Neutrino oscillations and future prospects

(Supposed to be WG1 summary)

Son Cao
(KEK/J-PARC)

Neutrino Group, IFIRSE

3 neutrinos and beyond,
ICISE, Quy Nhon, VN, August 4-10, 2019

What’s Working Group 1 supposed to do?

Present status of neutrino oscillations and future prospects

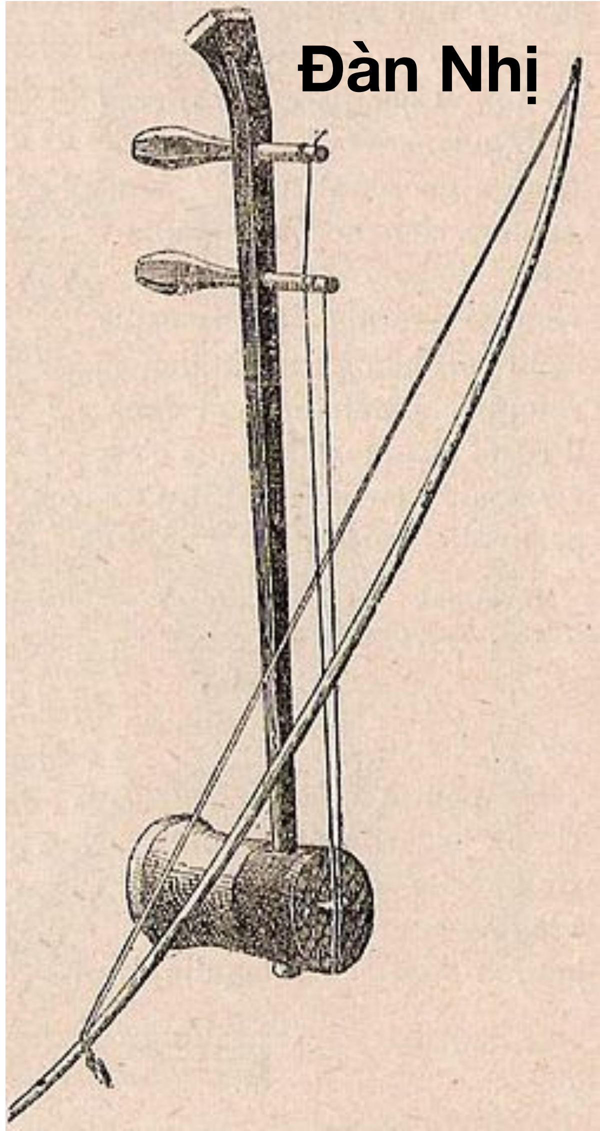
—including theoretical and experimental issues with cross-sections

(To cover a parallel section, not the plenary)

1,2,3 strings…

Đàn Bầu

1 string



2 string

Đàn Tam

3 string

Three? Why Three?
(introduction to the sterile neutrino session)
Boris Kayser (Fermilab, Batavia)

…or more strings

/string

2019 Physics scene, and how many new particles are needed?
Andre de Gouvea (Northwestern University, Evanston)

Practical tests on the PMNS paradigm
Osamu Yasuda (Tokyo Metropolitan University)

Brief history of neutrino physics

Adapted "The Growing Excitement of Neutrino Physics" by APS

- ★ 1930: On-paper appearance as "desperate" remedy by W. Pauli
- ★ 1956: Anti-ν_e first experimentally discovered by Reines & Cowan
- ★ 1962: ν_μ existence confirmed by Lederman *et al*
- ★ 1986: Existence of ν_τ was established (see Gary Feldman's talk)
- ★ 1998: Atmospheric ν oscillations discovered by Super-K
- ★ ~~2000: ν_τ first evidence reported by DONUT experiment~~
- ★ 2001: Solar ν oscillations detected by SNO (KamLAND 2002)
- ★ 2011: $\nu_\mu \rightarrow \nu_\tau$ transitions observed by OPERA
- ★ 2011-13: $\nu_\mu \rightarrow \nu_e$ observed by T2K and *anti*-$\nu_e \nrightarrow$ *anti*-ν_e by Daya Bay
- ★ 2015: Nobel prize for ν oscillations, Breakthrough prize (2016)
- ★ 2018: T2K hints on leptonic CP violation

T2K hints on leptonic CP violation

IceCUBE observes extragalactic ν

Nobel prize & Breakthrough prize for ν oscillation

T2K observe ν_e appeared from ν_μ

Daya Bay observe anti-ν_e disappeared

K2K confirm atmospheric ν oscillation

KamLAND confirms solar ν oscillation

Nobel prize for ν astrophysics

SNO observe solar ν oscillation to active flavor

Super-K confirms solar ν deficit and images the sun

Super-K observes ν oscillation

Nobel Prize for ν_μ discovery

Kamioka-II/ IMB observe supernova ν

SAGE/Gallex observe the solar ν deficit

LEP shows 3 active flavors

Kamioka-II confirms solar deficit

Pauli predicts the Neutrino — 1930

Fermi's theory of weak interactions

~25 years

Reines & Cowan discover (anti)neutrino — 1956

muon neutrinos discovery — 1962

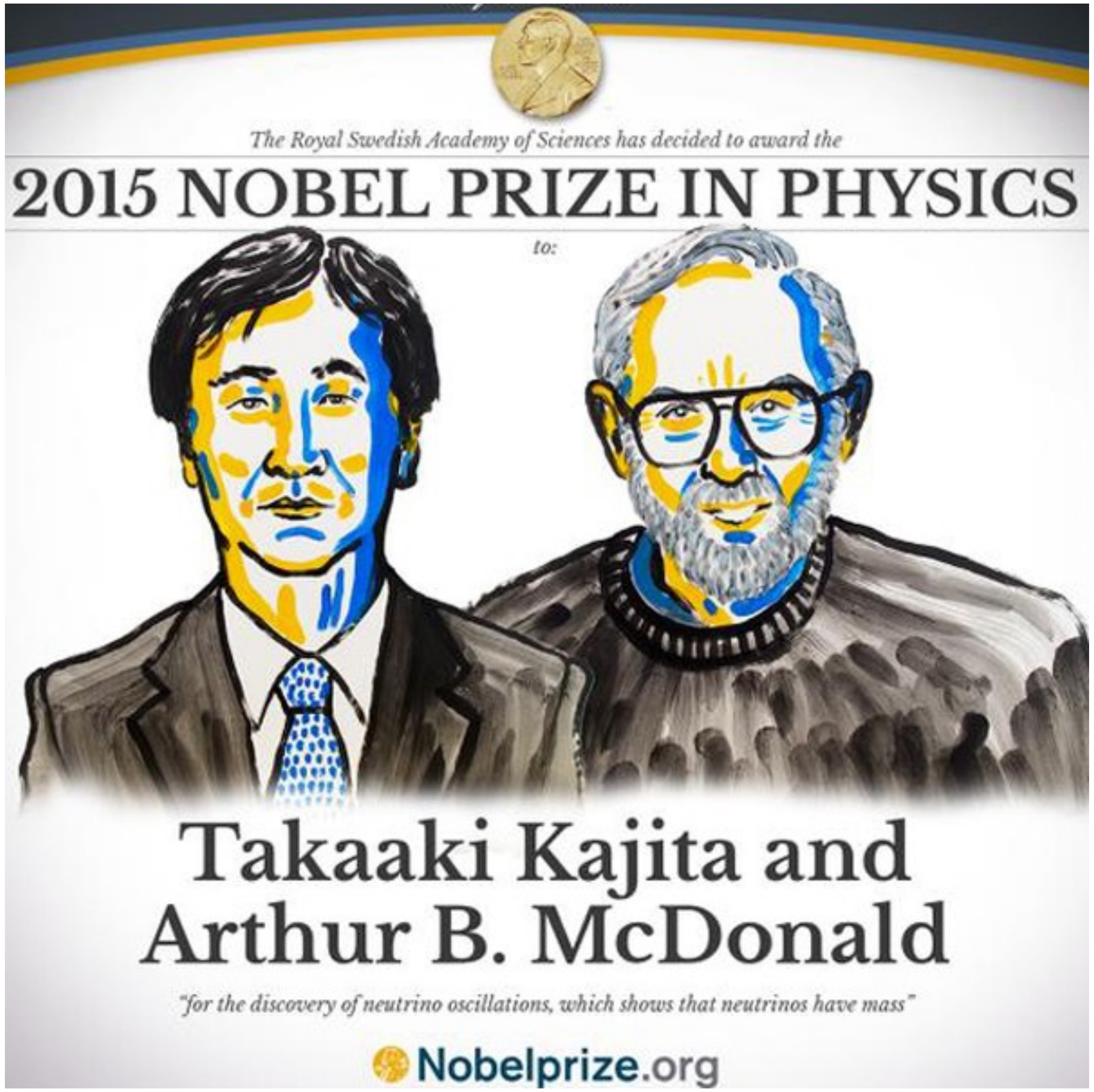
Solar neutrino anomaly — 1964

1980

1998

2018

Neutrino oscillations: A game-changer



"for the discovery of neutrino oscillations, which shows that neutrinos have mass"

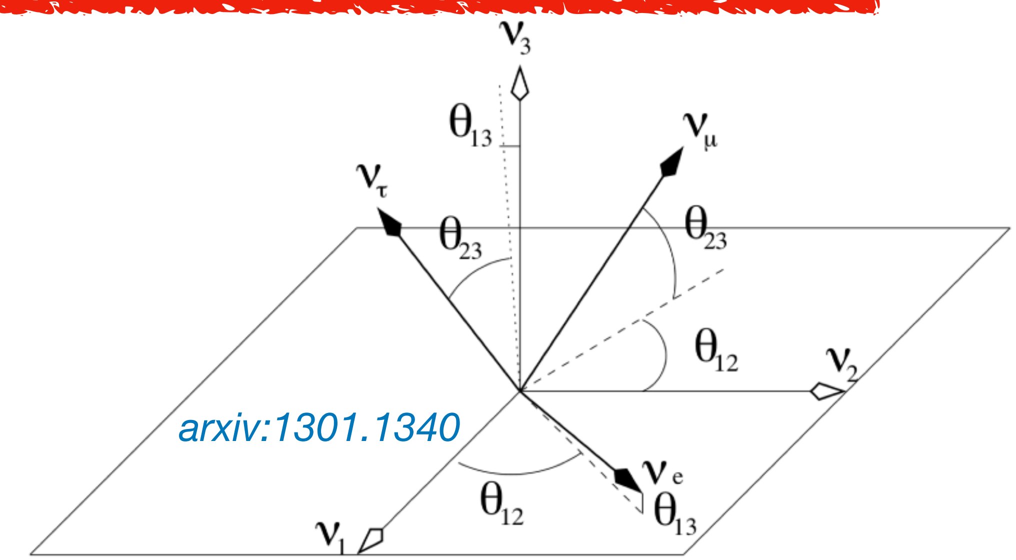
PMNS leptonic mixing matrix: Standard 3-flavor

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

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix}1 & 0 & 0\\ 0 & c_{23} & s_{23}\\ 0 & -s_{23} & c_{23}\end{pmatrix}\begin{pmatrix}c_{13} & 0 & s_{13}e^{-i\delta_{\rm CP}}\\ 0 & 1 & 0\\ -s_{13}e^{i\delta_{\rm CP}} & 0 & c_{13}\end{pmatrix}\begin{pmatrix}c_{12} & s_{12} & 0\\ -s_{12} & c_{12} & 0\\ 0 & 0 & 1\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}$$

PMNS matrix

- In 3-flavor paradigm, $U_{\rm PMNS}$ is 3x3 unitary matrix and parameterized with 3 mixing angles (θ_{12}, θ_{13}, θ_{23}) and one irreducible Dirac CP-violation phase ($\delta_{\rm CP}$)
- If neutrino is Majorana particle, i.e neutrino (mass eigenstate) and anti-neutrino are identical, there are two additional CP-violation phase, which play no role in neutrino oscillations
- Three mass eigenvalues are also fundamental parameters. Neutrino oscillation measurements provide only the mass^2 spectrum but not the absolute values of mass



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

Main goal is to measure these oscillation parameters and verify if $U_{\rm PMNS}$ is 3x3 unitary or not

What “global fit” tell us?

Normal mass hierarchy is favored at 3σ (2σ) with (without) Super-K atmospheric neutrino sample

(Normal hierarchy assumed)

$$\Delta m^2_{21} = 7.39^{+0.21}_{-0.20} \times 10^{-5} eV^2$$

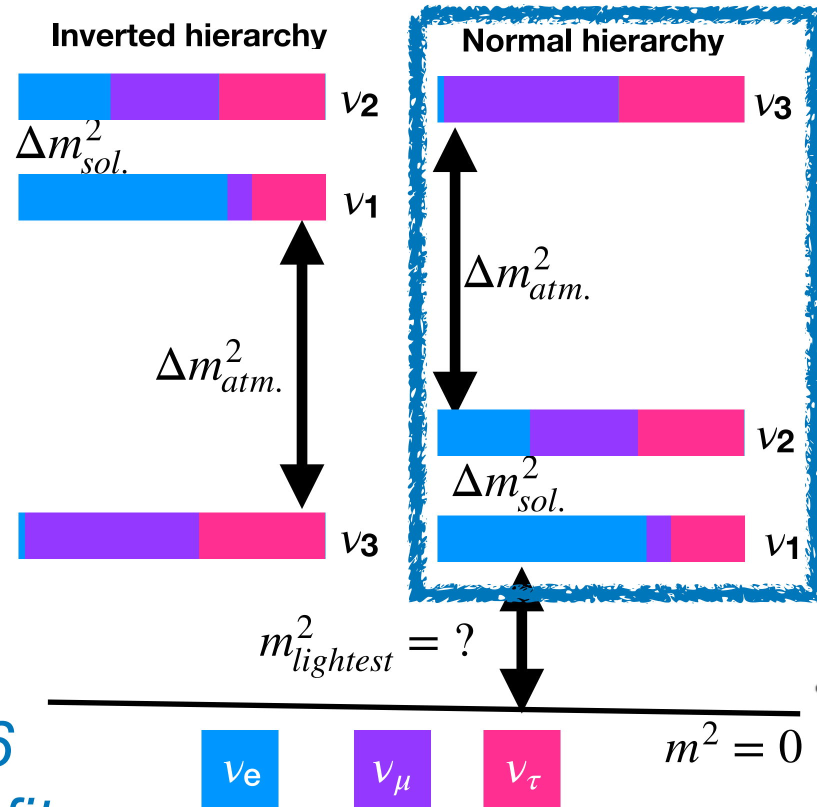
$$\Delta m^2_{31} = 2.525^{+0.033}_{-0.032} \times 10^{-3} eV^2$$

