HEP – CZ – Neutrinové experimenty* 2018

Jaroslav Zálešák, Fyzikální ústav AV ČR

17. prosinec, 2018

* In point of view of the European Particle Strategy

Future Opportunities in Accelarator* - based Neutrino Physics

European** Strategy for Particle Physics

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* NOT ONLY

** CERN

The European Strategy Discussions will take place in 2019/2020

- **deadline for written contributions (10 pages) 18 December 2018**
- **open Scientific Open Symposium in Granada, Spain, 13 to 16 May 2019,**
- **final writing (by strategy group) : Bad Honnef, Germany, 20 to 24 January 2020.**

to inform this process, a call was made to the particle-physics community across universities, laboratories and national institutes to submit written input by 18 December 2018.

"The Strategy process is about reviewing the state of particle physics by bringing together the whole community to discuss what Europe's long-term vision should be. It is about shaping the field for the next decade and beyond. We have to start discussing what we would like the landscape of particle physics research to look like in the post-LHC era," said the Chair of the European Strategy Group, Professor Halina Abramowicz.

It was proposed to organize a contribution by the European Neutrino community,
"TOWN" meeting 22-24 October 2018 at CERN

- open to the European neutrino community
- and others, especially if they carry out experiments at CERN.

European Neutrino "Town" meeting and ESPP 2019 discussion

22-24 October 2018
CERN
Europe/Zurich timezone

Search...

Contact

antonella.vignes-magno...

Dear colleagues,

The European Strategy Discussions will take place in 2019, and to inform this process, a call was made to the particle-physics community across universities, laboratories and national institutes to submit written input by 18 December 2018.

The aims of this meeting are as follows:

1. The first aim is to prepare a document expressing the views of the European community, in a context where there is no longer an accelerator neutrino beam in Europe and the community has invested in

131 participants

- 3 from Czech Rep: Rupert L., Vita V., Jaroslav Z.,

https://indico.cern.ch/event/740296/

Discussed Topics

1. **Panel Reports**
2. **From the Present Program to the Future**
   - Lessons from NOνA / T2K going into DUNE / T2HK
   - Complementarity of DUNE, T2HK, JUNO
   - Importance of ancillary measurements
3. **Role of CERN and the Neutrino Platform**
   - role when DUNE / T2HK are running
   - role beyond DUNE / T2HK
4. **Synergies & By-Products**
   - proton decay, supernova ν, neutrino interaction physics
   - technology development
5. **What comes after DUNE / HyperK?**
6. **Importance of Non-Accelerator Experiments**
   - $0\nu2\beta$ decay, direct ν mass measurements, SBL / sterile neutrino searches
   - beam dump experiments (SHiP, …), high-energy colliders
   - neutrino astronomy
7. **Summary Document from this Workshop**
   - first draft circulated in early November
   - final version to be submitted on December 18

Neutrino Town Meeting Summary Paper

Future Opportunities in Accelerator-based Neutrino Physics

The Participants of the European Neutrino Town Meeting
22–24 October, 2018
CERN, 1 Esplanade des Particules, 1211 Geneva 23, Switzerland

Editors: Alain Blondel[a], Joachim Kopp[b], Albert de Roeck[c]
(full author list in the appendix)

(Dated: December 2018)

This document summarizes the conclusions of the Neutrino Town Meeting held at CERN in October 2018 to review the neutrino field at large with the aim of defining a strategy for accelerator-based neutrino physics in Europe. The importance of the field across its many complementary components is stressed. Recommendations are presented regarding the accelerator based neutrino physics, pertinent to the European Strategy for Particle Physics. We address in particular i) the role of CERN and its neutrino platform, ii) the importance of ancillary neutrino cross-section experiments, and iii) the capability of fixed target experiments as well as present and future high energy colliders to search for the possible manifestations of neutrino mass generation mechanisms.

Panel 1: Standard active oscillation, 3-flavor oscillations

Status as of 2018

- Oscillations demonstrate neutrinos have mass ⟶ most direct evidence beyond SM.
- Aim to measure solar, atmospheric and reactor neutrino mixing angles with uncertainties down to 0.7%, 3%, 3% of $\sin^2\theta$ and CP phase uncertainty of 10 deg at 270 deg.
- Mass sq. differences Δm^2_{21} and Δm^2_{31} known at 3% and 1%, first is positive, sign Δm^2_{31} is unknown ⟶ "neutrino mass ordering", T2K & **NOvA** weakly prefer NO.
- Observing CP violation in the lepton sector (appearance experiments T2K and **NOvA**) would be of paramount interest as it may be related to the matter-antimatter asymmetry.
- First glimpses from anti-/neutrino appearance preference $-\pi/2$. excl. conserving values.

Next 5-10 years

- T2K and **NOvA** will collect more data in both anti/neutrino modes., In case of $\delta_{cp} = -\pi/2$ will exclude CP conservation > 3σ, mass ordering at 4σ and octant of theta 23 (1.7deg)
- **JUNO** will measure Δm^2_{21} and $\sin^2\theta_{12}$ with 0.6% and 0.7% precision and it is sensitive to mass ordering - 3σ significance on the sign of Δm^2_{31}.
- Atmospheric neutrino data sensitive to matter effects too – telescope ORCA and PINGU

Future Neutrino beams: DUNE and Hyper-Kamiokande

- Next generation long-baseline exp. **DUNE** and HyperK(T2HK) will study oscillation muon to electron (anti-)neutrinos for search CP violation, precise parameters measurement, new physics and non-accelerator neutrinos.
- With the **DUNE**, HyperK, and also **JUNO** collaborations becoming comparable in size to collider experiments, neutrino physics has taken center stage in the US and Asia.
- **DUNE** based on LarTPC technology with 1300km away detectors with 1.2/2.4 MW beam
- HyperK – 186 kton off-axis water Cherenkov detector 295 km away of 1.3M beam acc.
- Experiments will start operation 2026 and 2027 promise more 5σ (3σ) CP violation sensitivity for ~50% (75%) of possible δcp values after 10 years of operation.
- Even outside Europe, European scientists make up 35% of DUNE and 48% of HK

Importance of Controlling Systematic Uncertainties

Complementarity between experiments

- There are synergies and unique strengths in the future neutrino experiments.
- **JUNO** is only offering very measurements 'solar' parameters which in combination with T2K and **NOvA** (and ORCA) could lead to determine 'mass hierarchy' before DUNE/HK
- Complementarity between **DUNE** and HyperK more evident for tests of new physics

Beyond DUNE and HyperK, Second Oscillation Maximum

- T2HKK: Second detector of same size in Korea in the Hyper-K beam
- ESSνSB: 5MW beam from ESS to a large water Cerenkov detector over a 500 km baseline.
- P2O – Protvino beam to ORCA, much increased detector mass.

Panel 2: Beyond the standard 3-flavor framework

Light Sterile Neutrinos

- Light sterile neutrinos with masses < 100 eV could participate in neutrino oscillations.
- A number of > 3 sigma anomalies observed in short-baseline oscillation experiments – LSND and MiniBooNE – excess elmag. showers in muon neutrino beam, antineutrino flux deficit observed in the reactors experiments.
- Even some disfavored, a comprehensive global program is under way to study the dependence of the anomalies on distance and energy.
- Fermilab short-baseline program at the Booster beam uses liquid argon detectors, MicroBooNE (running), ICARUS-T600 (in operation 2019), and SBND (start in 2020)

Heavy Right-Handed Neutrinos at Fixed Target Experiments

- Sterile (or "right-handed") neutrinos are a very common prediction of neutrino mass (seesaw) models, but their masses can lie in a very broad range from eV to > 10^{10} GeV
- The SHiP collaboration proposes to exploit the high energy SPS beam impinging on a beam dump, with a detector of total length of about 50 m, much of it being a decay volume for long lived neutral particles.

Opportunities at Colliders

- High luminosity colliders (such as LHC, FCC) are sources of neutrinos via decays of heavy flavor particles and of W and Z bosons, with W and Z decays covering a larger mass rang

Panel 3: Neutrinos and the Universe

❑ Capacities at Future Neutrino Facilities

- Large-scale neutrino detectors **DUNE** and HyperK (and **JUNO** for reactors) are multi-purpose observatories.
- Evident potential when also considering non-accelerator-based data samples, or combining.
- Ability to determine the mass ordering with atmospheric neutrinos and to test 3 family oscillation paradigm.
- Galactic supernova explosion - SuperK, **JUNO**, **DUNE**, and HyperK are expected to record thousands of neutrino interactions within a few seconds. Unprecedented insights into supernova explosion and the formation of the heavy elements necessary for life.
- Sensitivity to nucleon decay - hallmark signature of Grand Unifed Theories (GUTs) Complementarity: HyperK dominates the sensitivity (up to 10^{35} y) to $p \rightarrow e^{+}\pi^{0}$ and **JUNO**, **DUNE** offers sensitivity to $p \rightarrow K^{+}\nu$ (op to 10^{35} years lifetime)

❑ Relevance of Non-Accelerator Probes

- Neutrinoless double beta decay - experiments pushing the frontiers of low-background physics, can discover fermion number violation due to the presence of a neutrino Majorana mass term, a prerequisite for explanations of the baryon asymmetry of the Universe and for the seesaw mechanism, leading explanation for the smallness of neutrino masses.
- European exp: GERDA (focusing on germanium), CUORE (tellurium) and NEXT (xenon)
- Absolute neutrino mass scale: direct KATRIN (tritium), ECHO and Holmes (holmium)

Panel 4: Ancillary measurements

- **Ancillary - any support activity to the main measurements.**
  - Main task is to reduce systematic errors
- **Hadroproduction experiments and Beam characterization**
  - Long-baseline oscillation experiments consist near detectors, to ensure the normalization of event rates between the near and far location. A proper extrapolation requires a good understanding of the phase space distribution of beam neutrinos, thus hadrons in targets
  - CERN NA61/SHINE provides data for measuring a replica of T2K and **NuMI.**
  - NUPRISM - to cover a variety of off-axis beam angles from 1-4 degrees.
- **Cross-section Experiments**
  - Important function of near detector systems will be the measurement of neutrino cross-sections and neutrino energy response functions for all relevant species.
  - Theoretically modelling neutrino cross-sections on nuclear targets in the 0.2 GeV to 3 GeV energy region is a formidable challenge.
  - ENUBET – direct flux measurement, narrow band beam with well defined energy
  - NuSTORM – Neutrinos from stored muons. offers similar and very well known fluxes. Muon capture and storage techniques could contribute to the R&D towards a Muon Collider or the Neutrino Factory proposals.

