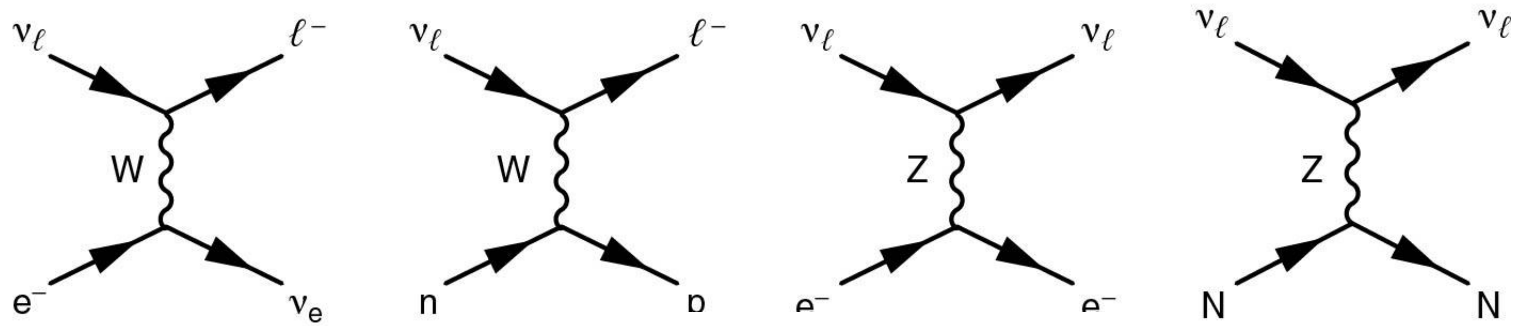
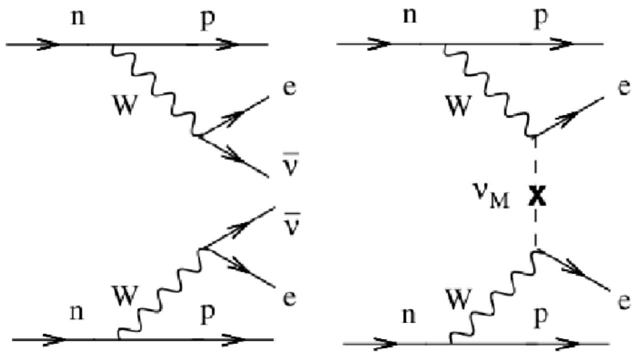
A Survey of Swiss Neutrino Physics

Richard Diurba (University of Bern)

Swiss Institute of Particle Physics



Feynman diagrams of the four most common neutrino interactions (From *Modern Particle Physics*)



Double beta decay Feynman diagrams (From University of Warwick)

Introduction

Neutrino physics detects the byproducts of neutrino interactions to measure:

- Neutrino oscillations
- Neutrino cross sections
- Astrophysical processes
- Nuclear effects
- Neutrino masses

The talk will discuss neutrino physics projects in Switzerland covering:

- Low-energy physics
    - 0νββ searches
    - Experiments: GERDA, LEGEND
- Medium-energy physics
    - Cross section measurements
    - Oscillation measurements
    - Experiments: T2K, SBN program
- High-energy physics
    - Astrophysics
    - Neutrino oscillations and cross sections
    - Experiments: IceCube, FASER and SND@LHC

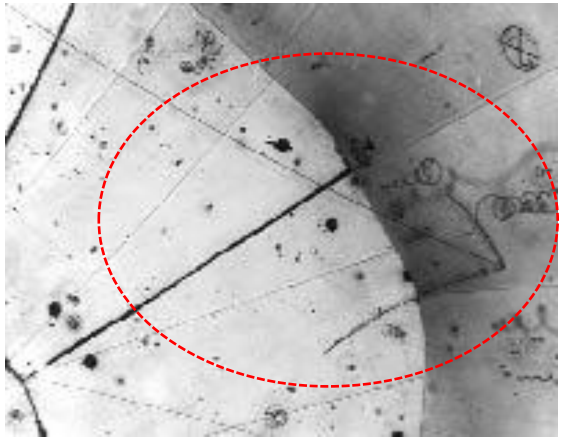


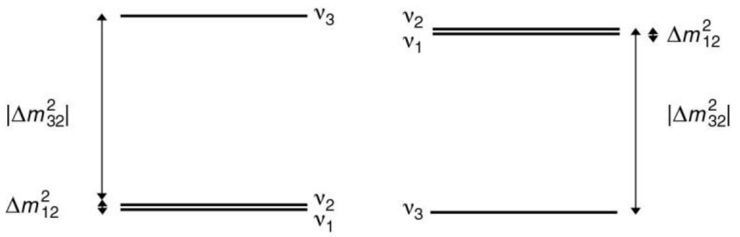
Image of first neutrino event display from Argonne National Laboratory in 1970 (From Argonne)

Thank you for input and information from:

- Stefania Bordoni (UniGe, T2K/HK)
- Davide Sgalaberna (ETH, T2K/HK)
- Pin-Jung Chiu (UZH, GERDA/LEGEND)
- Aki Ariga (UniBe, FASER/FASERnu)
- Umut Kose (ETH, FASER/FASERnu)
- Lesya Shchutska (EPFL, SND@LHC)
- Martina Ferrillo (UZH, SND@LHC)

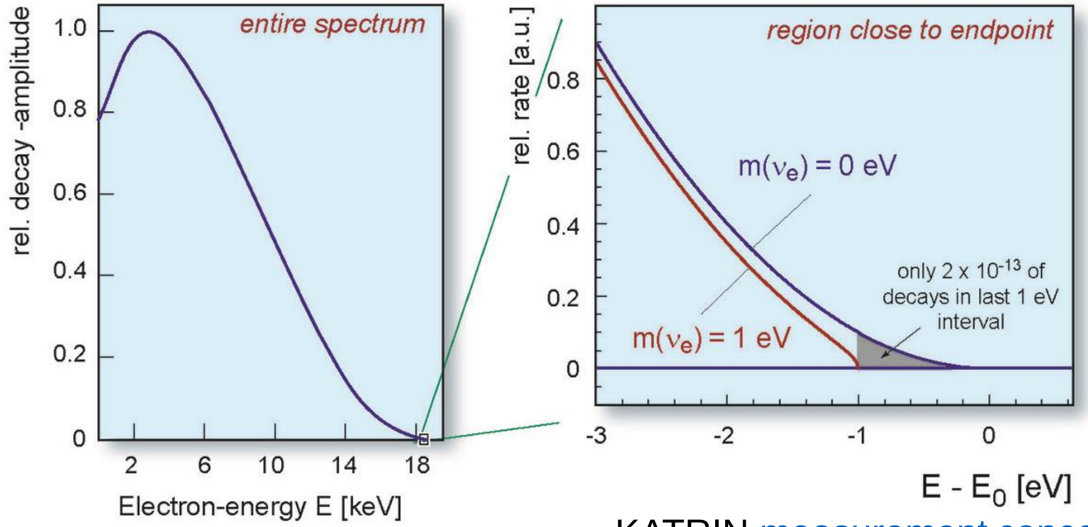
$$\begin{bmatrix} U_{e,1} & U_{e,2} & U_{e,3} \\ U_{\mu,1} & U_{\mu,2} & U_{\mu,3} \\ U_{\tau,1} & U_{\tau,2} & U_{\tau,3} \end{bmatrix} = \begin{bmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{CP}} \\ -(s_{12}c_{23} + c_{12}s_{13}s_{23}e^{i\delta_{CP}}) & c_{12}c_{23} - s_{12}s_{13}s_{23}e^{i\delta_{CP}} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}s_{13}c_{23}e^{i\delta_{CP}} & -(c_{12}s_{23} + s_{12}s_{13}c_{23}e^{i\delta_{CP}}) & c_{13}c_{23} \end{bmatrix}$$

PMNS matrix between neutrino flavor and mass states.



Possible mass hierarchies between the three neutrino mass eigenstates. (From *Modern Particle Physics*)

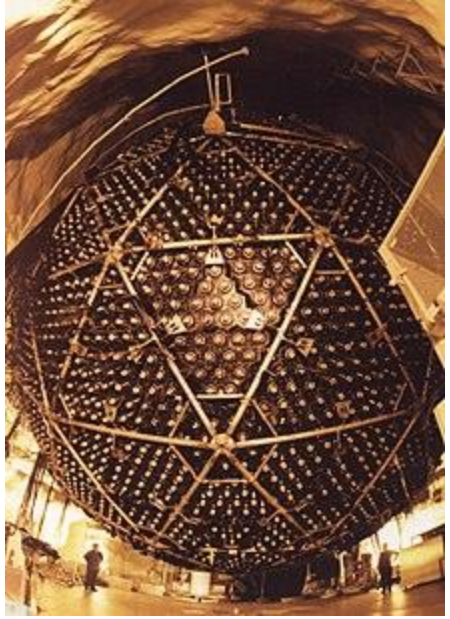
Low-Energy (<1 GeV)

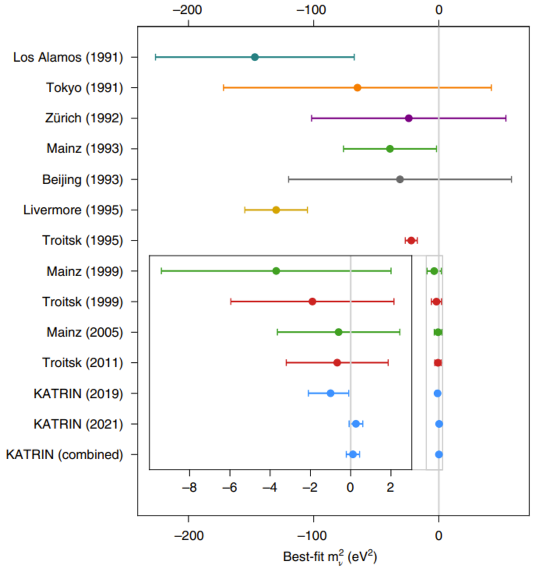


KATRIN [measurement concept](#)of the neutrino mass by measuring the highest possible energy.

