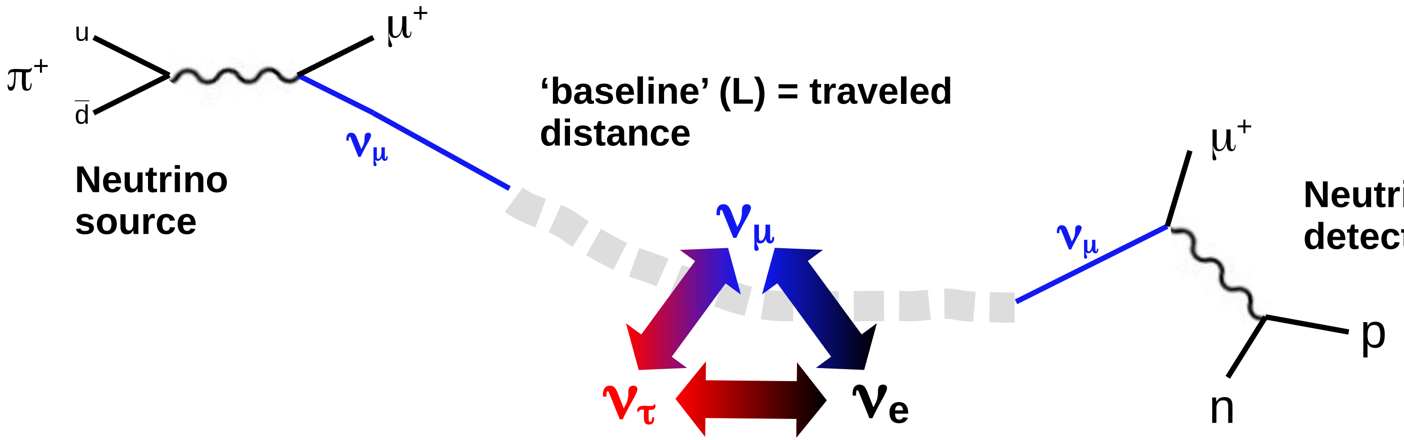
Sara Bolognesi (IRFU, CEA)

Results and prospects for **accelerator-based neutrino** physics

Exploting the Dark Side of the Universe (June 2024) – Ile de Noirmoutier

Neutrino oscillations

Exquisite QM effect : ν interact (production and detection) as flavour eigenstates ↔ propagate as mass eigenstates = coherent superposition of flavour states



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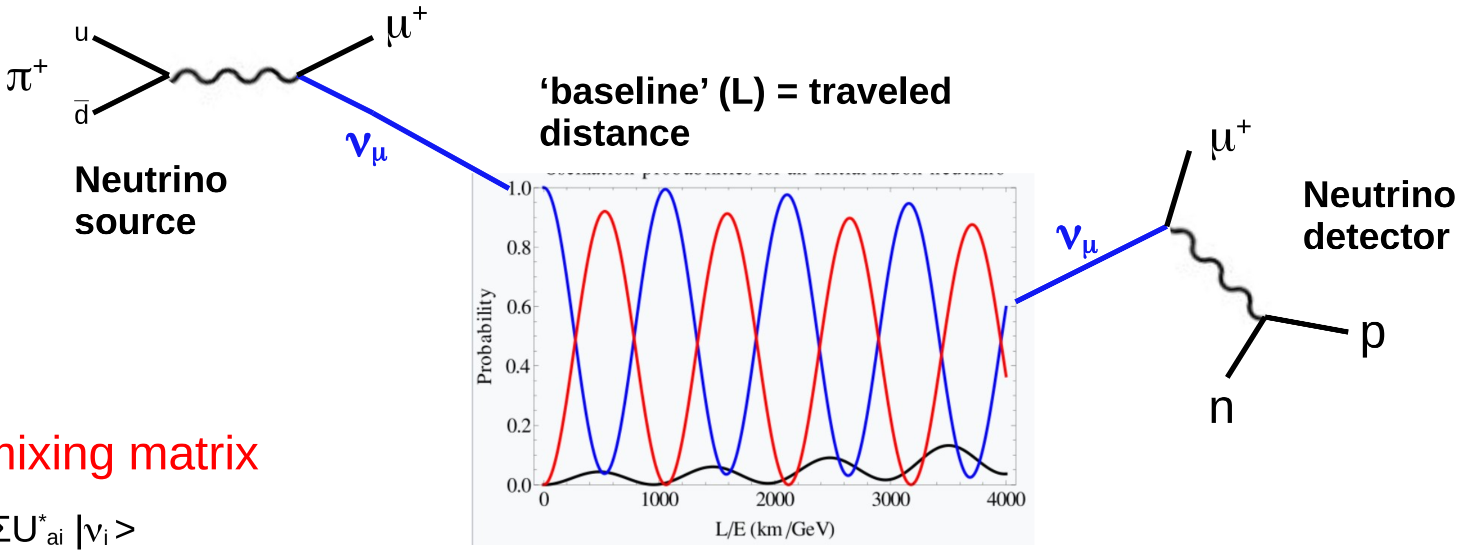
(localization and environmental effects induce tiny/negligible decoherence in the SM)



PMNS mixing matrix

$|\nu_\alpha\rangle = \Sigma U^*_{\alpha i} |\nu_i\rangle$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P_{\alpha\rightarrow\beta} = P(\nu_\alpha, t_0 \rightarrow \nu_\beta; t) = |\langle \nu_\beta(t) | \nu_\alpha(t_0) \rangle|^2$$

$$= |\sum_i U_{\beta i} e^{-iE_i(t-t_0)} U^*_{\alpha i}|^2$$

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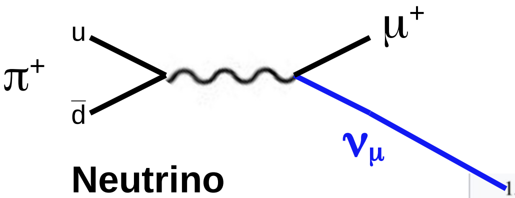
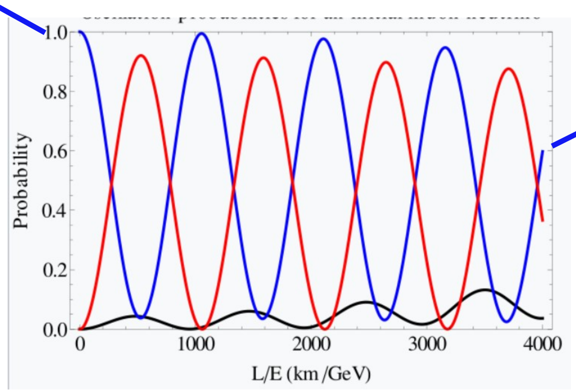
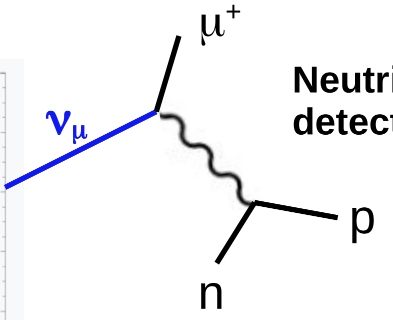


'baseline' (L) = traveled distance





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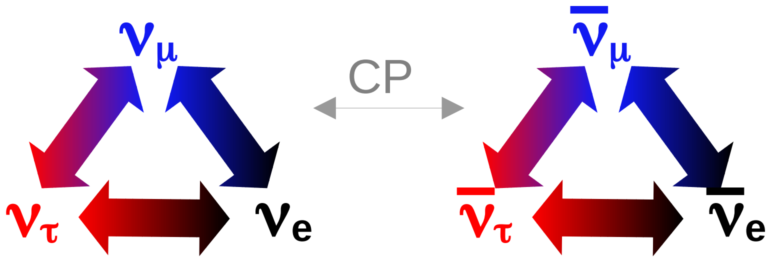
$$P_{\alpha\to\beta} = P(\nu_\alpha, t_0 \to \nu_\beta; t) = |\langle \nu_\beta(t) | \nu_\alpha(t_0) \rangle|^2$$

$$= |\sum_i U_{\beta i} e^{-iE_i(t-t_0)} U^*_{\alpha i}|^2 = |\sum_i U_{\beta i} U^*_{\alpha i} e^{-i m_i^2 L/2E}|^2$$

Neutrino oscillations : open questions

$P_{osc}(\overline{\nu}) \neq P_{osc}(\nu)$ direct probe to **a new source of fundamental Charge-Parity violation and first in leptonic sector**

→ **connected to matter/antimatter asymmetry through leptogenesis scenarios**



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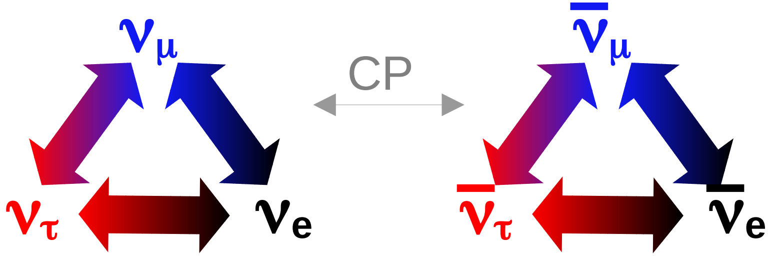
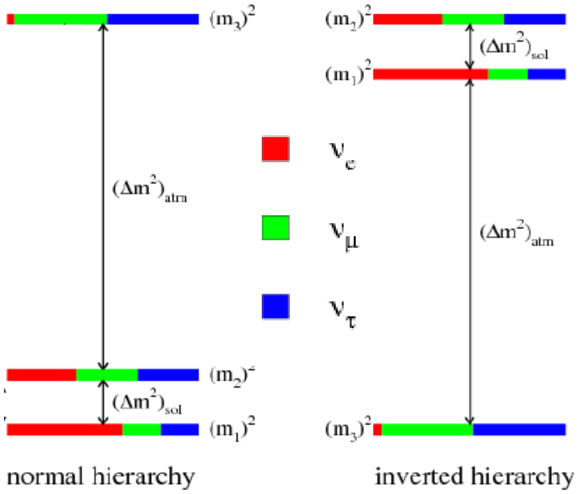


Many other interesting (a-)symmetries to test:

- is the mass ordering the same as charged leptons ?



