Experiments with **neutrinos**

8th mini-school on Particle and Astroparticle Physics

15 May 2023

LABORATÓRIO DE INSTRUMENTAÇÃO
E FÍSICA EXPERIMENTAL DE PARTÍCULAS
partículas e tecnologia

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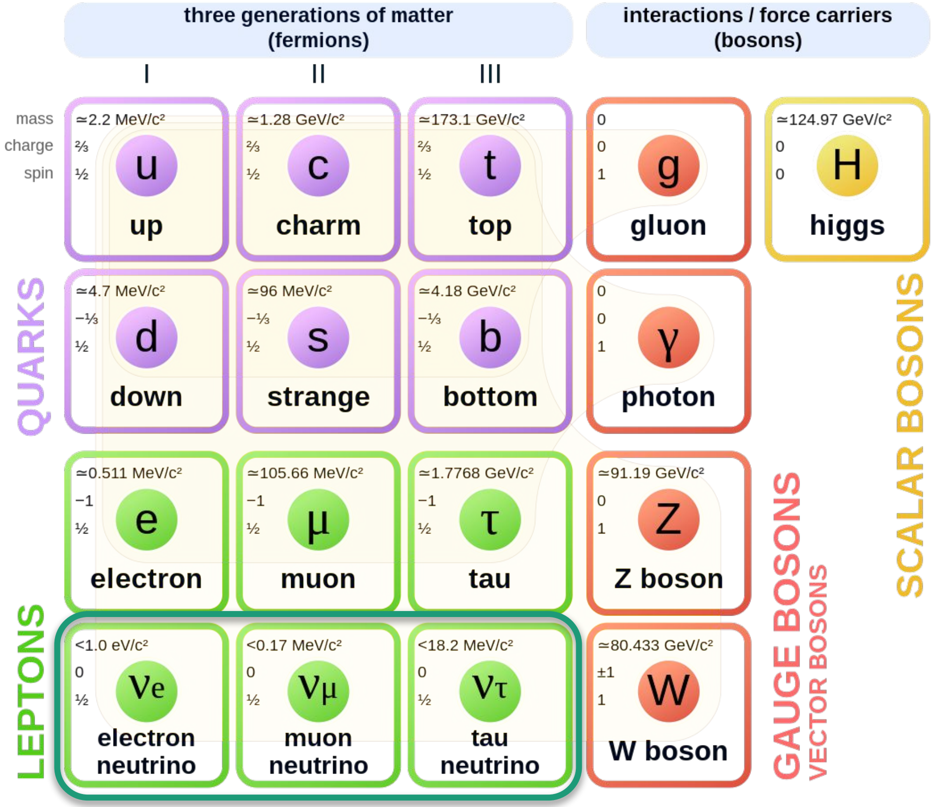
The Standard Model

- Neutrinos are *special*:
  - Electrically neutral fermions.
    - Only weak interactions.
  - Tiny (but non-zero!) masses.

- Neutrinos play important roles in our understanding of nature:
  - Matter-antimatter (a)symmetry?
  - Why three generations of matter?
  - What is the nature of mass?

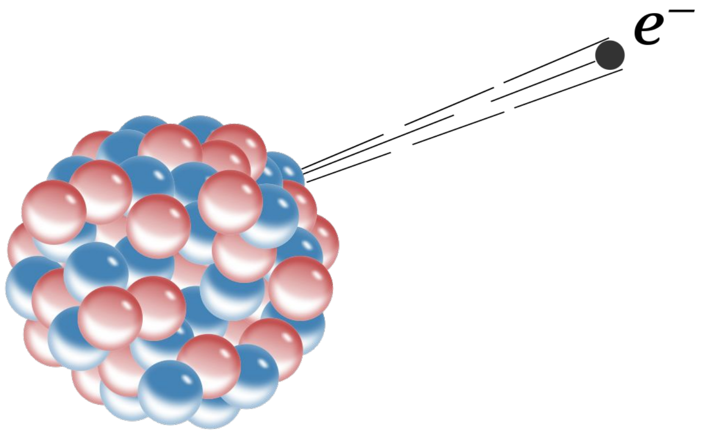


Neutrino history

Neutrino pre-history

- A radioactive puzzle: the continuous spectrum of "beta-rays".
  - Transition between two stable isotopes via the emission of a beta ray.
  - Radiation energy should be **equal to the difference** of the isotope **masses**.

> At the present stage of atomic theory, however, we may say that we have **no argument**, either empirical or theoretical, **for upholding the energy principle** in the case of β-ray disintegrations.
>
> Niels Bohr



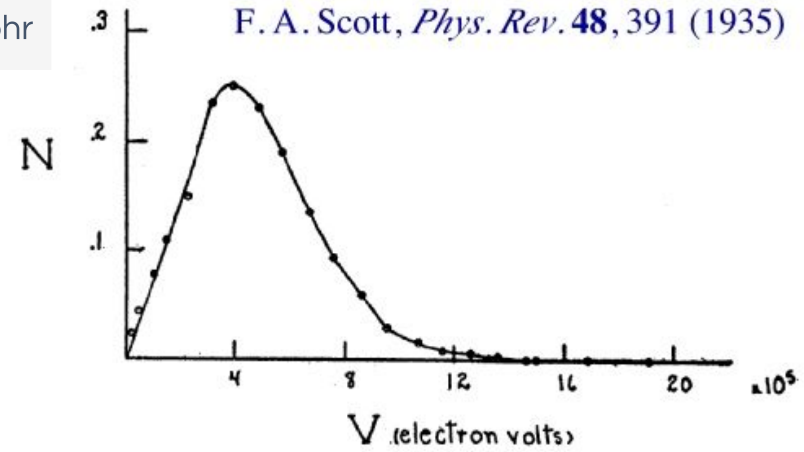
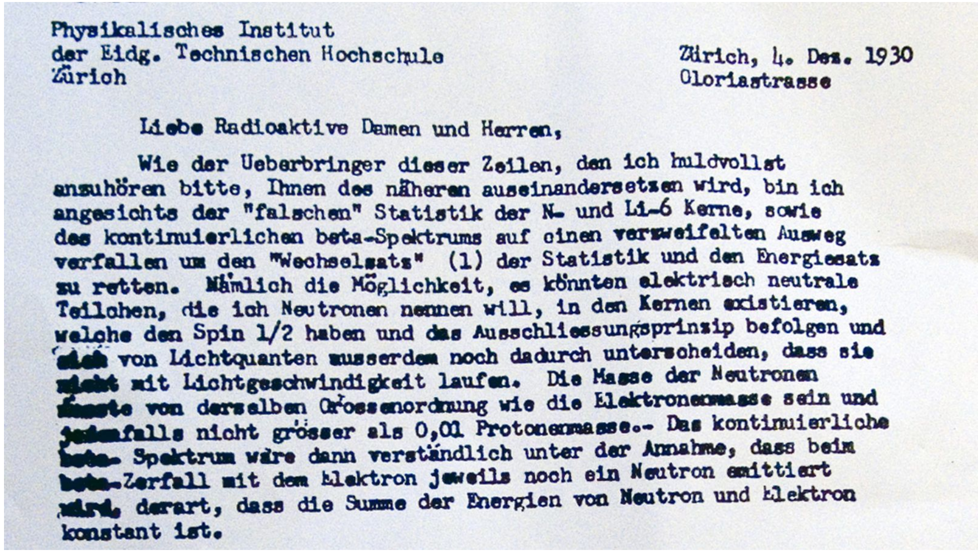


FIG. 5. Energy distribution curve of the beta-rays.

A desperate remedy (1930)

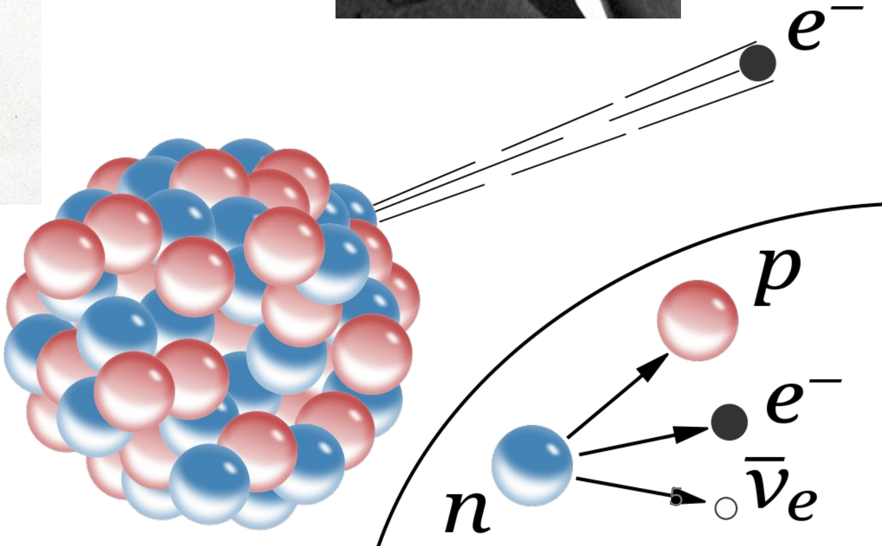


Physikalisches Institut
der Eidg. Technischen Hochschule
Zürich

Zürich, 4. Dez. 1930
Gloriastrasse

Liebe Radioaktive Damen und Herren,

Wie der Ueberbringer dieser Zeilen, den ich huldvollst anzuhören bitte, Ihnen des näheren auseinandersetzen wird, bin ich angesichts der "falschen" Statistik der N- und Li-6 Kerne, sowie des kontinuierlichen beta-Spektrums auf einen verzweifelten Ausweg verfallen um den "Wechselsatz" (1) der Statistik und den Energiesatz zu retten. Nämlich die Möglichkeit, es könnten elektrisch neutrale Teilchen, die ich Neutronen nennen will, in den Kernen existieren, welche den Spin 1/2 haben und das Ausschliessungsprinzip befolgen und sich von Lichtquanten ausserdem noch dadurch unterscheiden, dass sie nicht mit Lichtgeschwindigkeit laufen. Die Masse der Neutronen müsste von derselben Grössenordnung wie die Elektronenmasse sein und jedenfalls nicht grösser als 0,01 Protonenmasse.- Das kontinuierliche beta- Spektrum wäre dann verständlich unter der Annahme, dass beim beta-Zerfall mit dem Elektron jeweils noch ein Neutron emittiert wird, derart, dass die Summe der Energien von Neutron und Elektron konstant ist.



A desperate remedy (1930)

Dear Radioactive Ladies and Gentlemen,

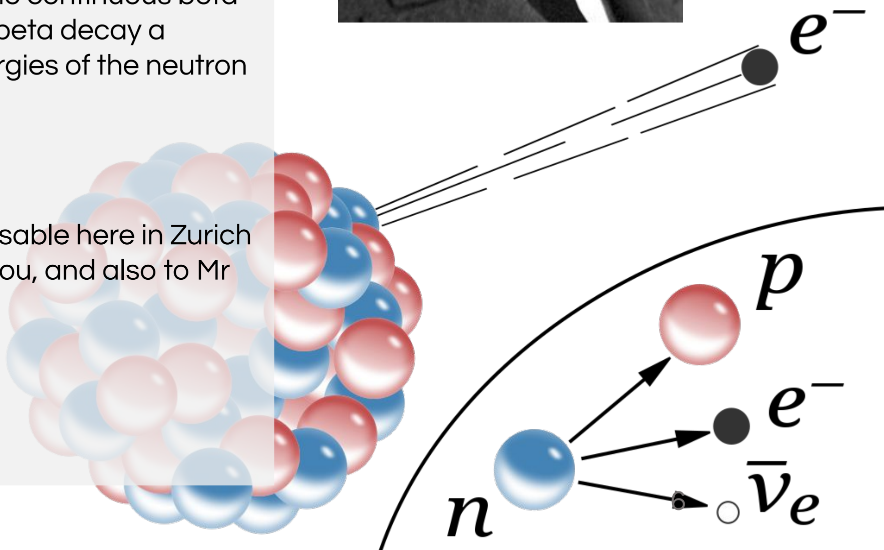
As the bearer of these lines, to whom I graciously ask you to listen, will explain to you in more detail, how because of the "wrong" statistics of the N and Li^6 nuclei and the continuous beta spectrum, **I have hit upon a desperate remedy to save the "exchange theorem" of statistics and the law of conservation of energy.** Namely, the possibility that **there could exist in the nuclei electrically neutral particles, that I wish to call neutrons, which have spin 1/2 and obey the exclusion principle** and which further differ from light quanta in that they do not travel with the velocity of light. The **mass of the neutrons should be of the same order of magnitude as the electron mass and in any event not larger than 0.01 proton masses.** The continuous beta spectrum would then become understandable by the assumption that in beta decay a neutron is emitted in addition to the electron such that the sum of the energies of the neutron and the electron is constant...

...

Unfortunately, I cannot appear in Tubingen personally since I am indispensable here in Zurich because of a ball on the night of 6/7 December. With my best regards to you, and also to Mr Back.

