WG1 – Neutrino Oscillations Summary

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WG1 Sessions

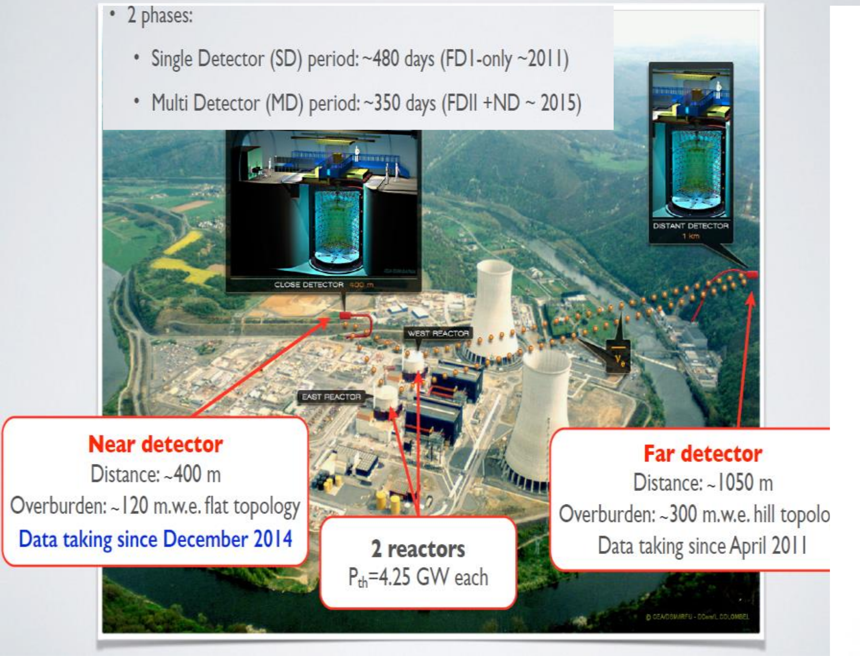
- A total of 6 sessions:
  - Monday 14:00 – Reactors
  - Tuesday 11:00 – Joint w/ WG5 [report in WG5 talk]
  - Tuesday 14:00 – Joint w/ WG2 [report In WG2 talk]
  - Wednesday 11:00 – Current LBN
  - Thursday 14:00 – Future LBN
  - Friday 11:00 – Joint w/ WG2 [report in this talk]
  - Friday 14:00 – Atmospherics
- A total of 6 posters

Reactors

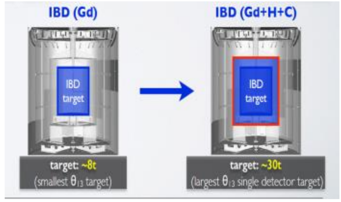
- Latest results of the Double Chooz reactor neutrino experiment, C. Jollet
- Recent results from RENO, M. Youl Pac
- Latest results from the Daya Bay experiment, J. Pedro Ochoa Ricoux
- Physics prospects of the JUNO experiment, B. Clerbaux
- Status of the JUNO experiment, J. Pedro Ochoa Ricoux

Reactor Experiments

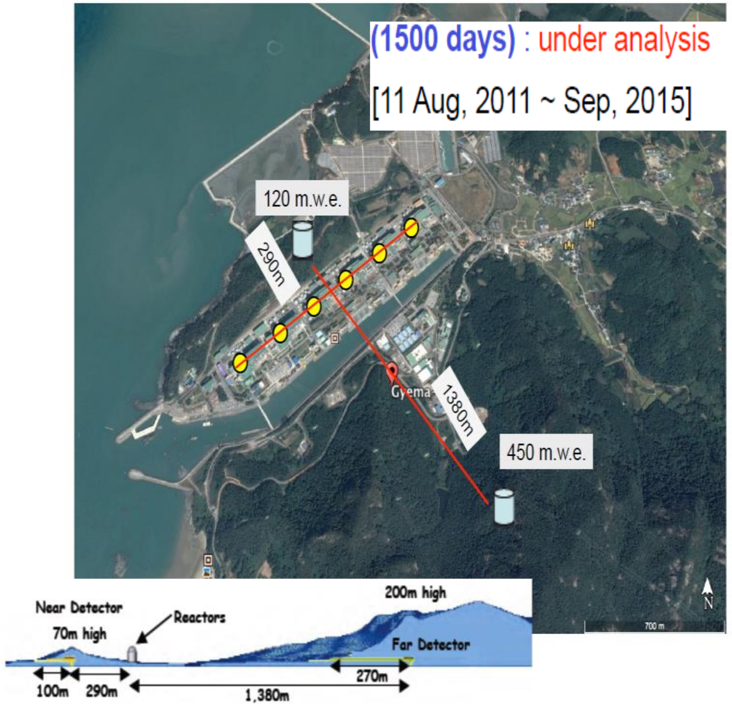
Double Chooz, C. Jollet



- Near detector
- Use Gamma Catcher as neutrino target

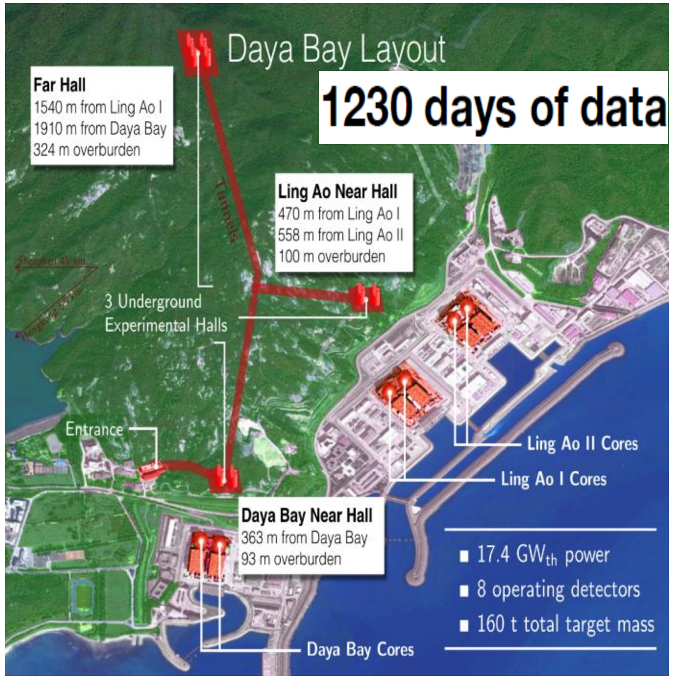


RENO, M. Youl Pac

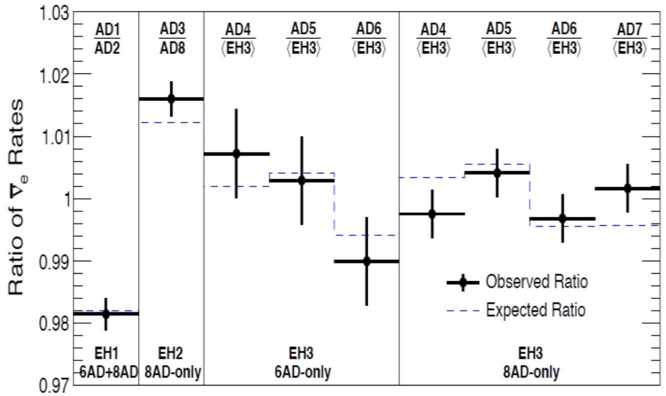


- Background reduction
- Larger stat of control samples

- All analysing nH as well

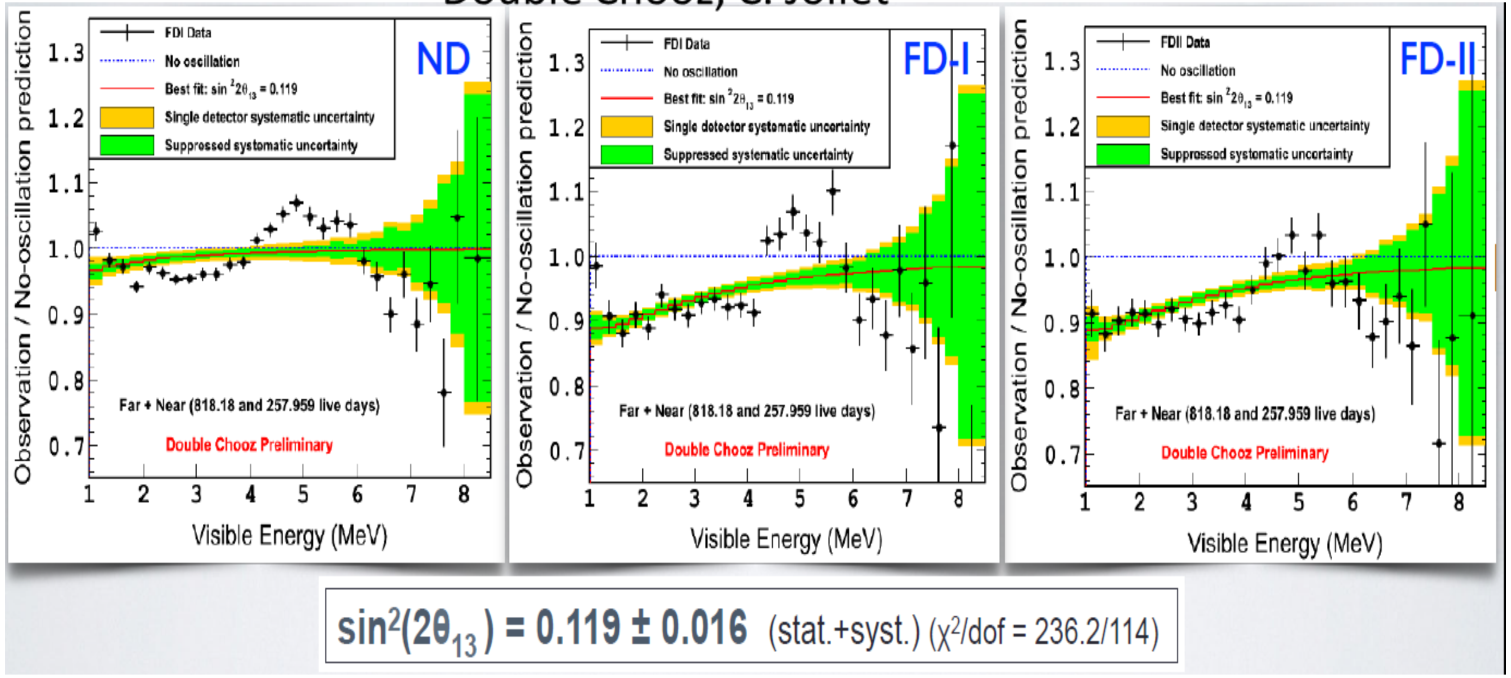


Daya Bay, J. Pedro Ochoa Ricoux

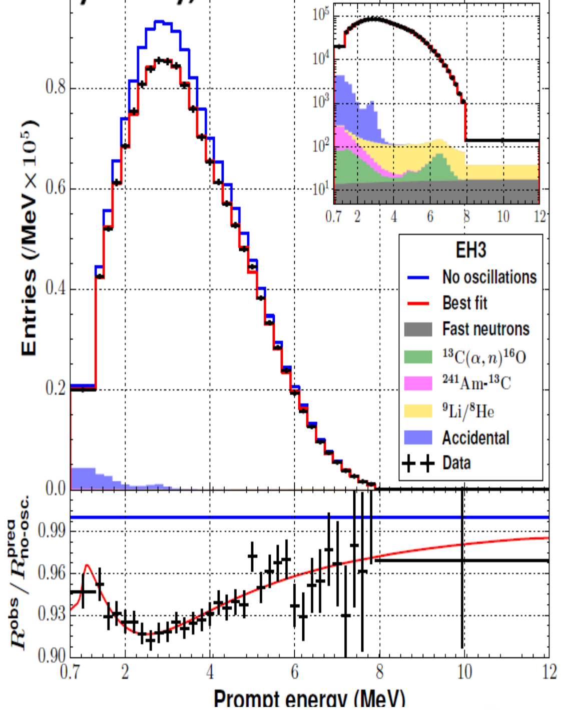


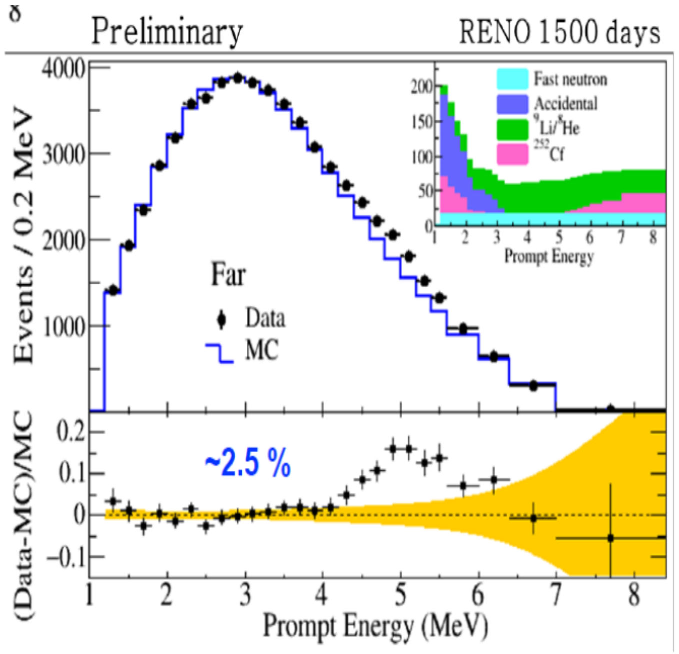
- One of main improvement: side-by-side comparison
- Reduction of relative detector efficiency uncertainty to 0.13%

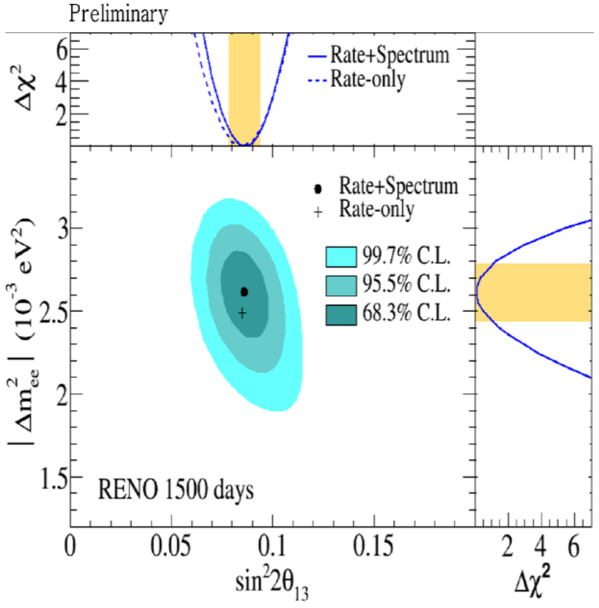
Double Chooz, C. Jollet



Daya Bay, J. Pedro Ochoa Ricoux



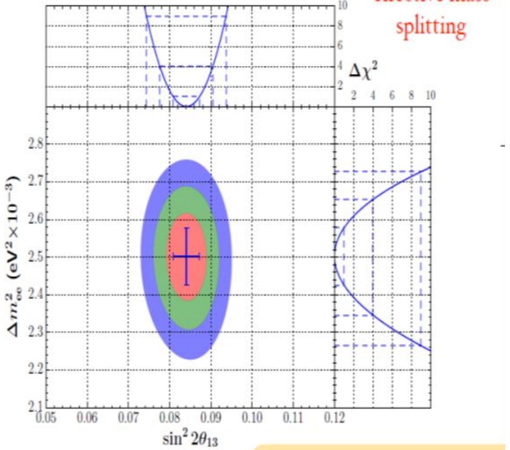




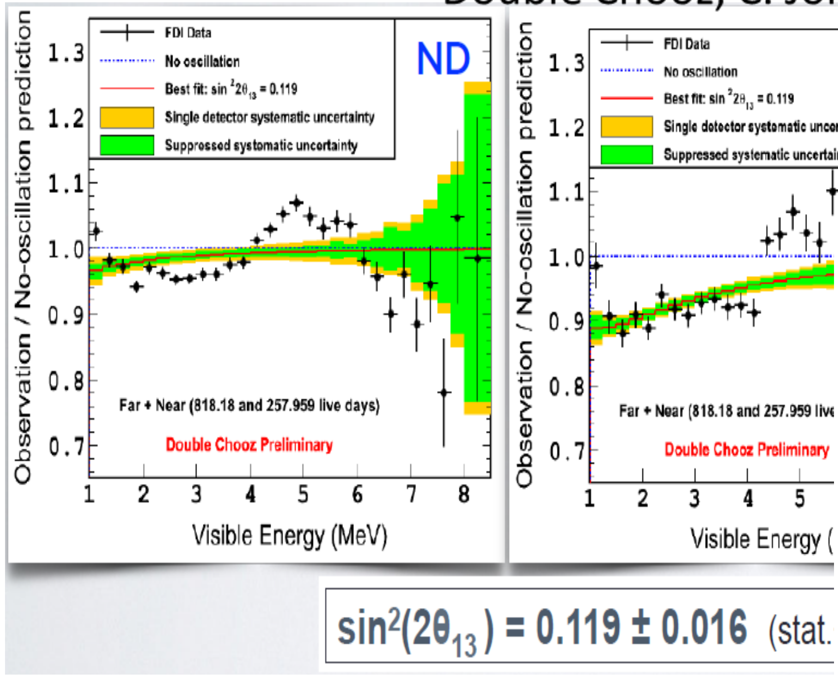
RENO, M. Youl Pac

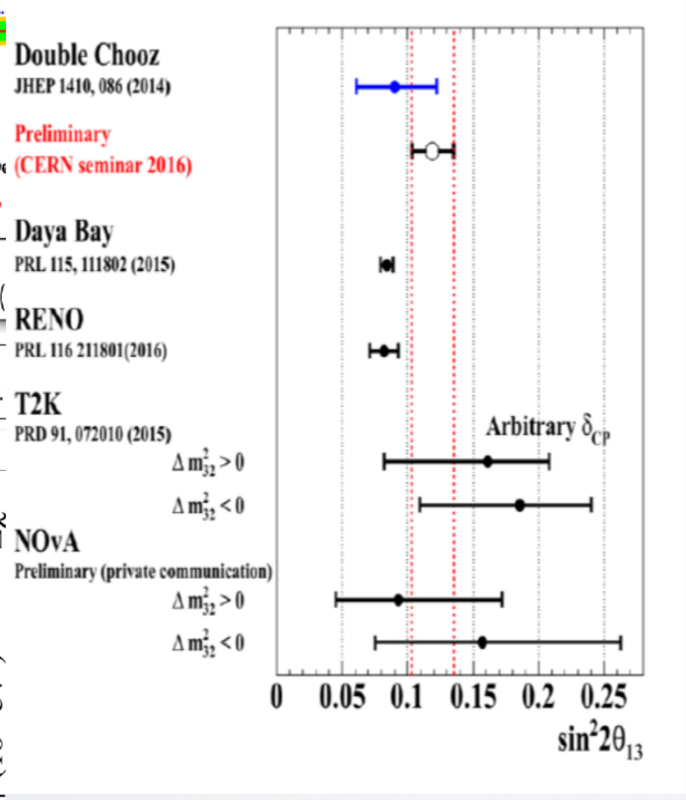
$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = 1 - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2 \frac{1.267\Delta m^2_{21} L}{E} - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E}$$

effective mass splitting

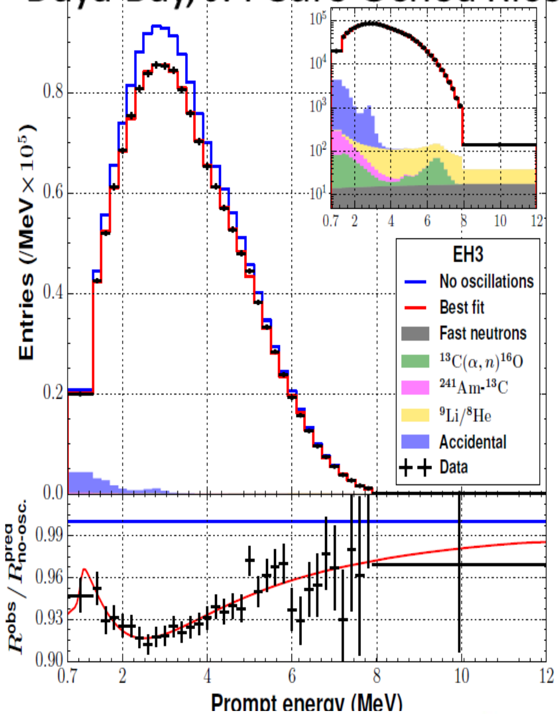


Double Chooz, C. Jollet





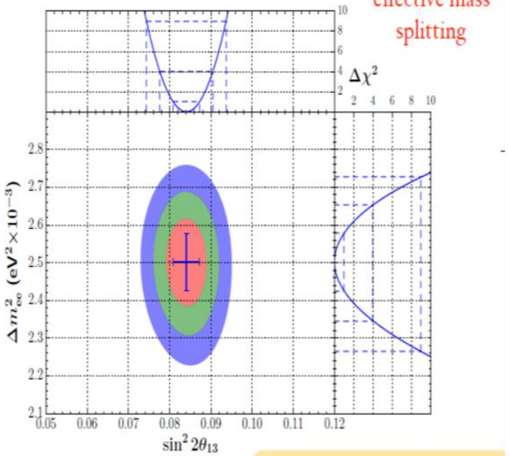
Daya Bay, J. Pedro Ochoa Ricoux

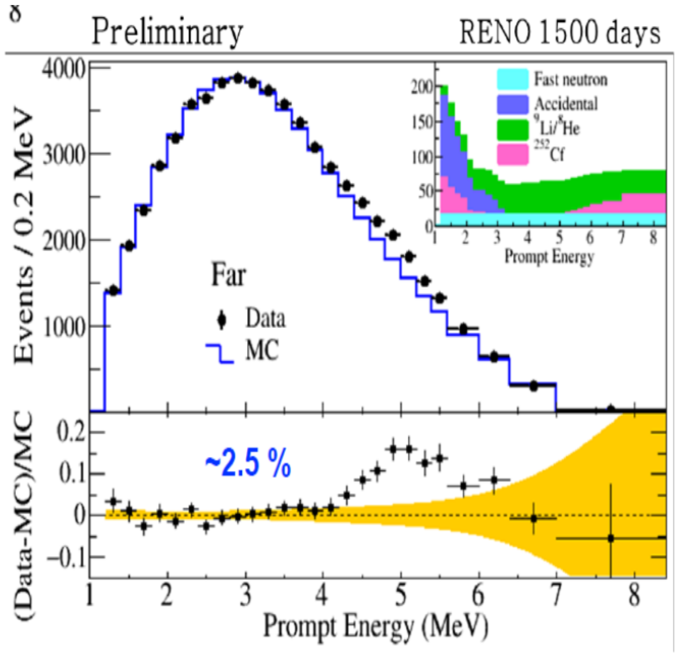


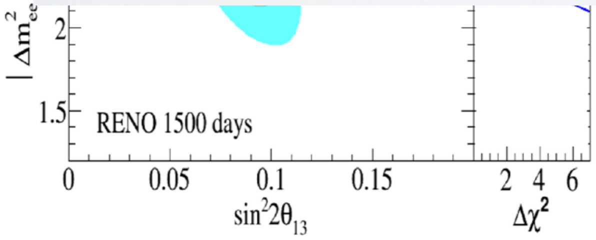
$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\frac{1.267\Delta m^2_{21}L}{E}$$

