Neutrino Physics: New Results and Perspectives

(Selected Topics with a Focus on Neutrino Oscillations)

Chang Kee Jung, Stony Brook University, SUNY

Conference on Physics of Fundamental Interactions

Section of Nuclear Physics of the Division of the Physical Sciences

Russian Academy of Science

Grand Physics Goals and Questions with Neutrino Studies

- Experimental input to the understanding of the matter-antimatter asymmetry in the universe
  - Leptogenesis (a new paradigm?)
  - Measurement of CPV (δ_{CP}) in the lepton sector
  - Clearer theoretical connection between low E CPV to high E CPV critical
  - Understanding of the neutrino mass and its impact on the evolution of the universe
  - Measurement of the absolute neutrino mass
  - Cosmological constraints
  - Is non-zero neutrino mass an evidence for Grand Unification?
    - Seesaw mechanism?

      Proton decay searches

Grand Physics Goals and Questions with Neutrino Studies

- Detection and study of astrophysical neutrinos
  - Identifying point sources of astrophysical neutrinos
    - Study of ultra high energy acceleration mechanism
  - Detection of neutrinos from core-collapse supernovae
    - Galactic supernova → detailed study of supernova mechanism
  - Detection of diffuse/relic supernova neutrinos
  - Neutrino astronomy
- Determining Dirac or Majorana nature of neutrino
  - Neutrino-less double beta decay experiments
- Exploration of new physics
  - Precision measurements of all neutrino oscillation parameters
    - Test of PMNS framework
  - Search for sterile neutrinos, non-standard interactions, etc.

Pontecorvo-Maki-Nakagawa-Sakata (PMNS) Lepton Mixing Matrix (a la CKM matrix)

weak eigenstates

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \mathrm{U}_{\mathrm{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

mass eigenstates

1 Dirac Phase ⇒ CPV

Three Angles

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

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

atm/accelerator accelerator/reactor solar/reactor

If ν is majorana particle, 2 more extra (Majorana) phases
# of extra phases = N - 1 (w/ N = 3)

3-flavor Neutrino Oscillations (in Vacuum)

In general,

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{i>j} \Re(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin^2\left(\frac{\Delta m^2_{ij} L}{4E}\right) + 2\sum_{i>j} \Im(U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j}) \sin\left(\frac{\Delta m^2_{ij} L}{2E}\right)$$

For three generation, ν_e appearance (accelerator experiments)

$$P(\nu_\mu \to \nu_e) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2 \frac{\Delta m^2_{32} L}{4E_\nu} + \text{subleading terms}$$

Sensitivity to θ_{23} octant

Full appearance probability includes term that goes as sin(δ):

CPV term $\quad \propto \pm \sin\theta_{12} \sin\theta_{13} \sin\theta_{23} \sin\delta$ *Sensitivity to CPV-δ*

Sign flip for neutrino vs. antineutrino

Need non-zero value for all three mixing angles including θ_{13}

Complementary

For anti-ν_e disappearance (reactor experiments)

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - 4C^2_{13} S^2_{13} \left(C^2_{12} \sin^2\Delta_{13} + S^2_{12} \sin^2\Delta_{23}\right) + 4S^2_{12} C^2_{12} C^4_{13} \sin^2\Delta_{12}$$

No CPV-δ dependence, Pure θ_{13} measurement

ν_e Appearance Including Matter Effect

$$P(\nu_\mu \to \nu_e) \sim \begin{array}{ll} \sin^2 2\theta_{13} & \times \sin^2\theta_{23} \frac{\sin^2[(1-x)\Delta]}{(1-x)^2} \\ -\alpha \sin 2\theta_{13} & \times \sin\delta \sin 2\theta_{12} \sin 2\theta_{23} \sin\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ +\alpha \sin 2\theta_{13} & \times \cos\delta \sin 2\theta_{12} \sin 2\theta_{23} \cos\Delta \frac{\sin(x\Delta)}{x} \frac{\sin[(1-x)\Delta]}{(1-x)} \\ +\alpha^2 & \times \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(x\Delta)}{x^2} \end{array}$$

M. Freund, Phys.Rev. D64 (2001) 053003

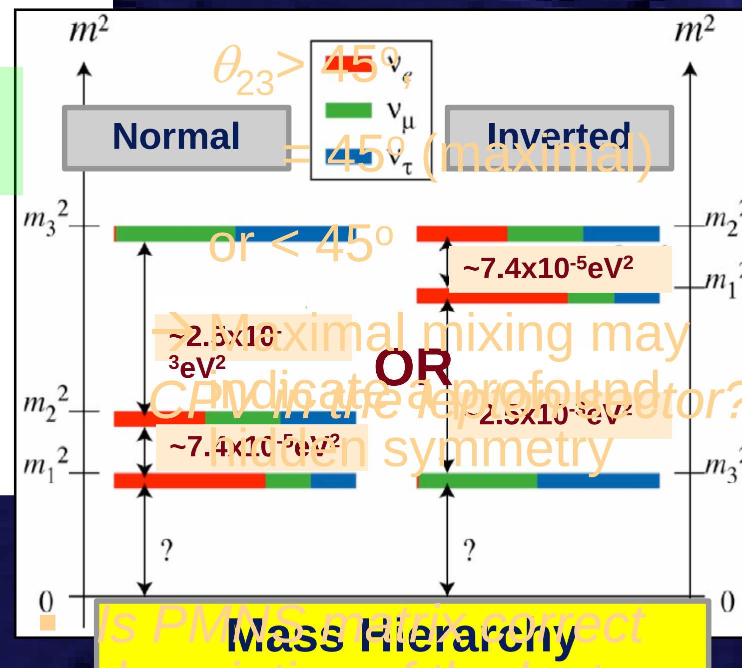
$$\alpha \equiv \frac{\Delta m^2_{21}}{\Delta m^2_{31}} \sim \frac{1}{30} \qquad \Delta \equiv \frac{\Delta m^2_{31} L}{4E} \qquad x \equiv \frac{2\sqrt{2} G_F N_e E}{\Delta m^2_{31}}$$

- The leading term contains $\sin^2\theta_{23}$ (not $\sin^2 2\theta_{23}$)
  - Sensitivity to the θ_{23} octant ($\theta_{23} > 45^o$, $\theta_{23} = 45^o$, $\theta_{23} < 45^o$)
- 1st order in α term contain $\sin\delta$ ➔ CP odd term
  - Allows CPV measurements in the lepton sector
  - Suppressed compared to the leading term
    - Requires large statistics ➔ powerful accelerator, large detector
- All terms contain x and Δm^2_{31} which change sign for anti-ν and inverse mass hierarchy
  - Allows experimental determination of mass hierarchy through matter effect

A Summary of Neutrino Oscillation Parameter Measurements

Parameter	best-fit	3σ
Δm^2_{21} $[10^{-5}$ eV $^2]$	7.37	6.93 – 7.96
$\Delta m^2_{31(23)}$ $[10^{-3}$ eV $^2]$	2.56 (2.54)	2.45 – 2.69 (2.42 – 2.66)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2_{31(32)} > 0$	0.425	0.381 – 0.615
$\sin^2\theta_{23}$, $\Delta m^2_{32(31)} < 0$	0.589	0.384 – 0.636
$\sin^2\theta_{13}$, $\Delta m^2_{31(32)} > 0$	0.0215	0.0190 – 0.0240
$\sin^2\theta_{13}$, $\Delta m^2_{32(31)} < 0$	0.0216	0.0190 – 0.0242
δ/π	1.38 (1.31)	2σ: (1.0 - 1.9) (2σ: (0.92-1.88))

PDG 2018 Summary



$\theta_{23} > 45°$
$= 45°$ (maximal)
or $< 45°$

→ Maximal mixing may indicate a profound hidden symmetry

CPV in the lepton sector?

Is PMNS matrix correct description of the lepton sector?

Recall, P (ν_μ → ν_e)

∝ leading term + …

+ term($\sin\theta_{12}\sin\theta_{23}\sin\theta_{13}\sin\delta_{CP}$)

Why is nature so kind to us?

Critical for the ν-less double-β decay searches → determination of the Majorana-nature of ν

In collider physics, theory has led experiment for the past decades, on the contrary in neutrino physics, experiment has led theory, especially in recent decades.

(ckj's personal opinion)

Mixing Matrices

Why are the mixing matrices for the lepton sector and quark sector so much different?

$$U_{CKM} \approx \begin{pmatrix} 0.97 & 0.23 & 0.004 \\ 0.23 & 0.97 & 0.04 \\ 0.008 & 0.04 & 1 \end{pmatrix}$$
$$\delta = 60^\circ$$

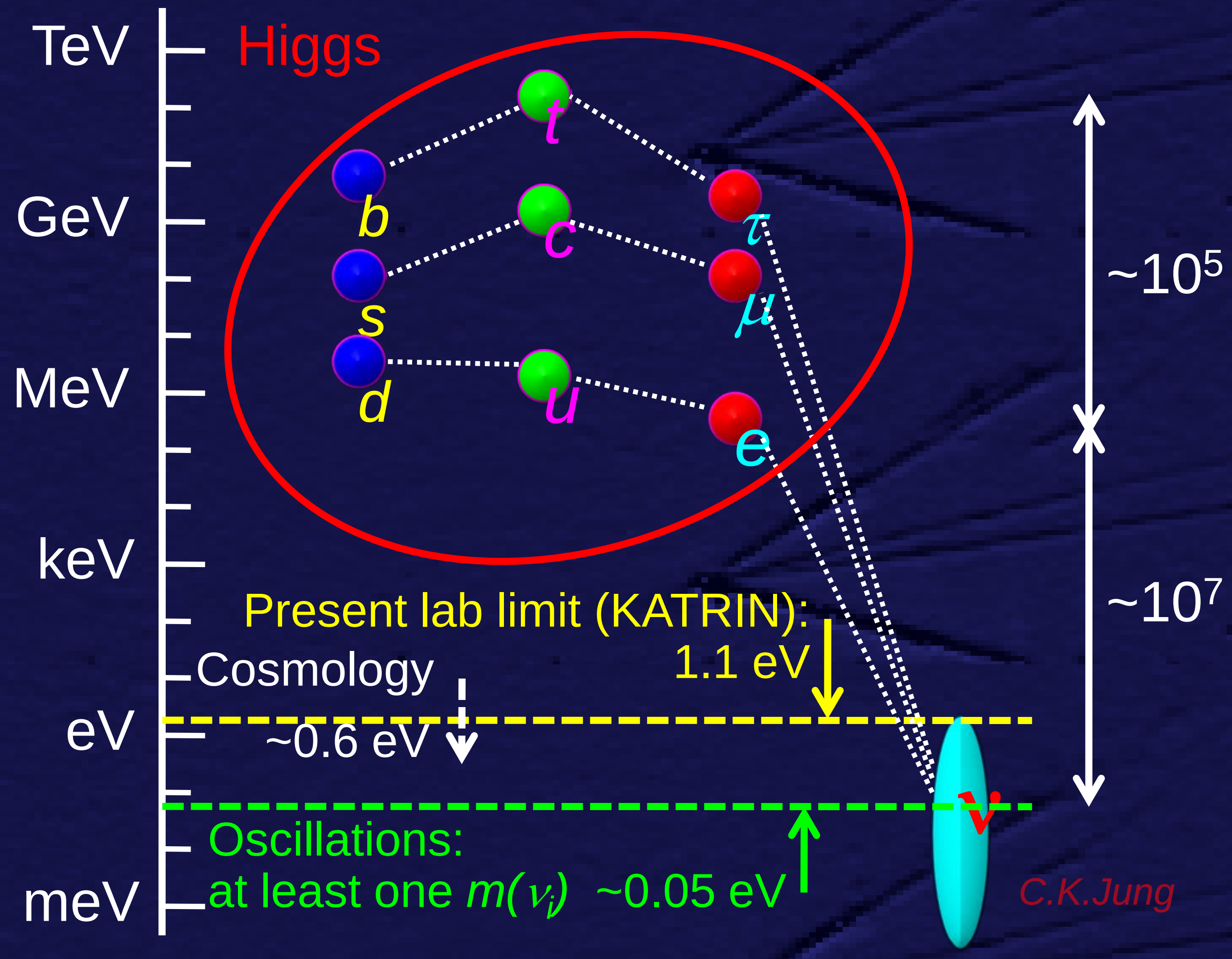
$$U_{PMNS} \approx \begin{pmatrix} 0.8 & 0.55 & 0.15 \\ -0.4 & 0.6 & 0.7 \\ 0.4 & -0.6 & 0.7 \end{pmatrix}$$
$$\delta = ?$$

For updated PMNS matrix values see:

I. Esteban, M. Gonzalez-Garcia, M. Maltoni, et al., J. High Energ. Phys., p. 87, 2017.

→ No change in the overall picture

Spin ½ Matter Field Particle Mass Spectrum



Are neutrino masses suppressed by new physics at very high energy?

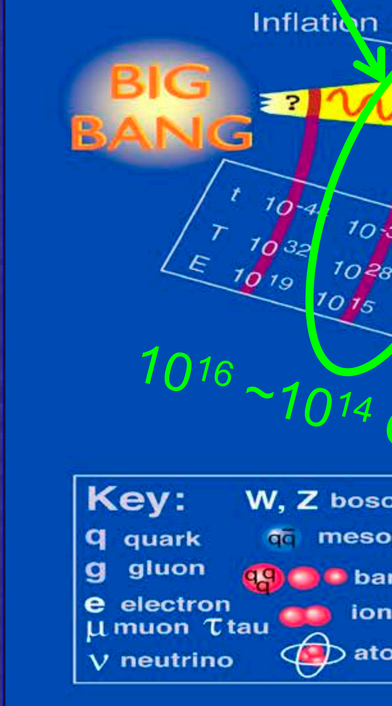
$m(\nu_i) = m^2_{Di} / M$

Seesaw in SO(10)

Matter/Anti-Matter Asymmetry in the Universe and Baryogenesis

At the onset of Big Bang (t ~ 0)
amount of antim
=amount of ma

proton decay
neutrino



10^{16} ~10^{14} GeV

Today (t = 13.8 Gy)
No antimatter
What happened?

