Future long-baseline experiments

F. Terranova

Univ. of Milano Bicocca and INFN

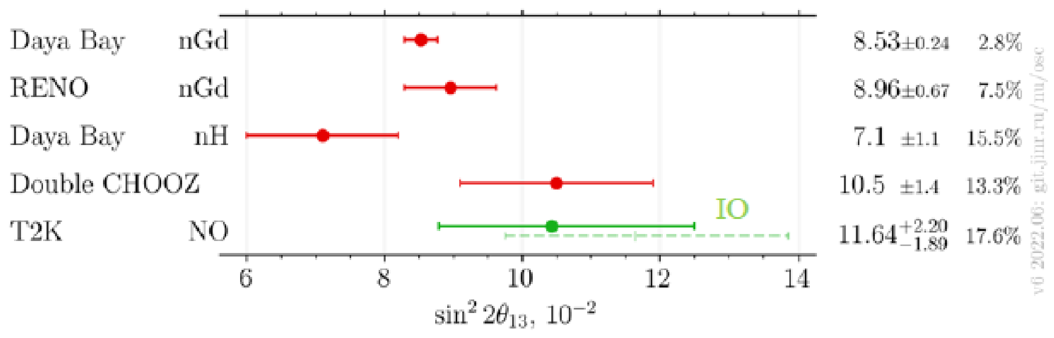
31st International Symposium on Lepton Photon Interactions at High Energies

Melbourne, July 18, 2023

The precision era of neutrino oscillation physics

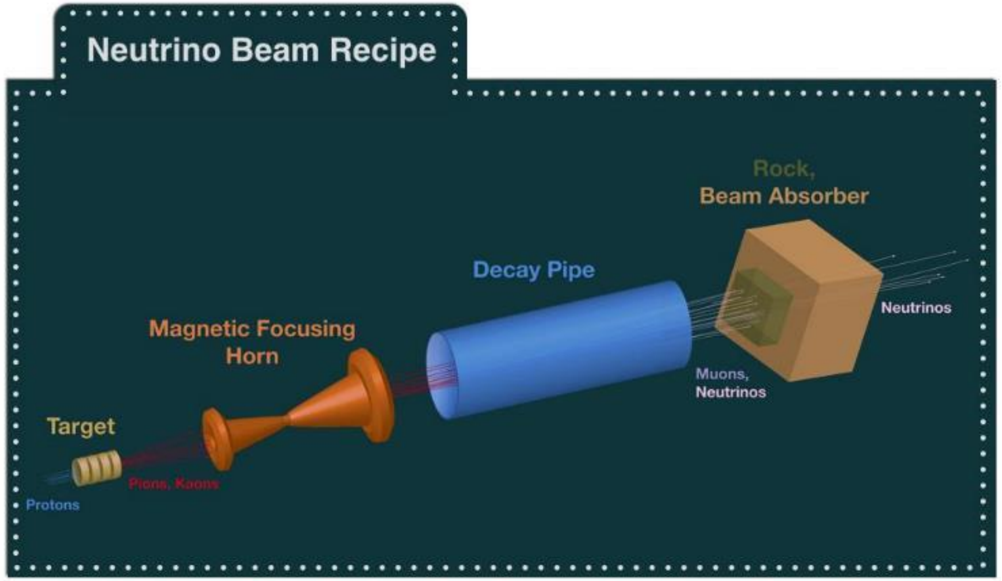
2012: all neutrino mixing angles are “large” compared with the CKM matrix and we can observe sizable oscillations at distances and energies that can be produced on earth by particle **accelerators** and **reactors**

This statement (“discovery of θ_{13}” – Breakthrough prize 2013) opened up the precision era of neutrino physics because artificial source offer an unprecedented control of the beam and mitigate systematics uncertainties well below any natural source (solar, atmospheric, supernova neutrinos).



A large value of θ_{13} is the portal to precision physics because (in principle ☺) a sufficiently powerful long baseline experiment might measure **all parameters of the lepton Yukawa sector of SM in one shot** – except for the size of the lightest mass eigenstate

Best-in-class: accelerator neutrino beams



$$
\begin{aligned}
P_{\nu_\mu\to\nu_e} &\simeq \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
&- \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

$$\Delta \equiv \Delta m^2_{31} L/(4E)$$

Year 2005 →

«**oscillation phase**» It is O(1) for
E= O(1 GeV) and L= O(500 km)
Cool, we can build experiment on Earth ☺

$$\alpha \equiv \Delta m^2_{21}/|\Delta m^2_{31}|$$

Year 2003 →

Must be <1. The larger the better.
We know now that is 0.03

$$\xi \equiv \cos\theta_{13}\, \sin 2\theta_{12}\, \sin 2\theta_{23}$$ ~1

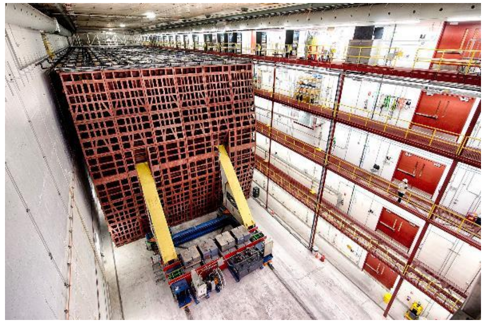
$$\sin^2 2\theta_{13}$$ ~0.1

Year 2012 →

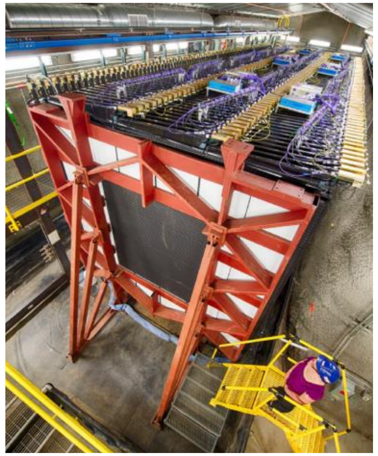
The larger the better! It is O(1) in neutrinos!
(it is tiny in quarks..)

NOvA

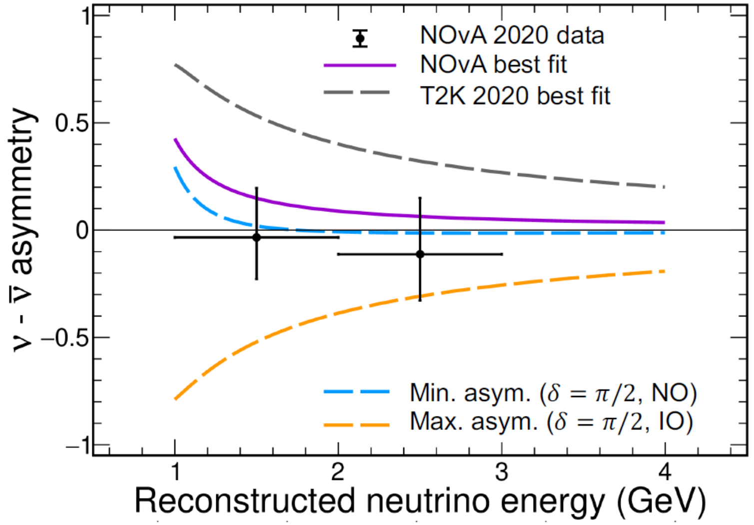
- NOvA is ideally suited for the measurement of the mass ordering because the baseline is long (L=810 km)



- NOvA and T2K are complimentary since their different baselines allow the effects of mass hierarchy and CP violation to be distinguished.
- Again, the detector mass and beam intensity is too small to gain a 5sigma evidence for CP violation and for normal (inverted) ordering (**rationale for DUNE**)

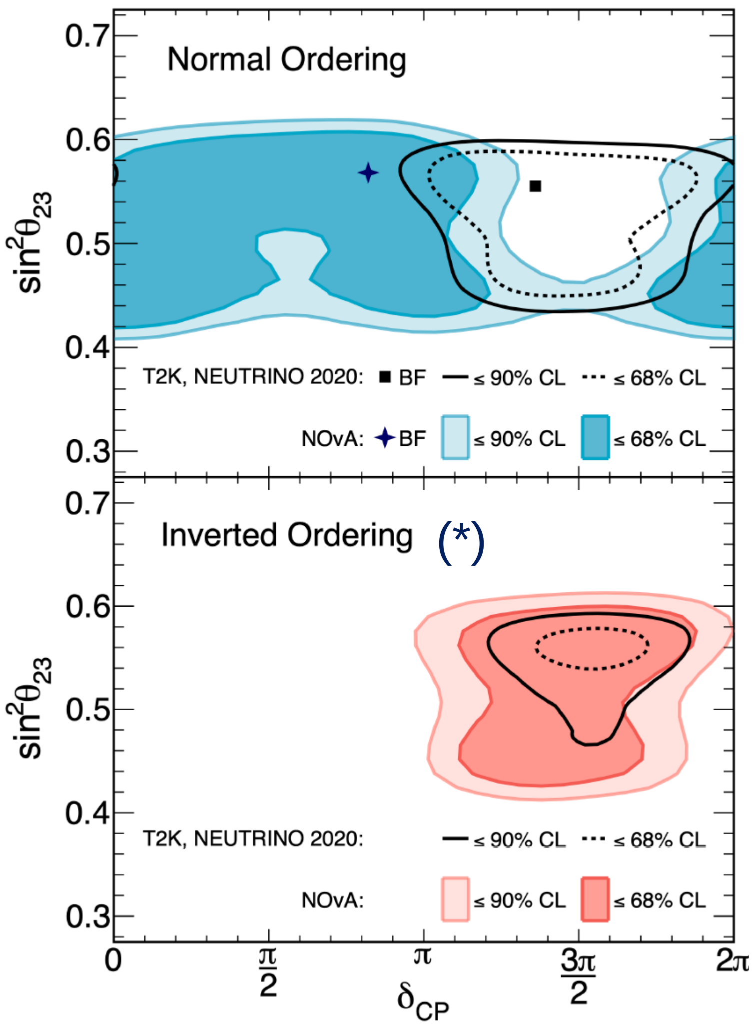


The two experiments are in mild tension on the asymmetry between neutrino and antineutrino appearance

