Neutrino oscillations

JOURNEE ANNUELLE DE P2I

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Neutrinos as door to New Physics

- **The SM cannot answer to many fundamental questions in cosmology and HEP**
  → **'fishing' expedition to the next energy scale of the necessary New Physics**
- **Expansion of Lagrangian in terms of NP energy scale (Λ_{UV}):** $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{UV}}\mathcal{L}_5 + \ldots$

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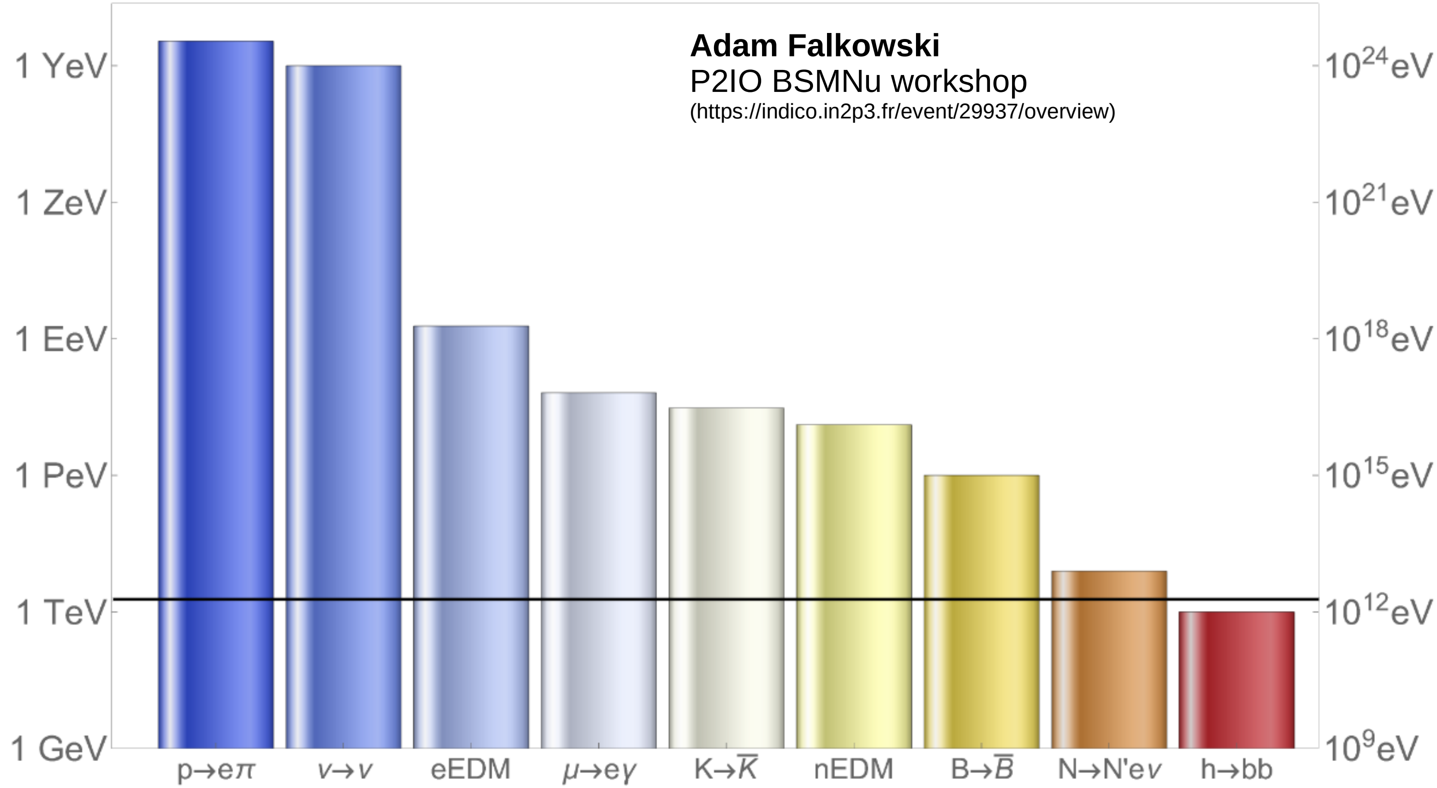
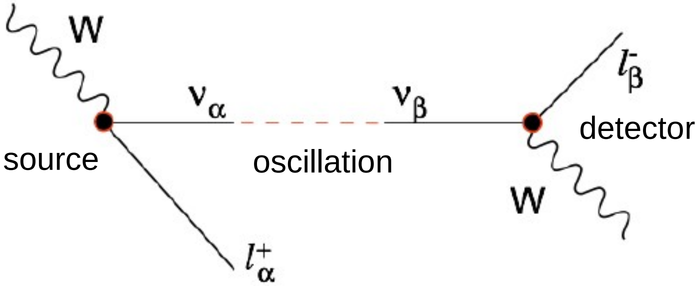
Neutrinos directly connected to the most economical expansion of SM physics
→ **neutrinos are a natural and very powerful door to New Physics**

The main subject of the BSMNu P2IO flagship project



Neutrinos oscillations

From the **discovery (Nobel prize in 2015)** to a ‘standard paradigm’ = **PMNS mixing matrix**



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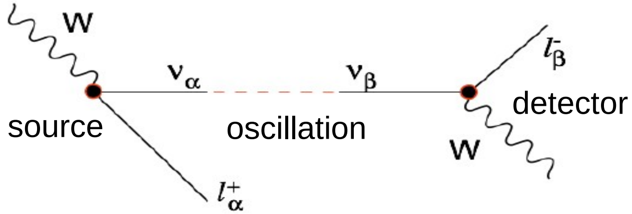
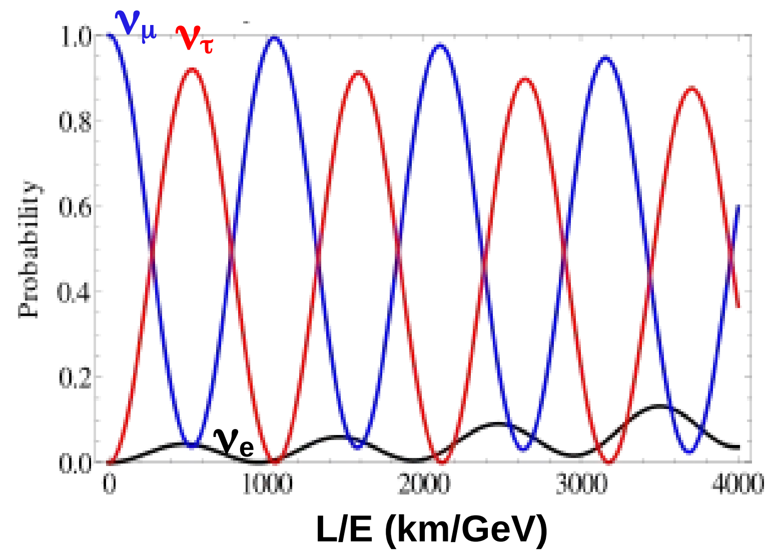
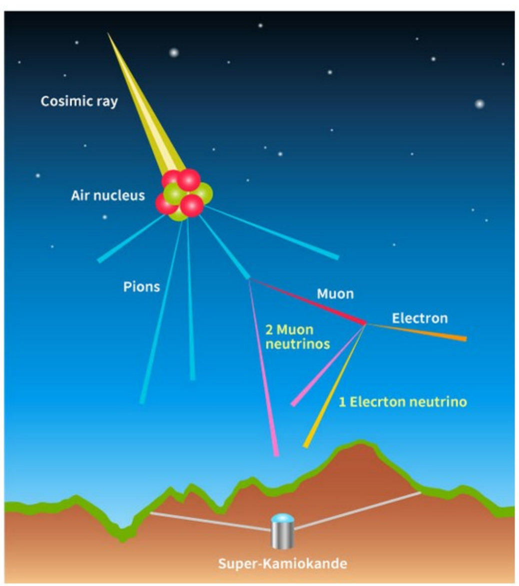


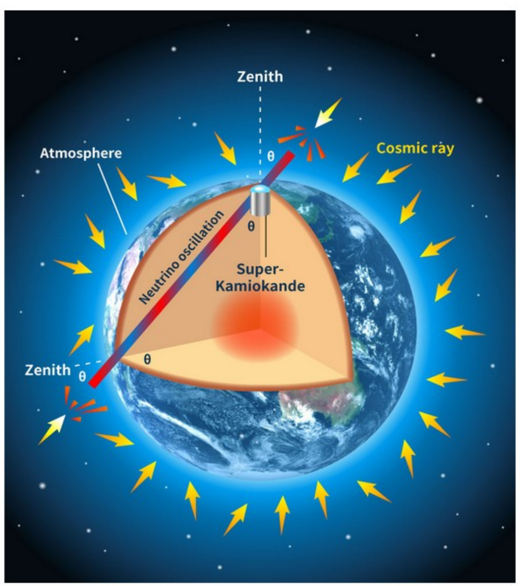
From the **discovery** (Nobel prize in 2015) to a 'standard paradigm' = PMNS mixing matrix

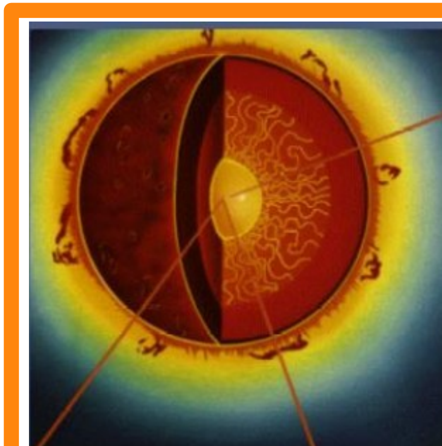
- Oscillation discovered with **atmospheric** and **solar** neutrinos by SuperKamiokande and SNO with '**natural**' **neutrino sources**

$$P(\nu_\alpha \rightarrow \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\textbf{amplitude}} \sin^2\left(\underbrace{1.27\frac{\Delta m^2_{ji}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}}_{\textbf{frequency}}\right)$$









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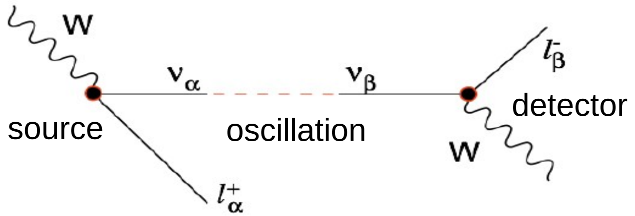

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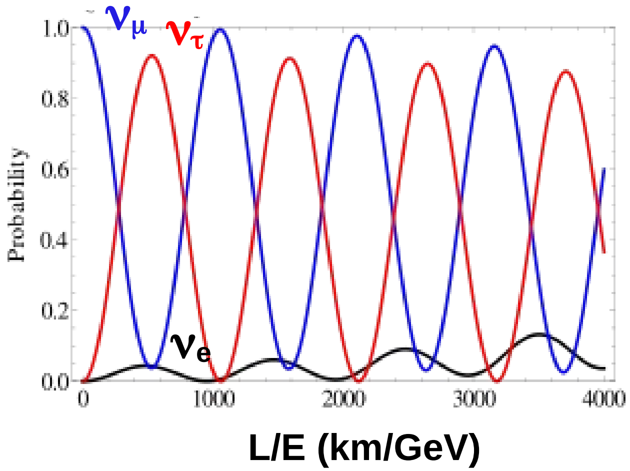


- Since then, **accelerator and reactor neutrinos** artificial sources with very large statistics and/or well controlled production

PMNS mixing matrix

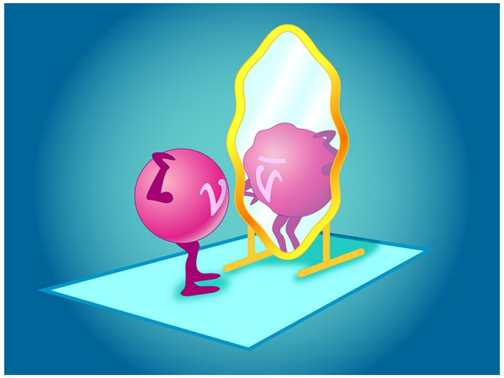
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu1} & U^*_{\mu2} & U^*_{\mu3} \\ U^*_{\tau1} & U^*_{\tau2} & U^*_{\tau3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

- $|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$ — $U_{\alpha i}$ are expressed in terms of 3 mixing angles (θ_{13}, θ_{23}, θ_{12}) and a phase δ_{CP}
- 3 mass states → two Δm^2: solar (small ~ 7.5×10^{-5} eV) and atm (large: 2.4×10^{-3} eV)

With many open questions ...

- Different oscillations for ν and $\bar{\nu}$? **New fundamental source of Charge-Parity violation (and first in leptonic sector!)**

  Linked to the matter-antimatter asymmetry in the Universe



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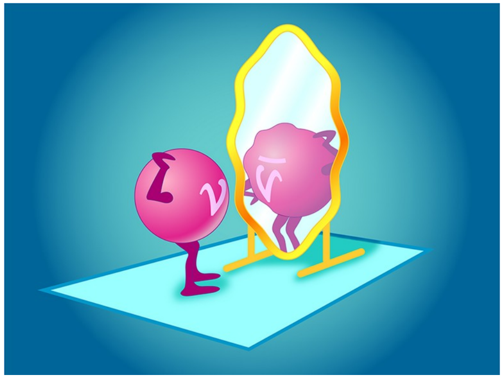

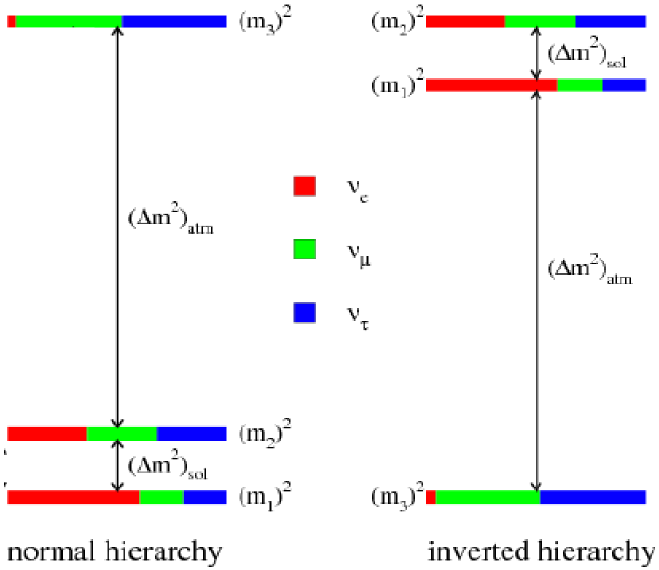

- **Mass Hierachy :** is the mass ordering the same for charged and neutral leptons?

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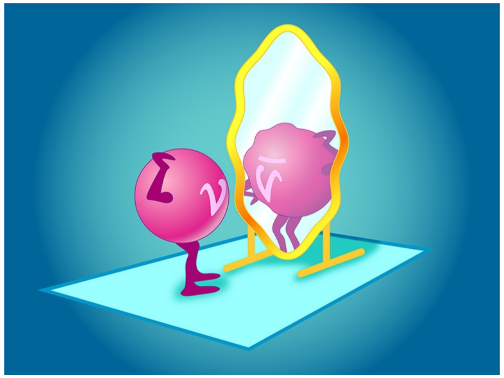

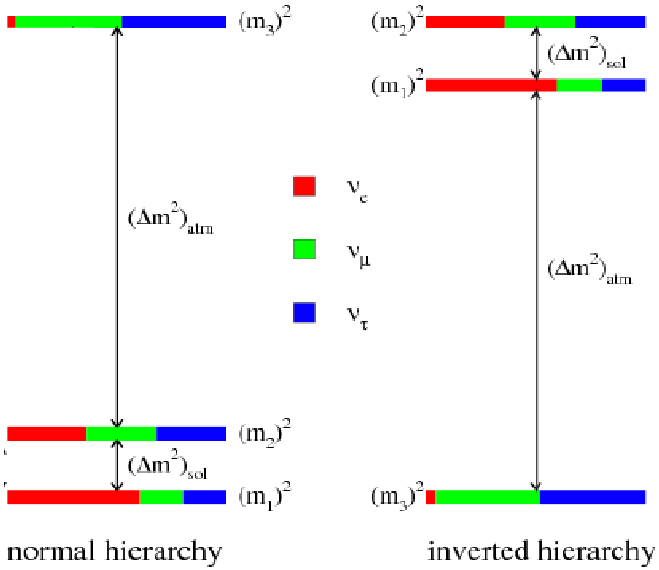

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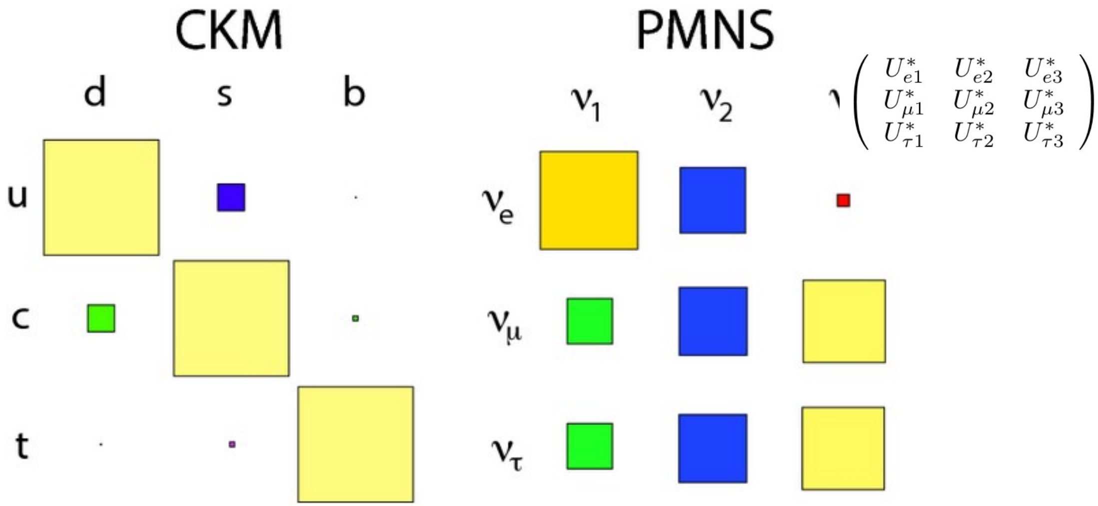
- **Precision measurements of flavour mixing pattern:**

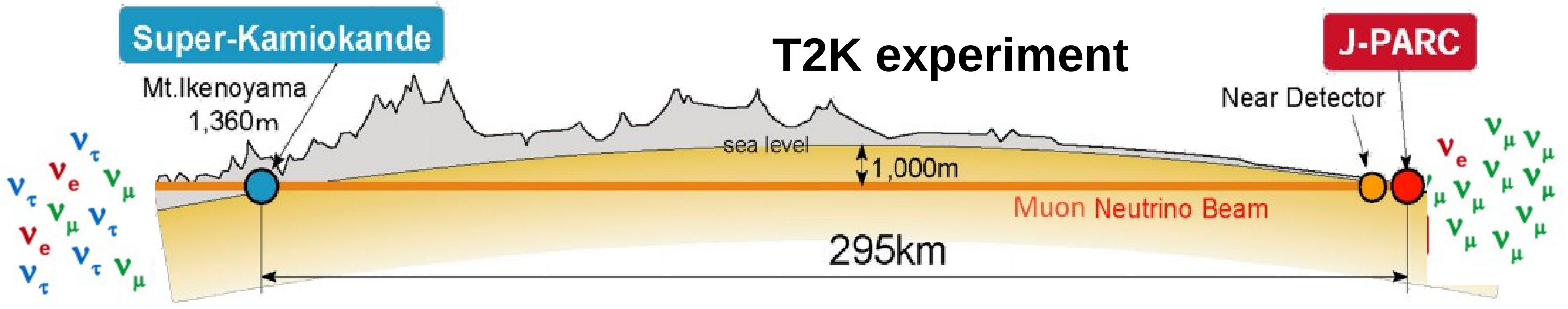
  - very large mixing ($\theta_{23} \sim \pi/4$ would imply maximal mixing, ie an interesting symmetry: $U_{\mu i} \sim U_{\tau i}$)



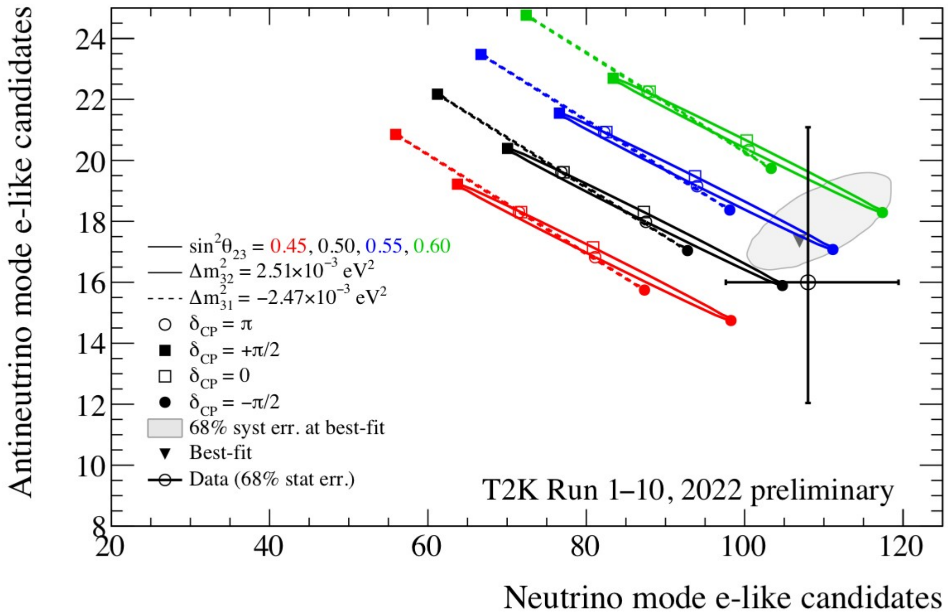
PMNS oscillations:
recent results

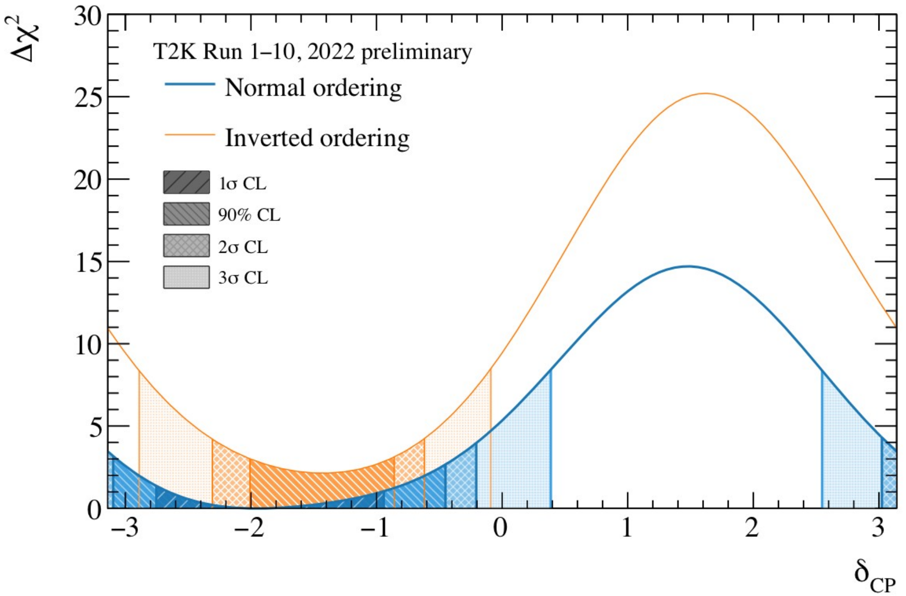
T2K

April 2020
Nature cover!



Beam of neutrino and antineutrino: **best sensitivity to CP-violation**

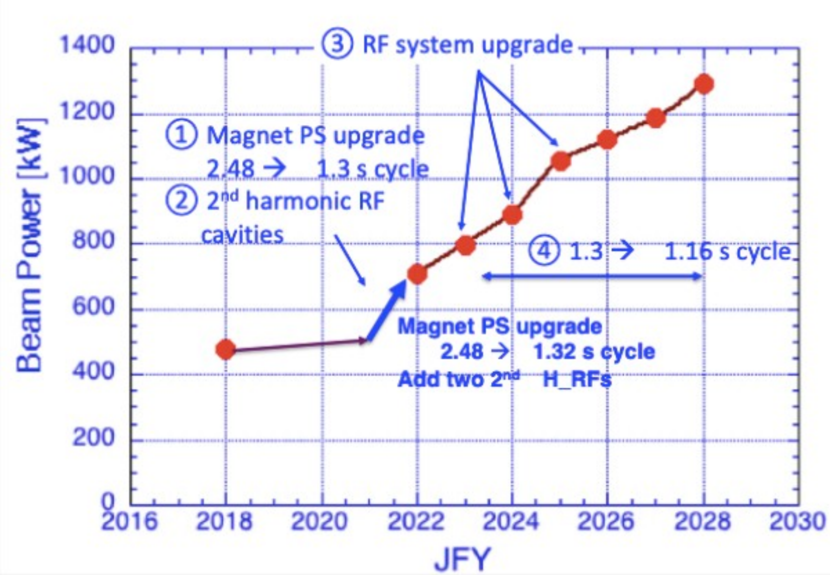




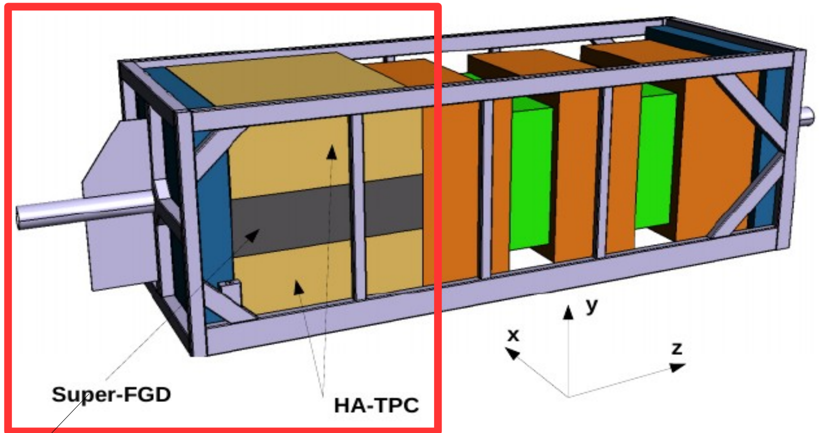
Statistically limited measurement!

T2K new data-taking era

- **Accelerator+beam upgrade** from 500kW to 750kW: started now

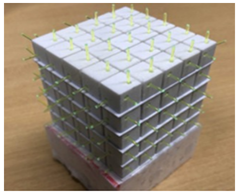


- **Near detector upgrade of ND280** being installed now!
For improved systematics to cope with increased statistics

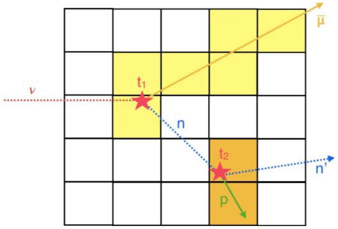


- **New target** with much lower threshold for track reconstruction (protons, pions) + !neutrons!

