Neutrinos!

Present Understanding & Future Prospects

Albert De Roeck
CERN, Geneva, Switzerland
30th August 2021
Outline

• Introduction to neutrinos
• Neutrinos oscillate and have mass
• Physics oscillation experiments
• Neutrino properties: mass and Majorana/Dirac nature
• Future experiments & CERN Neutrino Platform
  • (Cosmic Neutrinos)
• Neutrino experiments at the LHC
• Summary
Neutrinos

- Neutrinos at the CERN-Fermilab Hadron Collider Physics Summer School?
  - No neutrino collider any time soon 😊 (νν collisions do happen plentifully in supernova explosions…). Neutrino factory..?

- Fermilab has a strong ongoing program on neutrino physics
  - Eg DONUT, MINOS, MINERvA, MicroBooNE, MiniBooNE, NOvA…
  - And future: ICARUS, SBND, DUNE…

- CERN is coming back “on-line” in neutrino physics. Significant investment with the Neutrino Platform
  - ProtoDUNEs, participating in DUNE, SBN, T2K,..

- The LHC is also becoming a place to study neutrinos, via searches for new or heavy neutrinos, or more recently via news experiments that will measure high energy neutrino interactions (FASER(-Nu), SND@LHC)
The Large Neutrino Collider

by Pedro Machado (Fermilab)

📅 Wednesday 18 Nov 2020, 14:00 → 15:00 Europe/Zurich
📍 Zoom only (CERN)

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The Large Neutrino Collider

Pedro Machado
CERN Theory Colloquium
November 16th, 2020

or “Physics opportunities with future liquid argon time projection chambers”
Neutrinos are still mysterious particles

- Have only (left handed) weak interactions
- Are mass-less in the (minimal) SM until 1998
- Are the only neutral fermions in the SM
- Could be Majorana or Dirac fermions
- Neutrinos are produced everywhere
  - Solar neutrinos
  - Atmospheric neutrinos
  - Neutrinos from supernova explosions
  - Primordial neutrinos from the Big Bang
  - Nuclear reactor created neutrinos
  - Accelerator created neutrinos
  - Geoneutrinos, Radioactive decay, even from your body…
Neutrinos come in 3 Flavours

LEP e+e- collider at CERN (1988-2000)

Detailed study of the Z-boson

The width of the Z-boson gives the number of neutrinos

\[ \Gamma_Z = \Gamma_{\text{had}} + 3\Gamma_1 + \sum_{\nu} N_\nu \Gamma_\nu \]

\[ N_\nu = 2.99 \pm 0.02 \]

LEP: three active neutrinos with mass < 45 GeV
Neutrinos

Neutrino experiments today -> Open Questions!

- Neutrino mass values?
- Neutrino mass hierarchy? Normal or Inverted?
- CP violation in the lepton sector? Are neutrinos key the baryon asymmetry in the Universe?
- Are neutrinos their own antiparticles? -> LNV processes
- Do right-handed/sterile/heavy neutrinos exist?
- Are there non-standard neutrino interactions?
- Neutrinos and Dark Matter?
- Testing of CPT..
- Neutrinos are Chameleons: They can change flavour!!

Neutrinos are an essential part of our Universe and our very existence, and can provide answers to some of the key fundamental questions today.
Plenty of neutrinos in the Universe

For every proton/neutron/electron the Universe contains a billion of neutrinos from the Big Bang
Neutrinos give crucial insight on Supernovae explosions

99% of the energy in a supernova explosion is carried away by neutrinos
Neutrinos allow us to look into the heart of the sun. 

