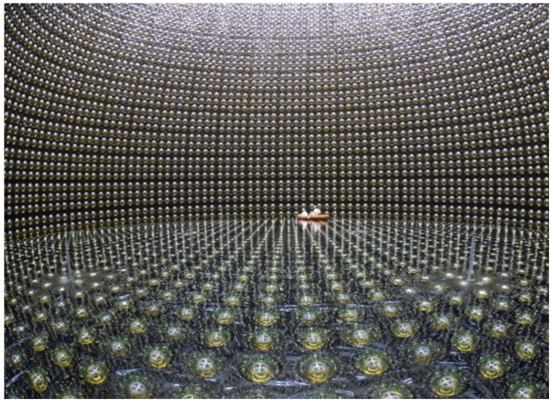
Giornate in ricordo di Milla Baldo Ceolin

Neutrino oscillations

S.Bolognesi (IRFU, CEA Saclay)

The era of neutrinos !



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NATURE | NEWS

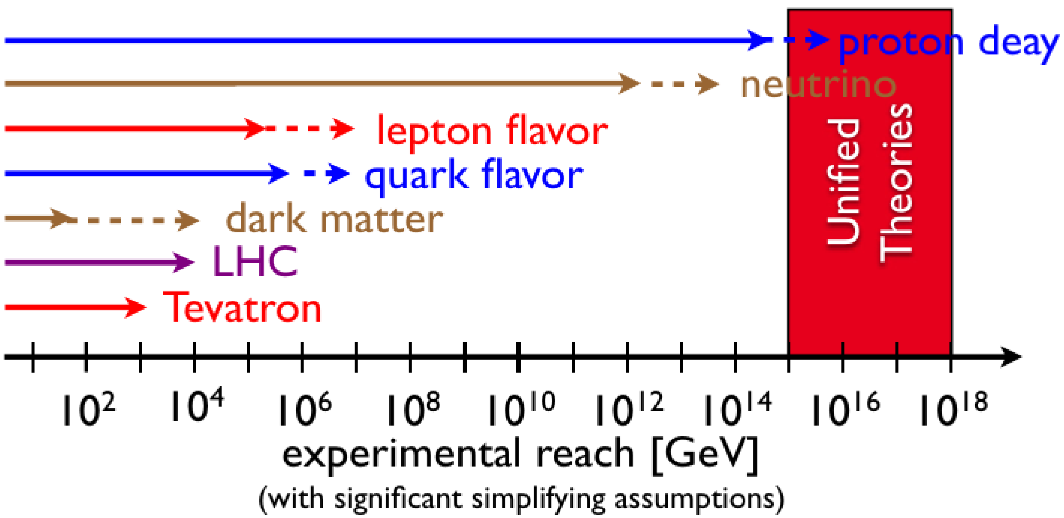
Morphing neutrinos provide clue to antimatter mystery

Excitement rises over chance of new physics from *particle-du-jour.*

Elizabeth Gibney

Why neutrinos?

+ Similarly, to the discovery of Fermi scale with nuclear β-decays, we are now on a **fishing expedition to the next energy scale of the (necessary!) New Physics:**



Hitoshi Murayama (Berkley, Kavli)
@ Higgs workshop 2013
(arXiv:1401.0966)

Neutrino oscillation are sensitive to very tiny effects similarly to interferometry.
Unique tool to study very high energy scale (today $\Lambda \sim 10^{14}$GeV)

+ Search of **Charge-Parity violation in the leptonic sector** (related with matter/antimatter asymmetry in the Universe)

Independently on model: a new fundamental source of CP violation!
→ **Major next discovery of HEP**

+ What is the **New Symmetry hidden behind the mass and flavour mixing?**

Neutrinos as door to New Physics

- **Expansion of Lagrangian in terms of NP energy scale (Λ_{UV}):** $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{UV}}\mathcal{L}_5 + \ldots$

  $\mathcal{L}_{SM}$ SM as effective theory valid until UV cutoff

$$\frac{1}{\Lambda_{UV}}\mathcal{L}_5 = \frac{v^2}{\Lambda_{UV}}\nu\nu. \qquad \frac{246^2}{10^{15}} GeV \approx 10^{-2} eV$$

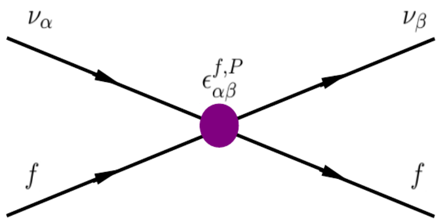
The only 5th order operator possible according to fundamental symmetries: neutrino (Majorana!) mass is the first order effect of NP

→ **New type of fundamental particle**

→ Discovery of **lepton number violation** (accidental conservation in SM: no symmetry supporting it)

→ Naturally emerging in **leptogenesis scenarios to create matter/antimatter asymmetry**

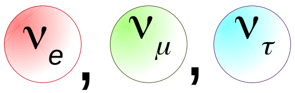
- Peculiar nature of ν and being in direct contact with Λ_{UV}: natural to expect new type of interactions for neutrinos: Non Standard Interactions



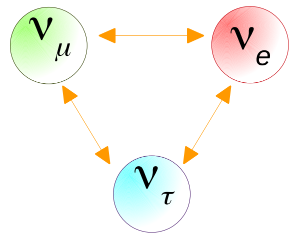
$$G_F \epsilon_{NSI} (\bar{\nu}\nu)(\bar{f} f)$$

A neutrino life

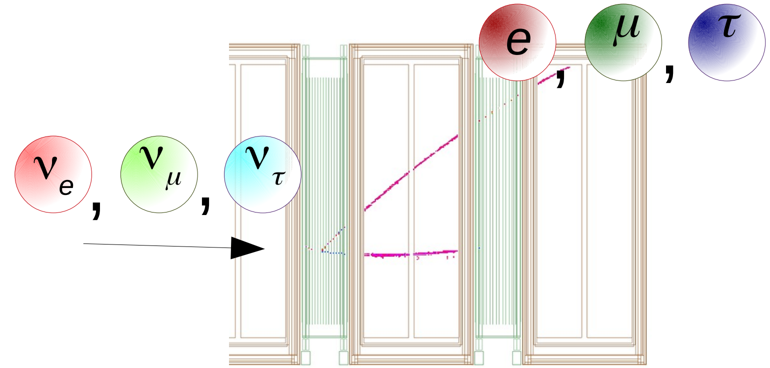
1 - production



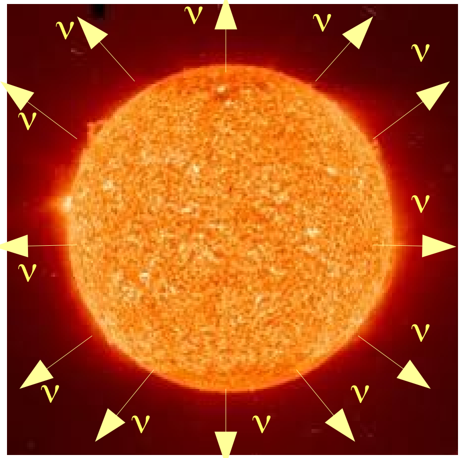
2 - oscillations



3 - detection



Neutrino sources



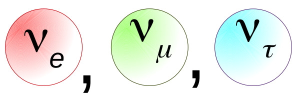
- astrophysics : sun, cosmics rays

- artificial : nuclear reactors, accelerators

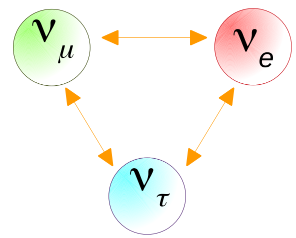
The topic I will focus on

A neutrino life

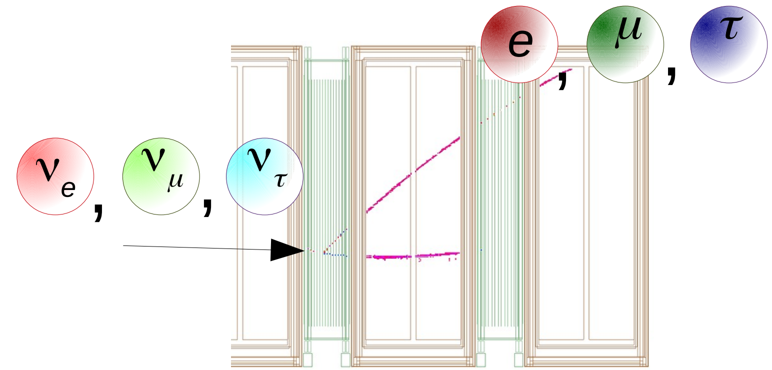
1 - production

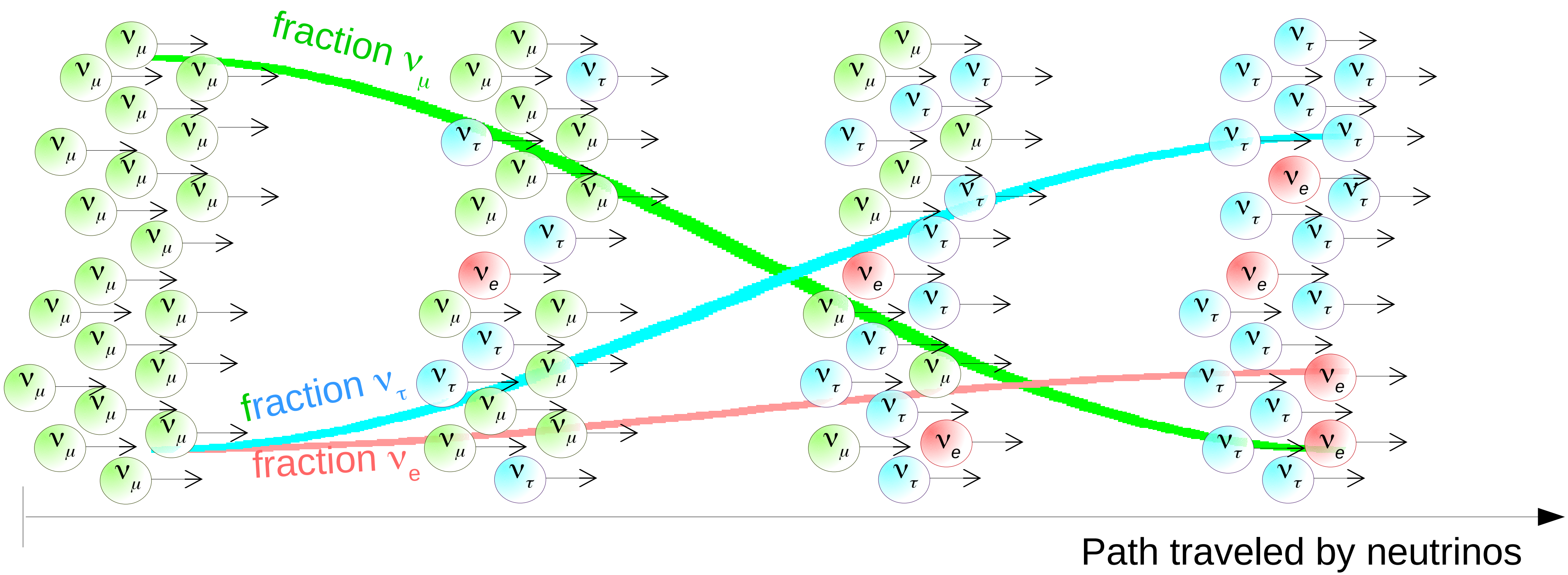


2 - oscillations



3 - détection





A neutrino life

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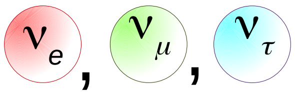

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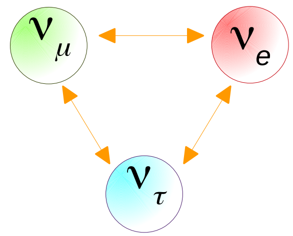

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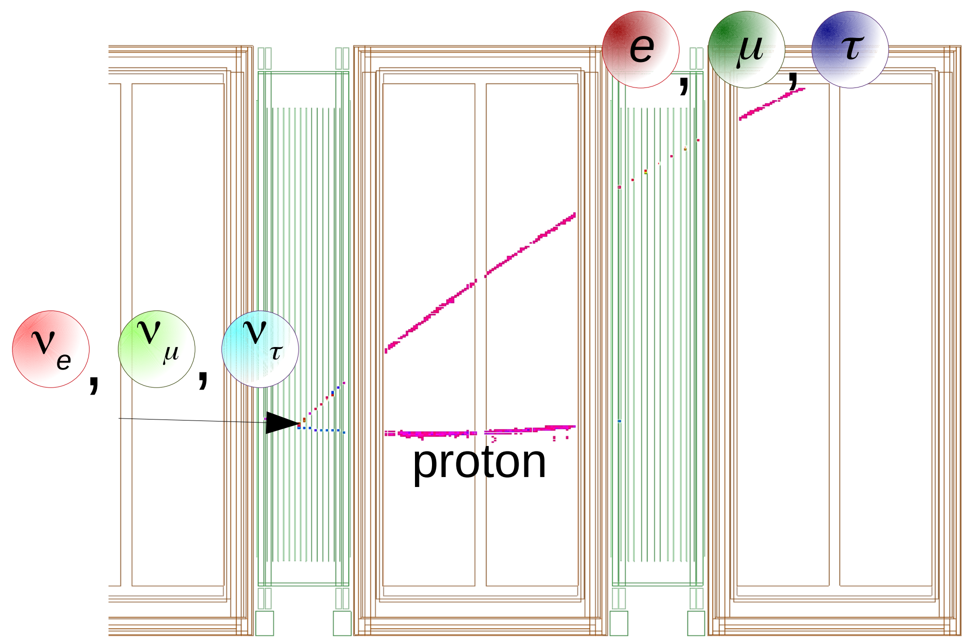


Charged current interactions used to identify the flavor of the neutrinos

Detectors typically composed of

- active targets (large mass needed)

- possibly additional detectors (eg Time Projection Chambers) to identify and measure outgoing particles

- external veto to reject background

With neutrino from accelerators measure oscillation by comparing ν flavor at **near detector nearby the source (before oscillation) and at far detectors far away (after oscillation)**

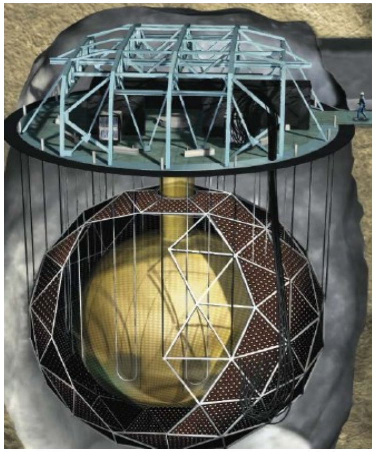
A bit of (recent) history...

SuperKamiokande
1996 – today!

1998 Discovery of ν oscillation from zenith angle dependence of atmospheric ν_μ rate

Sudbury Neutrino Observatory (SNO)
1999 – today!

2001 Solution of solar puzzle: $\nu_e / \Sigma\nu_\alpha \sim 1/3$



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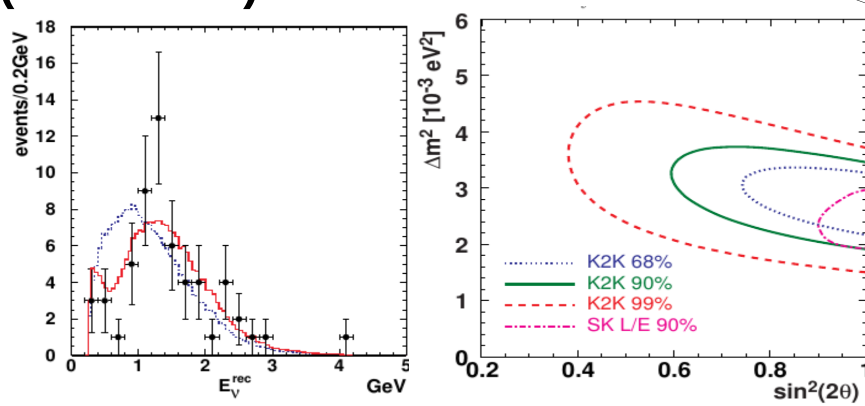
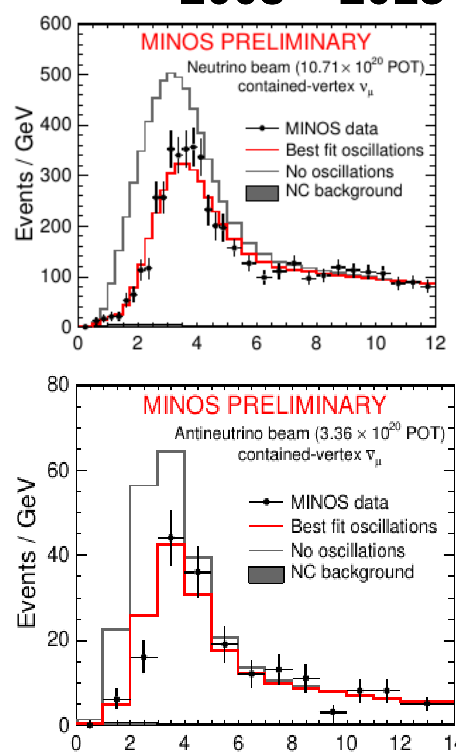
Need confirmation from accelerator experiment:
high purity and tunable neutrino flux

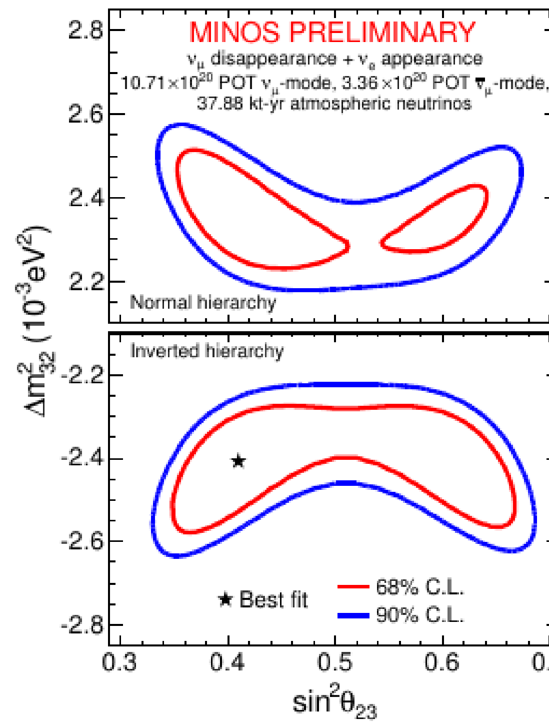
(1999-2006) K2K



(2008-2012) OPERA : 5 $\nu_\mu \rightarrow \nu_\tau$ events obs.