Your humble servant,

W. Pauli



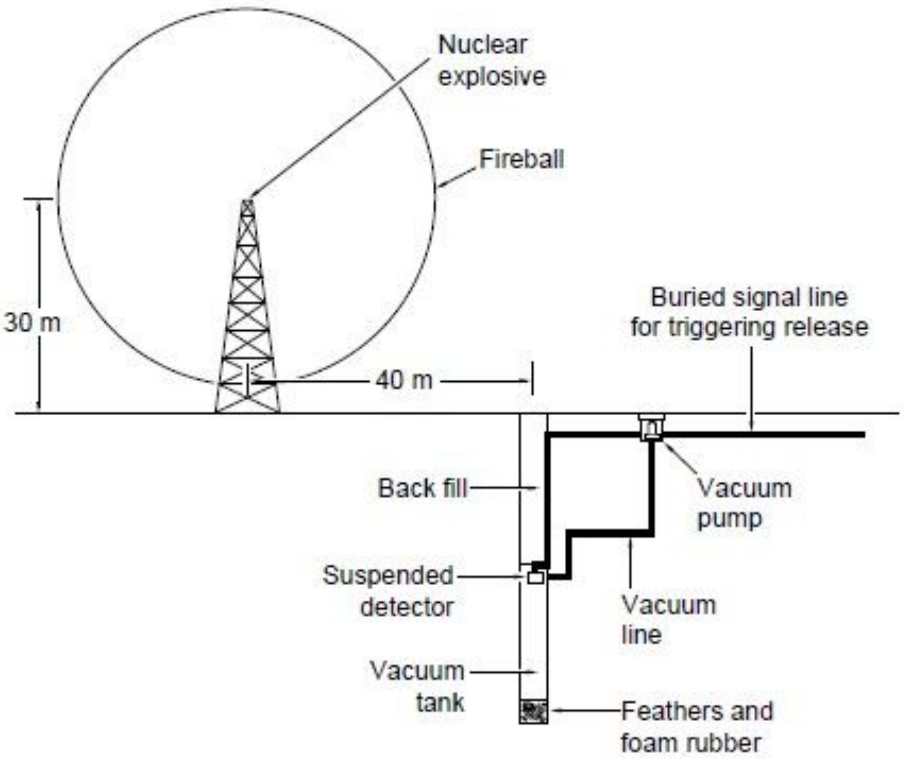
The discovery of neutrinos

- Experiment proposed by F. Reines and C. Cowan in 1951.

- Need a large flux of (anti)neutrinos:
  - Get as close as possible to a **nuclear explosive detonation.**

- Detector needs to be protected from the shockwave:
  - Dig a whole.
  - Create a **vacuum.**
  - **Drop the detector** in the vacuum when the nuclear explosive is detonated.

- This idea didn't materialise...

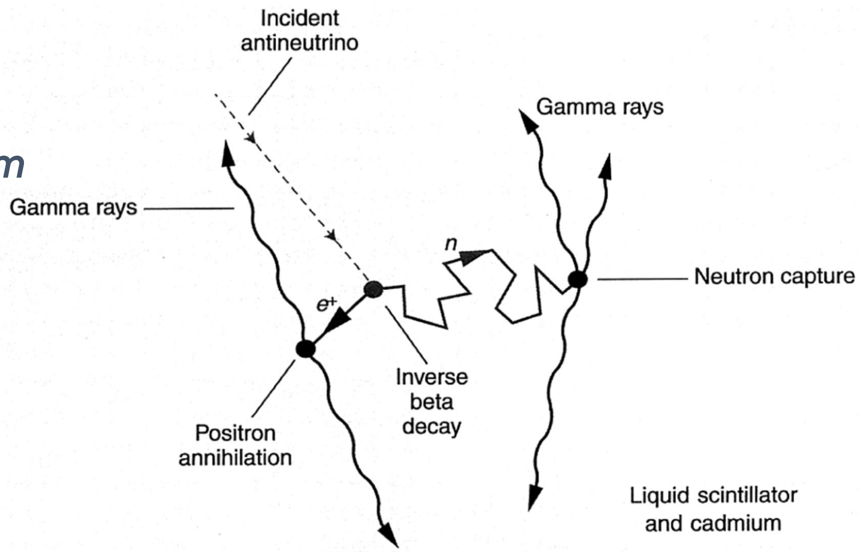


The discovery of neutrinos (1956)

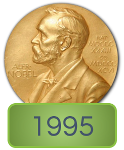
- Following the initial proposal, Reines and Cowan changed their strategy.

- Place detector very close to **nuclear reactor**: intense antineutrino flux.
- Large target tanks filled with water and ***cadmium*** chloride.
- Antineutrinos interact via inverse beta decay: $\overline{\nu} + p \rightarrow e^+ + n$.
  - e^+ annihilates to produce **pair of** γ
  - Capture of **n** on Cd produces ***delayed*** γ.

- Measured cross-section: **$\sim 10^{-44}$cm^2**.
  - Proton-proton collisions at LHC: $\sim 10^{-25}$ cm^2
  - Probability of ν interacting with an electron while traversing the earth: 10^{-11}



The discovery of neutrinos (1956)



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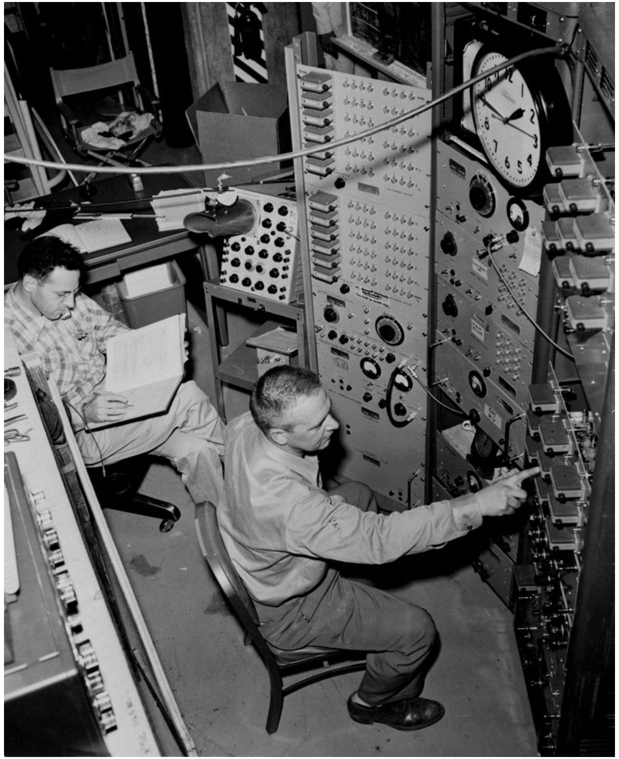
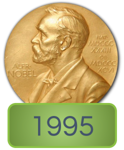
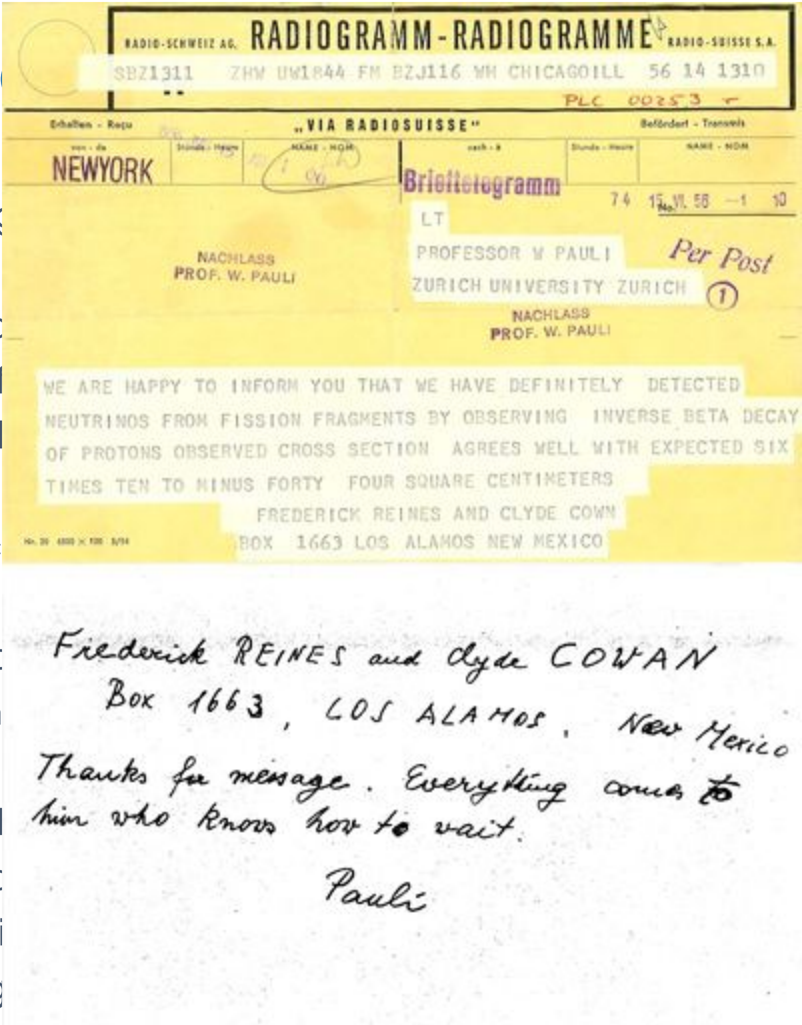


The disc… 1956)



- Following the initial p…
  changed their strateg…
- Place detector very c…
  intense antineutrino f…
- Large target tanks fill…
  chloride.
- Antineutrinos interac…
  $\overline{\nu} + p \rightarrow e^+ + n$.
  - e^+ annihilates to…
  - Capture of **n** on…
- Measured cross-sect…
  - Proton-proton c…
  - Probability of ν i…
    while traversing…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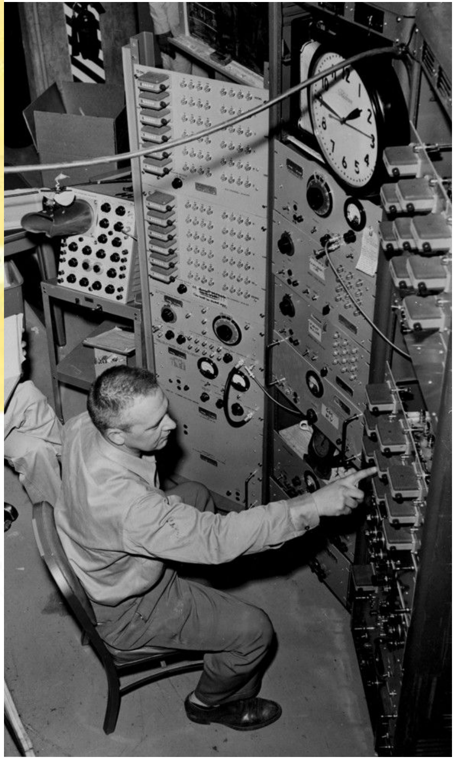
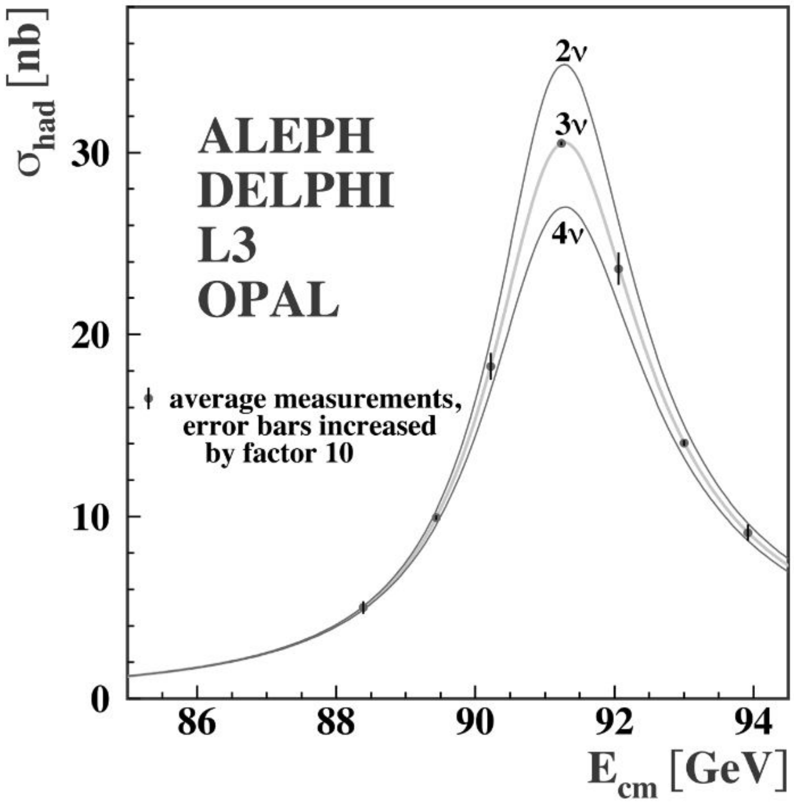
PROFESSOR W PAULI
ZURICH UNIVERSITY ZURICH
Per Post
NACHLASS PROF. W. PAULI
WE ARE HAPPY TO INFORM YOU THAT WE HAVE DEFINITELY DETECTED NEUTRINOS FROM FISSION FRAGMENTS BY OBSERVING INVERSE BETA DECAY OF PROTONS OBSERVED CROSS SECTION AGREES WELL WITH EXPECTED SIX TIMES TEN TO MINUS FORTY FOUR SQUARE CENTIMETERS
FREDERICK REINES AND CLYDE COWAN
BOX 1663 LOS ALAMOS NEW MEXICO

Frederick REINES and Clyde COWAN
Box 1663, LOS ALAMOS, New Mexico
Thanks for message. Everything comes to him who knows how to wait.
Pauli