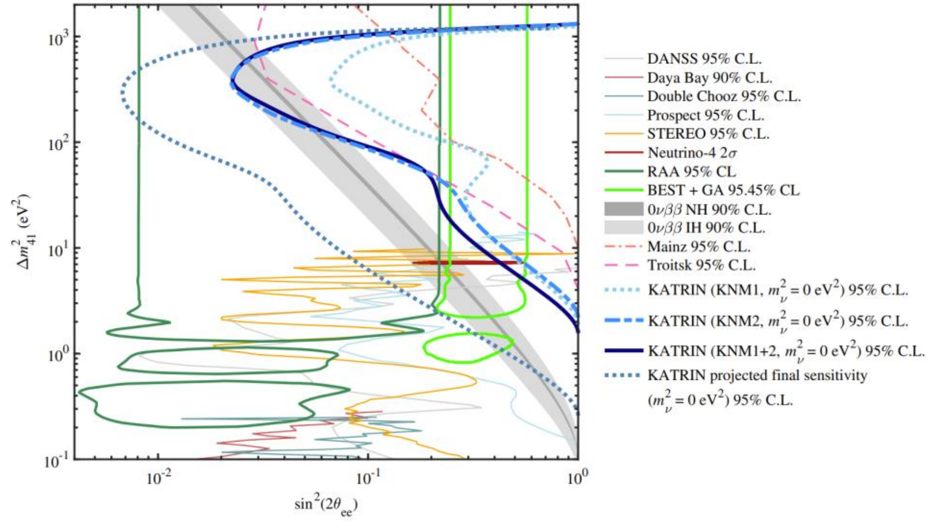
Sudbury Neutrino Observatory (now SNO+) which still takes data for solar and [reactor neutrinos](#).

It will study 0νββ double beta decay.





Recent neutrino mass measurements using precision measurements of the tail of the beta decay spectrum ([*Nature Physics* **18**, 160–166](#))

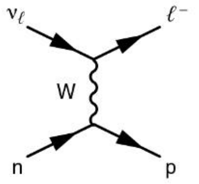


Sterile neutrino search in the reactor space using KATRIN beta decays ([*Phys. Rev. D* **105**, 072004](#))

Low-Energy (<1 GeV)

Nuclear reactor experiments aim to explore neutrino oscillations to tune the PMNS matrix and search for sterile neutrinos.

Detects neutrinos through inverse beta decay of anti-electron neutrinos.



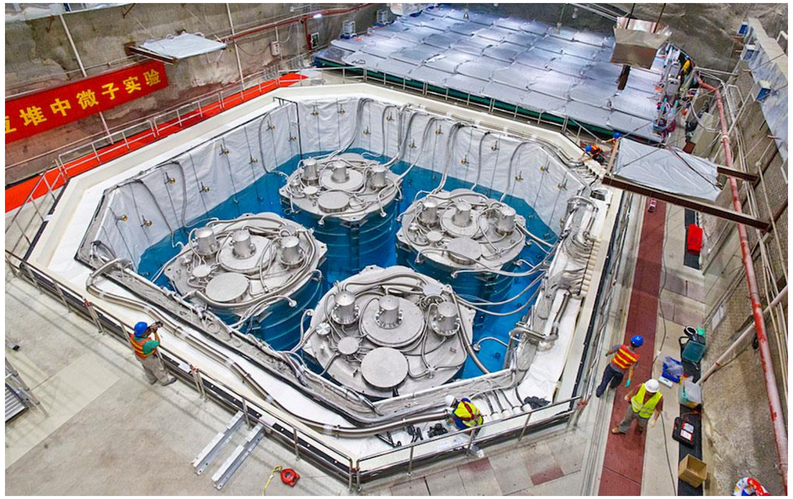
Experiments include:

- Daya Bay (left)
- JUNO (right, future)
- NEUTRINO-4
- DANNS
- PROSPECT
- STEREO
- And many more . . .

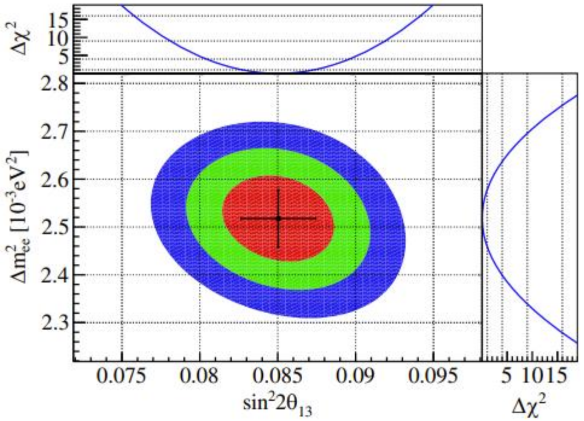
Some experiments disagree on if there is a sterile neutrino in the reactor sector

- Mass ~eV scale, $\sin(\theta_{14})^2$ ~0.1

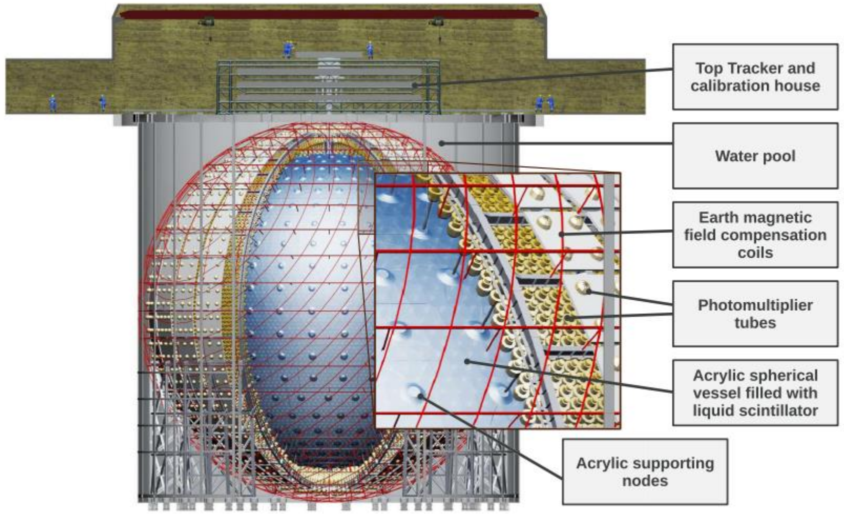
or if it is a flux disagreement. Check out the links above for more info.



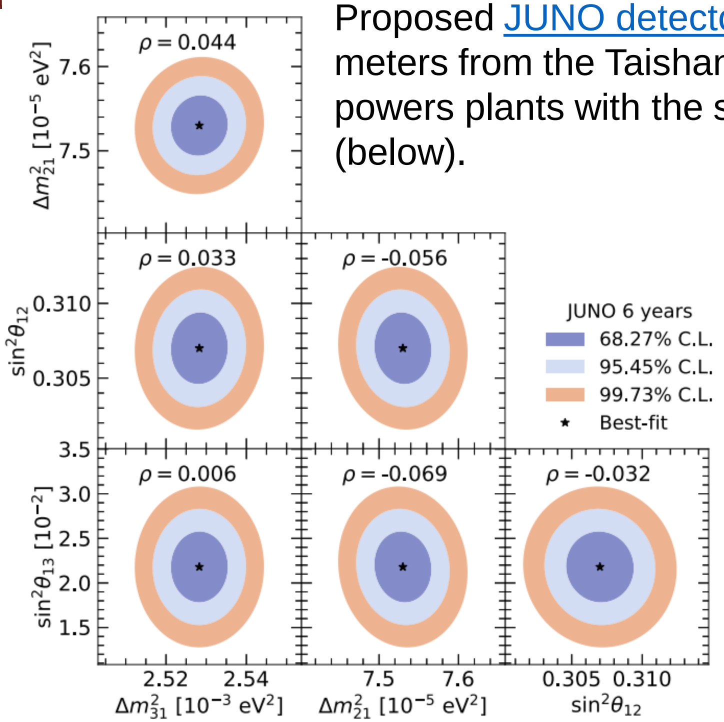
Daya Bay Experimental Hall 3 which measures neutrino oscillation from nuclear reactors kilometers away at energies ~4 MeV.



Daya Bay's most recent results of measuring oscillation parameters.



Proposed JUNO detector (top) 52.5 meters from the Taishan and Yangjiang powers plants with the sensitivities (below).



0νββ Searches

Are neutrinos their own antiparticles?

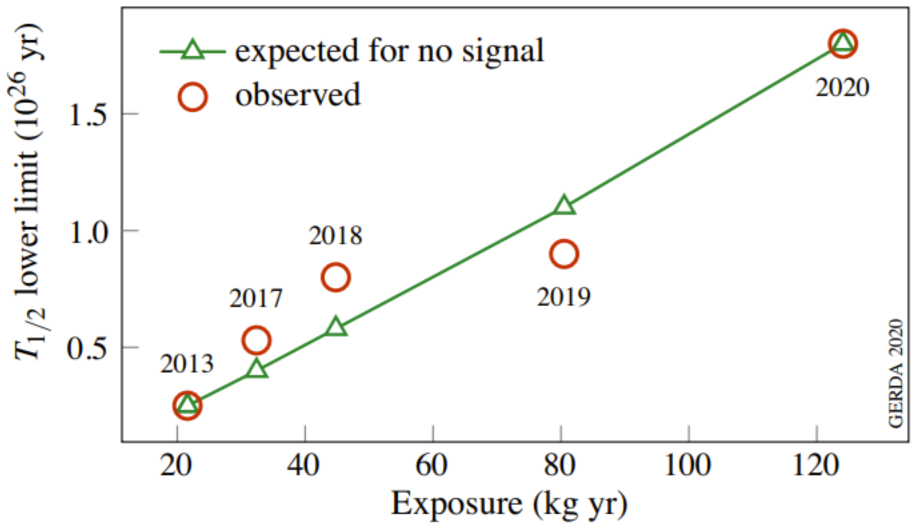
What are the mass eigenstates?