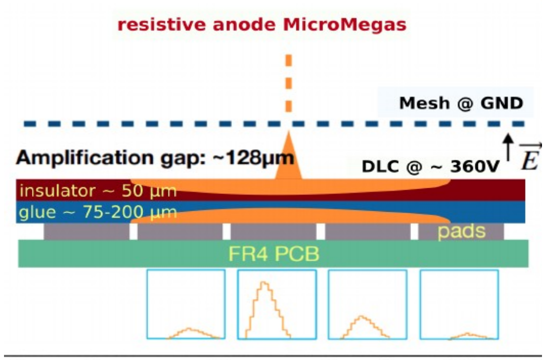
3D 'pixeled' scintillator (1cm^3 cubes)



Neutron measurement

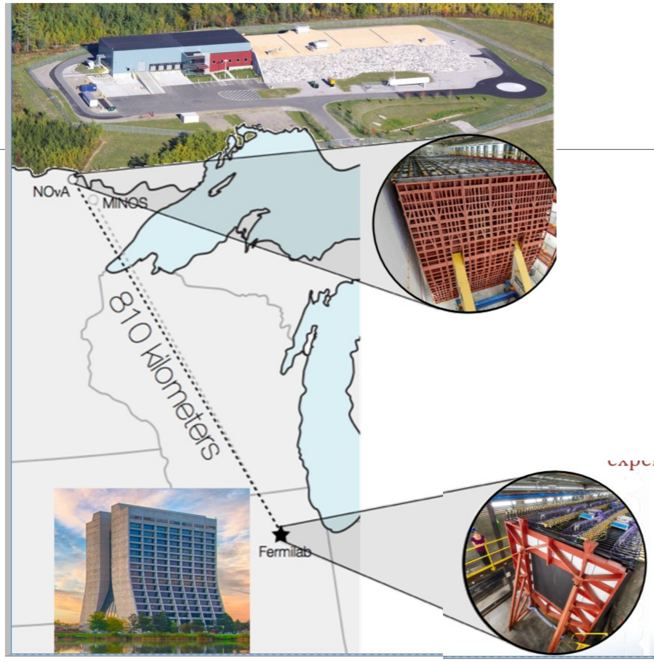


- **TPCs with resistive Micromegas:** coverage at high angle and improved momentum resolution

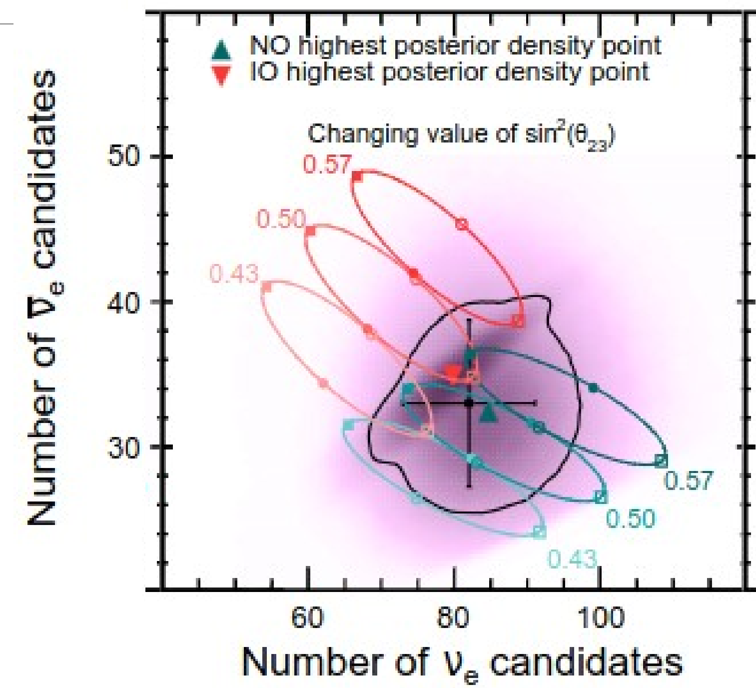


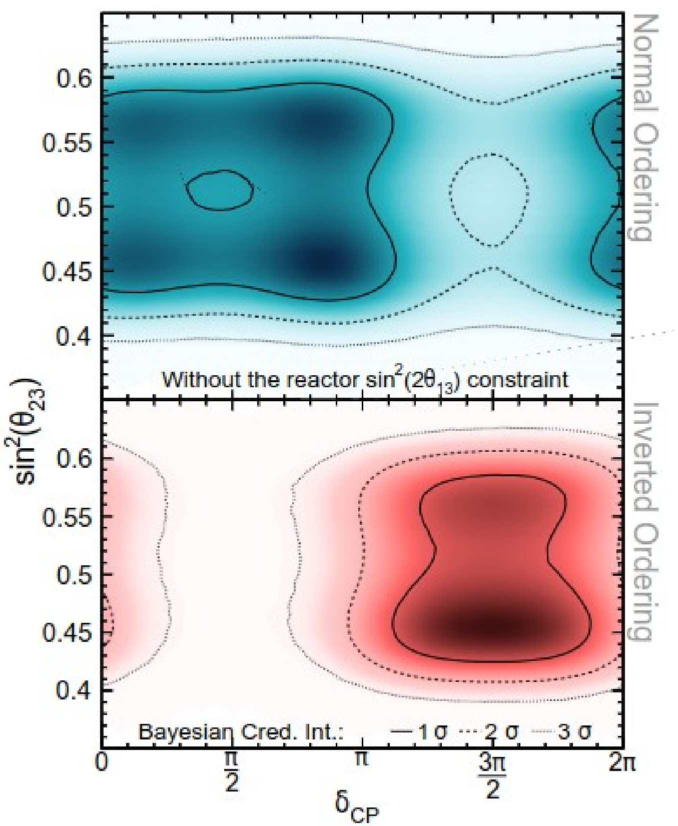
- Scintillator planes all around the **new detectors for Time of Flight measurement of charged particles**

NOVA

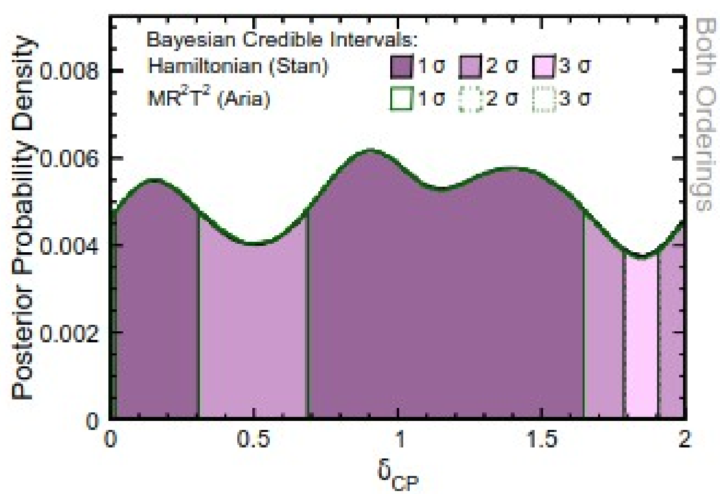


Long baseline and neutrino energy of few GeV:
matter effects along the propagation → **oscillation affected by both CPV and MO**





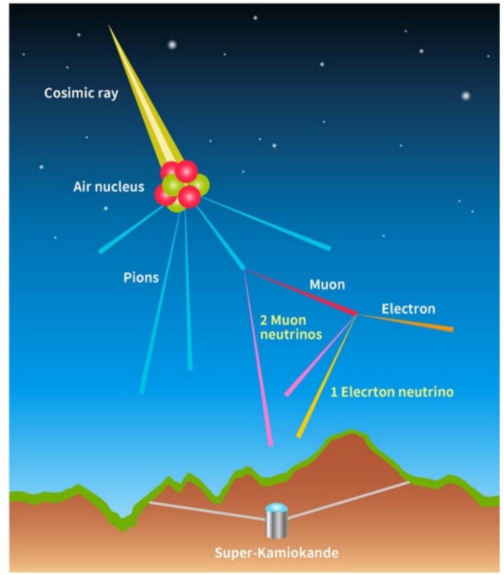
CPV results:

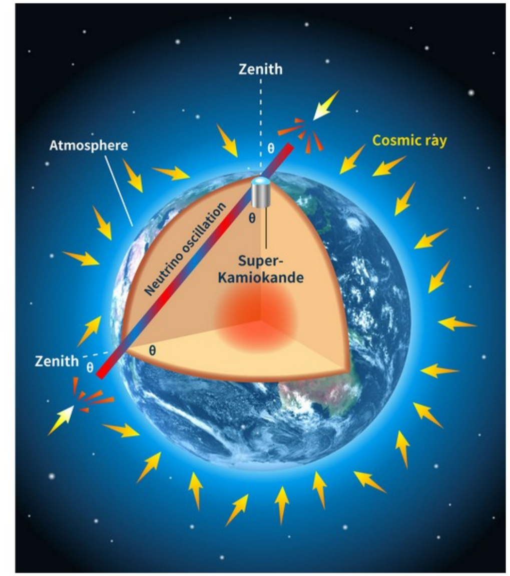


Mass ordering posterior probabilities:
NO 63%, IO 37%

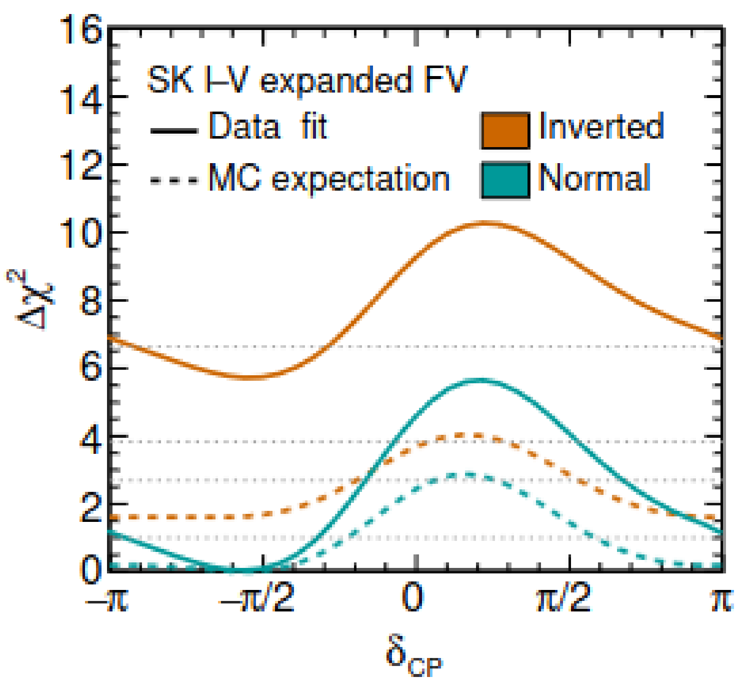
SuperKamiokande

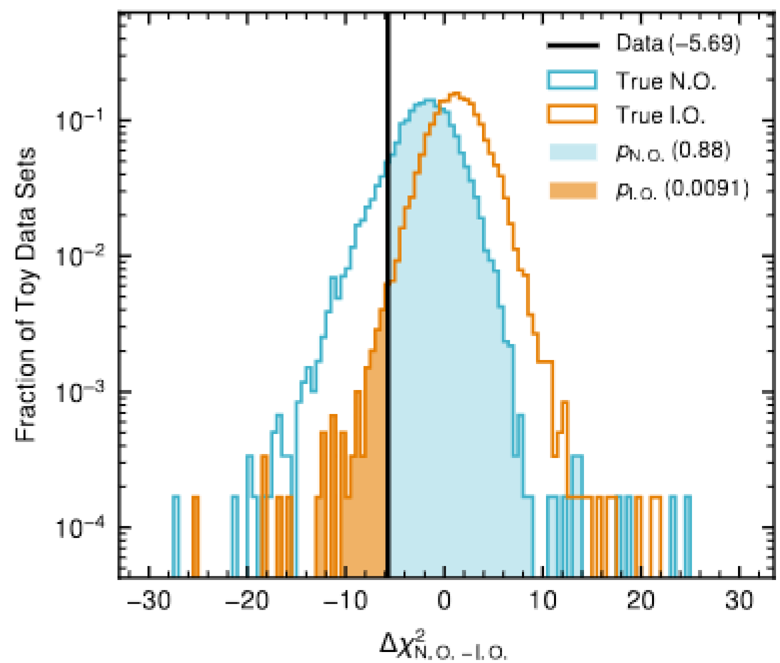
Neutrino from cosmic rays:
oscillation in the Earth matter
→ **best mass ordering sensitivity today**





Preference for NO (92.3% C.L.)
same δ_{CP} preferred region as T2K



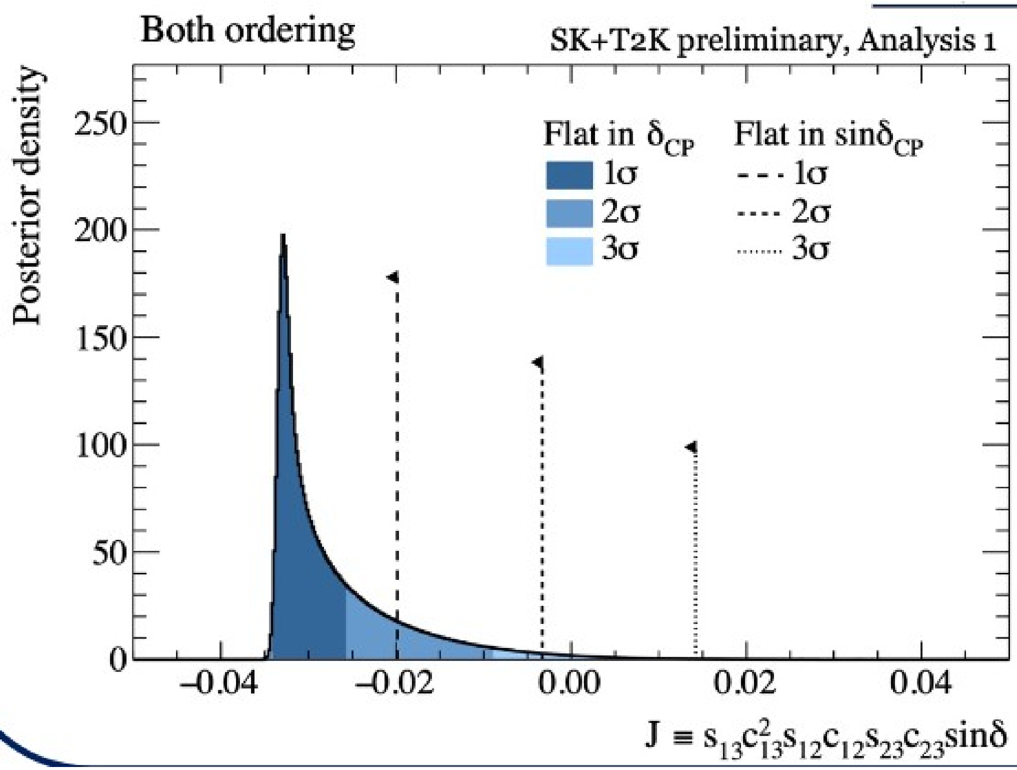


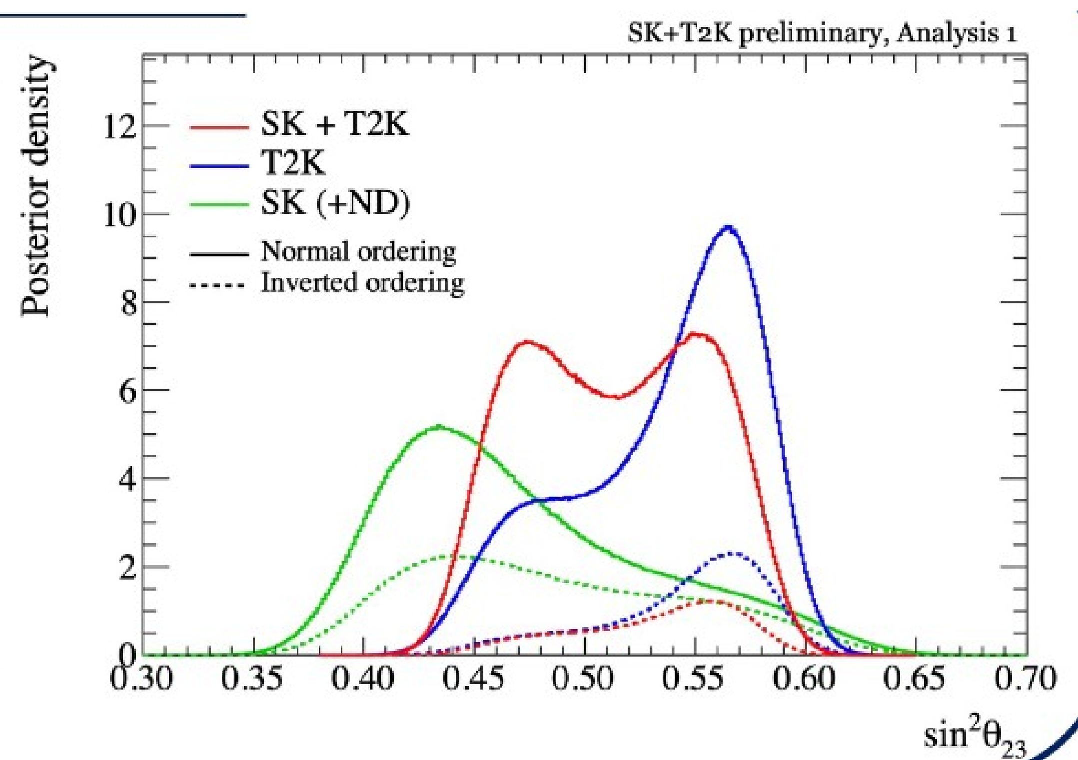
T2K-SK joint fit

Joint analysis with proper correlations on systematics: detector modeling (same far detector) and neutrino-nucleus xsec modeling (overlap in neutrino energies below 1 GeV)

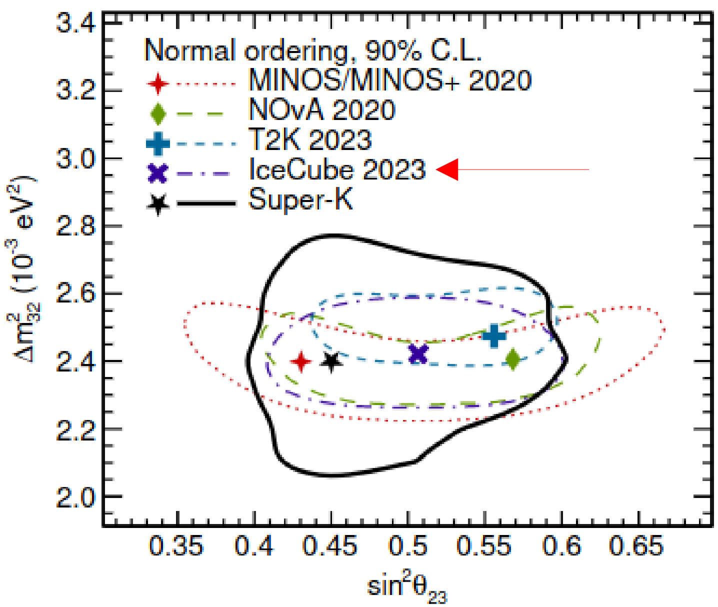
- CP-conservation (J=0) excluded at 1.5-2σ (depending on the prior)

- preference for normal mass ordering: Bayes factor of ~9: "substantial evidence"



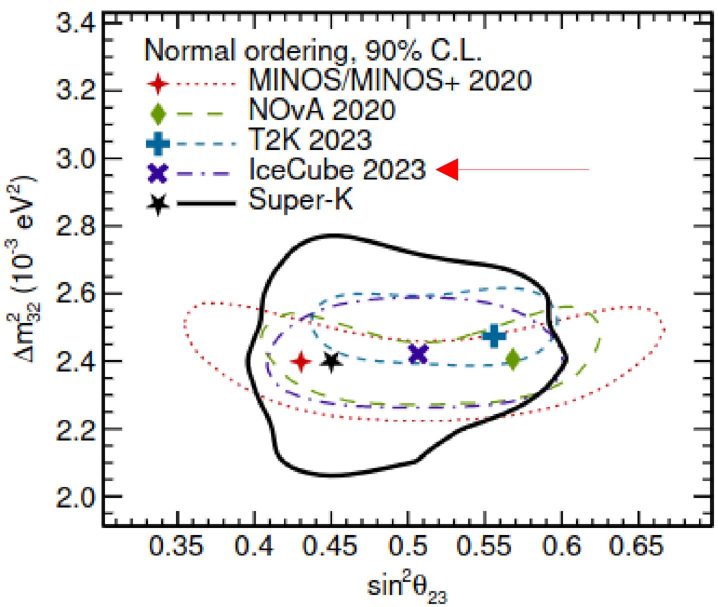


Joint fits


Normal ordering, 90% C.L.
MINOS/MINOS+ 2020
NOvA 2020
T2K 2023
IceCube 2023
Super-K
3.4
3.2
3.0
2.8
2.6
2.4
2.2
2.0
Δm^2_{32} (10^{-3} eV^2)
0.35
0.4
0.45
0.5
0.55
0.6
0.65
$\sin^2\theta_{23}$

Joint fits

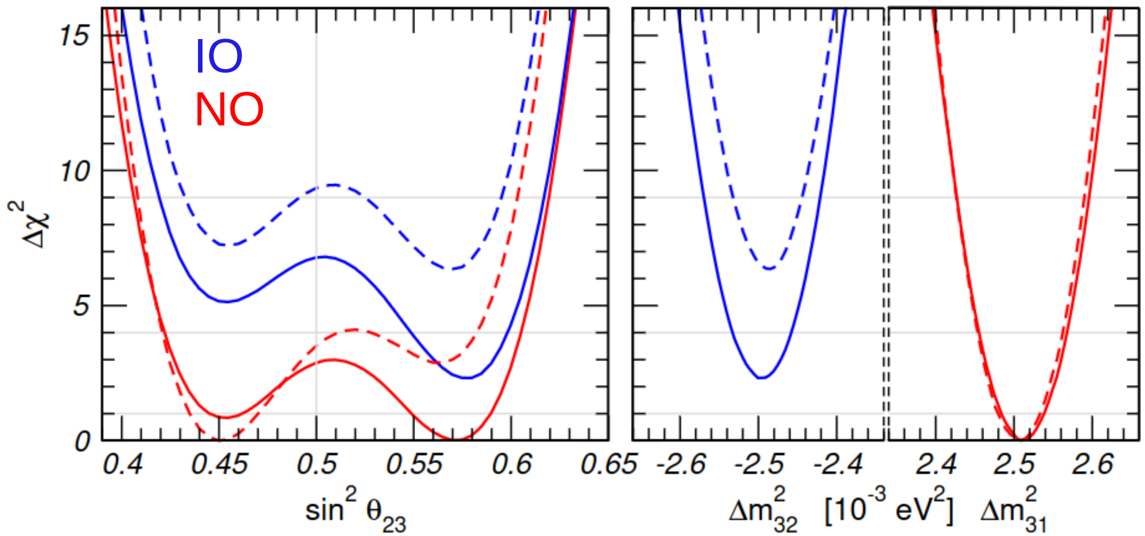
NuFIT 5.2 (2022)



Precision on atmospheric parameters:

- θ_{23} **~few%** precision @1σ but **~25%** precision @3σ: octant degeneracy,

- **$|\Delta m^2_{31(32)}|$ ~1%** (not so robust...) → challenging to control systematics uncertainties



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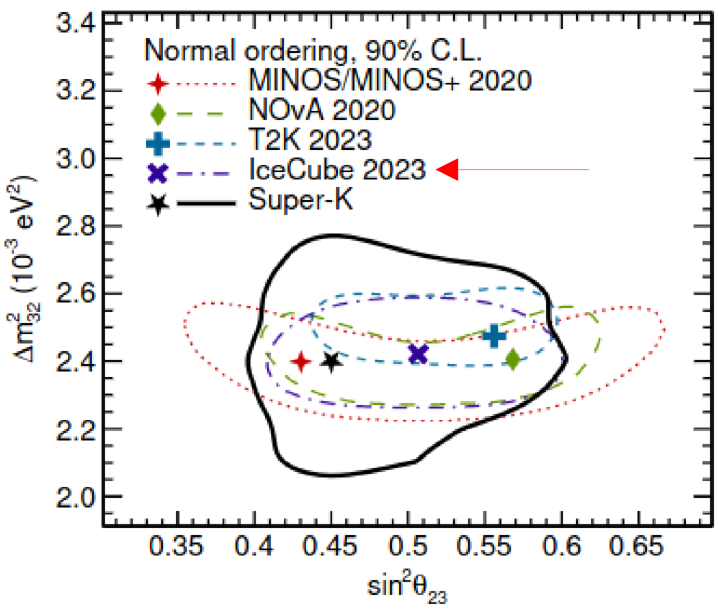

Solve degeneracies between different experiments (eg, CPV vs MO in T2K-SK joint fit)

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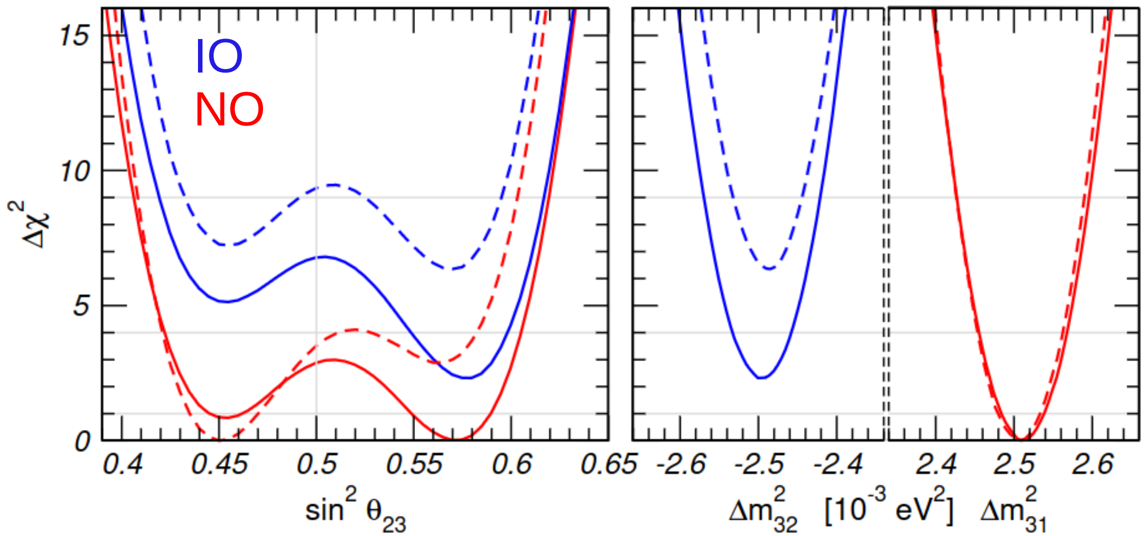

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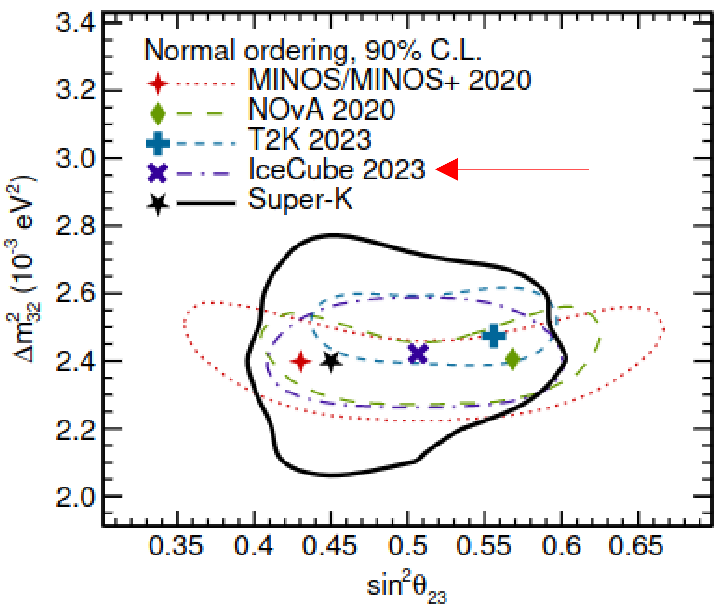

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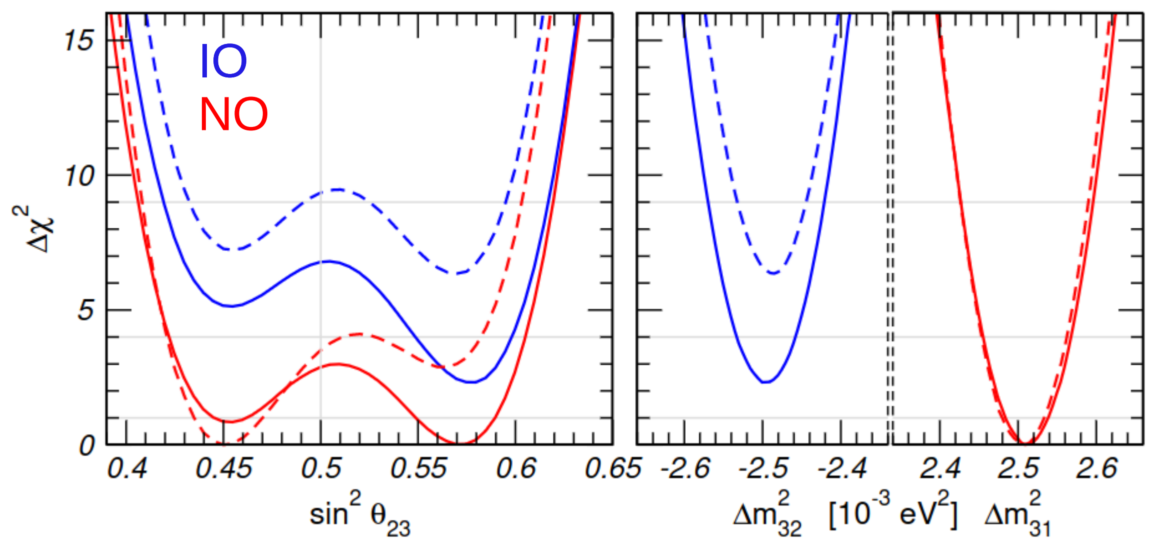

