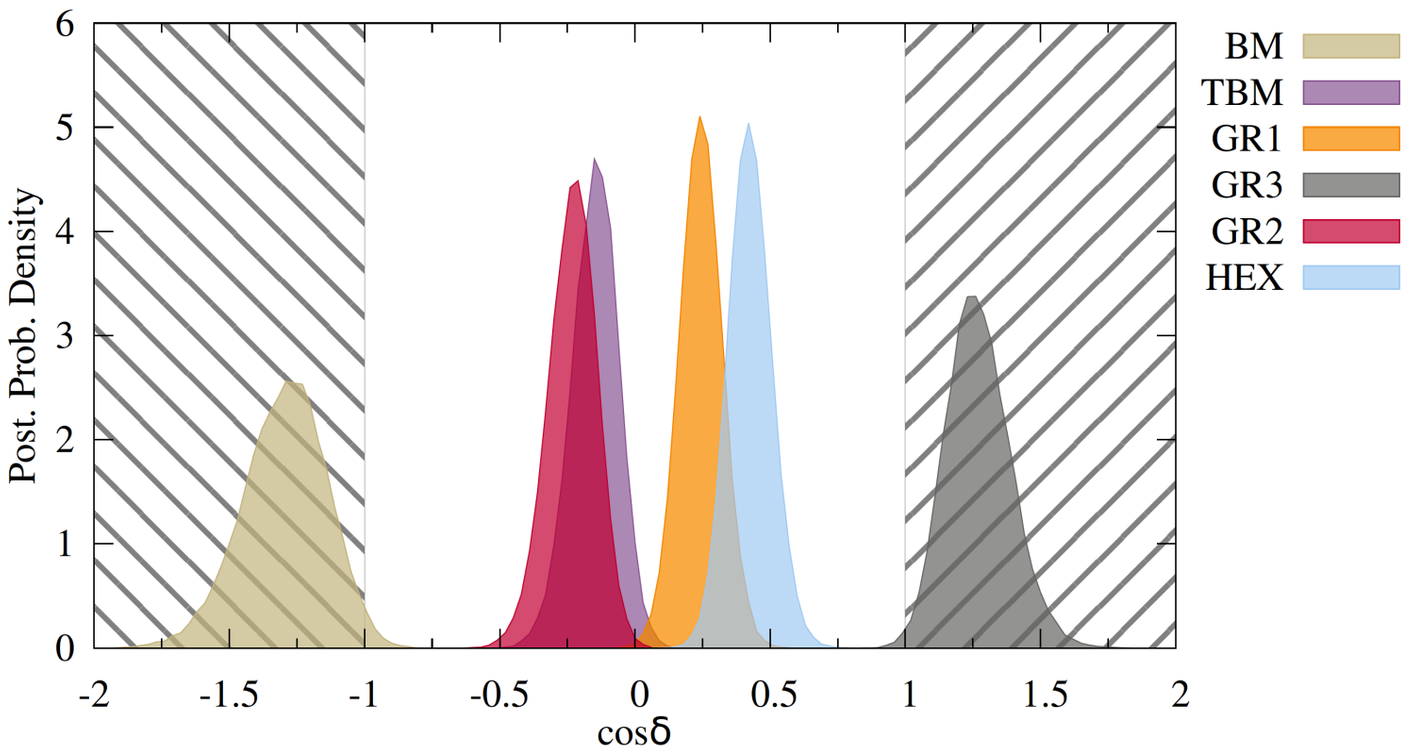
TABLE I. Numerical predictions for the correlations found in this paper. The dimensionless parameter $r \equiv \sqrt{2}\sin\theta_{13}$ is constrained by global data to lie in the interval $0.19 \lesssim r \lesssim 0.22$ at 3σ. The predictions for θ_{12} and θ_{23} shown here neglect terms of order $\mathcal{O}(r^4)$ and $\mathcal{O}(r^2)$, respectively.

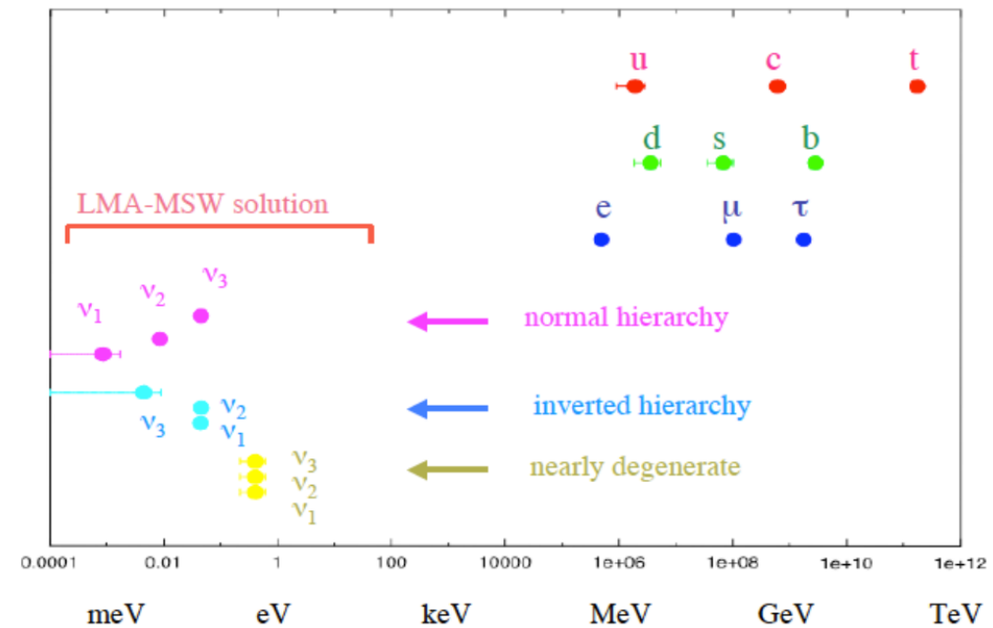
ν Mass and Flavor Models

$m_\nu \ll m_{e,\,u,\,d}$

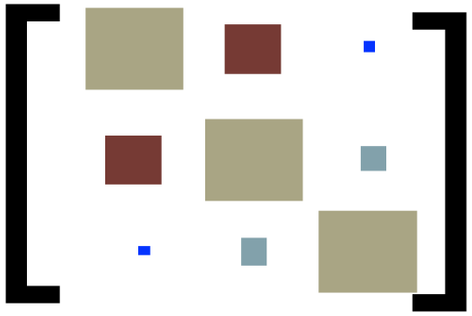
- **Alan Bross - Panel Discussion**

Ballet et al., arXiv:1410.7573v2





leptonic mixing



quark mixing

- Allowing 3σ ranges on mixing angle measurements

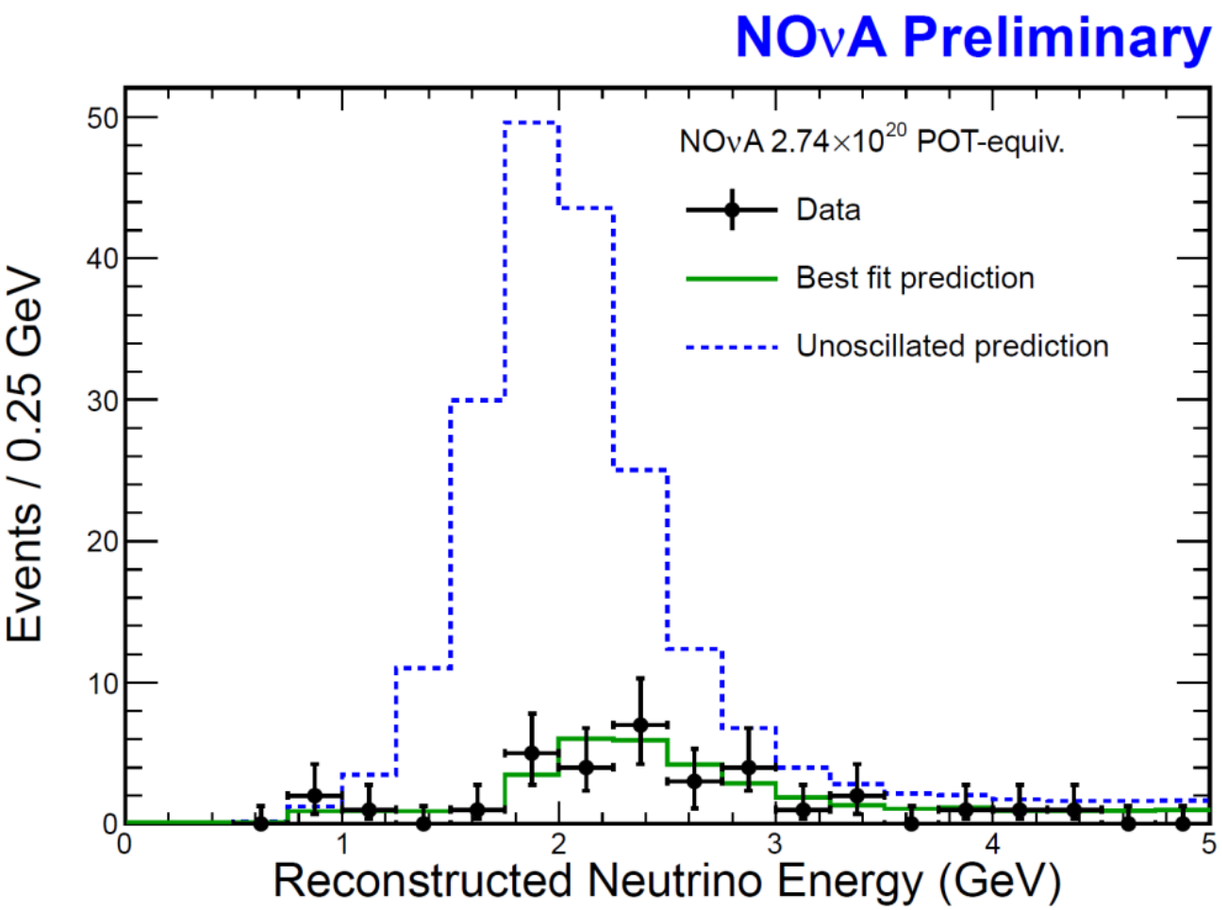
$$\theta_{12} = \theta_{12}^{\nu} + \theta_{13}\cos\delta \cdot$$

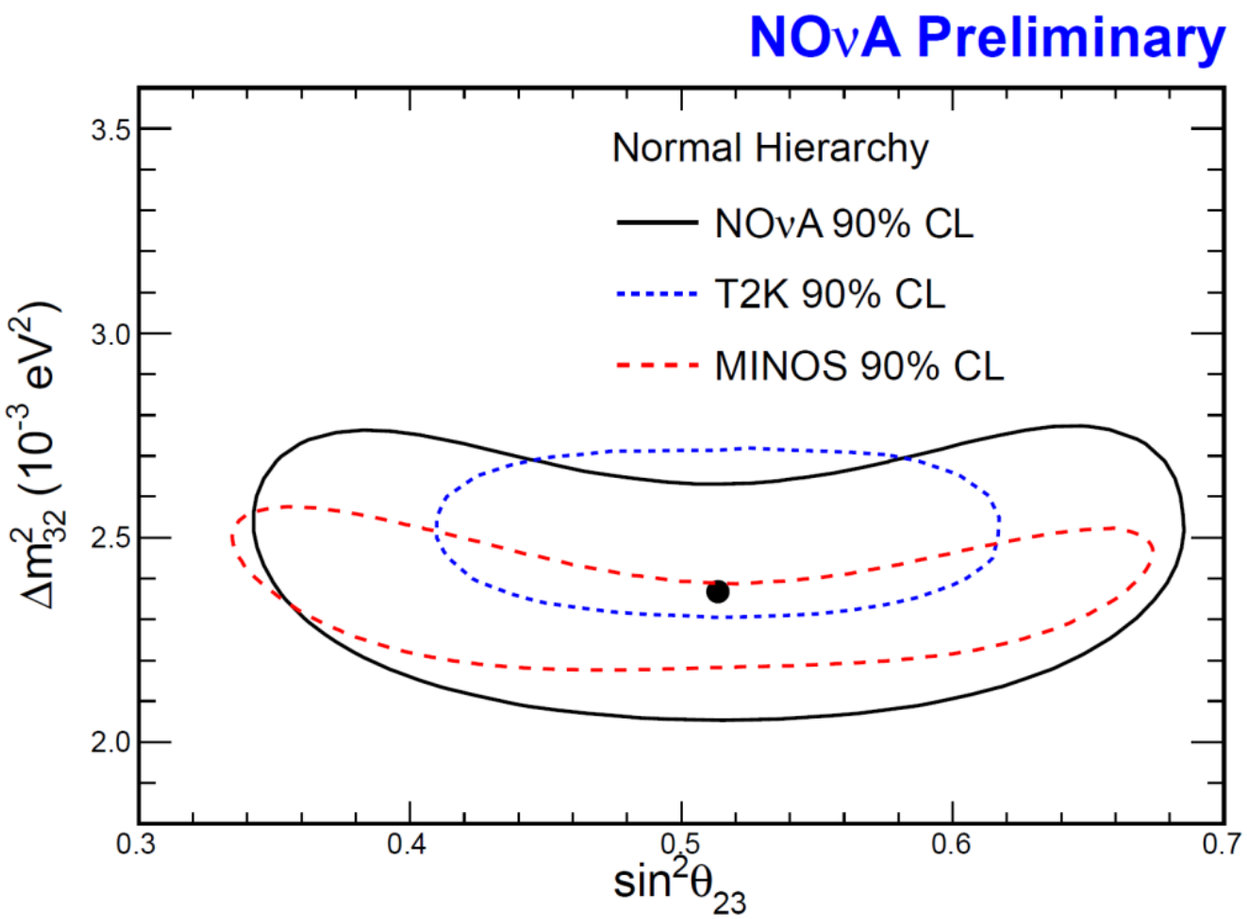
- More precise measurements of mixing angles and precision measurement of δ needed!

New and Current Results

- NOvA - Mayly Sanchez

Numu Disappearance



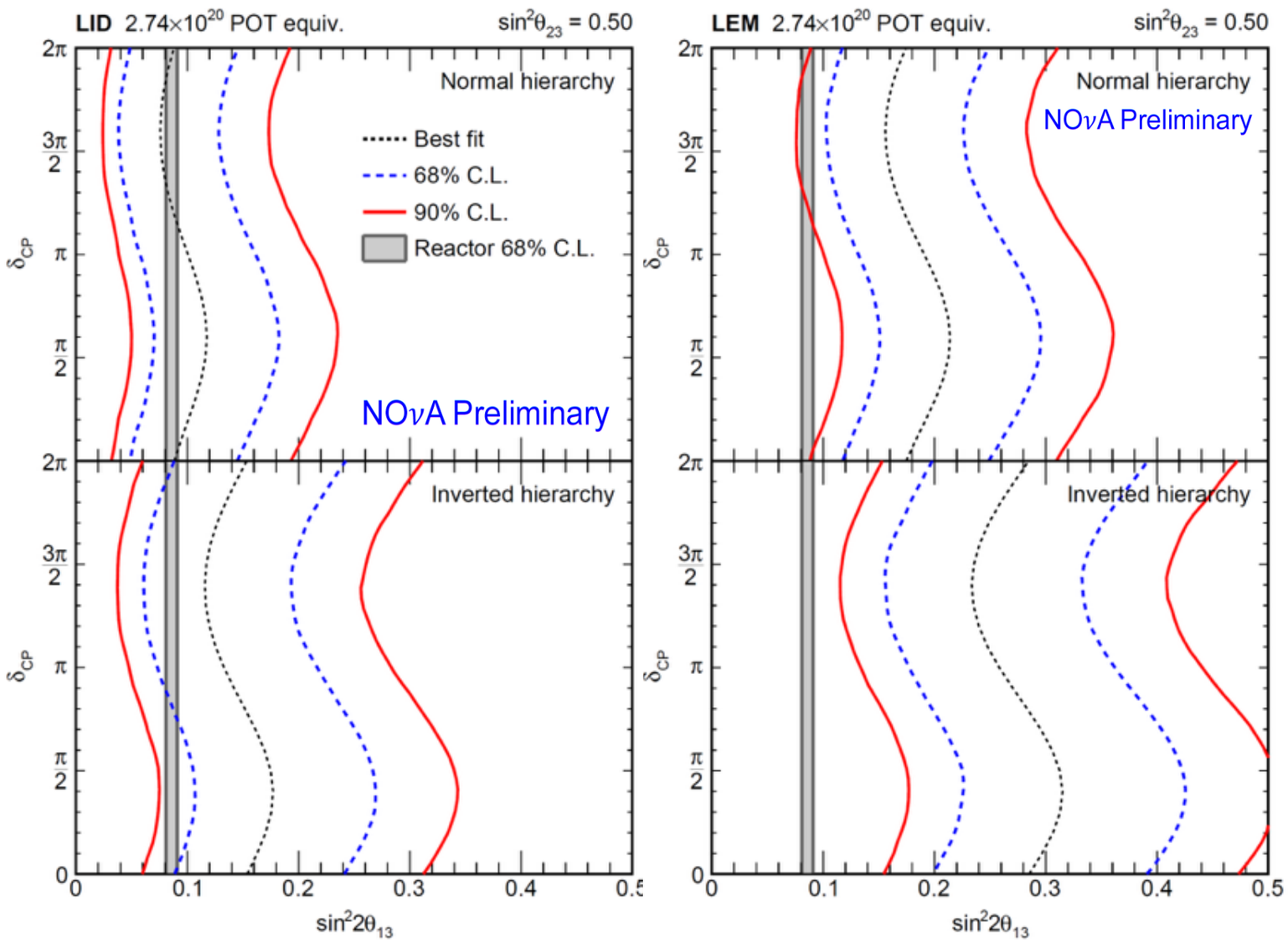


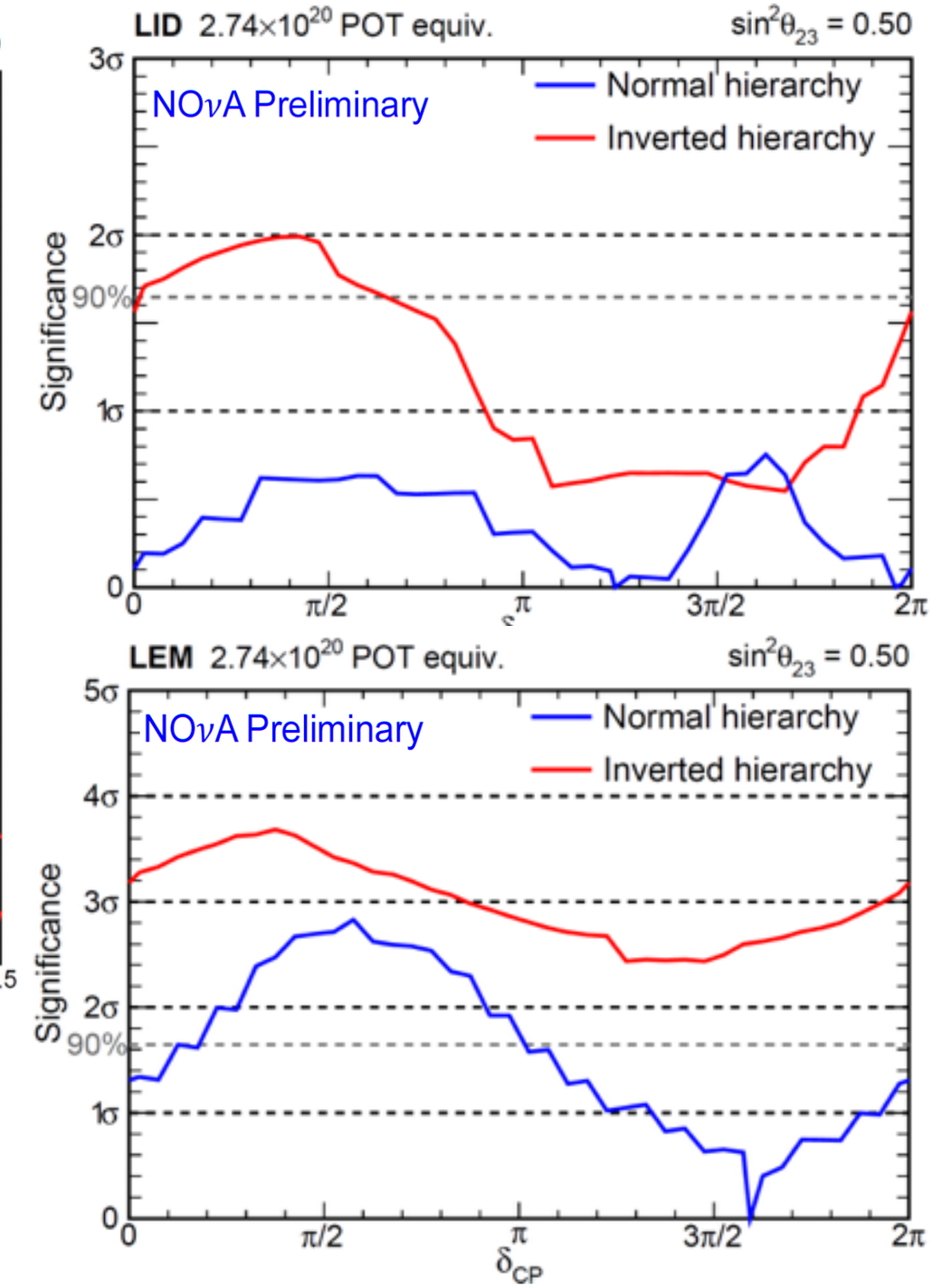
- 201 ν_μ CC candidates predicted, 33 observed
  - Starting to be competitive with existing measurements with just 8% of nominal exposure

$$\Delta m^2_{32} = +\,2.37^{+0.16}_{-0.15}\ \text{[normal ordering]}$$
$$\Delta m^2_{32} = -\,2.40^{+0.14}_{-0.17}\ \text{[inverted ordering]}$$
$$\sin^2\theta_{23} = 0.51 \pm 0.10$$

New and Current Results

- **NOvA - Mayly Sanchez** **Nue Appearance**





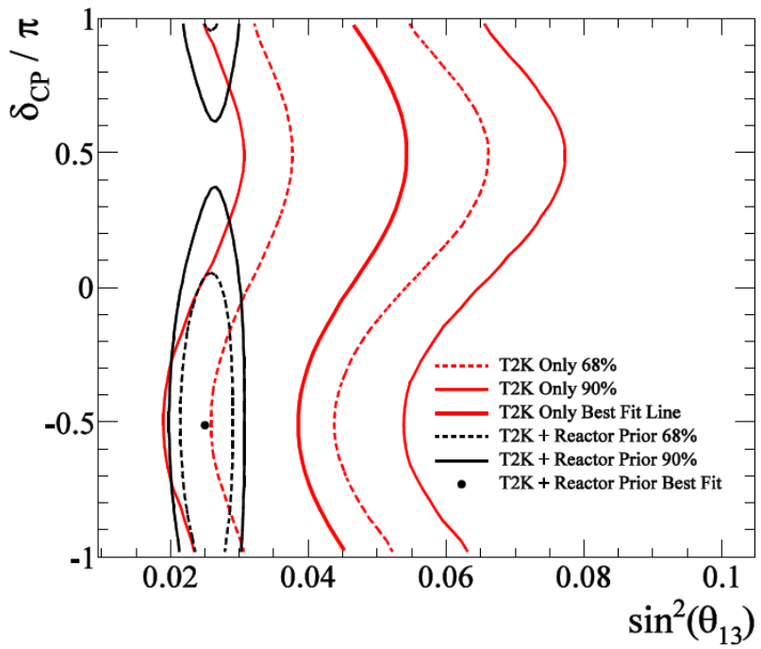
- **6 (LID) and 11 (LEM) ν_e CC candidates found**
  - **Consistent with reactor measurements of θ_{13}**
  - **Both selectors prefer Normal Hierarchy**
  - **Both selectors prefer δ_{CP} near $3\pi/2$**

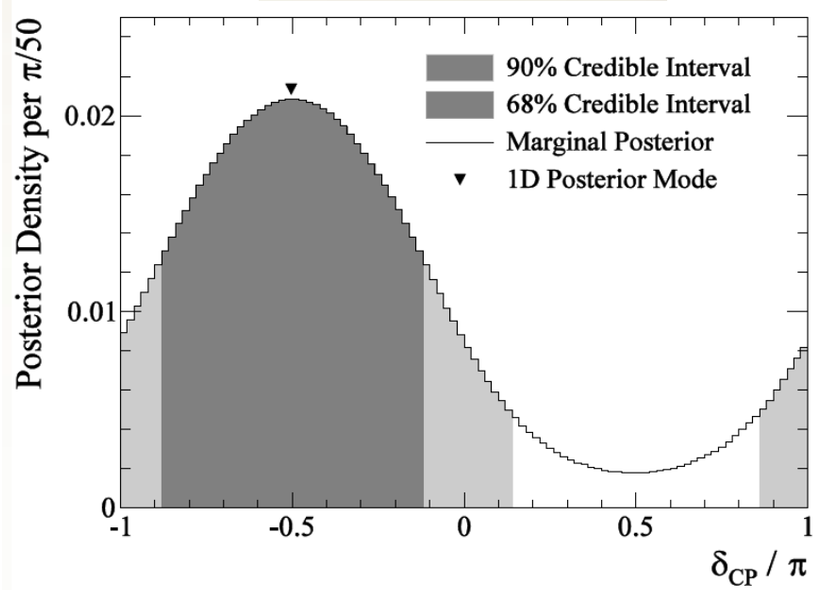
New and Current Results

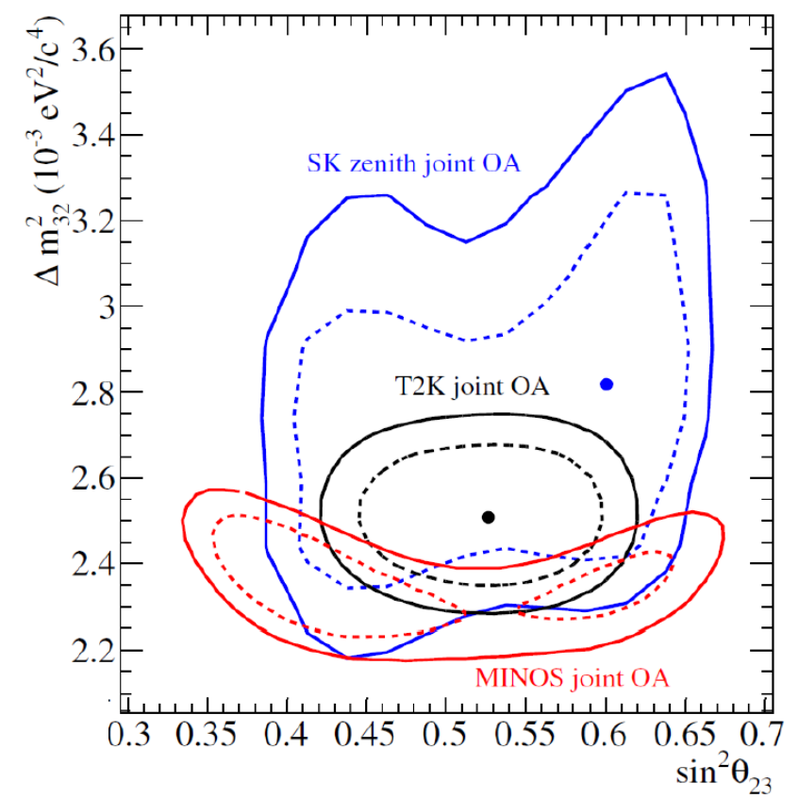
- **T2K - Kirsty Duffy**

7.00x10^{20} POT in ν-mode

Current Results







First measurement of ν_e appearance (7.3σ). Independent measurement of θ_{13} (analyses performed with and without reactor constraint on θ_{13}, $sin^2 2\overline{\theta}_{13} = 0.095 \pm 0.01$)

90% constraint on δ_{CP}

- **Preference for normal hierarchy**
- **Preference for δ_{CP} = -π/2**

World-leading measurement of θ_{23}. Significant measurement of $\Delta m^2{}_{32}$.

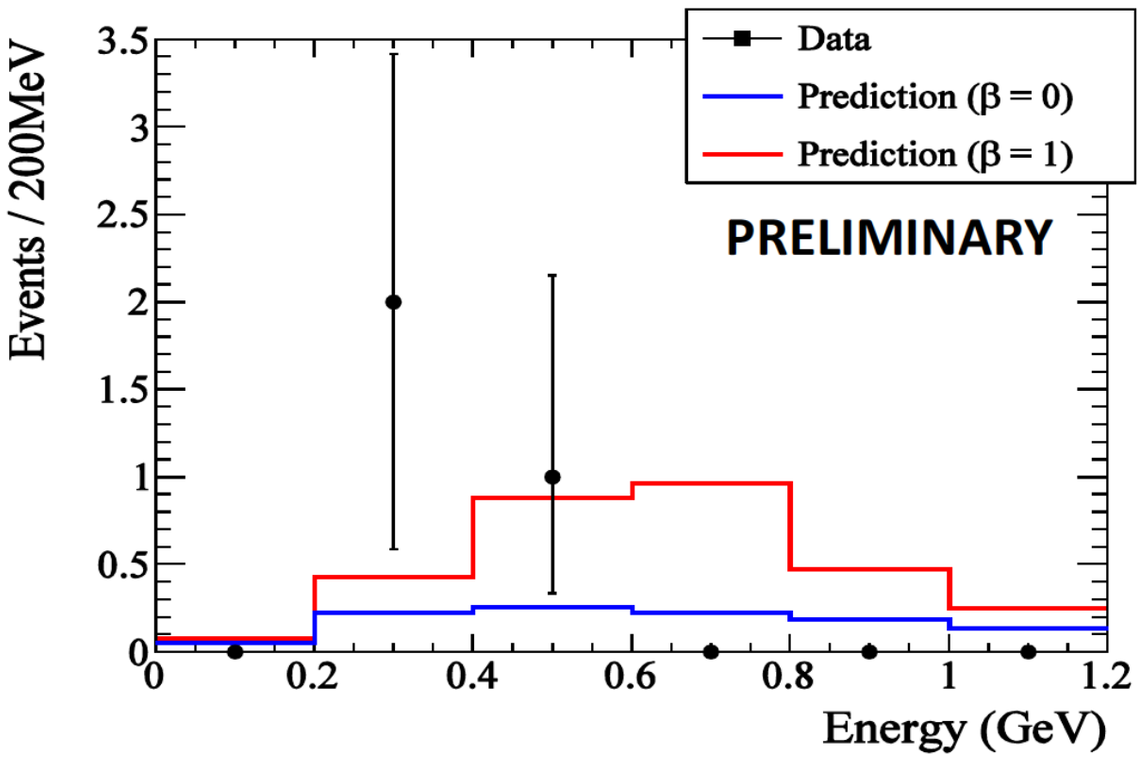
Abe, K. et al, Physical Review D 91.7 (2015): 072010

New and Current Results

- T2K - Kirsty Duffy

4.04x10^{20} POT in $\bar{\nu}$-mode

Anti-Nue Appearance

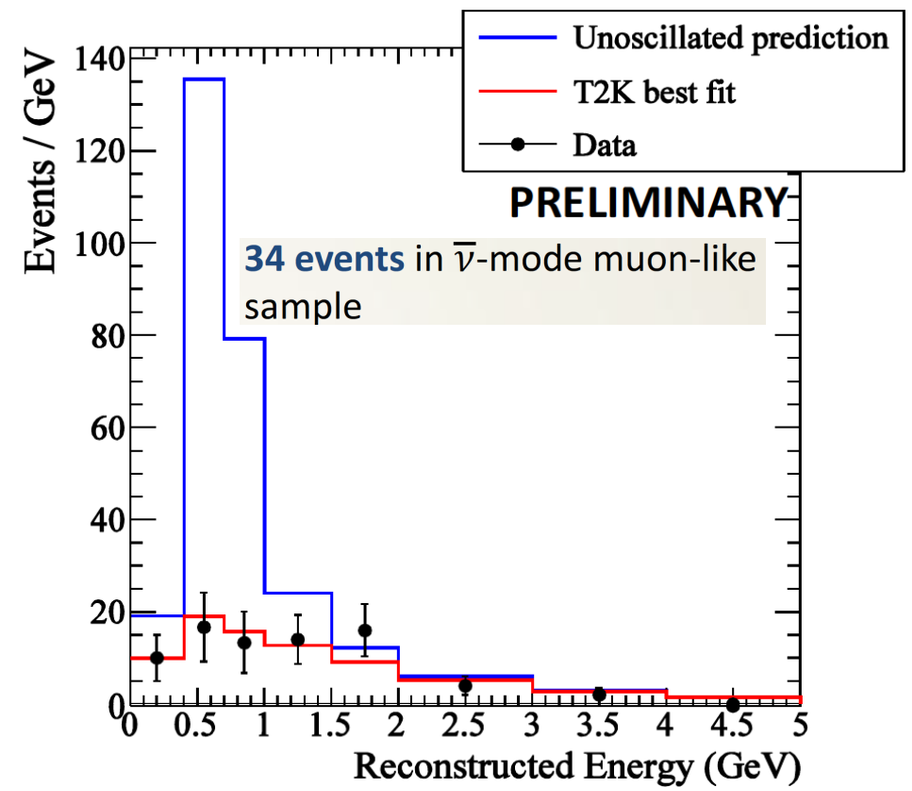


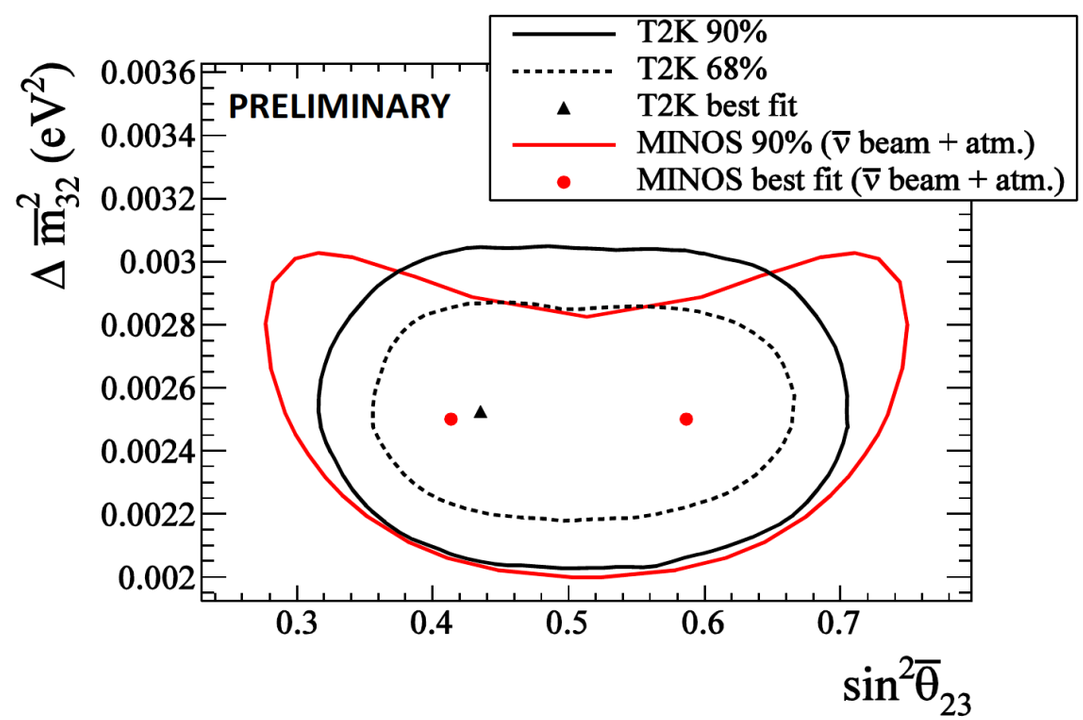
- The current data set contains 3 events
- Prediction (using T2K ν-mode oscillation parameters) is **3.7 events** under β = 1 and **1.3 events** under β = 0

$$P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) = \beta \times P_{PMNS}(\bar{\nu}_\mu \rightarrow \bar{\nu}_e)$$

- Current data set does not provide sufficient evidence to support β=1 over β-0
- Consistent with NH, δ = -π /2 (with large statistical uncertainty)