$10^{38}$ neutrinos per second are produced by the Sun, with a flux of $\sim 10^{11}/\text{cm}^2/\text{sec}$ at the Earth.
Solar Neutrinos

Neutrino measurements allow to understand how the sun works

2020: Borexino measured the CNO cycle -> Nature 687 (220) 577
very high energy neutrinos from outer space

A 290 TeV neutrino originated from a flaring blazar (black hole at the center of a galaxy) was detected by IceCube.
Reactors produce $> 10^{21}$ neutrinos per second
Radioactive beta-decay
The process that led to the postulation of the neutrino
Neutrinos are Everywhere!

from Big Bang 300 nus / cm$^3$
2 or more v/c $<< 1$

SuperNovae $> 10^{58}$

Sun’s $\sim 10^{38}$ nu/sec

Daya Bay $3 \times 10^{21}$ nu/sec

Neutrinos are Forever!!!
(except for the highest energy neutrino’s)

therefore in the Universe: \[ \frac{\partial N_\nu}{\partial t} > 0 \]
Neutrino Sources, Flux and Cross Sections

C. Spiering, arXiv:1207.4952


Cosmological and background from old supernovae neutrinos not yet observed!
Detecting neutrinos is challenging. Very large detectors are needed.
SuperKamiokande

50,000 tons of ultra-pure water, watched by 13,000 photomultipliers
1998: The Super-Kamiokande experiment in Japan used a massive underground detector filled with ultrapure water.

They announced first evidence of neutrino oscillations. The experiment showed that muon neutrinos disappear as they travel through the earth to the detector. It also offered an explanation for the observed solar neutrino discrepancy.
• Important discovery in 1998: neutrino oscillations

• Neutrino oscillation is a quantum mechanical phenomenon whereby a neutrino created with a specific lepton flavor (electron, muon, or tau) can later be measured to have a different flavor. The probability of measuring a particular flavor for a neutrino varies between 3 known states as it propagates through space.

• Neutrino oscillations only possible if neutrinos have a non-zero mass! Neutrino oscillations -> Neutrinos have mass!!
Neutrino oscillations

Each flavour state is a linear combination of mass states:

\[ |\nu_\alpha\rangle = \sum_i U_{\alpha i}^* |\nu_i\rangle \]

- Neutrino interaction
- Neutrino travel through space
- Flavor states
- (*) Pontecorvo-Maki-Nakagawa-Sakata Matrix
Neutrino Oscillations

The bizarre world of Quantum Mechanics: particles and waves

Take that the neutrino particle is a hybrid of two mass states $v_1$ and $v_2$ as it travels through space the associated waves of these mass states advance at a different rate.

Hence the picture looks as follows: (propagation as a superposition of two masses)

The neutrinos change identity (flavor) along the way...!!
Two Flavour Oscillations

Flavour states

\[
\begin{pmatrix}
\nu_\alpha \\
\nu_\beta
\end{pmatrix}
= \begin{pmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2
\end{pmatrix}
\]

"Rotation Matrix"

Mass states

| \nu(t = 0) \rangle = | \nu_\alpha \rangle = \cos \theta | \nu_1 \rangle + \sin \theta | \nu_2 \rangle
Two Flavour Oscillations

\[ |\nu(t)\rangle = e^{i(E_1 t - pL)} \cos(\theta) |\nu_1\rangle + e^{i(E_2 t - pL)} \sin(\theta) |\nu_2\rangle \]

\[ \langle \nu_\beta | \nu(t) \rangle = \sin(\theta) \cos(\theta) (e^{i(E_2 t - pL)} - e^{i(E_1 t - pL)}) \]

\[ E \approx p + \frac{m_i^2}{2E} \quad \text{and} \quad t = \frac{L}{c} \]

\[ \langle \nu_\beta | \nu(t) \rangle = \sin(\theta) \cos(\theta) (e^{i \frac{m_2^2 L}{2E}} - e^{i \frac{m_1^2 L}{2E}}) = \sin(\theta) \cos(\theta) e^{i \frac{\Delta m_i^2 L}{2E}} \]

\[ P(\nu_\alpha \to \nu_\beta) = \langle \nu_\beta | \nu(t) \rangle^2 = \sin^2(2\theta) \sin^2 \left( \frac{\Delta m_i^2 L}{2E} \right) \]
Neutrino Oscillations