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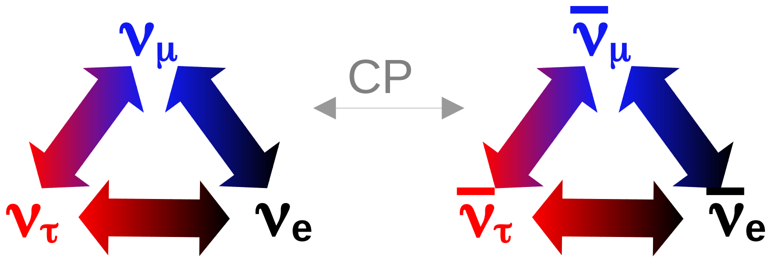

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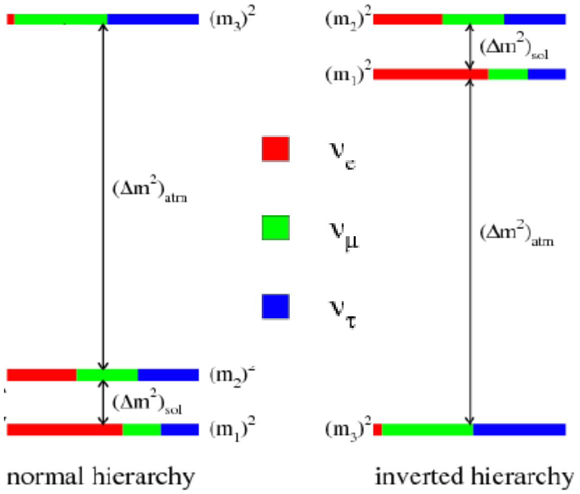
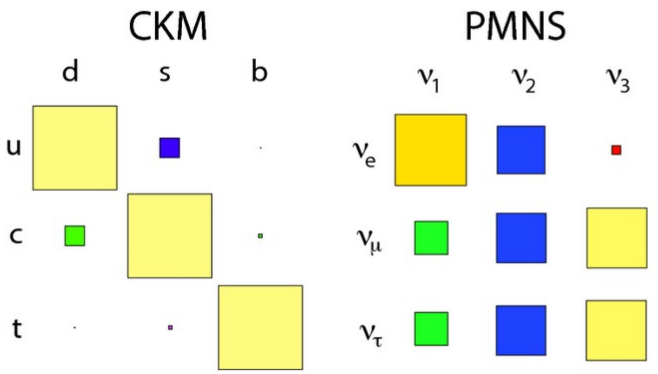
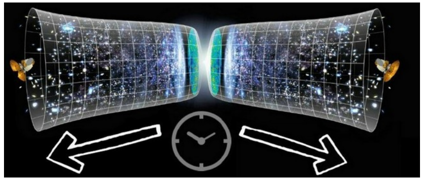


- why mixing so different between quarks and neutrinos ?



Neutrinos as a tool



ν as a ‘’clock’’ :
could be the largest fundamental T-reversal asymmetry in particle physics

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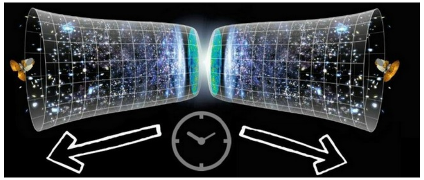

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probe for deformed space-time from Minkowski metrics

$$P_{\nu_\alpha \to \nu_\beta}(t) = \sum_{jk} U_{\alpha j} U^*_{\beta j} U^*_{\alpha k} U_{\beta k} e^{-i\left(\frac{(m_j^2 - m_k^2)c^3}{2\hbar p}\right)^{\eta} t^{\eta}}$$

Sci.Rep. 13 (2023) 1, 12651

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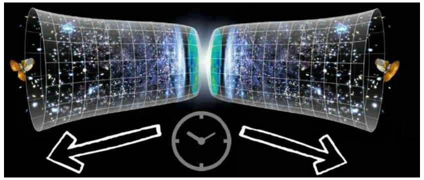

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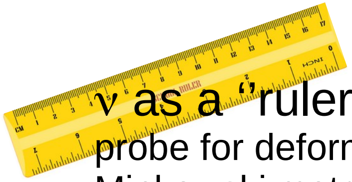

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ν as an ‘interferometer’ :
decoherence from
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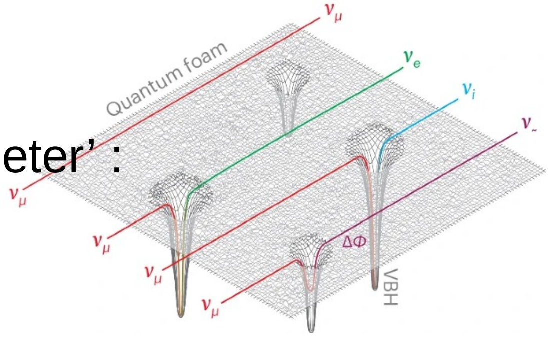

Nat. Phys. (2024). https://doi.org/10.1038/s41567-024-02436-w

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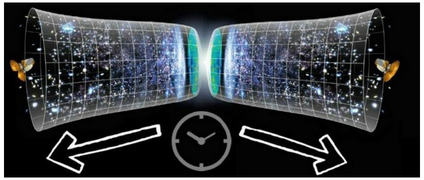

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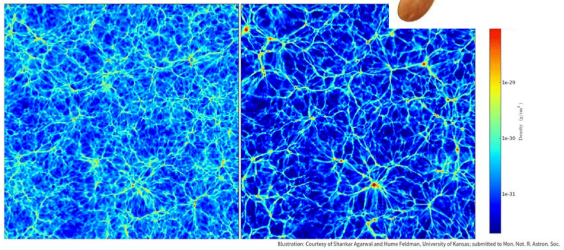
matter distribution in the universe depends on m_ν



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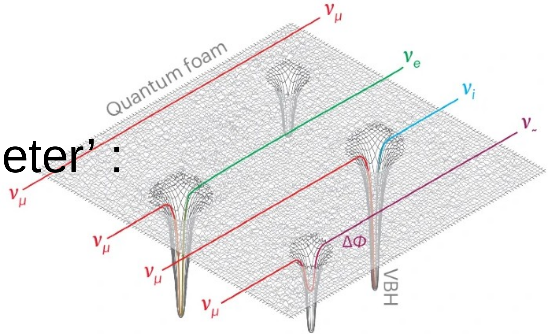

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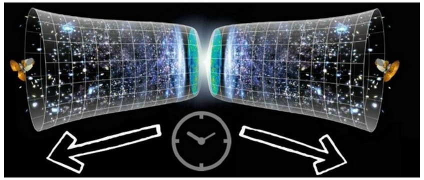

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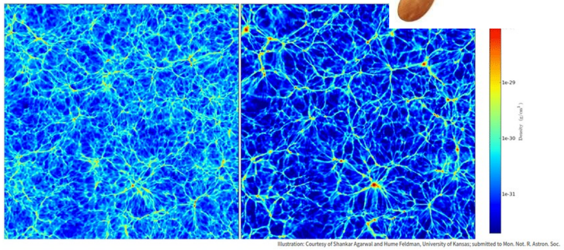

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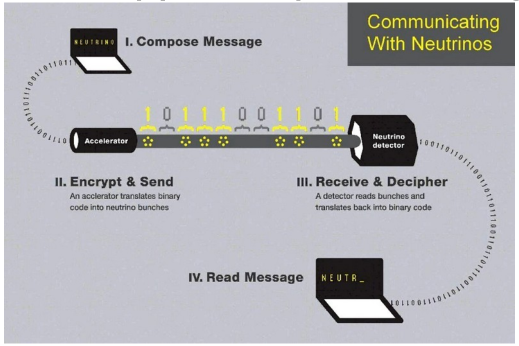
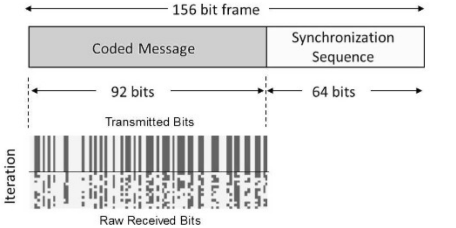
ν as (quantic) ‘messanger’ :





Mod. Phys. Lett. A 27 (2012) 1250077

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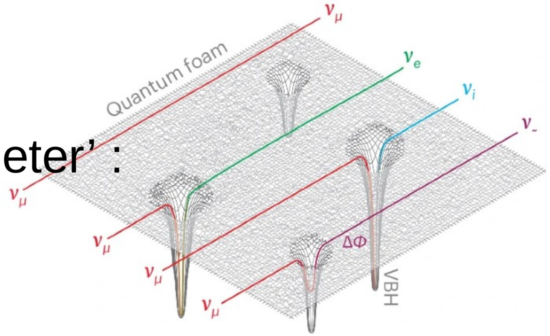
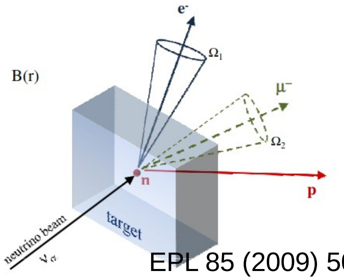


Communication with coherence on large distance, single-particle entangled state



EPL 85 (2009) 50002

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Tools for neutrinos

We need to better measure neutrinos, in particular their oscillations, to fully exploit their potential

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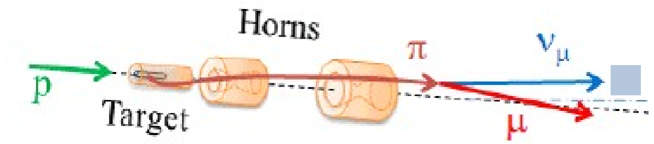
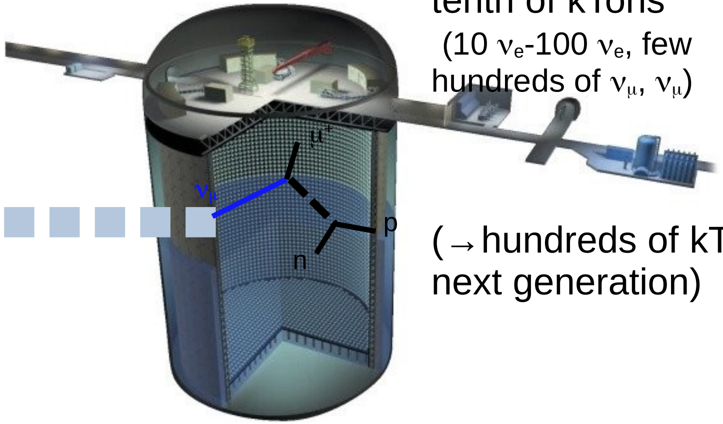


~500kW
(→ 2MW next generation)

baseline L~
hundreds of km



Gigantic detector :
tenth of kTons
(10 ν_e-100 ν_e, few hundreds of ν_μ, ν_μ)

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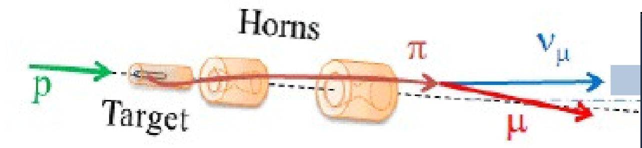

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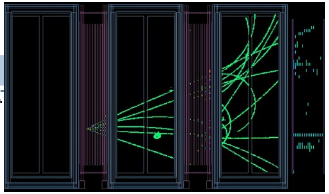
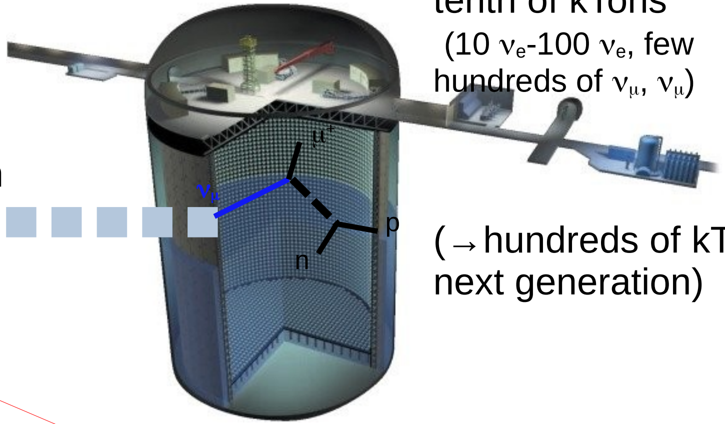


Highly capable near detectors (few tons, >10000 ν_μ, before oscillations)

baseline L~ hundreds of km



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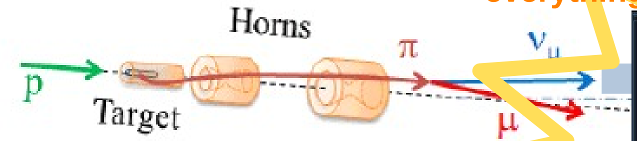

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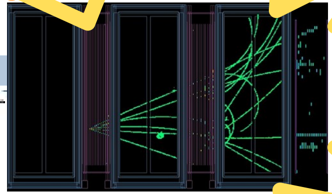
And this change everything !