Searches for monoenergetic observed kinetic energy transfer between initial and final state

Swiss involvement in GERDA (past) and LEGEND (future) in calibration and analyses.

- Using enriched Germanium.

LEGEND-200 is currently taking data (200 kg Germanium) with plans for LEGEND-1000



Final measurement of GERDA data.

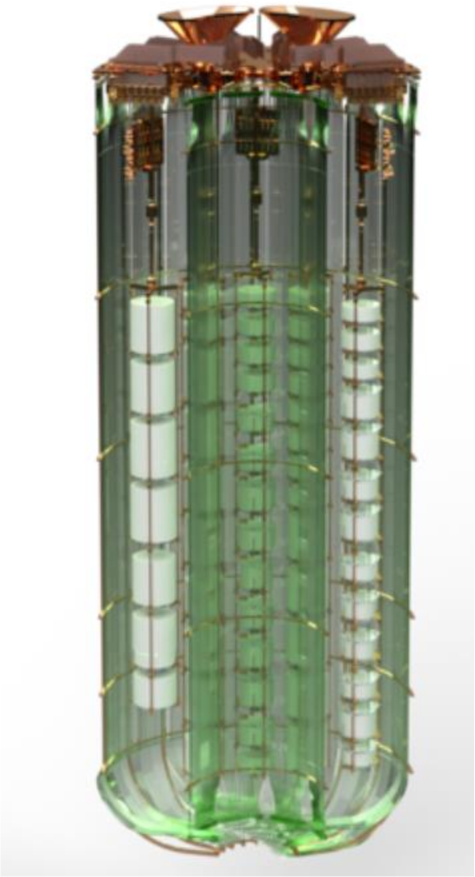


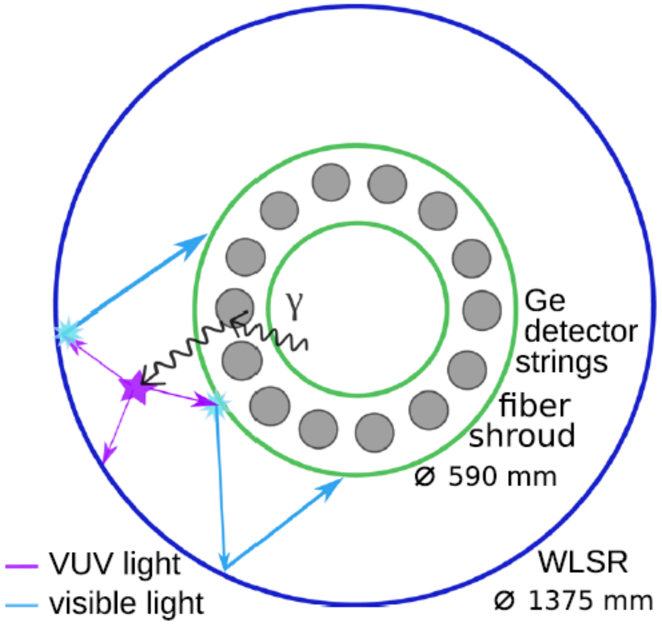
Diagram of the light detection fibers surrounding the Ge target. Detector is surrounded by LAr.

Talk on LEGEND

Other neutrino projects being pursued in the xenon-sector by UZH right after this talk.

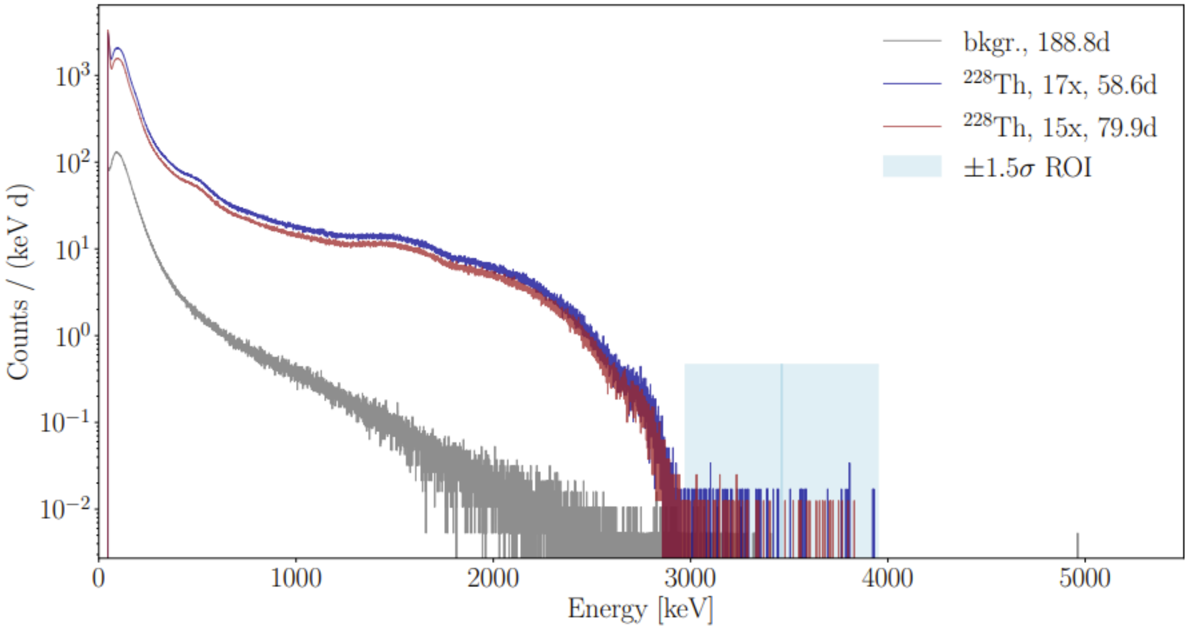
University of Zurich[UZH]

0νββ Detector Development



Optical light detection concept in LAr.

Developed Thorium calibration system.



Neutron energy spectrum measured from the calibration source. The source has a Q-value of 2.6 MeV. Four rods will be placed to calibrate regularly.

Explored detector parameters of VUV light detection with PEN and evaluated quantum efficiency of PEN and TPB for upscaling options in LEGEND-1000.

University of Zurich UZH

Medium Energy (~1 GeV): Short Baseline

Short Baseline Neutrino Program

Measures cross sections, oscillations, and serves as a liquid argon time projection chamber R and D platform.

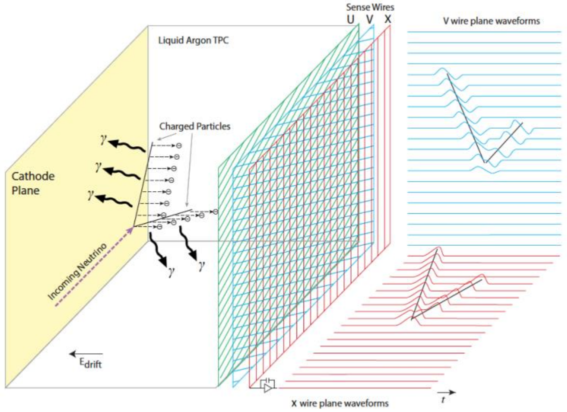
Main "Basic Physics" Goal:

- Solve the MiniBooNE anomaly

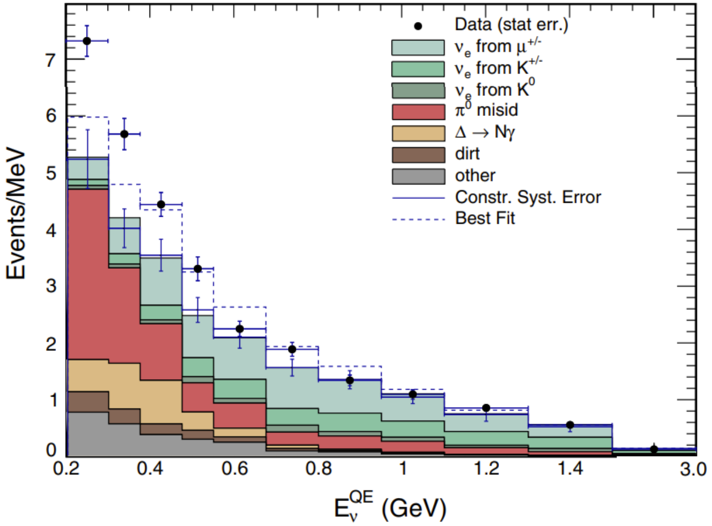
Oscillation basics:

$N_{far\ detector}$=Flux*Cross Section*Det. Eff.*Osc. prob.

$N_{near\ detector}$=Flux*Cross Section*Det. Eff.