Neutrino oscillations is a pure Quantum Mechanical effect. The effect depends on the mass difference between flavor states.

\[
\begin{bmatrix}
\nu_\mu \\
\nu_\tau \\
\end{bmatrix} =
\begin{bmatrix}
\cos \theta & \sin \theta \\
-\sin \theta & \cos \theta \\
\end{bmatrix}
\begin{bmatrix}
\nu_1 \\
\nu_2 \\
\end{bmatrix}
\]

\[
P(\nu_\mu \rightarrow \nu_\tau) = \sin^2(2\theta)\sin^2\left(\frac{1.27\Delta m^2 L}{E_\nu}\right)
\]

- Measure prob.
  - Survival
  - Appearance
- Result
  - Mixing angle
  - Mass differences

\[\Delta m^2_{21} = m_2^2 - m_1^2 \approx 8 \times 10^{-5} \text{ eV}^2 \Rightarrow \text{wavelength of } \sim 100\text{km}\]

\[|\Delta m^2_{31}| \approx |\Delta m^2_{32}| \approx 2 \times 10^{-3} \text{ eV}^2 \Rightarrow \text{wavelength of } \sim 1\text{km}\]
Neutrino Oscillations

Since >20 years an active field of study and data from many experiments collected:

- Long baseline accelerator experiments (LBL)
- Short baseline reactor experiments
- Atmospheric neutrinos
- Solar Neutrinos
- Neutrinoless double beta decay experiments

LBL experiments in the US and Japan
SuperKamiokande, Icecube
Neutrino Oscillations

Mixings and phases: CKM → PMNS (Pontecorvo-Maki-Nakagawa-Sakata)

\[ U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

\( \theta_{23} \) rotation \hspace{1cm} \( \theta_{13} \) rotation \hspace{1cm} \( \theta_{12} \) rotation

+ CPV “Dirac” phase \( \delta \)

\[ c_{ij} = \cos \theta_{ij}; \ s_{ij} = \sin \theta_{ij} \]

Mass [squared] spectrum

(E ~ p + m^2/2E + “interaction energy”)

“Normal” Ordering

N.O.

\( +\Delta m^2 \)

\( \delta m^2 \)

+ interactions in matter \( \rightarrow \) effective terms \( \sim G_F \cdot E \cdot \text{density} \)

“Inverted” Ordering

I.O.

\( -\Delta m^2 \)

In total 6 parameters to determine

- 3 angles
- 2 mass differences
- 1 CP violation phase
Neutrino Oscillations

\[ U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\delta_2} & 0 \\ 0 & 0 & e^{i\delta_3} \end{pmatrix} \]

- **Atmospheric**
  - $\nu_\mu$ disappearance
  - $\nu_e$ appearance in $\nu_\mu$ beam
  - Or reactor neutrino experiments

- **Solar**
  - Solar neutrino oscillation
  - $\nu$-less double beta decay
Short Baseline Experiments

Measuring the mixing angle $\theta_{13}$

**Daya Bay (China)**
Eight anti-neutrino detectors (liquid scintillator based) within 2 km of 6 reactors

**RENO (South Korea)**
Two anti-neutrino detectors (liquid scintillator based) ~up to 1.5 km of 6 reactors

**Double Chooz (France)**
Two anti-neutrino detectors (liquid scintillator based) within 0.4-1 km of the reactors

\[
\sin^2 \theta_{13} = 0.0220 \pm 0.0007
\]

(PDG2021 using Double Chooz, Reno, Daya Bay)
Accelerator Based Neutrino Experiments

Neutrinos from accelerators

T2K

- Super Kamiokande
- Near Detector
- J-PARC
- Baseline: 295 km
- Peak $E_\nu$: $\sim$0.6 GeV (off-axis)
- Near detector: ND280 (~2 T C/O targets, TPC tracking, magnetised)
- Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

- Baseline: 810 km
- Peak $E_\nu$: $\sim$2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)
Muon Neutrino Disappearance

211 events, 8.2 background

105 events, 2.1 background
Neutrino Experiments

Atmospheric parameter determinations by several experiments.
Results are consistent.
Do neutrinos and anti-neutrinos oscillate differently?