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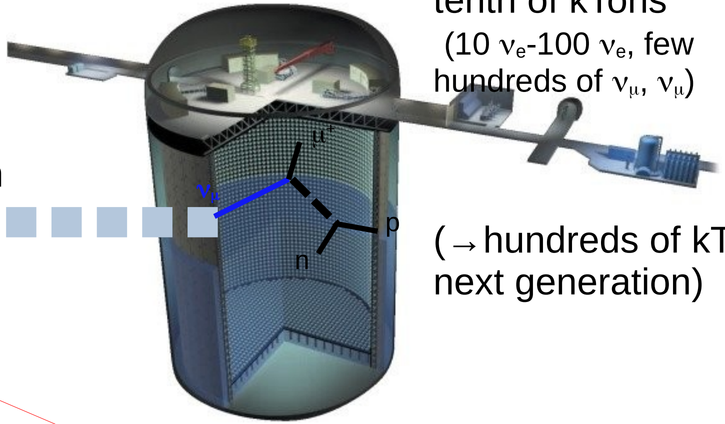

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Tools for neutrino analysis

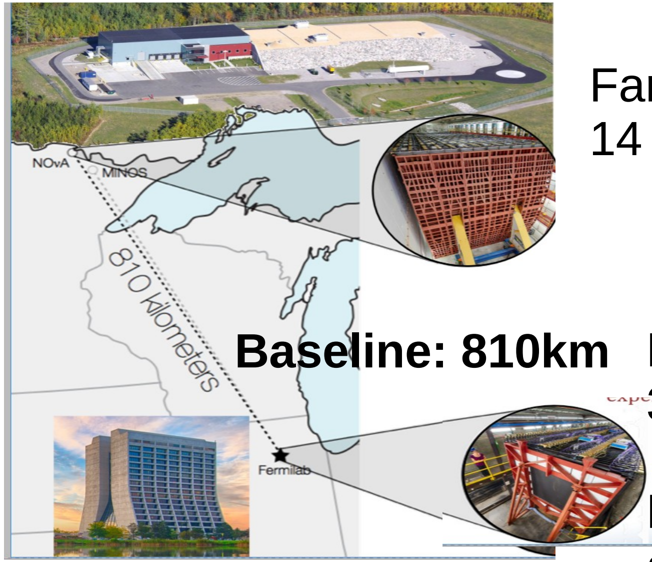
- Reconstruction of tracks, events selection : extract ν information from reconstructed final state particles of neutrino interactions

- Data-MC fit to extract oscillation measurements :

  → statistical methods (combination of datasets : near+far detectors, different experiments)

See next talks in this section !

NOVA



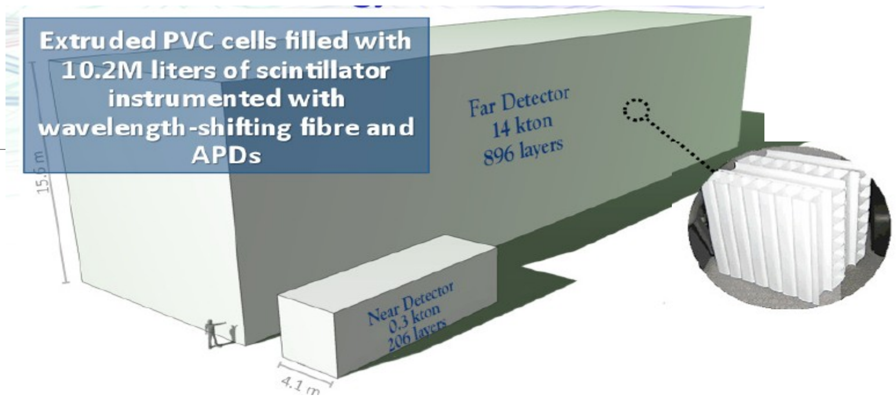
Far detector:
14 kT on surface

Baseline: 810km

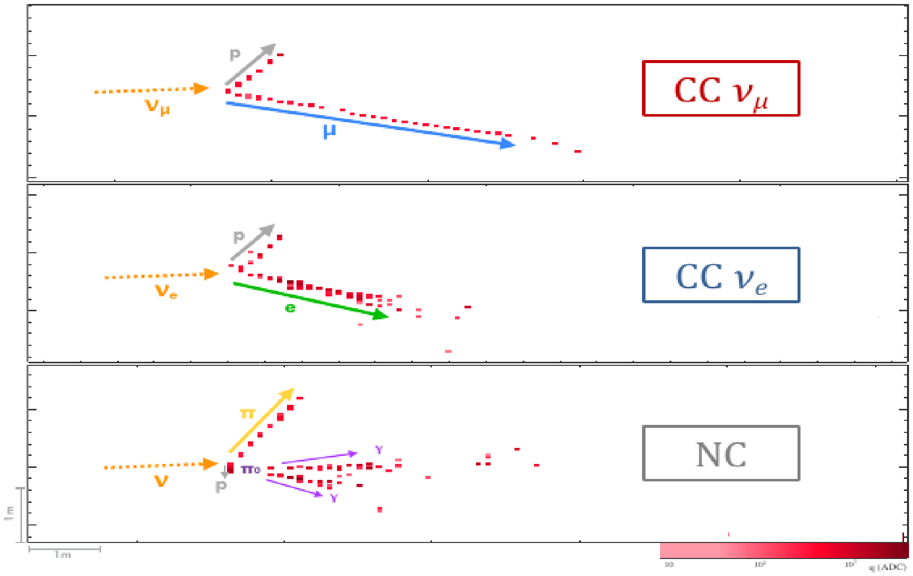
Near Detector:
300T underground

NUMI beam
at FNAL

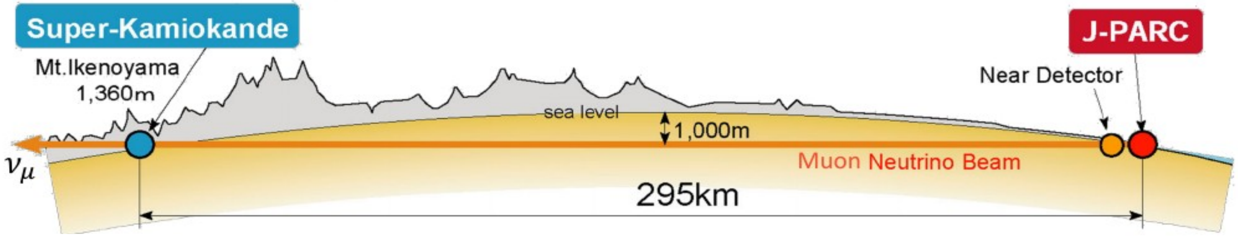
– Placed 14mrad off-axis to produce a narrow-band spectrum



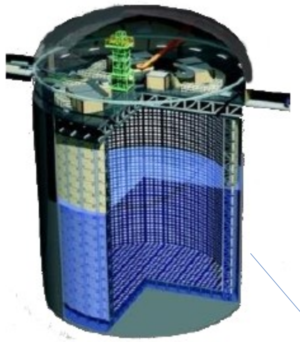
– **Functionally identical near and far detectors : liquid scintillator**



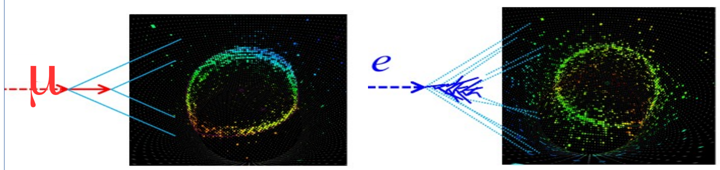
T2K



- JPARC beam (Japan Proton Accelerator Research Center)



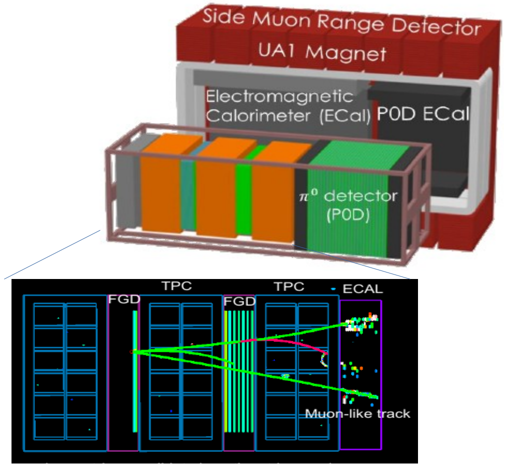
- **Huge water cherenkov detector** (50 kTon)



clear ring

fuzzy ring

ND280

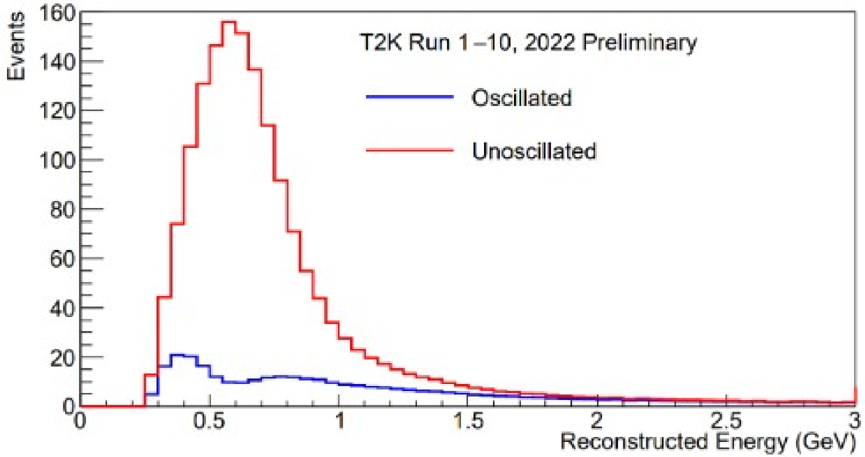


- **Multipurpose magnetized near detector :** full tracking and particle reconstruction (few tons)

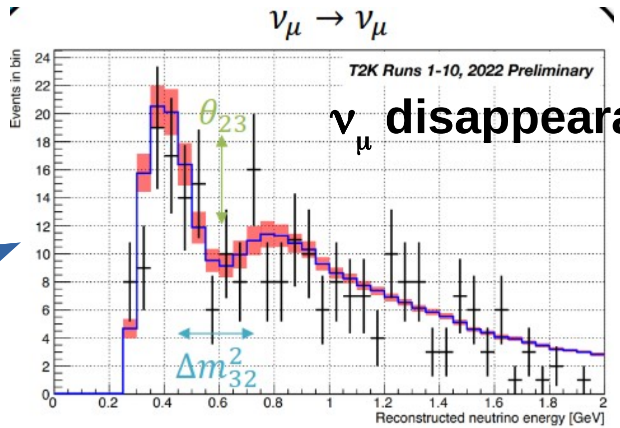
- Placed 2.5deg off-axis to produce narrow-band flux

