WG1 - Neutrino Oscillations Summary

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NUFACT2018, Blacksburg, Virginia

WG1 Sessions

Presentations: 7 plenary talks, 27 Parallel Talks and 6 Posters

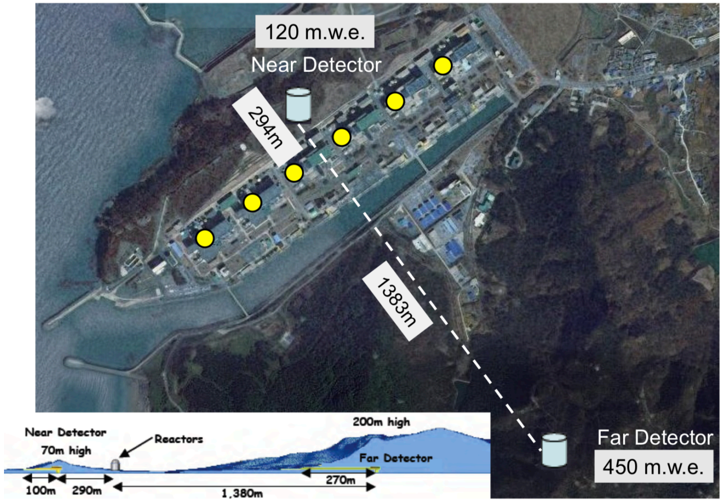
A total of 7 parallel sessions:

- Monday 14:00-16:00 – Reactors
- Monday 16:30-18:00 – Atmospherics
- Tuesday 14:00-16:00 - Joint w/ WG2 [report in WG2 talk]
- Thursday 14:00-16:00 Current Accelerator + Global fit
- Thursday 16:30-18:00 Future LBN
- Friday 14:00-16:00 - Joint w/ WG2 [report in WG2 talk]
- Friday 16:30-17:00 - Joint w/ WG5 [report in WG5 talk]

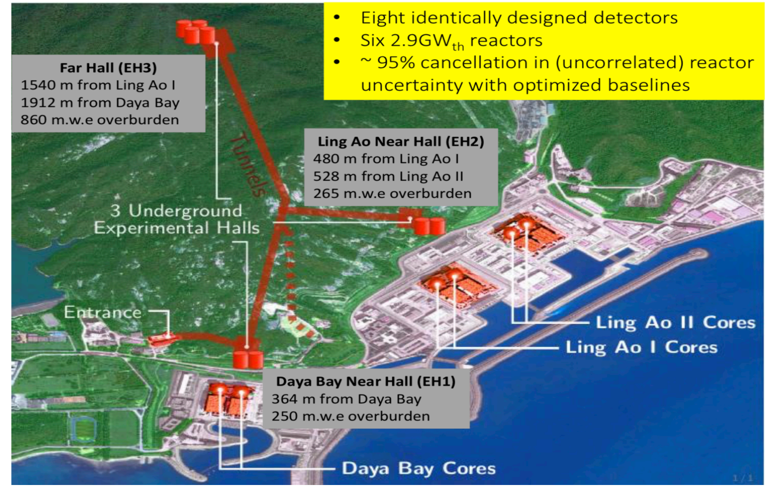
Reactors

- New Results from RENO, JeeSeung Jang, GIST
- Latest Results from the Daya Bay Reactor Neutrino Experiment, Wenqiang Gu, BNL
- JUNO physics, Xuefeng Ding, GSSI
- The design and research progresses of the Central Detector in JUNO, Yukun Heng, IHEP

RENO Experimental Set-up



Daya Bay Experimental Layout



New RENO Results

- Precise measurement of $|\Delta m_{ee}^2|$ and θ_{13} using ~2200 days of data (Aug. 2011 – Feb 2018)

"Measurement of Reactor Antineutrino Oscillation Amplitude and Frequency at RENO" → submitted to PRL (arXiv:1806.00248)

- Fuel-composition dependent reactor antineutrino yield →

"Fuel-composition dependent reactor antineutrino yield and spectrum at RENO" → submitted to PRL (arXiv: 1806.00574)

- Measurement of absolute reactor neutrino flux and spectrum

- Independent measurement of $|\Delta m_{ee}^2|$ and θ_{13} with delayed n-H signals

New Daya Bay experiment

- New oscillation measurement
  - ~ 4 million $\bar{\nu}_e$'s 1958 days
- Improved measurement of reactor $\bar{\nu}_e$ flux
  - Neutron calibration campaign 1230 days
- Search for a time-varying electron $\bar{\nu}_e$ signal

Also

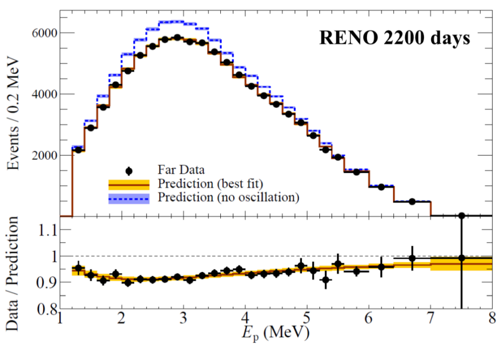
- Seasonal Variation of the Underground Cosmic Muon Flux
- Cosmogenic neutron production

RENO, JeeSeung Jang/ Daya Bay, Wenqiang Gu

Oscillation Results

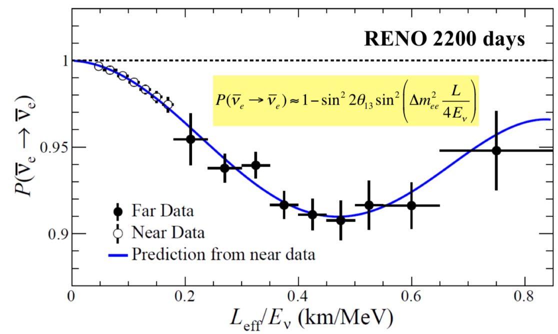
RENO

Spectral shape of Far / Near



Energy-dependent disappearance of reactor antineutrinos

Survival probability of reactor antineutrinos



Clear L/E-dependent disappearance of reactor antineutrinos

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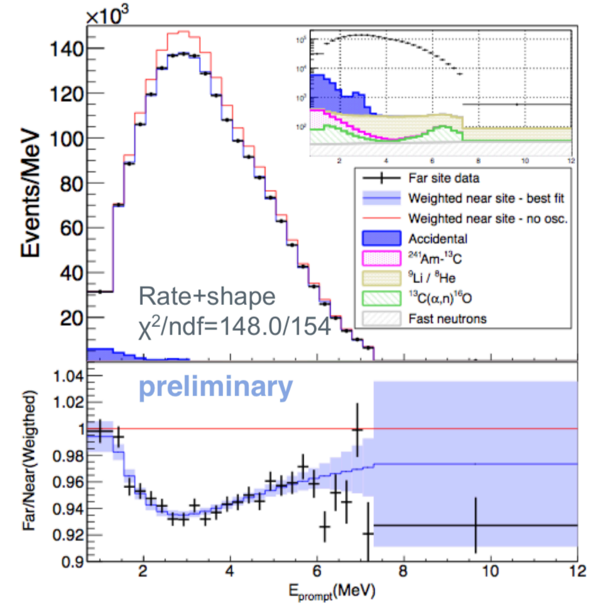
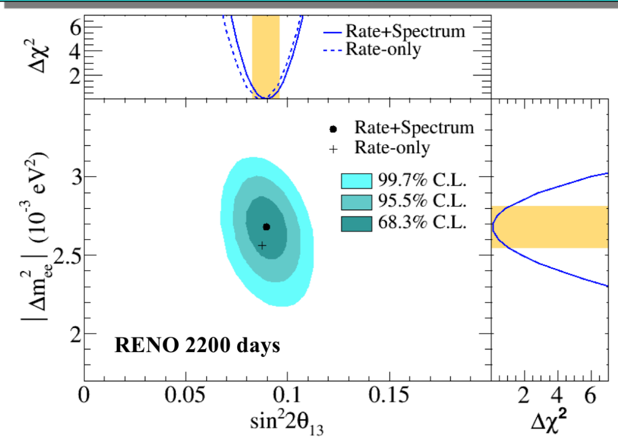
DayaBay



Allow regions for θ_{13} and $|\Delta m^2_{ee}|$



$\sin^2 2\theta_{13} = 0.0896 \pm 0.0048(\text{stat.}) \pm 0.0047(\text{syst.})$ (± 7.6%)

$|\triangle m_{ee}^2| = 2.68 \pm 0.12(\text{stat.}) \pm 0.07(\text{syst.})$ ($\times 10^{-3}$ eV^2) (± 5.2 %)

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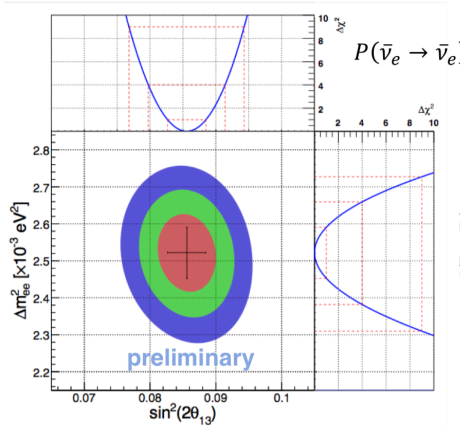
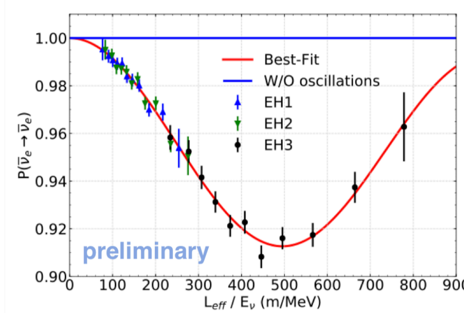
Jianming B

Oscillation Results with 1958 Days

- Measure $\sin^2 2\theta_{13}$ and $|\Delta m^2_{ee}|$ to **3.4%** and **2.8%** respectively



$$P(\bar{\nu}_e \to \bar{\nu}_e) \approx 1 - \sin^2 2\theta_{13} \sin^2 \frac{1.267 \Delta m^2_{ee} L}{E} - \text{solar term}$$



$\sin^2 2\theta_{13} = 0.0856 \pm 0.0029$
$|\Delta m^2_{ee}| = (2.52 \pm 0.07) \times 10^{-3}$ eV^2

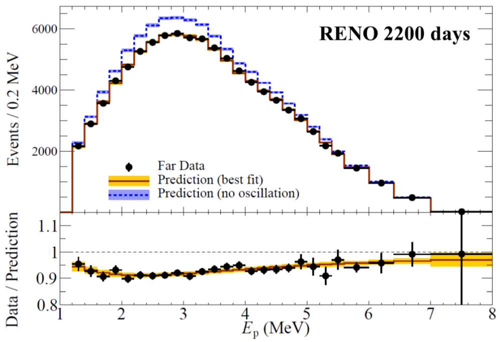
The statistical uncertainty contributes about 60% (50%) of the total θ_{13} (Δm^2_{ee}) uncertainty.

RENO, JeeSeung Jang/ Day

Oscilla

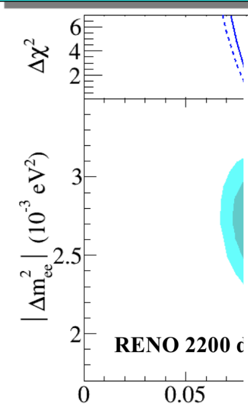
RENO

Spectral shape of Far / Near



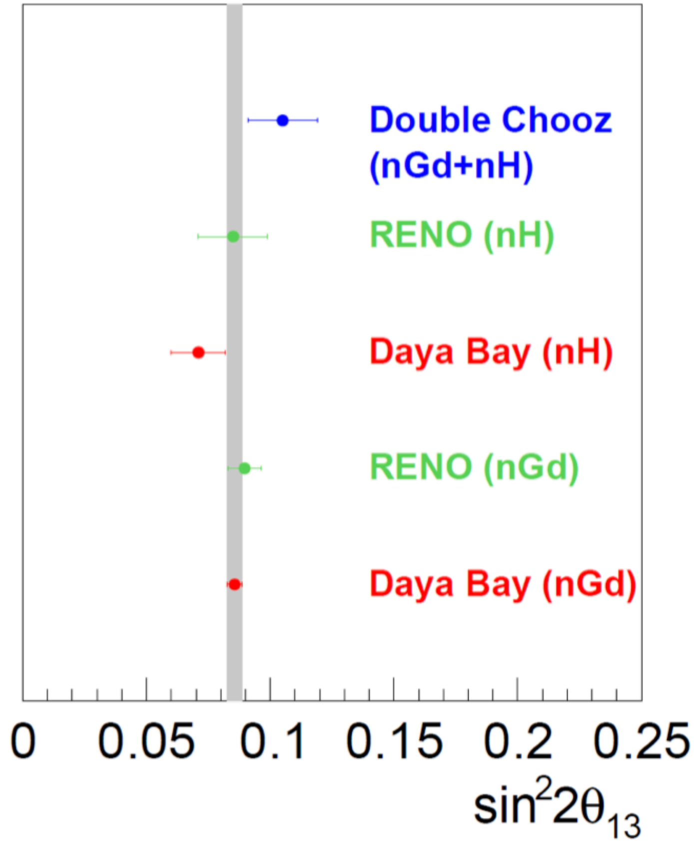
Energy-dependent disappearance of reactor antineutrinos

Allow regions for θ_{13} and |Δ



$\sin^2 2\theta_{13} = 0.0896 \pm 0.0($

$|\triangle m_{ee}^2| = 2.68 \pm 0.12($st



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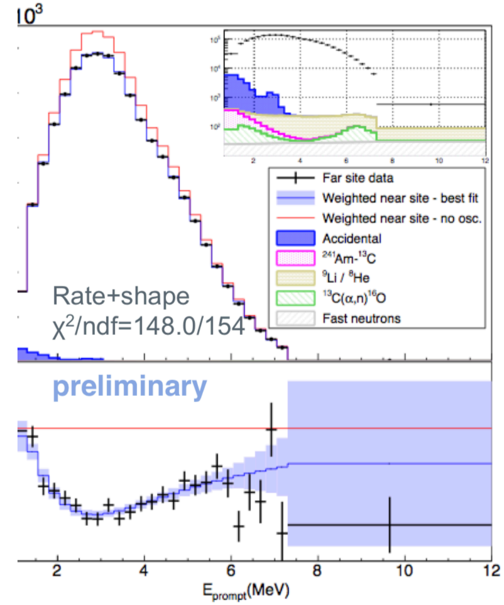
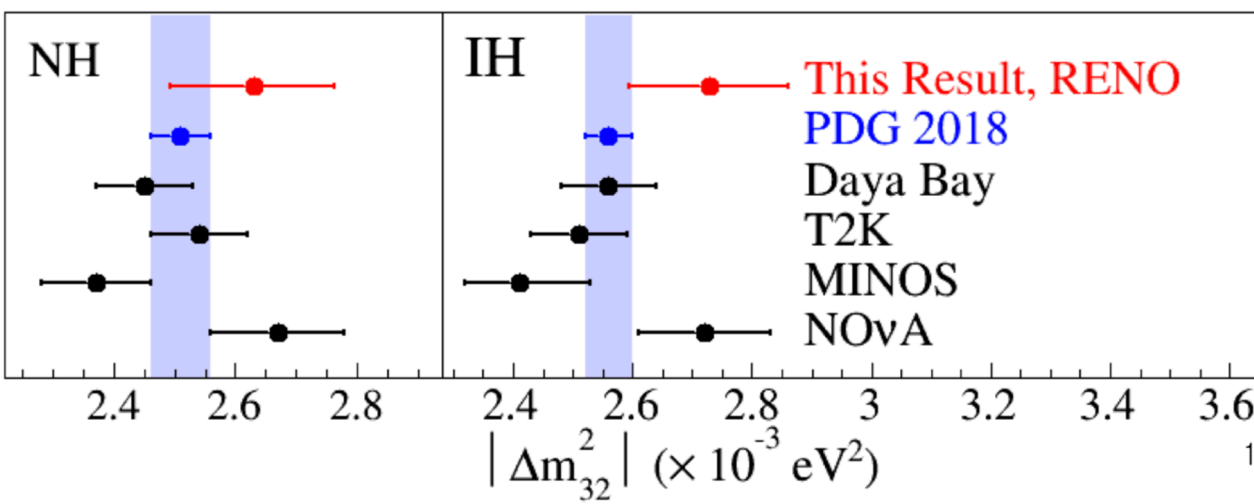
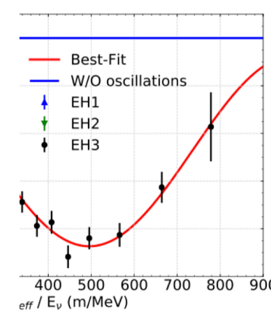


esults with 1958 Days

n$^2_{ee}$| to **3.4%** and **2.8%** respectively



$n^2 \frac{1.267\Delta m^2_{ee} L}{E}$ − solar term



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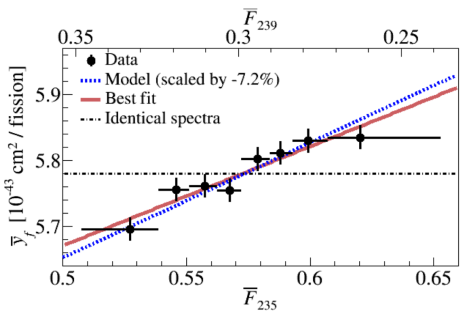
he total θ_{13} (Δm^2_{ee}) uncertainty.