Panel (5): CERN role & Neutrino Platform

❑ CERN Neutrino Platform

- Response to the recommendations of the 2013 European Strategy Group Report, the Neutrino Platform was established at CERN in 2014, followed the decision that CERN would not develop an accelerator based neutrino program.
- Essential contributions to the R&D of future experiments in the short and medium term.
- Provides the community with a test beam infrastructure.
- CERN reinstated its Neutrino experimental group with mandate participating off-site.

❑ Single and Dual Phase ProtoDUNE

- LArTPC (time projection chambers) technology as the solution adopted in both short and long baseline experiments in the US.
- Two large (700 ton) LArTPC prototypes for the DUNE far detector have been constructed and completed in 2018
- **Single Phase** porotype record millions of charged particle interactions in fall 2018.
- New project studies new technologies proposed for near detectors for T2K and **DUNE**.
- Strong interest expressed from the broader neutrino community to collaborate with CERN for non-accelerator neutrino projects (neutrino mass, WIMP dark matter, $0\nu2\beta$ decay)

❑ Theory group support

- Essential for the success of the future accelerator-based neutrino program.

Recommendations

A. Neutrino physics is one of the most promising areas where to find answers to some of the big questions of modern physics; it covers many disciplines of physics complementing each other. Some coordination needed.

B. Neutrinos at accelerators, pertinent to ESPP, are an important component:
   1. search for CP violation, and the full determination of the oscillation parameters;
   2. possibility to discover heavy neutrinos or other manifestations of the mechanism for neutrino mass generation.

   Consequently Europe (and CERN in particular) should provide a balanced support in the world-wide LBL effort, with its two complementary experiments DUNE and T2K/HyperKamiokande (and its possible extension with a detector in Korea), in both of which strong EU communities are involved, to secure the determination of oscillation parameters, aim at the discovery of CP violation and test the validity of the 3-family oscillation framework; these experiments also have an outstanding and complementary non-accelerator physics program.

Recommendations

C. Extracting the most physics out of DUNE and HyperK will require ancillary experiments:

1. CERN should continue improving NA61/SHINE towards percent level flux determinations;
2. a study should be set-up to evaluate the possible implementation, performance and impact of a percent-level electron and muon neutrino cross-section measurement facility (based on e.g. ENUBET or NuSTORM) with conclusion in a few years;
3. a strong theory effort should accompany these experimental endeavors.

Recommendations

D. If, for instance, the CP phase is close to $\pm \pi/2$ or of $\sin \delta cp = 0$, improved precision w.r.t. DUNE and HyperK should be considered. Studies of feasibility and performance of and ESSnuSB and Protvino to Orca (P2O) should be pursued to quantify their feasibility, realistic potential and complementarity with the present program.

E. Fixed target and collider experiments have significant discovery potential for heavy neutrinos and the other manifestations of the neutrino mass generation mechanisms, especially in Z and W decays. The capability to probe massive neutrino mechanisms for generating the matter antimatter asymmetry in the Universe should be a central consideration in the selection and design of future colliders.

Role for Europe

- The next generation of large neutrino experiments are hosted in Asia and the U.S.
- The European physics community is involved in all three of them at a significant level.
- CERN made a significant investment into the protoDUNEs via the Neutrino Platform.
- There is number of ideas to address the systematics challenge (ESSνSB, Enubet, nuSTORM, etc.) which all could be hosted in Europe and span a range of scales in terms of cost and effort.

Role for the Czech Republic

- **Czech HEP community in the point of view of the European Strategy for Particle Physics should support DUNE, JUNO a HyperKamiokande experiments.**

- **Currently involved in DUNE and JUNO collaborations.**

BACK UP

Goals of the meeting

The aims are as follows:

1. The first aim is to prepare a document expressing the views of the European community, in a context where there is no longer an accelerator neutrino beam in Europe and the community has invested in projects in China, Japan and the USA.

2013 Strategy:

f) Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. *CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading long-baseline neutrino projects in the US and Japan.*

2. The document should take stock of the properties of the "present" LBL program (T2K+SK+NOvA, JUNO, T2K upgrade, HyperK and DUNE) in physics terms, identifying and quantifying who measures what and how well, and what is the **complementarity in quantitative and qualitative terms** and under which time scale.

3. It should also **address** the status and possible future of the **short baseline neutrino experiments in search for 'sterile neutrinos' and 'anomalies'.**

4. Address possible contributions or support of CERN to this program and discuss the best possible investment based the above physics considerations.

5. address the question of the future of the field

-- with neutrinos beams to complete the present LBL program

-- includes HP-TPC, nustorm, moment, P2O and R&D on supplementary detector methods

-- searches for 'sterile/Right-handed neutrinos' with the existing or foreseen neutrino near detectors as well as with beam dump experiments such as SHIP, and at high energy (LHC, Future Colliders)

-- neutrinoless double beta decay experiments

‘Hot’ events:

-- 10 minute ‘hot news’ Monday 17:50
on activities of CERN’s neutrino platform
(we must walk to CERN main building before 19:00)

-- 10 minute ‘hot news’ on Tuesday 12:30
Hiroaki Aihara: 2020 start of construction of Hyperl

Panel 1. Standard active oscillations

Patrick Huber (chair), [***pahuber@vt.edu***](mailto:pahuber@vt.edu)
Serguei Petcov [***petcov@sissa.it***](mailto:petcov@sissa.it)
Ryan Patterson [***rbpatter@caltech.edu***](mailto:rbpatter@caltech.edu)
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The panel should take stock of the properties of the "present" LBL program (T2K+SK+NOvA, JUNO, T2K upgrade, HyperK and DUNE, atmospheric experiments). Questions to address are for instance:

- What are the relevant physics questions to be addressed by the LBL program?
- In physics terms, identifying and quantify who measures what and how well?
- What is the complementarity in quantitative and qualitative terms and under which time scale?
- What risks are involved (technological and physics-related)?
- What is needed from the theory community? What can we learn with increasing precision on the measurements?
- What would be a continuation of that program in the long term what are big issues that could require a parallel experimental program. (Complementarity and possible synergies)

Panel 2. Beyond PMNS (Majorana and/or Dirac mass term, Heavy Neutral lepton searches from meV to ZeV, NSI, etc…)

Oliver Fischer and Stefan Schoenert(Chairs) *oliver.fischer@kit.edu* , *schoenert@ph.tum.de*
Antonin Vacheret *antonin.vacheret@imperial.ac.uk*
Jacobo Lopez Pavaon *jacobo.lopez.pavon@cern.ch*
Cristiano Galbati *galbiati@Princeton.EDU*
Maura Pavan *Maura.Pavan@mib.infn.it*

Questions to address are for instance:

- Which extensions of the SM can we probe (Majorana masses, light and heavy sterile neutrinos, neutrinos as dark matter)
- What are the relevant experiments (0nu2beta, SBL oscillations, SHiP and other fixed-target experiments, LHC and future colliders)
- What is needed from the theory community?
- What risks are involved (technological and physics-related)?
  How do you see this field develop?

Panel 3. Neutrinos and the Universe (Nν, mν, BAU, etc..)

Mikhail Shaposhnikov (chair) [*Mikhail.Shaposhnikov@epfl.ch*](mailto:Mikhail.Shaposhnikov@epfl.ch)
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Susanne Mertens [*mertens@mpp.mpg.de*](mailto:mertens@mpp.mpg.de)
Marek Kowalski [*marek.kowalski@desy.de*](mailto:marek.kowalski@desy.de)

Questions to address are for instance:

- What are the relevant questions (neutrino masses, number of neutrino species, leptogenesis/baryogenesis, origin of UHE neutrinos, ...)
- What are the relevant experiments, measurements, and observations now and in the future (CMB, BBN, Neutrino Telescopes, KATRIN, Project 8, ...)
- What is needed from the theory community?
- What is the complementarity between different approaches?
- What risks are involved (technological and physics-related)?

First draft was delivered – minor comments and suggestions

Panel 4. Ancillary measurements (cross-sections, Nustorm, NA61, etc.)

Federico Sanchez (chair) Federico.SanchezNieto@unige.ch
Boris Popov popovb@mail.cern.ch
Morgan Wascko m.wascko@imperial.ac.uk
Natalie Jachowicz Natalie.Jachowicz@UGent.be
Francesco Terranova francesco.terranova@cern.ch

Questions to address are for instance:

- What are the requirements and opportunities raised by the LBL, SBL, and other neutrino programs neutrino fluxes and neutrino cross sections, energy response function and calibration, for ($\nu e/\nu\mu/\nu\tau$)? …
- What is their relevance to other neutrino experiments (e.g. LBL)?
- What are the relevant experiments (NA61 and other hadroproduction, near detectors, NUPRISM, HPTPC, NuSTORM, …)?
- What is needed from the theory community?
- What is the complementarity between different approaches?
- What risks are involved (technological and physics-related)?