Evidence of oscillation

ν_μ spectrum at the far detector

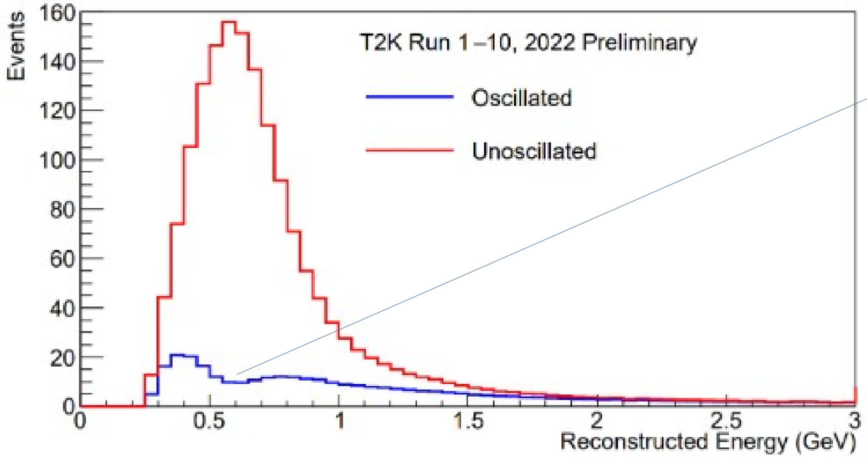


Precision era



ν_μ disappearance

ν_μ spectrum at the far detector



Global fit from all experiments

NuFIT 5.3 (2024)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$

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

amplitude

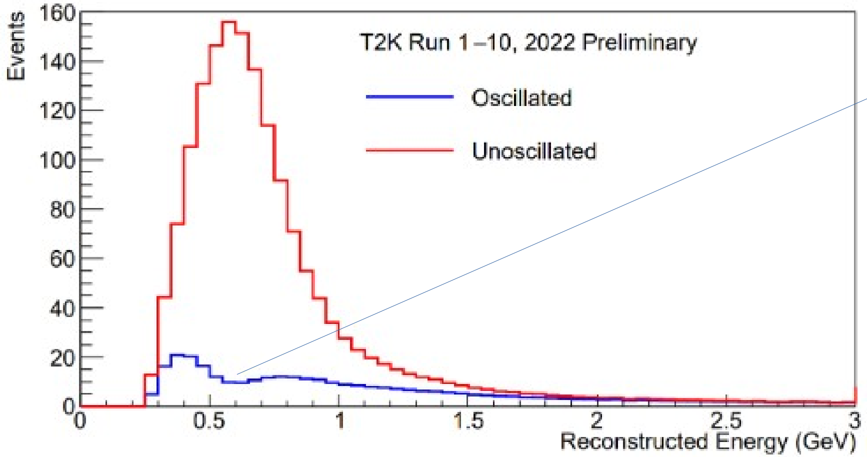
~3.5% precision : octant unkown, maximal oscillation possible

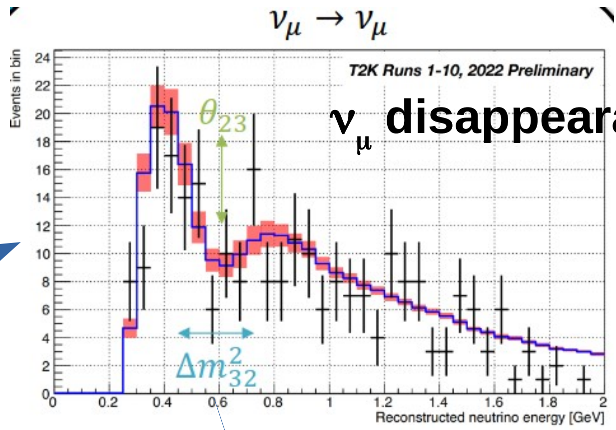
frequency

~1.5% precision (systematics starts to limit the measurement)
No sensitivity to sign !

Precision era

ν_μ spectrum at the far detector





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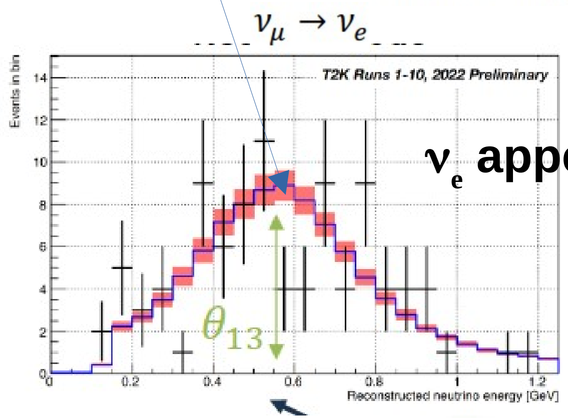

ν_e appearance

ν_τ mostly not accessible ($E_\nu < m_\tau$)

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NuFIT 5.3 (2024)

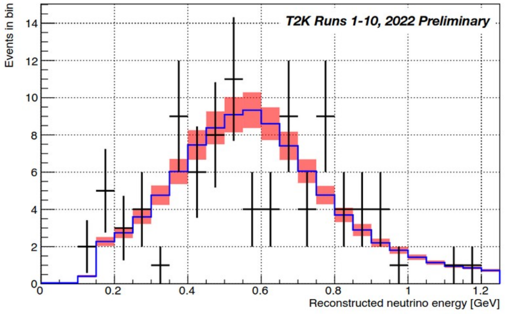
	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.407 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.027}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.024}$	$-2.581 \to -2.409$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00058}$	$0.02029 \to 0.02391$	$0.02219^{+0.00059}_{-0.00057}$	$0.02047 \to 0.02396$

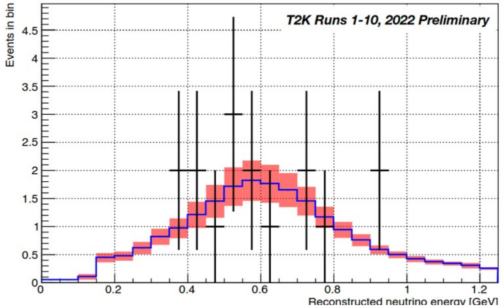
$$P(\nu_\mu \to \nu_e) \approx \boxed{\sin^2 2\theta_{13}} \sin^2\theta_{23} \sin^2 \frac{\Delta m^2_{32} L}{4E}$$

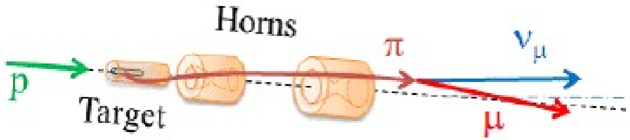
<3% precision from reactor experiments

Charge-Parity violation : the strenght of accelerator ν experiments

$\nu_\mu \rightarrow \nu_e$ $\xleftrightarrow{\text{CP}}$ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$







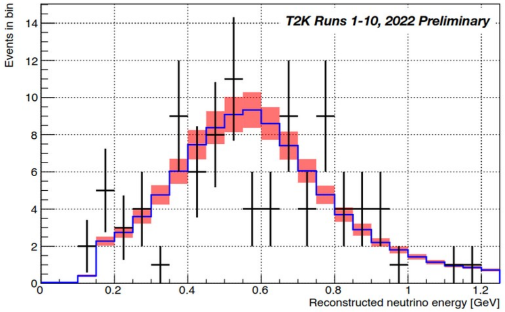
Switching magnets polarity :

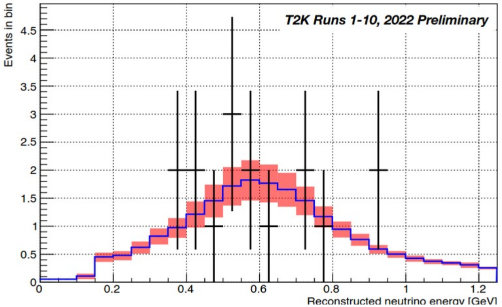
$\pi^+ \rightarrow \mu^+ \nu_\mu \quad \leftrightarrow \quad \pi^- \rightarrow \mu^- \bar{\nu}_\mu$

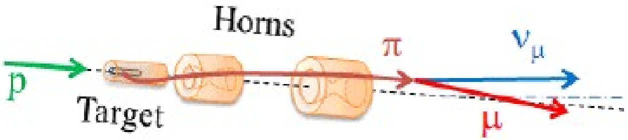
$$\mathcal{A}_{\rm CP} \equiv \frac{P(\nu_\mu \rightarrow \nu_e) - P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)}{P(\nu_\mu \rightarrow \nu_e) + P(\overline{\nu}_\mu \rightarrow \overline{\nu}_e)} \simeq -\frac{\sin 2\theta_{12} \sin\delta}{\sin\theta_{13}\tan\theta_{23}}\Delta_{21}$$

Charge-Parity violation & matter effects → mass ordering (MO)

$\nu_\mu \rightarrow \nu_e$ ⟵ CP ⟶ $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$







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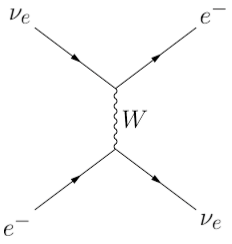
- ν_e makes charged current interactions with electrons in matter : additional potential in matter of opposite sign for $\nu_e/\bar{\nu}_e$

- larger neutrino energy and longer baseline → larger the matter effect



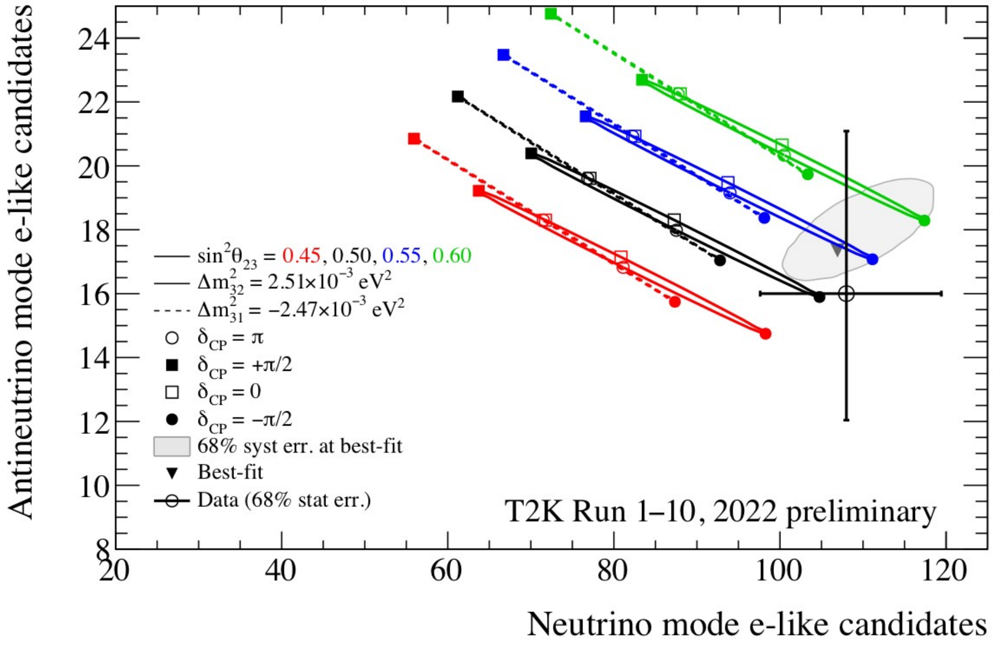
$$\Delta m^2_{eff} = \Delta m^2 \sqrt{\sin^2 2\theta_{13} + (\Gamma - \cos 2\theta_{13})^2}$$

$$\sin^2 2\theta_{13,eff} = \frac{\sin^2 2\theta_{13}}{\sin^2 2\theta_{13} + (\Gamma - \cos 2\theta_{13})^2}$$