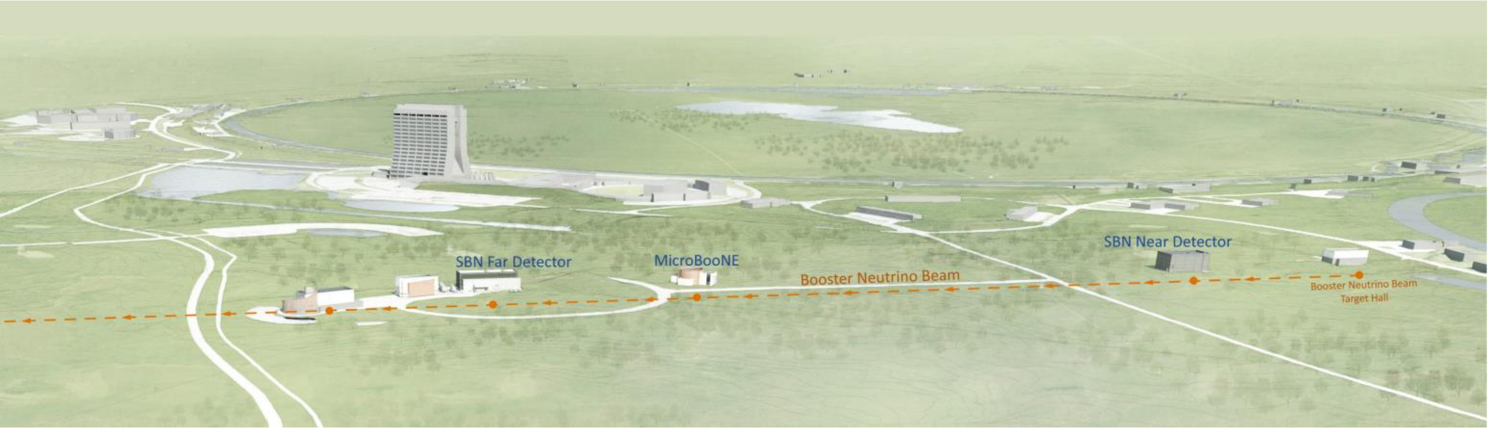
Operating concept for neutrino interaction detection for a liquid argon time projection chamber with wire readouts (arXiv:2002.03005).



MiniBooNE electron neutrino energy distribution for CCQE events. An observe excess is observed, deemed the MiniBooNE anomaly. Could it be oscillations from a fourth neutrino state? (*Phys. Rev. D* **103**, 052002).

Had no dedicated flux/cross section measurement detector.

Fermilab Short Baseline Neutrino Program consisting of Short Baseline Near Detector, MicroBooNE, and ICARUS which aims to solve the MiniBooNE anomaly. (Image from Fermilab)

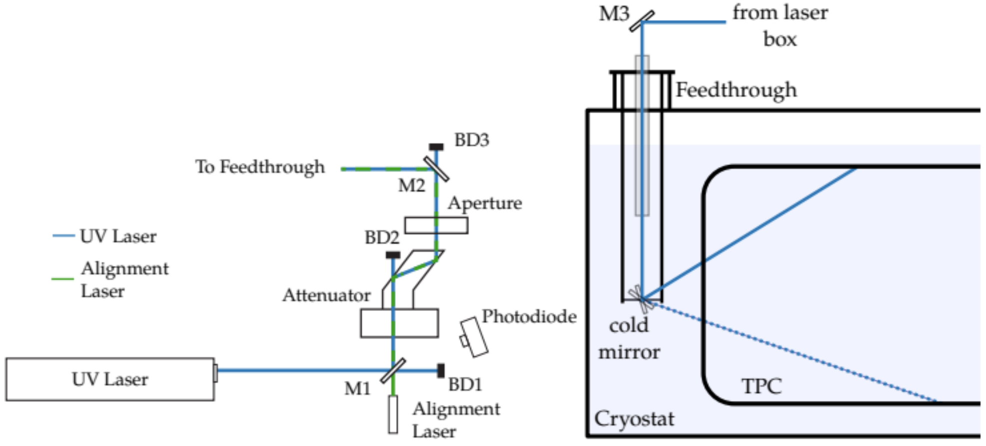


Short Baseline Neutrino Program: America

Contributions on the auxiliary calibration systems from Switzerland for SBND and MicroBooNE.

UV Laser Calibration:

- Scans the volume of the argon to measure ionization parameters and tracking parameters.
- Intended to calibrate the electric field distortions (*JINST* **15** P12037).



Concept of the laser (left) and the application of the laser into the time projection chamber (right) (*JINST* **15** P07010)

Image of a top layer CRT for MicroBooNE, below it is the cryostat (*JINST* **14** P04004)

Cosmic Ray Tagger (CRT):

- Scintillator strips surrounding the whole cryostat.
- Can operate as a veto, generate a timestamp, and provide reconstructed tracks.
- Example analysis measuring diffusion of electrons in argon for MicroBooNE.

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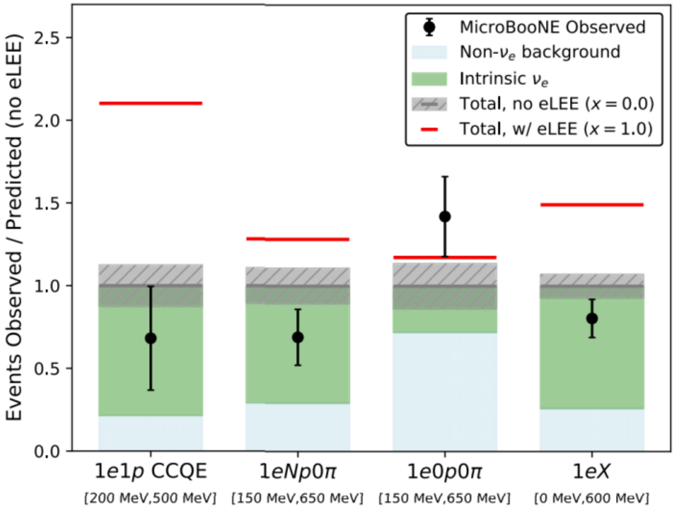
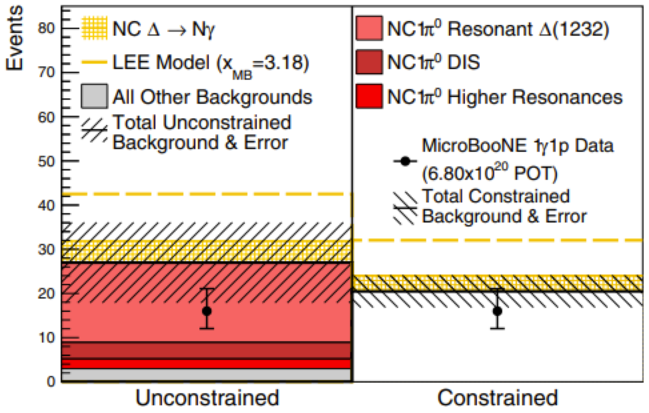
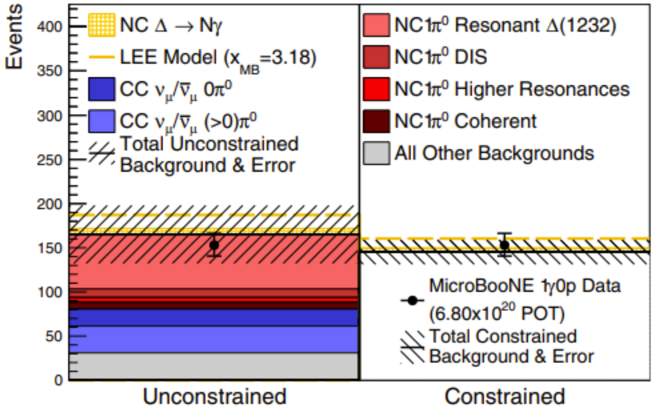
Short Baseline Neutrino Program: MicroBooNE



(Left) Measurement of the total event rate for various channels compared to the prediction from a MiniBooNE-like mode ([*Phys. Rev. Lett.* **128**, 241801](#))



(a)



(b)

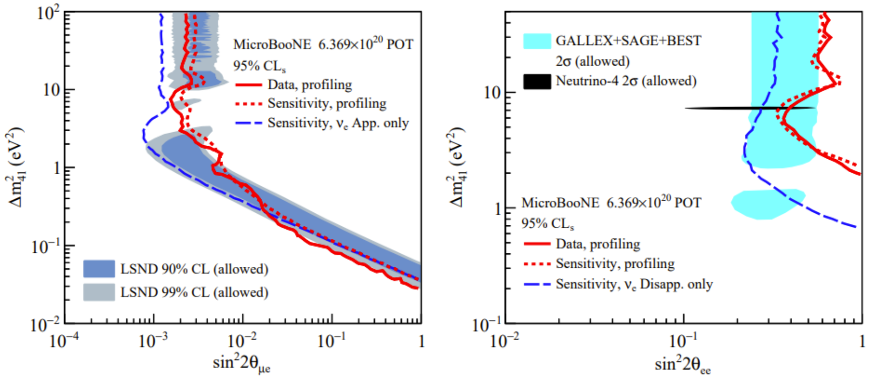
Measurement of the event rate of 1 photon events with 1 proton (top) and 0 protons (bottom) compared to a MiniBooNE model that assumes the excess is from radiative decays from Neutral Current Deltas ([*Phys. Rev. Lett.* **128**, 111801](#))

Analyses on the MiniBooNE excesses look at multiple topologies and found no definite confirmation but has not ruled out a sterile.

Relied on a [tuned cross section model](#) with no external flux measurement, so no constraints from a "near detector".

- Still needs the full SBN program!

(Bottom) Exclusion contour for mixing with a fourth neutrino for the 1eX analysis ([*Phys. Rev. Lett.* **130**, 011801](#))



Also, producing numerous new cross section [results](#).

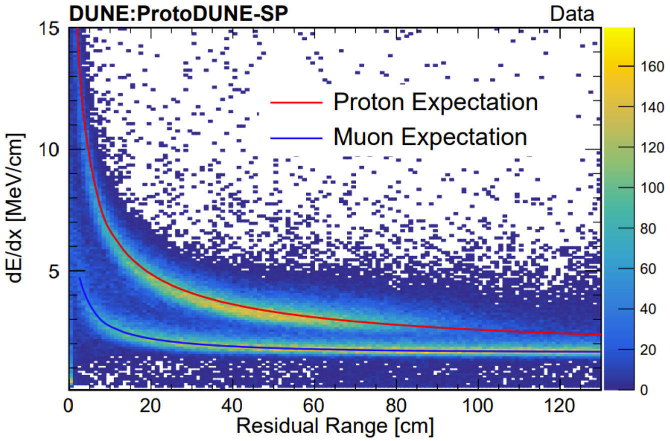
Short Baseline Hadron Measurements: Swiss

ProtoDUNE Single Phase (SP) is an approximately 700-ton monolithic liquid argon time projection chamber (TPC) prototype for DUNE.