$$\theta_{12} = 33.82^{+0.78}_{-0.76}$$

$$\theta_{23} = 49.6^{+1.0}_{-1.2}$$

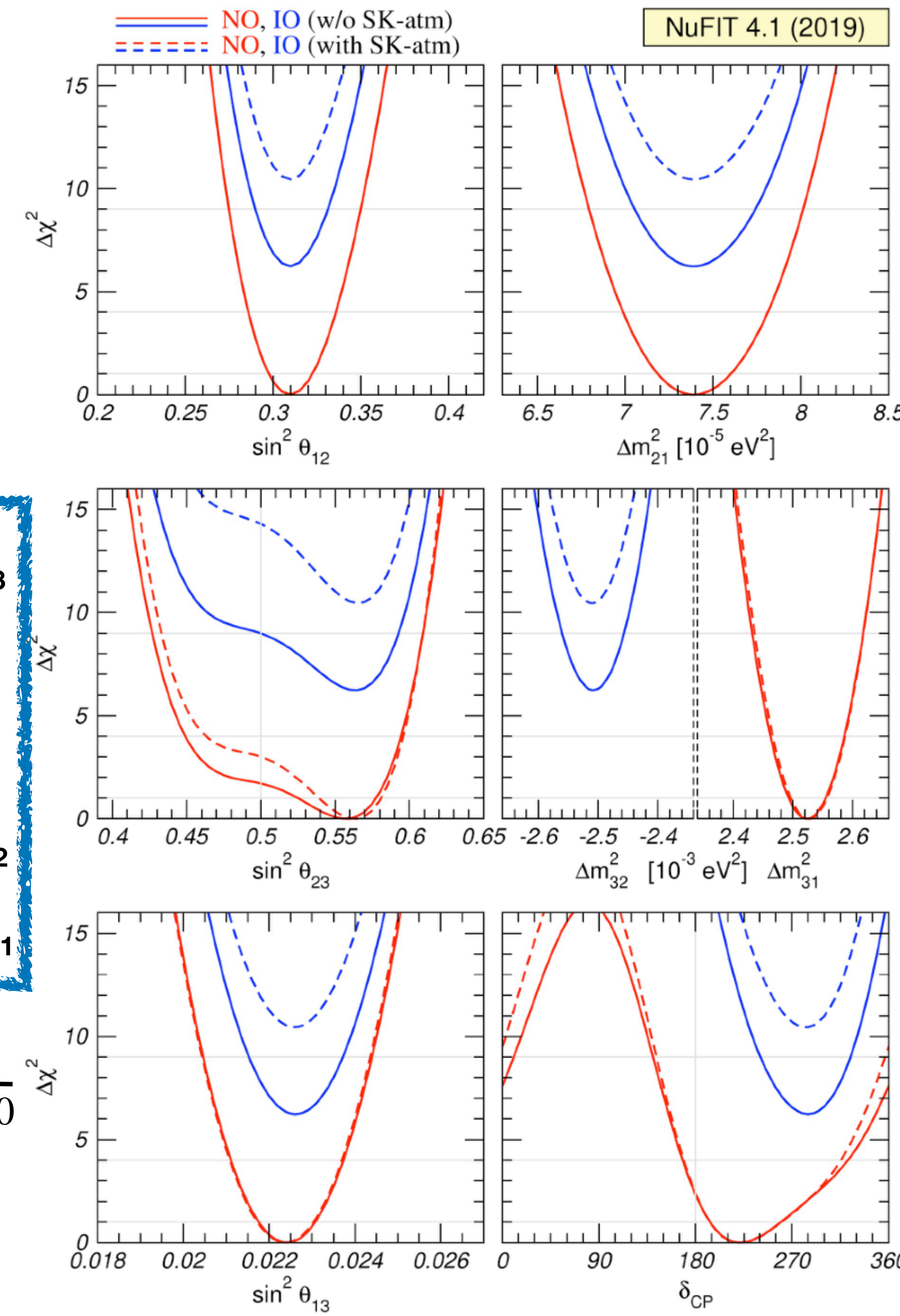
$$\theta_{13} = 8.61^{+0.13}_{-0.13}$$

$$\delta_{CP} = 215^{+40}_{-29}$$



JHEP 01 (2019) 106
Global neutrino exp. fit

MINOS, T2K, NOvA; Daya Bay, RENO, Double Chooz, KamLAND; SNO, Borexino; IceCube, Super-K



Wait! Is "global fit" reliable?

Bari: Capozzi, Lisi, Marrone, Palazzo, PPNP 102 (2018) 48;
Lisi @ NuInt 18, 15 October

NuFit: Esteban, Gonzalez-Garcia, Hernandez-Cabezudo, Maltoni, Martinez-Soler, Schwetz, `http://www.nu-fit.org`;
NuFit 4.0: Gonzalez-Garcia @ NuTown 2018, 23 October

Valencia: de Salas, Forero, Ternes, Tortola, Valle, PLB 782 (2018) 633;
`http://globalfit.astroparticles.es`;
Tortola @ Neutrino 2018, 5 June

(on Mass hierarchy)

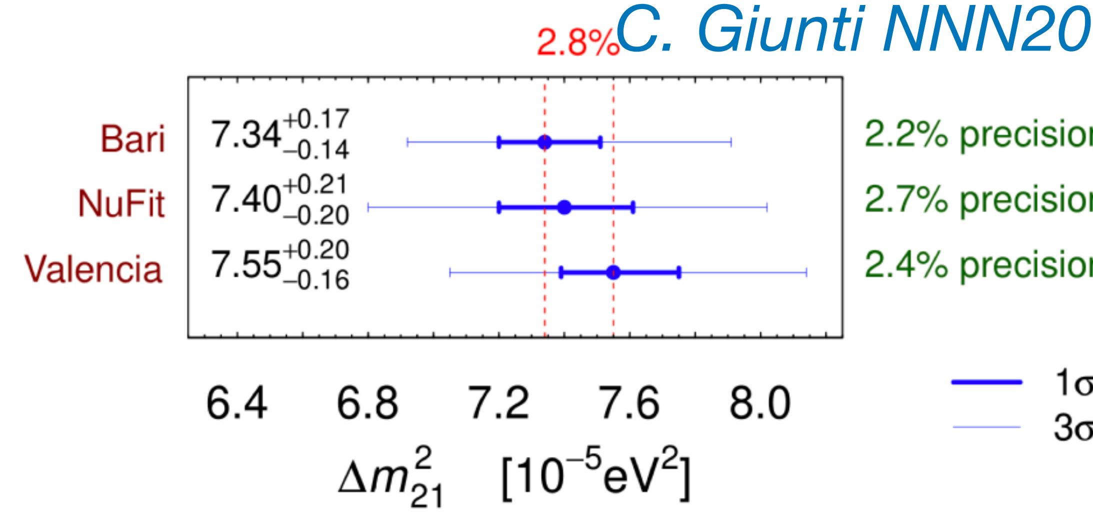
$$\text{Bari:} \quad \chi^2_{\text{IO}} - \chi^2_{\text{NO}} = 9.5 \quad (\approx 3.1\sigma)$$
$$\text{NuFit:} \quad \chi^2_{\text{IO}} - \chi^2_{\text{NO}} = 9.1 \quad (\approx 3.0\sigma)$$
$$\text{Valencia:} \quad \chi^2_{\text{IO}} - \chi^2_{\text{NO}} = 11.7 \quad (\approx 3.4\sigma)$$

Jiajie Ling on JUNO prospects

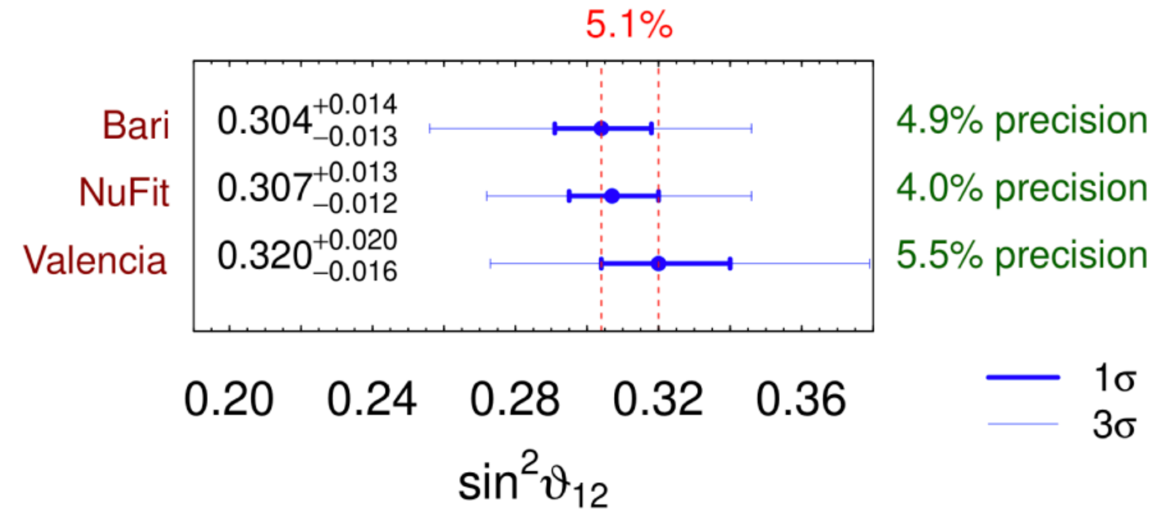
JUNO is under construction and will start data taking ~2021.

	Statistics	+BG, +1% b2b +1% EScale , +1% EnonL
$\sin^2\theta_{12}$	0.54%	**0.67%**
Δm^2_{21}	0.24%	**0.59%**
Δm^2_{32}	0.27%	**0.44%**

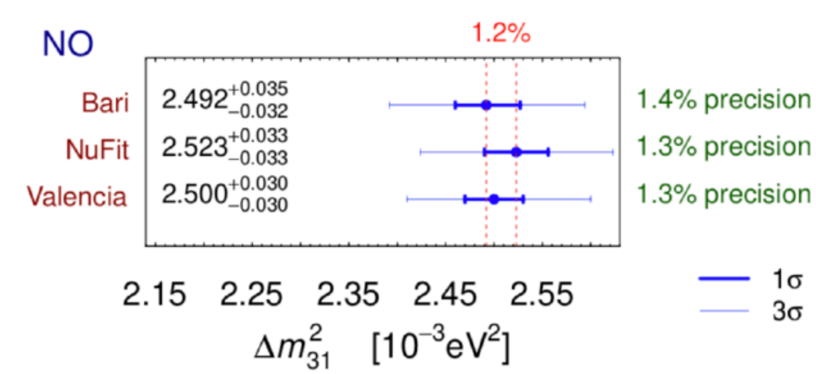
C. Giunti NNN2018



Nominal Precision + 2.8% Systematic Uncertainty !



Nominal Precision + 5.1% Systematic Uncertainty !



Nominal Precision + 1.2% Systematic Uncertainty !

Comment on “global fit”

- It’s nice to see a big picture with data from many experiments since each is sensitive to specific set of parameters
- However, it’s very challenging to reproduce experiment results, particularly when start to be dominated by systematics and the experiment doesn’t describe detail/ release systematic covariance matrices (can be more than 100 parameters for flux, cross section and detector systematics)

“Near detector” observation*

$$\boxed{N^{\nu_\alpha}(E_\nu^{reco.}, \vec{s}\,) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\alpha}_{int.}(E_\nu^{true}, \vec{s}\,) \times M_{det.} \times \epsilon^{\nu_\alpha}_{det.}(E_\nu^{true}, \vec{s}\,) \times M(E_\nu^{true.}, E_\nu^{reco.})}$$

$\vec{s}$ limited phase space of final state particles detected by detector

“Far detector” observation

$$\boxed{N^{\nu_\beta}(E_\nu^{reco.}, \vec{s}\,) = \Phi^{\nu_\alpha}_{flux}(E_\nu^{true}) \times \sigma^{\nu_\beta}_{int.}(E_\nu^{true}, \vec{s}\,) \times M_{det.} \times \epsilon^{\nu_\beta}_{det.}(E_\nu^{true}, \vec{s}\,) \times M(E_\nu^{true.}, E_\nu^{reco.})} \times \boxed{P(\nu_\alpha \rightarrow \nu_\beta)}$$

ν_α flux wo/ oscillation

Neutrino-nucleus cross sections

Number of target nuclei

Detection efficiency

Detection response

Oscillation prob.

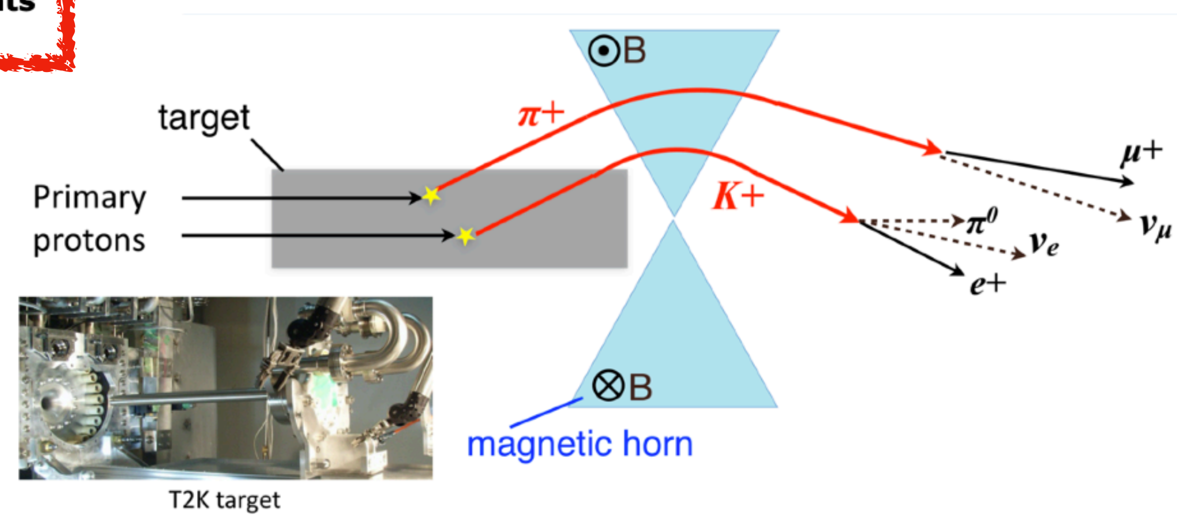
Need precise measurement for every elements

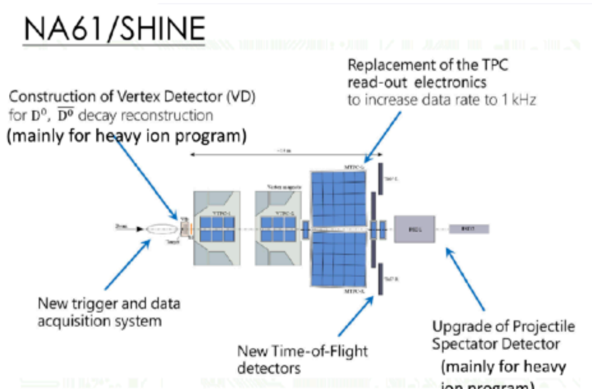
On flux understanding: Precise hadron prod.