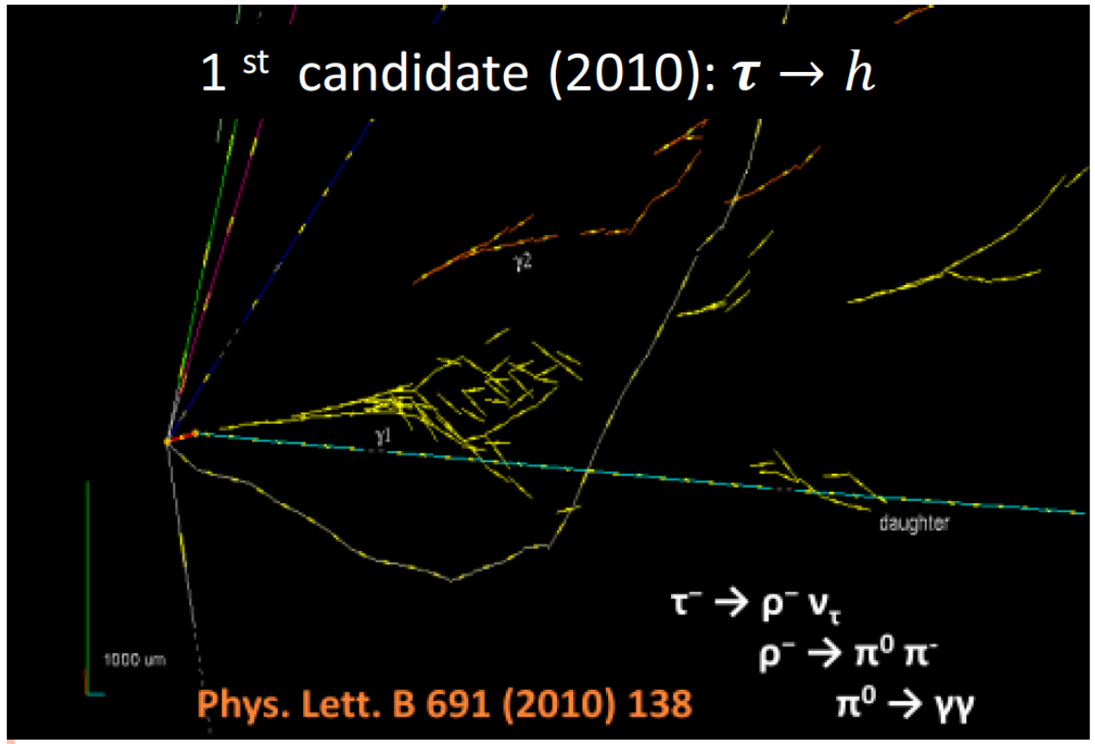
Anti-Numu Disappearance

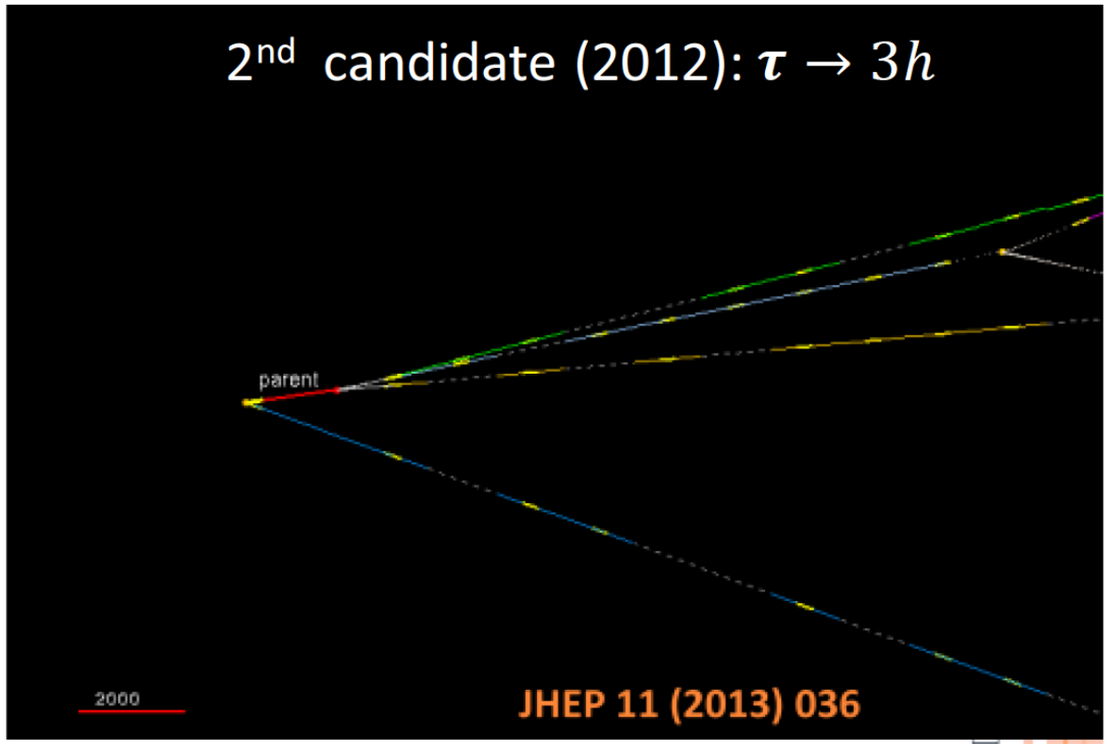


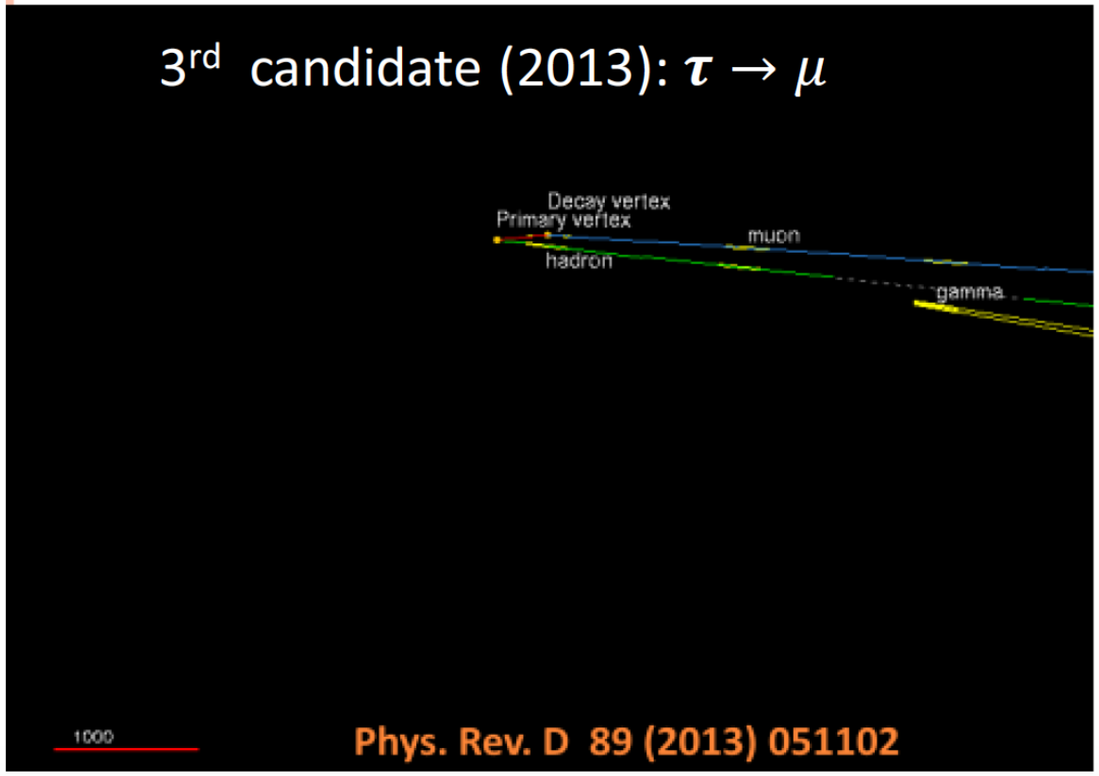


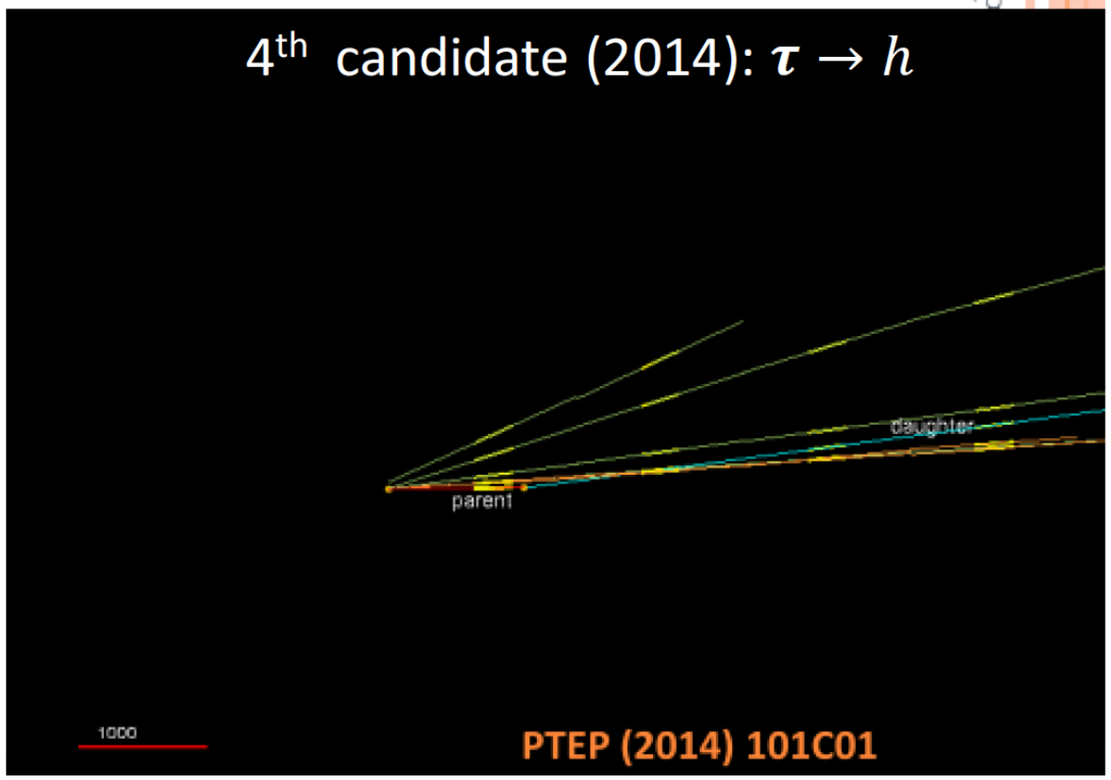
New and Current Results

- OPERA - Chiara Sirignano



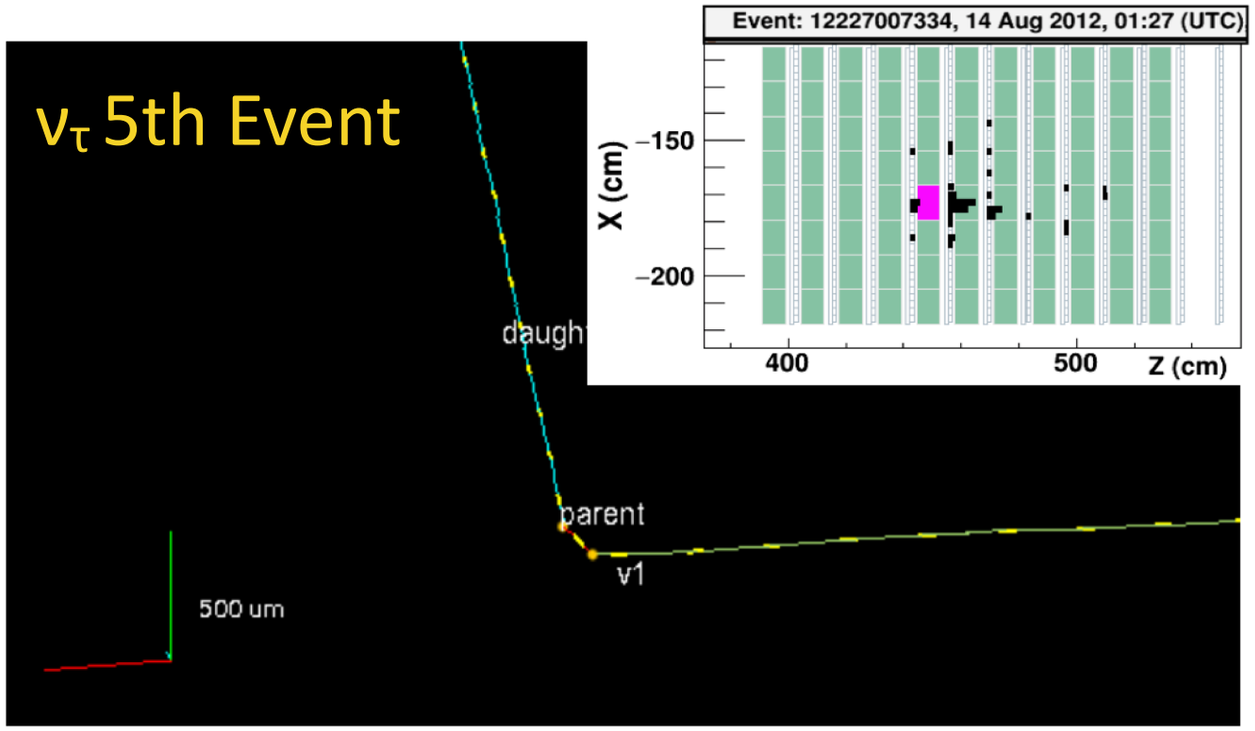






New and Current Results

- **OPERA - Chiara Sirignano**



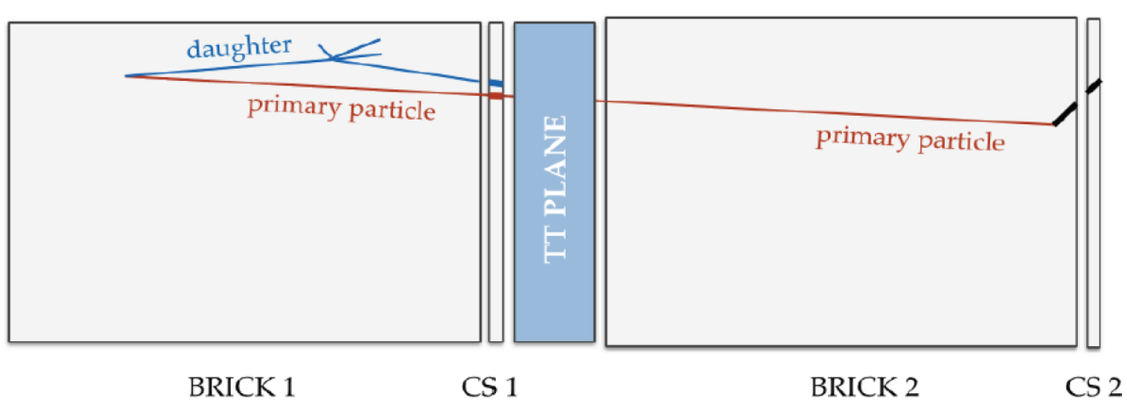
[arXiv:1507.01417] submitted to PRL

Channel	Expected background	Expected signal	Observed
$\tau \to 1h$	0.04 ± 0.01	0.52 ± 0.10	3
$\tau \to 3h$	0.17 ± 0.03	0.73 ± 0.14	1
$\tau \to \mu$	0.004 ± 0.001	0.61 ± 0.12	1
$\tau \to e$	0.03 ± 0.01	0.78 ± 0.16	0
Total	0.25 ± 0.05	2.64 ± 0.53	5

P-value $=1.1 \cdot 10^{-7}$

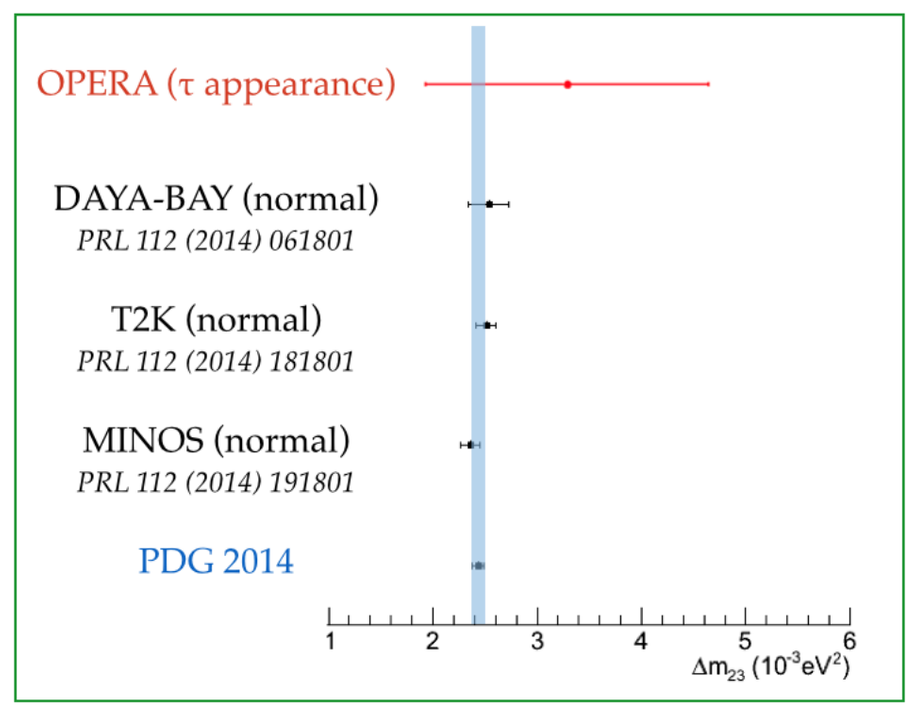
Exclusion of background-only hypothesis: 5.1 σ

→ discovery of ν_τ appearance in the CNGS beam



Primary particle
Followed in the downstream brick
Hadronic re-interaction: 1 visible particle
→ **Charm hypothesis discarded**

Daughter
Hadronic re-interaction in the first brick
→ **Hadronic decay channel**



$$\Delta m^2_{23} = [2.0 - 4.7]\ 10^{-3}\ \text{eV}^2$$

(assuming full mixing)

New and Current Results

- **MINOS/MINOS+ - João Coelho**
- MINOS+ has accumulated 6.4E20 POT NuMI beam data. Focusing on exotic searches.
- Combined MINOS/MINOS+ fit consistent with reported MINOS results

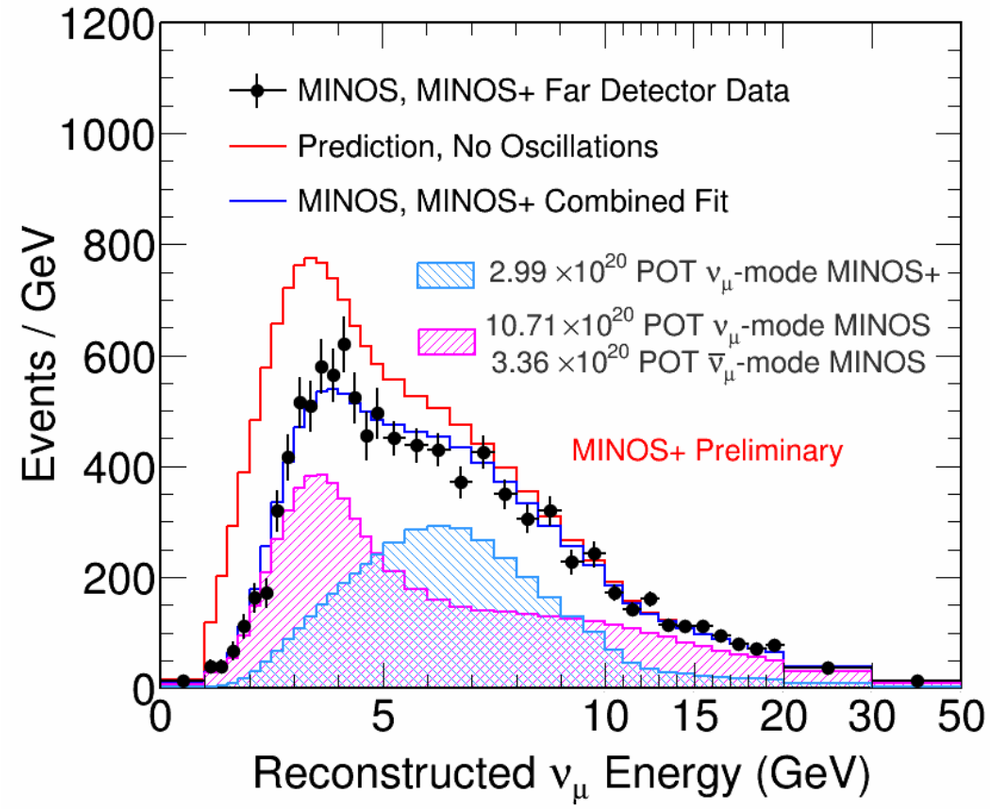
Three-Flavor Oscillations Best Fit

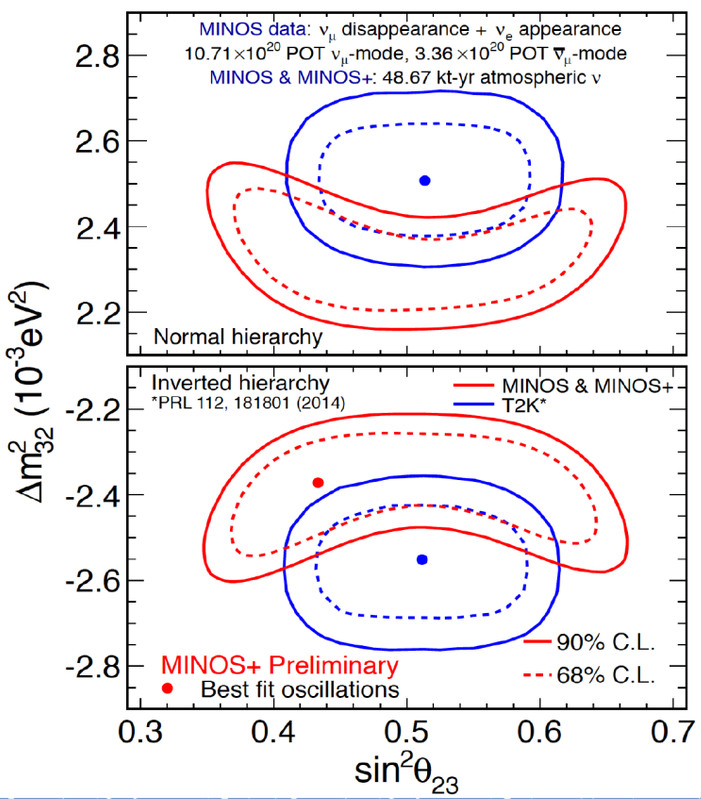
Inverted Hierarchy

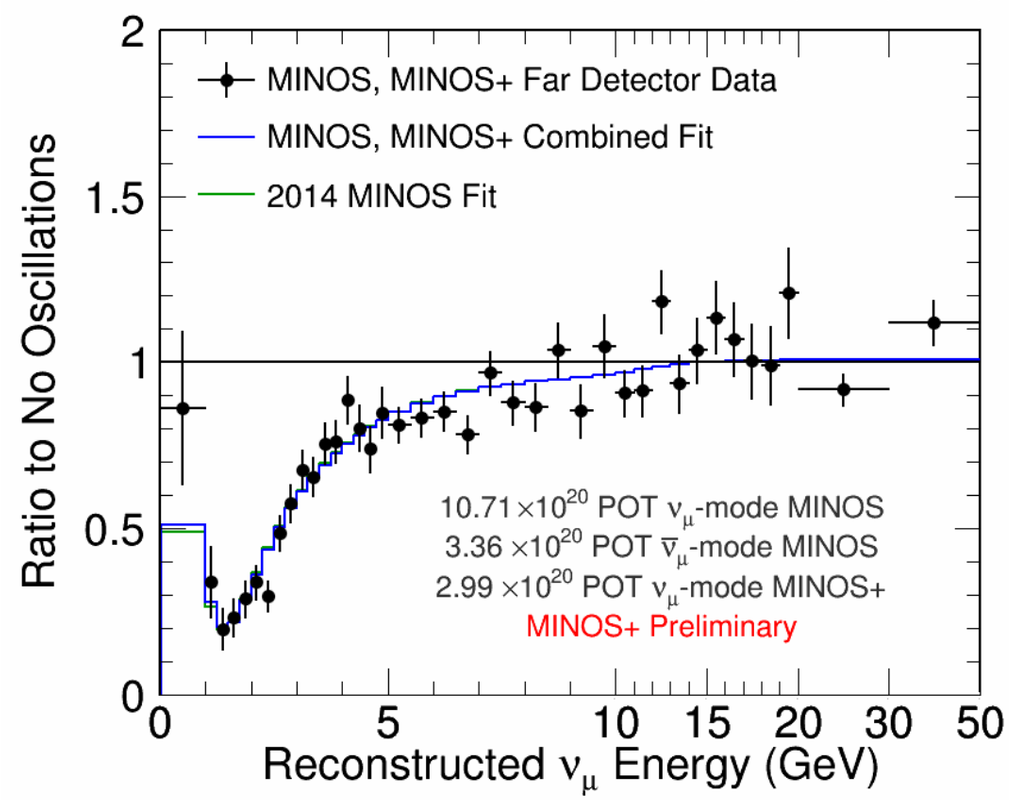
$|\Delta m^2_{32}| = 2.37^{+0.11}_{-0.07} \times 10^{-3} eV^2$

$\sin^2\theta_{23} = 0.43^{+0.19}_{-0.05}$

$0.36 < \sin^2\theta_{23} < 0.65$ (90% C.L.)

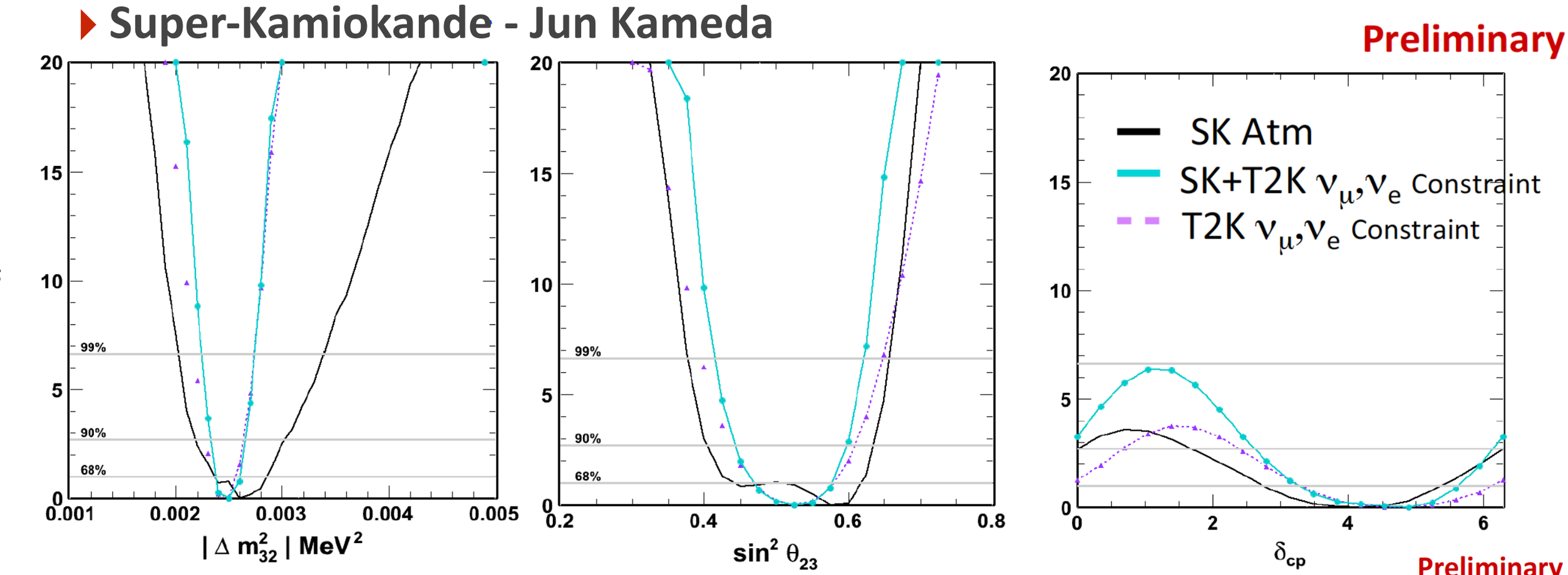






New and Current Results

- Super-Kamiokande - Jun Kameda

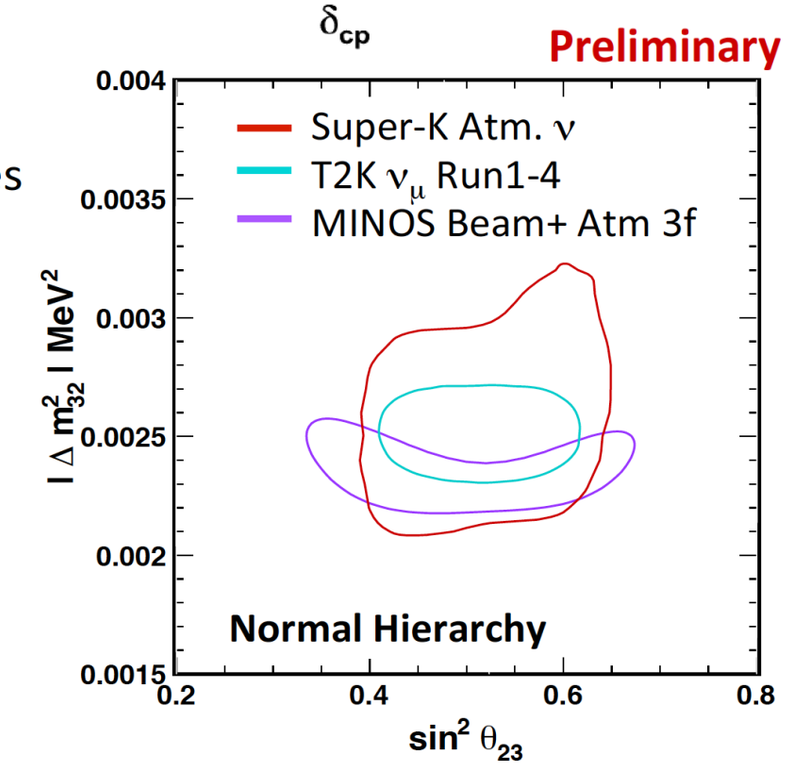


- **Normal** hierarchy favored at: $\chi^2_{NH} - \chi^2_{IH}$ = **-3.2** (-3.0 SK only)
- CP Conservation ($\sin\delta_{cp} = 0$) allowed at (at least) 90% C.L. for both hierarchies

new result with 4972 days SK data

SK-I (1996-2001) SK-II (2003-2005)

SK-III(2005-2008) SK-IV(2008-Present) → total 4972days

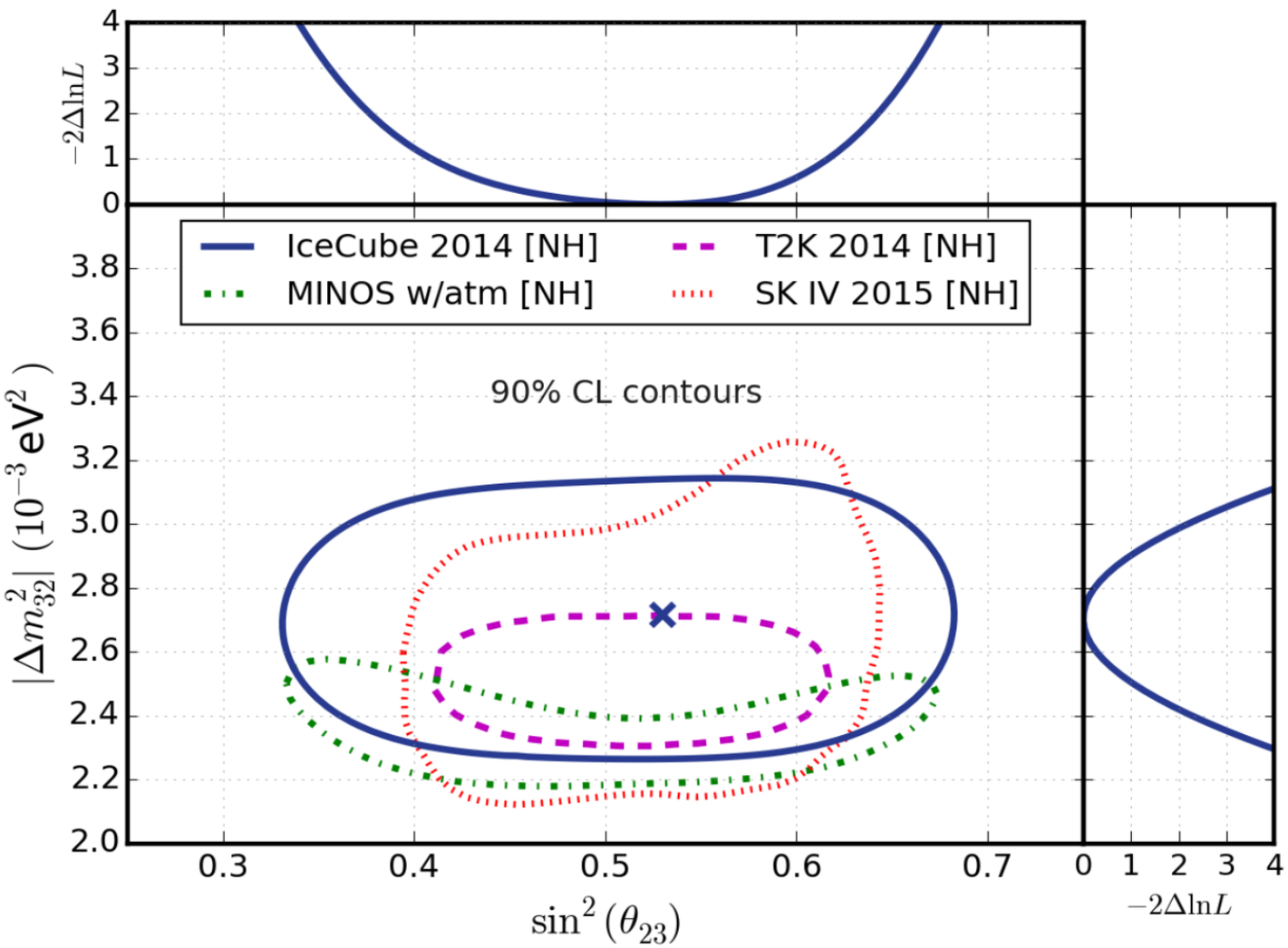


- Super-K-Gd Project approved!
  - High efficiency neutron tagging by adding 0.2% $Gd_2(SO_4)_3$
  - Allows neutrino/antineutrino discrimination

New and Current Results

- **IceCube/DeepCore - JP Athayde Marcondes de André**

PRD 91, 072004 (2015) with SK result updated



$$|\Delta m^2_{32}| = 2.72^{+0.19}_{-0.20} 10^{-3} \mathrm{eV}^2$$

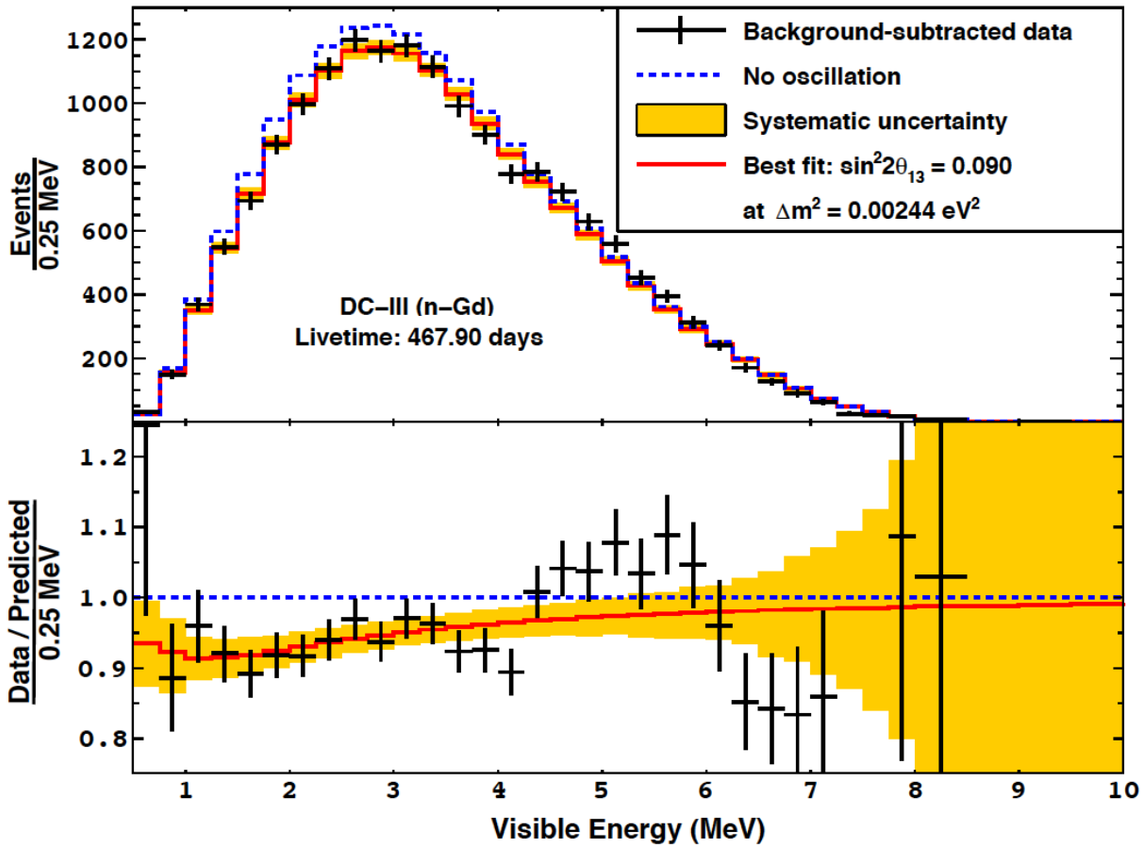
$$\sin^2(\theta_{23}) = 0.53^{+0.09}_{-0.12}$$

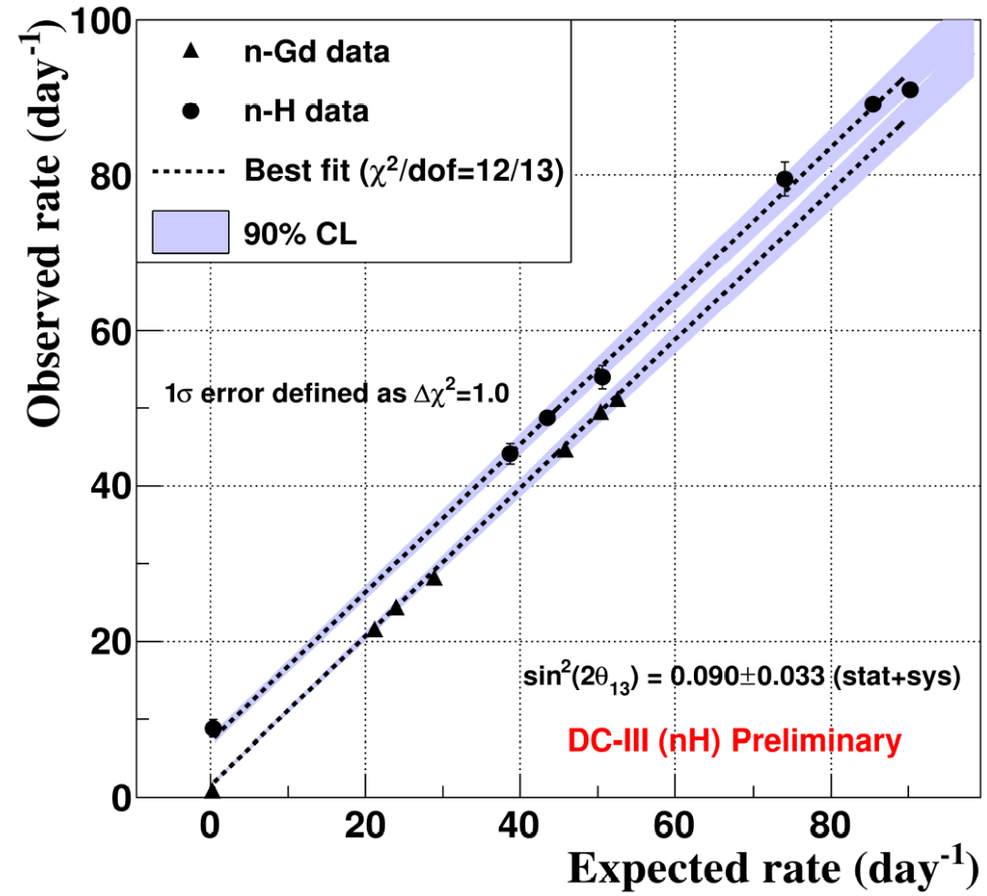
This measurement is still statistics limited!