2003 – 2015 MINOS (→ MINOS+)





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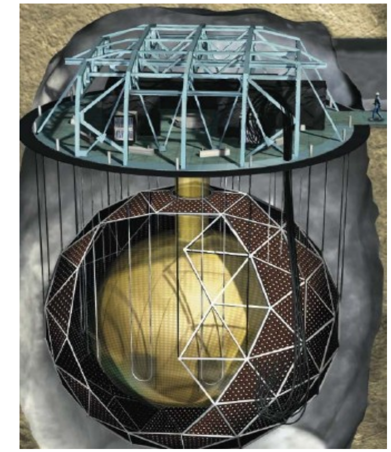

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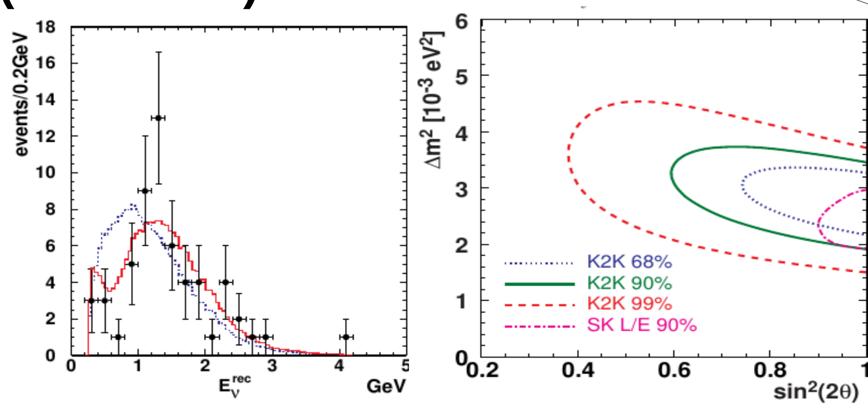

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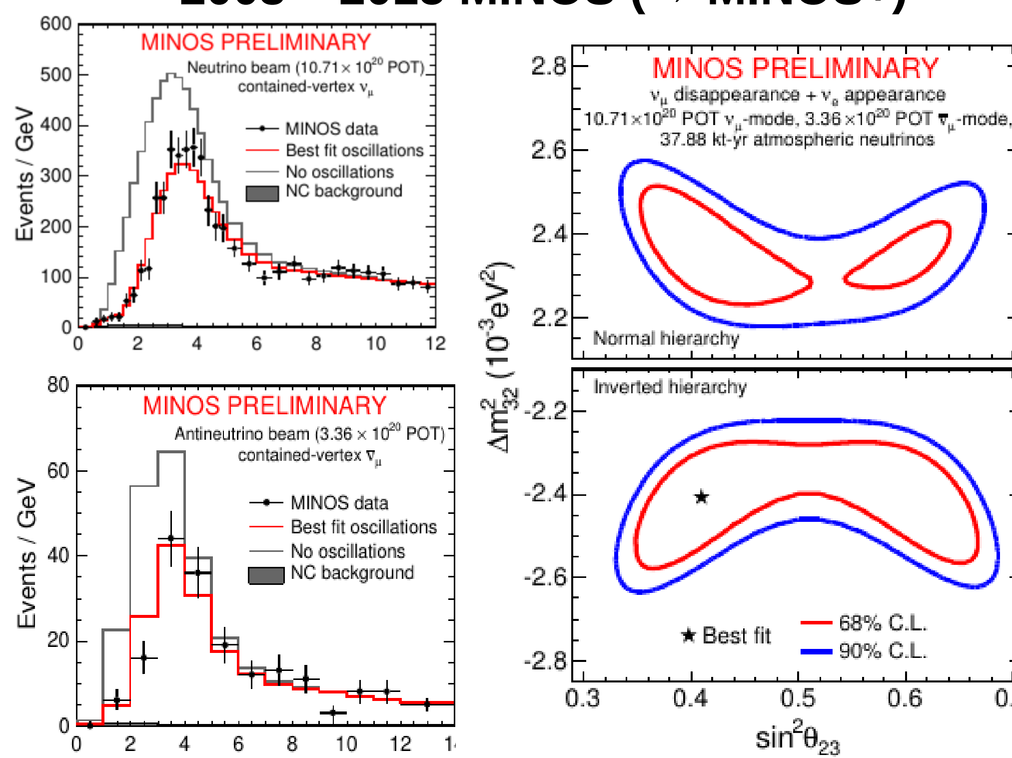


(2008-2012) OPERA : 5 $\nu_\mu \rightarrow \nu_\tau$ events obs.

Beyond ν_μ disappearance:

T2K (2010 - today)

→ observation of ν_e apperance

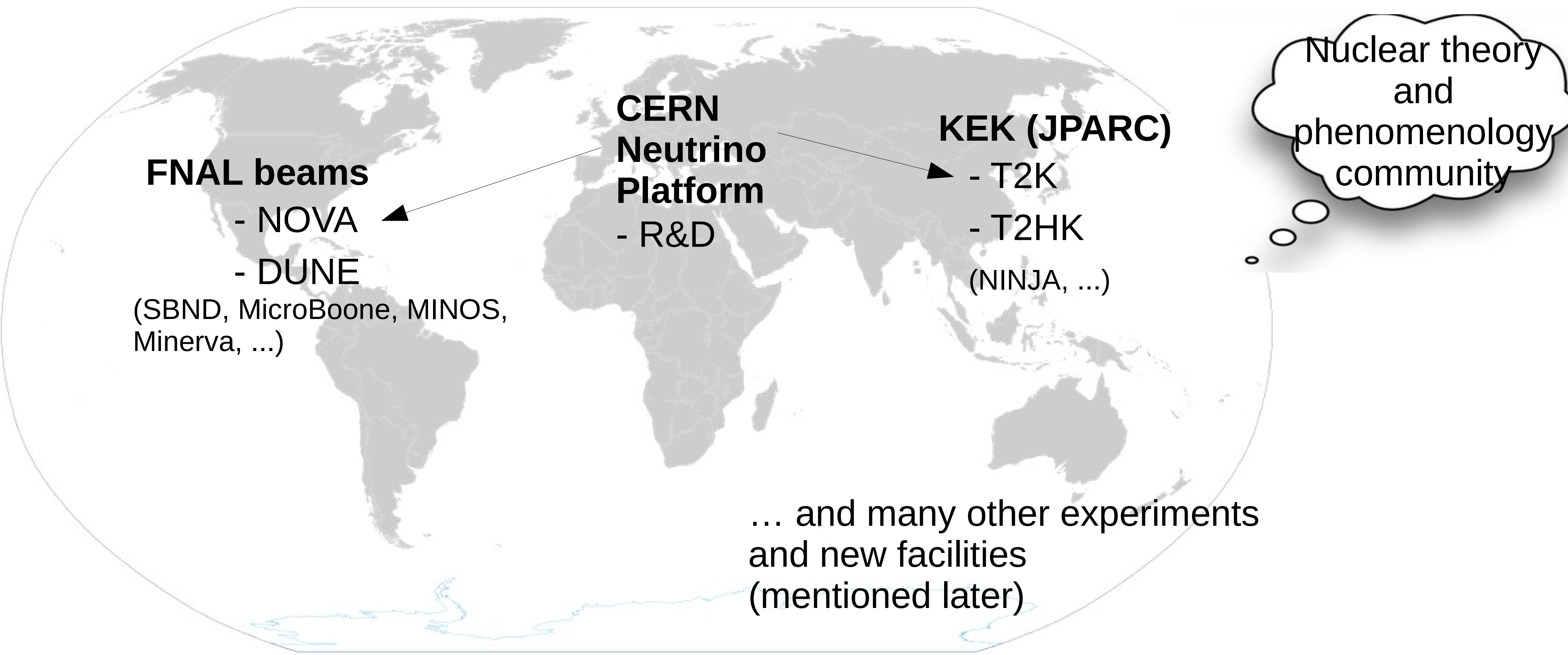
→ first results on CP violation

NOVA (2013 - today)

→ first hints on Mass Ordering

Neutrinos with beams around the world

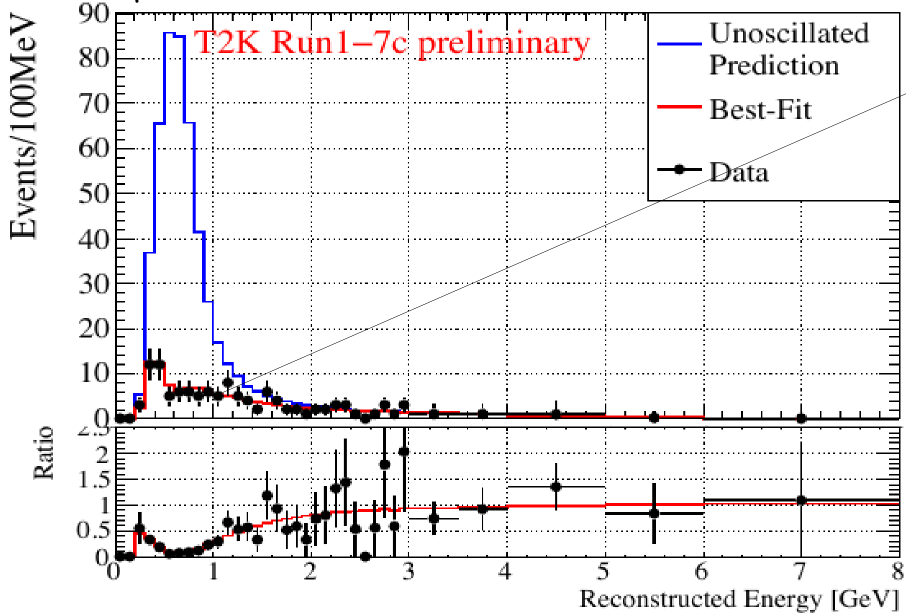
Neutrino oscillation physics with accelerators entered the precision era with NOVA and T2K → next generation experiments will be worldwide efforts comparable to collider experiments

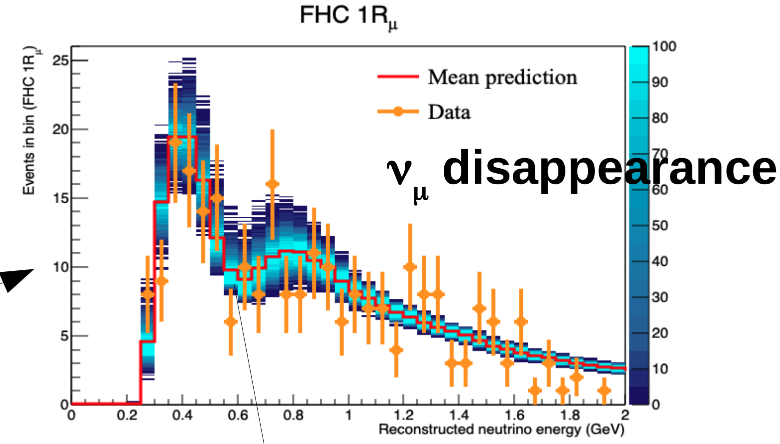


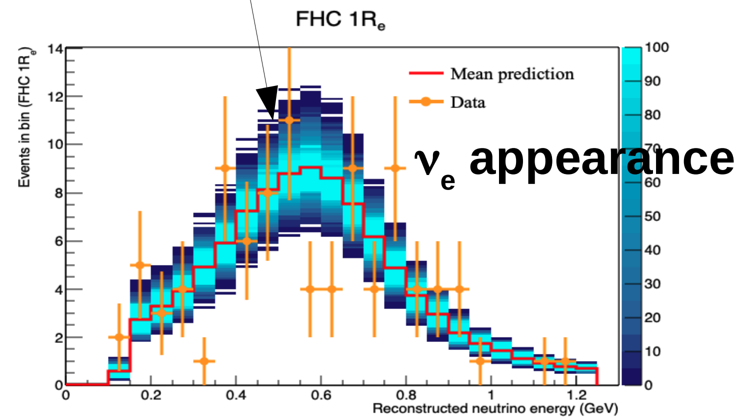
Neutrino physics has a rich present and a bright future!

Neutrino oscillations

ν_μ spectrum at the far detector







T2K preliminary Run1-10

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

(simplified 2-flavors approximation)

amplitude **frequency**

Full 3-flavors formalism: Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle \qquad \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U^*_{e1} & U^*_{e2} & U^*_{e3} \\ U^*_{\mu 1} & U^*_{\mu 2} & U^*_{\mu 3} \\ U^*_{\tau 1} & U^*_{\tau 2} & U^*_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$U_{\alpha i}$ 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) and atmospheric (large)

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

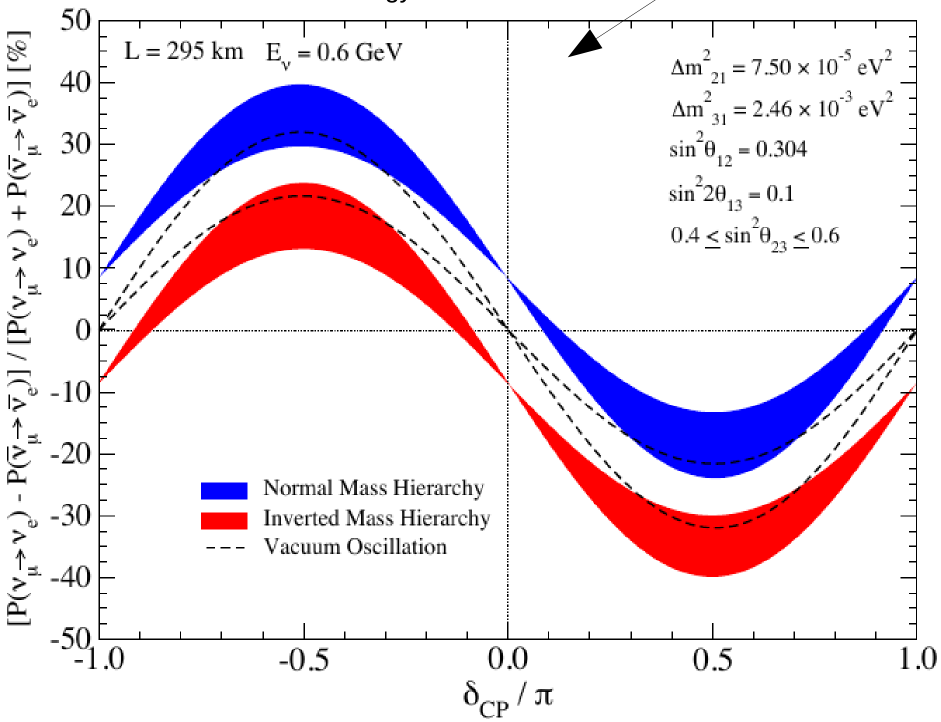
δ_{CP} parametrizes different oscillations for ν and $\overline{\nu}$ → **new fundamental source of CP violation (and first in leptonic sector!)**