$$-\sin^2 2\theta_{13}\sin^2\frac{1.267\Delta m^2_{ee}L}{E}$$

effective mass splitting





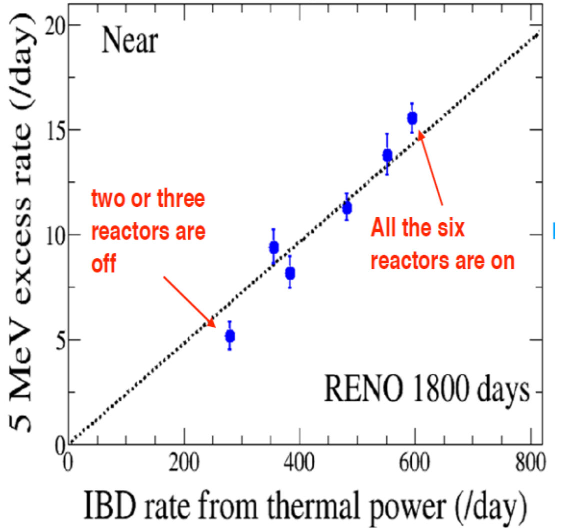


RENO, M. Youl Pac

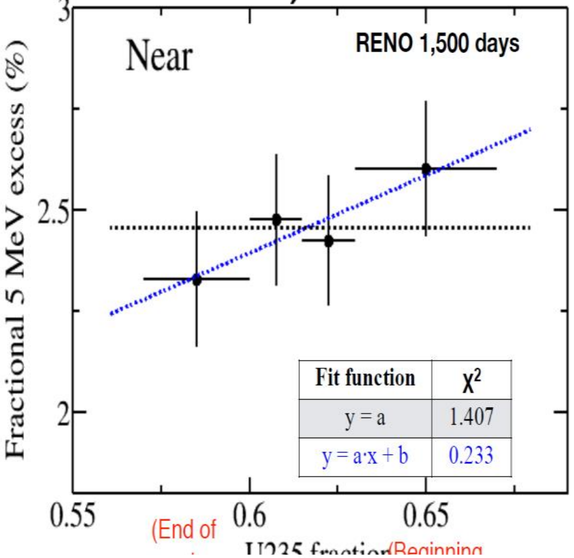
5MeV Bump and Fuel Evolution

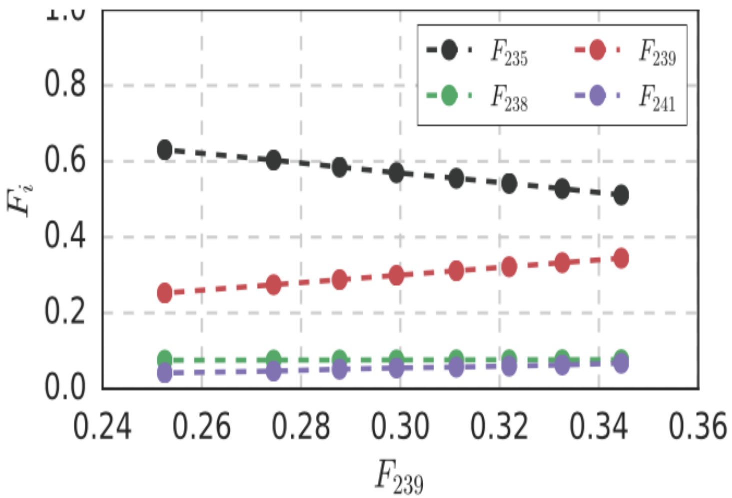
- As the nuclear fuel burns, the effective fission fractions (F) change
- Clear changes in flux and shape vs. F239
- Evolution of yield/fission is inconsistent with prediction from Huber + Mueller model at ~3σ

Preliminary RENO, M. Youl Pac

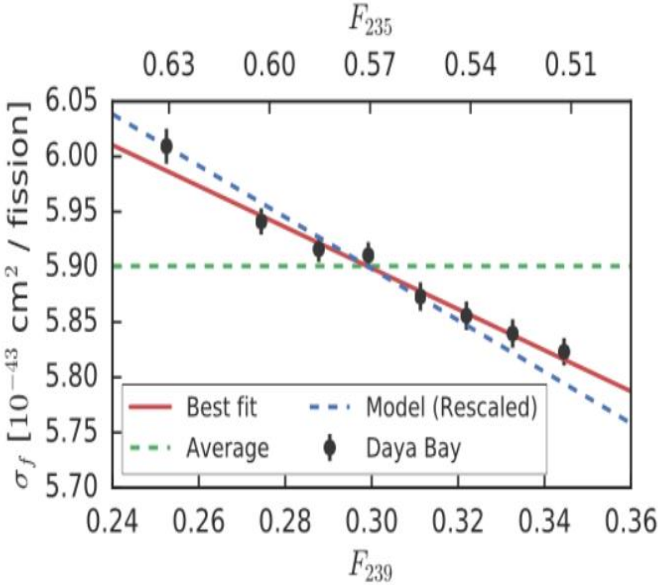


Preliminary RENO, M. Youl Pac

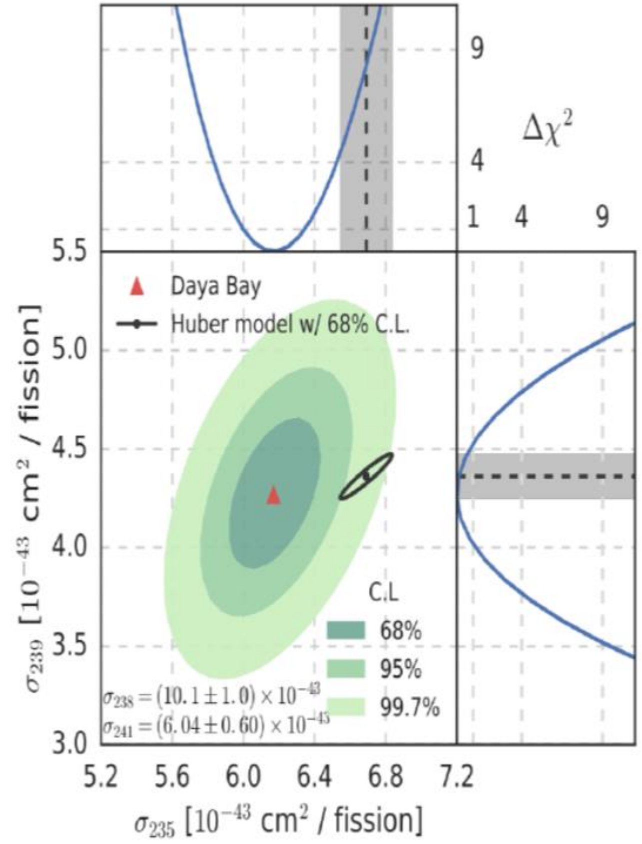




Daya Bay, J. Pedro Ochoa Ricoux

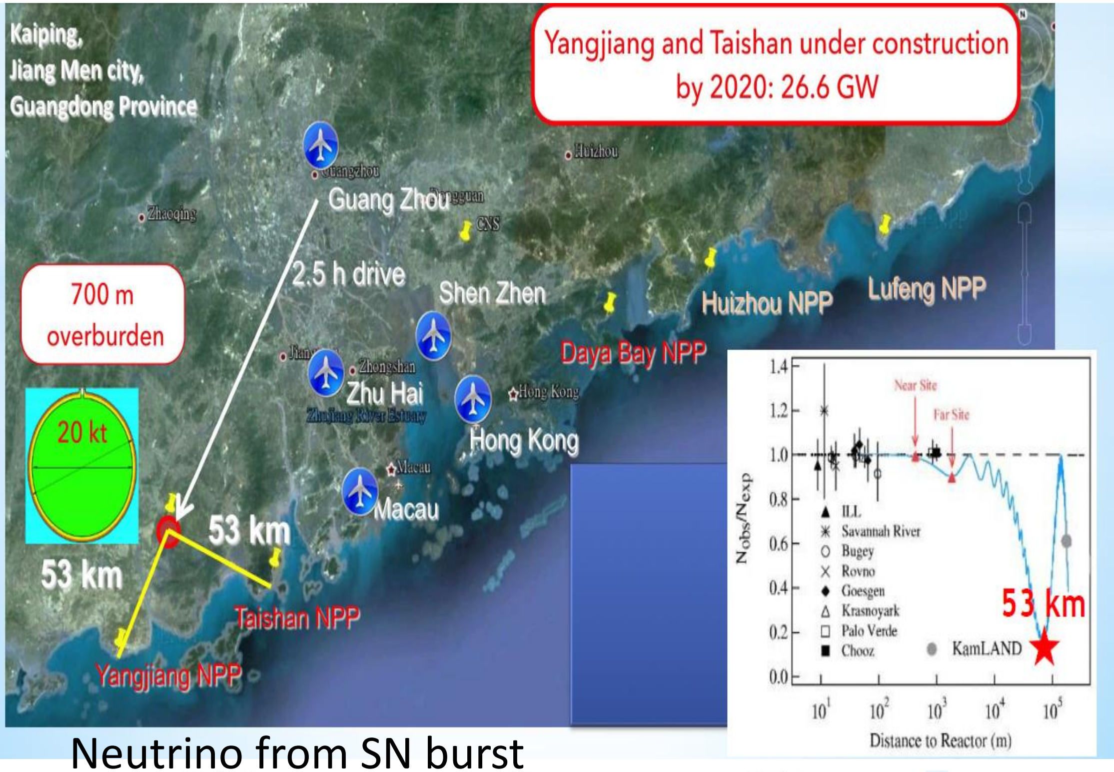


Daya Bay, J. Pedro Ochoa Ricoux



Daya Bay, J. Pedro Ochoa Ricoux

JUNO, B. Clerbaux



[F. Capozzi et al., arXiv: 1703.04471]

Parameter	Value		Uncertainty (1σ)
	NH	IH	
$\sin^2\theta_{12}$	0.297		5%
$\sin^2\theta_{13}$	0.0214	0.0218	4%
θ_{23}	~45°		octant is unknown
Δm^2_{21}	$7.37\cdot10^{-5}$ eV^2		2.3%
$\lvert\Delta m^2_{31}\rvert$	$2.50\cdot10^{-3}$ eV^2	$2.46\cdot10^{-3}$ eV^2	2.5%, sign is unknown
δ^{CP}	1.35	1.32	~50%

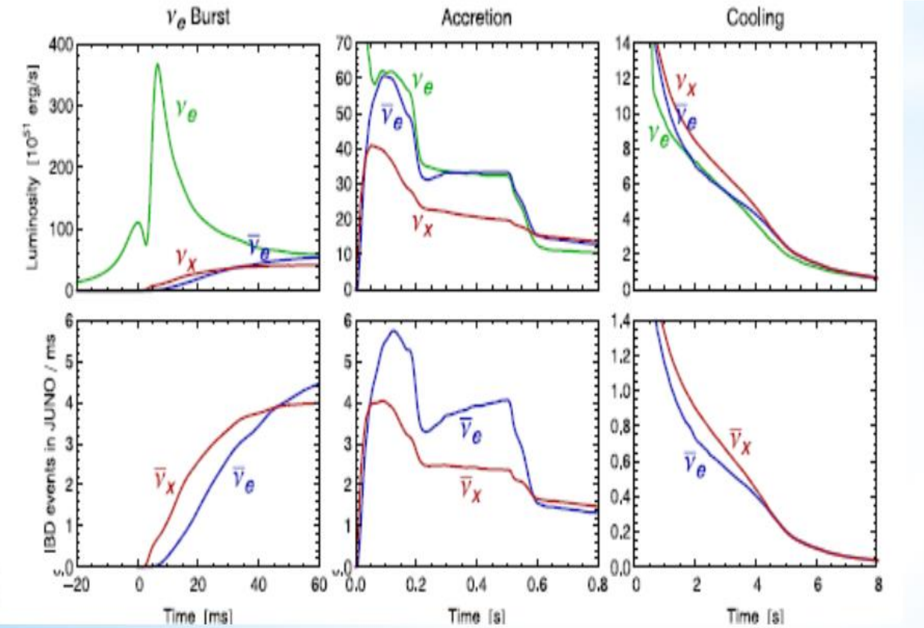
Expected JUNO precision :

→ < 1%

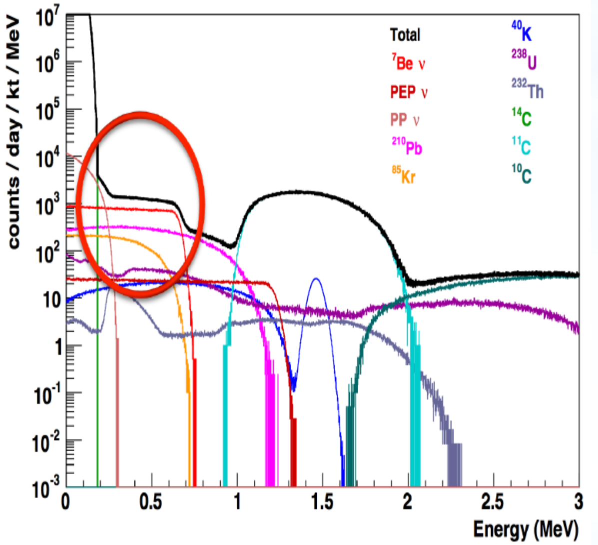
→ < 1%

→ sign

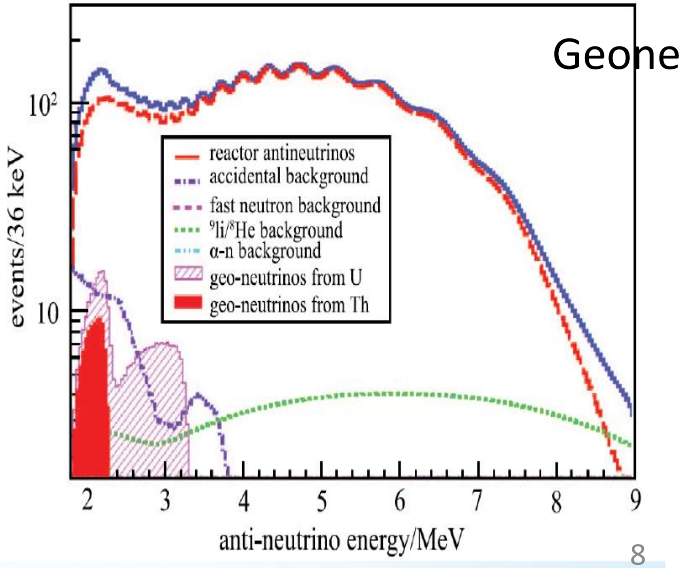
Neutrino from SN burst



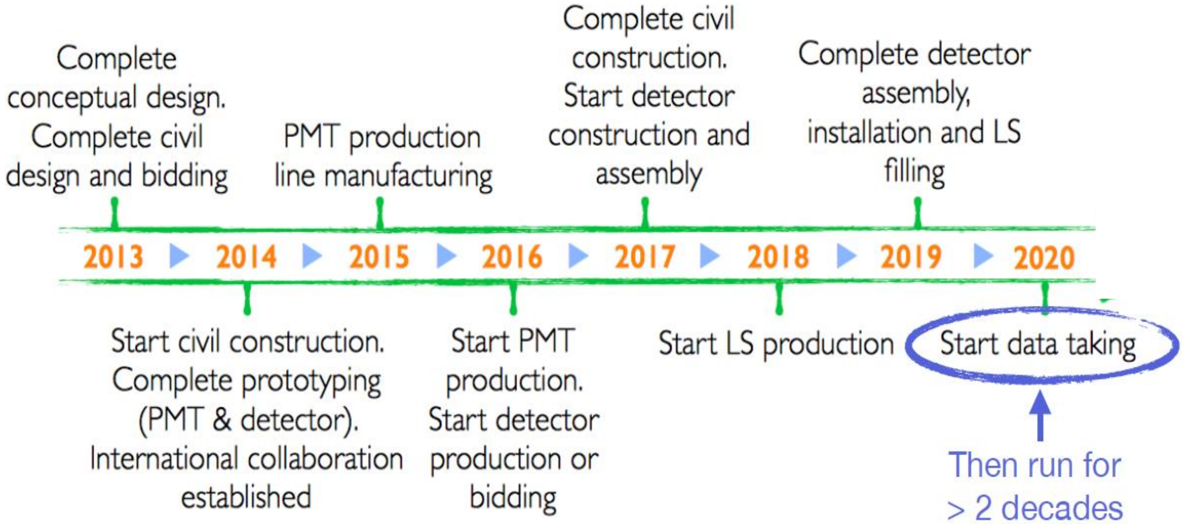
Solar neutrinos



Geoneutrinos



Chinese Phys. C40 N3 (2016) 033003



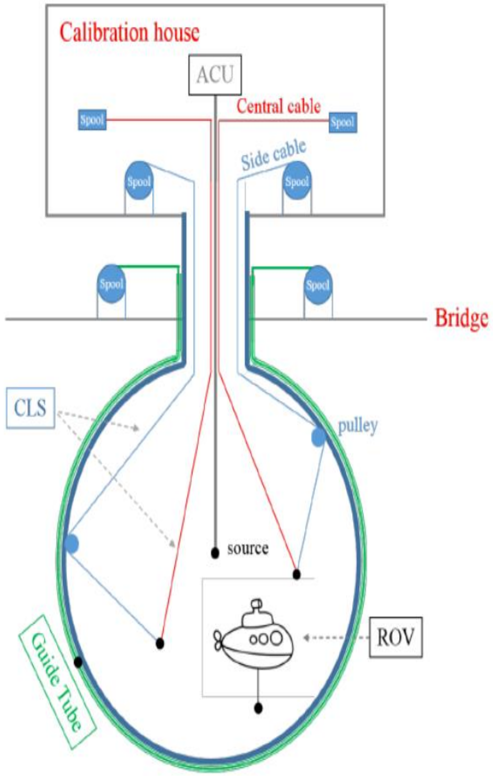
JUNO will have to control the non-stochastic term of the resolution at an unprecedented level (≲1%)

LS Detectors	Daya Bay	Borexino	KamLAND	JUNO
Target Mass	**20 t x 8**	**300 t**	**1 kt**	**20 kt**

	KamLAND	JUNO	Relative Gain
Total light level	**250 p.e. / MeV**	**1200 p.e. / MeV**	**5**
Photocathode coverage	34%	75%	~2
Light yield	1.5 g/l PPO	3-5 g/l PPO	~1.5
Attenuation length / R	15/16 m	25/35 m	~0.8
PMT QE×CE	20%×60% ~ 12%	~30%	~2

use KamLAND as reference (Relative Gain)

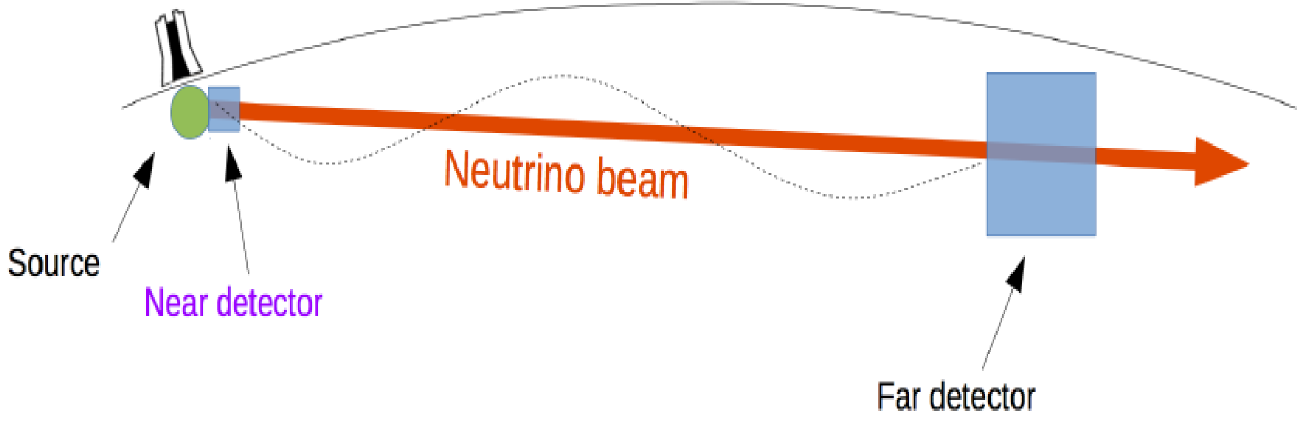
goal (Total light level: 5)