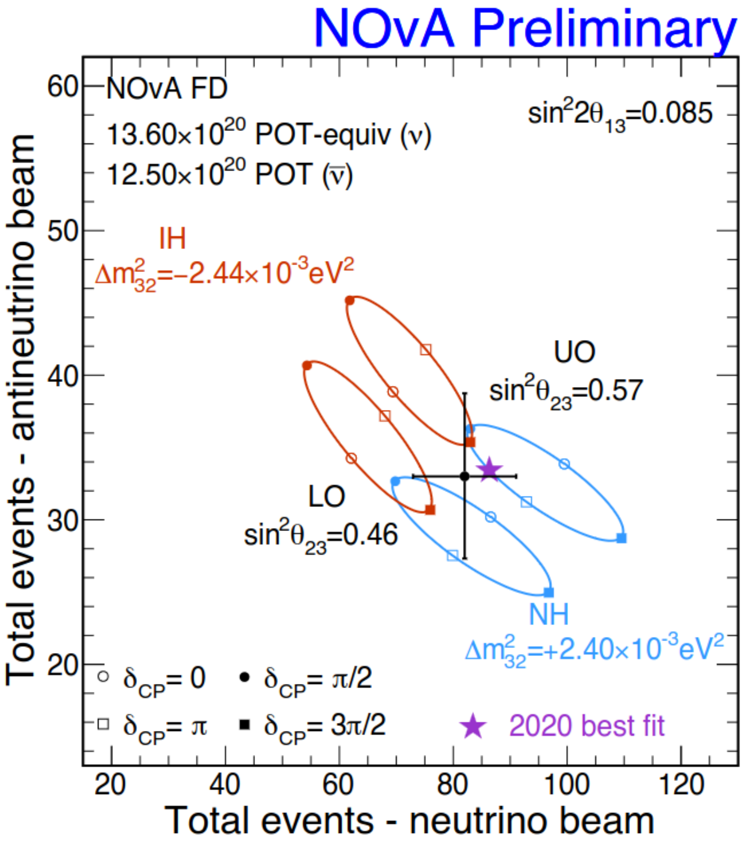
$$\Gamma = \pm 2\sqrt{2} G_F N_e E / \Delta m^2$$

Sensitivity to Δm^2 sign : MO !

CPV & MO : data

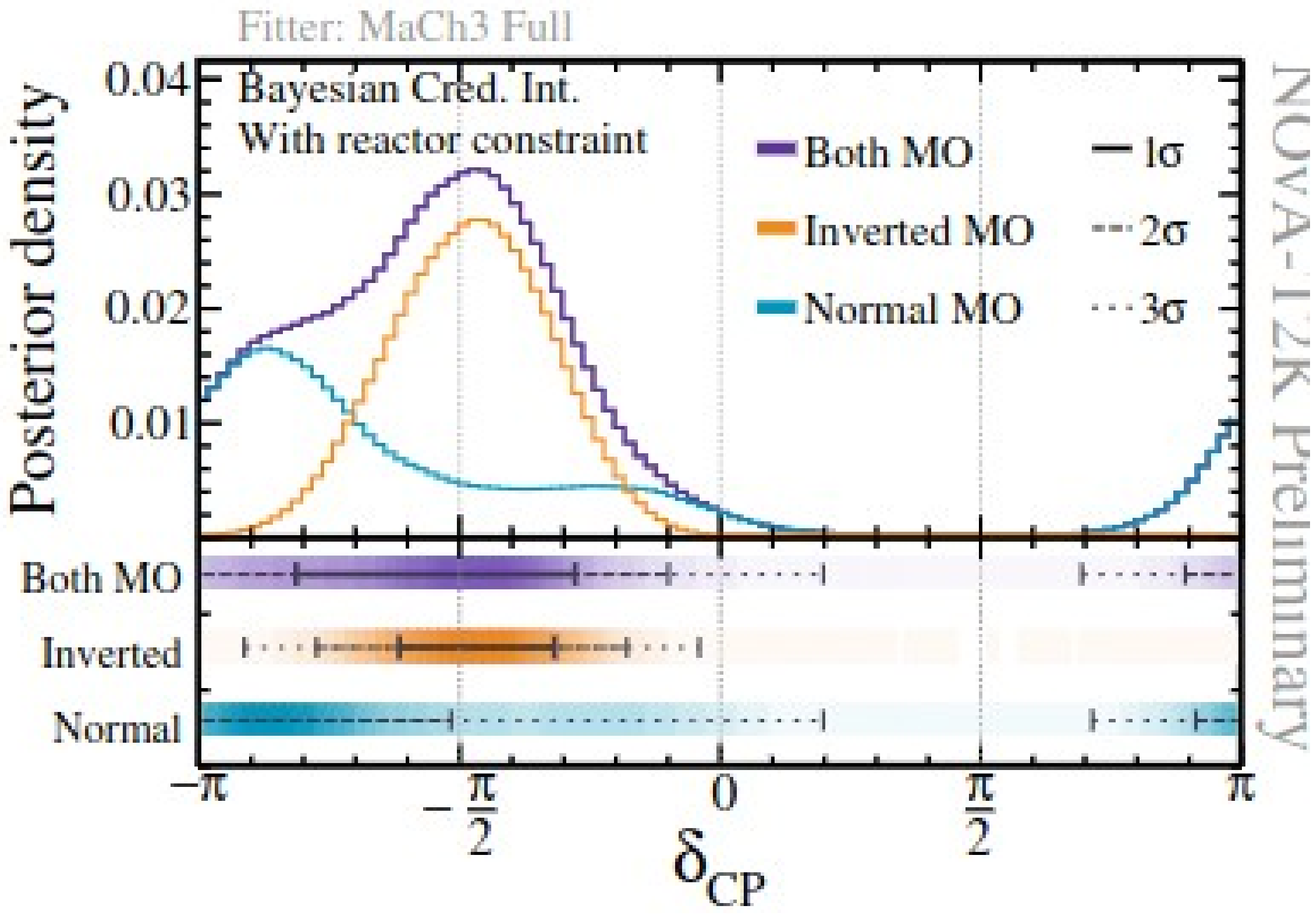


Antineutrino mode e-like candidates
Neutrino mode e-like candidates
sin²θ23 = 0.45, 0.50, 0.55, 0.60
Δm²32 = 2.51×10⁻³ eV²
Δm²31 = −2.47×10⁻³ eV²
δCP = π
δCP = +π/2
δCP = 0
δCP = −π/2
68% syst err. at best-fit
Best-fit
Data (68% stat err.)
T2K Run 1–10, 2022 preliminary



NOvA Preliminary
NOvA FD
13.60×10²⁰ POT-equiv (ν)
12.50×10²⁰ POT (ν̄)
sin²2θ13=0.085
IH
Δm²32=−2.44×10⁻³eV²
UO
sin²θ23=0.57
LO
sin²θ23=0.46
NH
Δm²32=+2.40×10⁻³eV²
δCP= 0
δCP= π/2
δCP= π
δCP= 3π/2
2020 best fit
Total events - antineutrino beam
Total events - neutrino beam

CPV results : T2K - NOVA



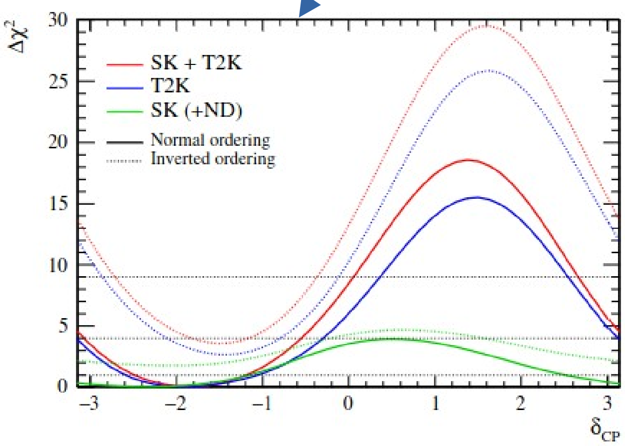
Comparison T2K and NOVA → joint fit
(see Clarence talk for details)

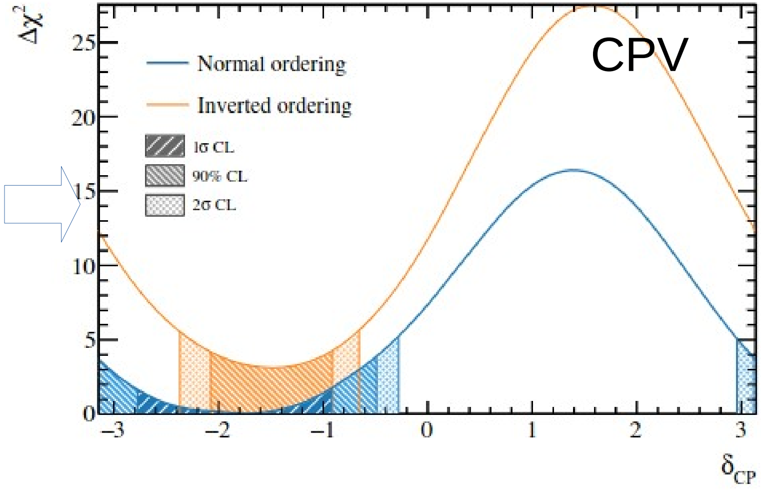
Mass ordering results : T2K - SK

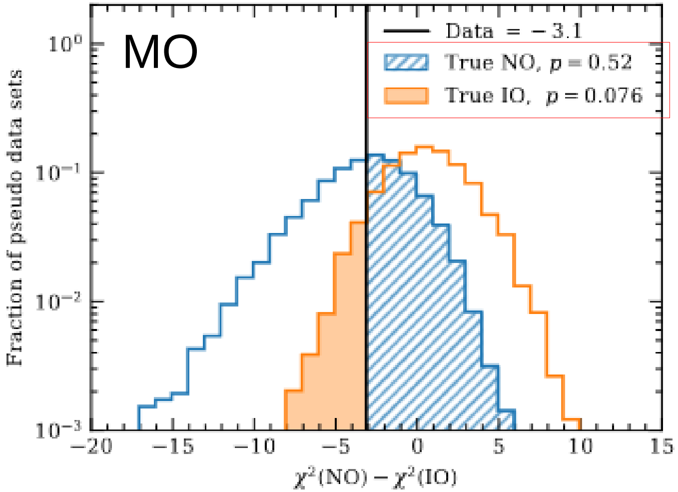
SuperKamiokande leading MO results with atmospheric neutrinos : $\Delta\chi^2$(IO-NO) = 5.69

+ mild δ_{CP} sensitivity in agreement with T2K

Joint fit T2K+SK (see Clarence talk for details)





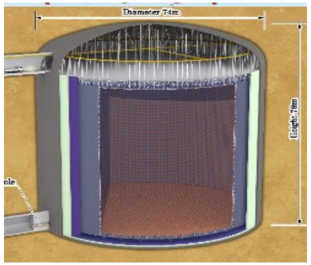


Next future :

- MO from combination **reactor+accelerator** of different precision measurements of Δm^2
- JUNO reactor experiment: from **oscillation in vacuum**