Precise Determination of Neutrino Flux with Hadron Production Measurements
Yoshikazu Nagai (University of Colorado, Boulder)

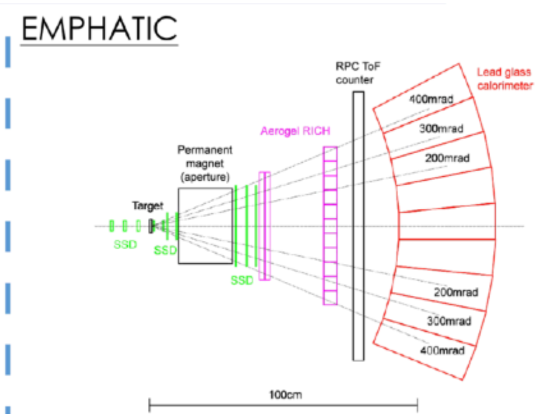
The ENUBET Project
Andrea Longhin (Padova University and INFN)

NUSTORM
Alain Blondel (Université de Genève)

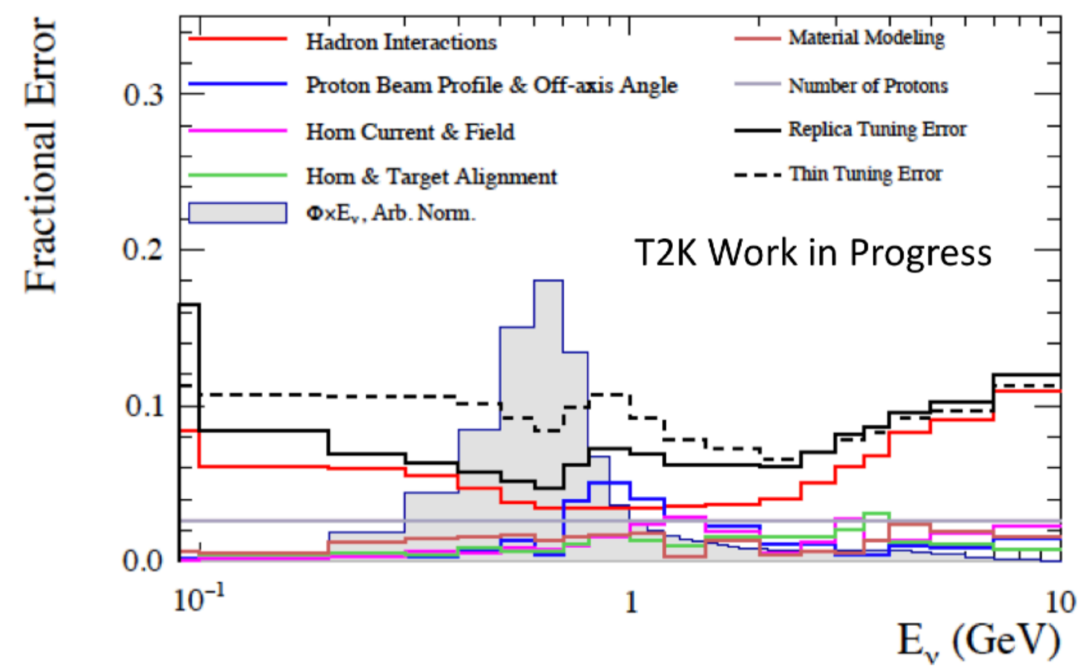




- Facility upgrades in progress
  - DAQ upgrade: ~1kHz TPC readout
  - new ToF walls with mRPC
- Various ideas under consideration
  - Construction of low momentum beamline
  - New target tracking detector



- Facility upgrades under consideration
  - Beam particle ID below 15 GeV/c
  - Large acceptance
  - Momentum measurement with magnet



- Thin target measurements improved T2K flux uncertainty down to 10%
- Replica target measurements will improve uncertainty down to ~5%
  (Replica tuning in figure only considers pions.
  Result will further improve with kaons and protons taken into account !!)

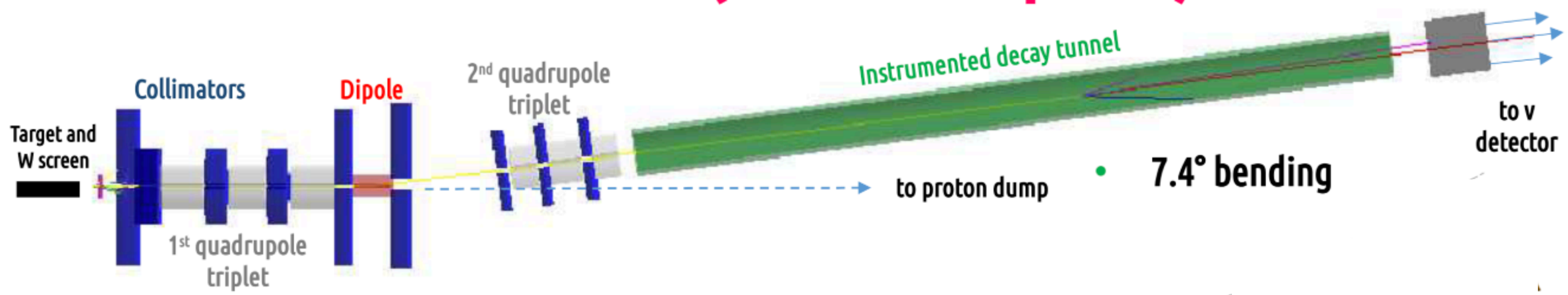
On flux understanding: A novel approach

Precise Determination of Neutrino Flux with Hadron Pro
Yoshikazu Nagai (University of Colorado, Boulder)

The ENUBET Project
Andrea Longhin (Padova University and INFN)

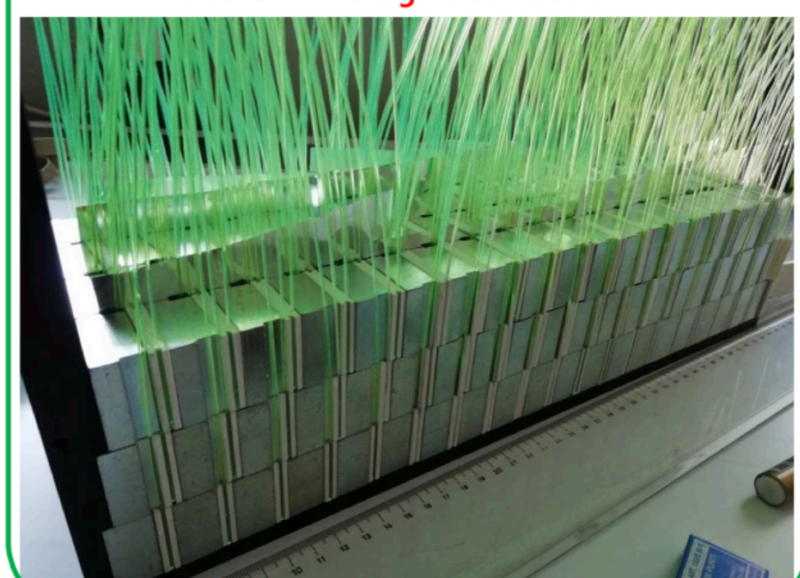
NUSTORM
Alain Blondel (Université de Genève)

The ENUBET beamline (baseline option)



aiming for a 1% precision on the ν_e flux

Sampling calorimeter with lateral WLS light collection



- Monitor (~ inclusively) the **decays** in which ν are produced **event-by-event**
- "By-pass" **hadro-production, PoT, beam-line efficiency** uncertainties

- **Fully instrumented decay region**

  $K^+ \rightarrow e^+ \nu_e \pi^0 \rightarrow$ large angle e^+

- **ν_e flux prediction = e^+ counting**

Removes the **leading source of uncertainty in ν cross section measurements**

To get the correct spectra and avoid swamping the instrumentation → needs a **collimated momentum selected hadron beam** → only decay products in the tagger
→ Correlations with interaction radius allows an **a priori knowledge of the ν spectra**

Radiation-harness is important

On flux understanding: Storm is coming?

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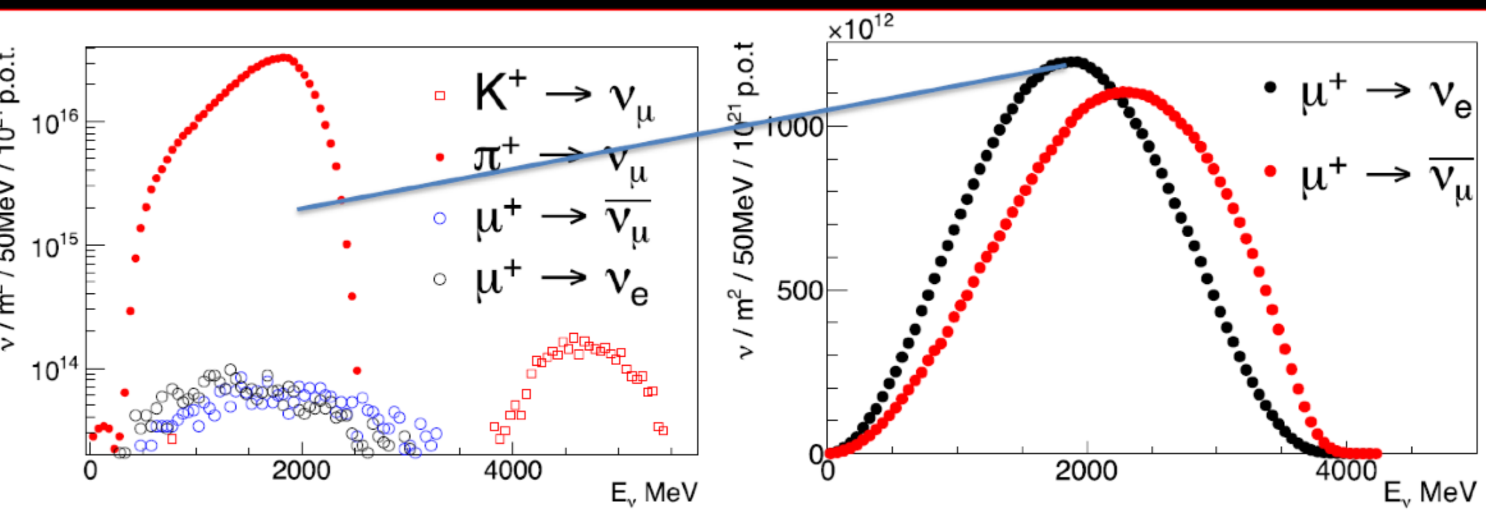
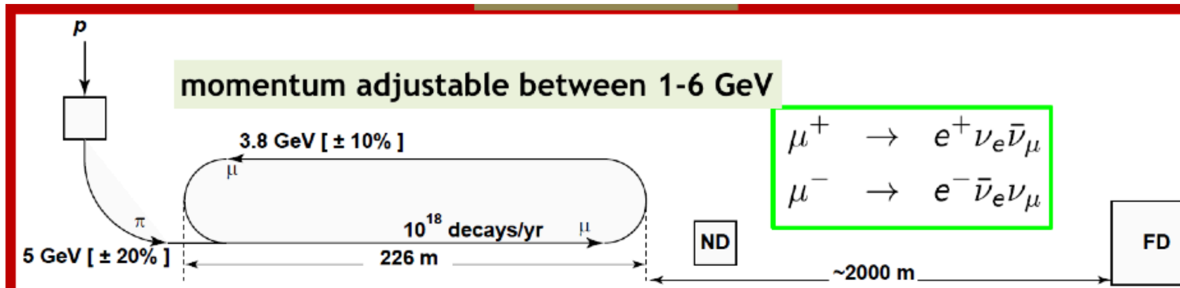
10.1146/annurev-nucl-102014-021930

Neutrino flux



- ν_μ flash:
  - Pion: 6.3×10^{16} m^{-2} at 50m
  - Kaon: 3.8×10^{14} m^{-2} at 50m
    - Well separated from pion neutrinos
- ν_e and ν_μ from muon decay:
  - ~10 times as many ν_e as, e.g. J-PARC beam
  - Flavour composition, energy spectrum
    - Use for energy calibration



-- first flash of muon (anti) neutrinos from the decay of injected pions.

-- then muons from pion decay are stored in the ring.

-- cross-sections to be measured in near detector similar to HyperK or DUNE ND
(water, scintillator and Liq. Argon targets -- also probably iron)
→ preferably magnetized for energy reconstruction?

-- require precise instrumentation for number of stored muons and polarization

-- storage time at 6 GeV is 5x144μs (fast extraction of short spill required)

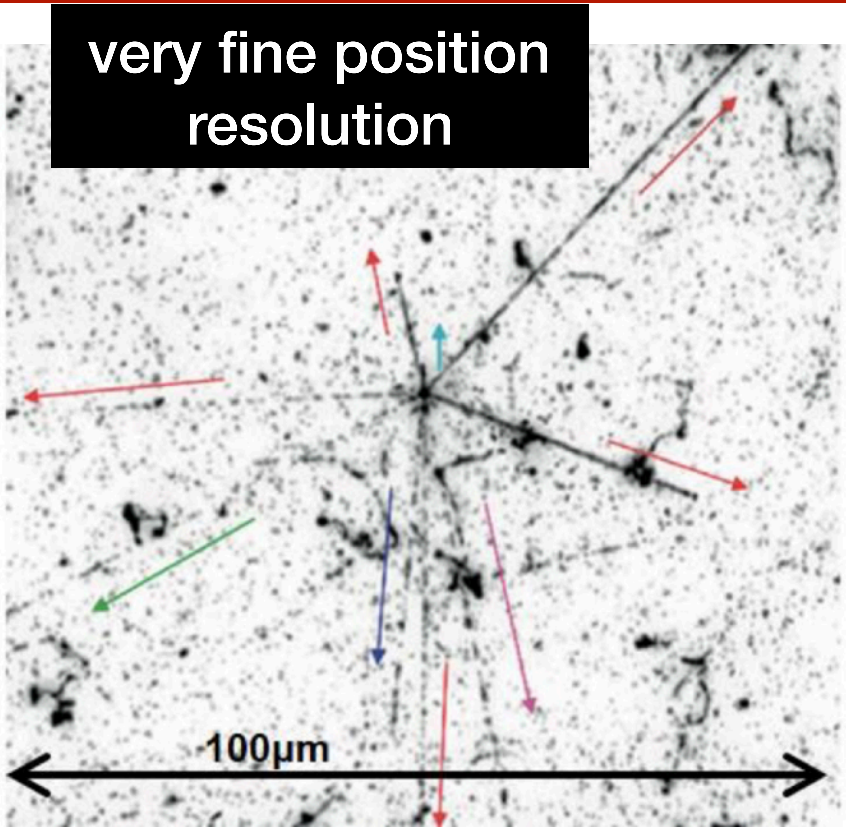
2) a study should be set-up to evaluate the possible implementation, performance and impact of a percent-level electron and muon neutrino cross-section measurement facility
(based one.g. ENUBET or NuSTORM) with conclusion in a few years;