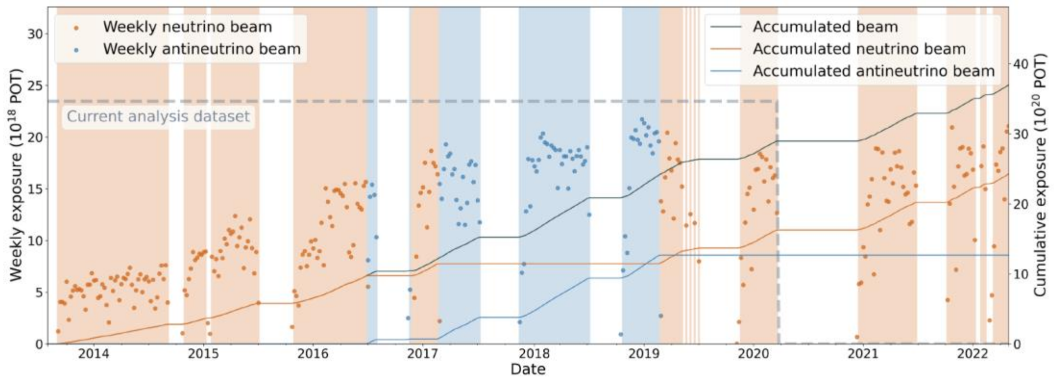


2020 data set: https://arxiv.org/abs/2108.0821!

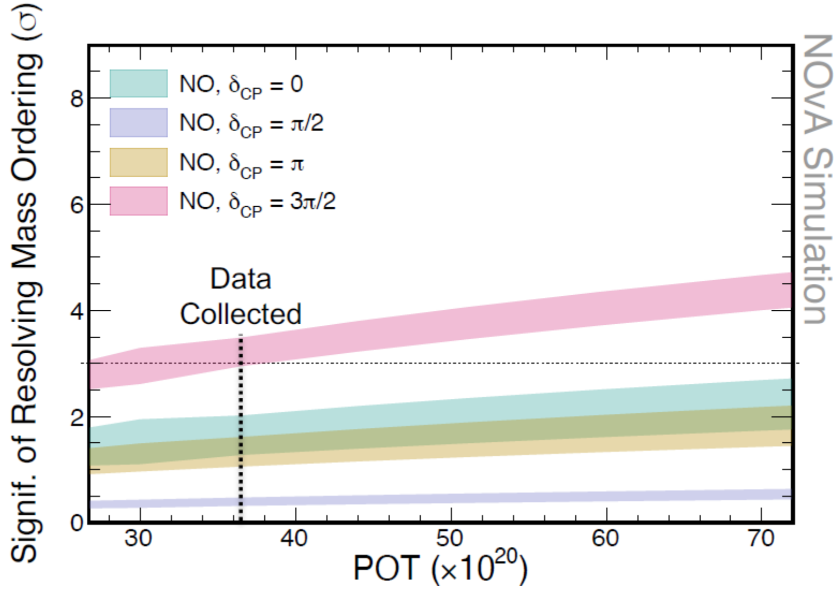
J. Hartnell, Talk at Neutrino2022



(*) In addition, inverted order not supported by SuperKamiokande atmospheric data



Projected sensitivity to mass ordering



Joint T2K-NOvA analysis expected soon

The rationale of DUNE and Hyperkamiokande

To reap the "large θ_{13}" opportunity and address in a conclusive manner the missing parameters of the lepton Yukawa sector (mass ordering, θ_{23} octant, and CP violation) we need experiments that increase by about one order of magnitude the sensitivity of T2K and NOνA.

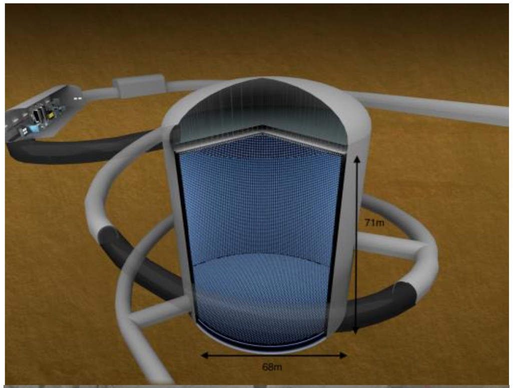
Hyperkamiokande
building upon the success of T2K

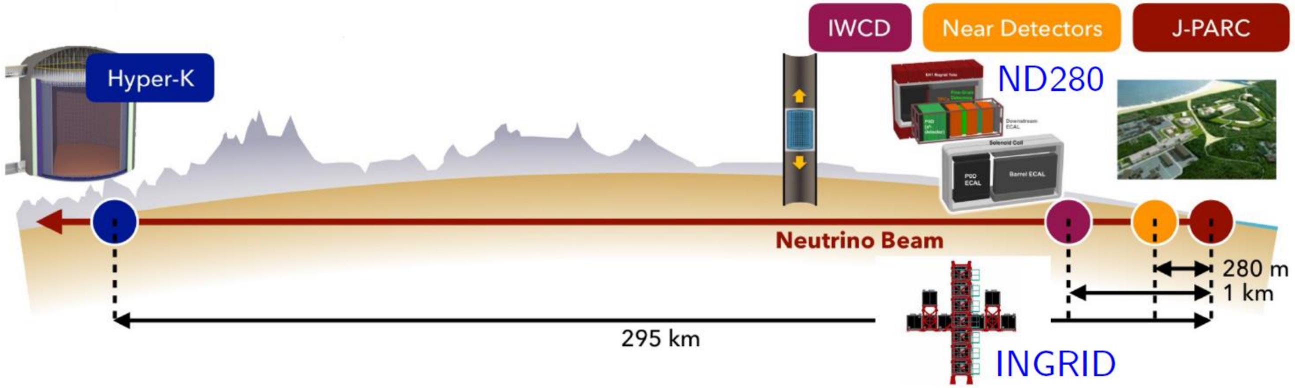
- Exploit the outstanding **masses** that can be achieved by water Cherenkov detectors with an improvement of the JPARC neutrino beam
- Exploit the outstanding sensitivity to CP given by the **JPARC-Kamioka baseline** (295 km)
- Enhance the physics reach of SuperKamiokande for atmospheric neutrinos (mass hierarchy!), solar, supernova neutrinos (SN) and proton decay

DUNE
a leap over NOνA

- Exploit a high-power, **wide-band neutrino beam** originating from the upgrade of the Fermilab accelerator complex
- Exploit the outstanding resolution of **liquid argon TPCs**
- Exploit matter effects **(1300 km baseline)** to reach unprecedented sensitivity to mass hierarchy
- Explore astrophysical channel that cannot be addressed by SuperK (flavor dependent SN neutrino interaction, Kν in proton decay, solar HEP neutrinos)

HyperKamiokande

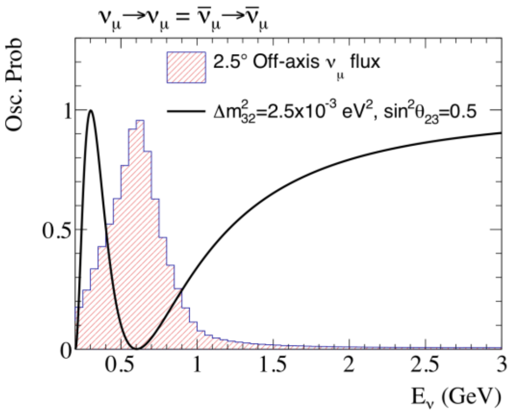


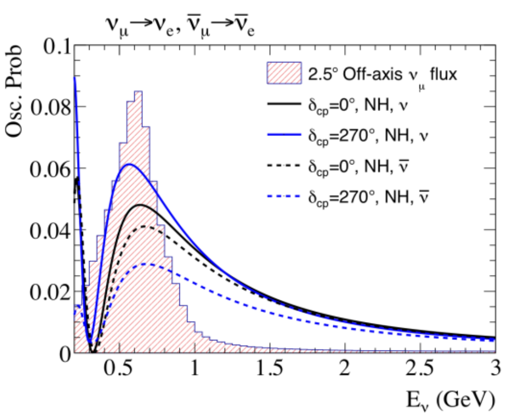


Upgraded beam power to 1.3 MW w.r.t. T2K ($\sim$ 500 kW)

Upgraded ND280 (off-axis detector of T2K)