Prospects

New generation of experiments with thousands of events in ν_e and $\bar{\nu}_e$

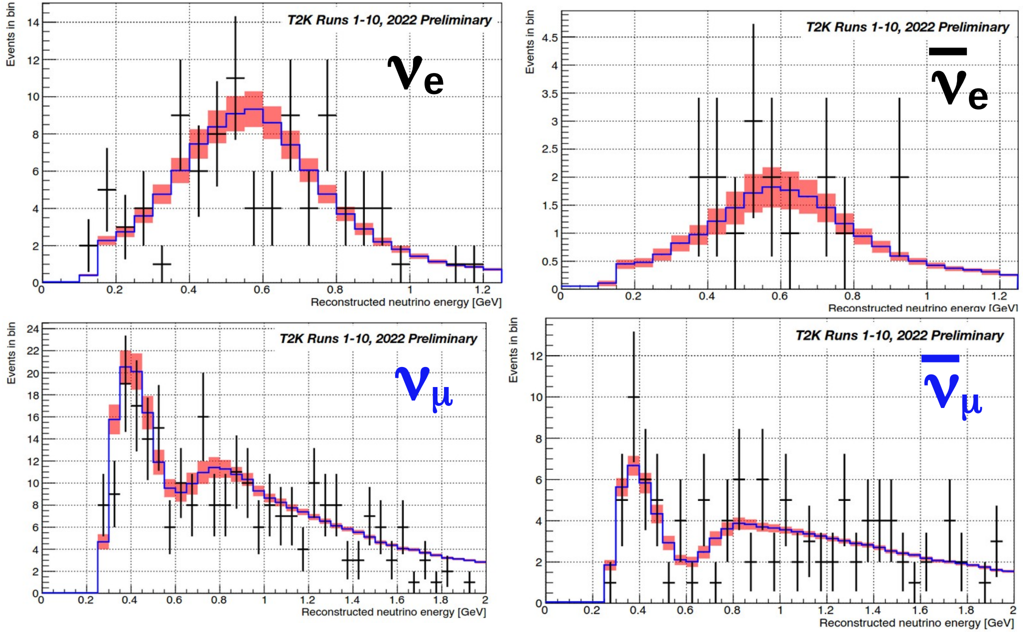


HyperKamiokande : T2K x8 mass x2.5beam power

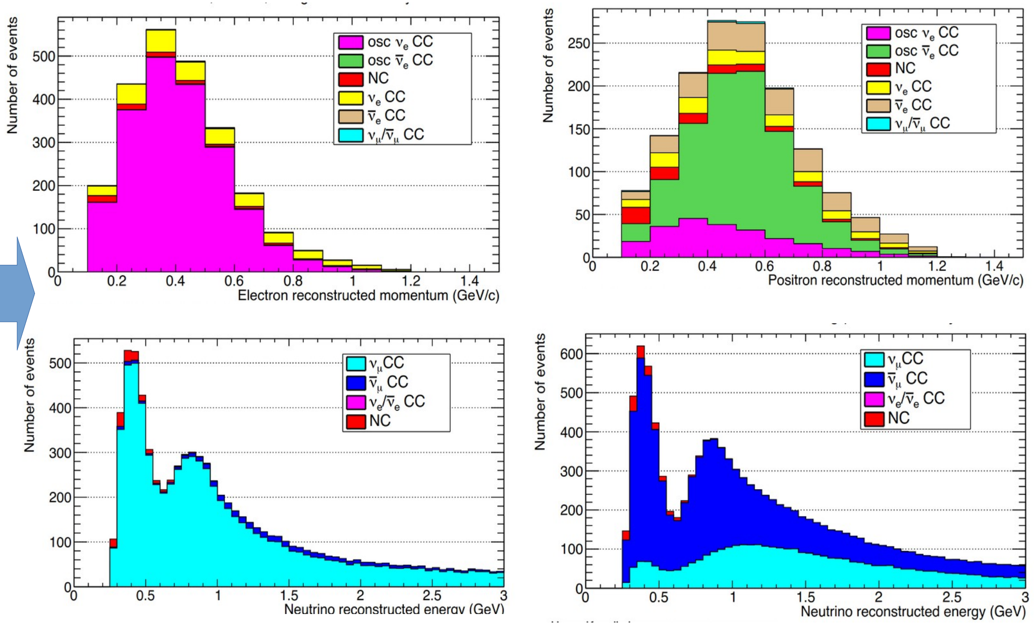
CPV discovery at 5σ for >60% of possible δ_{CP} values

Sub-percent precision on $|\Delta m_{23}^2|$ and $\sin^2\theta_{23}$

T2K data

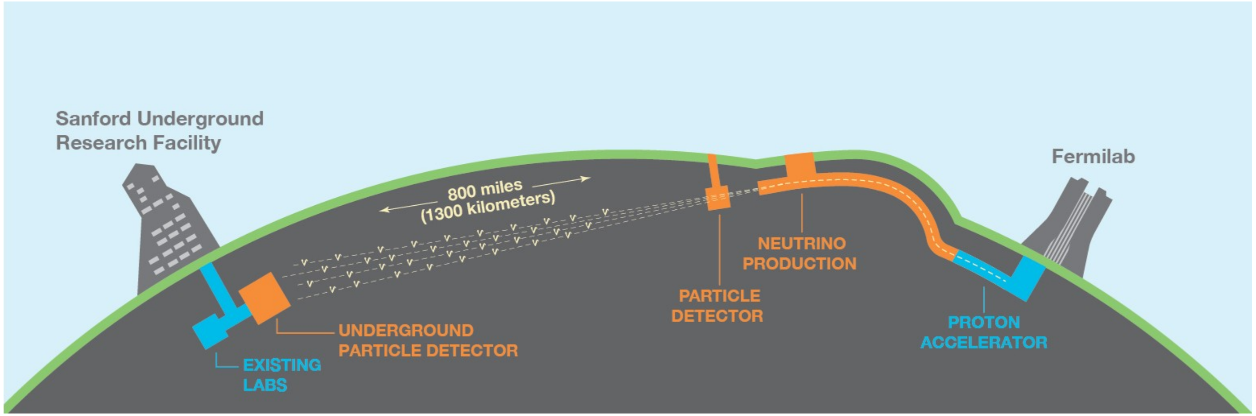


HK projections

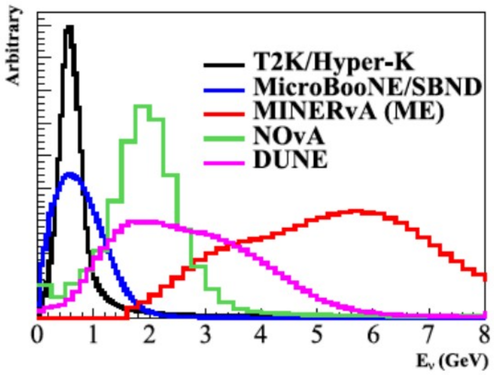


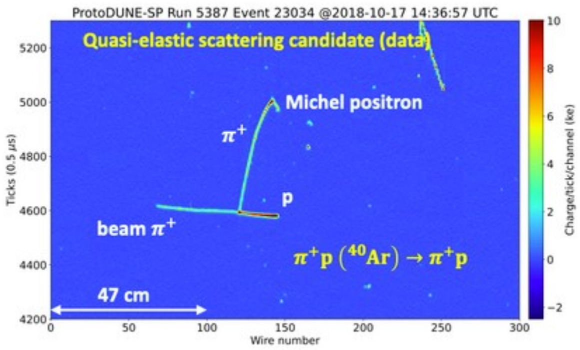
Prospects

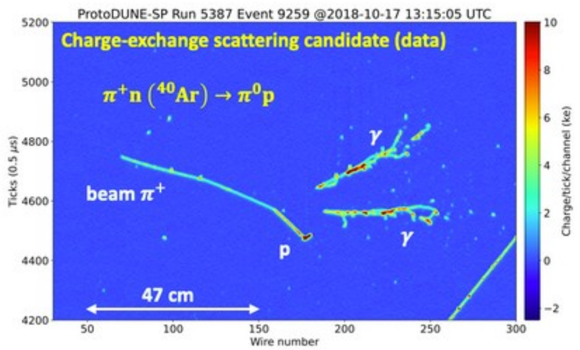
New : large energy coverage and different baselines to measure the oscillation pattern in a more agnostic/open-mind way (beyond PMNS paradigm)



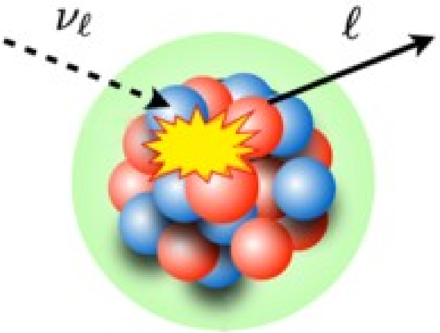
DUNE : 1300 km baseline, energy up to few GeV, Liquid Argon TPCs



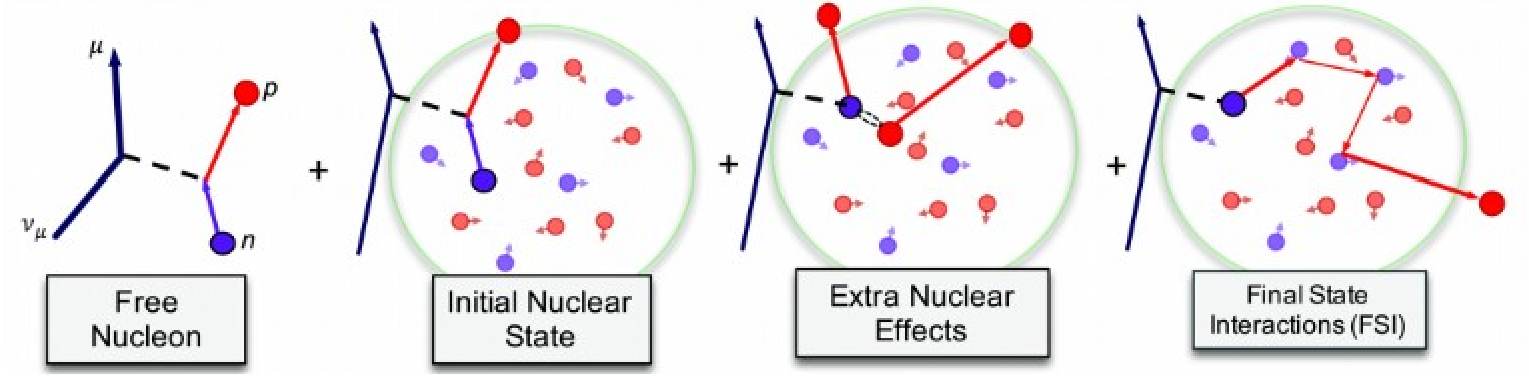




Entering in the precision era



→ **Main challenge : precise energy reconstruction**
From final state particles to neutrino : complex nuclear effects to correct for



Crucial importance of a new generation of highly capable near detectors

BSM ‘surprises’ ?