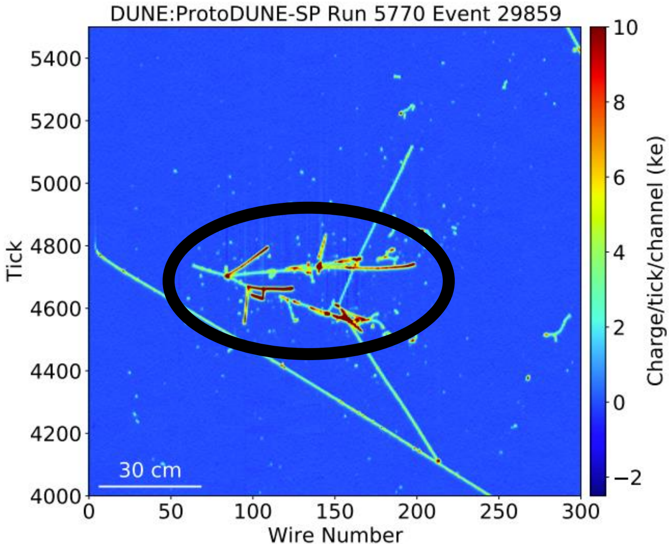
Upcoming hadron-argon cross sections measurements will be released (Significant uncertainty for oscillation analyses).

ProtoDUNE-VD and ProtoDUNE-HD (SP II) will operate within a year's time.

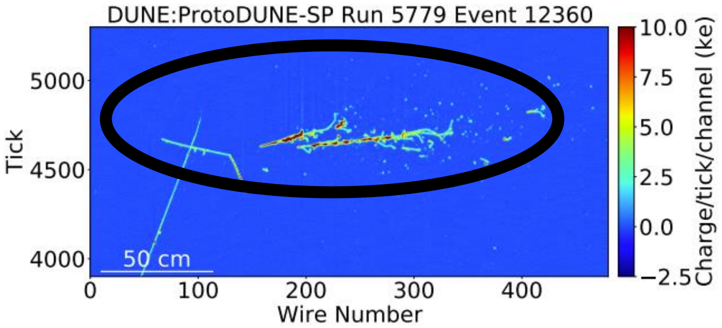
ProtoDUNE-SP (bottom) in the CERN Neutrino Platform



dE/dx measurements of stopping muons and protons.



6 GeV/c kaon candidate interaction



2 GeV/c pion candidate charge exchange interaction

MOËNS
CERN Plateforme Neutrino
Rte des Marlis
D35
Appart Hôtel - Residhome Prévessin-Moëns Le Carr...
Rte de Ferney
E.Leclerc FERNEY VOLTAIRE
FRANCE
SCHWEIZ
QUARTIER CHAMPS-FRÉCHETS
Globe de la science et de l'innovation (CERN)
Hôtel du CERN
Top rated
Jardin botanique alpin de Meyrin

Short Baseline Hadron Measurements: France

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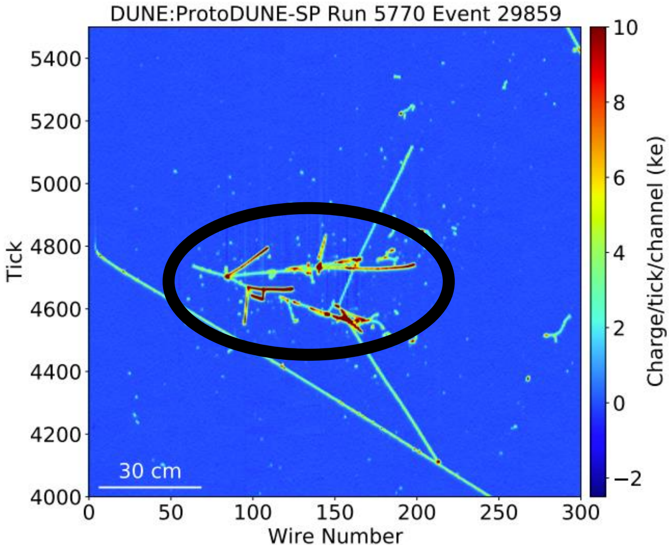
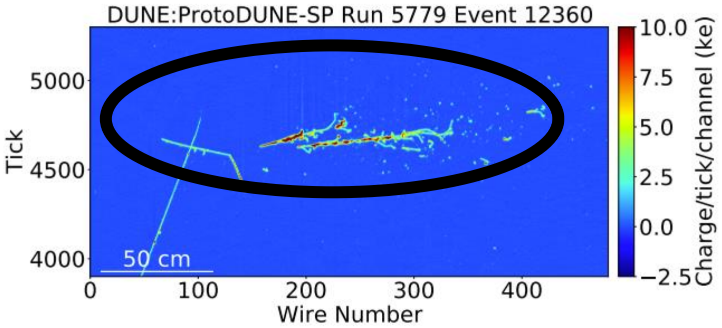
ProtoDUNE-SP (bottom) in the CERN Neutrino Platform



6 GeV/c kaon candidate interaction



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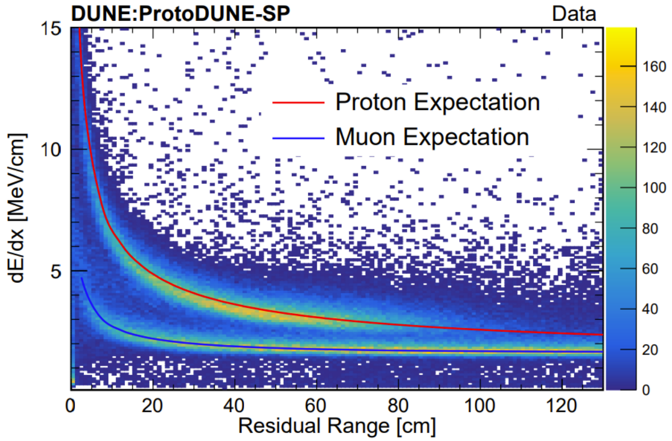
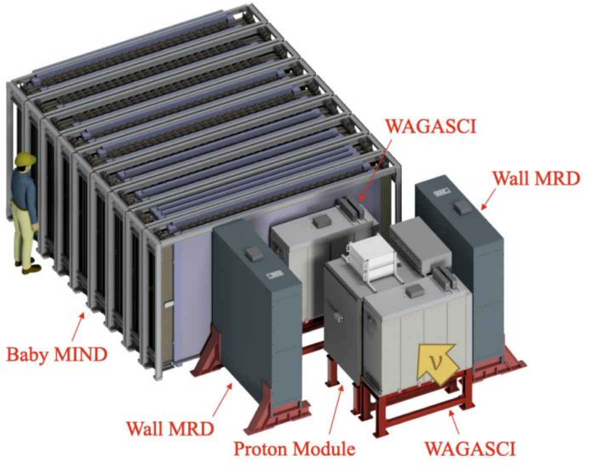


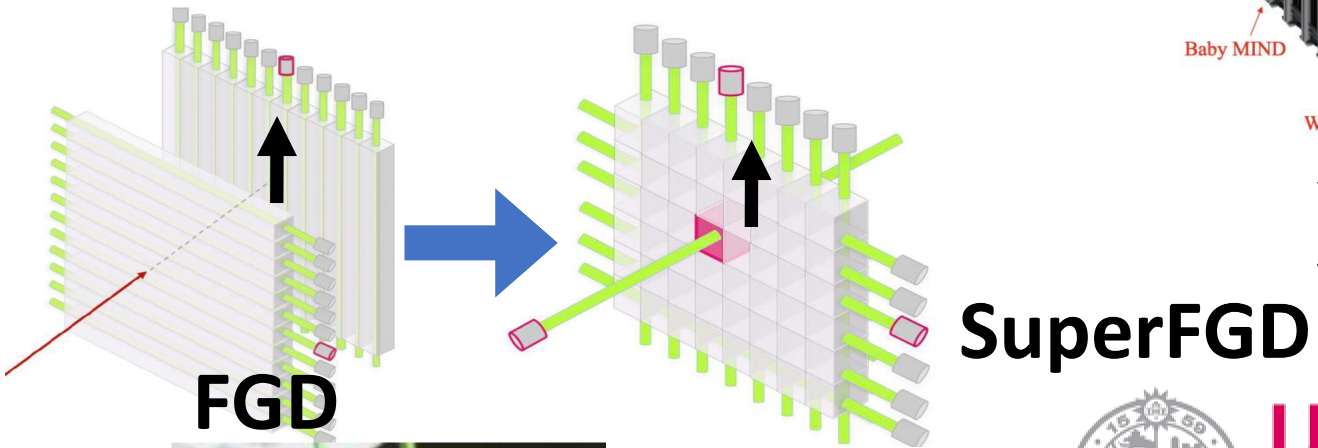
dE/dx measurements of stopping muons and protons.