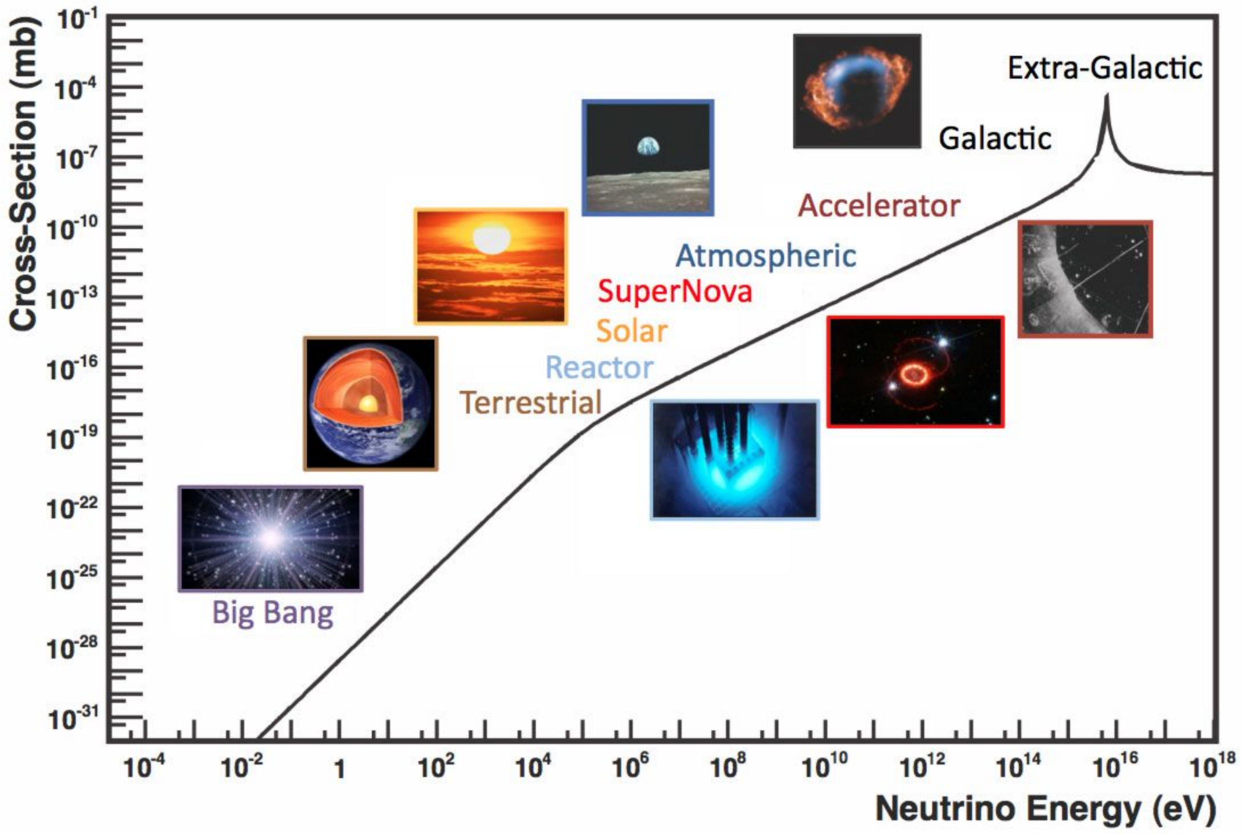


How many neutrinos?

- In the early 90s, the large electron-positron collider (**LEP**) at CERN made very precise measurements of the **Z-boson width.**
- The width is related to the particle lifetime by the uncertainty principle.
  - The **more decay final states**, the faster the decay, the **wider the resonance.**
  - **Each neutrino flavour** corresponds to **one** decay final state.
- Number of neutrinos: 2.9840 ± 0.0082.
  - **Three fermion generations!**
- Smallprint: only counts "**light**" neutrinos ($m << m_Z$) that **couple** to the Z boson.

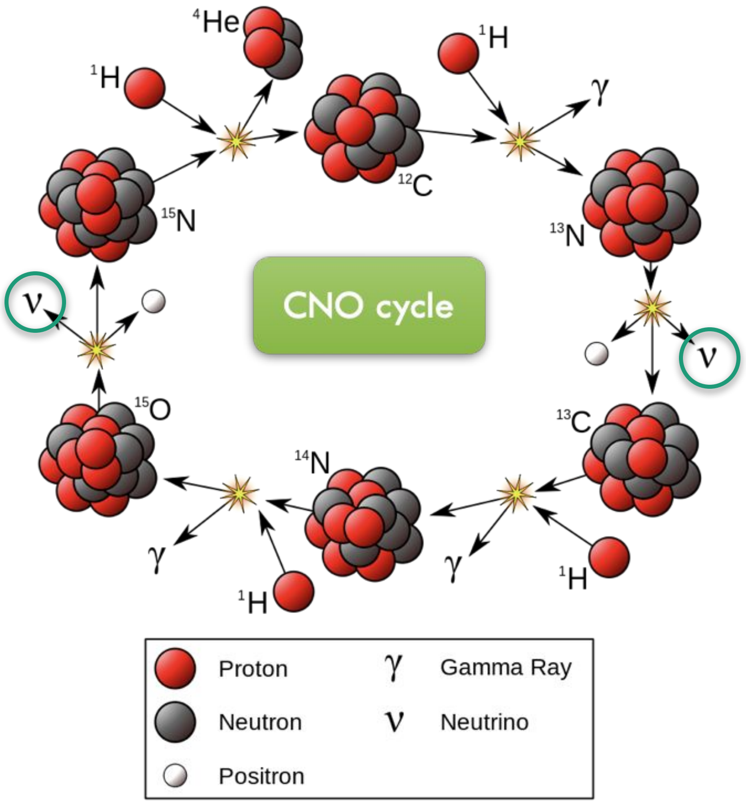


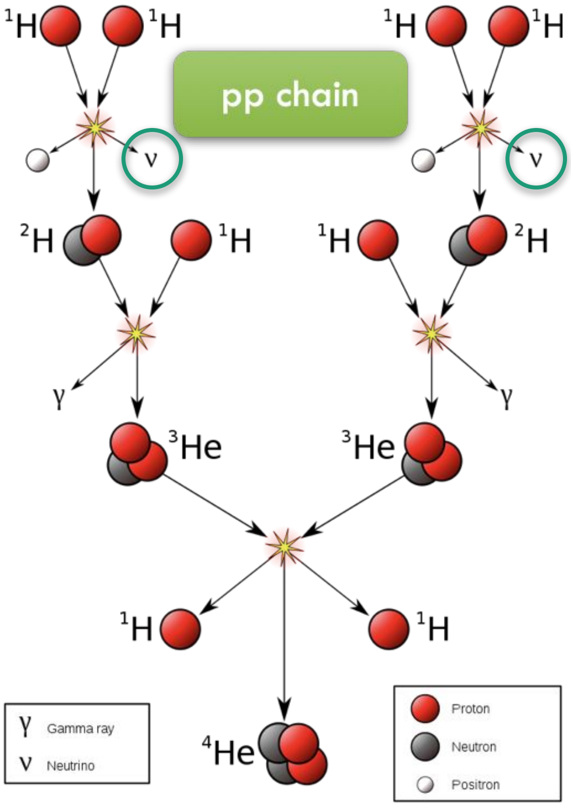
Neutrino sources



Neutrino mixing and oscillations

The Standard Solar Model





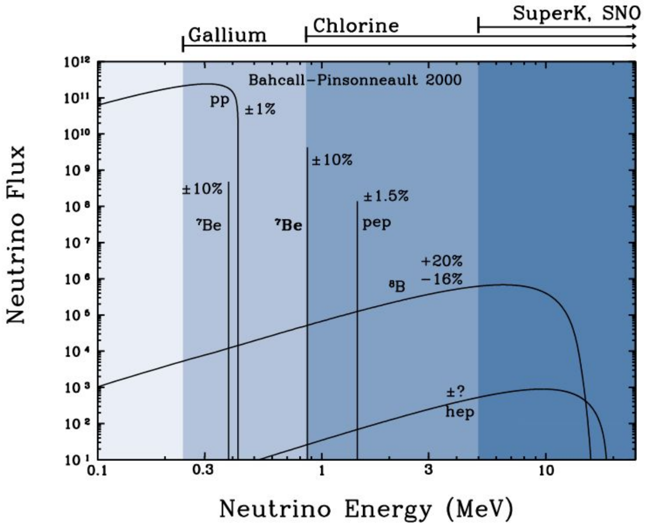
Solar neutrino puzzle

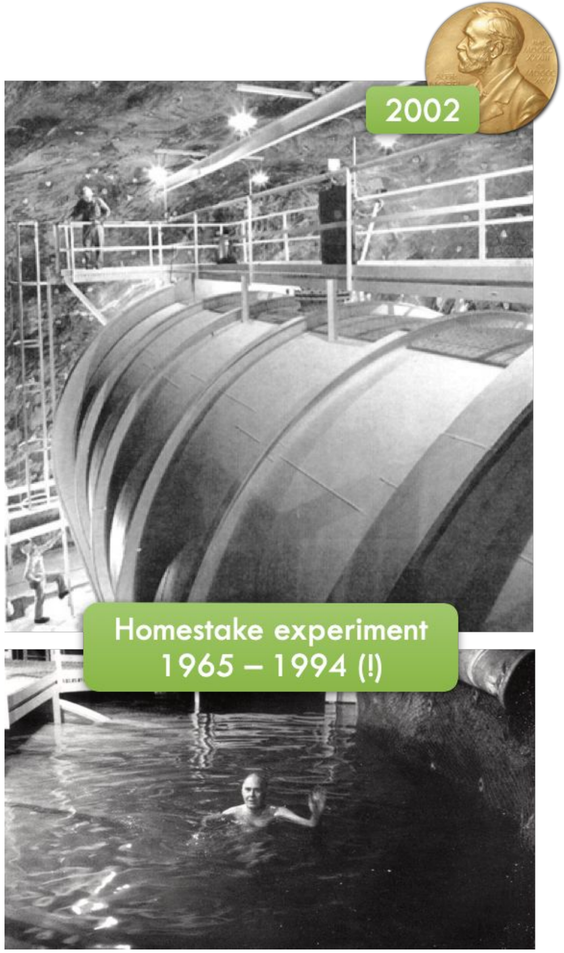
- In the late 1960s Ray Davis and John Bahcall set up an experiment to try to detect these solar neutrinos.

$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

- They detected the neutrinos, but not as many as they expected.
- This was soon confirmed by a number of other experiments.
  - Kamiokande, SAGE, GALLEX.

Problem with the Standard Solar Model?

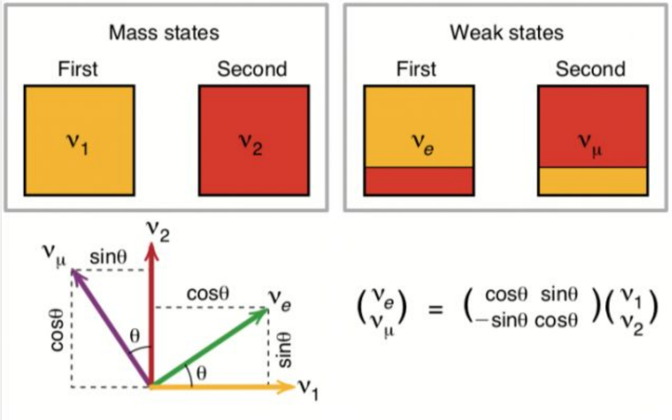


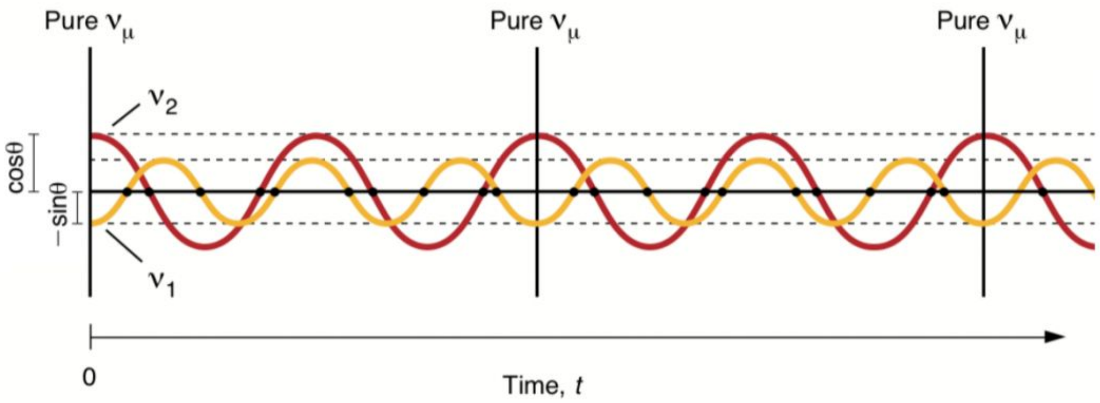


Neutrino mixing

- Neutrinos:
  - **Evolve** in (space-)time, obeying the Schrödinger equation (and relativistic counterparts).
  - **Interact** weakly with the other Standard Model fermions.

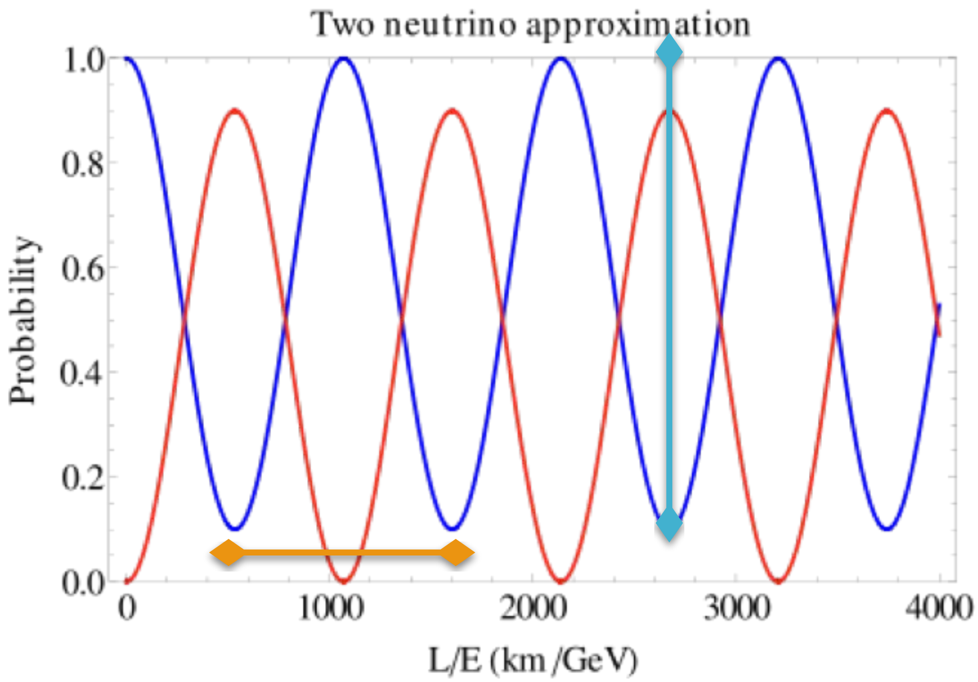
- The basis for describing the time-evolution of neutrinos and their weak interactions need not be the same.
  - **Mass** *vs* **Weak** interaction eigenstates.
  - **Consequence: neutrino oscillations!**





Credit: SLAC neutrino group; "Celebrating the neutrino", Los Alamos Science, 1997.