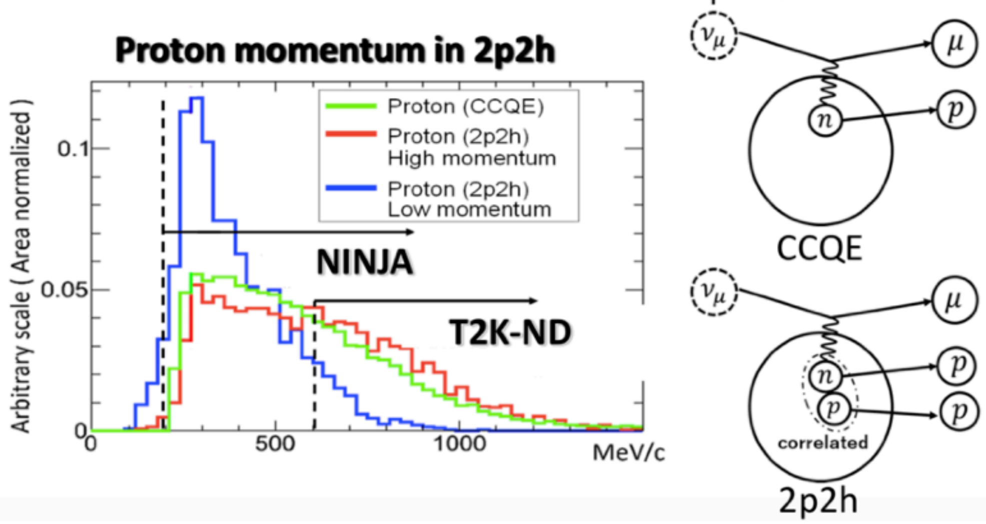
On neutrino-nucleus interaction

Cross section measurement with NINJA: Status and Prospects
Yosuke Suzuki (Nagoya University)

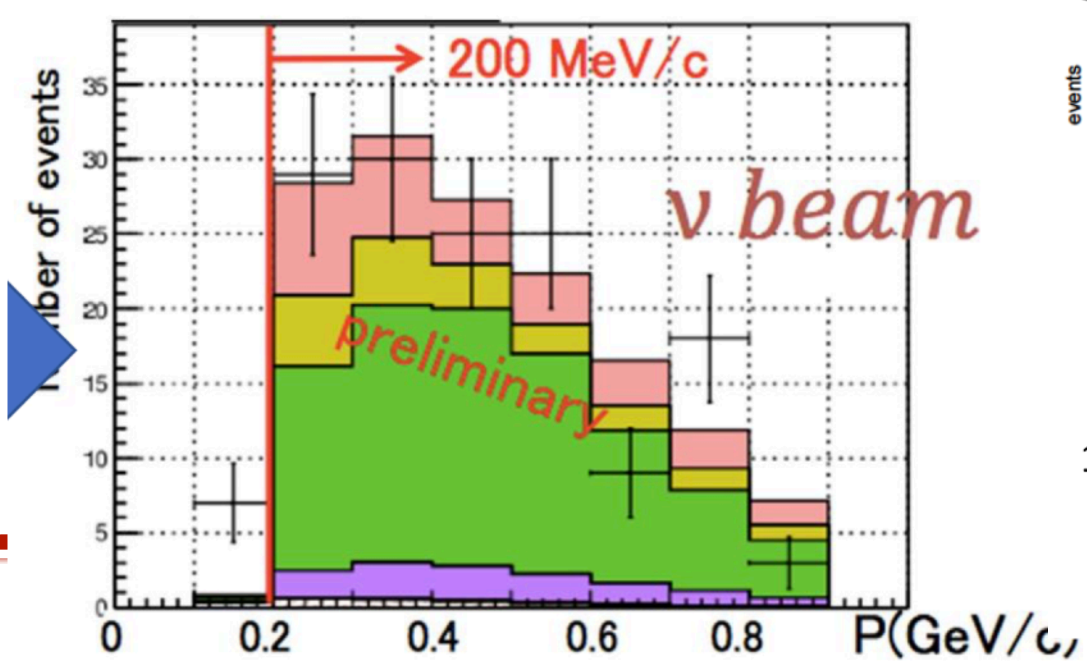
Recent results and prospects of WAGASCI-BabyMIND
Son Cao (KEK, Tsukuba)

1. Confirmation and cross-section measurement of 2p2h int.
2. Exclusive measurement of ν_μ,ν_e cross-sections



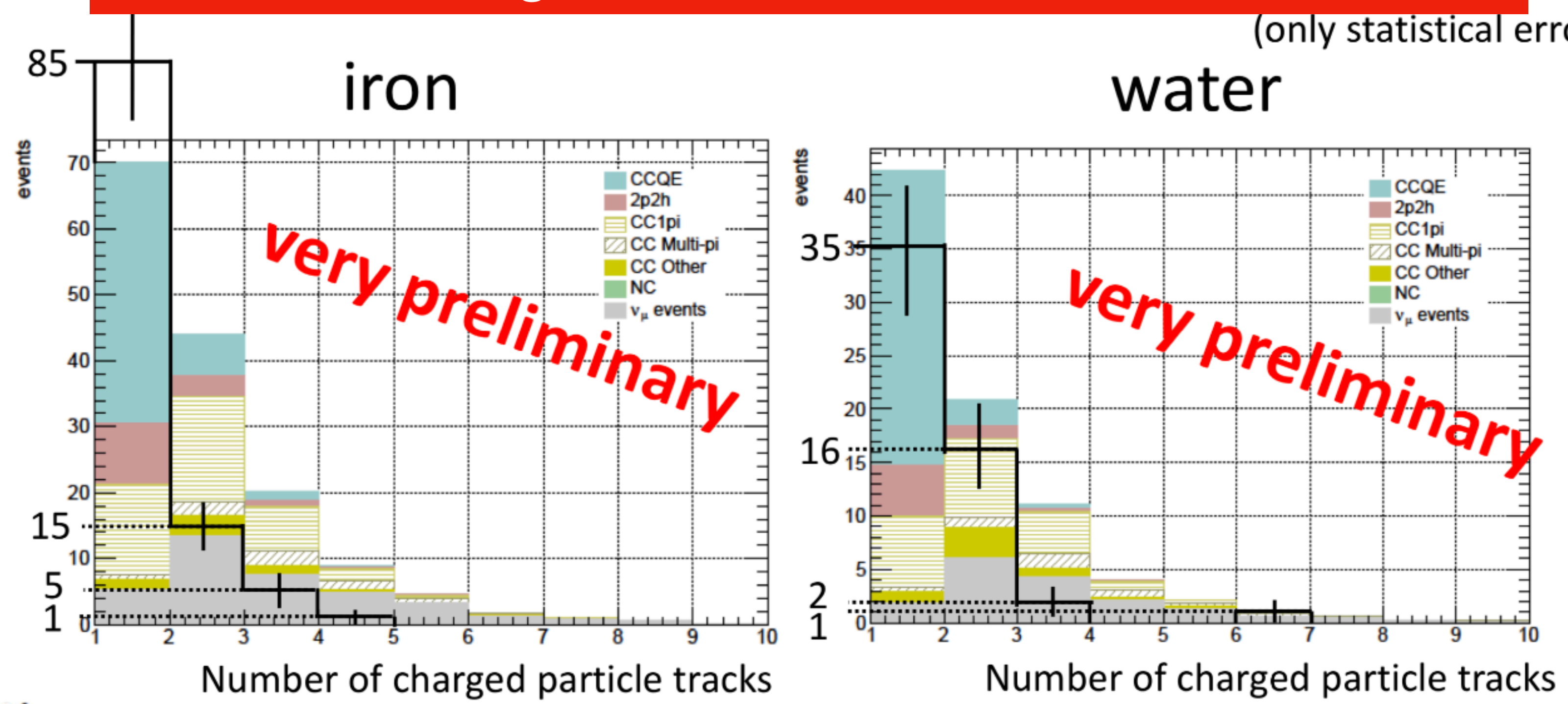


Detection of (slow) proton
→high purity event selection



Some interesting results showed. More to come soon

(only statistical error)



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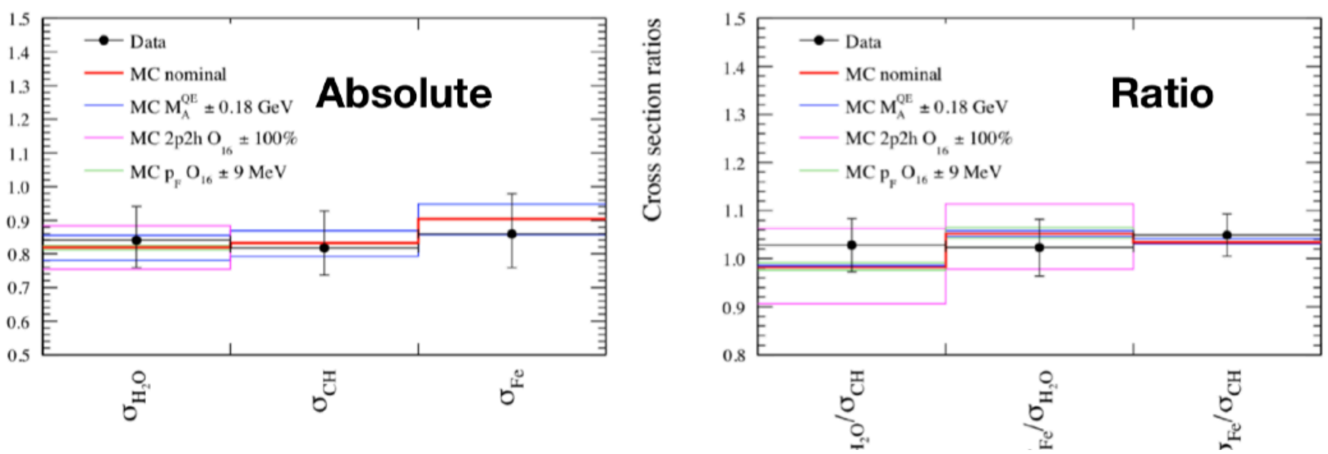
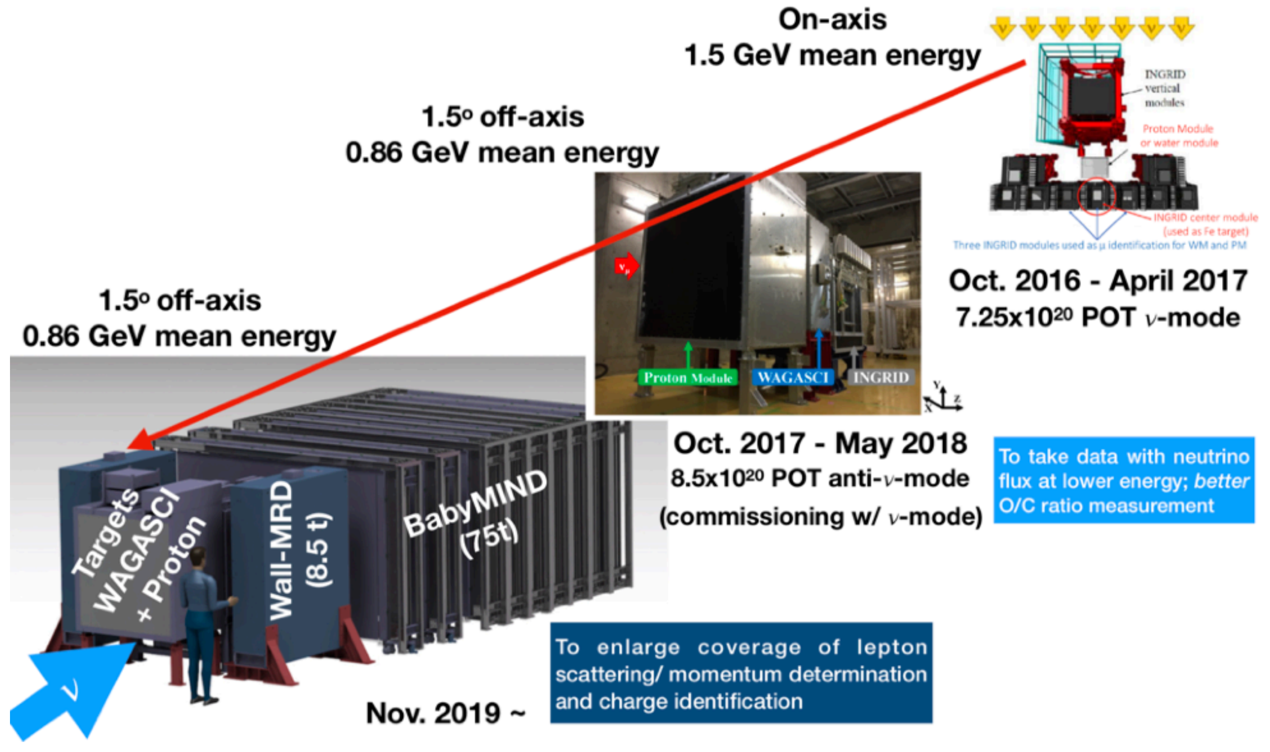




- 10%-14% errors for absolute measurement; 5% for ratio measurements
- Unprecedented precision for the measurements of neutrino-water interactions
- Good agreements with interaction models used in T2K exp.

Ready to take data from Nov. 2019 with final detector configuration

On neutrino-nucleus interaction

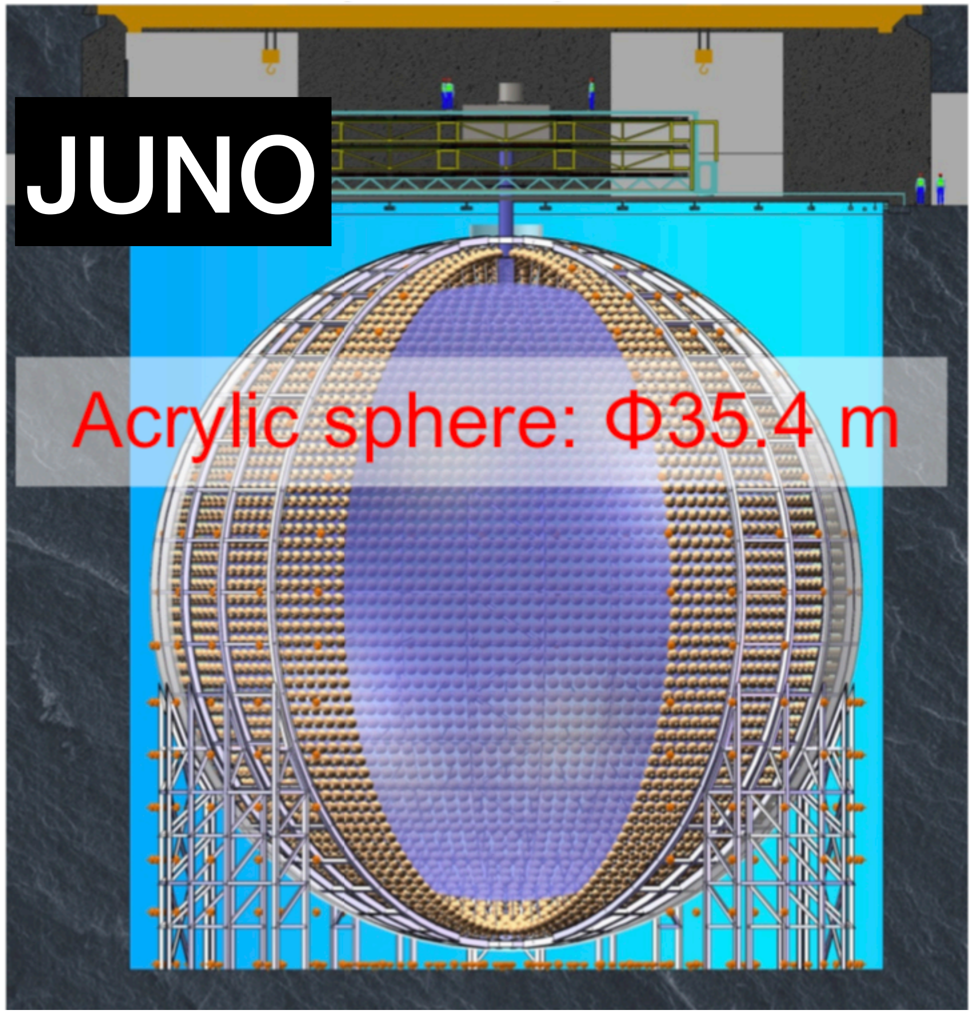
More clean data, more model-indepent analysis approaches, more theoretical calculation & prediction implemented in neutrino event generator are vital to pave the way toward "the best" nuclear model