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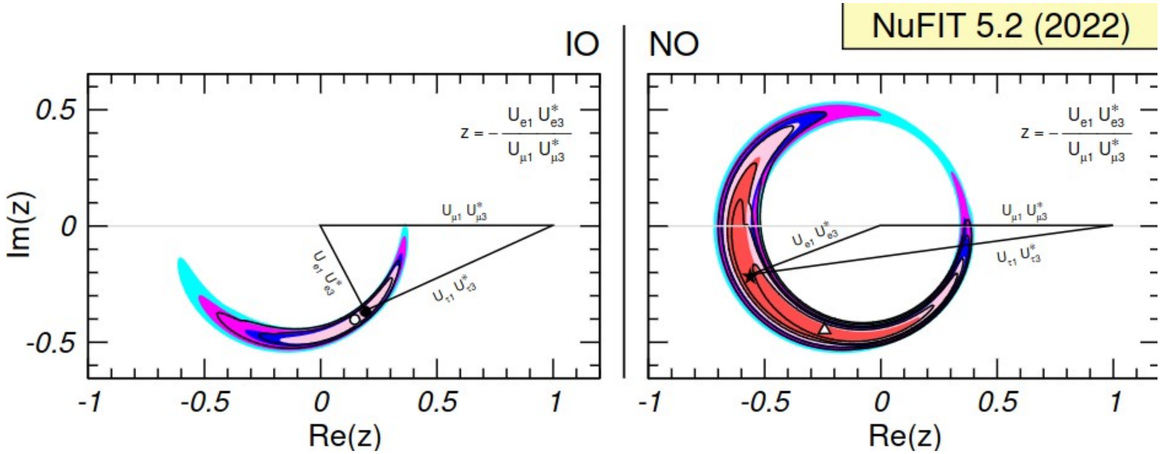
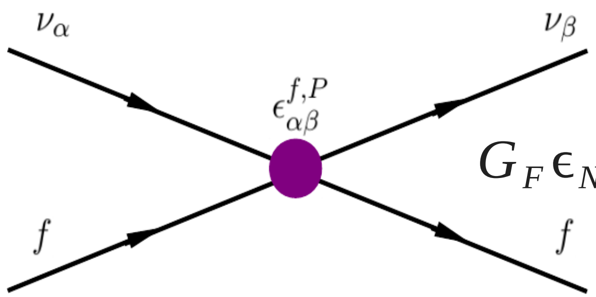


Test the PMNS paradigm: unitarity triangles (as in CKM quark-flavor physics)

Joint fits for BSM

- Peculiar nature of ν and being in direct contact with Λ_{UV}: natural to expect new type of interactions for neutrinos: Non Standard Interactions



$$G_F \epsilon_{NSI} (\bar{\nu}\nu)(\bar{f} f)$$

NSI constraints from T2K-NOVA joint fit: sensitivity from very different baselines

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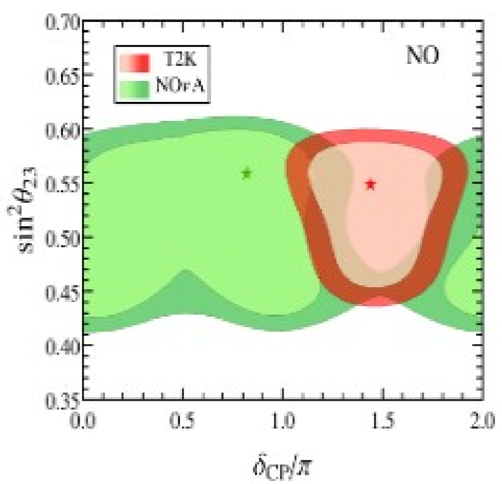
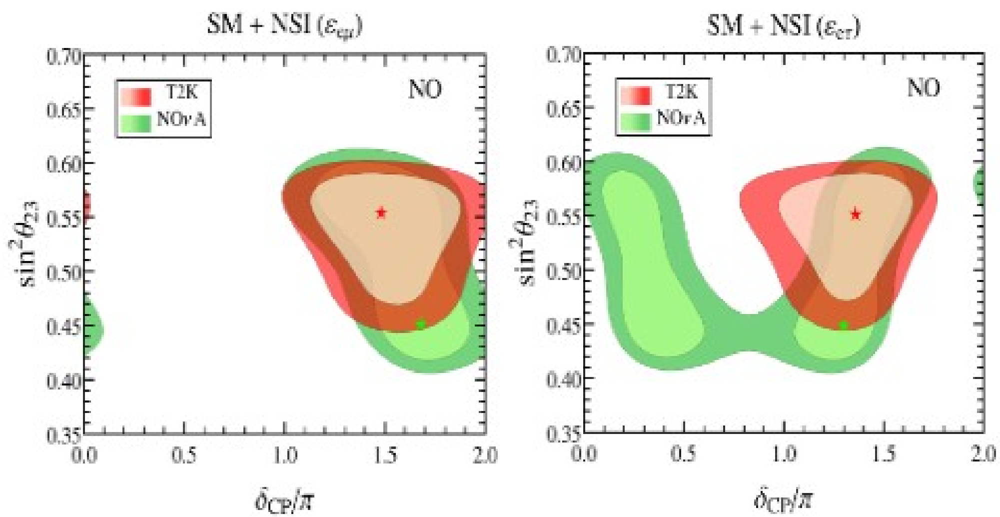
SM



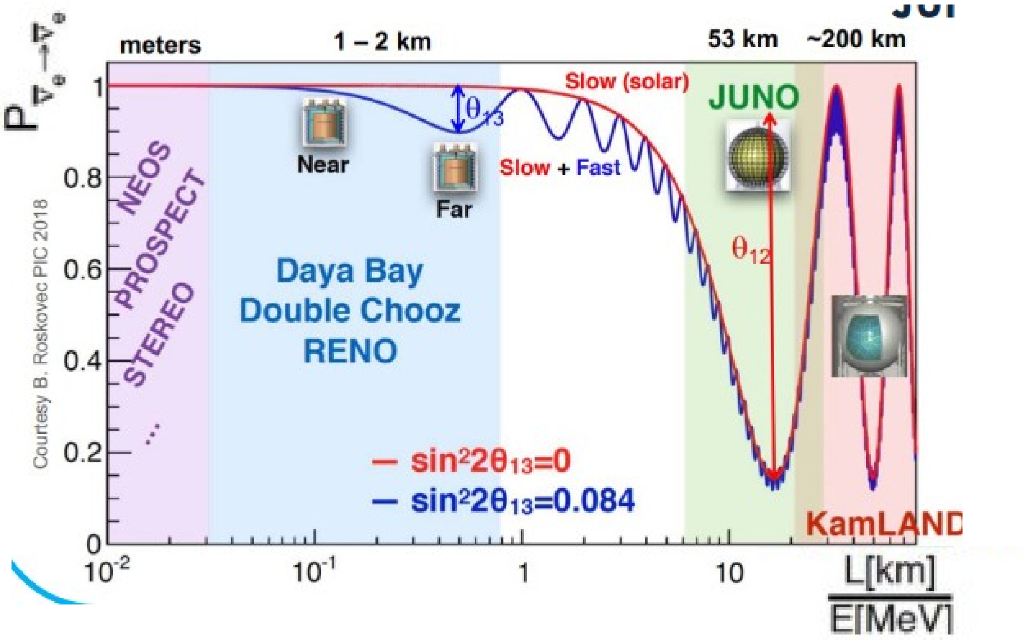
BSM



Where do we go from here?

New experiments starting now

Reactors → JUNO

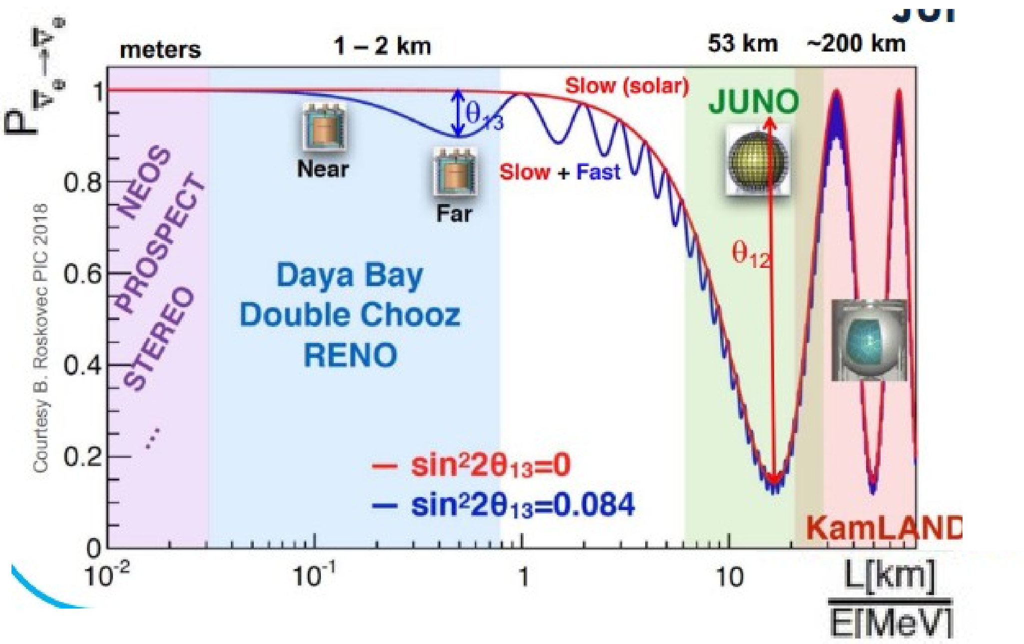


Reactors: $\bar{\nu}_e \rightarrow \bar{\nu}_e$ survival probability

Previous generation

→ precise measurement of **θ_{13} (~1%)** and **$|\Delta m^2_{ee}|$** = $|\Delta m^2_{32}| \pm \cos{}^2\theta_{12}\, \Delta m^2_{21}$ **(~2%)**

Reactors → JUNO



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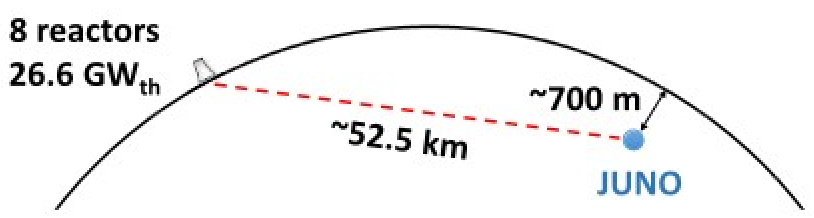
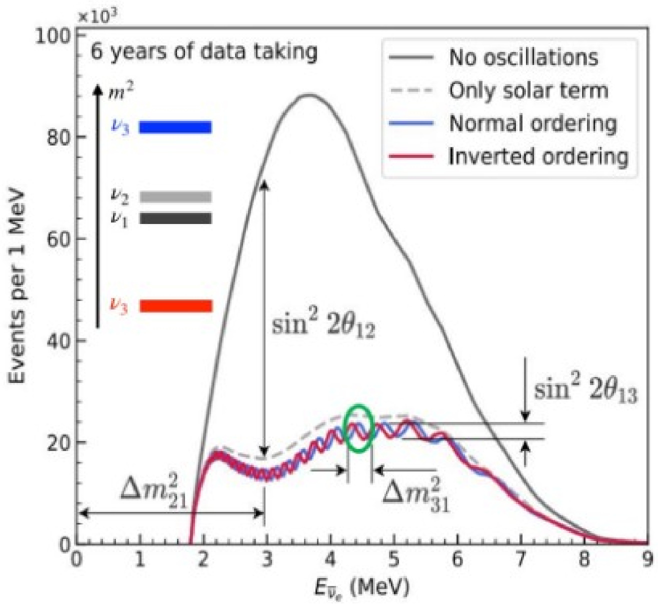
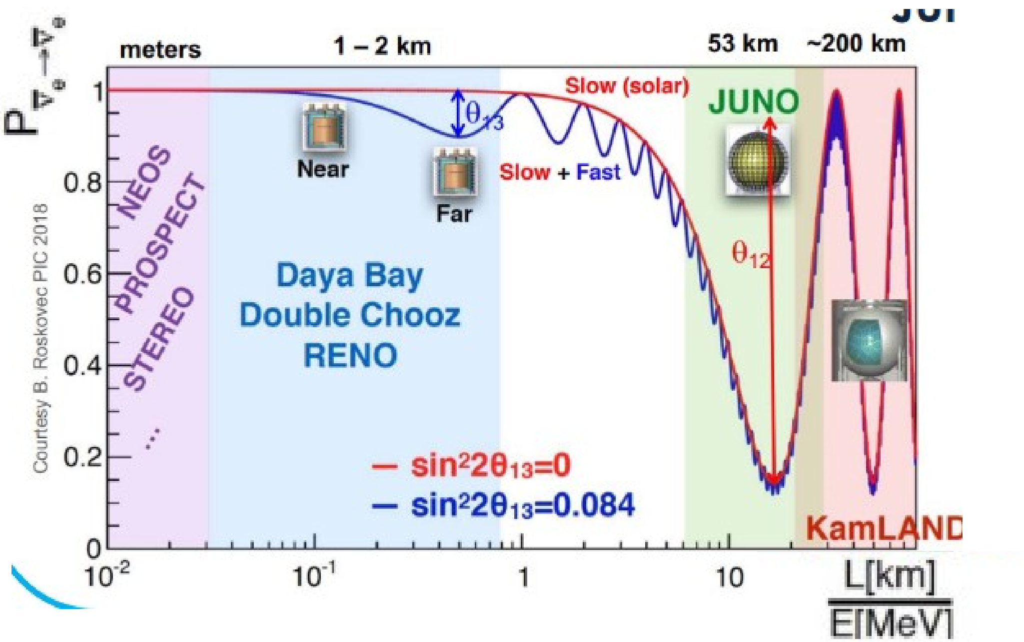
JUNO





MO as a change of phase in the oscillation:
3-4 σ sensitivity

Reactors → JUNO



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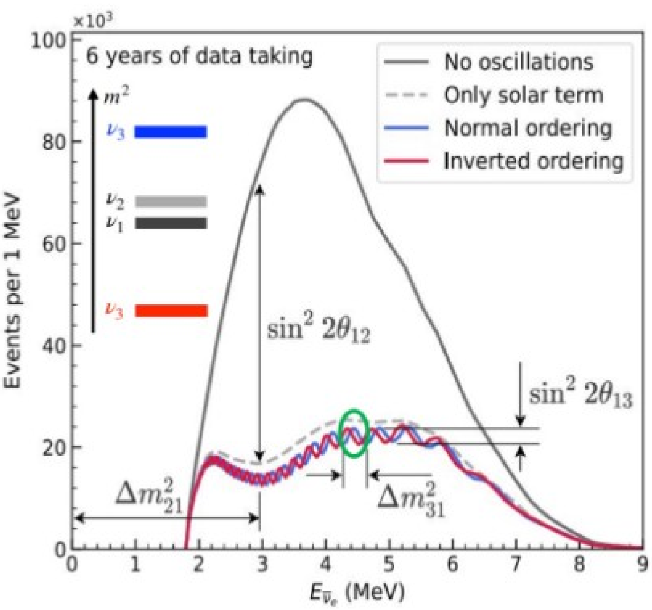
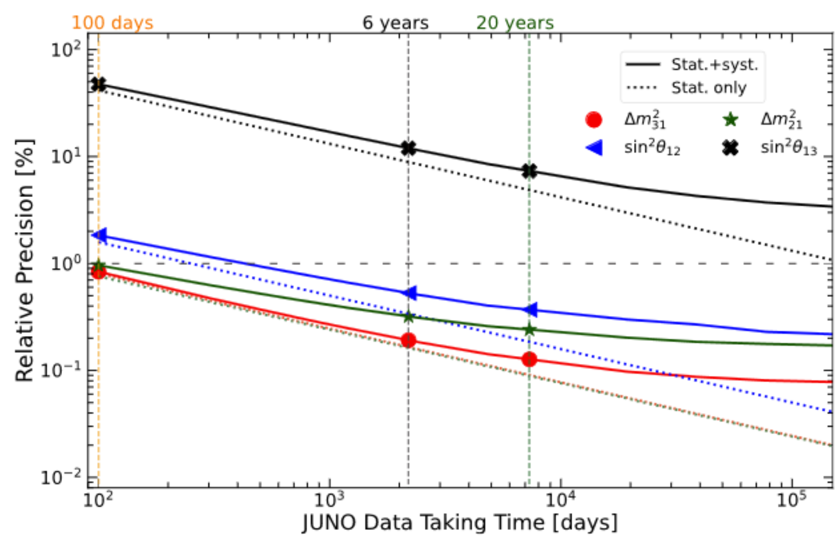


MO as a change of phase in the oscillation: **3-4 σ sensitivity**

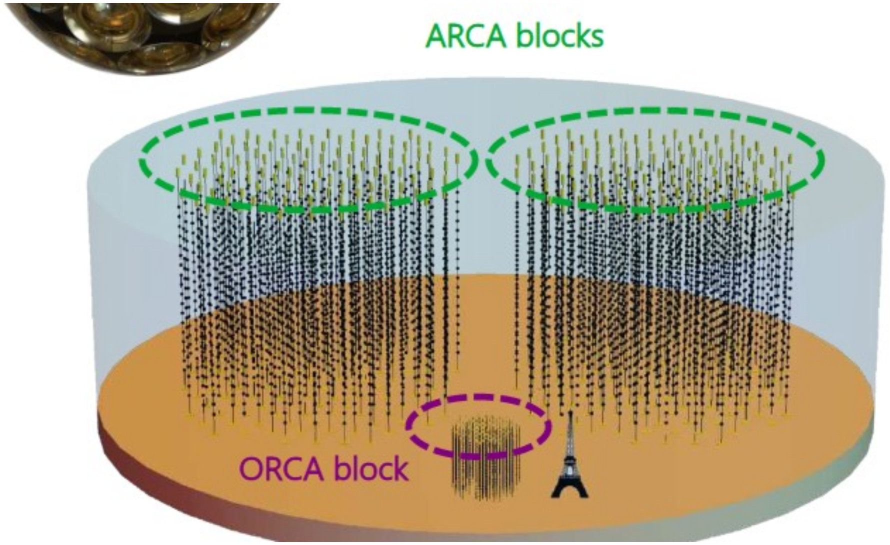
Sub-percent precision on solar sector **(θ_{12}, Δm^2_{21}** → big role in PMNS-unitarity tests)

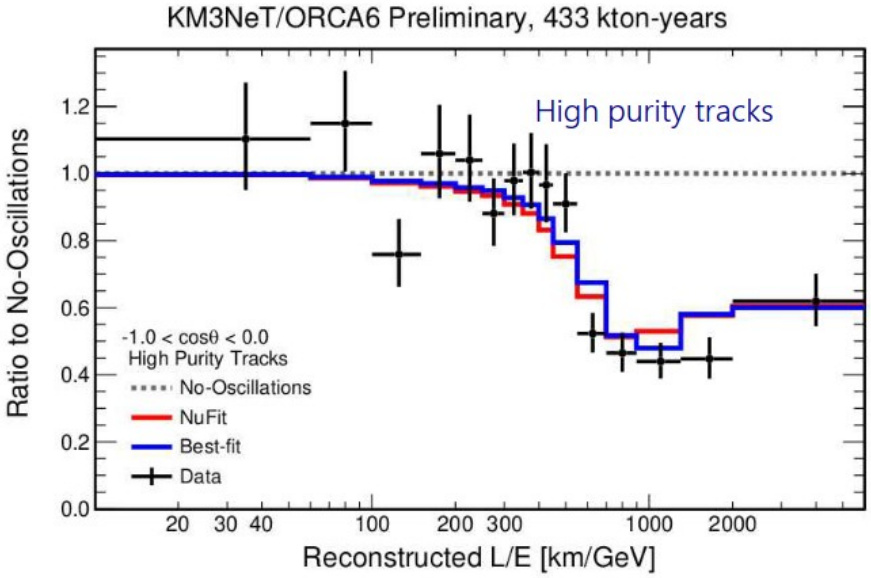


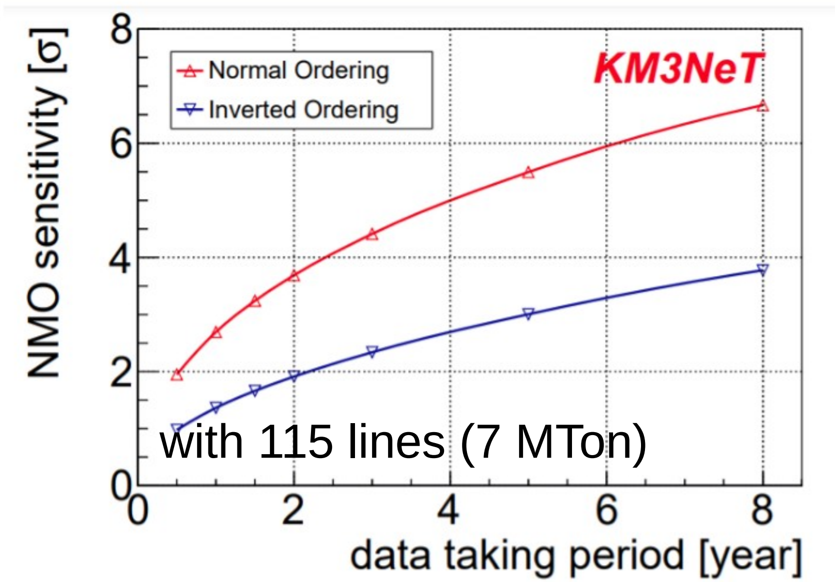
KM3NeT/ORCA

KM3NeT neutrino telescope in the Mediterranean sea open the opportunity for **ORCA: atmospheric neutrino oscillation** with region instrumented with more dense lines of PMTs (under construction)

Another road to MO determination



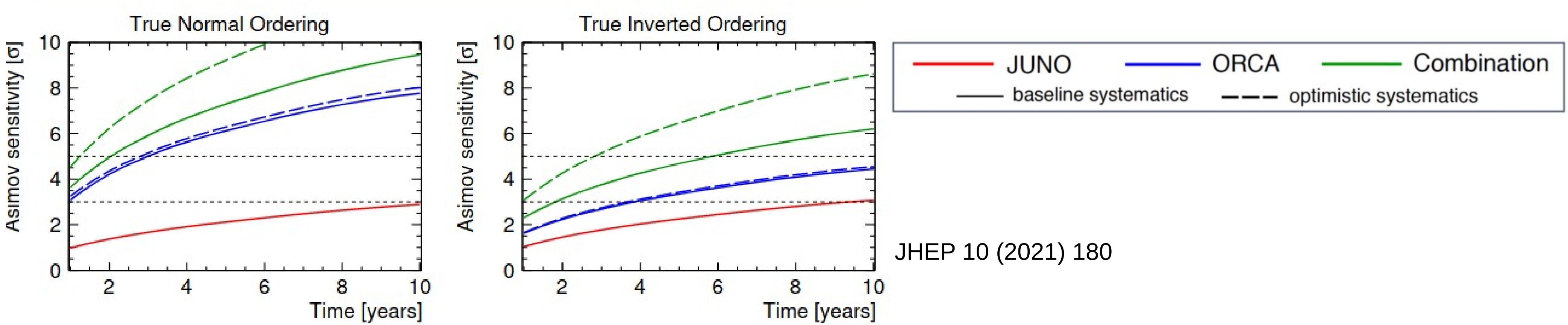




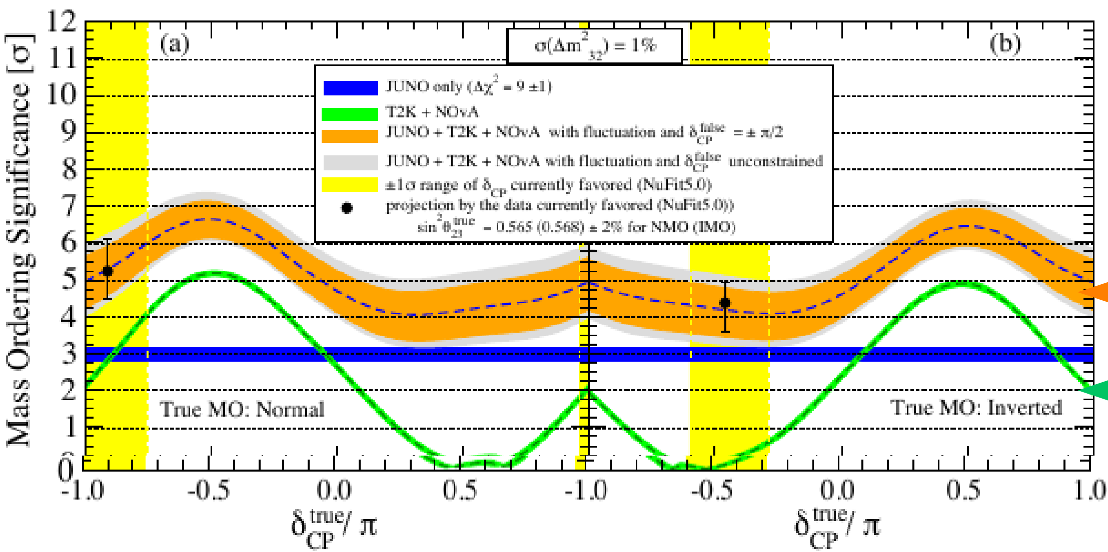
Combinations for MO

Combination of **present data (dominated by SuperKamiokande) prefers NO to 2-3σ**

Prospects for future: >5σ from JUNO+ORCA , 4-5σ from T2K+NOVA+JUNO



JHEP 10 (2021) 180



T2K+NOVA+JUNO

T2K+NOVA

Sci.Rep. 12 (2022) 1, 5393

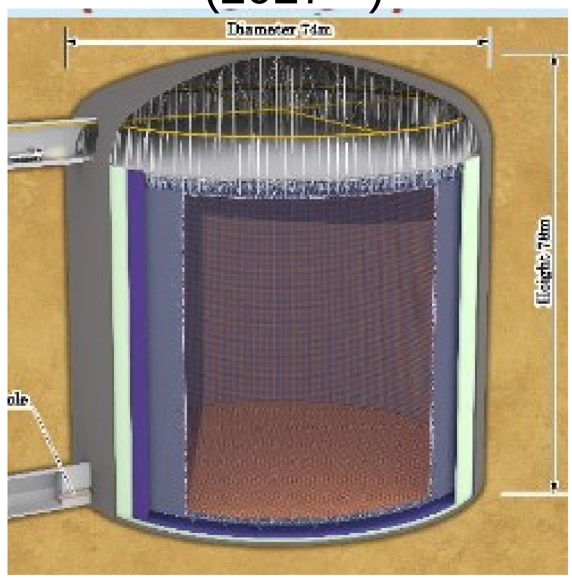
The next generation of LBL: ”5σ experiments” $\rightarrow$ BSM

T2K → T2HK (HyperKamiokande)

Super-Kamiokande
(1996-)

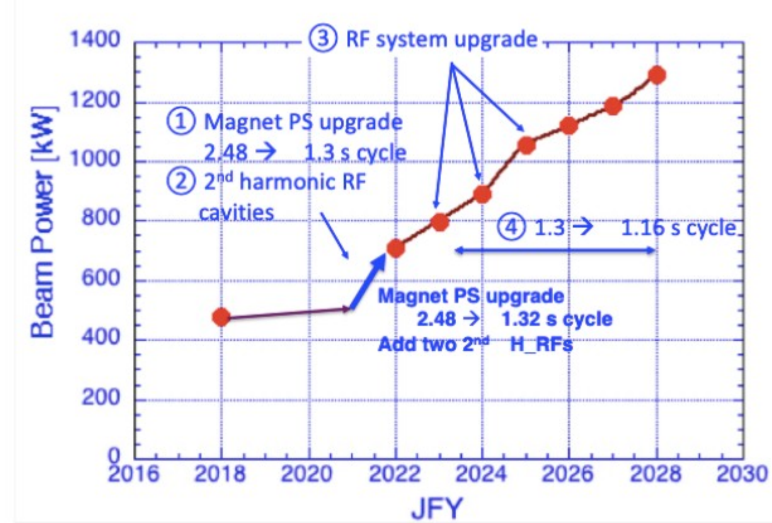
50 kTon

HyperKamiokande
(2027 -)



260 kTon

- Beam upgrade from 500kW to 750kW in 2022 for T2K → **1.3MW in HyperKamiokande era**



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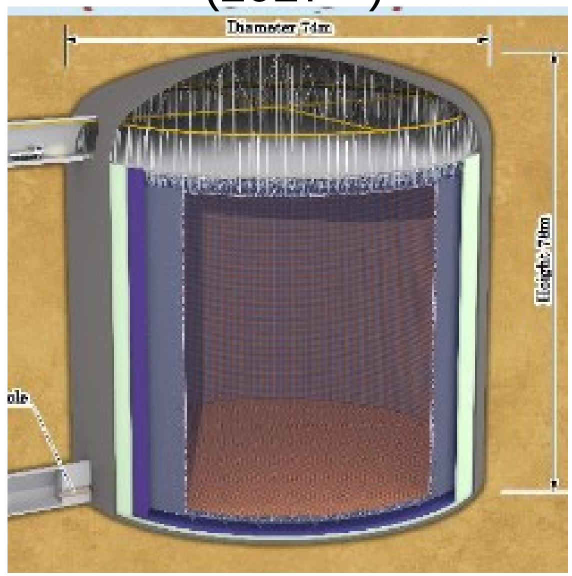