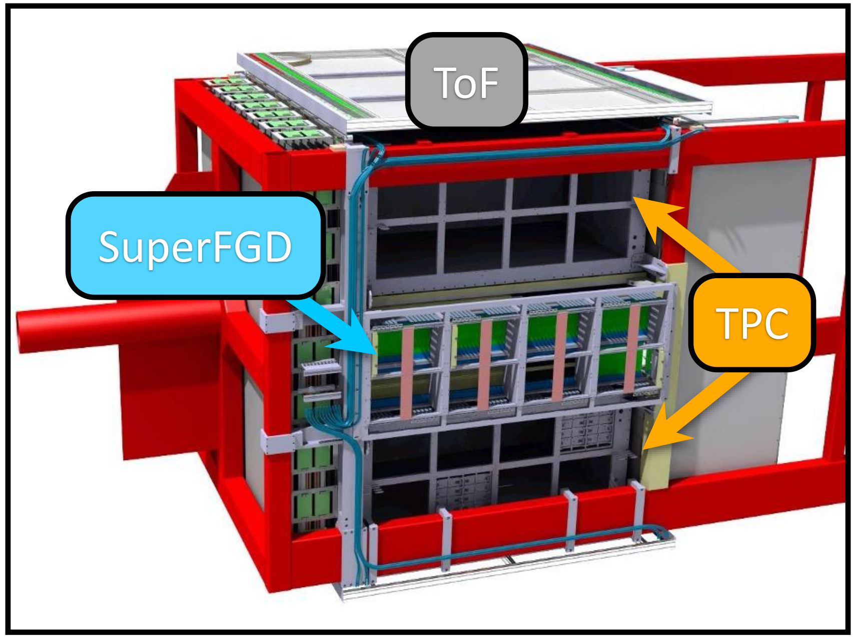
Short Baseline Detector Development: France/Japan

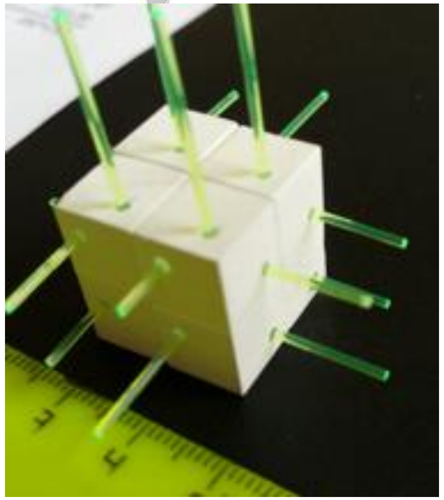
- Ongoing upgrades for T2K Near Detector to improve energy and tracking resolutions.
- Efforts on ND280 and, previously, WAGASCI
- Hotbed of cross section results important for tuning neutrino interactions at GeV-scale.



WAGASCI detector with the Baby MIND detector, which was prototyped at CERN

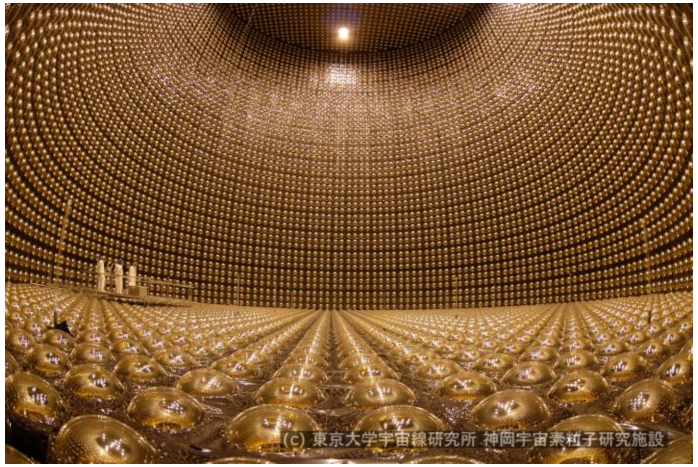






Updated ND280 T2K detector with new 3D scintillator cubes replacing FGD (Fine-Grained Detector) and new TPCs.

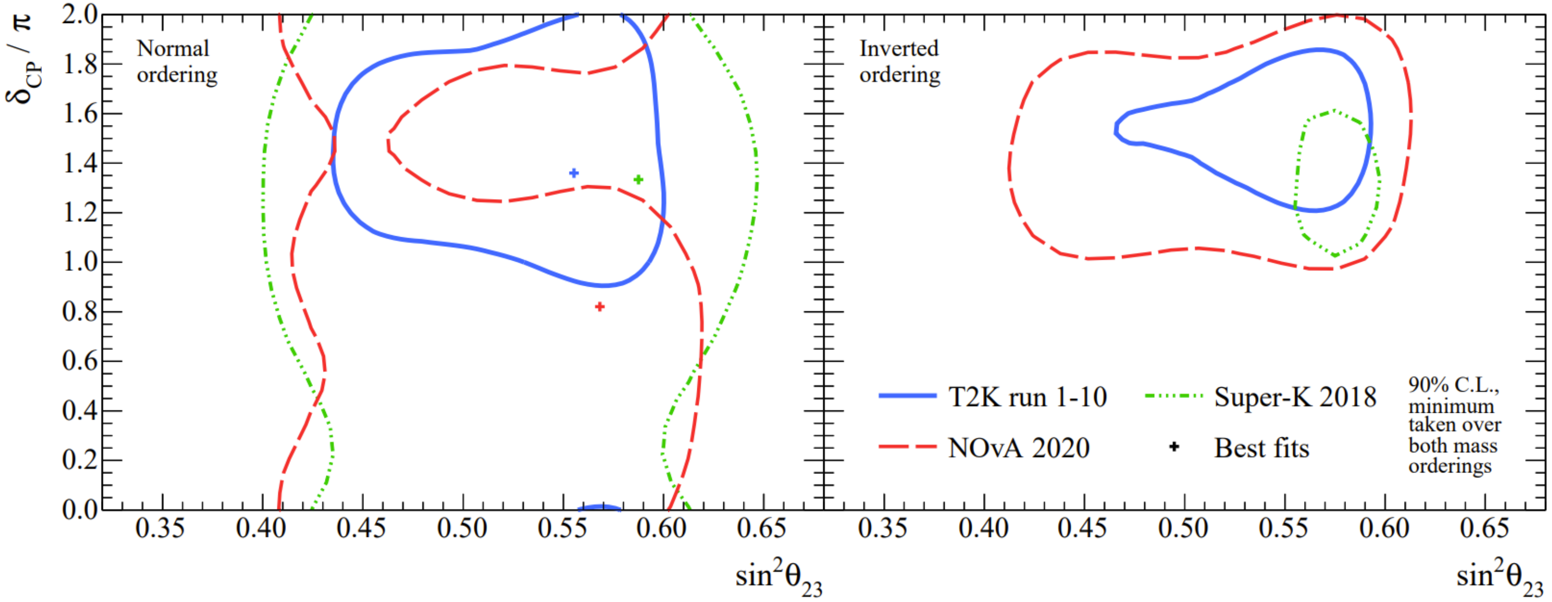
Medium Energy Searches (~1 GeV): Long Baseline T2K/NOvA



Super Kamiokande during construction in the late 1990s. (Picture from SK)

- Two competing/cooperating experiments of NOvA and T2K measure neutrino oscillations over hundreds of kilometers.
  - Measure (anti) electron neutrino rates for comparisons that test CP-violating phase.

Most recent results from T2K

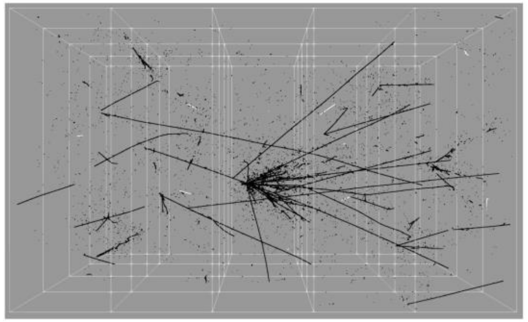


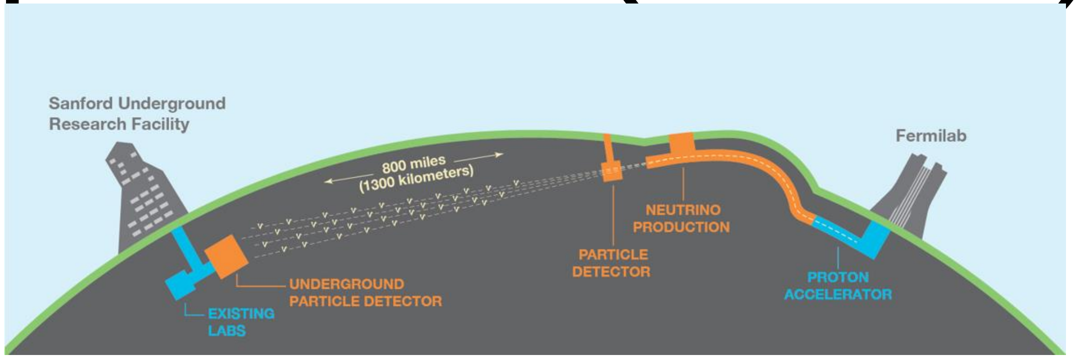
NOvA Far Detector, consists of liquid scintillator covered in PVC pipes (Picture from Fermilab)

$N_{far\ detector}$=Flux*Cross Section*Det. Eff.*Osc. prob.