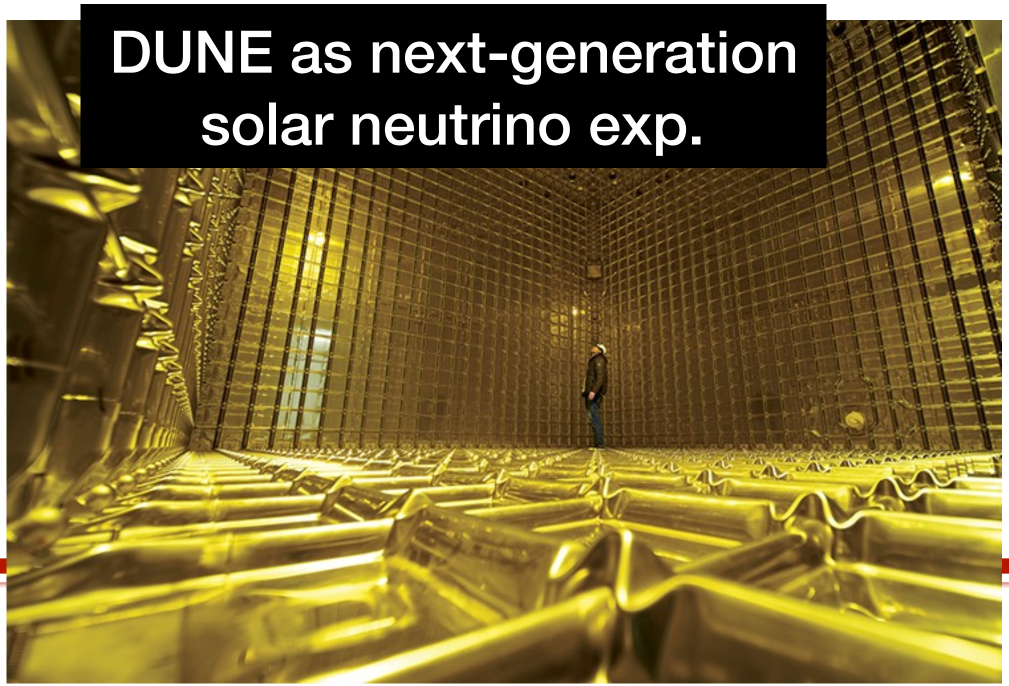
Kevin McFaland @ NuINT18

We need to collaborate w/ nuclear physicists

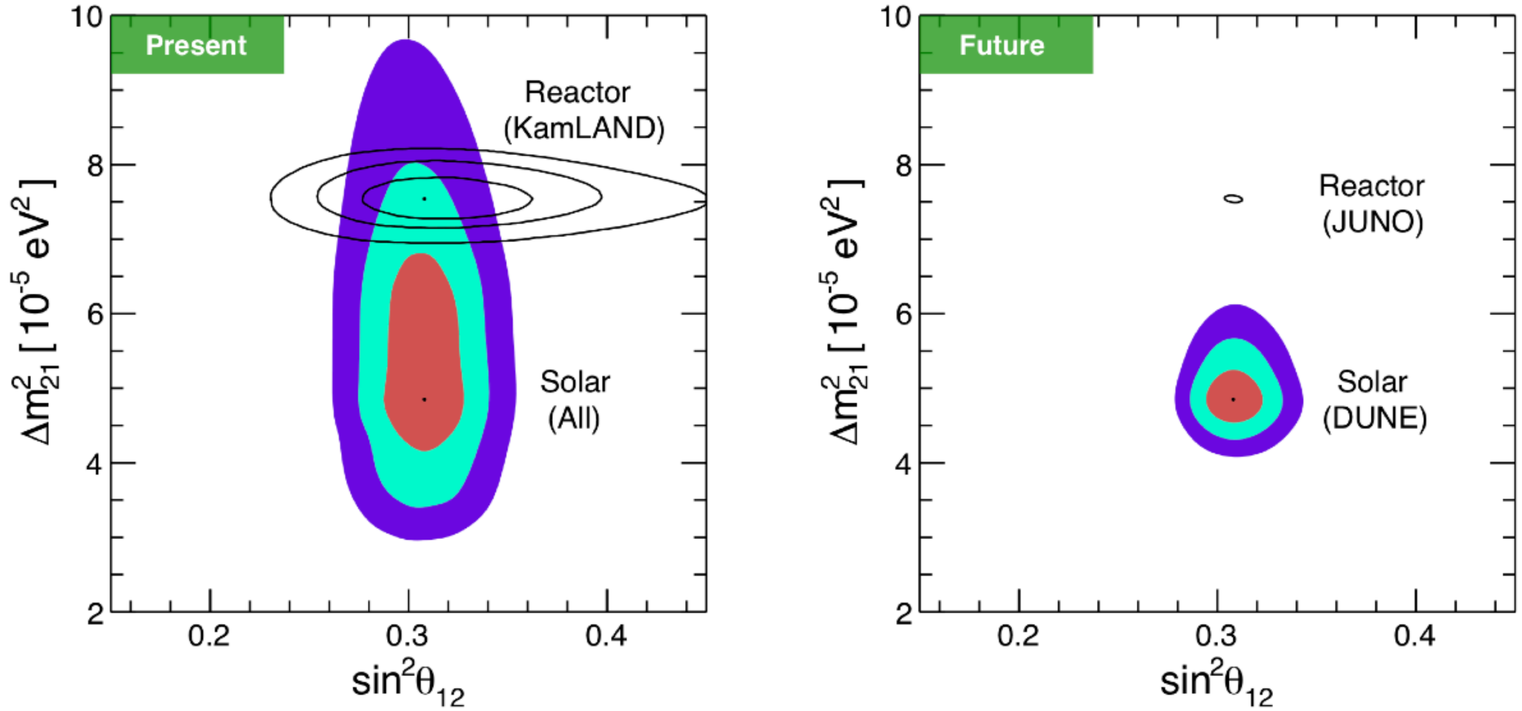
Precision era & PMNS formalism testing

Solar ν sector: Tension & solver(?)





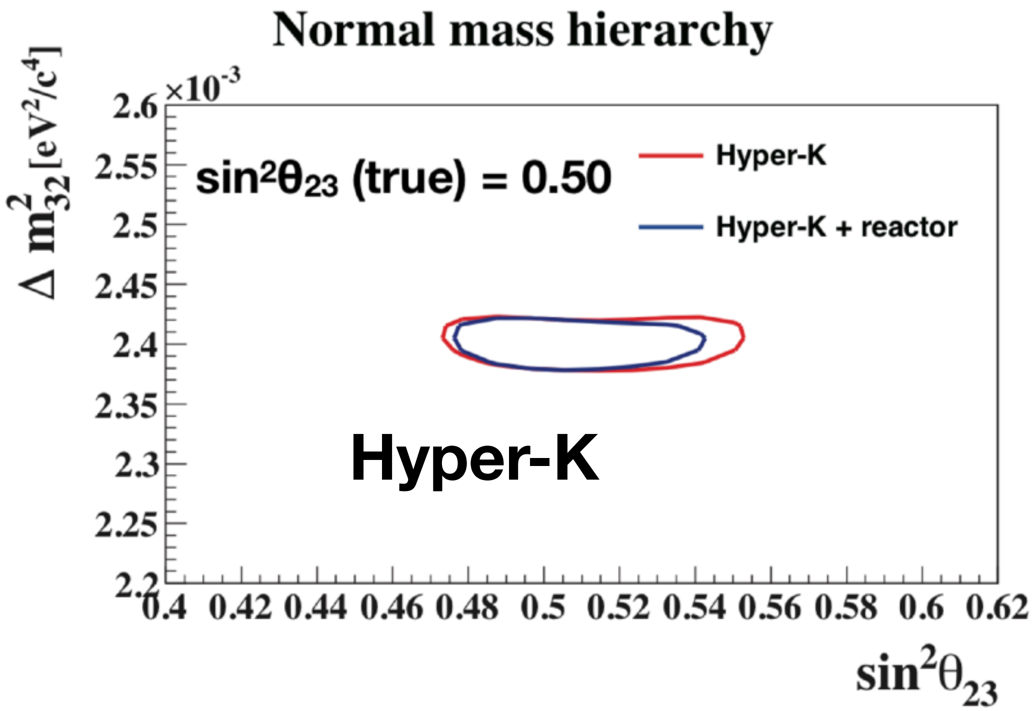
arXiv:1808.08232



2σ tension btw. KamLAND and solar neutrino experiments (SNO, Borexino, Super-K). JUNO & DUNE will be solvers?

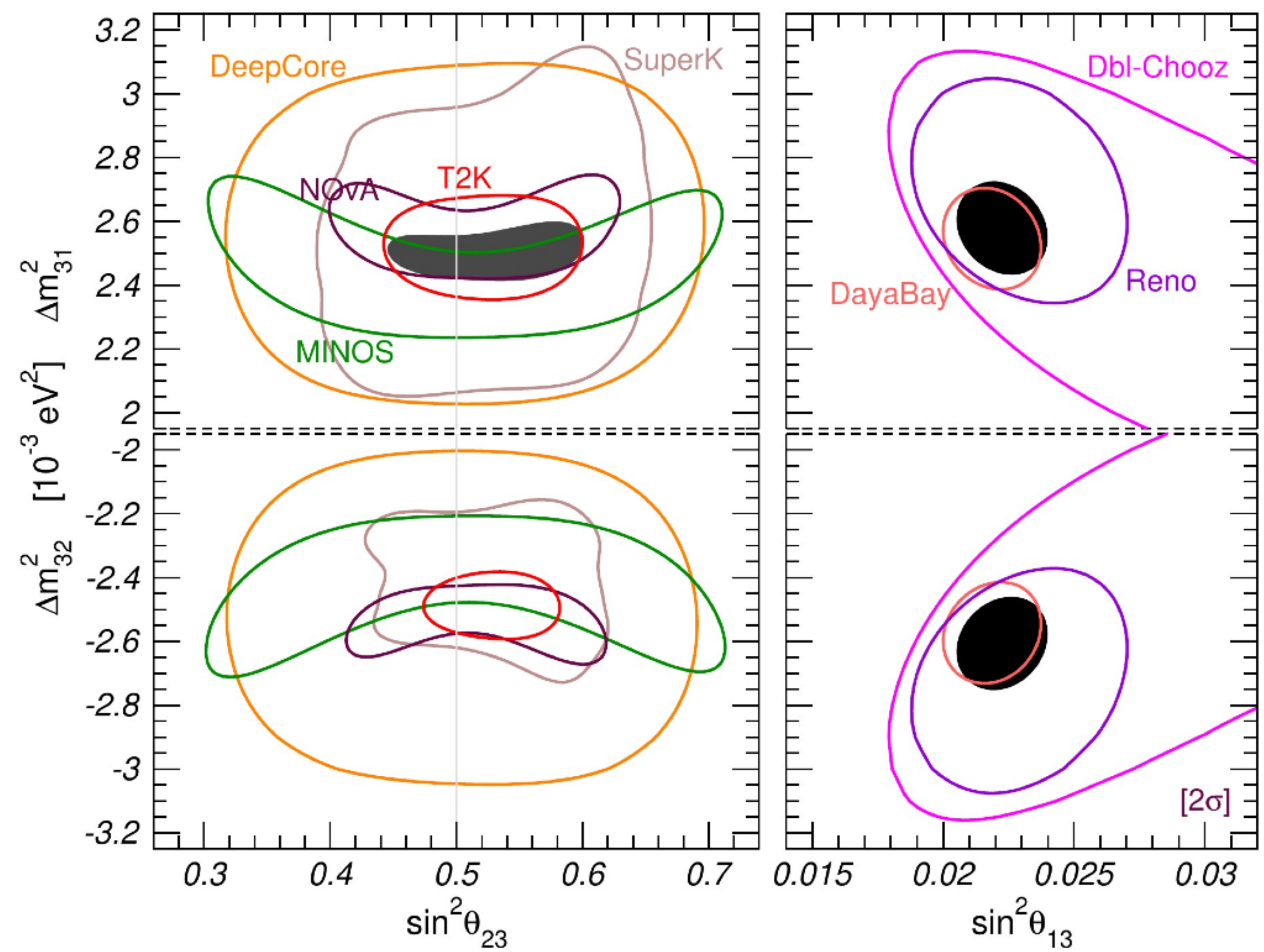
Atmospheric ν sector: θ_{23}

T2K(-II)/NOvA/Hyper-K/ DUNE & atmospheric exp.