- Still working on strategy ❷: relax "golden event" requirements $\Rightarrow$ expected increase by an order of magnitude of number ν in sample

New and Current Results

- Double Chooz - Guillaume Pronost



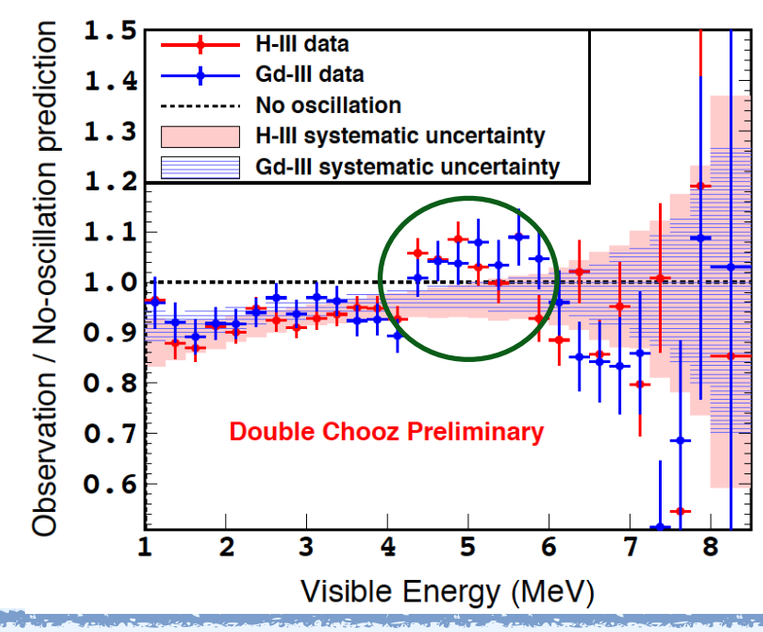


- New improved H-n analysis combined with 2014 Gd-n analysis improves statistical significance

$$\sin^2 2\theta_{13} = 0.090 \pm 0.033$$

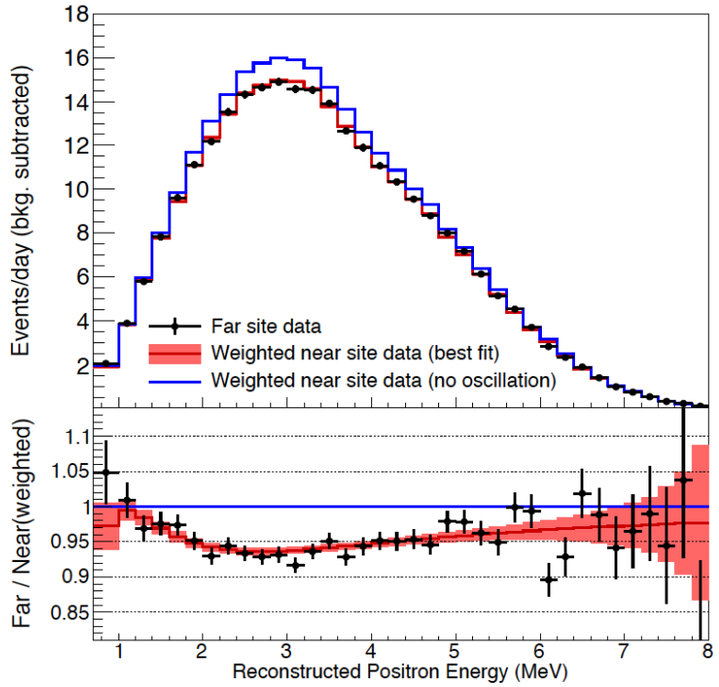
H only: $\sin^2 2\theta_{13} = 0.098^{+0.038}_{-0.039}$, Gd only: $\sin^2 2\theta_{13} = 0.090^{+0.034}_{-0.035}$

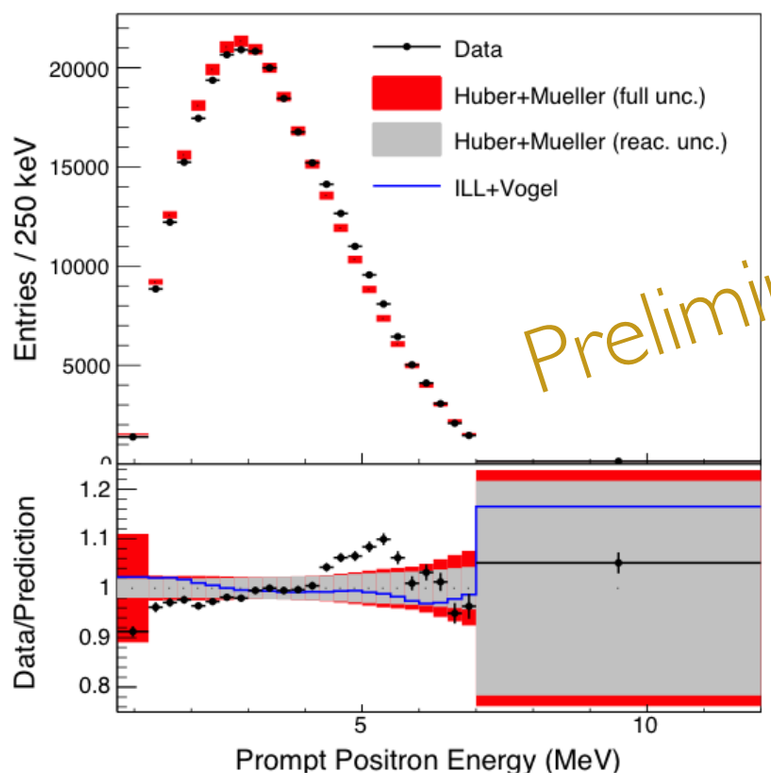
- Working on understanding 5 MeV bump
- 6 months data taking with ND, Two-detector analysis in progress

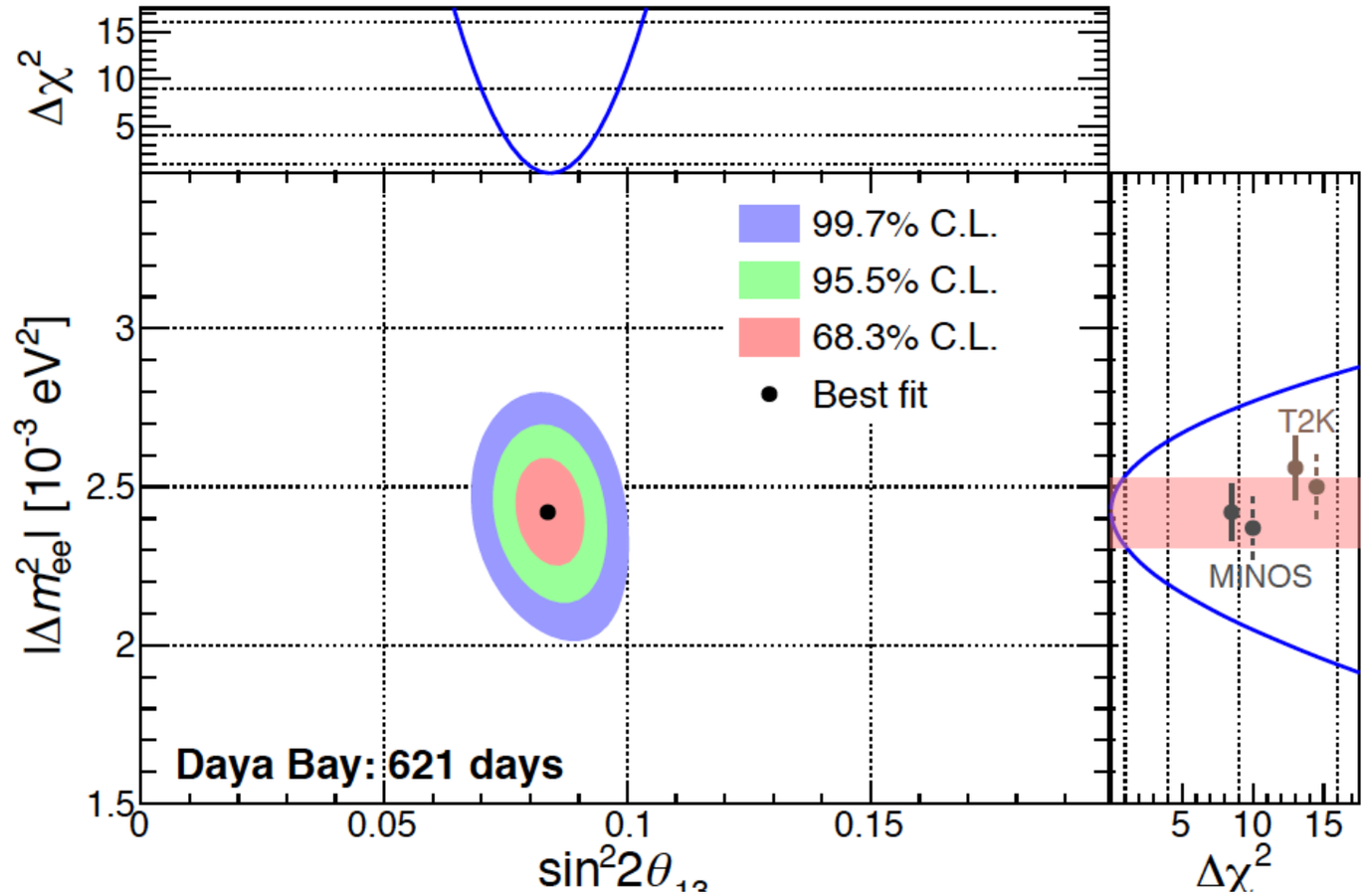


New and Current Results

- Daya Bay - Wei Wang







$$\begin{cases} \sin^2 2\theta_{13} = 0.084 \pm 0.005 \\ |\Delta m^2_{ee}| = (2.42 \pm 0.11) \times 10^{-3} eV^2 \end{cases}$$

to appear on ***Phys. Rev. Lett., arXiv:1505.03456***

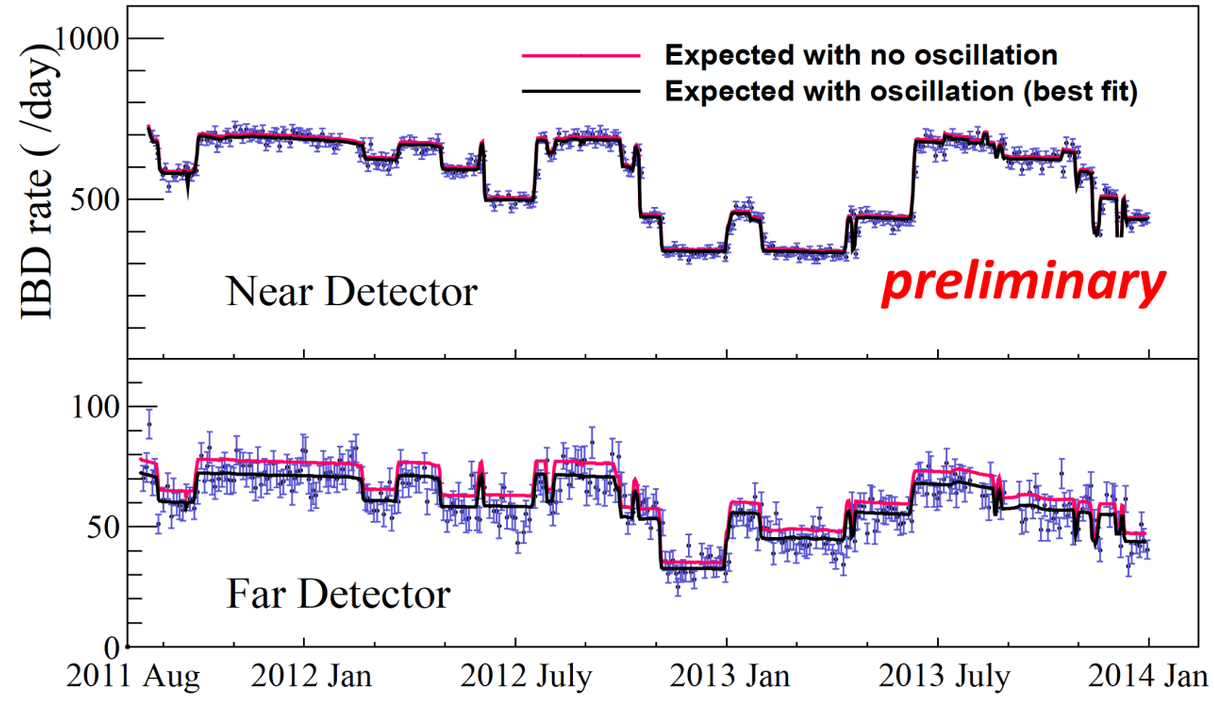
- Most precise measurement of θ_{13} and Δm^2_{ee}
- 5 MeV bump also seen by Daya Bay

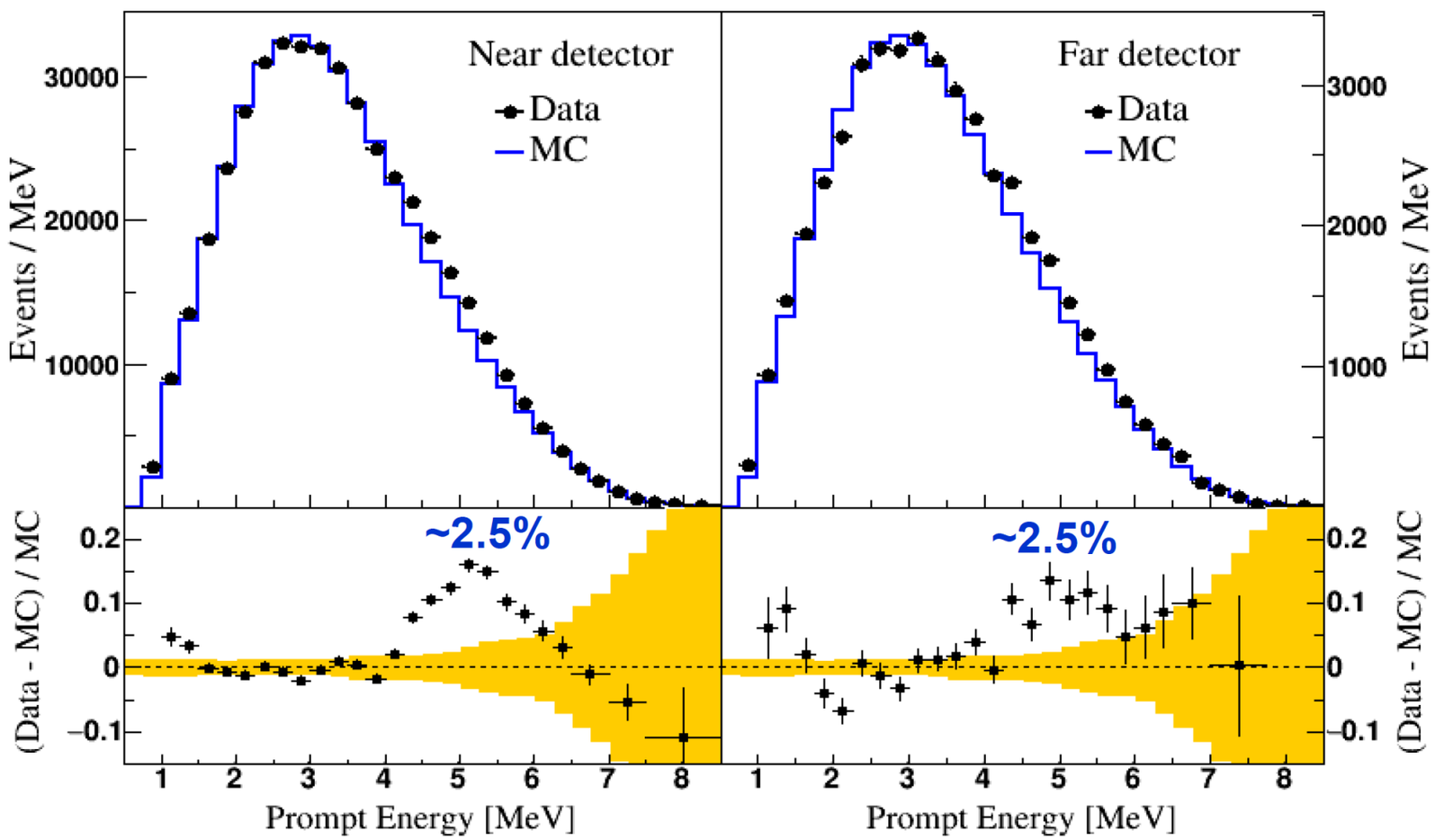
New and Current Results

- **RENO - Kyungkwang Joo**
- Analyzed 800 days of data
- New rate-only measurement of θ_{13}

$$\sin^2 2\theta_{13} = 0.087 \pm 0.008(\text{stat}) \pm 0.008(\text{syst})$$

- Shape analysis coming soon!



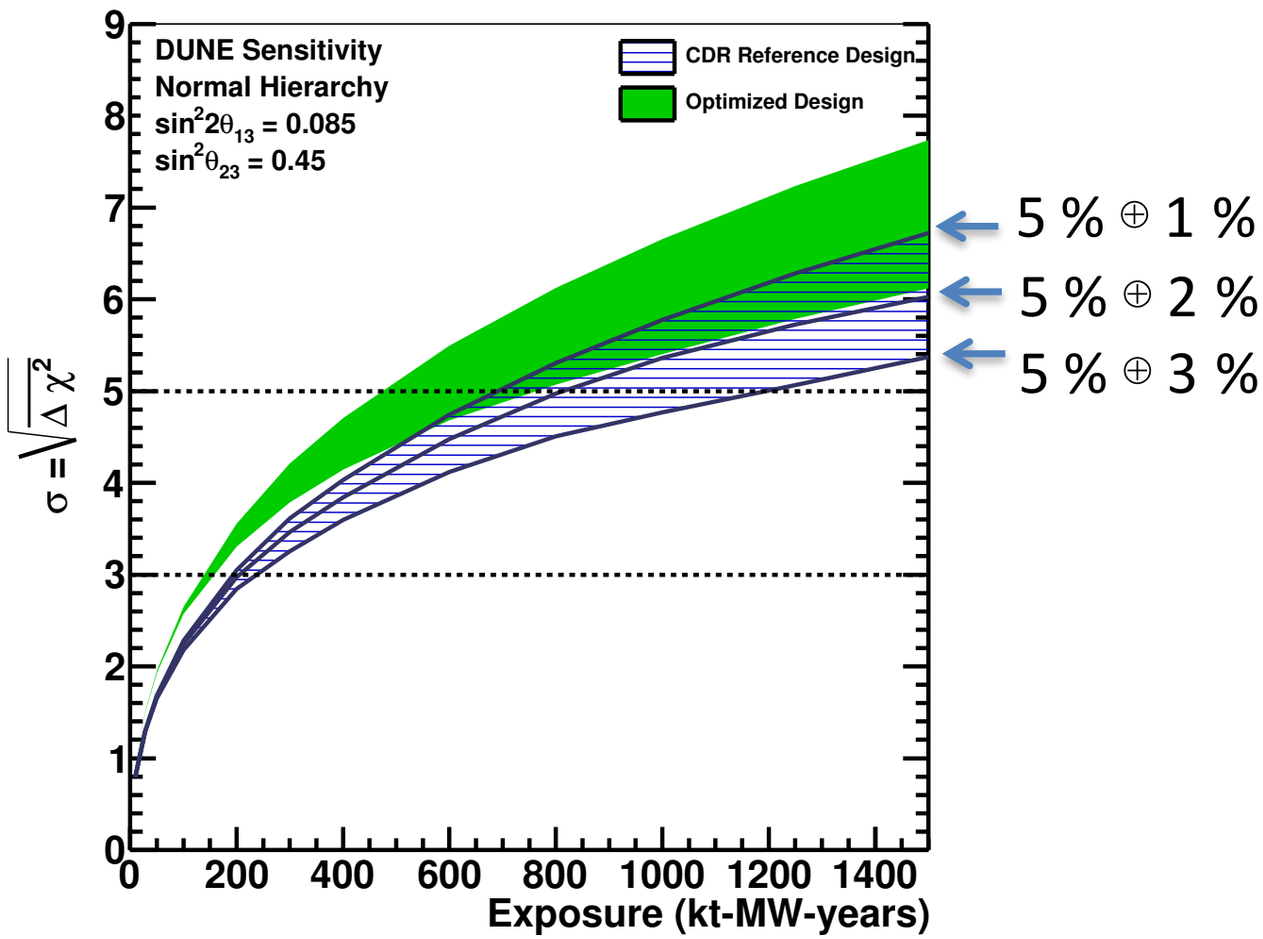


- Clear excess at E=5 MeV
- Recent ab initio calculation *[D. Dwyer and T.J. Langford, PRL 114, 012502 (2015)]* :
- Excess may be explained by addition of eight isotopes, such as ^{96}Y and ^{92}Rb

Future Prospects

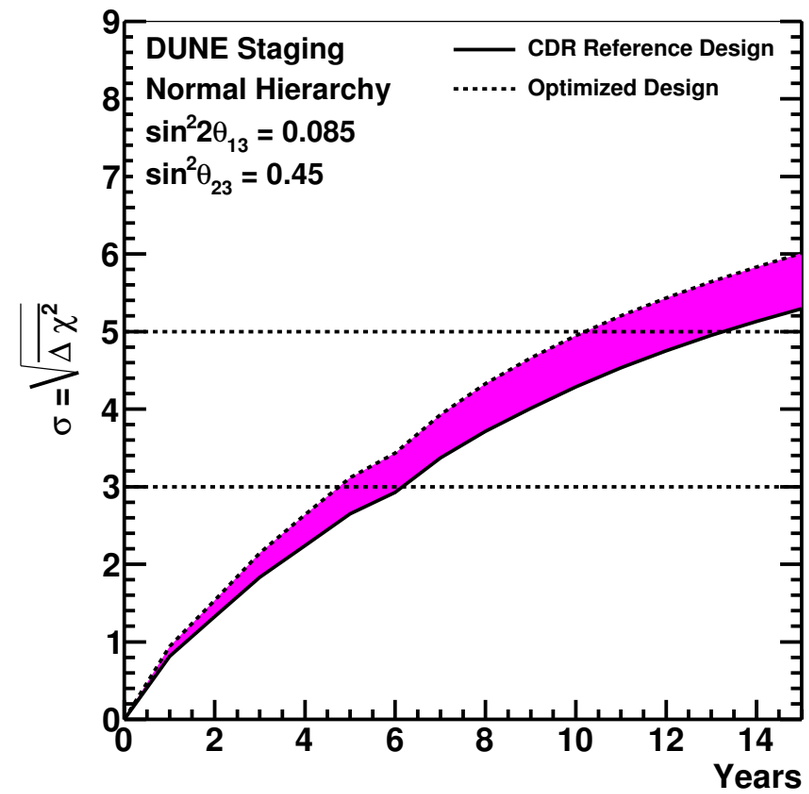
- **DUNE - Jim Strait**

50 % CP Violation Sensitivity

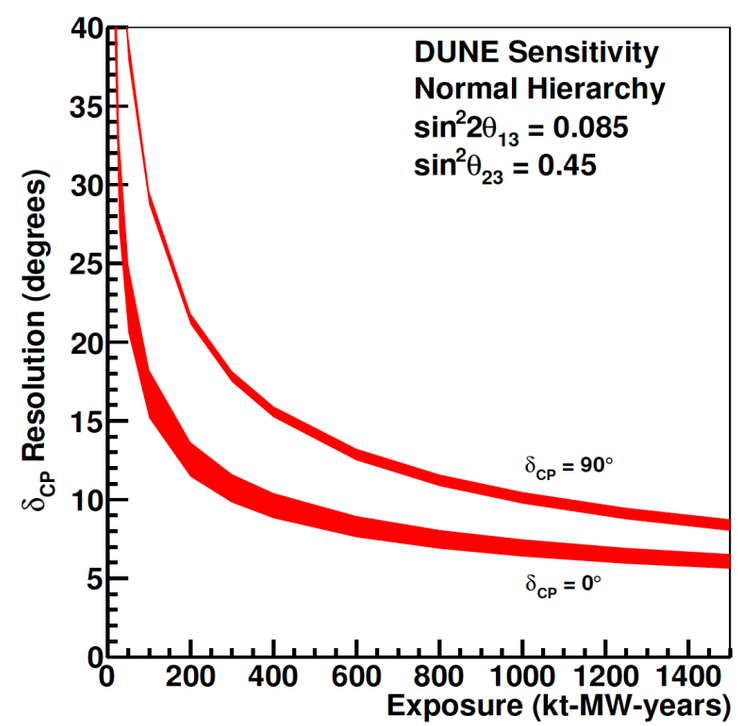


Significance	CDR Reference Design	Optimized Design
3σ for 75% of δ_{CP} values	1320 kt · MW · year	850 kt · MW · year
5σ for 50% of δ_{CP} values	810 kt · MW · year	550 kt · MW · year

50% CP Violation Sensitivity



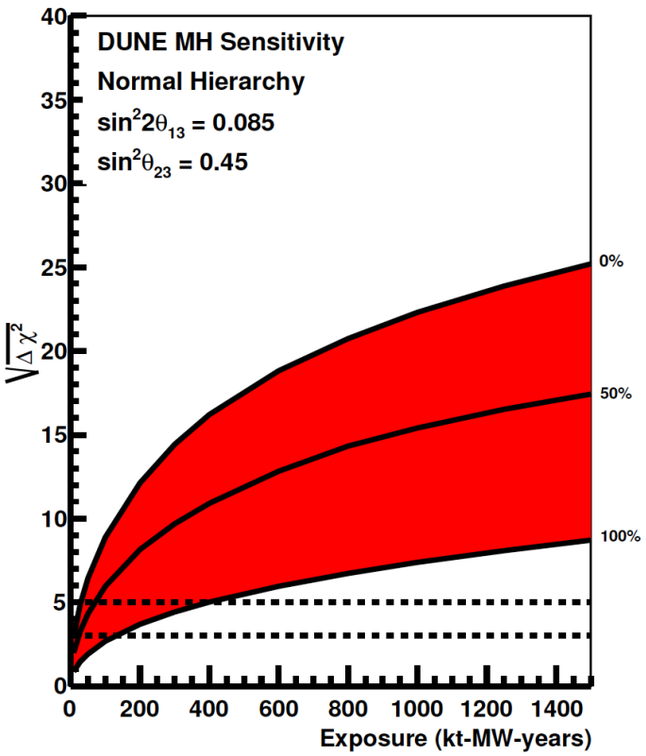
δ_{CP} Resolution

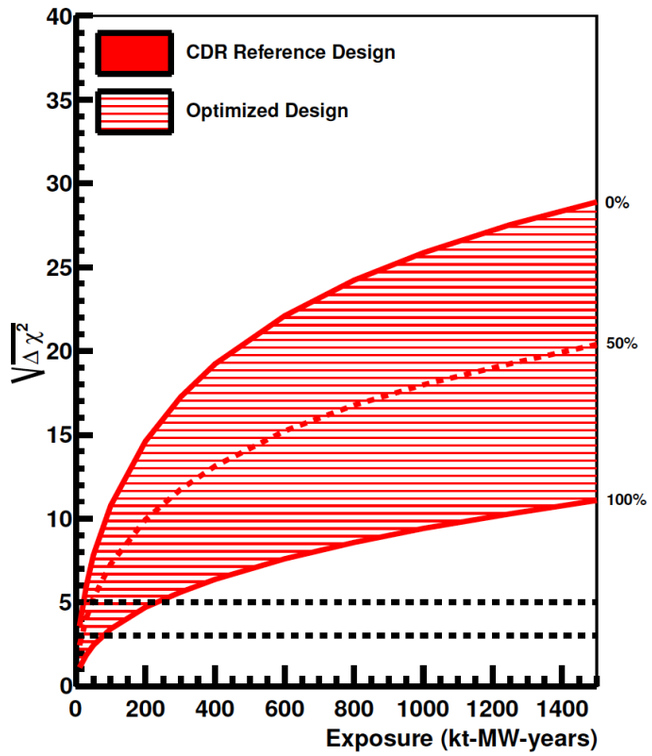


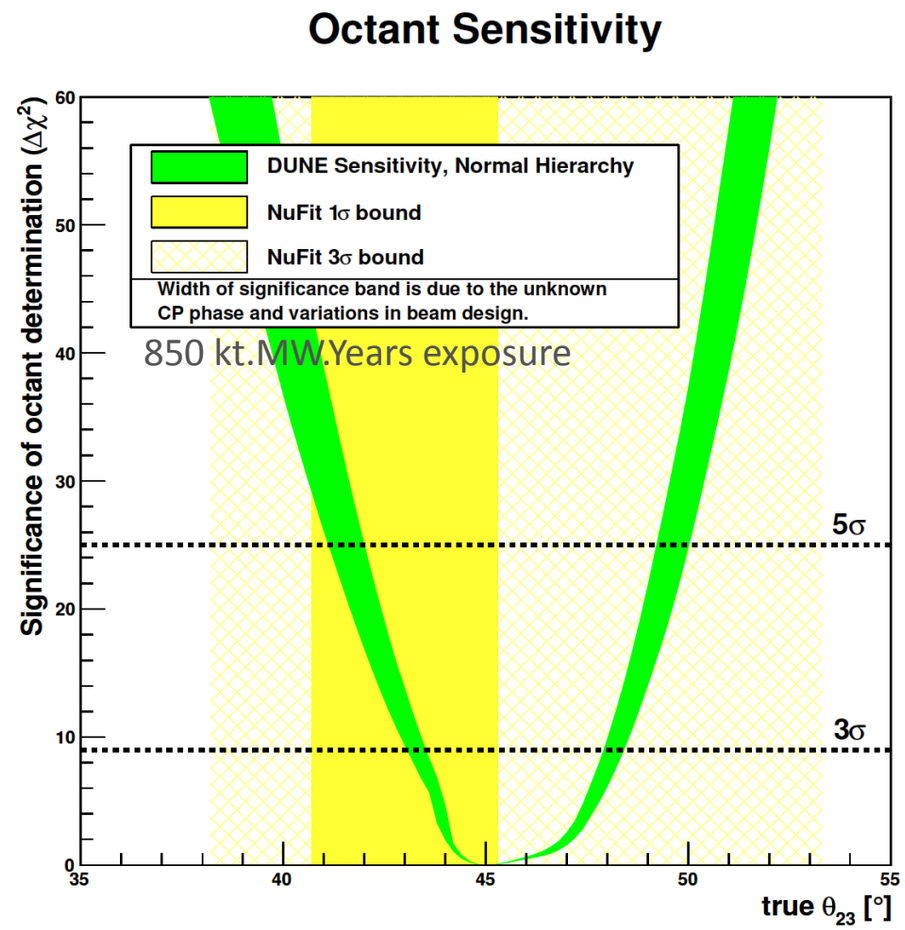
- Sensitivity to CP violation
  - With present staging plan and optimized design, can reach 5σ for 50% CP space in ~10 years
  - Δδ~10° (15°) for δ=0° (90°) after 10 years

Future Prospects

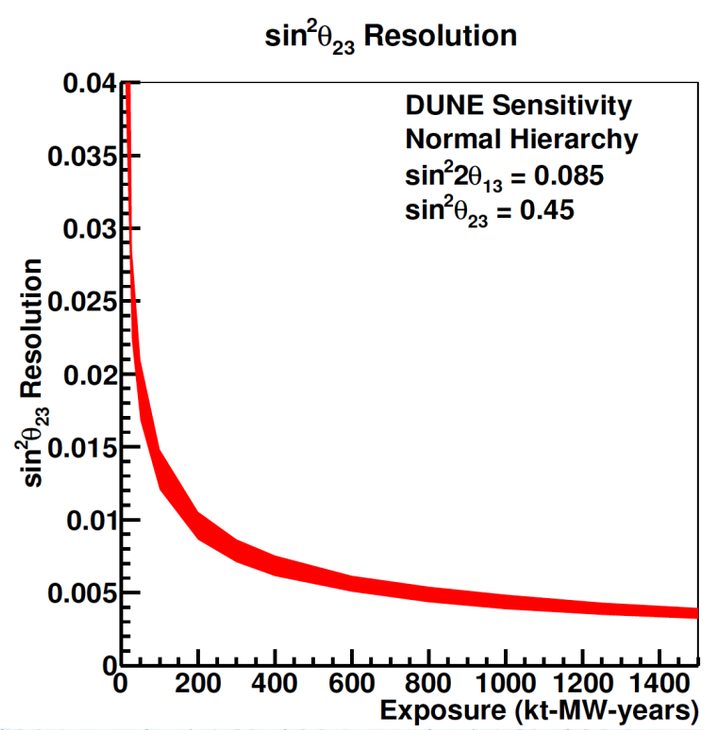
- DUNE - Jim Strait

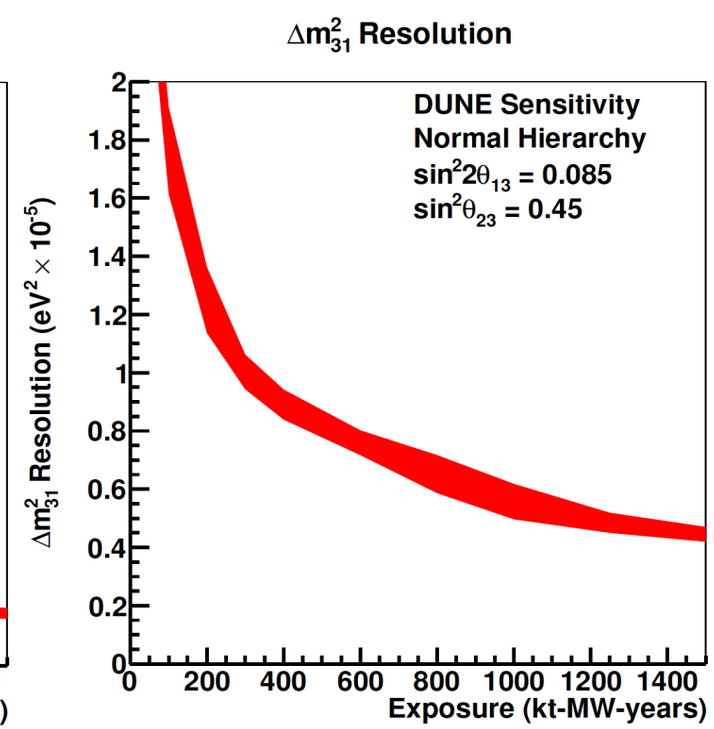






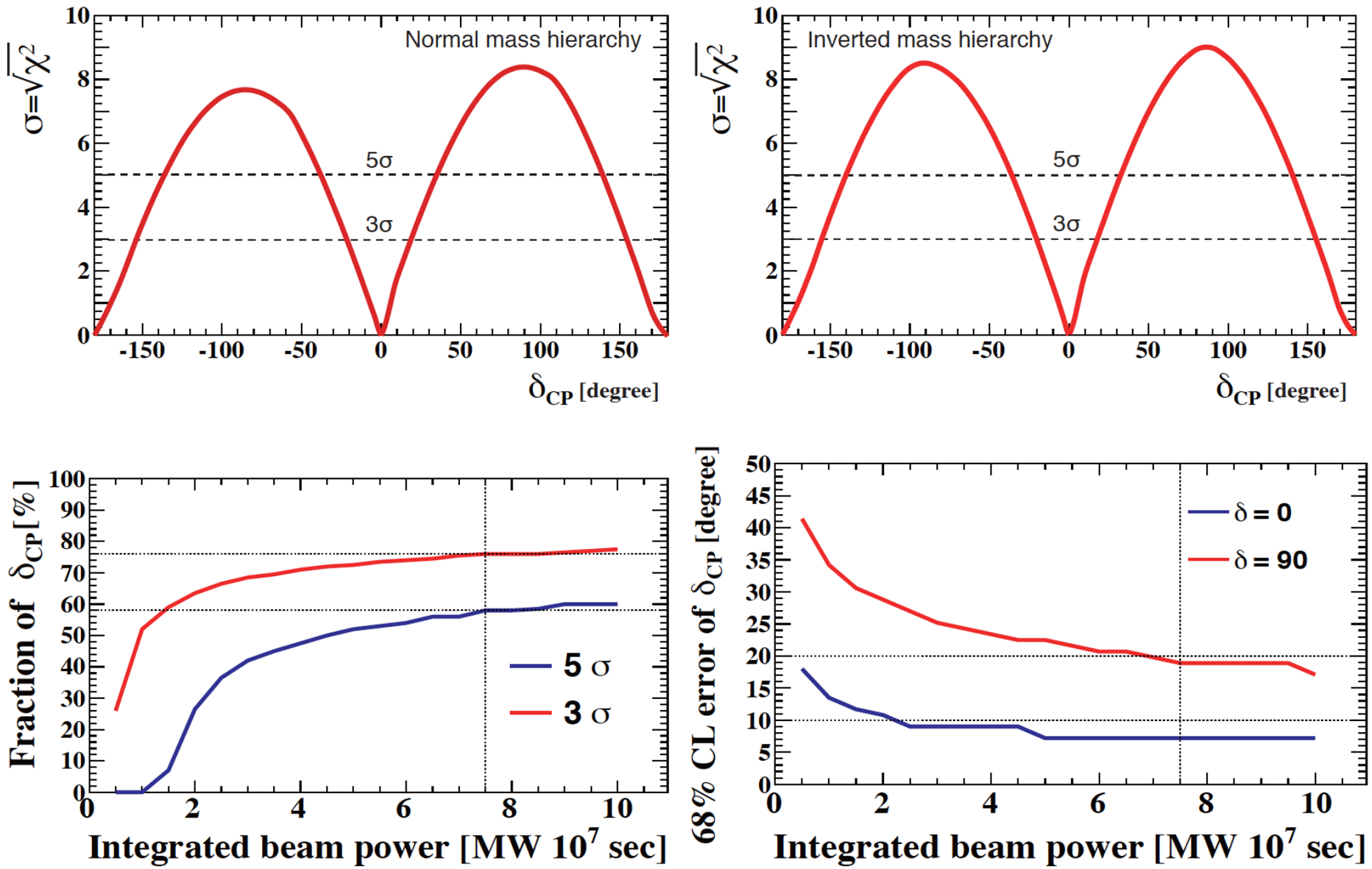
- Sensitivity to mass hierarchy and octant of θ_{23}
- < 1% precision on atmospheric oscillation parameters





Future Prospects

- **HyperK - Tom Feusels**

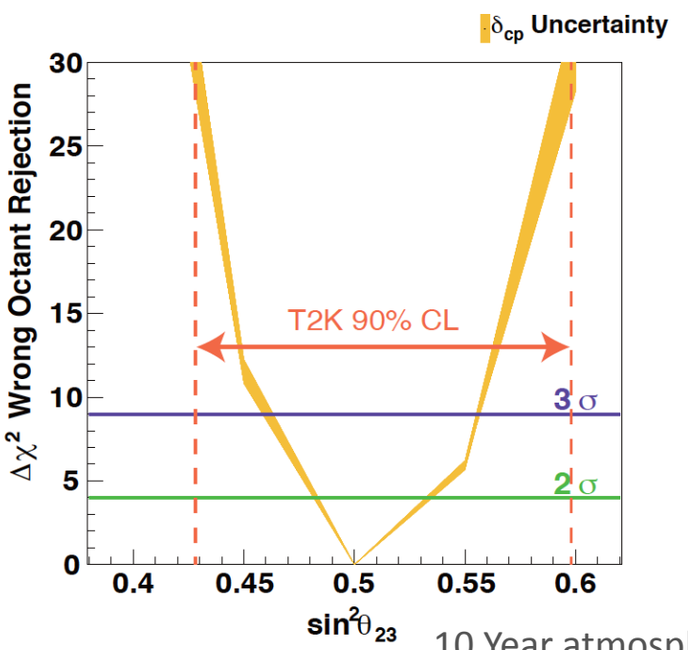


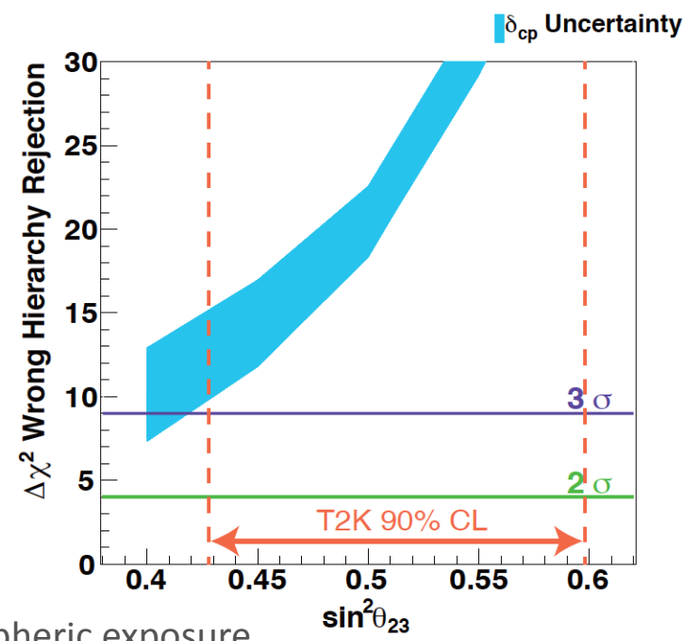
If Mass Hierarchy known:

- Fraction for which $\sin\delta_{CP}=0$ can be excluded with more than $3(5)\sigma$ is 76%(58%).
- δ_{CP} precision is better than 19° for $7.5\text{MW}\times10^7$s.