Measured versus expected electron-(anti)neutrino events in SK as function of the assumed CP-angle

<table>
<thead>
<tr>
<th></th>
<th>Observed</th>
<th>$\delta_{CP} = -90^\circ$</th>
<th>$\delta_{CP} = +90^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron neutrino</td>
<td>90</td>
<td>82</td>
<td>56</td>
</tr>
<tr>
<td>Electron antineutrino</td>
<td>15</td>
<td>17</td>
<td>22</td>
</tr>
</tbody>
</table>

Electron Neutrino

Electron Antineutrino
The gray region is disfavored by 99.7% (3σ) CL. The values 0 and 180 degrees are disfavored at 95% CL.

Some tension between NOvA and T2K results! Joint analysis required? -> more experimental data needed ... (and coming..)

Good to have different methods and experiments!

Jury is still out!!
Taking all available data together...

To explore Beyond the Standard Model ~ 10 times better precision needed

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal Ordering (best fit)</th>
<th>Inverted Ordering ($\Delta \chi^2 = 7.1$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sin^2 \theta_{12}$</td>
<td>$0.304^{+0.012}_{-0.012}$</td>
<td>$0.304^{+0.013}_{-0.012}$</td>
</tr>
<tr>
<td>$\theta_{12}/^\circ$</td>
<td>$33.4^{+0.77}_{-0.74}$</td>
<td>$33.45^{+0.78}_{-0.75}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}$</td>
<td>$0.573^{+0.016}_{-0.020}$</td>
<td>$0.575^{+0.016}_{-0.019}$</td>
</tr>
<tr>
<td>$\theta_{23}/^\circ$</td>
<td>$49.2^{+0.9}_{-1.2}$</td>
<td>$49.3^{+0.9}_{-1.1}$</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}$</td>
<td>$0.02219^{+0.00062}_{-0.00063}$</td>
<td>$0.02238^{+0.00063}_{-0.00062}$</td>
</tr>
<tr>
<td>$\theta_{13}/^\circ$</td>
<td>$8.57^{+0.12}_{-0.12}$</td>
<td>$8.60^{+0.12}_{-0.12}$</td>
</tr>
<tr>
<td>$\delta_{CP}/^\circ$</td>
<td>$197^{+27}_{-24}$</td>
<td>$282^{+26}_{-30}$</td>
</tr>
<tr>
<td>$\Delta m^2_{21}/10^{-5}$ eV$^2$</td>
<td>$7.42^{+0.21}_{-0.20}$</td>
<td>$7.42^{+0.21}_{-0.20}$</td>
</tr>
<tr>
<td>$\Delta m^2_{3\ell}/10^{-3}$ eV$^2$</td>
<td>$+2.517^{+0.026}_{-0.028}$</td>
<td>$-2.498^{+0.028}_{-0.028}$</td>
</tr>
</tbody>
</table>

with SK atmospheric data
Taking all available data together...

Minimized $\Delta \chi$ distributions for the 3 neutrino hypothesis fit off all data

Inverse mass ordering is disfavoured slightly compared to the normal mass ordering in the global fit by about 1.6 sigma (2.7 sigma when including SK)

Data mainly from reactors, long baseline experiments, atmospheric, solar neutrinos...

But the Jury is still out..

arXiv:2007.14792
Neutrino Oscillations

Neutrino Mass EigenStates or Propagation States:

\[
\text{Propagator } \nu_j \rightarrow \nu_k = \delta_{jk} e^{-i \left( \frac{m_j^2 L}{2E_\nu} \right)}
\]

\[\nu_1\]
most \(\nu_e\)

\[\nu_2\]

\[\nu_3\]
least \(\nu_e\)

\(\nu_e = \) Solar Exp, SNO, KamiLAND, Daya Bay, RENO, ...