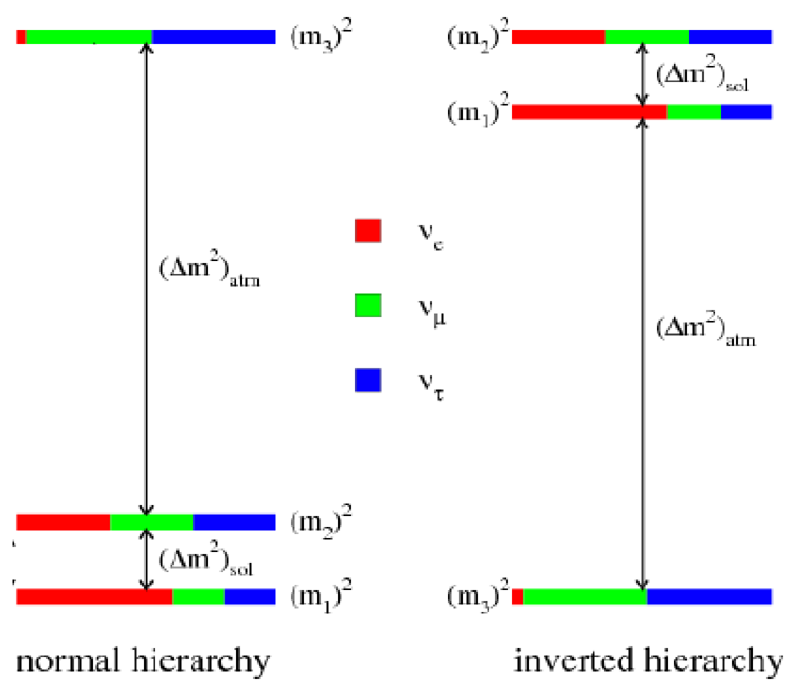
Mass Hierachy : is the mass ordering the same for charged and neutral leptons? **(→what is the fundamental symmetry hidden behind neutrino oscillation)**

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

longer the baseline → larger MH sensitivity

T2K baseline and energy



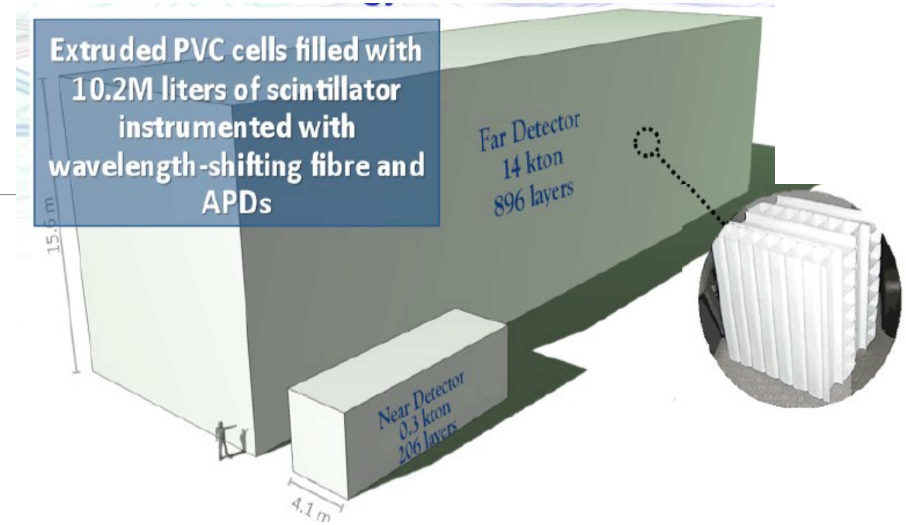


NOVA

Far: 14 kT on the surface

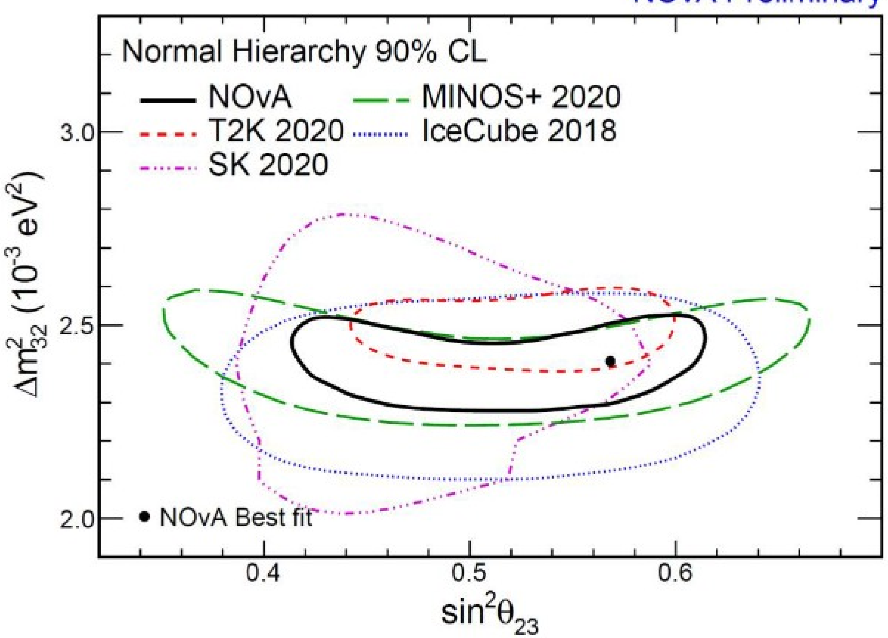
Baseline: 810km

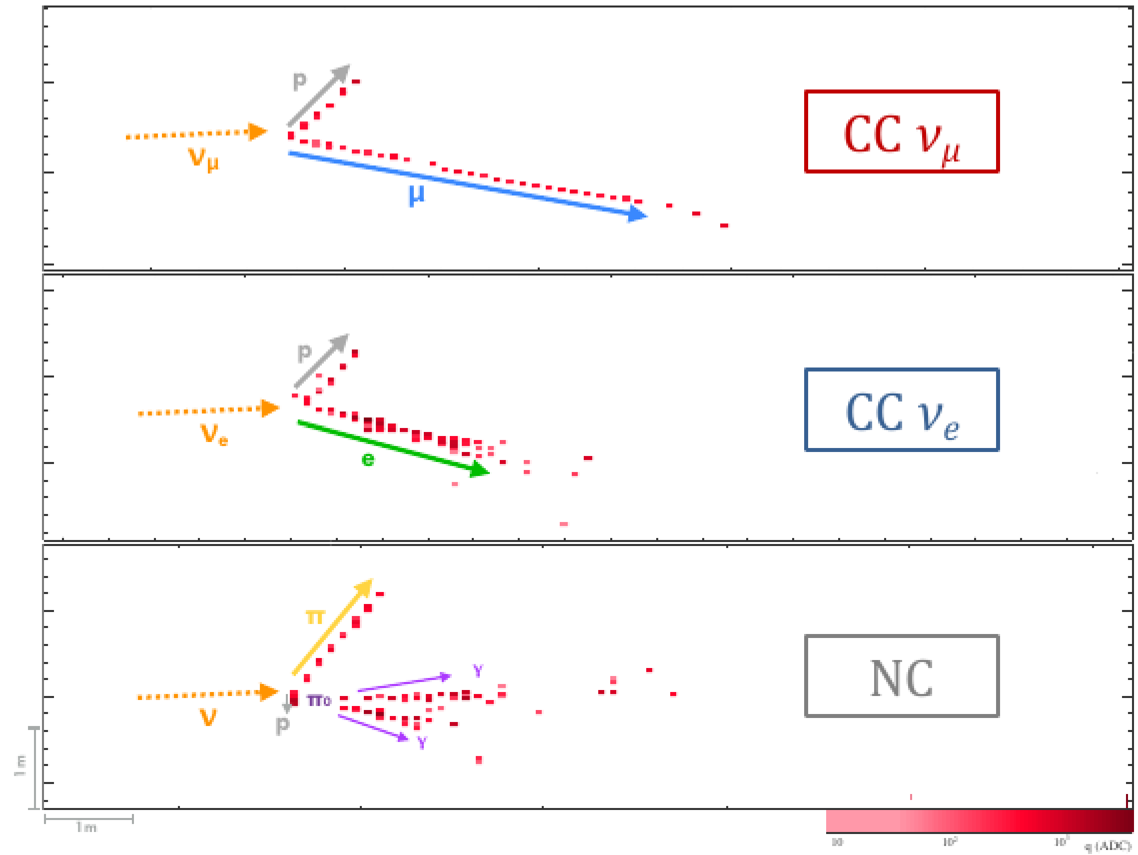
NUMI beam at FNAL
Near Detector: 300T underground



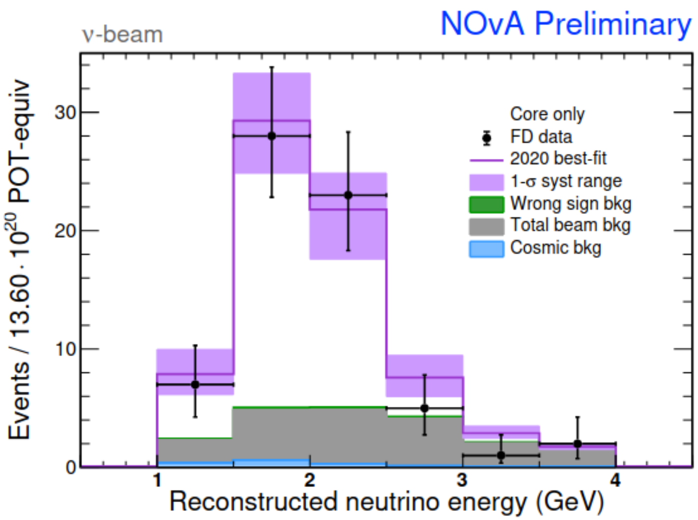
– **Functionally identical near and far detectors**

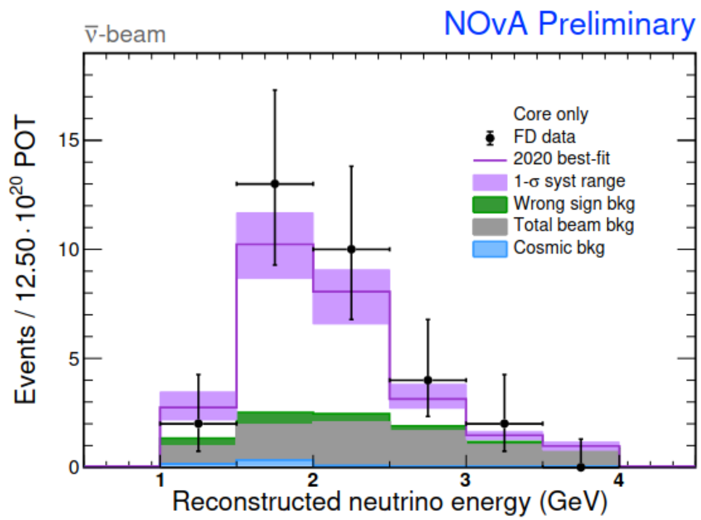
– Placed 14mrad off-axis to produce a narrow-band spectrum



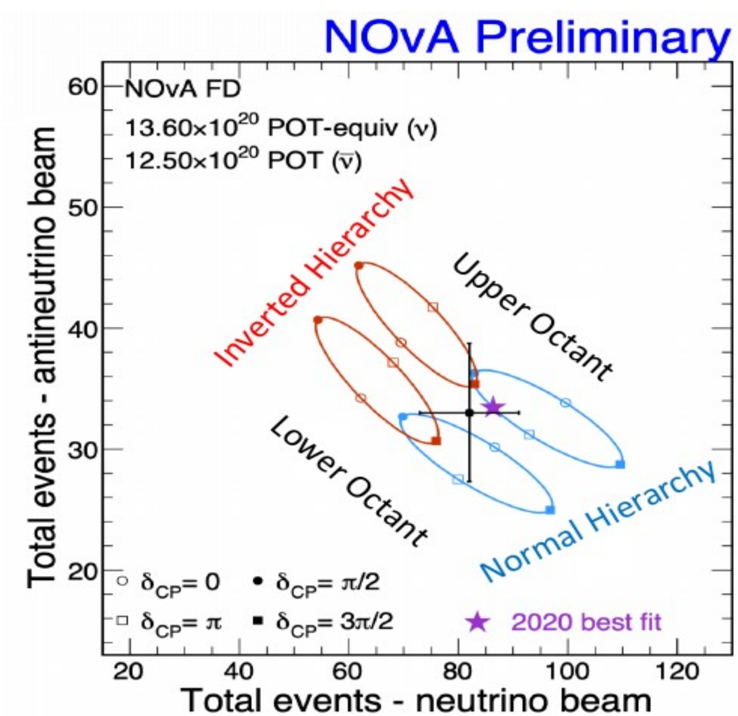


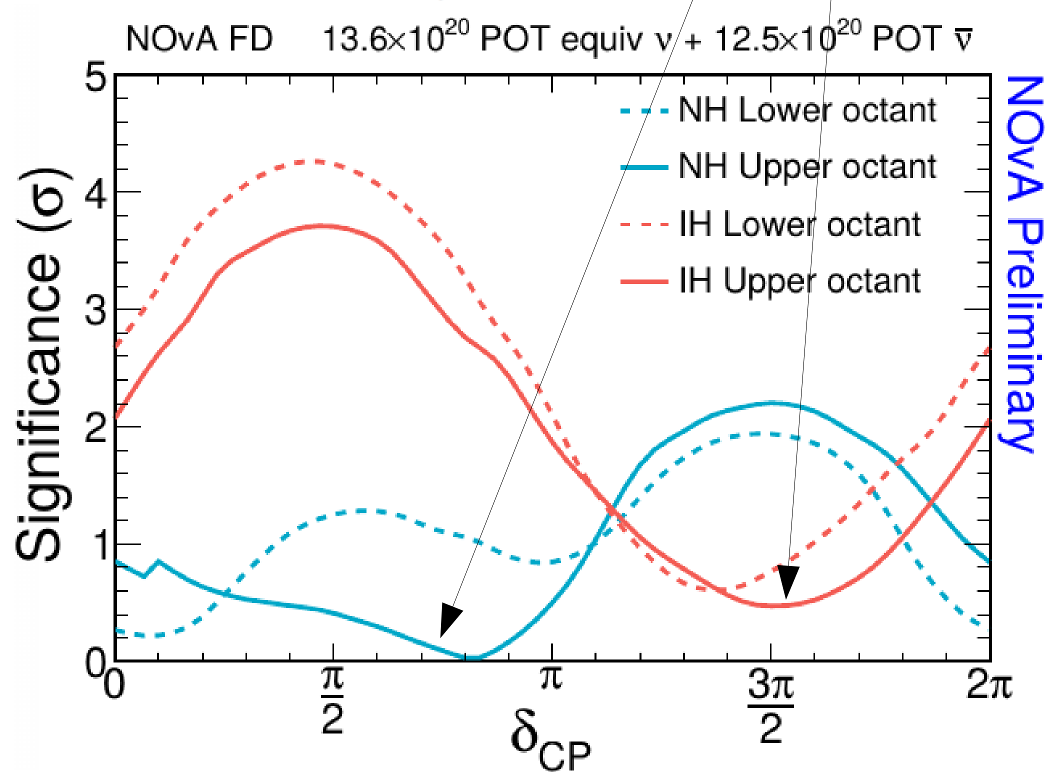
NOVA: δ_{CP} and MH



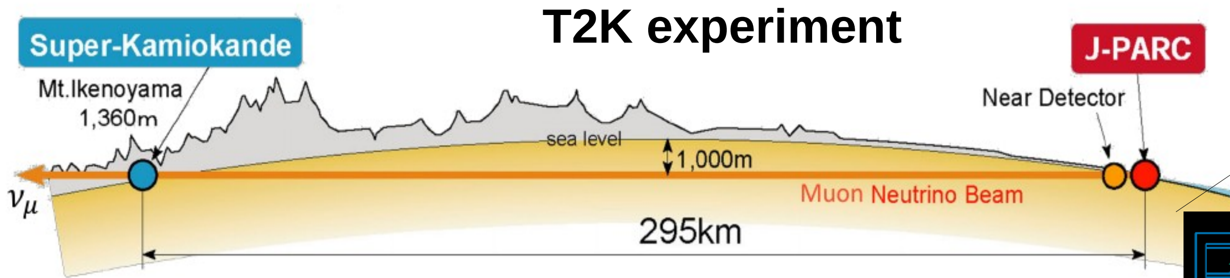


Sensitive to both δ_{CP} and MH with some degeneracies

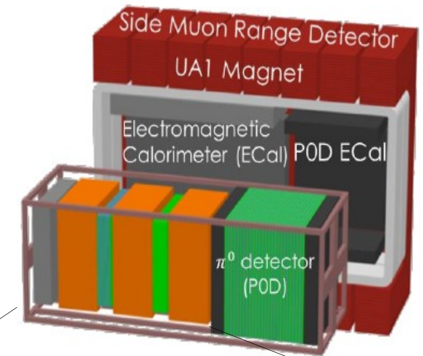


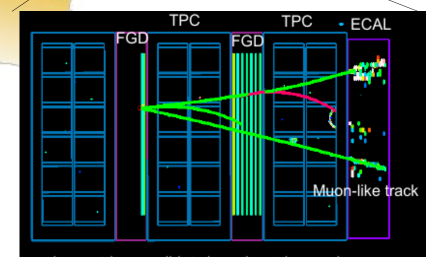


T2K



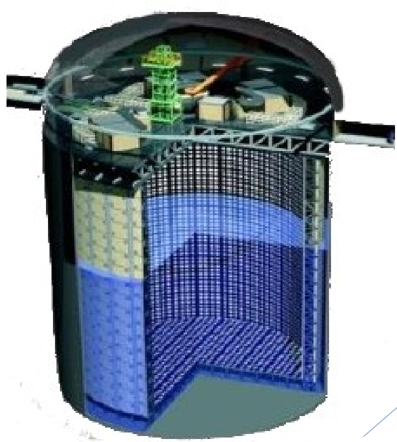
ND280 near detector



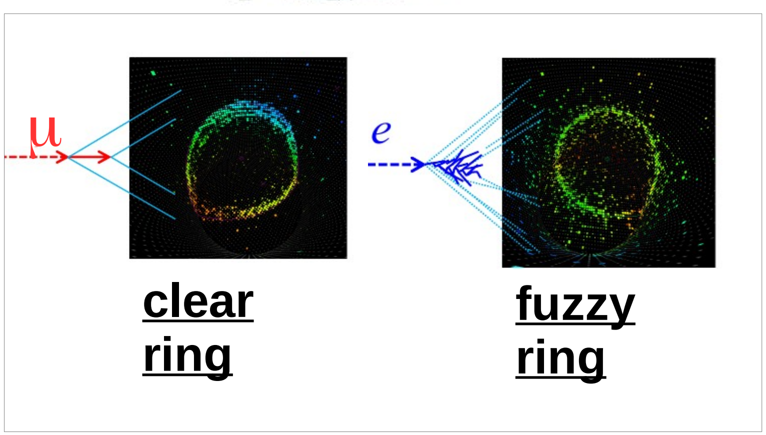


- Full tracking and particle reconstruction (**magnetized!**): measure precisely neutrino and antineutrino rate before oscillation