Neutrino oscillations



- **Mixing angle** determines the **amplitude.**
- **Squared-mass difference** determines the **frequency.**

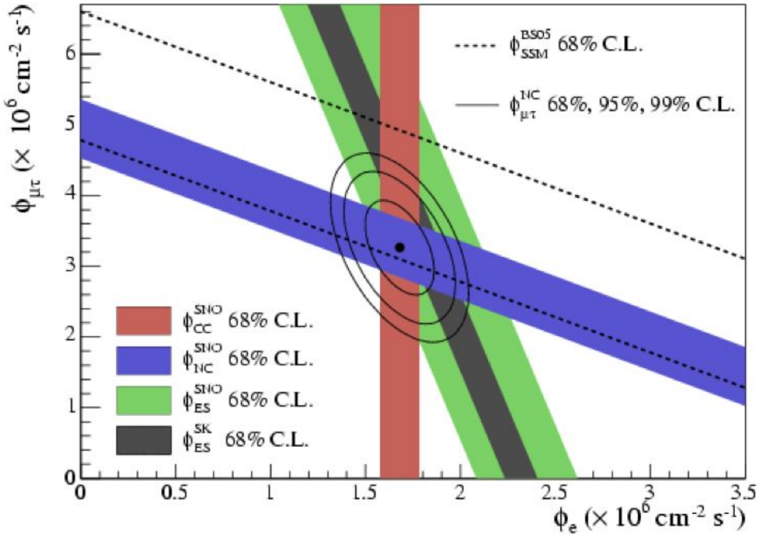
$$P(\nu_e \rightarrow \nu_\mu) = sin^2(2\theta)sin^2(1.27\Delta m^2 \frac{L}{E_\nu})$$

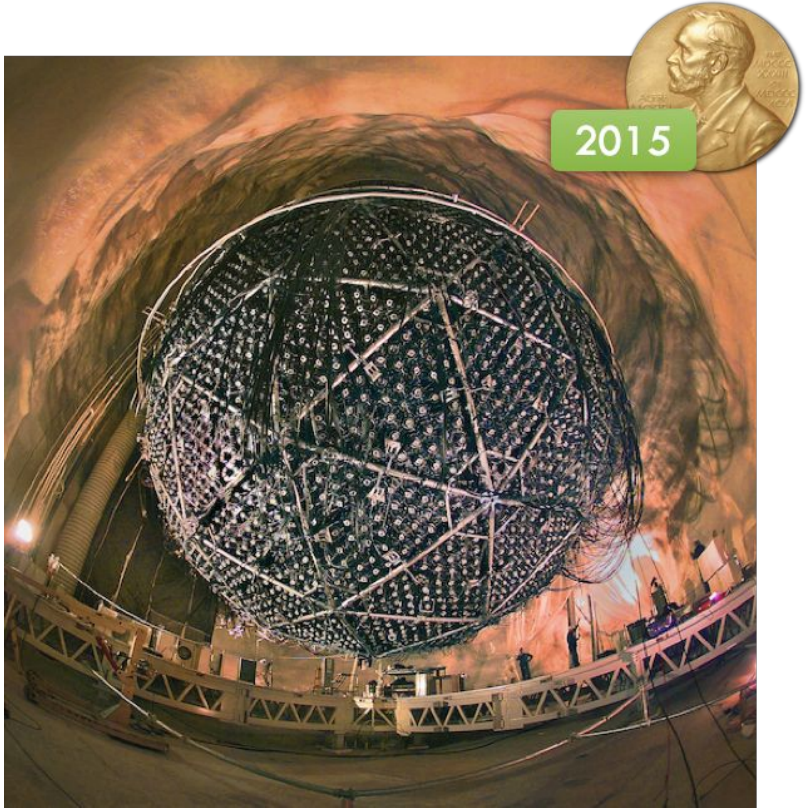
Oscillation amplitude

Oscillation frequency

The solar neutrino solution

- Two experiments provided confirmation of Ray Davis' observations: **Super-Kamiokande** and **SNO.**
- **SNO** measured **total neutrino flux** and **electron neutrino flux** independently.
- Confirmation that **total neutrino flux** from Standard Solar Model is **correct.**
- **Electron neutrinos** really are disappearing!





Pontecorvo-Maki-Nakagawa-Sakata

- **Three-flavour** neutrino mixing is described by the PMNS matrix.
    - Includes complex phase that **violates CP symmetry** if different from zero or pi.

Weak / Flavor states

"Atmospheric" parameters

Neutrinos may hold the key to explain how **matter** came to dominate over **antimatter** in the history of the Universe!

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}$$

$$\begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -\sin\theta_{13} e^{+i\delta_{CP}} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

"Reactor" parameters

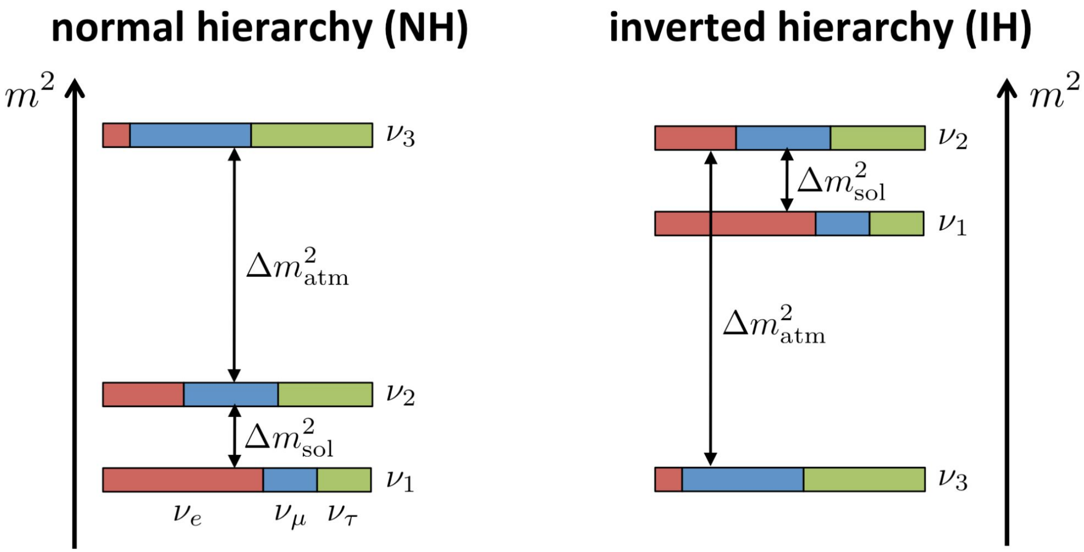
CP violating phase

"Solar" parameters

Mass states

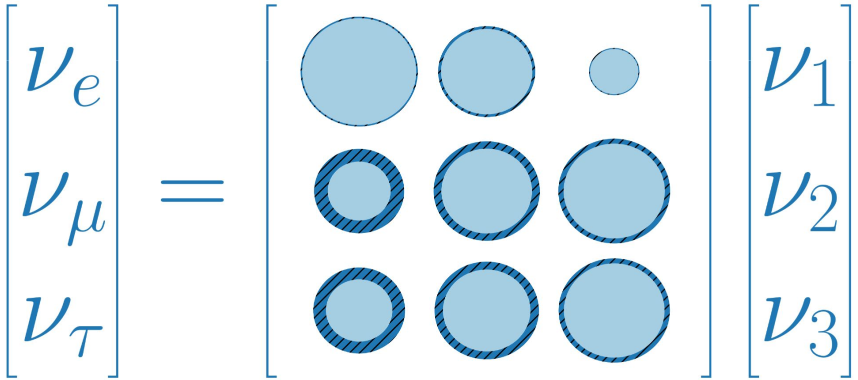
Neutrino mass ordering

- To **first order**, neutrino oscillation experiments are not sensitive to the sign of the squared-mass differences...
  - Currently, we do not know if $m_1 < m_3$ (**normal ordering**) or if $m_3 < m_1$ (**inverted ordering**).
- However, at **high energies**, coherent interactions with **matter** have an effect on **electron (anti)neutrinos**, but not on the other flavours!

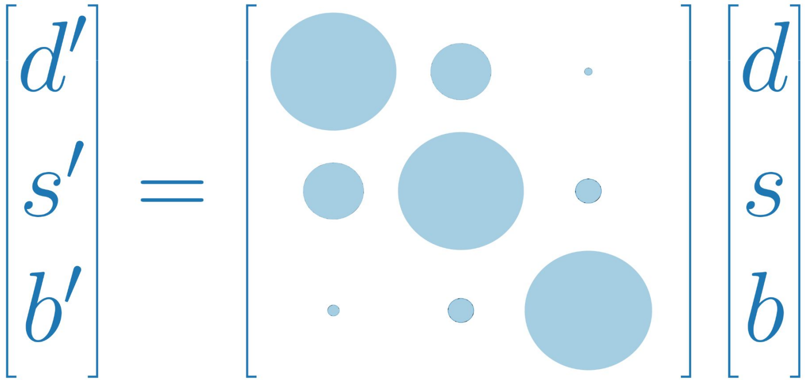


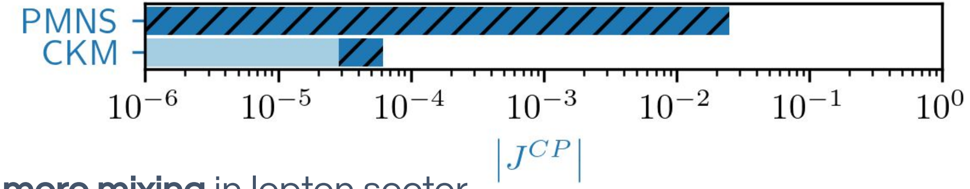
Lepton *vs* quark mixing

PMNS NuFit 5.1 (2021)



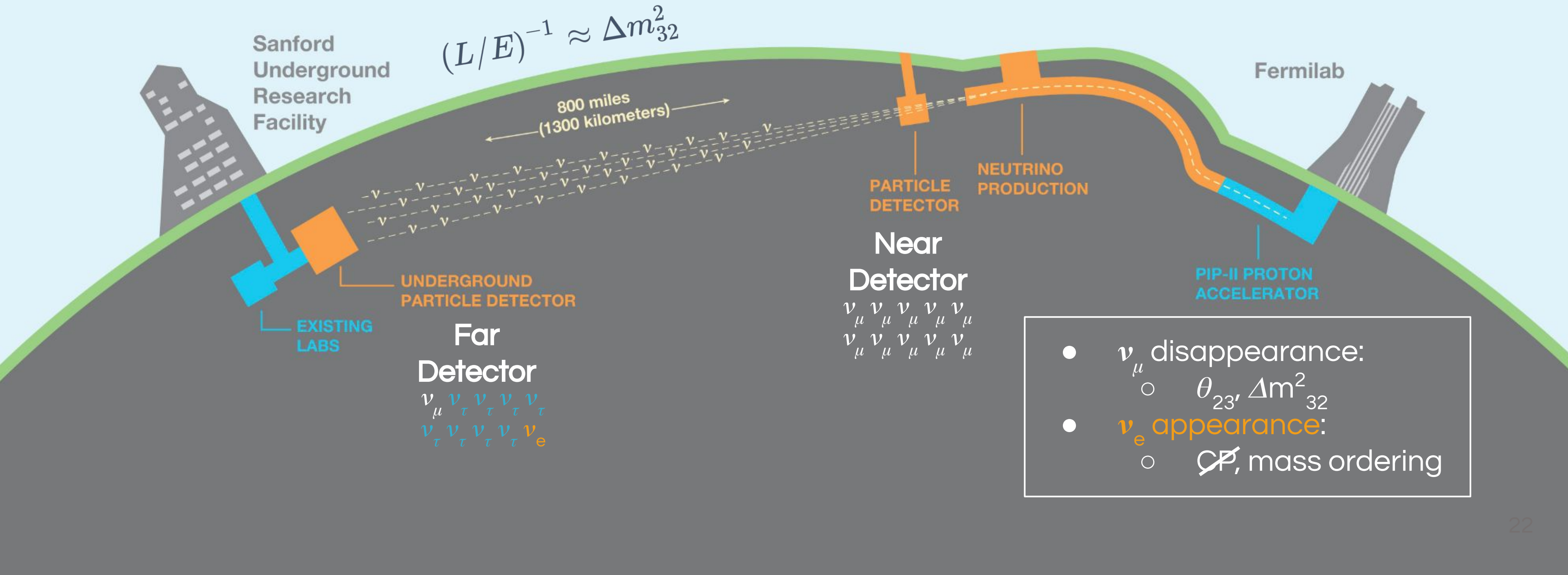
CKM CKMfitter Spring 21





- Much **more mixing** in lepton sector.
- **CP violation** can be up to three orders of magnitude larger!