Zkoumání Reaktorových Antineutrin na MFF UK

2016 version

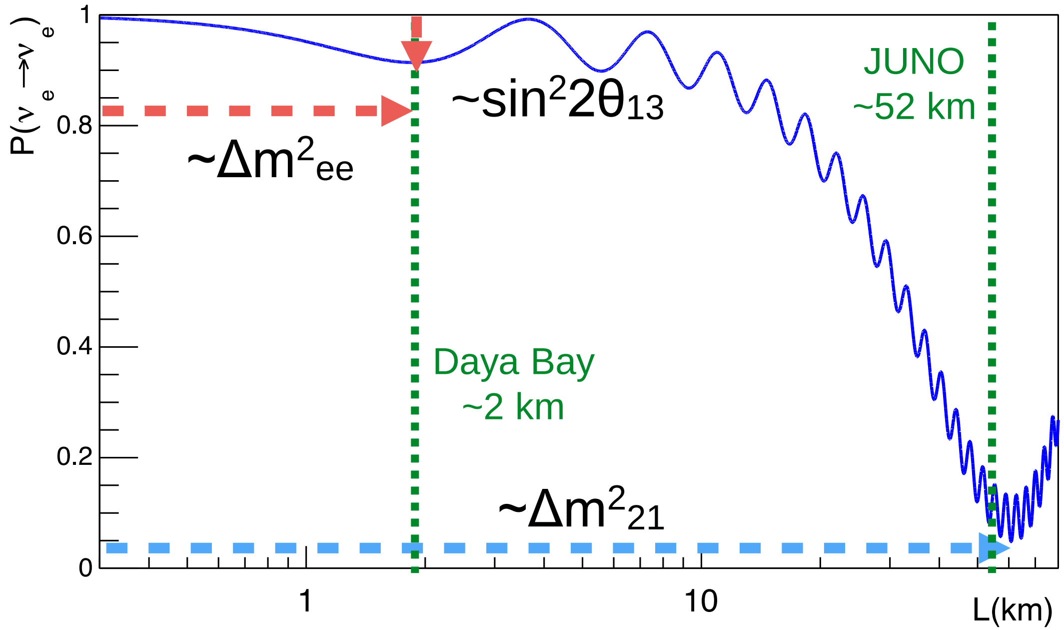
Experimenty a Členové Týmu

- Experiment Daya Bay
  - Rupert Leitner
  - Viktor Pěč
  - Bedřich Roskovec
  - Vít Vorobel
- Experiment JUNO
  - Rupert Leitner
  - Tadeáš Dohnal
  - Martin Dvořák
  - Viktor Pěč
  - Bedřich Roskovec
  - Ondřej Šrámek*
  - Vít Vorobel

* Katedra geofyziky, ostatní Ústav částicové a jaderné fyziky

Měření Oscilací Reaktorových Antineutrin

- Oscilace:



Oscilace na střední vzdálenosti - JUNO

$$P(\bar{\nu}_e \to \bar{\nu}_e) = 1 - \sin^2 2\theta_{12} \cos^4 \theta_{13} \sin^2\left(\frac{\Delta m^2_{21} L}{4E}\right) - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{ee} L}{4E}\right)$$

Oscilace na krátké vzdálenosti - Daya Bay

- Detekce:

promptní signál zpožděný signál

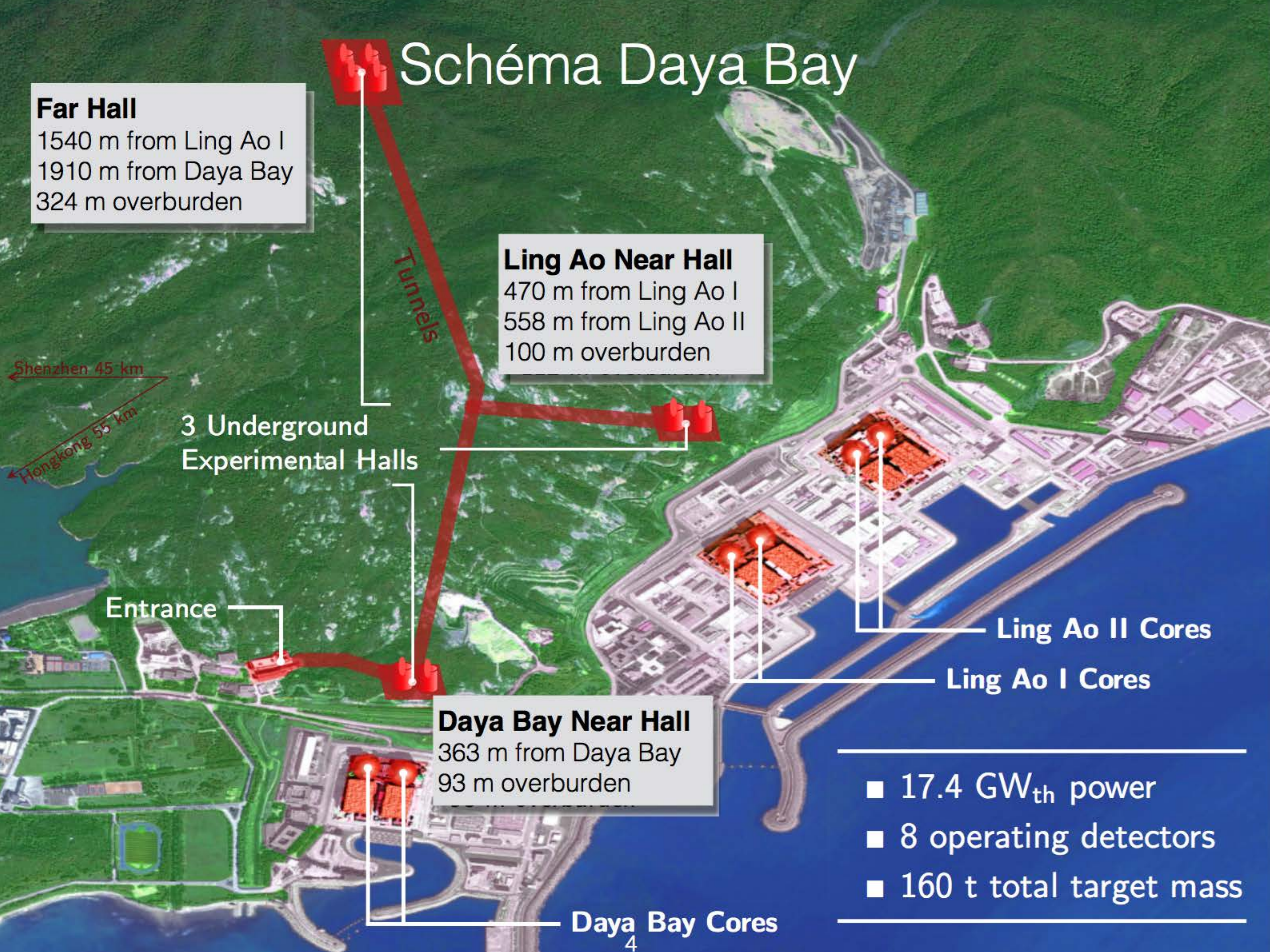
Inverzní beta rozpad:

$$\bar{\nu}_e + p \to e^+ + n$$

$$30\ \mu s \rightsquigarrow n + Gd \to Gd^* \to Gd + \gamma s\ (8\ \text{MeV})$$

$$200\ \mu s \rightsquigarrow n + H \to D + \gamma\ (2.22\ \text{MeV})$$

Schéma Daya Bay



- 17.4 GW_{th} power
- 8 operating detectors
- 160 t total target mass

Přesné Měření Oscilačních Parametrů

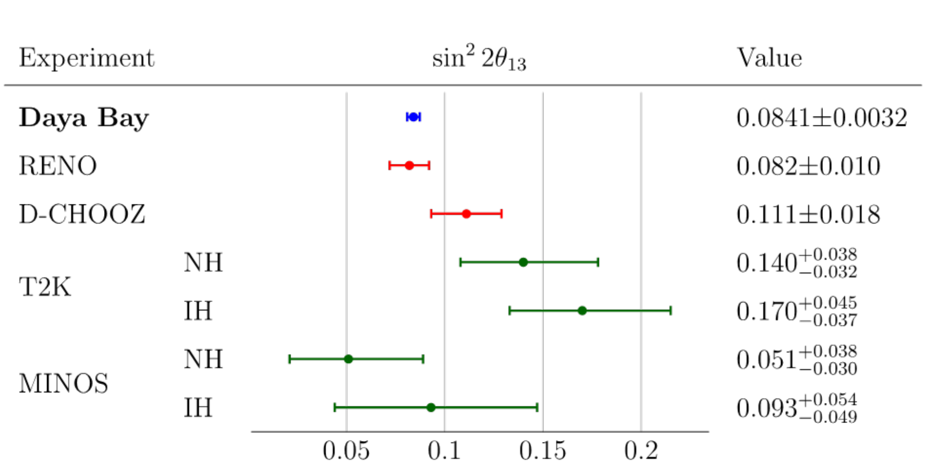
- Měření parametrů θ_{13} a Δm^2_{ee} pomocí záchytu na gadaoliniu (1230 dní dat)

$$\sin^2 2\theta_{13} = 0.0841 \pm 0.0027(\text{stat.}) \pm 0.0019(\text{syst.})$$