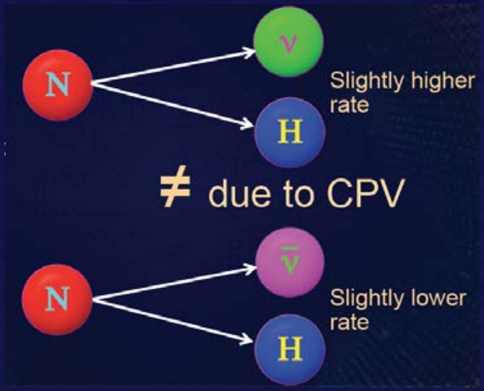
Sakharov's 3 Conditions:

1) At least one baryon number violating process e.g. sphaleron process
2) C- and **CP-violation**
3) Interactions outside of thermal equilibrium

➔ The observed CP-violations in the quark sector are not enough to explain the large asymmetry

Leptogenesis

- Generate a large lepton excess through CPV in the lepton sector
  - CPV decay of heavy Majorana neutrinos of masses related to the GUT scale, $M_{GUT} \sim 10^{16}$ GeV (required by the seesaw mechanism as in SO(10))



$$\varepsilon = \frac{\Gamma(N_1 \to \nu_i H) - \Gamma(N_1 \to \bar{\nu}_i H)}{\Gamma(N_1 \to \nu_i H) + \Gamma(N_1 \to \bar{\nu}_i H)} \neq 0$$

- Use B - L conserving sphaleron interactions (transitions between gauge vacua not by tunneling but through thermal fluctuation over the barrier) to turn lepton excess to baryon excess
- Became a new paradigm to explain matter-antimatter asymmetry

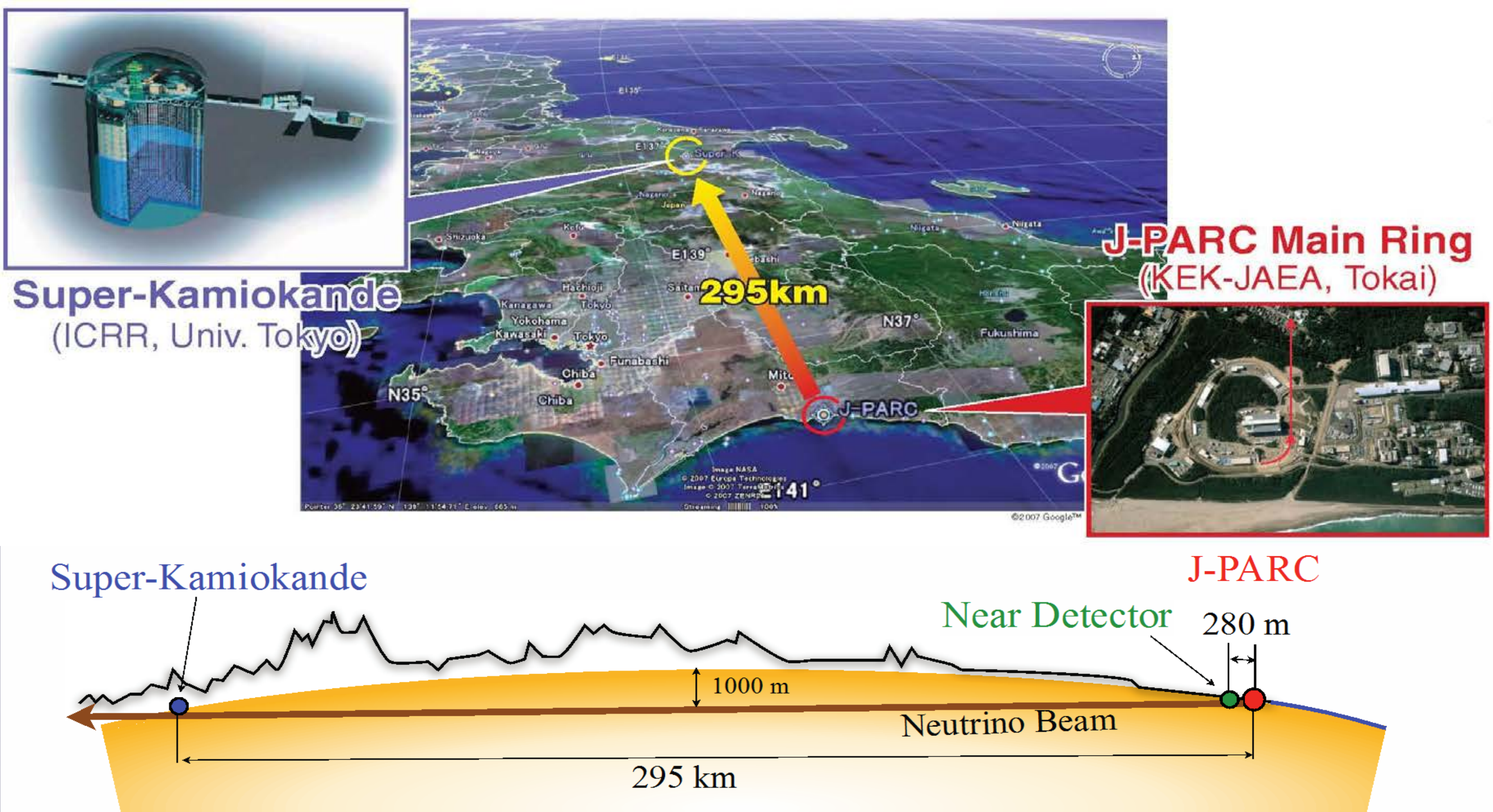
➔ Strong motivation to look for CPV in the lepton sector

➔ Currently the only viable way to search for CPV in the lepton sector experimentally is through neutrino oscillation processes

Remaining Unknown Neutrino Properties

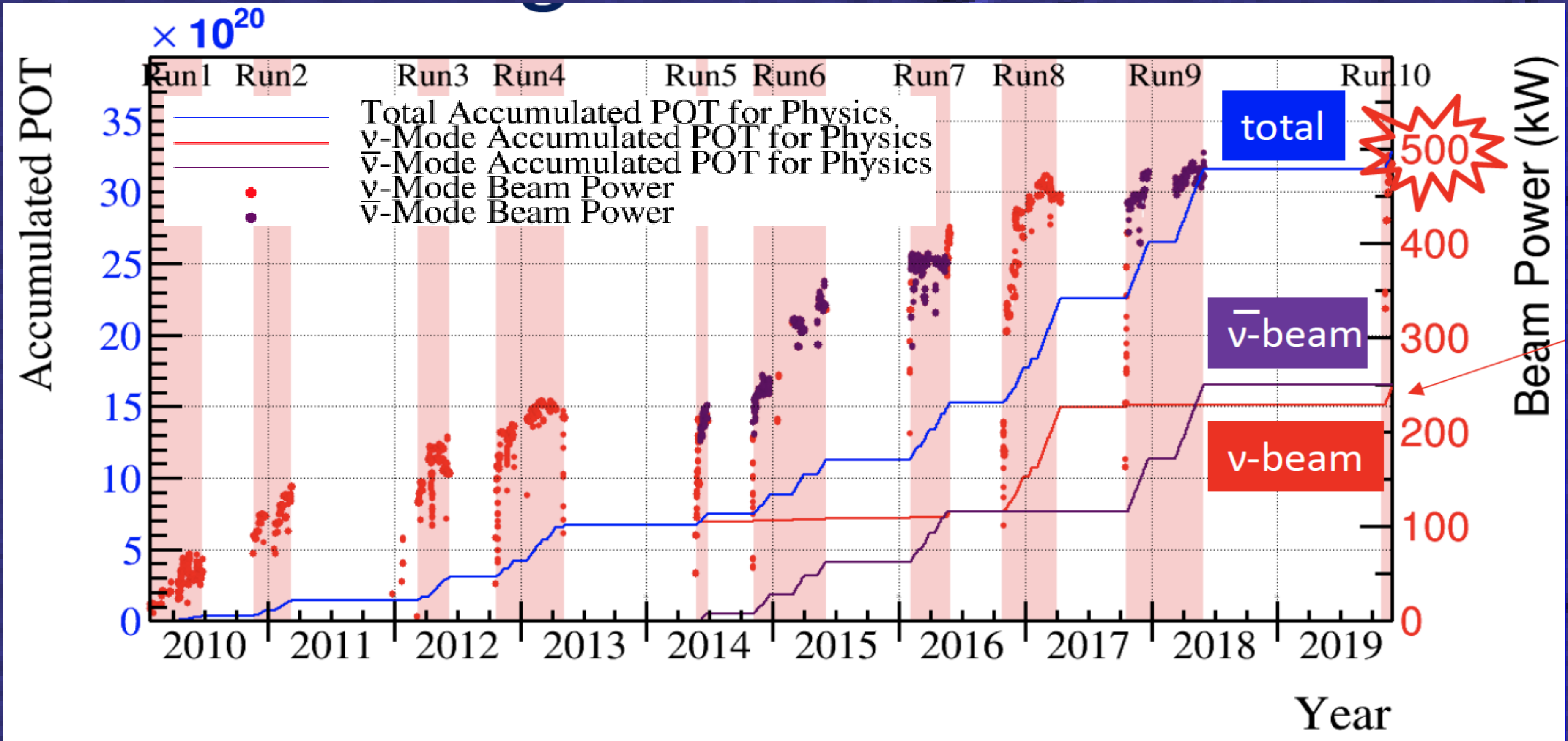
- θ_{23}> 45º, = 45º (maximal) or < 45º
  → maximal mixing may indicate a profound hidden symmetry
- δ_{CP} (≠ 0, i.e. CPV?)
- Mass ordering (NH or IH?)
- Absolute m_ν
- Dirac/Majorana
- Any sterile ν

The T2K (Tokai to Kamioka) Experiment
(http://t2k-experiment.org/)



"The T2K Experiment", K. Abe, et al., Nucl. Instr. and Meth. A **659**, 106 (2011)

T2K Data Taking in Neutrino and Antineutrino Beam Modes

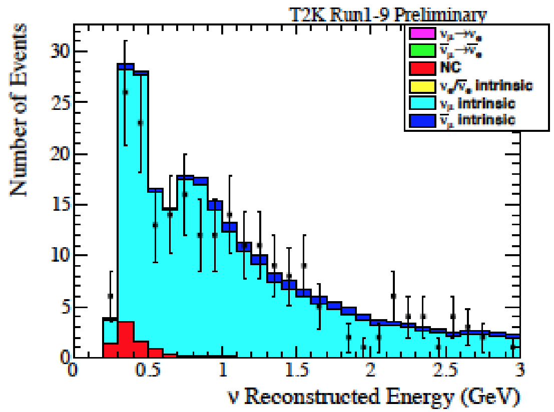


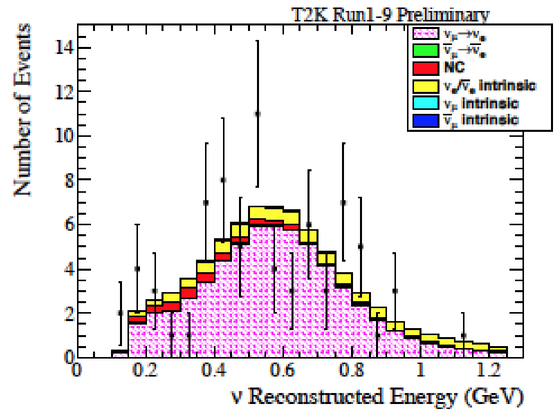
- Total POT for physics: 1.63×10^{21} (nu-mode), 1.65×10^{21} (antinu-mode) → 3.29×10^{21} ~ 42% of the total approved POT (7.8×10^{21})
- Recently (Jan. 2020) ran stably at 500 kW beam power (design: 750 kW)