New Intermediate Water Cherenkov Detector @ 1 km

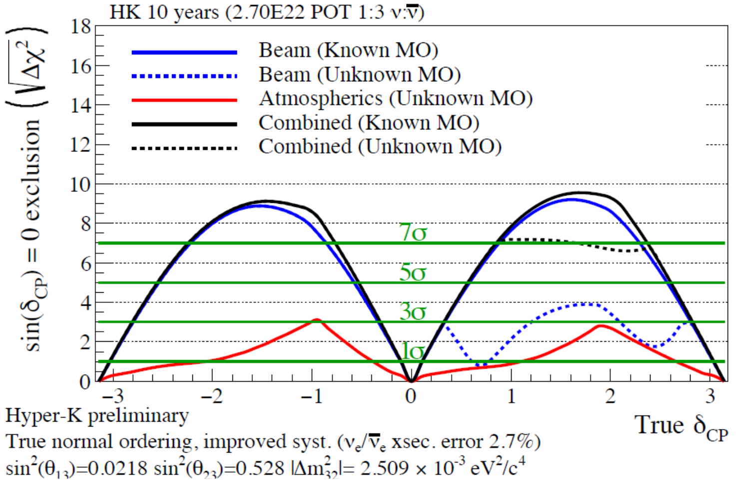


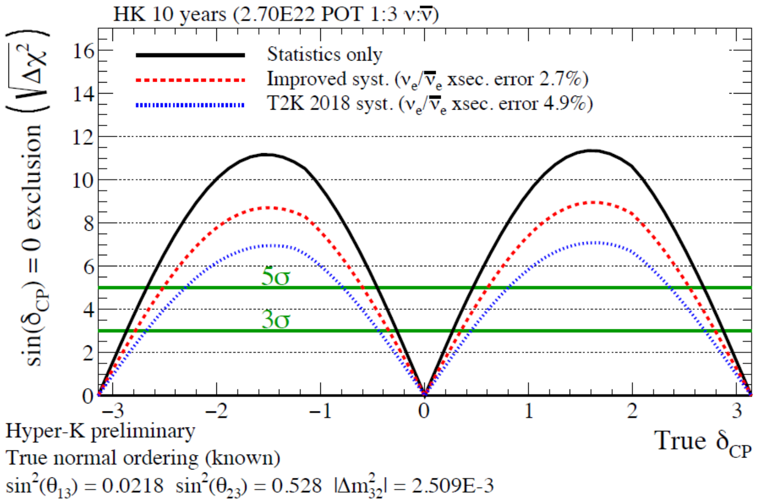


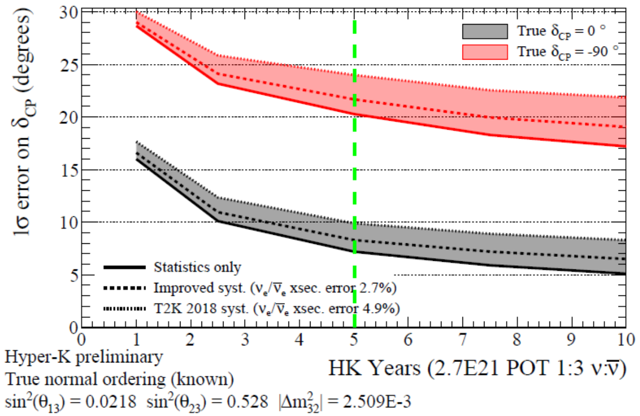
	Super-K	Hyper-K
Site	Mozumi	Tochibora
Overburden	2780 m.w.e.	1700 m.w.e.
Number of ID PMTs	11129	20000
Photo-coverage	40%	20% ($\times$2 efficiency)
Mass / Fiducial Mass	50 kton / 22.5 kton	258 kton / 186 kton

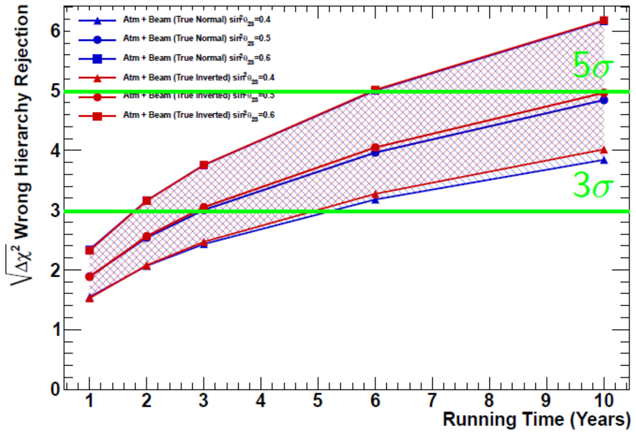
Beam physics with HyperKamiokande

The HK beamline is optimal for the study of CP violation provided that mass hierarchy is known (either from other experiment – T2K+NoVA, JUNO or from **atmospheric neutrinos in HK**)



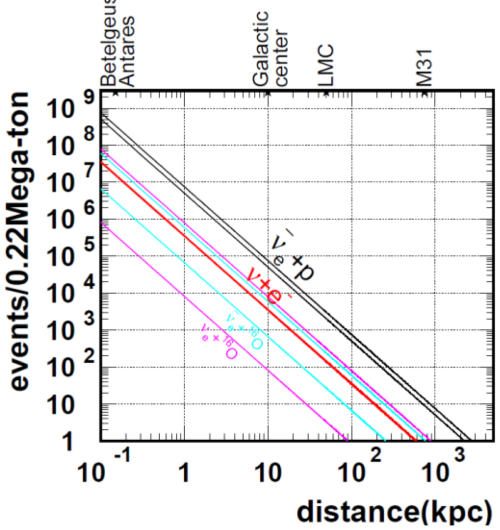






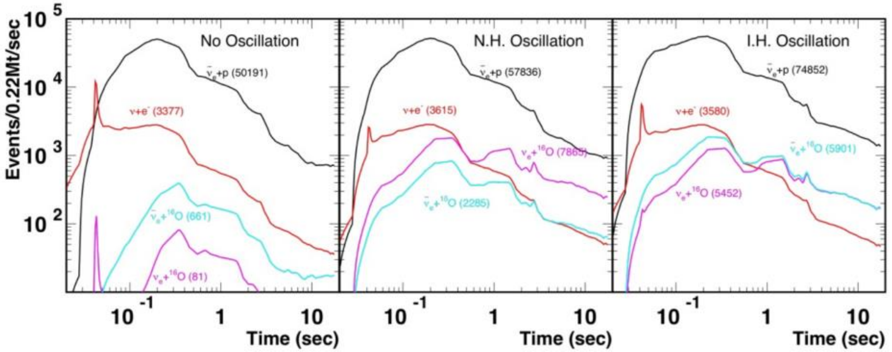
Astroparticle physics with Hyperkamiokande

[HK LOI, arXiv:1109.3262]