Prospects of the Hyper-Kamiokande project
Yasuhiro Nakajima (ICRR The University of Tokyo)

NuFIT 4.1 (2019)

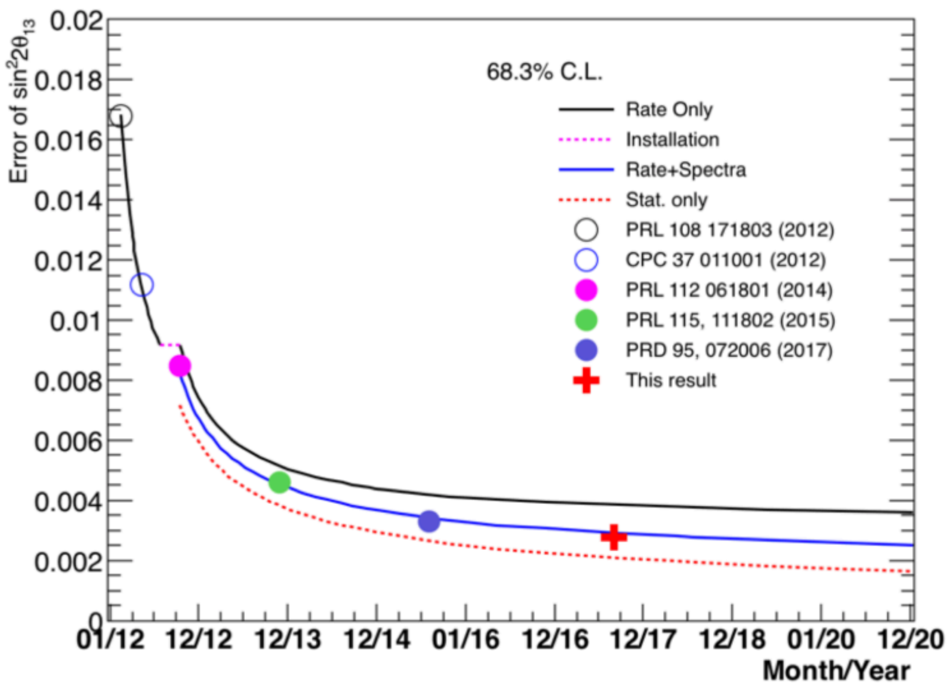


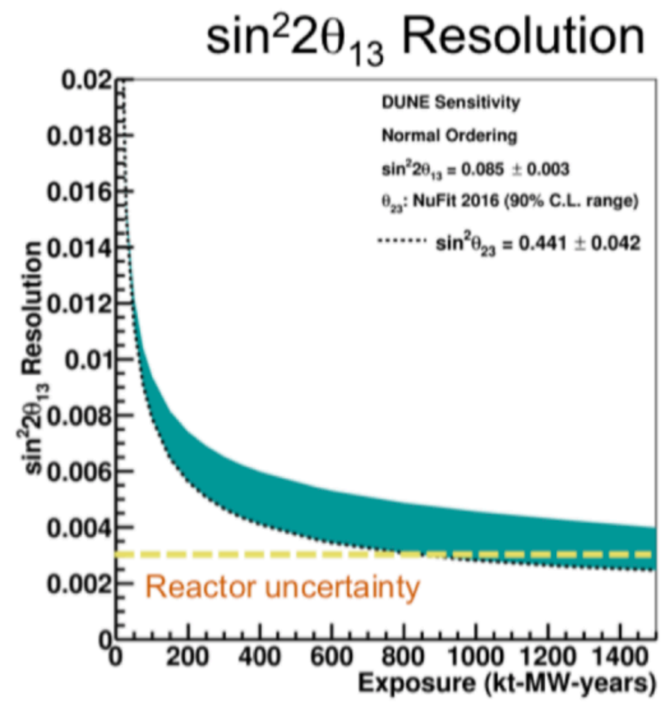
Reasonably consistent among experiments

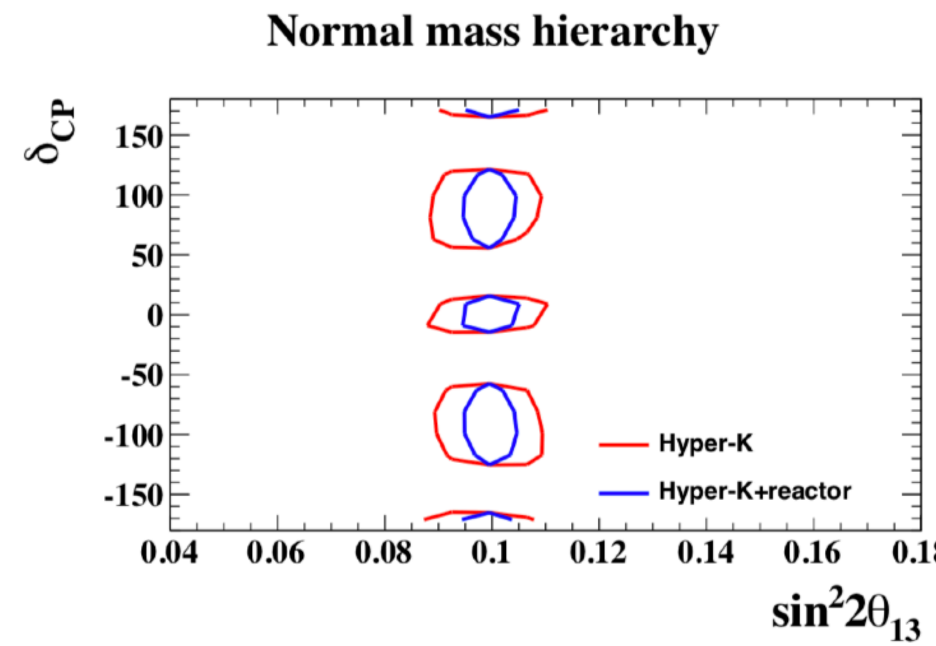
- My hunch is the nuclear model may play an important role for this. It can lurk the effect of (non-) maximal
- With high statistics, appearance channel in Hyper-K/DUNE will be very interesting, to not just compare with reactor measurement on θ_{13} but its sensitivity to octant of θ_{23}

Precision of mixing angle θ_{13}

Measurement & expectation from Daya Bay







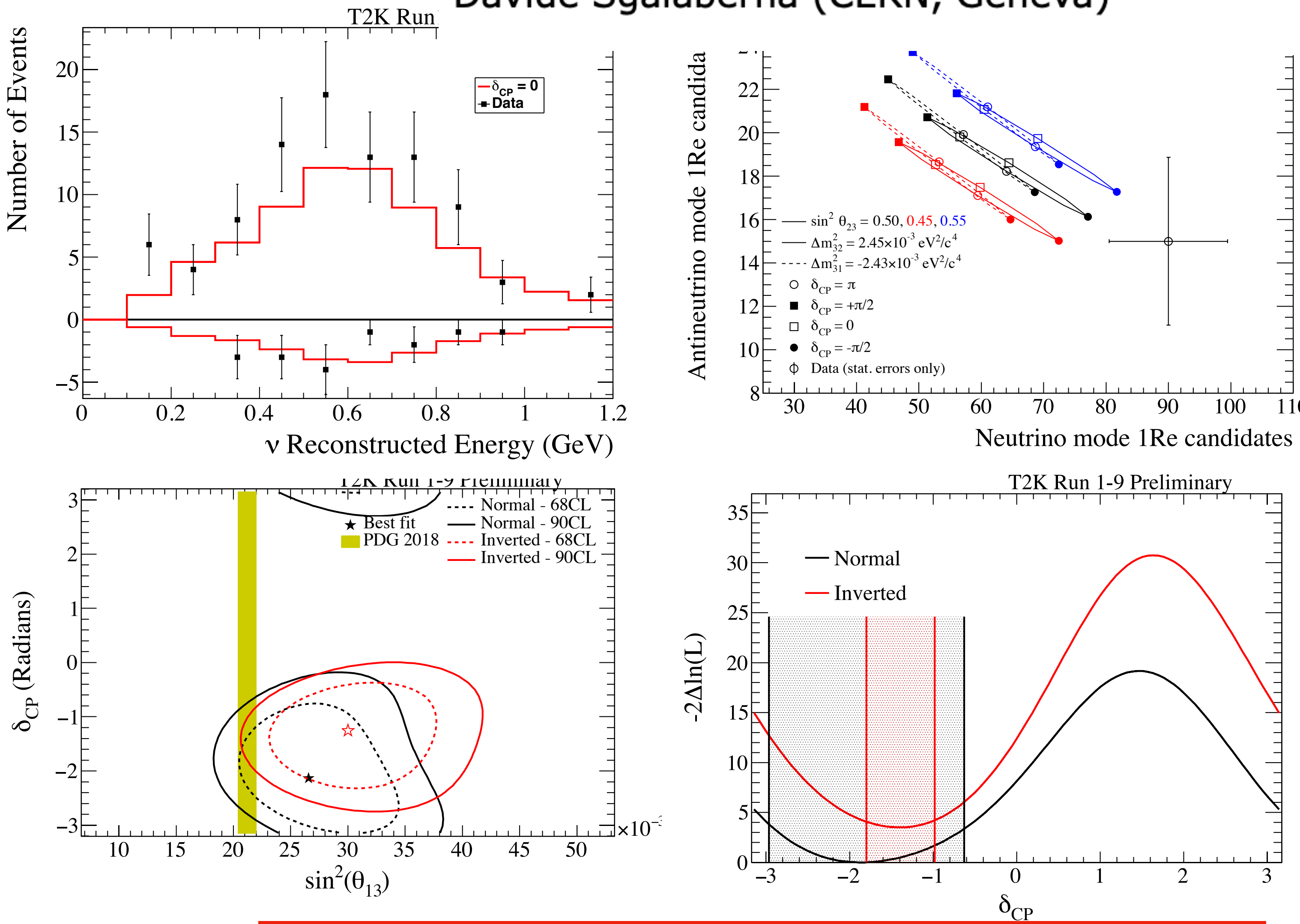
@Jiajia Ling

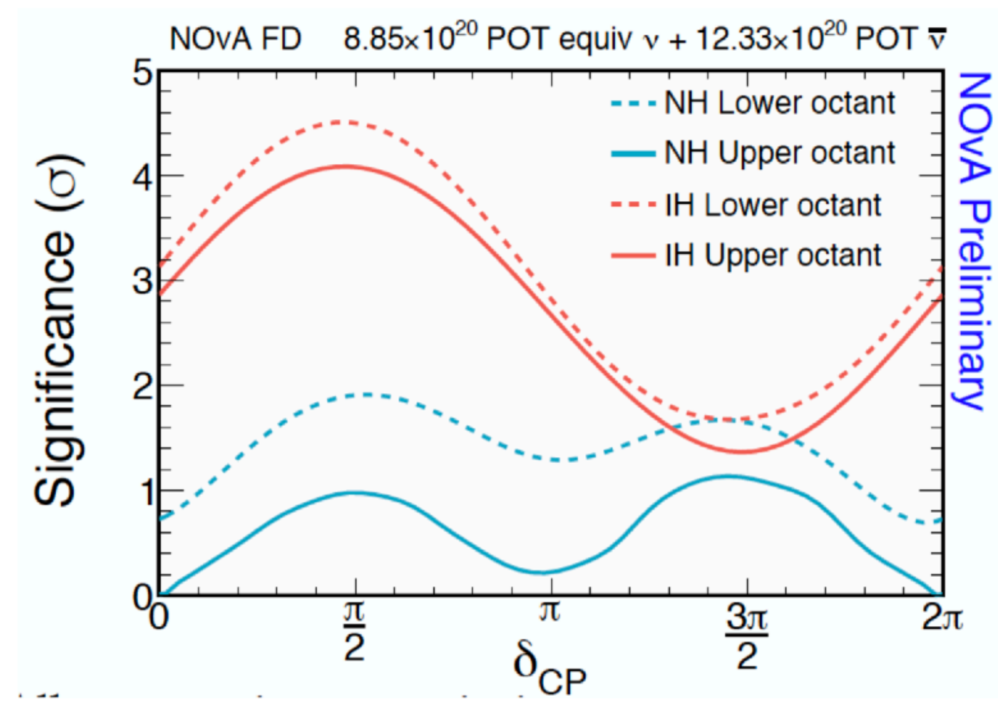
- Does ~3% uncertainty on θ_{13} meet our need, particularly for solving θ_{13} -δ_{CP}- θ_{23} - mass hierarchy degeneracies
- It will be interesting to compare between reactor-based & accelerator-based experiments on this mixing angle

Indication of CP violation in the lepton sector

It's really exciting time.

Experimental status of T2K and NOvA
Davide Sgalaberna (CERN, Geneva)





But NOvA point to other direction

T2K: CP-conserving values of δ_{CP} are out of its 2σ C.L measured range

No doubt, we need more data

Leptonic CP violation

- Amplitude of leptonic CP violation can be presented model-independently by Jarlskog invariant

$$J_{CP}^{Lepton} = Im[U_{\alpha i} U^*_{\alpha j} U^*_{\beta i} U_{\beta j}]$$
$$= \frac{1}{8} \sin 2\theta_{12} \sin 2\theta_{23} \sin 2\theta_{13} \cos \theta_{13} \sin \delta_{CP}$$

- Jarlskog invariant is 2 times of area of unitary triangle

$J_{CP}^{Lepton} = -0.019$ **at best fitted parameters**

- Compare to quarks

$J_{CP}^{quarks} = (3.18 \pm 0.15) \times 10^{-5}$ (*pdg2018*)

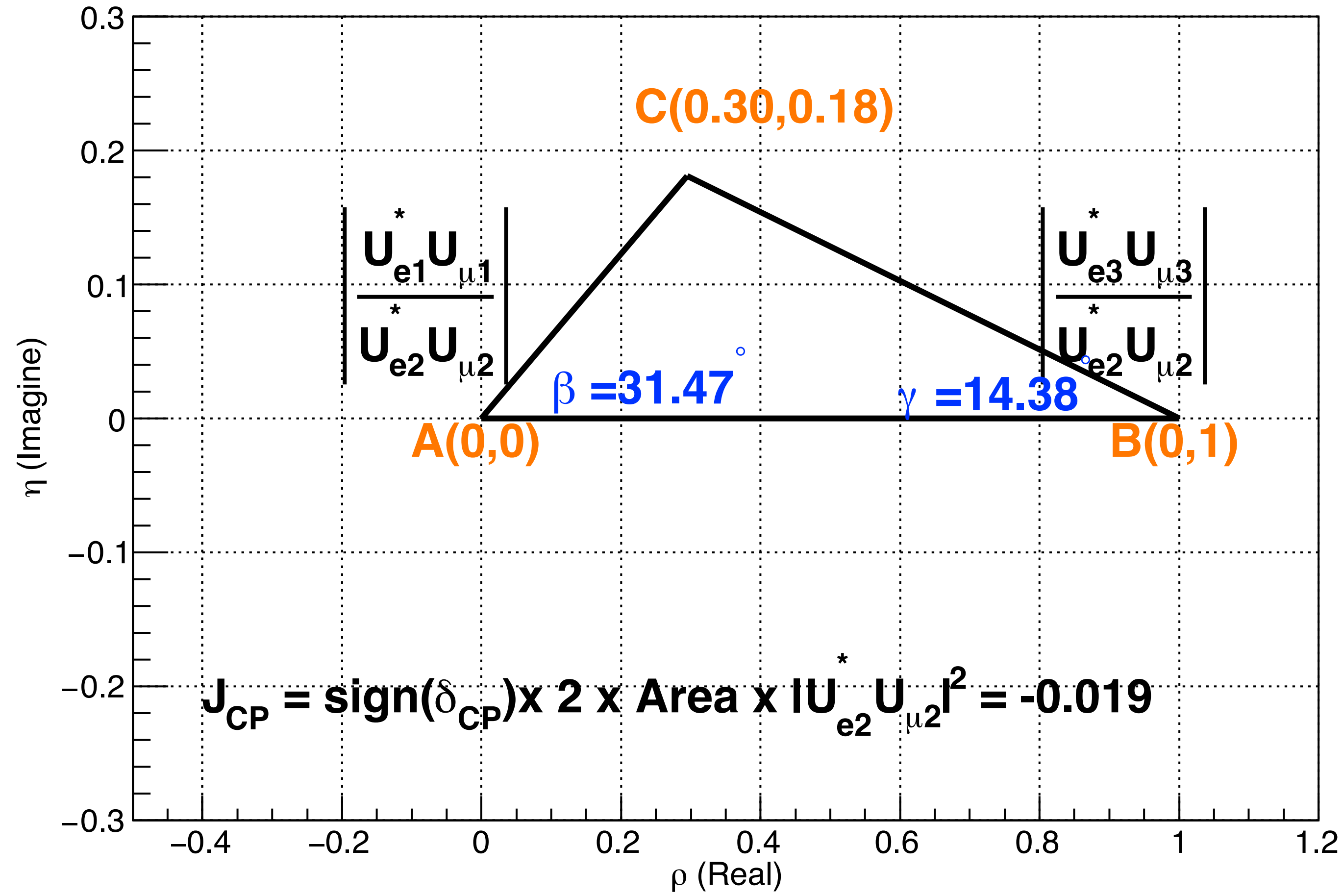
Amplitude of the leptonic CP violation can be much larger than its of quarks