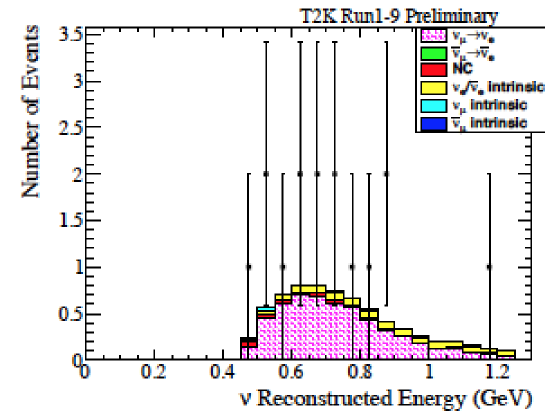
Observed Energy Spectra of 5 Samples

1-ring CCQE-μ-like | 1-ring CCQE-e-like | 1-ring CC1π-e-like

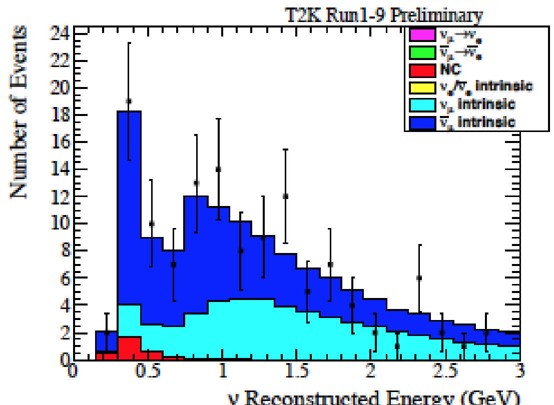
ν-mode

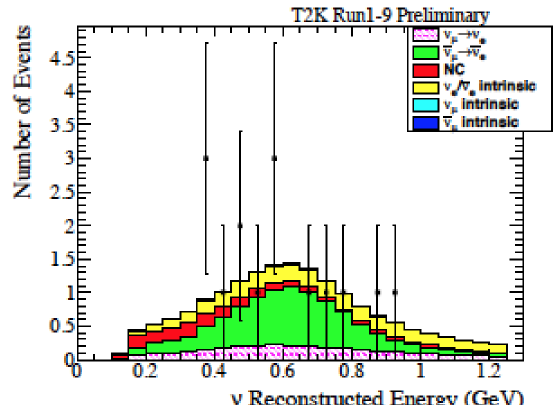






$\bar{\nu}$-mode





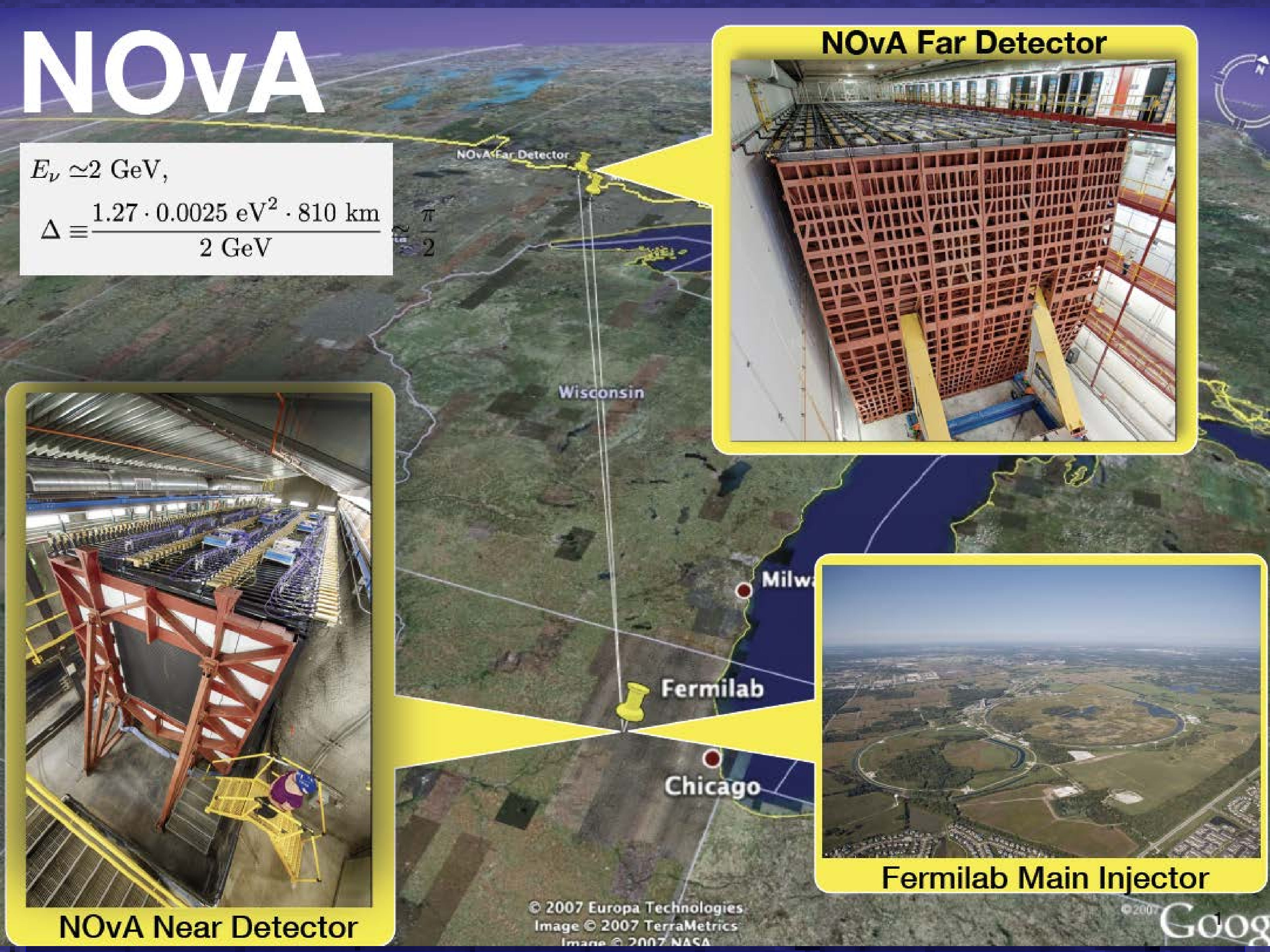
MC assumption :
$\delta_{CP} = -\pi/2$
Normal Hierarchy
$\sin^2\theta_{23} = 0.528$
$\sin^2\theta_{13} = 0.0212$

	μ-like exp.	μ-like meas.	e-like exp.	e-like meas.
$\bar{\nu}$ Previous	92.7	102	11.7	9
$\bar{\nu}$ Updated	139.5	140	17.1	15
ν Updated	272.4	243	74.4(7.0cc1π)	75(15cc1π)

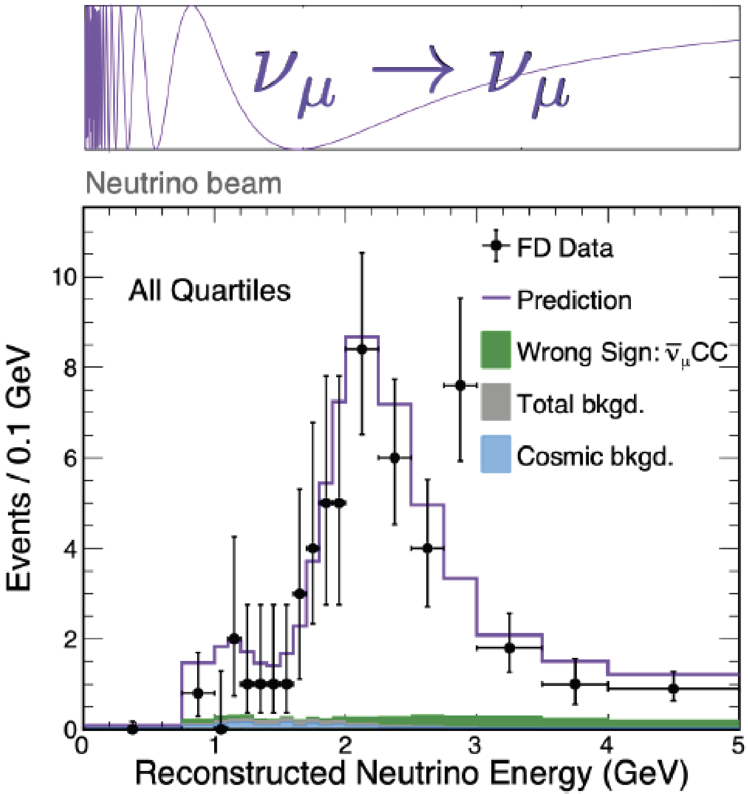
NOvA

$$E_\nu \simeq 2\ \mathrm{GeV},$$

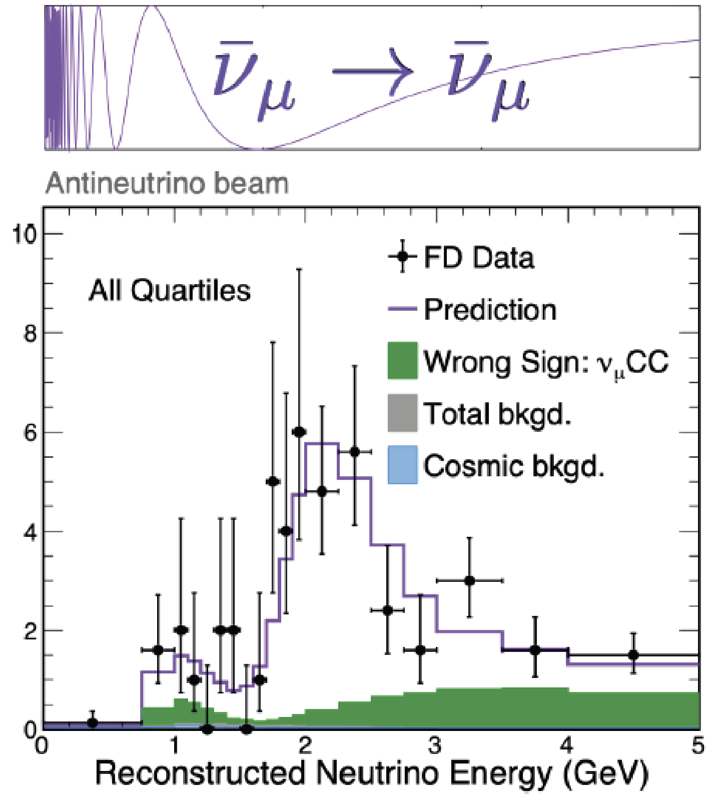
$$\Delta \equiv \frac{1.27 \cdot 0.0025\ \mathrm{eV}^2 \cdot 810\ \mathrm{km}}{2\ \mathrm{GeV}} \simeq \frac{\pi}{2}$$



NOvA Muon Neutrino and Antineutrino Disappearance



No oscillations	730
Best Fit	124
Cosmic bkg	2.1
Beam bkg	2.1
Observerd	113

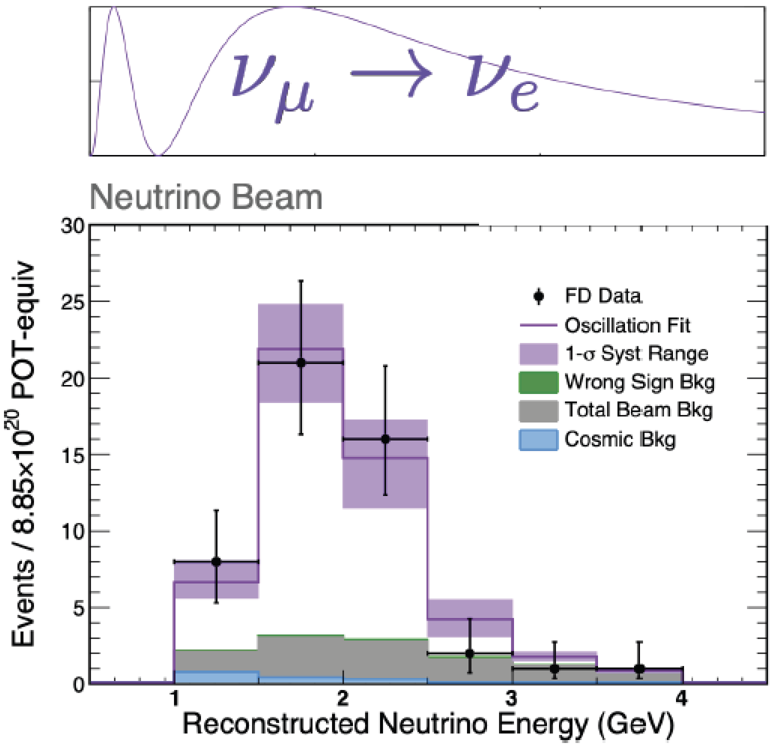


No oscillations	476
Best Fit	96
Cosmic bkg	0.8
Beam bkg	1.4
Observerd	102

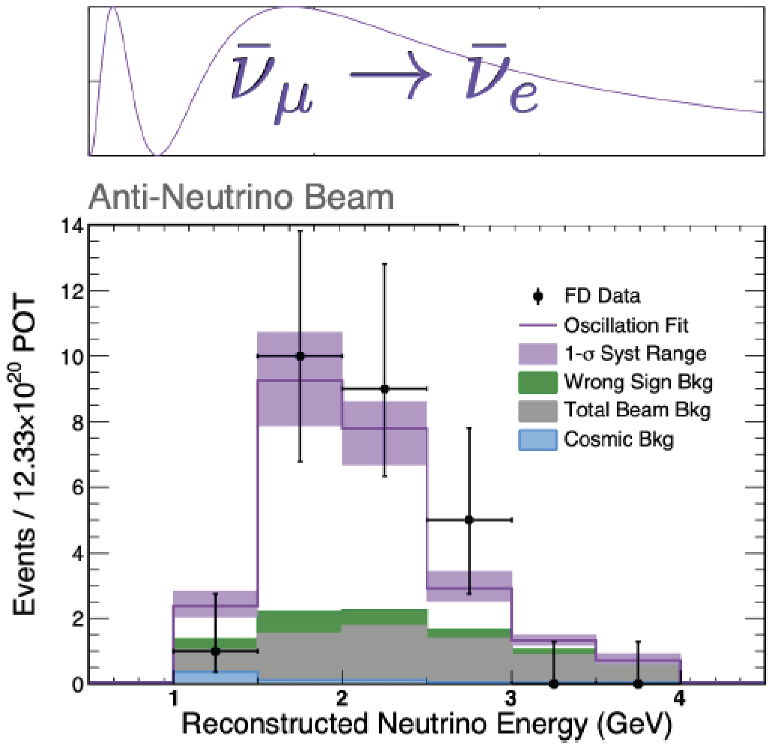
PRL 123 (2019) 151803

M. Messier

NOvA Electron Neutrino and Antineutrino Appearance



Best fit	59
Total bkg	15.0
Wrong-sign bkg	0.7
Beam bkg	11.1
Cosmic bkg	3.3
Observed	58

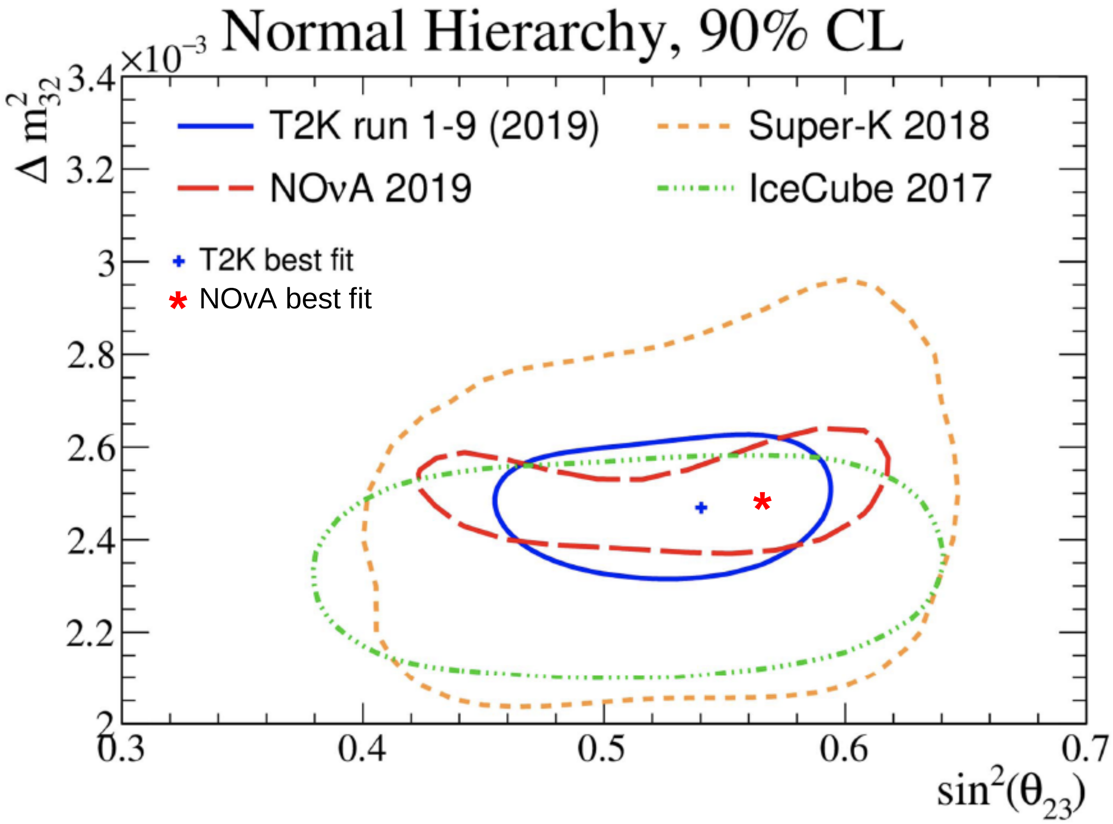


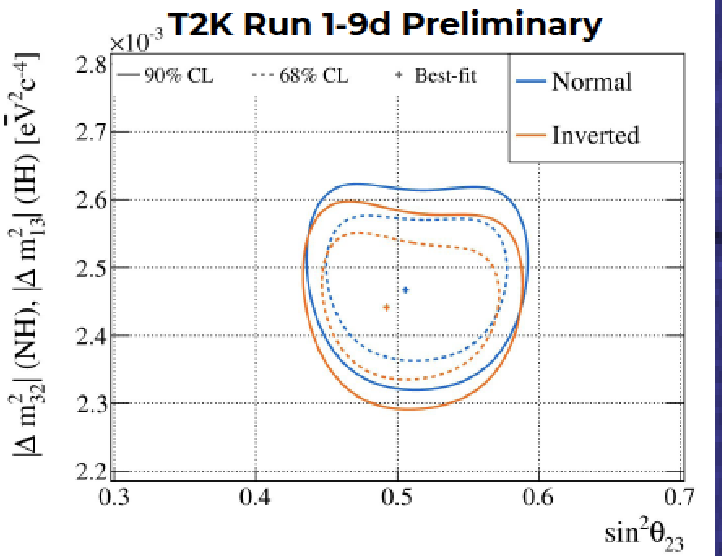
Best fit	27
Total bkg	10.3
Wrong-sign bkg	2.2
Beam bkg	7.0
Cosmic bkg	1.1
Observed	27