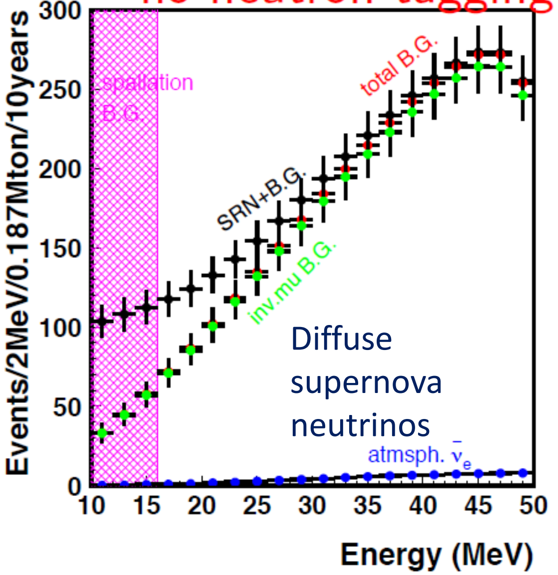


supernova burst

J. Wilson, Talk at Neutrino2022

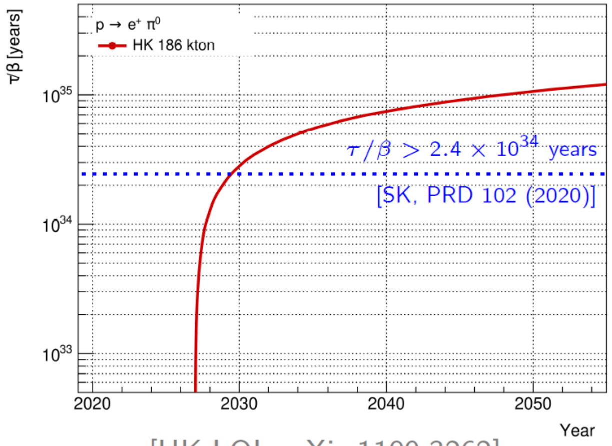


no neutron-tagging



Proton decay

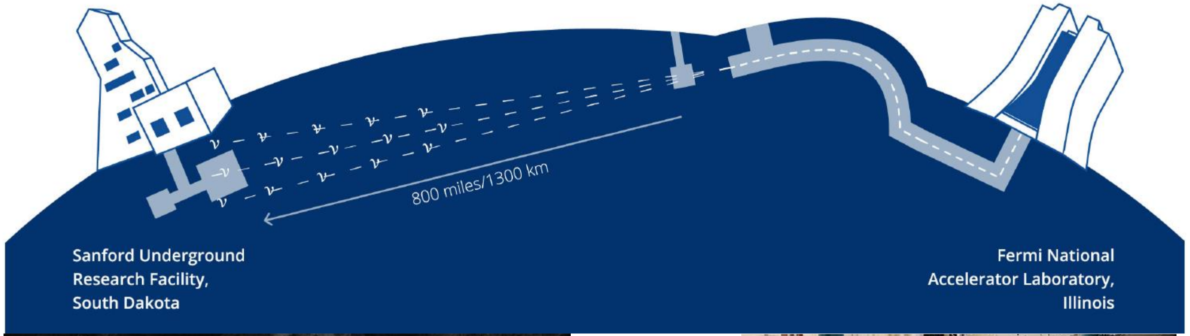
3σ sensitivity $p \to e^+ + \pi^0$

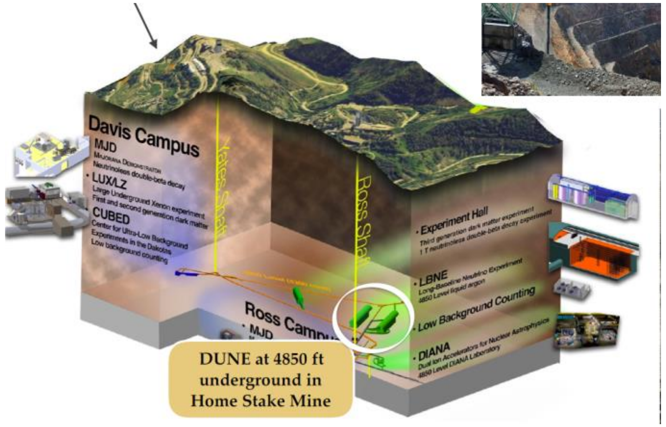


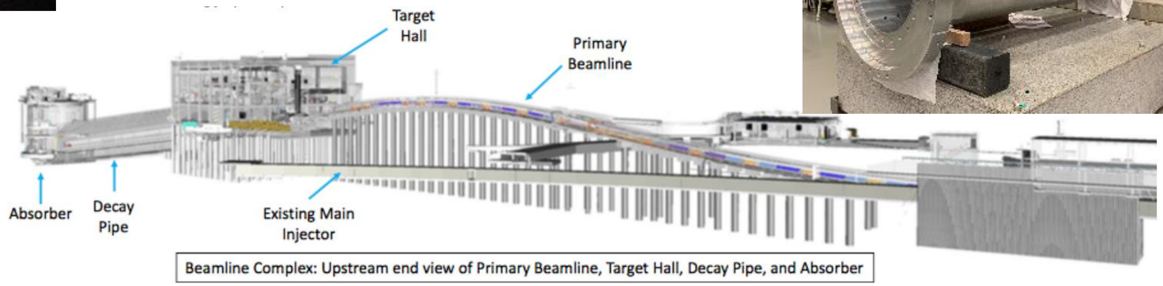
[HK LOI, arXiv:1109.3262]

The Long Baseline Neutrino Facility and SURF

The implementation of the DUNE science require two major facilities: a broad-band neutrino beam with 1.2 MW power upgradable to 2.4 MW power and the SURF laboratories in South Dakota. They are aimed at feeding a broad, top-class programme in neutrino physics, astroparticle and multi-messenger astronomy, rare event search and physics beyond the standard model for decades.



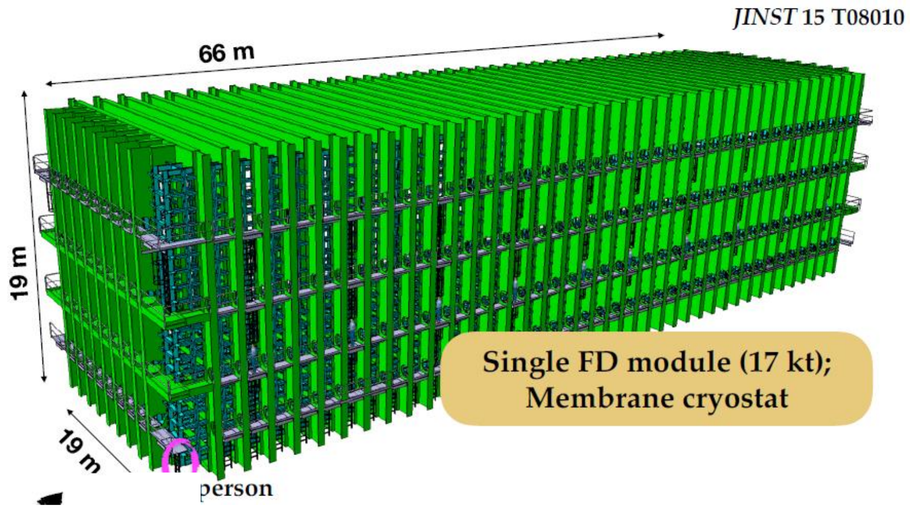




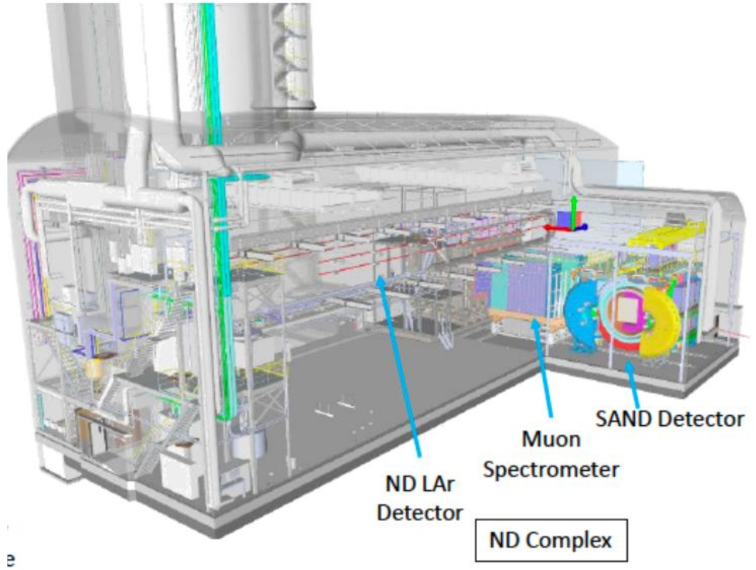
DUNE

Mass: the DUNE far detector comprises 4 modules of liquid argon for a **total mass of 70 kton**.

Resolution: DUNE is based on the technique with **the best particle imaging capability** available at kton scale: the Liquid Argon TPC (C. Rubbia, 1977)



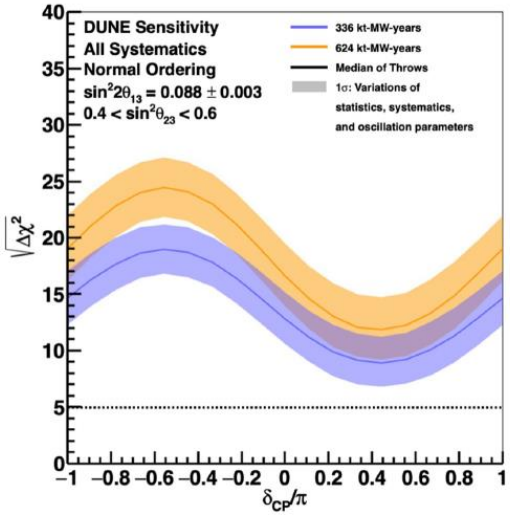
Precision: DUNE employs a **near detector complex** for beam characterization based on a movable (ND liquid argon TPC, the DMS muon spectrometer/NDGAr) + on-axis beam monitor (SAND).



Beam observables: $\nu_\mu \rightarrow \nu_e$ oscillations and its CP conjugate $\nu_\mu \rightarrow \nu_e$; ν_μ survival probability at the far detector. **Natural sources**: atmospheric and solar neutrinos. Transient sources like supernova neutrinos. Forbidden decays like $p \rightarrow K\nu$ proton decay

Beam physics with DUNE

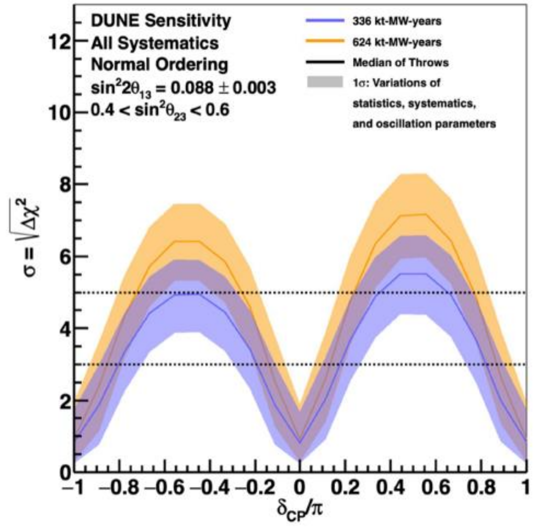
Mass Ordering

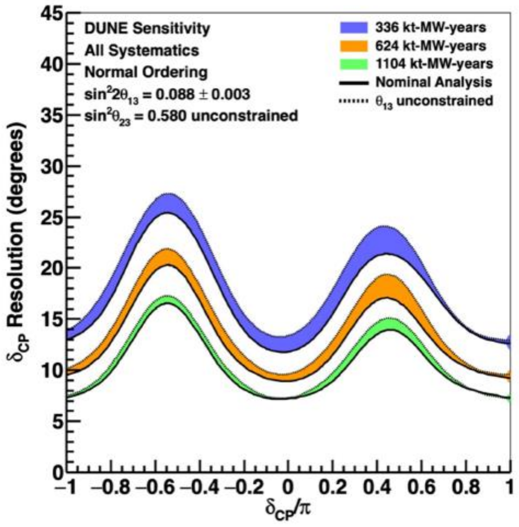


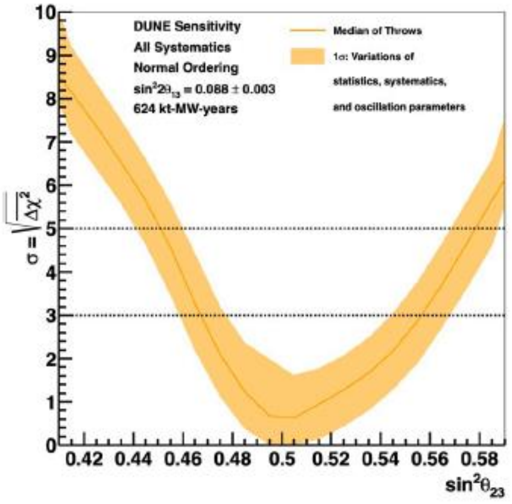
EPJC 80 (2020) 978

- Early data: 5 sigma determination of mass ordering in <2 y for any value of δ
- No use of external parameters but for solar ones
- 7-16º resolution thanks to the use of a wide band beam