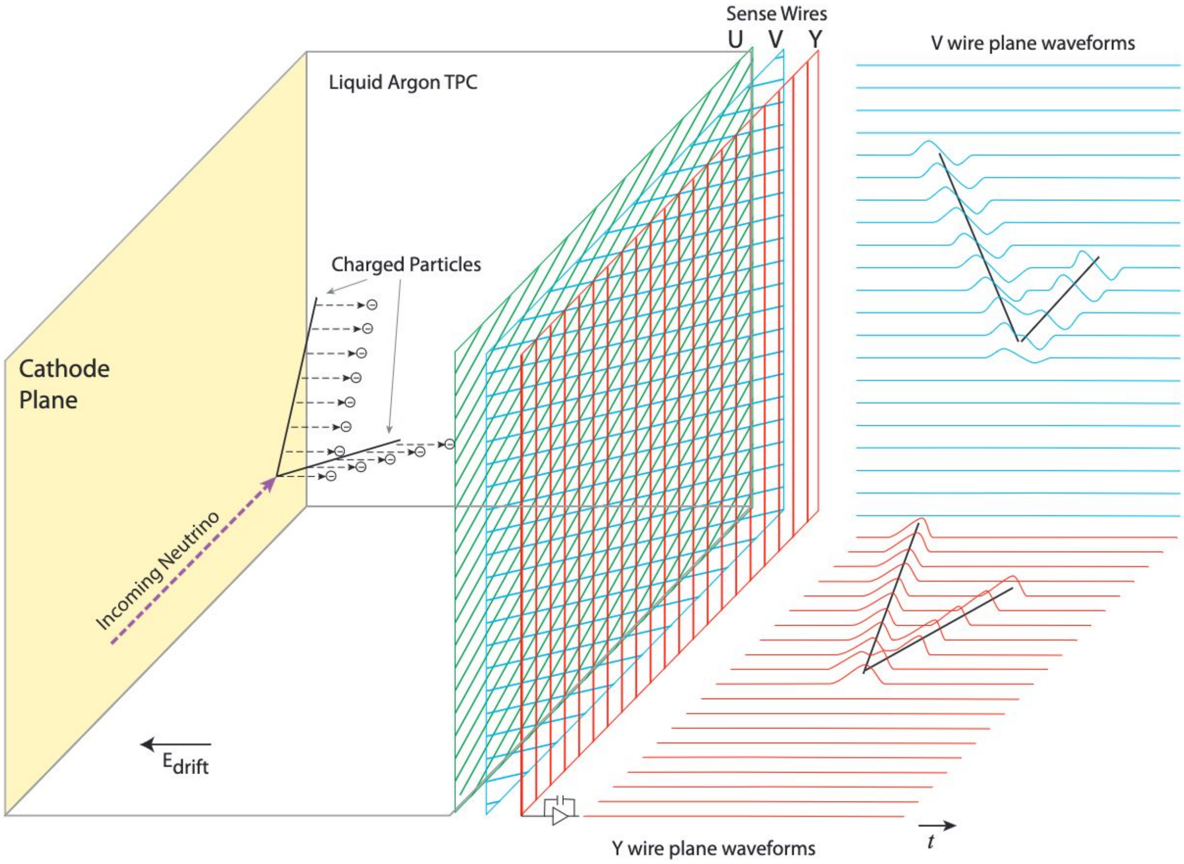
DEEP UNDERGROUND NEUTRINO EXPERIMENT

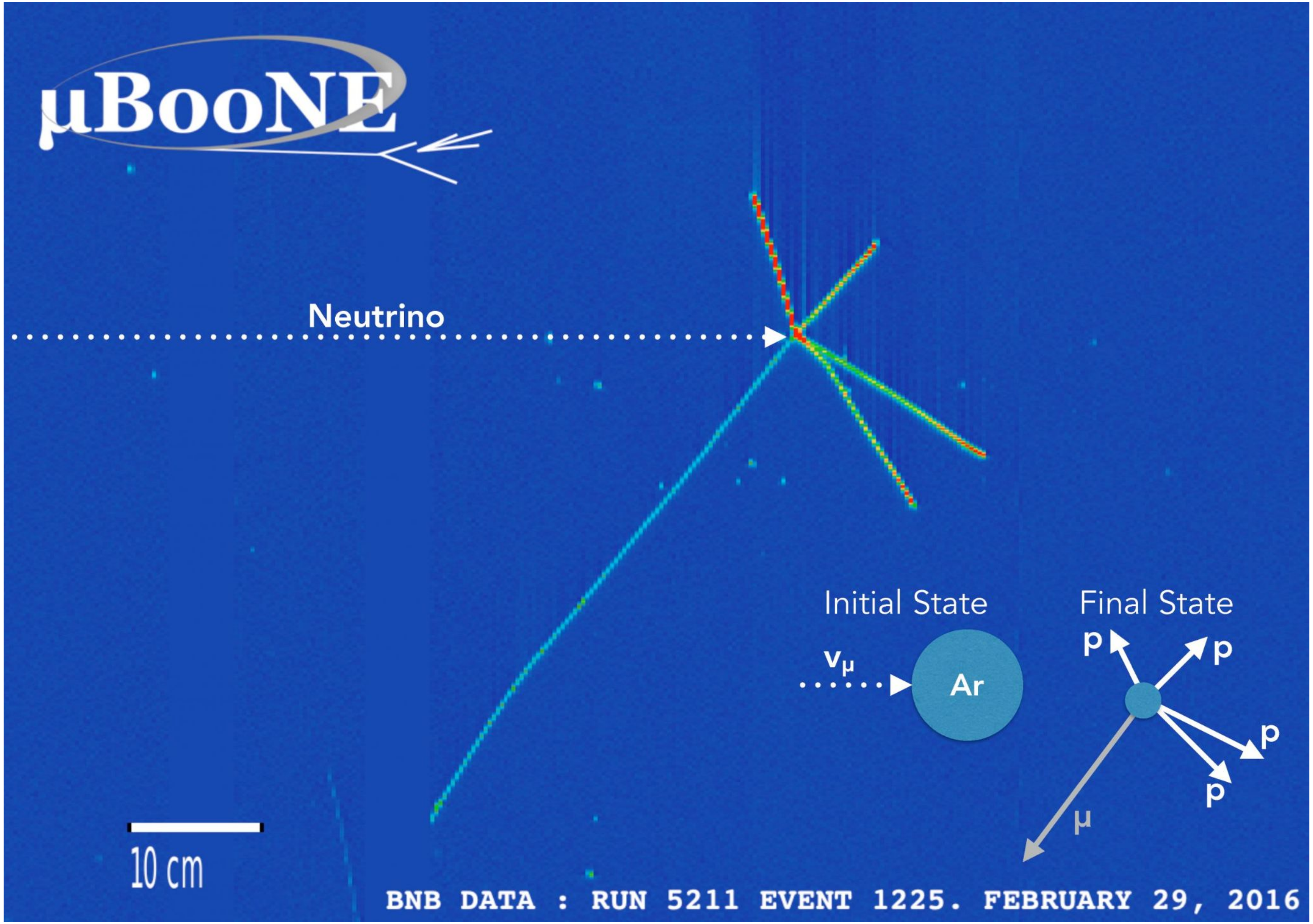


- ν_μ disappearance:
  - θ_{23}, Δm^2_{32}
- ν_e appearance:
  - ~~CP~~, mass ordering

Liquid-argon time-projection chamber

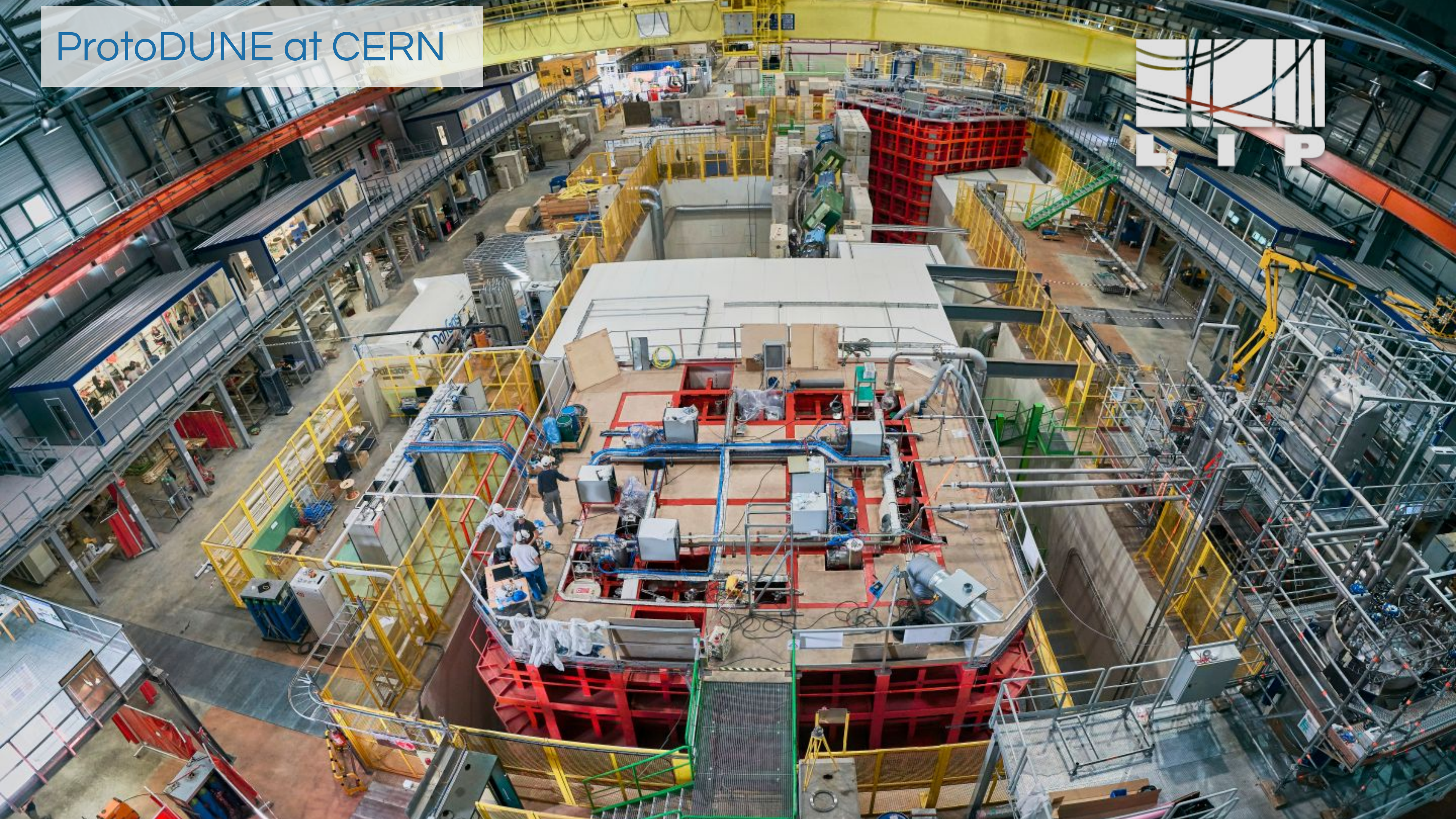
Advanced detector technology to meet DUNE's high-precision requirements.