NOvA sees electron antineutrino appearance w/ **4.4 σ** significance

M. Messier

Results on θ_{23} & Δm^2_{32} (2019) – NNN19





➔ All measurements are consistent with the maximal mixing; NOvA has a slight preference (1.6 σ) for upper octant

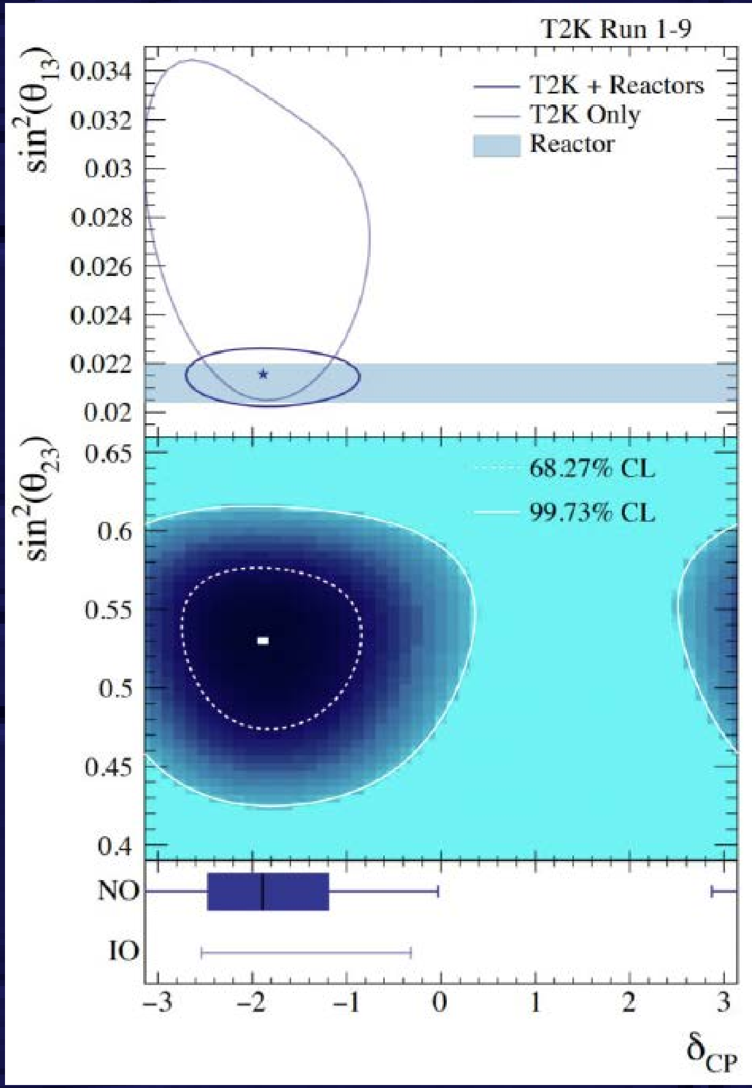
Note: oscillation maximum occurs at $\sin^2\theta_{23} \sim 0.51$ or $\theta_{23} \sim 45.6^o \neq 45^o$ maximal mixing

$$P(\nu_\mu \to \nu_\mu) \sim 1 - \Big(\underbrace{c^4_{13}\ \sin^2 2\theta_{23}}_{\text{Leading}} + \underbrace{s^2_{23}\ \sin^2 2\theta_{13}}_{\text{Next-to-leading}}\Big) \sin^2 \frac{\Delta m^2_{31} L}{4E},$$

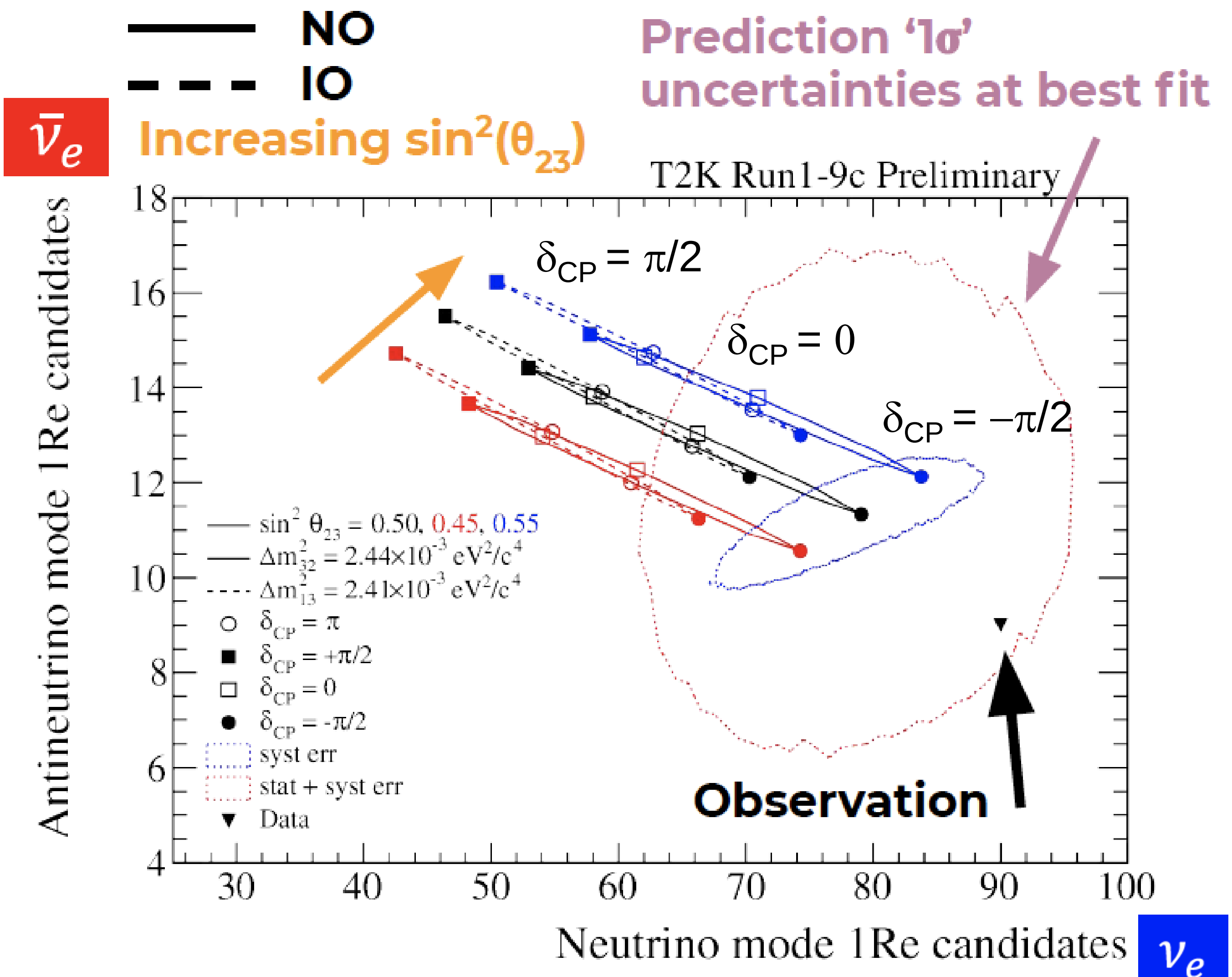
is different between 1st/2nd octants

T2K 3σ Exclusion of δ_{CP}

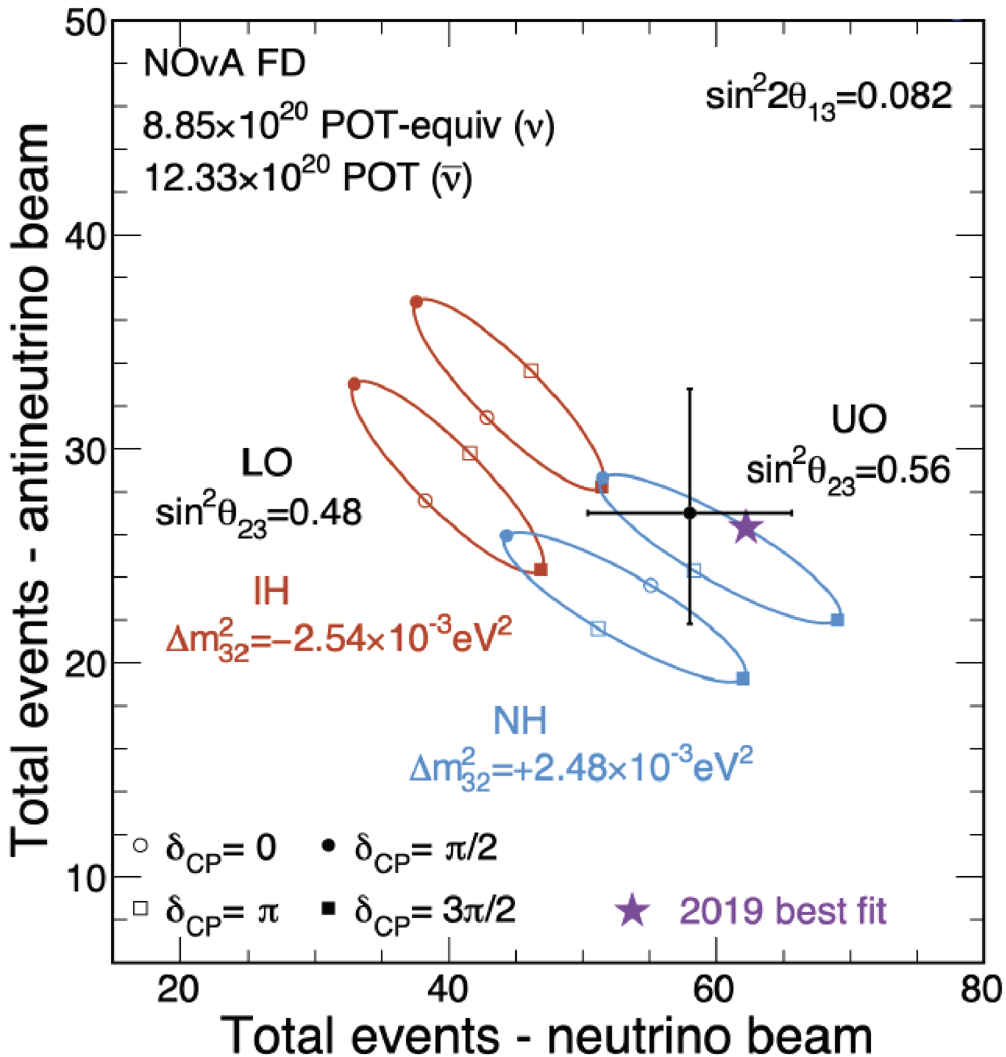
- Obtain 3σ confidence intervals using T2K Run 1-9 data
  - ¬ Closed 3σ intervals for both NO and IO
  - ¬ 3σ exclusion of CP-conserving values in IO
- Accepted for publication in Nature
  - ¬ arXIv: 1910.03887 [hep-ex]
  - → Expected to be published soon