Additional info available in EPJC 80 (2020) 987 and Phys.Rev.D 105 (2022) 7, 072006

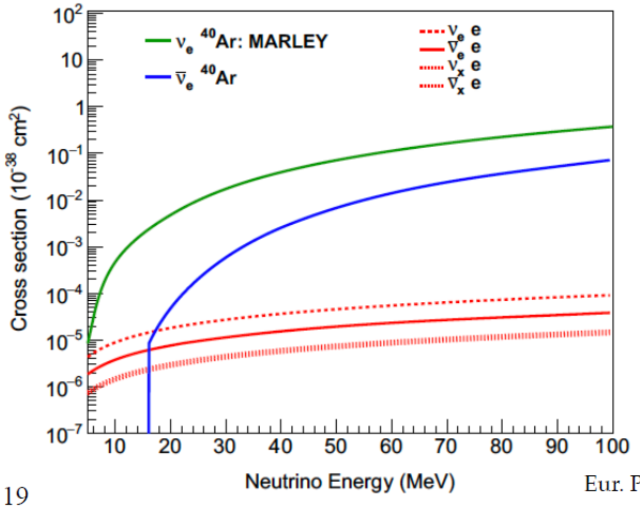




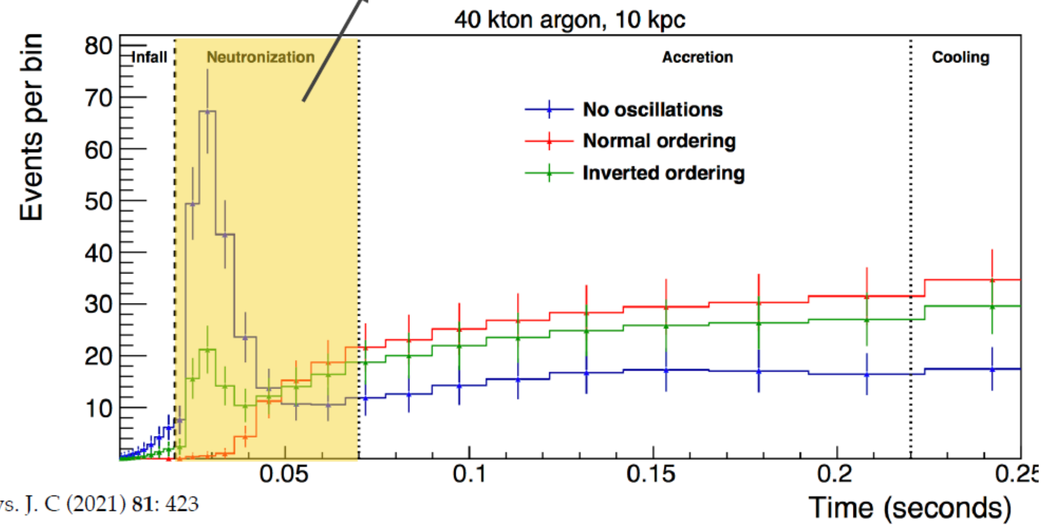


Astroparticle physics with DUNE

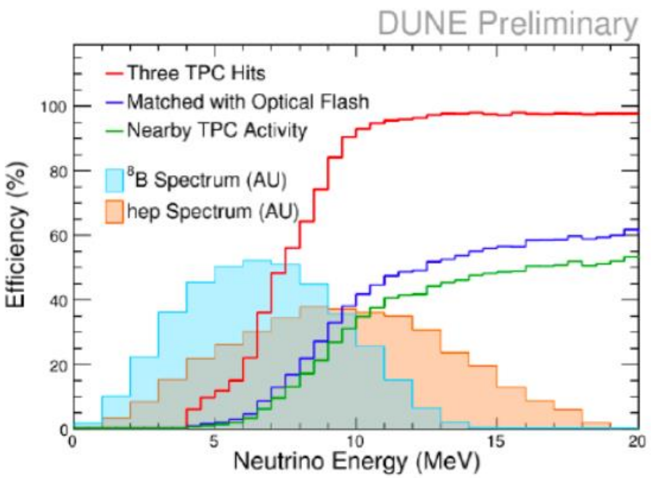
DUNE is sensitive to ν_e CC events by $\nu_e\ {}^{40}Ar \rightarrow {}^{40}K\ e^+$ thanks to the LArTPC technology and to e-ν scattering thanks to its unprecedented mass.



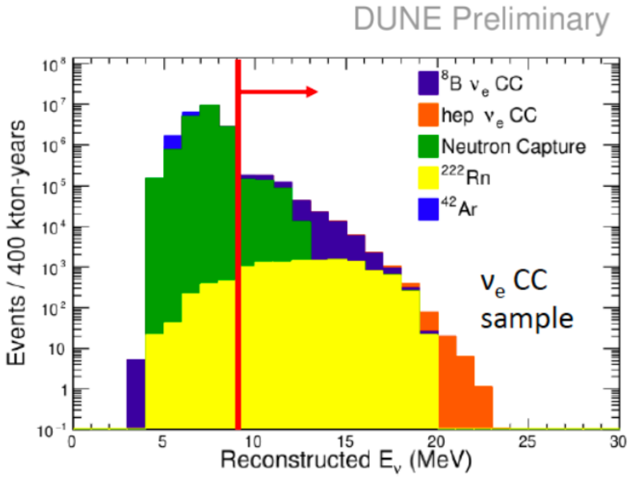
19



Eur. Phys. J. C (2021) 81: 423

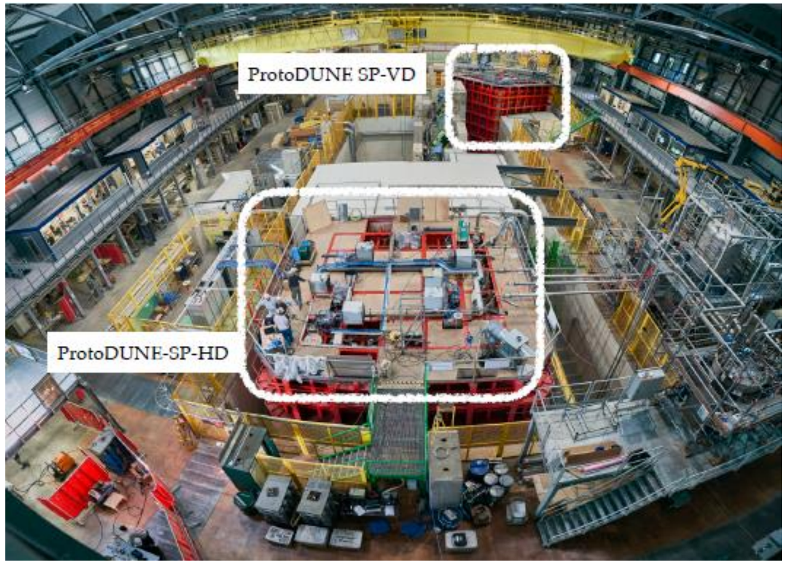


First evidence of HEP neutrinos



The CERN Neutrino Platform

CERN does not have (yet ☺) a neutrino beam but plays a pivotal role in the field thanks to the tremendous breakthrough gained at the CERN Neutrino Platform



NP04/ProtoDUNE-SP: demonstration of the DUNE technology, of membrane cryostats, and modular LArTPCs

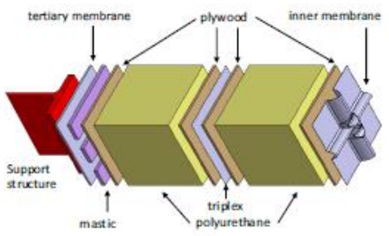
NP02/ProtoDUNE-DP: large drift distance, "wireless" TPC (inspired the second DUNE module and now, ProtoDUNE-VD)

NP07/T2K_ND: invention of the 3D fine-grained scintillator and TPCs for the T2K/HK Near Detector