Based on JHEP 01 (2019) 106

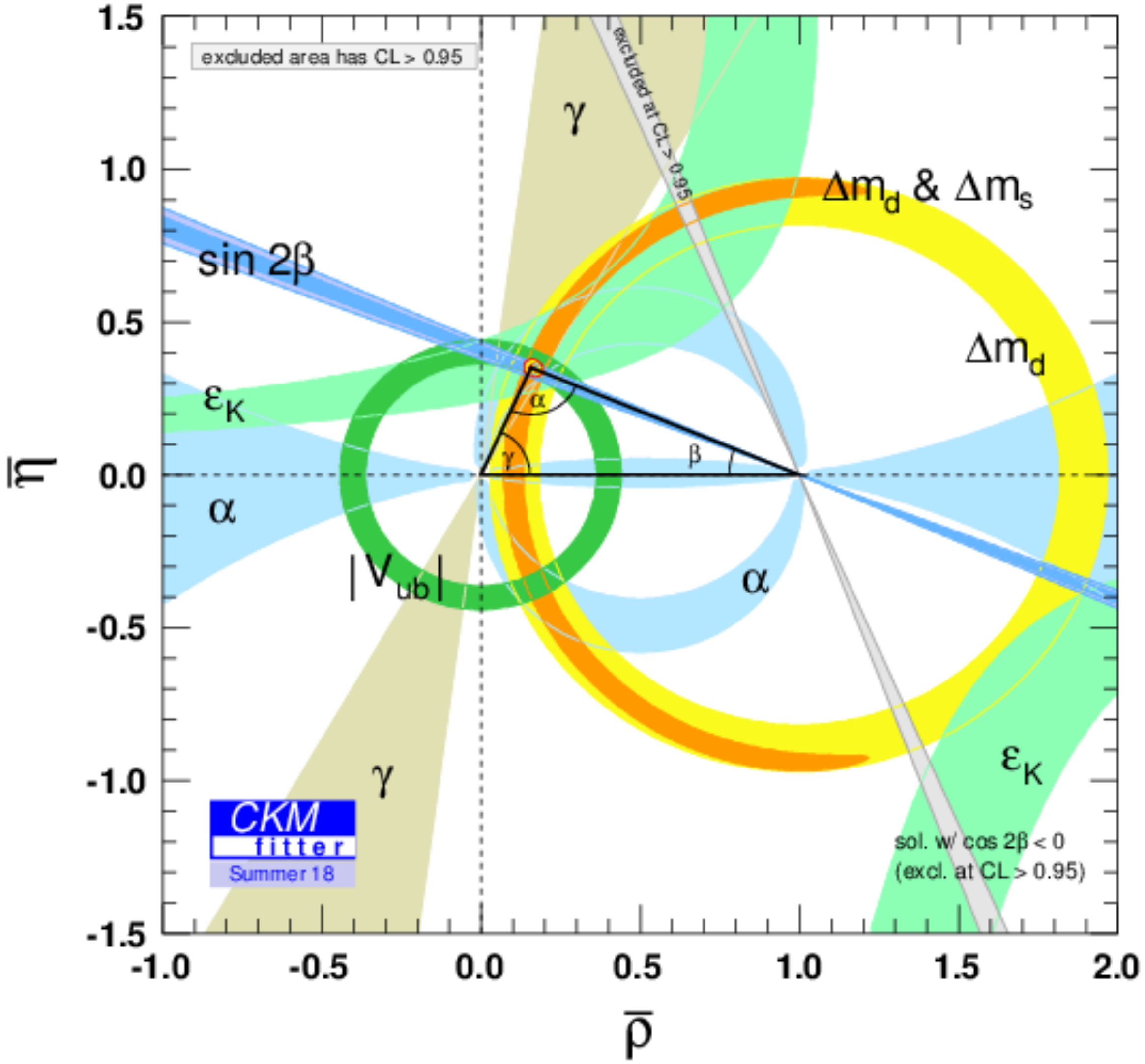
$$U_{PMNS}^{@Bestfit} = \begin{pmatrix} 0.821 & 0.551 & -0.123 + i*0.086 \\ -0.283 + i*0.054 & 0.590 + i*0.036 & 0.753 \\ 0.490 + i*0.046 & -0.588 + i*0.031 & 0.641 \end{pmatrix}$$

Unitary of PMNS can write down in six relations (scalar product of any row/column vector), which can be presented by "unitary" triangles

$$U^*_{e1} U_{\mu 1} + U^*_{e2} U_{\mu 2} + U^*_{e3} U_{\mu 3} = 0$$



Leptonic CP violation



Andre de Gouvea

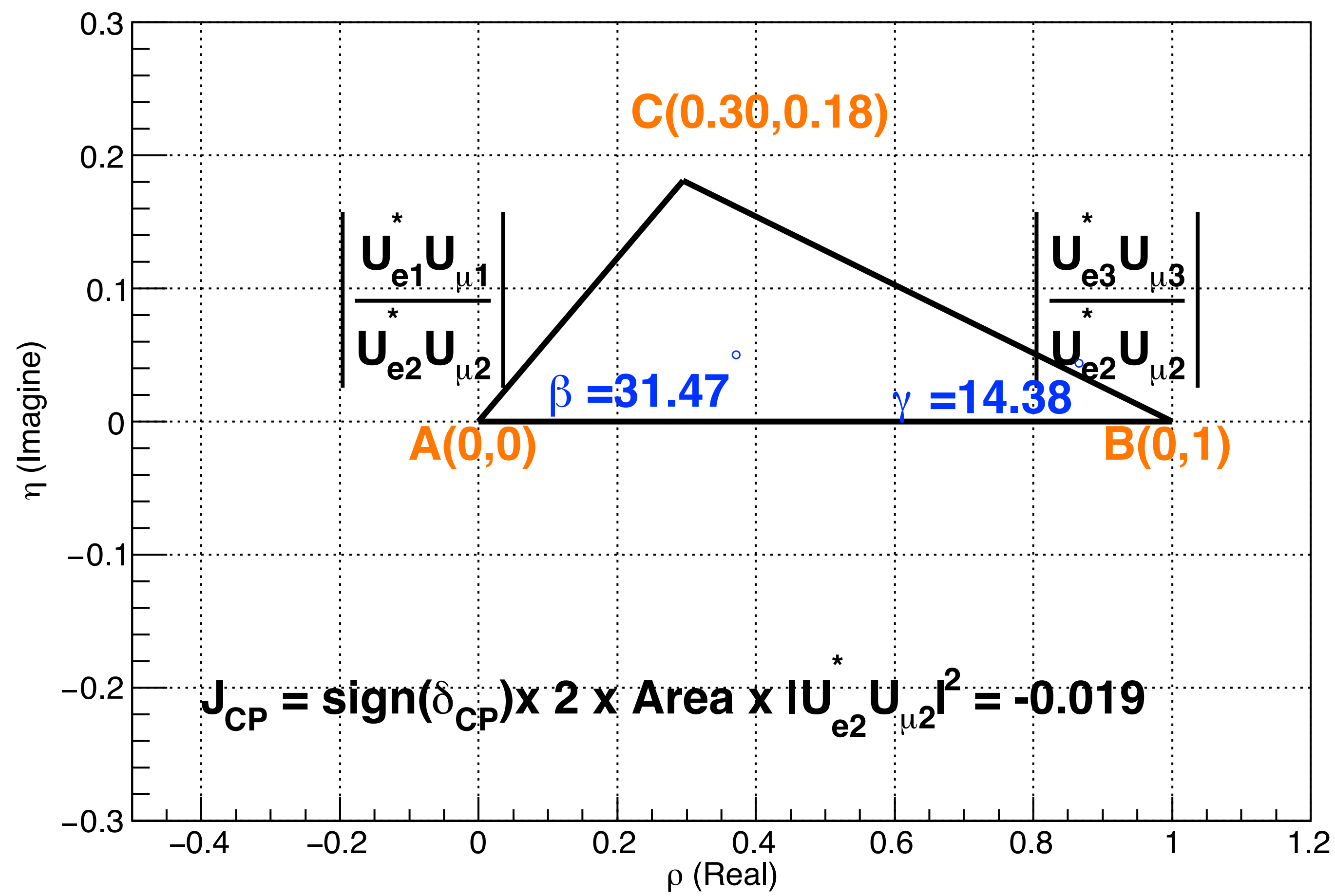
We need to do <u>this</u> in the lepton sector!

Based on JHEP 01 (2019) 106

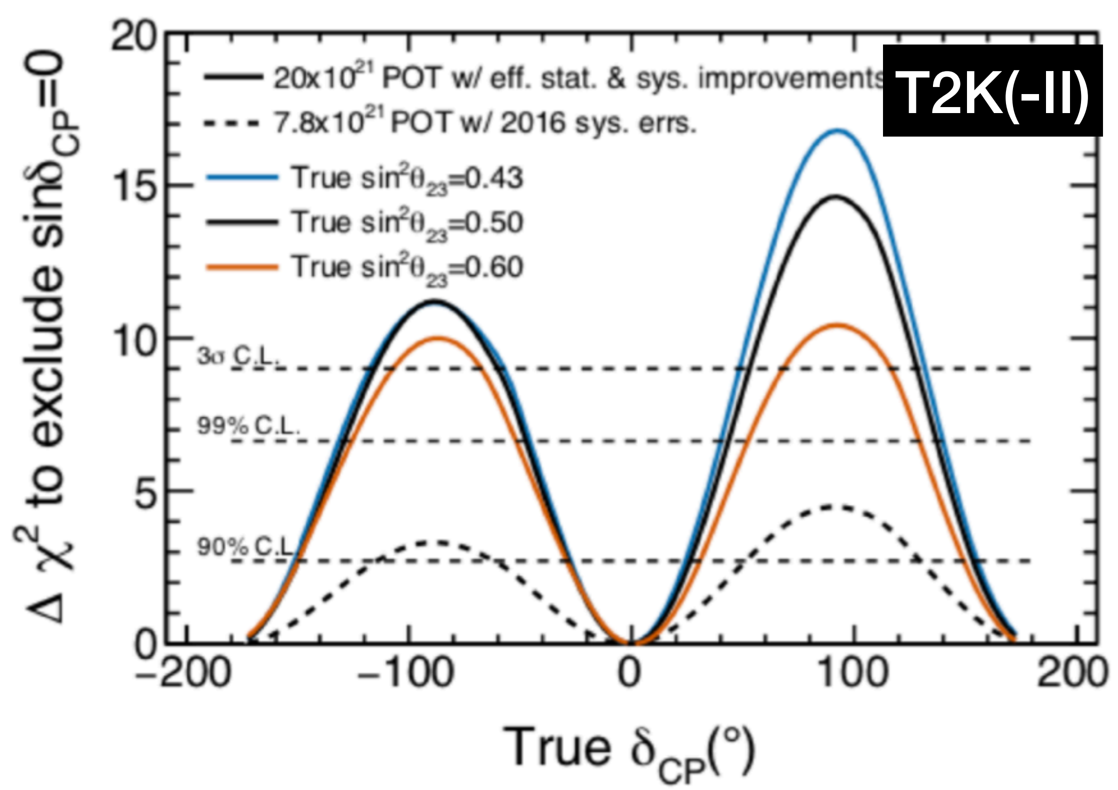
$$U_{PMNS}^{@Bestfit} = \begin{pmatrix} 0.821 & 0.551 & -0.123 + i*0.086 \\ -0.283 + i*0.054 & 0.590 + i*0.036 & 0.753 \\ 0.490 + i*0.046 & -0.588 + i*0.031 & 0.641 \end{pmatrix}$$

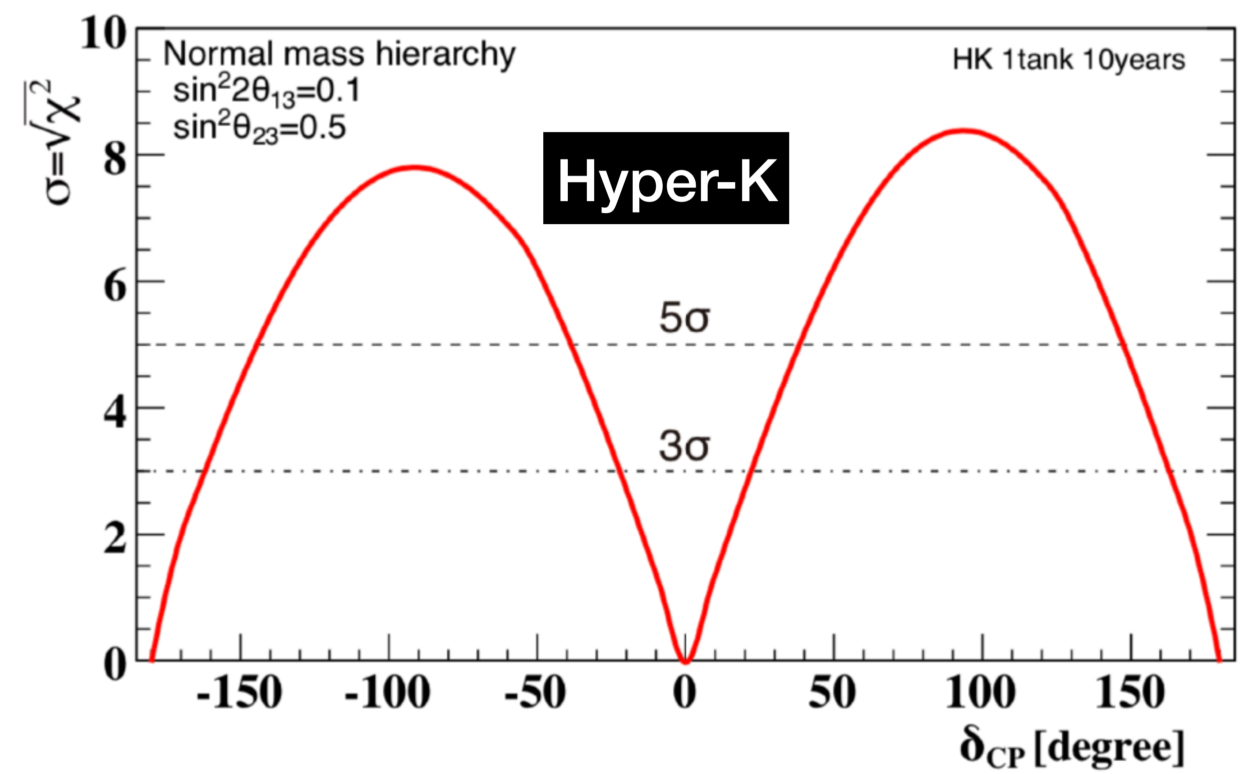
Unitary of PMNS can write down in six relations (scalar product of any row/column vector), which can be presented by "unitary" triangles