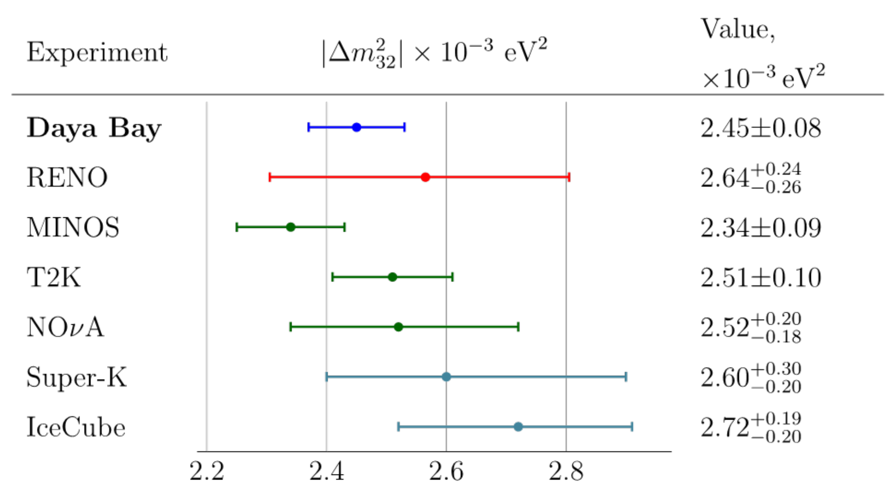
$$|\Delta m^2_{ee}| = (2.50 \pm 0.06(\text{stat.}) \pm 0.06(\text{syst.})) \times 10^{-3}\ \text{eV}^2$$

arXiv:1610.04802v1

Nejpřesnější měření úhlu θ_{13}



Nejpřesnější měření $|\Delta m^2_{32}|$ (NH)

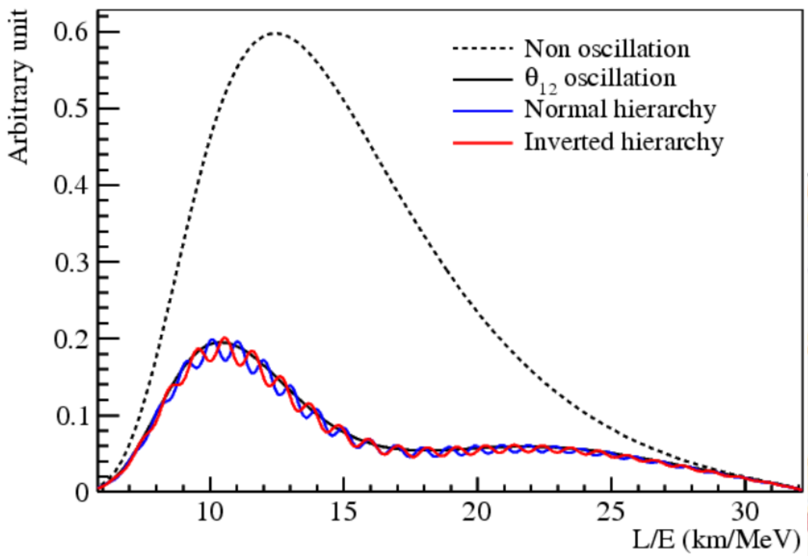


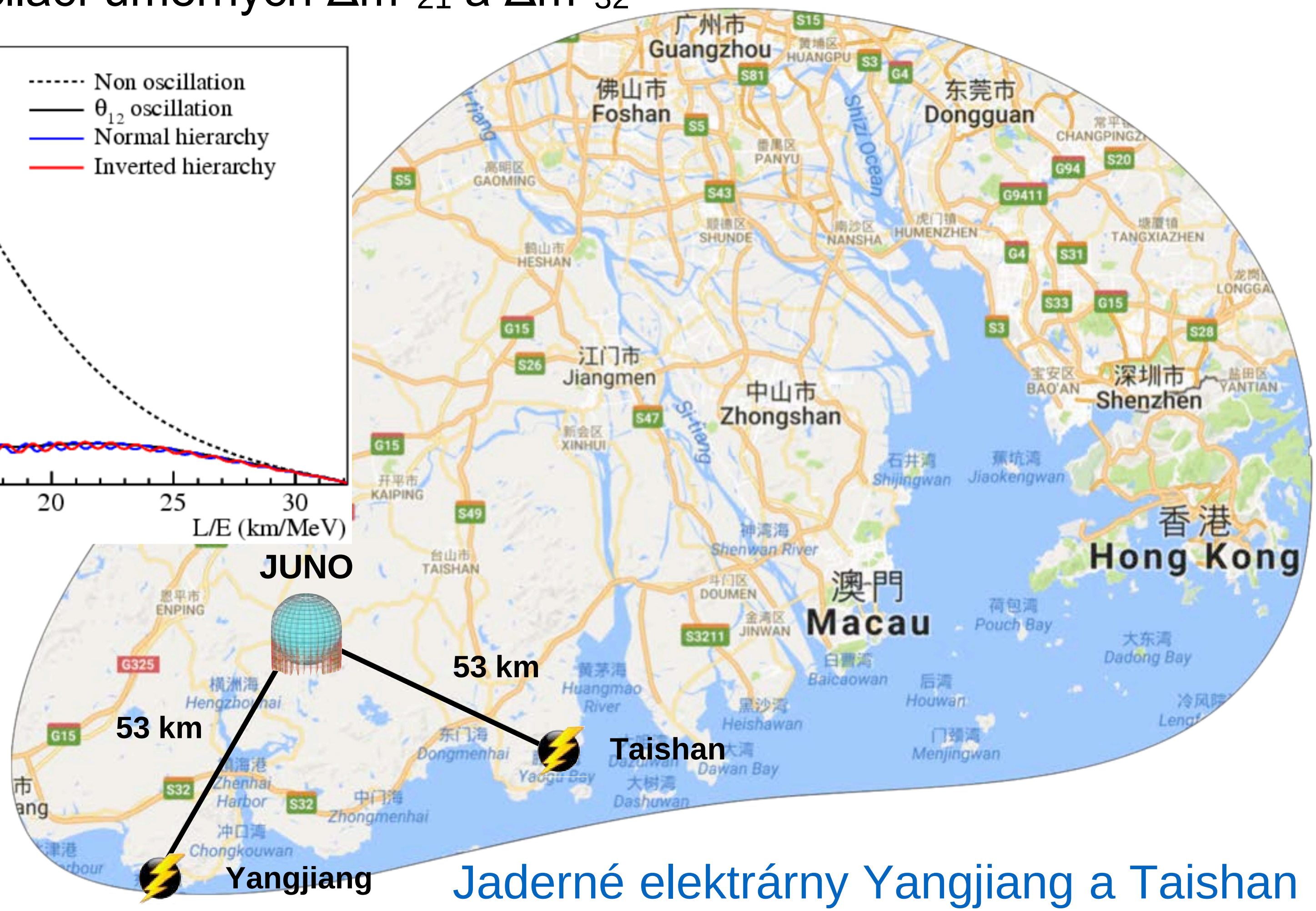
Experiment Daya Bay bude měřit do roku 2020 nadále i s českou účastí

Experiment JUNO - Základní Informace

Měření oscilací ve vzádlenosti 53 km

Pozorování oscilací úměrných Δm^2_{21} a Δm^2_{32}





Jaderné elektrárny Yangjiang a Taishan

Plánovaný výkon 35.73 GW_{th}

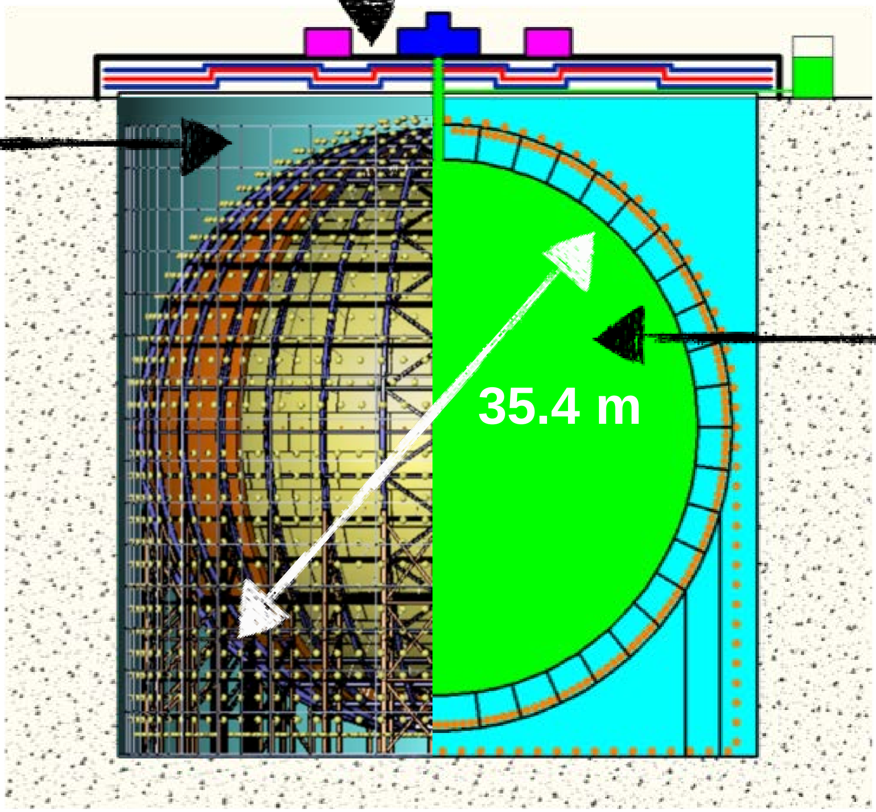
(26.55 GW_{th} v 2020)

Experiment JUNO - Detektor

Top Tracker
3 vrstvy plastického scintilátoru
z experimentu OPERA

Centrální detektor
20 kt tekutého scintilátoru
~17000 20” PMT
~25000 3” PMT
Rozlišení <3%/√E(MeV)

Vodní bazén
Čerekovský detektor mionů
~2000 20” PMT



Experiment JUNO – Fyzika

- První experiment měřící zároveň oscilace úměrné Δm^2_{21} a Δm^2_{32}!
- Primární cíl - Určení hierarchie s významností >3σ (6 roků dat)
- Zpřesnění oscilačních parametrů (6 roků dat)