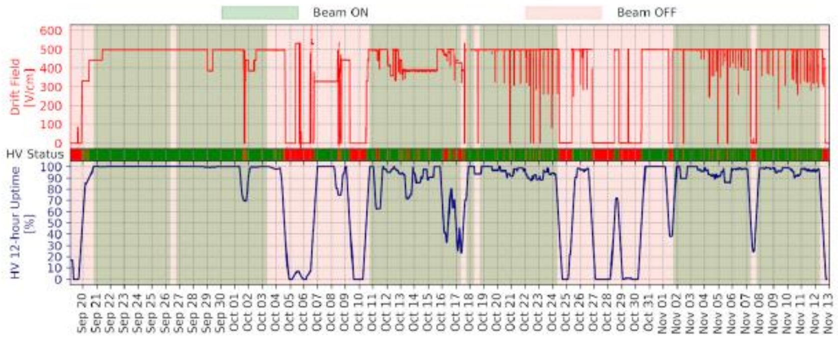
NP04/ProtoDUNE-SP

ProtoDUNE SP-HD

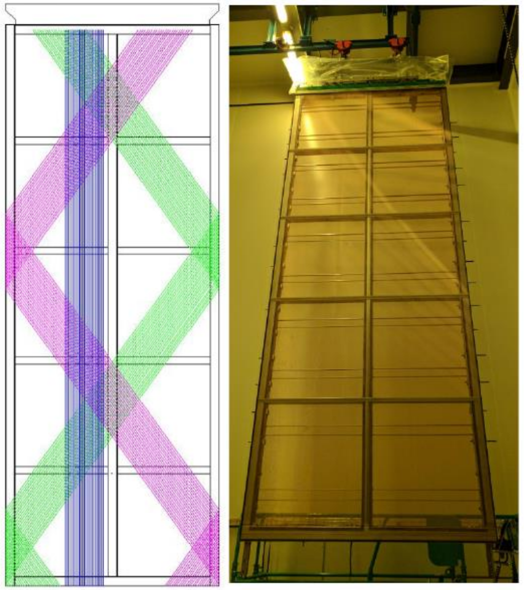
- *Largest LArTPC constructed to date!*
- Ran successfully from 2018-20 collecting over 4 million events!
- Charged particle beam and cosmic runs
- Low noise, stable HV, high purity, neutron calibration, Xe doping
- Calibration & detector physics; hadron-argon cross section measurement program