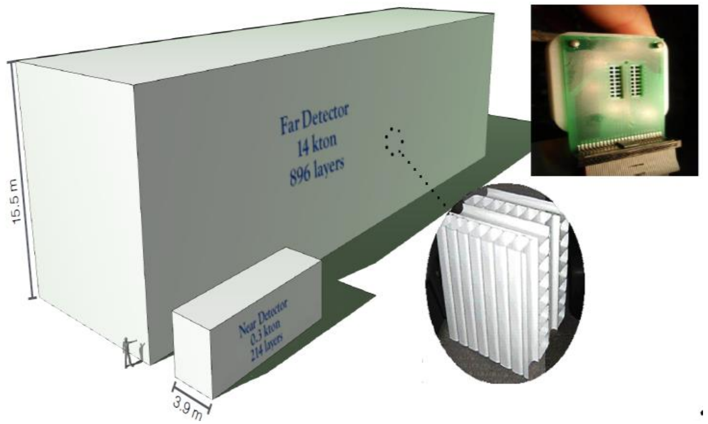
Aggressive calibration program

Current Long Baseline Neutrino Experiments

- Details of the NOvA ν_μ disappearance analysis, L. Cremonesi
- Oscillation results and plans from the T2K experiment, P. Dunne



NOvA, L. Cremonesi

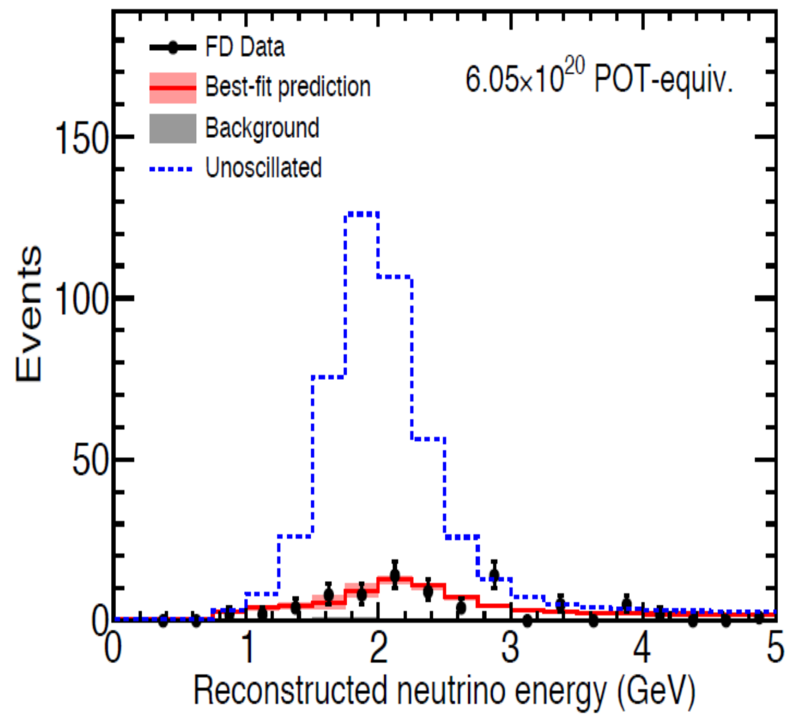


- The 2015 analysis was dominated by a large systematic uncertainty placed on the hadronic energy component (which has since been significantly reduced.)

Systematic (*)	Effect on $\sin^2(\theta_{23})$	Effect on Δm^2_{32}
Normalisation	± 1.0%	± 0.2 %
Muon E scale	± 2.2%	± 0.8 %
Calibration	± 2.0 %	± 0.2 %
Relative E scale	± 2.0 %	± 0.9 %
Cross sections + FSI	± 0.6 %	± 0.5 %
Osc. parameters	± 0.7 %	± 1.5 %
Beam backgrounds	± 0.9 %	± 0.5 %
Scintillation model	± 0.7 %	± 0.1 %
All systematics	**± 3.4 %**	**± 2.4 %**
Stat. Uncertainty	**± 4.1 %**	**± 3.5 %**

(*) Relative contribution evaluated at $\sin^2(\theta_{23}) = 0.514$ and $\Delta m^2_{32} = 2.52 \times 10^{-3}$ eV^2

NOvA Preliminary

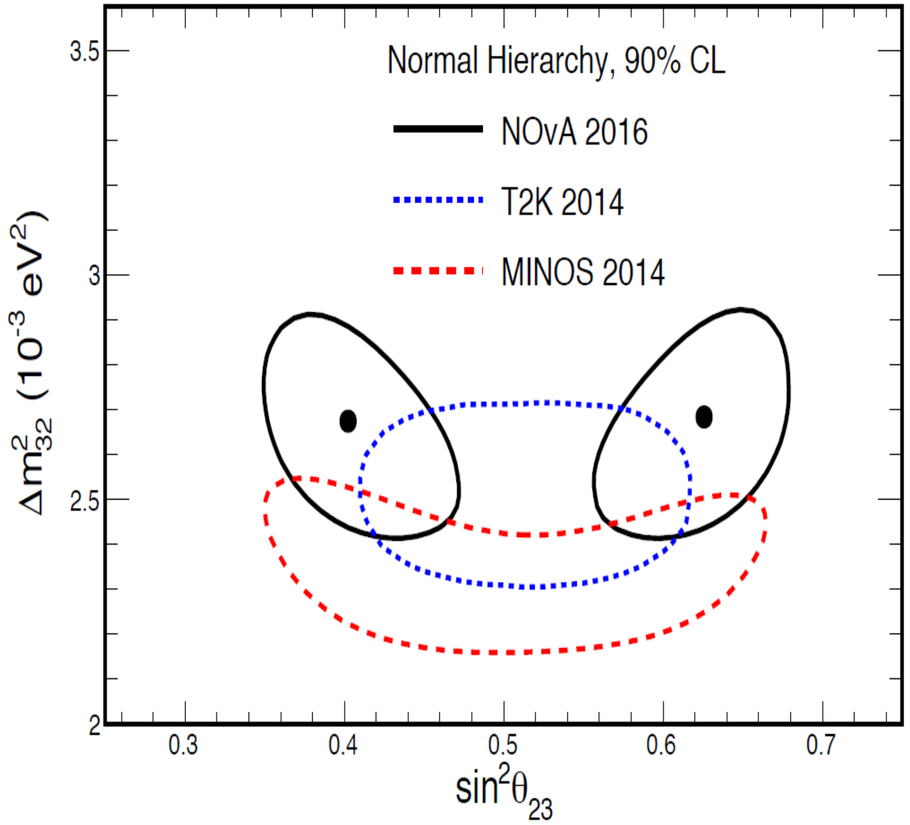


Maximal Mixing Disfavoured at 2.56 σ

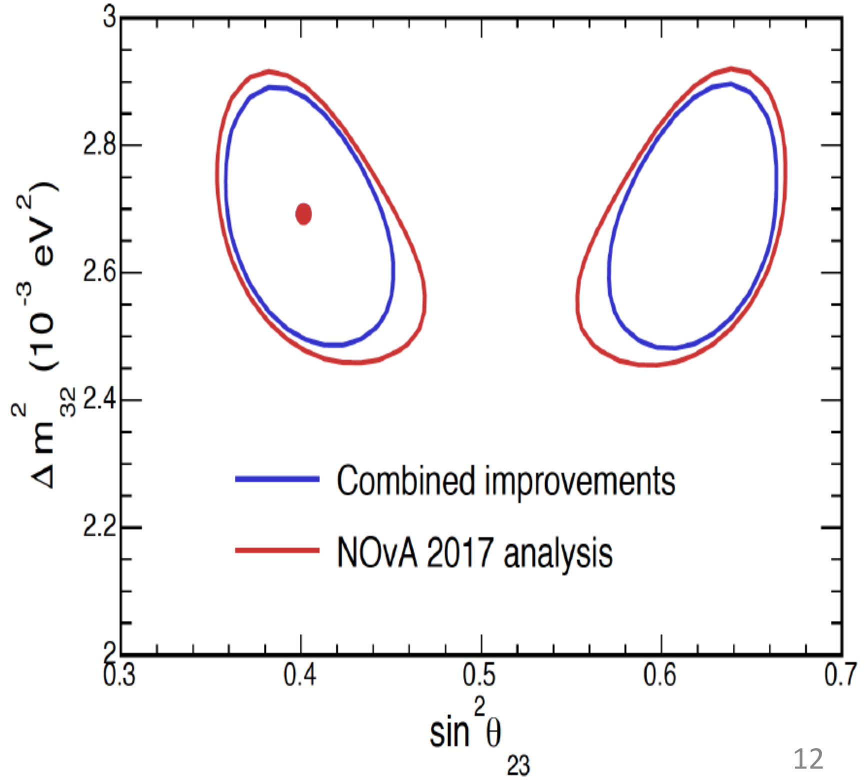
$$|\Delta m^2_{32}| = 2.67 \pm 0.11 \times 10^{-3}\mathrm{eV}^2$$

$$\sin^2\theta_{23} = 0.404^{+0.030}_{-0.022}(0.624^{+0.022}_{-0.030})$$

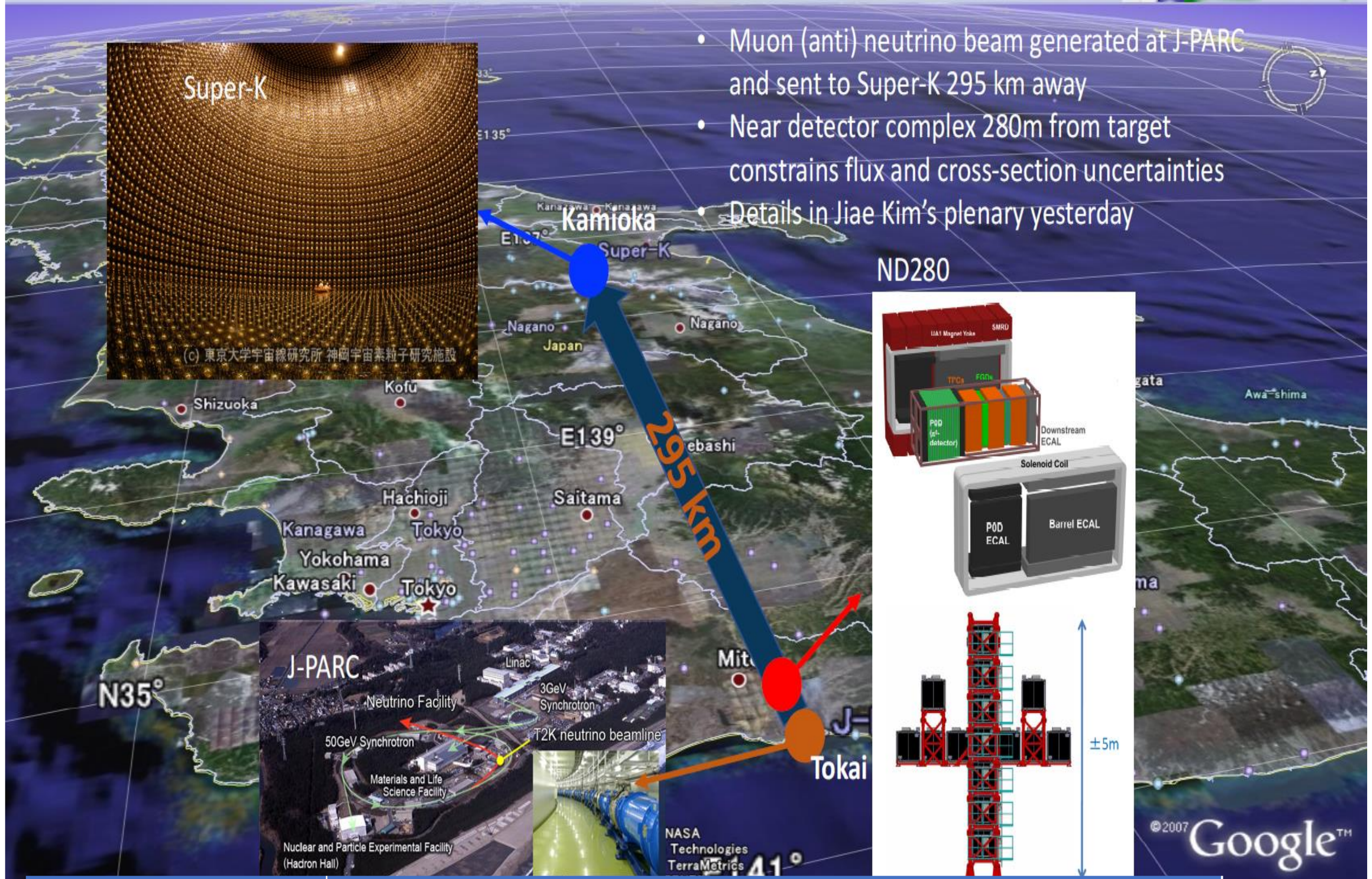
Best Fit in NO:



- Several improvements under way (energy resolution, PID, binning)
- Systematic uncertainties will be reduced from 2.2% to 2.0% on Δm232 and from a 2.1% to 1.5% on sin2θ23



T2K, P. Dunne



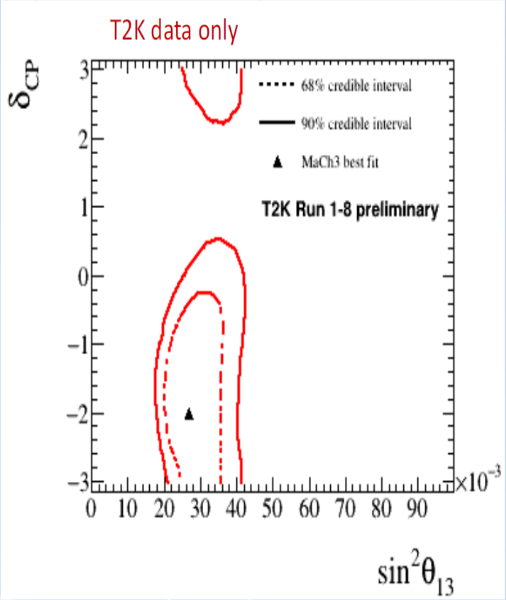
	% Errors on predicted event rates, Osc. Parameters as for rates					
	1R μ-like		1R e-like			
Error Source	ν-mode	$\bar{\nu}$-mode	ν-mode	$\bar{\nu}$-mode	ν-mode CC1π	ν-mode/$\bar{\nu}$-mode
SK Detector	1.86	1.51	3.03	4.22	16.69	1.60
SK FSI+SI+PN	2.20	1.98	3.01	2.31	11.43	1.57
ND280 const. flux & xsec	3.22	2.72	3.22	2.88	4.05	2.50
$\sigma(\nu_e)/\sigma(\bar{\nu}_e)$	0.00	0.00	2.63	1.46	2.62	3.03
NC1γ	0.00	0.00	1.08	2.59	0.33	1.39
NC Other	0.25	0.25	0.14	0.33	0.98	0.18
Total Systematic Error	4.40	3.76	6.10	6.51	20.94	4.77

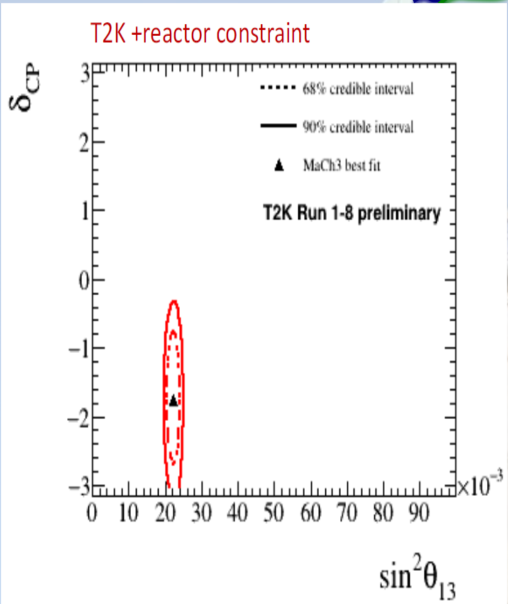
- Main improvements in new analysis:
- New reconstruction code (fiTQun) -> 20% increase in Fiducial Volume
- New sample CC1pi
- New cross section model

Two approaches used for fitting:

1. Use ND data fit to constrain flux and cross-section models first then fit far detector
   - Computationally easier
   - Makes more assumptions
2. Perform simultaneous fit of both detectors
   - Computationally more demanding
   - Makes fewer assumptions

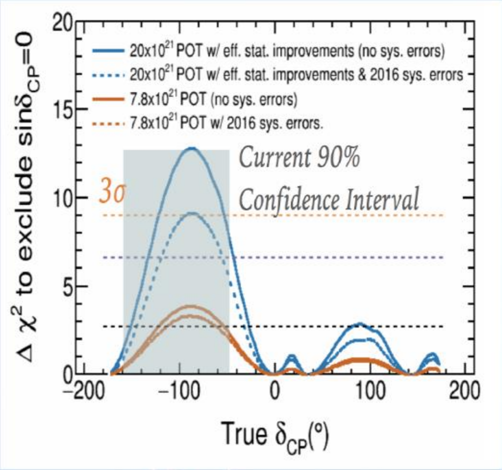
Appearance parameter constraints

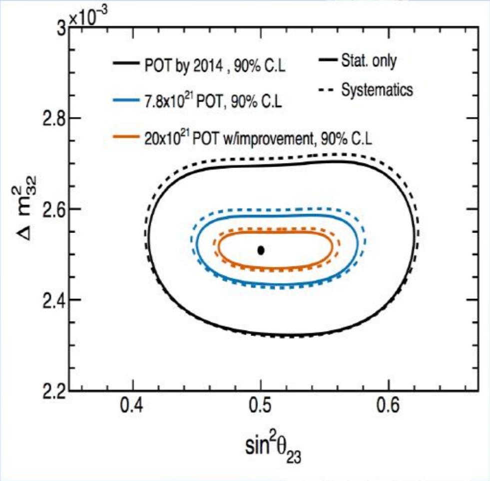




- T2K value for $\sin^2\theta_{13}$ is consistent with PDG 2016 average (0.0219)

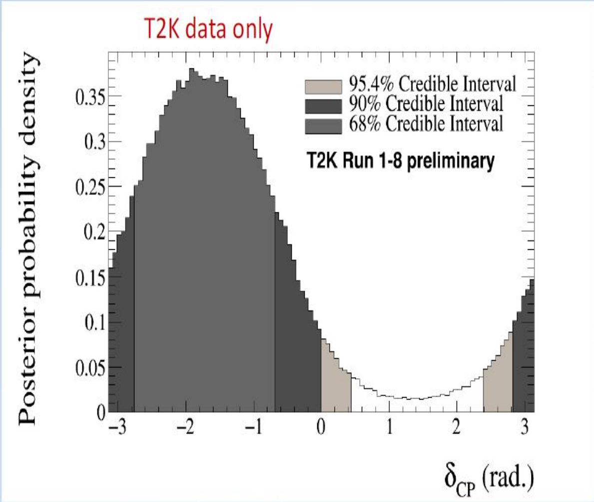
T2K-II sensitivity

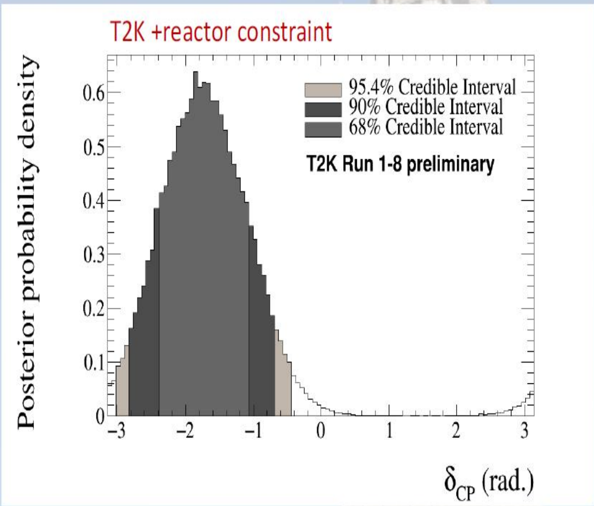




- If current preferred δ_{CP} is true T2K-II has potential for 3σ discovery
- Size of systematic uncertainties has large effect on sensitivity

δ_{CP} Constraint





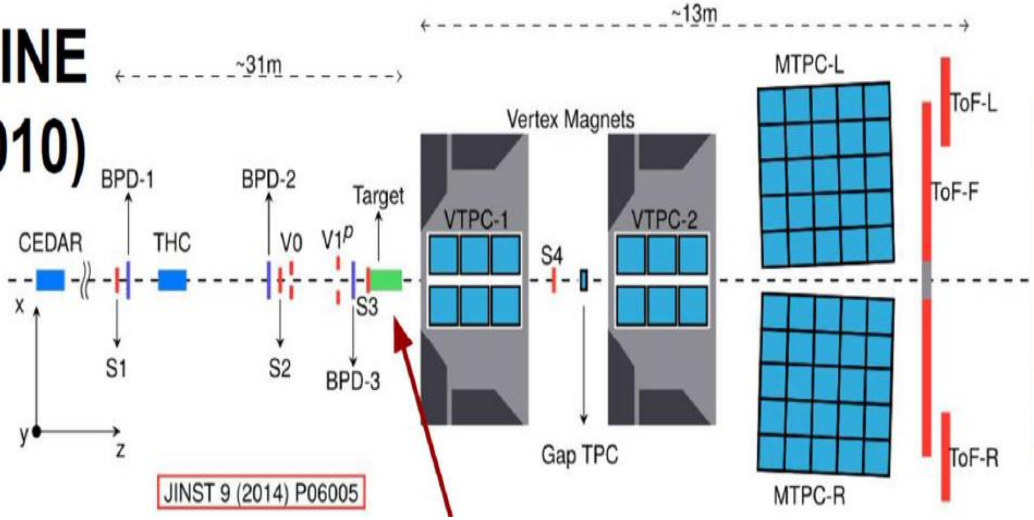
- CP conserving values outside 2σ (95.4%) interval for T2K+reactor constraint