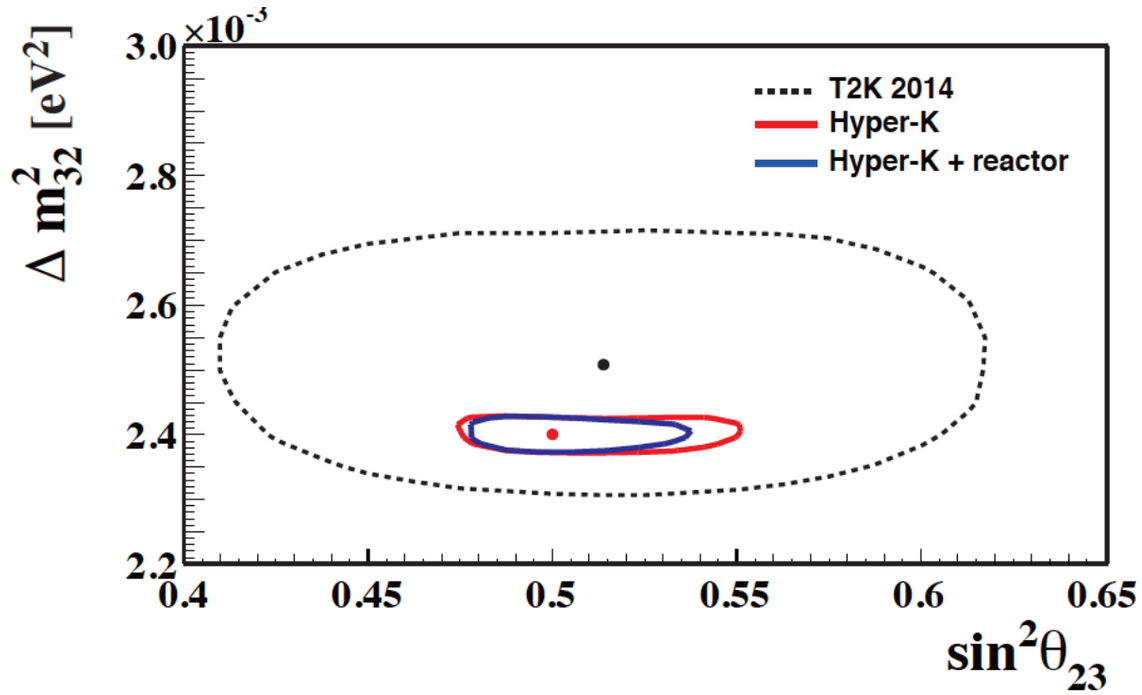
Future Prospects

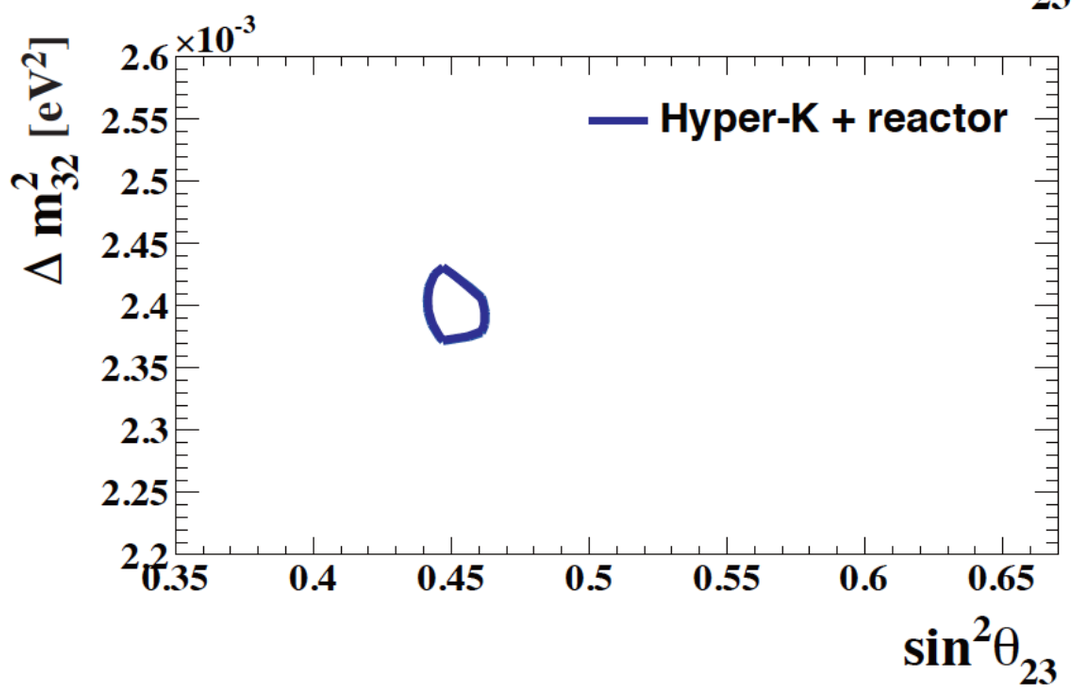
- HyperK - Tom Feusels





10 Year atmospheric exposure



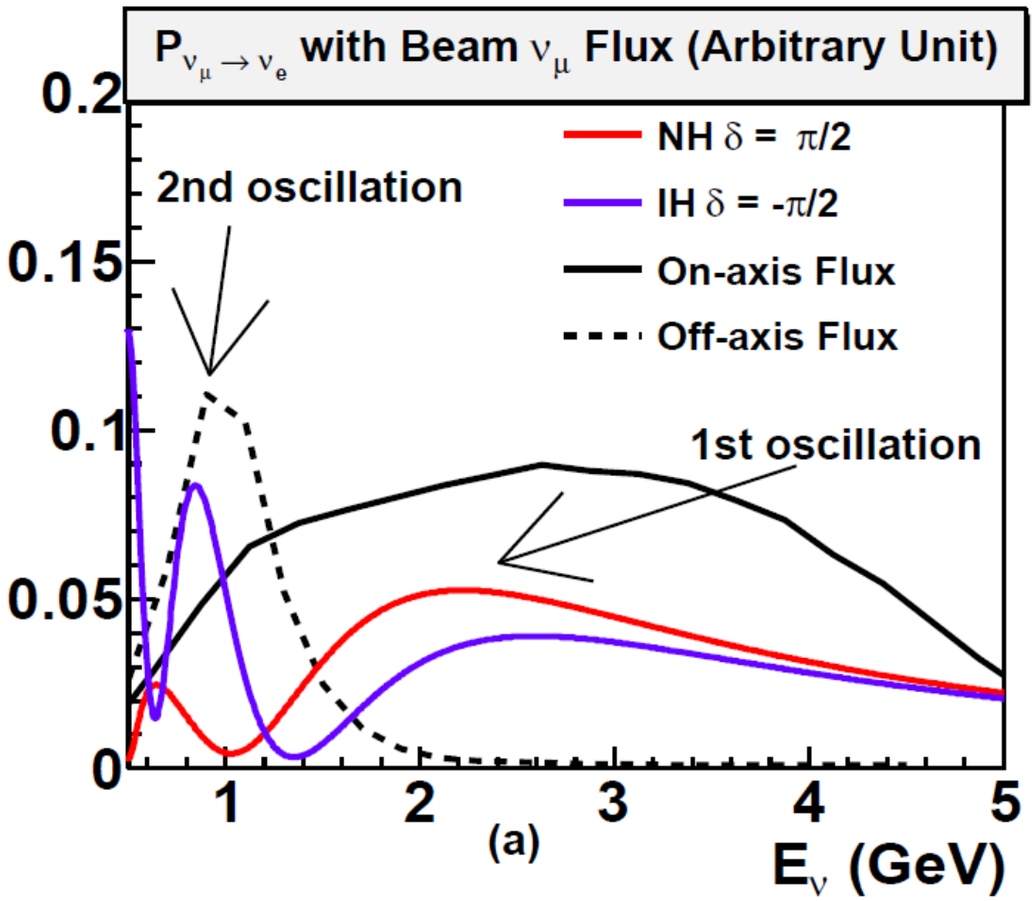


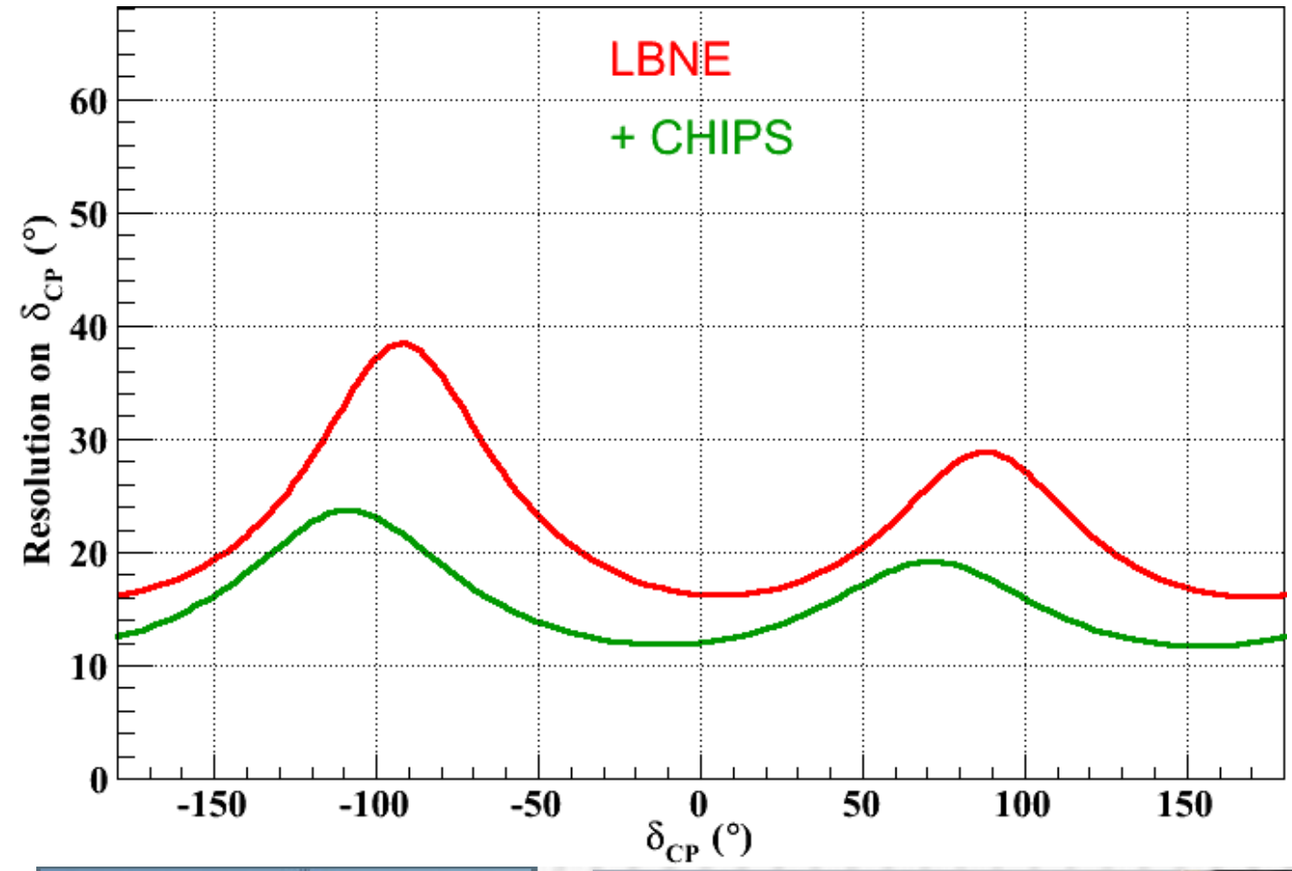
- Can determine octant of θ_{23} with constraint from reactor
- Also sensitivity to octant of θ_{23} and mass hierarchy (atmospheric sample)
- < 1% precision on atmospheric oscillation parameters

True $\sin^2\theta_{23}$	$\sin^2\theta_{23}$	Δm^2_{32} (10^{-5}eV^2)
0.45	0.006	1.4
0.50	0.015	1.4
0.55	0.009	1.5

Future Prospects

- CHIPS - João Coelho



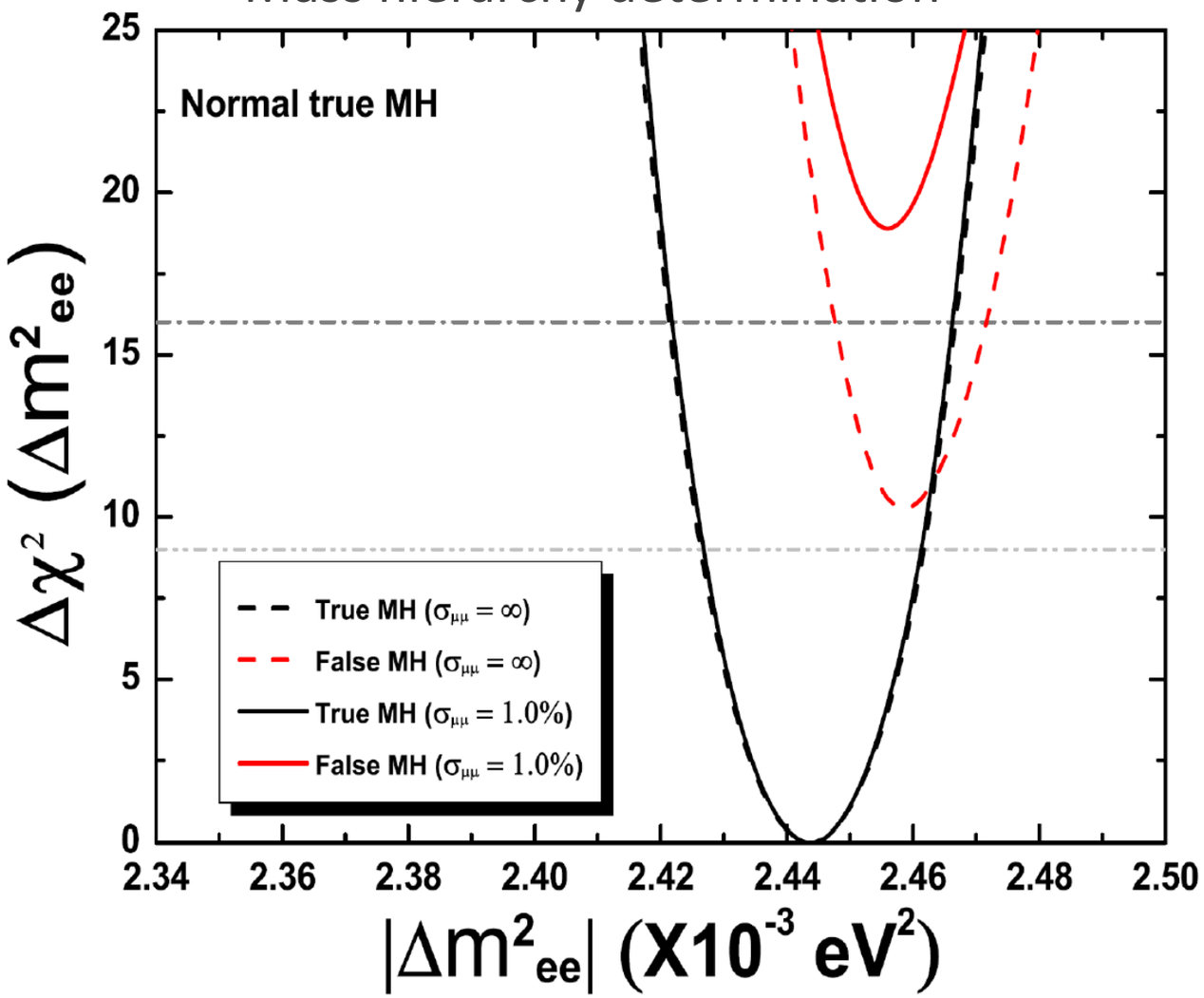


- Placing a WC detector in a lake 20 mrad off LBNF beam axis provides sensitivity to second osc. maximum and would improve DUNE CPV sensitivity.
- Can also be placed at mine pit 7 mrad off the NuMI beam axis
- Ongoing R&D with 30 ton prototype

Future Prospects

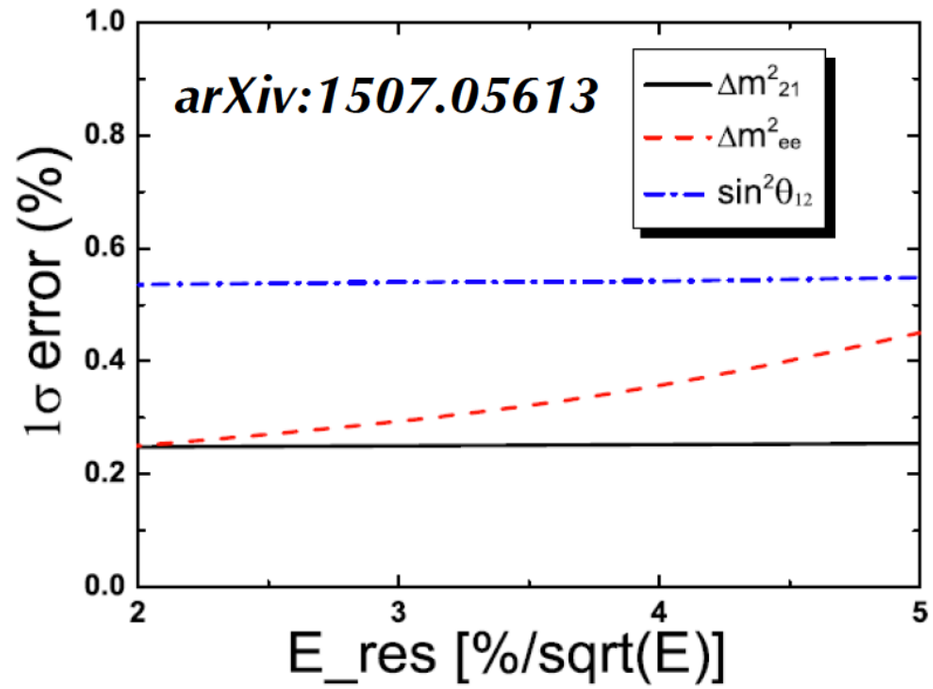
- **JUNO - Wei Wang**

Mass hierarchy determination



- ~3-sigma if only a relative spectral measurement without external atmospheric mass-squared splitting
- ~4-sigma with an external Δm^2 measured to ~1% level in ν_μ beam oscillation experiments

- <1% measurements of θ_{12}, Δm^2_{12} and Δm^2_{ee}



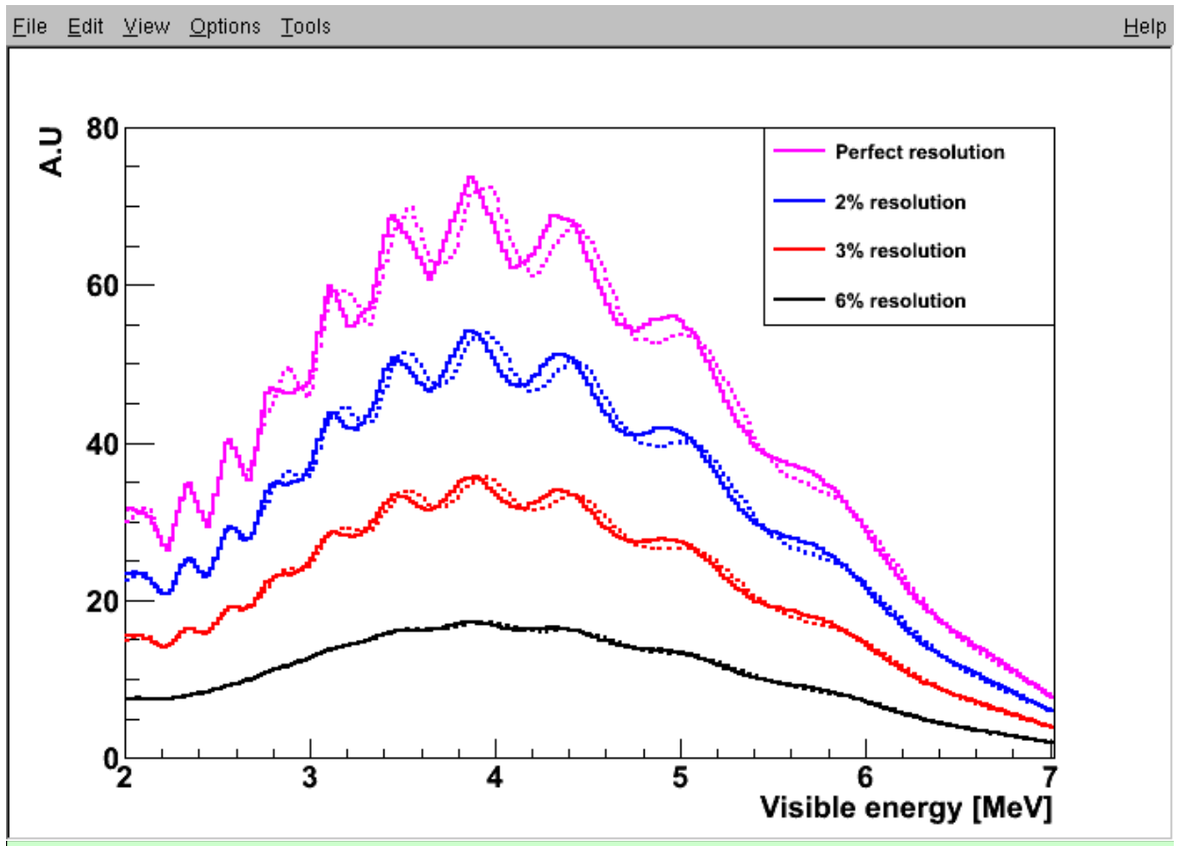
JUNO: 100k evts
arXiv:1507.05613

	Nominal	+ B2B (1%)	+ BG	+ EL (1%)	+ NL (1%)
$\sin^2\theta_{12}$	0.54%	0.60%	0.62%	0.64%	0.67%
Δm^2_{21}	0.24%	0.27%	0.29%	0.44%	0.59%
$\lvert\Delta m^2_{ee}\rvert$	0.27%	0.31%	0.31%	0.35%	0.44%

- Construction underway!

Future Prospects

- **RENO-50 - Kyungkwang Joo**



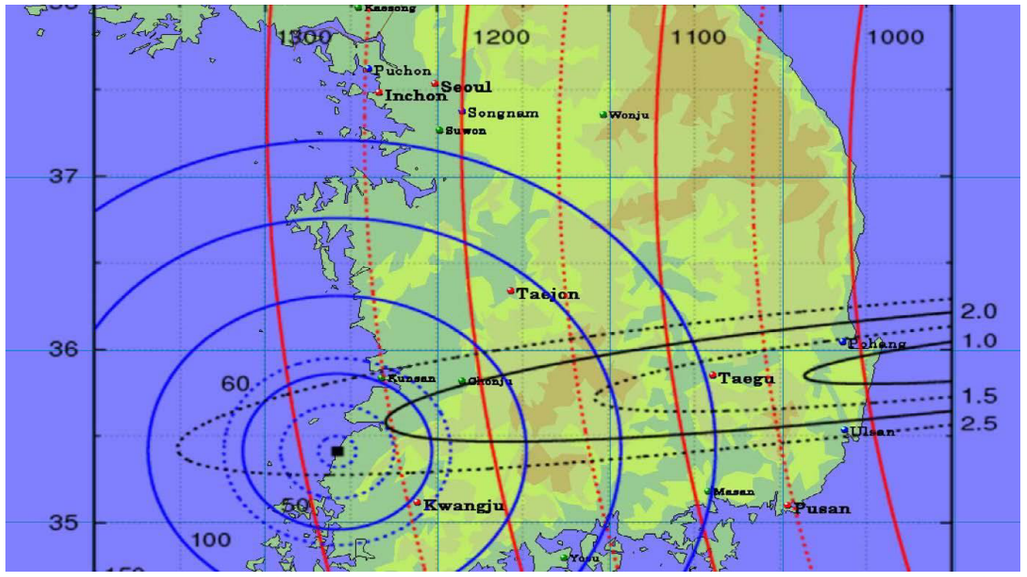
3% energy resolution essential for distinguishing the oscillation effects between normal and inverted mass hierarchies

- Proposal submitted for full funding

- Precise measurement of θ_{12}, Δm^2_{21} and Δm^2_{32}

$$\frac{\delta \sin^2\theta_{12}}{\sin^2\theta_{12}} < 1.0\%(1\sigma) \quad (\leftarrow 5.4\%) \qquad \frac{\delta \Delta m^2_{21}}{\Delta m^2_{21}} < 1.0\%(1\sigma) \quad (\leftarrow 2.7\%) \qquad \frac{\delta \Delta m^2_{32}}{\Delta m^2_{32}} < 1.0\%(1\sigma) \quad (\leftarrow 5.2\%)$$

- Neutrino burst from a Supernova in our Galaxy
  - ~5,600 events (@8 kpc)
  - A long-term neutrino telescope
- Geo-neutrinos : ~ 1,000 geo-neutrinos for 5 years
  - Study the heat generation mechanism inside the Earth
- Solar neutrinos : with ultra low radioacitivity
  - MSW effect on neutrino oscillation
  - Probe the center of the Sun and test the solar models
- Neutrinoless double beta decay search : possible modification like KamLAND-Zen
- Detection of J-PARC beam : ~200 events/year

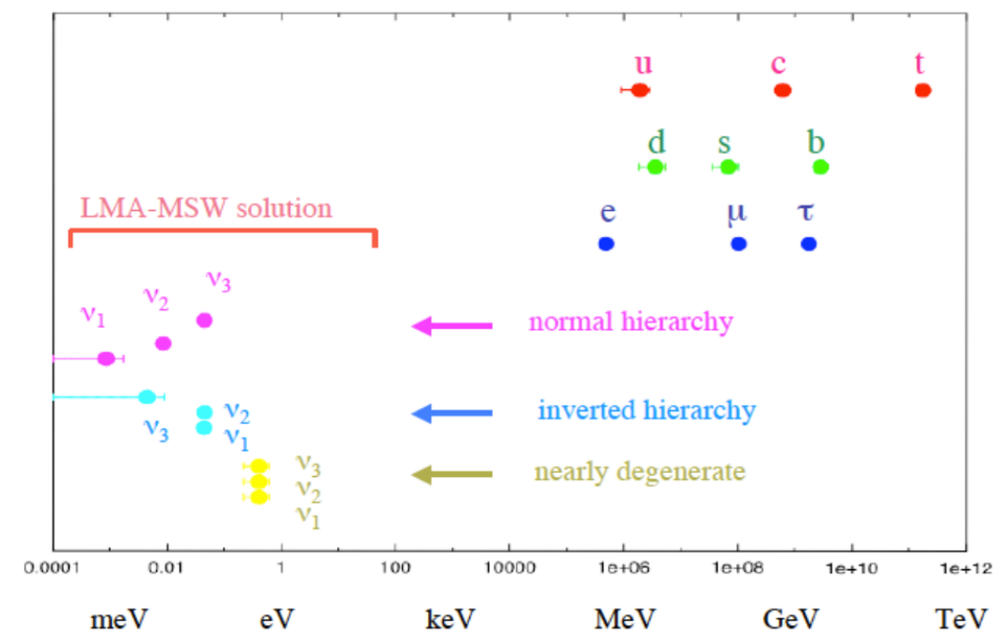


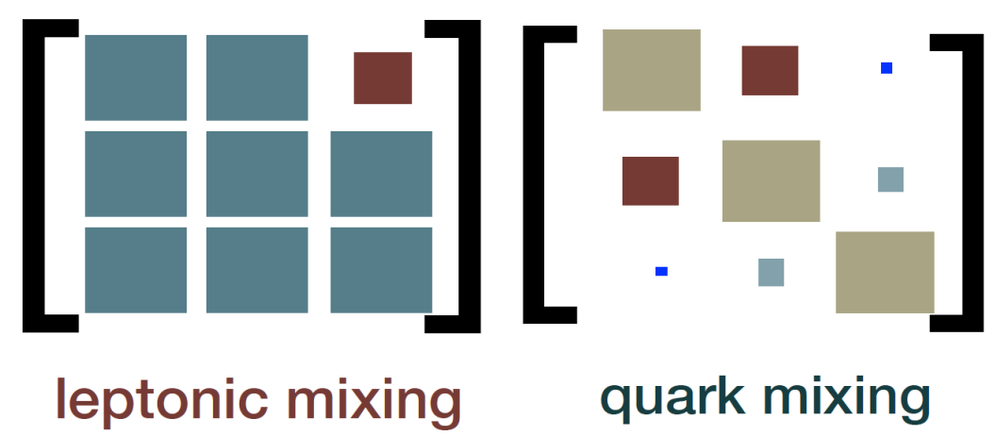
Answer to Q1

Question from NuFact '14: *What are the new developments and predictions from flavor models on neutrino oscillation parameters? What precision do we need to achieve to probe them? Which parameters (or combinations of them) are more powerful to test them?*

$m_\nu \ll m_{e,\,u,\,d}$

- Non-zero value of θ_{13} rules out models like tribimaximal mixing and golden ratio models
- Perturbative corrections to TBM result in sum rules correlating mixing angles and CP phase, which can be tested by precision measurements of θ_{12}, θ_{23}, δ_{CP}
- Present experimental data still allows for a wide variety of models
- <1% precision on mixing angles achievable in next 10-15 years. 10°-15° precision on δ_{CP} achievable after several years of DUNE and/or HyperK running.