Large scale validation of membrane cryostat

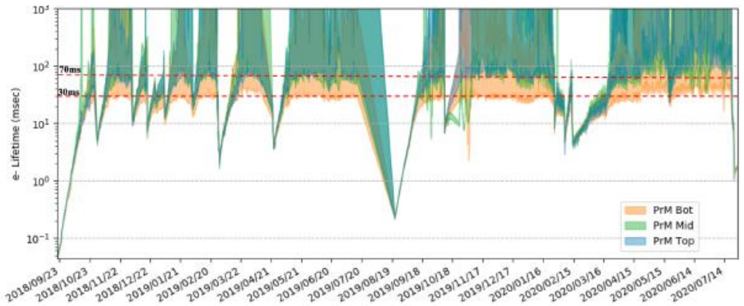


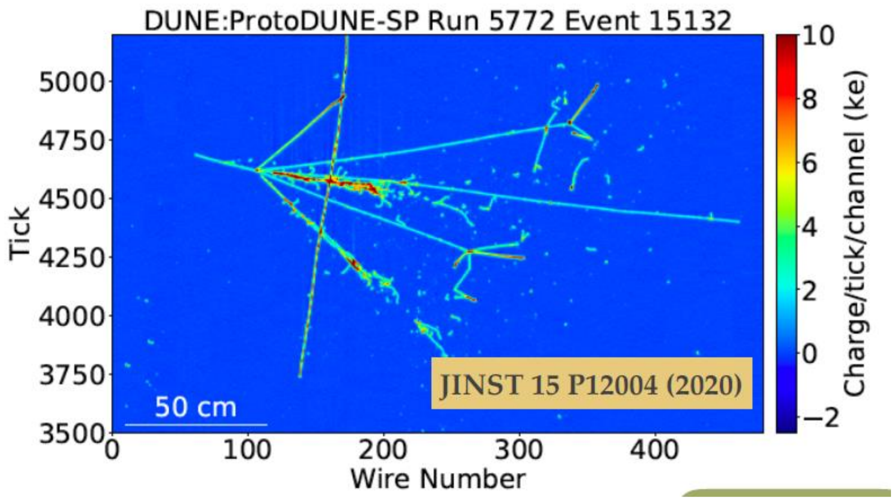
Flawless performance of the HV system

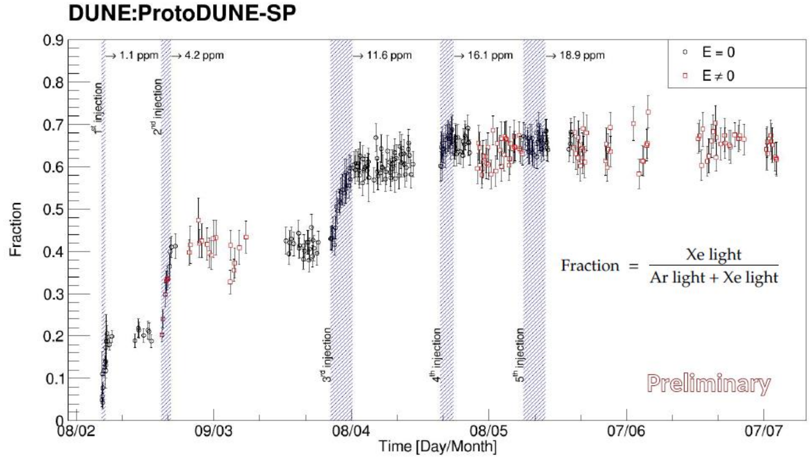


Large scale validation of APA

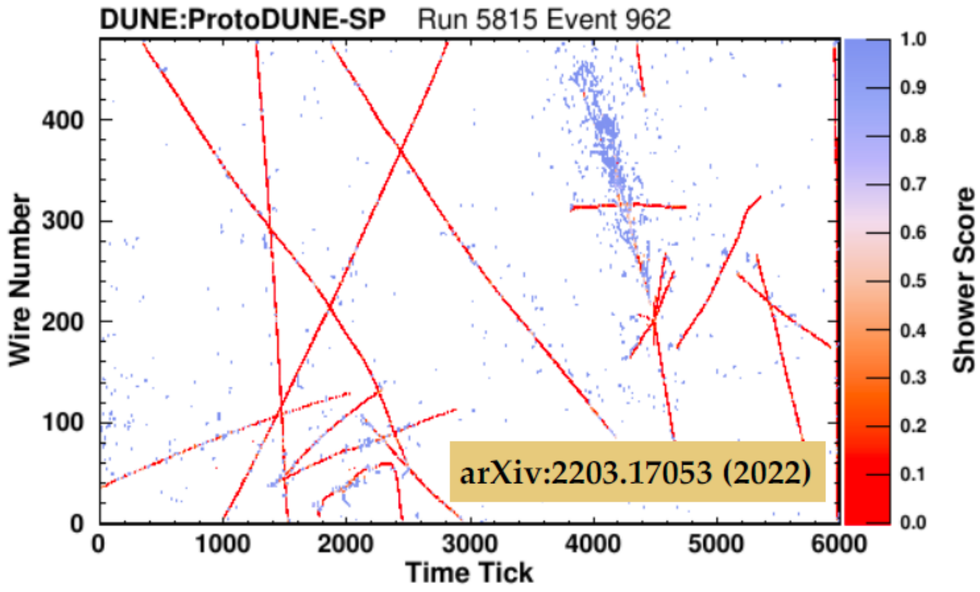
Validation of the purification system

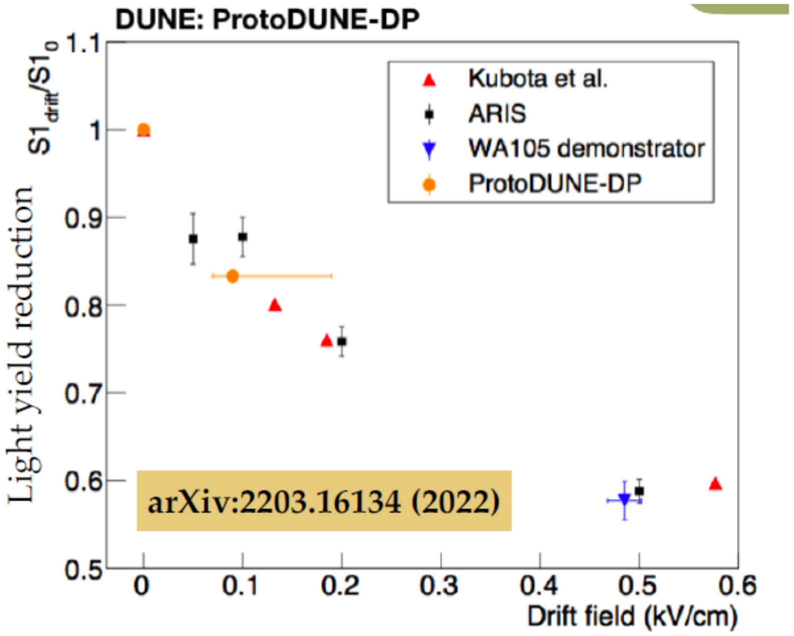






Xenon doping! N. Gallice @Lidine 2022

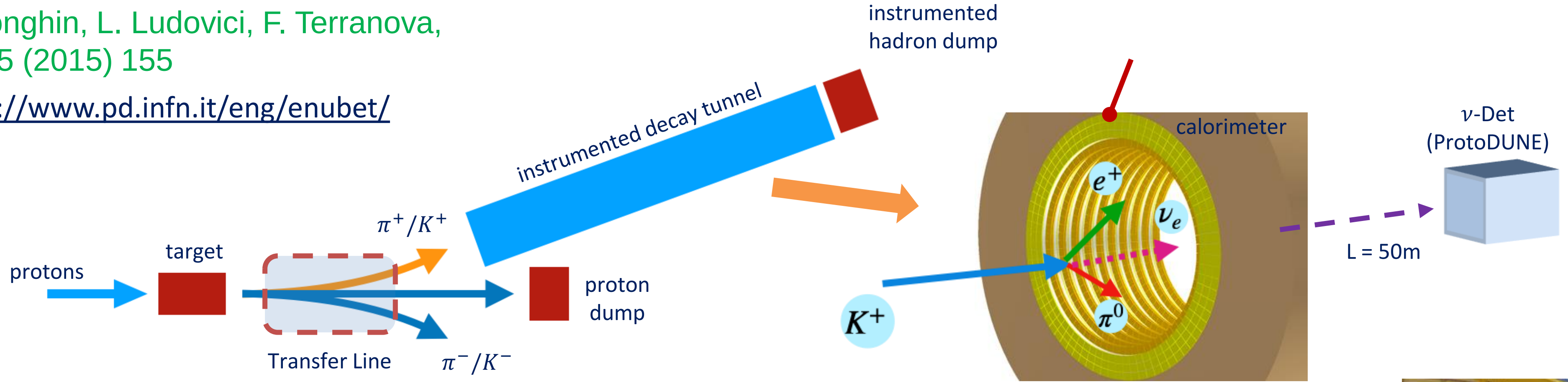


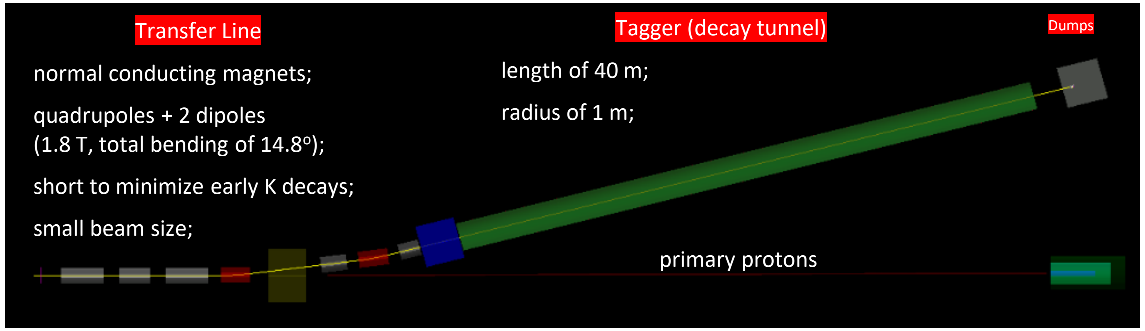


NP06/ENUBET: the first "monitored neutrino beam" (*)

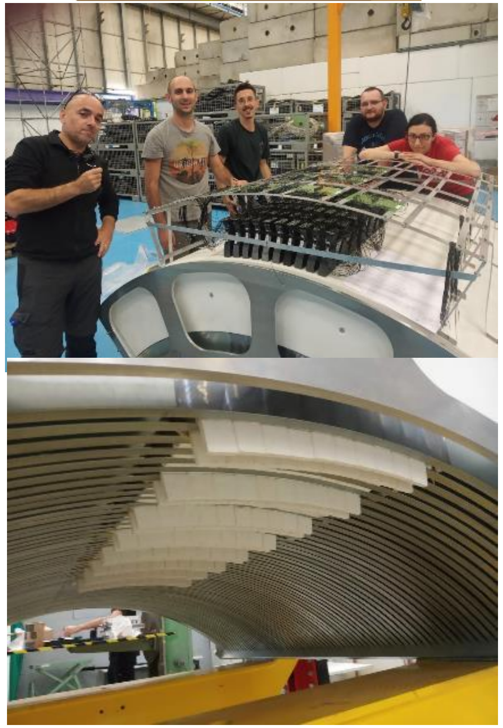
(*) A. Longhin, L. Ludovici, F. Terranova, EPJ C75 (2015) 155

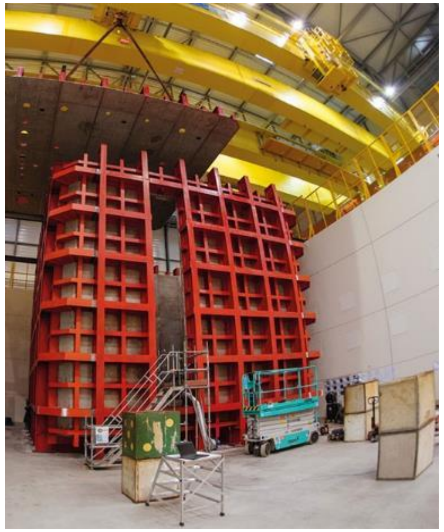
https://www.pd.infn.it/eng/enubet/





CERN SPS



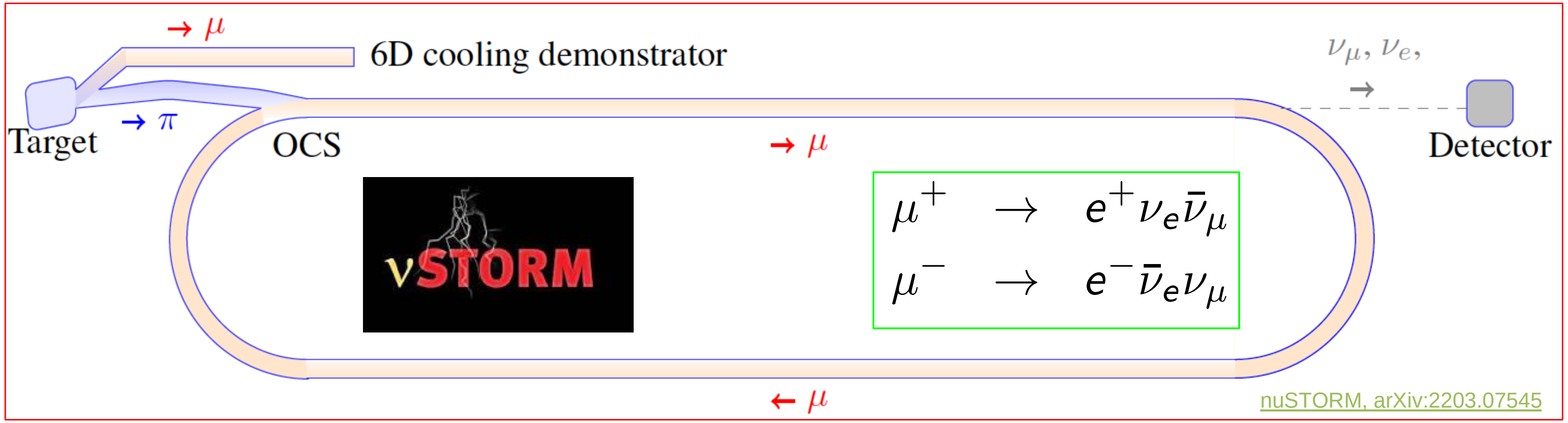


This successful R&D (2016-2024) gives – for the first time – the opportunity to have **a CERN neutrino beam** employing ProtoDUNE for ultimate precision (1%) cross section measurements in the region of interest for DUNE and HyperKamiokande.

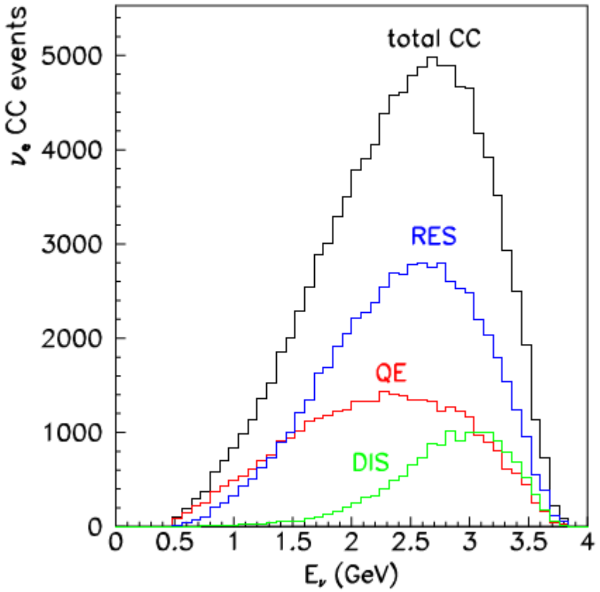
A glimpse to future

Goal	Timescale	Facility	Note
Measurement of all Yukawa parameters (save m_1)	present-2040	T2K, NoVA, DUNE, Hyper-Kamiokande	We will get them – at least with 5-10% precision. CP known with a 10^o precision
Sterile neutrinos at the eV scale	present-2035	SBN, DUNE, Hyper-Kamiokande	It is very likely that a full test of current anomalies will be carried out. If anomalies are confirmed, you can forget about my talk ☺
Unitarity tests and CKM-like precision	>2035	DUNE, HyperKamiokande, Neutrino Factory	We miss a key facility for CKM-like precision and unitarity tests: a powerful ν_e source for $\nu_e \rightarrow \nu_\tau$ oscillations. Technology advances toward a neutrino factory or muon collider may be a game changer
Measurement of standard neutrino interactions and cross sections	present-2035	DUNE and HyperK near detectors, ENUBET, nuSTORM	Room for substantial improvements with respect to current precisions (10-30%). Goal: 1%