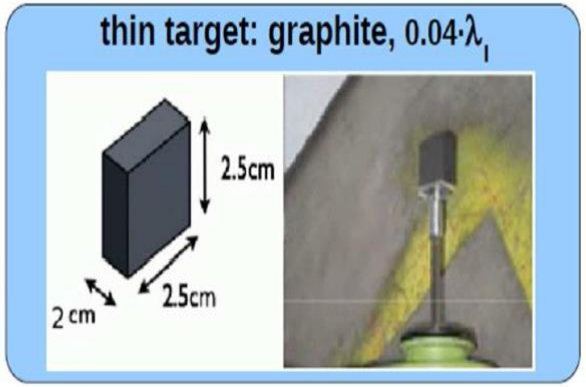
- With new analysis CP conserving values of δ_{CP} are excluded at 2σ in both Bayesian and frequentist frameworks

Future Long Baseline Neutrino Experiments

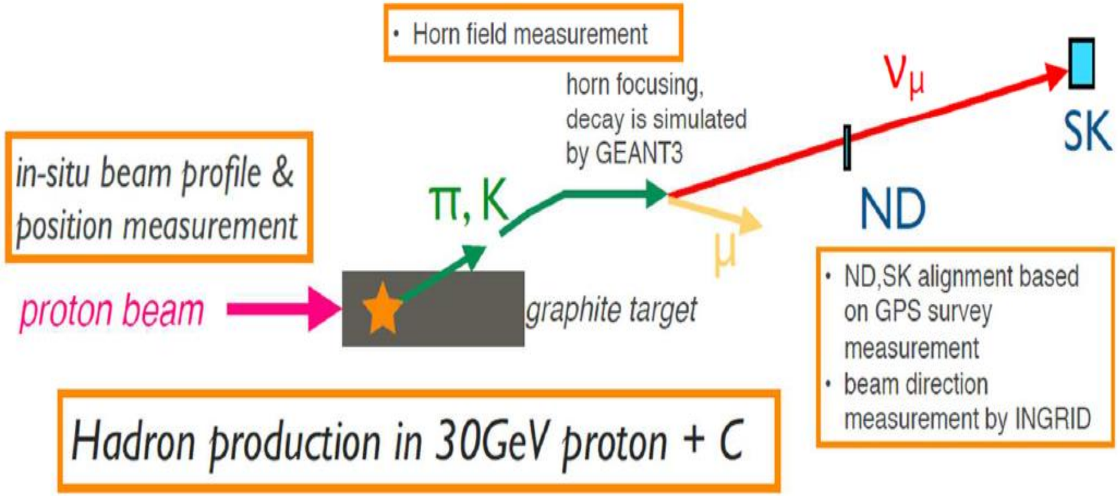
- Hadron production measurements for neutrino experiments, A. Blondel
- DUNE oscillation physics, N. Grant
- Physics potential of Hyper-Kamiokande for neutrino oscillations, C. Bronner
- Physics potential of the ESSnuSB, M. Blennow
- Analytic Neutrino Oscillation Probabilities in Matter Revisited, S. Parke

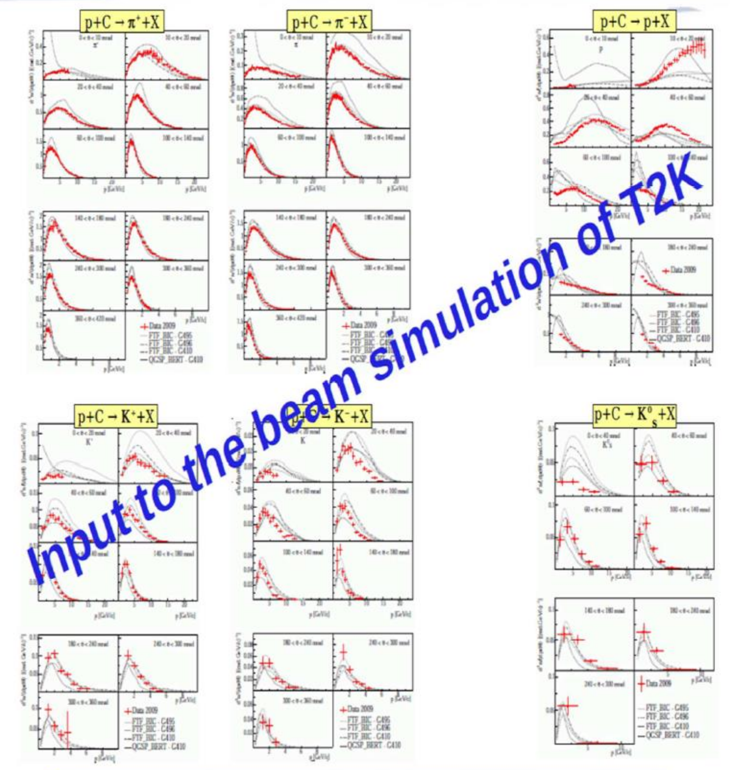
NA61/SHINE setup (2010)





T2K Neutrino beam simulation based on "measurement"

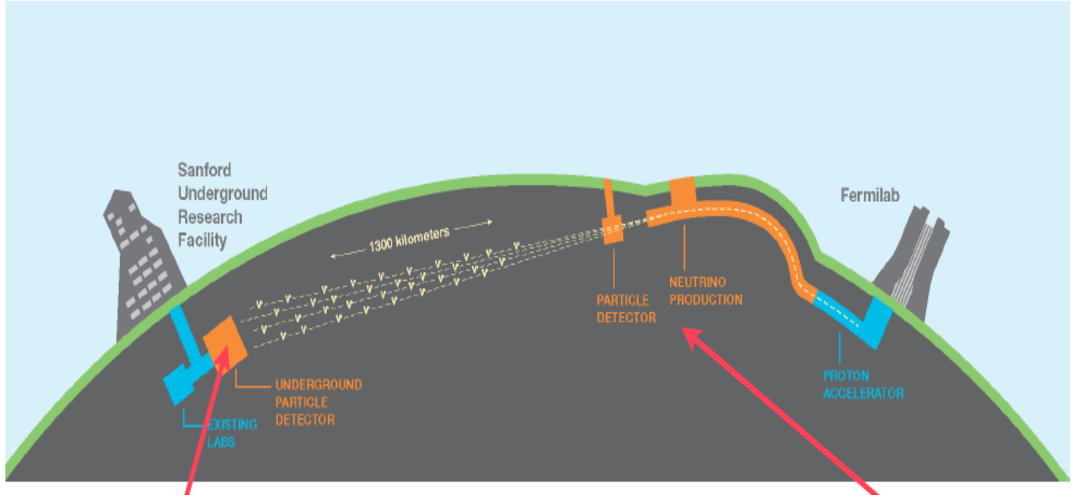




Models are not good at reproducing the proton rates at all

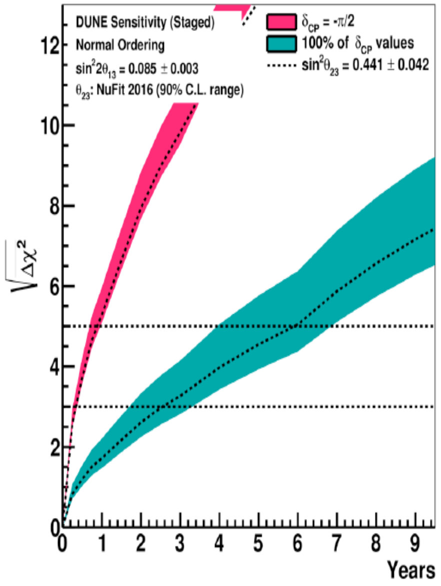
- Future programme to address hadron production needs of future experiments

DUNE

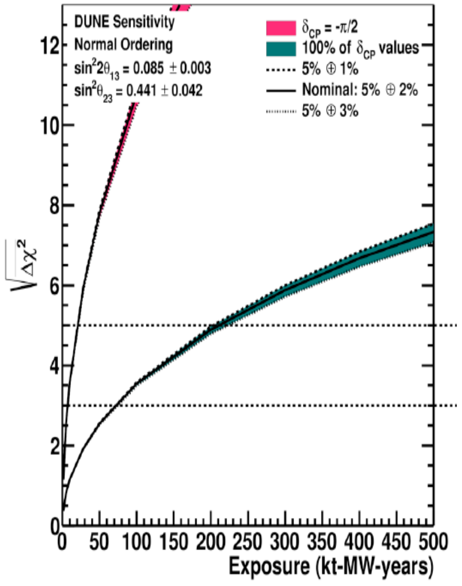


- Due to the 1300 km baseline, the asymmetry due to matter effects is ~40% in region of peak flux, which is greater than largest possible asymmetry from CP violation. The sign of this difference depends on the mass hierarchy.
- This means that the mass hierarchy can be resolved by DUNE irrespective of the value of δCP.

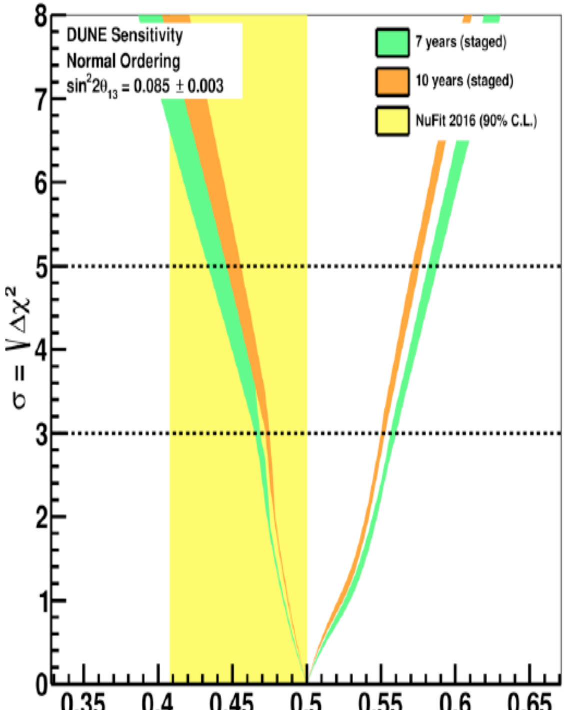
Bands represent range of sensitivity for different values of θ_{23} (NuFit 2016 90% C.L. range)



Bands represent difference between 1% and 3% uncertainty in ν_e signal normalisation

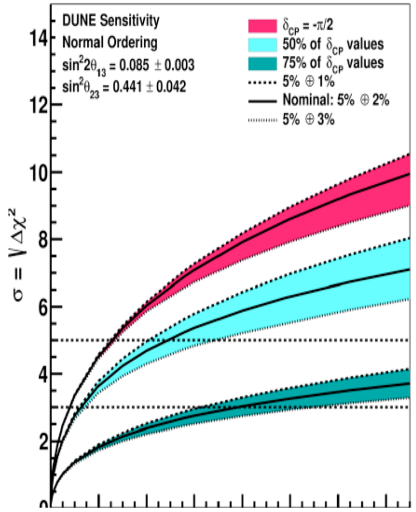


(300 kt MW years ≈ 7 years running)

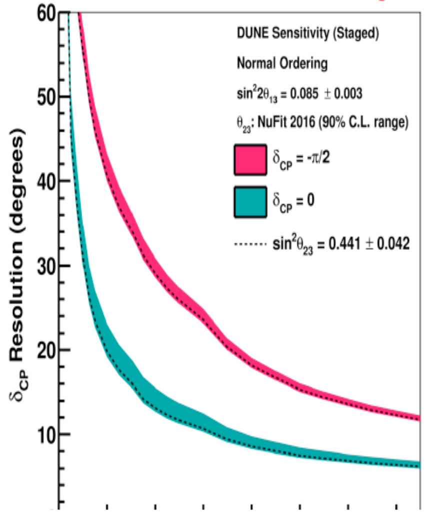


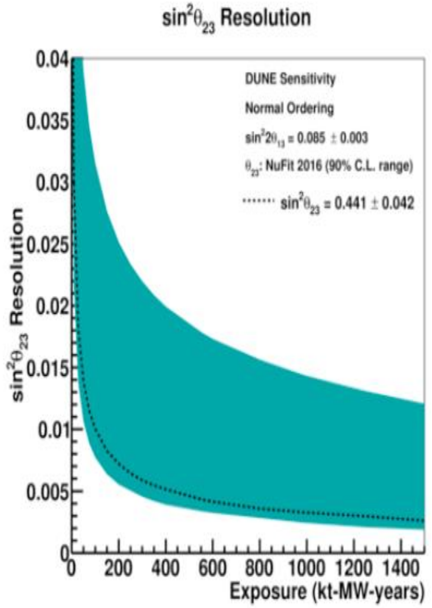
Significance with which CP violation (δCP ≠0 or π) can be determined (left) and δCP resolution (right) as a function of time.

Bands represent difference between 1% and 3% uncertainty in ν_e signal normalisation

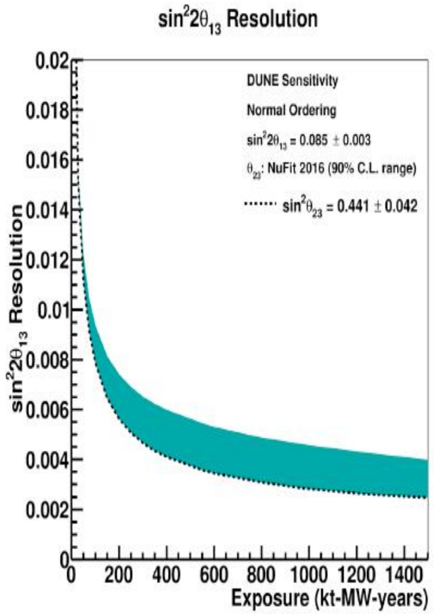


Bands represent resolution for different values of θ_{23} (NuFit 2016 90% C.L. range). Resolution worsens with increasing θ_{23}

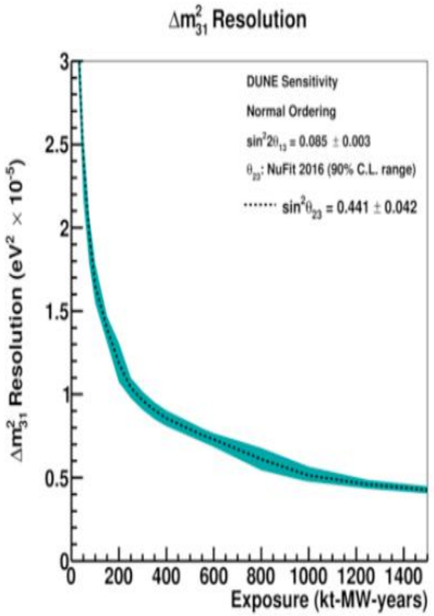




Resolution worsens with increasing θ_{23}.

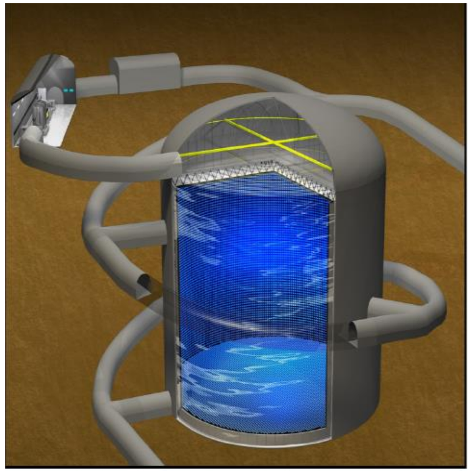


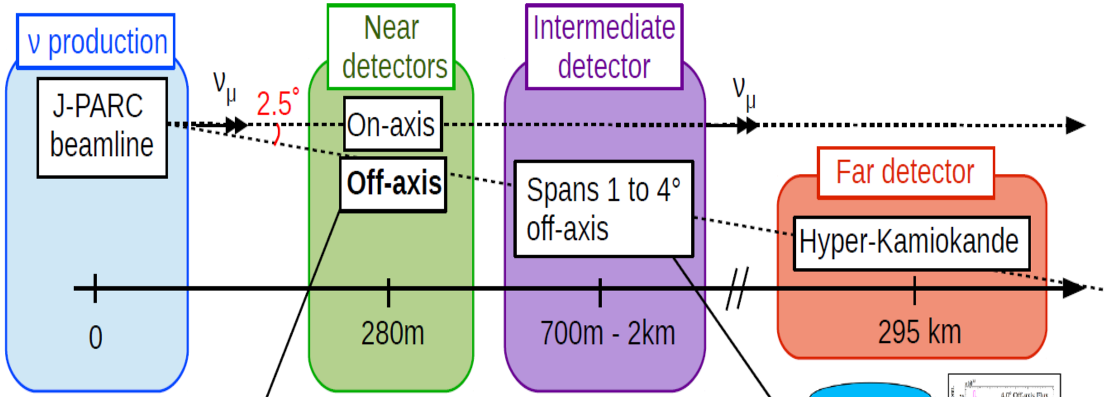
Resolution best at nominal value of θ_{23}, worst at highest value of θ_{23}.

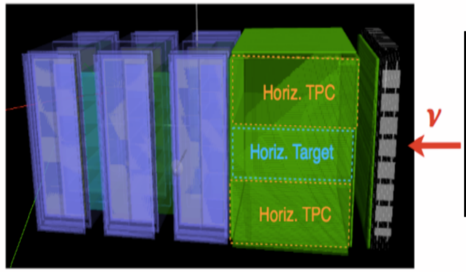


Resolution improves with increasing θ_{23}.

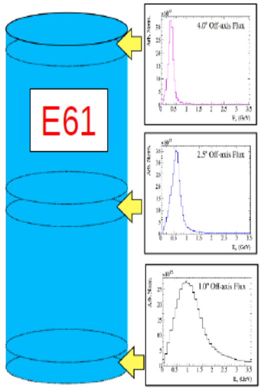
Resolutions of measurements of $\sin 2\theta_{23}$, $\sin^2 2\theta_{13}$ and Δm^2_{31}







Updated ND and new ID to reduce systematics

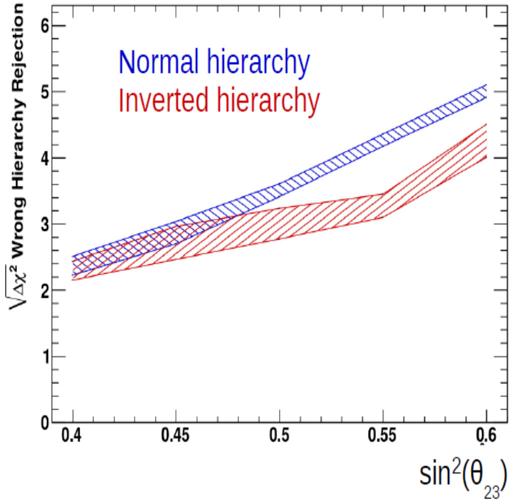


ND280 upgrade: official T2K project

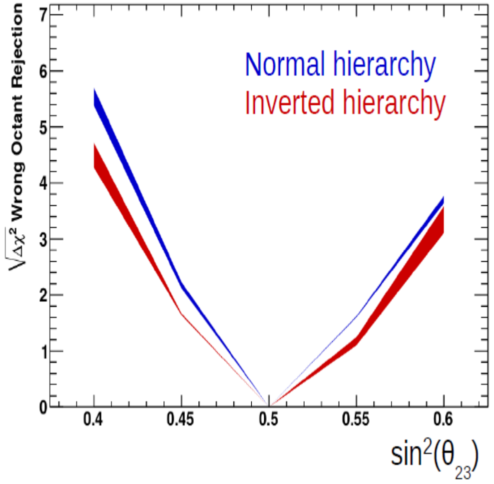
E61: currently separate collaboration

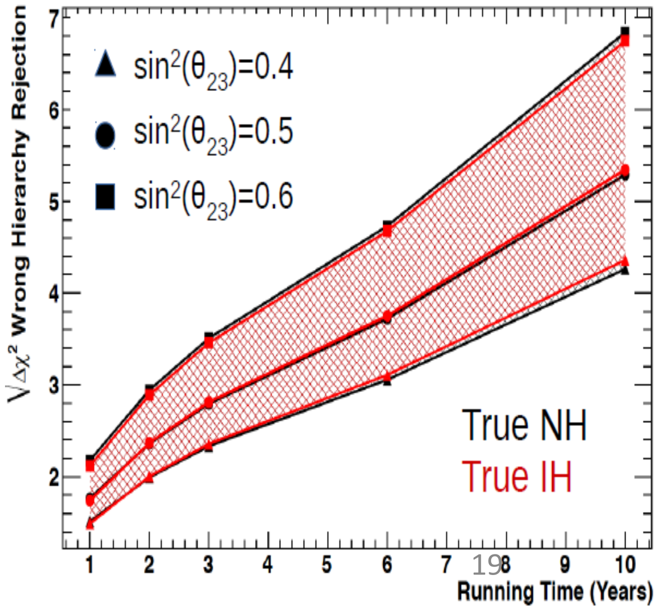
Mass hierarchy determination (beam + atmospheric)