Fuel Evolution and 5MeV Excess, Time Variation

Fuel-Composition Dependent Reactor Neutrino Yield



Average of IBD yield per fission

$\bar{y}_f = \sum \bar{F}_i y_i$

$\bar{F}_i$: time averaged fission fraction of isotope i

RENO

No fuel-dependent variation of IBD yield per fission is ruled out with 6.7 σ

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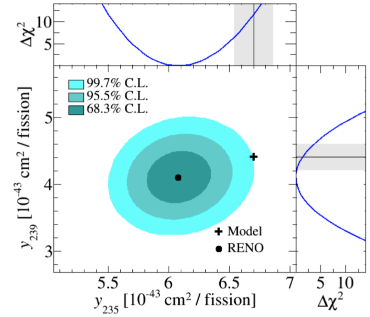
Best-fit result of IBD yields per fission of ^{235}U (^{239}Pu)



^{235}U: 3.5σ deficit relative to Huber-Mueller (H-M) prediction
^{239}Pu: 1.2σ deficit

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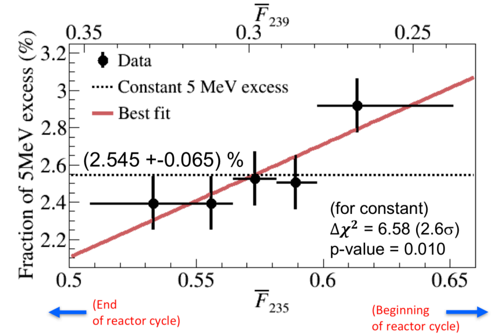
Correlation of 5 MeV excess with ^{235}U isotope fraction



2.6σ indication of 5 MeV excess coming from ^{235}U fuel isotope fission

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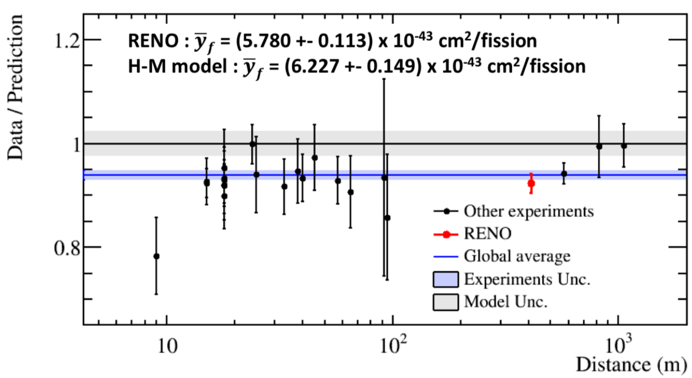
Measurement of Absolute Reactor Neutrino Flux

Cross section calculation
- Fayans 85 formalism
- τ_n= 880.2s (PDG2017)

Data / Prediction, RENO 2200 days at near detector
0.924 +- 0.018 (for Huber + Mueller model)
0.966 +- 0.019 (for ILL + Vogel model)



RENO

Deficit of observed reactor neutrino fluxes relative to the prediction (Huber + Mueller model) indicates an overestimated flux or possible oscillation to sterile neutrinos

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Improved Absolute Antineutrino Flux

DayaBay

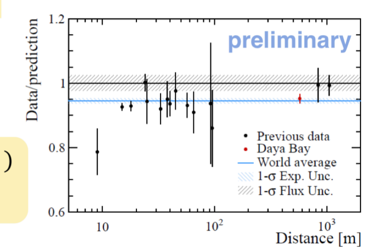
- The ε_n estimated by
  - MC simulation of best-fit model
  - A correction obtained from a linear regression analysis of the remaining data-MC difference
- Uncertainty estimated with spread of models

$$\varepsilon_n = (81.48 \pm 0.60)\%$$

Target achieved: uncertainty improved by a factor of 2

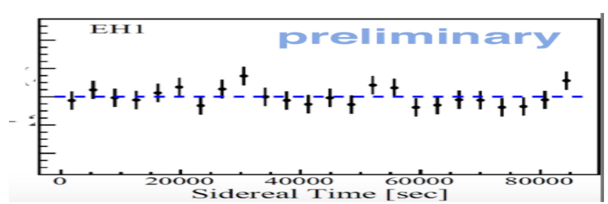
results with 1230 days

$R_{data/pred}$ (Huber-Mueller) $= 0.952 \pm 0.014$(exp.)
$\sigma_f = (5.91 \pm 0.09) \times 10^{-43}$cm²/fission



DayaBay

- Time-varying $\bar{\nu}_e$ signal search over 704 calendar days
- Set limits on the Lorentz and CPT violation under standard model extension (SME) framework

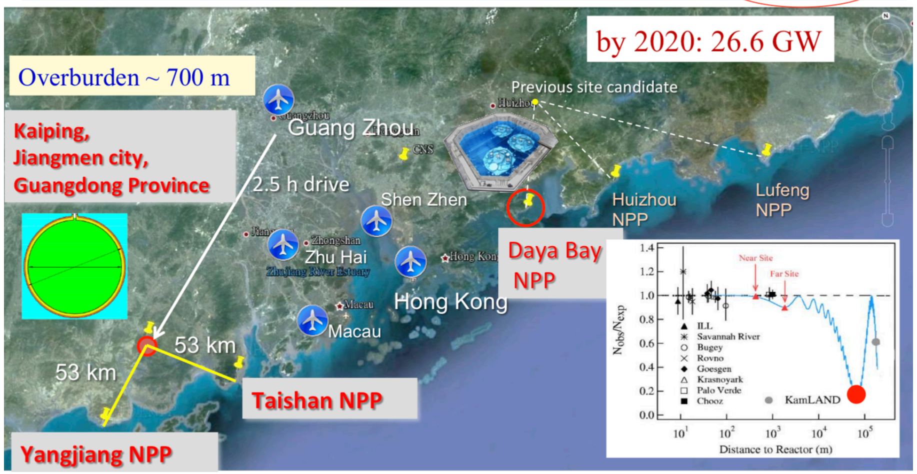


JUNO, Xuefeng Ding

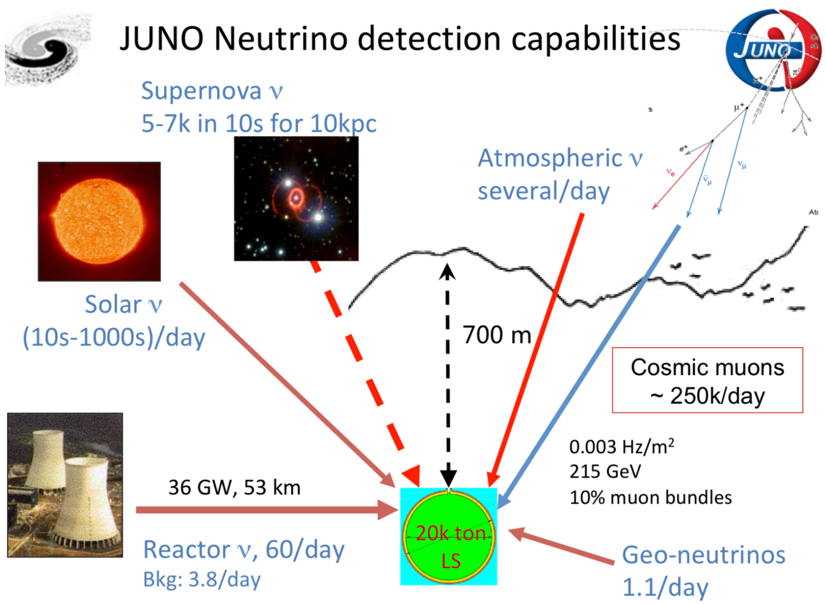
JUNO Site

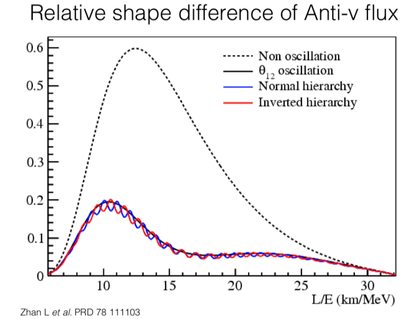
JUNO has been approved in Feb. 2013. with ~ 300 M$ support by China

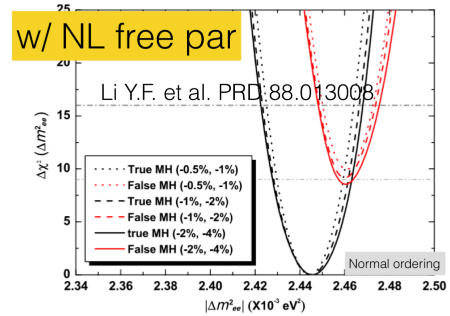
NPP	Daya Bay	Huizhou	Lufeng	Yangjiang	Taishan
Status	Operational	Planned	Planned	Under construction	Under construction
Power	17.4 GW	17.4 GW	17.4 GW	17.4 GW	18.4 GW



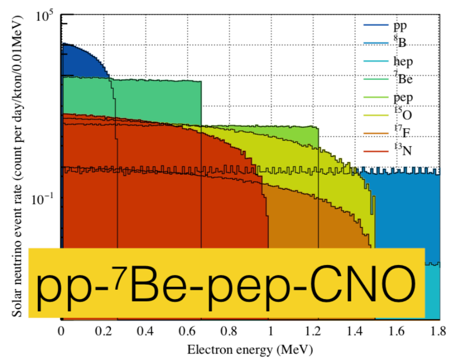
JUNO Neutrino detection capabilities

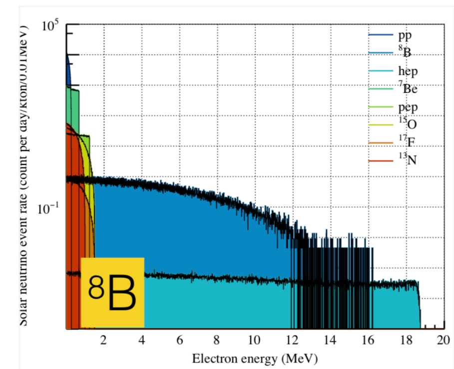






- JUNO's median sensitivity on determining **Neutrino Mass Ordering** is **~3.4σ with 6 years of data**
  - 3% energy resolution ($\frac{\sigma_0}{1.6} \oplus \sigma_1 \oplus 1.6\sigma_2 < 3\%$) is required.
  - Degeneration from residual NL removed by using free NL par.
  - Using multivariate fit can improve sensitivity



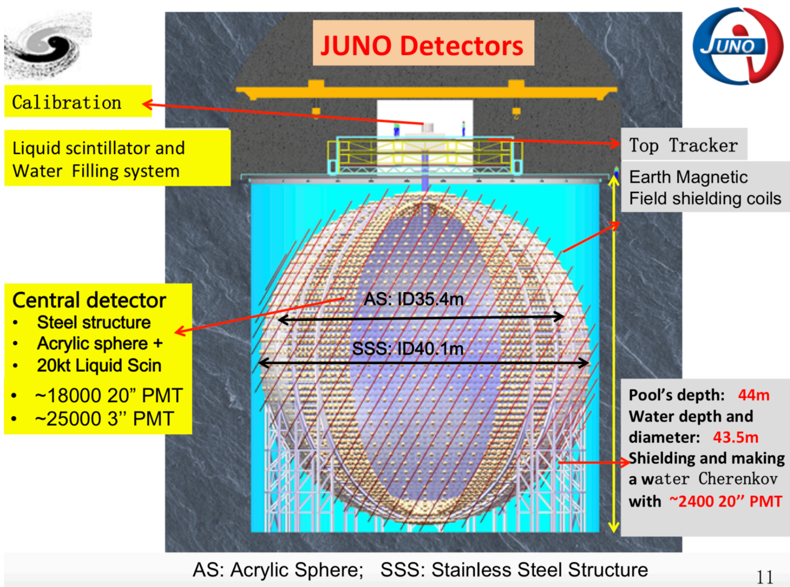


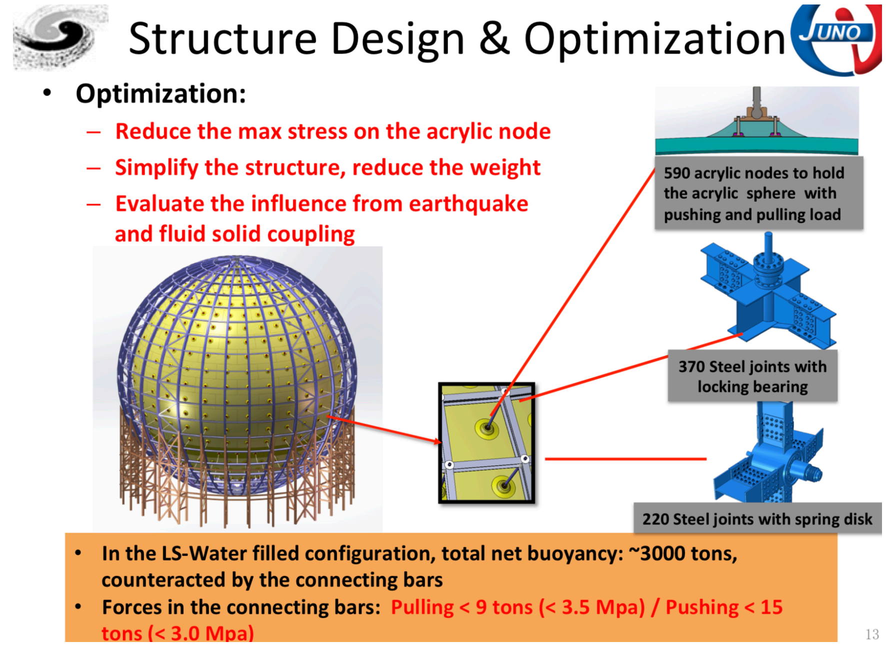
what is rate? **is there upturn?**

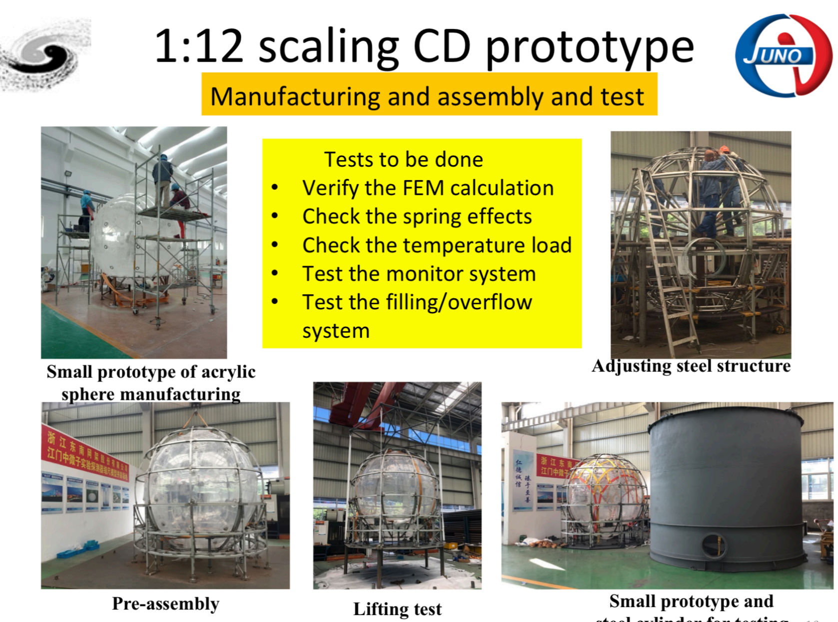
- **Expected precision on solar neutrinos** assuming 10^{-16} g/g ^{238}U etc. LS purity is at percent level. **Shape systematics** not included yet.
- **The S/B for solar ^{8}B neutrino** for JUNO depends on **the efficiency of removal of ^{10}C** with μ-n tagging algorithms
  - From Fluka it can reach 98%. Then **S/B ~ 1:1**
  - 6 yr 6000 ν ev. in [2,2.5] MeV: **touch transition zone**

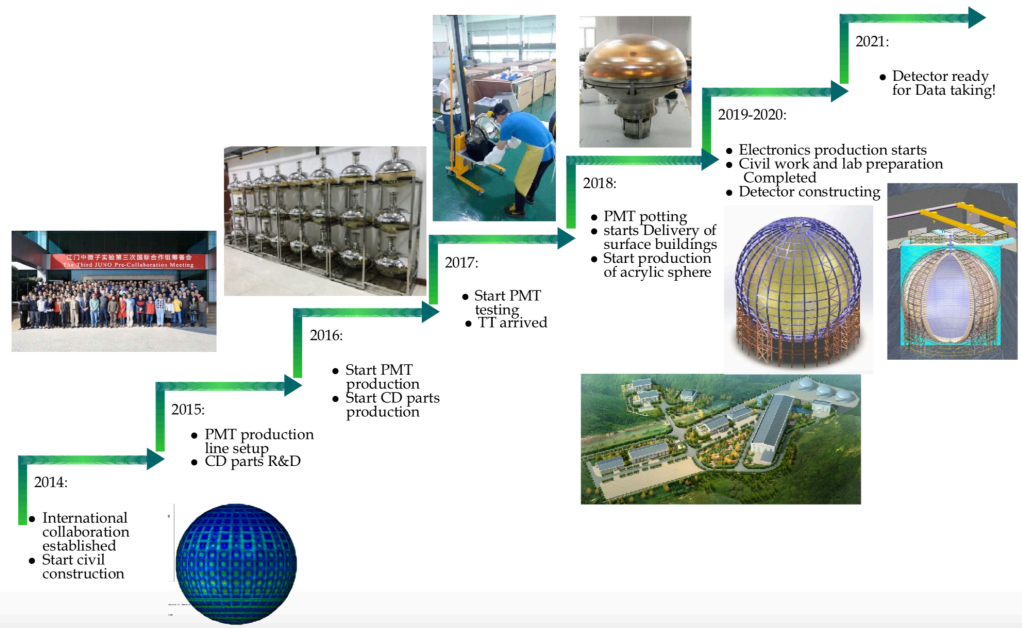
ng Bian

JUNO, Xuefeng Ding/Yuekun Heng





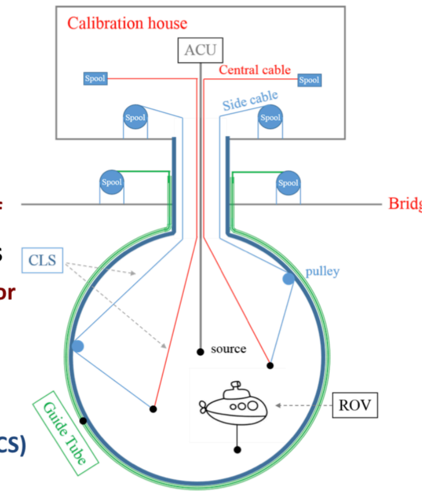




JUNO,Yuekun Heng

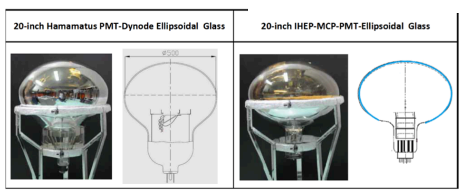
	KamLAND	BOREXINO	Daya Bay	JUNO
Target Mass	1 kt	300 t	20 t x 8	20 kt
PE Collection (PE/MeV)	250	500	160	1200
Photocathode Coverage	34%	34%	12%	75%
Energy Resolution	6%/√E	5%/√E	7.5%/√E	3%/√E
Energy Calibration	2%	1%	1.5%	<1%

- **The goal:**
  - **Overall energy resolution: ≤ 3%/√E**
  - **Energy scale uncertainty: <1%**
- **Radioactive sources:**
  - **γ: ^{40}K, ^{54}Mn, ^{60}Co, ^{137}Cs**
  - **e+: ^{22}Na, ^{68}Ge**
  - **n: ^{241}Am-Be, ^{241}Am- ^{13}C or ^{241}Pu- ^{13}C, ^{252}Cf**
- **Four complementary calibration systems**
  - **1-D: Automatic Calibration Unit (ACU) → for central axis scan,**
  - **2-D:**
    - **Cable Loop System (CLS) → scan vertical planes,**
    - **Guide Tube Calibration System (GTCS) → CD outer surface scan,**
  - **3-D: Remotely Operated under-LS Vehicle (ROV) → full detector scan**

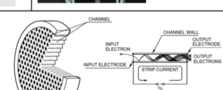


20000 20" PMT 10000 arrived

- Contracts were signed in 2015
- 15000 MCP-PMT (75%) from NNVT
- 5000 Dynode (25%) from Hamamatsu