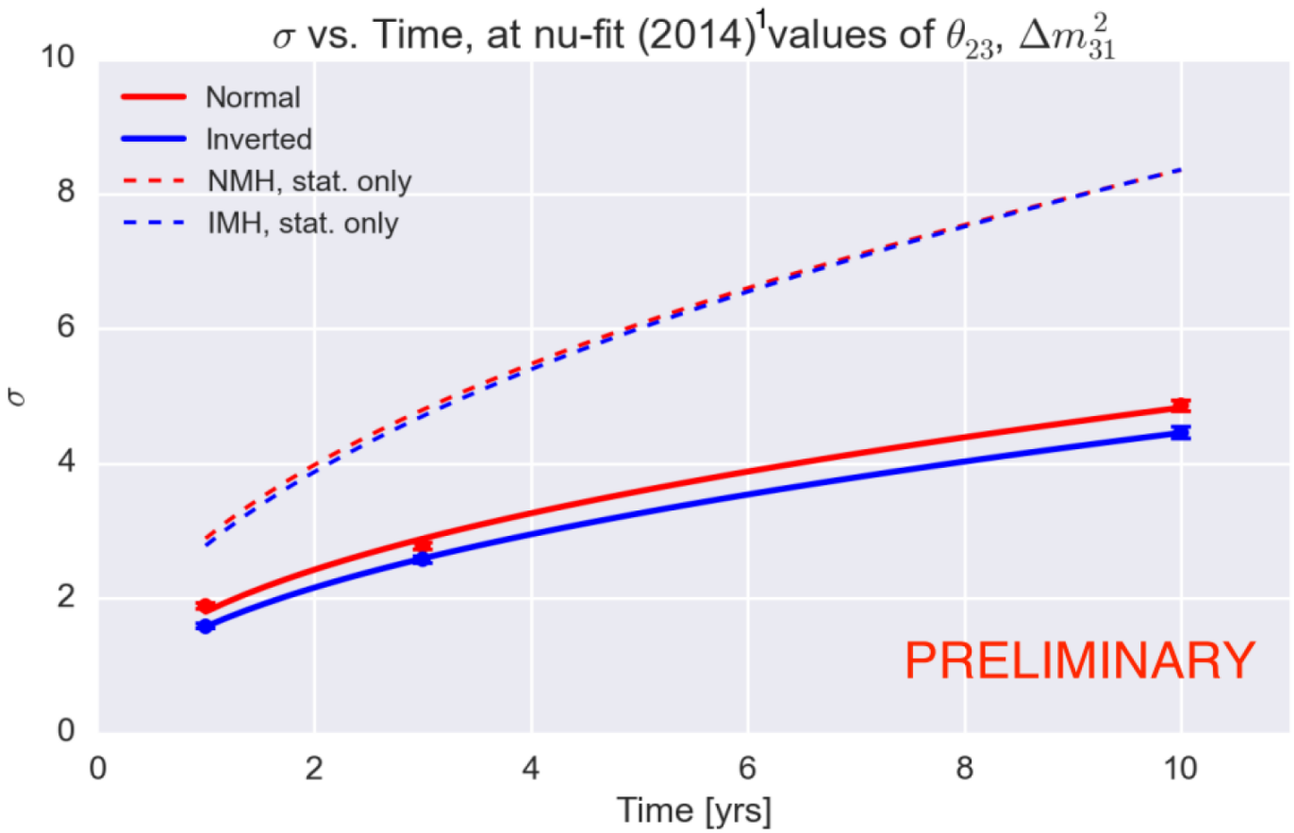


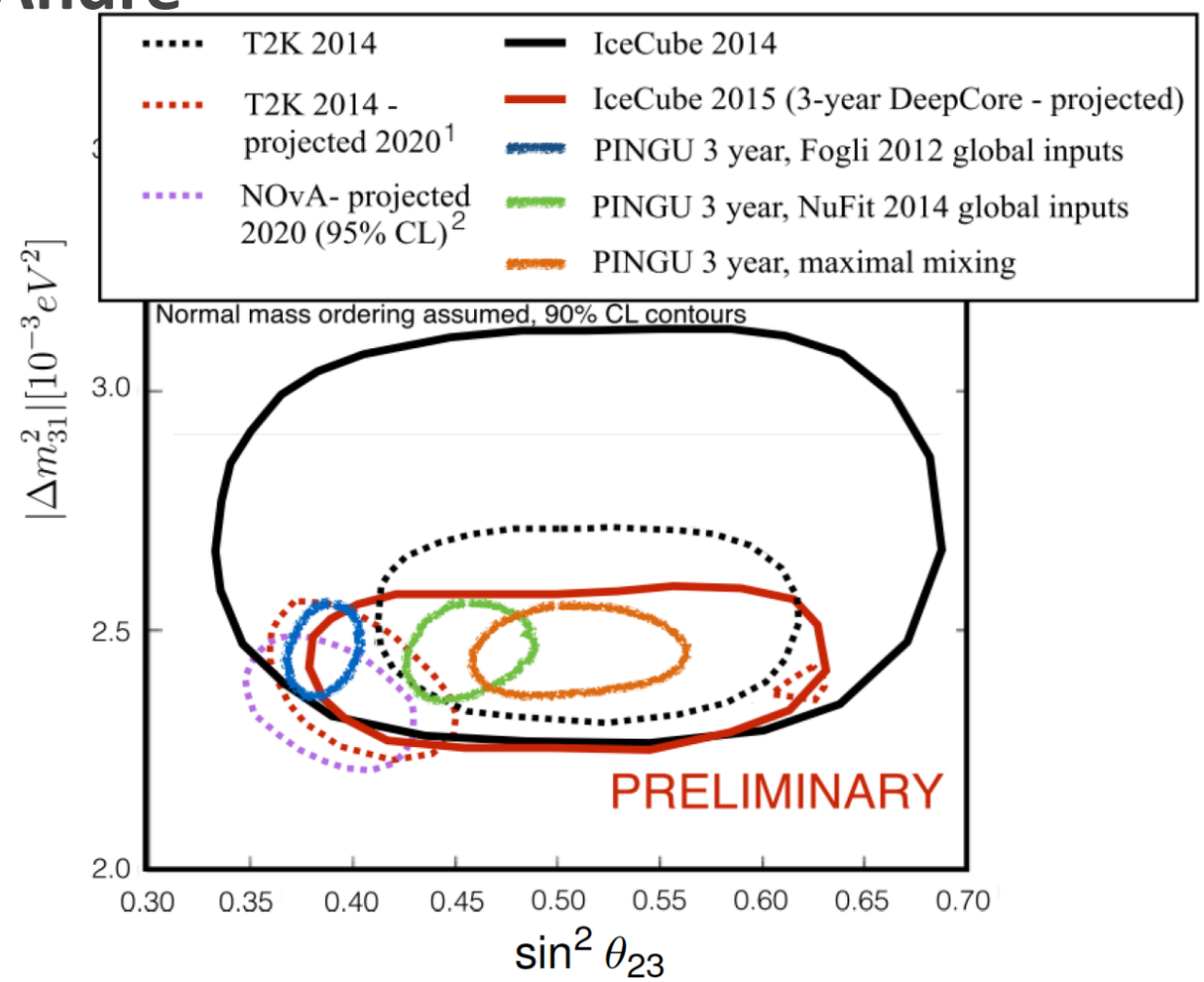
Q2: Atmospheric and LBL

Question from NUFACT '14: *Are atmospheric neutrino measurements competitive with next generation long-baseline facilities in the determination of the mass hierarchy? And the octant of θ_{23}? How much complementarity is there between them?*

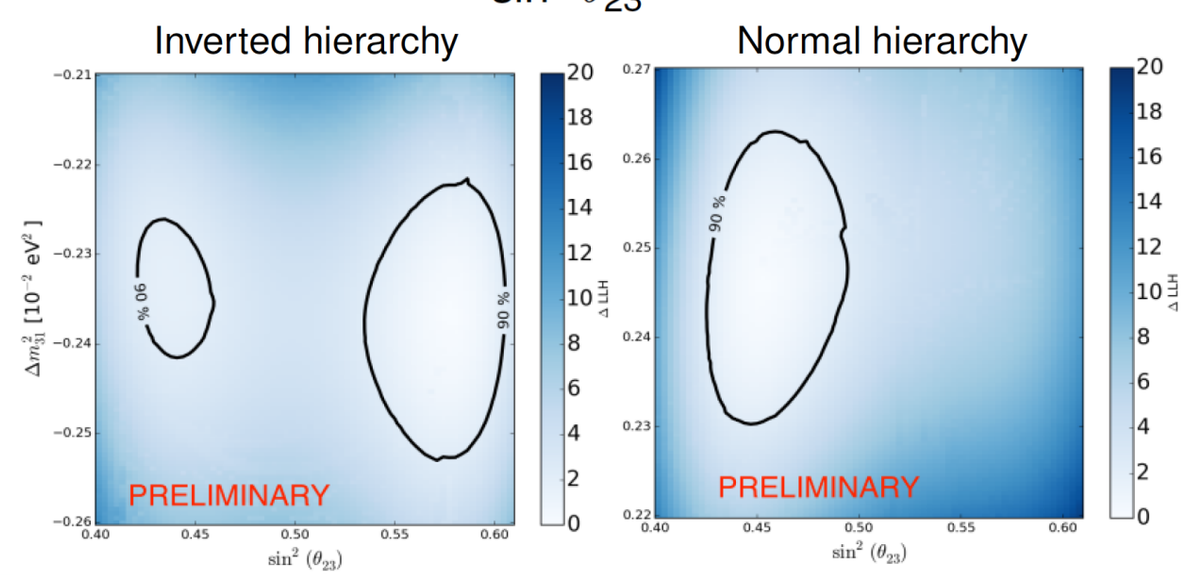
Atmospheric ν Future Projects

- **PINGU - JP Athayde Marcondes de André**



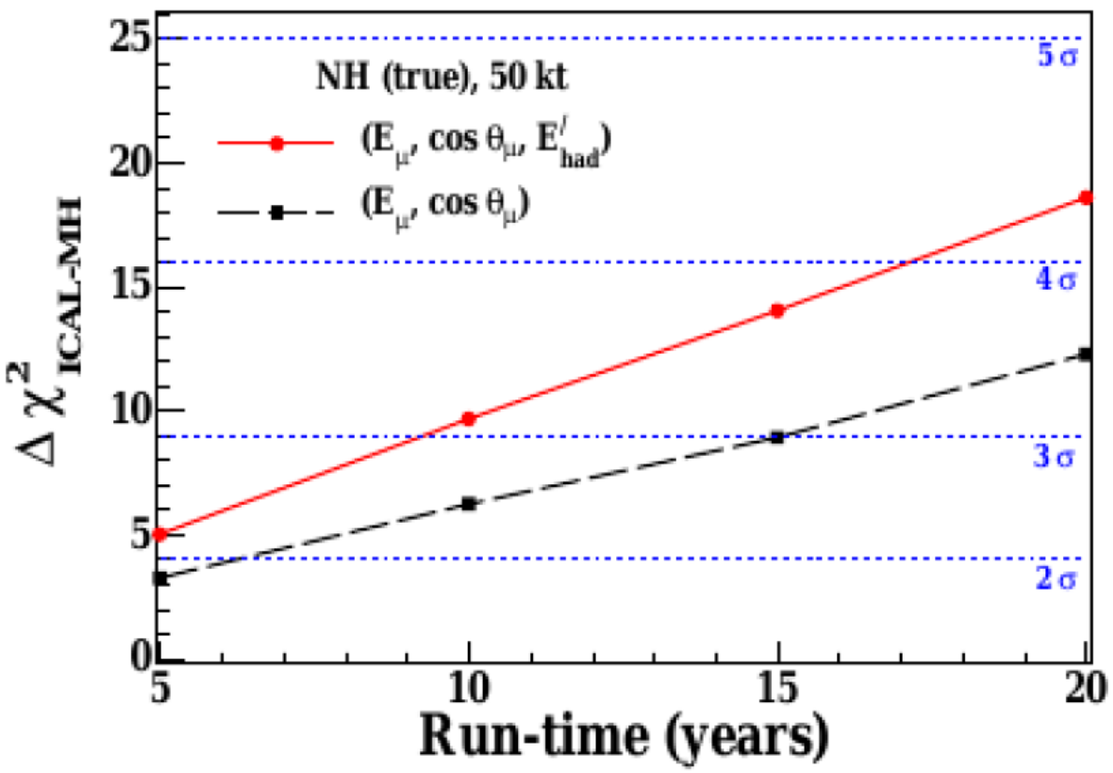


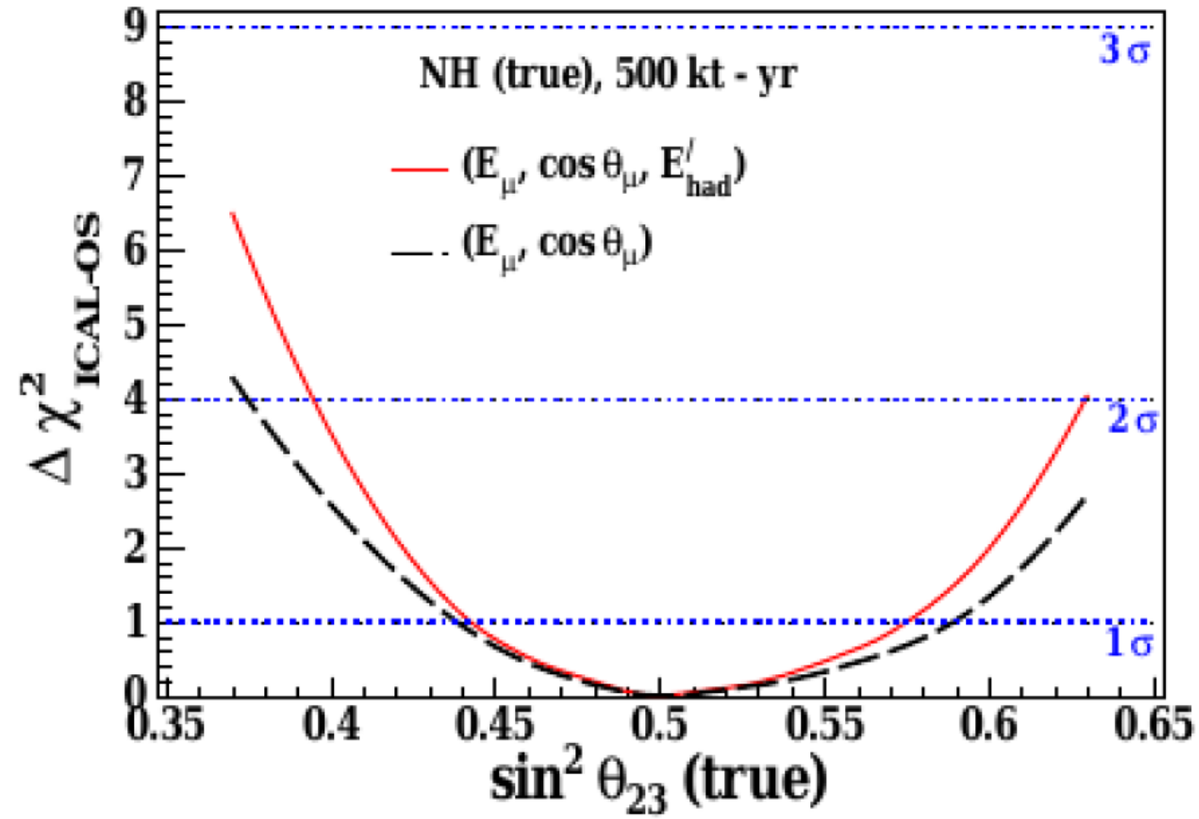
- Can reach 3σ resolution of mass hierarchy after 3 years of running.
- Mass hierarchy sensitivity strongly dependent on value of θ_{23}
- Expect to achieve similar θ_{23} and Δm^2_{32} precision as NOvA and T2K



Atmospheric ν Future Projects

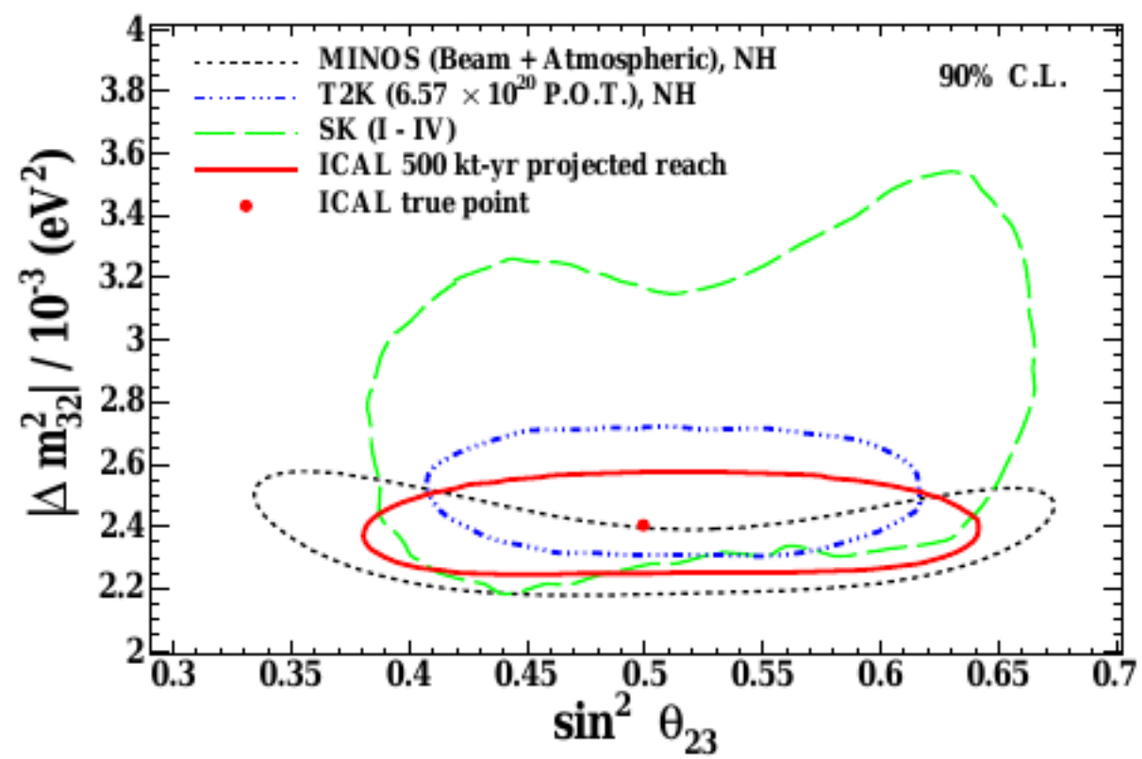
- INO - Sanjeev Kumar Veerma





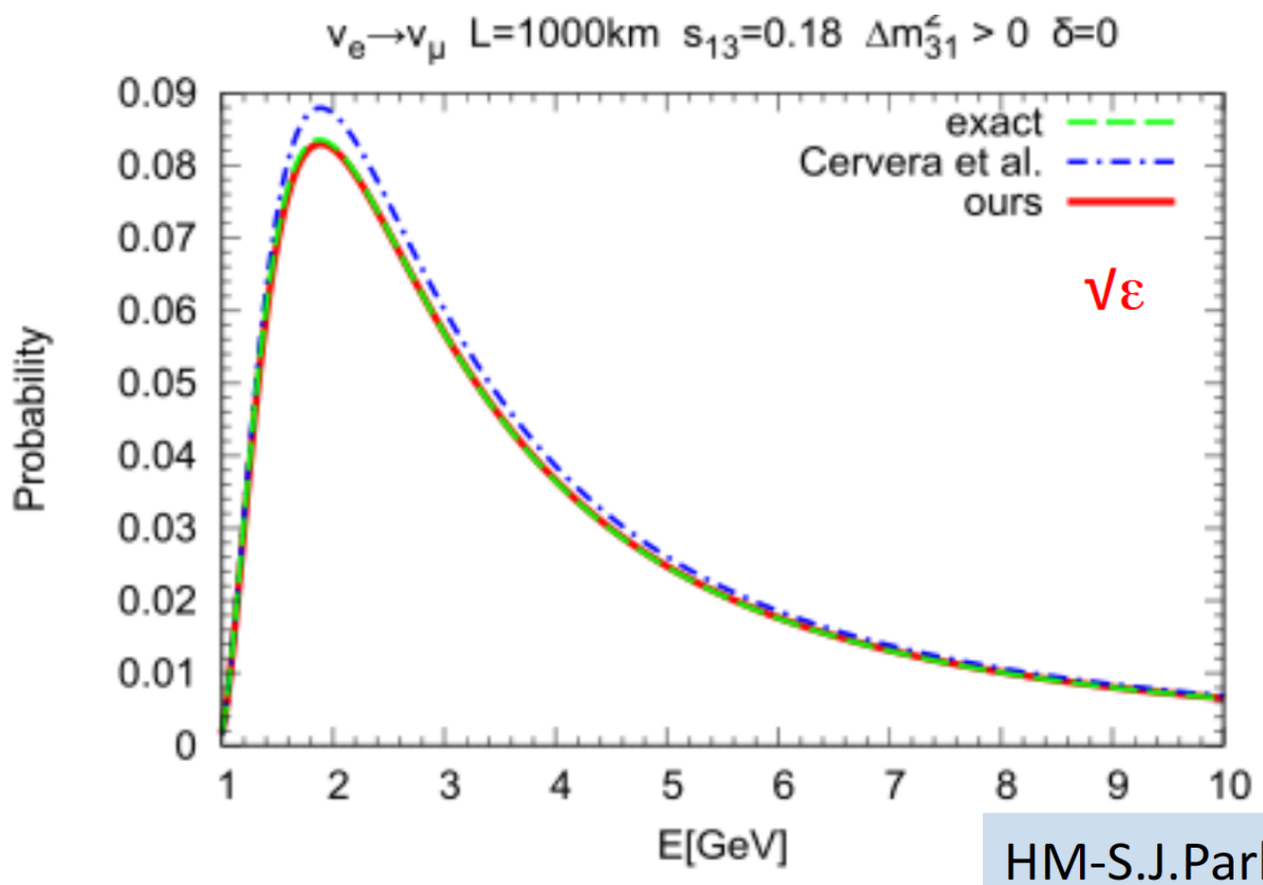
- Can reach 3σ resolution of mass hierarchy after 10 years of running. Improved to 6 years if combined with NOvA and T2K

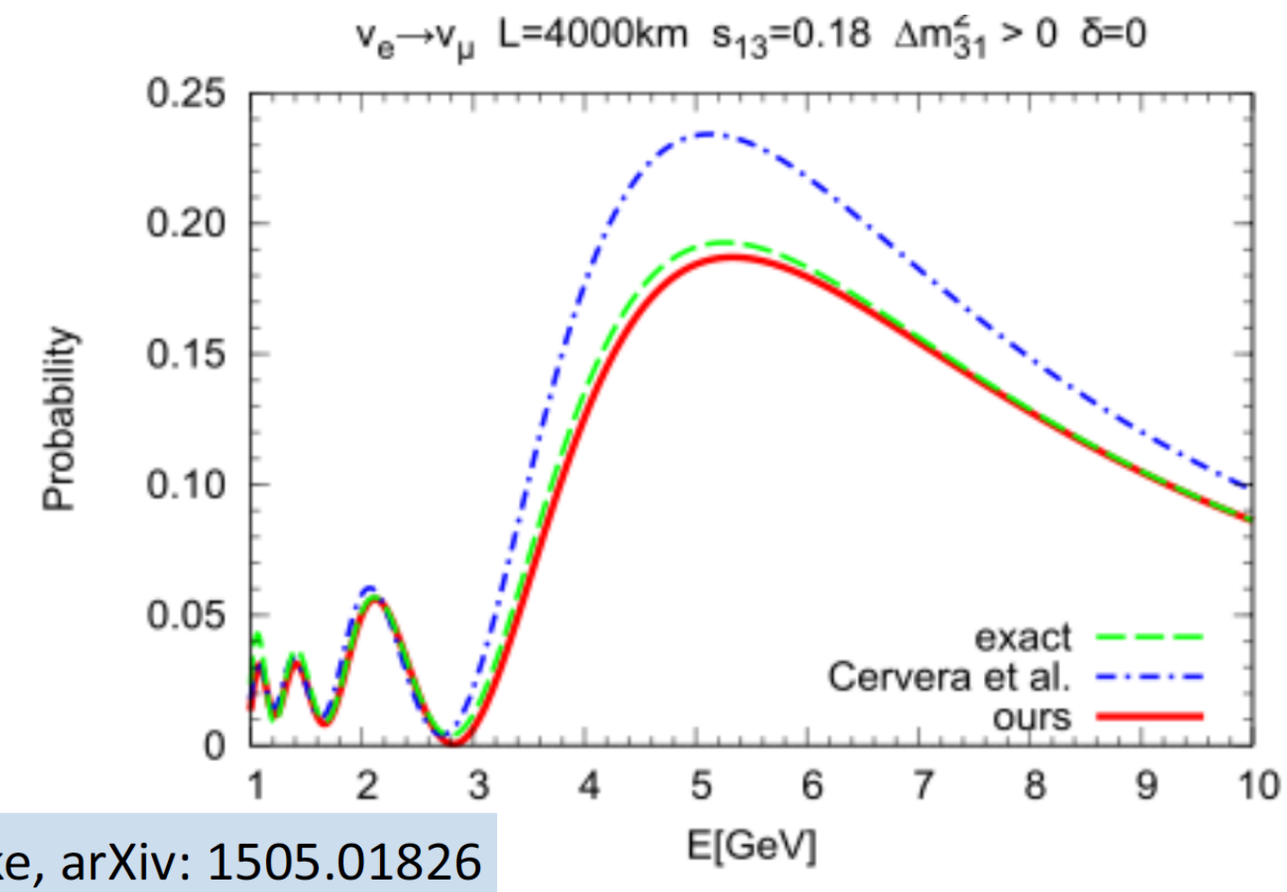
- 2σ sensitivity to octant of θ_{23} after 10 years of running.



ν Osc. Formulae

- **Hisakazu Minakata - Compact formulas for ν oscillations in matter**





HM-S.J.Parke, arXiv: 1505.01826

- Expansion of 3-flavor formulae in $\varepsilon = \Delta m^2_{21} / \Delta m^2_{31}$
- Good match to exact formulation for large distances relevant to atmospheric neutrino propagation
- Should improve computational time w.r.t to exact formulation
- Evaluating validity for expansions in $O(\varepsilon^2)$

Answer to Q2

Question from NUFACT '14: *Are atmospheric neutrino measurements competitive with next generation long-baseline facilities in the determination of the mass hierarchy? And the octant of θ_{23}? How much complementarity is there between them?*

- Projects like PINGU or ORCA may potentially reach over 3σ in mass hierarchy determination before turn-on of next generation long-baseline facilities

- In combination with INO, and atmospheric data from HyperK and DUNE, they will reinforce global measurements of mass hierarchy

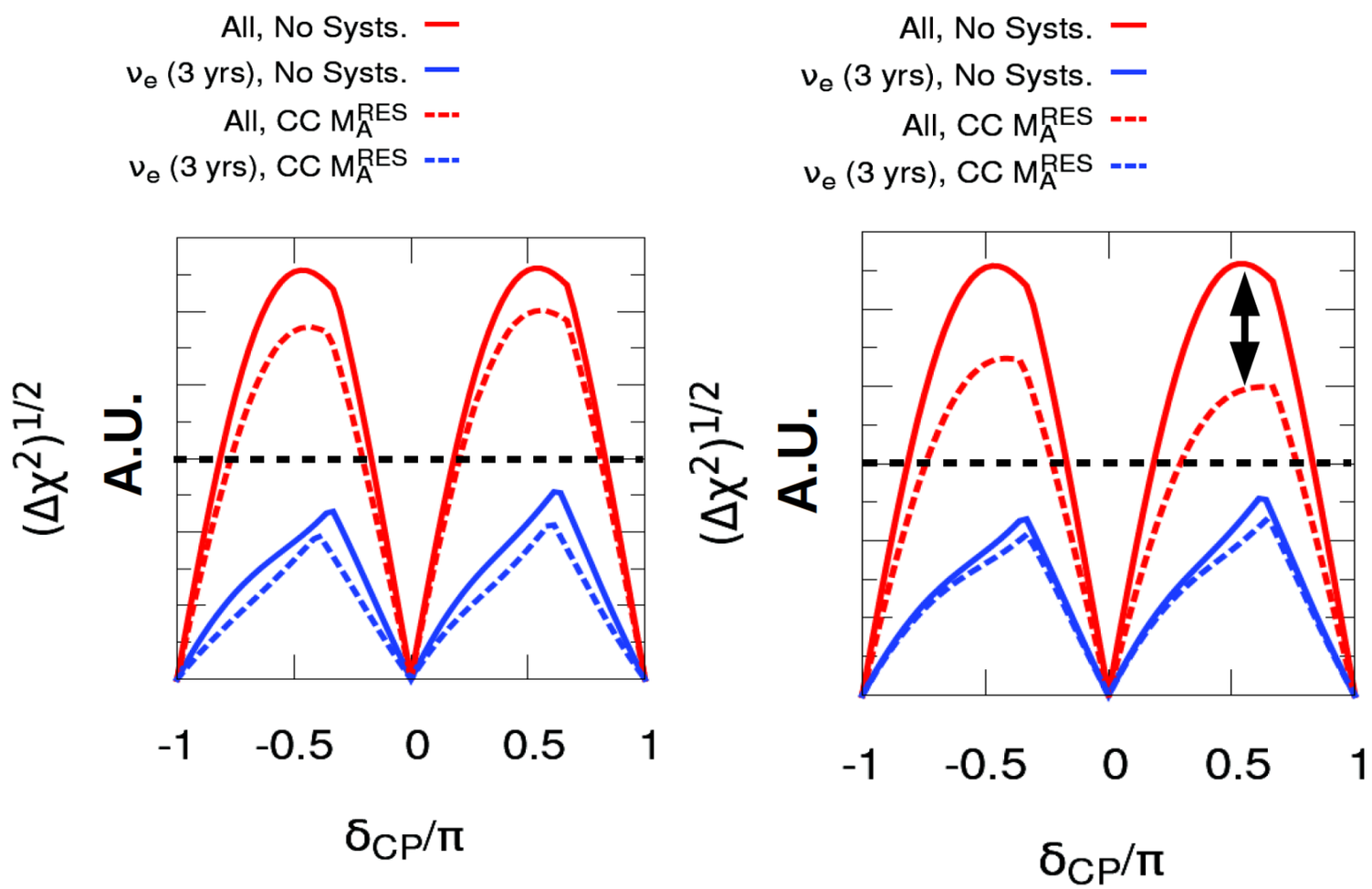
- Determination of octant of θ_{23} from atmospheric data difficult for proposed atmospheric detectors. To be continued at future NuFacts

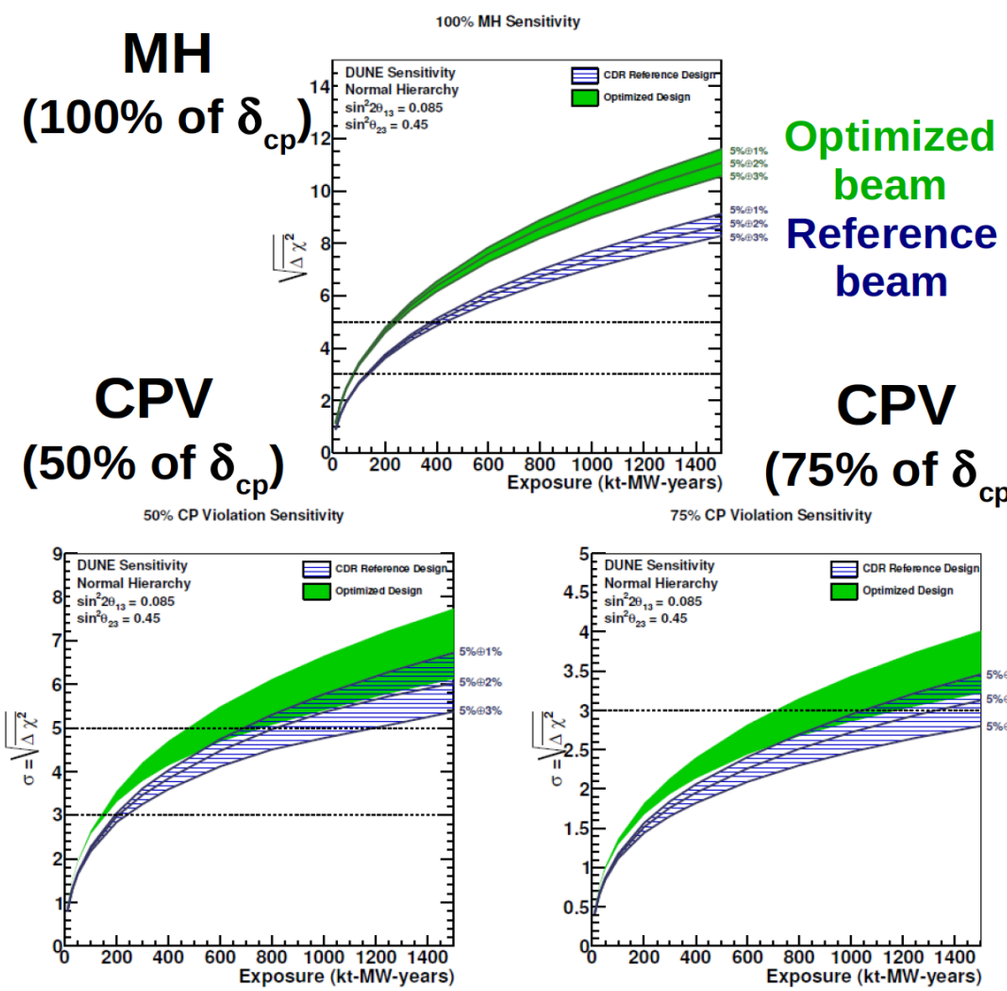
Q3: Systematics

Question from NUFACT '14: What is the target for the systematic error budget of next generation facilities? What do we need to reach this level? How much improvement in constraining flux uncertainties can we expect from dedicated hadron production efforts?

Systematics

- **DUNE - Dan Cherdack**
  - Showing effect of cross-section systematics (left) + flux uncertainties (right) on CP Violation sensitivity for FD-only fits
  - Smaller effect on mass hierarchy





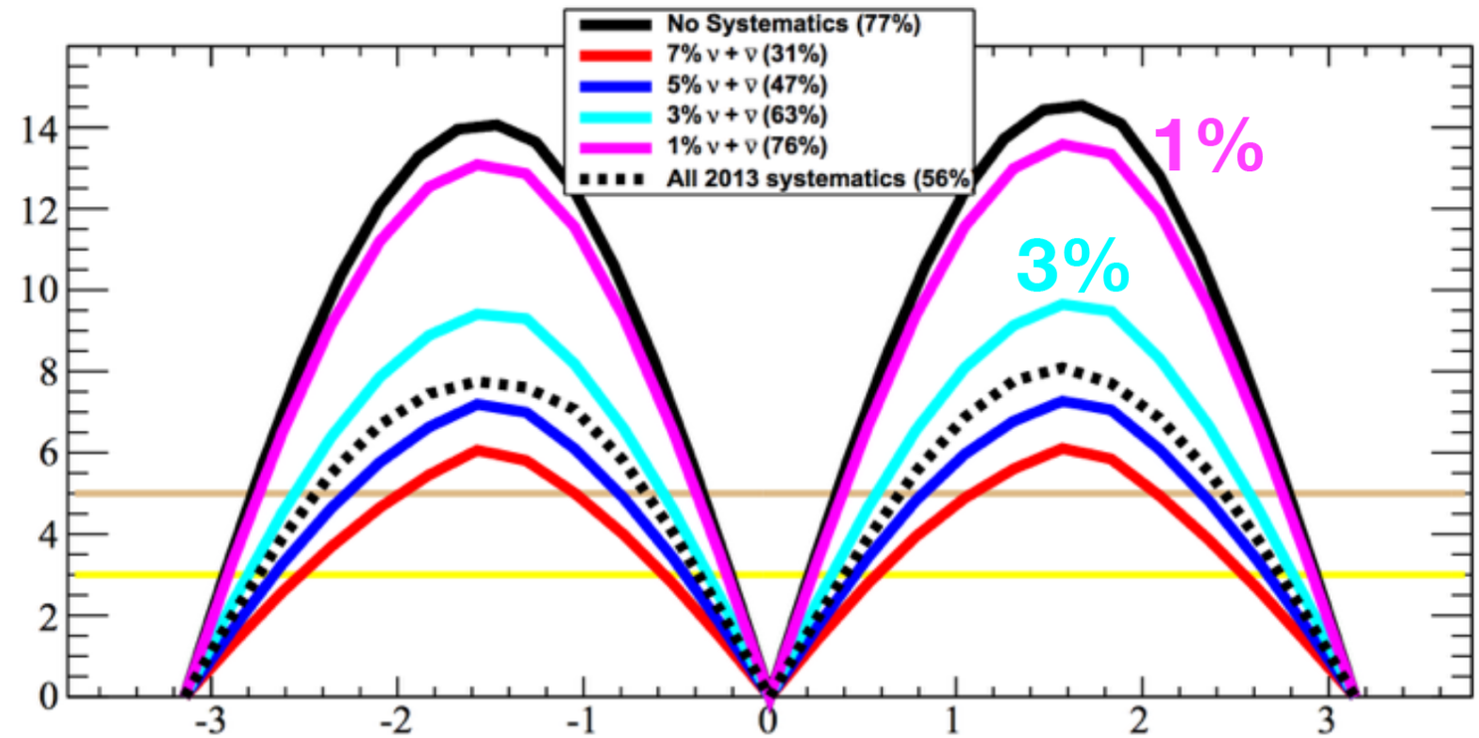
- For systematics to be dangerous they must be able to replicate the effects of shifting δ_{cp} in all 4 analysis samples
- Absolute flux normalization and shape
  - Secondary and tertiary hadron production
  - Flux shape differences at the Near and Far detectors
- Uncertainties from cross section models and nuclear initial state models need to be factorized
- A coherent picture of nuclear initial state effects is required
- Cross section flavor differences and rates for exclusive final state channels require theoretical input
- The convolution of flux, cross section, FSI and detector effects in determining energy scale will be difficult to untangle
  - Both FSI and detector effects can be different for ν and $\bar{\nu}$
  - Relative $\bar{\nu}/\nu$ uncertainties currently provide freedom to mimic δ_{cp}-like effects
- Biases in the energy scale from mis-reconstruction and/or poorly modeled/constrained missing energy (neutrons) must be eliminated

Systematics

- **HyperK - Mark Hartz**

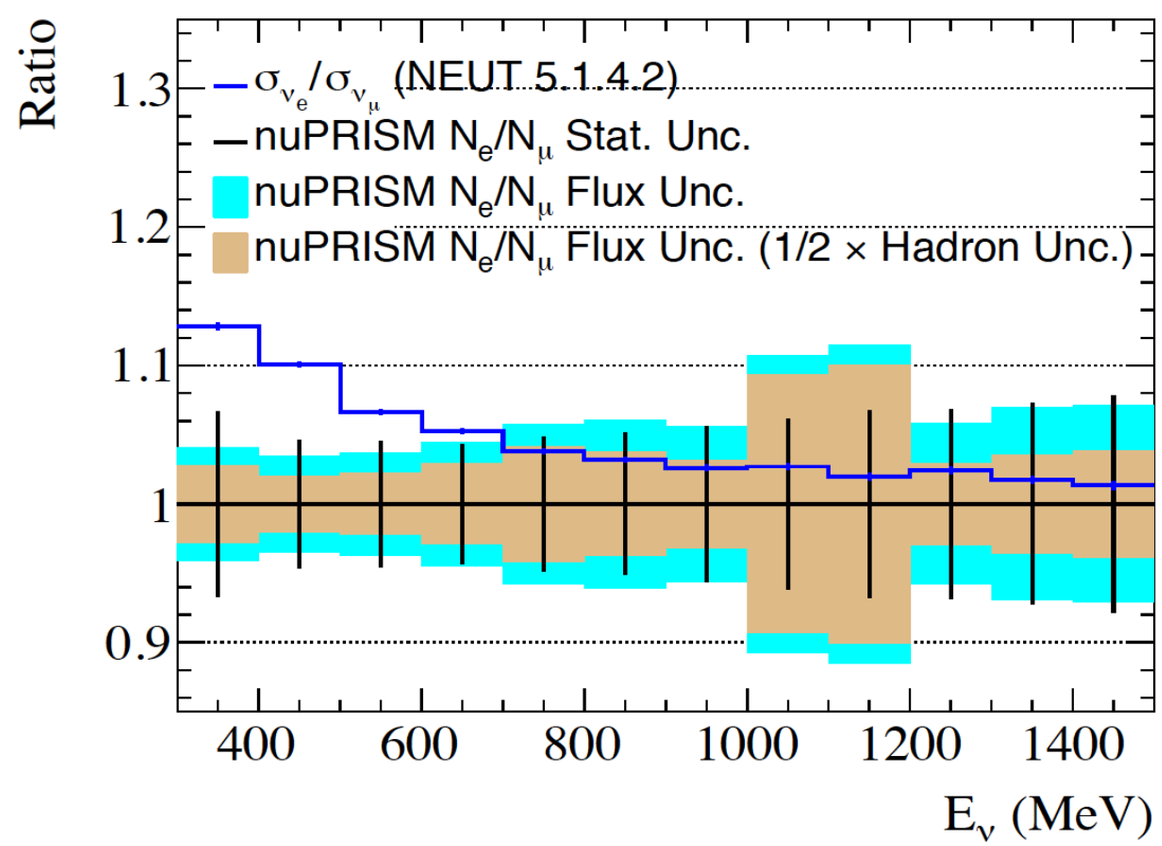
$\sigma = \sqrt{\Delta\chi^2}$

- Showing impact of cross sections in measurement of CPV
- Need <1-2% systematic to minimize impact.