Mass hierarchy determination

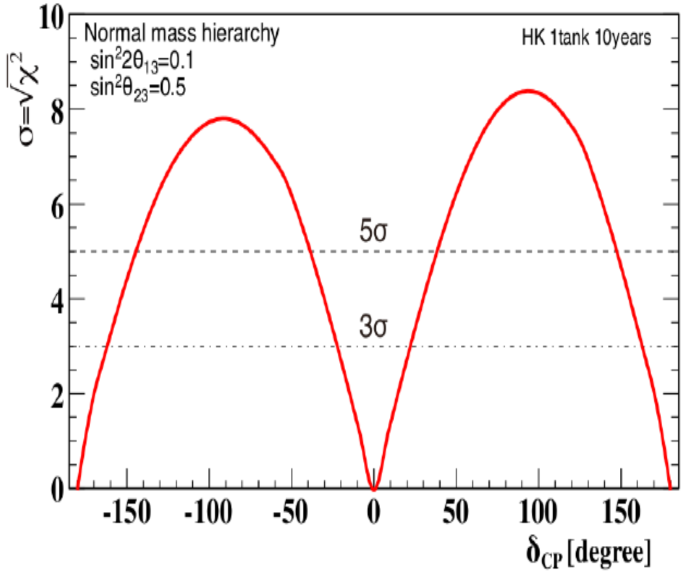


Octant determination

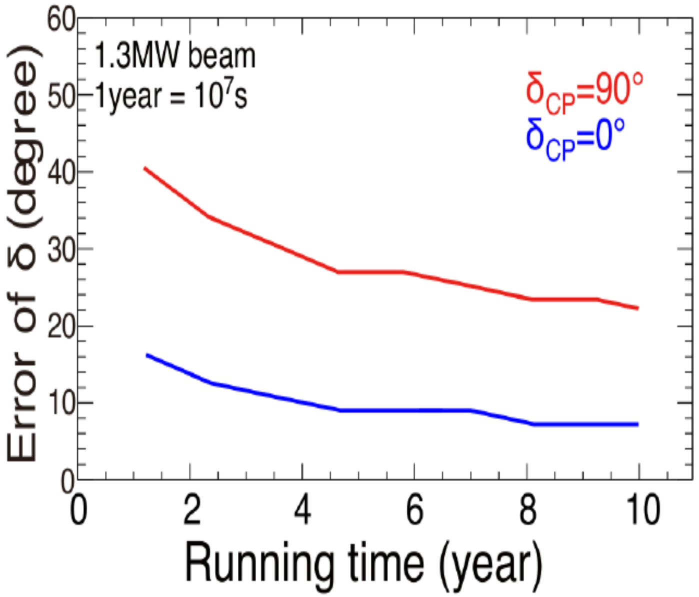




Ability to exclude CP conservation

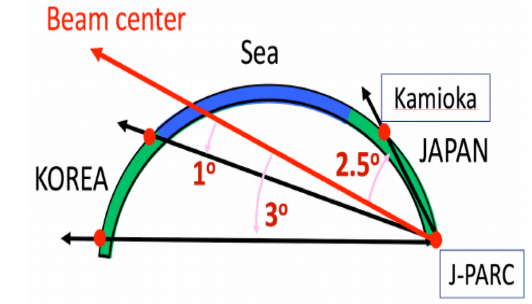


Precision of δ measurement



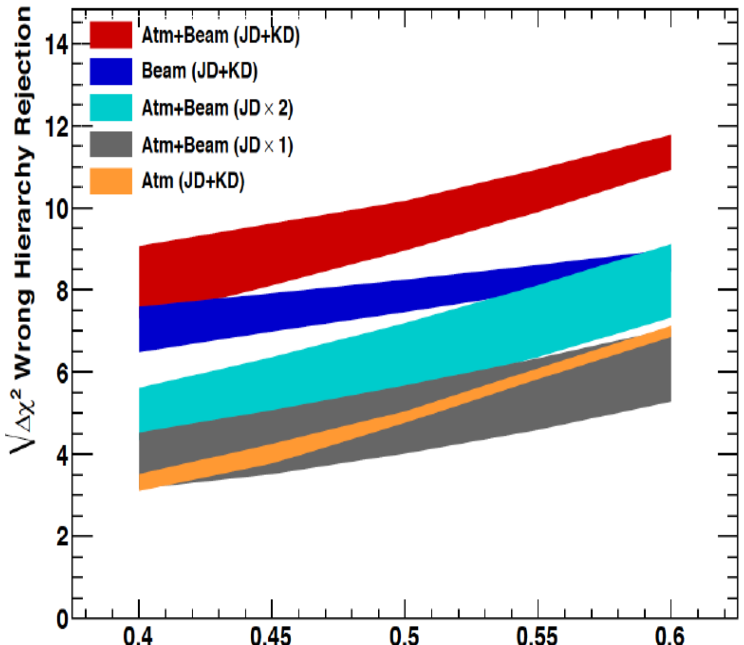
After 10 years of running:

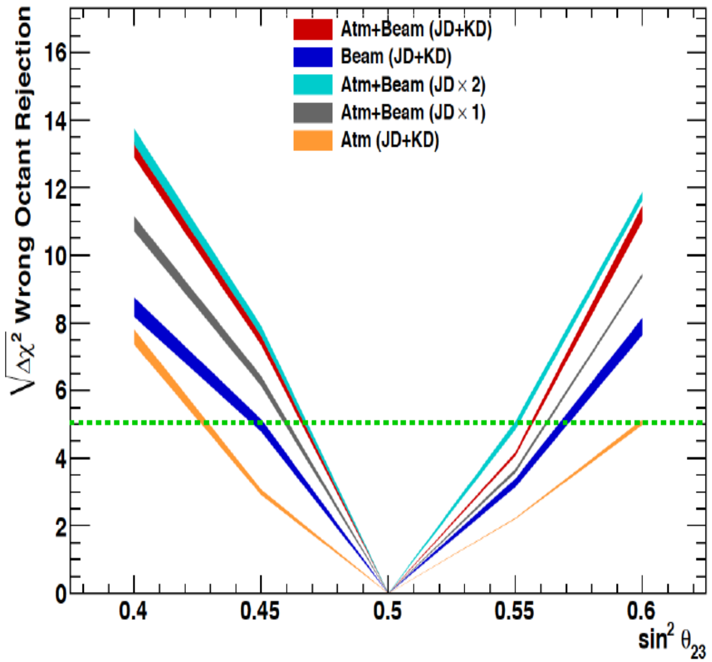
- Exclude CP conservation at 5σ (3σ) for 57% (76%) of possible true values of δ
- Measure δ with 7° (true δ=0) to 23° (true δ=90°) precision



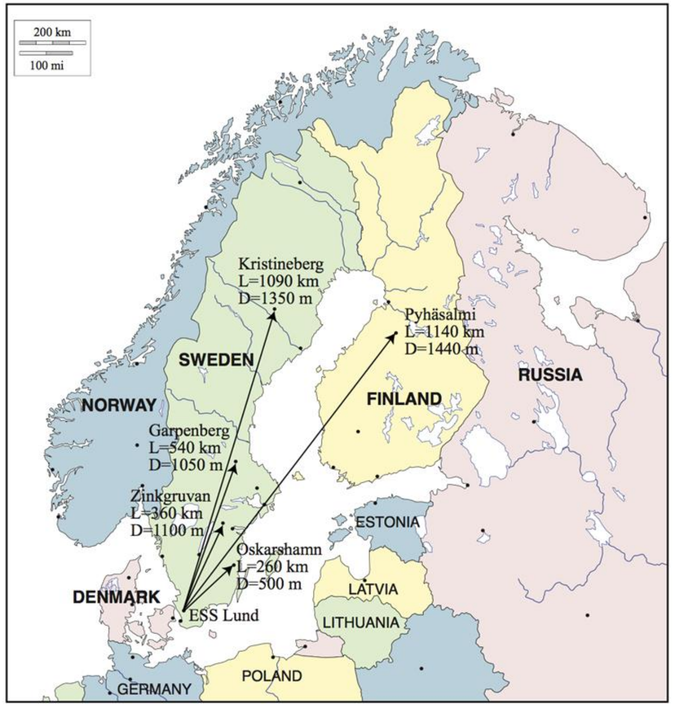
Candidate sites at different OAA and L

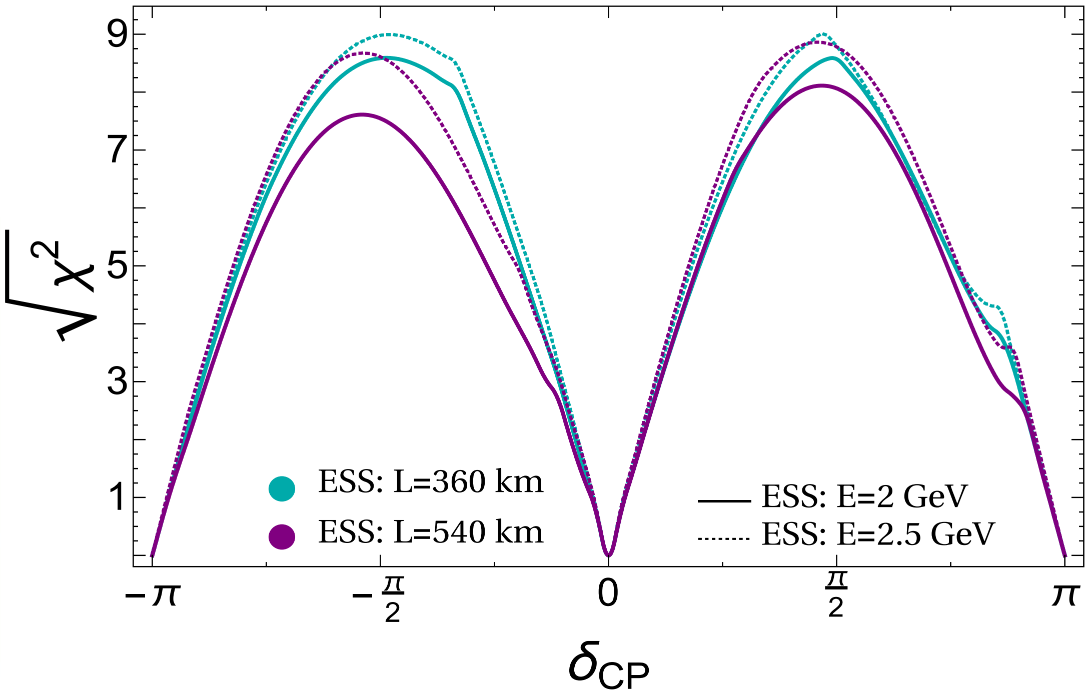
	Off-axis angle	Baseline
Mt. Bisul	1.3°	1088 km
Mt. Bohyun	2.2°	1040 km

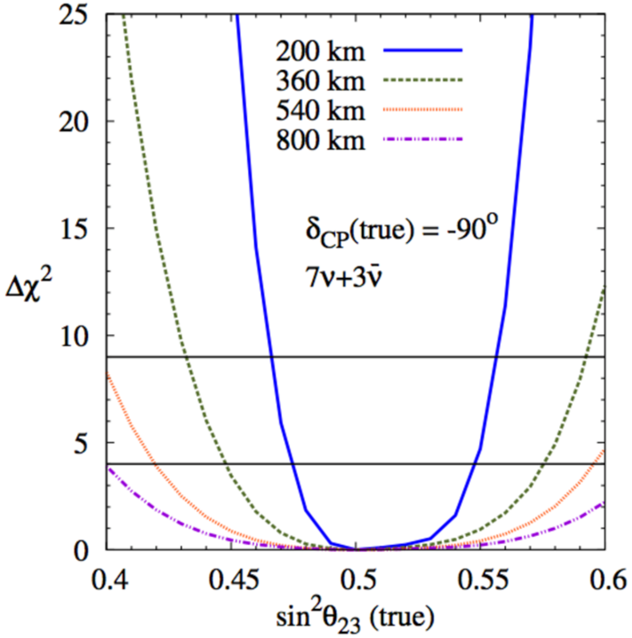


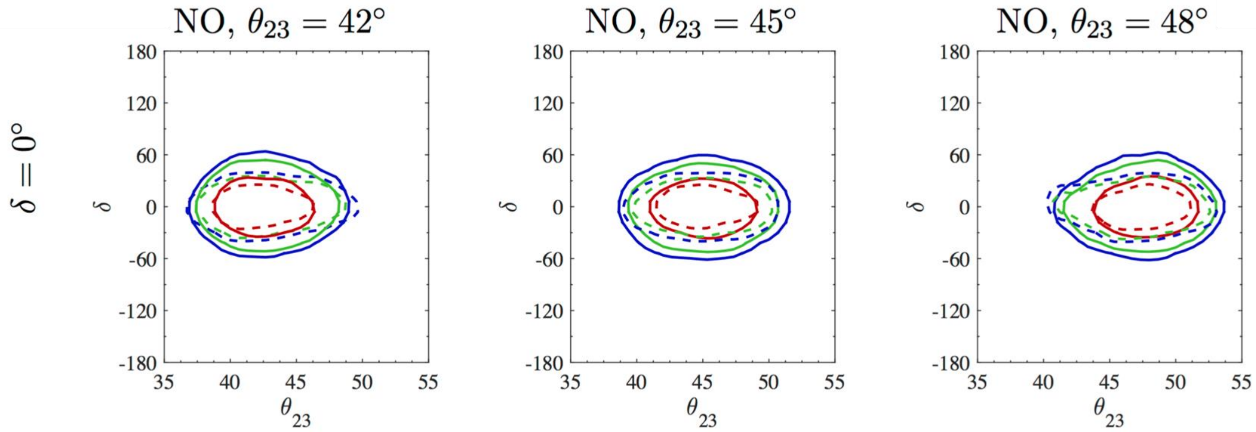


ESSnuSB, M. Blennow

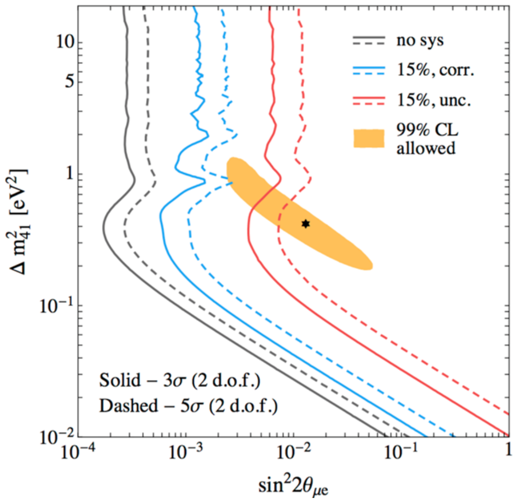


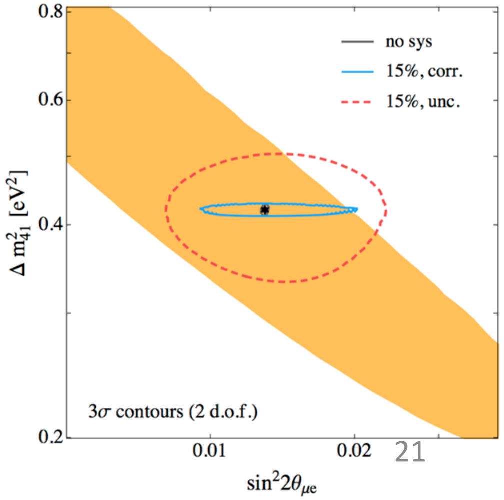






MB, et al, JHEP 09(2015)096, 1507.02868





- Harmony between

Perturbation Theory & General Expression

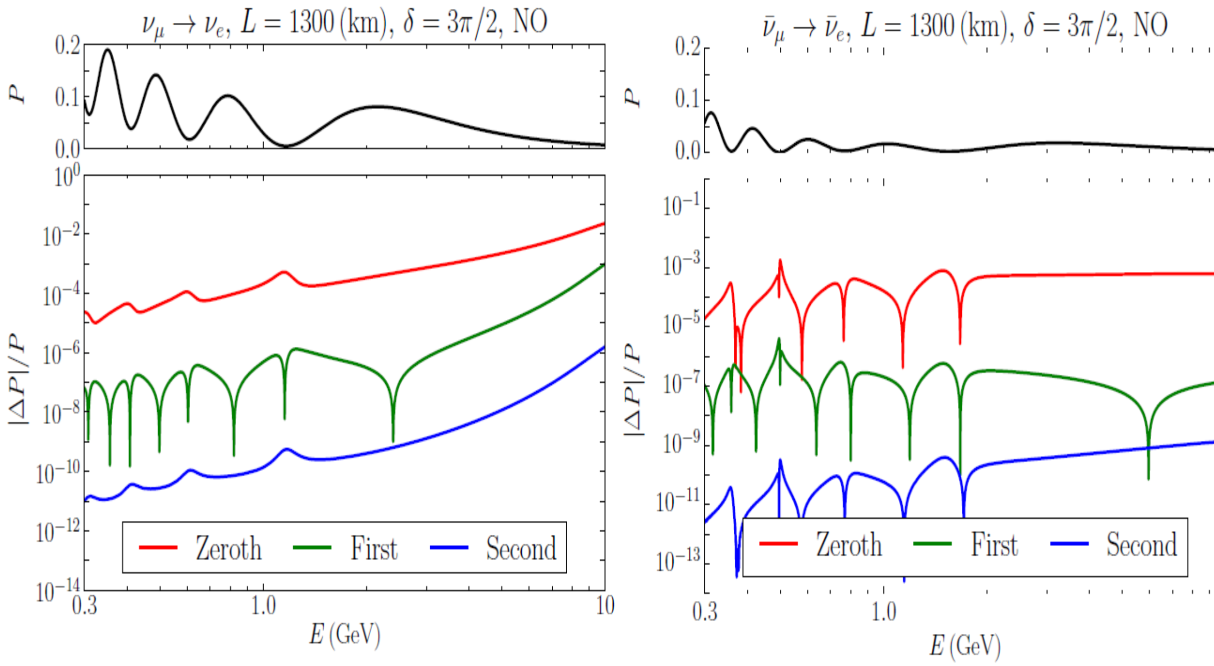
$$P(\nu_\beta \to \nu_\alpha) = \delta_{\alpha\beta} - 4\sum_{j>i}^{3} \mathrm{Re}[V_{\alpha i}V^*_{\beta i}V^*_{\alpha j}V_{\beta j}] \sin^2\frac{(\lambda_j-\lambda_i)L}{4E}$$

$$+\ 8\ \mathrm{Im}[V_{\alpha 1}V^*_{\beta 1}V^*_{\alpha 2}V_{\beta 2}]\ \sin\frac{(\lambda_3-\lambda_2)L}{4E}\sin\frac{(\lambda_2-\lambda_1)L}{4E}\sin\frac{(\lambda_1-\lambda_3)L}{4E}$$

- New Perturbation Theory reveals

Structure, Simplicity and Universal Form
of Oscillation Probabilities in Matter

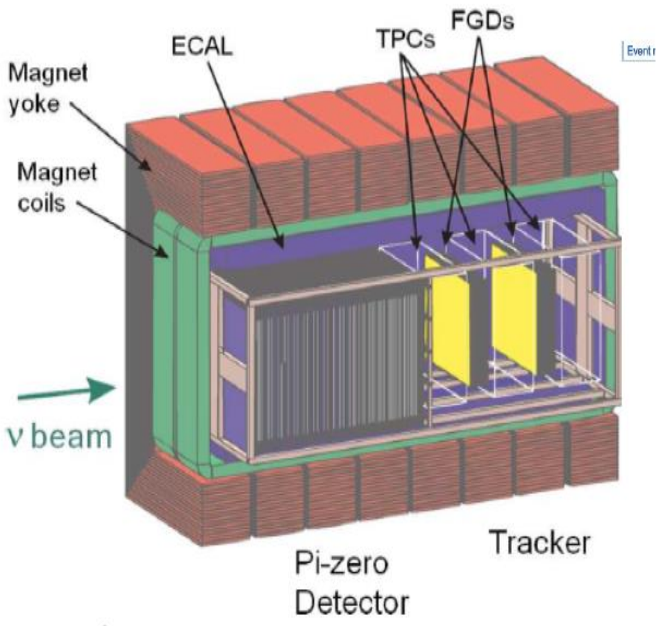
New Perturbation Theory for Osc. Probabilities



Near Detectors

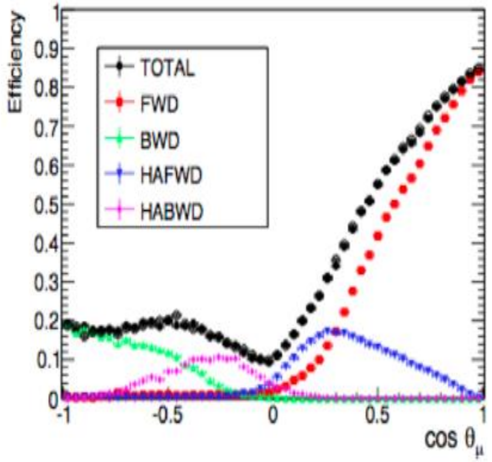
- Upgrade of the T2K near detector ND280: effect on oscillation and cross section analyses, M. Lamoureux
- J-PARC E61 experiment, C. Vilela
- DUNE near detectors: oscillations and cross sections: H. Duyang

ND280 upgrade, M. Lamoureux



Systematic uncertainty on the predicted event rate of ν_μ and ν_e at the far detector [Phys.Rev.Lett. 118, 151801]

Source [%]	ν_μ	ν_e
ND280-unconstrained cross section	0.7	3.0
Flux and ND280-constrained cross section	**2.8**	**2.9**
SK detector systematics	3.9	2.4
Final or secondary hadron interactions	1.5	2.5
Total	5.0	5.4