Characteristics	unit	MCP-PMT (NNVT)	R12860 (Hamamatsu)
Detection Efficiency (QE*CE*area)	%	27%, > 24%	27%, > 24%
P/V of SPE		3.5, > 2.8	3, > 2.5
TTS on the top point	ns	~12, < 15	2.7, < 3.5
Rise time/ Fall time	ns	R~2, F~12	R~5, F~9
Anode Dark Count	Hz	20K, < 30K	10K, < 50K
After Pulse Rate	%	1, <2	10, < 15
Radioactivity of glass	ppb	238U:50 232Th:50 40K: 20	238U:400 232Th:400 40K: 40



2 MCPs to replace Dynodes

PMT assembly

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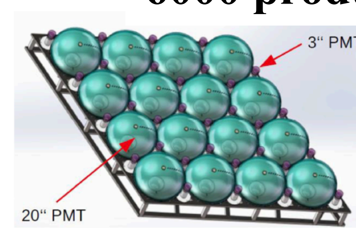
25000 3" PMT 6000 produced

- Work together with the 20-in PMT to provide a double calorimeter system
  - Energy measurement via "photon counting", better control of systematics
  - Muon tracking, supernova detection …
  - Increase the dynamic range.
  - Increase photon statistics by ~2.5%
- 25000 3-inch PMTs, contracted to HZC (China), which has produced ~6000 3-inch PMTs

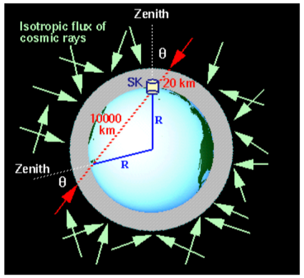


Atmospherics

- Atmospheric neutrino results from Super-Kamiokande, Christophe Bronner, ICRR
- Atmospheric Neutrino Oscillations with IceCube/DeepCore, Doug Cowan, Penn State
- Neutrino physics with KM3NeT/ORCA, Dmitry Zaborov, CPPM

Super-Kamiokande, Christophe Bronner

L from 10 to 13000km



- Large range of neutrino energies and propagation lengths
- Oscillations dominated by $\nu_\mu \rightarrow \nu_\tau$
- Large statistics allow to study sub-dominant effects

Atmospheric neutrino results

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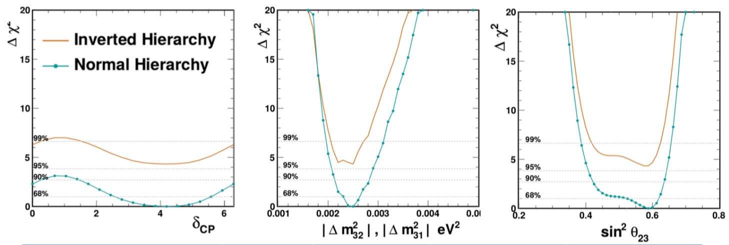

	χ^2	$\|\Delta m^2_{32/31}\|$	$\sin^2(\theta_{23})$	δ_{CP}
Normal hierarchy	571.33	2.5 x 10^{-3}	0.5875	4.18
Inverted hierarchy	575.66	2.5 x 10^{-3}	0.575	4.18

- **χ^2(NH)-χ^2(IH)=-4.33**
- P-value for this $\Delta\chi^2$ (true values of the parameters corresponding to the NH best fit point) is 0.027 for true IH
  → **Preference for the normal hierarchy hypothesis**

Results with external constraints

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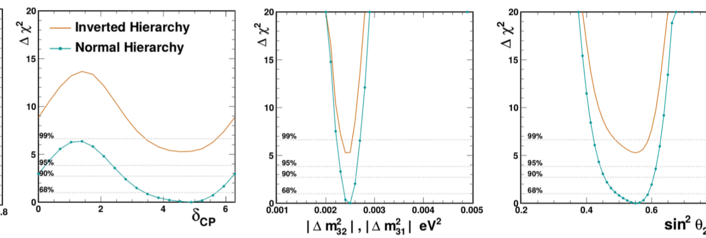
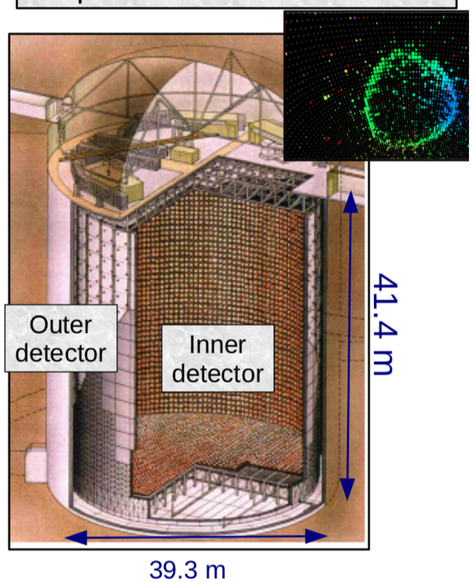
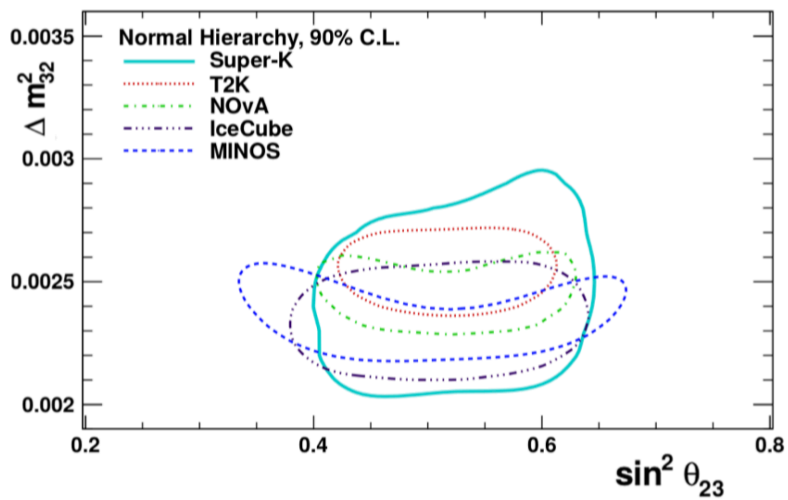


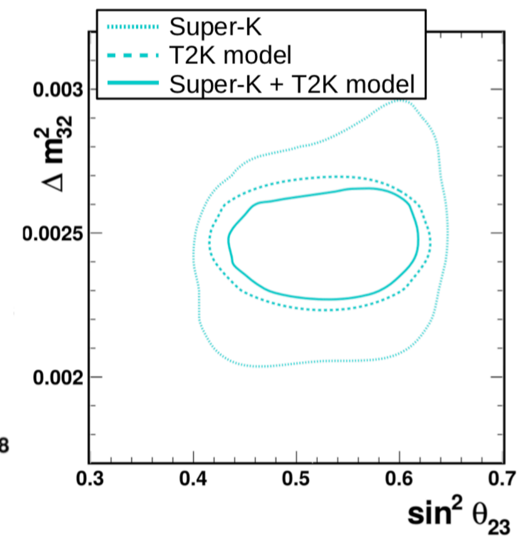
	χ^2	$\|\Delta m^2_{32/31}\|$	$\sin^2(\theta_{23})$	δ_{CP}
Normal hierarchy	639.43	2.50x 10^{-3}	0.550	4.88
Inverted hierarchy	644.70	2.40x 10^{-3}	0.550	4.54

- **χ^2(NH)-χ^2(IH)=-5.27**
- P-value for this $\Delta\chi^2$ (true values of the parameters corresponding to the NH best fit point) is 0.023 for true IH
  → **Slightly stronger preference for the normal hierarchy**

- 50 kt (22.5 kt fiducial) water Cherenkov detector
- 1000m overburden
- Operational since 1996







Super-Kamiokande, Christophe Bronner

ν_τ appearance

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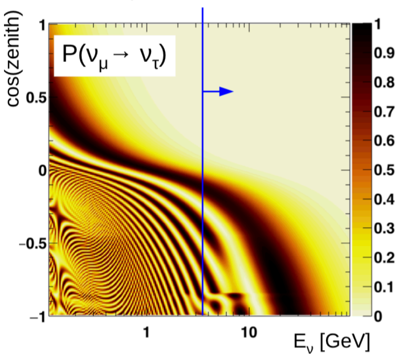
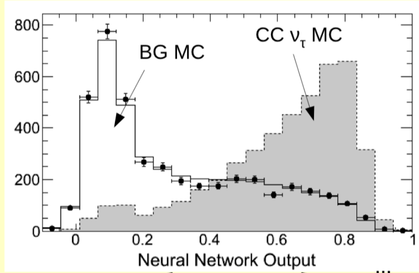
- No primary ν_τ atmospheric flux, but appear from oscillations
- Expect to detect ~1 ν_τ/year/kton in Super-K
- Only upward going (need L>4100 km)
  → down going sample can be used as a control sample for background



Can use NN to separate CC ν_τ events (τ hadronic decay) from ν_e/ν_μ bkg



ν_τ appearance Results

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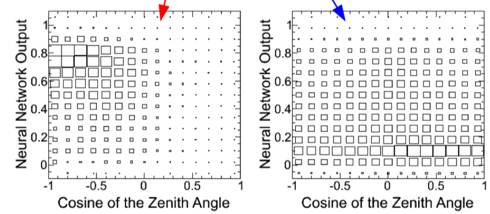
- Unbinned maximal likelihood fit of 2D PDF
- Fit for CC ν_τ normalization "α"

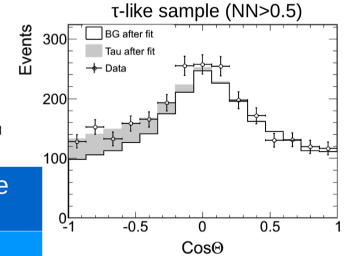
Data = **α** x Signal + Background + syst.

Variation of syst i in σ (has gaussian constraint)

$$\sum_i \epsilon_i \left(PDF_i^{BG} + PDF_i^{sig} \right)$$

Effect of 1σ variation of syst i on 2D PDF





Mass Hierarchy	α	Significance
Normal	1.47 ± 0.32	4.6σ
Inverted	1.57 ± 0.31	5.0σ

arXiv:1711.09436 [hep-ex]

ν_τ appearance Cross-section measurement

16

- Can use this dataset to measure ν_τ cross-section
- Scale theoretical (MC) cross section by α from ν_τ appearance fit
- Cannot separate ν_τ and $\bar{\nu}_\tau$ → flux average of ν_τ and $\bar{\nu}_\tau$ cross-sections

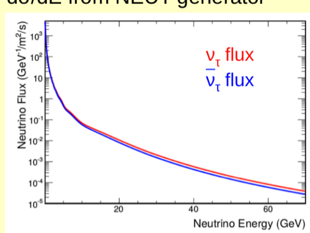
$< \sigma_{measured} > = \alpha \times < \sigma_{theory} >$

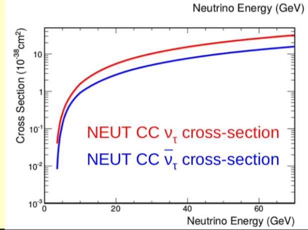
$< \sigma_{theory} > = 0.64 \times 10^{-38}$ cm²
α = 1.47 ± 0.32

$< \sigma_{measured} > = (0.94 \pm 0.20) \times 10^{-38}$ cm²
Agrees with theory within 1.5σ

(Flux average on 3.5-70 GeV)

$< \sigma_{theory} >$ = MC flux x dσ/dE
dσ/dE from NEUT generator

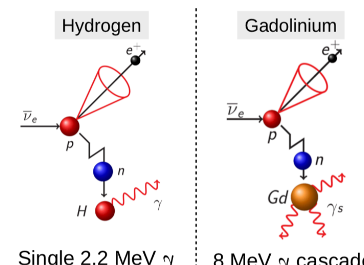




Future improvements Neutron tagging with Gd

20

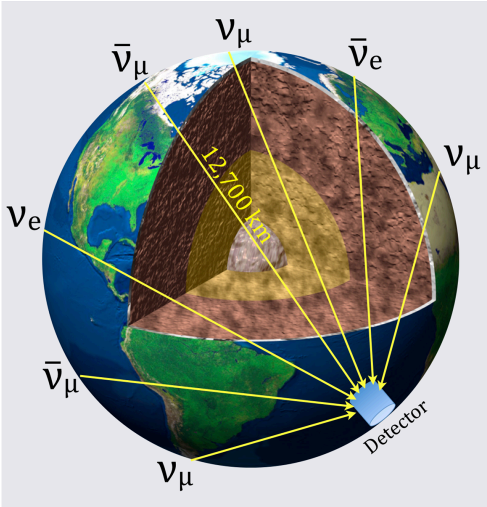
- Gd: large neutron capture cross-section
- Signal is easier to detect than for H capture
- Future **SK-Gd**: use capture on Gd by dissolving Gd in SK water
- **Efficiency~80%** at 0.1% Gd loading

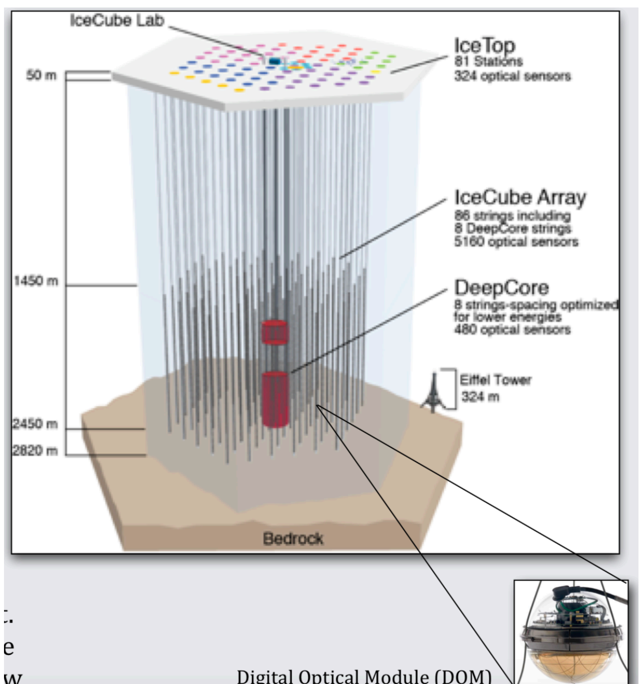


SK tank currently being refurbished to prepare for SK-Gd

nming

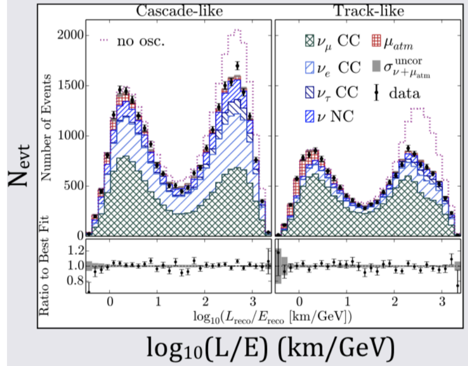
ICECUBE, Doug Cowan





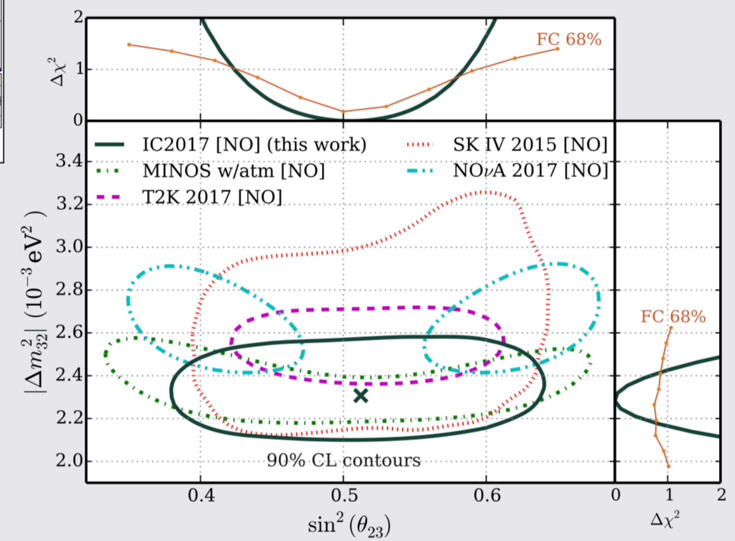
ν_μ Disappearance: Results

PRL 120 071801 (2018)

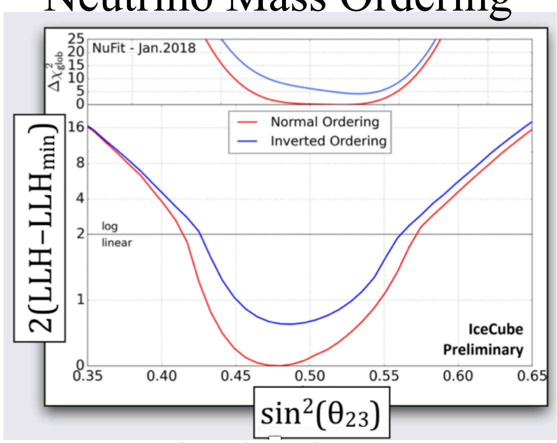


- 1,020 live days (2012-14)
- 41,599 events (full sky)
  - 15,138 track; 26,461 cascade
- Estimate 5.2% atm μ background

$$\sin^2\theta_{23} = 0.51^{+0.07}_{-0.09}$$
$$\Delta m^2_{32} = 2.31^{+0.11}_{-0.13} \times 10^{-3}\,\mathrm{eV}^2$$



Neutrino Mass Ordering

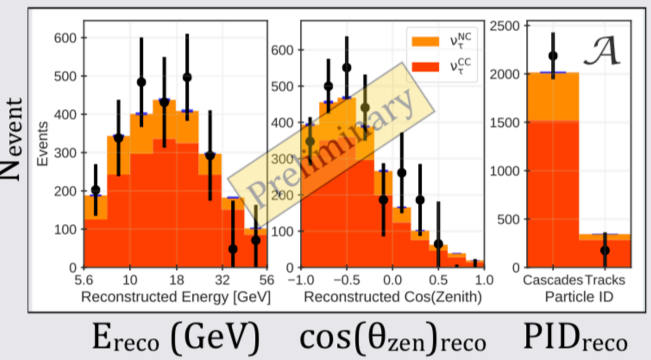


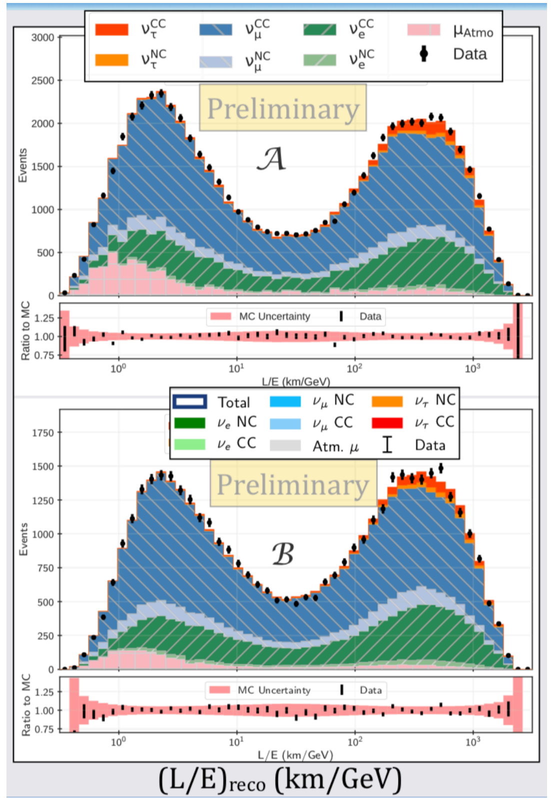
Use 3 yrs of IceCube data (~43k events), proof-of-principle measurement of NMO

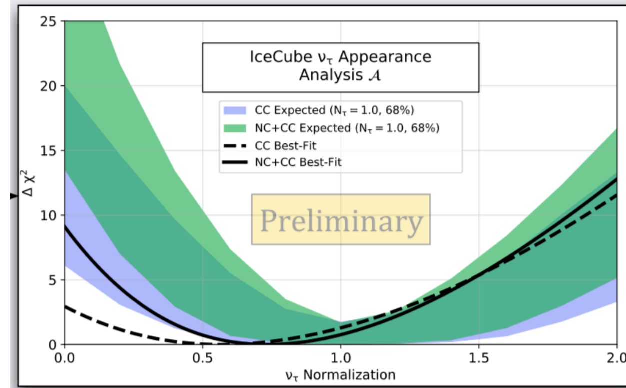
prefers NO over IO at p = 15% and in first octant close to maximal mixing

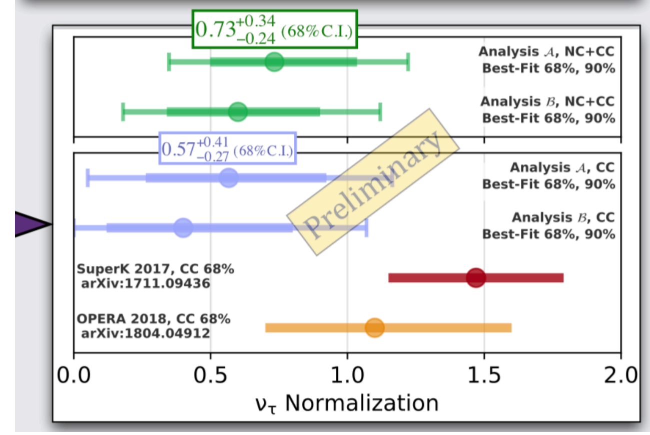
ICECUBE, Doug Cowan

Data distributions with best-fit $\nu_e+\nu_\mu$ and μ backgrounds subtracted (points with stat. error bars), overlaid with best fit ν_τ hypotheses.