Parameter	Current rel. uncertainty	Improved uncertainty by JUNO
$\sin^2\theta_{12}$	4.1%	0.67%
Δm^2_{21}	2.6%	0.59%
Δm^2_{ee}	3.2%	0.44%

- Komplexní detektor -> Bohatý fyzikální program
  - Geoneutrina - nejvyšší statistika geoneutrin s pouhým rokem dat
  - Neutrina ze supernov

- **Začátek sběru dat v roce 2020**
- **Zástupci MFF před podepsáním Memorandum of Understanding**

NOvA a DUNE

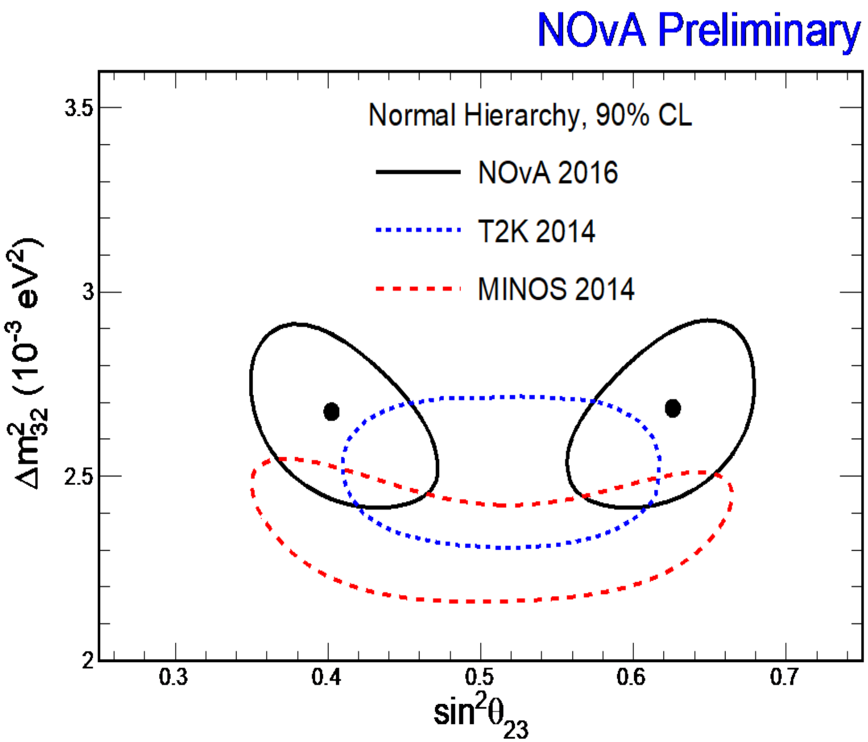
2016 version

NuMI Off-axis electron neutrino [ν_e] Appearance

NOvA experiment

The NOvA experiment is a long-baseline neutrino experiment designed to make measurements to determine the neutrino mass hierarchy, neutrino mixing parameters and CP violation in the neutrino sector. The NOvA collaboration has designed and built a highly distributed, synchronized, continuous digitization and readout system that is able to acquire and correlate data from the Fermilab accelerator complex (NuMI), the NOvA near detector at the Fermilab site and the NOvA far detector which is located 810 km away at Ash River, MN..

Muon Neutrino FD Data



- 78 events observed in FD
  - 473±30 with no oscillation
  - 82 at best oscillation fit
  - 3.7 beam BG + 2.9 cosmic

Maximal mixing excluded at 2.5σ

Best Fit (in NH):

$$|\Delta m^2_{32}| = 2.67 \pm 0.12 \times 10^{-3}\mathrm{eV}^2$$
$$\sin^2\theta_{23} = 0.40^{+0.03}_{-0.02}(0.63^{+0.02}_{-0.03})$$

Electron Neutrino FD Data

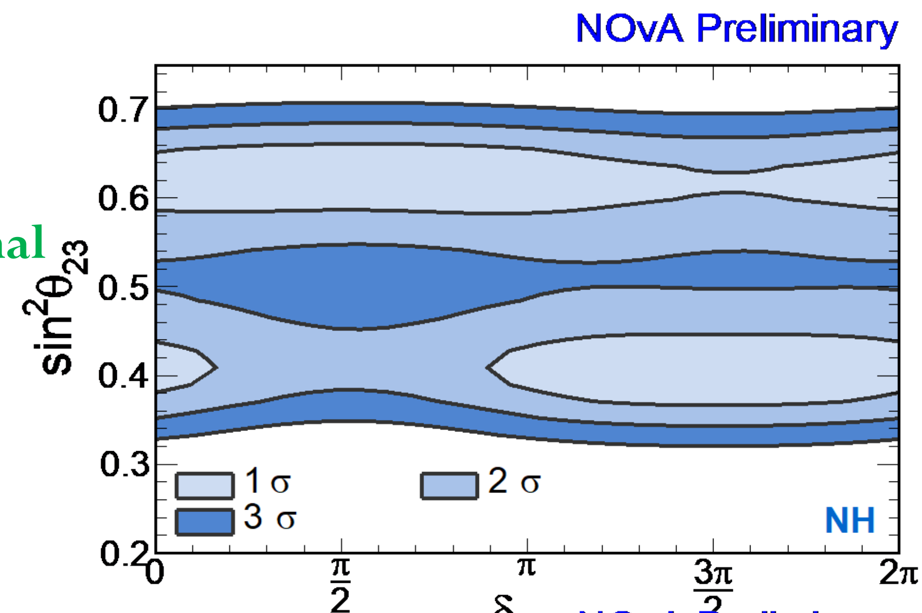
- Observe 33 events in FD
  - background 8.2±0.8

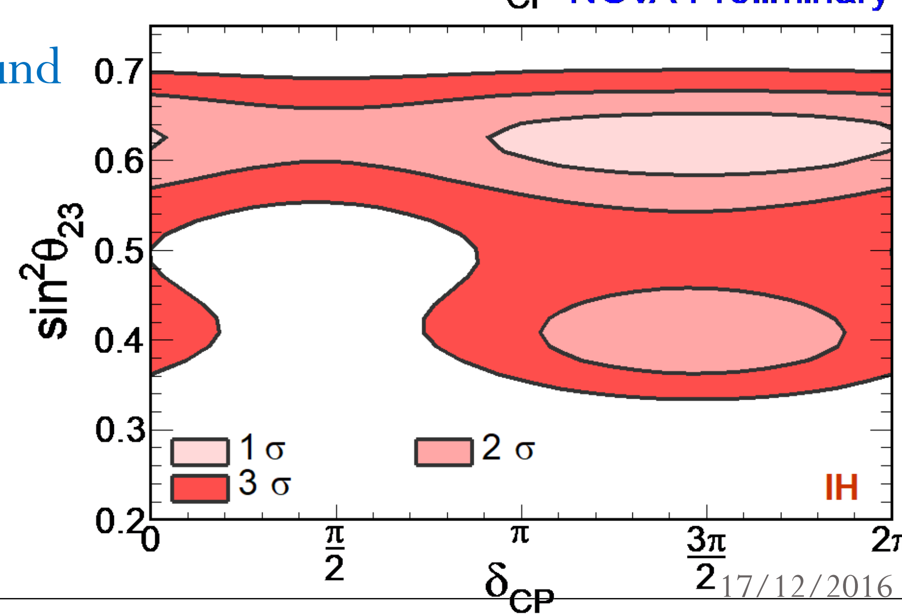
>8σ electron neutrino appearance signal

- Global best fit Normal Hierarchy

$$\delta_{CP} = 1.49\pi$$
$$\sin^2(\theta_{23}) = 0.40$$

- 3σ exclusion in IH, lower octant around $\boldsymbol{\delta}_{\mathrm{CP}}=\pi/2$





Antineutrino data will help resolve degeneracies, particularly for non-maximal mixing

Planned for Spring 2017

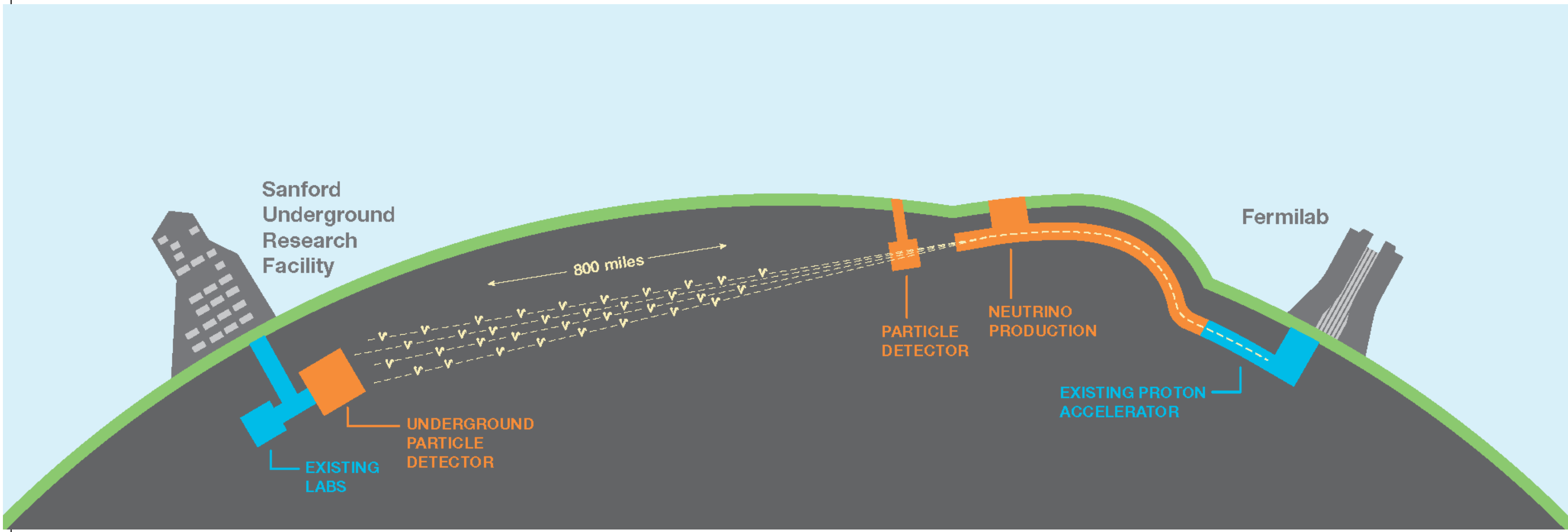
Summary

With 6.05×10^{20} POT, NOvA finds:

- Muon neutrinos disappear
  - Best fit is non-maximal
  - Maximal mixing excluded at 2.5σ
- Neutral current event rate shows no evidence of steriles
- Electron neutrinos appear
  - Data prefers NH at low significance
  - Region in IH, lower octant around $\delta_{CP}=\pi/2$ is excluded
- Looking forward to more neutrinos and antineutrino running planned, Spring 2017

- **Next 2 years (FY17+18) – 9e20 neutrino in total + 9e20 antineutrino.**
- **Experiment NOvA will take data through FY2024 (27+27 e20 POTs)**
- **1+ MW beyond yaer 2024?**

DUNE



The Deep Underground Neutrino Experiment will be:

- a 40 kton fiducial liquid argon neutrino detector…
- located 1.5 km underground…
- 1300 km from Fermilab, which will host a 1.2 MW at 120 GeV neutrino beam…
- and a highly-capable near detector.

DUNE Experimental Scope

Physics Goals Driving Design

- Make precise measurements of neutrino oscillations, including determining the mass hierarchy and the potential discovery of leptonic *CP* violation.

Requires…
- Large detector mass
- Long baseline
- Good energy resolution
- Efficient electron neutrino identification

…liquid argon

- Search for nucleon decay.

Requires…
- Low cosmic ray backgrounds

…deep underground

- Timing for non-beam events

…photon detection

- Measure the spectrum and flavor composition of a supernova burst in our galaxy.

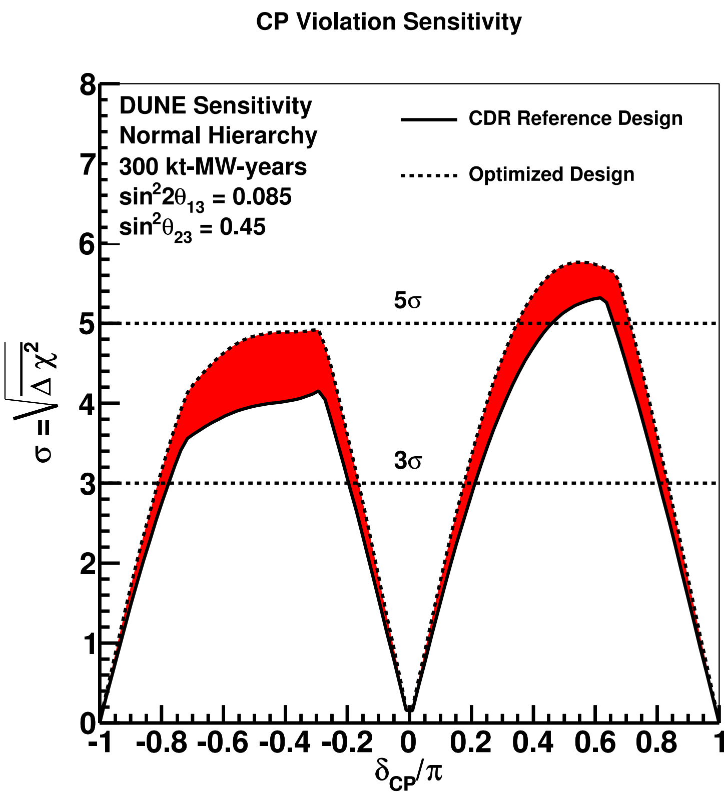
Requires…
- Several MeV energy threshold

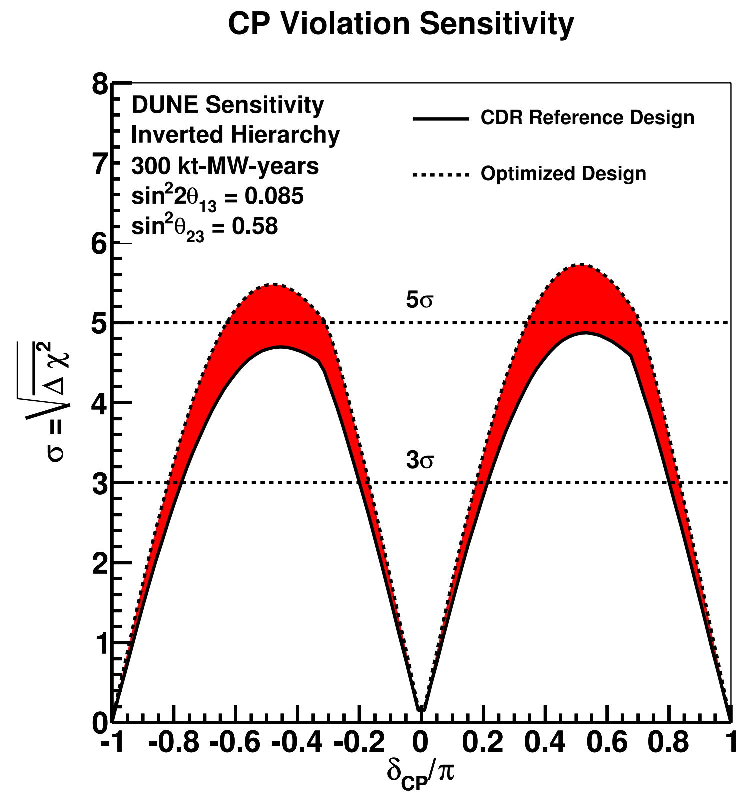
…good signal/noise

DUNE Physics Landscape:

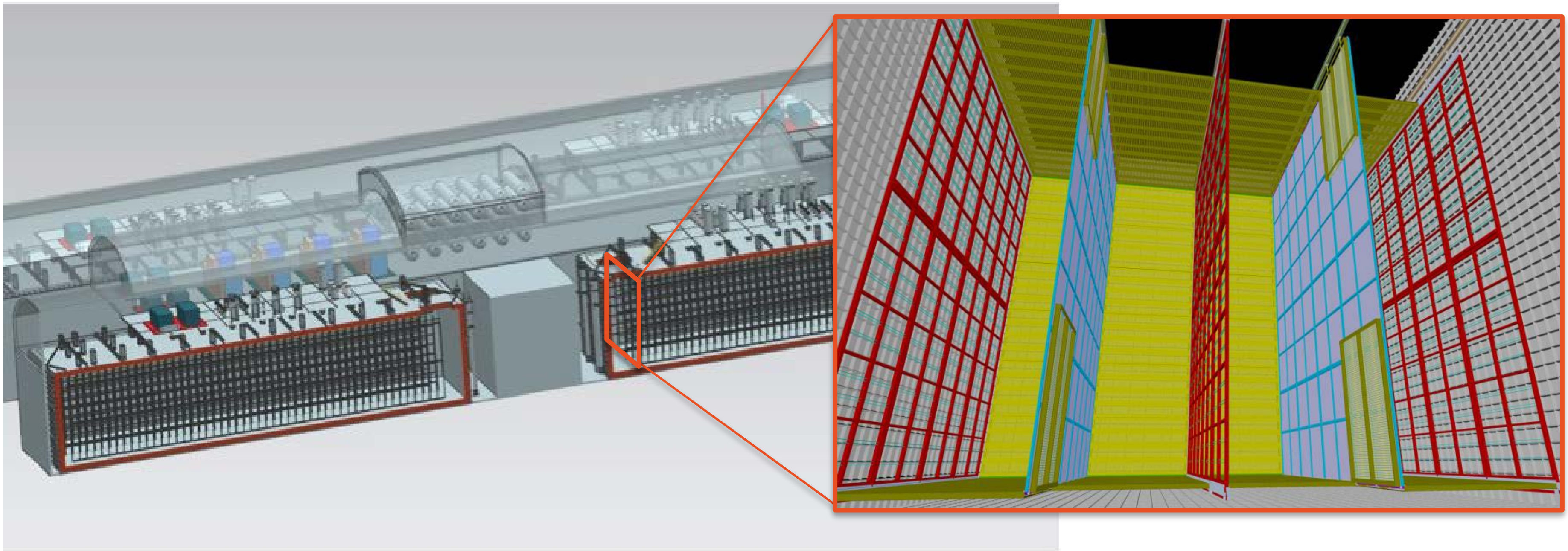
CP Violation Sensitivity as a function of δ_{cp} / MH

Sensitivity to CP Violation, after 300 kt-MW-yrs
(3.5+3.5 yrs x 40kt @ 1.07 MW)