The road toward a powerful ν_e source: short baseline

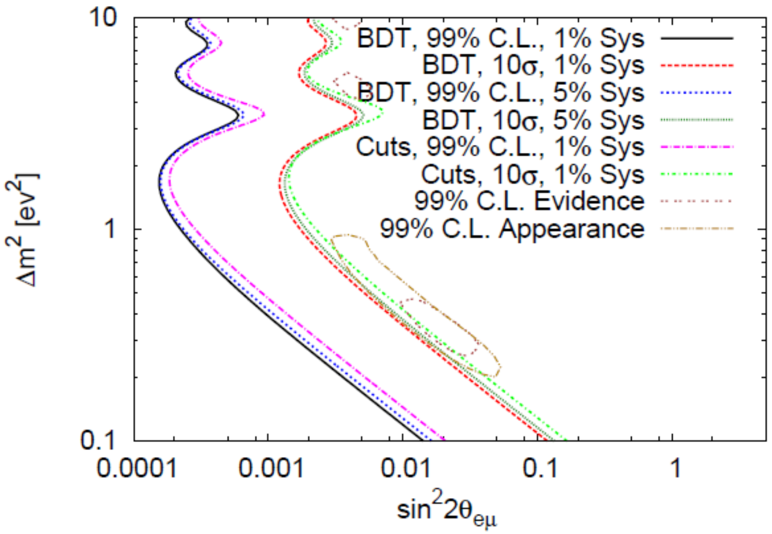


nuSTORM, arXiv:2203.07545

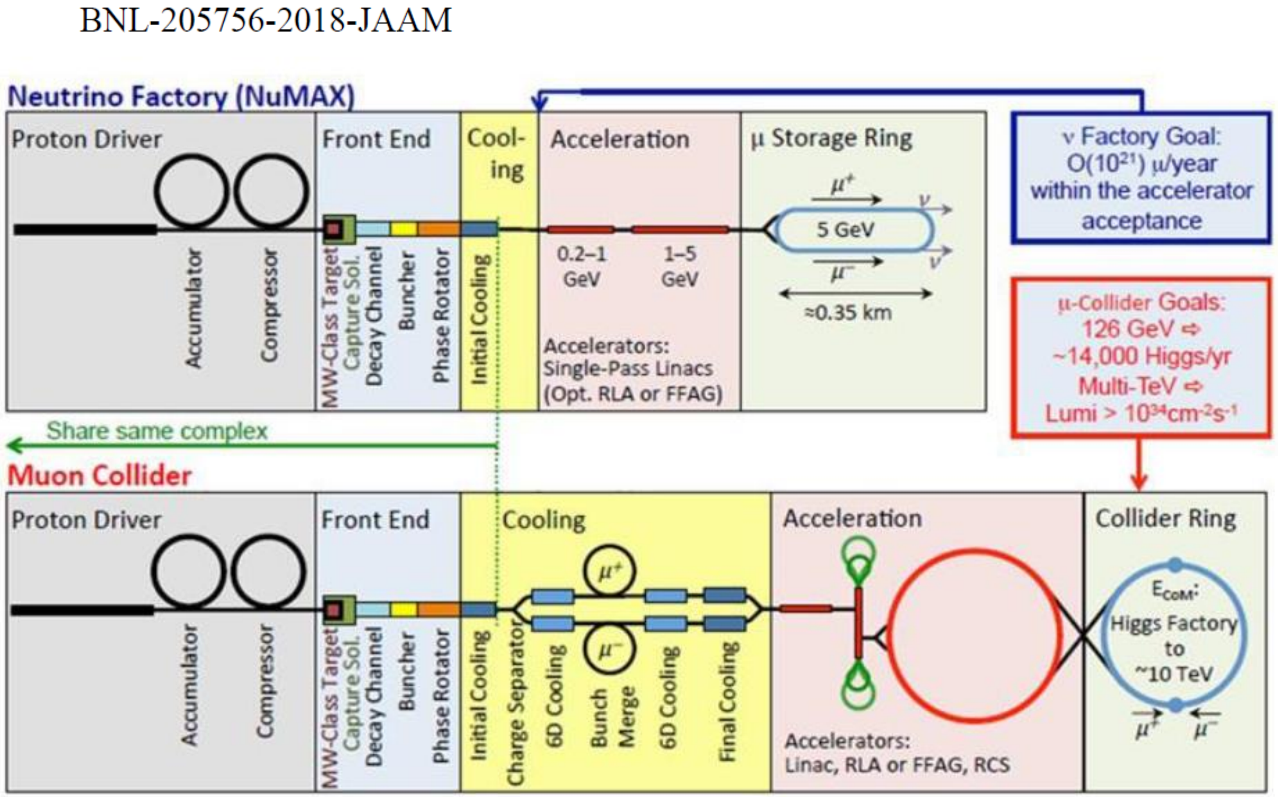


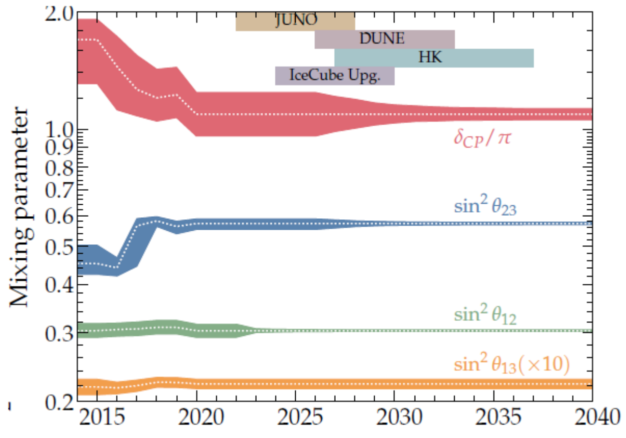
μ^+ Channel	N_{evts}	μ^- Channel	N_{ev}
$\bar{\nu}_\mu$ NC	844,793	$\bar{\nu}_e$ NC	709,57
ν_e NC	1,387,698	ν_μ NC	1,584,00
$\bar{\nu}_\mu$ CC	2,145,632	$\bar{\nu}_e$ CC	1,784,09
ν_e CC	3,960,421	ν_μ CC	4,626,48

arXiv:1308.6822v1

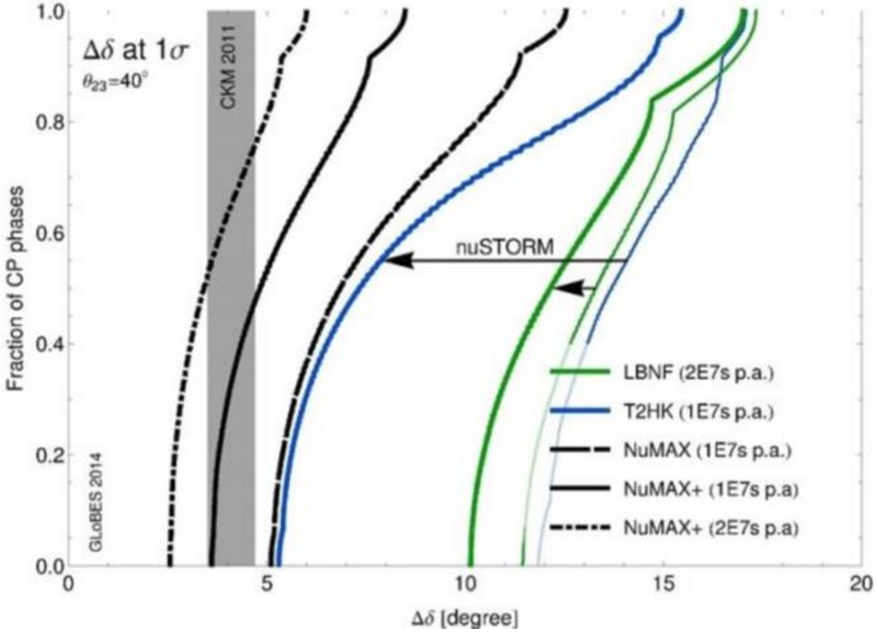


The road toward a powerful ν_e source: long baseline





N. Song et al., 2012.12893



Conclusions

- The “large θ_{13}” opportunity makes accelerator neutrino beams the ideal tool to study the lepton Yukawa sector of the Standard Model
- T2K and NOvA are doing a great job thanks to the large size of θ_{13}
- a new generation of large-exposure long-baseline experiments is needed to fully reap this opportunity
- Hyperkamiokande and DUNE offer unprecedented sensitivity to CP violation, full access to the unknown parameters of the neutrino sector, and a remarkable astrophysics programme
- It is fortunate to have both of them up and running in the forthcoming years: they are complementary both in beam and astroparticle physics
- These experiments benefited from the technology breakthroughs occurred at the CERN Neutrino Platform and CERN has played a pivotal role in the field.
- Technology advances offer a bright future for:
  - high precision cross section measurements (NP06/ENUBET)
  - a powerful ν_e source for short baseline experiments (NuSTORM)
  - precision physics and unitarity tests at a Neutrino Factory