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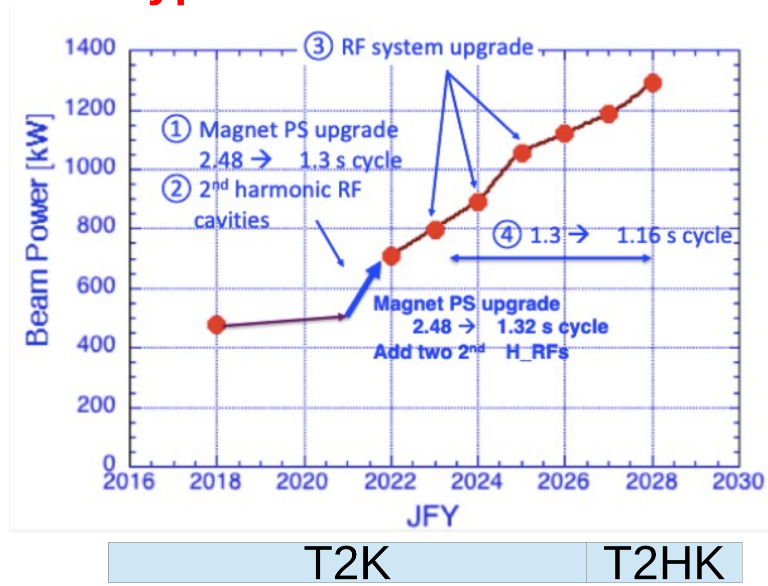
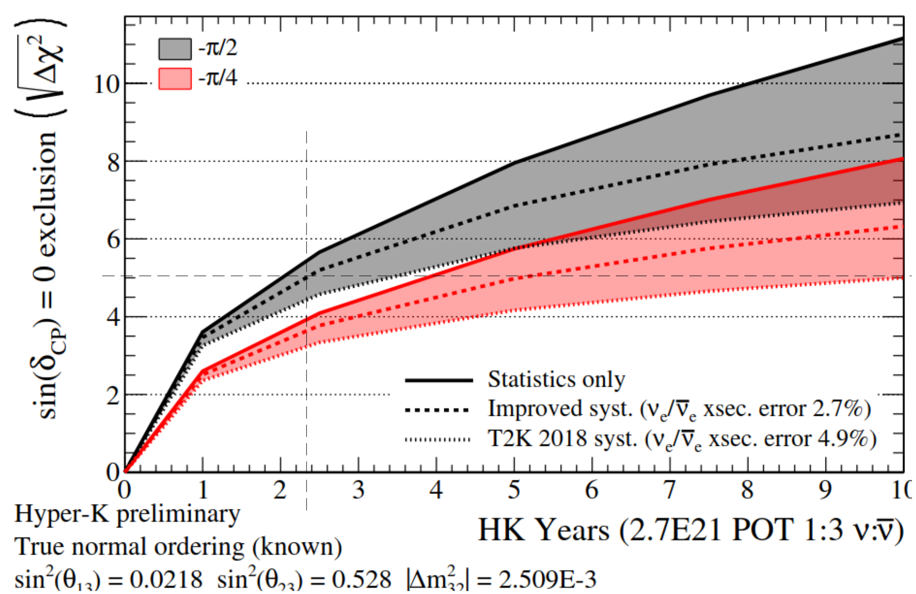


- **M**ore than x20 SuperKamiokande beam neutrino rate **enabling very fast CP-violation discovery**



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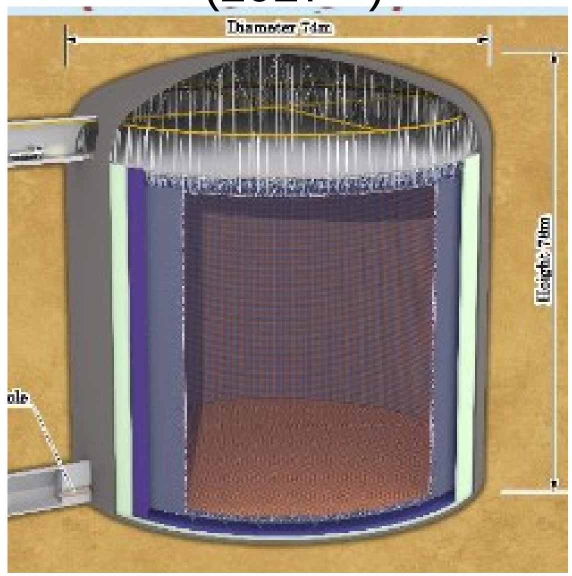

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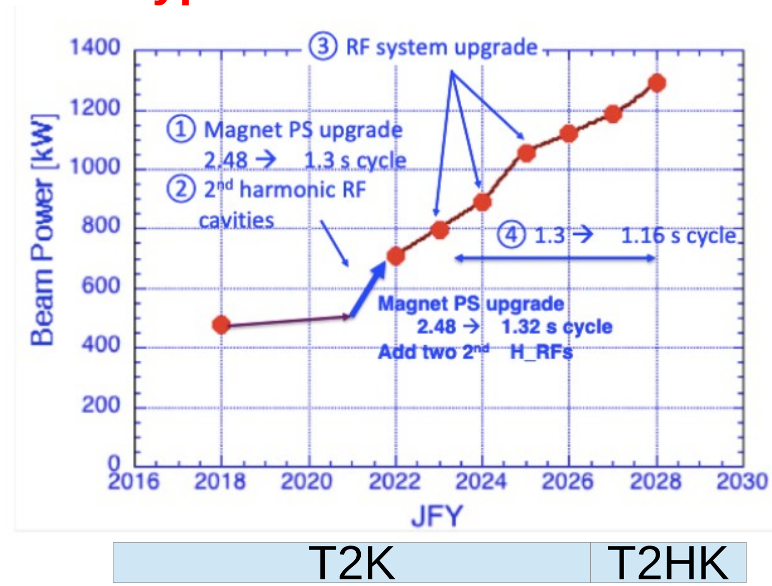
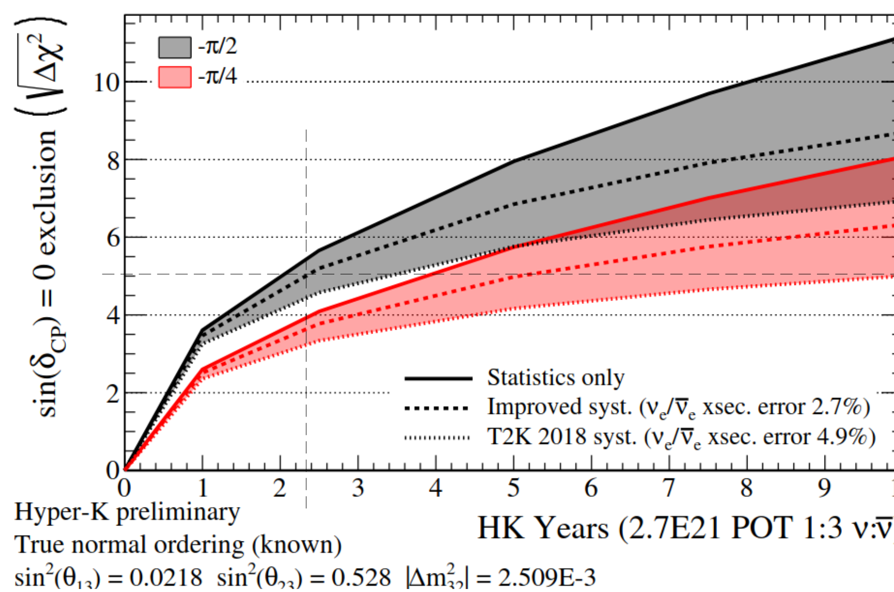


- **More than x20 SuperKamiokande beam neutrino rate enabling very fast CP-violation discovery**

- **Seamless program of neutrino beam**

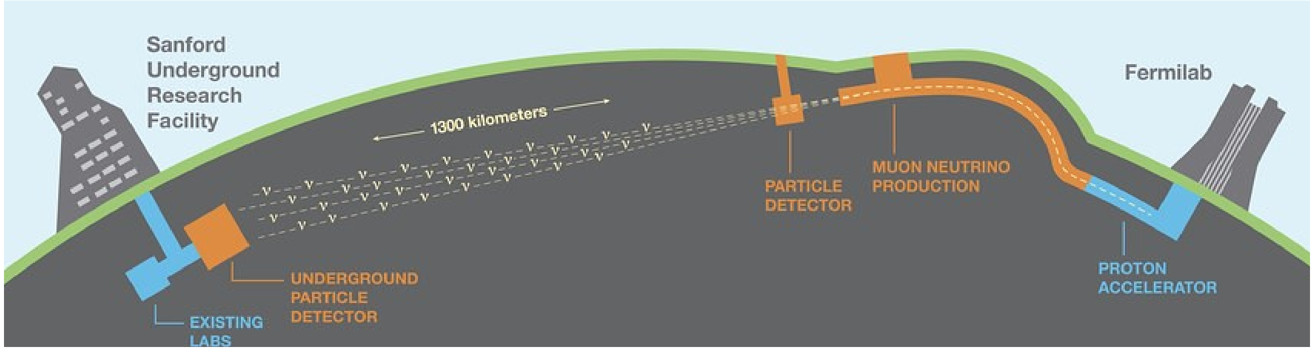
- T2K-"2" will push further the study of systematics at % level with upgrade of near detector ND280.

- ND280 upgrade will be ported from T2K to HK: robust path to calibration/systematic understanding from day 1 of HK



DUNE

New neutrino beam at Fermilab



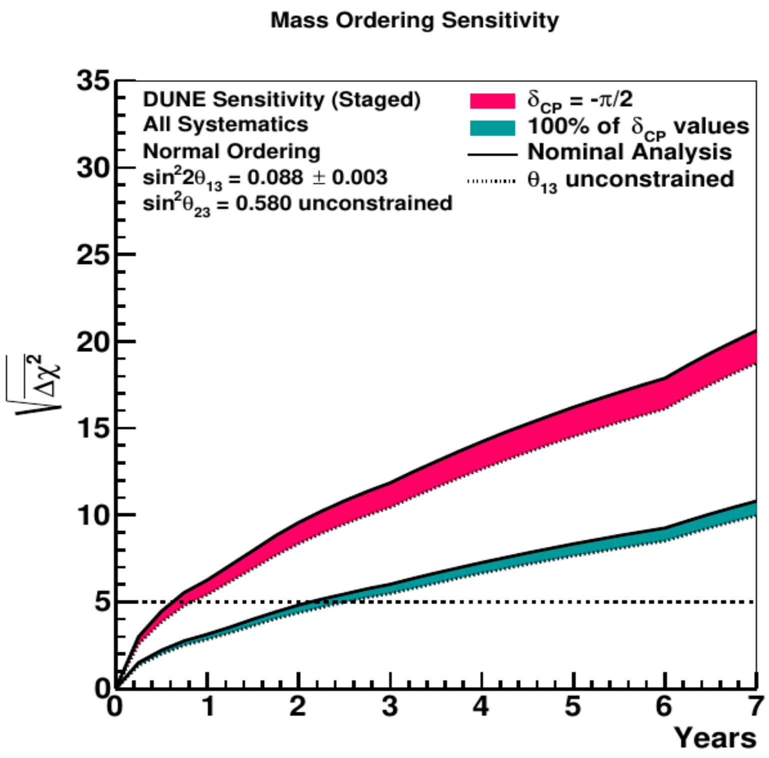
- engagement of US in neutrino physics: **huge enlargement of neutrino oscillation community and resources**

(Relatively) new technology to be deployed to unprecedented scale: 4 large LAr TPCs with charge readout (staged approach)

- Very long baseline and high neutrino energy → fast sensitivity of mass-hierarchy
- Opening **new window** with wide-band neutrino energy flux: a lot of shape information to exploit for precision physics on PMNS paradigm + BSM

- Extension to high energy **where ν-nucleus model less known:** systematics control at ND

- To exploit full sensitivity a shape analysis is needed → **need extremely good resolution on neutrino energy reconstruction**



HK & DUNE

- **HyperKamiokande** has prospects of very fast CP violation discovery, MH from atmospheric neutrinos and precise measurements of sinθ and Δm^2.
  - It is a **"safe"** technology based on existing beam (being upgraded) and with **robust** sensitivity studies based on T2K experience.
  - The timeline is **realistic**

- **JUNO+ORCA+SK+NOVA** has prospects to establish 5σ Mass Hierarchy

- **DUNE** will open a new window with large energy span and very long baseline

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Why both HK and DUNE?

The question is: do we expect the study of neutrino oscillations to have a future beyond the low-hanging fruits of CPV and MH?
If so, we should look at the topic from a **wider prospective** (beyond the present “simplistic” paradigm of the measurement of PMNS parameters)

What we want to do is to characterize **precisely** the oscillation as a function of the fundamental variable **L/E**

→ **different baselines** → characterizing oscillations beyond PMNS

→ study oscillations at **different neutrino energies**

→ reconstruct neutrino energy with **different technologies**

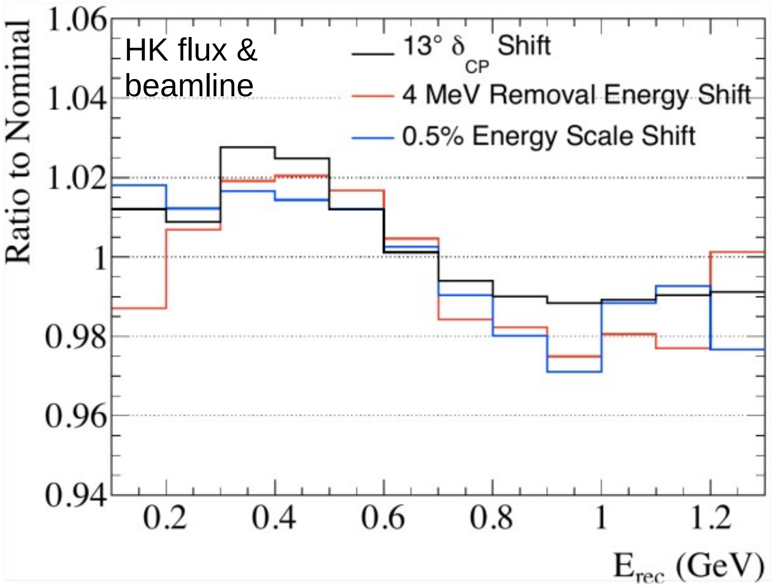
I will make few examples of **complementarity and importance of combination: PMNS precision + beyond PMNS**

Precision measurements of PMNS parameters

- Precision physics will be dominated by systematics

  - ~2000 of ν_e ($\overline{\nu}_e$) and ~10000 events ν_μ ($\overline{\nu}_\mu$)

  → precision measurements require very good control of **neutrino energy spectrum shape**



Both HK and DUNE aim to same precision targets:

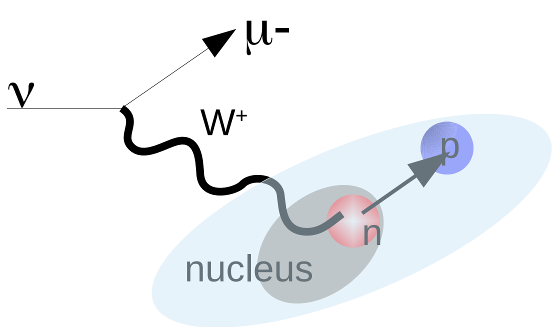
measurement of δ_{CP} <15deg and of Δm^2 ~ 1% require control of energy scale (calibration + nuclear effects) <1%

- Crucial role of **present experiments (T2K – NOVA) to open the road to % systematics** and indicating analysis strategies and detector design enabling such precision

- Crucial role of **near detectors**

Systematics: ν energy reconstruction

HK: quasi-elastic interactions reconstructed from final state muon



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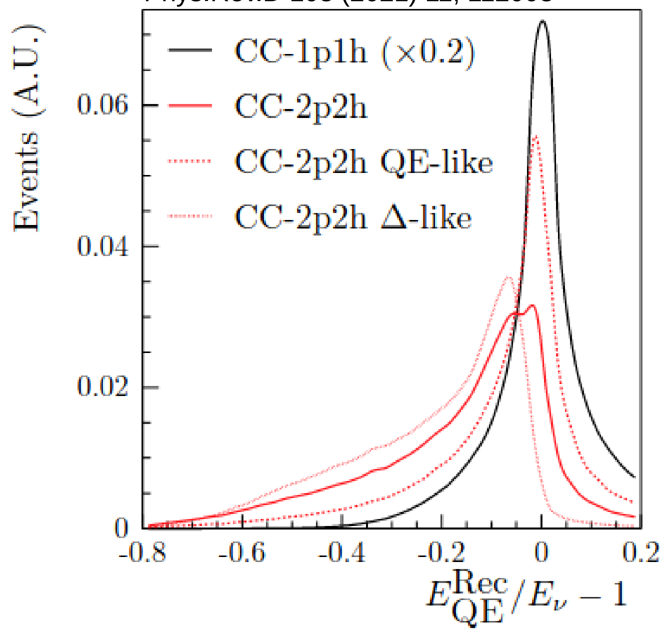
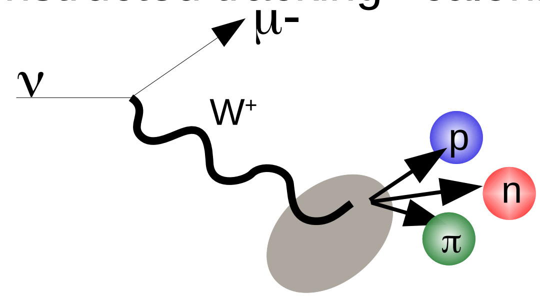
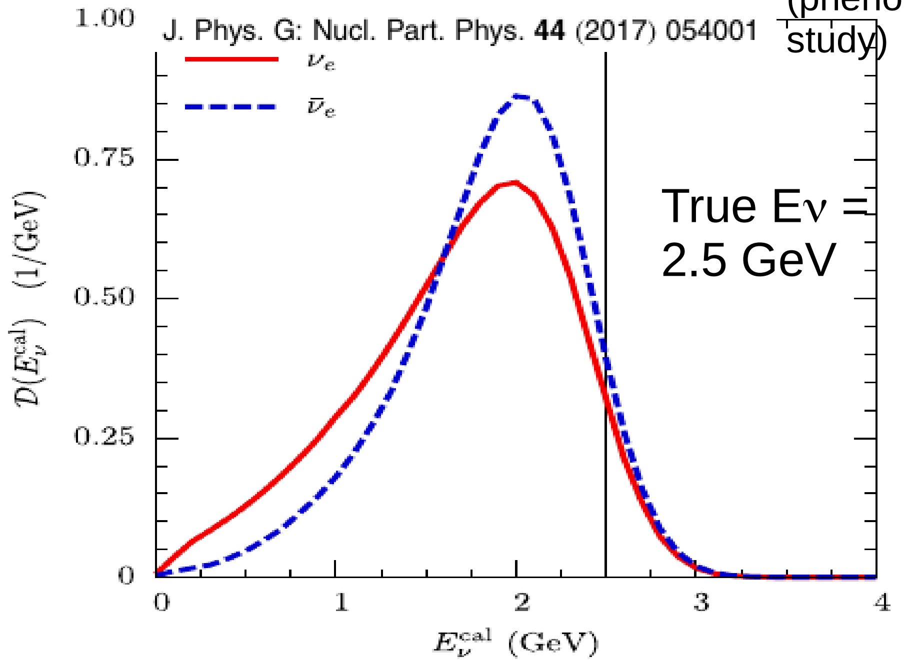


- Bias due to **non-QE reactions**

DUNE: high-energy → non-quasi-elastic interactions reconstructed tracking+'calorimetric'



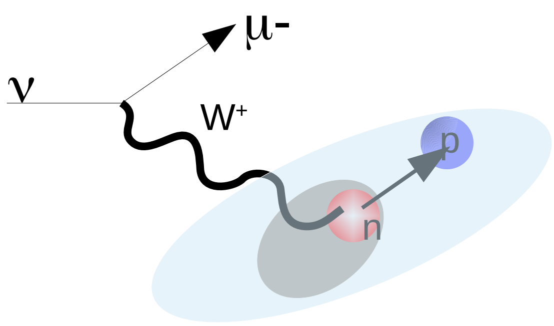
(phenomenological study)



- Bias due to 'missing energy': **neutrons (entangled with detector calibration for hadrons below tracking threshold)**

Systematics: ν energy reconstruction

HK: quasi-elastic interactions reconstructed from final state muon



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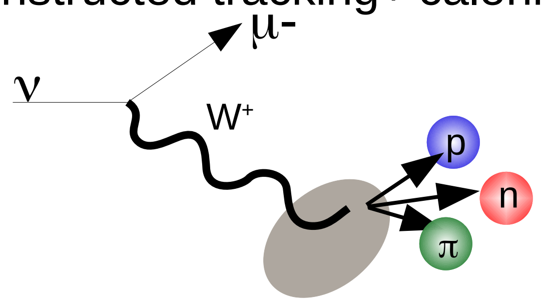

The impact of nuclear effects is different in DUNE and HK: their comparison is extremely powerful to build confidence on precision measurements

Systematics: the role of near detectors

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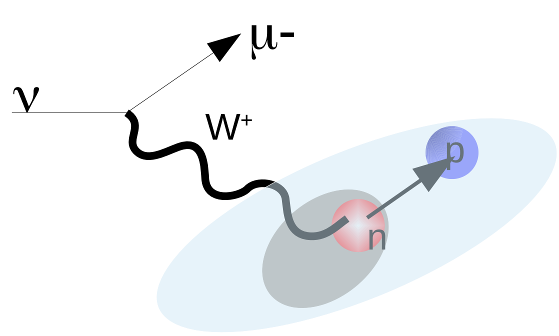

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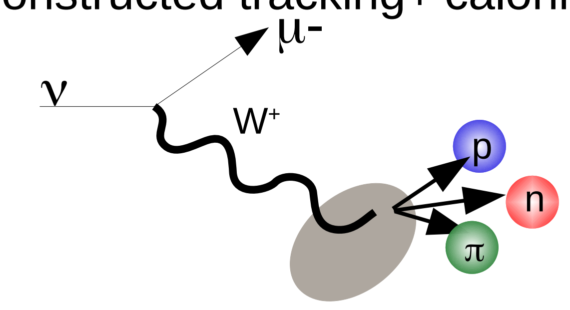
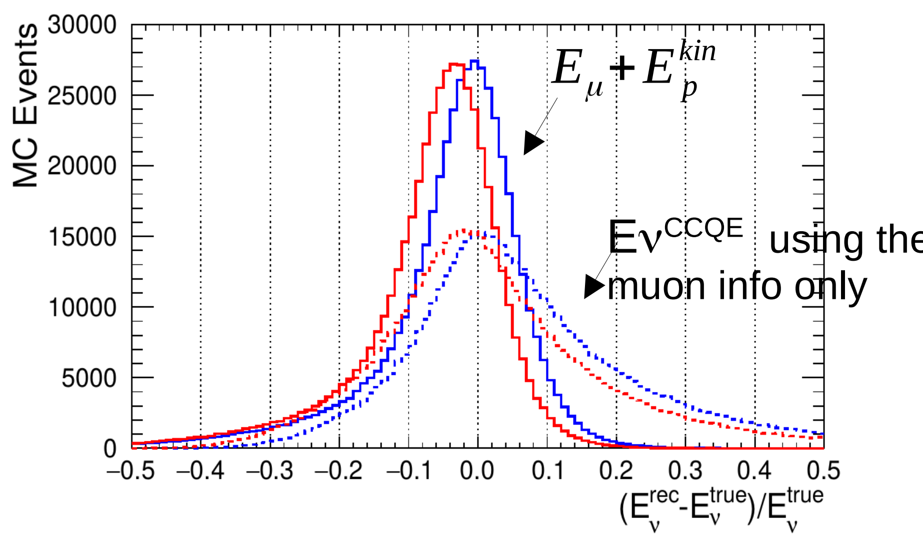


The impact of nuclear effects is different in DUNE and HK:
their comparison is extremely powerful to build confidence on precision measurements

The role of near detectors is crucial to constrain the systematics and provide **measurements able to cross-validate the two experiments**

need for a coherent program of ND measurements between HK and DUNE + establish a common language in terms of nuclear physics systematics

T2K ND280 upgrade: measure everything (also neutrons!) and compare/constrain the different nuclear effects



Beyond PMNS

- **The 'standard' oscillation paradigm (PMNS-based) is very strict and not motivated by fundamental symmetries** (mixing angles and neutrino masses are 'accidental' numbers).

In particular it assumes

- minimal 3-flavour scenario
- standard neutrino interactions for production and detection
- standard matter effects along propagation

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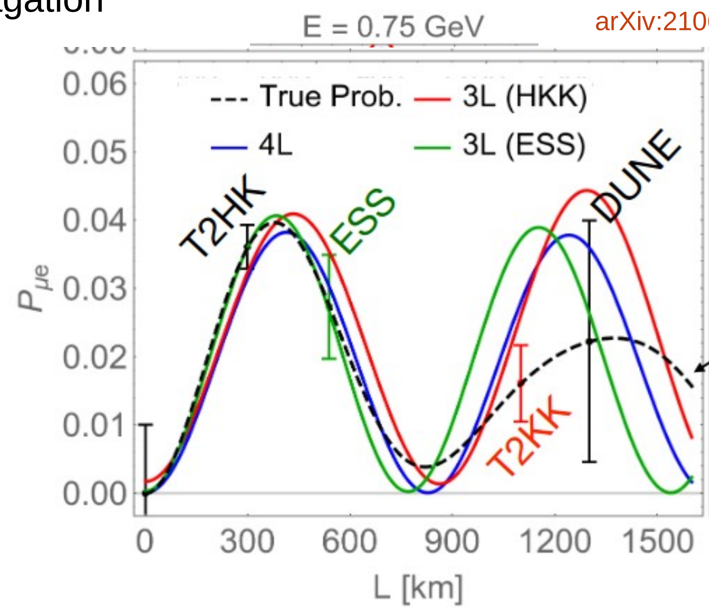
Example of **general beyond-PMNS 'effective' approach:** can we search for **fundamental CP violation in a more model-independent way?**

- allow for arbitrary (non-standard) matter effect
- allow for arbitrary (non-unitary) mixing between flavour and energy eigenstates

→ **search for T-violation** → **look for L dependency of oscillations at fixed energy**

arXiv:2106.16099 [hep-ph]



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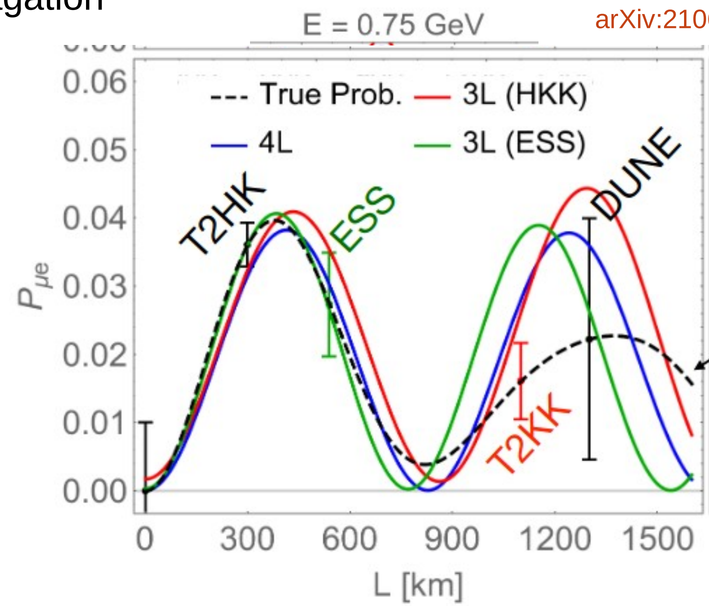

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3nu probability with $\delta_{CP} = 90°$

- **Combination of experiments will be crucial for a comprehensive, precise and open-minded characterization of ν oscillations**

A reharsal: T2K+NOVA combination (really though!!)
It is difficult and it could impact the way we design the analysis and the near detectors! → Start to plan for it now!