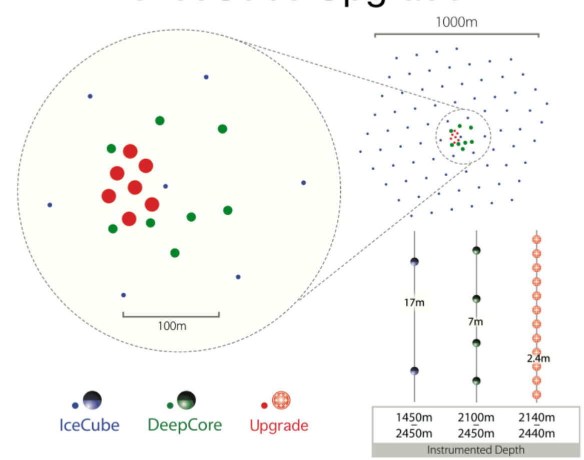




Comparison of all results.

- IceCube $\mathcal{A}$ & $\mathcal{B}$ results internally consistent.
- Super-K, OPERA and IceCube results mutually consistent.
- All results consistent with PMNS unitarity.

The IceCube Upgrade



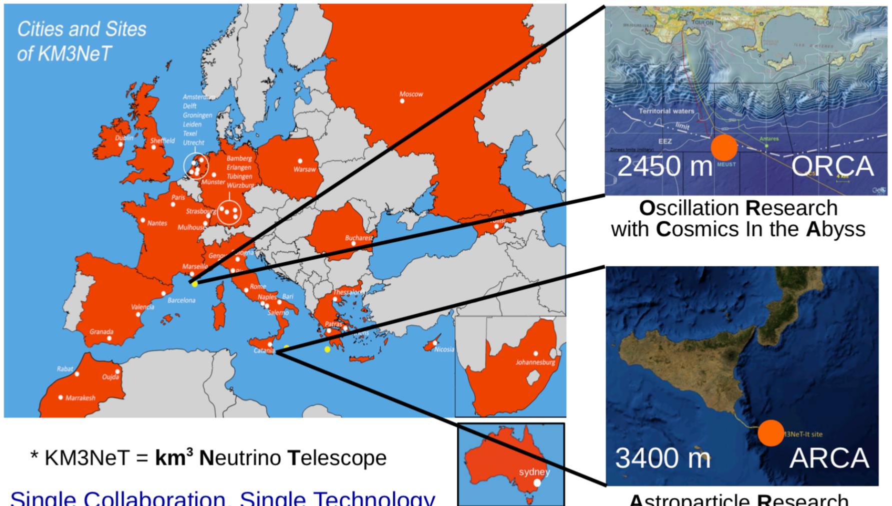
7 strings with 875 advanced DOMs and improved calibration devices

- IceCube Upgrade likely to be approved soon
  - Add 7 new strings in DeepCore fiducial volume to
    - improve ν_τ normalization to better than 10%
    - improve understanding of ice properties for better reconstruction and reduced systematics at low *and* high E_ν

KM3NeT/ORCA, Dmitry Zaborov

KM3NeT sites and participating countries

A distributed research infrastructure at two sites



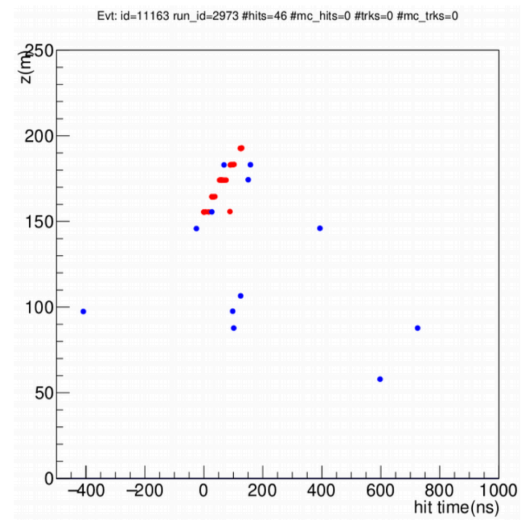
Oscillation **R**esearch with **C**osmics In the **A**byss

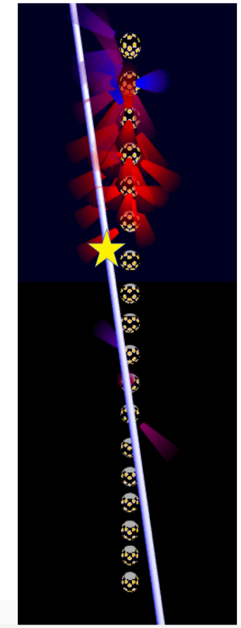
Astroparticle **R**esearch with **C**osmics In the **A**byss

* KM3NeT = **km³ N**eutrino **T**elescope

Single Collaboration, Single Technology

A neutrino candidate from ORCA

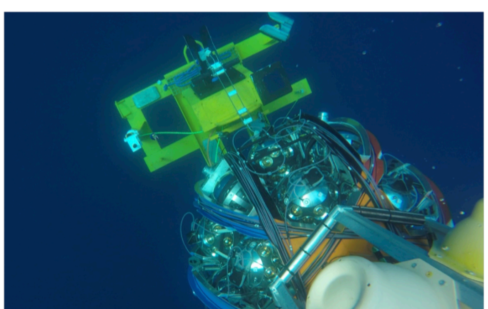




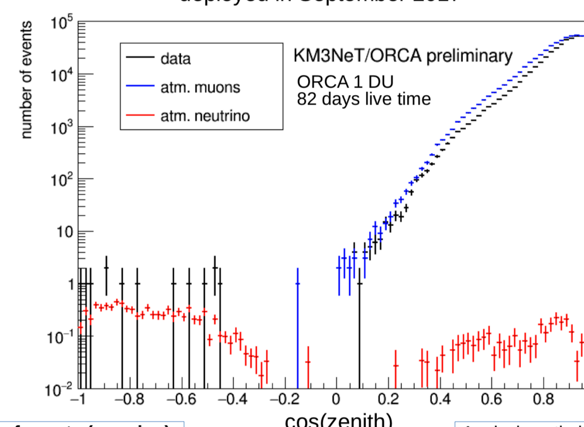
Energy ~ 10 GeV

August 13, 2018 D. Zaborov - KM3NeT/ORCA

22/9/2017 : First DU successfully deployed and connected



deployed in September 2017



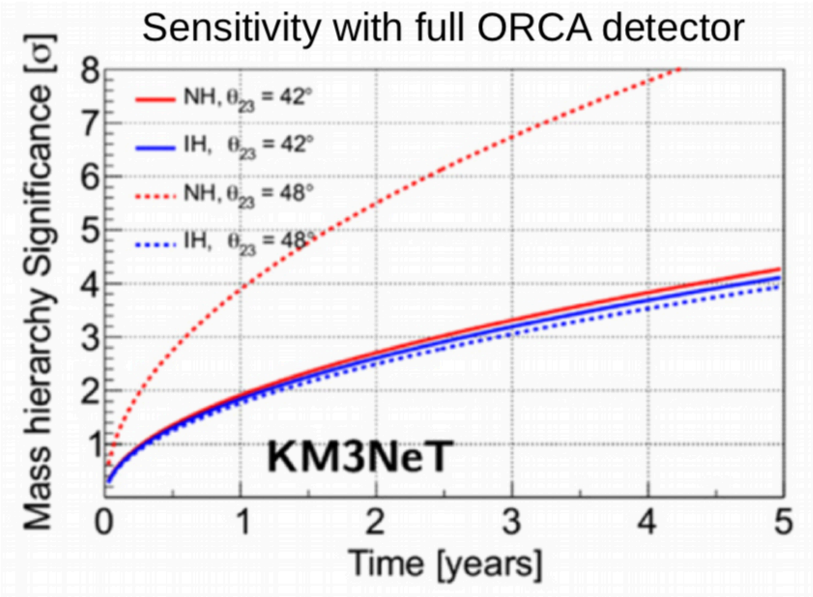
Number of events (upgoing):
MC atm neutrinos : 8.33
MC atm. muons : ~ 1
observed : 13

D. Zaborov - KM3NeT/ORCA

Analysis optimized for vertical upgoing tracks (horizontal tracks suppressed)

19

KM3NeT/ORCA, Dmitry Zaborov



ORCA sensitivity to Mass Hierarchy

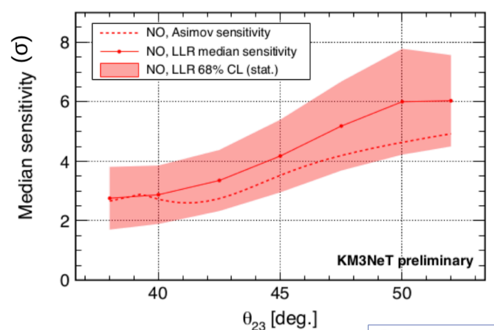
osc. parameters

param.	*treatment*	*true value*	*prior*
ΔM^2	fitted	$2.48\ 10^{-3}\ eV^2$	free
Δm^2_{21}	fix	$7.53\ 10^{-5}\ eV^2$	–
θ_{13}	fitted	8.42°	0.26
θ_{12}	fix	33.4°	–
θ_{23}	fitted	38° – 52°	free
δ_{CP}	fitted	0 – 2 π	free

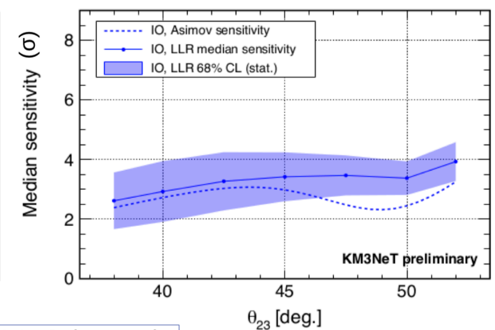
Systematics

Parameter	*treatment*	*true value*	*prior*
Flux spectral tilt	fitted	0	free
ν/ν̄ skew	fitted	0	0.03
Track normalization	fitted	1	free
Cascade normalization	fitted	1	free
NC events normalization	fitted	1	0.1

ORCA sensitivity after 3 yr (NH, δ_{CP}=0)

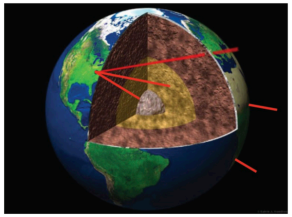


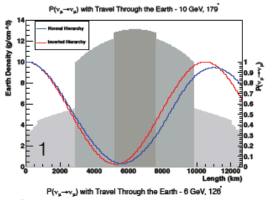
ORCA sensitivity after 3 yr (IH, δ_{CP}=0)

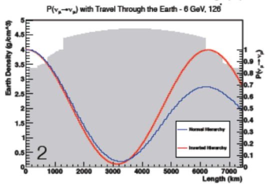


S. Bourret & L. Quinn, et al, @ Neutrino 2018

Sensitivity to Earth electron density profile



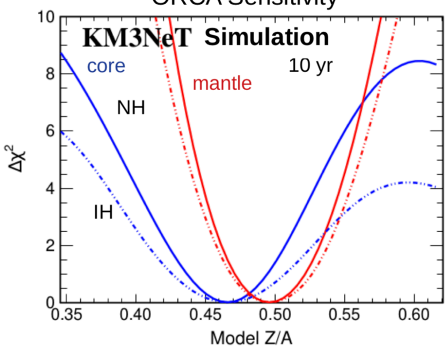




Earth density 4-13 g/cm³
Relevant: $E_\nu \sim 3\text{–}10$ GeV

ORCA 10 yr:
5-6% precision for mantle
6-9% precision for core

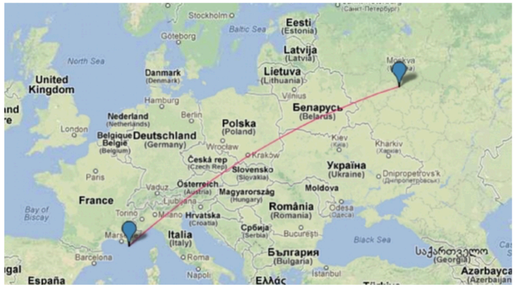
ORCA Sensitivity



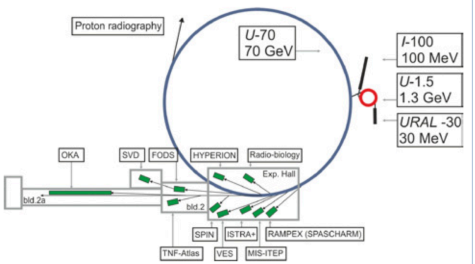
7% wt Hydrogen content in core (Z/A ~ 0.53) could be excluded at 90% C.L.

S. Bourret, J. Coelho, V. Van Elewyck, et al., Neutrino oscillation tomography of the Earth with KM3NeT-ORCA, ICRC 2017

P2O : Protvino to ORCA



Protvino accelerator complex



- Baseline 2588 km
- Beam inclination : 11.7° (cos θ = 0.2)
- Deepest point : 134 km (3.3 g/cm³)
- First oscillation maximum 5.1 GeV
- Sensitivity to mass hierarchy and CP violation

Current operation:
- Protons up to **70 GeV**
- **15 kW** beam power
- 5 µs spill every 9 s

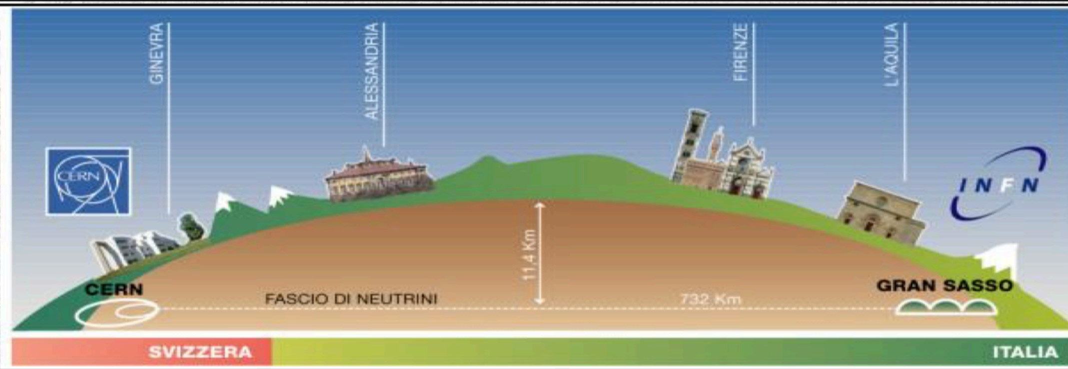
Upgradable up to 90 – 450 kW

Current Accelerator

- Final results from the OPERA experiment in the CNGS neutrino beam, Matteo Tenti, INFN-Bologna
- Details of the NOvA oscillation analyses, Erica Smith, Indiana
- Details of the T2K oscillation analyses, Davide Sgalaberna, CERN
- Global analysis of neutrino oscillation experiments
- MicroBooNE Search for Low-Energy Excess Using Deep Learning Algorithms, Lauren Yates

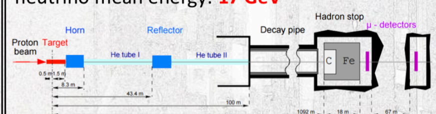
OPERA, Matteo Tenti

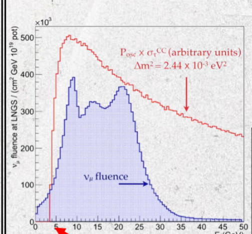
- **Long baseline** experiment: 735 km
- Aim: **verify the $\nu_\mu \to \nu_\tau$** oscillations at atmospheric Δm^2 scale
- How: observe ν_τ appearance on **event-by-event** basis in a conventional ν_μ beam



Conventional muon neutrino beam

neutrino mean energy: **17 GeV**

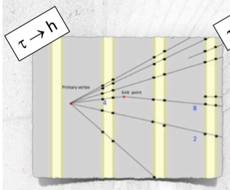




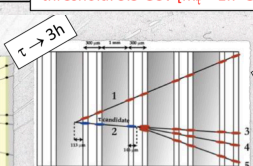
threshold: 3.5 GeV [m_τ = 1.7 GeV]

- Optimized for ν_τ appearance at LNGS
- Maximize the number of ν_τ CC interactions