Good acceptance only for forward tracks

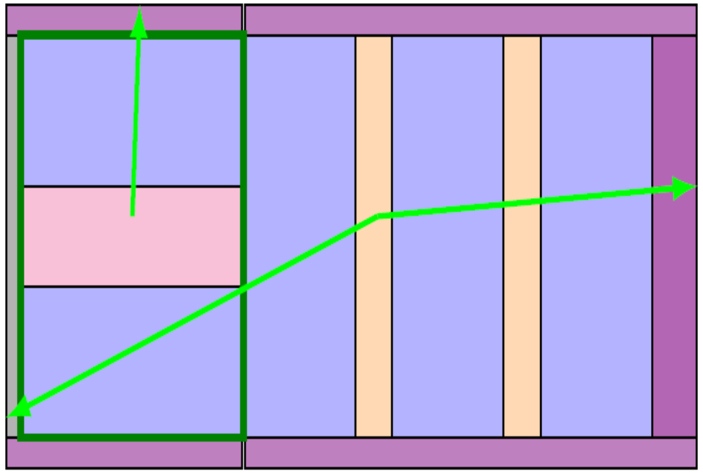
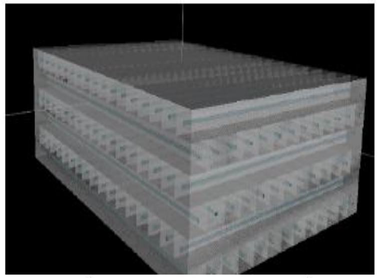


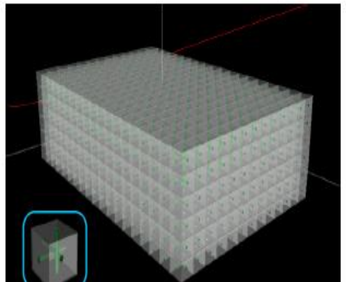
Figure: Schematics of upgrade detector central region, colors: New target, FGD, TPC, ECal, ToF counters

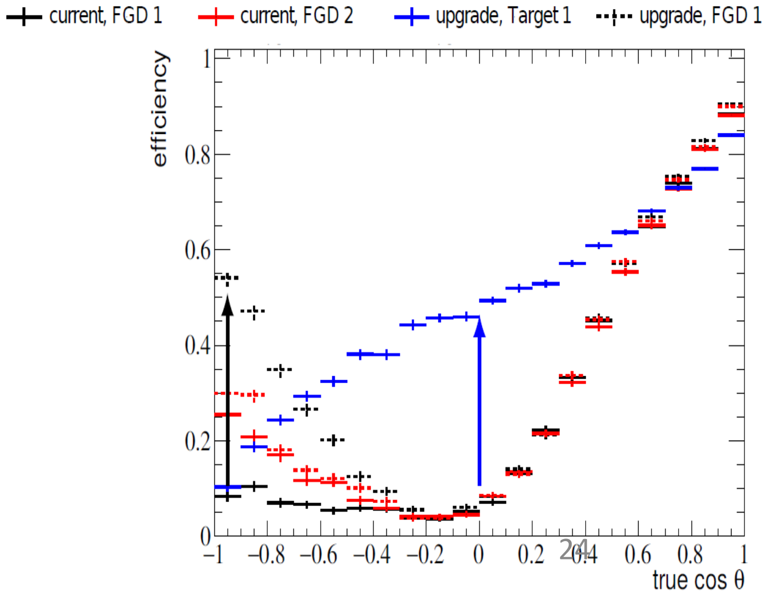
	Current	Upgrade
Total target mass (tons)	2.2	4.3

FGD XZ

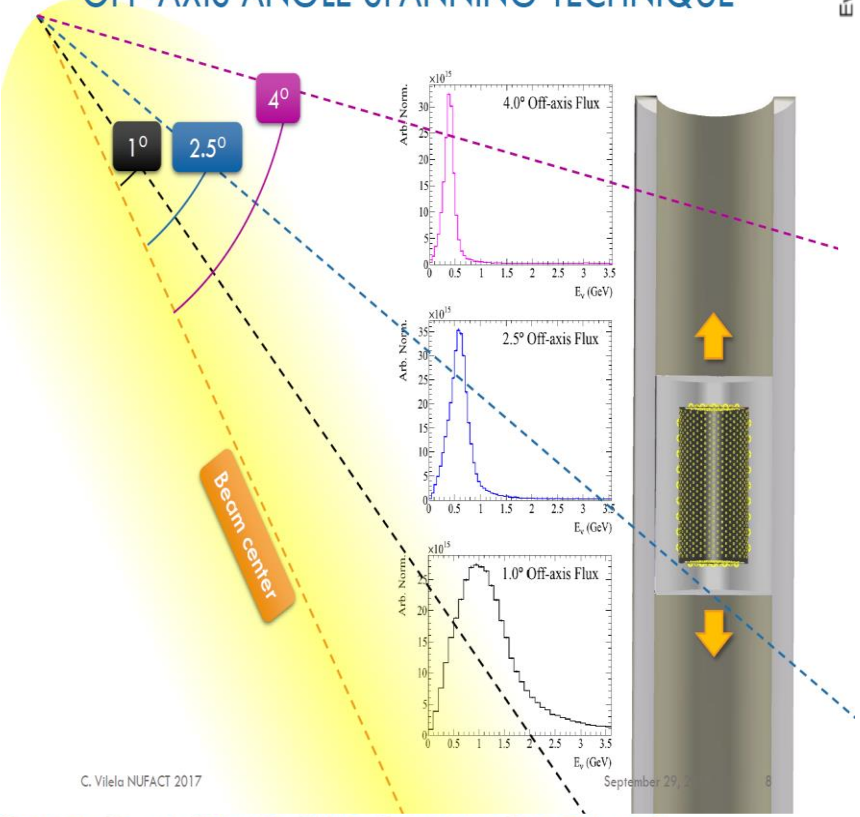


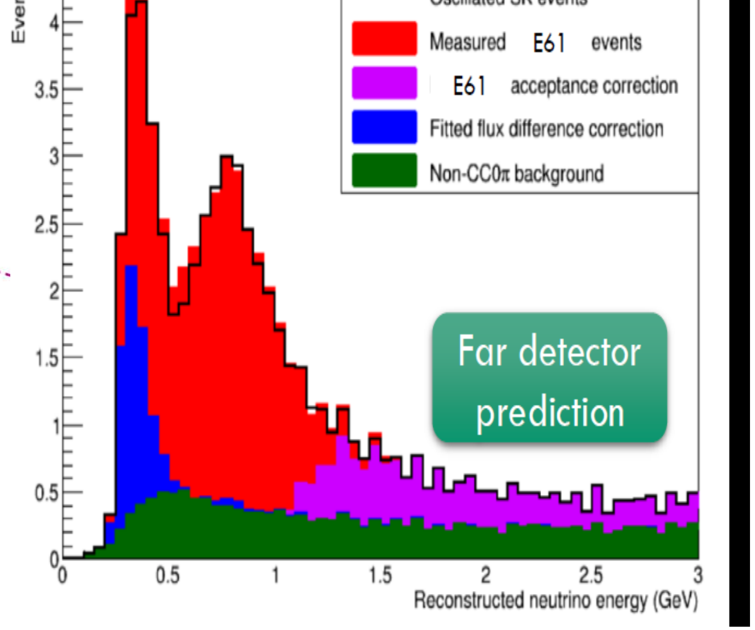
SuperFGD

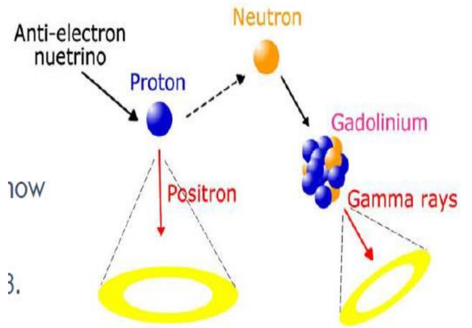


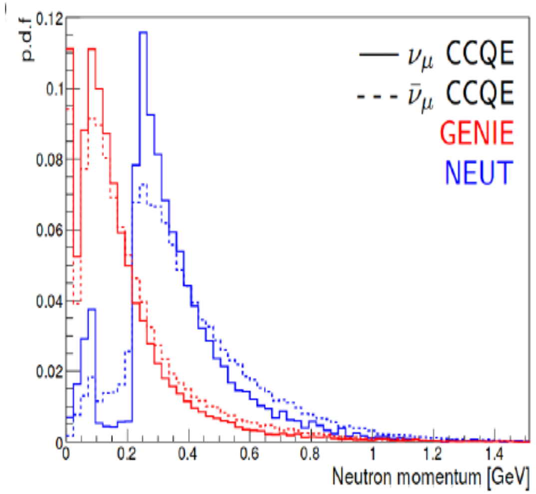


OFF-AXIS ANGLE SPANNING TECHNIQUE





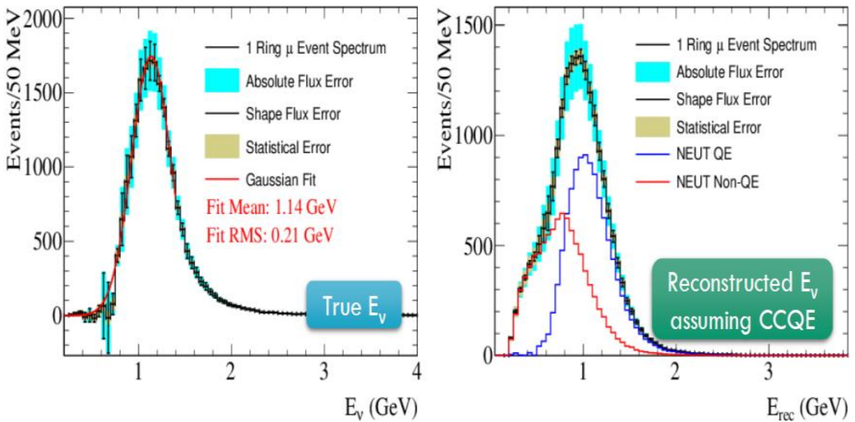


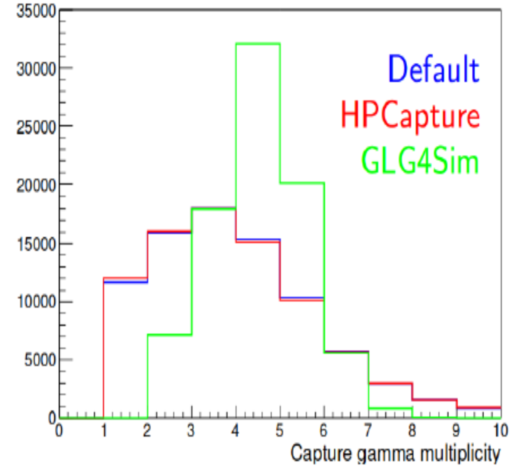


- A staged approach

PSEUDO-MONOCHROMATIC BEAMS

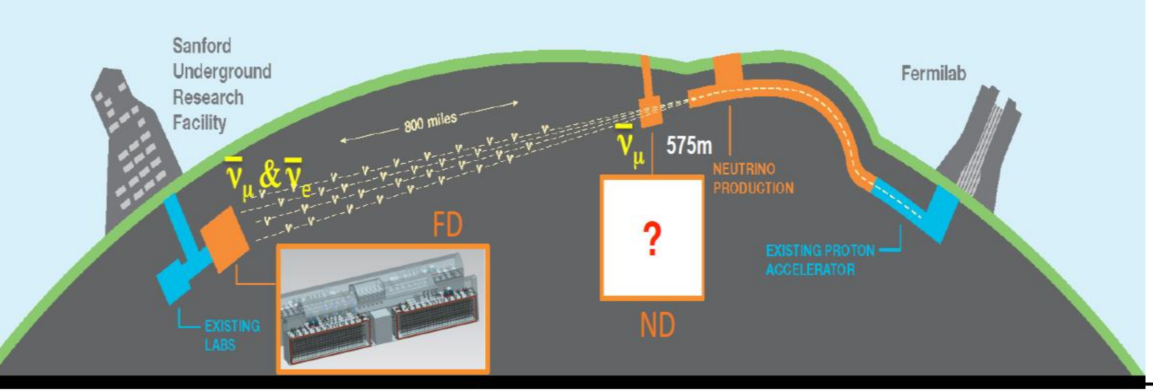
- Single muon candidate events after off-axis coefficients are applied to give monochromatic flux centered at 1.2 GeV.





September 29, 2017 17

DUNE Near Detectors, H. Duyang



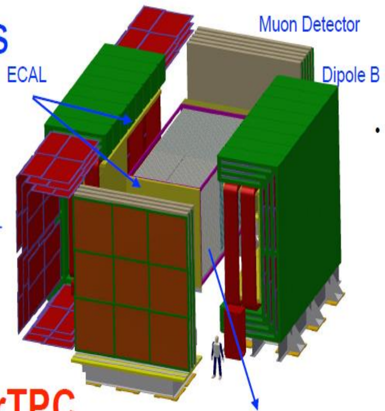
Near Detector Roles

- Constrain the systematics for oscillation measurement.
  - Measure spectra of all four species of neutrinos: ν_μ, $\bar{\nu}_\mu$, ν_e, $\bar{\nu}_e$
  - Measure the absolute and relative flux (FD/ND(E_ν))
  - Constrain energy scale.
  - Differences between neutrino and antineutrino
  - Constrain background: $\pi^0/\pi^+/\pi/$etc.
  - Constrain detector respond.
- Precision measurement for neutrino interaction:
  - Inclusive cross sections
  - exclusive cross sections
  - Nuclear effects
- Search for new physics:
  - sterile neutrinos
  - light Dark Matter candidates etc.

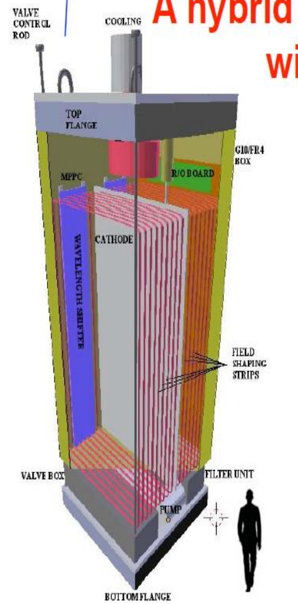
7

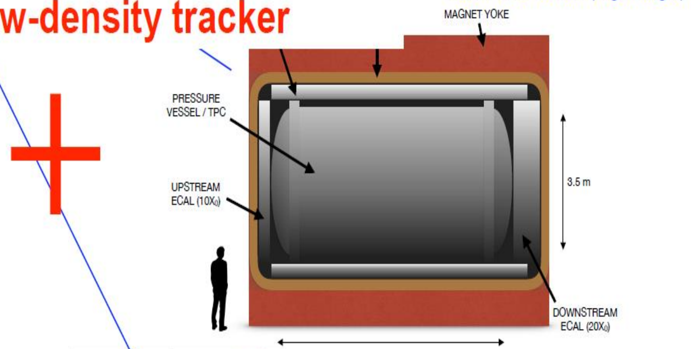
Near Detector Options

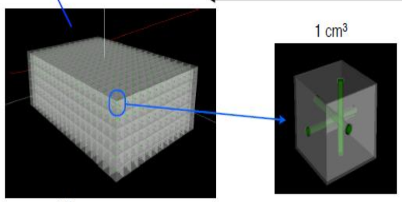
- Currently we have several ND options under study:
  - LAr TPC
  - Straw Tube Tracker (STT, CDR reference design)
  - High-Pressure Ar Gas TPC
  - Scintillating plastic tracker



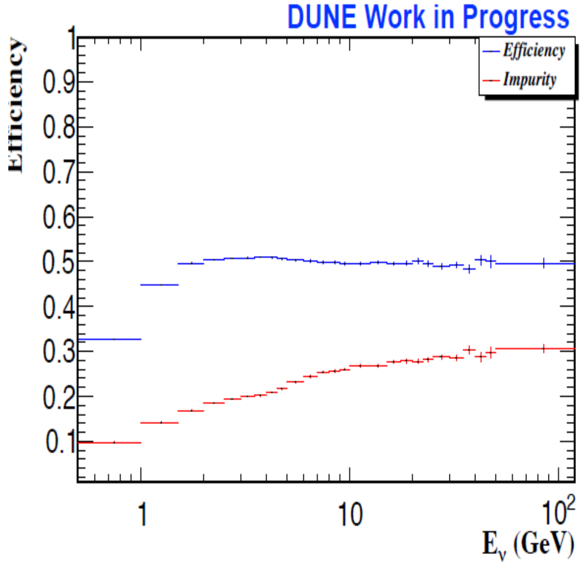
A hybrid detector combining a LArTPC with a low-density tracker

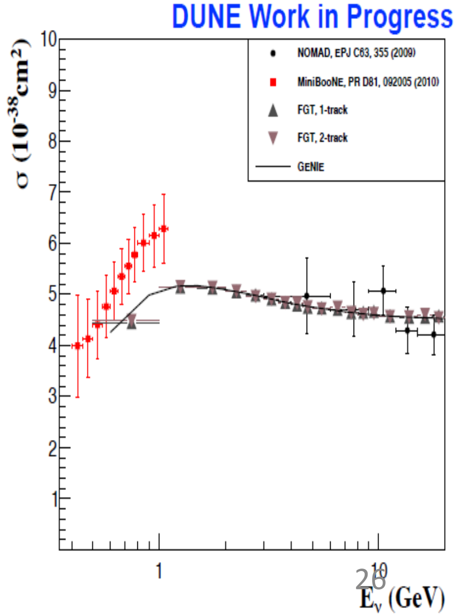






- Sensitivity study using fast MC shows signal **efficiency ~48%, purity ~76%** (STT).





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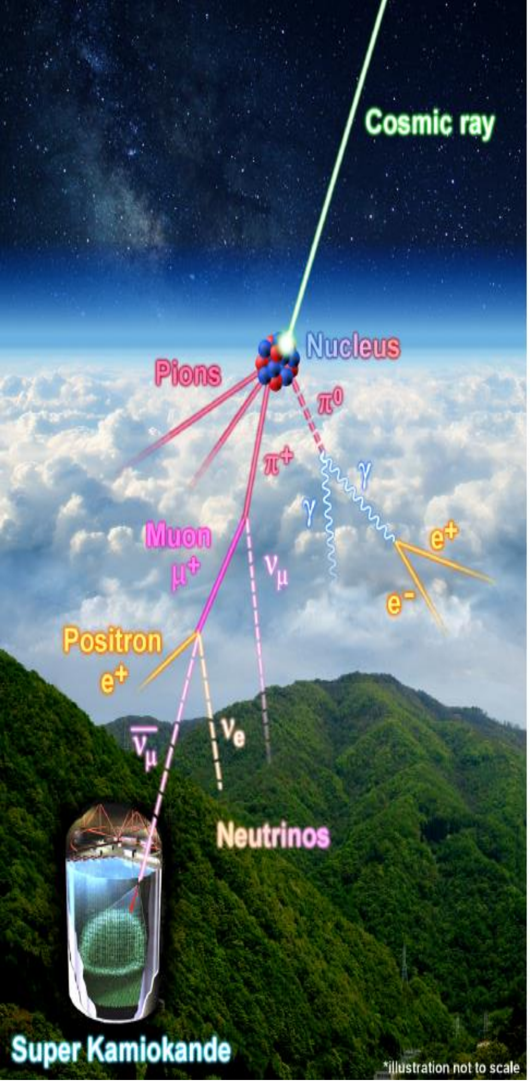
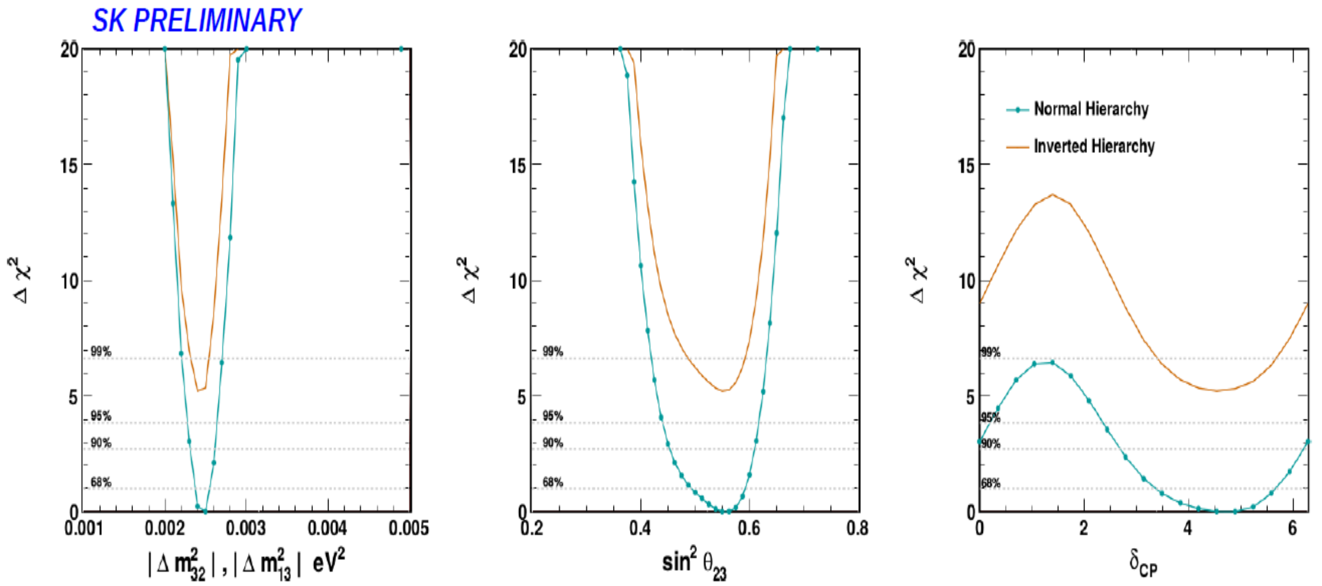
Atmospherics