Bi-Event Rate: A Global Look at the T2K Data



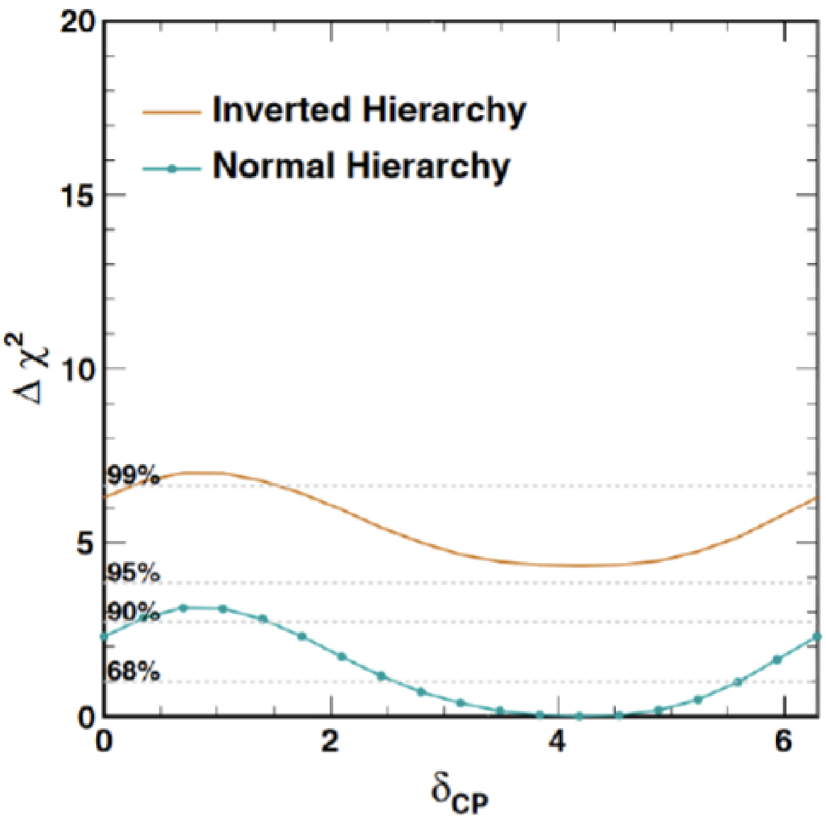
Bi-Event Rate: NOvA Data

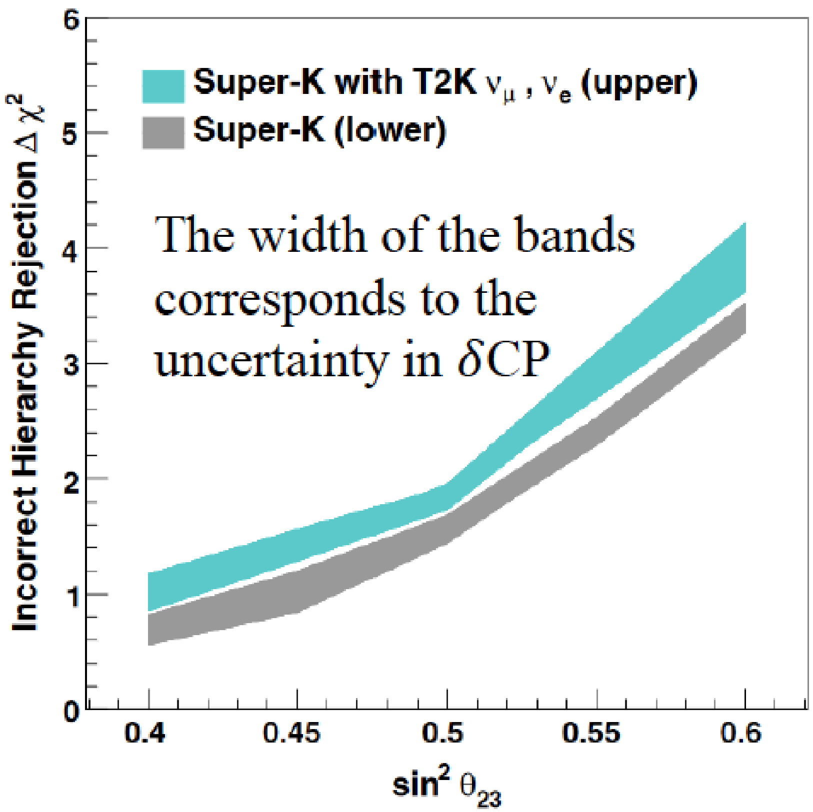


NOvA data prefers **upper θ_{23} octant by 1.6σ** and **Normal neutrino mass hierarchy by 1.9σ** but has **no preferred value of δ_{CP}**

M. Messier

SuperK Atmospheric Neutrino Results





The width of the bands corresponds to the uncertainty in δCP

δCP best-fit at 4.18 for both MHs.

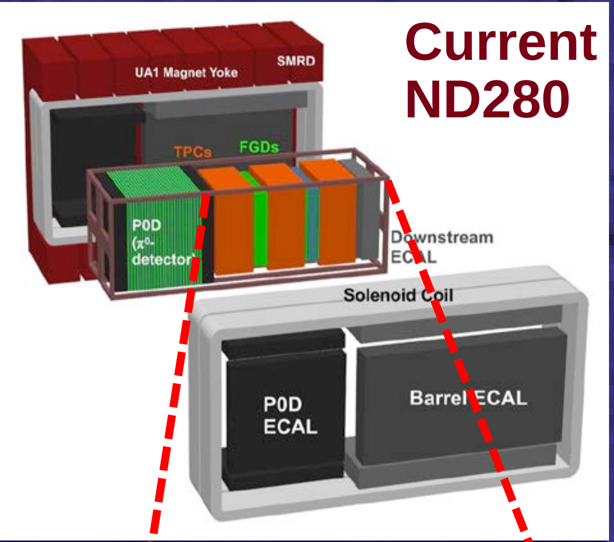
IH disfavored by 81.9-96.7% @ 90% CL

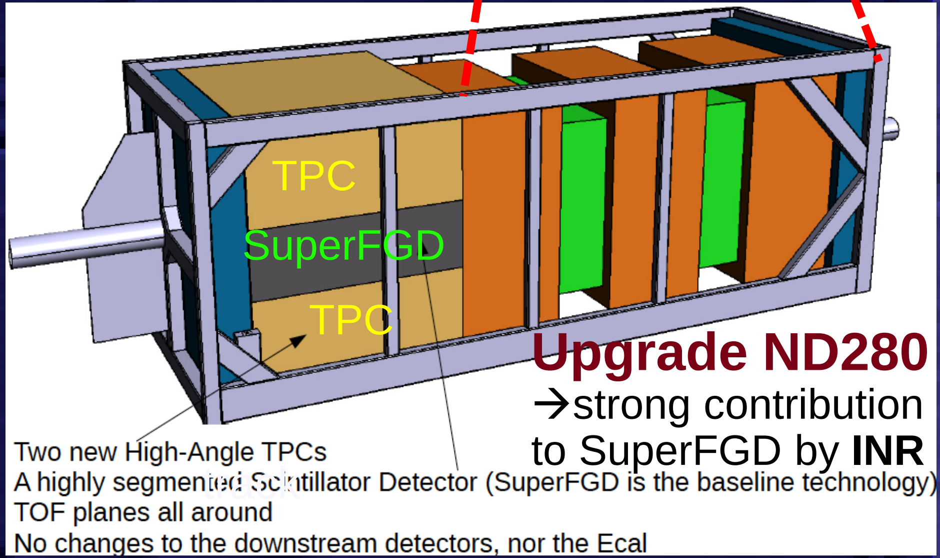
L. Wan, NNN19

Looking into the Future …

T2K ND280 Upgrade

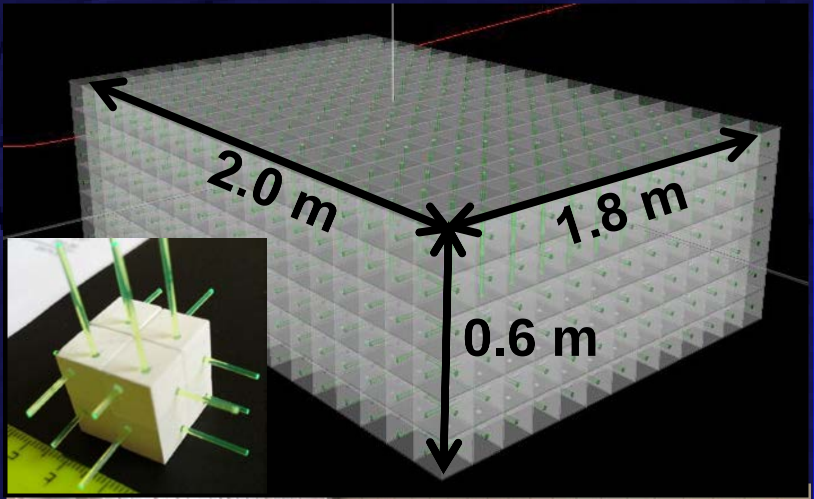
- Current ND280: excellent performance
  - Critical input for OA, and rich data for cross-section measurements and interaction model studies
  - Limited acceptance by design
    - High efficiency only for mostly forward direction
- ND280 Upgrade: improved performance to reduce sys. errors (<4%) for demanding CPV measurement
  - Improved kinematic acceptance to cover the full cosθ range
  - Larger target mass: ~2.2 tons
  - High efficiency for short tracks
    - Improved vertex determination
    - Lower energy threshold, especially for protons and pions
    - e/γ separation in target
  - Good timing (<1 ns) to determine direction





T2K SuperFGD

- Fully active target (2.2 tons)
  - ¬ Plastic scintillator + WLS fiber + MPPC
  - ¬ 1x1x1 cm^3 scintillator cubes assembled in rows and columns
  - ¬ Provide 3D projected views w/ fine segmentation
  - ¬ 4π acceptance w/ low momentum threshold for protons (~300 MeV)
  - ¬ Possible event-by-event neutron KE measurement using TOF
- Synergy w/ proposed DUNE ND 3DST

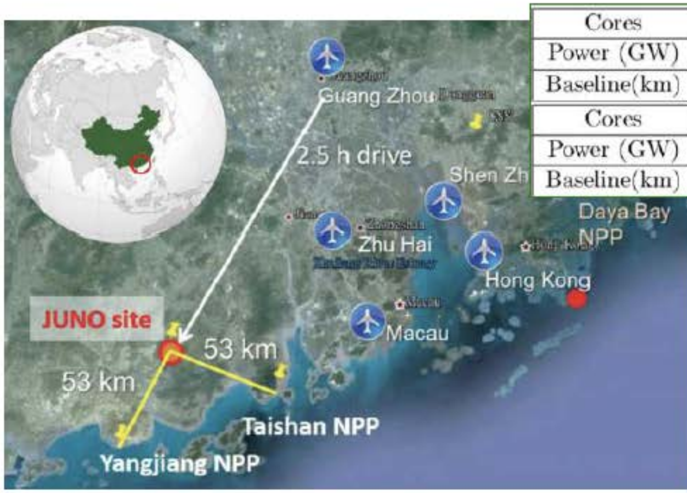


JUNO

The **J**iangmen **U**nderground **N**eutrino **O**bservatory (**JUNO**)

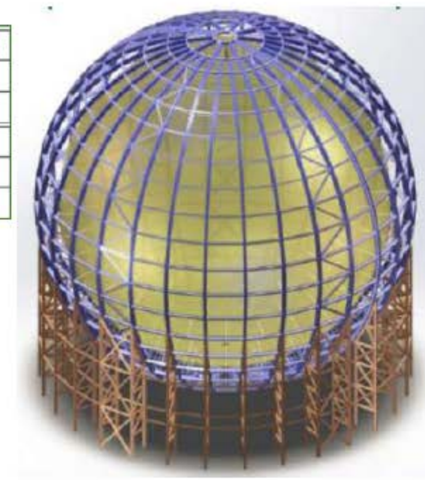
will be the largest liquid scintillator detector an it is under construction in China.

- ~ **20 ktons** of liquid scintillator contained in an Acrylic Sphere of **35.4 m in diameter**
- **~53 km** from two nuclear power plants: Yangjian and Taishan



Cores	YJ-C1	YJ-C2	YJ-C3	YJ-C4	YJ-C5	YJ-C6
Power (GW)	2.9	2.9	2.9	2.9	2.9	2.9
Baseline(km)	52.75	52.84	52.42	52.51	52.12	52.21
Cores	TS-C1	TS-C2	TS-C3	TS-C4	DYB	HZ
Power (GW)	4.6	4.6	4.6	4.6	17.4	17.4
Baseline(km)	52.76	52.63	52.32	52.20	215	265

Total power: 35.8 GW
by 2020: **26.6 GW**



Experiment	Daya Bay	Borexino	KamLAND	JUNO
LS mass (tons)	20 /detector	~300	~1,000	20,000
Nb of collected p.e. per MeV	~160	~500	~250	~1200
Energy resolution @ 1 MeV	~7.5%	~5%	~6%	~3%

E. Catano-Mur
NNN19

3

JUNO Goals on Oscillation Parameters

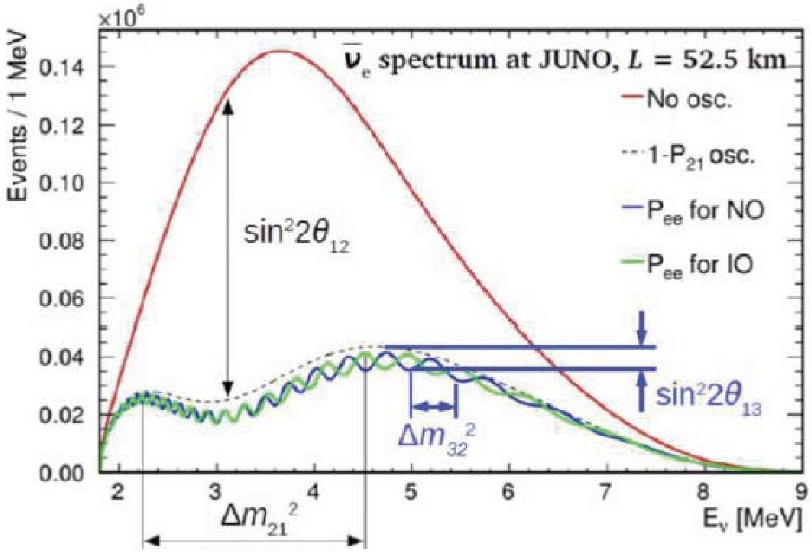
JUNO will measure the 3 Oscillation parameters at a subpercent precision level

In particular the solar oscillation parameters [Δm^2_{21} and $\sin^2(2\theta_{12})$] in order to solve the **tension** between solar ν_e and KamLAND results

Oscillation parameters	Current precision at 1σ level *	JUNO only**
$\lvert\Delta m_{31}^2\rvert$	~1.6%	~0.5%
Δm_{21}^2	~2.3%	~0.6%
$\sin^2(2\theta_{12})$	~5.8%	~0.7%
Mass hierarchy	N/A	3-4 σ
$\sin^2(\theta_{13})$	~3.9%	~15%