DUNE LArTPC Far Detector Design



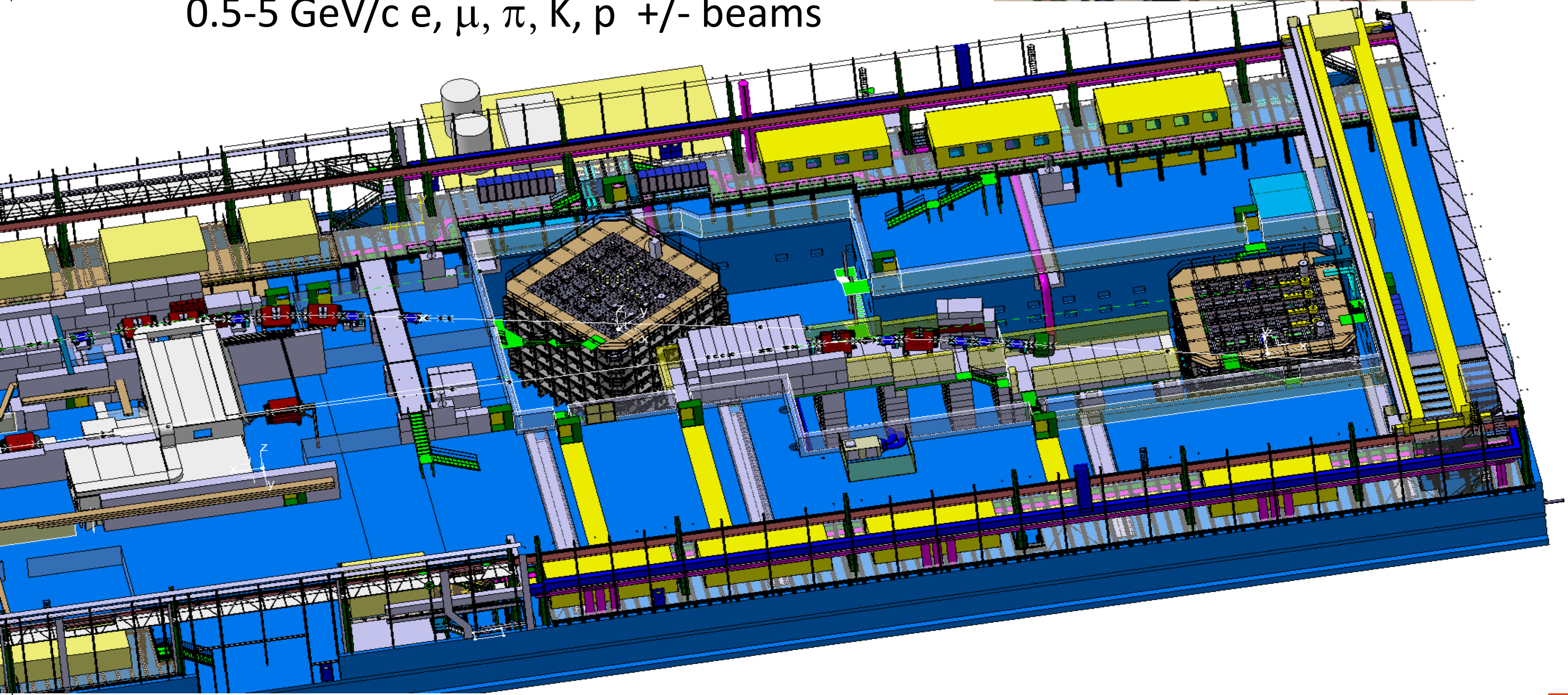
Single-phase TPC design based on LBNE modular drift cells.

- Suspended Anode and Cathode Plane Assemblies (APAs & CPAs).
- 3.6 m drift with a 500 V/cm E-field
- Cold digital electronics reduce noise.
- 3 views: collection wires vertical, induction wires at a 35.7° wrapped around APA.
  - Wrapping reduces the cold cable plant and number of readout channels.

ProtoDUNE's:

- EHN1 Extension now constructed
- Beneficial Occupancy, Sept. '16
- Cryostats complete, April '17
- Test-Beam Operations in 2018
- H2/H4 tertiary beam lines:

  0.5-5 GeV/c e, μ, π, K, p +/- beams



The Path to DUNE

- ✓ New collaboration structure with LBNF and DUNE
  - ❖ Based on the LHC model

- 2016 ✓ Conceptual Design Report, CD-1 refresh, CD3-a for LBNF
- 2017 ➢ Start of excavation at the far site
- 2018 ➢ **Two ProtoDUNE Detectors (SP & DP) operational at CERN**
- 2019 ➢ DUNE Technical Design Report for DOE and international organizations
- 2020
- 2021 ➢ Start of FD installation: 1st module (single phase)
- 2022
- 2023 ➢ Continue FD installation: 2nd module (not necessarily the same design)
- 2024 ➢ 20 kt operational
- 2025
- 2026 ➢ Beam operations at 1.2 MW at 120 GeV

Česká účast: NOvA (D=DUNE)

Fyzikální ústav, Akademie Věd ČR

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- Petr Vokáč D
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Ústav informatiky, Akademie věd ČR

- František Hakl

➢ Finanční podpora INGO 2016-17, VI Fermilab-CZ 2016-19 (+22?)

BACK UP
2016

BACK UP
– Accelerators ν's –

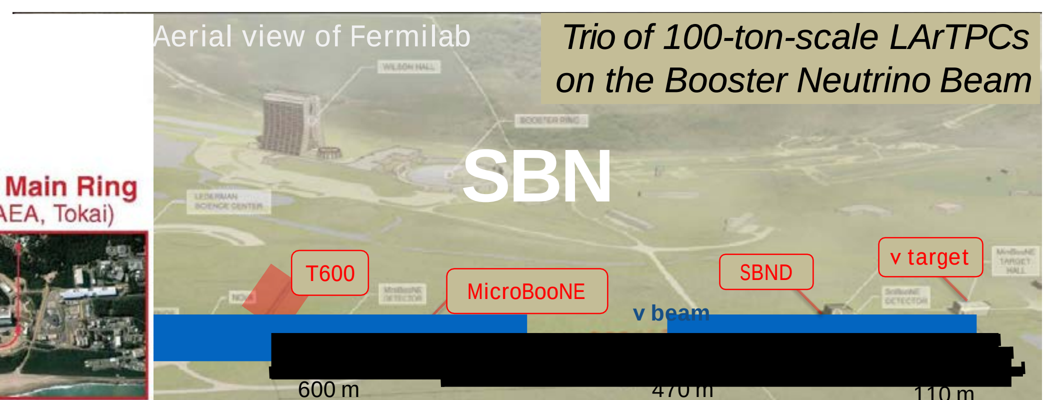
Neutrinos masses and mixing

What we do not know in 3-flavor neutrino mixing?

- **CP violation in the lepton sector has NOT been measured.**
  - May explain matter asymmetry through leptogenesis.
  - Measuring δ_{CP} precisely is needed to understand structure of PMNS matrix and their symmetries.
- **Mass hierarchy or ordering is NOT known for atmospheric neutrinos.**
  - Important to be able to understand reach of experiments that study if neutrinos are Majorana or Dirac particles.
- **The octant of the large mixing angle is NOT known!**
  - In the case non-maximal mixing this uncertainty impacts our knowledge of mass hierarchy and CP violation.
  - Precision measurements of θ_{23} are important for testing PMNS unitarity and for models building.

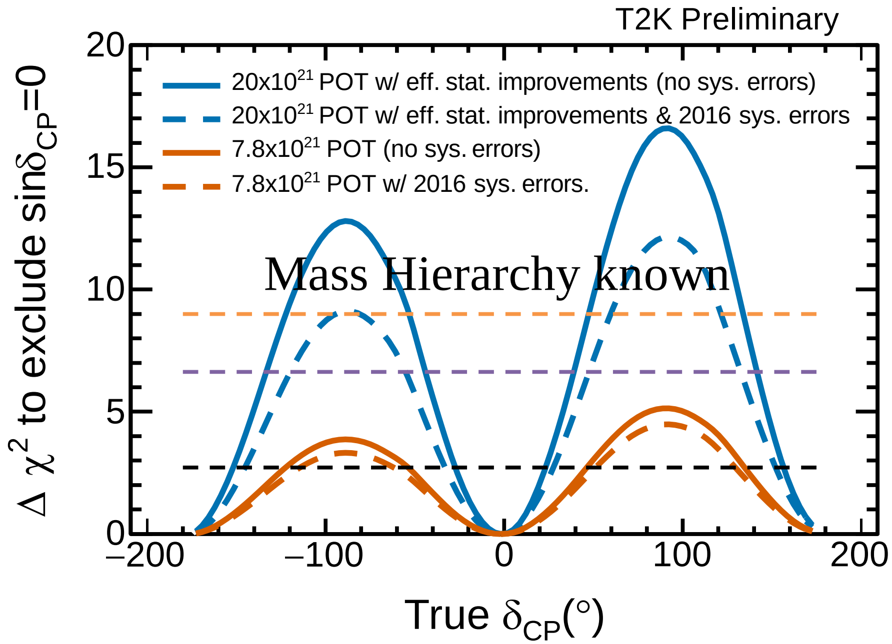
Using accelerators for neutrinos

- Neutrino oscillation experiments have been built using neutrino beams produced by accelerators around the World: US (NuMI and Booster), Europe (CNGS) and Japan (JPARC).
- The baseline of these experiments go from few hundreds of meters (short-baseline) to hundreds (300-1300) of km (long-baseline).