\(\nu_\mu = \) SuperK, K2K, T2K, MINOS, NOvA, ICECUBE

\(\nu_\tau = \) Unitarity, SK, Opera, ICECUBE ?
CMK vs PMNS

Why is Neutrino mixing so different from quark mixing? What does that tell us?

The CKM matrix is almost diagonal, while the PMNS matrix is almost uniform.
Neutrino Mass

Neutrinos versus other known fermions

Upper bound from laboratory measurements

Lower bound from oscillation experiments
## Neutrino Mass Measurements

### Complementary paths to the $\nu$ mass scale

<table>
<thead>
<tr>
<th>Method</th>
<th>Cosmology</th>
<th>Search for $0\nu\beta\beta$</th>
<th>Kinematics of weak decays</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Method</strong></td>
<td>Structure of Universe at early and evolved stages</td>
<td>$\beta\beta$-decay of $^{76}$Ge, $^{130}$Te, $^{136}$Xe, …</td>
<td>$\beta$-decay of $^3$H, EC of $^{163}$Ho</td>
</tr>
<tr>
<td><strong>Observable</strong></td>
<td>$M_\nu = \sum_i m_i$</td>
<td>$m_{\beta\beta}^2 = \left</td>
<td>\sum_i U_{ei}^2 m_i \right</td>
</tr>
<tr>
<td><strong>Model assumptions</strong></td>
<td>Multi-parameter cosmological model ($\Lambda$CDM)</td>
<td>- Majorana nature of neutrinos?</td>
<td>Only kinematics; “direct” measurement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- No BSM contributions other than $m(\nu)$?</td>
<td></td>
</tr>
</tbody>
</table>
Neutrino mass measurements

The KATRIN experiment: endpoint measurement of tritium decay

What is measured really in this experiment is the effective electron antineutrino mass defined by

\[ m^2(\nu_e) = \sum_i |U_{ei}|^2 \cdot m_i^2 \]

with \( U_{ei} \) the PMNS mixing elements.
The KArlsruhe TRItium Neutrino experiment (KATRIN) is designed to measure the mass up to projected sensitivity of 0.2 eV. To achieve this, KATRIN will perform high-precision spectroscopy of the endpoint region of the tritium beta-decay spectrum.

Recent result $M_{\nu_e} < 0.8$ eV (May 2021)
Neutrinoless Double Beta Decay

- Are neutrinos their own antiparticle? We do not know this yet!
- The highly anticipated experimental test is the observation of neutrino-less double beta decay, i.e., two simultaneous beta-decays within one nucleons, without neutrino emission.
- This would be the first evidence of lepton violation!
Neutrinoless Double Beta Decay

GERDA (GERmanium Detector Array) experiment at LNGS (Gran Sasso/IT)


127.2 kg.year exposure between 2011-2019

Experiment now completed
No $0\nu\beta\beta$ signal observed 😞

Upper mass limit: $m_{\beta\beta} < 79 - 180$ meV

- Present best limits:
  - $^{136}$Xe (KamLAND-Zen): $T_{1/2} > 10^{26}$ yrs
  - $^{76}$Ge (GERDA): $T_{1/2} > 10^{26}$ yrs
  - $^{130}$Te (CUORE): $T_{1/2} > 3 \times 10^{25}$ yrs

- Future goal:
  - ~2 OoM improvement in $T_{1/2}$
  - Covers IO
  - Up to 50% of NO
  - Factor of ~few in $\Lambda$
  - An aggressive experimental goal

Many experiments operating, planned or in R&D: LEGEND, SNO+, NEXT...
Future Neutrino Experiments

Eg. experiments that will contribute to the mass ordering question

We would like to be convinced the neutrino mass ordering by consistent results from several different technologies/methods with $> 3 \sigma$ CL from each exp.
Future Neutrino Experiments