- Recent results from Super-Kamiokande, F. Blaszczyk
- ICECUBE/DeepCore results and PINGU, Ehrhardt
- Tau neutrino appearance in ICECUBE, P. Eller
- Measuring the neutrino mass ordering and other oscillation parameters with KM3NET/ORCA, M. Circella



- Three different fits are done:
  1) Super-K atmospheric only (θ_{12} and Δm^2_{12} fixed), θ_{13} free
  2) Super-K atmospheric only, $\sin^2\theta_{13} = 0.0219$ (Daya Bay + RENO + Double Chooz)
  3) Super-K atmospheric + T2K model, $\sin^2\theta_{13} = 0.0219$

3) Super-K atm. + θ_{13} fixed + T2K constraint

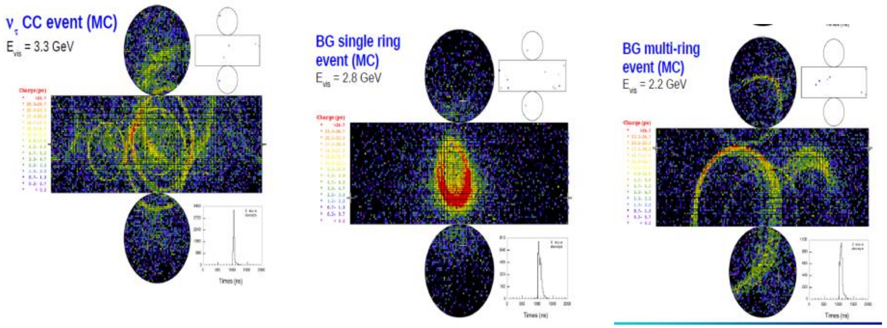


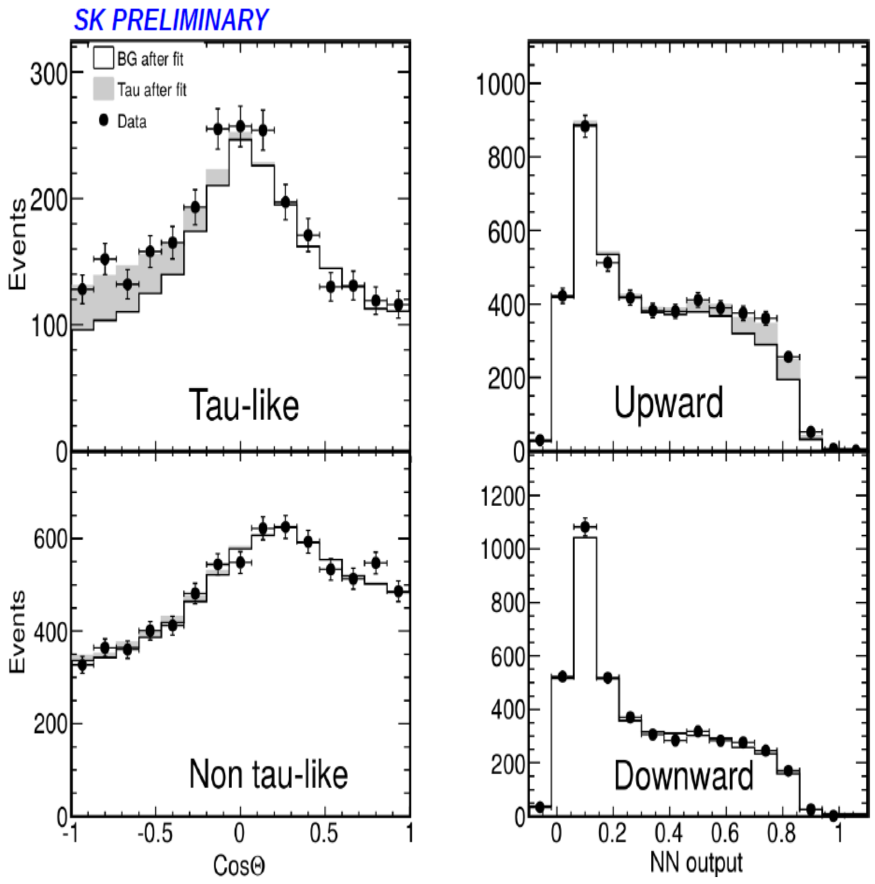
- **Use only published T2K beam flux bins** : reweight atmospheric ν MC using T2K beam flux

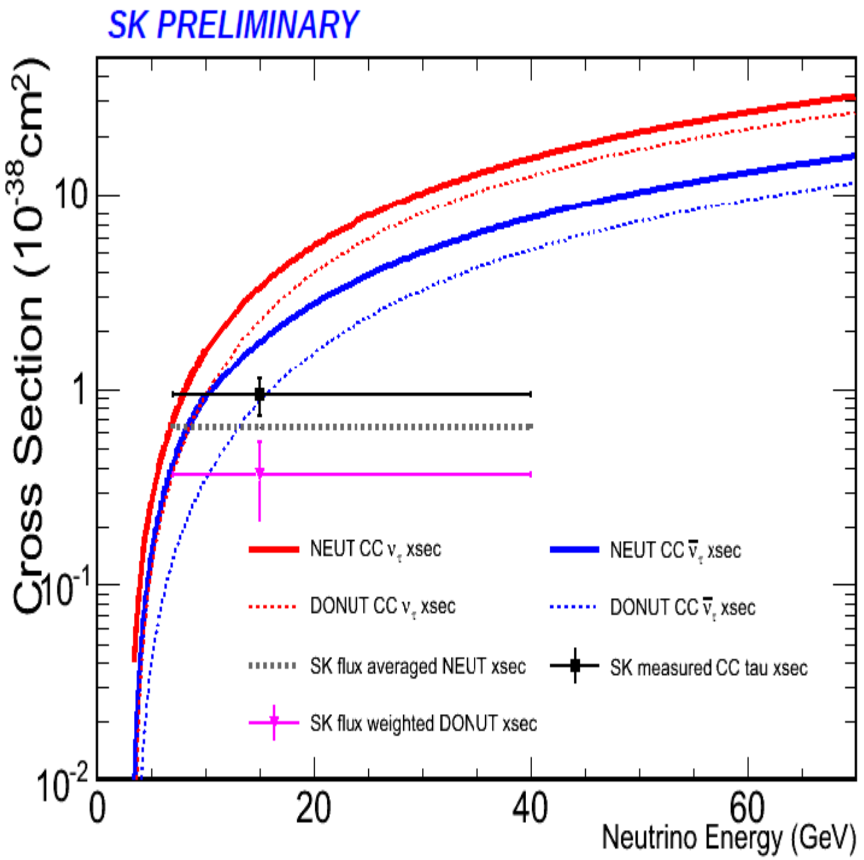
$\Delta\chi^2 = -5.2$ → **normal hierarchy preference strengthened**

- Best fit $\sin^2\theta_{23} = 0.550^{+0.040}_{-0.059}$ ($0.550^{+0.040}_{-0.059}$) → closer to maximal but still **2nd octant**
- Best fit $\delta_{CP} = 4.89^{+0.84}_{-1.45}$ ($4.54^{+0.99}_{-0.96}$) → still ~3π/2, stronger constraint

Super-Kamiokande, F. Blaszczyk







- Assume CC ν_τ cross-section has linear dependence on neutrino energy

$$\sigma(E) = \sigma_{const} \cdot E \cdot K(E)$$

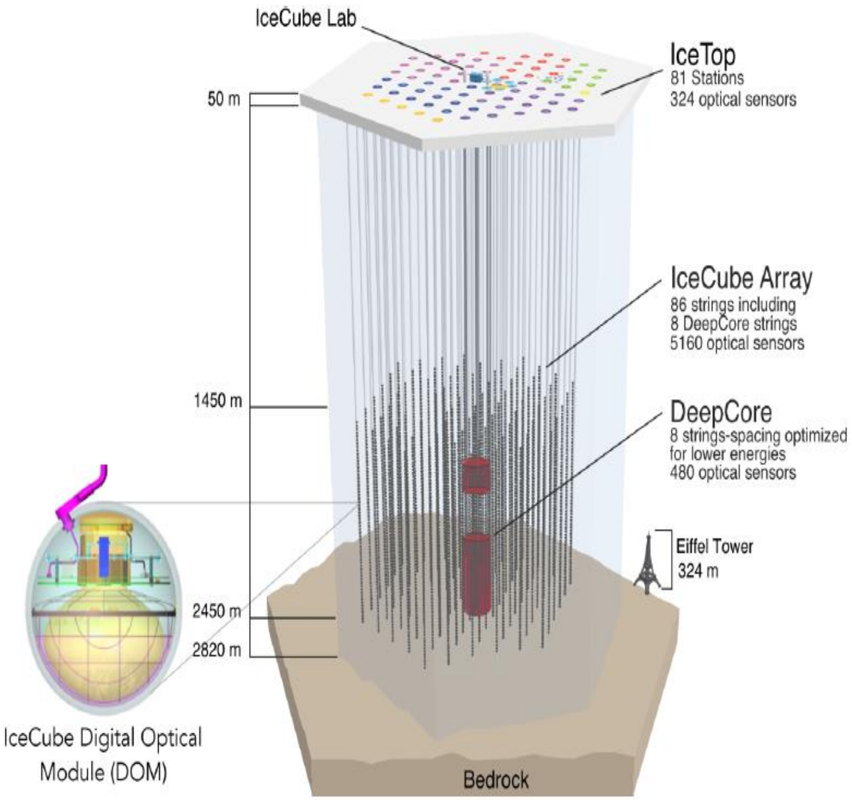
→ extrapolate to SK energies

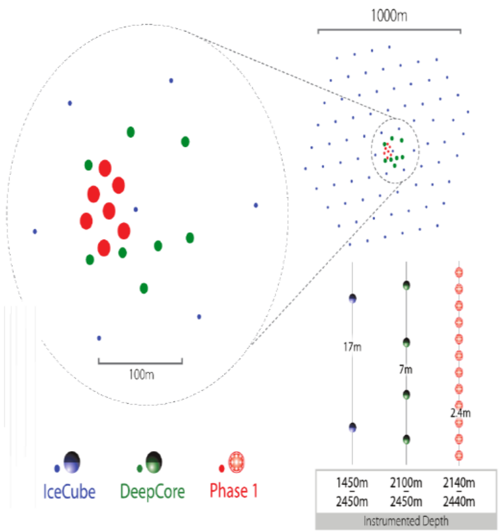
$\langle\sigma_{SK\text{-}DONUT}\rangle = (0.37\pm0.18)\times10^{-38}\ cm^2$

- Lower than Super-K measurement

$\langle\sigma_{SK}\rangle = (0.94\pm0.20)\times10^{-38}\ cm^2$

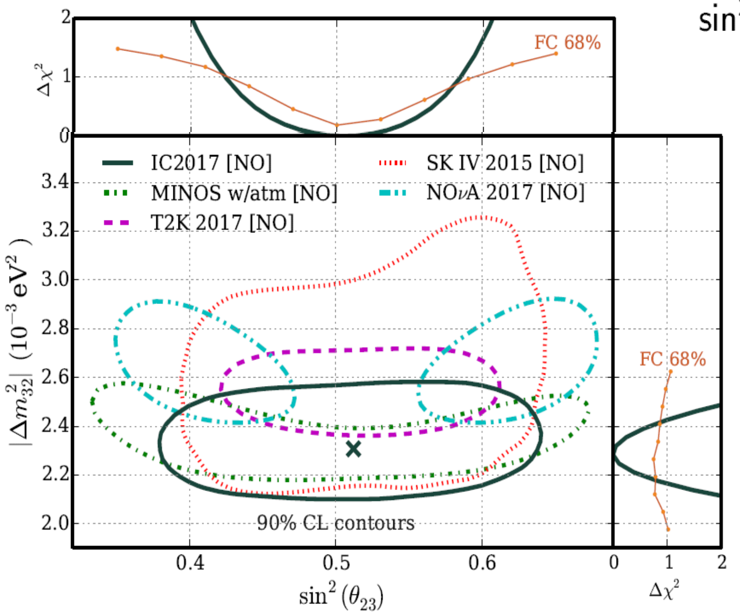
→extrapolation missing contribution from other CC cross-sections

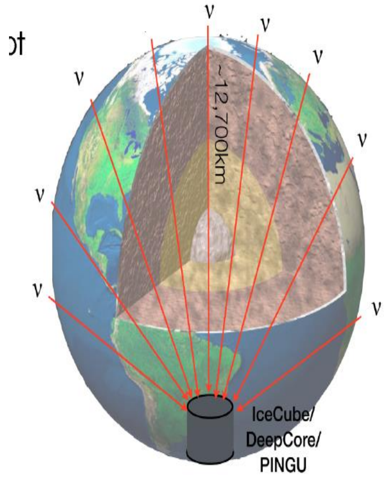




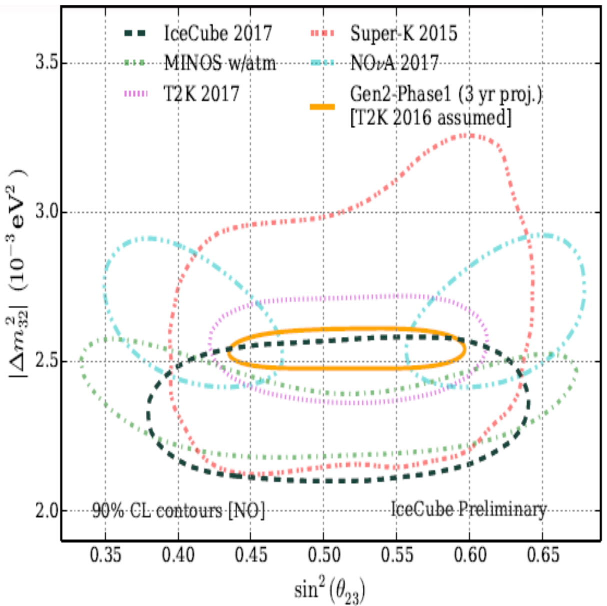
best fit (normal ordering): $\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\,\text{eV}^2$,

$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$



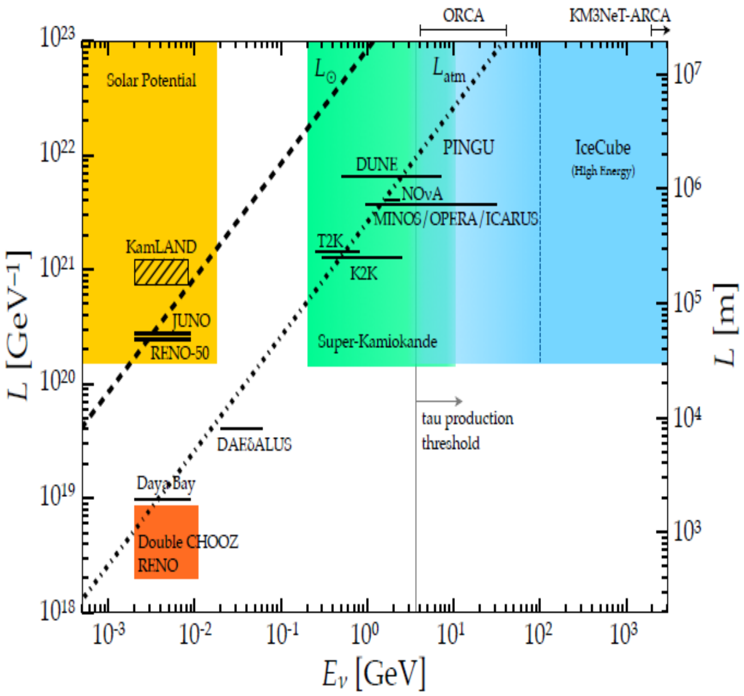


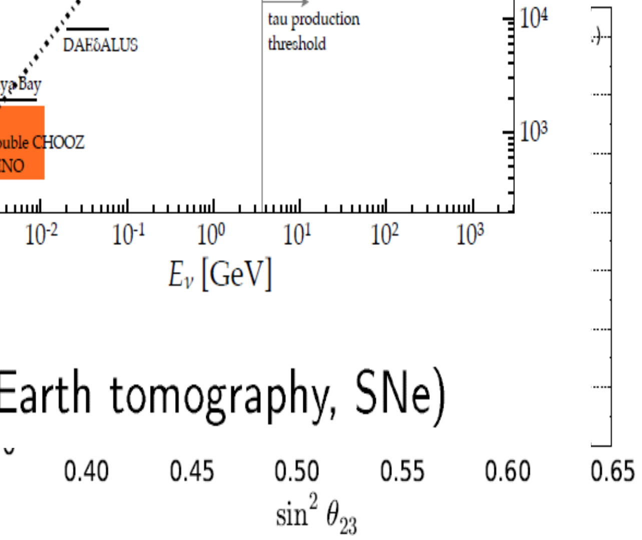
underway: follow-on analyses with this same + a higher-statistics data set

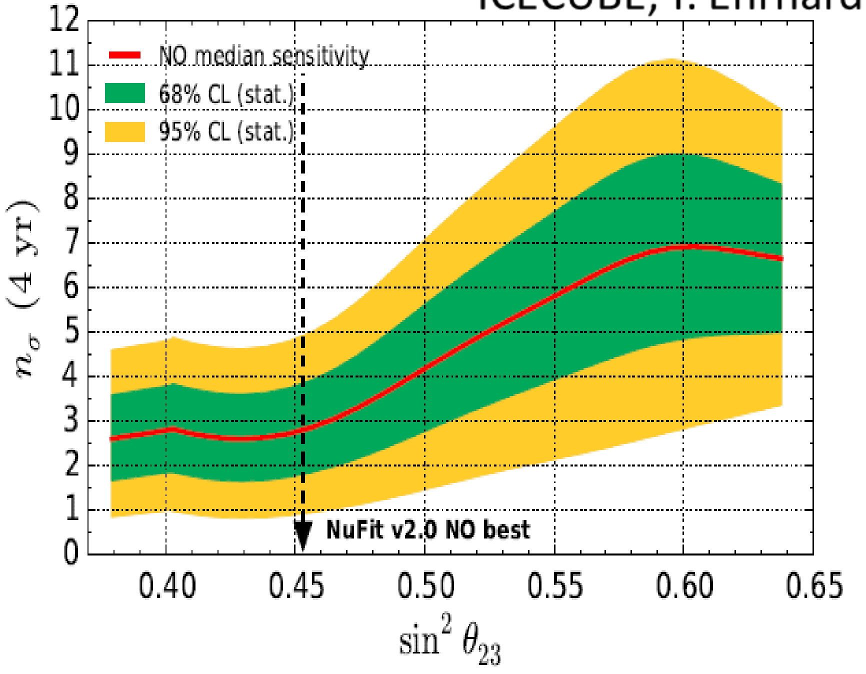


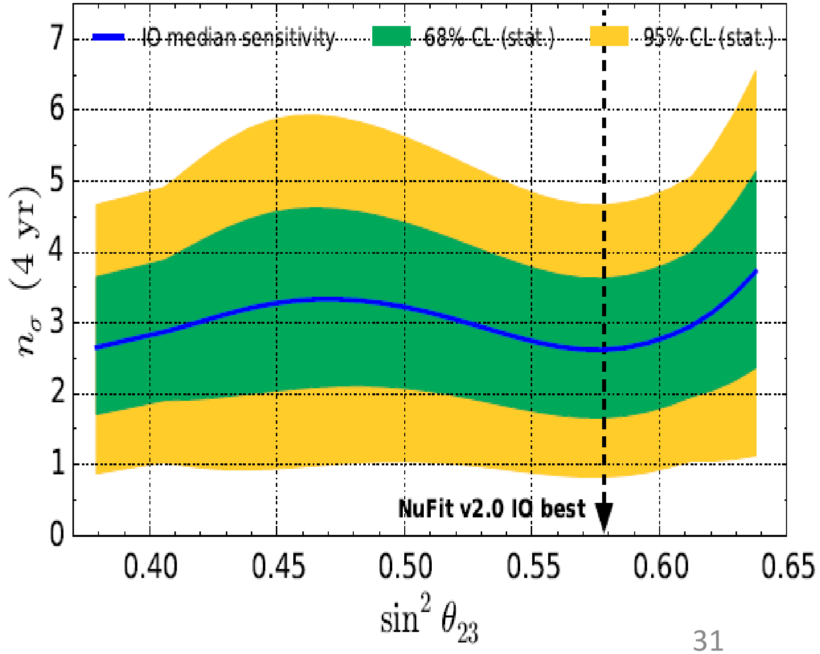
ICECUBE, T. Ehrhardt

- improve on Phase 1 sensitivities across the board
- around 70k upgoing atmospheric neutrinos per year
- neutrino mass ordering and θ_{23} octant sensitivity
- tau neutrino appearance
- + additional science (WIMP dark matter, Earth tomography, SNe)