ββ solar reactor accelerator atmospheric coherent scattering BSM P2IO

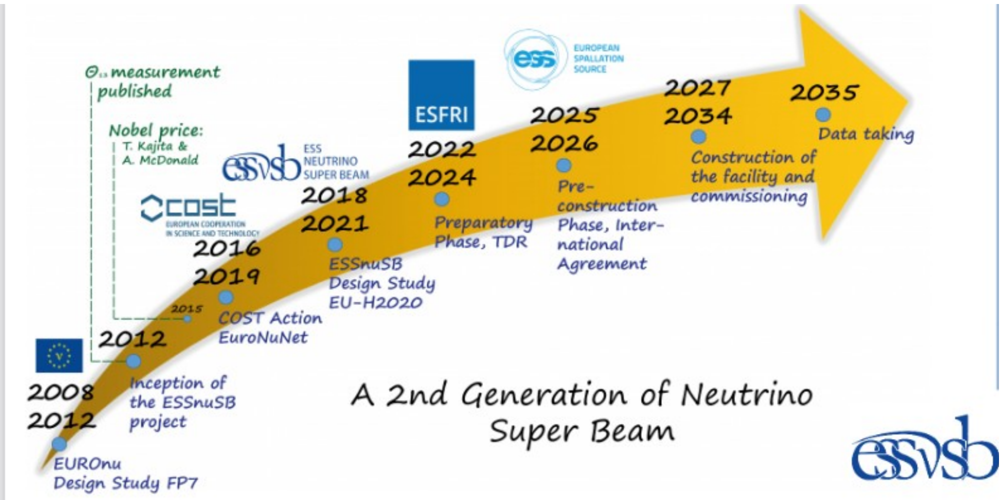
Eg: BSMNu project financed by the P2IO labex → **French (Paris-Saclay) community covering multiple experiments is an ideal position to lead this effort**

Looking further into the future

- **T2KK:** second HK tank in Korea

- **ESSνSuperBeam:**
covering 2nd oscillation peak
+ HIFI
(demonstrator for low energy
νSTORM)

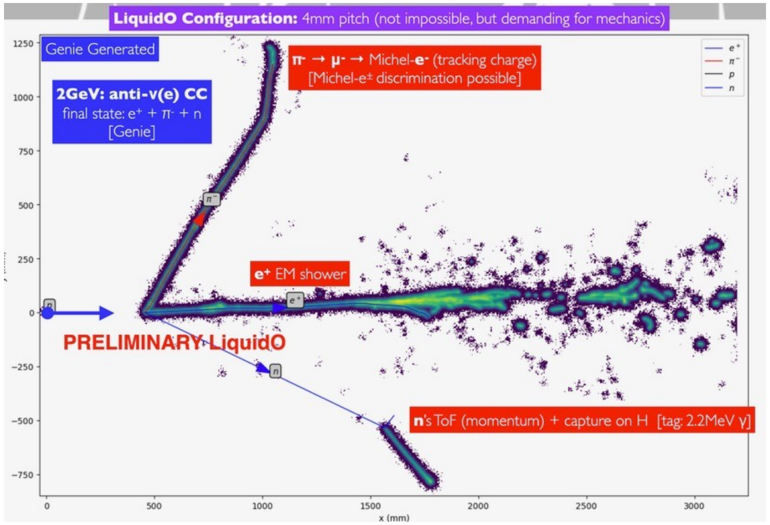
https://arxiv.org/abs/2107.07585



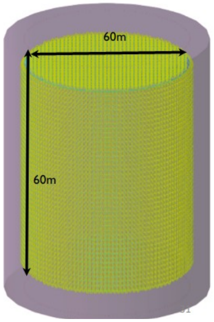
- **νSTORM:** muon storage ring giving very well known ν_e and ν_μ fluxes
(R&D toward Neutrino Factories)

- **LiquidO:** studies for even improved S/B and resolution
→ θ_{13}, non-unitarity, solar neutrinos...

Opaque target readout by many fibers
→ SuperCHOOZ



- **THEIA:** water based (doped) optical detector for comprehensive neutrino program (scintillation + Cherenkov)



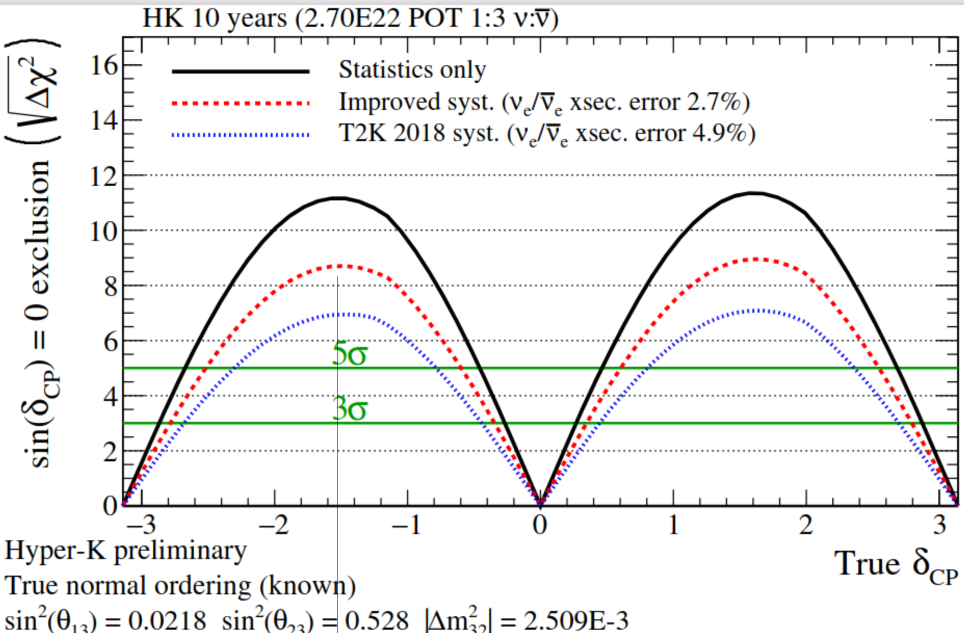
BACK-UP

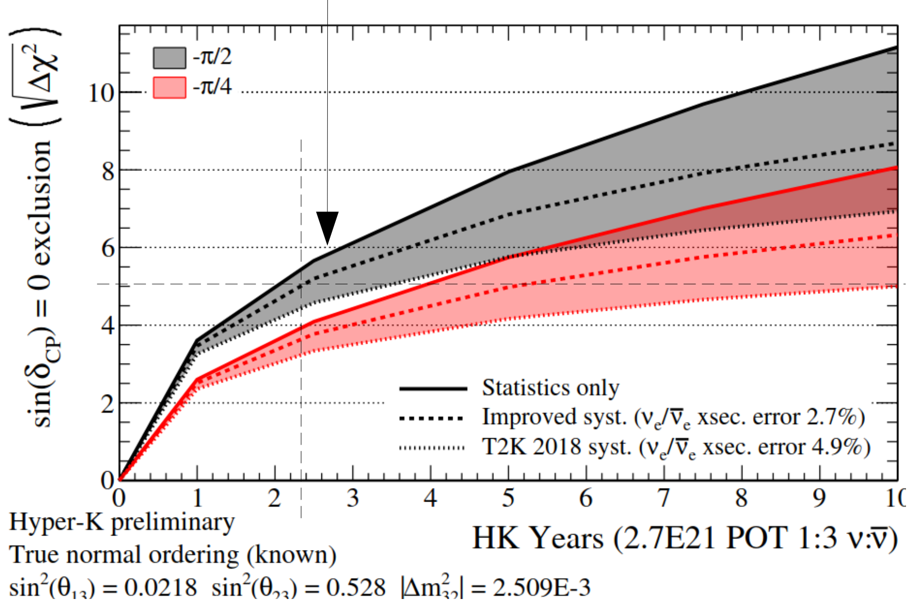
HyperKamiokande sensitivity

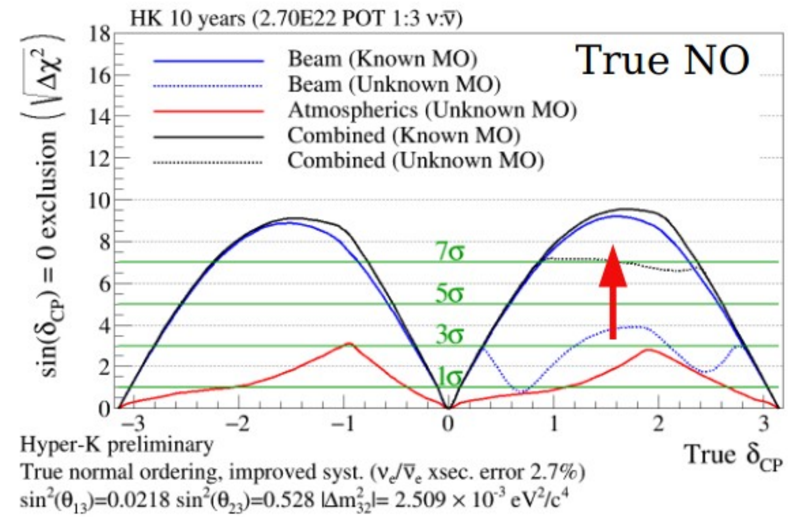
CP-violation sensitivity with known mass hierarchy:

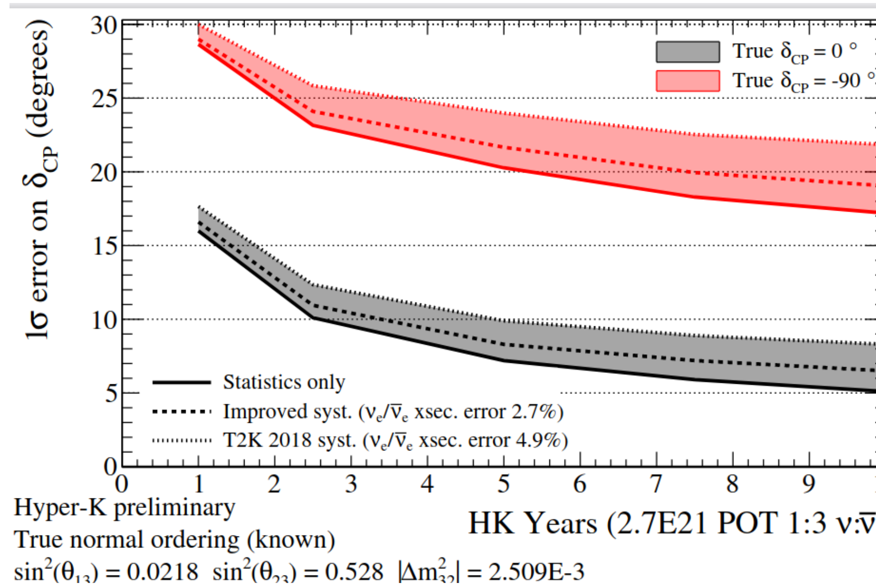
Unknown MH: combination of atm and beam neutrinos to measure δCP and MH

→ x8 SuperKamiokande natural neutrino rate









Study of L

- Expand the oscillation study with a **more general paradigm: with next generation of experiments we will look at oscillations with a much more open-mind approach:** we want to characterize the L/E dependency of flavour mixing

Eg: can we search for **fundamental CP violation in a more model-independent way?**

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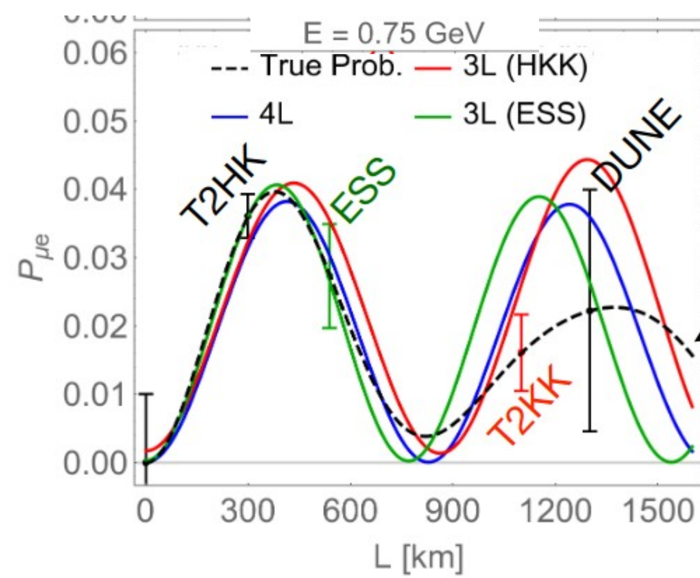

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3nu probability with $\delta_{CP} = 90°$

- Combination of experiments will be crucial for a **comprehensive, precise and open-minded** characterization of ν oscillations

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It is difficult! → Start to plan for it well in advance!

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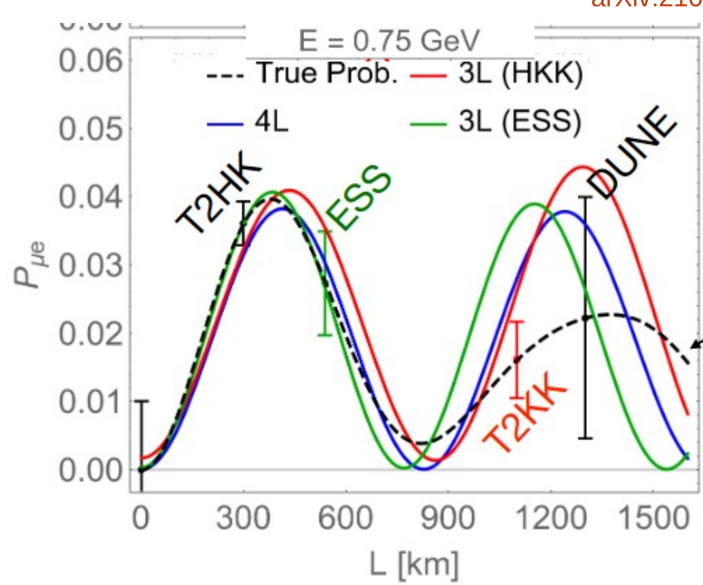

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BSM in neutrinos

- Very good position of France to study BSM at Long-Baselines:

  - strong role at Near detectors: light steriles (appearance at short baseline), heavy sterile produced in the beam and decaying/interacting in the ND

  - degeneracies between BSM and PMNS (eg new CP-violation sources in NSI) can be resolved by combining different L/E (already studied for atmospheric ν vs beam ν)

  → **complementarity of DUNE and HK: different baselines, different energy**

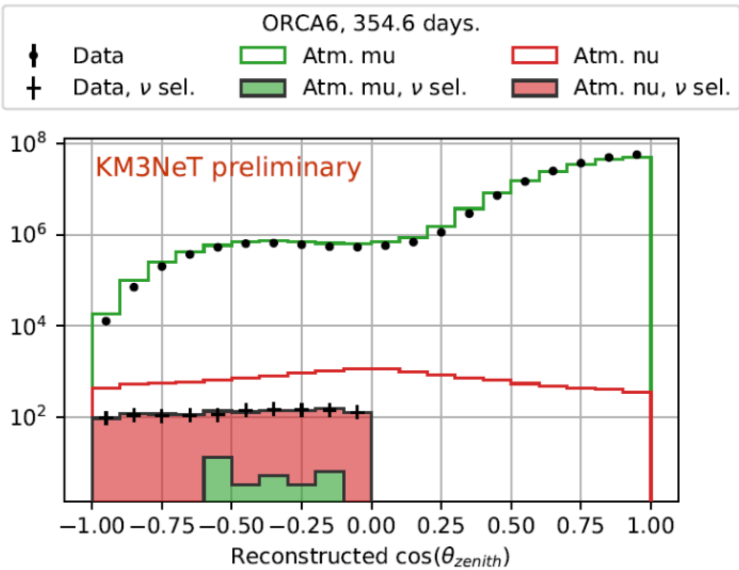
    - should be investigated more even in the framework of control of systematic uncertainties in “standard” oscillation measurements!

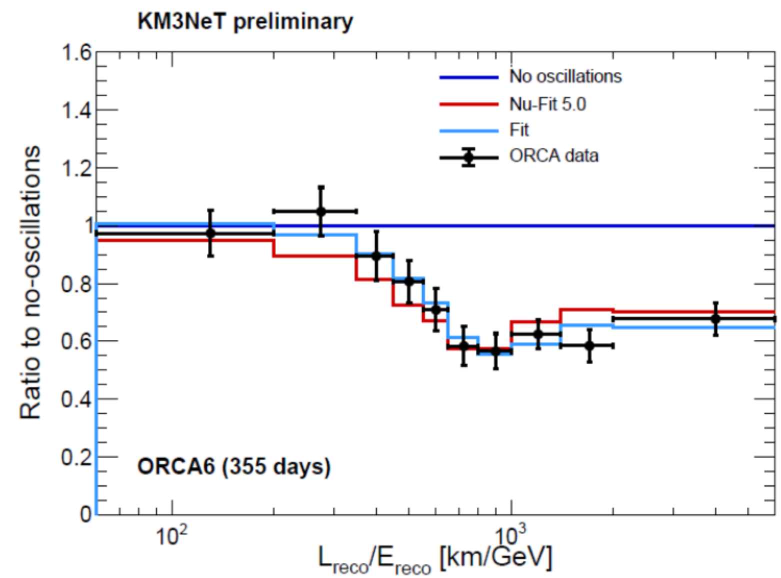
- France effort for **overall comprehensive look at neutrinos to build a coherent model (BSMNu project in P2IO)**

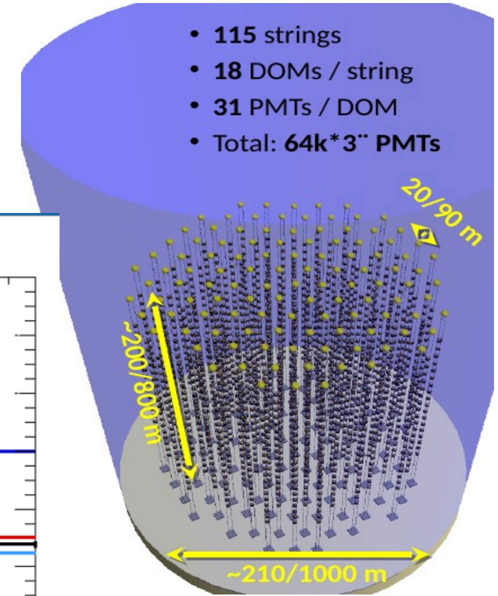
  - PMNS unitarity with JUNO vs direct search of steriles and NSI (coherent scattering) at reactors

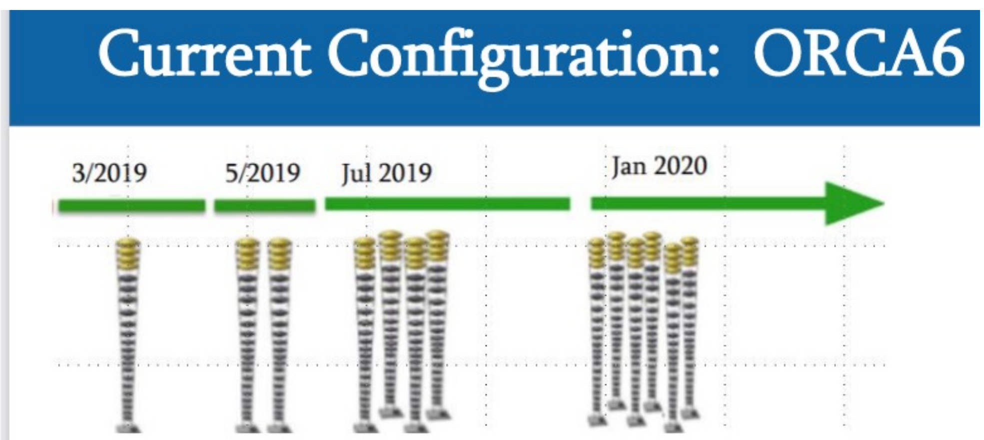
  - $0\nu\beta\beta$ search for Majorana vs Dirac nature of neutrinos: already imposing limits in BSM scenarios!

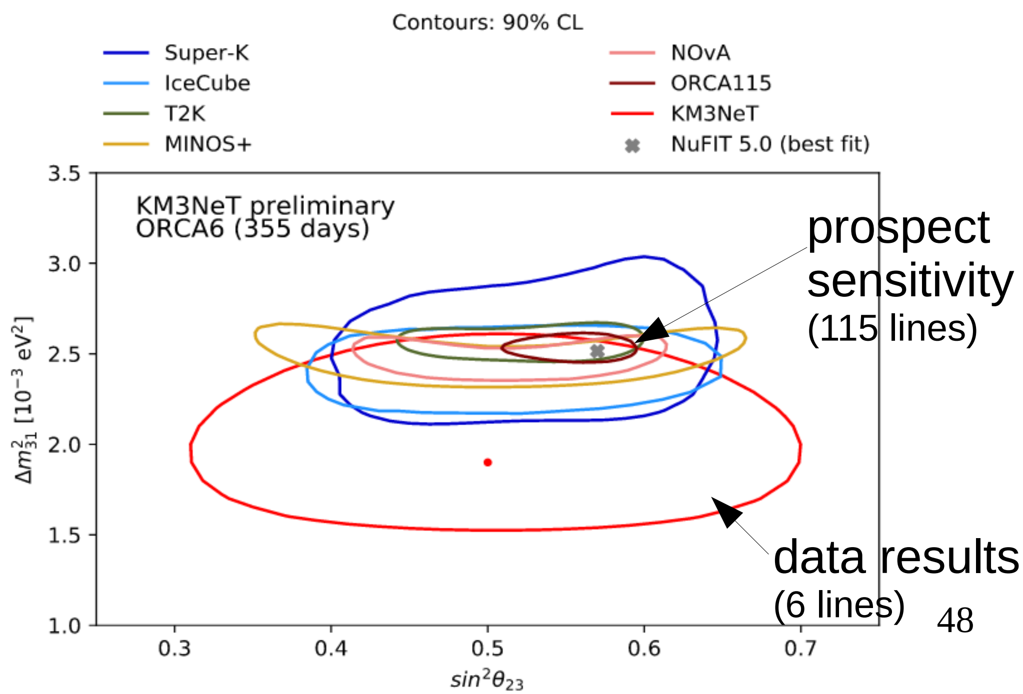
ORCA: first results!









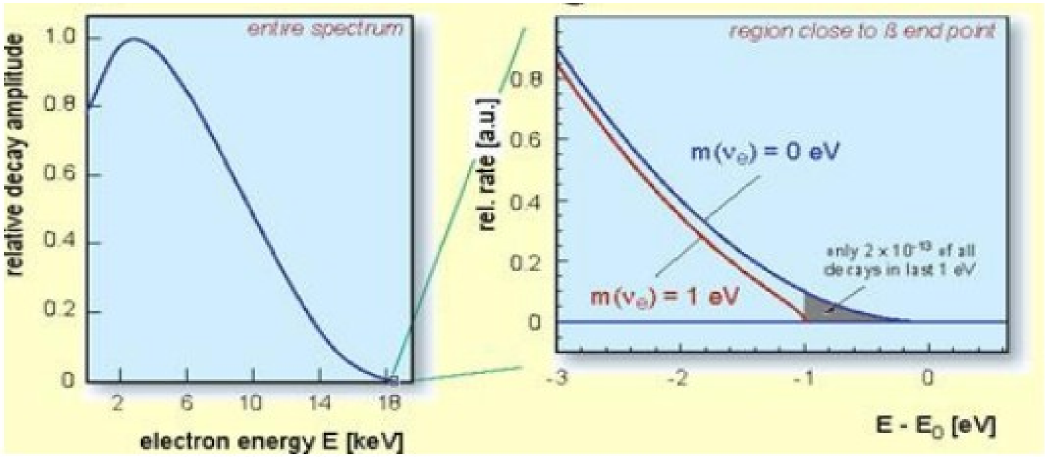


Mass measurement

- **Direct measurement:**
  KATRIN <0.9eV @95% (FC limits)
  → ultimate sensitivity 0.2eV

$$dN/dE = |U_{e1}|^2 m_1^2 + |U_{e2}|^2 m_2^2 + |U_{e3}|^2 m_3^2$$

Electron energy spectrum in b decay

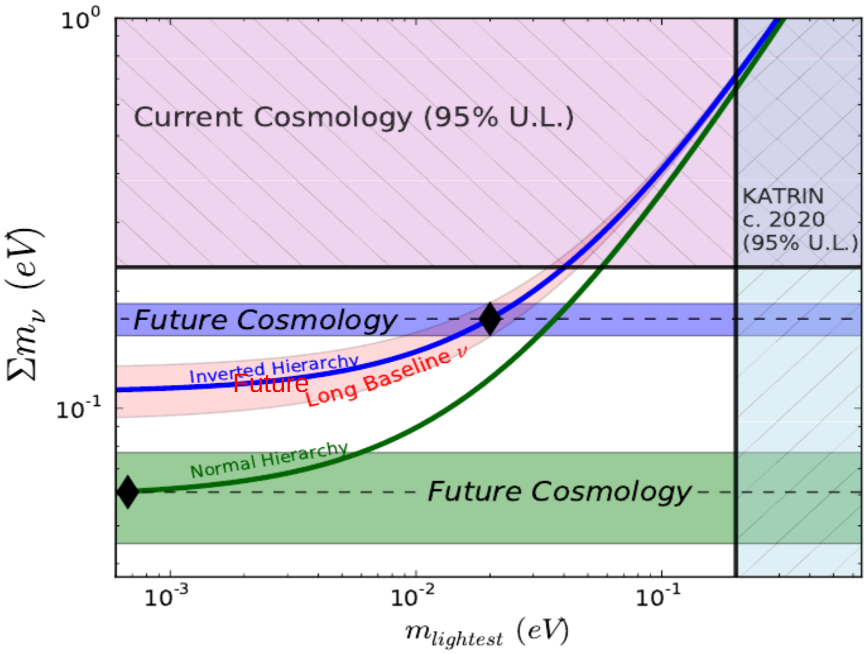


- **Cosmology** (Σm): impact of ν free streaming in matter clustering (captured by Galaxy surveys, BAO, CMB lensing)
  ~< 150 meV @95%

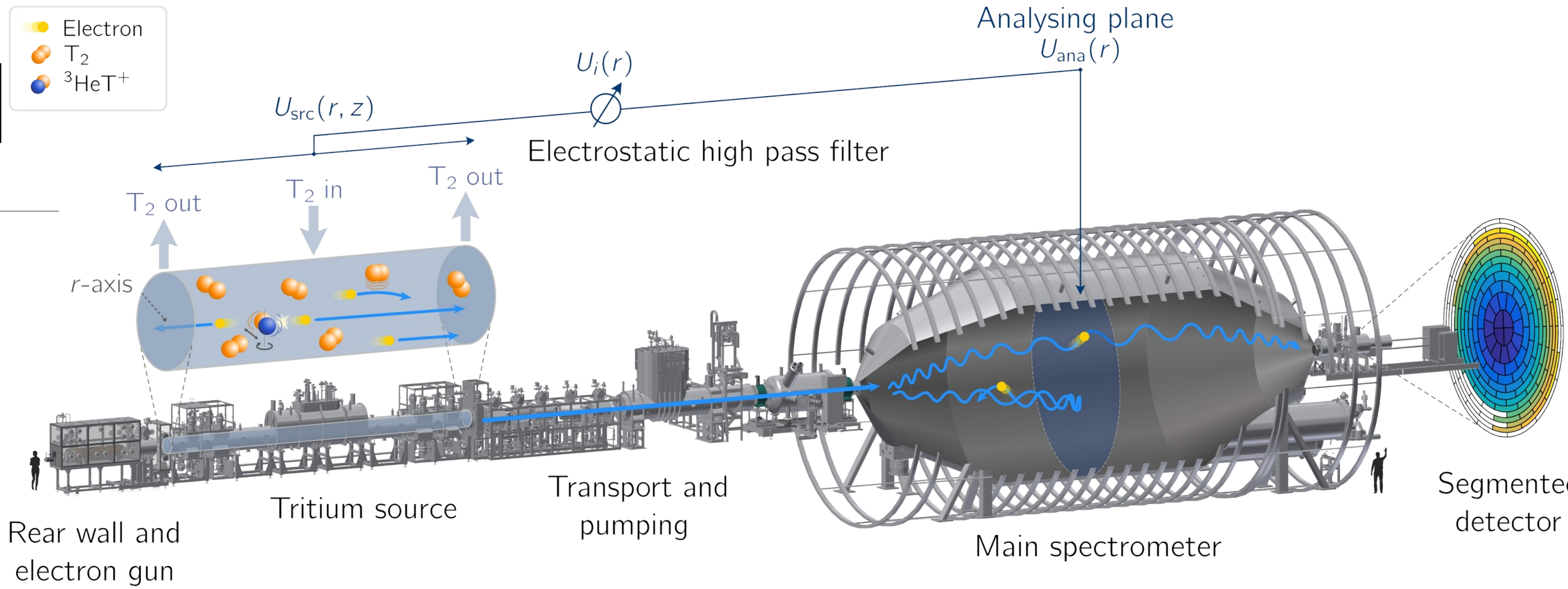
- Lower bound on mass sum depends on mass ordering from oscillation experiments

$$\Sigma \equiv \sum_{i=1}^{3} m_i = \begin{cases} m_0 + \sqrt{\Delta m_{21}^2 + m_0^2} + \sqrt{\Delta m_{31}^2 + m_0^2} & \text{(NO)} \\ m_0 + \sqrt{|\Delta m_{32}^2| + m_0^2} + \sqrt{|\Delta m_{32}^2| - \Delta m_{21}^2 + m_0^2} & \text{(IO)} \end{cases}$$