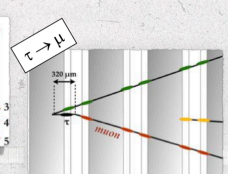
$(\nu_e + \bar{\nu}_e)/\nu_\mu$	0.9 %
$\bar{\nu}_\mu/\nu_\mu$	2.1%
ν_τ prompt	negligible



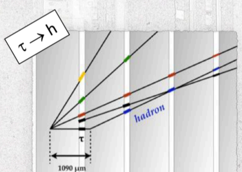
Phys. Lett. B 691 (2010) 138



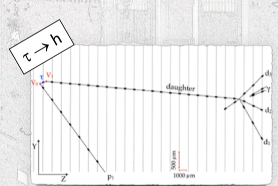
JHEP 11 (2013) 036



Phys. Rev. D 89 (2014) 051102



PTEP 2014 (2014) 10, 101C01



Phys.Rev.Lett. 115 (2015) no.12, 121802

Loosing ν_τ event selection

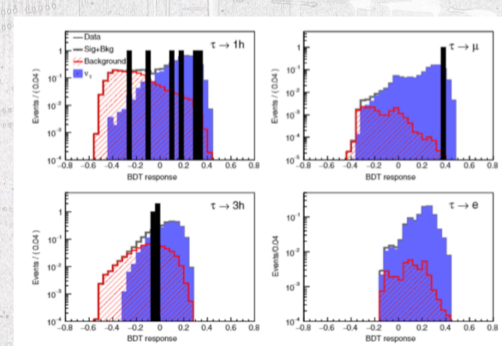
[Phys.Rev.Lett. 120 (2018) no.21, 211801]

- Loose kinematical cuts:
  - **Minimal requirements** to identify the topologies showing 2 vertices
  - **Negligible additional background** from K/π decays

Variable	$\tau \to 1h$	$\tau \to 3h$	$\tau \to \mu$	$\tau \to e$
z_{dec} (mm)	<2.6	<2.6	<2.6	<2.6
θ_{kink} (rad)	>0.02	>0.02	>0.02	>0.02
p_{2ry} (GeV/c)	>1	>1	[1, 15]	>1
p_{2ry}^T (GeV/c)	>0.15		>0.1	>0.1
Charge$_{2ry}$			Negative or unknown	

- **Increased statistics** of the ν_τ sample: ***x2***
- **Reduction of S/B** from ***~10 to ~3***

	Expected background	ν_τ expected	Observed
Total	2.0 ± 0.4	6.8 ± 1.4	10



$\Rightarrow$ Improvement in $|\Delta m^2_{23}|$ or alternatively $\langle \sigma \rangle$ measurement

- **Multivariate approach** (based on BDT)
  - Use kinematical, topological variables and their correlations
    → **higher discrimination power**

OPERA, Matteo Tenti

Sterile neutrino search

ν_τ appaearance

- Likelihood:

$$\mathcal{L}(\mu,\beta_c)=\prod_{c=1}^{4}\left(\mathcal{P}(n_c|\mu s_c+\beta_c)\prod_{i=1}^{n_c}f_c(x_{ci})\right)\times\prod_{c=1}^{4}\mathcal{G}(b_c|\beta_c,\sigma_{b_c})$$

- where

$$f_c(x_{ci})=\frac{\mu s_c}{\mu s_c+\beta_c}\mathrm{PDF}_c^{\mathrm{sig}}+\frac{\beta_c}{\mu s_c+\beta_c}\mathrm{PDF}_c^{\mathrm{bkg}}$$

- Test statistic: **profile likelihood ratio**
- Using **asymptotic approximation** [Eur.Phys.J.C71:1554,2011], null hypothesis excluded with **6.1σ** significance
- Best-fit signal strength:

$$\boldsymbol{\mu=1.1^{+0.5}_{-0.4}}$$

$$\mu \propto \left|\Delta m^2_{32}\right|^2\cdot\langle\sigma\rangle$$

$$\left|\Delta m^2_{32}\right|=\left(2.7^{+0.7}_{-0.6}\right)\times10^{-3}\ eV^2$$

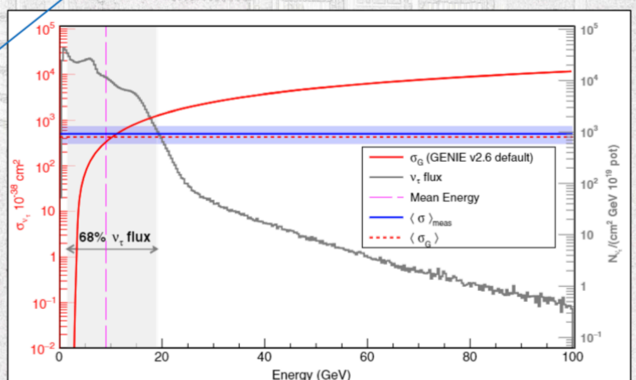
assuming maximal mixing

first measure in appearance mode

$$\langle\sigma\rangle=\left(5.1^{+2.4}_{-2.0}\right)\times10^{-36}\ cm^2$$

assuming maximal mixing and $\left|\Delta m^2_{32}\right|=2.5\times10^{-3}\ eV^2$

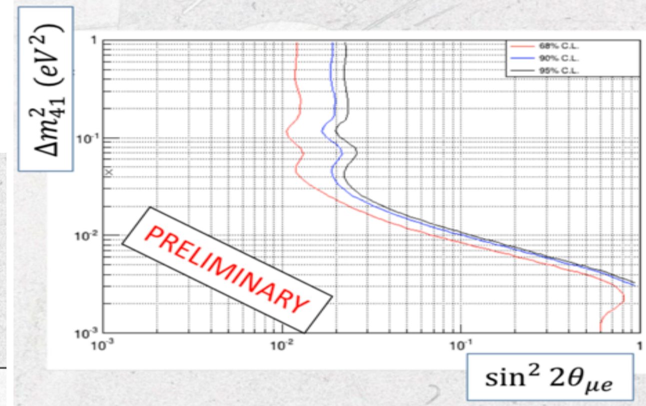
$$\langle\sigma_{Genie}\rangle=4.29\pm0.04\times10^{-36}\ cm^2$$



Exploiting **simultaneously** results of

- ν_τ search: 10 candidates
- ν_e search: 35 candidates

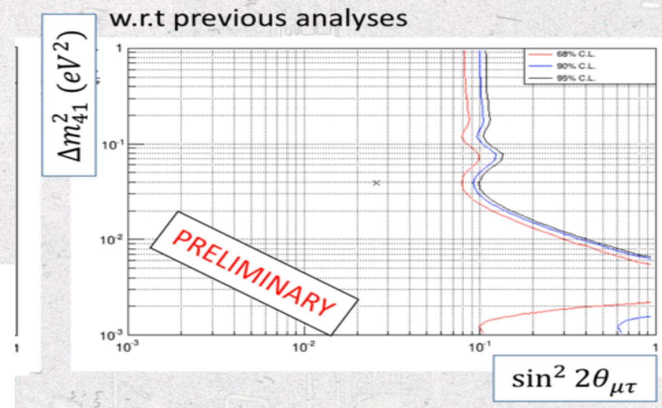
....



$\sin^2 2\theta_{\mu e}$ < 0.019 [90% C.L.] @ Δm^2_{41} ~ 1 eV²

... to extract limits on the parameters of the 3 + 1 neutrino model

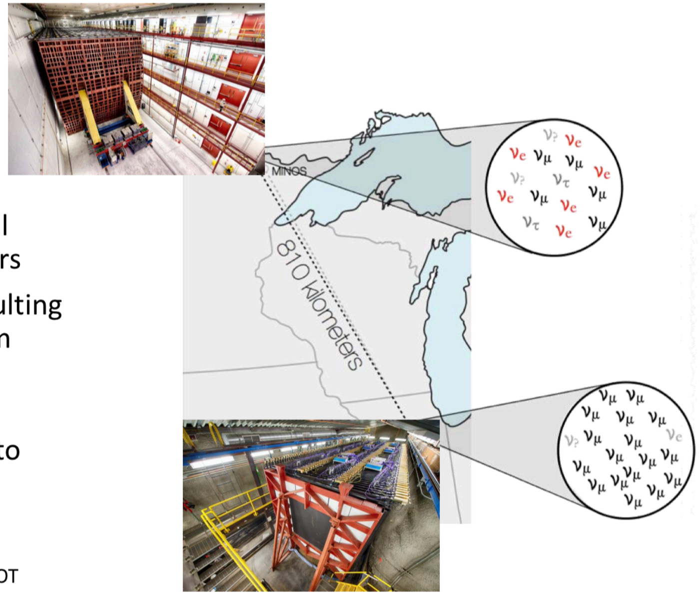
(Small) **exclusion power enhancement** w.r.t previous analyses



$\sin^2 2\theta_{\mu\tau}$ < 0.099 [90% C.L.] @ Δm^2_{41} ~ 1 eV²

NOvA, Erica Smith

NOvA

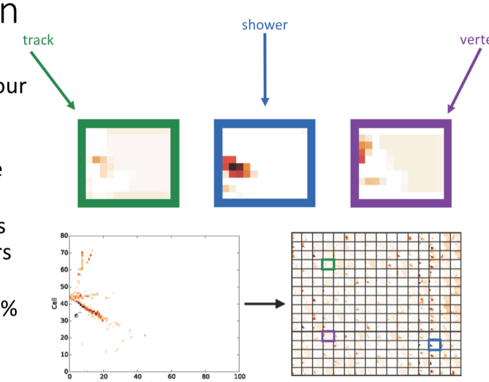


- Functionally identical near and far detectors
- 14mrad off-axis, resulting in narrow band beam peaked at 2 GeV
- Planes of cells are layered, alternating to provide 3D tracking

Neutrino mode: 8.85 x 10^{20} POT
Anti-neutrino mode: 6.9 x 10^{20} POT

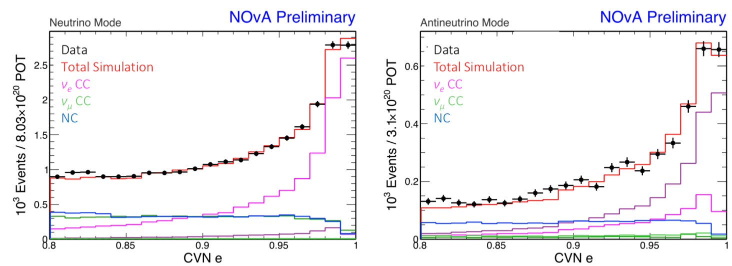
Signal Identification

- Signal identification done by our CVN (convolutional visual network)
  - Trained on 2D views of the event's calibrated hits
  - Information of each view is combined in the final layers of the network
  - An effective increase of 30% exposure from previous traditional reconstruction methods



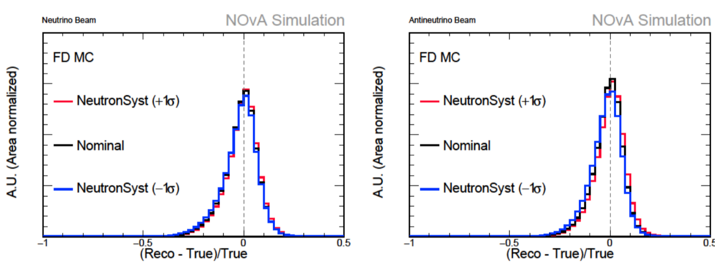
See also - Poster 206, Fernanda Psihas

CVN Performance – Data/MC



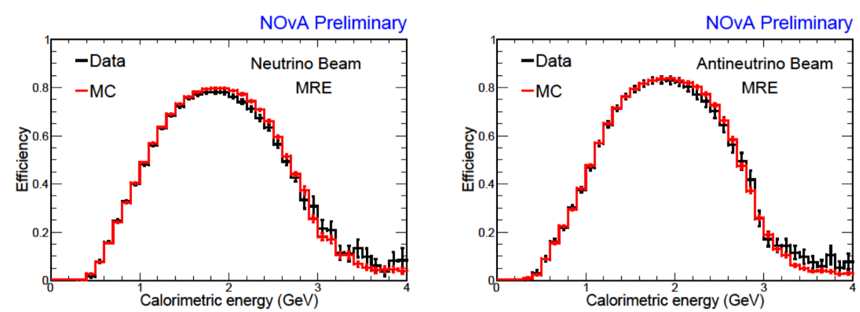
- Separate training for neutrino and anti-neutrino beams to capture differences in kinematics, topologies
  - Wrong sign treated as signal in the training
  - Improved efficiency with a dedicated anti-neutrino network

Impact of Neutron Response



Shifts mean energy by 1% in anti-neutrino mode, 0.5% in neutrino mode
Negligible impact on selection efficiency

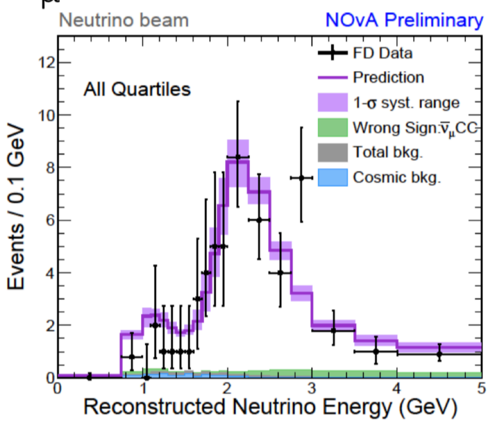
ianming Bian -



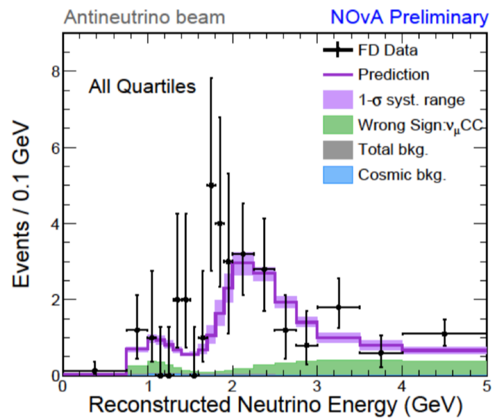
- Works at the Near Detector where there is a large statistics ν_μ sample
- Allows us to focus on the effect of the hadronic shower on efficiency
- Data/MC agreement is within 3% for neutrino mode, 2% for anti-neutrino mode – covered by systematics

NOvA, Erica Smith

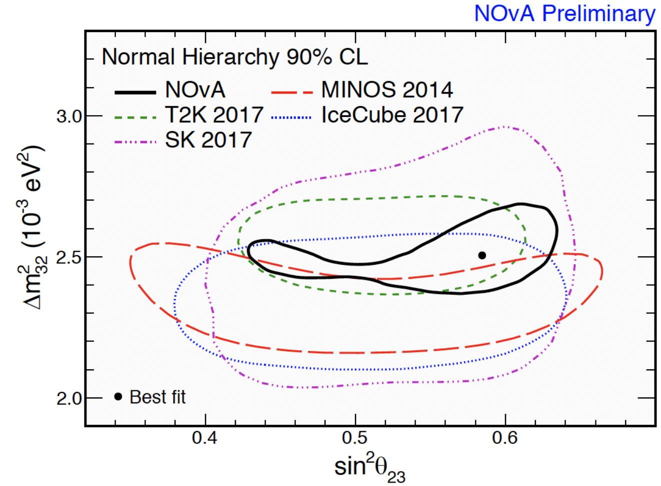
ν_μ at the Far Detector



Total Observed	113
Best fit prediction	121
Cosmic Bkgd.	2.1
Beam Bkgd.	1.2
Unoscillated	730

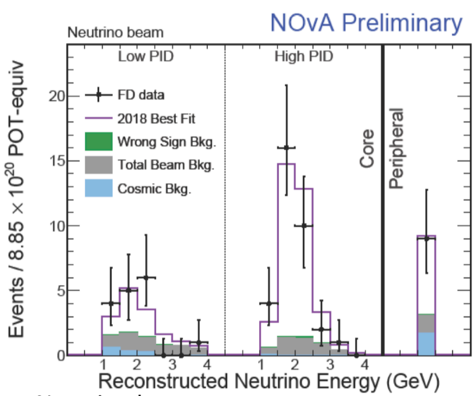


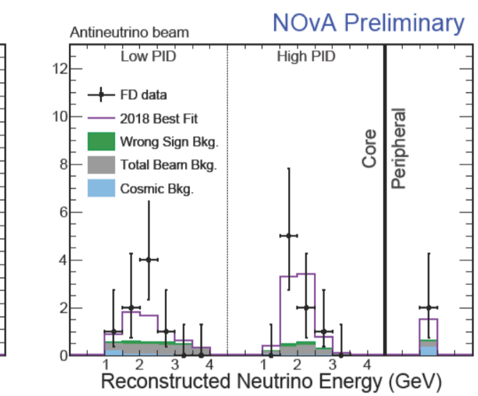
Total Observed	65
Best fit prediction	50
Cosmic Bkgd.	0.5
Beam Bkgd.	0.6
Unoscillated	266



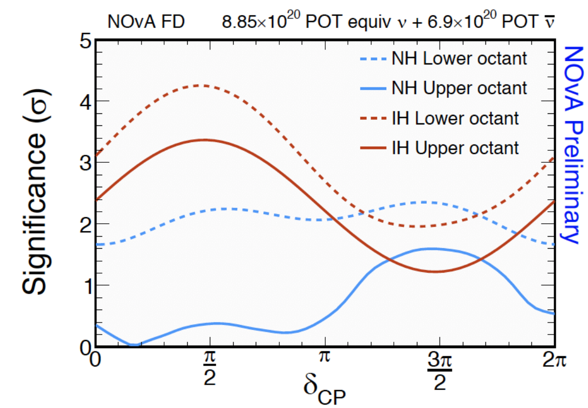
- Normal Hierarchy
- $\sin^2\theta_{23} = 0.58\pm0.03$ (UO)
- $\Delta m^2_{32} = (2.51+0.12-0.08)*10^{-3}$ eV^2

- Prefer non-maximal at 1.8σ, favor upper octant at similar level





- Neutrino beam:
  - Observe 58 events, expect 15 background events
- Anti-neutrino beam
  - Observe 18 events, expect 5.3 background events
- > 4σ $\bar{\nu}_e$ appearance



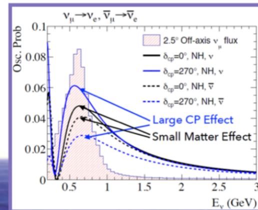
- Normal Hierarchy
- δCP= 0.17π
- $\sin^2\theta_{23} = 0.58\pm0.03$ (UO)
- $\Delta m^2_{32} = (2.51+0.12-0.08)*10^{-3}$ eV^2