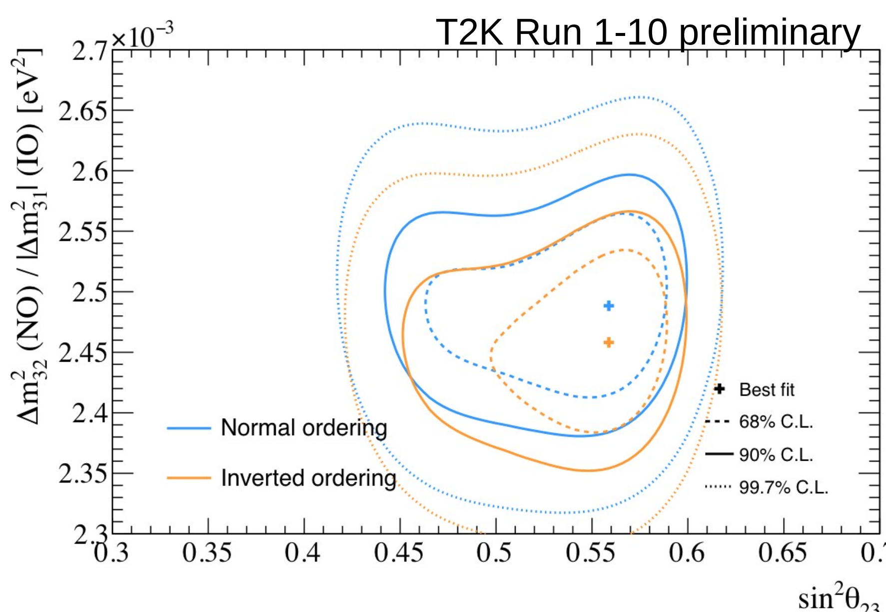
Super-Kamiokande



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

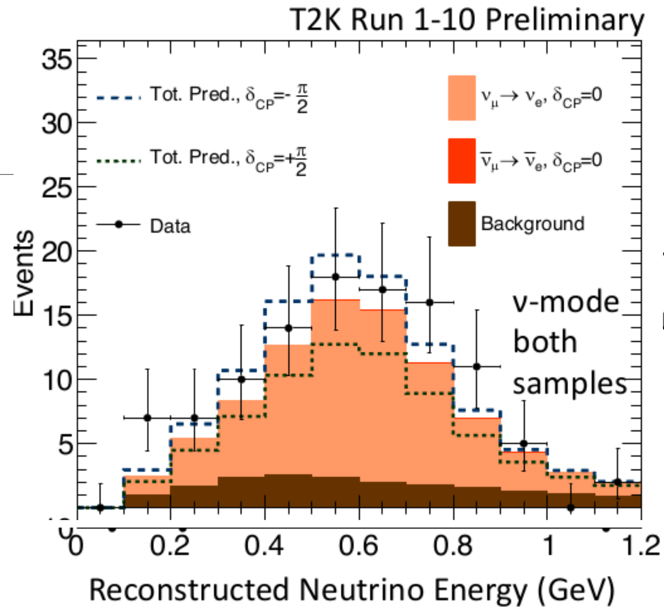


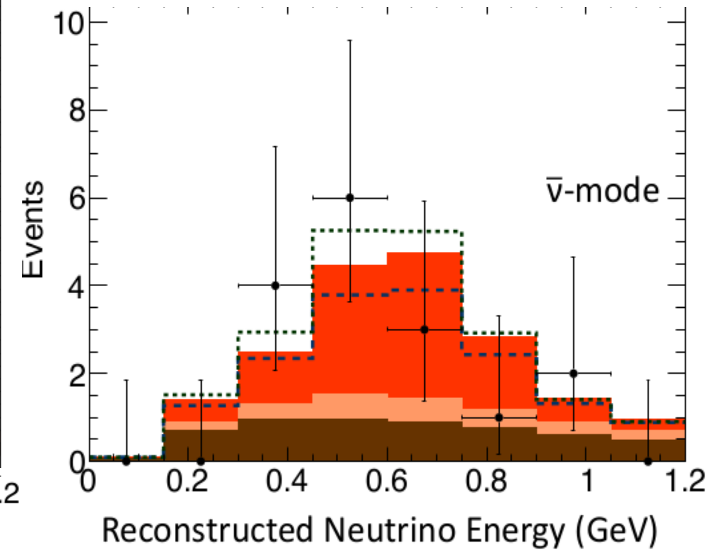
- Placed 2.5deg off-axis to produce narrow-band flux

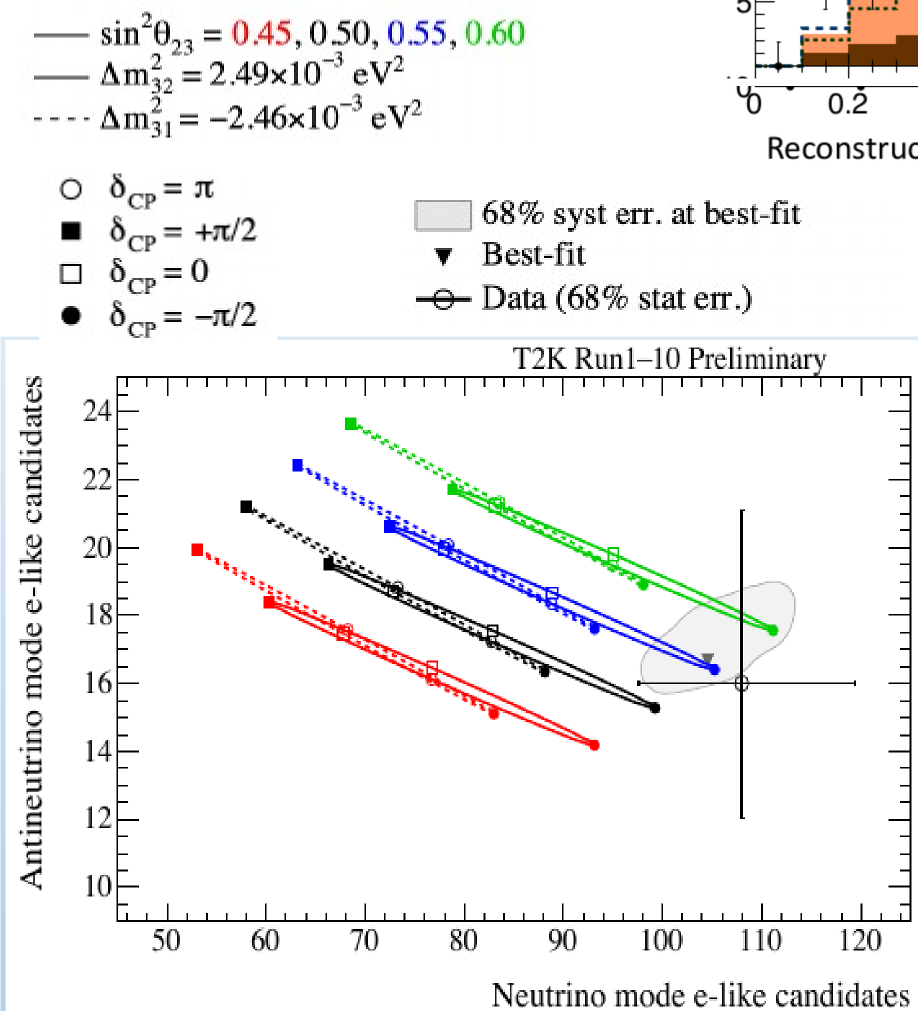


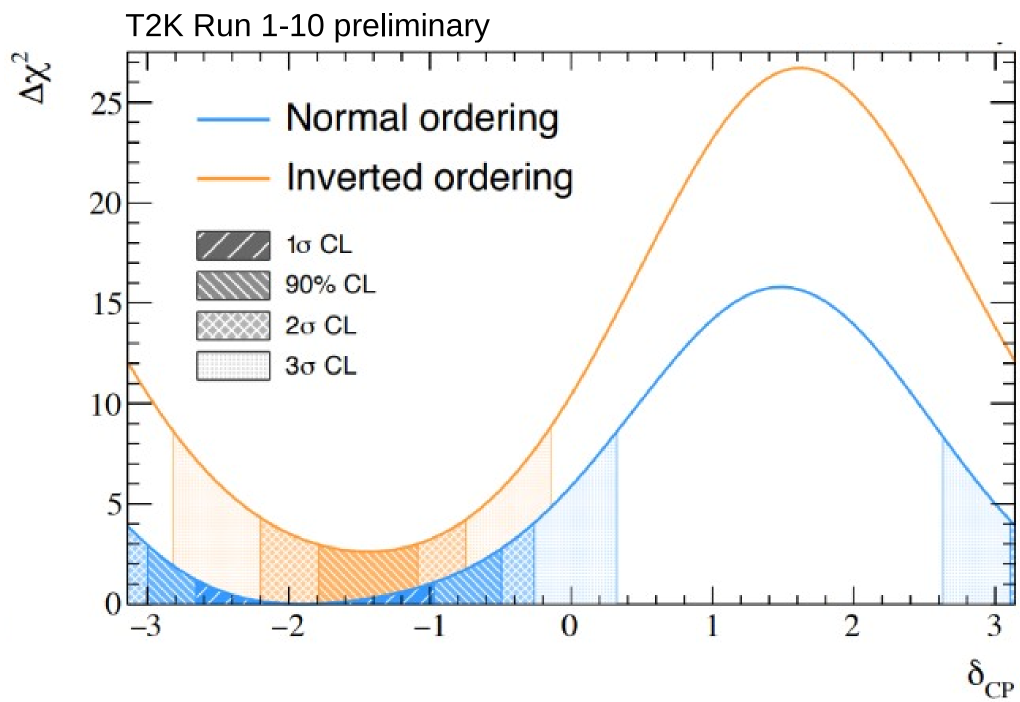
T2K: δ_{CP}

Small MH sensitivity → clean measurement of δ_{CP}



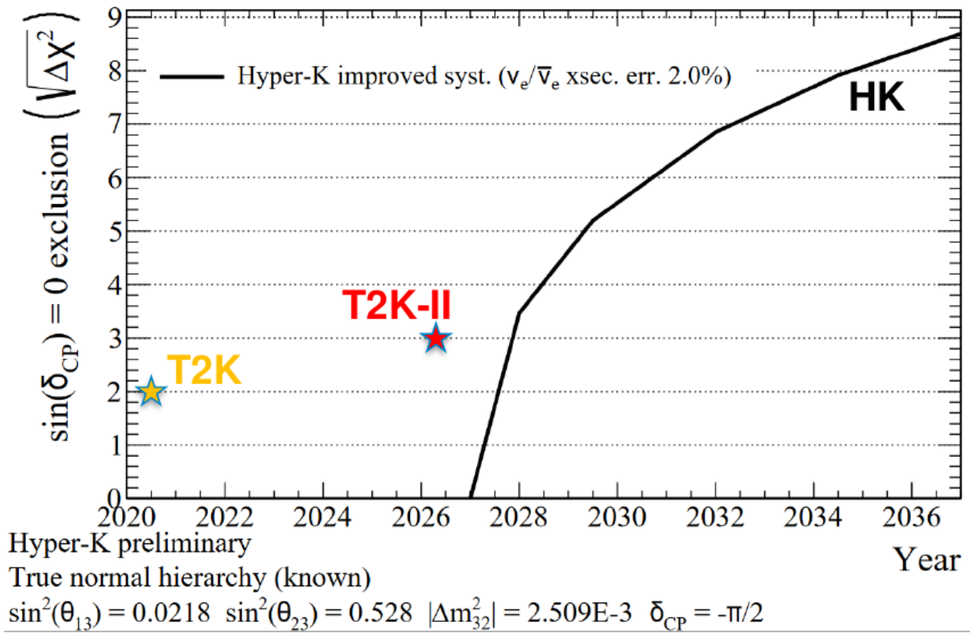


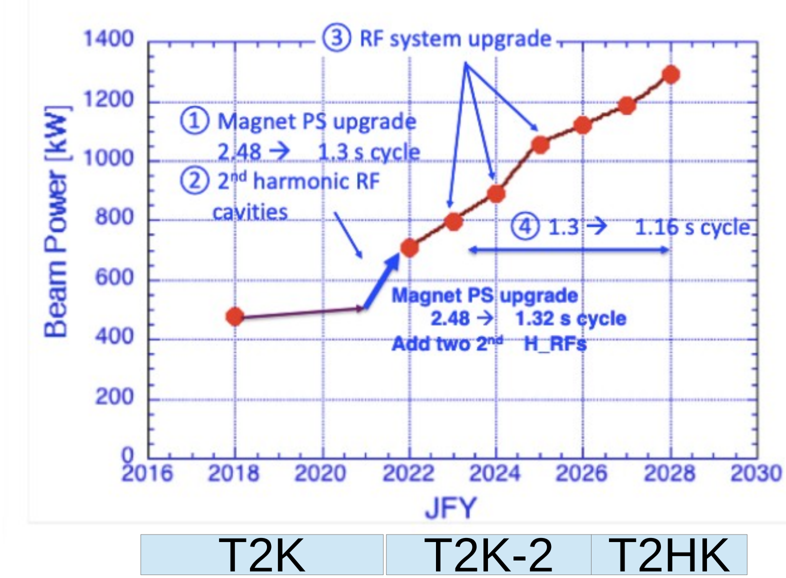




T2K → T2K-"2" → T2HK

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





- **Hyperkamiokande: huge water cherenkov detector on JPARC beam**

- 190kTon fiducial mass (x8.4 SuperKamiokande)

- PMTs with double sensitivity of SuperKamiokande → more than x20 SuperKamiokande beam neutrino rate

- **Seamless program of neutrino beam**

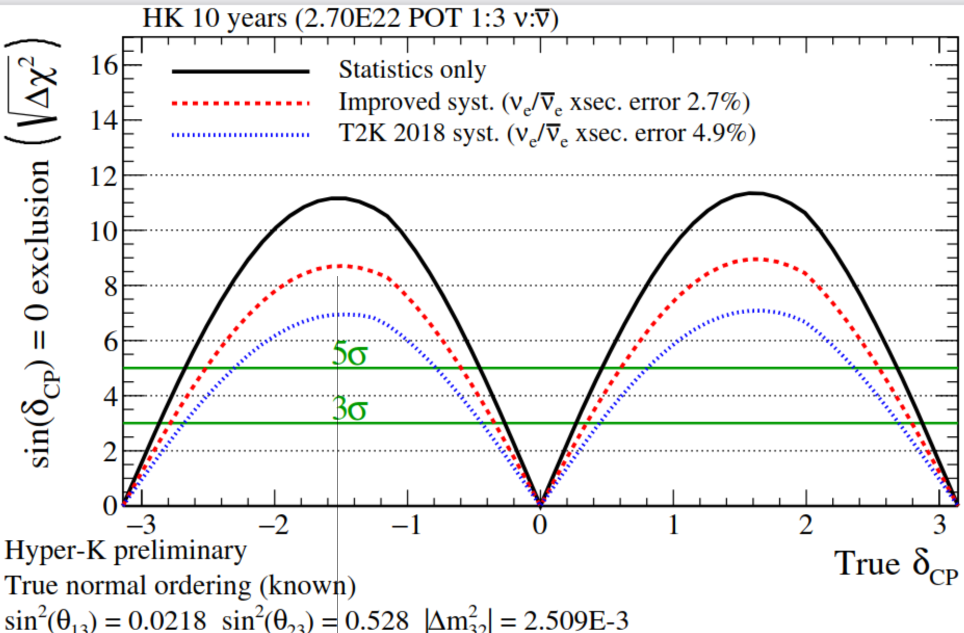
- T2K-"2" will push further the study of systematics at % level with upgrade of near detector ND280.