Long-baseline experiments: T2HK and DUNE

- Towards the measurement of the CP violating phase and Mass Hierarchy
  - Search for different $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities


DUNE

Fiducial mass ~ 40 kton

2.5° off-axis

DUNE:ProtoDUNE-SP Run 5772 Event 15132

DUNE “Observatory”

- “Deep Underground Neutrino Experiment”
  - 1300 km baseline
  - Large (70 kt) LArTPC far detector 1.5 km underground
  - Near detector w/ LAr component

- Primary physics goals:
  - $\nu$ oscillations ($\nu_\mu/\bar{\nu}_\mu$ disappearance, $\nu_e/\bar{\nu}_e$ appearance)
    - $\delta_{CP}$, $\theta_{23}$, $\theta_{13}$
  - Ordering of $\nu$ masses
  - Supernova burst neutrinos
  - BSM processes (baryon number violation, NSI, etc.)
DUNE – a global collaboration

Status October 2020:
- 1229 collaborators from
- 184 institutions in
- 31 countries + CERN

Still more groups joining

Collaboration meeting at CERN end of January 2020  ->  350 participants!
DUNE Far Detector

- 40-kt (fiducial) LAr TPC
- Installed as four 10-kt modules at 4850’ level of SURF

16x16x60m³

- First module will be a single phase LAr TPC
- Modules installed in stages. Not necessarily identical
No neutrino beam since switching-off the LNS beam to Gran Sasso in 2015

As of 2000: No neutrino experiments at CERN since CHORUS and NOMAD

In 2014, as a result of the European Strategy for Particle Physics at the time it was decided CERN would engage again in accelerator based neutrino experiments

• Creation of the Neutrino platform
• Creation of a Neutrino experimental Group in 2016 (and Theory forum)

2022: Neutrino experiments will be back at CERN ... see later

ProtoDUNE: Prototype at scale 1/20 of a DUNE far detector module
Present Status of NP Projects

7 MOUs signed:
- NP01: ICARUS overhauling + FNAL activities
- NP02: R&D on a double phase LAr TPC technology (protoDUNE DP)
- NP03: generic R&D on neutrino detectors and facilities
- NP04: R&D on a single phase LAr TPC technology (protoDUNE SP)
- NP05: Baby Mind muon spectrometer for a T2K near detector
- NP06: ENUBET, R&D on a neutrino beta beam
- NP07: ND280, a new T2K Near Detector

Cooperation agreements
- CERN participation in the USA LBNF/DUNE project
- CERN delivery in kind to USA of the first large LBNF cryostat
- CERN participation in the FNAL short baseline Neutrino program
- CERN technical participation in the Darkside project at LNGS

Other activities
- NP participation in the CERN FASER and SND@LHC project
NP01: ICARUS

SBN will verify the sterile neutrino hypothesis both in appearance and disappearance channels.

ICARUS was a detector operational at the LNGS, Gran Sasso, and was refurbished to operate on surface at CERN and transported to FNAL in 2017.

CERN activities
- Bring the 2 ICARUS active detectors from LNGS to CERN
- Construct new cryostats (cold and warm)
- Bring the two cold cryostats to FNAL
- Provide a large muon tagger for tagging cosmics
- Participate in the commissioning and physics exploitation
ICARUS at FNAL

Leaving CERN 12 June 2017

ICARUS filled with liquid argon in 2020

Positioning of the two ICARUS modules (cold cryostats) in final position in a new building at FNAL

First neutrino BNB candidates in ICARUS June 2021
First production run will start in October

Quasi-Elastic Charged-Current: $\nu_\mu n \rightarrow p \mu$
ProtoDUNE as the necessary step to demonstrate the feasibility of the LAr technology for large detectors

- Largest liquid argon time projection chambers (LArTPCs) ever built
- Prototypes at the scale 1:20, with modules at the DUNE scale
- Two technologies investigated (LAr single phase, LAr double phase)
The EHN1 Hall at CERN

Next step: ~800 ton LAr prototypes

SPS: new EHN1-1 experimental area

The Neutrino Platform hall
Virtual Visit to the Neutrino Platform

Recent visit on 12/8/2021

Video on the agenda of the school
https://indico.cern.ch/event/1011452/
Liquid Argon Time Projection Chamber

The ‘electronic’ bubble chamber for neutrino experiments
The ProtoDUNES

The Dual Phase turned out to be very complex and this idea for the technology has now been replaced by a so-called "vertical drift" LArTPC technique.