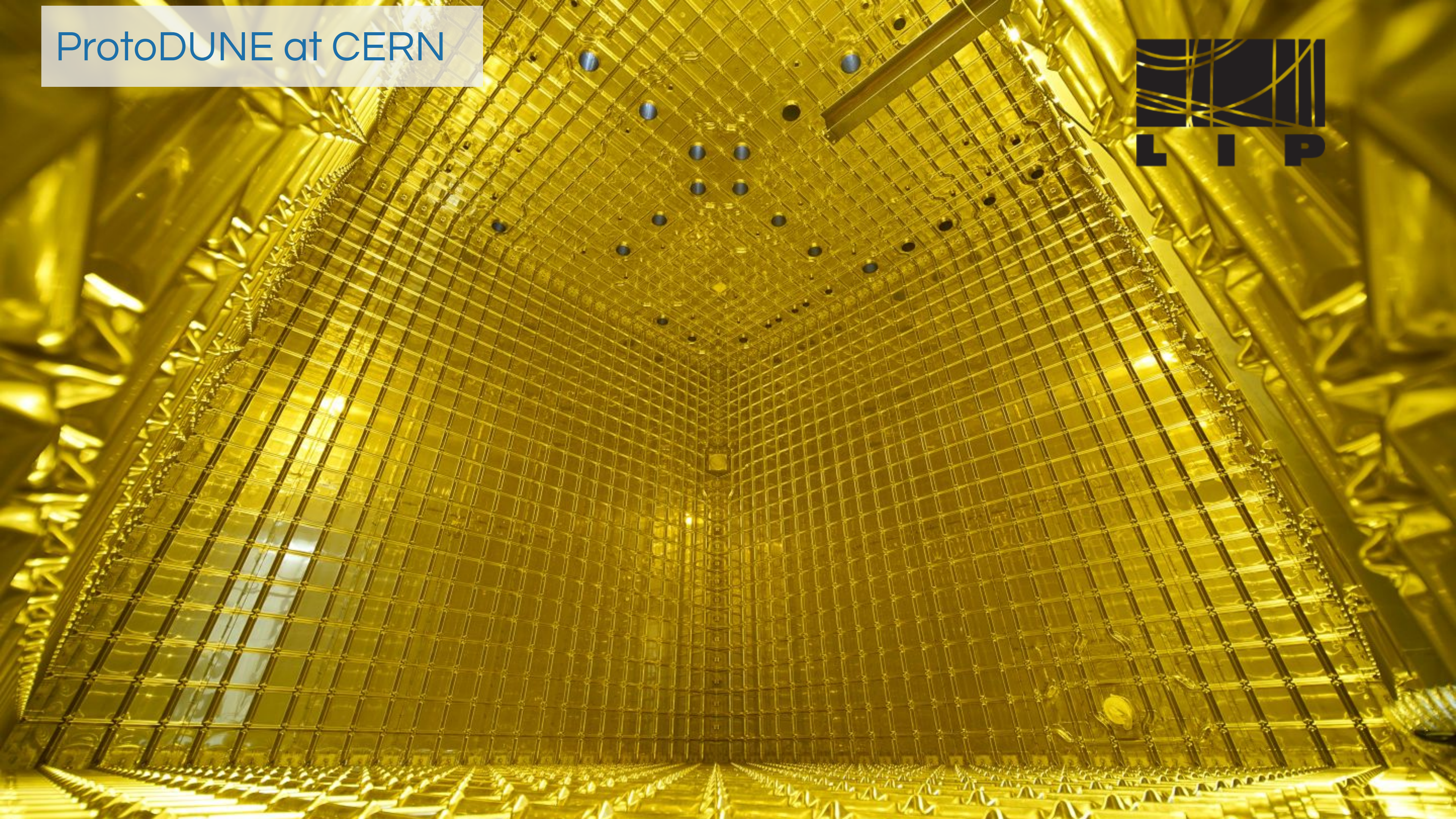


Credit: Fermilab

ProtoDUNE at CERN



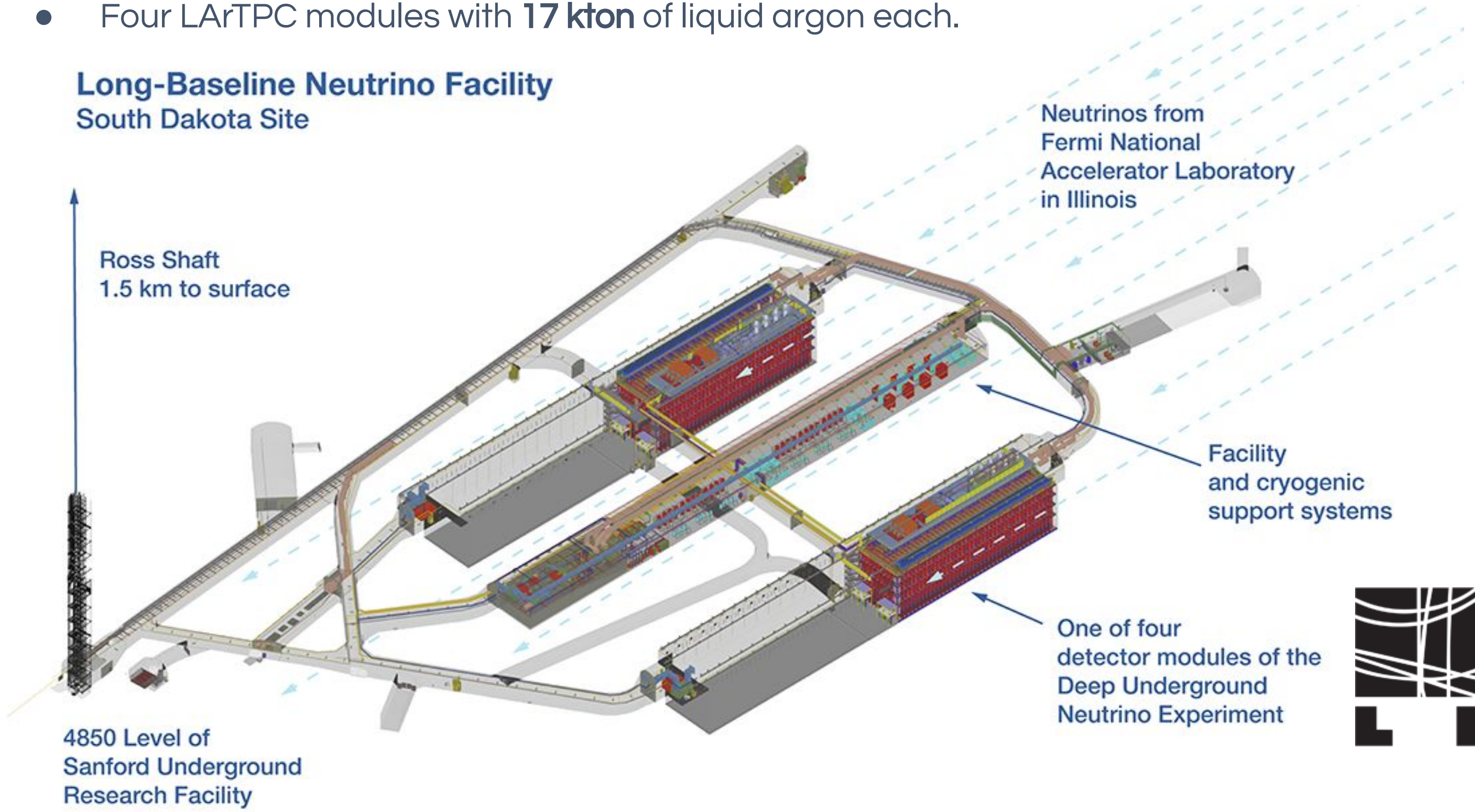
ProtoDUNE at CERN



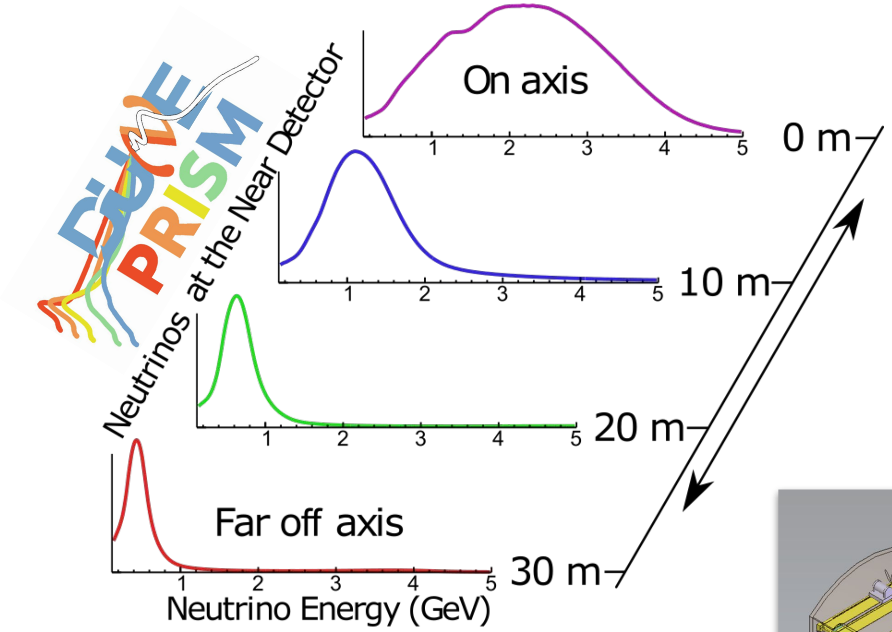
ProtoDUNE at CERN

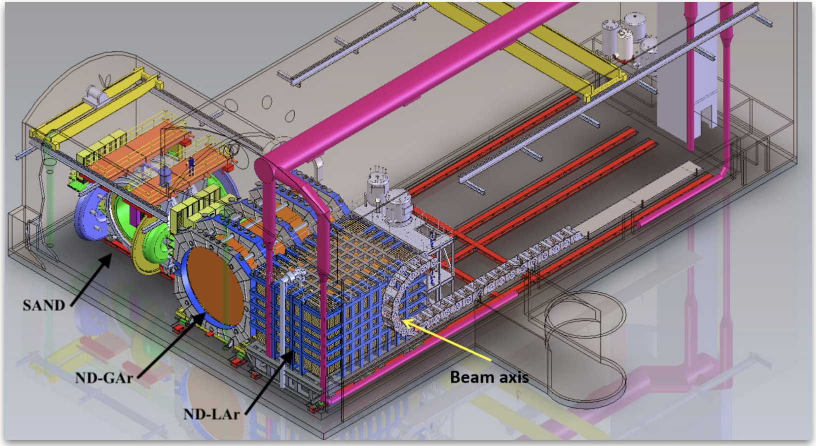
The DUNE far detectors

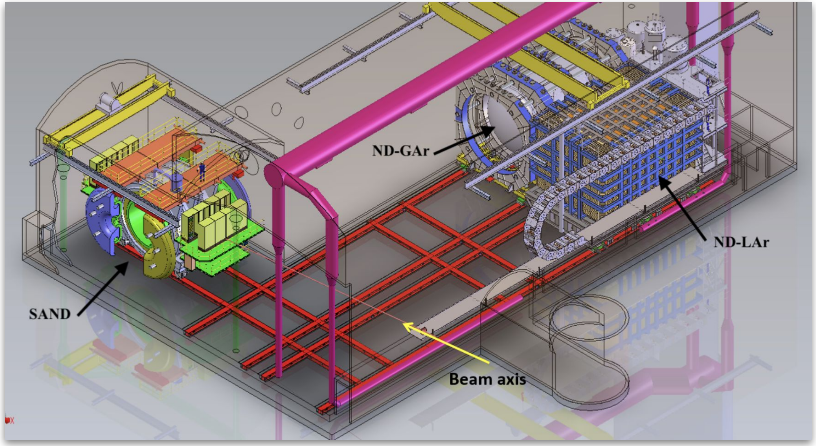
- 1.5 km underground in South Dakota.
- Four LArTPC modules with **17 kton** of liquid argon each.



DUNE near detectors

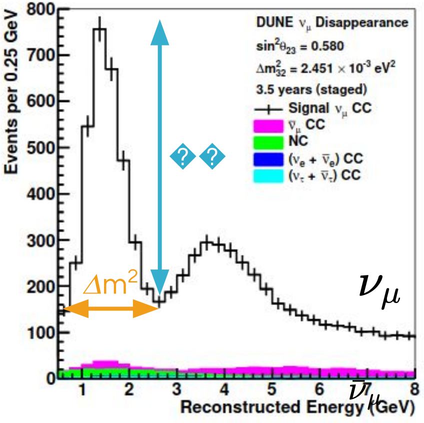


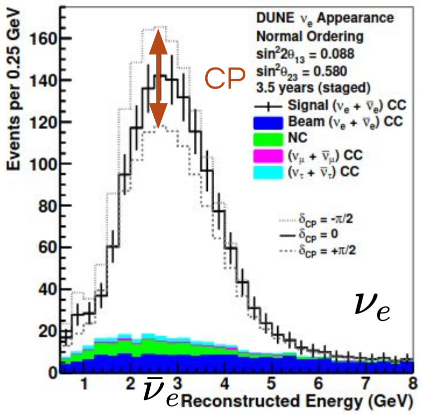




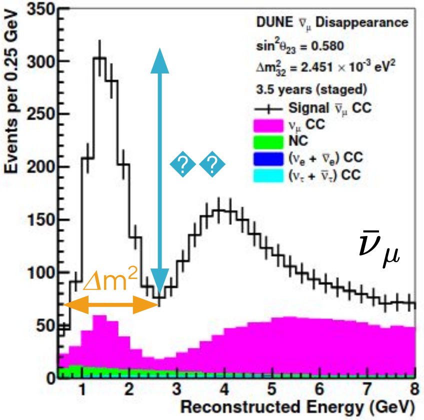
- Liquid and gaseous argon TPCs.
- **Moveable!**
    - "PRISM" effect allows for precise measurements of neutrino interactions.