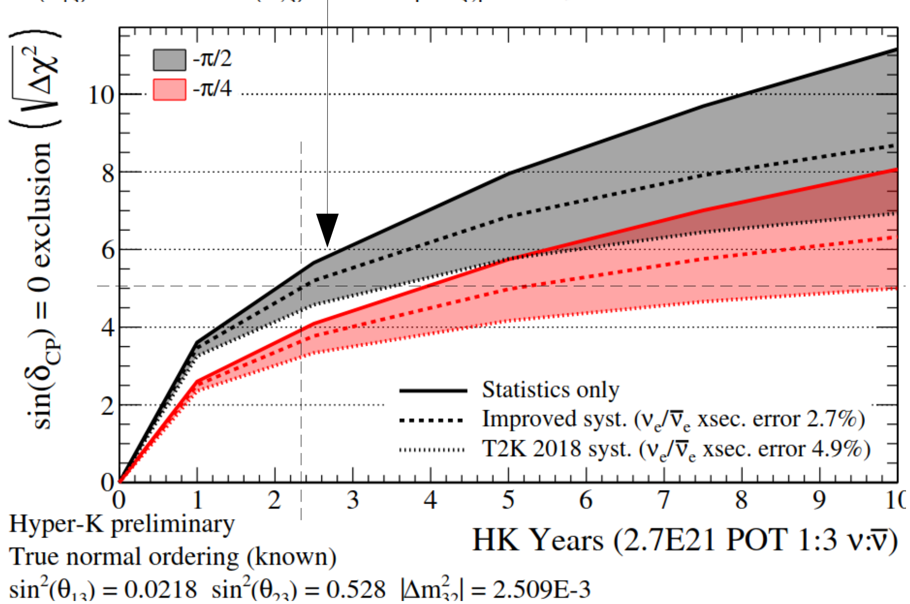
- ND280 upgrade will be ported from T2K to HK: robust path to calibration/systematic understanding from day 1 of HK

→ **enabling very fast CP-violation discovery**

HyperKamiokande sensitivity

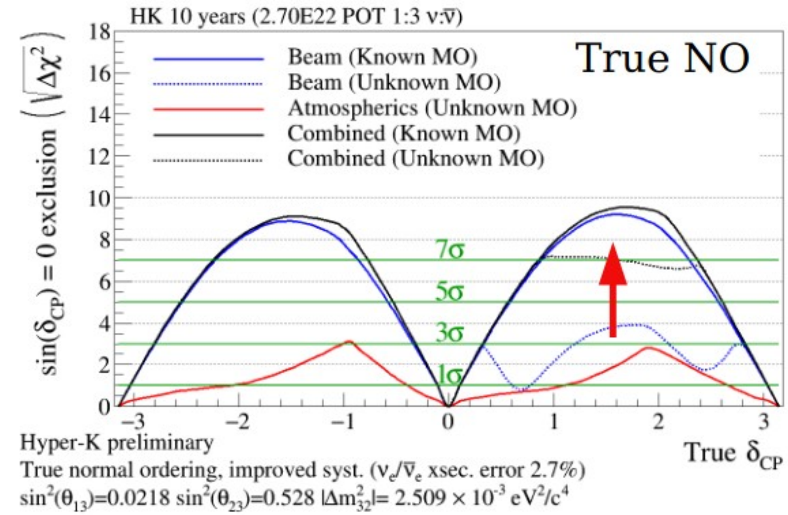
CP-violation sensitivity with known mass hierarchy:

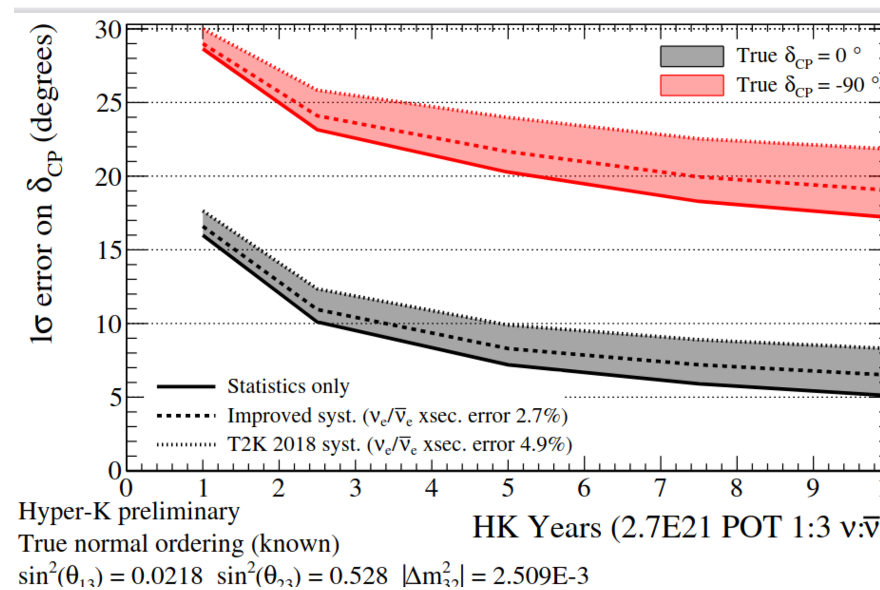




Unknown MH: combination of atm and beam neutrinos to measure δCP and MH

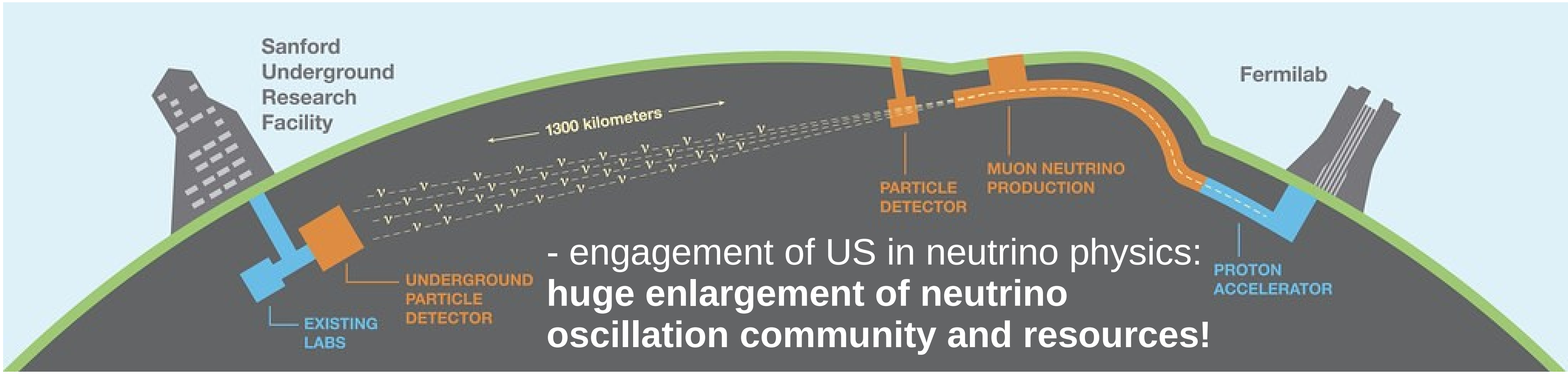
→ x8 SuperKamiokande natural neutrino rate



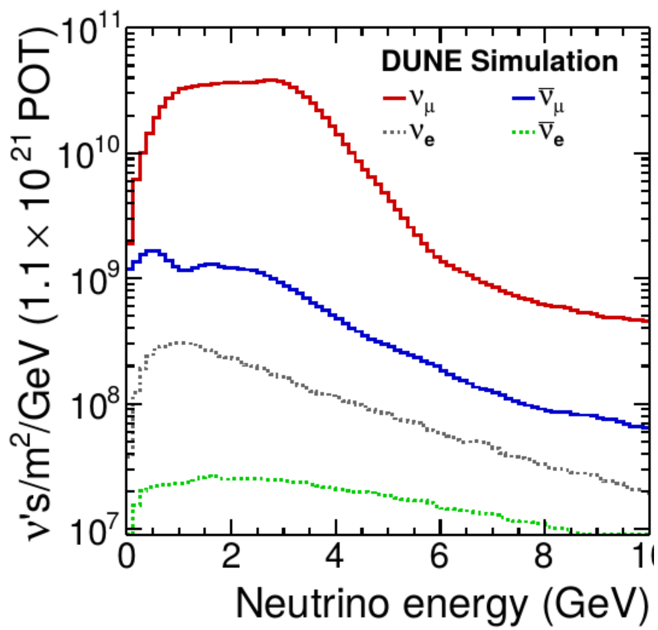


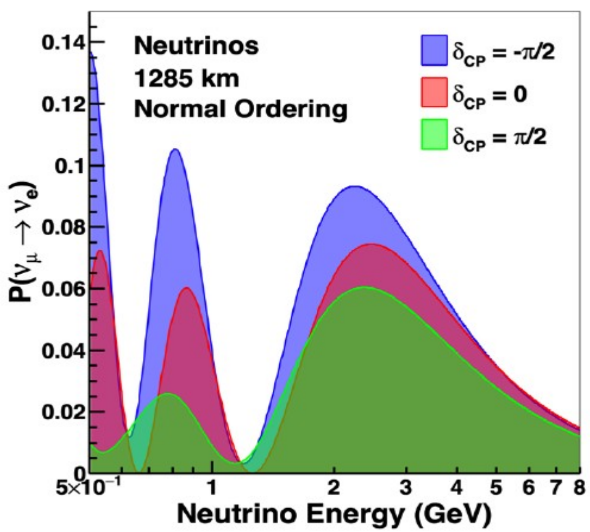
DUNE

New wide-band neutrino beam at Fermilab: 1.2MW → 2.4MW with a 1300km baseline



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





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

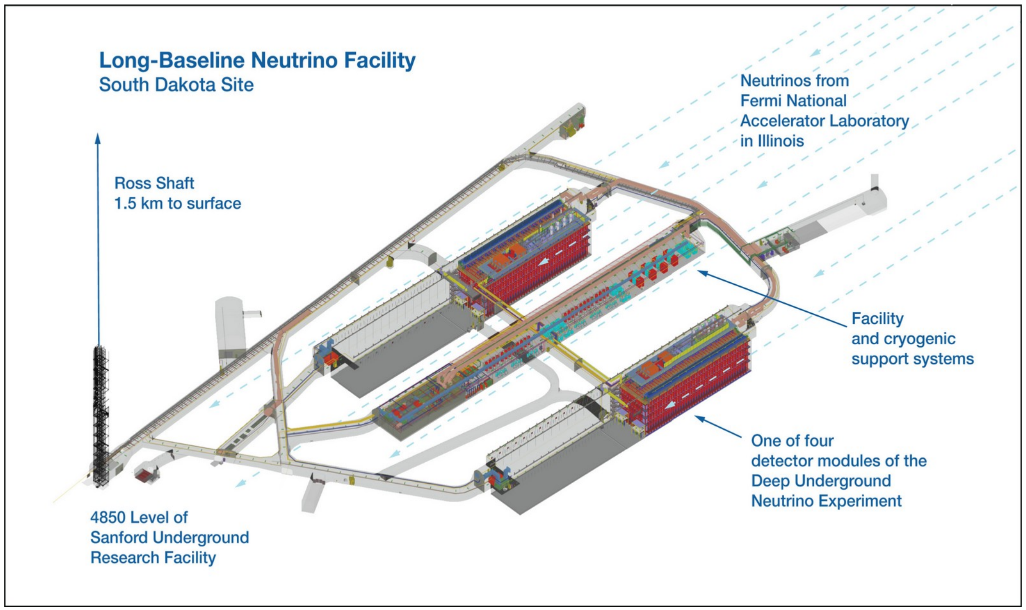
- To exploit full sensitivity a shape analysis is needed **→ need extremely good resolution on neutrino energy reconstruction**

DUNE technology

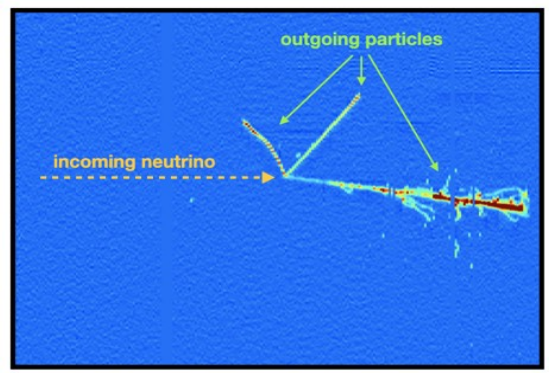
(Relatively) new technology to be deployed to unprecedented scale: huge LAr TPCs with charge readout

- **4 LAr TPC:** 4 x 10kTon fiducial mass with staged approach

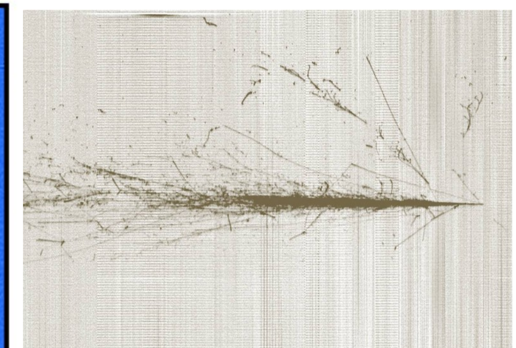
- Full reconstruction of final state particles (~bubble chamber)



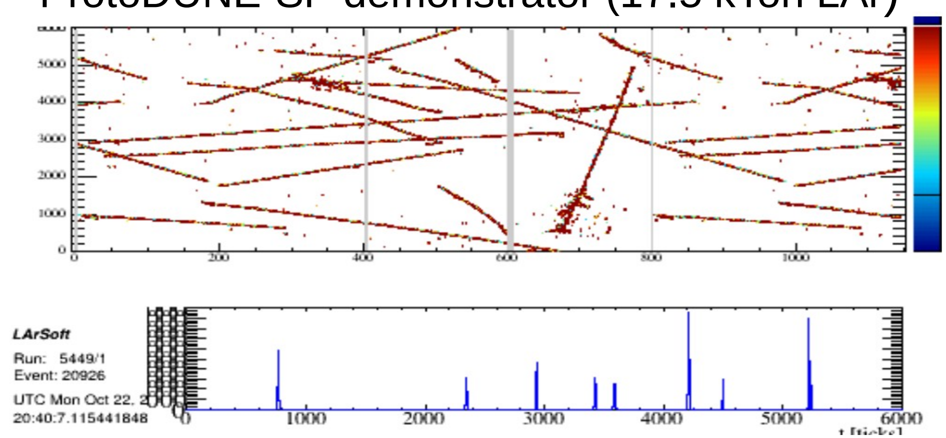
ArgoNeut (~250 kg LAr)



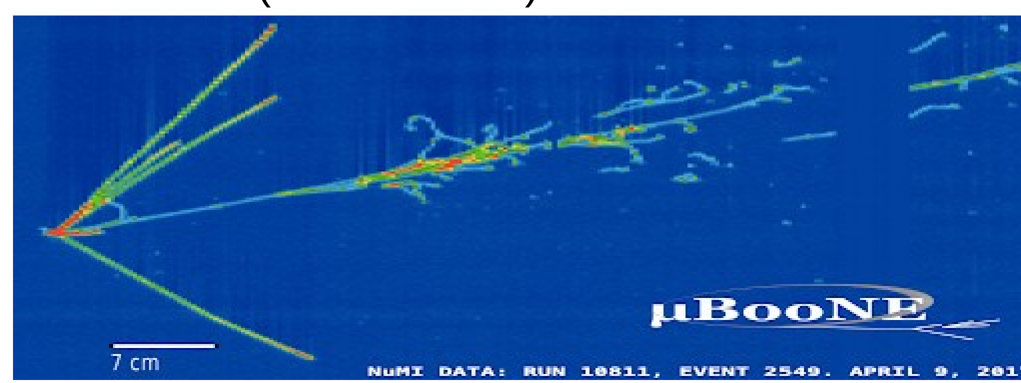
ICARUS (~500 Ton LAr)



ProtoDUNE-SP demonstrator (17.5 kTon LAr)

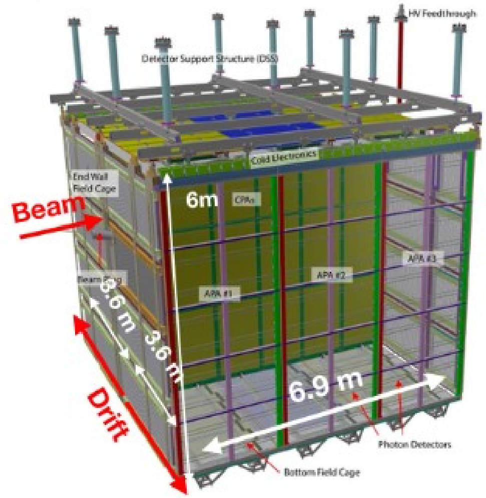


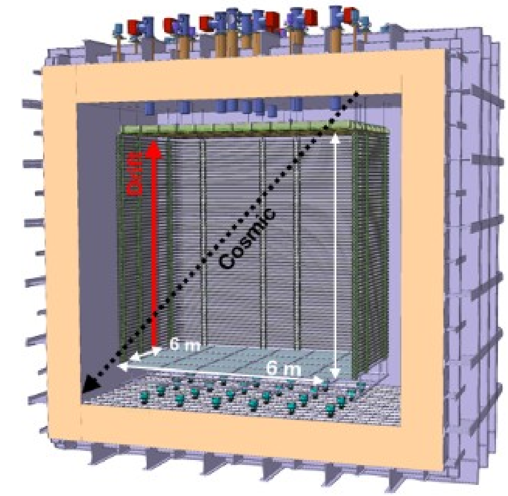
MicroBoone (~170 Ton LAr)