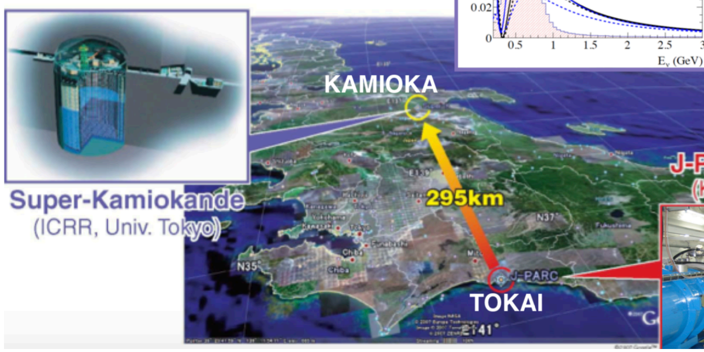
- Consistent with all δCP values in NH at < 1.6σ
- Exclude δ=π/2 in IH at > 3σ
- Prefer NH at 1.8σ

T2K, Davide Sgalaberna

The T2K experiment

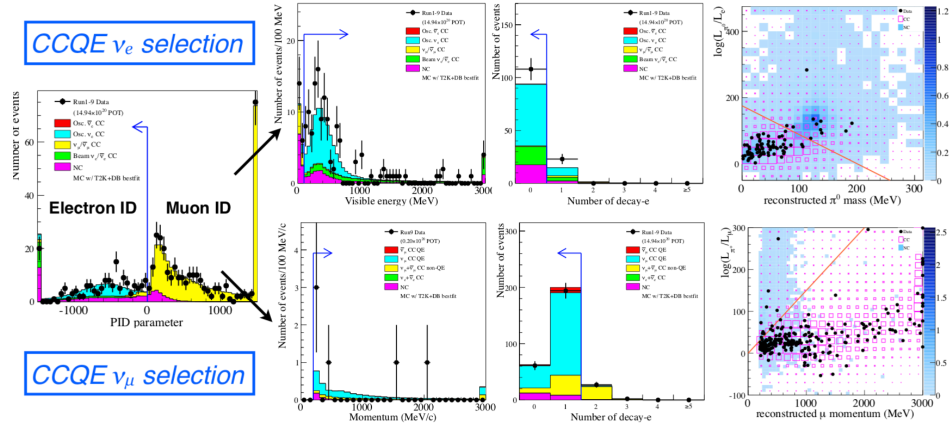
- Intense muon (anti)neutrino beam from J-PARC to Super-Kamiokande (295 km from target production): measure oscillated neutrino flux
- Unoscillated neutrino event rate is measured at the near detector (~280m)
- Observation at far detector (295km) of
  - ✦ muon (anti)neutrino disappearance
  - ✦ electron (anti)neutrino appearance





Event selection at Far Detector

- Cuts common to all event sample selections:
  - ✦ fully contained in fiducial volume, single ring event, PID cut



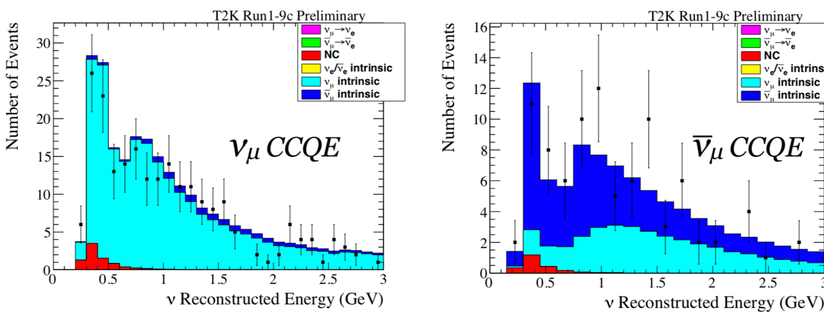
- ν_μ CCQE: 1 muon ring and ≤ 1 decay electron (ν and $\bar{\nu}$)
- ν_e CCQE: 1 electron and 0 decay electrons (ν and $\bar{\nu}$)
- ν_e CC1π: 1 electron and 1 decay electron (no $\bar{\nu}$ due to π^- abosorption)

New reconstruction algorithm for pion rejection

15

doubled the data since 2017 last data analysis

Far Detector ν_μ / $\bar{\nu}_\mu$ event samples

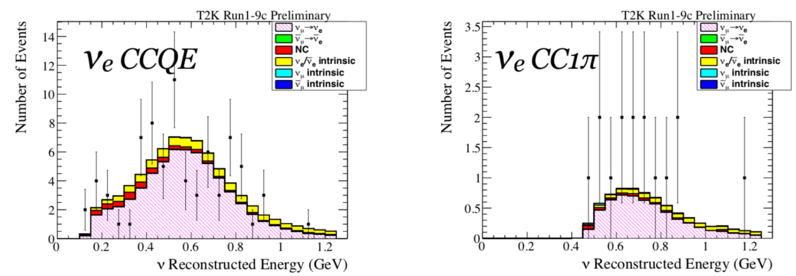


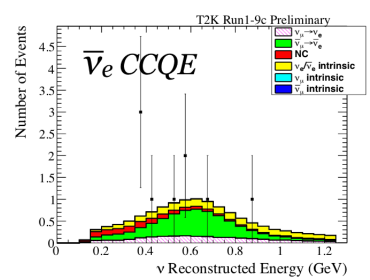
Event rate			
Beam mode	Not Oscillated	Oscillated (maximal mixing)	Observed
neutrino	1211.4	268.2	243
antineutrino	314.3	95.3	102

Systematic error		
Beam mode	w/o ND280	ND280 constrained
neutrino	14.5%	4.9%
antineutrino	12.2%	4.3%

- Event rate very close to prediction for maximal mixing hypothesis

Far Detector ν_e / $\bar{\nu}_e$ event samples



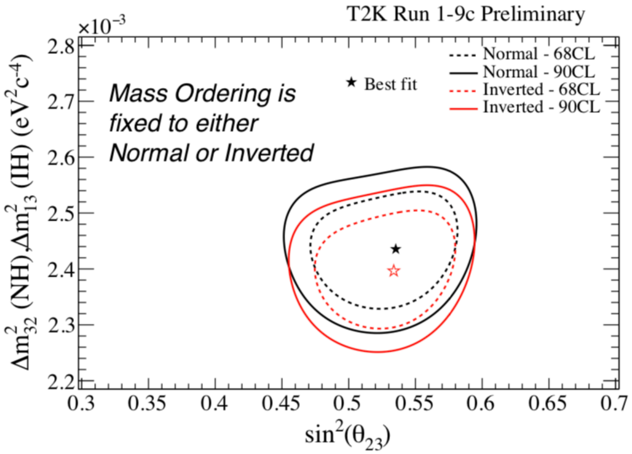


True δ_{CP} - Normal Ordering					
	-π/2	0	π	+π/2	Observed
ν_e CCQE	73.8	61.6	62.2	50.1	75
$\bar{\nu}_e$ CCQE	11.8	13.4	13.3	14.9	9
ν_e CC1π	6.9	6.0	5.8	4.9	15

Systematic errors		
Sample	w/o ND280	ND280 constrained
ν_e CCQE	17.1%	8.8%
$\bar{\nu}_e$ CCQE	14.1%	7.0%
ν_e CC1π	21.6%	18.3%

- Observed number of events shows a slightly larger asymmetry compared to the prediction for δ_{CP}=-π/2 and Normal Ordering

T2K, Davide Sgalaberna

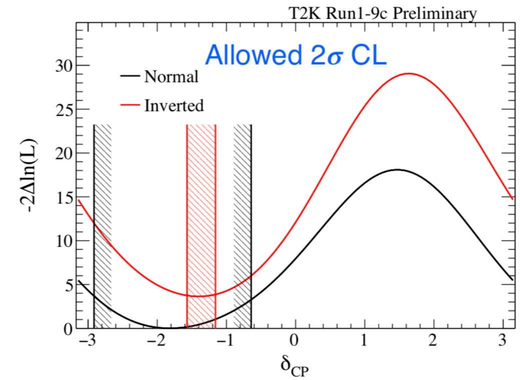


T2K data consistent with maximal disappearance

	Normal Ordering		Inverted Ordering	
	Best-fit	1σ Interval	Best-fit	1σ Interval
$\sin^2\theta_{23}$	0.536	0.490 - 0.567	0.536	0.495 - 0.567
$\vert\Delta m^2_{32}\vert$ ($\times10^{-3}$ eV^2)	2.43	2.37 - 2.50	2.49	2.42 - 2.55

Confidence intervals of δ_{CP}

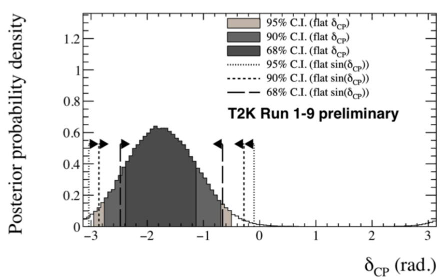
- Confidence intervals were computed with Feldman-Cousins method
- Integrate over θ_{13} using the PDF from reactors' measurement (PDG-2016)



- The best-fit is δ_{CP} = -1.82 radians and Normal Ordering
- Both δ_{CP} = 0 and π are excluded at 2σ CL
- Allowed 2σ CL region: - Normal Ordering: [-2.91,-0.64]
  - Inverted Ordering: [-1.57,-1.16]
- Preference for maximal CP violation and Normal Ordering

The Bayesian analysis

- Estimate Credible Intervals (CI) with MCMC
- Joint analysis of Near and Far Detectors datasets



- Results with different priors:
  - Flat prior on δ_{CP}
  - Flat on $\sin(\delta_{CP})$
- Both δ_{CP} = 0,π outside 95% CI

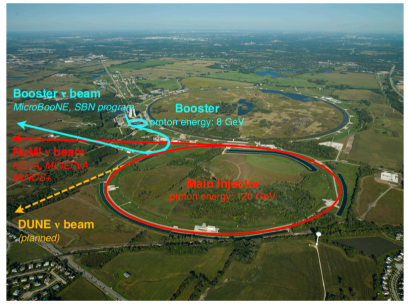
- Bayes factor shows the preferred octant and Mass Ordering hypothesis
- Same prior probability to each Octant / Mass Ordering option

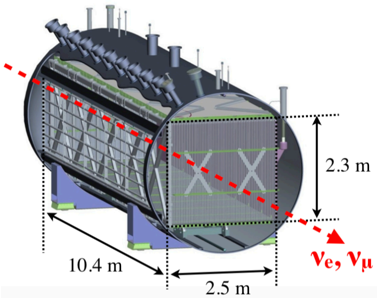
	$\sin^2\theta_{23} < 0.5$	$\sin^2\theta_{23} > 0.5$	Sum
NH ($\Delta m^2_{32} > 0$)	0.204	0.684	0.888
IH ($\Delta m^2_{32} < 0$)	0.023	0.089	0.112
Sum	0.227	0.773	1

- Preference for upper Octant and Normal Ordering

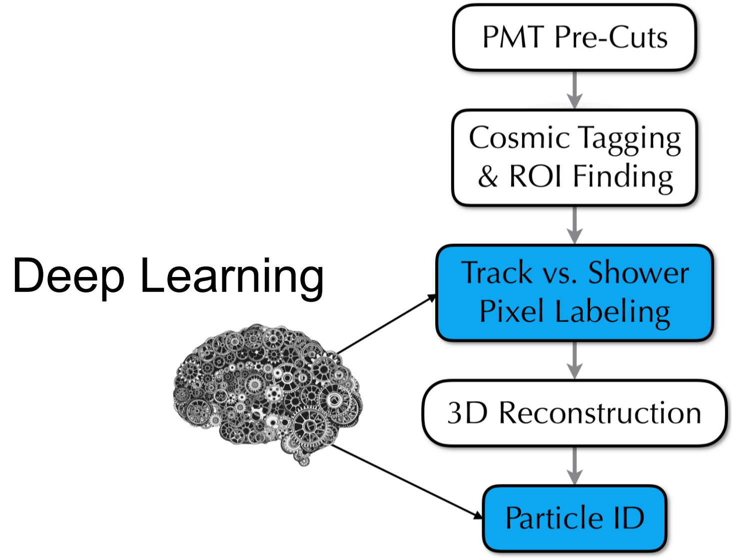
- Almost doubled the data since 2017 last data analysis
- No evidence for $\overline{\nu}_e$ appearance yet
- T2K data prefer maximal ν_μ disappearance
- Exclude CP conservation hypothesis with significance of 2σ CL
- T2K data favor δ_{CP} ~ -π/2 and NH
- Proposal for extending T2K to reach 3σ sensitivity to CP violation

MicroBOONE, Lauren Yates



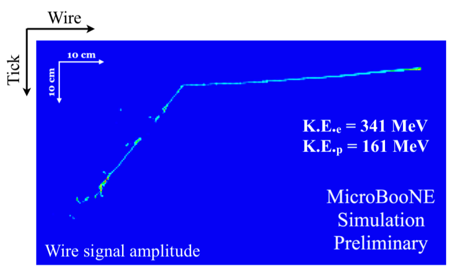


- **Micro Boo**ster **N**eutrino **E**xperiment
- 85 tonne **L**iquid **Ar**gon **T**ime **P**rojection **C**hamber (active mass)
- Located in the Fermilab **Boo**ster **N**eutrino **B**eam
- $\nu_\mu \rightarrow \nu_e$ appearance experiment
- >95% detector uptime
- 9.6×10^{20} POT on tape to date

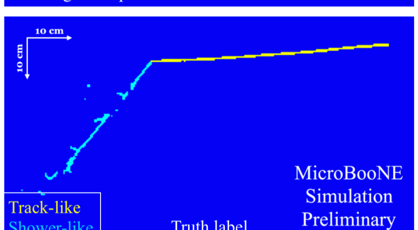


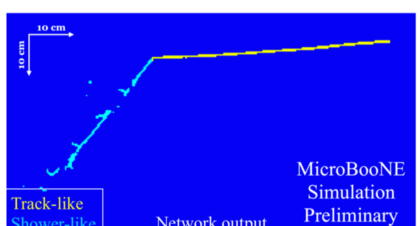
Track vs. Shower Pixel Labeling

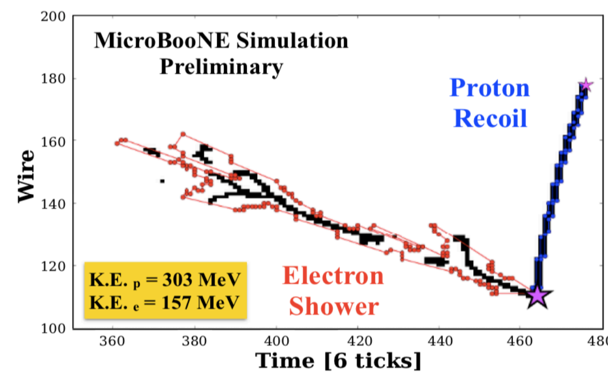
μBooNE



- Goal: separate tracks and showers to help provide vertex candidates
- Semantic segmentation network takes in the wire information and labels each pixel in the image as “track-like” (yellow) or “shower-like” (cyan)

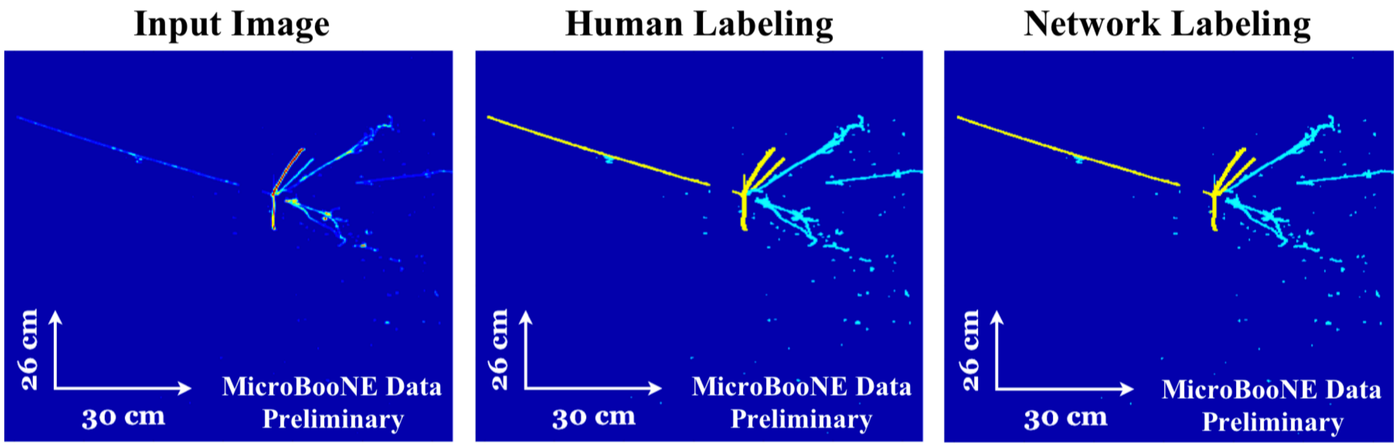






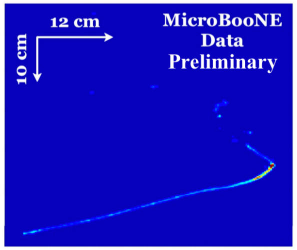
“Convolutional Neural Networks Applied to Neutrino Events in a LArTPC” JINST 12, P03011 (2017)

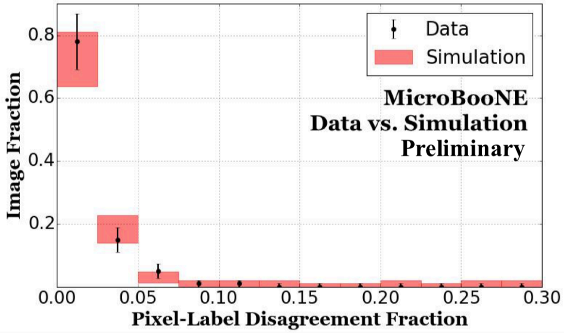
Particle	Correct ID
e^-	77.8 ± 0.7%
γ	83.4 ± 0.6%
μ^-	89.7 ± 0.5%
π^-	71.0 ± 0.7%
p	91.2 ± 0.5%



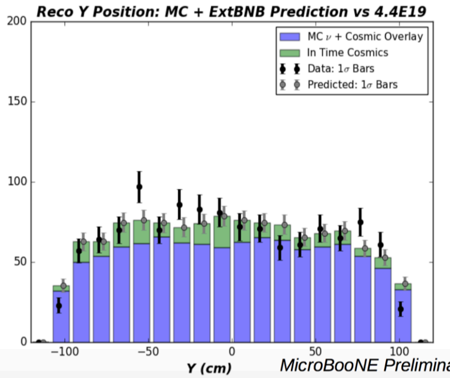
ν_μ Selection Performance

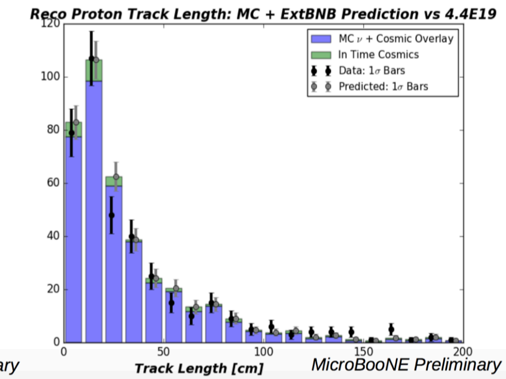
- To quantify network's performance, look at level of disagreement in pixel labels between human and network over many images
  - In this case, looking at Michel electron events
- Disagreement is generally below 2.5% of non-empty pixels
- Level of agreement is consistent between data and simulation