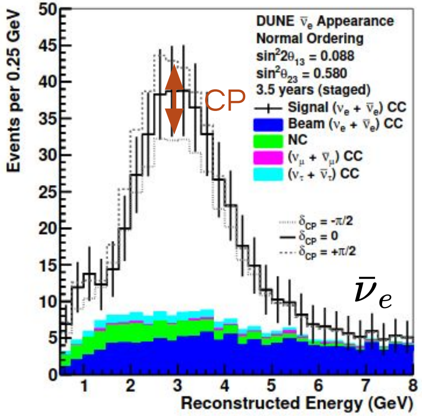
Neutrino oscillations with DUNE





Neutrinos

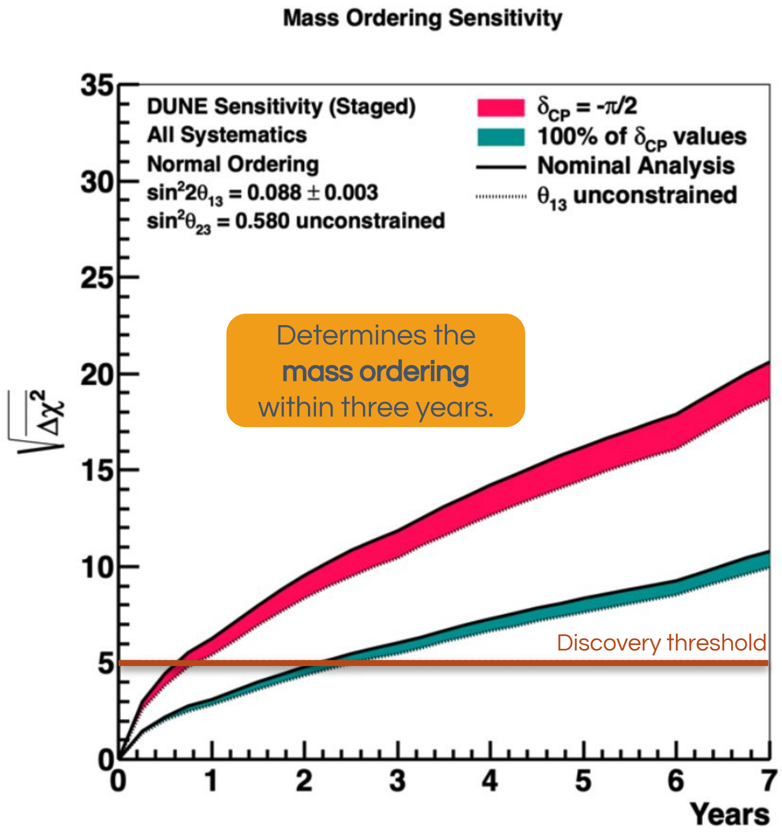


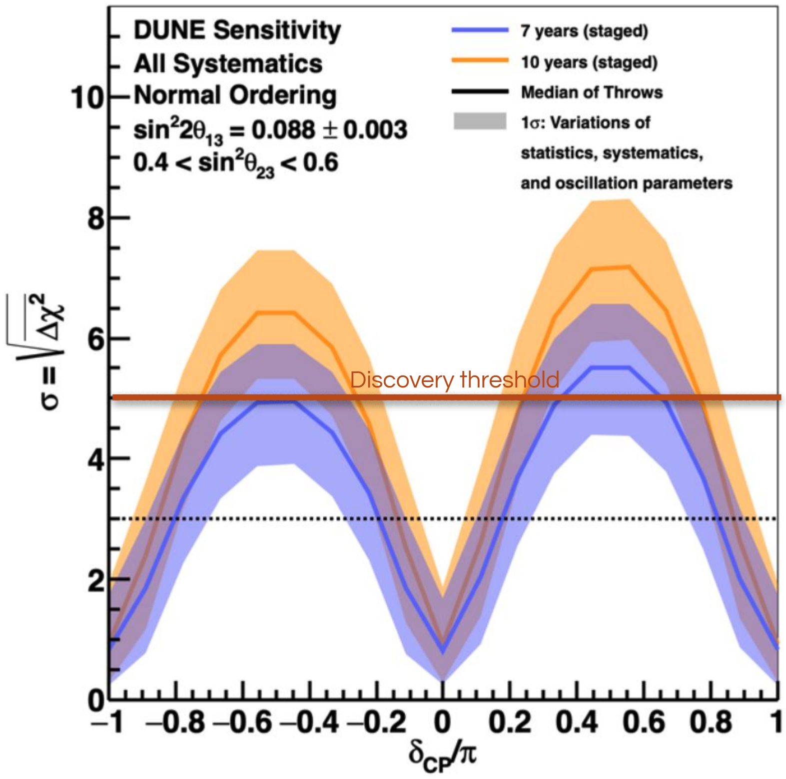


Antineutrinos

DUNE sensitivity

Discovers **CP** violation unless it is very small

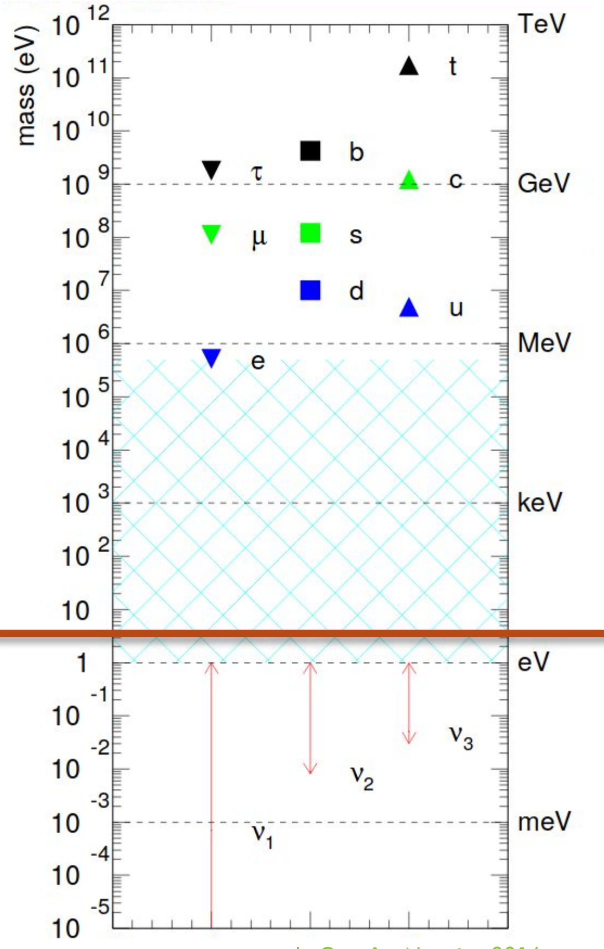




Neutrino mass and double-beta decay

Neutrino mass

- There are **six orders of magnitude** between the **electron** mass and the **upper limit** on **neutrino** mass.
- The Higgs mechanism explains **how** particles get mass but it **doesn't predict their masses.**
- The **very large difference** between the masses of neutrinos and that of other particles hints at a **different mechanism** for neutrino mass.
- The mass of the charged fermions is described by **Dirac mass** terms.
- Because they are neutral, neutrinos may be described by **Majorana mass** terms.

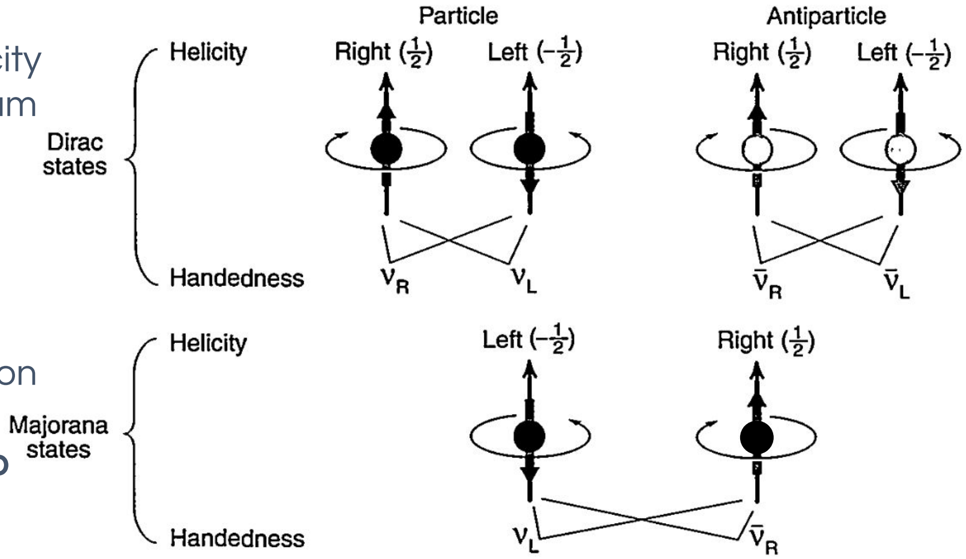


de Gouvêa, Neutrino 2016

Dirac or Majorana?

- To turn a particle into an antiparticle:
  - Flip its charge (**C**)
  - Flip its direction (**P**), resulting in opposite helicity
    - Helicity: "alignment" between momentum and spin.
- But what does it mean to "flip the charge" of a neutrino?!
- Neutrinos can have a more economic representation than the other fermions.
  - Instead of four **Dirac** states, we only need **two Majorana states.**
  - The only difference between Majorana neutrinos and antineutrinos is the direction of their spin!

→ Neutrinos may be their own antiparticles!



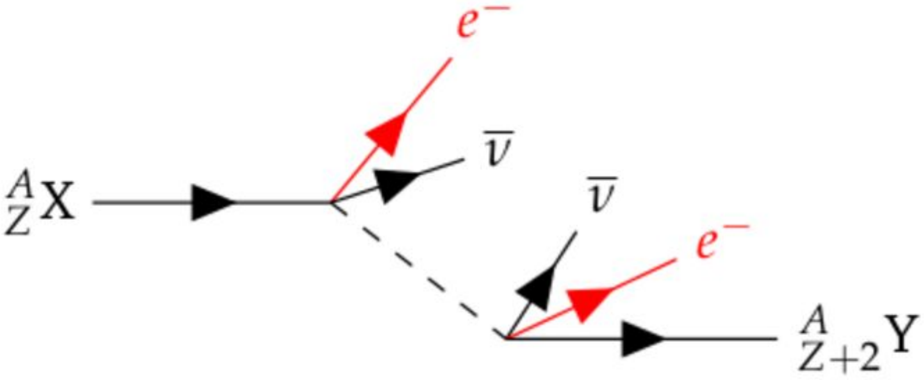
Credit: "Celebrating the neutrino", Los Alamos Science, 1997.

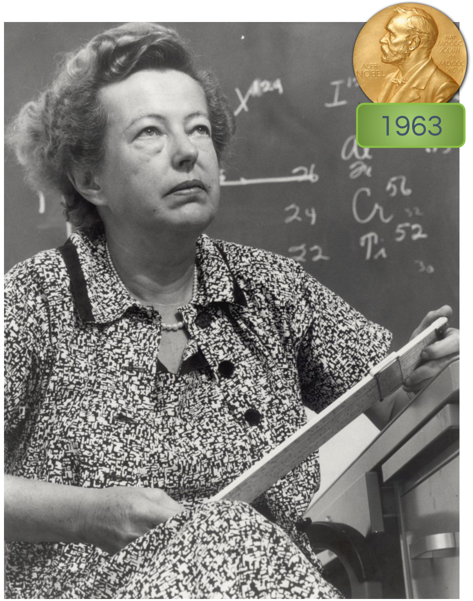
The see-saw mechanism

- Two **"active"** neutrino states (per generation) are sufficient to explain all known neutrino interactions.
- We can **speculate** the existence of two additional states.
    - In analogy to the four states necessary to describe the charged fermions.
    - These additional **"sterile"** states **do not interact** with the Standard Model.
    - **However**, the masses of the **sterile** and **active** neutrinos **mix**.
        - **Large** sterile neutrino **masses** would result in the **very small** active **neutrino masses we observe**.
        - Requires neutrinos to be **Majorana** particles!

Double-beta decay

- Second order weak interaction process.
  - Extremely rare.
- Typical half-life is around 10^{21} years!
  - Much, much longer than the age of the Universe!
  - Process observed for 12 nuclei.
- Sum of the electrons' energies has similar distribution to beta-decay spectrum.

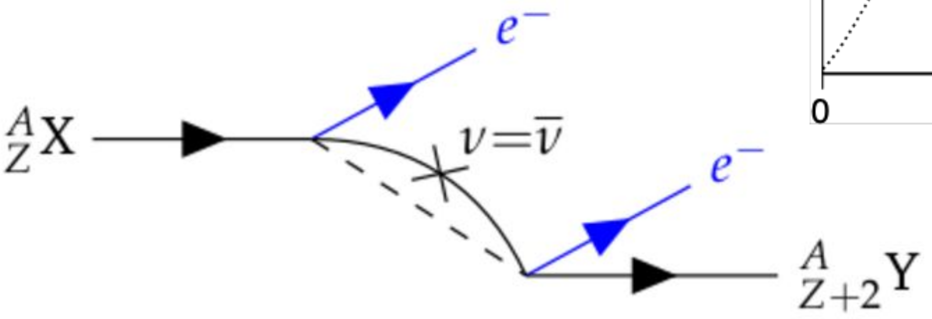


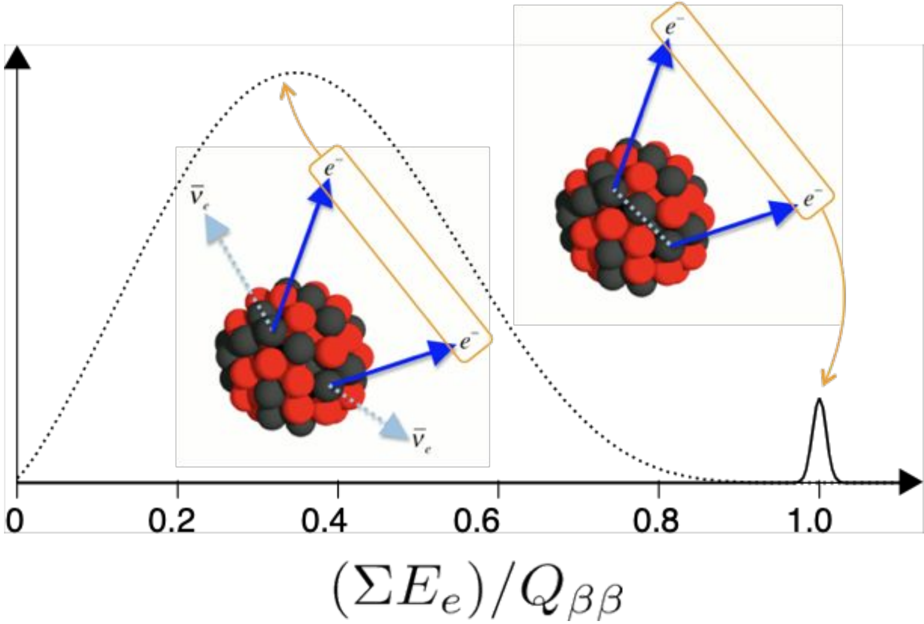


Maria Goeppert-Mayer

Neutrinoless double-beta decay

- **Only if** neutrinos are their own antiparticles:
    - **Neutrinoless** double-beta decay!
- No neutrinos in the final state.
    - Electron energies add up to $Q_{\beta\beta}$
- This is the only experimental method to search for Majorana neutrinos.
- Decay rate depends on neutrino mass.
    - Bonus: neutrino **mass measurement**.





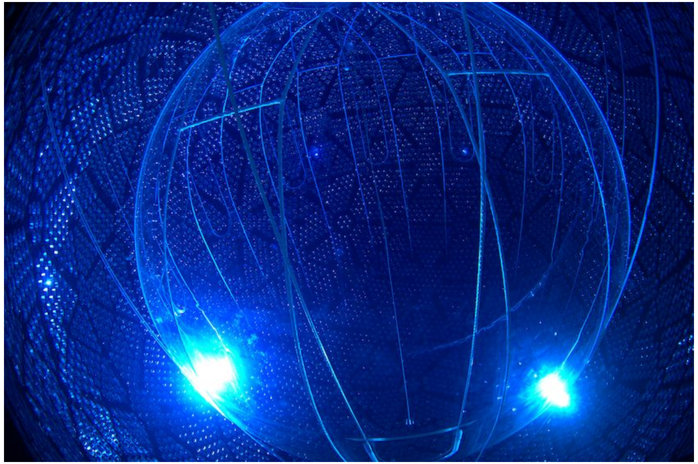
C. Wiesinger

SNO+

- Large acrylic sphere filled with **790 tons** of **liquid scintillator**.
  - Scintillator emits light when traversed by charged particles.
  - About 9300 photomultiplier tubes detect the scintillation photons.
- 2 km underground in SNOLAB, Canada.

- **Double-beta decay isotope** ^{130}Te will be diluted in the scintillator.
  - Extremely challenging process.