LAr measurements

Proto-DUNE prototypes at CERN to validate the technology on large scale
(1:20 scale to the final detector)

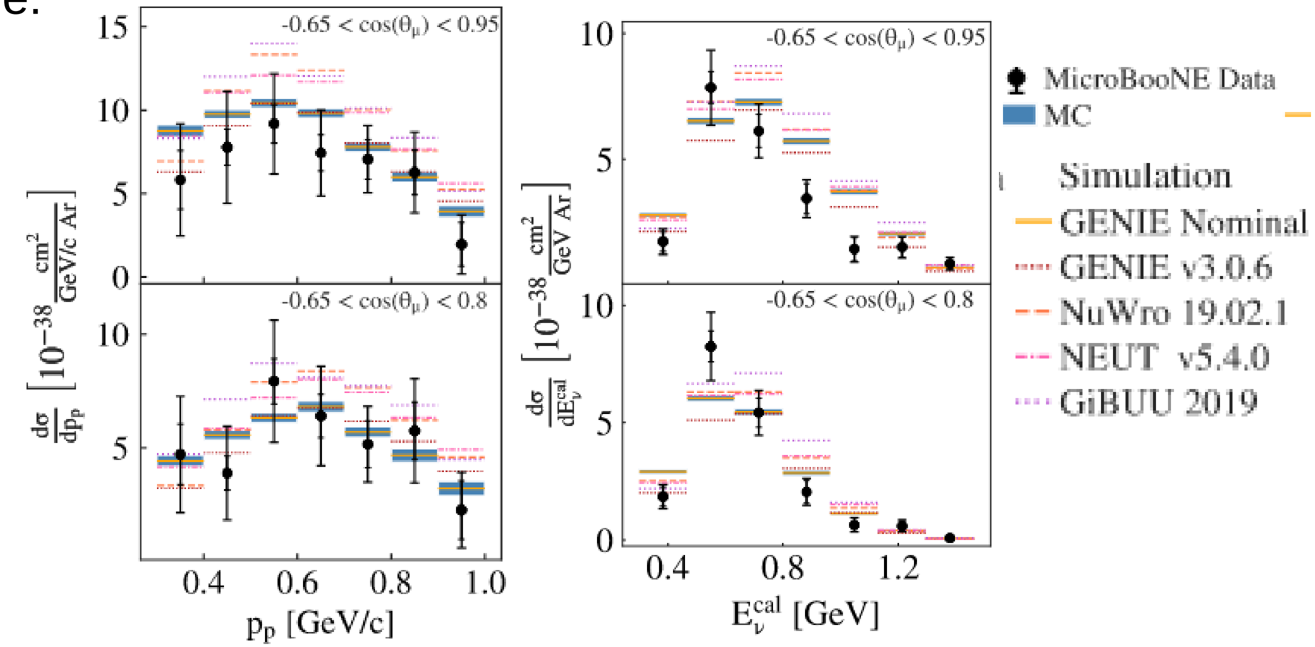


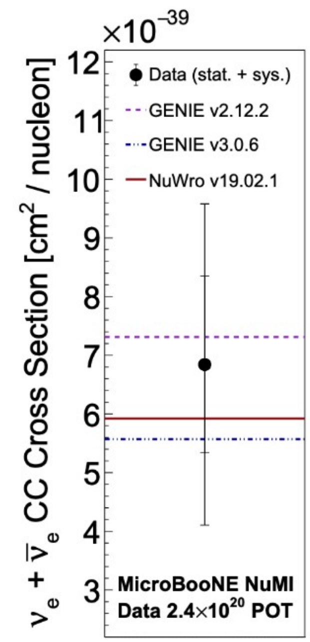


Not only R&D for technology but also measurements to control nuclear model in Argon

- MicroBoone:

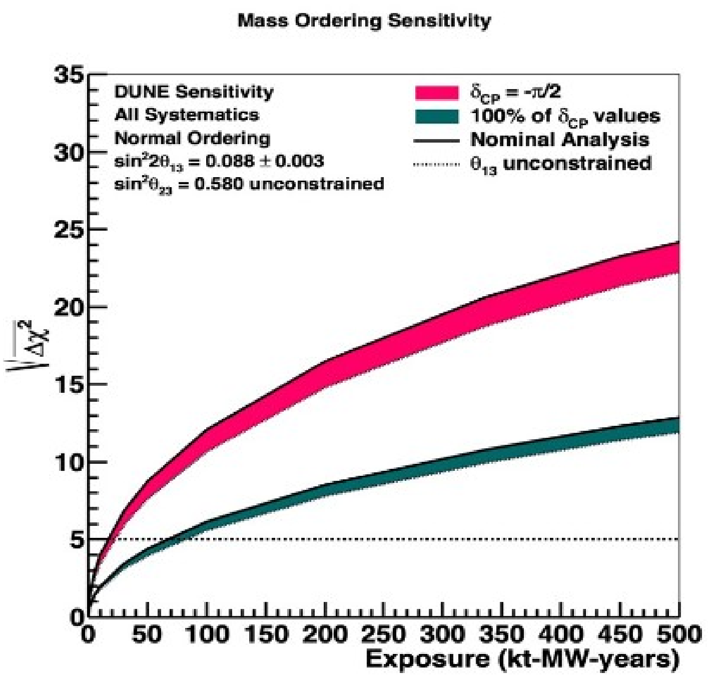
PHYSICAL REVIEW LETTERS125,201803 (2020)

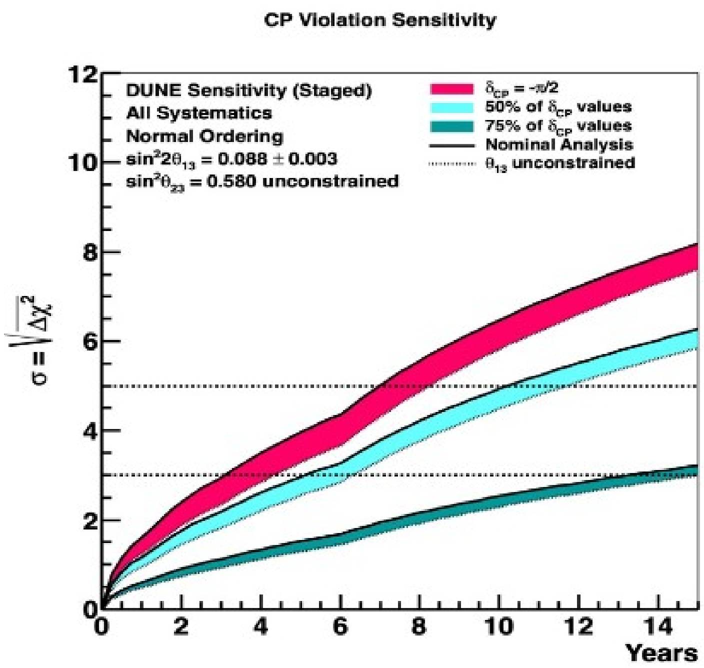




arXiv:2101.04228 [hep-ex]

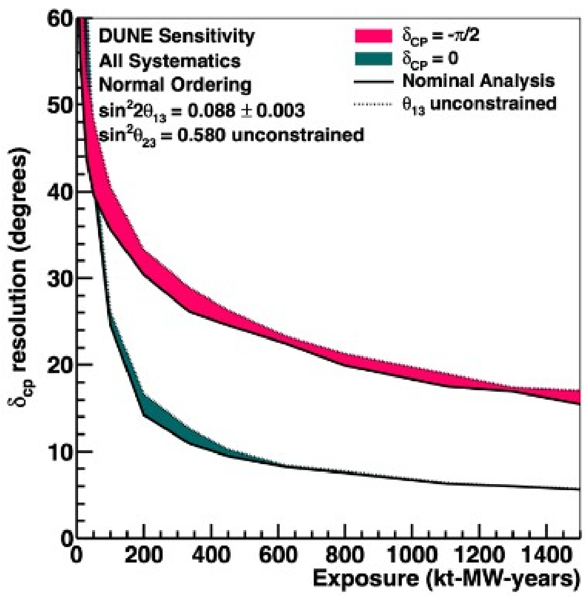
DUNE sensitivity

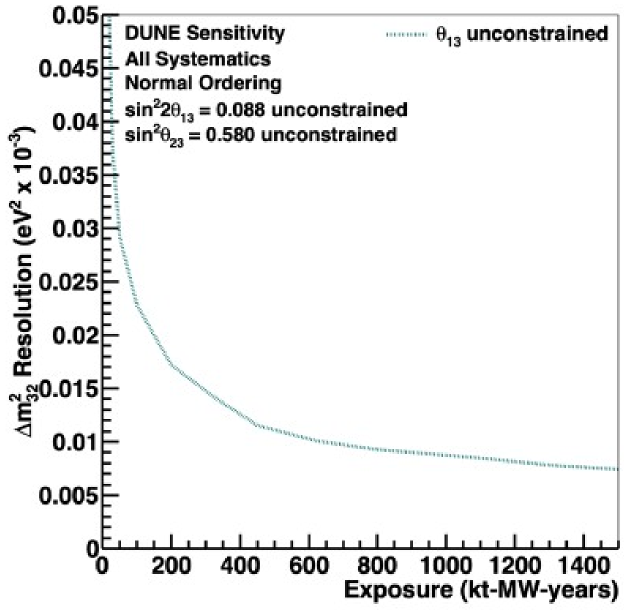




- **Very fast MH determination at 5σ**

- **Precision physics: prospects for δ_{CP}, Δm^2 resolution**





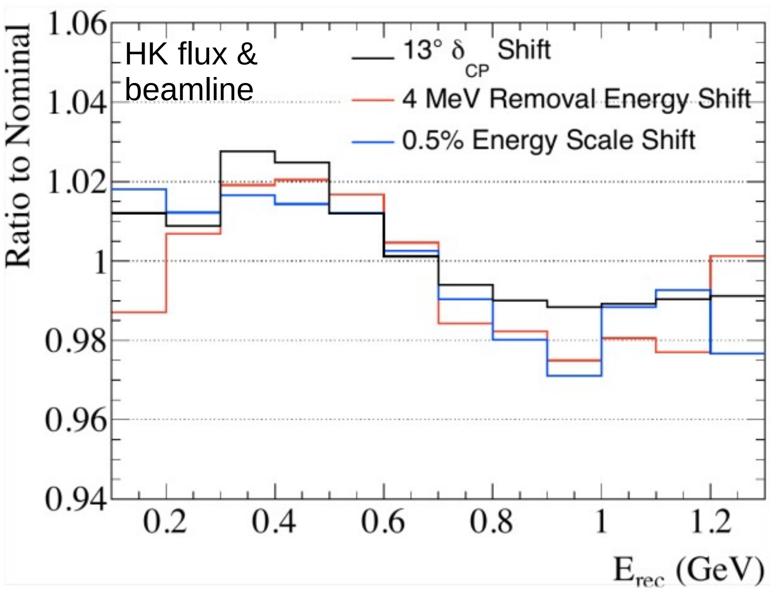
Importance of systematics

- Precision physics will be dominated by systematics

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

  → **first order systematic is the normalization of ν_e / $\bar{\nu}_e$ for CPV and MH**

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



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**

  Without forgetting crucial ancillary measurements like EMPHATIC, ANNIE, electron-scattering at JLab...

Near detectors and nuclear theory

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

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

$$R_{FD}^{\nu'} = \int \Phi^{\nu}(E_\nu)\, P_{osc}^{\nu\rightarrow\nu'}(E_\nu) \frac{d\sigma^{\nu'}}{dE_\nu} dE_\nu$$

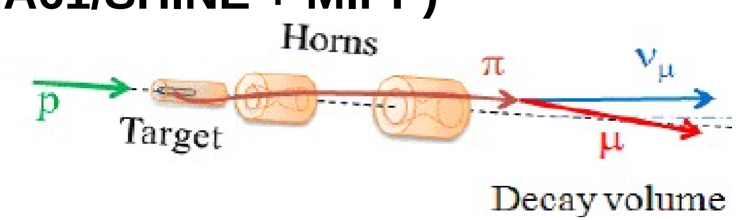
~same flux at ND and FD

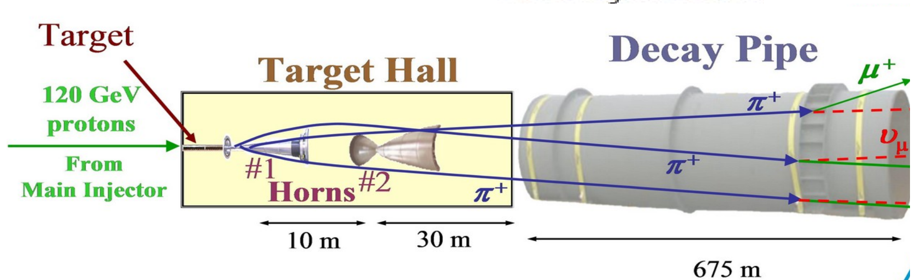
what we want to measure: oscillation probability

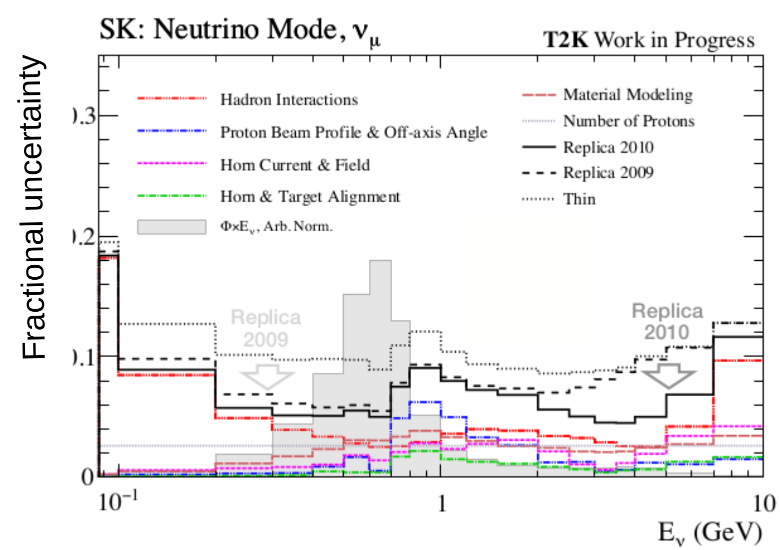
cross-section must be extrapolated from ND to FD:
- different neutrino energy distribution
- ND measure flux times xsec

Need nuclear theory models!

Flux simulation and tuning (NA61/SHINE + MIPP)







Near detectors and nuclear theory

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

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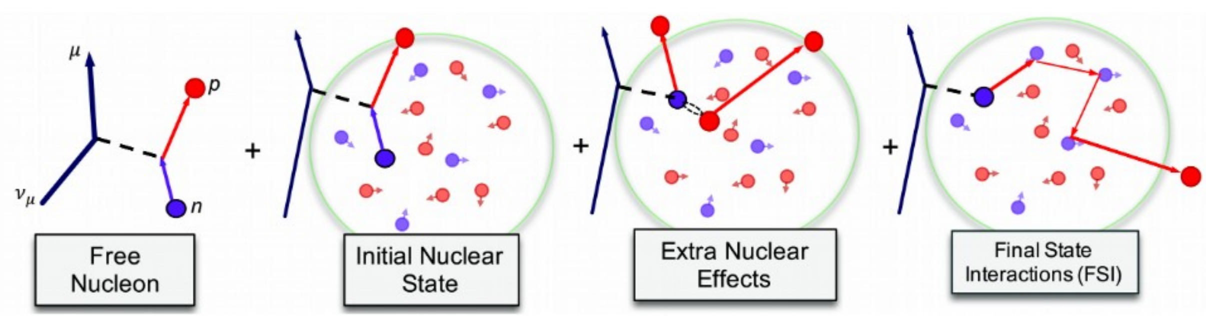
~same flux at ND and FD

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



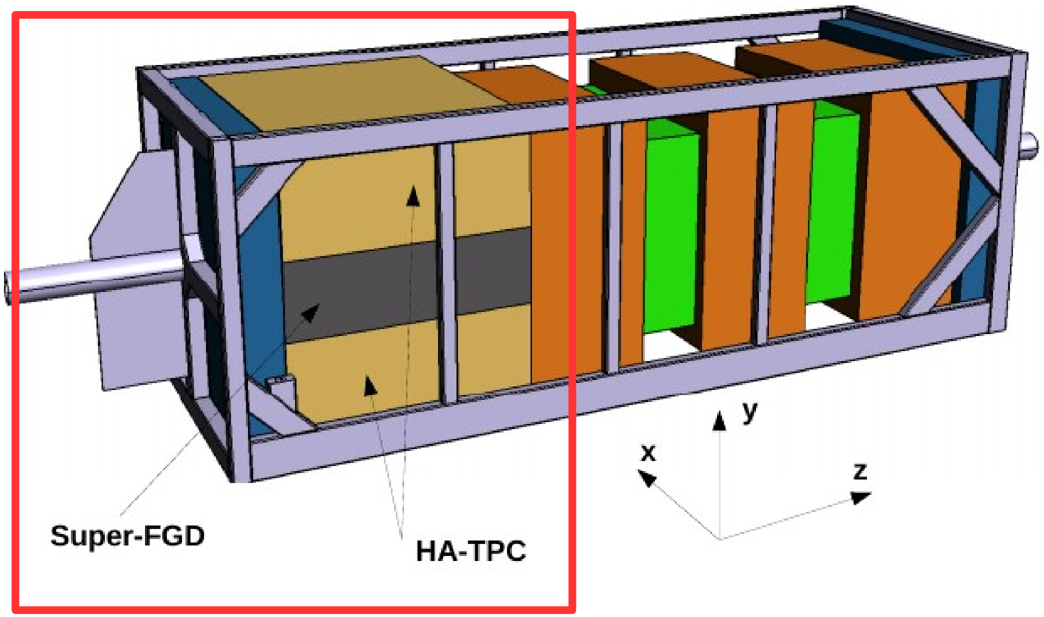
(and similarly for pion(s) production)