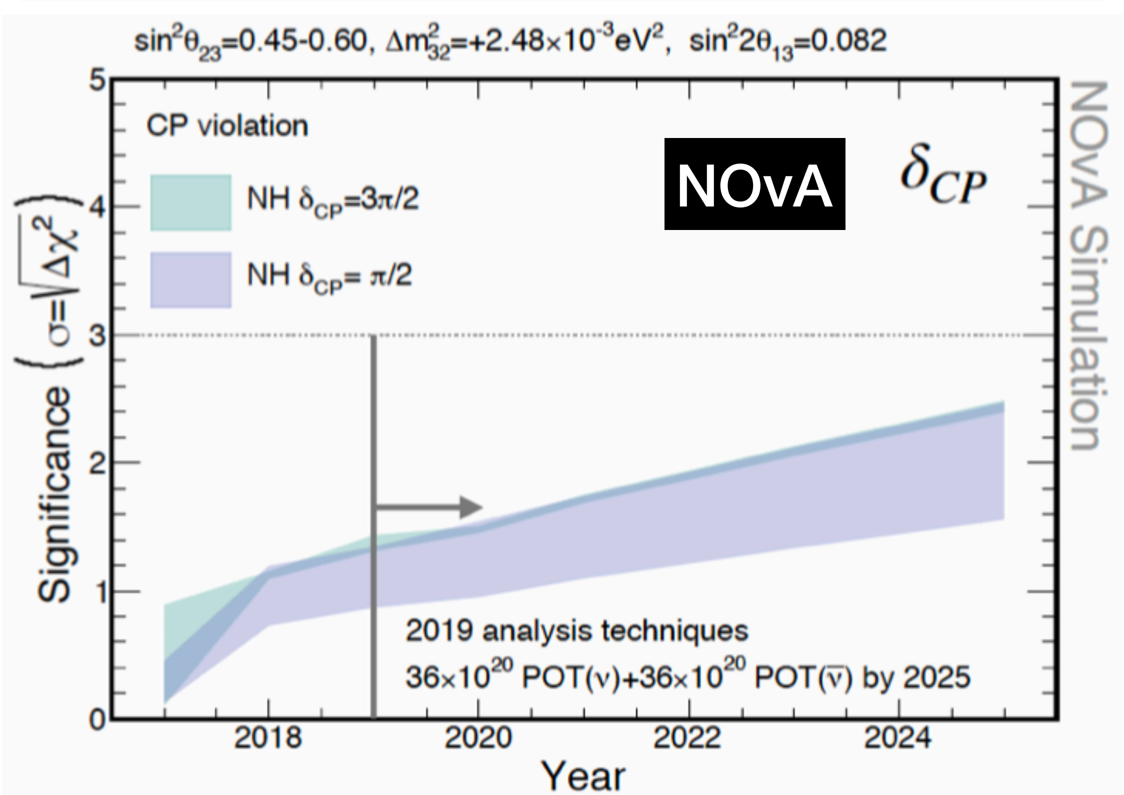
$$U_{e1}^* U_{\mu 1} + U_{e2}^* U_{\mu 2} + U_{e3}^* U_{\mu 3} = 0$$

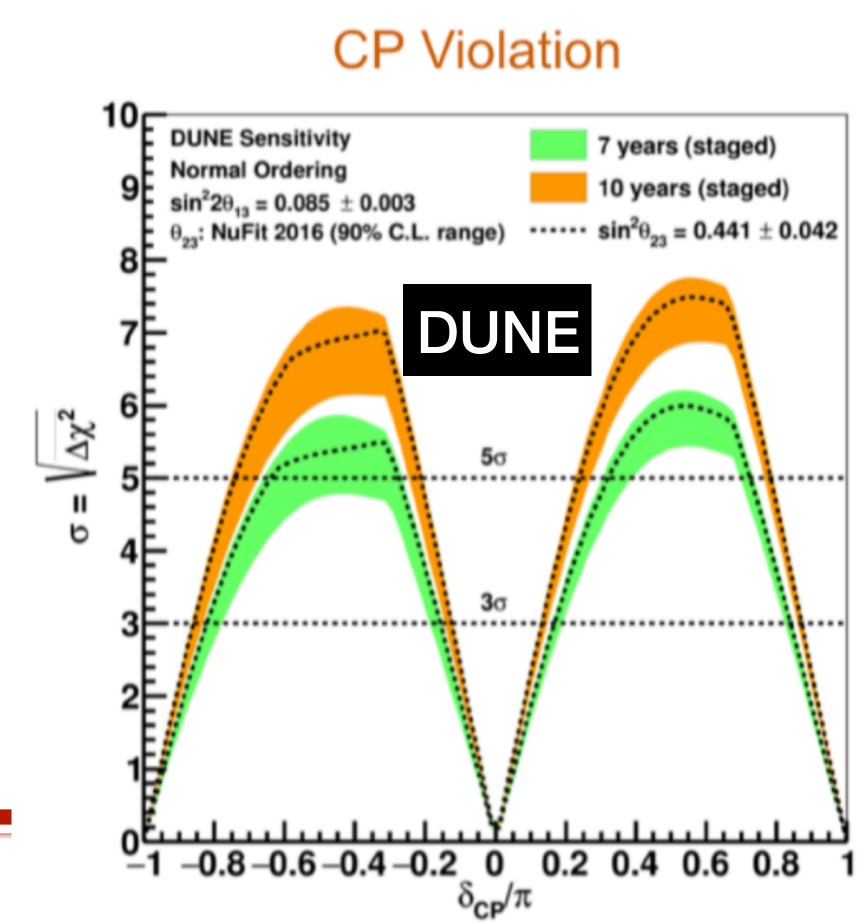


Leptonic CP violation: Race already started



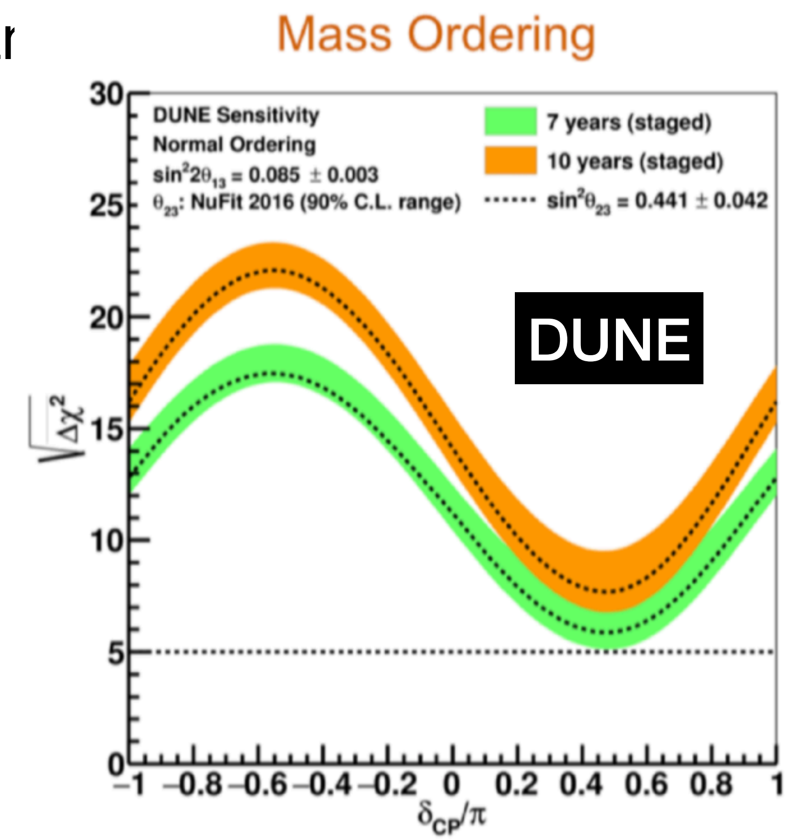


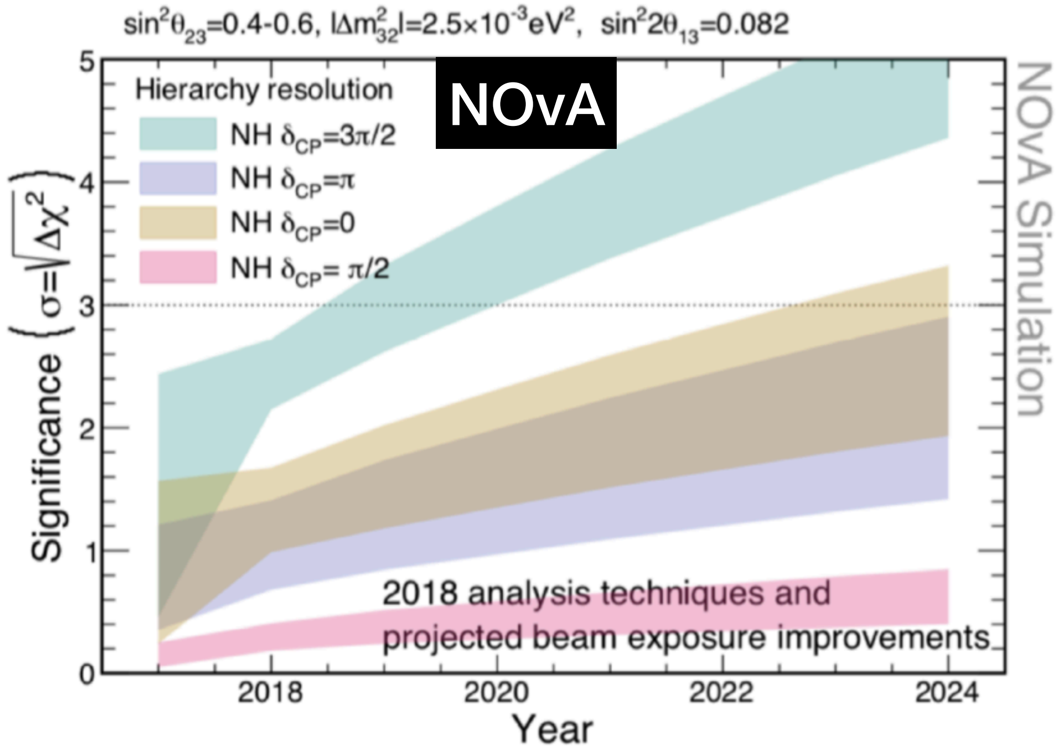




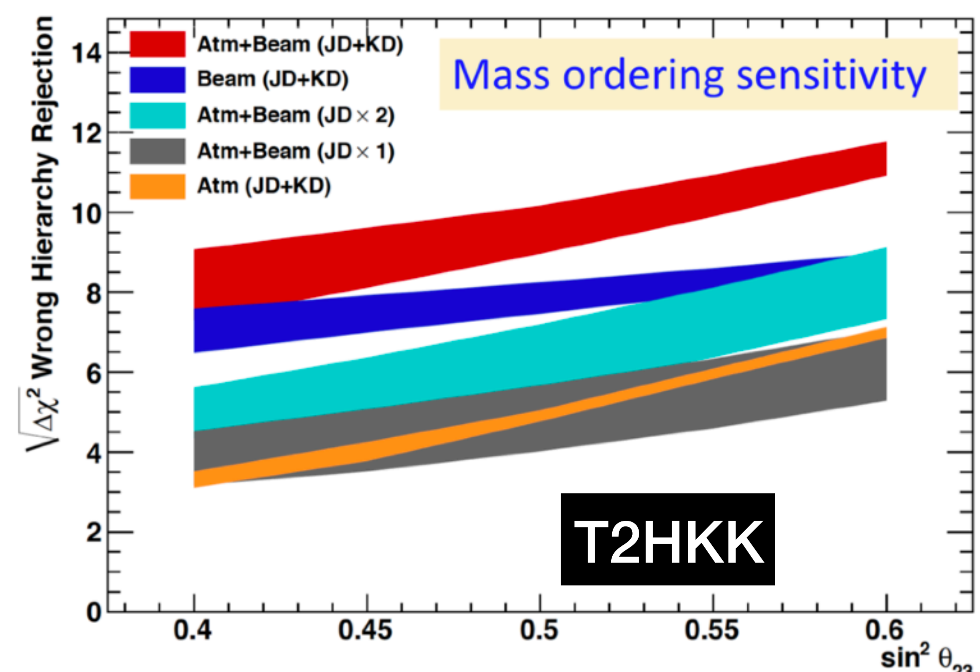
Mass hierarchy: Another intriguing race

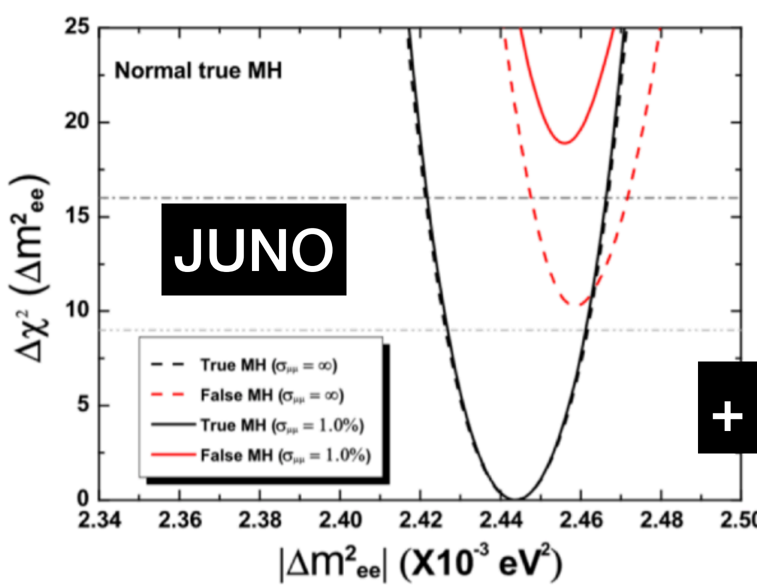
From NuFIT2019: Normal mass hierarchy is favored at 3σ (2σ) with (without) Super-K atmospheric neutrino sa





Technical analysis may not be trivial since to tell something on mass hierarchy, one needs to marginalize all nuisance systematic parameters and oscillation parameters





+ Super-K/ IceCUBE..

How to test PMNS paradigm?

Practical tests on the PMNS paradigm
amu Yasuda (Tokyo Metropolitan University)

3. Tests Before HK & DUNE

(1) ν_s

To test the hypothesis of sterile ν, (i) we get the constraints on the **extra mixing angles** θ_{14} , θ_{24} , θ_{34} or (ii) we get the constraints on **different matter effect.**

(1-1) Neutral current interactions of π^0 at T2K

By measuring #(π^0 ->2γ) due to NC, we can determine
$P(\nu_\mu \to \nu_e) + P(\nu_\mu \to \nu_\mu) + P(\nu_\mu \to \nu_\tau) = 1 - P(\nu_\mu \to \nu_s)$

(1-2) Appearance & disappearance probabilities at T2K

(1-3) ν_{atm} (SK, IceCUBE)

(1-4) SK ν_{atm} : τ appearance

HK & DUNE can give us enough ingredients to test PMNS paradigm at some significant C.L?

Global effort.

We find neutrino very interesting & this center has “ν” shape. It can be a “signal” (*for a neutrino group development*) or just “coincidence”.

Thank you for coming & we hope to continue working with you.