* *M. Tanabashi et al. (PDG), Phys. Rev. D 98, 030001 (2018).*

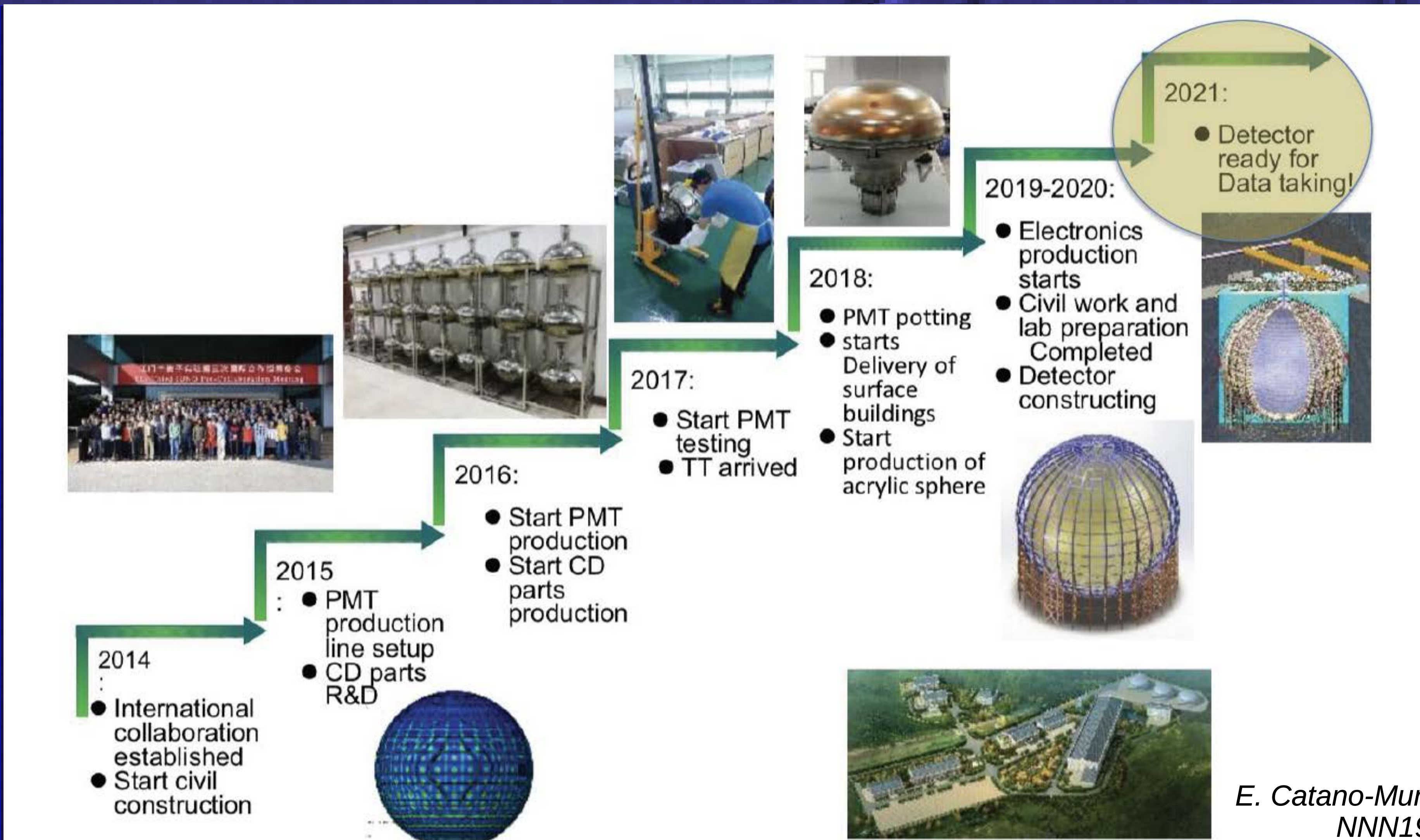
** *JUNO collaboration, J. Phys. G 43 (2016) no.3, 030401*



Controlling energy scale and energy resolution would be the key to the success of the experiment -ckj

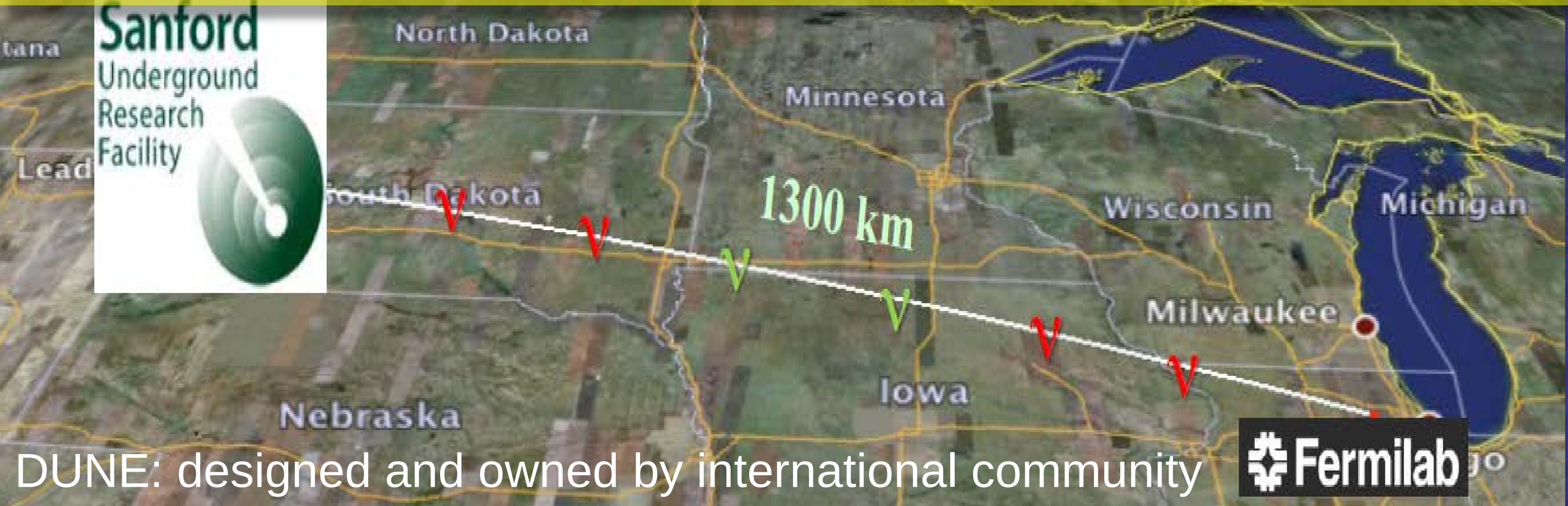
E. Catano-Mur NNN19

JUNO Timeline



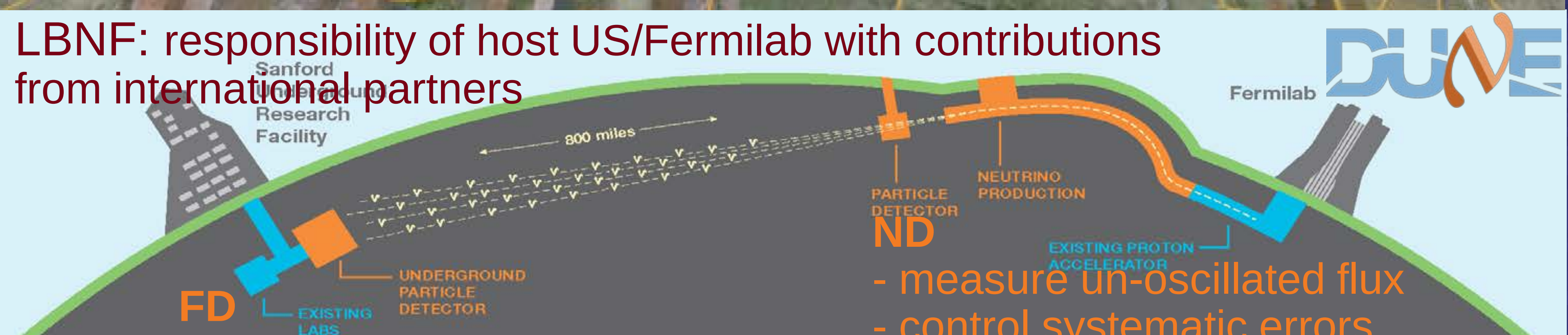
E. Catano-Mur NNN19

The Deep Underground Neutrino Experiment (DUNE) at the Long Baseline Neutrino Facility (LBNF)



DUNE: designed and owned by international community

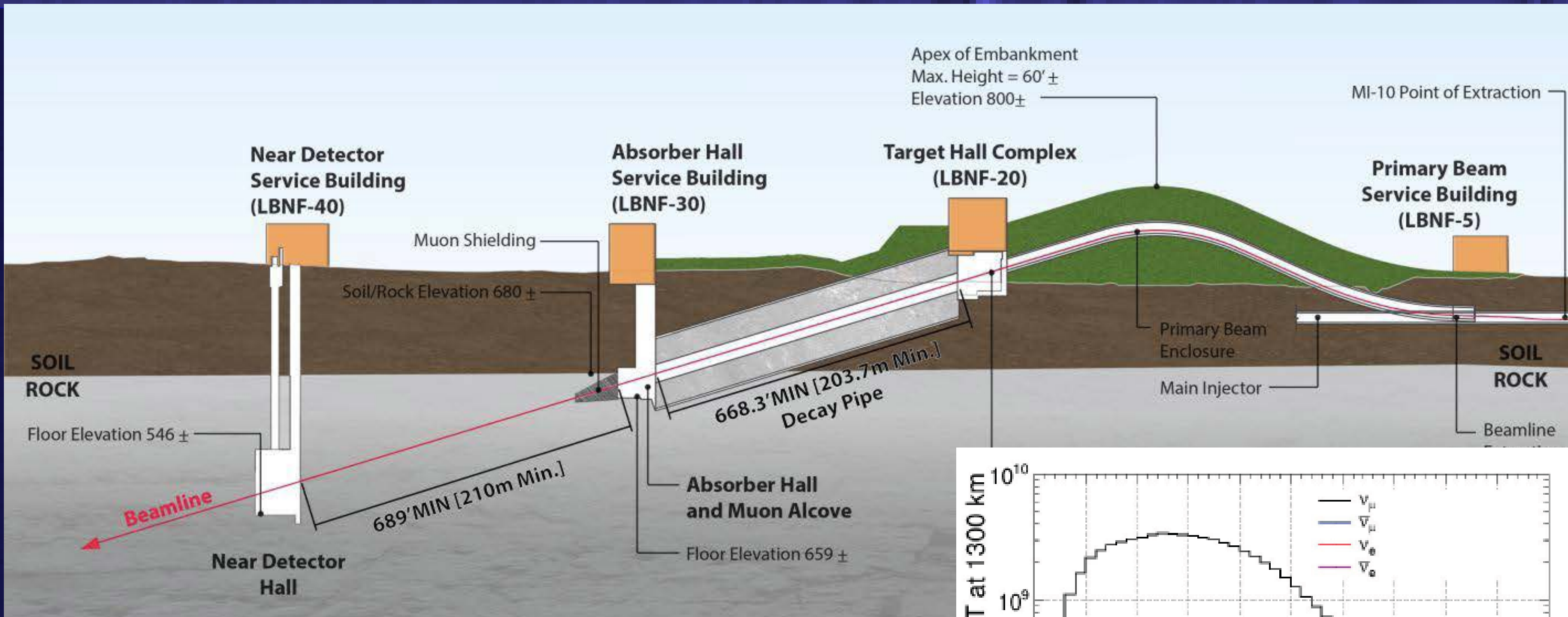
LBNF: responsibility of host US/Fermilab with contributions from international partners

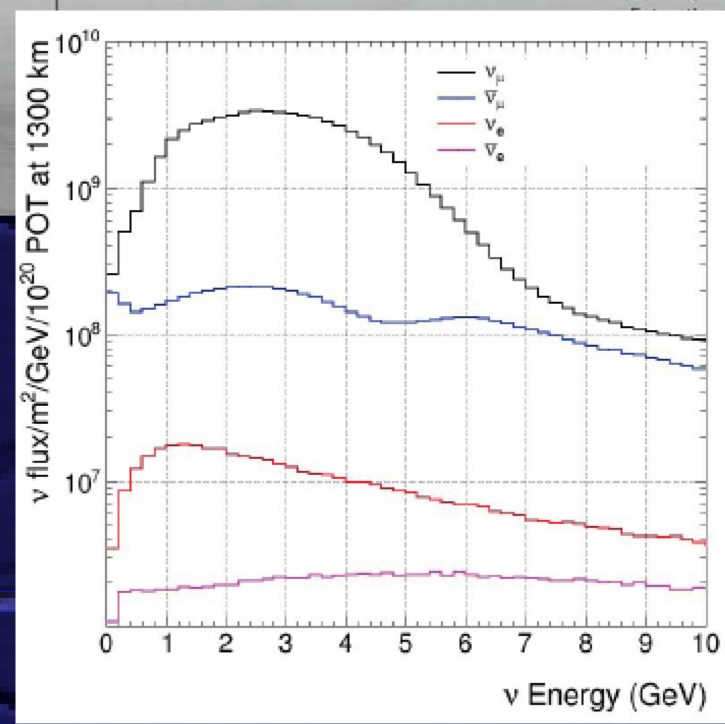


ND
- measure un-oscillated flux
- control systematic errors

FD
- measure oscillated flux

DUNE/LBNF Beam Line





- 60-120 GeV proton beam energy
  - 1.2 MW initial power (PIP II), upgradable to 2.4 MW
  - Critical contributions from CERN & UK
- 10^{21} POT per year

LBNF Cavern Configuration for the DUNE Far Detector: LArTPCs

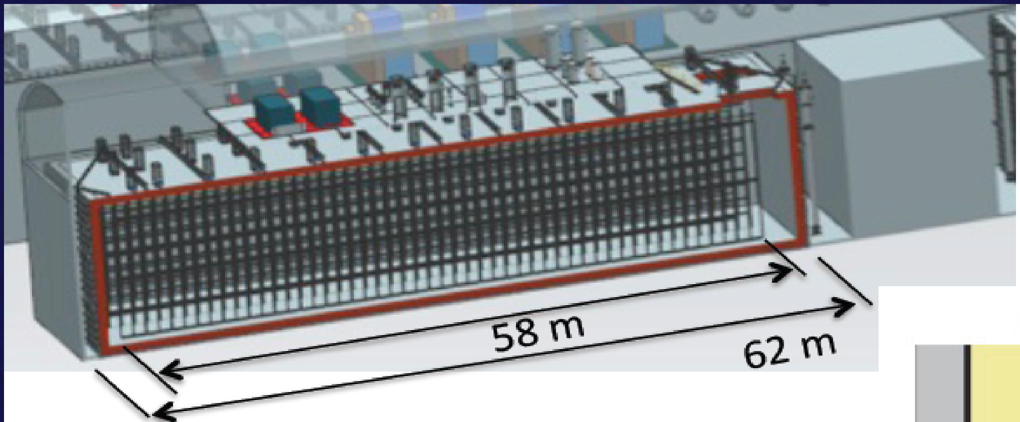
Each Cryostat holds 17.1kt LAr

Free standing steel supported membrane cryostat design
- CERN-FNAL design team

FD Site Ground Breaking Ceremony
Actual underground site, July 21, 2017

Central Utility Cavern holds Cold boxes,
LN2 dewars, booster compressors, LAr/GAr filters