- 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

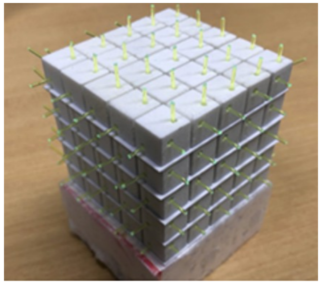
New generation of near detectors

- T2K is preparing an **upgrade of ND280** to be installed in 2022 to cope with increased statistics after beam upgrade and for HyperKamiokande



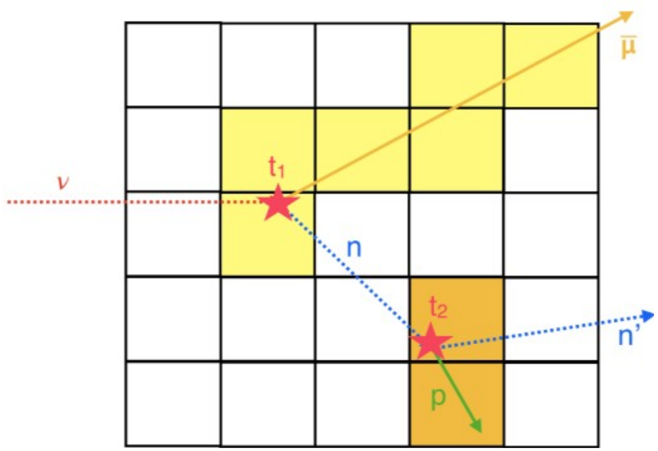
Horizontal TPCs to enlarge angular acceptance

Scintillator with 3D track reconstruction capabilities



→ low threshold on proton, pion momentum

→ measurement of neutrons with ToF



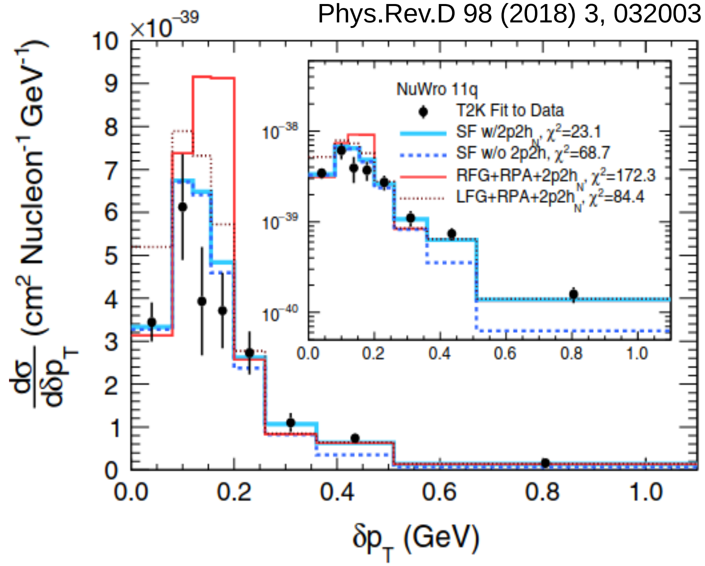
- Full **exclusive reconstruction of final state for best neutrino energy 'reconstruction'** from outgoing interaction particles

→ for the first time neutron reconstruction event by event!

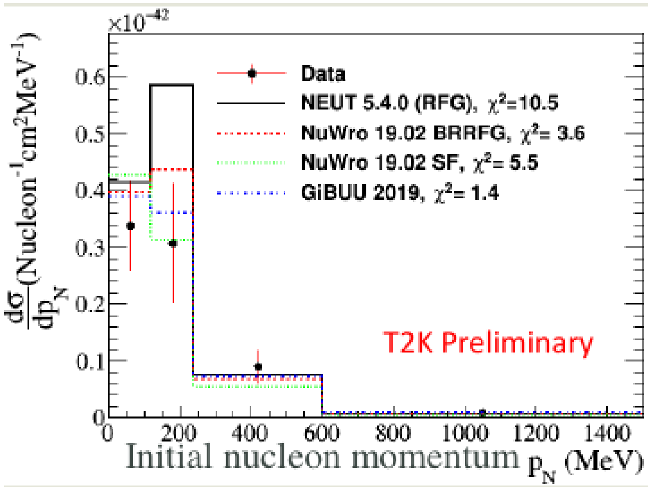
Opening the road...

- Hadron-muon transverse momentum unbalance for 'direct' measuring of nuclear effects
(ND280)

Phys.Rev.D 98 (2018) 3, 032003

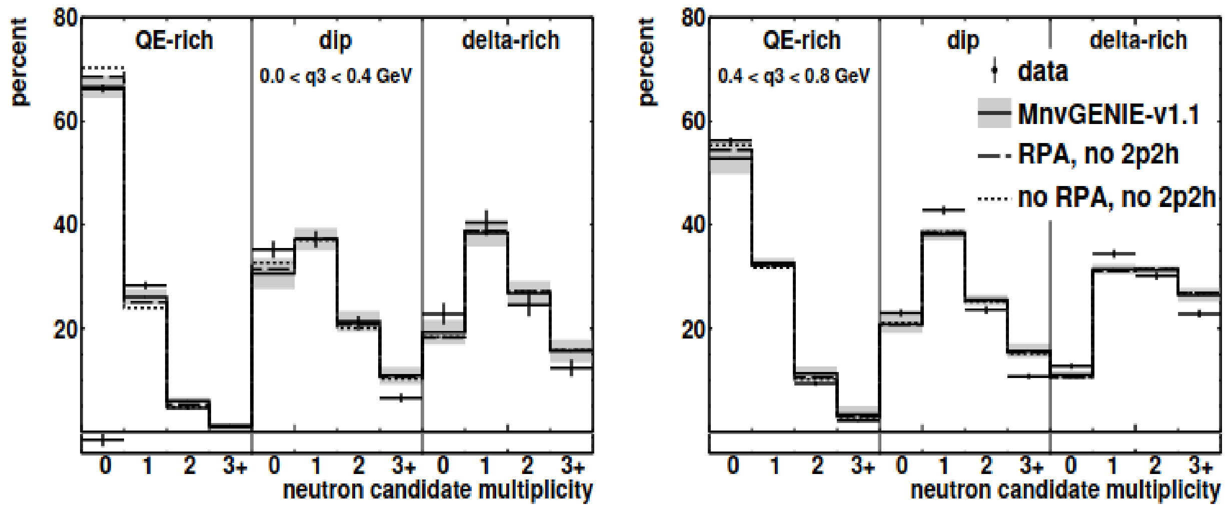


Phys.Rev.D 103 (2021) 11, 112009



- First usage of neutrons in neutrino-nucleus scattering
(Minerva)

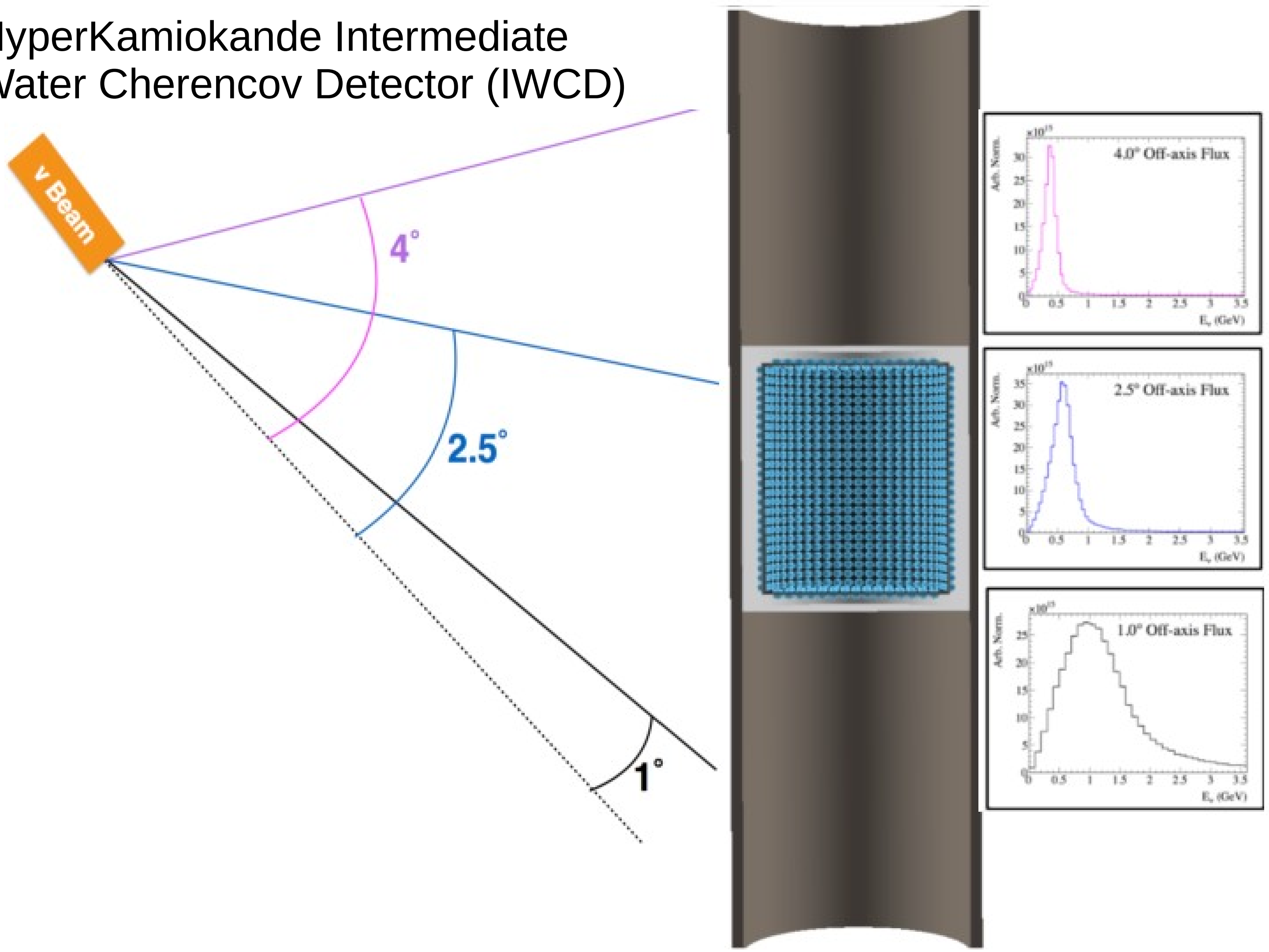
Phys. Rev. D 100, 052002 (2019)



New approach to near to far extrapolation

Extract Eν dependence from off-axis angle

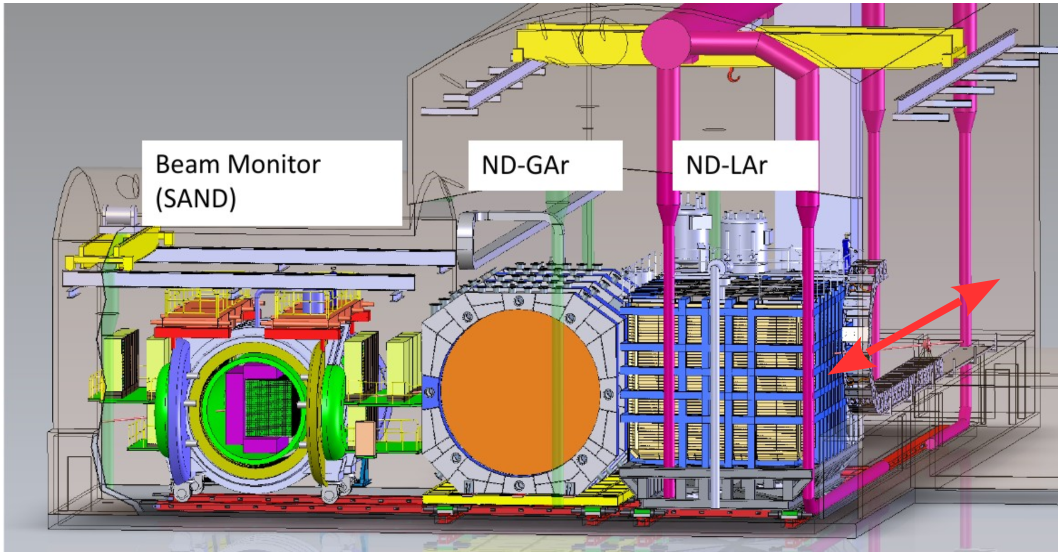
HyperKamiokande Intermediate Water Cherencov Detector (IWCD)

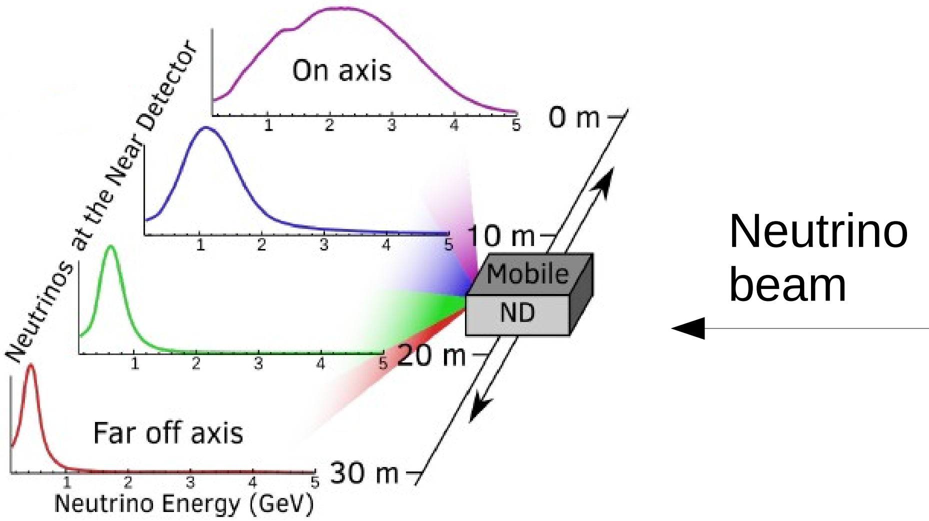


New approach to near to far extrapolation

Extract Eν dependence from off-axis angle

DUNE LAr and GAr TPCs as movable near detectors: DUNE-Prism





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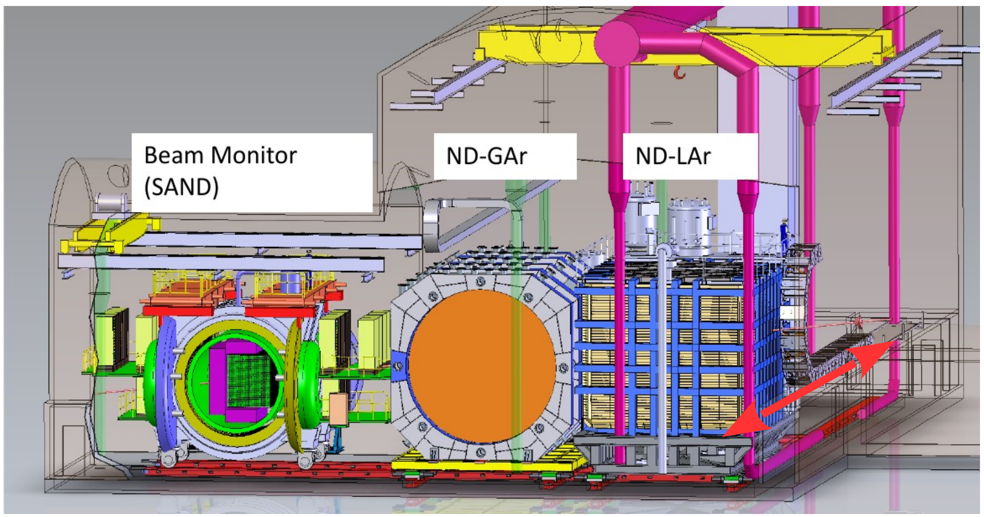
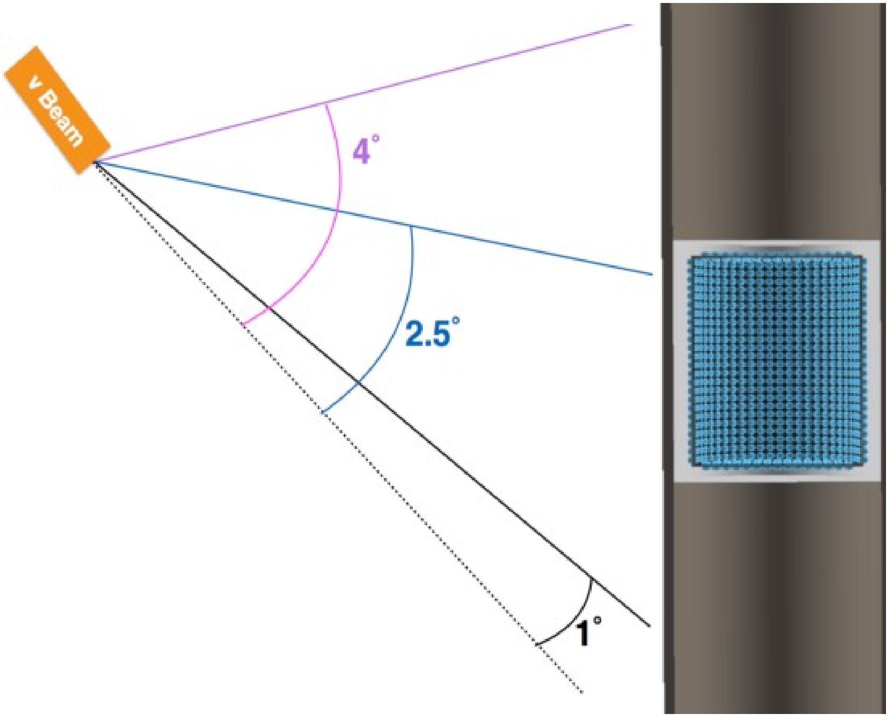




- Nuclear-level systematics becomes 'second order'
→ quantification on-going (acceptance, finite statistics, ...)