Sterile **‘conventional’ searches** as modifications of active neutrinos oscillations
→ sterile mass scales accessible driven by oscillation frequency

$$\Delta m^2 \frac{L}{E}$$

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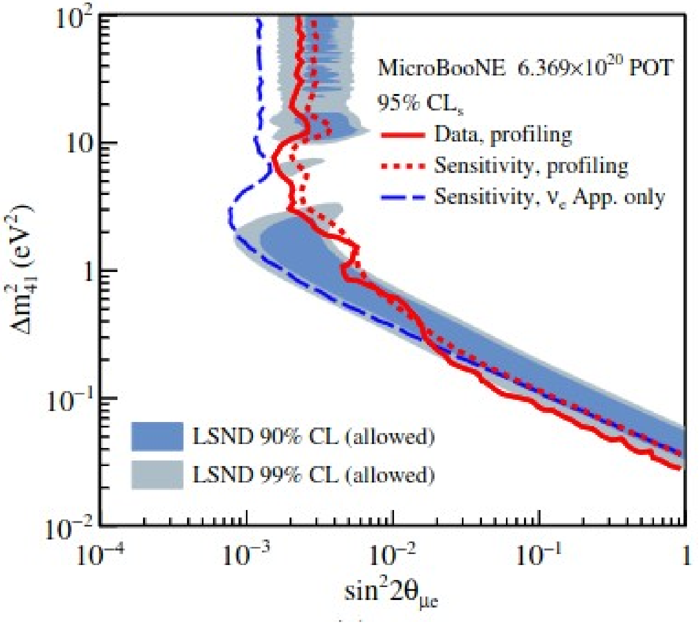
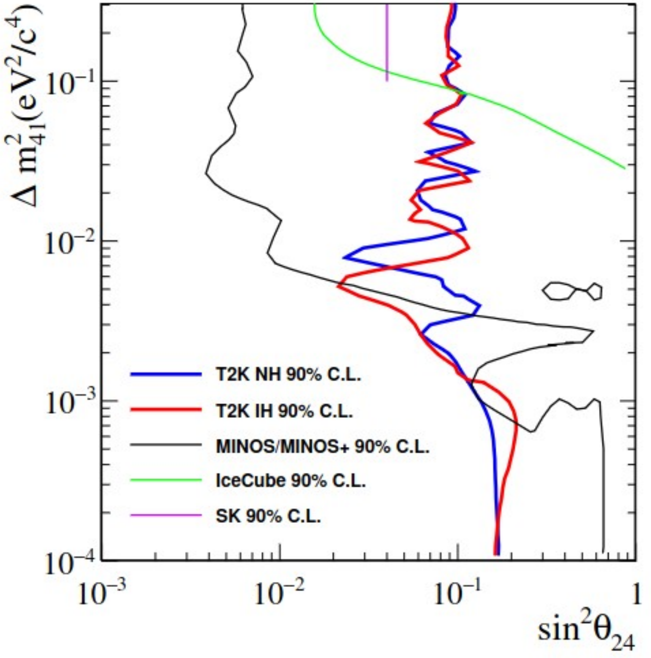
Sterile **‘conventional’ searches** as modifications of active neutrinos oscillations
→ sterile mass scales accessible driven by oscillation frequency

$$\Delta m^2 \frac{L}{E}$$

Near detectors (short baseline L)
→ test for >1eV Δm^2



Phys.Rev.Lett. 130 (2023) 1, 011801



Phys. Rev. D 99, 071103 (2019) Phys.Rev.Lett. 122 (2019) 9, 091803

Far detectors (long baseline L)
→ test for lower Δm^2
Use ne appearance, nm disappearance but also Neutral Current

BSM ‘surprises’ ?

Sterile searches at **‘unconventional’ mass scales (hundreds of MeV):** well motivated in models of bariogenesis through leptogenesis, and in νMSM

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- Challenge : creative strategies to suppress the background from interactions of active neutrinos

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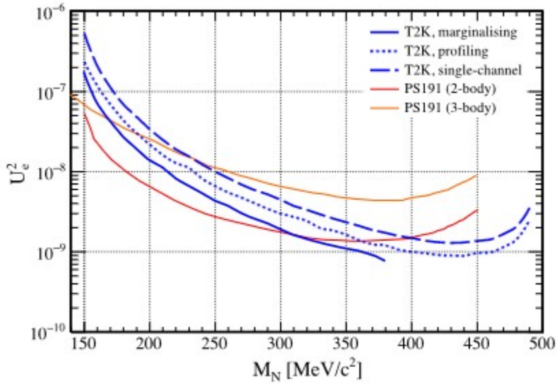
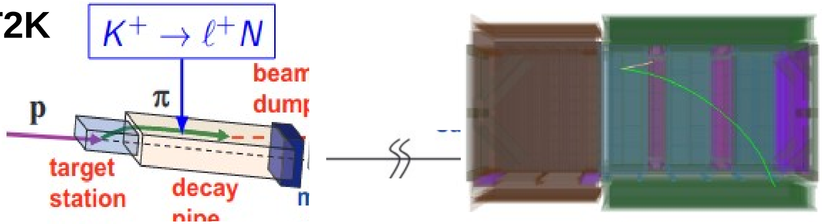
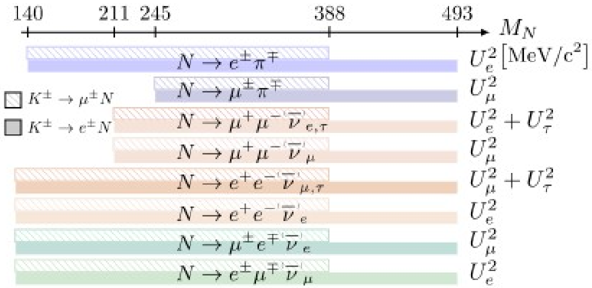
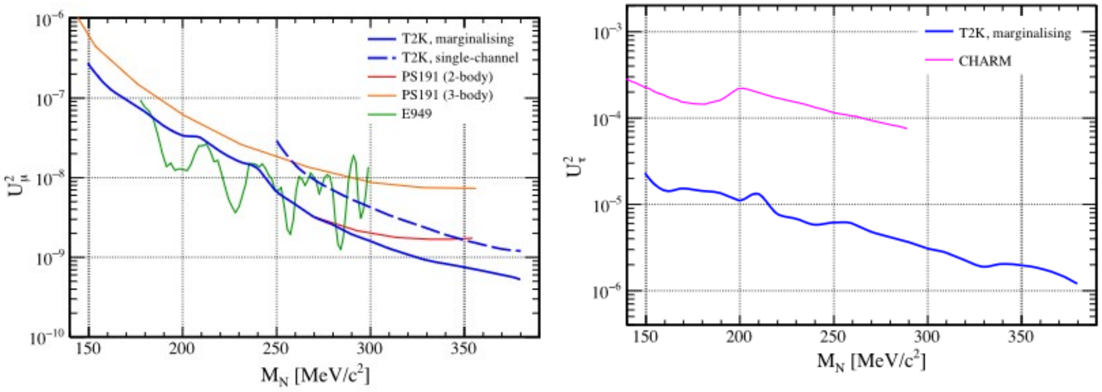


T2K



- ND280: decay of sterile neutrinos in TPC gas volume

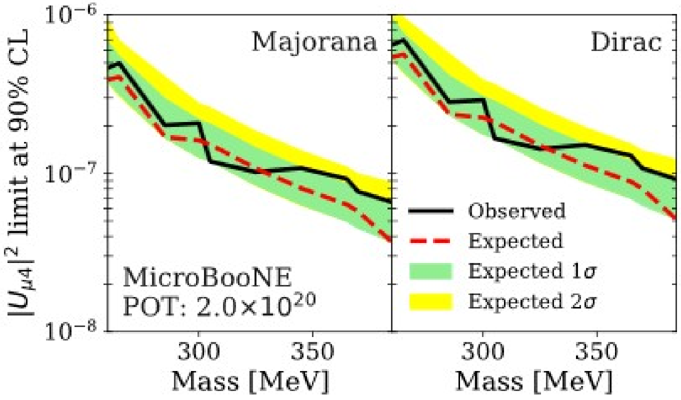




Phys. Rev. D 100, 052006 (2019)

BSM ‘surprises’ ?

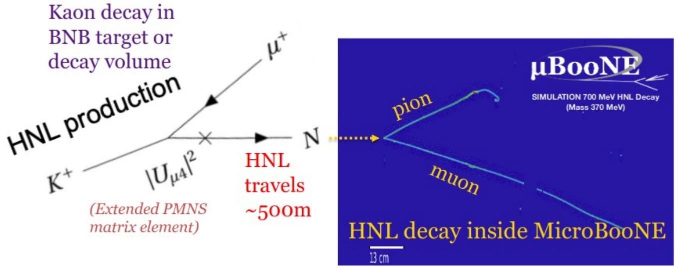
Sterile searches at **‘unconventional’ mass scales (hundreds of MeV):** well motivated in models of bariogenesis through leptogenesis, and in νMSM



- ‘’Heavy neutral lepton’’ from **decays of Kaons in the beamline** → HNL into the near detector volume

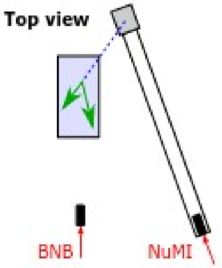
- Challenge : creative strategies to suppress the background from interactions of active neutrinos

MicroBooNE:



- heavy sterile delayed (larger ToF) with respect to interactions of standard neutrino

Phys. Rev. D 101, 052001 (2020)



- heavy sterile from a nearby beam not pointing directly to MicroBoone

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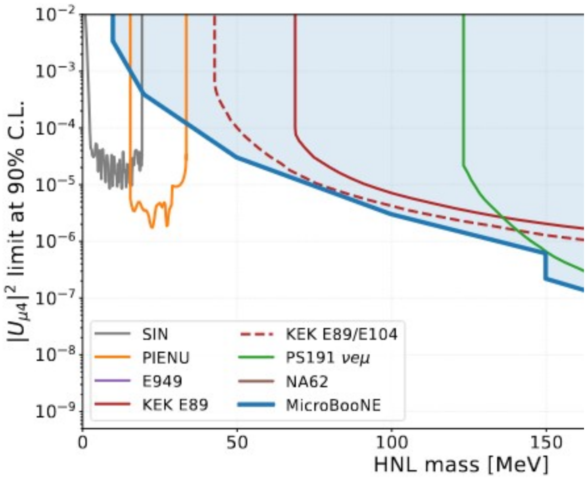
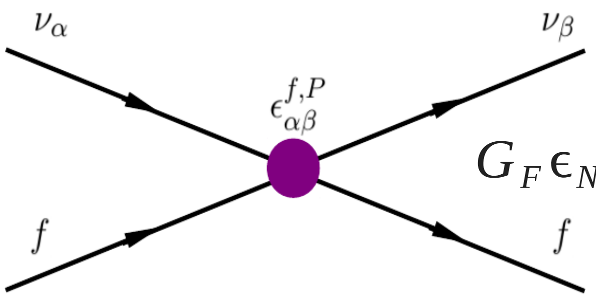


BSM ‘surprises’ ?