10 kt Single-Phase Far Detector Reference Design



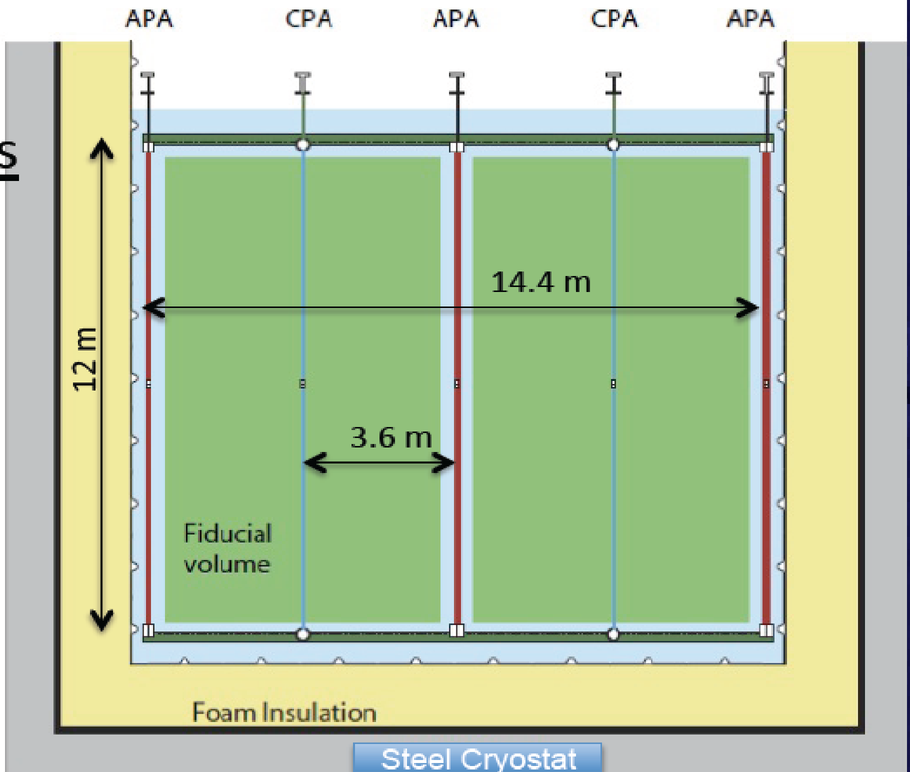
Liquid Argon Time projection chamber with both charge and optical readout.

First 10kt detector will be single phase

LAr Detector Module Characteristics

- 17.1/13.8/11.6 Total/Active/Fiducial mass
- 3 Anode Plane Assemblies (APA) wide (wire planes)
  - Cold electronics 384,000 channels
- Cathode planes (CPA) at 180kV
  - 3.6 m max drift length
- Photon detection for event interaction time determination for underground physics

The first 10 kt module will be a single-phase LArTPC



DUNE ND Current Concept Configuration (A robust system of complementary subsystems)

Scintillator based Spectrometer (SAND)

- 3DST+low den. tracker
- KLOE ECAL & magnet
- On-axis beam monitor
- **High stat on C target**

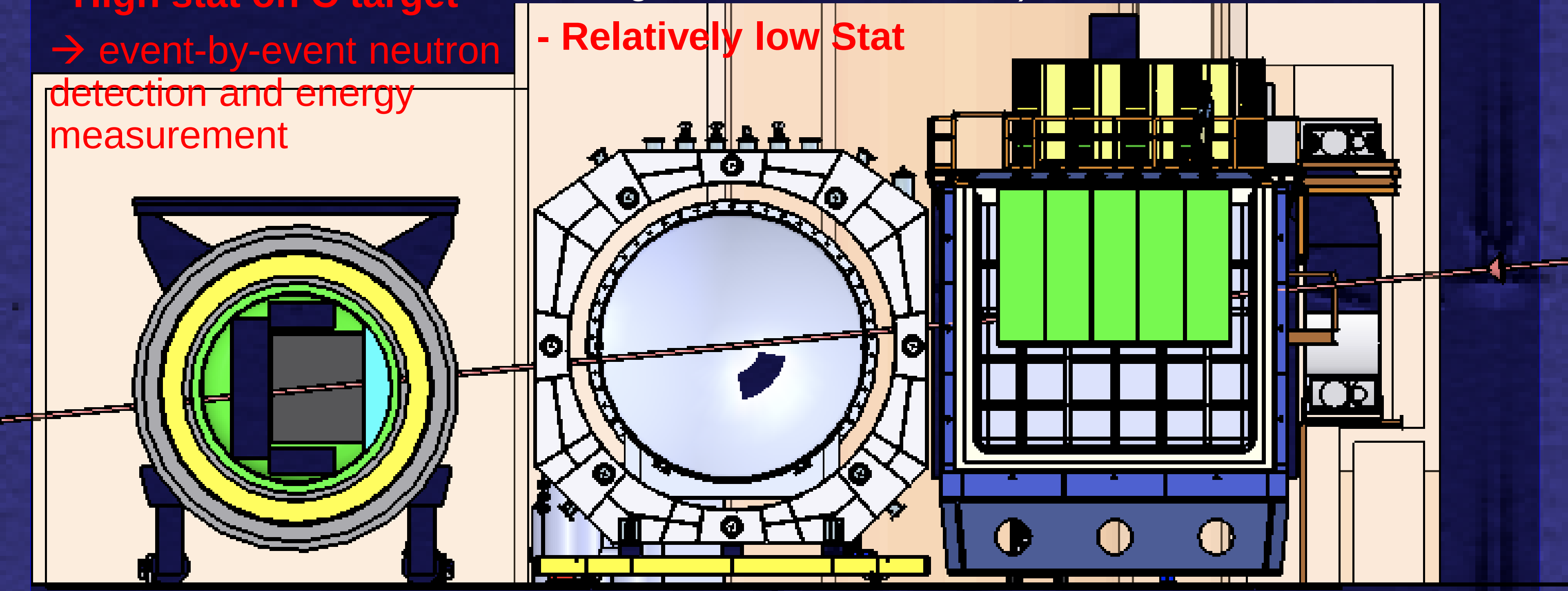
→ event-by-event neutron detection and energy measurement

Multi-Purpose Detector

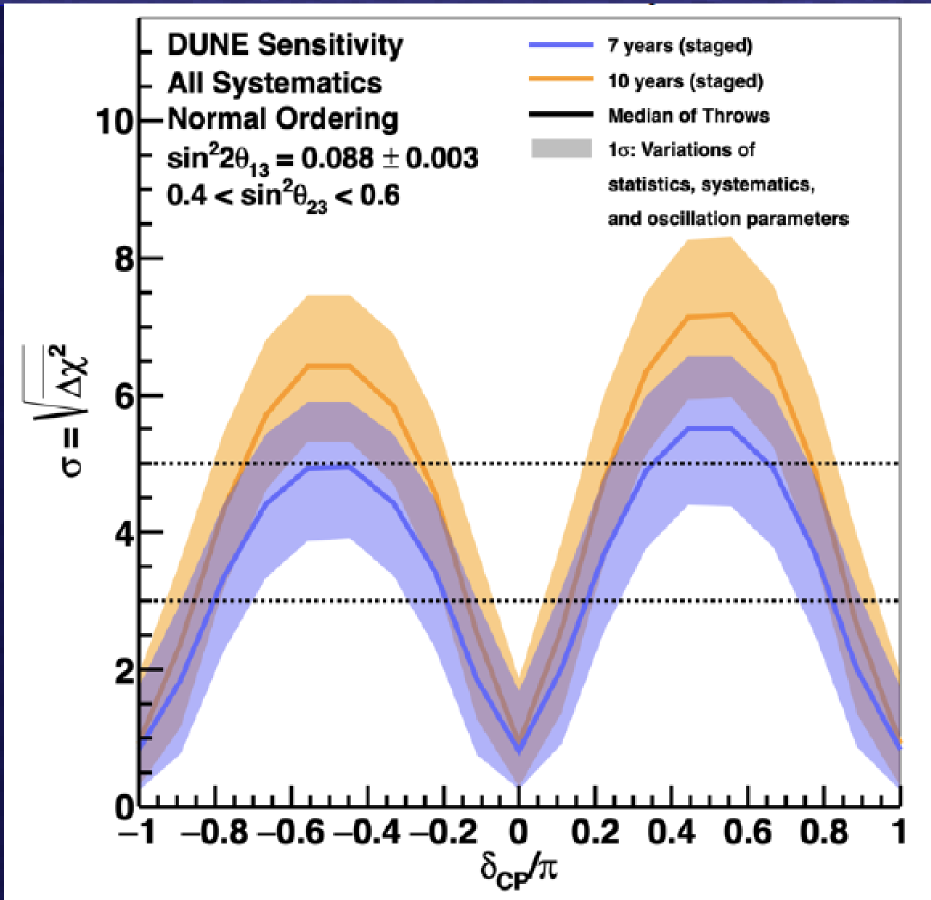
- HPgTPC (high res. & low E threshold on Ar target)
- ECAL (high performance)
- B-field (spectrometry of the exiting muons from LArTPC)
- **Relatively low Stat**

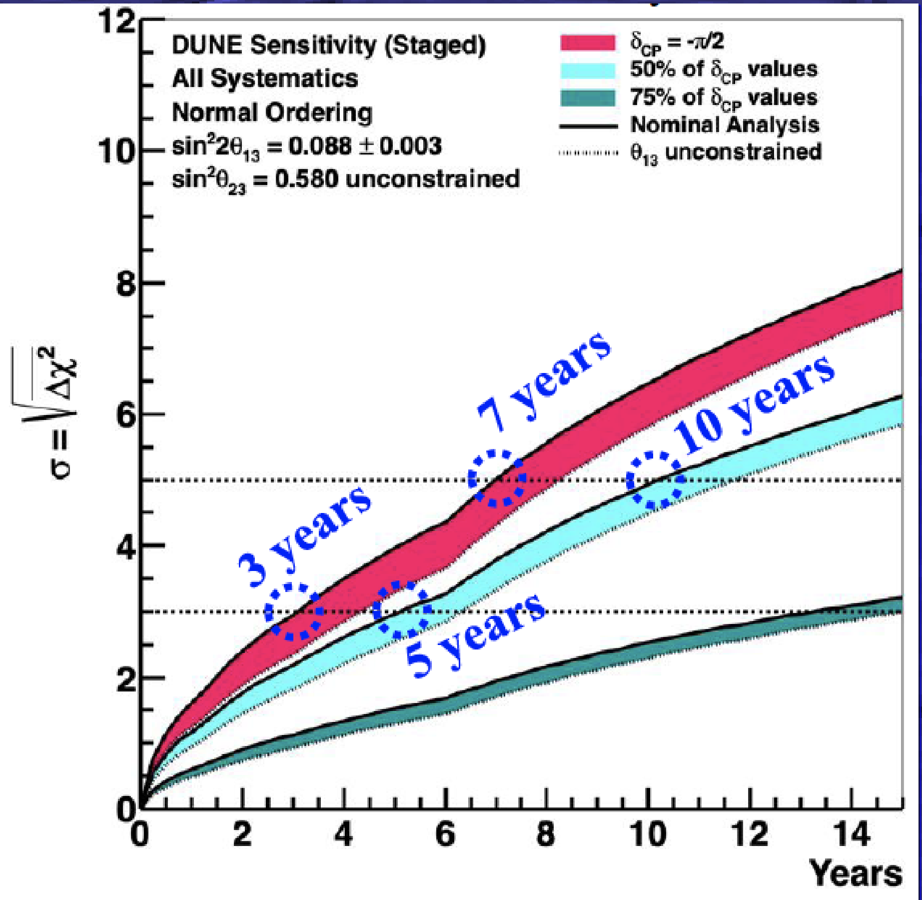
LArTPC as FD

- Modular design w/ pixel readout
- High Stat on Ar target
- No B-field



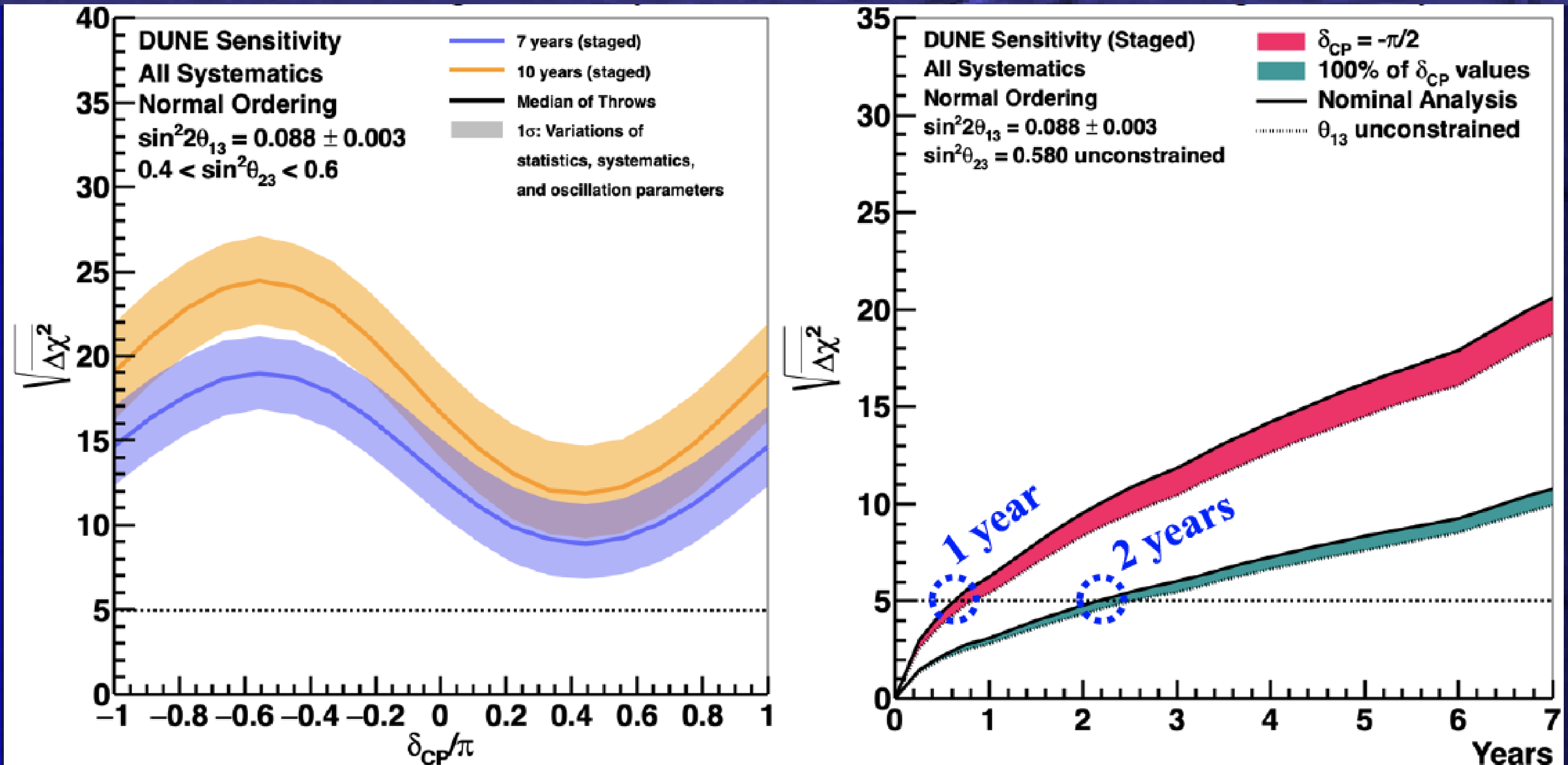
DUNE CPV Sensitivity





- 2019 Updated Sensitivities
- 5σ discovery of CP violation in 7 years of running, if $\delta_{CP} \sim -\pi/2$