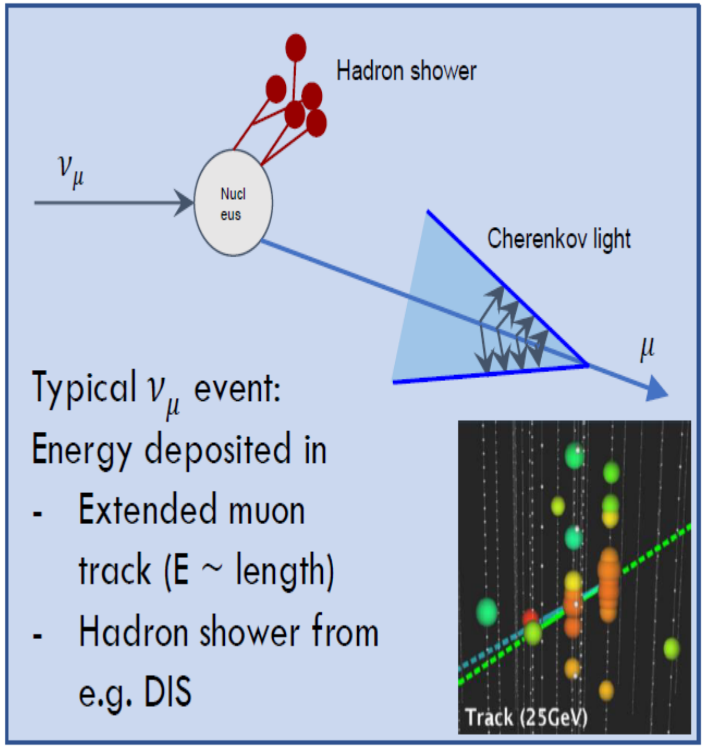




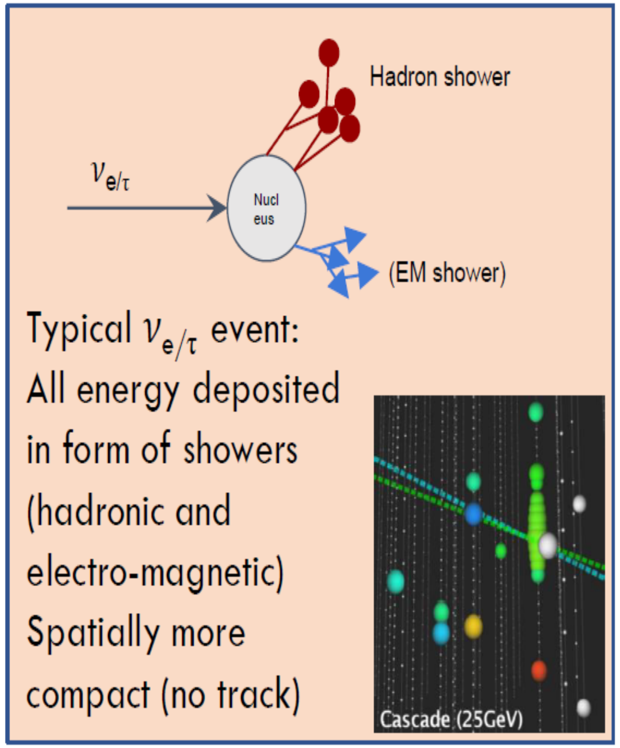




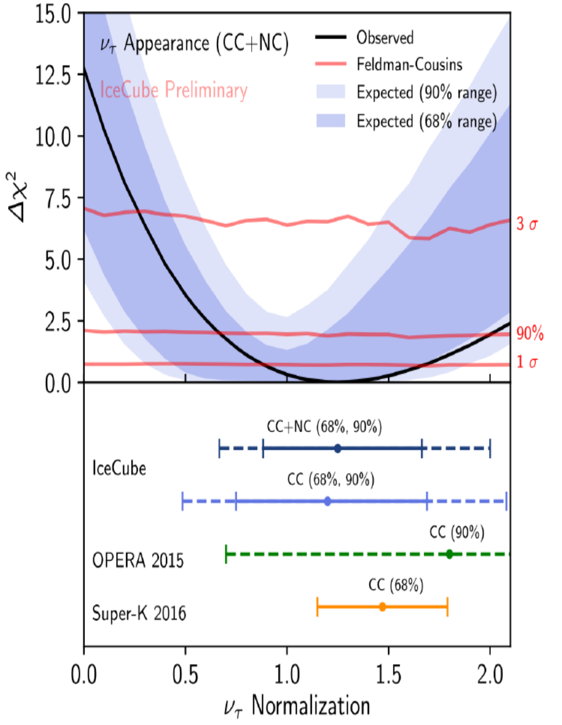
Track like



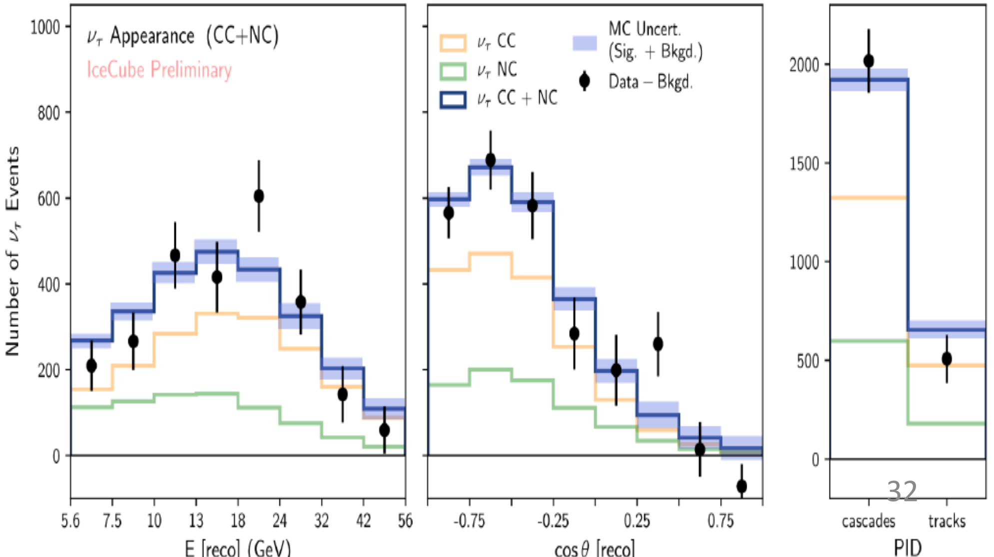
Cascade like

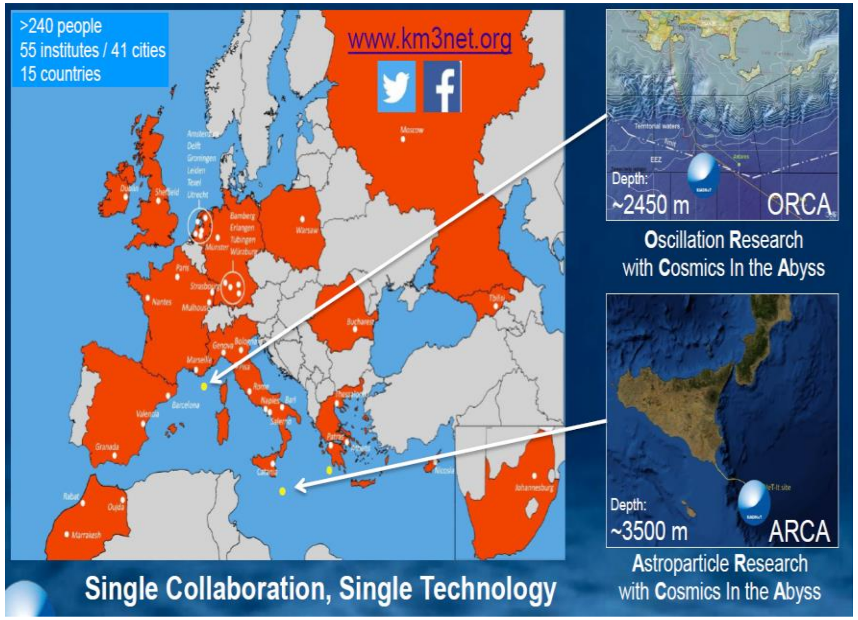


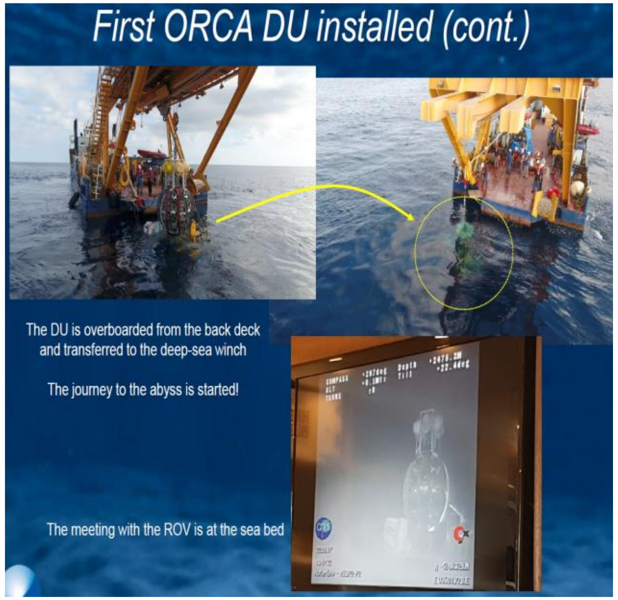
- ν_τ normalization (with 68% C.I.)
  - CC+NC: **1.25 +0.42 -0.37**
  - CC-only: **1.20 +0.49 -0.45**
- ν_τ appearance significance (exclusion of no-appearance)
  - CC+NC: **4.1 σ**
  - CC-only: **3.0 σ**
- c.f. talk "IceCube/DeepCore Results and PINGU" from this session, PINGU able to constrain ν_τ norm < 10%

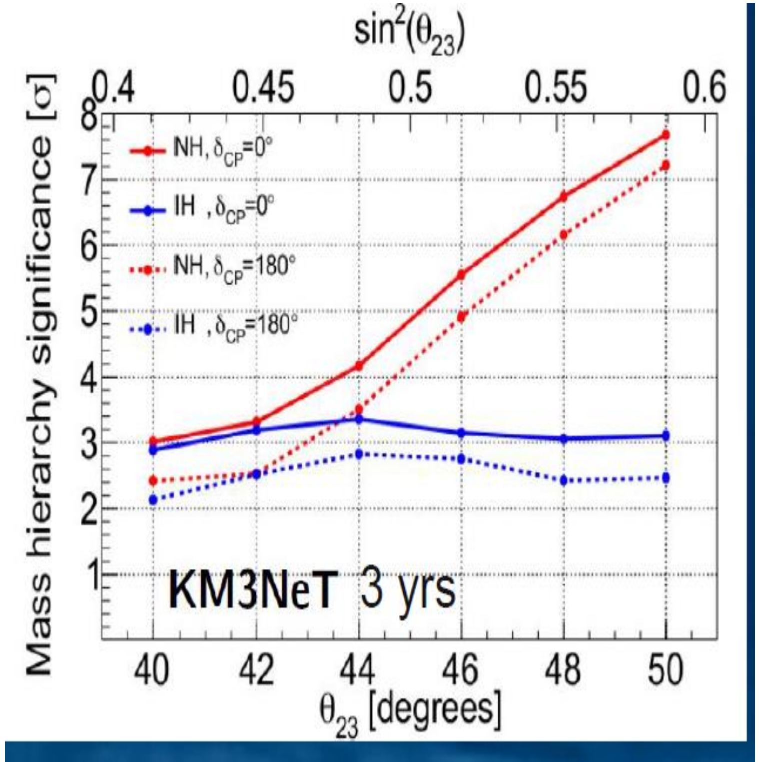


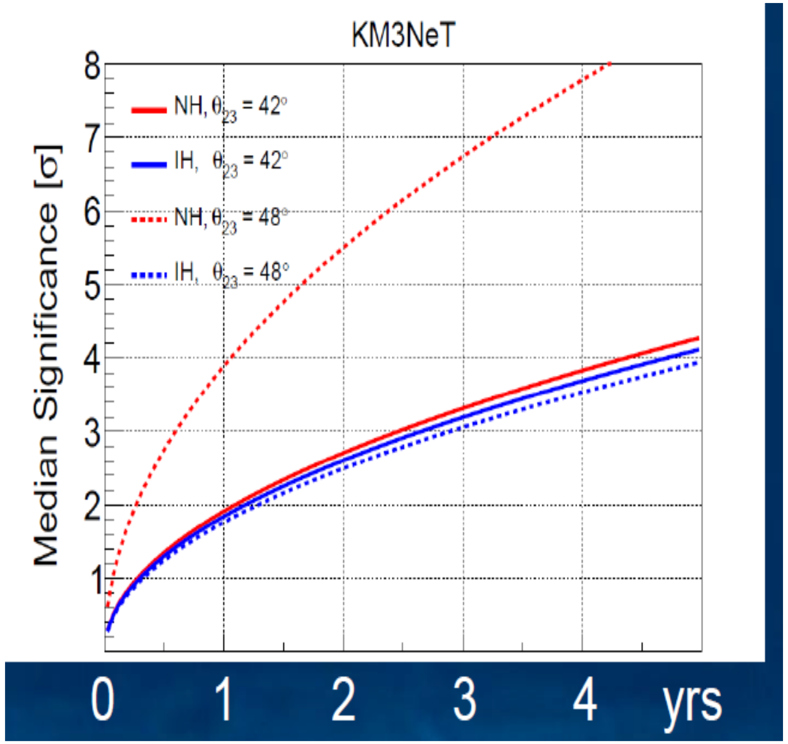
- First tau neutrino appearance in ICECUBE

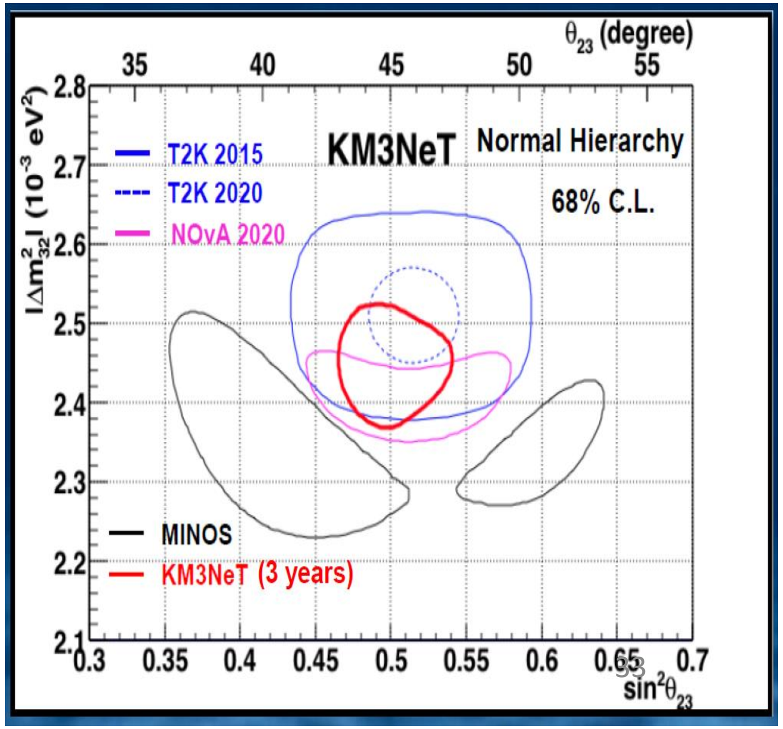


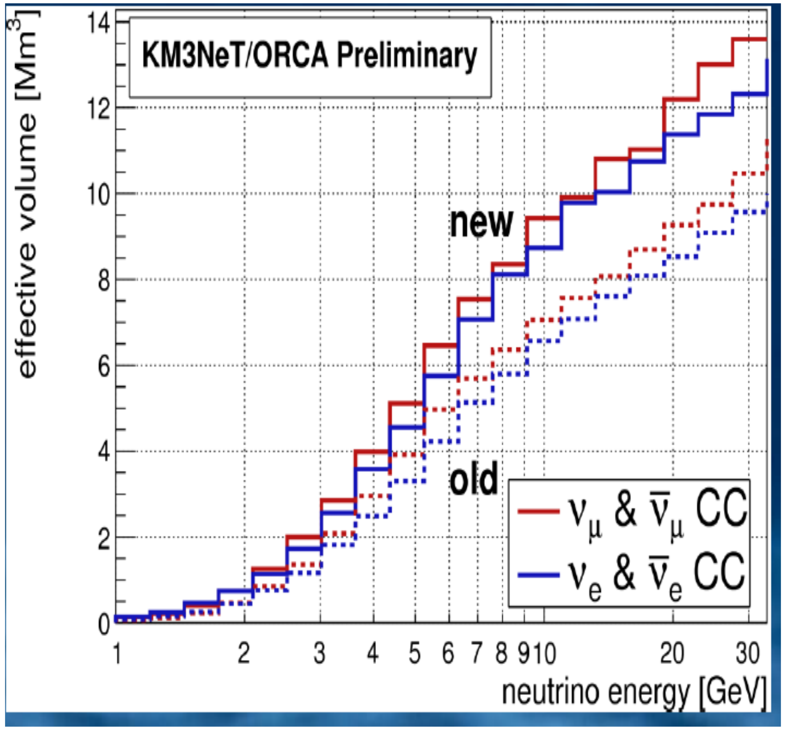

>240 people
55 institutes / 41 cities
15 countries
www.km3net.org
Depth:
~2450 m
ORCA
Oscillation Research with Cosmics In the Abyss
Depth:
~3500 m
ARCA
Astroparticle Research with Cosmics In the Abyss
Single Collaboration, Single Technology

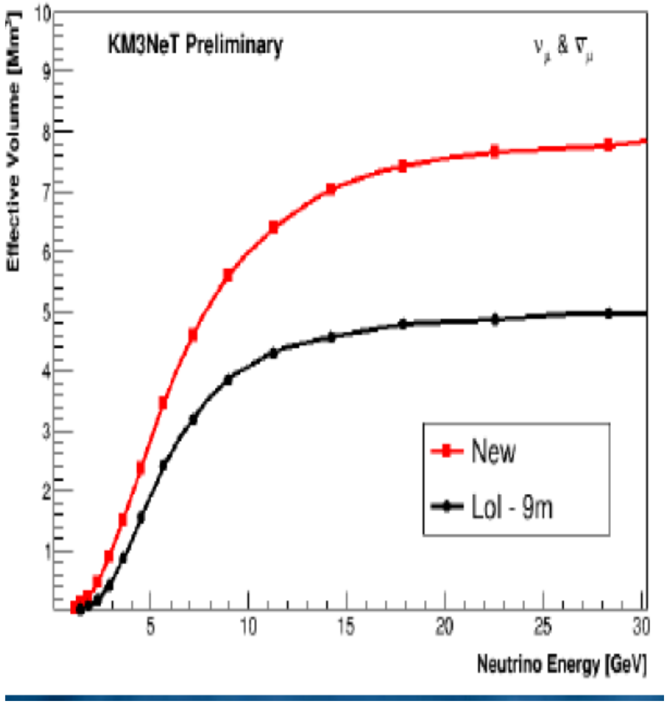

First ORCA DU installed (cont.)
The DU is overboarded from the back deck and transferred to the deep-sea winch
The journey to the abyss is started!
The meeting with the ROV is at the sea bed

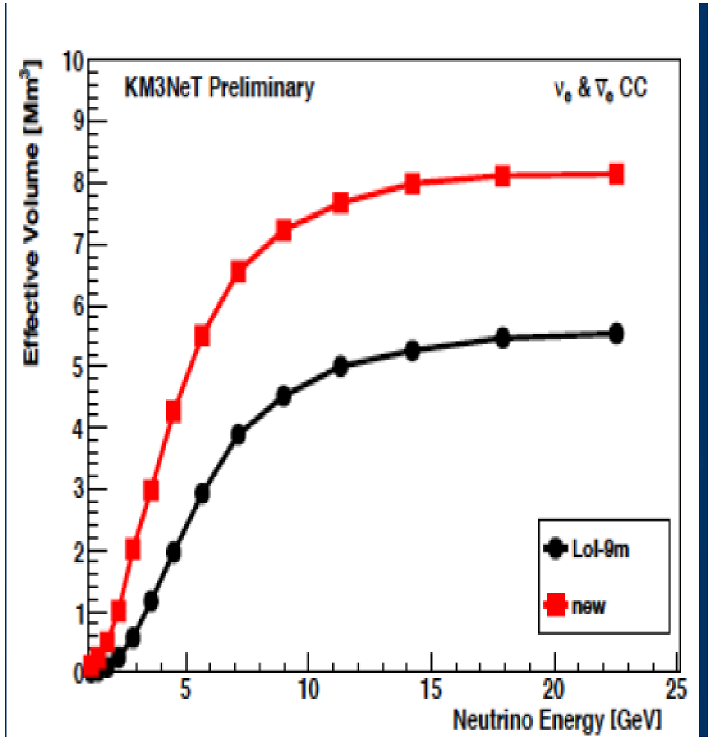

$\sin^2(\theta_{23})$
0.4
0.45
0.5
0.55
0.6
Mass hierarchy significance [σ]
NH, δ_{CP}=0°
IH, δ_{CP}=0°
NH, δ_{CP}=180°
IH, δ_{CP}=180°
KM3NeT 3 yrs
θ_{23} [degrees]


KM3NeT
Median Significance [σ]
NH, θ_{23} = 42°
IH, θ_{23} = 42°
NH, θ_{23} = 48°
IH, θ_{23} = 48°
0
1
2
3
4
yrs


θ_{23} (degree)
$|\Delta m^2_{32}|$ (10^{-3} eV^2)
T2K 2015
T2K 2020
NOvA 2020
KM3NeT
Normal Hierarchy
68% C.L.
MINOS
KM3NeT (3 years)
$\sin^2\theta_{23}$


KM3NeT/ORCA Preliminary
effective volume [Mm^3]
new
old
ν_μ & $\bar{\nu}_\mu$ CC
ν_e & $\bar{\nu}_e$ CC
neutrino energy [GeV]


KM3NeT Preliminary
ν_μ & $\bar{\nu}_\mu$
Effective Volume [Mm^3]
New
LoI - 9m
Neutrino Energy [GeV]


KM3NeT Preliminary
ν_e & $\bar{\nu}_e$ CC
Effective Volume [Mm^3]
LoI-9m
new
Neutrino Energy [GeV]

Questions

- What are the next steps for a unitarity test?
- What are the needs for the hadron production measurements for the future experiments?
- How can we address the reactor anomaly (now that the “bump” is being “understood”)?
- How can we address the “tension” between NOvA and T2K for the maximal mixing?
- What are the implications of the most likely value of δ_{CP} for the future experiments?

Thank you to all the WG1 speakers and participants