- Achievable by nuSTORM. With nuPRISM concept, 3% level on $\sigma_{\nu_e}/\sigma_{\nu_\mu}$ is plausible

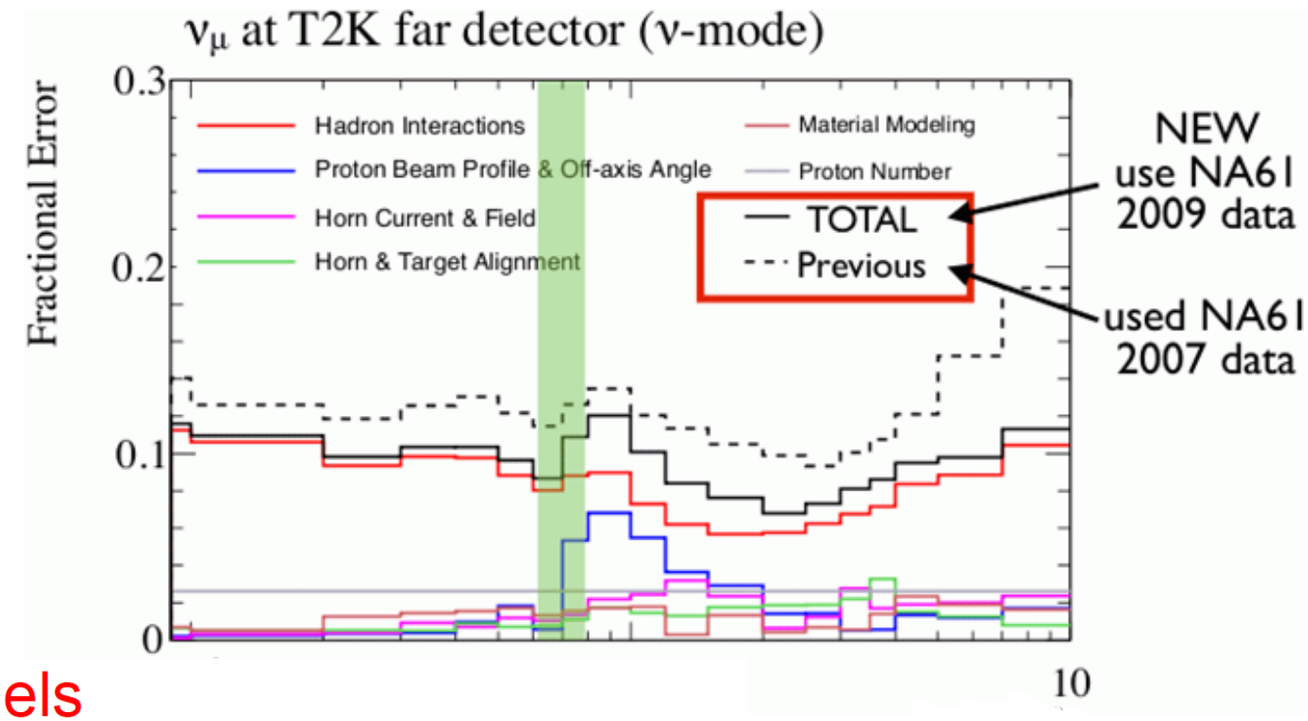
	Flux Error	Hadron x1/2	Stat. Error
300-600 MeV	3.2%	1.7%	2.9%
600-900 MeV	5.2%	3.4%	2.7%



Systematics

- **Alessandro Bravar - Prospects for reduction of beam flux uncertainties**

To improve on NA61 results:
increase statistics by a factor of 10
better understanding of interaction and production cross sections
forward acceptance (upgrades under way)
vertexing (replica targets)



None of the existing hadroproduction models
describes satisfactorily the ensemble of NA61 data (same for MIPP)!

Use "in situ" measurements to further constraint the flux
neutrino – electron elastic scattering (only "standard candle" in neutrino scattering)
muon monitors

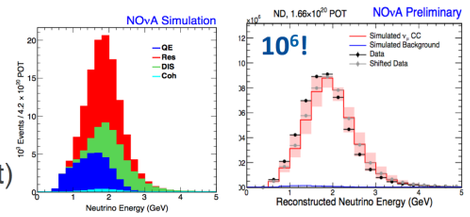
Expect that uncertainties on neutrino fluxes
will decrease down to 5% from the current ~10 %
over the next 5+ years

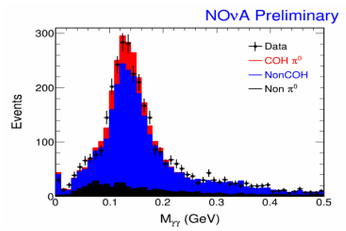
Systematics

Debbie Harris - Prospects for precision cross section measurements

Upcoming results from NOvA

- Analyses Underway (J. Paley, NuFact15)
  - ν_μ CC
  - ν_e + A
  - ν + e (flux constraint)
  - Coherent π^0
- Dominant ν_e + A Systematics
  - Flux (21%)
  - Energy scale (10-15%)
  - Improve both with MIPP and supporting ν_μ analyses



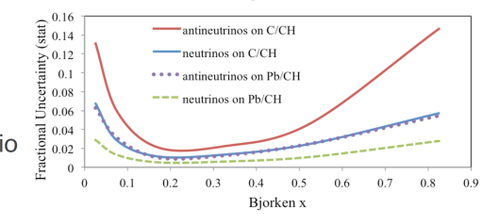


Upcoming results from T2K

- On Axis
  - QE two-track versus QE-like
    - Multi-nucleon searches
  - QE double differential
  - Charged pion double differential
  - Neutral Pions
  - Coherent charged (neutral?)
  - More ν_e cross sections
  - Nuclear Ratios (w/$H_2$0, Pb, CH) for model comparisons
  - Pion multiplicities
- On Axis
  - Energy dependent ν_μ CC inclusive on Fe
  - ν_μ CC Coherent pion production on C
  - ν_μ CC 0π differential on C

Upcoming results from MINERvA

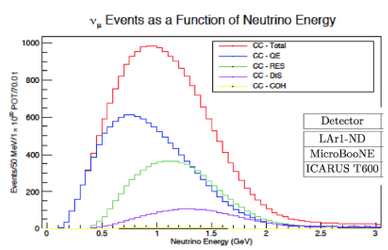
- ν_e CCQE cross sections (Ghosh)
- Nuclear target ratios for DIS events (Bravar)
- ν_μ CCQE double differential (Carneiro)
- CCQE on Fe, Pb, C compared to CH in Low Energy Beam
- Medium Energy results will feature much higher statistics
  - Higher flux and cross section, higher numbers of protons on target collected
  - Exclusive channel ratio results for Fe, Pb, C, compared to CH
  - Chance to look at nuclear effects in DIS at few per cent level!



DH, FNAL PAC 6/15

Next Step for 1GeV LAr Measurements

- 3 detectors, statistics at 5M!
- Mix of CCQE, Resonance
- Events below for 6.6E20POT
- LAr1-ND: 3M CCQE, >1M pion production events
- All detectors have fine granularity

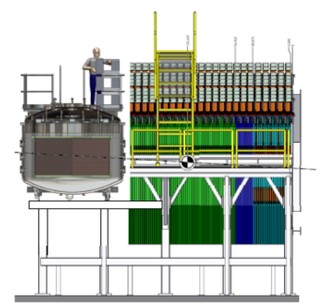


F. Cavanna, WINP

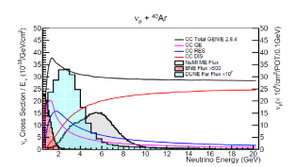
Detector	Distance	Fiducial Mass	CC ν_μ events	CC ν_e events
MicroBooNE	470m	61t	122k	800
LAr1-ND	110m	112t	5.2M	38k
ICARUS	600m	476t	550k	2k

Next step for 3-6GeV LAr precision: CAPTAIN MINERvA

- Install the CAPTAIN detector in MINERvA to study neutrino-argon interactions in the medium-energy NuMI beam
- CAPTAIN-MINERvA can measure cross section ratios (i.e., argon to carbon)
  - More stringent tests of the models can be performed with ratios due to cancellation of large systematic uncertainties such as the neutrino flux
- Stage I approval from Fermilab Director

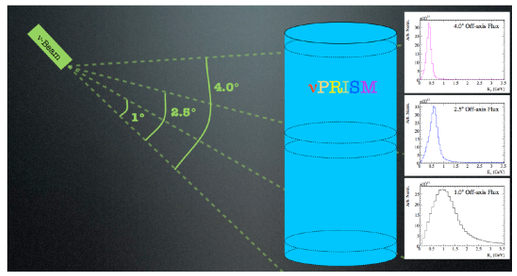


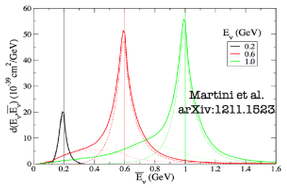
@6x1020 POT	Events with reco. μ	Events with reco.μ + chg
CCQE-like	900k	800k
CC 1$\pi^\pm$	2000k	1000k
CC 1π^0	1600k	600k



Getting to a MonoChromatic Neutrino Beams

- NUPRISM:
  - Take advantage of 2-body decay kinematics to "create" monochromatic energy beams
  - Not for the faint of heart, will need a lot of statistics to do subtractions from different locations
  - Best chance at directly quantifying this picture
- What about other targets?



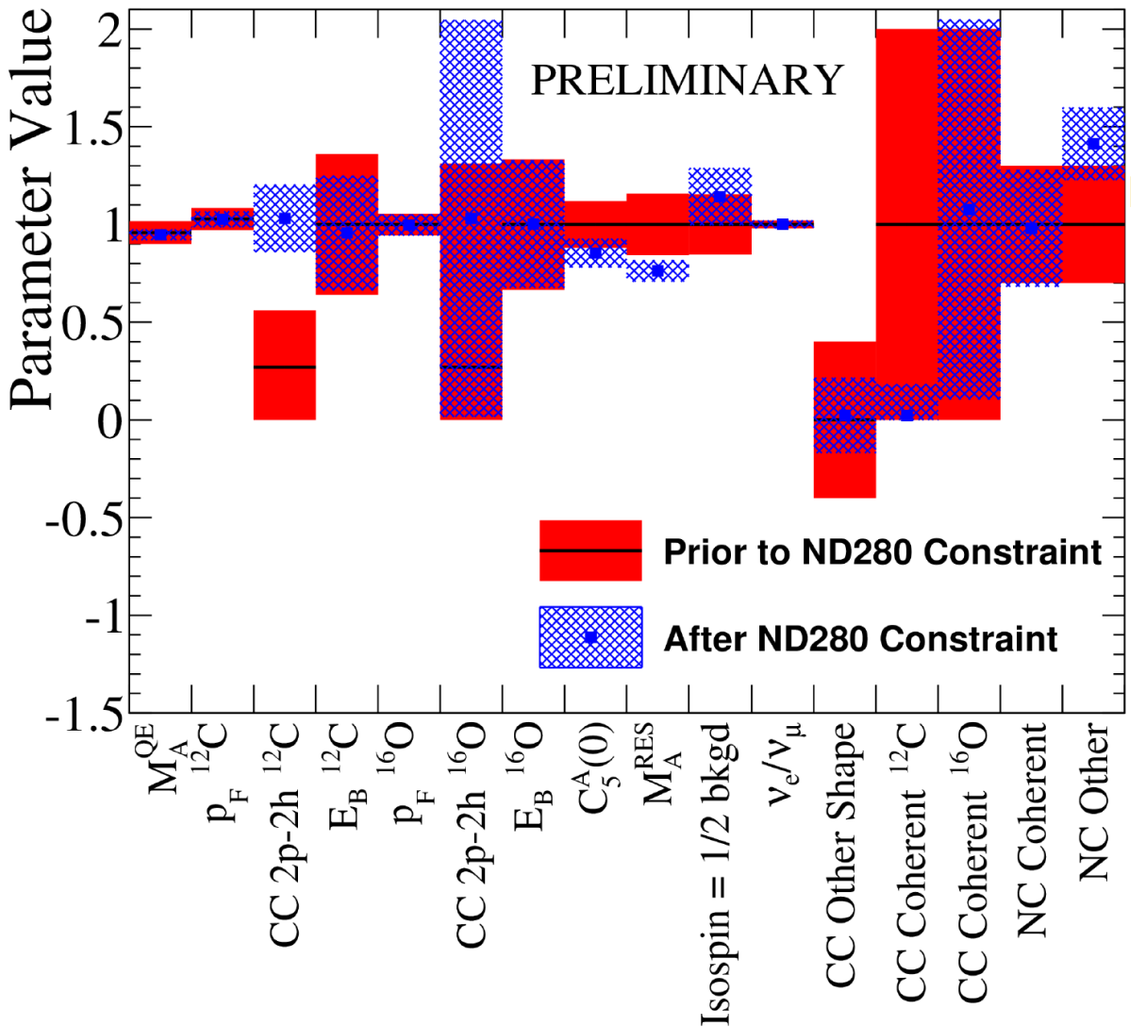


Fermilab

- We need to harvest the impressive data that is already recorded
- Need to get good statistics in anti-neutrino mode and harvest that data as well!

Systematics

- **ND Session - T2K - Kendall Mahn**



Some cross section parameters (2p2h on C, M_A^{RES}) changed significantly compared to external data prior

$\bar{\nu}_\mu$ disappearance analysis		w/o ND measurement	w/ ND measurement
ν flux and cross section	flux	7.1%	3.5 %
	cross section cmn to ND280	5.8%	1.4 %
	(flux) × (cross section cmn to ND280)	9.2%	3.4 %
	cross section (SK only, include ↓)	10.0 %	
	multi-nucleon effect on oxygen	9.5%	
	total	13.0%	10.1%
Final or Secondary Hadronic Interaction		2.1%	
Super-K detector		3.8%	
total		14.4%	11.6%

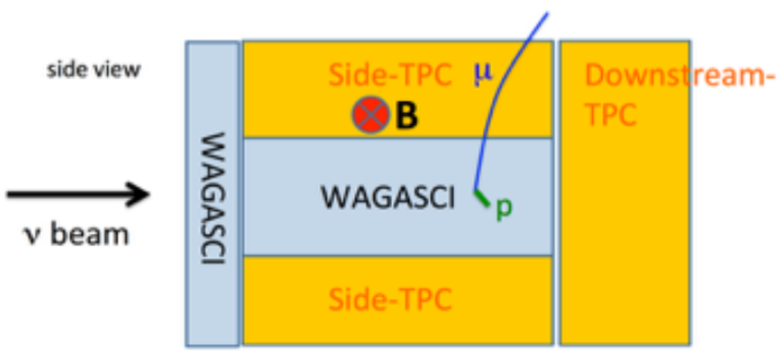
Fractional error on number-of-event prediction

- ND impact on T2K's analysis
  - Tuning of cross sections
  - Large reduction in flux uncertainties

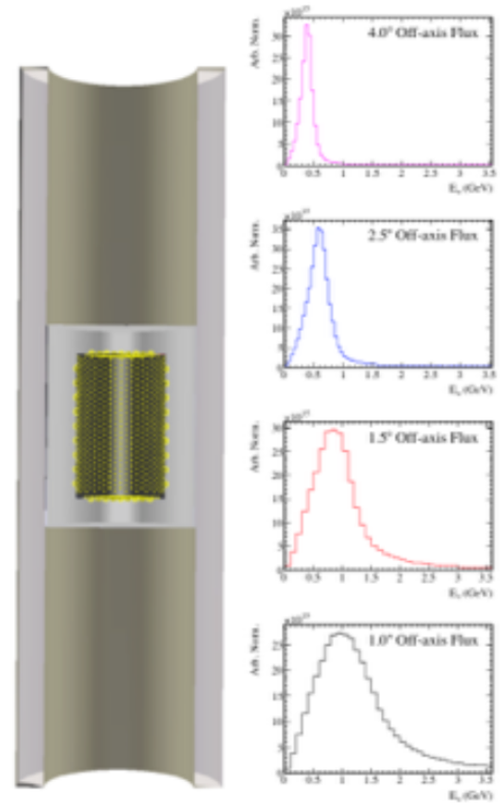
Systematics

- **ND Session - HyperK - Akihiro Minamino; DUNE - Kirk McDonald**

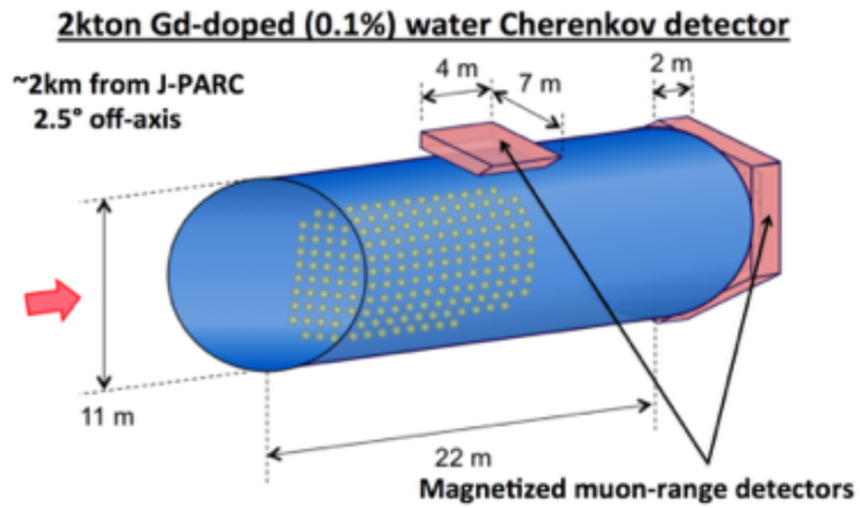
WAGASCI in ND280 magnet



NuPRISM



TITUS



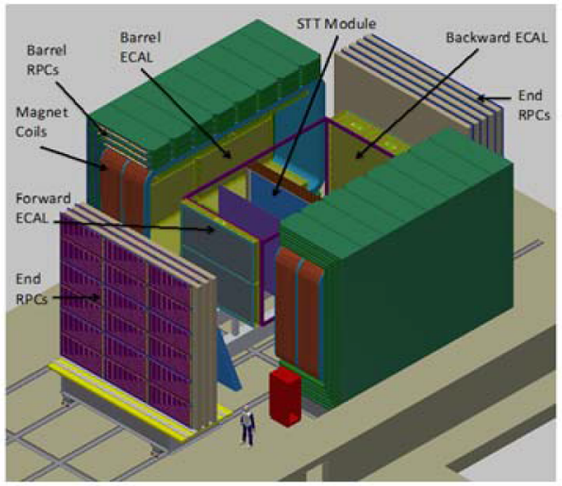
	ν_e cross section	H_2O target	4π accep.	Wrong sign BG	NC, Int. ν_e BG	Muon FS vs. ν	Hadronic FS	# of neutron (Gd)	$CC\pi^0$
Current ND280									
ND280 (WAGASCI)									
ND280 (HP-TPC)									
ND280 (WbLS)									
ND280 (Emulsion)									
νPRISM									
TITUS									

= Good = OK = Not Good

26

The NOMAD-inspired Fine-Grained Tracker (FGT)

- **It consists of:**
  - Central straw-tube tracking system
  - Lead-scintillator sampling ECAL
  - Large-bore warm dipole magnet
  - RPC-based muon tracking systems
- **It provides:**
  - Constraints on cross sections and the neutrino flux
  - A rich self-contained non-oscillation neutrino physics program

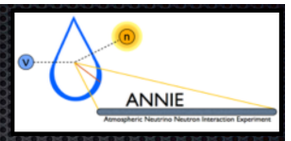


Quantifying the benefits of augmenting the ref. design with a LArTPC or high-pressure gaseous argon TPC

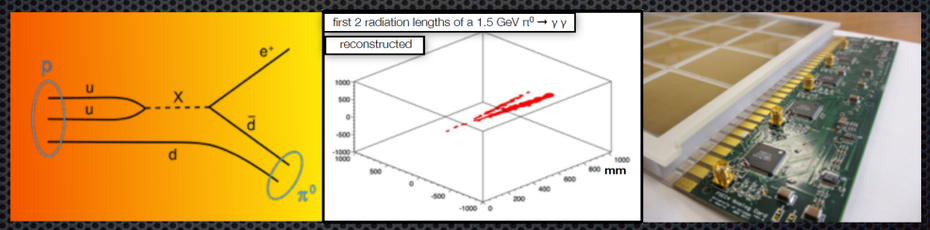
Systematics

- **ND Session - ANNIE - Mayly Sanchez; CAPTAIN and LArIAT - Jason**

The ANNIE experiment



- ANNIE, seeks to measure the abundance of final state neutrons from neutrino interactions in water, as a function of energy (see arXiv:1409.5864 and arXiv:1504.01480).
- It is also the first application in a HEP experiment of LAPPDs (Large-Area Picosecond Photo-Detectors).



- A key physics measurement in understanding the nature neutrino-nucleus interactions.
- Application of a promising technology for detecting neutrinos.

MiniCAPTAIN

1m Ø LArTPC in neutron beam at Weapons Neutron Research facility

Physics goals:

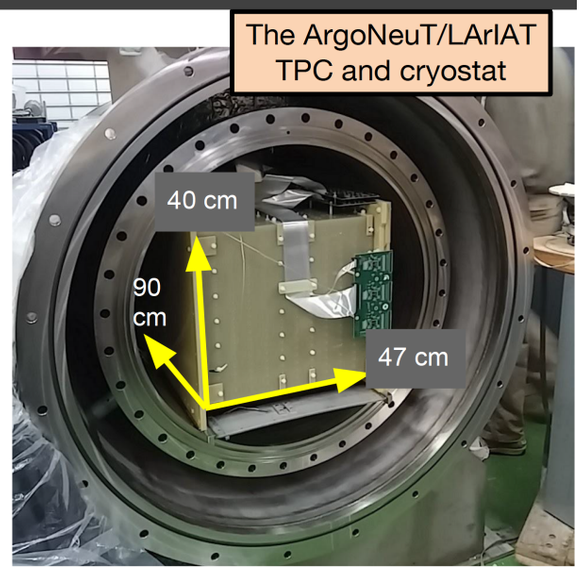
Ar* nuclear de-excitations
Neutron scatters at known E_n
Neutron-induced $\pi^{\pm}$ production

The mini-CAPTAIN cryostat

LArIAT

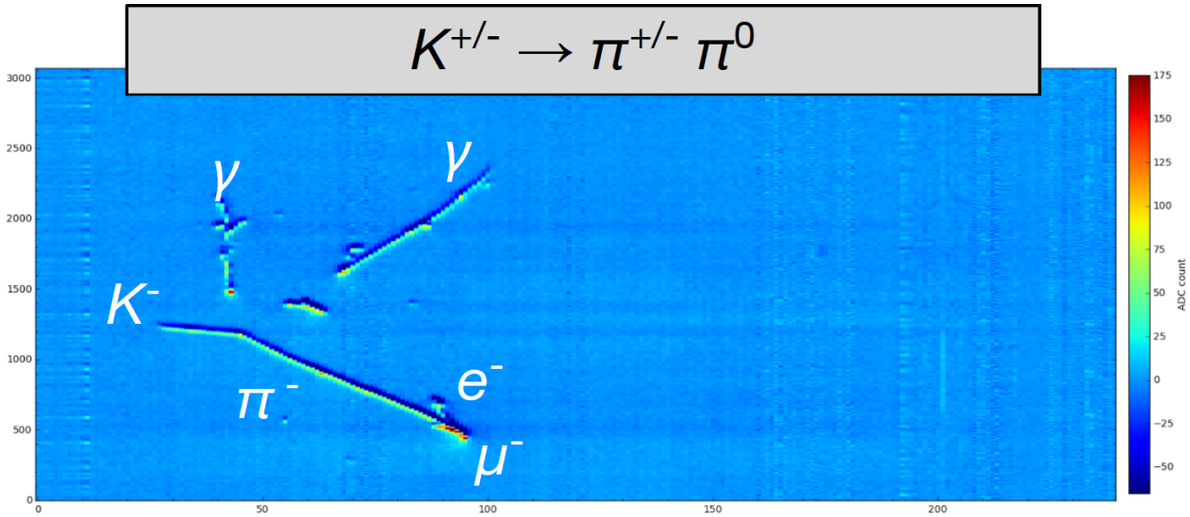
"Table-top" (170L) LArTPC in a test beam at Fermilab Test Beam Facility

- Repurposed ArgoNeuT detector
- **Physics goals:**
  - π-Ar interactions
  - e/γ shower ID
  - μ-Ar capture
  - non-magnetic charge determination
  - kaon studies
  - Geant4 validation
- **R&D goals:**
  Optimize PID algorithm, calorimetry with charge & light, and 2D/3D event reconstruction



The ArgoNeuT/LArIAT TPC and cryostat

- Taking data since April 30, 2015



Answer to Q3

Question from NUFACT '14: *What is the target for the systematic error budget of next generation facilities? What do we need to reach this level? How much improvement in constraining flux uncertainties can we expect from dedicated hadron production efforts?*

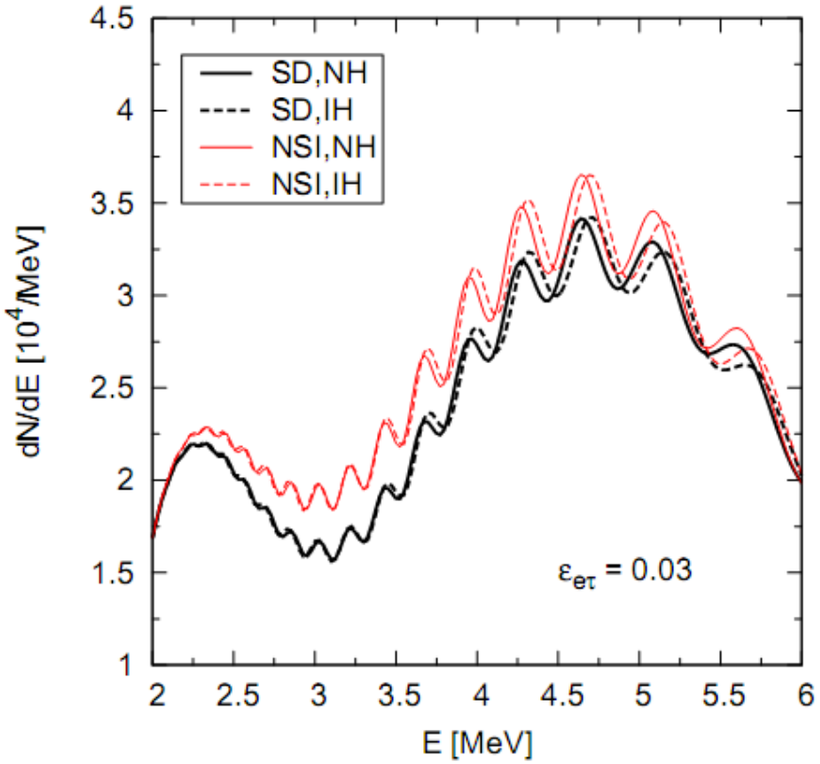
- Absolute beam flux uncertainties can be reduced from 10% to 5% in next 5 years
- <1%-2% precision on cross sections required for ultimate sensitivity to CPV
- nuSTORM would be ideal, but have comprehensive program of cross section measurements in H_2O and Ar throughout the World over the next decade
- Multi-purpose Near Detectors essential in reducing flux and cross section uncertainties.
- To assess cross section systematics in more focused way, Hugh Gallagher proposed creation of mock data challenge samples by generator groups in consultation with experiments and theorists.

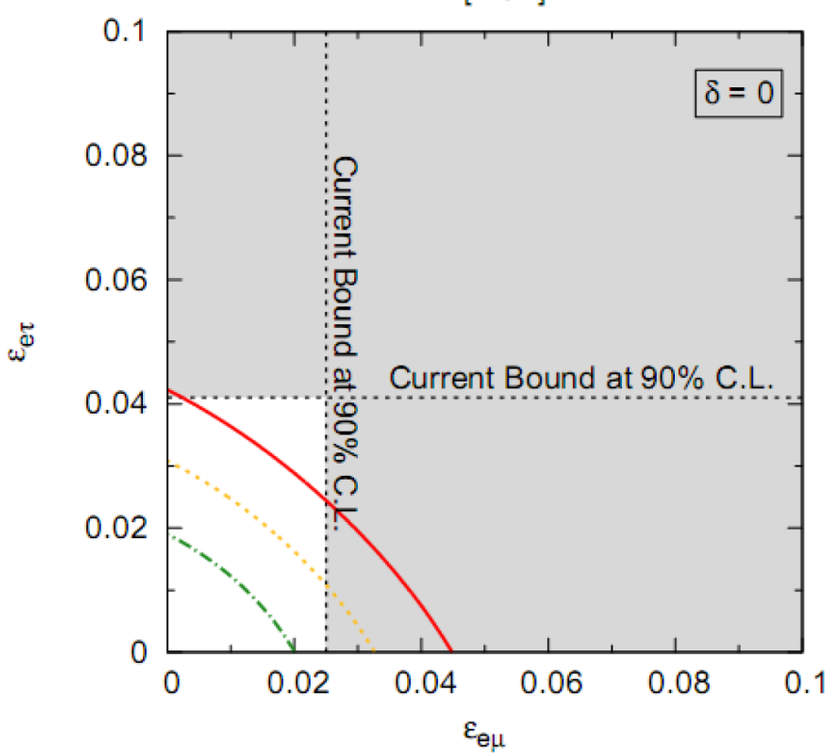
Q4: New Physics and ν CPV

Question from NUFACT '14: Do the current bounds on new physics in the neutrino sector (NSI, non-unitarity, steriles…) allow for effects large enough to interfere with CPV searches? Which experimental setups can improve these bounds?

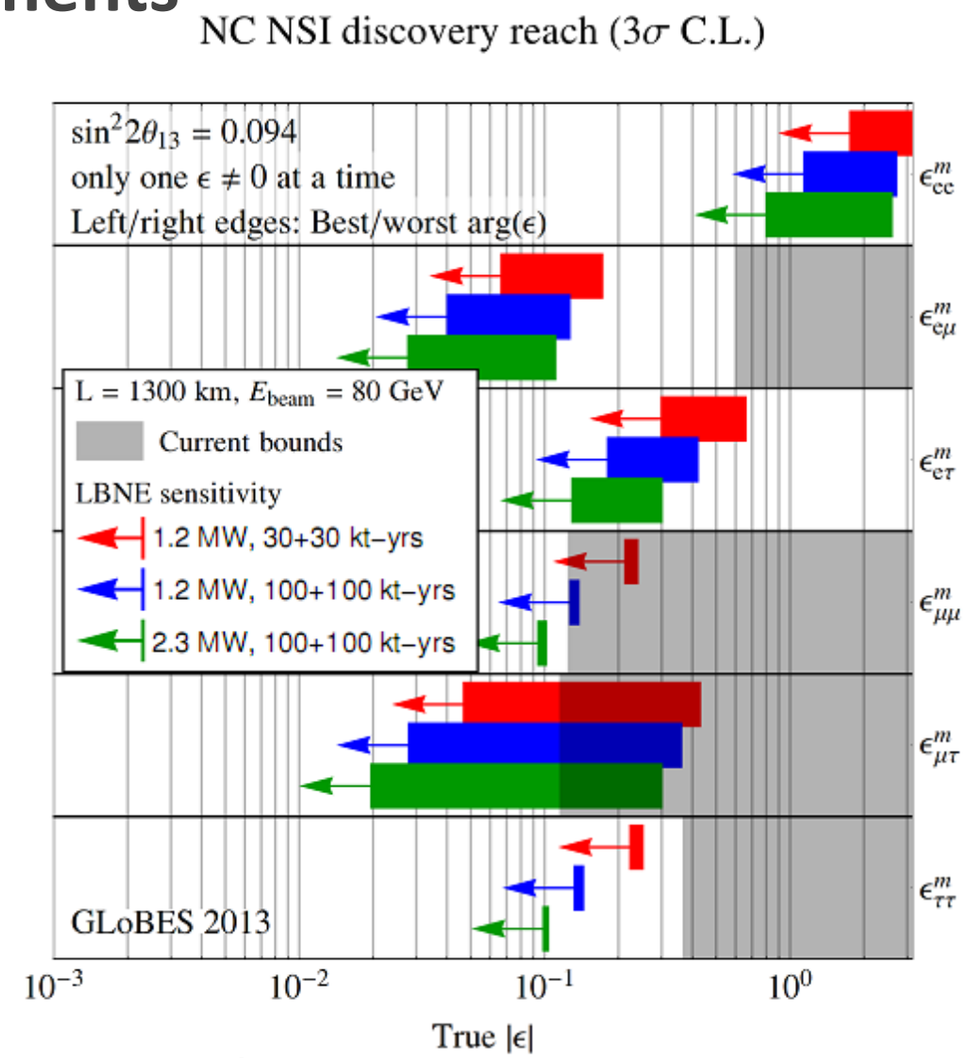
New Physics and ν CPV

- **Sushant Raut - Effect of NSIs on CPV measurements**





Matter NSI bounds: DUNE



Source/detector NSI bounds: ESSνSB

Parameter	ESSνSB limits	Existing limits
$\varepsilon^{s}_{\mu e}$	0.014	0.026
$\varepsilon^{d}_{\mu e}$	0.014	0.025

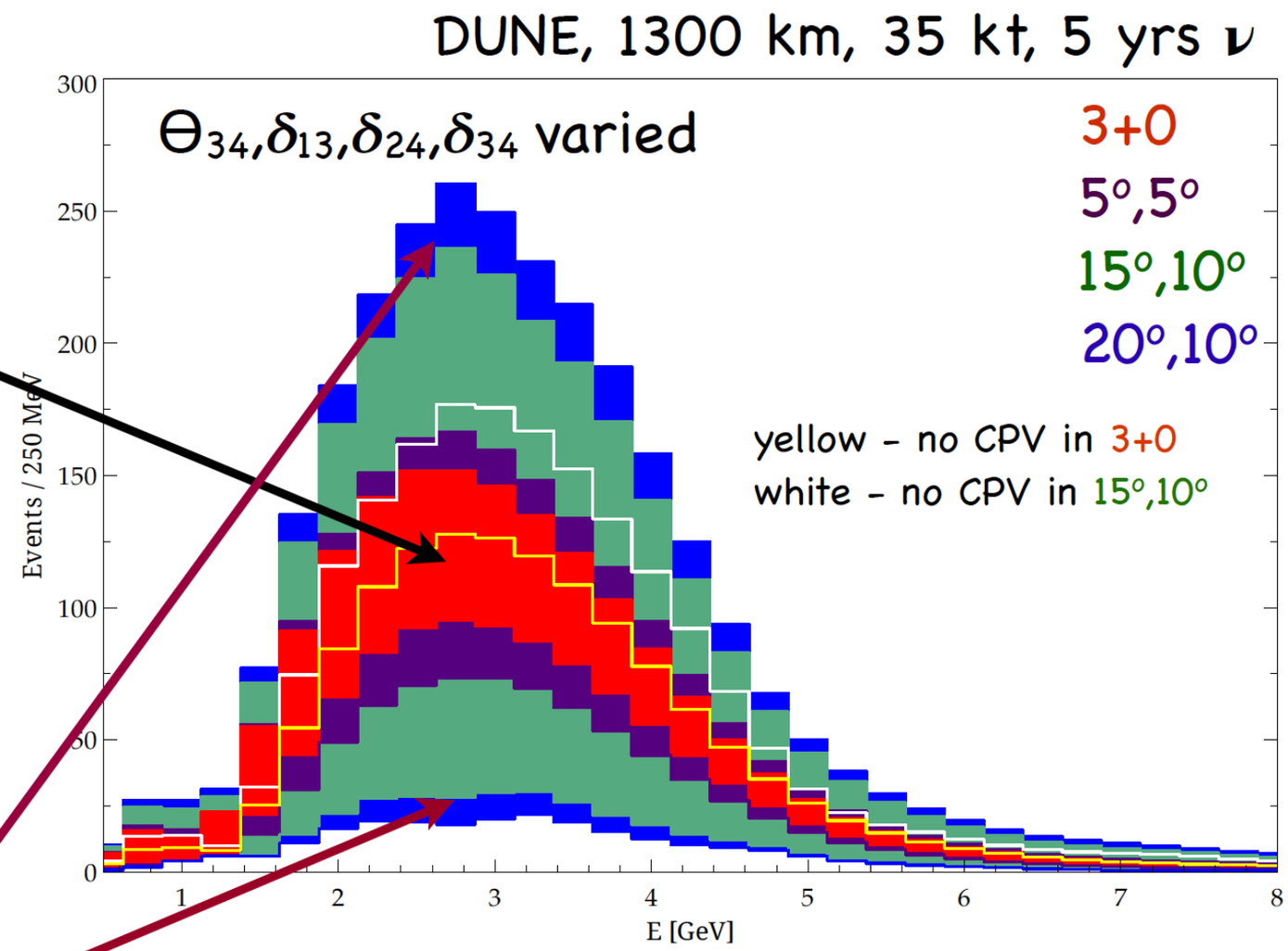
New Physics and ν CPV

- **Suprabh Prakash - Effect of sterile neutrinos on CPV measurements**

We consider a O(1 eV^2) mass sterile neutrino, heavier than the other 3 mass eigenstates => Δm^2_{41} = +1 eV^2. Δm^2_{31} can be + or -

In producing these plots, we have averaged over the Δm^2_{4i} induced oscillations.