DUNE Mass Hierarchy/Ordering Sensitivity



- DUNE will definitely determine the mass hierarchy
- For favorable CP phase this can be achieved within a few years

DUNE/LBNF Selected Timeline

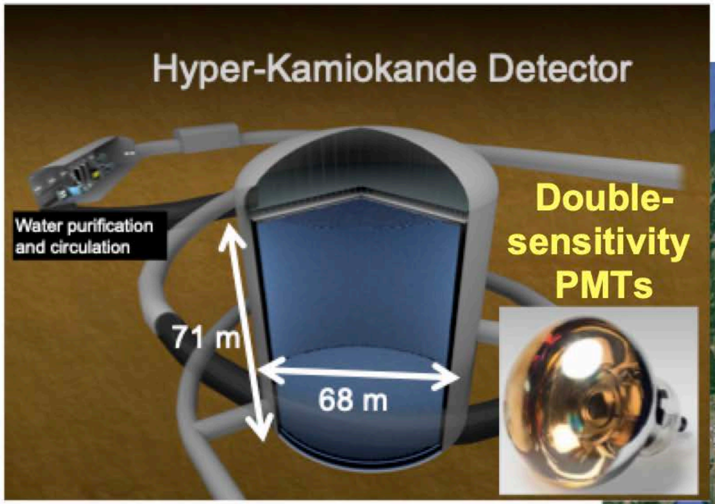
- End 2018: Successful completion of ProtoDUNE-SP
- July 2019: Completion of FD TDR (~2,000 pages, 5 volumes)
- Sep 2019: ProtoDUNE-DP First track
- Mid 2010: DOE CD2/3b Review of LBNF and DUNE US FD scope
  - ¬ Baselining of the US project → defines the final schedule
- End 2020: Near Detector TDR
- 2021/2022: Post-LS2 running of ProtoDUNE
- 2024: Start of FD module 1 installation
- 2025: Start of FD module 2 installation

DUNE Summary

- Fermilab has developed unprecedented **strong partnership** with CERN intertwining LHC & neutrinos
  - CERN is investing **outside of Europe** for the first time in 60 years
- Many international funding agencies informed and involved
  - Numerous agreements with countries/funding agencies and individual institutions around the world, including iCRADA w/ Chung-Ang University
- Project (DUNE/LBNF) enjoys **strong DOE, administration, and congressional support in U.S.**
- Strong international interest to participate in design and construction of LAr TPC far detectors, hybrid near detector, and MW-class neutrino beam
  - Significant progress on responsibility matrix
- The stunning success of ProtoDUNE-SP makes the future very bright
- Near Detector design is being finalized for CDR and TDR
- Pre-excavation construction at the FD site is fully underway
- Final design of the FD facility is complete

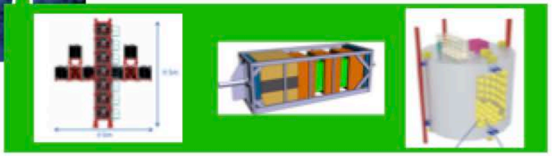
HYPER-KAMIOKANDE:

	Super-K	Hyper-K
Site (overburden)	Mozumi, 1,000m	Tochibora, 650m
Number of ID PMTs	11,129	40,000
Photo-coverage	40%	40% (x2 sensitivity)
Total / Fiducial Mass	50 / 22.5 kton	260 / 187 kton



Hyper-Kamiokande
(hosted by the University of Tokyo)

High power proton beams
J-PARC
(hosted by KEK)



1. Hyper-K detector to be built with **8.4 times larger fiducial mass** (190 kiloton) than Super-K and to be instrumented with **double-sensitivity PMTs**.
2. J-PARC neutrino beam to be **upgraded from 0.5 to 1.3 Mega Watt**
   - **x8.4** Natural Neutrino Rate and **x22** Accelerator Neutrino Rate
3. New and upgraded near detectors to control systematic errors

M. Shiozawa

Broad Science and Discovery potential

✓Complehensive ν oscillation study

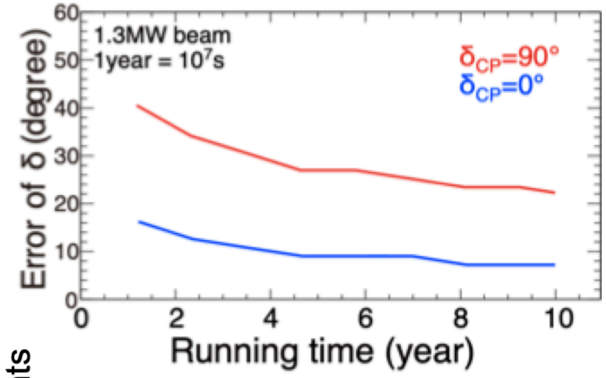
- ✓By accelerator, atmospheric, and solar ν
- ✓incl. CP violation, Mass hierarchy determination

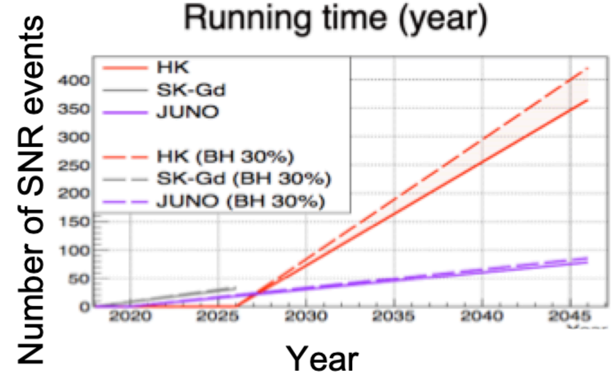
✓Neutrino Astronomy to explore

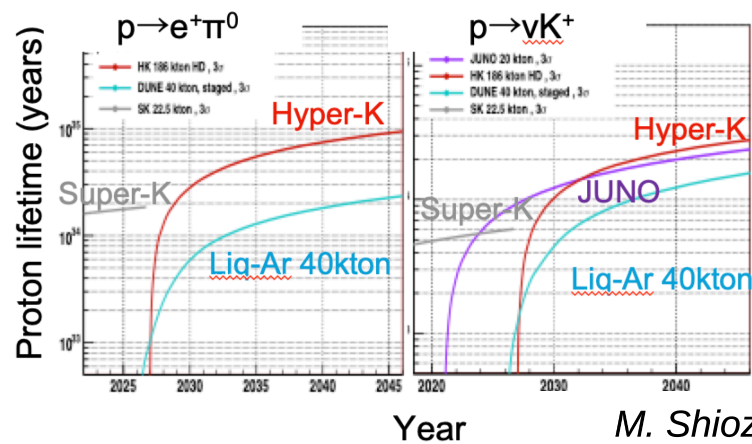
- Solar ν_e : ~2σ tension in Δm^2_{21} w/ reactor. Hep ν measurement.
- Supernova ν burst w/ reach to ~Mpc
  - Explosion mechanism: ν plays key role to achieve explosion
  - ~1° pointing accuracy → Alert for multi-messenger astronomy
- SN diffuse ν
  - History of start formation and heavy nucleus

✓Proton Decay discovery

- ✓Aim to extract unification scale, gauge group etc







M. Shiozawa

M. Shiozawa

OFFICIAL APPROVAL:

- The supplementary budget for FY2019 which includes the first-year construction budget of 3.5 billion yen was approved by the Japanese Diet.

(The University of Tokyo) http://www.icrr.u-tokyo.ac.jp/en/news/8503/
(KEK) https://www.kek.jp/en/newsroom/2020/02/12/0930/
(J-PARC) http://www.j-parc.jp/c/en/topics/2020/02/12000416.html

- The Hyper-K project has officially started. The operations will begin in 2027 after ~7 years construction.

- We are open to participation of new countries/institutes to the collaboration:

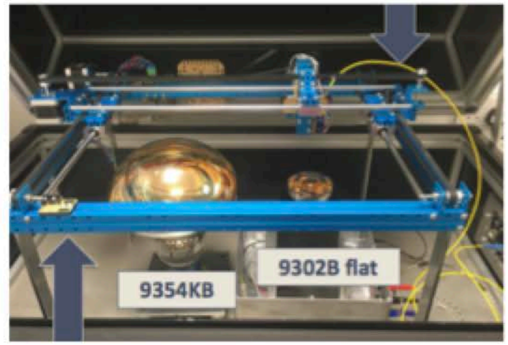
Proto-collaboratipn: 340 members from 18 countries (as of 2020/2)

International Cooperation

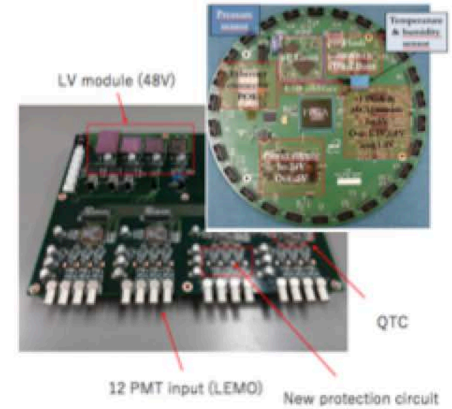
M. Shiozawa

Inner-Detector

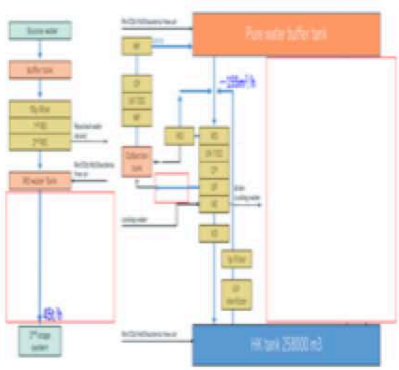
Outer-Detector



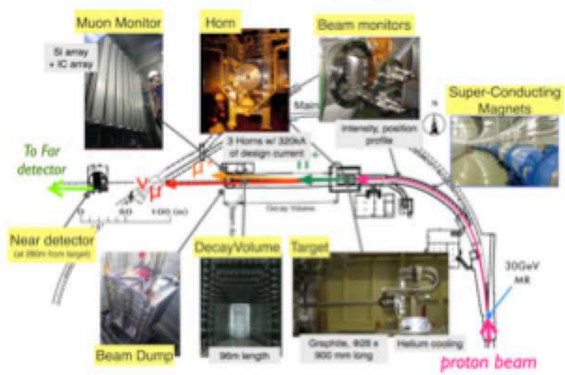
Elec./DAQ



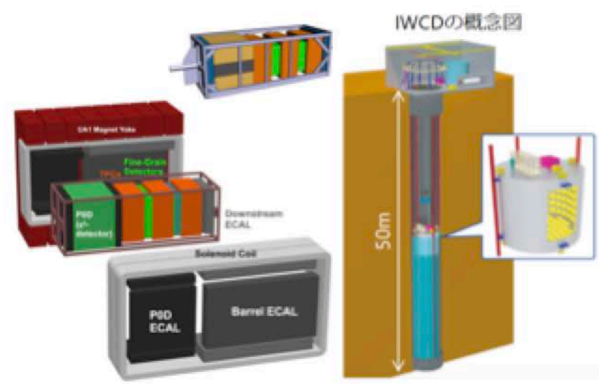
Water system



beam-line upgrade



Near/Intermediate Det.



Many area where international contributions are needed.

CONSTRUCTION 2020:

M. Shiozawa

- Geological survey for detailed cavern design
  - 1 year for borehole coring, in-situ rock stress, in-situ rock property meas. etc.
- Access tunnel designing
- Entrance yard const.
  - Yard leveling, power distribution, water supply, waste water treatment facility
- PMT production start
  - 6 year production time is anticipated.

Conclusions

- Two great decades for neutrinos w/ 4 Nobel Prizes & 5 Breakthrough Prizes
  - Reflection of the exciting and remarkable progresses made in the last two decades
- Physics goals for the post non-zero θ_{13} / ν_e appearance era are now clearly defined for the world neutrino oscillation community
  - Determination of δ_{CP}, mass hierarchy and θ_{23} (=45, <45, >45?)
    - **We may have an initial hint that $\delta_{CP} = -\pi/2$**
  - T2K and NOvA will lead the world in determining these parameters at least for the next several years
    - NOvA-T2K Joint Fit
    - SuperK-T2K Joint Fit
  - Next generation experiments such as JUNO, DUNE and HyperK are poised to follow **within this decade** in order to ensure the 5σ discoveries these parameters and further precision measurements of other neutrino oscillation parameters

Conclusions

- Neutrino oscillation (i.e. the existence of massive neutrino states) is the only phenomena beyond the Standard Model observed in laboratory venue today
- Measurement of CPV in the lepton sector will provide critical experimental input to our understanding of the matter–antimatter asymmetry in the universe
- Nature kindly gave us the non-zero neutrino mixing angles and ν_e **appearance** in order for us to be able to probe CP violation


CPV (Lepton)
MH
Mount Everest (8848 m)
Nuptse (7861 m)
JUNO
T2K pass Camp 2
Global Race to Reach the Summit!
Khumbu Gletscher
NOvA @ Camp 1
Base Camp
DUNE, HyperK
?
PINGU

The End