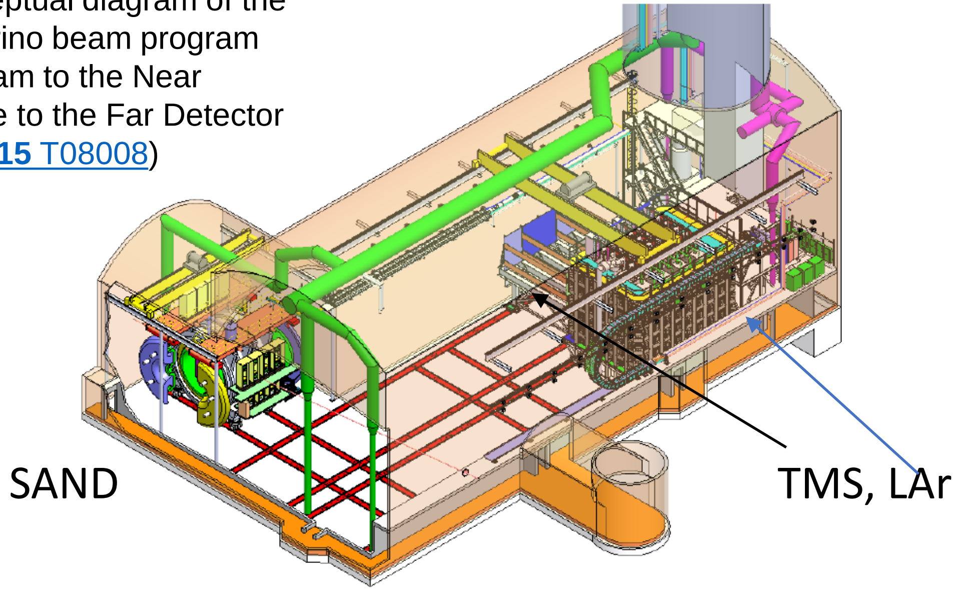
$N_{near\ detector}$=Flux*Cross Section*Det. Eff.

Deep Underground Neutrino Experiment (DUNE)

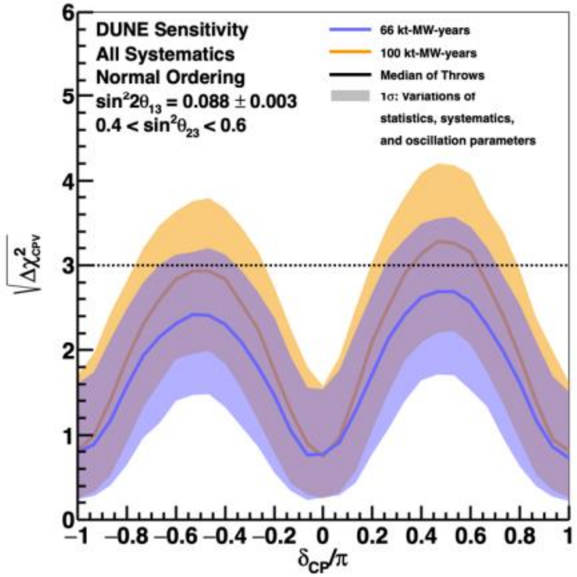


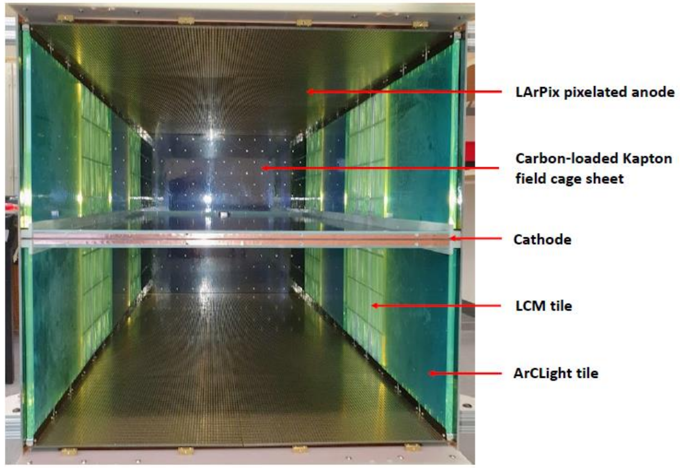


(Left) Conceptual diagram of the DUNE neutrino beam program from the beam to the Near Detector site to the Far Detector site (*JINST* **15** T08008)



[Proposed sensitivity](#) for two Far Detector modules operating under the standard 1.2 MW beam for 3 and 5 years, respectively.





[Module](#) for ND-LAr. There will be a total of 35 modules. Four prototypes will operate in the NuMI beam and take neutrino data this year.

(Top) Simulation of a beam spill in ND-LAr with pile-up. (Bottom) [Diagram](#) of the proposed Near Detector site with a beamline monitor, muon spectrometer, and liquid argon detector.

University of Basel

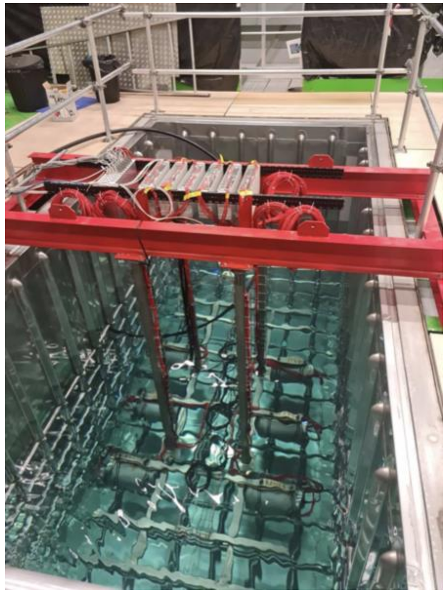
Universität Bern

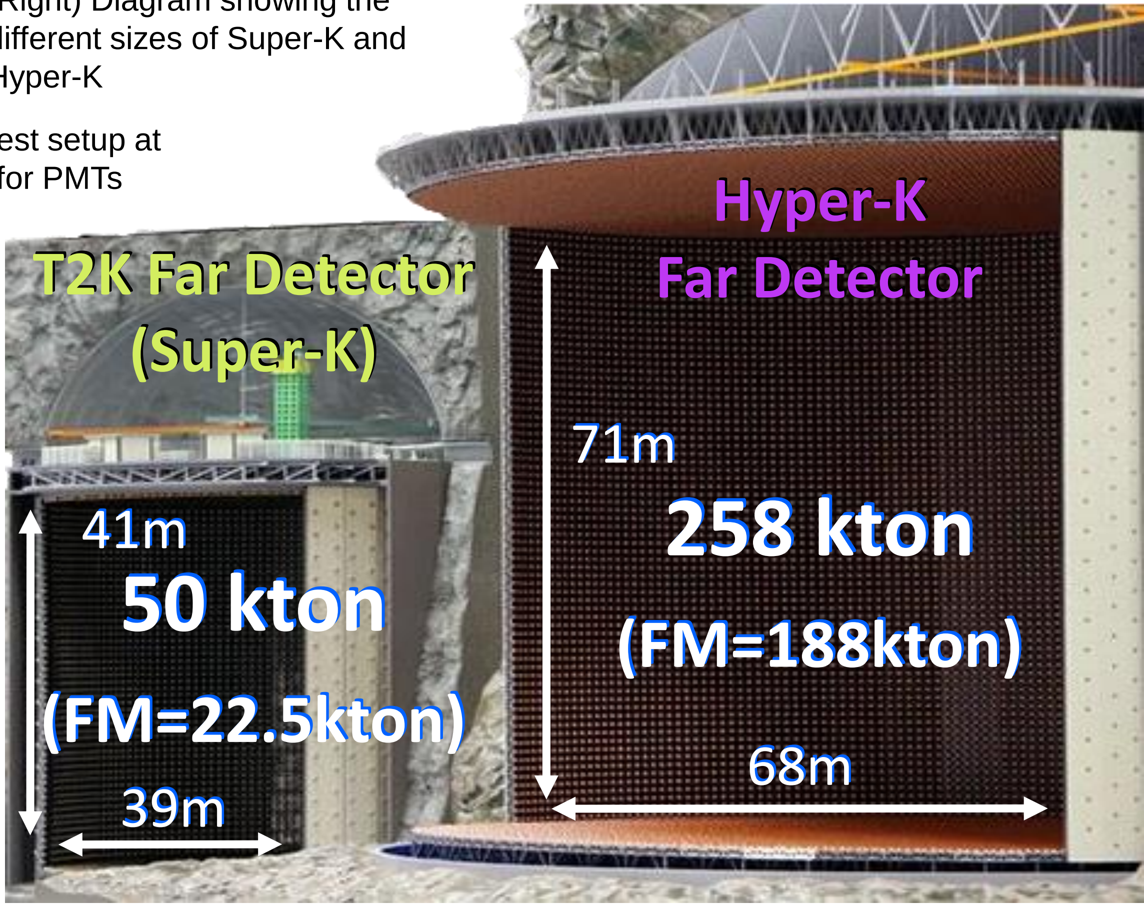
Hyper-Kamiokande

- New detector at Kamioka, 5x bigger than Super-K.
- Preparations being made here by testing PMTs at CERN.
- With detector and beam upgrade, Hyper-K will probe most phase space for two CP-violating phase values.

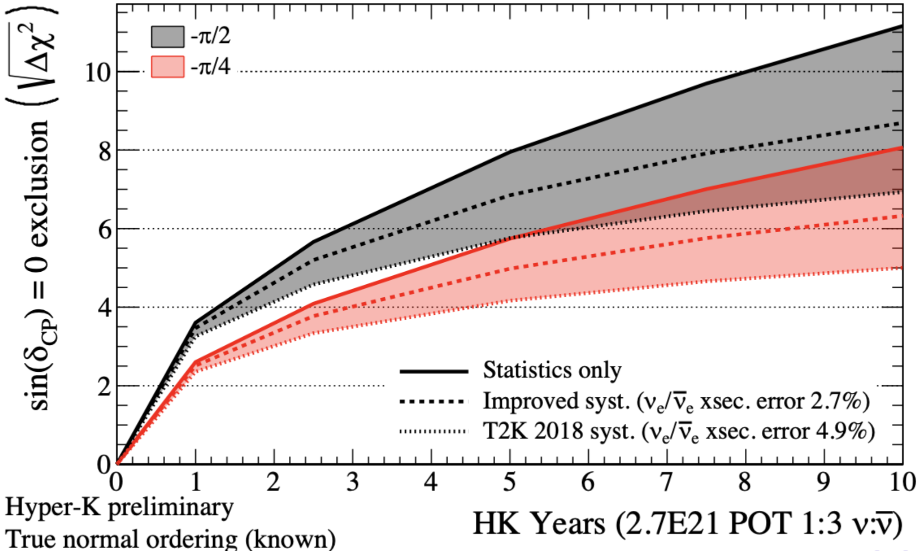
(Right) Diagram showing the different sizes of Super-K and Hyper-K