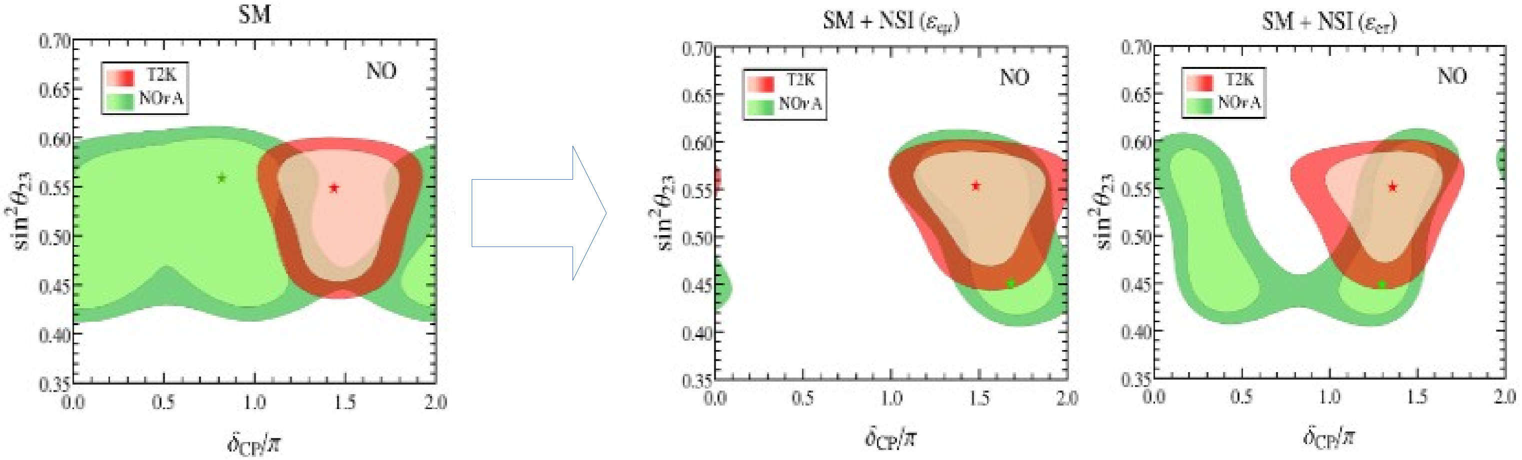
- Peculiar nature of ν and being in direct contact with Λ_{UV}: natural to expect new type of interactions for neutrinos: Non Standard Interactions



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

This is a quite open paradigm (difficult to falsify) but one clear signature would be modified oscillation results depending on L (while standard oscillations go as L/E)

Eg : NSI constraints from T2K-NOVA joint fit



Phys. Rev. Lett. 126 (2021) 051802

~~Conclusions~~ → Prospects

Neutrinos could be a wonderful tool to **probe fundamental physics**

Many neutrinos characteristics are still only partially known : we are bulding a much better knowledge of neutrino oscillation thanks to accelerator long-baseline experiments

Era of precision physics on disappearance parameters (mixing angles and mass differences) → need precise controls of neutrino flux and cross-section :
Crucial role of **highly performing near detectors** !

First hints of CP-violation in leptonic sector but still degeneracies with MO
→ the **combination of different experiments** (including atmospheric and reactor experiments) will solve the issue

Next generation of experiments (HyperKamiokande and DUNE)
→ ultimate precision physics on PMNS + opening new ways to look at oscillation with more model-independent / open-mind approaches

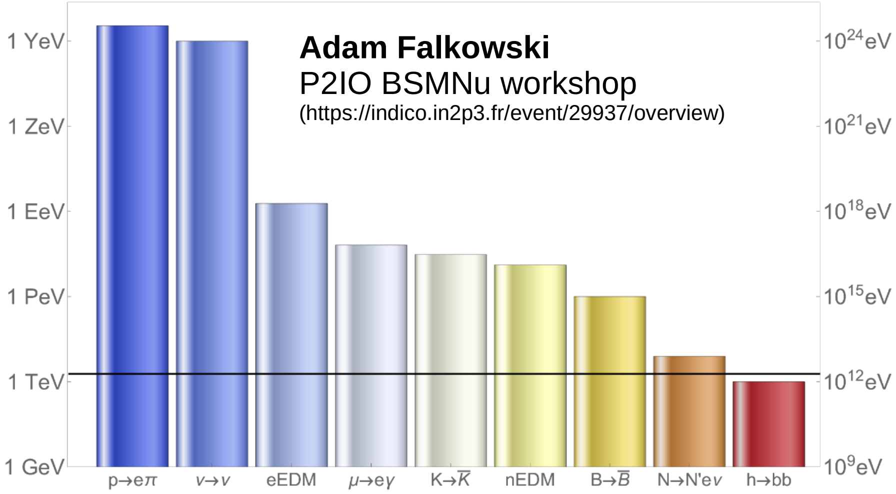
Neutrinos as door to New Physics (HEP)

- **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}):** $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{UV}}\mathcal{L}_5 + \ldots$

$$\frac{1}{\Lambda_{UV}}\mathcal{L}_5 = \frac{1}{2}\sum_{J,K=e,\mu,\tau} v^2 C_{JK}(\nu_J \nu_K) = -\frac{1}{2}(\nu M \nu)$$

The only 5th order operator possible according to fundamental symmetries: neutrino (Majorana!) mass is the first order effect of NP

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



Charge-Parity violation

$\nu_\mu \Rightarrow \nu_e$ $\xleftrightarrow{CP}$ $\bar{\nu}_\mu \Rightarrow \bar{\nu}_e$

Aside note :

$\nu_\mu \Rightarrow \nu_e$ $\xleftrightarrow{T}$ $\nu_e \Rightarrow \nu_\mu$

Charge-Parity violation

$$\nu_\mu \rightarrow \nu_e \quad \xleftrightarrow{\text{CP}} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$$

Aside note :

$$\nu_\mu \rightarrow \nu_e \quad \xleftrightarrow{\text{T}} \quad \nu_e \rightarrow \nu_\mu$$

$$\nu_\mu \rightarrow \nu_\mu \quad \xleftrightarrow{\text{T}} \quad \nu_\mu \rightarrow \nu_\mu$$ No CPV !

$$\nu_\mu \rightarrow \nu_\mu \quad \xleftrightarrow{\text{CPT}} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$$

Charge-Parity violation

$\nu_\mu \rightarrow \nu_e \quad \xleftrightarrow{\text{CP}} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_e$

Aside note :

$\nu_\mu \rightarrow \nu_e \quad \xleftrightarrow{\text{T}} \quad \nu_e \rightarrow \nu_\mu$

$\nu_\mu \rightarrow \nu_\mu \quad \xleftrightarrow{\text{T}} \quad \nu_\mu \rightarrow \nu_\mu$ No CPV !

$\nu_\mu \rightarrow \nu_\mu \quad \xleftrightarrow{\text{CPT}} \quad \bar{\nu}_\mu \rightarrow \bar{\nu}_\mu$

3 flavors necessary to allow CP violation !

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).

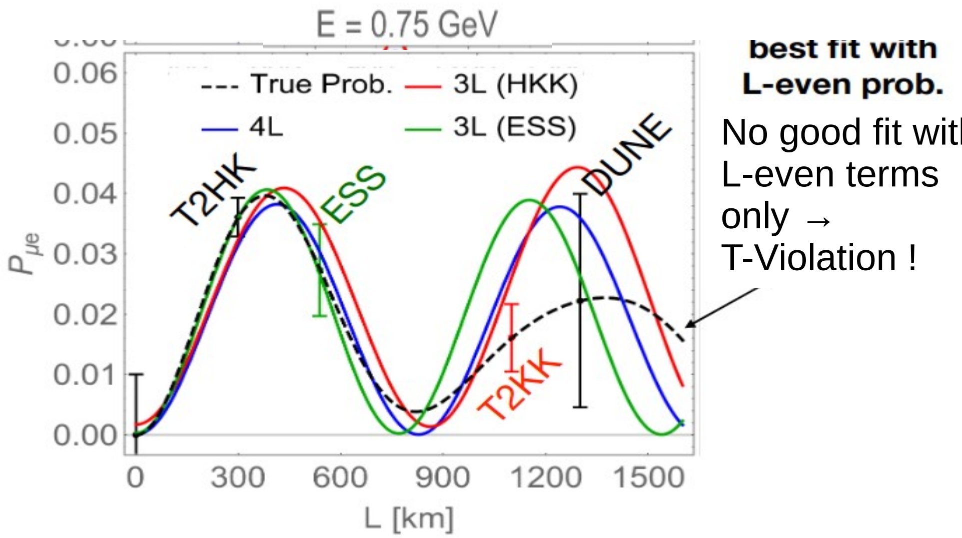
In particular it assumes
- minimal 3-flavour scenario
- standard neutrino interactions for production and detection
- standard matter effects along propagation

arXiv:2106.16099 [hep-ph]

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**

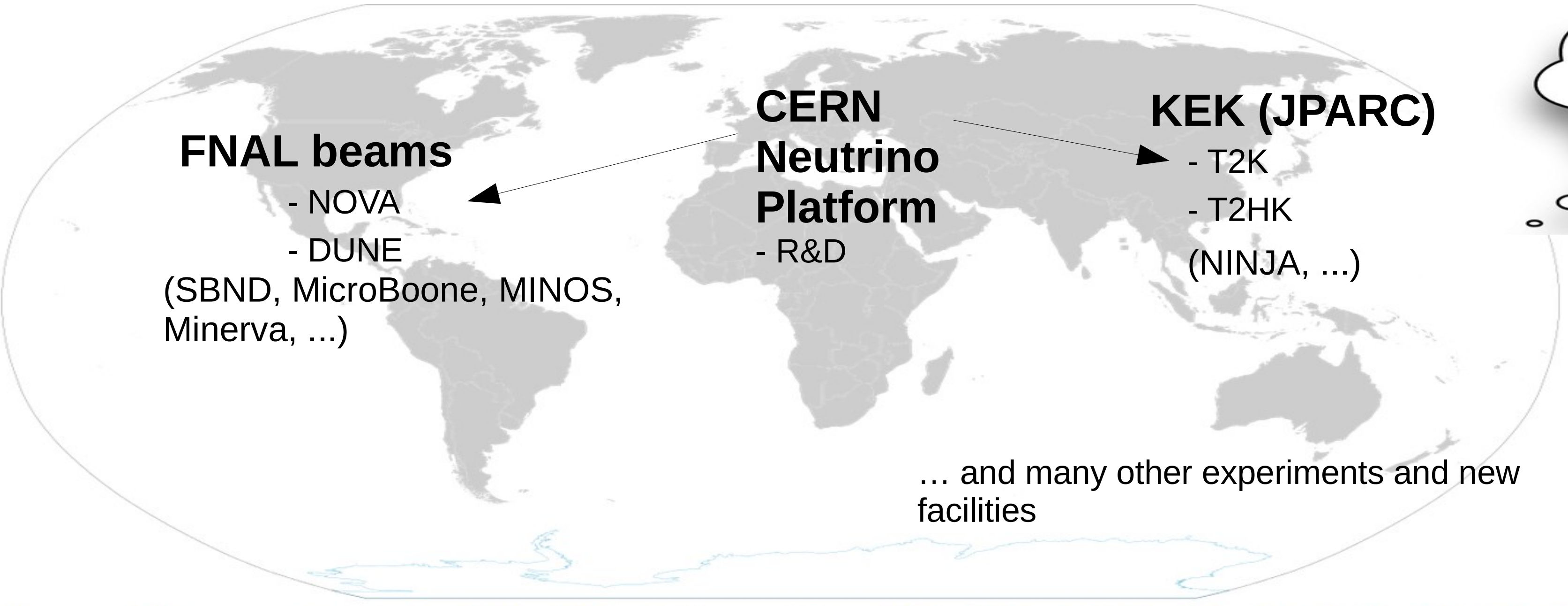


No good fit with L-even terms only → T-Violation !

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

Neutrinos with beams around the world

Neutrino oscillation physics with accelerators entered the precision era with NOVA and T2K → next generation experiments will be worldwide efforts comparable to collider experiments



Nuclear theory community