→ indirect way to exclude IH

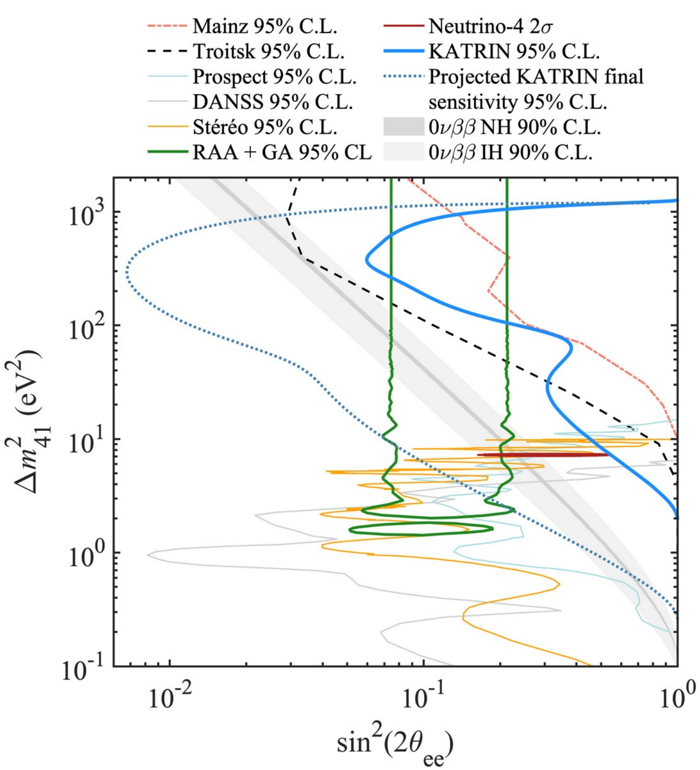


KATRIN



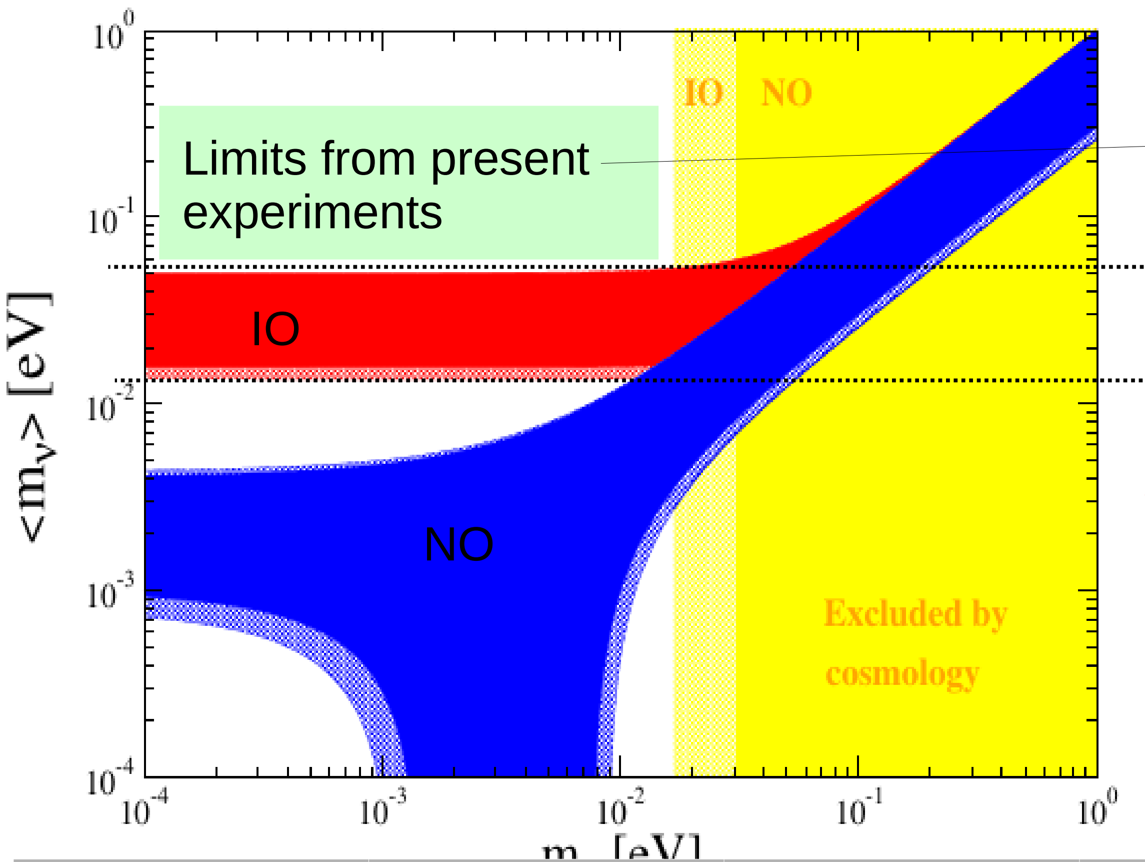
- New world-best direct neutrino mass measurement: **m_ν < 1.1 eV (90% C.L.)**

Sterile limits:



0νββ prospects

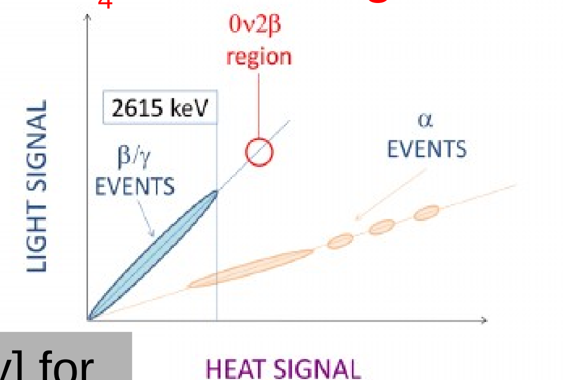
	Results on m_{bb} upper limit
CUORE	75-350 meV
GERDA	100-230 meV
Kaml-Zen	61-165 meV
EXO-200	93-286 meV



5 - 50 counts/ y ton

0.5 - 5 counts/ y ton

20-30meV baseline sensitivity of CUPID with Li_2MoO_4 **scintillating** bolometers

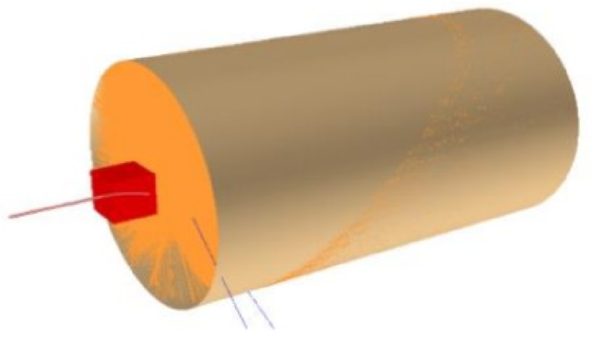


	FWHM	Backgr. (cts/y/ton)	$T_{1/2}$ [10^{26} y] for $m_{\beta\beta}$=0.1eV	
GERDA	~3.5	4	1 - 10	Ge detectors
Kamland-Zen	270	120	~0.5	Liquid Xenon baloon
EXO-200	170	71	~0.5	Liquid Xenon TPC
Cupid-Mo	5	few	0.1 - 1	Scintillating bolometers

More about ESSnSB

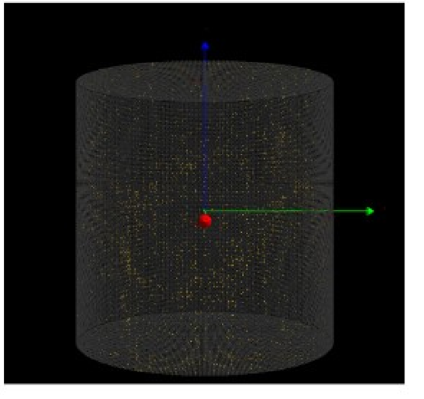
The Near and Far Detectors

ESS NEUTRINO SUPER BEAM



- **Near Detector**:
  - A magnetized Super Fine Grained Detector (SFGD) for cross-section measurements.
  - 1 kton WC detector for event rate measurements, flux normalization and event reconstruction comparison with FD.
  - Emulsion setup, similar to NINJA experiment [1], upstram of the SFGD, for cross-section measurements.

- **Far Detector**:
  - 538 kt fiducial volume (~10 × SuperK).
  - Readout: 20” PMTs (40% optical coverage).
  - Event reconstruction with fiTQun [2,3].
  - New migration matrices obtained.
  - Significant improvements in the reconstruction efficiency (more details in future publication).



For further information on near detector, see in this conference:

- A. Burgman: *The ESS Neutrino Super-Beam Near Detector* (26.07).
- K. Krhac: *Constraining ESSnuSB neutrino flux by observing elastic scattering of neutrinos on electrons* (Poster).

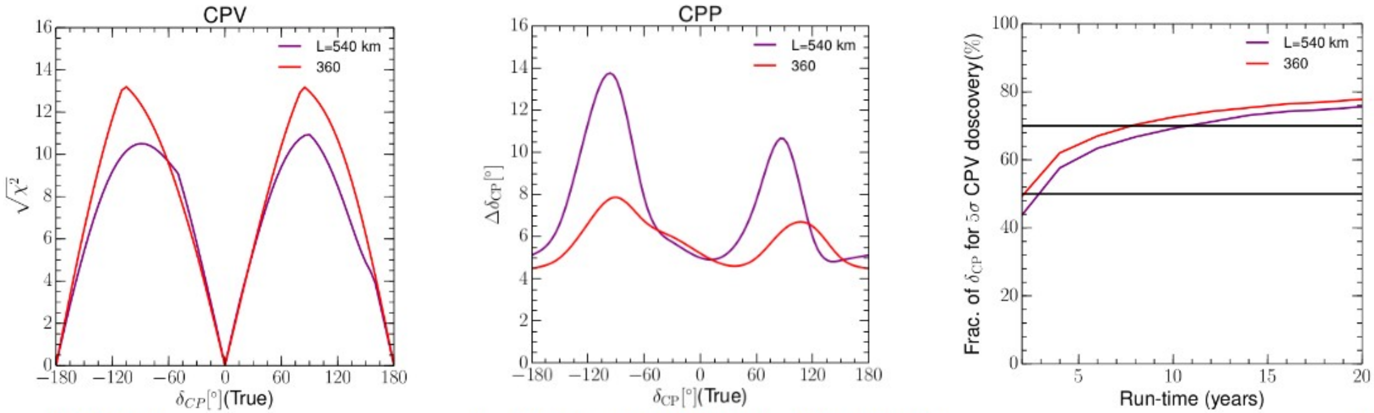
[1] A. Hiramoto et al., Phys. Rev. D 102, 072006 (2020), arXiv:2008.03895.
[2] T2K Collaboration, A. D. Missert, J. Phys. Conf. Ser. 888 (2017), no. 1 012066
[3] Super-Kamiokande Collaboration, M. Jiang et al., PTEP 2019 (2019), no. 5 053F01, [arXiv:1901.03230].

More about ESSnSB

Physics Performance of the Experiment

ESS NEUTRIN SUPER BE

- The optimized geometry of the Target Station and the improved efficiency in the ev reconstruction at the FD, lead to an unprecedented precision which can be achieved in measurement of the δ_{CP} oscillation parameter [1]. Under a conservative estimate of systematic errors signal/background of **5/10%** , respectively, we observe that:
  - More than 12σ C.L. for δ_{CP}=-90° can be achieved for the location of the FD at 360 (Zinkgruvan).
  - ~8° uncertainty on δ_{CP} measurement for δ_{CP}=-90° for the same location.
  - More than 70% coverage of δ_{CP} values covered at 5σ in 10 years running time (5 years neutrino mode + 5 years in antineutrino mode).

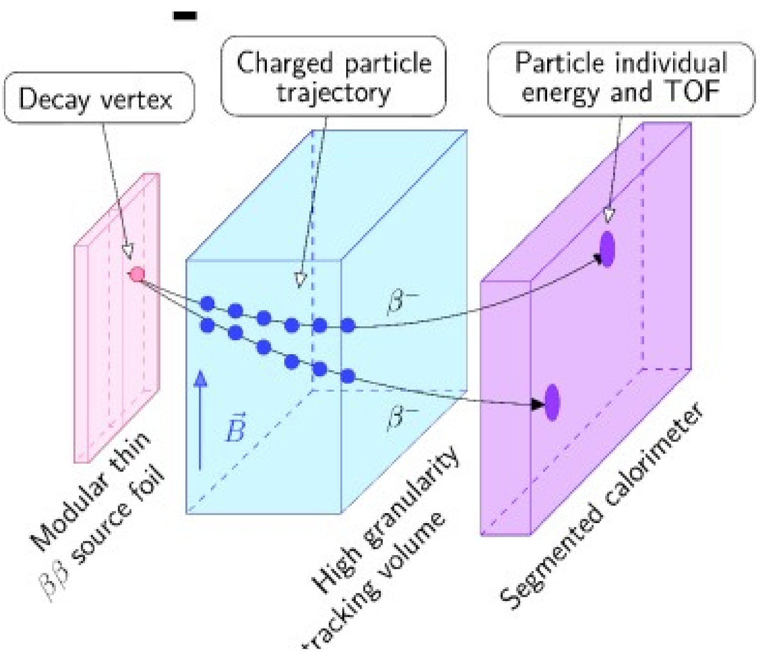


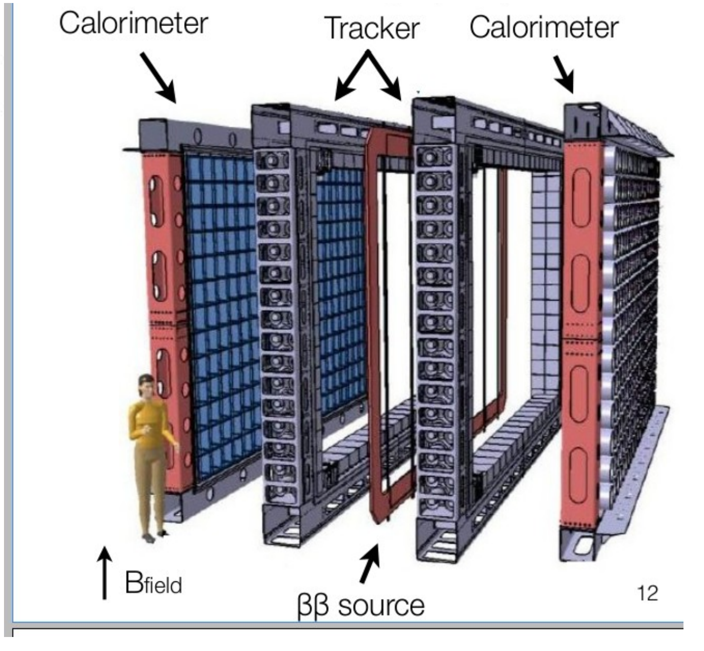
26.07.2021 L. D'Alessi - ESSnSB/HIFI - EPS-HEP2021 13

Further 0νββ possibilities with multiple isotopes

SuperNEMO at Modane laboratories

BiPo dedicated detector + enable different isotopes.
Demonstrator being built





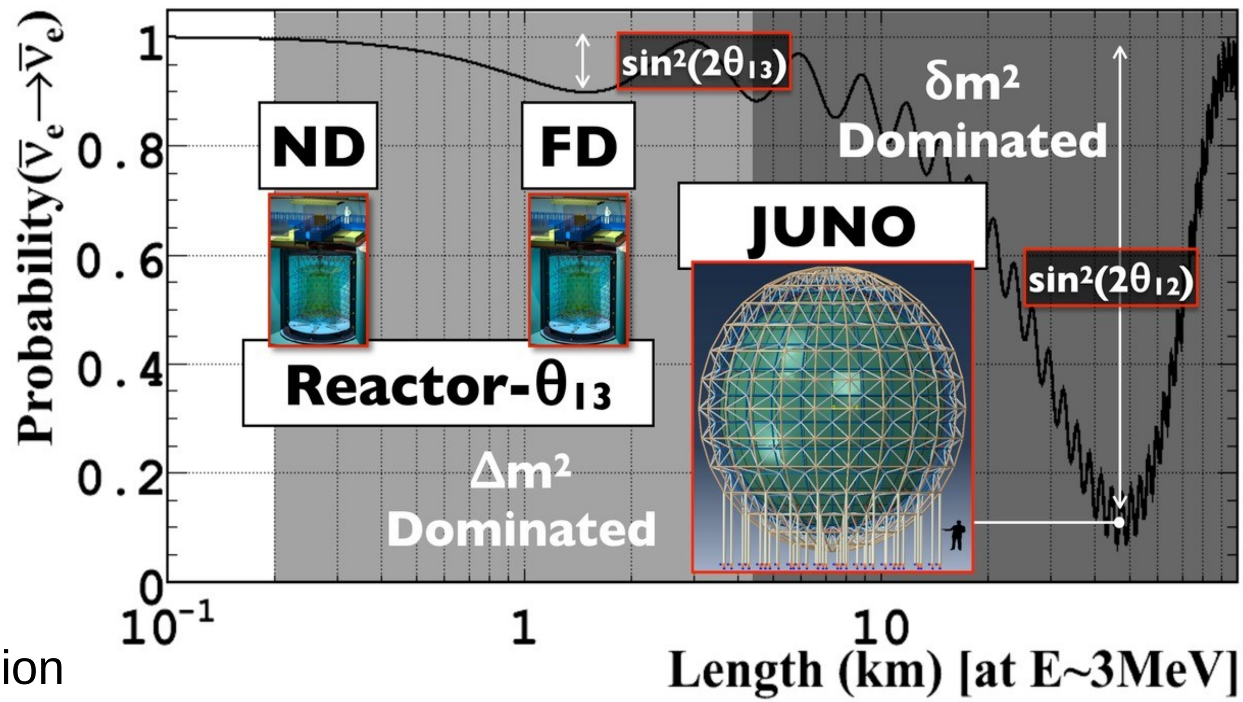
Oscillation measurements

- **Neutrinos from reactors:** disappearance of ν_e

~few MeV, L~1 km

$\sin^2 q_{13}$ = 2.18+/-0.07 (Daya-Bay, Double Chooz, RENO)

- JUNO: 50km baseline → precision measurement θ_{12} and MH sensitivity

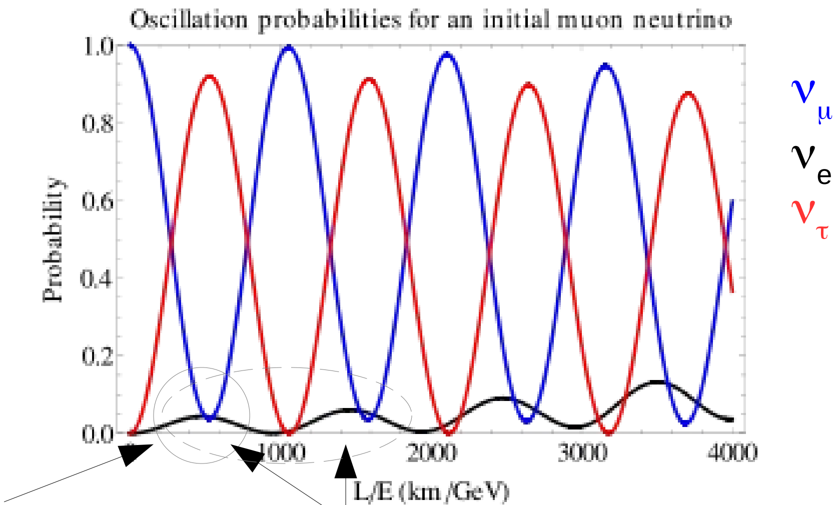


- **Neutrino from accelerator**: flux of n_m ($\bar{\nu}_\mu$) → ν_μ ($\bar{\nu}_\mu$) disappearance, ν_e ($\bar{\nu}_e$) appearance

Experiment	Energy	Baseline
T2K (T2HK)	0.6 GeV	295 km
Nova	2 GeV	810 km
DUNE	1-3 GeV	1300 km

(to exploit ν_τ need $E_\nu > m_\tau$ 1.78 GeV)

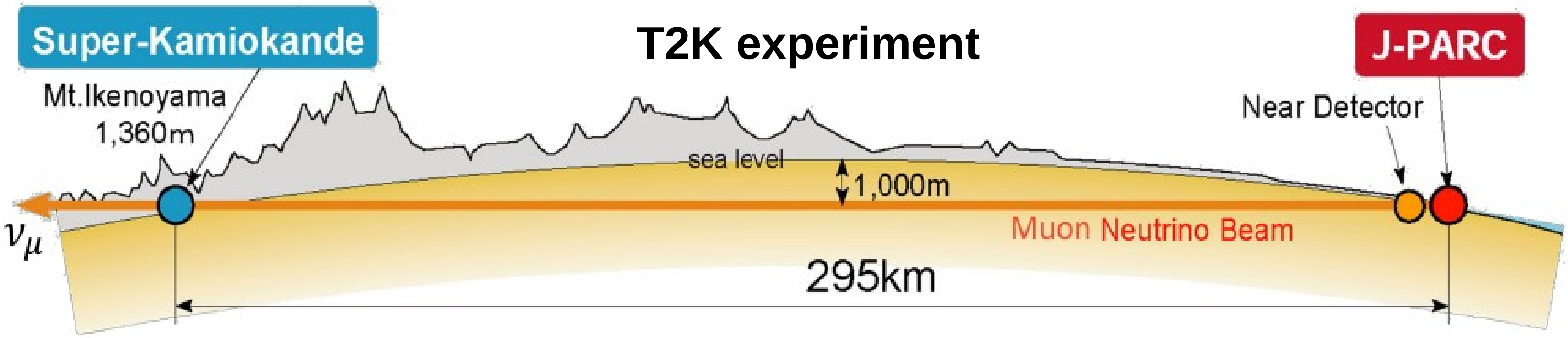
In the atmospheric sector $\Delta m^2_{32} = 2.5 \times 10^{-3}\ \mathrm{eV}^2$

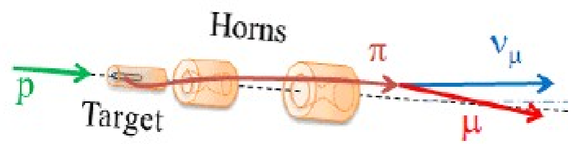


T2K (T2HK) and NOVA working point

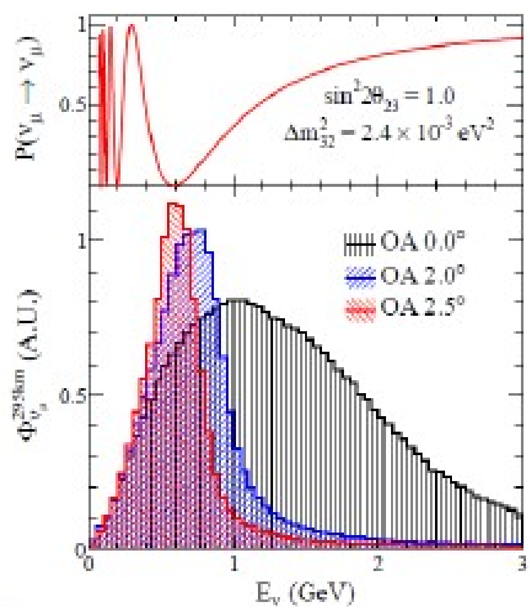
DUNE wideband beam covers (at low energy) also the second oscillation maximum

How do we measure oscillations in LBL?



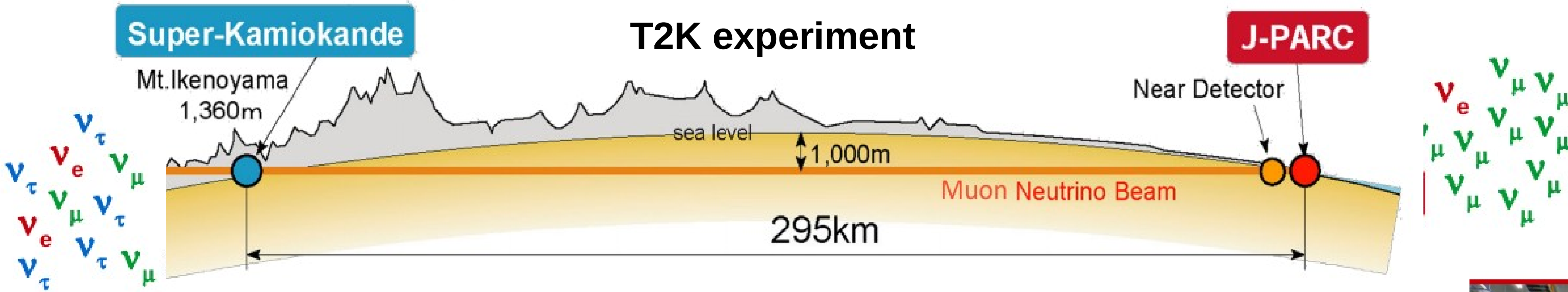


Off-axis
narrow-band flux

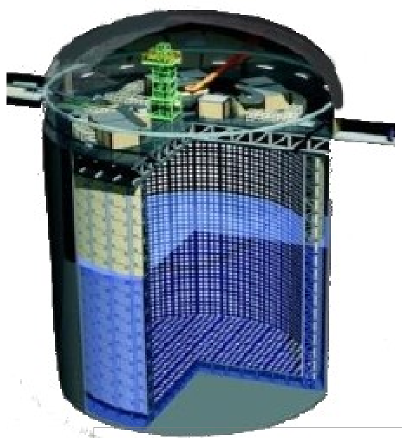


J-PARC facility:
neutrino beam

How do we measure oscillations in LBL?