The 3+1 band can potentially encompass the 3+0 band, leading to substantial degeneracy.



For large active-sterile mixings, an excess or shortage of events, esp. at osc. max. will be pointers to the existence of new physics.

Θ_{12} = 33.48°, Θ_{13} = 8.5°, Θ_{23} = 45°

Δm^2_{31} = +2.457e-3 eV^2, Δm^2_{21} = 7.5e-5 eV^2

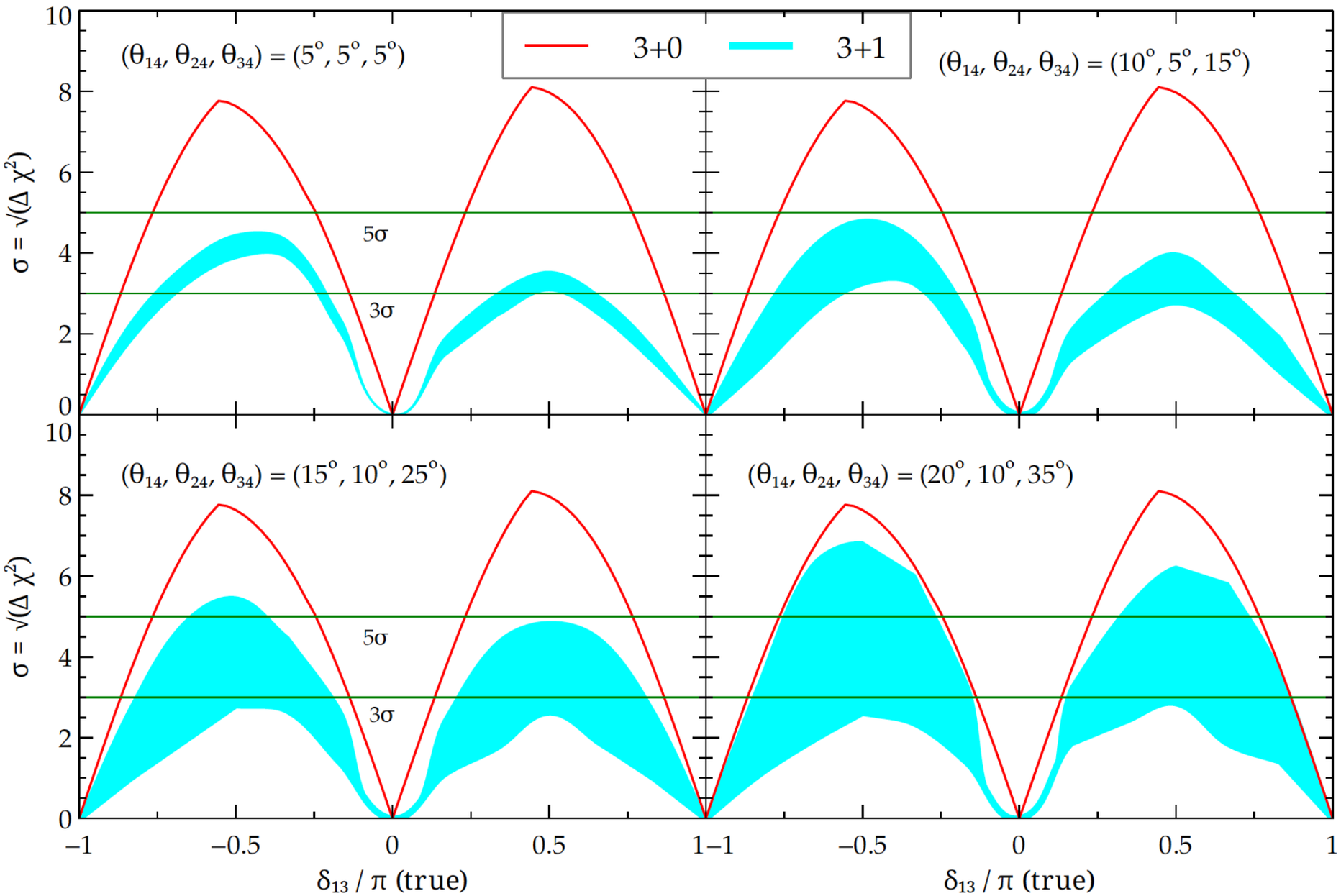
Q4: New Physics and ν CPV

- **Suprabh Prakash - Effect of sterile neutrinos on CPV measurements**

Cyan band - variation of true δ_{24} and δ_{34}

DUNE, 1300 km, 35 kt, 5+5

1% signal norm. error & 5% back norm. error



$\Theta_{12} = 33.48^\circ$, $\Theta_{13} = 8.5^\circ$, $\Theta_{23} = 45^\circ$ $\Delta m^2_{31} = +2.457e\text{-}3\ eV^2$, $\Delta m^2_{21} = 7.5e\text{-}5\ eV^2$

Answer to Q4

Question from NUFACT '14: *Do the current bounds on new physics in the neutrino sector (NSI, non-unitarity, steriles…) allow for effects large enough to interfere with CPV searches? Which experimental setups can improve these bounds?*

- Answer is yes
- However, more work is required to understand how other parameter measurements may be affected, and how effects will change with more sterile neutrinos and active-sterile mixing driven by different mass scales
- We did not discuss specific experimental setups that could potentially disentangle these effects, but should be kept in mind for future NuFacts.

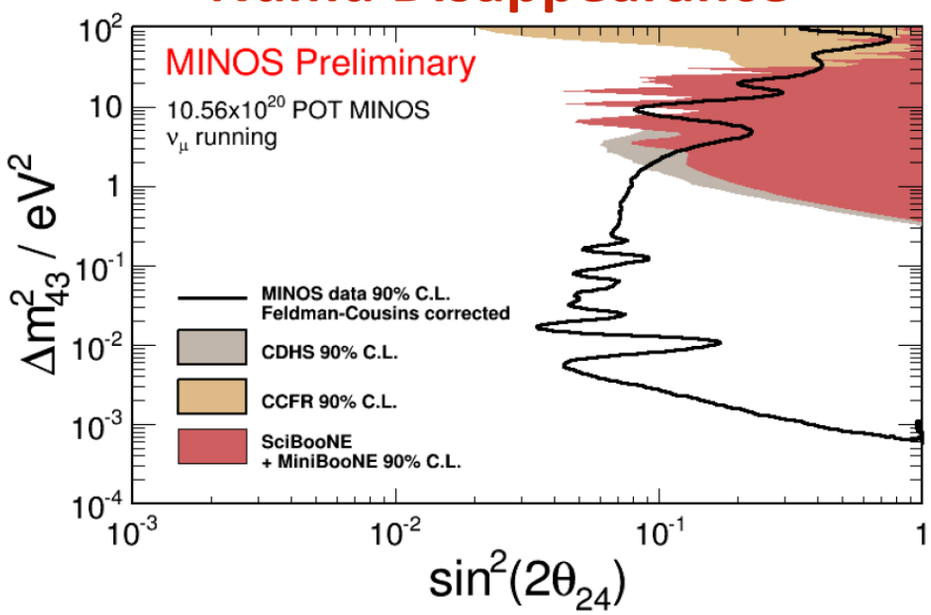
Q5: Sterile Neutrinos

Question from NUFACT '14: *What is the best strategy to fully probe the LSND anomaly? And the reactor/gallium anomaly?*

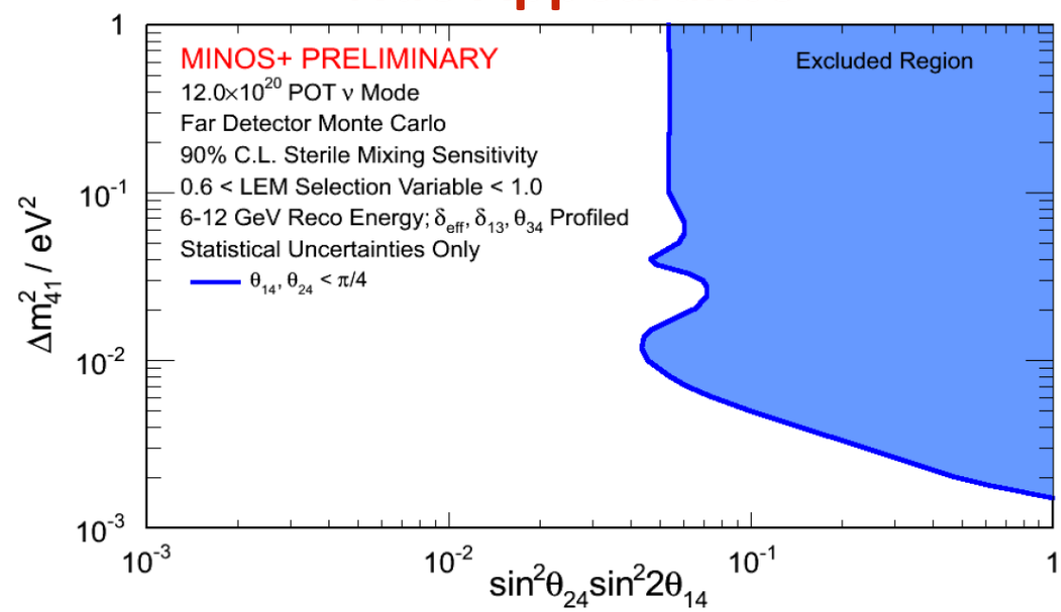
Sterile Neutrinos

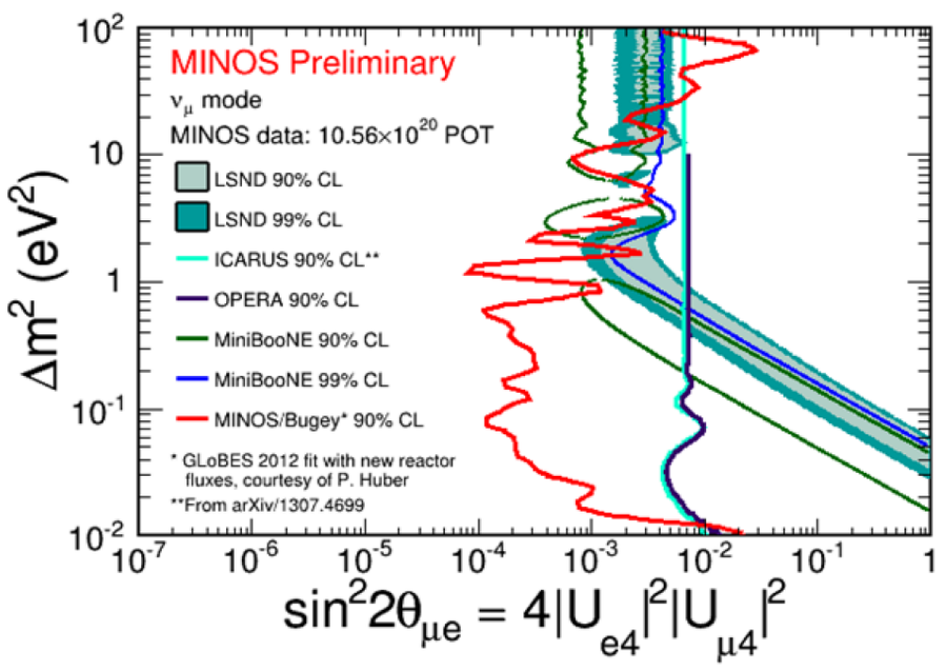
- **MINOS/MINOS+ - João Coelho**

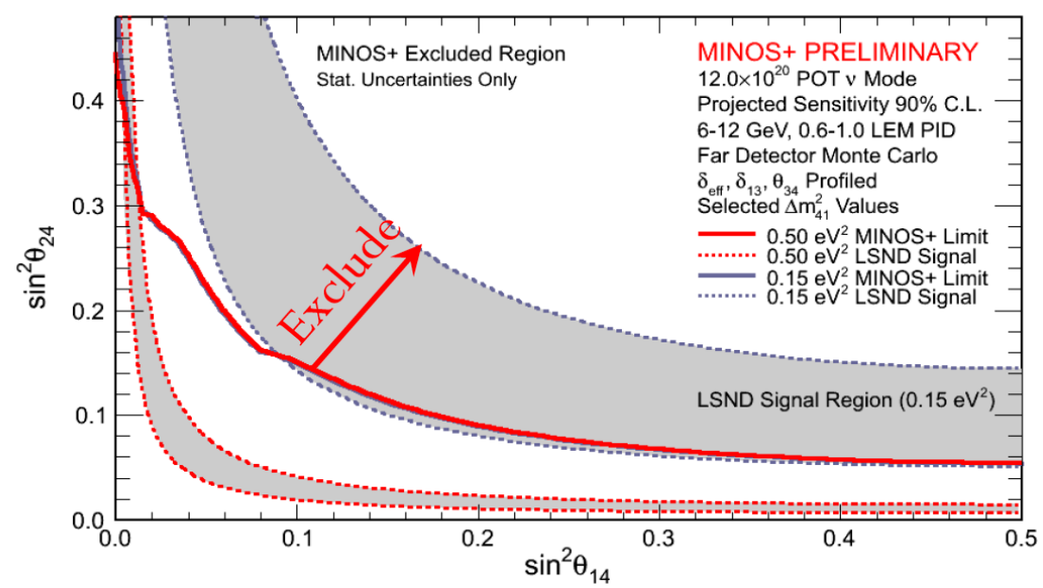
Numu Disappearance



Nue Appearance







- **Excluded large unexplored region** at low values of Δm^2_{43}

Combined **MINOS & Bugey** data **exclude** most of the region allowed by **LSND & MiniBooNE**

- Background dominated, but 2σ significance for appearance
- Difficult measurement due to interference of 3-flavor and 4-flavor oscillation terms

Sterile Neutrinos

- **SuperK - Jun Kameda**

$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4} & \cdots \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & U_{\tau 4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

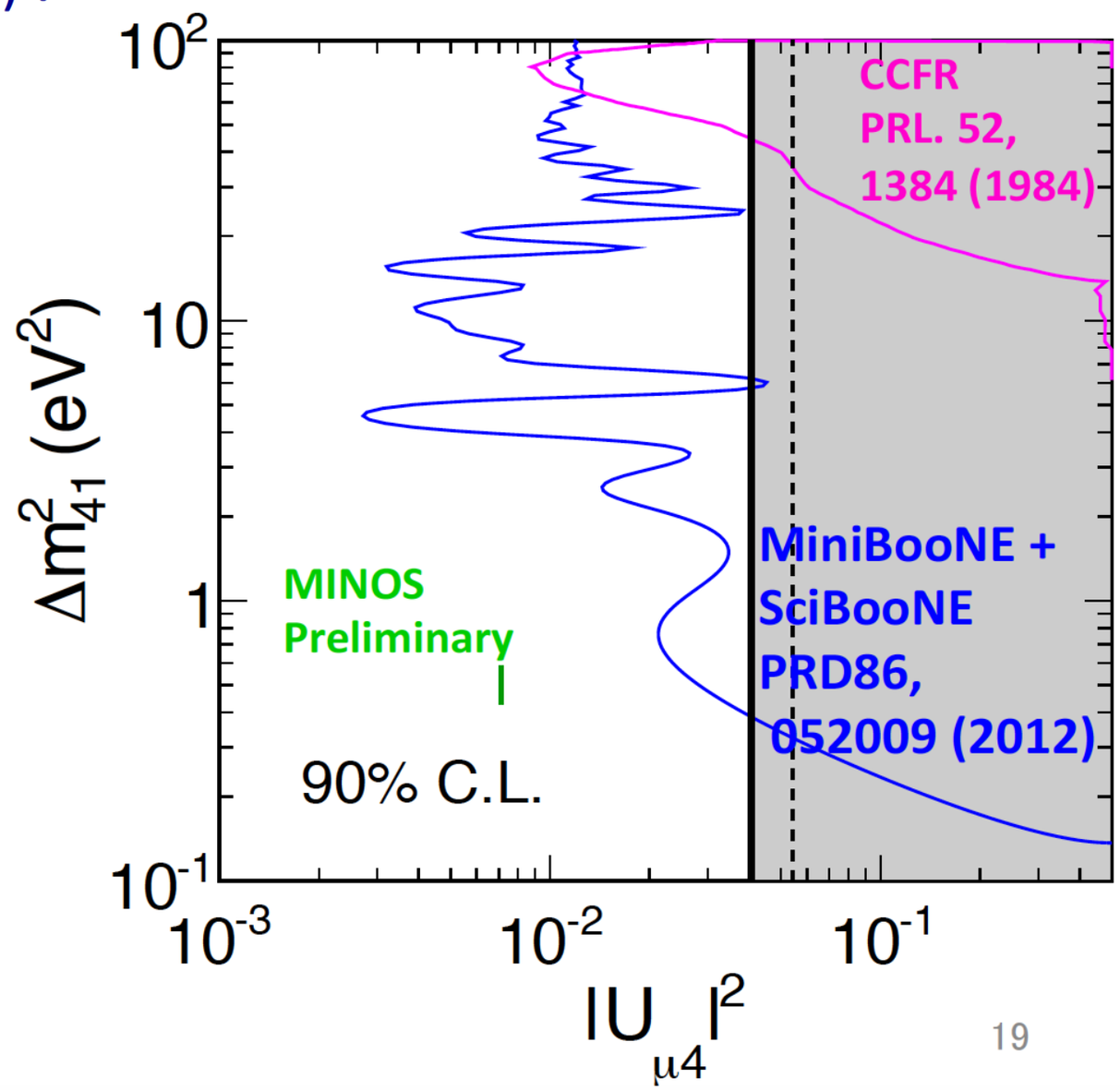
PMNS

Sterile

- (Standard neutrinos + sterile neutrinos) is tested for large Δm^2_{41} region (>0.01eV^2) .

As with similar experiments, no strong sterile-driven ν_μ disappearance

$|U_{\mu 4}|^2 < 0.041$ at 90% C.L.



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Sterile Neutrinos

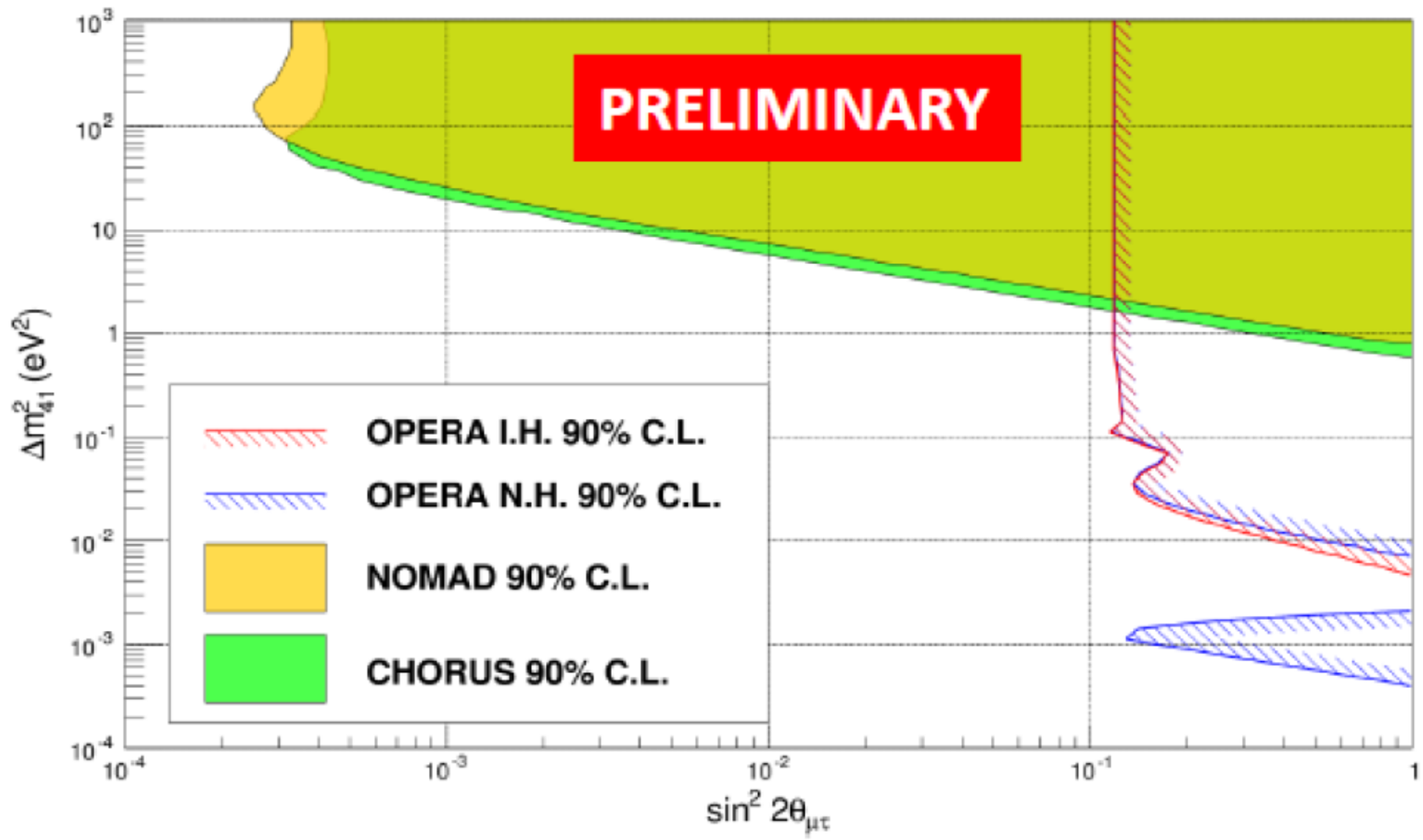
- **OPERA - Chiara Sirignano**

~ standard oscillation | pure exotic oscillation

$$P_{\nu_\mu\to\nu_\tau} = 4|U_{\mu3}|^2|U_{\tau3}|^2\sin^2\frac{\Delta_{31}}{2} + 4|U_{\mu4}|^2|U_{\tau4}|^2\sin^2\frac{\Delta_{41}}{2}$$
$$+ 2\Re[U^*_{\mu4}U_{\tau4}U_{\mu3}U^*_{\tau3}]\sin\Delta_{31}\sin\Delta_{41}$$
$$- 4\Im[U^*_{\mu4}U_{\tau4}U_{\mu3}U^*_{\tau3}]\sin^2\frac{\Delta_{31}}{2}\sin\Delta_{41}$$
$$+ 8\Re[U^*_{\mu4}U_{\tau4}U_{\mu3}U^*_{\tau3}]\sin^2\frac{\Delta_{31}}{2}\sin^2\frac{\Delta_{41}}{2}$$
$$+ 4\Im[U^*_{\mu4}U_{\tau4}U_{\mu3}U^*_{\tau3}]\sin\Delta_{31}\sin^2\frac{\Delta_{41}}{2}$$

interference terms

$\nu_\mu \to \nu_\tau$



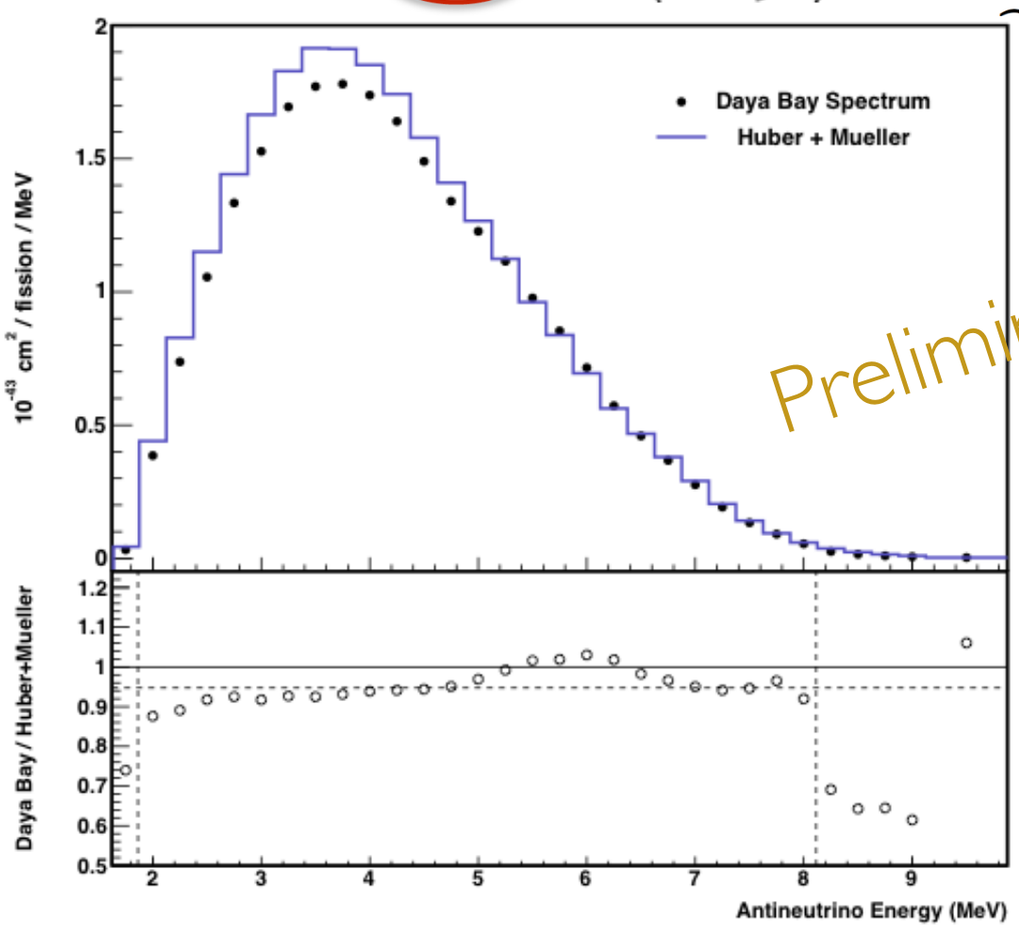
- Showing analysis updated to include 5 ν_τ events
- 4 event results published in **[JHEP 074 (2015) 0315]**

First limits on $|U_{\mu4}|^2|U_{\tau4}|^2$ from direct measurement of ν_τ

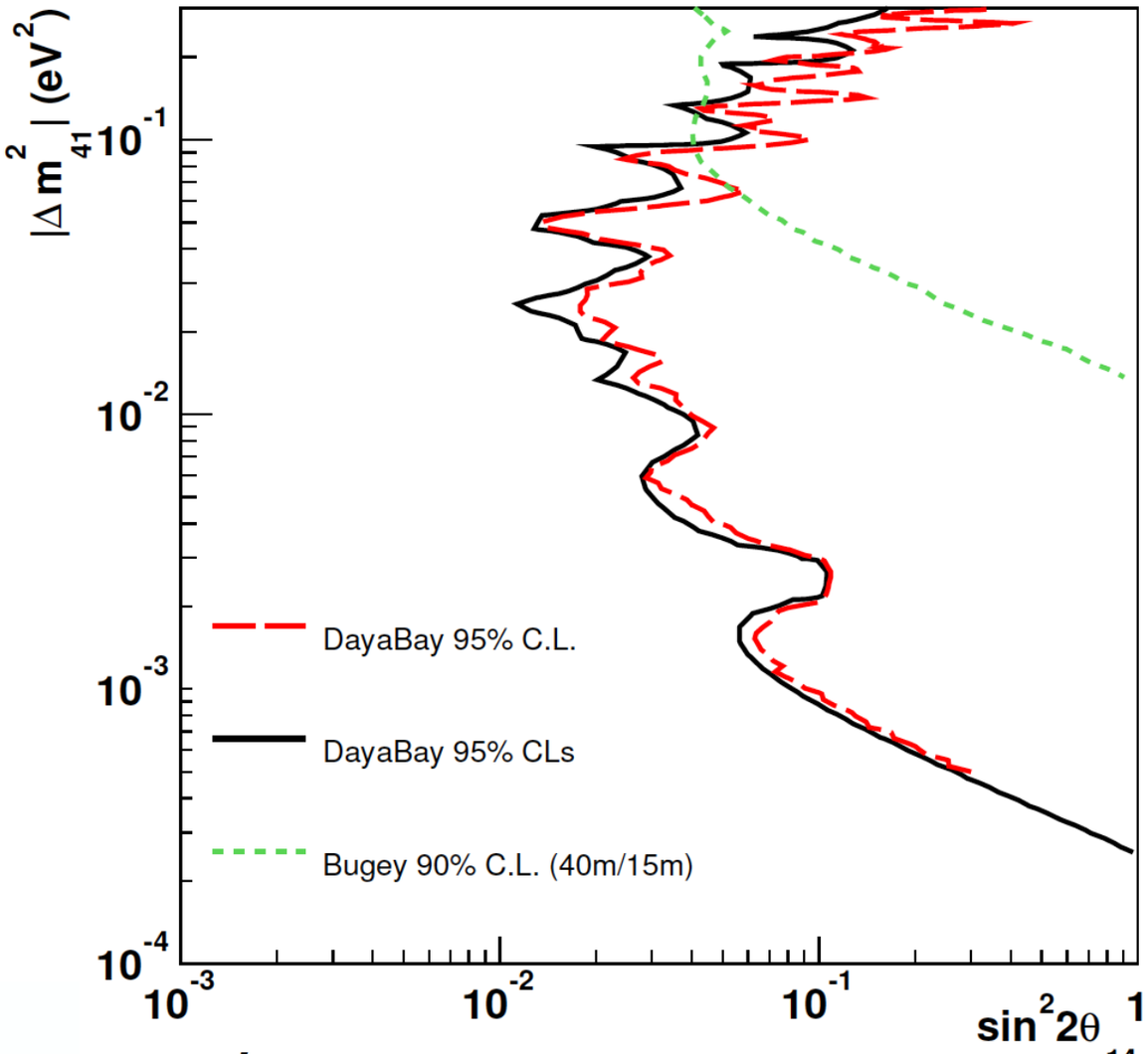
Sterile Neutrinos

- Daya Bay - Wei Wang

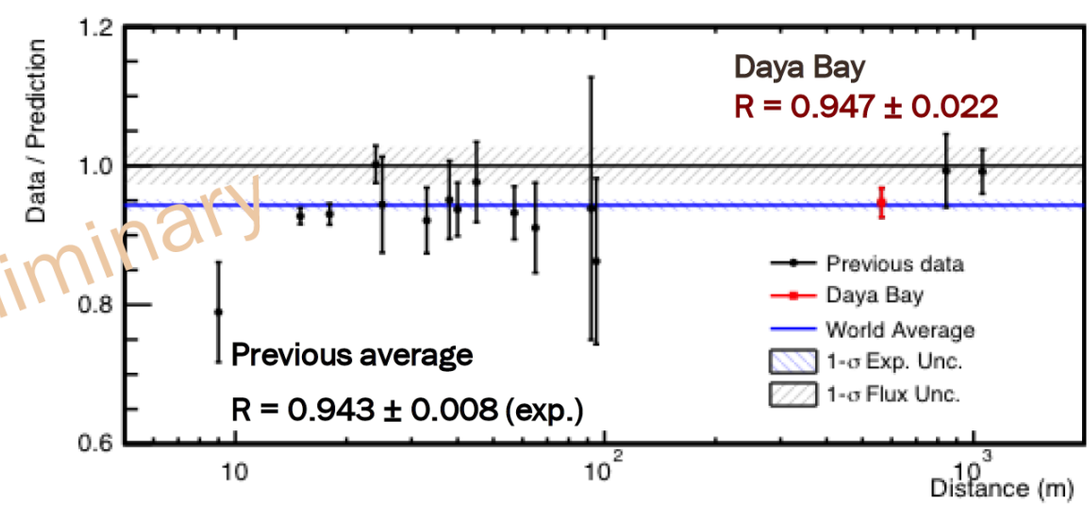
$$P(\bar{\nu}_e \to \bar{\nu}_e) \simeq 1 - \cos^4\theta_{14}\sin^2 2\theta_{13}\sin^2\left(\frac{\Delta m^2_{ee}L}{4E_\nu}\right) - \sin^2 2\theta_{14}\sin^2\left(\frac{\Delta m^2_{41}L}{4E_\nu}\right)$$



Preliminary



Phys. Rev. Lett. 113, 141802 (2014)

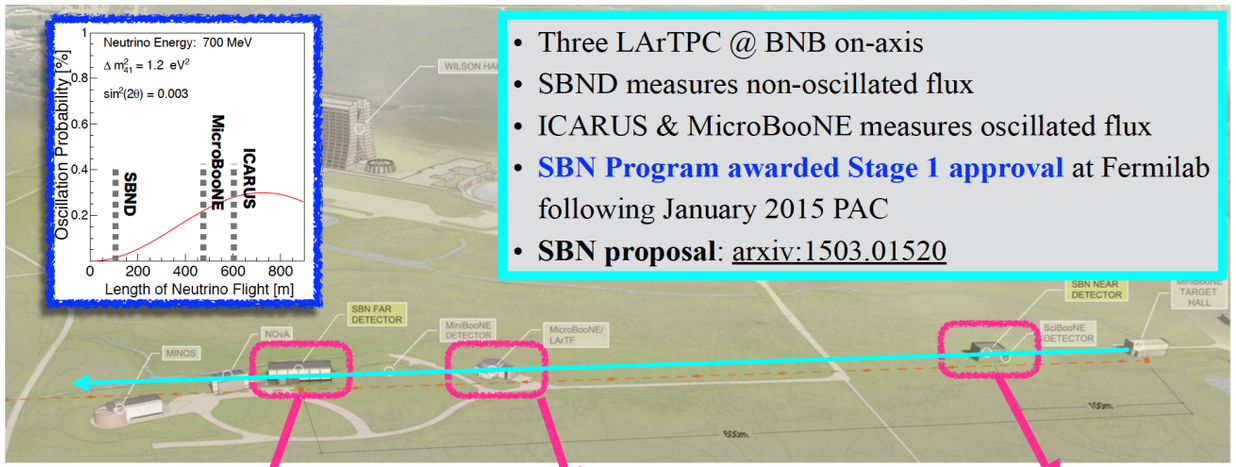


Preliminary

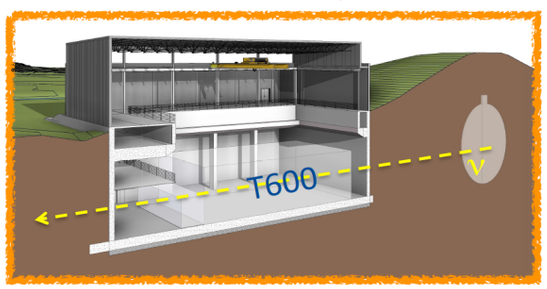
- Daya Bay agrees with reactor flux average from previous experiments
- Have produced unfolded flux spectrum to be used for flux and spectrum predictions

Sterile Neutrinos - Future

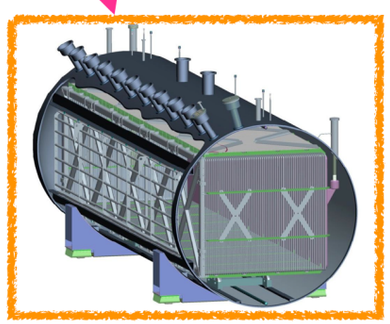
Short-Baseline Program @ Fermilab - Kazuhiro Terao



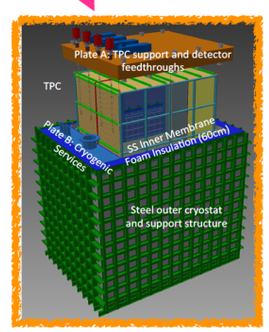
- Three LArTPC @ BNB on-axis
- SBND measures non-oscillated flux
- ICARUS & MicroBooNE measures oscillated flux
- **SBN Program awarded Stage 1 approval** at Fermilab following January 2015 PAC
- **SBN proposal**: arxiv:1503.01520