- Very successful at rejection cosmics, such that remaining backgrounds are dominated by neutrino events that do not meet signal definition
- Have achieved 18% efficiency, 47% purity for $1\mu 1p$
- Optimized for low energy reconstruction relevant to MiniBooNE excess





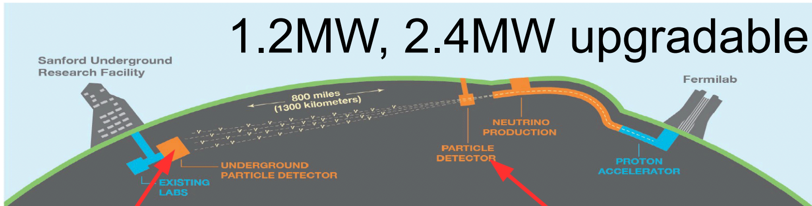
Future Accelerator

- DUNE Oscillation Physics, Animesh Chatterjee, University of Texas at Arlington
- Physics potential of Hyper-Kamiokande for neutrino oscillation measurements, Tetsuro Sekiguchi, KEK
- Physics potential of the ESSvS, Salvador Rosauro-Alcaraz, UAM and IFT UAM-CSIC
- Status of ProtoDUNE, Jingbo Wang, University of California, Davis

DUNE

Deep Underground Neutrino Experiment

A next generation experiment for **neutrino science, nucleon decay,** and **supernova physics**



Far detector at Sanford Underground Research Facility (SURF)

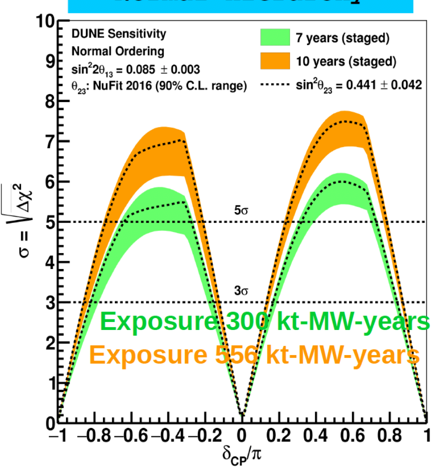
Neutrino beam and nea detector at Fermilab

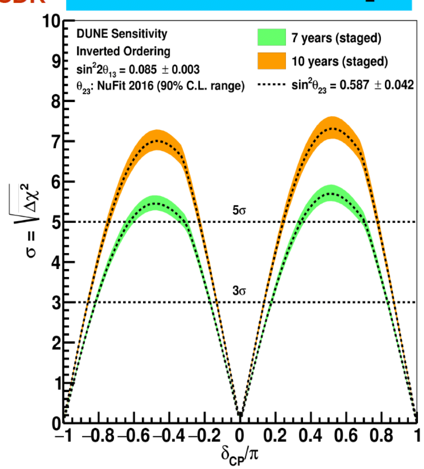
- 2018 : protoDUNEs at CERN
- 2019 : Technical Design Report
- 2019 : Far Site Primary Excavation Begins
- 2022 : First Module Installation Begins
- 2024 : Physics data Begins
- 2026 : Neutrino Beam Available(1.2MW)

* DUNE Far Detector Interim Design Reports are available (on arXiv:1807.10334, 1807.10327,1807.10340)

CP sensitivity

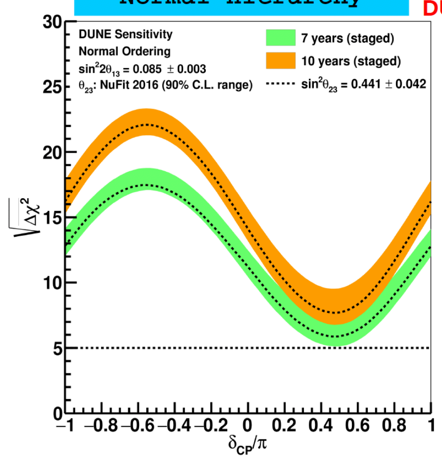
Normal hierarchy — DUNE CDR — Inverted hierarchy

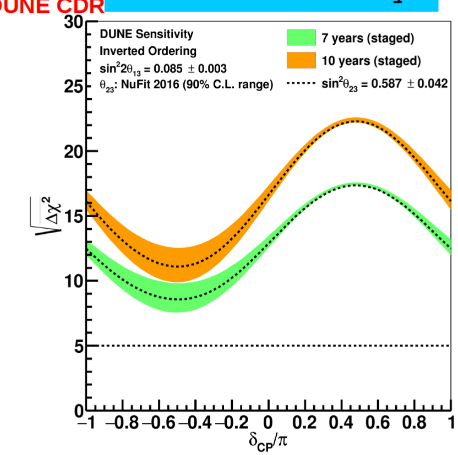




MH sensitivity

Normal hierarchy — DUNE CDR — Inverted hierarchy



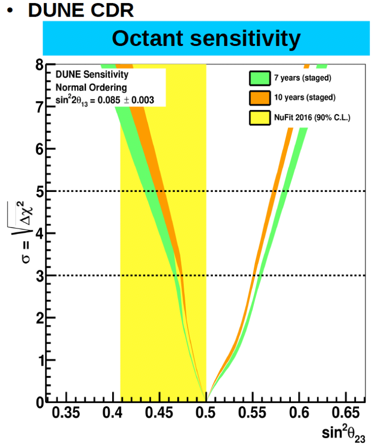


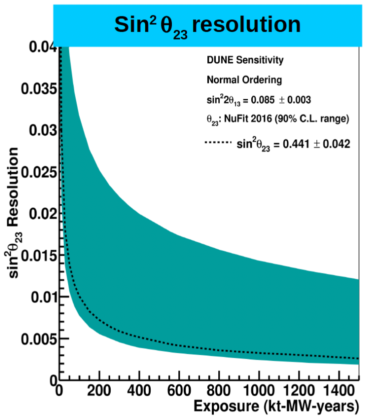
Width of band corresponds to 90% C.L. variations in value of θ_{23} based on NuFit 2016 fit values

DUNE, Animesh Chatterjee

Sensitivity to θ_{23} Octant and θ_{23} resolution

- DUNE CDR





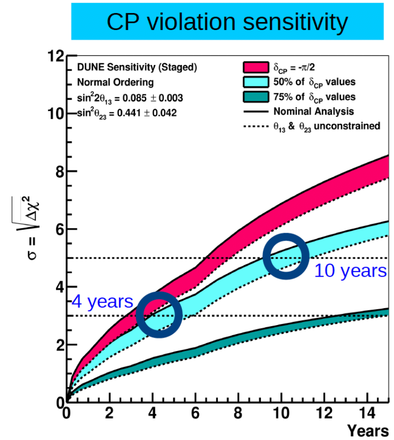
Yellow shaded band represents 90% C.L. allowed region for value of $\sin^2\theta_{23}$ from NuFit 2016

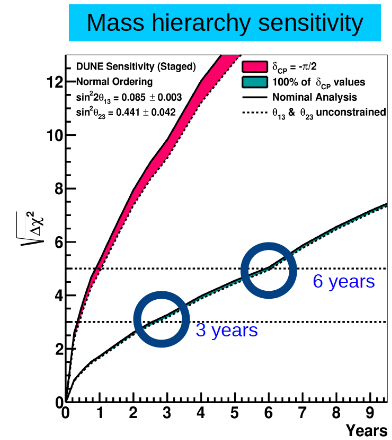
Resolution worsens with increasing θ_{23} .

Sensitivity vs.time

Significant milestones within few years of beam run

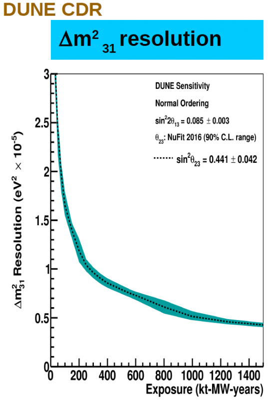
DUNE CDR

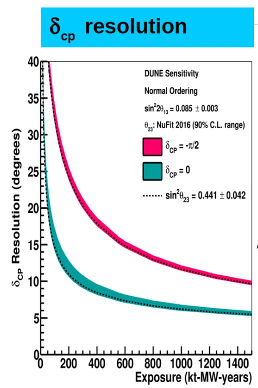


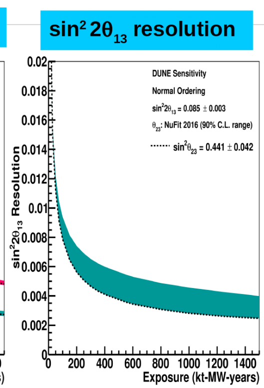


Normal hierarchy :

DUNE CDR

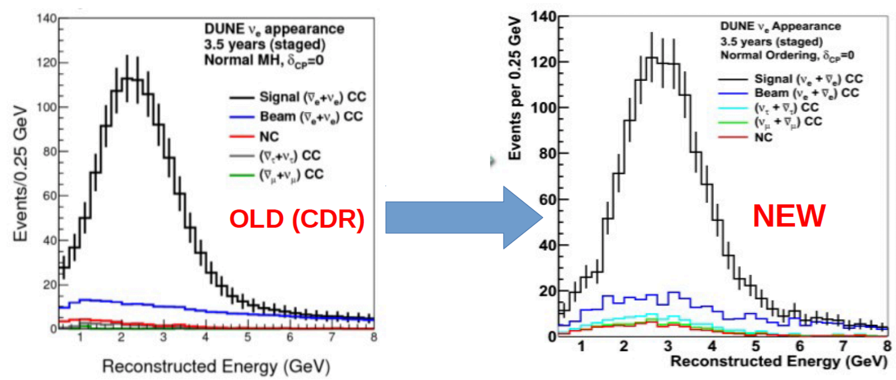






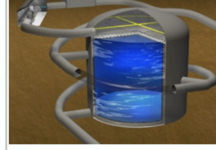
Monte-Carlo Studies (New!)

- GEANT4 beam simulation of updated beam design
- Full LArSoft Monte Carlo simulation
- Automated energy reconstruction
- Event selection using convolutional visual network (CVN)
- CDR-style systematics analysis



- Sensitivity from MC-based analysis with automated reconstruction and event selection exceeds CDR sensitivity!
- Full update planned for TDR 2019!

Hyper-K, Tetsuro Sekiguchi



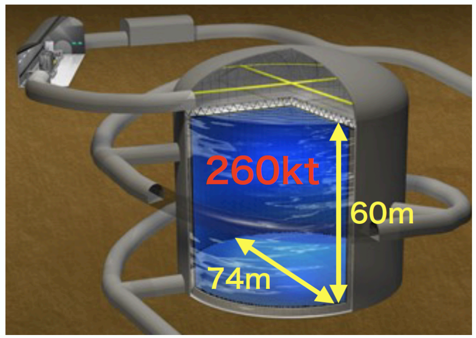
Hyper-K
(Water Č)

J-PARC
Accelerator Complex

1.3MW

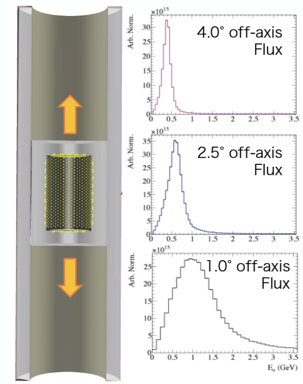
Hyper-Kamiokande

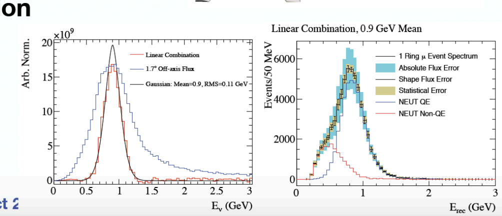
- **Next generation water Cherenkov detector**
  - **Construct two detectors in stage**
    - **Realize the first detector as soon as possible**
    - **An option of second detector in Korea**
- **Rich physics**
  - **Nucleon decay**
  - **Neutrino oscillation (CPV, MH)**
  - **Neutrino astronomy/Astrophysics**
- **Detector**
  - **Φ74m x H60m**
  - **260 kton total mass**
  - **190 kton fiducial volume**
    - **~10 x Super-K**
  - **40% Photo coverage (ID)**
    - **40,000 x new 20" PMTs**
      - **x2 higher photon detection efficiency**



Intermediate Water Cherenkov Detector

- **~10kton water Cherenkov detector**
  - **Same technology as far detector (FD)**
    - **Water target**
    - **4π coverage**
- **Located 1~2km from target**
  - **Same neutrino energy spectrum as FD**
- **Vertically spanning (50~100m deep)**
  - **Linear combination of fluxes at different off-axis (1~4°) gives**
    - **Pseudo-monochromatic spectrum to estimate non-QE interaction**



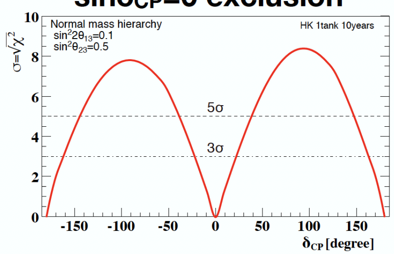


CPV

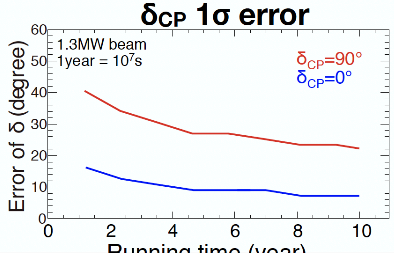
- **Exclusion of $\sin\delta_{CP}=0$**
  - **>8σ (6σ) for δ=-90° (-45°)**
  - **~80% coverage of δ parameter space with >3σ**
- **δ_{CP} measurement precision**
  - **22° at δ=±90°**
  - **7° at δ=0°, 180°**

Sensitivity study adopt analysis techniques and systematic uncertainties used in T2K
- **Realistic systematic uncertainties plus expected reduction of errors**
- **3~4% syst. Error (6~7% in T2K)**

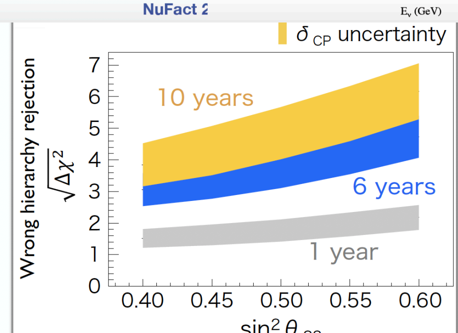
$\sin\delta_{CP}=0$ exclusion



δ_{CP} 1σ error

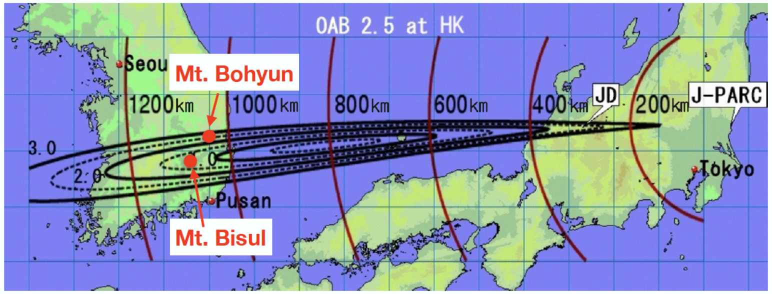


MH

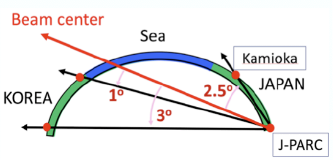


- **Hyper-K can determine Mass hierarchy in ~5 years ($\sin^2\theta_{23}=0.5$) using atmospheric and beam neutrinos, even if MH not determined before Hyper-K era**

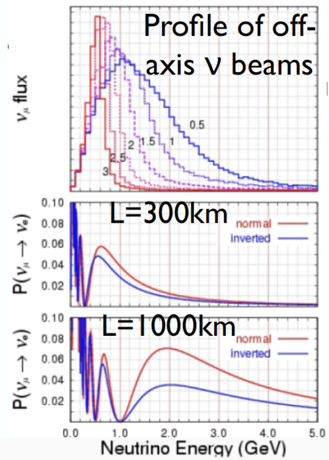
Korean Option for 2nd Tank



PTEP 2018, 063C01

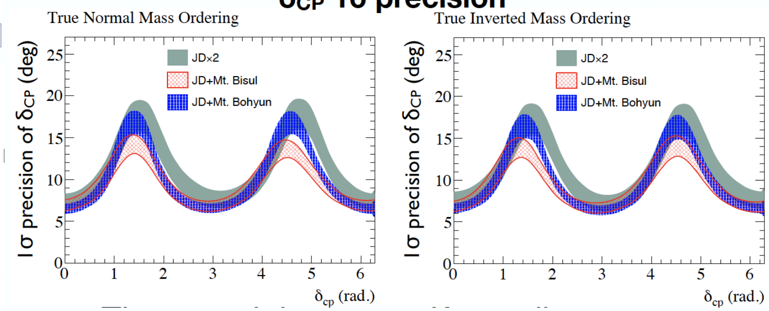


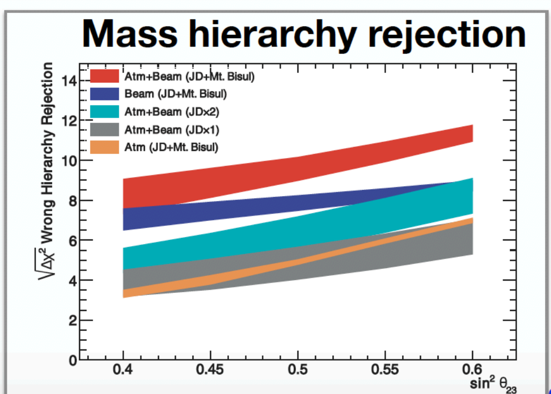
- **Second tank option in Korea is being considered**
- **Advantage**
  - **Large CP effect at second oscillation maximum**
  - **Higher mass hierarchy sensitivity with longer baseline**
- **Possible site**
  - **Mt. Bisul at L=1,088km, OA=1.3°**
  - **Mt. Bohyun at L=1,043km, OA=2.3°**



CPV

δ_{CP} 1σ precision





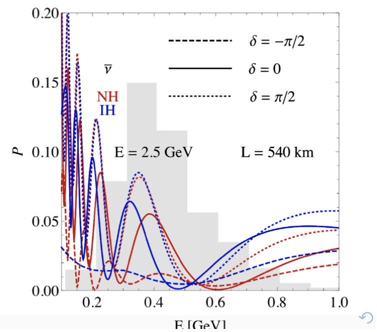
- **Korean detector gives us**
  - **better δ_{CP} measurement precision**
    22°(1tank)→<15° at δ_{CP}=-90°
  - **higher mass hierarchy sensitivity**
    4.5σ(1tank)→9σ at $\sin^2\theta_{23}$=0.5

ct 2018, Virgini

The ESSνSB

E. Baussan *et al.* hep-ex/1309.7022

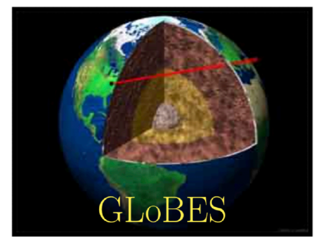
- Modification of the ESS linac to produce neutrinos 14Hz $\rightarrow$ 28Hz
- 5 MW at 2.5GeV proton beam
- MEMPHYS-like WC detector
  - 500 kt fiducial volume
  - Best locations at **540** and 360 km