- Need to control well flux systematic uncertainties vs angle and flux stability vs time (DUNE SAND, T2(H)K INGRID)

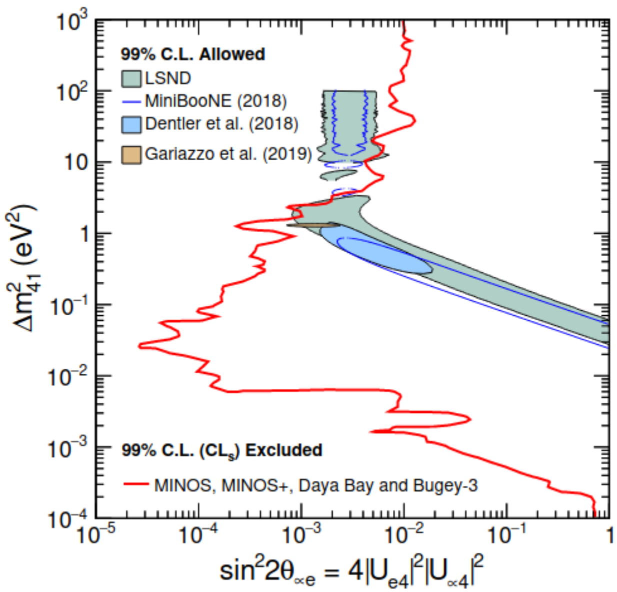
Beyond PMNS

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

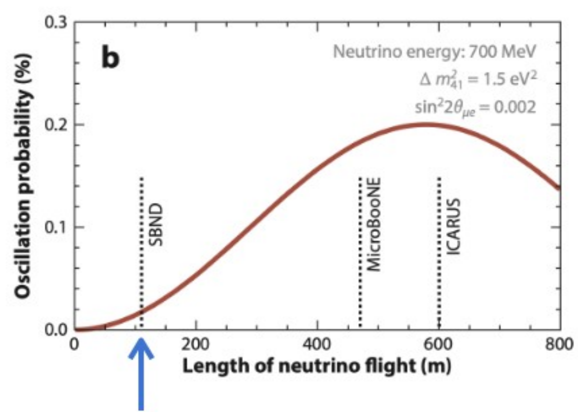
In particular it assumes
- minimal 3-flavour scenario
- standard neutrino interactions for production and detection
- standard matter effects along propagation

Steriles: new neutrino states with different Dm2 → oscillations at different L/E

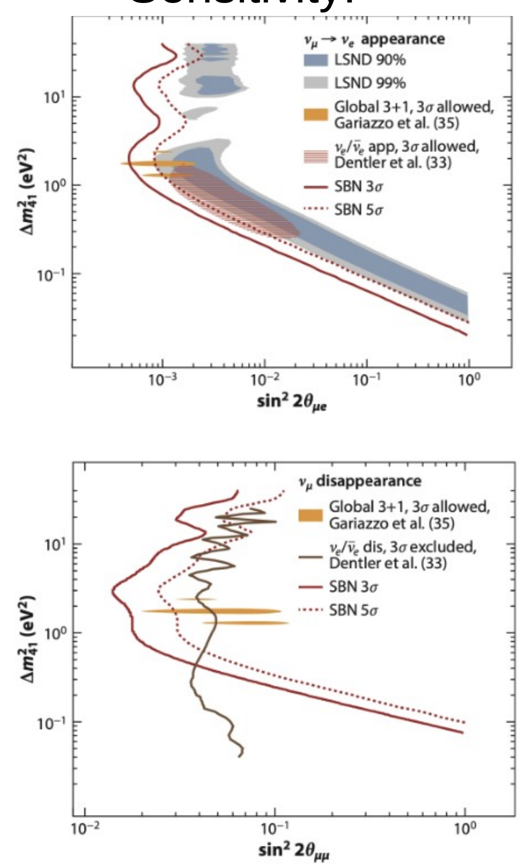
MINOS/MINOS+/reactors results



Short Baseline Neutrino program at FNAL.



Sensitivity:

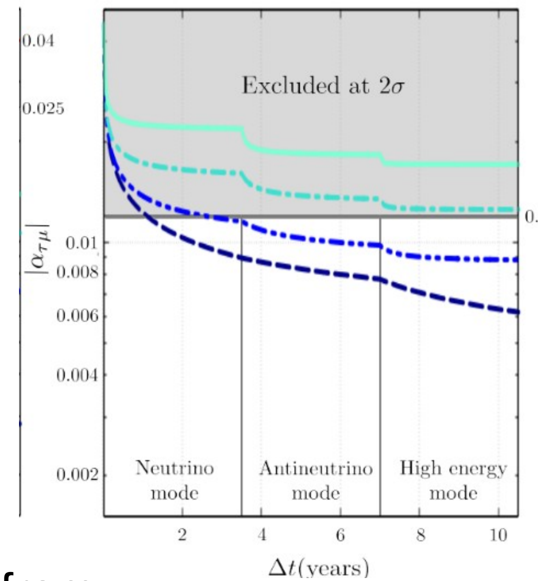


Annu. Rev. Nucl. Part. Sci. 2019 DOI 10.1146
(Reproduced from SBN Proposal assuming 6.6 E20 POT)

BSM surpises?

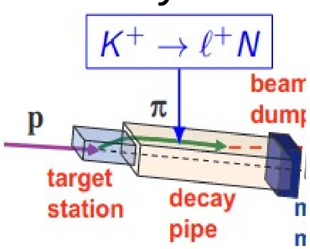
Steriles (of many different types) → inventive ways of use near detectors

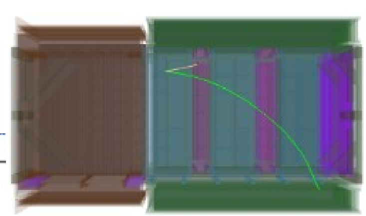
- DUNE tau ν appearance at near detectors



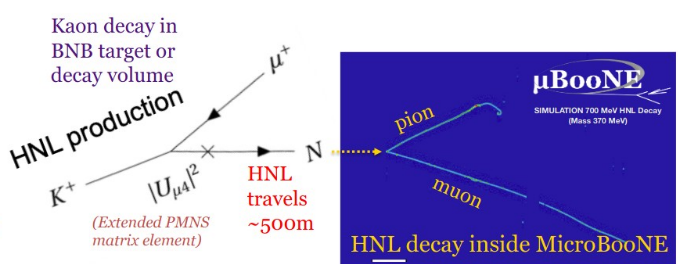
Sensitivity depending on energy shape uncertainty

- Heavy Neutral Leptons from K decays in the beam



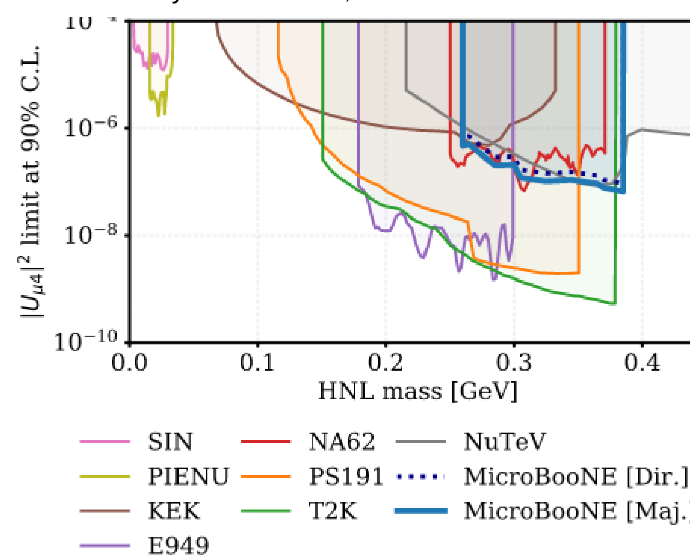


- ND280: decay of N in TPC gas volume (~no background)



- MicroBooNE: delayed N decays

Phys. Rev. D 100, 052006 (2019)
Phys. Rev. D 101, 052001



Beyond PMNS

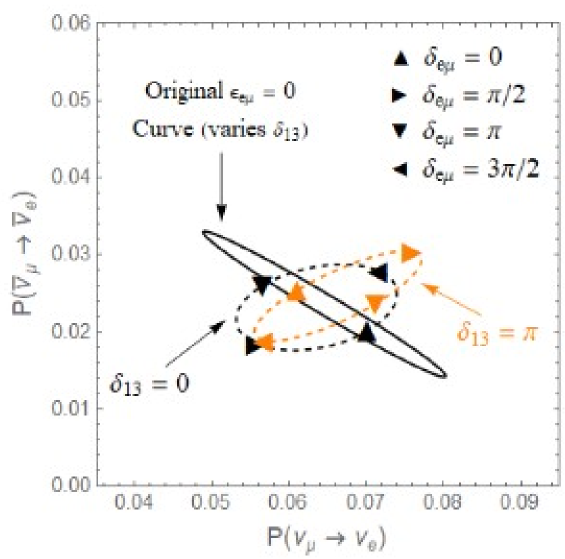
- **The ‘standard’ oscillation paradigm (PMNS-based) is very strict and not motivated by fundamental symmetries** (mixing angles and neutrino masses are ‘accidental’ numbers).

In particular it assumes

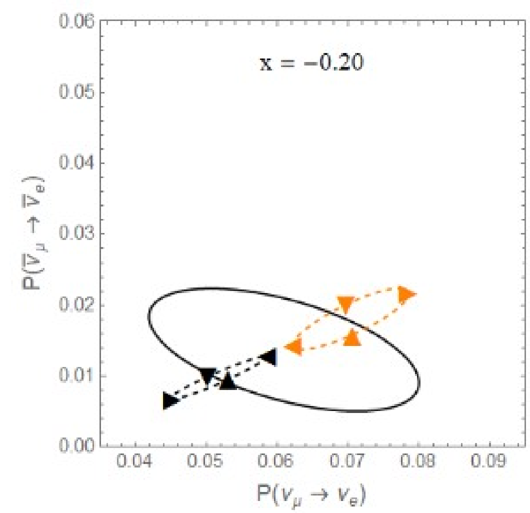
- minimal 3-flavour scenario
- standard neutrino interactions for production and detection
- standard matter effects along propagation

Non Standard Interactions: a door to new physics. (And more: CPT-violation, ...)
Need to able to disentangle from “standard” oscillation effects

Eg: new sources of CP-violation in NSI from non-diagonal terms in matter potential



moving to different (L/)E



CIPANP 2018, Print:1809.11128 [hep-ph]

Most general paradigm

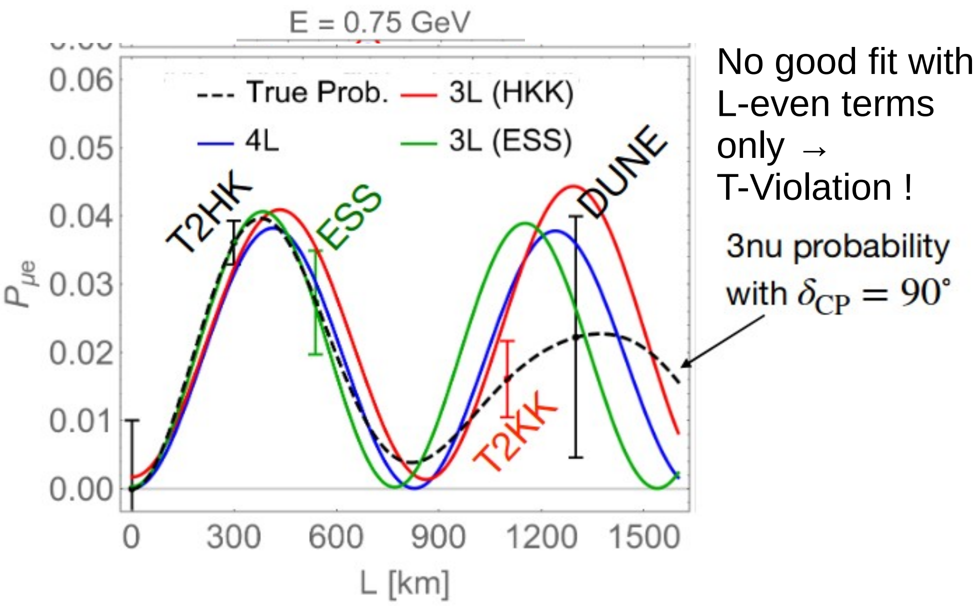
- Expand the oscillation study with a **more general paradigm: with next generation of experiments we will look at oscillations with a much more open-mind approach:** we want to characterize the L/E dependency of flavour mixing

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

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

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

arXiv:2106.16099 [hep-ph]

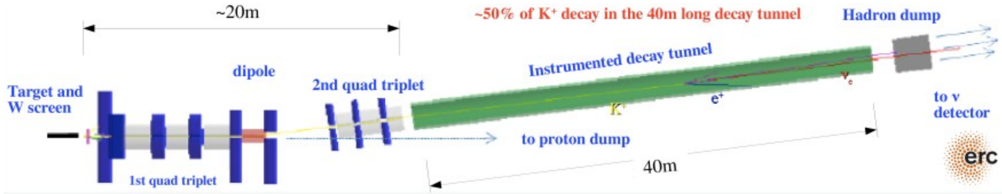


No good fit with L-even terms only → T-Violation !

New ideas and new facilities

- **Improved beams for more precise control of neutrino flux**

  - **EνBET:** instrumented decay tunnel for precise (1%) measurement of ν_e from K decays

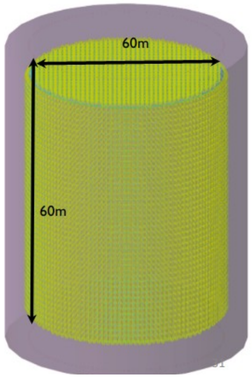


  - **νSTORM:** muon storage ring giving very well known ν_e and ν_μ fluxes (R&D toward Neutrino Factories)

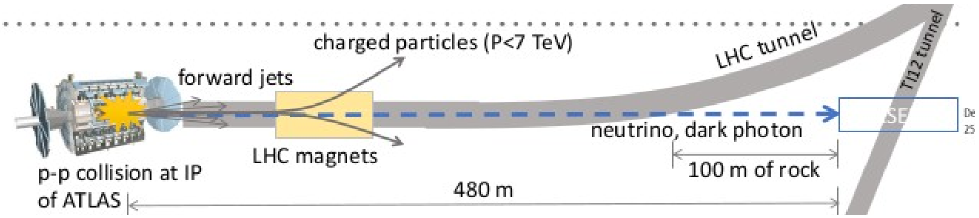
  - **ESSνSuperBeam:** 2nd oscillation + HIFI (demonstrator for low energy νSTORM)

- **Next-to-next generation detectors:**

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



- **Neutrinos at LHC: FASER** in forward region after defocusing charged particles → Eν~TeV



Summary

- Oscillation measurements made the cover of Nature in April 2020 with a statistically limited measurement: join us for interesting physics ahead!

- Neutrino oscillation physics with "neutrino beams" entering the precision era with NOVA and T2K → next generation experiments are worldwide efforts comparable to collider experiments

- Next generation of experiments (DUNE, HK) relies on control of systematics at % level → crucial role of near detectors: a new generation coming

  - T2K and NOVA are opening to road to exercise new near detectors, new analyses techniques, …

  - … long term work in collaboration with **nuclear theory community**

  - Important **R&D** involved (CERN Neutrino Platform)

- A vibrant community ready to react to the 'unexpected': new systematics and/or BSM signs → **inventive in the usage of near detectors and in the exploration of complementarity between HK and DUNE**