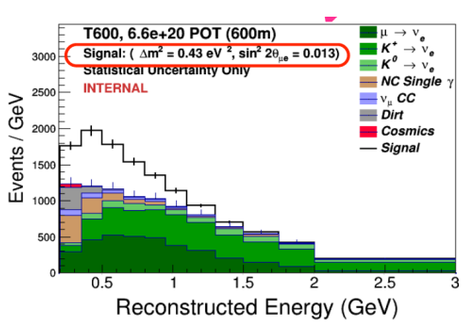
ICARUS T600
~476 ton @ 600 m

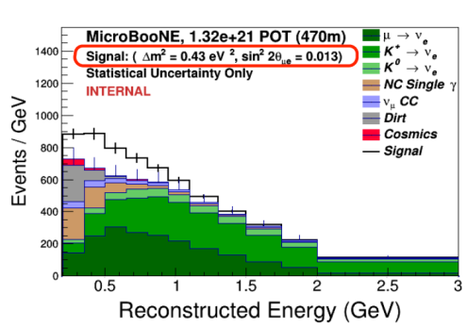


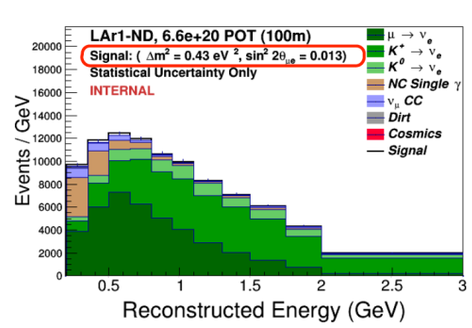
MicroBooNE
~87 ton @ L = 470 m

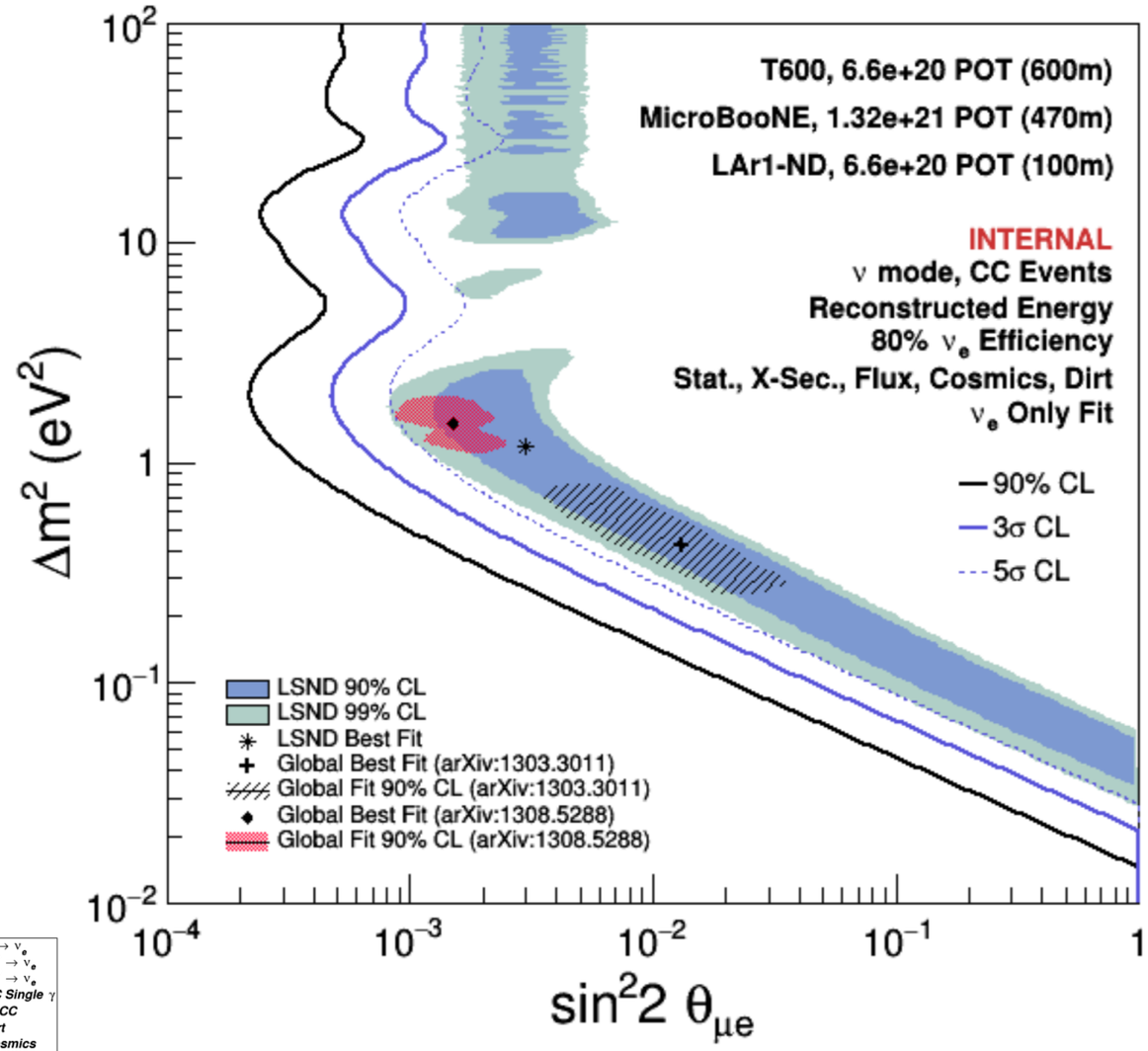


SBND
~112 ton @ L = 110 m





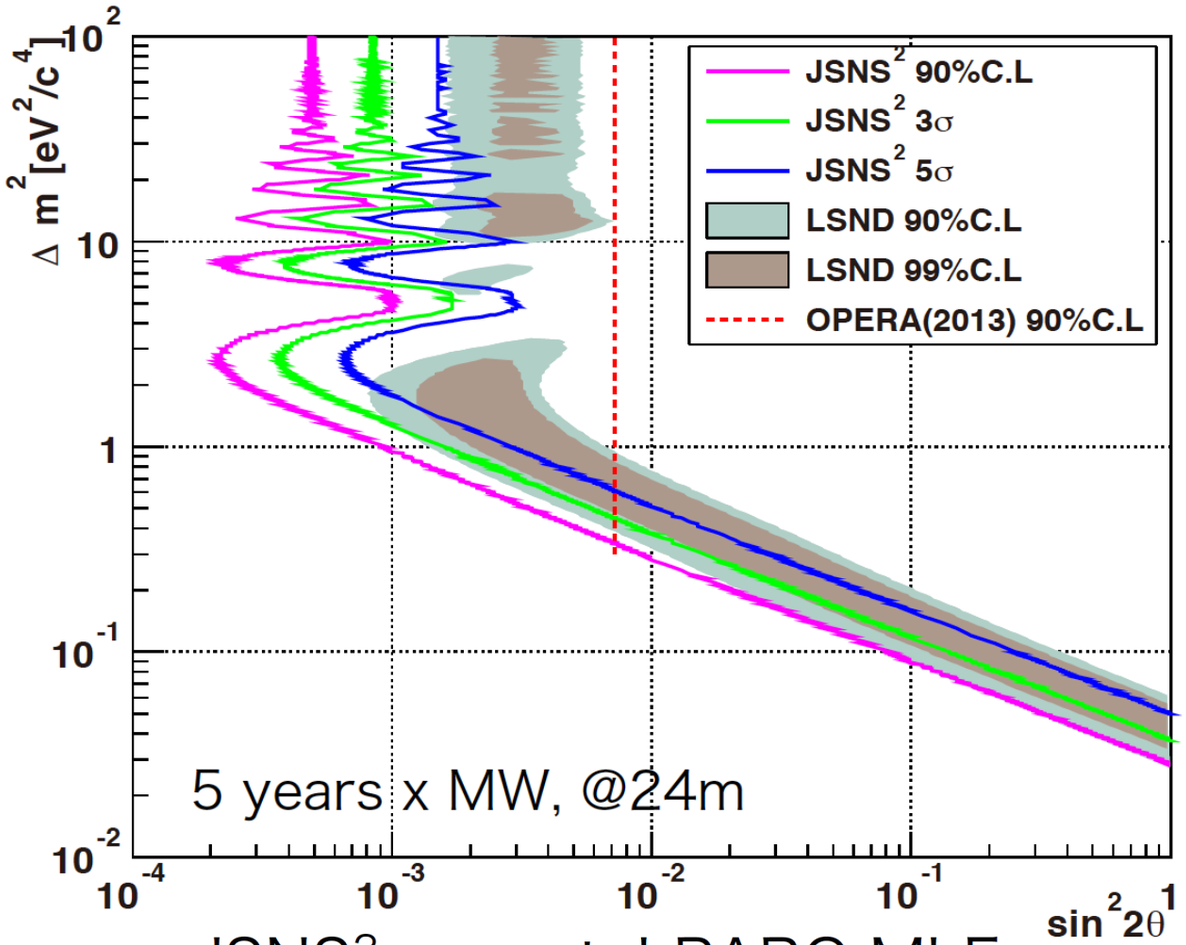




- MicroBooNE taking cosmic data!
- ICARUS undergoing refurbishment at CERN. Deployment at Fermilab in 2017
- Ongoing R&D program for SBND

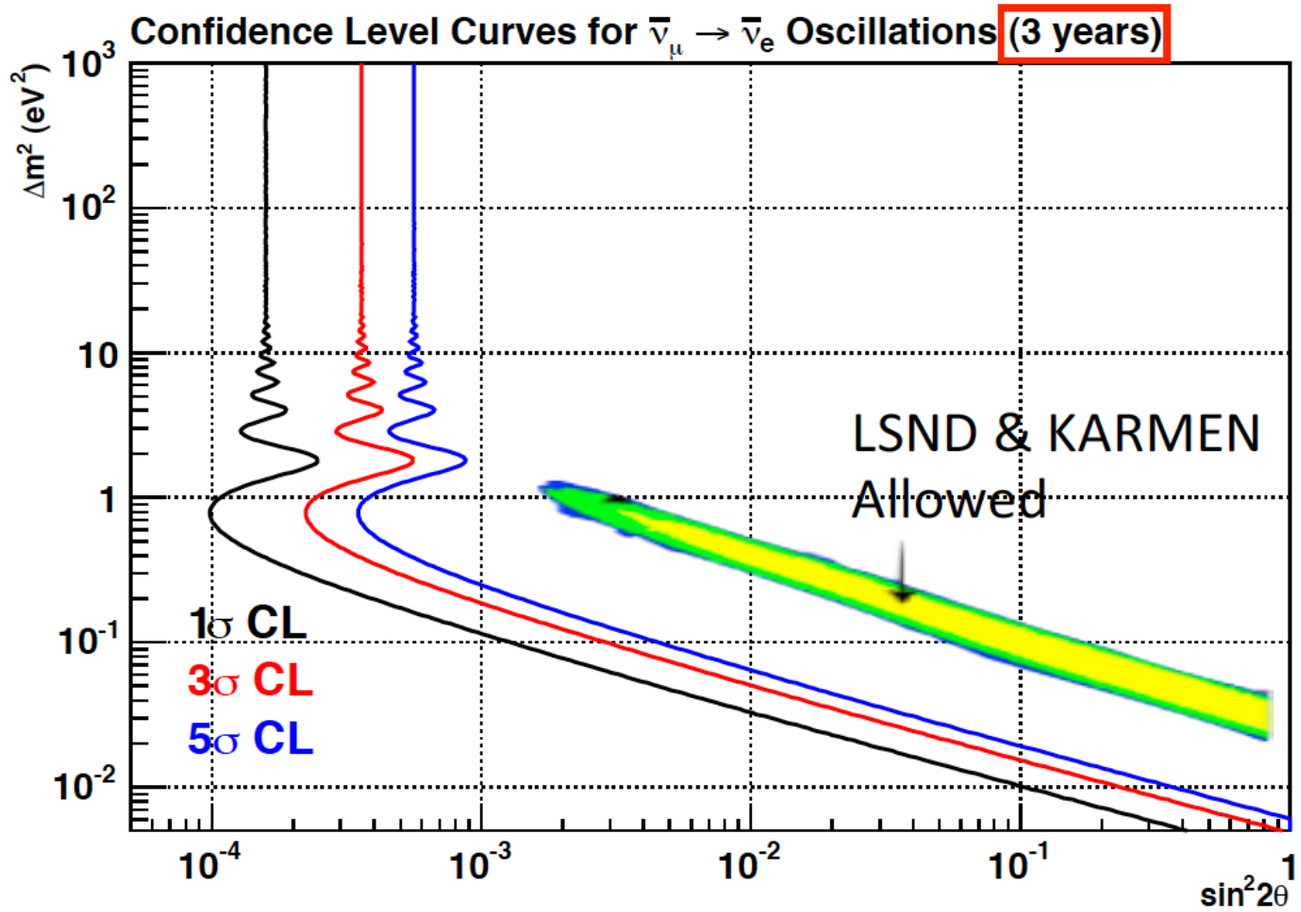
Sterile Neutrinos - Future

- Decay-at-rest Experiments - Eito Iwai



JSNS² exp. at J-PARC MLF

- beam energy: 3GeV
- beam power: 1MW designed, 500kW continuous
  - 24 m baseline
  - 2x50t LS detectors in phase 1 for $4M
  - Phase 2 would use 1 kt detector



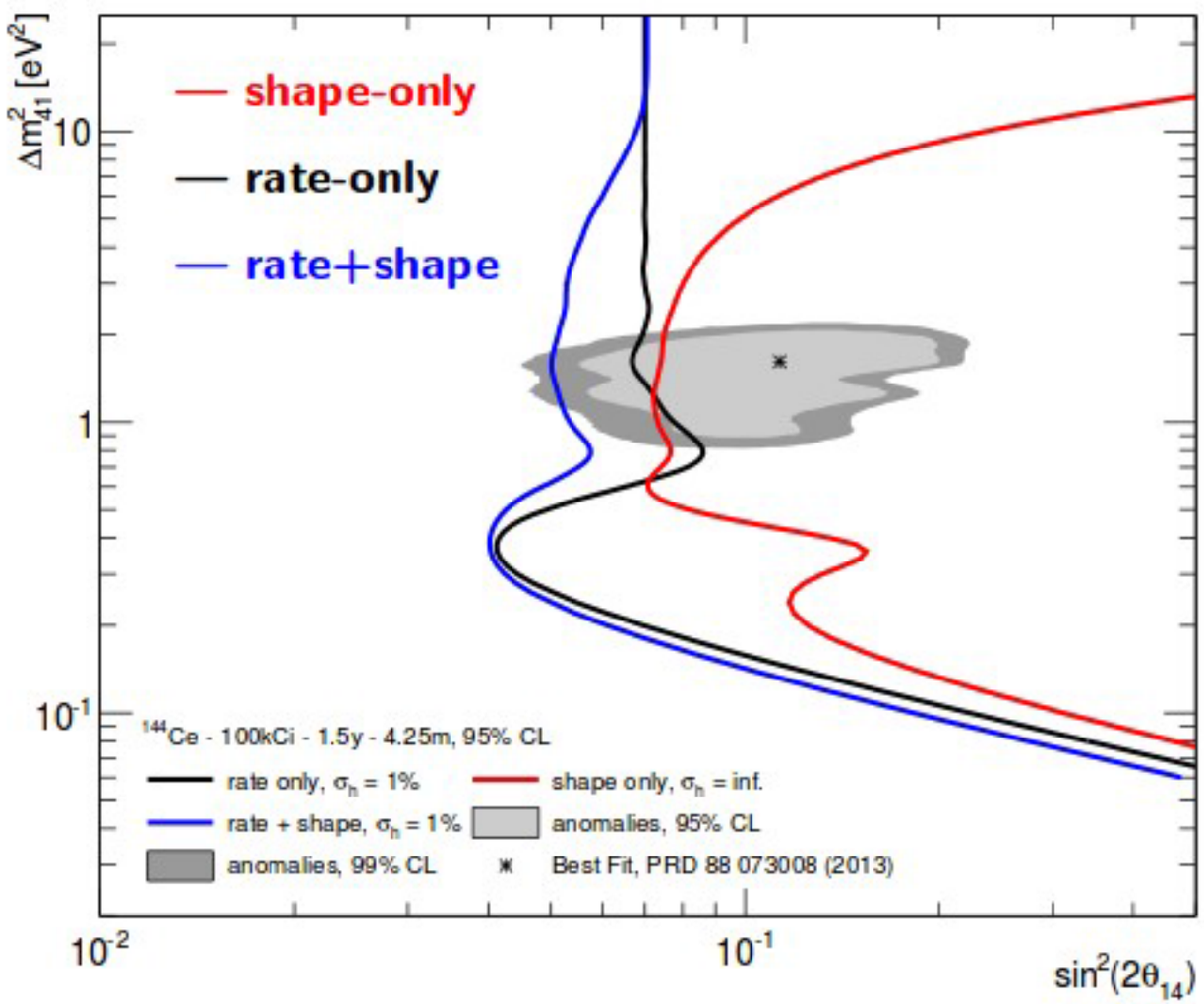
OscSNS at Oak Ridge National Laboratory

- proton beam: 1GeV, 1.4MW
  - 60 m baseline
  - 450t fiducial LS detector for $22M
  - 3 years from ground breaking to operations

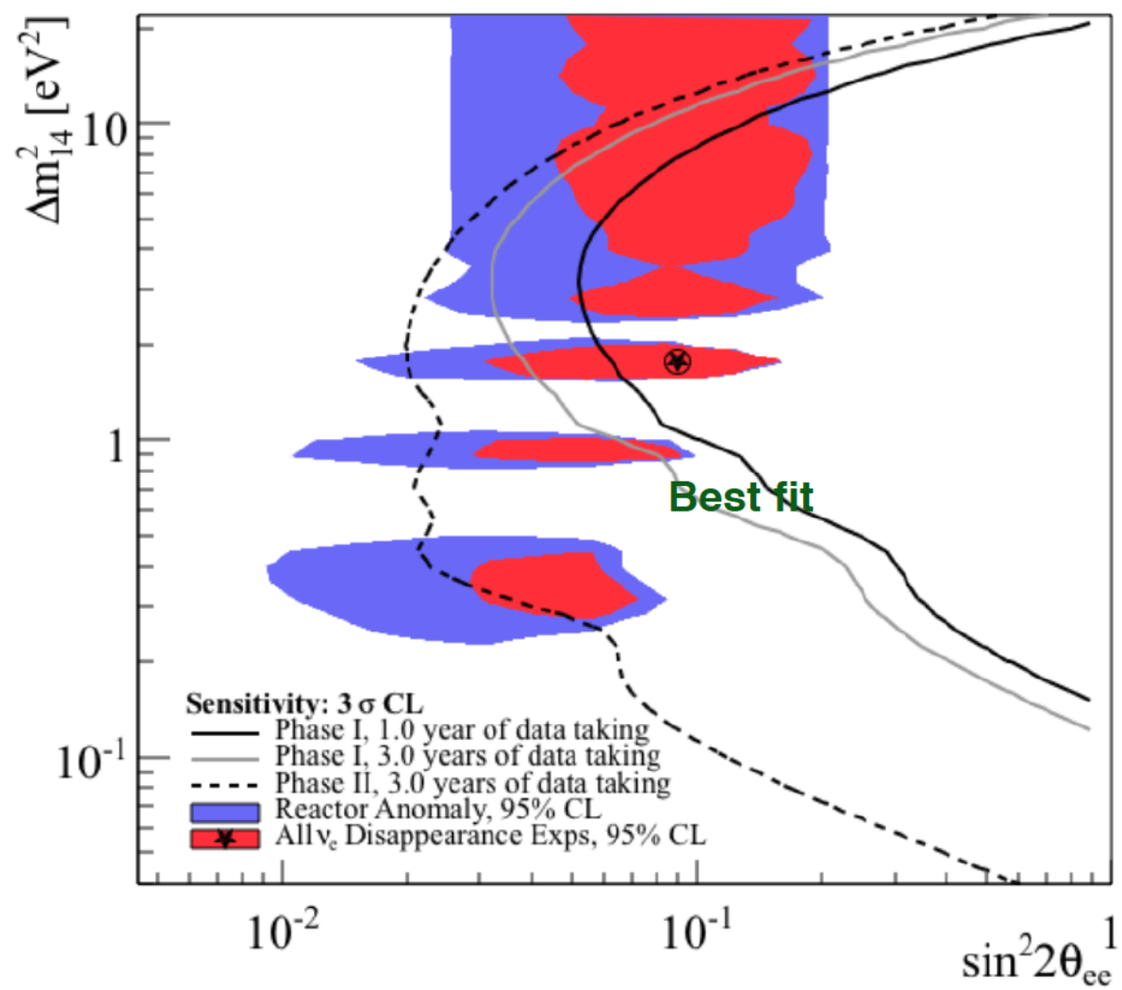
Sterile Neutrinos - Future

- Source Experiments - Chiara Ghiano; SBL Reactors - David Martinez

SOX-CE



PROSPECT



- 3.7 Pbq ^{144}Ce measured at Borexino
- Can exclude most of reactor/gallium anomalies at 95% CL from rate+oscillometry measurements
- Data taking starting in 2016, results in 2017

- Place 2.5 ton LS detector at Oak Ridge Research reactor
- Measure L-dependence of osc. prob.
- Ongoing R&D, seeking funding for Phase 1

Answer to Q5

Question from NUFACT '14: *What is the best strategy to fully probe the LSND anomaly? And the reactor/gallium anomaly?*

- Muon decay-at-rest experiments provide the most direct test of the LSND anomaly, but pion decay-in-flight SBN program at Fermilab has best near-term sensitivity to probe LSND region

- Long-baseline experiments provide complementary probes of disappearance and appearance due to sterile neutrino mixing

- Source experiments and SBL reactor experiments will both provide powerful tests of the reactor and gallium anomalies.

	Experiment	ν Source	ν Type	Channel	Host	Cost Category[1]
radioactive	CeLAND [259]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	Kamioka, Japan	small[2]
	Daya Bay Source [260]	^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.	China	small
	SOX [261]	^{51}Cr	ν_e	disapp.	LNGS, Italy	small[2]
		^{144}Ce-^{144}Pr	$\bar{\nu}_e$	disapp.		
	BEST [64]	^{51}Cr	ν_e	disapp.	Russia	small
reactor	PROSPECT [262]	Reactor	$\bar{\nu}_e$	disapp.	US[3]	small
	STEREO	Reactor	$\bar{\nu}_e$	disapp.	ILL, France	N/A[4]
	DANSS [263]	Reactor	$\bar{\nu}_e$	disapp.	Russia	N/A[4]

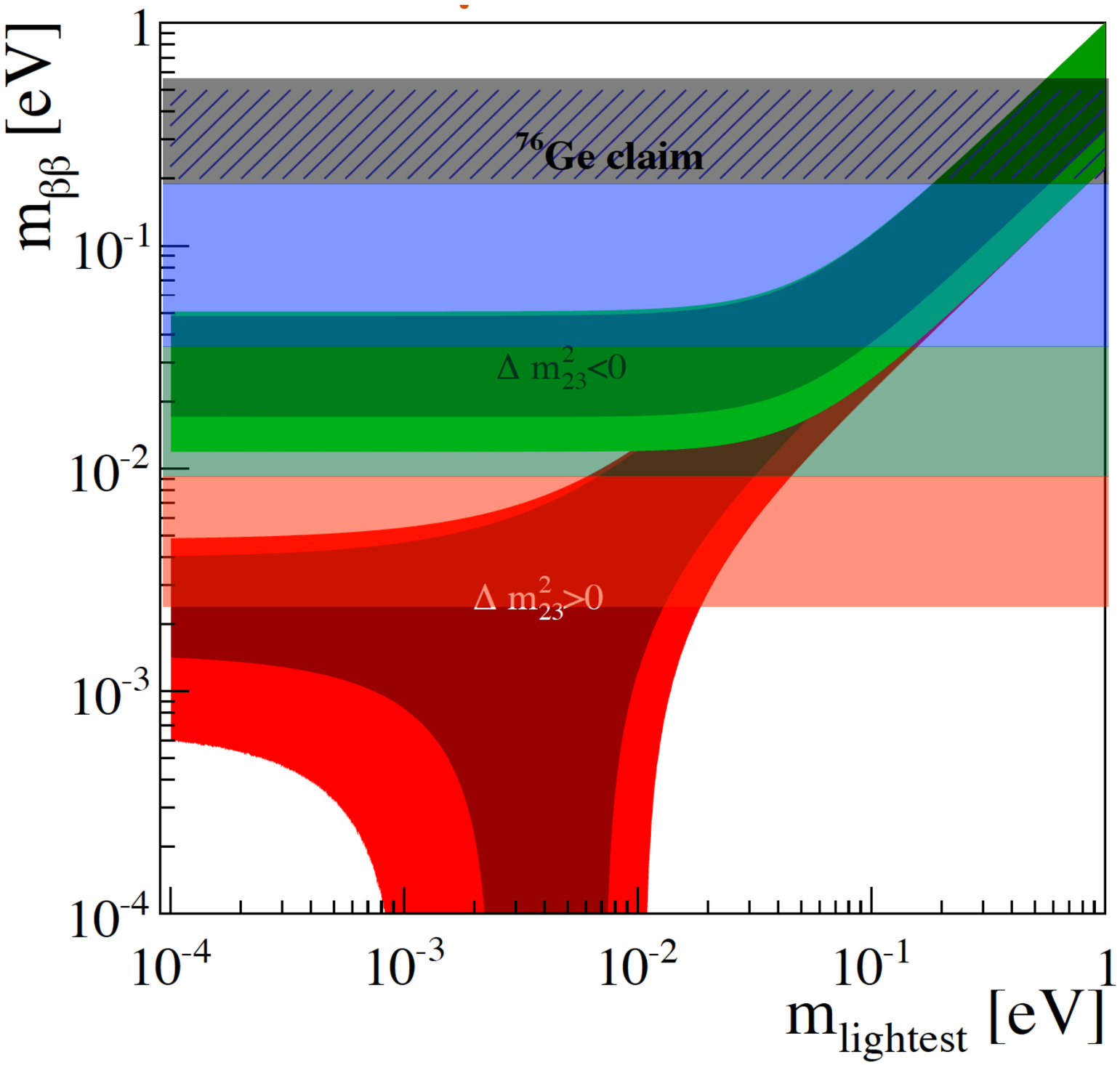
CSS 2013 (Snowmass) Neutrino Report, arXiv:1310.4340 (2013)

Q6: Majorana mass scale

Question from NUFACT '14: What can we say about the new Majorana mass scale implied by neutrino masses? What are the current bounds and how much will they improve over the next decade?

Q6: Majorana mass scale

- Yury Kolomensky - Review of neutrinoless double beta decay



Past and present (~10 kg)

Present and near future (~100 kg)

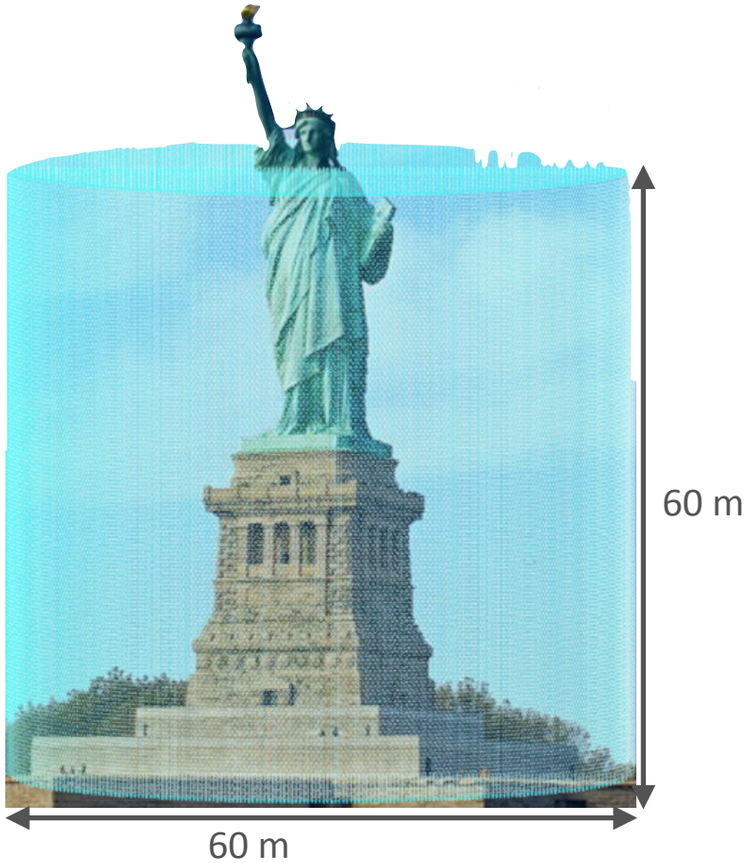
Future (~1000 kg)

Dreams ? (~10000+ kg?)

$$m_{\beta\beta} = |\sum_i m_i \cdot U_{ie}^2|$$

Majorana mass scale

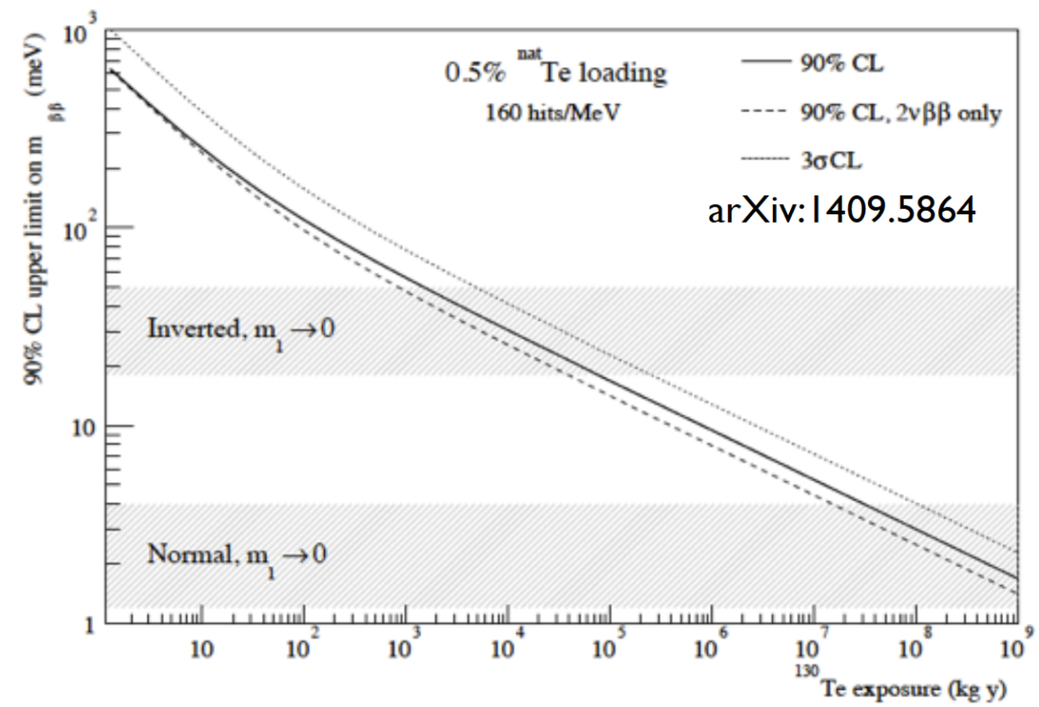
THEIA - Gabriel Orebi Gann



- Large-scale detector (50-100 kton)
- WbLS target
- Fast, high-efficiency photon detection with high coverage
- Deep u/ground (Pyhäsalmi, Homestake)
- Isotope loading (Gd, Te, Li...)
- ***Flexible***! Target, loading, configuration

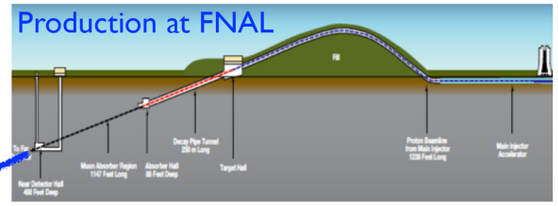
➡ **Broad physics program!**

1. Neutrinoless double beta decay
2. Solar neutrinos (solar metallicity, luminosity)
3. Geo-neutrinos
4. Supernova burst neutrinos & DSNB
5. Source-based sterile searches
6. Nucleon decay
7. Long-baseline physics (mass hierarchy, CP violation)

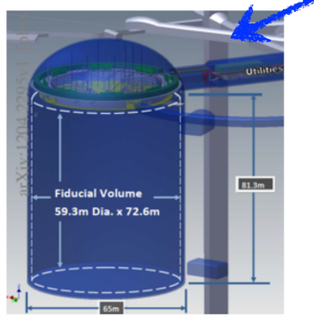


⇛ **3σ discovery for $m_{\beta\beta}$=15meV in 10 yrs**

- Large-scale detector at Homestake, in the LBNF beam
- Complementary program to proposed LArTPC
- Build on WCD studies (arXiv:1204.2295)



1300km



Images from arXiv:1204.2295

- Ring-imaging of a water Cherenkov detector
- Particle ID from Cher/scint separation
- n and low-E hadron detection (low threshold)
  - reduce wrong-sign component (nu vs anti-nu)
  - reduce NC background by detecting $\pi^0 \rightarrow \gamma\gamma$
- Large size → sensitivity to 2nd oscn max

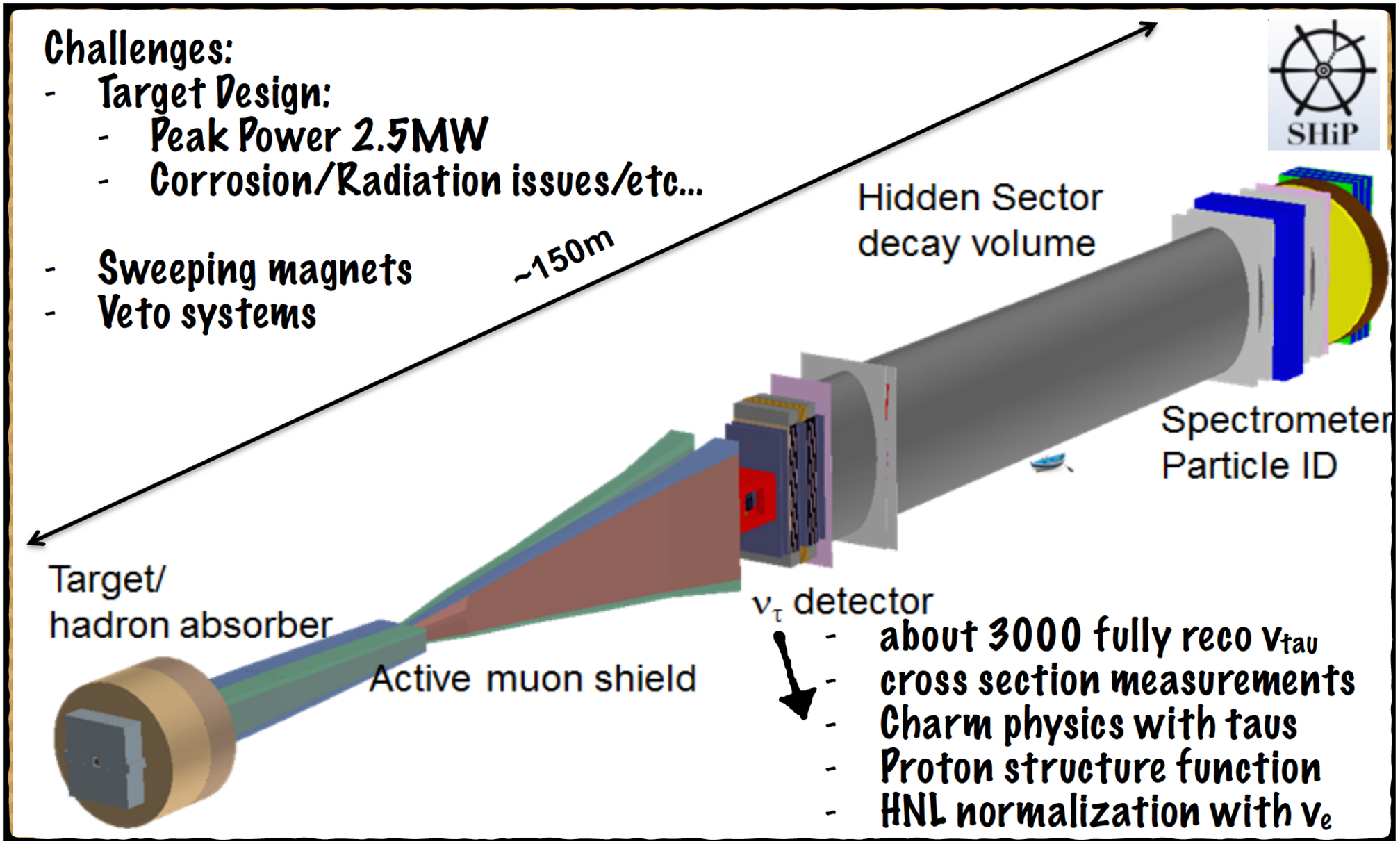
MH sensitivity for 34kT WbLS alone > 4.8 σ

- Ongoing R&D for modeling of light production in WbLS, isotope loading, photon detectors (LAPPD), etc.

Q7: Non-Oscillation Constraints

Question from NUFACT '14: How can we explore synergies between neutrino oscillations and other experiments (absolute mass searches, cosmological constraints, CLFV) to constrain new physics?

- **Heavy Neutrinos - Nicola Serra (ShiP Experiment@CERN)**



New Questions For Next NuFact

Question: *What are the new developments and predictions from flavor models on neutrino oscillation parameters? What precision do we need to achieve to probe them? Which parameters (or combinations of them) are more powerful to test them?*

Question: *Are atmospheric neutrino and medium-baseline reactor measurements competitive with next generation long-baseline facilities in the determination of the mass hierarchy? And the octant of θ_{23}? How much complementarity is there between them?*

Question: *What is the best statistical metric to report sensitivity of experiments to mass hierarchy and CP violation?*

Question: *How important is it to account for correlations between systematic uncertainties in different experiments when producing global fits? How do we increase involvement of experiments in production of joint results?*

New Questions For Next NuFact

Question: *What do we need to do to reach the required systematic error budget level? How much improvement in constraining flux and cross section uncertainties can we expect from dedicated hadron production, cross-section measurements, and near detector efforts? How can we improve knowledge of nue cross sections and improve energy reconstruction?*

Question: *Do the current bounds on new physics in the neutrino sector (NSI, non-unitarity, steriles…) allow for effects large enough to interfere with CPV searches? And with other parameters like mass hierarchy ? Which experimental setups can improve these bounds?*

Question: *Is the current landscape of proposed experiments able to conclusively probe the LSND anomaly? And the reactor/gallium anomaly?*

New Questions For Next NuFact

Question: *What can we say about the Majorana mass scale implied by neutrino masses? How much will the current bounds improve over the next decade?*
If normal hierarchy is confirmed, what new strategies are available to probe the Majorana/Dirac nature of the neutrino.

Question: *How can we explore synergies between neutrino oscillations and other experiments (absolute mass searches, cosmological constraints, CLFV) to constrain new physics?*

Question: *What could an R&D program leading to a neutrino factory look like in the present landscape of LBL experiments? What physics could we probe with it and how complementary would it be to the ongoing LBL efforts?*

Many Thanks to all WG1 Speakers
and a very lively Audience!