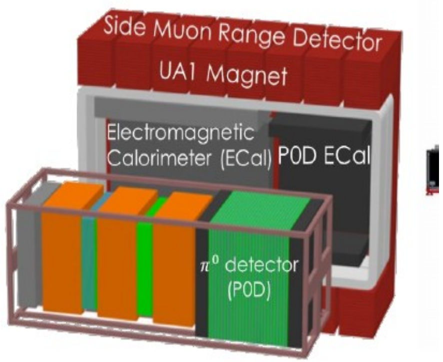


Super-Kamiokande

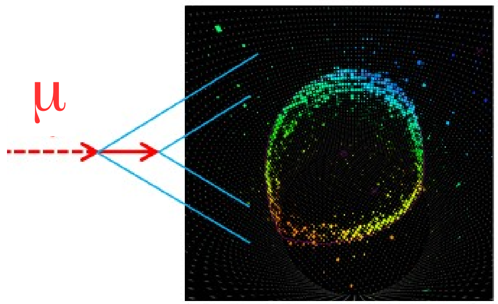


huge water cherenkov detector (50 kTon) with optimal μ/e identification to distinguish ν_e, ν_μ

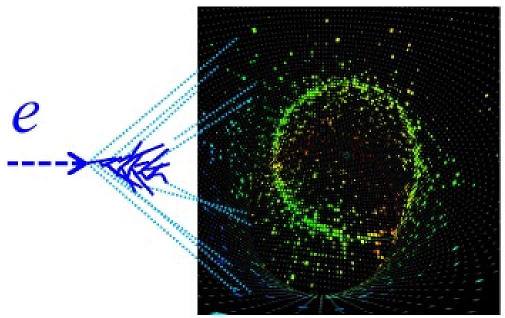
ND280 near detector



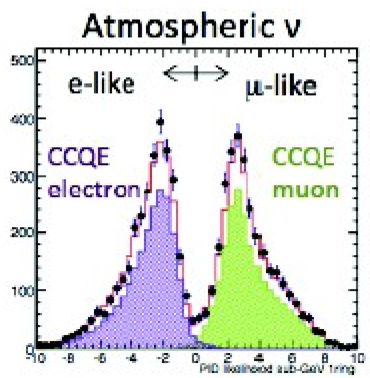
J-PARC facility:
neutrino beam



clear ring



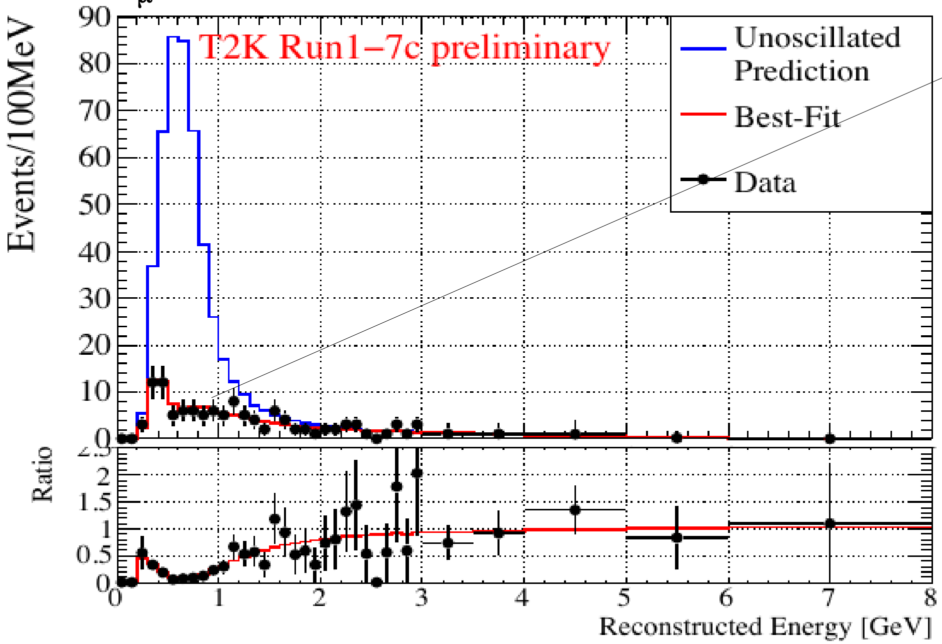
fuzzy ring

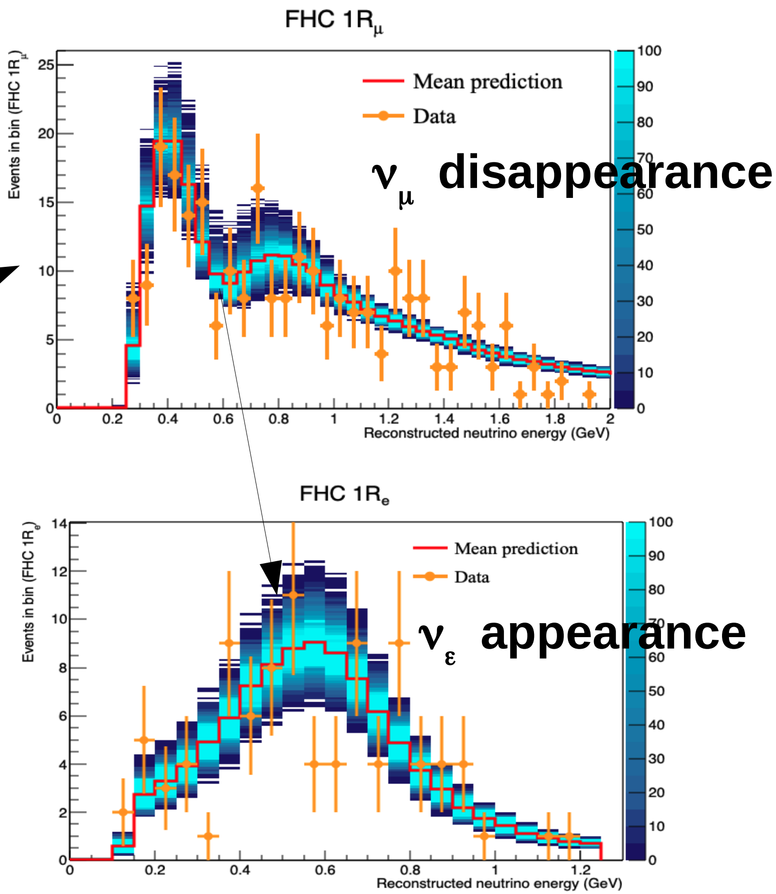


1% mis-id

ν oscillation spectra

ν_μ events at the far detector vs energy





T2K preliminary Run1-10

- $$P(\nu_\alpha \to \nu_\beta) = \underbrace{\sin^2(2\theta)}_{\textbf{amplitude}} \sin^2\underbrace{\left(1.27\frac{\Delta m^2_{ji}[\mathrm{eV}^2]L[\mathrm{km}]}{E_\nu[\mathrm{GeV}]}\right)}_{\textbf{frequency}}$$

(simplified 2-flavors approximation)

- $\sin\theta_{23}$ ~ amplitude of the ν_μ ($\bar{\nu}_\mu$) disappearance (height of spectrum minimum)
- $\Delta m^2_{31(32)}$ ~ frequency of the disappearance (position of spectrum minimum)

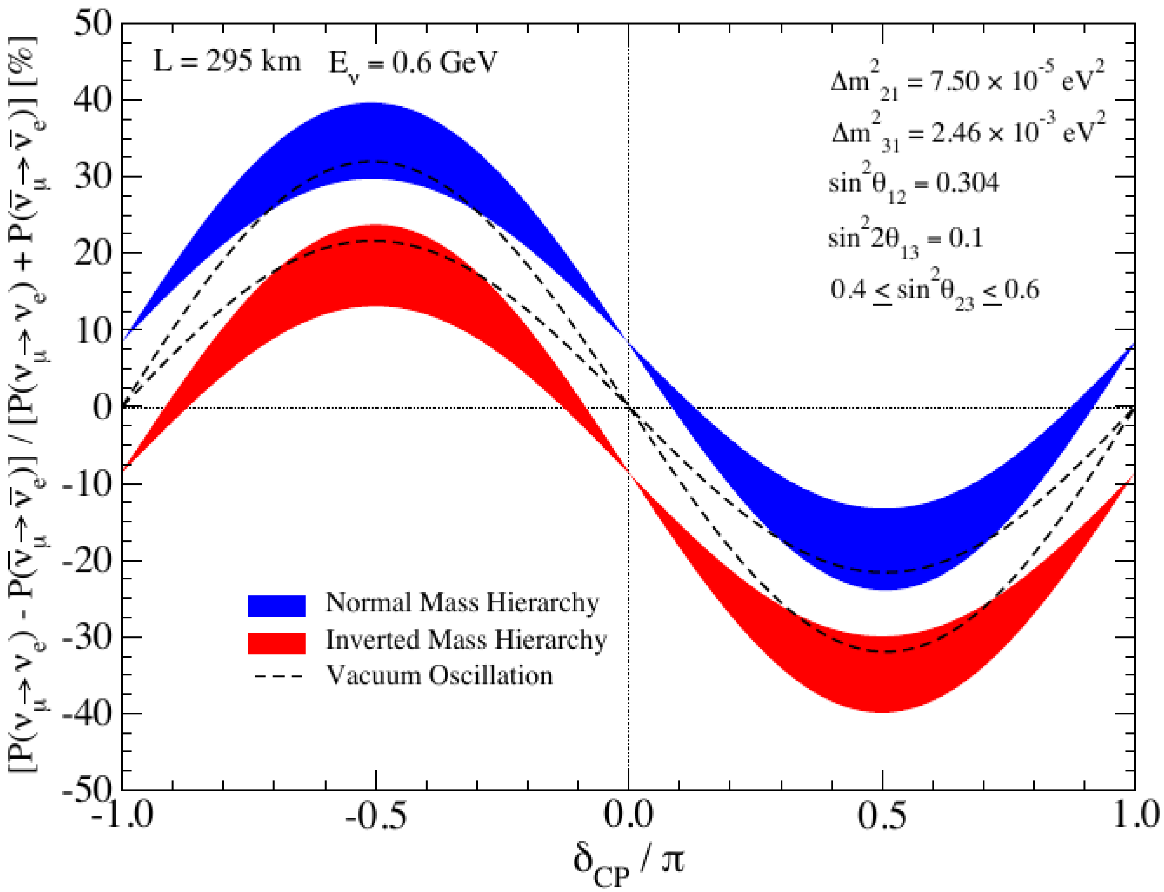
$\nu_e/\overline{\nu}_e$ appearance: δ_{CP} and MH

$$\mathcal{A}_{\rm CP} \equiv \frac{P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\overline{\nu}_\mu \to \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin\delta}{\sin\theta_{13} \tan\theta_{23}} \Delta_{21} + \text{matter effects},$$

→ sensitivity to MH

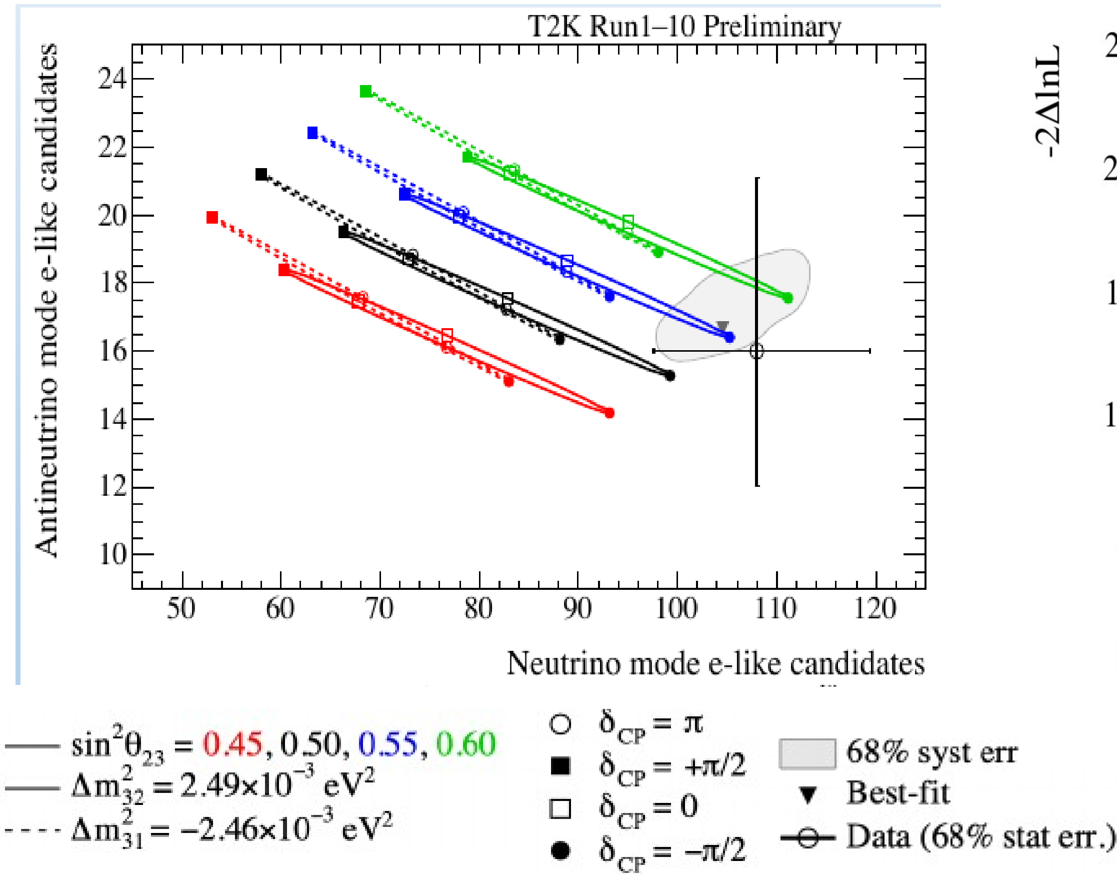
- δ_{CP} measurement is mostly a **counting experiment** by comparing number of ν_e and $\bar{\nu}_e$

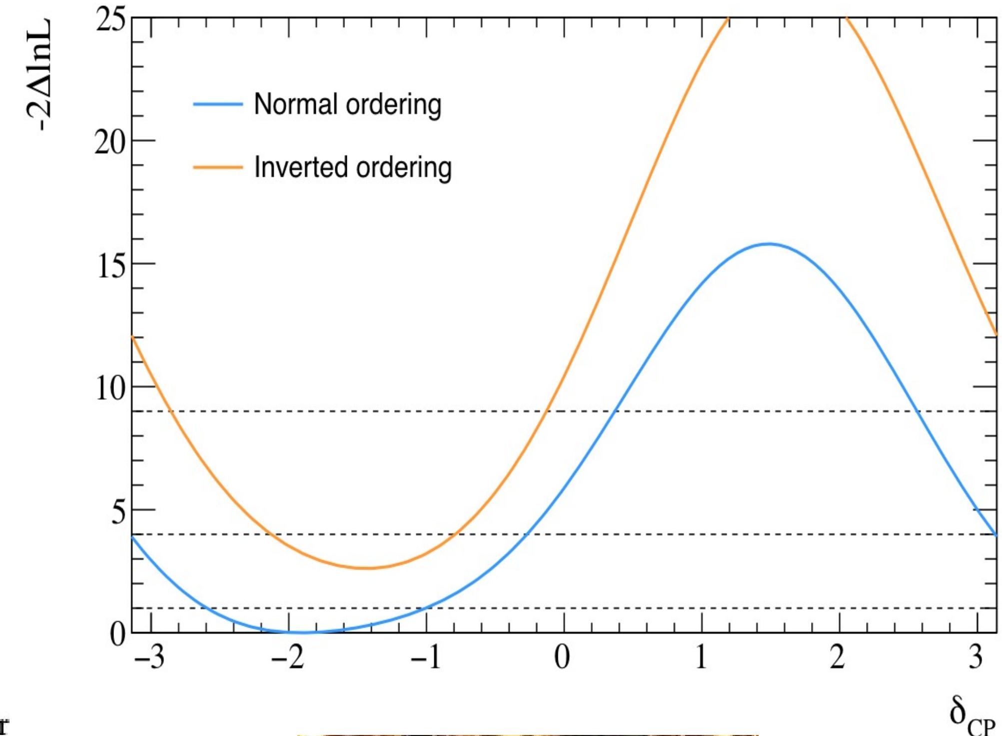
  (especially at the narrow energy neutrino flux of T2(H)K)



- MH sensitivity comes from change of sign in term dominated by matter effects: the longer the baseline → the larger the term

$\nu_e/\bar{\nu}_e$ appearance: T2K results



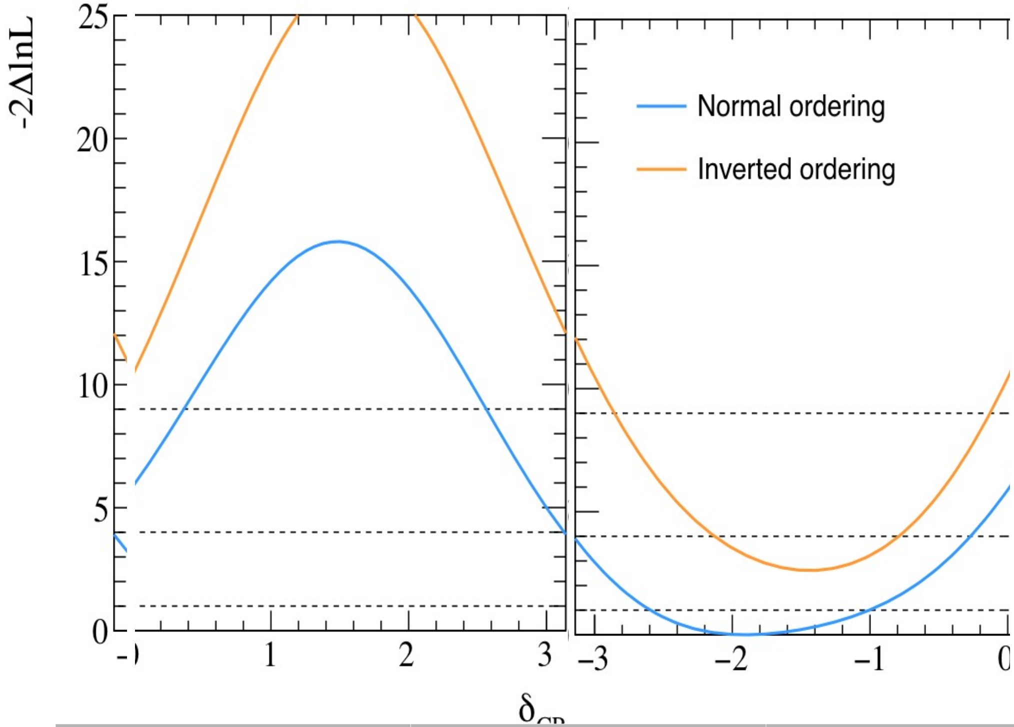


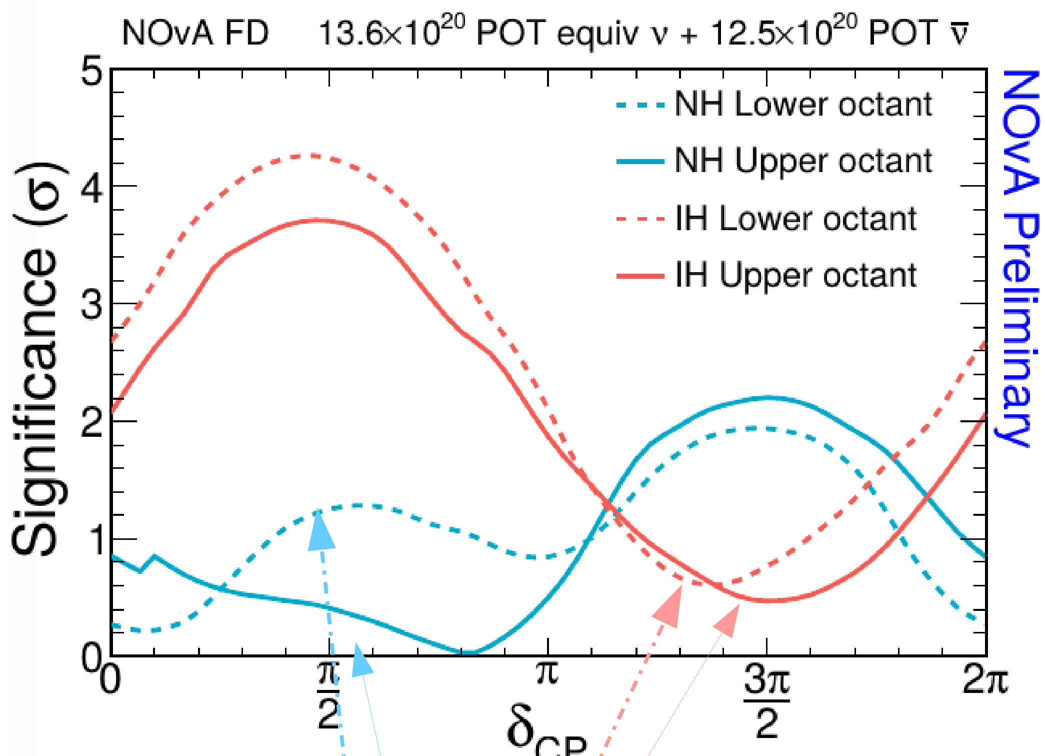
April 2020 Nature cover!

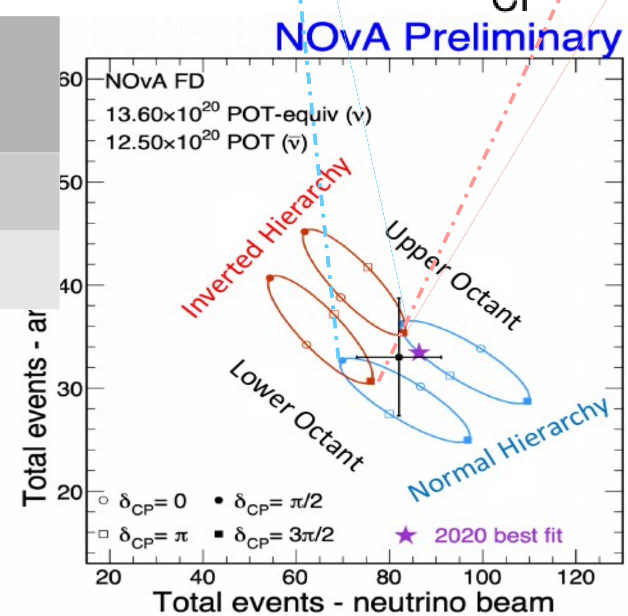
- T2K exclusion at 3σ of 50% of δ_{CP} values and ~2σ hints for CP violation: Nature 580 (2020) 7803, 339-344
- **Statistically limited measurement!**

Results: T2K vs NOVA

T2K preliminary 19.7x10^20 POT n + 16.3x10^20 POT







Experiment	CP asymmetry	Mass Hierarchy
T2K (T2HK)	~30%	~10%
Nova	~30%	~30%

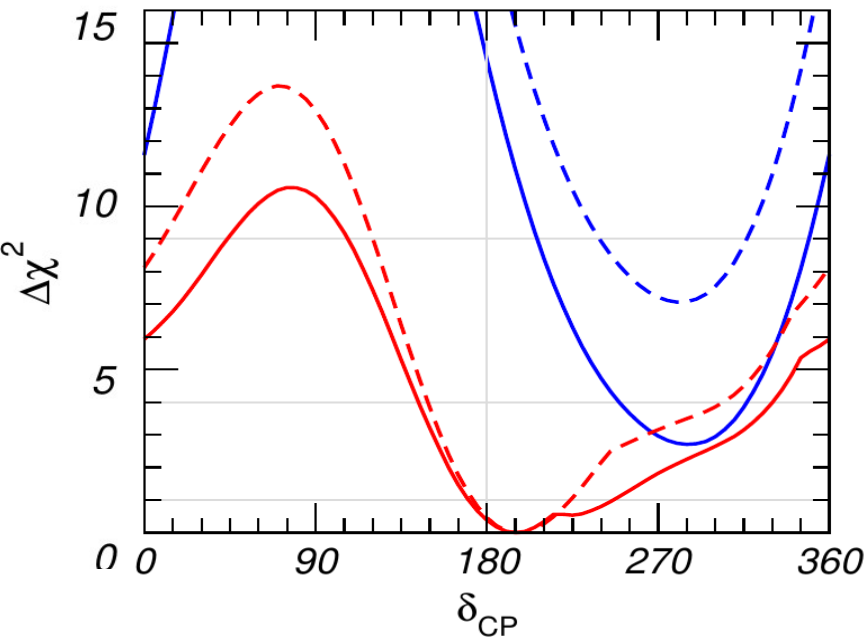
all these possibilities inside 1σ

- **T2K: clean δ_{CP} measurement with small MH sensitivity**

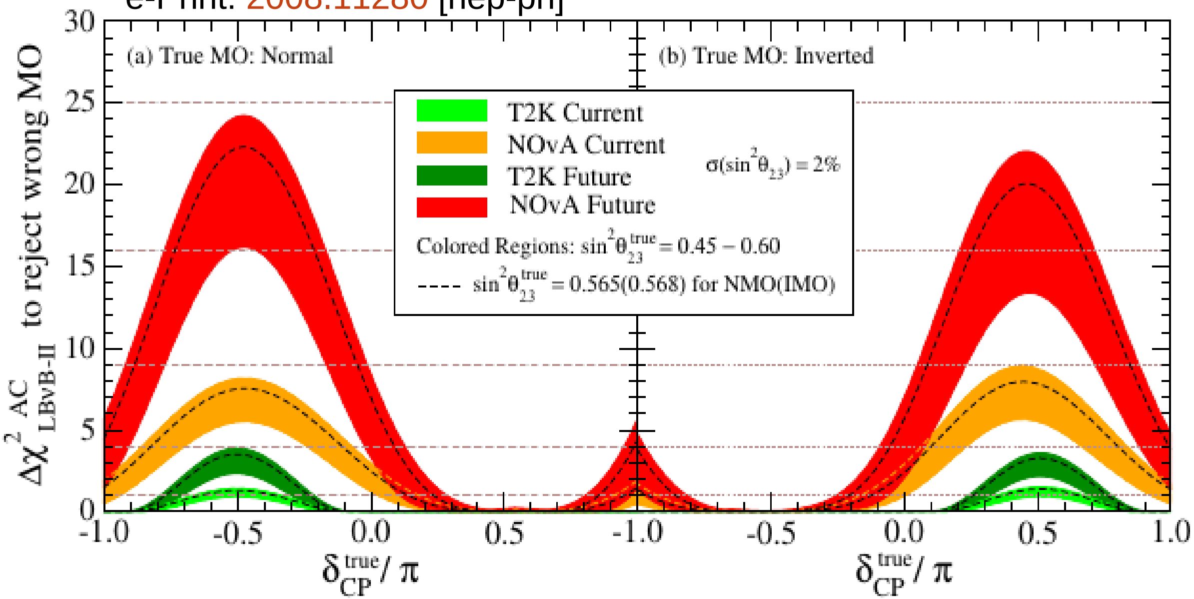
- **NOVA: degenerate δ_{CP} and MH:**
(δ_{CP} $3\pi/2$ and IH = δ_{CP} $\pi/2$ and NH)

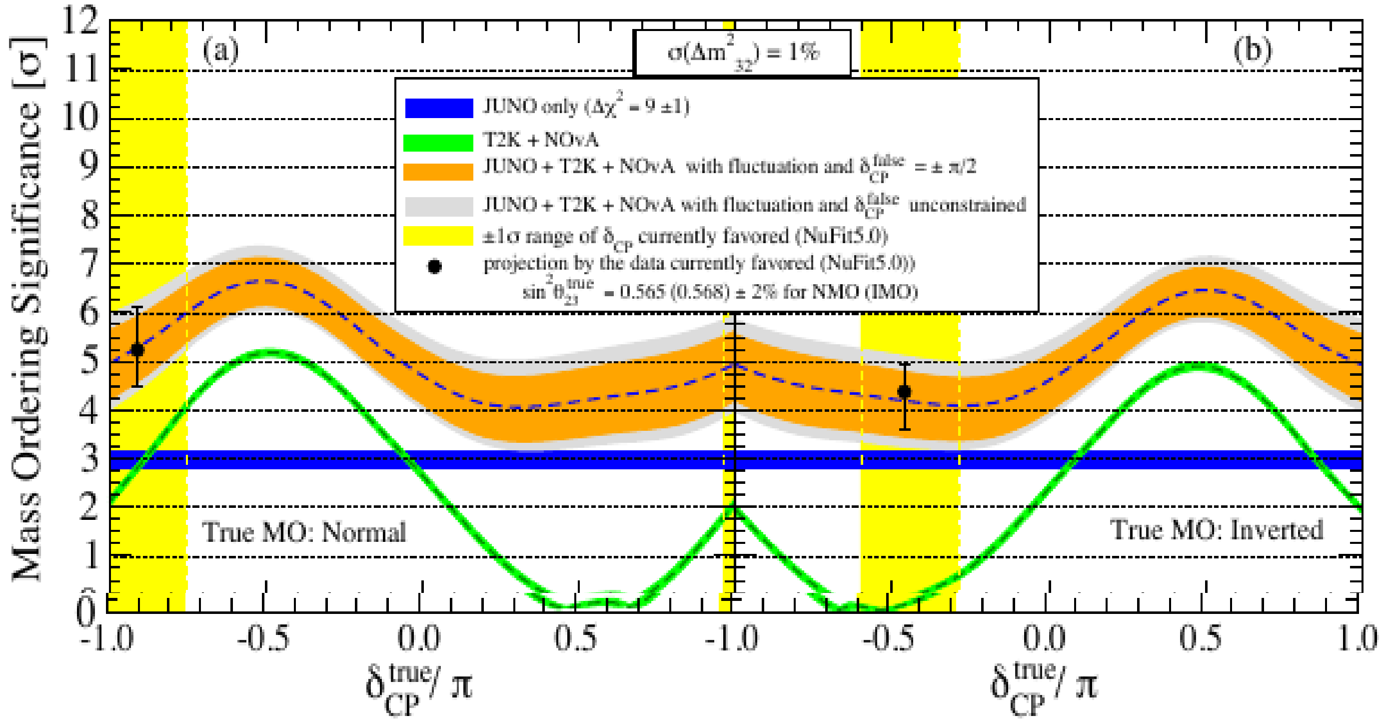
Mass hierachy

NuFit 2020 results



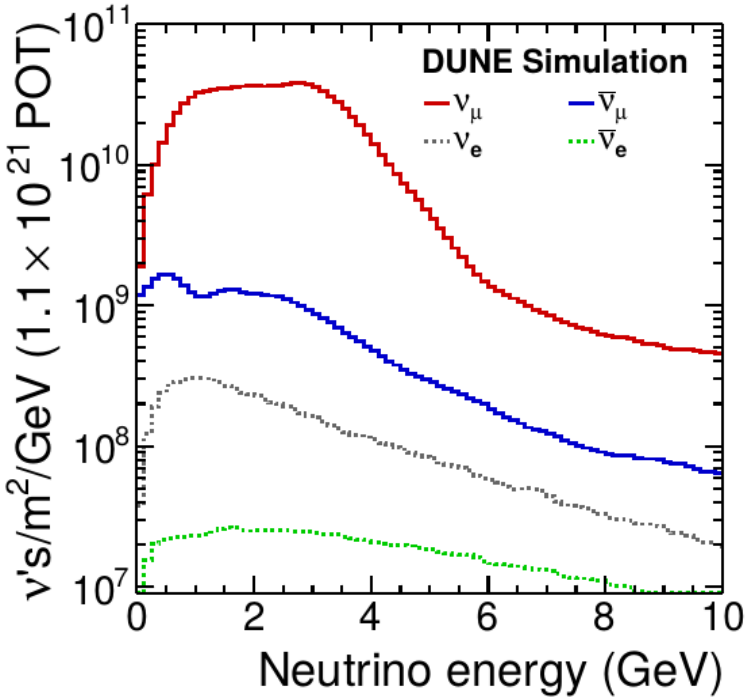
e-Print: 2008.11280 [hep-ph]



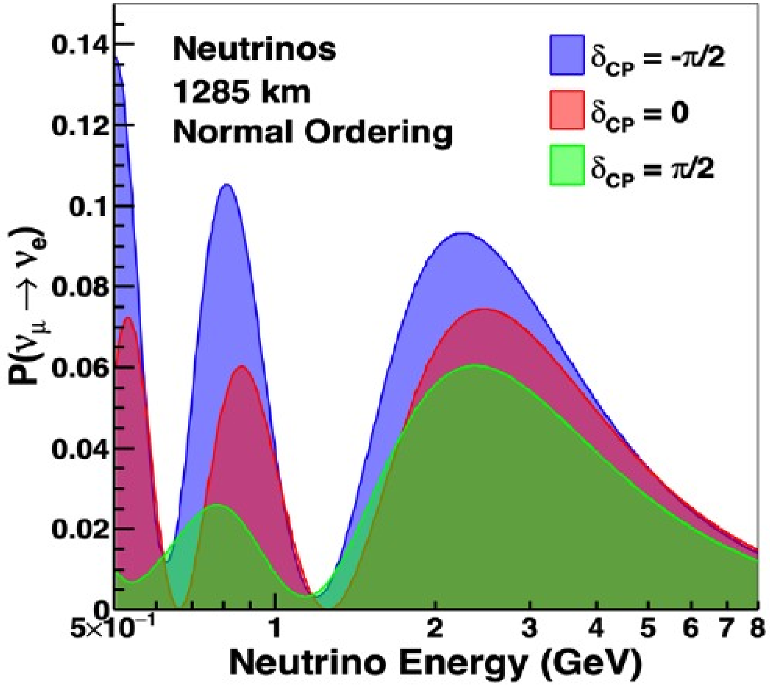


DUNE: beam

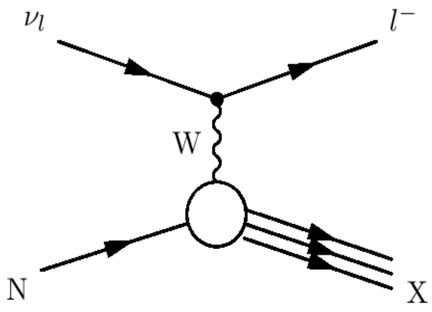
New wide-band neutrino beam at Fermilab: 1.2MW → 2.4MW



Cover two oscillation maxima → a lot of shape information to exploit for precision physics on PMNS paradigm



Largest contribution from single and multiple pion production
→ very poorly known region in terms of nuclear physics modeling



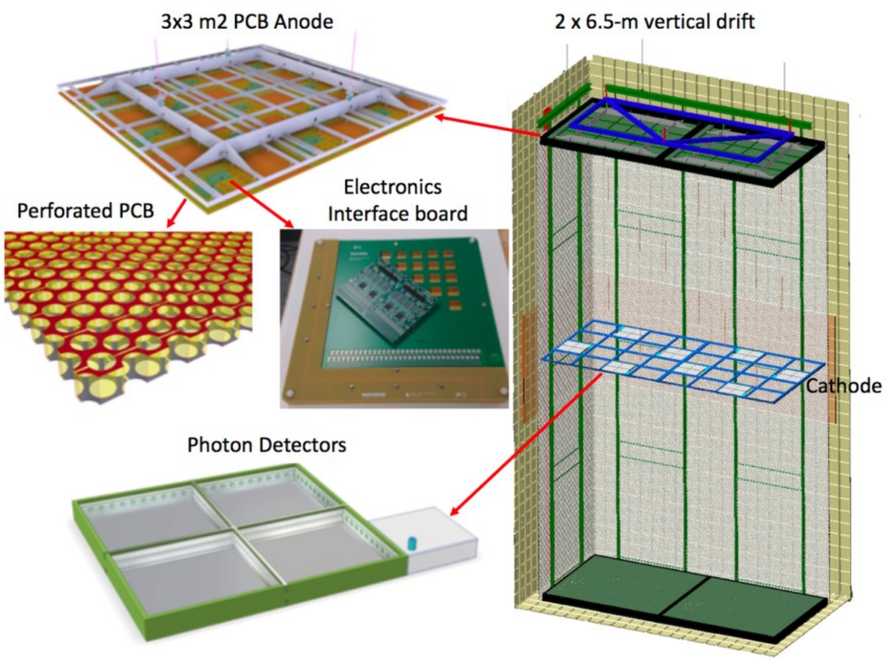
To exploit full sensitivity a shape analysis is needed
→ need extremely good resolution on neutrino energy reconstruction

Crucial role of near detectors !