(Left) Test setup at CERN for PMTs





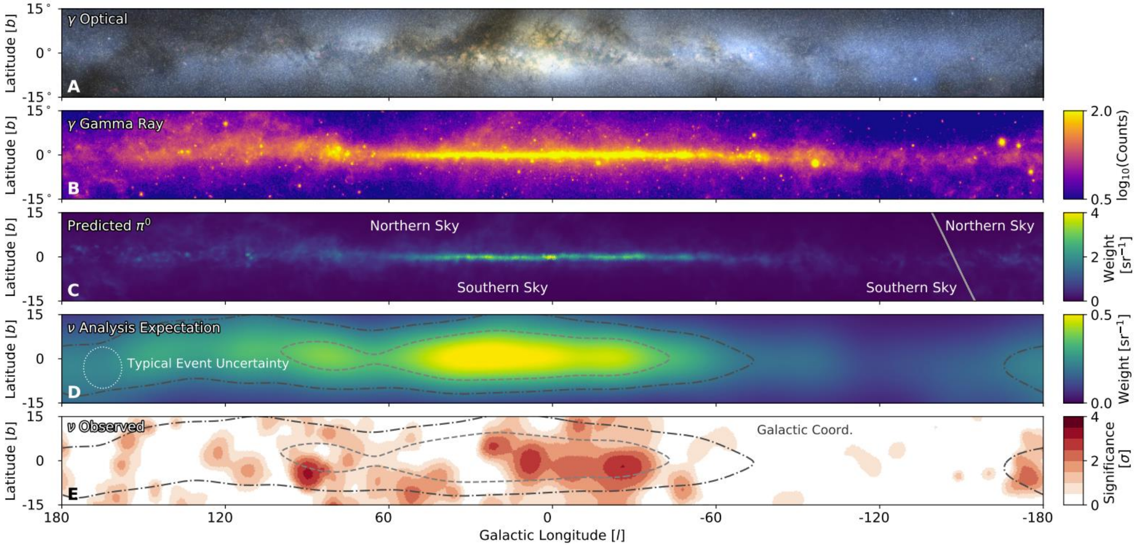
CP-violating phase sensitivity given beam upgrade and Hyper-K detector.

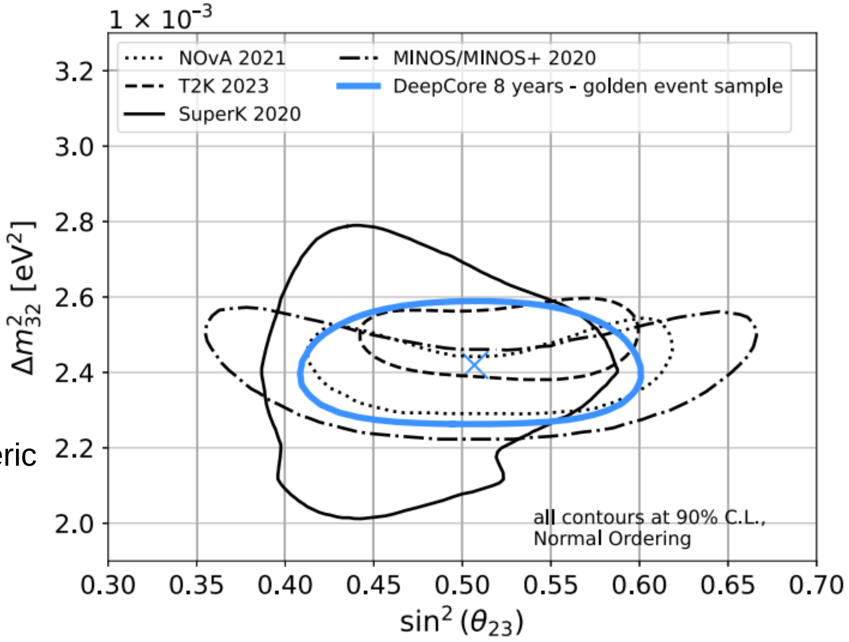


High Energy (>>1 GeV): IceCube

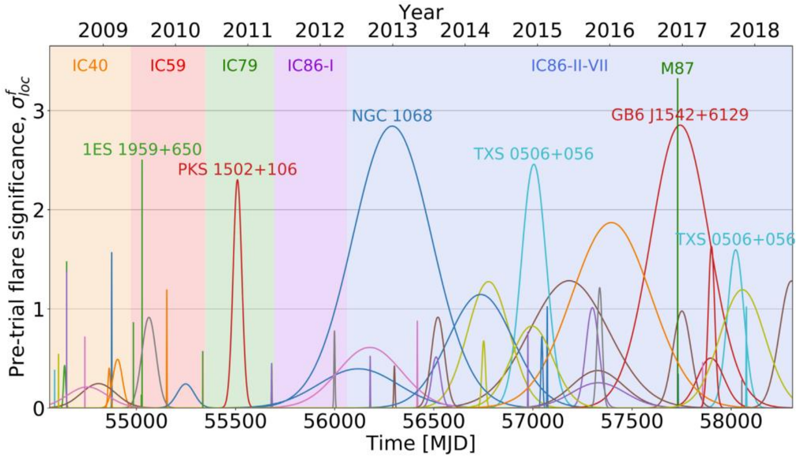
- A cubic kilometer water Cherenkov detector of PMTs buried in a kilometer of ice.
- Combination of astronomy using neutrinos and atmospheric neutrino oscillation measurements.

Observation of neutrinos from the galactic core.





Recent neutrino oscillation results from IceCube and DeepCore using atmospheric neutrino data.



Analysis of astrophysical neutrinos from various sources plotted as a function of time. Combining every source provides an excess of >3 compared to background only.

UNIVERSITÉ DE GENÈVE

FASER/FASERnu and SND@LHC

Detection of neutrinos from emulsion data announced.

Combination of emulsion detectors (FASERnu) and scintillating detectors.

More information from yesterday's talk.

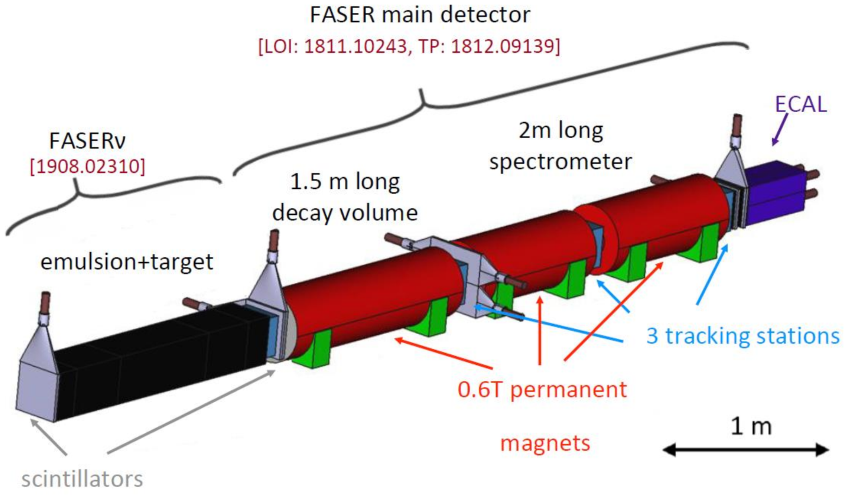


Diagram of FASER

Please see the exciting talks from yesterday!

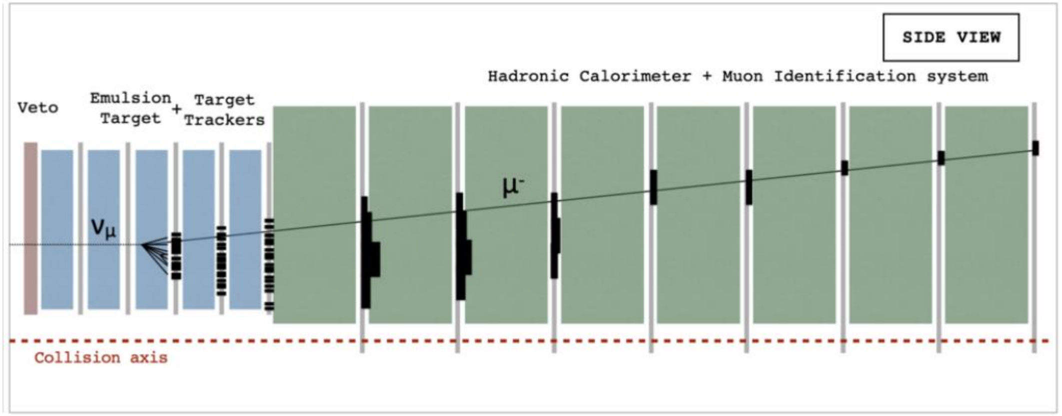


Diagram of the SND@LHC detector.

Conclusion

- Wide range of neutrino physics being done in Switzerland with different detector techniques and implications throughout high energy physics.
- Presentation surveyed:
  - Lowest energies:
    - $0\nu\beta\beta$ searches
    - Development of detection methods in future $0\nu\beta\beta$ searches
  - GeV-scale energy:
    - Detector development for T2K, Fermilab's SBN program, and ProtoDUNE Single-Phase
    - Oscillation analysis from MicroBooNE of the MiniBooNE anomaly
    - Future detector development for DUNE and Hyper-Kamiokande
  - Highest energies:
    - Astrophysical detection of neutrinos from IceCube
    - Detection of collider-induced neutrinos from FASER and SND@LHC

Many exciting adventures on the horizon for all universities in relevant projects with new detectors, new analyses, and new frontiers.

Cows excited about neutrino physics
(Images from SRF/RTS)