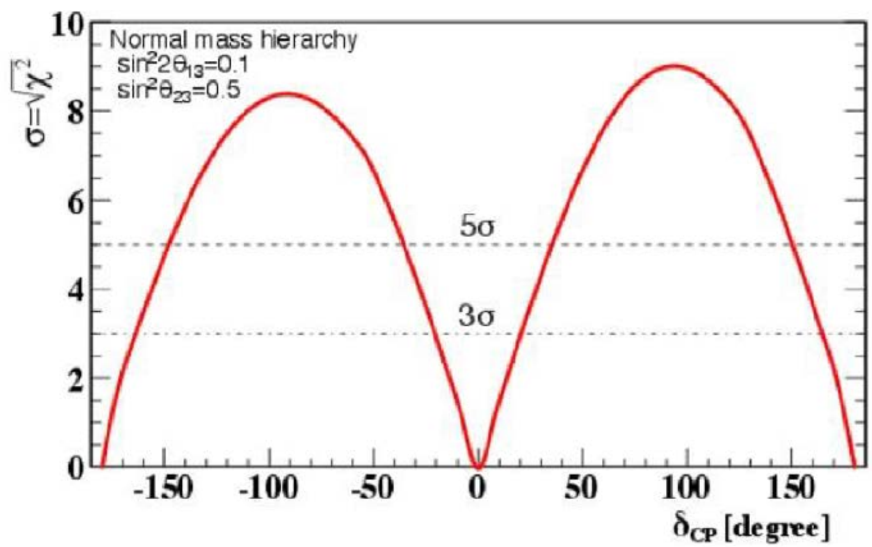


Future in Japan

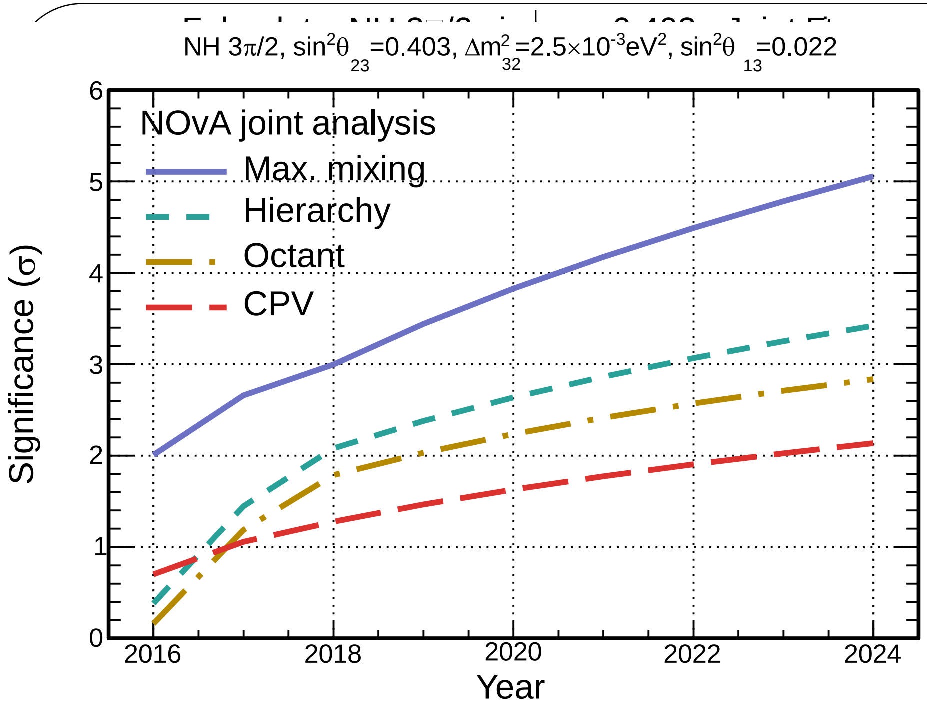
- Current T2K program expects 7.8 x 10^{21} Protons on Target (POT) by 2020.
- Potential extension (T2K-II) would have 20 x 10^{21} POT by 2026.
  - ~3σ sensitivity to δ_{CP}.

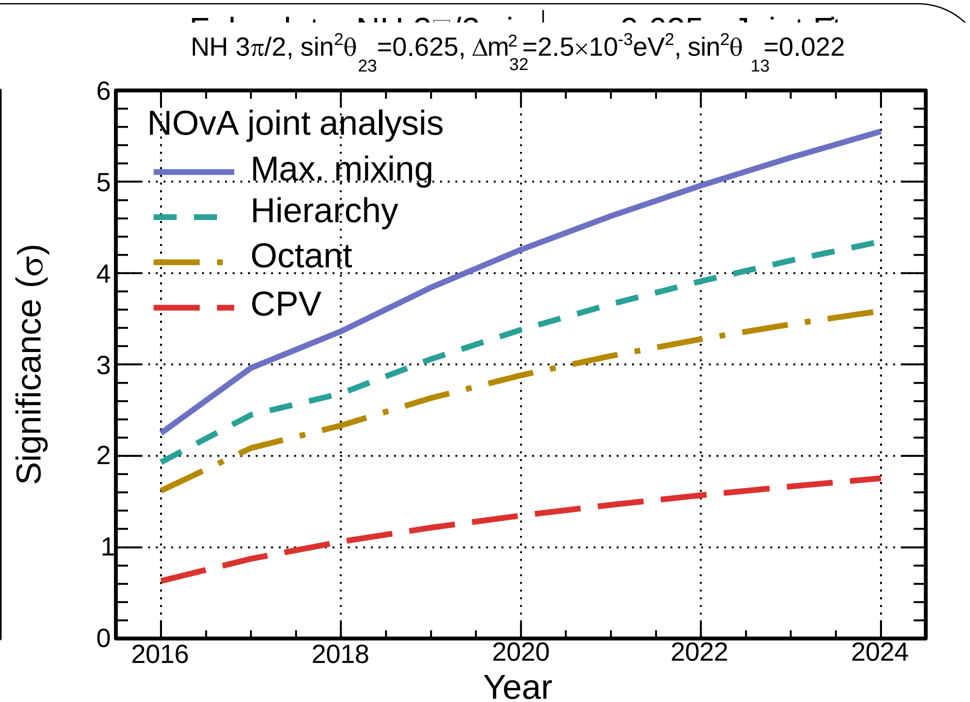


- Requires accelerator and beam-line upgrades to reach 1.3 MW. Currently at 420 kW.
- While T2K-II is running, construction of the next generation detector (Hyper-Kamiokande) begins:
  - By 2026 build 2 large Water Cherenkov of 260 kton each.
  - >5σ sensitivity to δ_{CP}.



BACK UP
– NOvA future –





with projected systematics

➢ For Normal Hierarchy at dcp = 3pi/2:

1.FY2018 we have IH hierarchy rejection at 2 sigma for all theta23 scenarios for dcp 3pi/2.

2. FY2018 we have maximal mixing rejection at 3 sigma or better

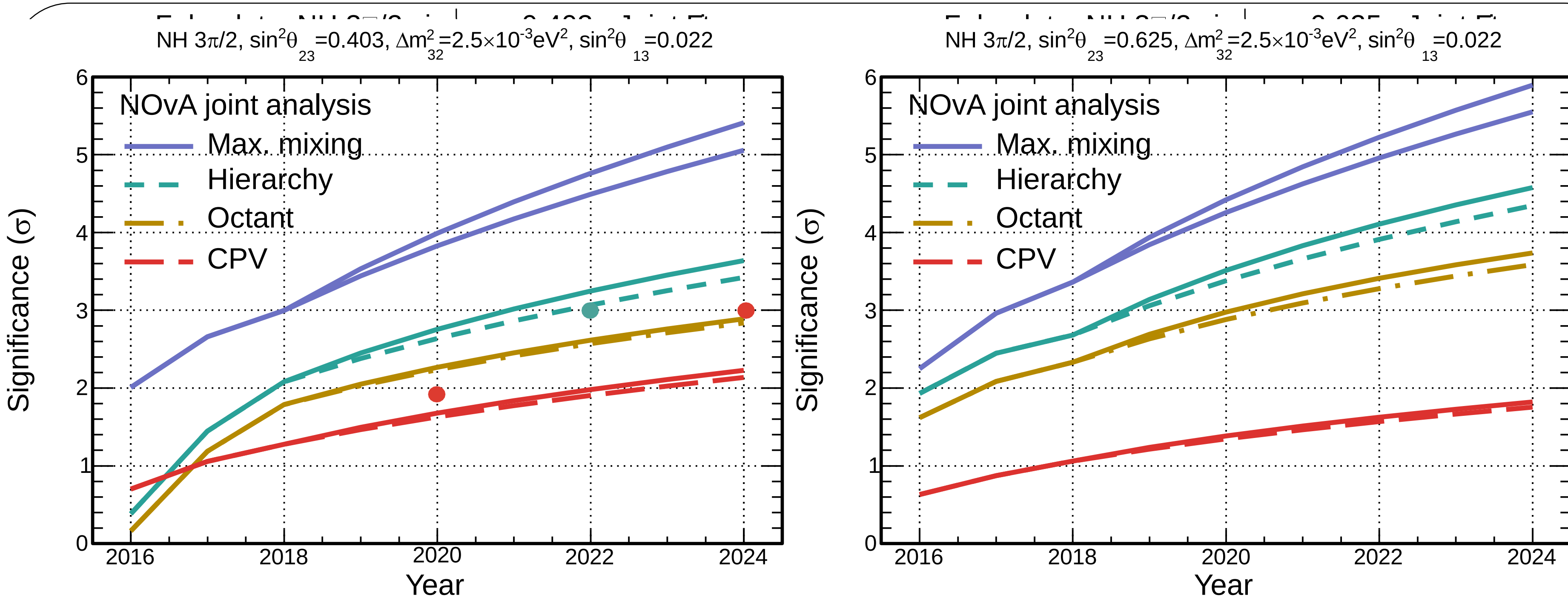
3. FY2020 we have 2-3 sigma sensitivity to the octant depending on lower vs higher octant.

4. FY2022 we have 3-4 sigma on IH hierarchy rejection.

5.FY 2024 potentially reach 5 sigma to maximal mixing rejection in all octant scenarios dependent on numu background levels and systematics.

6. FY2024 potentially ~2 sigma for CPV.

7. Beyond FY2024 potentially reach 3 sigma in wrong octant rejection for both octants.



with projected systematics

- Same with an additional 1e20 POT per year from 2019. Few milestones can be done earlier.
- **Big picture:**
  - DUNE expects beam by 2026, start of beam construction expected at least 18 months ahead. So 2024+ is a good guess for extended running.
  - JUNO starts data taking in 2020. Expects 3 sigma mass hierarchy 2022-2025 and 5 sigma in 2030. SuperK + T2K has some sensitivity, currently 2 sigma.
  - T2K reaches 3 sigma by 2024 considering analysis and beam improvements. However we are competitive to CPV with their sensitivity (not observed) up to 2020.