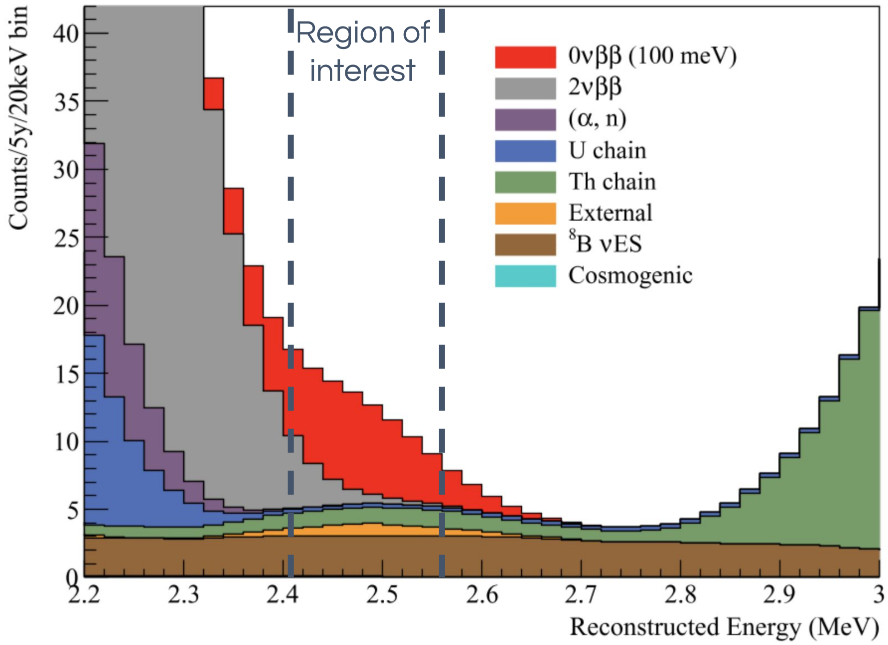
LIP is a founding member of the experiment.



SNO+

- Main physics program is the **search for neutrinoless double-beta decay**.
  - In 5 years, will be able to exclude decay half-lives shorter than **2×10^{26} years**.
  - Corresponds to neutrino mass of **37 to 89 meV.**

- Will also measure:
  - Solar neutrinos
    - Oscillations, solar metallicity
  - Geoneutrinos.
  - Reactor antineutrinos.



SNO+ News

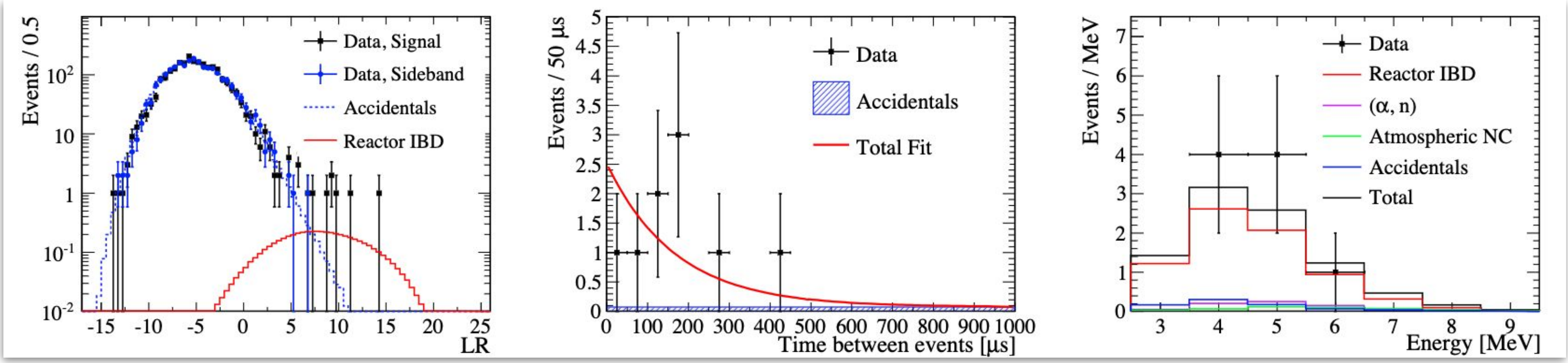
Antineutrinos from nuclear reactors detected by water

LIP-ECO/SNO+ | 01 Março, 2023

"The SNO+ collaboration has captured the signal of antineutrinos from nuclear reactors using a water-filled neutrino detector, a first for such a device. The result was selected as Editor's Suggestion in PRL. LIP researcher Sofia Andringa co-coordinates the SNO+ group that performed the analysis."

- Data collected with detector filled with pure water.
  - Before scintillator loading.
- First detection of reactor antineutrinos with **pure water** experiment!

Data analysis led by LIP.

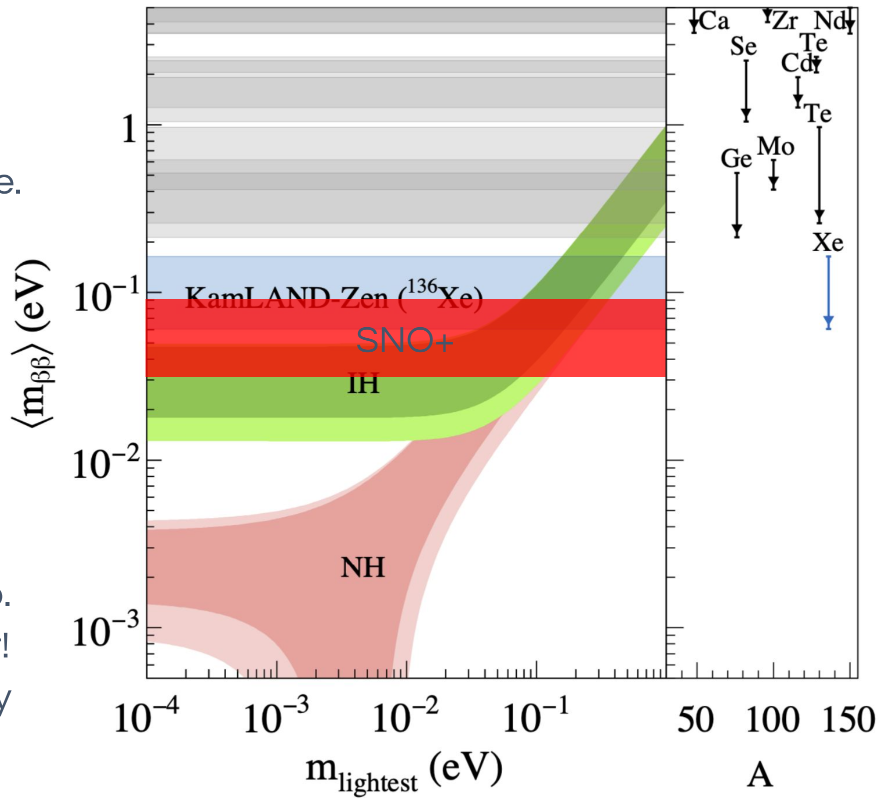


Putting it all together

- No observation of neutrinoless double-beta decay so far…
    - But we have upper limits on the decay rate.

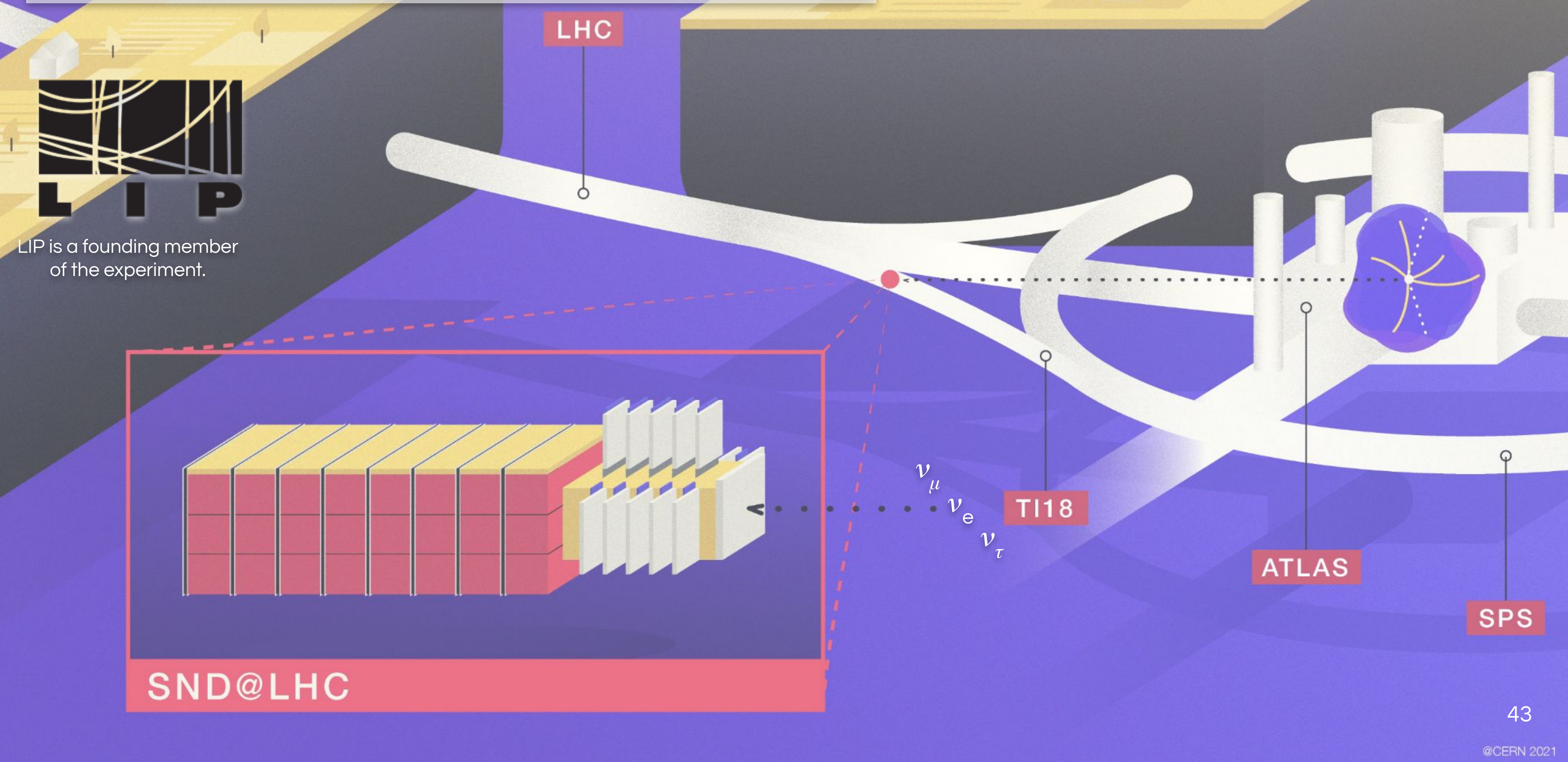
- Connection between neutrinoless double-beta decay rates and neutrino mass depends on:
    - Neutrino **mixing** parameters.
    - Neutrino **mass ordering**.

- It may be that neutrinos are Majorana particles and neutrinoless double-beta decay rate is zero.
    - In this case we will never know the answer!
- If the neutrino mass ordering is **inverted**, we may know the answer *soon* (few of decades?).



Neutrinos at the LHC

SND@LHC experiment



LIP is a founding member of the experiment.

Observation of collider neutrinos at the LHC

CERN
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Voir en français

New LHC experiments enter uncharted territory

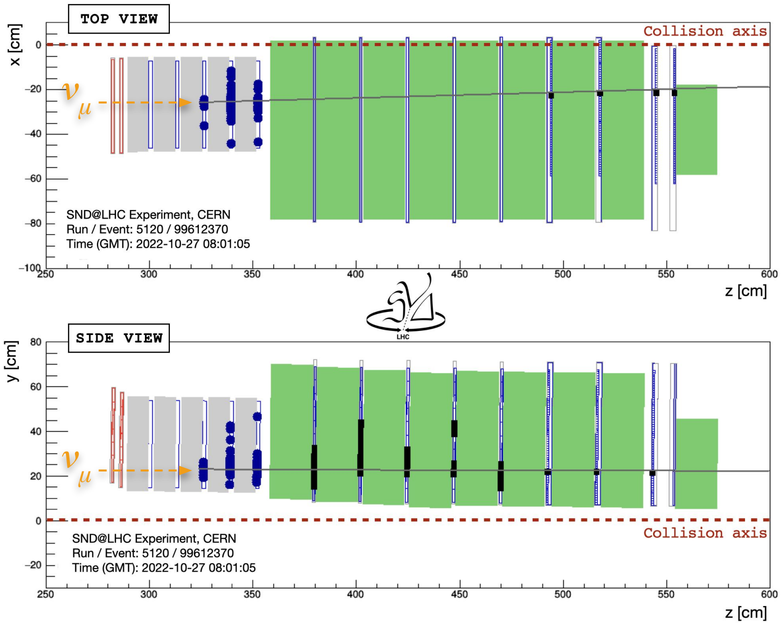
The first observation of collider neutrinos at the LHC paves the way for exploring new physics scenarios

22 MARCH, 2023 | By Kristiane Bernhard-Novotny & Chetna Krishna

First observation of collider neutrinos by SND@LHC and FASER

LIP-ECO/CERN/N.Leonardo | 23 Março, 2023

"The new LHC experiments SND@LHC and FASER reported the first-ever observation of neutrinos produced in a particle collider. The results were announced at the Rencontres de Moriond taking place this week in La Thuile, Valle d'Aosta, Italy. "



Data analysis led by LIP.

Summary

- Neutrinos interact only through the weak interaction.
    - Very small cross-sections.
        - Challenging experiments!
    - May be responsible for the observed asymmetry between matter and antimatter in the Universe.

- The discovery of neutrino oscillations implies:
    - **Non-zero neutrino masses**
    - A new source of **CP violation** in the Standard Model.

- Neutrinos **may be their own antiparticles.**
    - Search for Majorana neutrinos with neutrinoless double-beta decay experiments.
    - Could help explain the smallness of neutrino mass.

- Neutrinos from proton-proton collisions **observed for the first time**!

DEEP UNDERGROUND NEUTRINO EXPERIMENT

LHC

Scattering and Neutrino Detector at the LHC