Simulation framework

P. Huber *et al.* hep-ph/0701187

- Implemented in GLoBES
- Simulation with a ND
- 2.5 GeV proton beam



P. Coloma *et al.* hep-ph/1209.5973

Systematic errors

	SB		
Systematics	Opt.	Def.	Cons.
Fiducial volume ND	0.2%	0.5%	1%
Fiducial volume FD (incl. near-far extrap.)	1%	2.5%	5%
Flux error signal ν	5%	7.5%	10%
Flux error background ν	10%	15%	20%
Flux error signal $\bar{\nu}$	10%	15%	20%
Flux error background $\bar{\nu}$	20%	30%	40%
Background uncertainty	5%	7.5%	10%
Cross secs $\times$ eff. QE†	10%	15%	20%
Cross secs $\times$ eff. RES†	10%	15%	20%
Cross secs $\times$ eff. DIS†	5%	7.5%	10%
Effec. ratio ν_e/ν_μ QE*	3.5%	11%	–
Effec. ratio ν_e/ν_μ RES*	2.7%	5.4%	–
Effec. ratio ν_e/ν_μ DIS*	2.5%	5.1%	–
Matter density	1%	2%	5%

MH

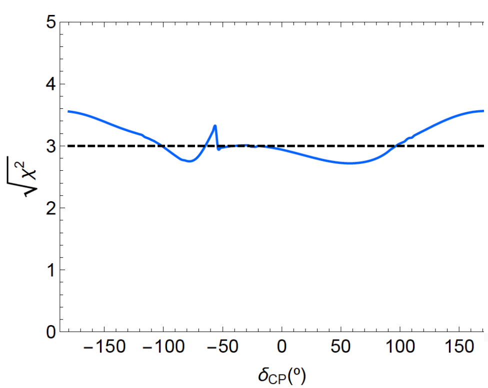
Matter effects relevant when

- High energy ν
  $E_\nu \sim 6$ GeV

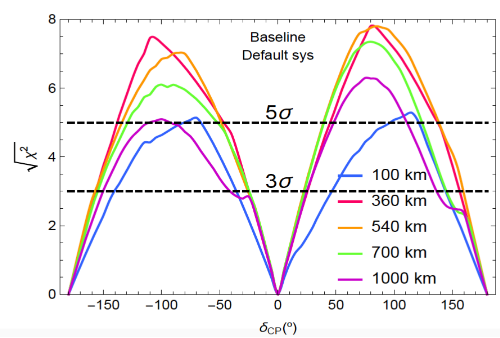
ESSνSB

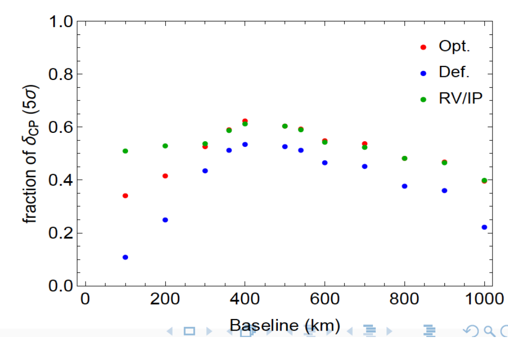
- $L \sim 500km$
- $E_\nu \sim \mathcal{O}(300\text{MeV})$

Sensitivity around **3σ**



CPV

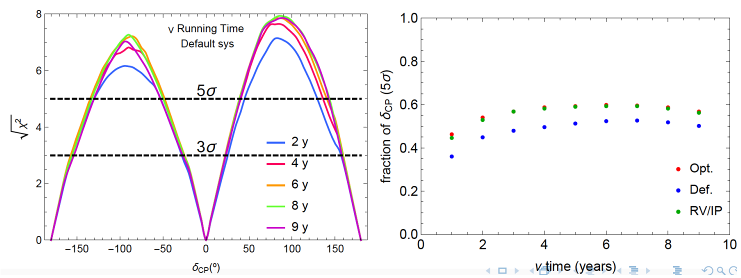




ESSvSB, Salvador Rosauro-Alcaraz

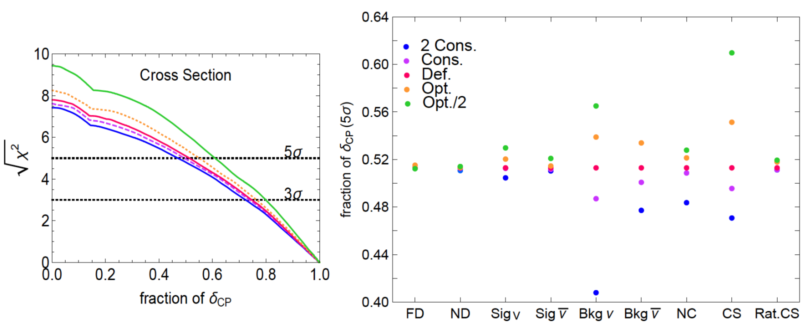
Impact of ν mode running time

- Up to now studies with 2+8 years
- Preference for 5+5 years



Most important systematics

- ν background
- Cross section uncertainties



Conclusions

- **ESSνSB**
  Complementarity with *DUNE*. **Lower energy ν**.
- Mass hierarchy
  It could exclude the wrong hierarchy at $\sim$ **3σ**
- ν mode running time
  Better a symmetric **5+5 setup**
- Baseline
  - $L < 300$km systematics relevant$\rightarrow$ RV/IP better as $\mathcal{O}(3\%)$ sys.
  - $L_{optimal} \sim$ **400km** for **5 + 5** yrs running
- Impact of systematic errors
  ν background and **cross section**

$L = 540$ km and $5 + 5$ yrs

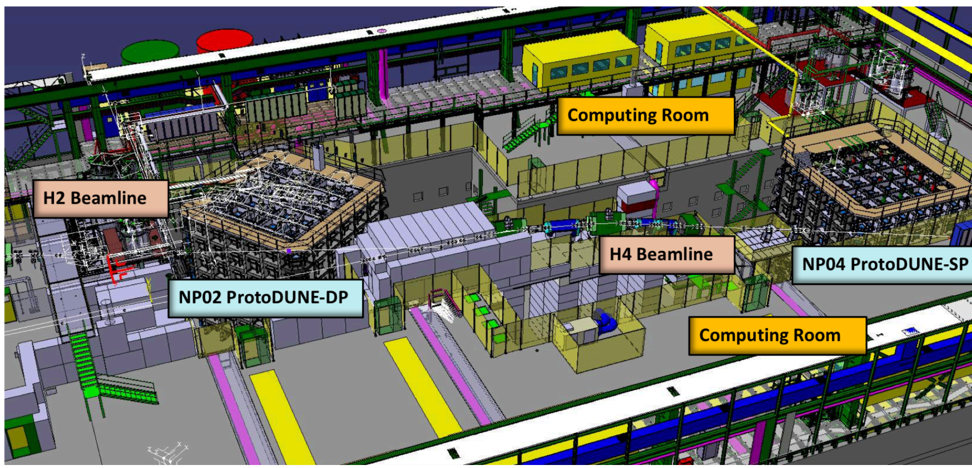
CP violation could be discovered above **5σ** for a **51.2 – 59.2**% of values of δ depending on the systematics

ProtoDUNE, Jingbo Wang

CERN beam particles: , e, μ, p, $K^{\pm}$, $\pi^{\pm}$ from (500 MeV – few GeV)

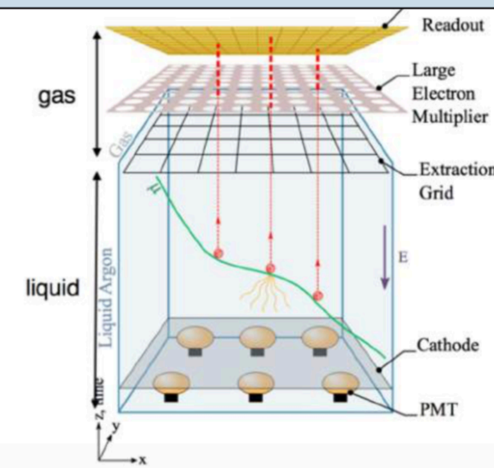
ProtoDUNE Layout @EHN1

- Both single phase and dual phase detectors are located in the north area extension at CERN EHN1
- The CERN neutrino platform is responsible for the cryostat, the cryogenic system, and the beam facilities.



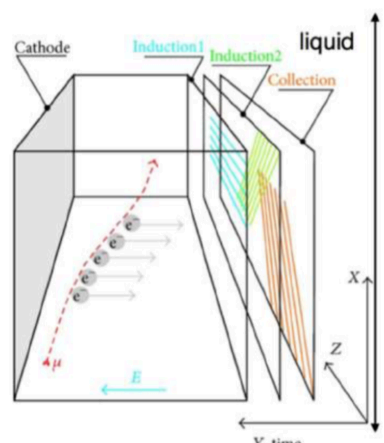
Dual Phase Detector:

- Liquid argon and gaseous argon
- Ionization in liquid argon
- Ionization charges drift in liquid phase, are amplified in LEM and are collected on anode readout board in gaseous phase
- Expect higher signal-to-noise ratio: high field requires careful design



Single Phase Detector:

- Only liquid argon
- Ionization and collection in liquid phase
- Ionization charges drift in liquid, pass by induction plane(s) and are collected by anode collection plane
- No amplification of the initial ionization charge: grounding is important

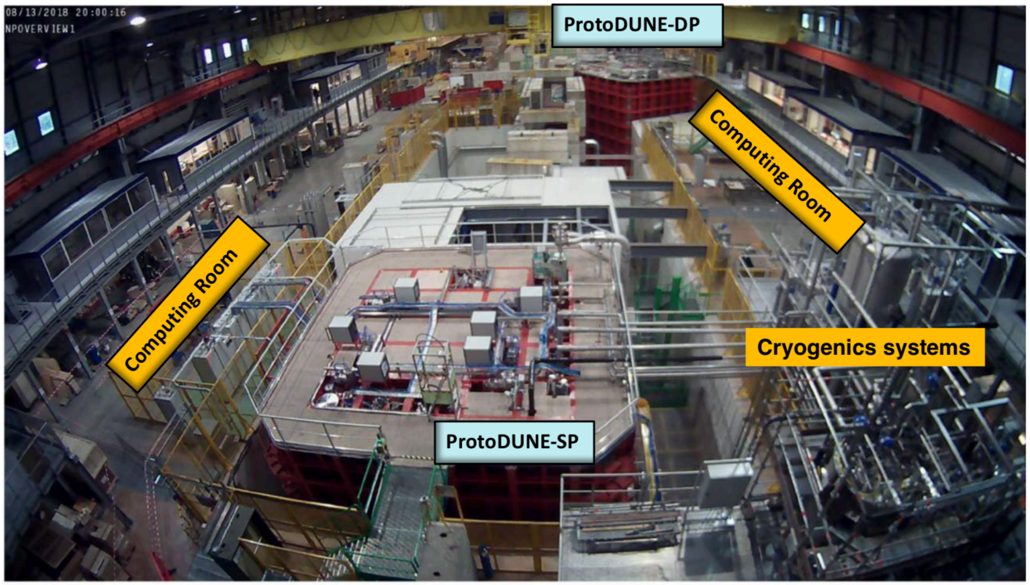


VS

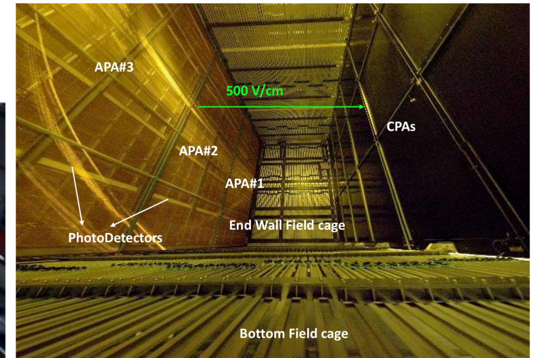
S. Murphy, https://indico.cern.ch/event/649662/

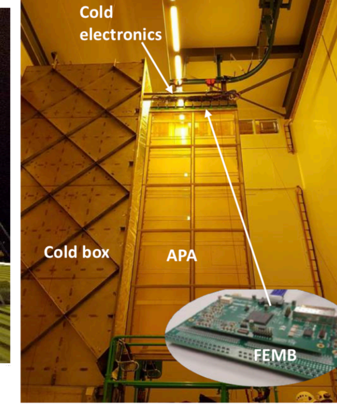
ProtoDUNE, Jingbo Wang

SP



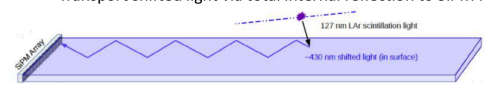
Latest webcam_1 image from the inside-work of the Neutrino Platform Hall (EHN1). (Images updated every 30'.)





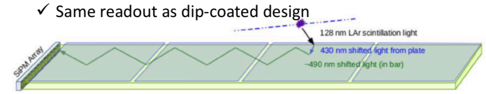
Design#1: Dip-coated light guide (MIT and Fermilab)

- ✓ Acrylic light guide bar dip-coated with wavelength shifting material.
- ✓ Transport shifted light via total internal reflection to SiPM readout



Design#2: Double-shift light guide (Indiana University)

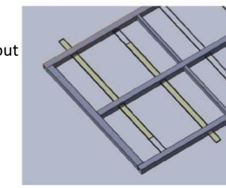
- ✓ Wavelength shifting plates + wavelength shifting light guide
- ✓ Same readout as dip-coated design



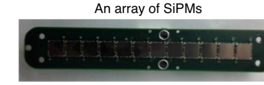
- **Design#3: ARAPUCA (Campinas University and Fermilab)**

Photo Detection

PDS module inserted into an APA frame

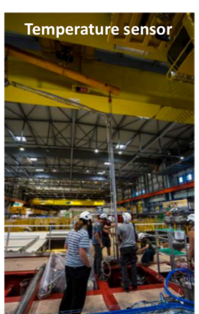


An array of SiPMs



ProtoDUNE-SP: Current Status

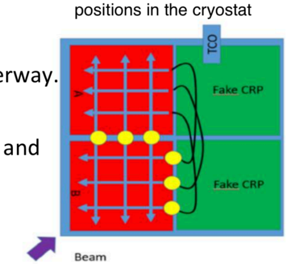
- April 27th 2018, all detector elements were completed, tested and inserted.
- August 8th 2018, cryostat filling has started.
- Purity monitor, temperature sensor and camera operational during the cryostat filling
- Cosmic Ray Tagger (CRT) is being installed
- **August 29th 2018, ProtoDUNE-SP will be ON for beam data!**



ProtoDUNE-DP: Current Status

- Apr 2018, completed field cage installation and demonstrated stable operation at 150 kV
- Aug 2018, CRP construction and cold box test underway.
- Sep 2018, Photon detection system installation
- Oct 2018, plan to close cryostat with 2 active CRPs and 2 non-instrumented CRP frames
- Dec 2018, start taking cosmic data

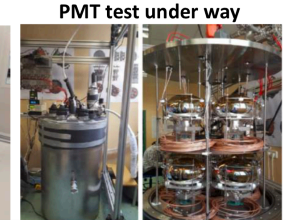
Top view of the CRP positions in the cryostat



Field Cage assembled on April 4th

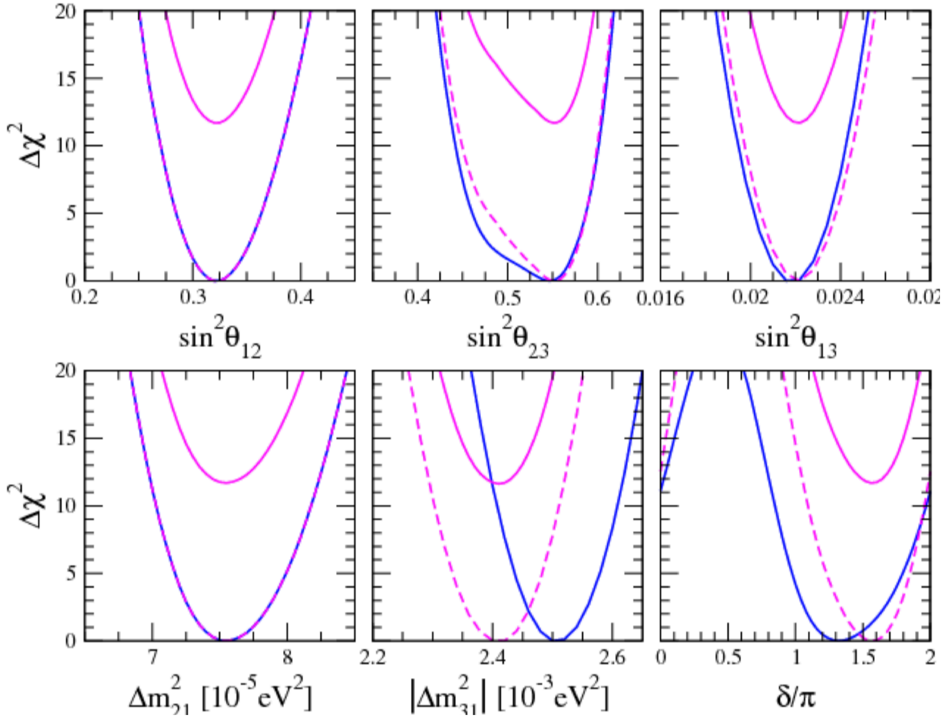
CRP being assembled

PMT test under way



Global analysis of neutrino oscillation experiments, Christoph Andreas Ternes, IFIC, Universitat de València/CSIC

Summary of the global fit



Summary of the global fit

parameter	best fit $\pm$ 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (NO)	2.50 ± 0.03	2.41–2.60
$\lvert\Delta m^2_{31}\rvert$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
$\sin^2\theta_{23}/10^{-1}$ (IO)	$5.51^{+0.18}_{-0.30}$	4.53–5.98
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94

- Inverted mass ordering is now disfavored at more than 3σ, with $\Delta\chi^2 = 11.7$
- If we exclude SK from the fit we obtain $\Delta\chi^2 = 7.7$
- This is due to the combination of LBL+Reactors, since LBL alone gives $\Delta\chi^2 = 2.0$
- By combining several datasets, including cosmological observations and 0νββ-data we disfavor inverted mass ordering with 3.5σ

- The solar parameters, the reactor angle and absolute value of the atmospheric mass splitting are very well measured (errors 5% and below)
- We exclude a large part for of the parameter space for the CP phase
- The octant problem remains unsolved, although the value now tends towards the second octant