DUNE: SPVD details

- Photon Detection:
  - Double-sided X-Arapuca modules in the cathode structure (at HV, challenge of power and readout via fibers)
  - Additional (single-sided) modules on the side walls (behind an adapted field-cage)
  - Xenon doping of the argon

Altogether, an expected significant increase in light yield compared to HD



- Cathode near -300 kV for a drift field of 450 V/cm

Near detectors and nuclear theory

ND measures rate vs neutrino energy before oscillation
→ characterize flux and xsec

$$R^{\nu'}_{ND} = \int \Phi^{\nu}(E_\nu) \frac{d\sigma^{\nu'}}{dE_\nu} dE_\nu$$

$$R^{\nu'}_{FD} = \int \Phi^{\nu}(E_\nu) P^{\nu \rightarrow \nu'}_{osc}(E_\nu) \frac{d\sigma^{\nu'}}{dE_\nu} dE_\nu$$

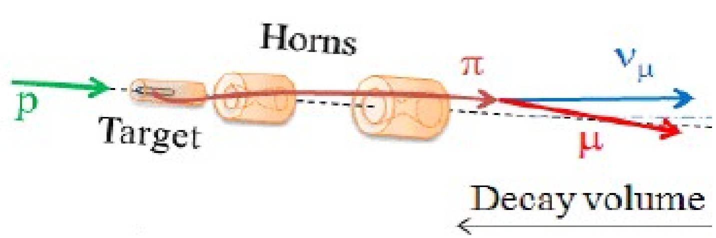
~same flux at ND and FD

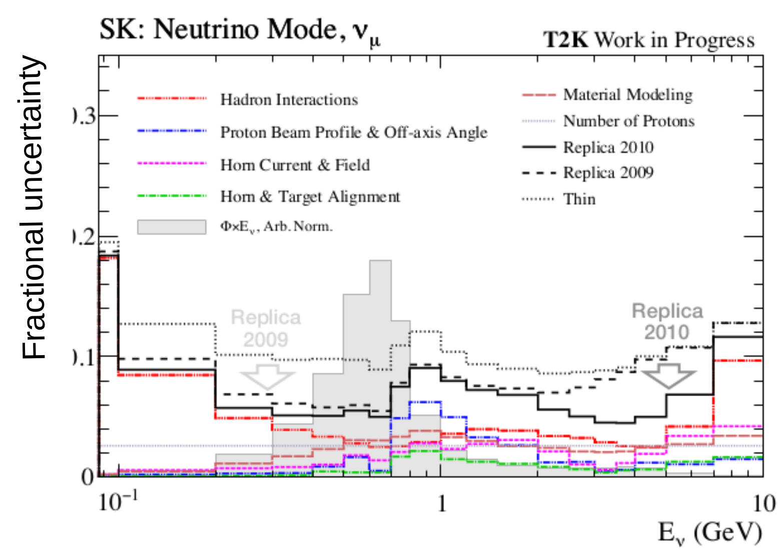
what we want to measure: oscillation probability

cross-section must be extrapolated from ND to FD:
- different neutrino energy distribution
- ND measure flux times xsec

Need nuclear theory models!

Flux simulation and tuning (NA61/SHINE with French contribution)





Near detectors and nuclear theory

ND measures rate vs neutrino energy before oscillation
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$$R^{\nu'}_{ND} = \int \Phi^{\nu}(E_\nu) \frac{d\sigma^{\nu'}}{dE_\nu} dE_\nu$$

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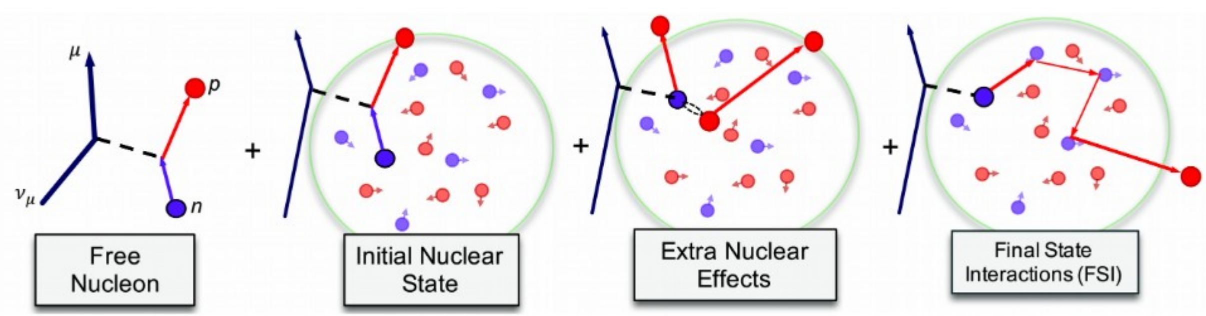
~same flux at ND and FD

what we want to measure: oscillation probability

cross-section must be extrapolated from ND to FD:
- different neutrino energy distribution
- ND measure flux times xsec

Need nuclear theory models!

ν-nucleus interaction modeling and tuning



(and similarly for pion(s) production)

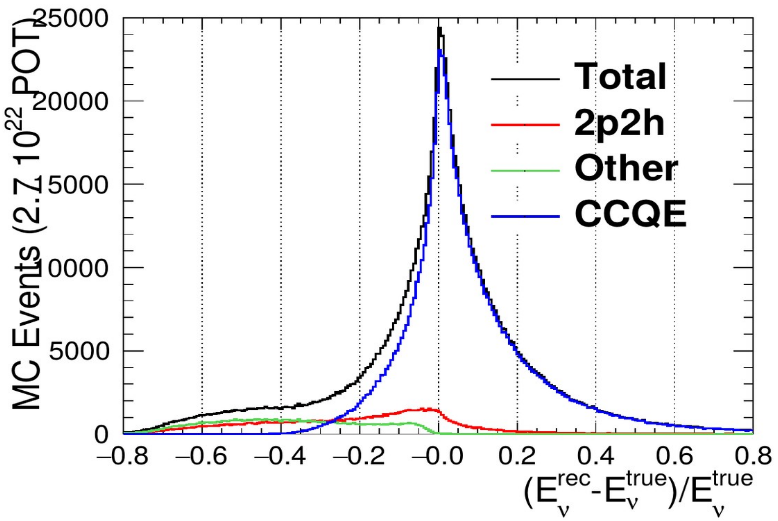
- Nuclear theory
- External data (eg e-scattering)
- ν-nucleus xsec measurements at near detectors and dedicated experiments (Minerva, ArgoNeuT, ..)

→ fundamentally the name of the game: precise Eν reconstruction

Neutrino energy reconstruction

Resolution of neutrino energy intrinsically limited by the nuclear effects

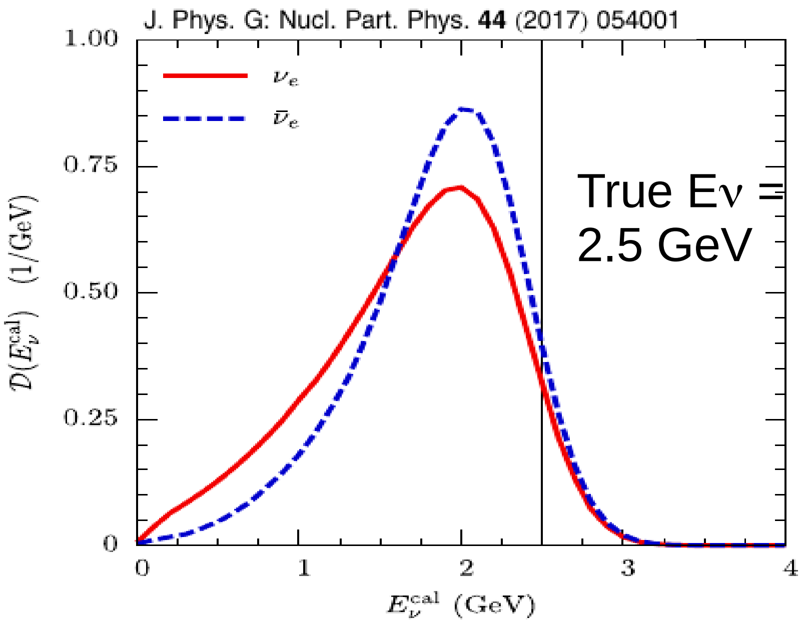
Neutrino energy resolution without detector effects



- Water-cherenkov far detector: only muon (and π,p above threshold) are visible

- ND280 detector today: mostly measure muon/electron and pions only with ~same~ resolution as far detector

- ND280 detector today: mostly measure muon/electron and pions → ND280 upgrade measures all visible energy to conatrin nuclear effects



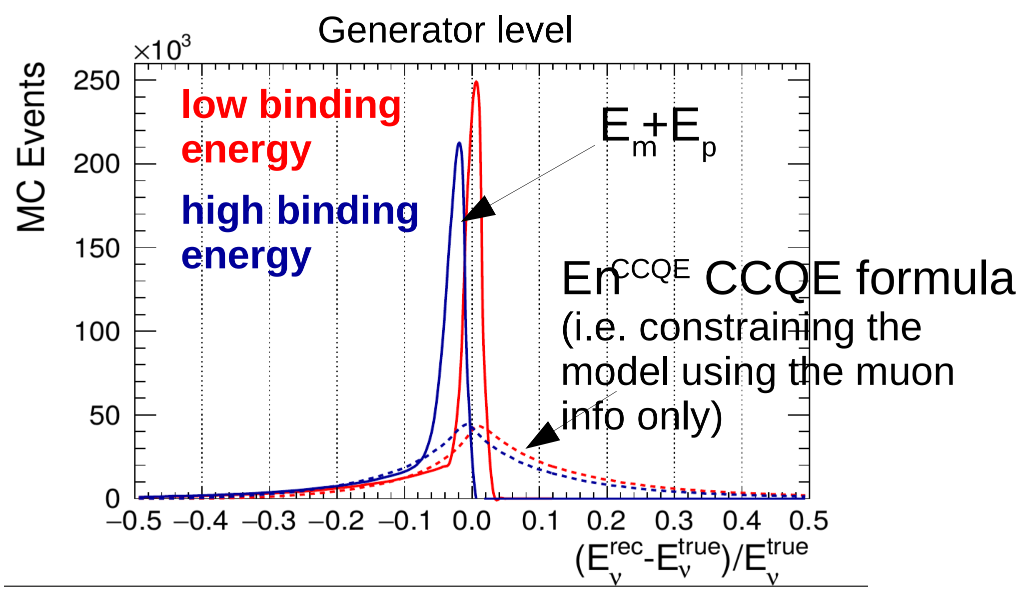
- Impact of missing energy on DUNE-like calorimetric energy reconstruction

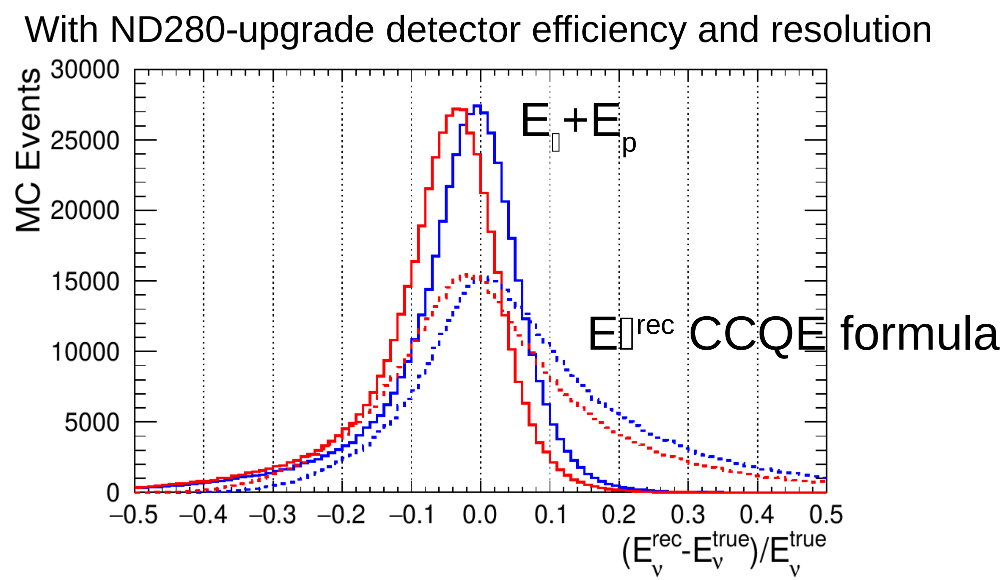
- Large contribution from nuclear effects (neutrons!) and entangled with detector calibration

- Neutrons can bias ν/ν̄ Eν reconstruction since different neutron rate for ν/ν̄ interactions

Physics improvements

Great improvement on the resolution of neutrino energy reconstruction



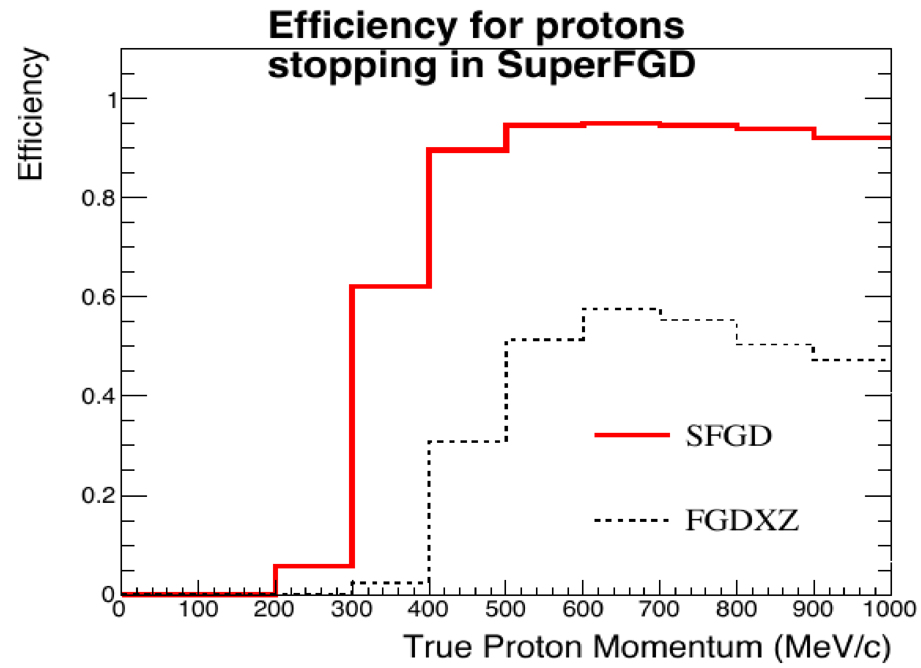


- **A new generation of analysis** is being developed at T2K, with ND280 upgrade, which fully exploits the proton/neutron measurement. The Saclay group is leader in this development

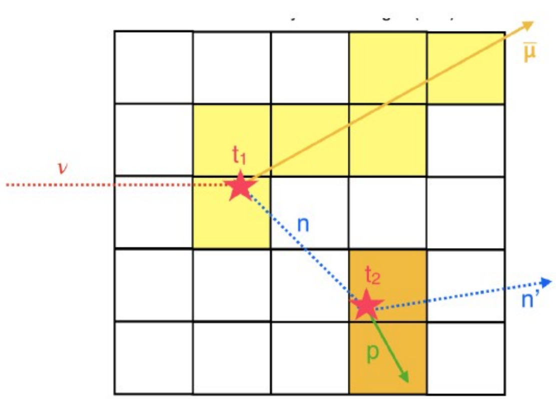
- **The reconstruction of proton and neutron is even more crucial for DUNE!**
Proposal to deploy the 'same' detector design of ND280 upgrade as DUNE near detector: SAND

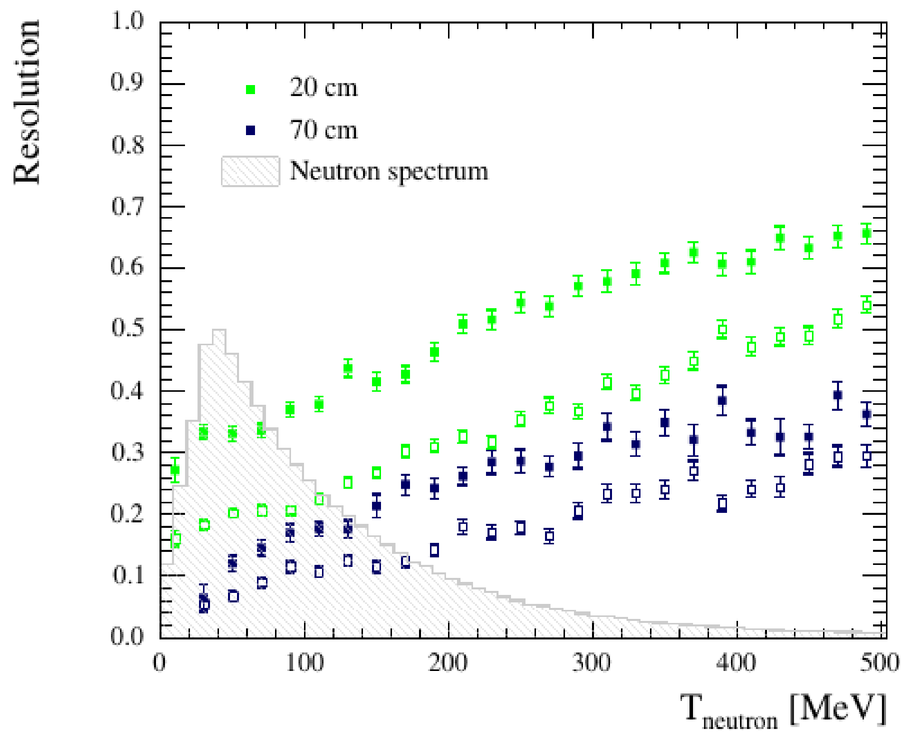
Physics improvements

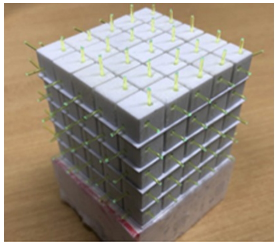
Much lower threshold of reconstruction for protons



And capability of measuring neutrons!



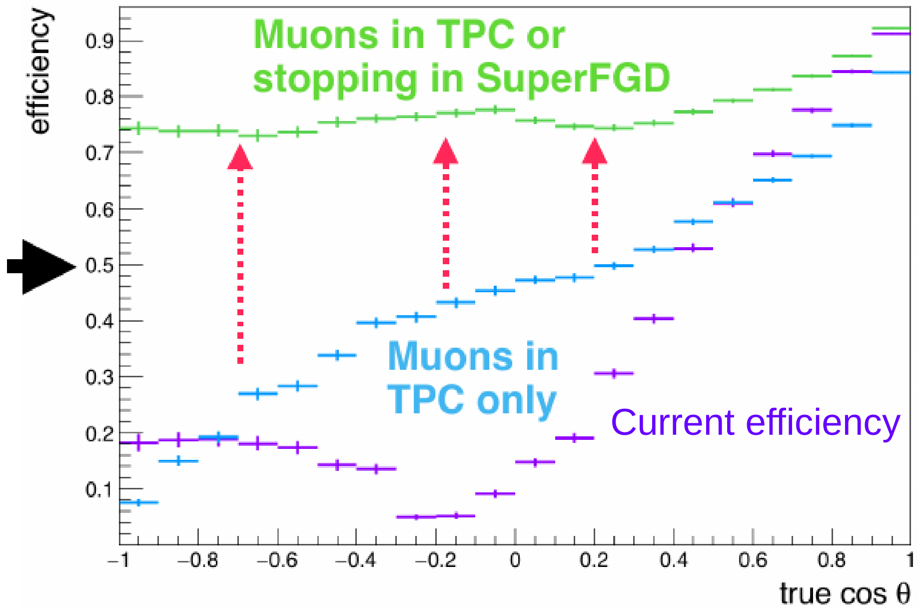




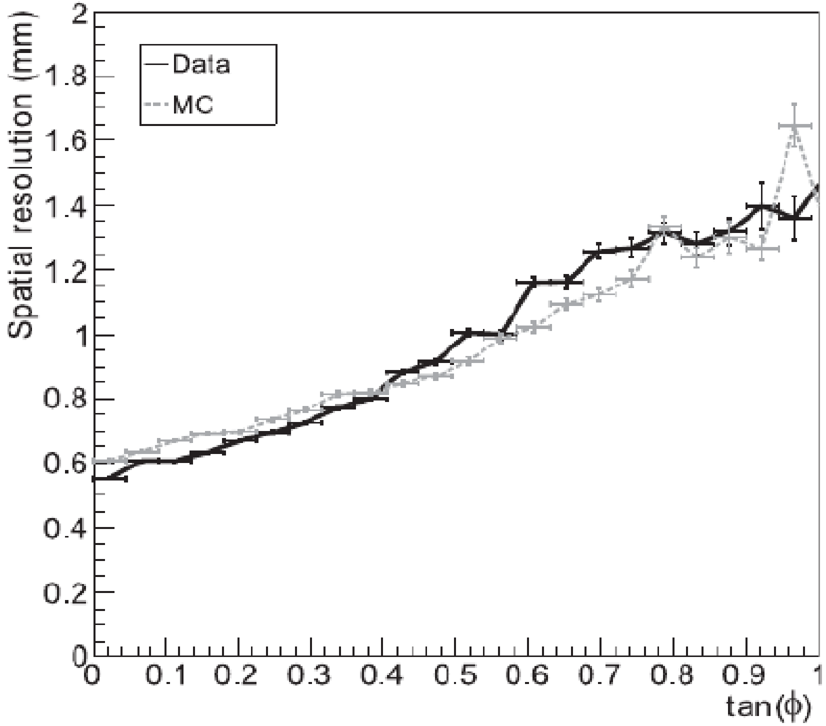
Physics improvements

- **Improvement of angular coverage** for charged particles

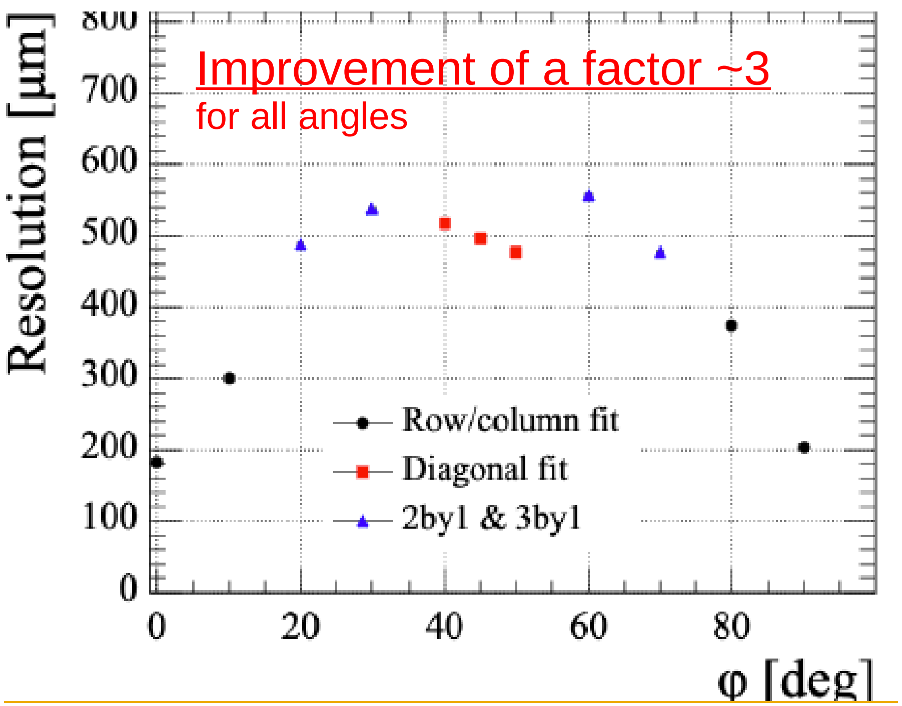
- **Improved TPC spatial resolution** → improved momentum resolution (10% in previous TPCs)



ND280 vertical TPCs



Resistive Micromegas prototype for ND280 upgrade at 2019 DESY test beam



BSM in neutrinos

- Very good position of France to study BSM at Long-Baselines:

  - strong role at Near detectors: light steriles (appearance at short baseline), heavy sterile produced in the beam and decaying/interacting in the ND

  - degeneracies between BSM and PMNS (eg new CP-violation sources in NSI) can be resolved by combining different L/E (already studied for atmospheric ν vs beam ν)

  → **complementarity of DUNE and HK: different baselines, different energy**

    - should be investigated more even in the framework of control of systematic uncertainties in “standard” oscillation measurements!

- France effort for **overall comprehensive look at neutrinos to build a coherent model (BSMNu project in P2IO)**

  - PMNS unitarity with JUNO vs direct search of steriles and NSI (coherent scattering) at reactors

  - $0\nu\beta\beta$ search for Majorana vs Dirac nature of neutrinos: already imposing limits in BSM scenarios!