This new idea will be fully tested within 1-2 years using the NP02.
DUNE: CP Violation and Mass Ordering

**CPv sensitivity**

- Updated Sensitivity with realistic systematics and reconstruction
  - Move quickly to potential *CP violation discovery* [arXiv:2002.03005]
  - Rapid, definitive *mass ordering determination* (>5σ)
The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton multi-purpose liquid scintillator detector (~20 times the size of present detectors, including 18000 20’’ PMTs) being built in a dedicated underground laboratory (700 m underground) in China and expected to start data taking end 2022/start 2023.

Determination of the neutrino mass ordering using electron antineutrinos from two nuclear power plants at a baseline of about 53 km. With an unprecedented energy resolution of 3% at 1 MeV, JUNO will be able to determine the mass ordering with a significance of 3 sigma within six years of running. (4-5 sigma with acc. exp. and IceCube)
Neutrinos & Cosmos

- Neutrinos very relevant for cosmological studies. Examples:
  - Neutrinos affecting the Big Bang nucleo-synthesis.
  - Relic neutrinos from the Big Bang: cosmic neutrino background, probe beyond the CMB horizon
  - Neutrinos from supernova explosions: study supernova dynamics
  - Mass limits on neutrinos and number of different neutrinos from cosmology (eg from Planck)

- Sum of the mass of all the neutrinos in the Universe is larger than the mass of all the stars
Study of Supernova Explosions

Supernova 1987A in the Large Magellanic Cloud (55 kpc away)

For comparison: the Milky Way is about 34 kpc across

In 1987 in total ~24 events were detected in 3 experiments
Neutrino Astronomy

Build gigantic detectors 1 km$^3$ of size and beyond...
Use the resources of planet Earth

The IceCube Experiment: operational
-> In the ice of Antarctica

The KM3NET Experiment: 6 strings now/ full detector by 2025
-> In the Mediterranean sea

+ANTARES
+Lake Baikal
Neutrinos? Perfect Messenger

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
- reveal the sources of cosmic rays
- … but difficult to detect

Now: neutrinods + photons
Next? neutrinos and gravitational waves?
Observation of a Glashow Resonance

Scattering on electrons to form a W boson
Electron antineutrino with energy of $\sim 6.3$ TeV required

Event seen with an estimated energy of 6.05 TeV
(8/12/2016)

$E_{\nu} = \frac{M_W^2 - (m_e^2 + m_{\nu_e}^2)}{2m_e} \approx \frac{M_W^2}{2m_e}$

Nature. 591: 220–224
New Opportunities with New Facilities

- The new facilities are generally large, often based on cutting edge detector technologies.
- These detectors allow for programs for searches for new physics not directly related to neutrinos.
- This is drawing increasing attention in the community, in particular related to the “high intensity frontier”.
- Reversely, the Large Hadron Collider can also contribute to the neutrino physics program:
  - Searches for right-handed neutrinos (heavy and light)
  - BSM physics (extra dimensions, SUSY…)
  - New: Neutrino experiments at the LHC!
NDs as Beam Dump Experiments

High intensity frontier for low mass particles with very weak couplings

-> upcoming neutrino experiments (SBL, LBL) foresee very high intensity beams

These experiments can perform searches for low mass New Physics particles eg
- HNL/sterile neutrinos
- dark photons
- ALPs
- mini/millicharges

Example millicharges:

Near Detector: few 100m away from the dump

White Paper on New Opportunities at the Next-Generation Neutrino Experiments
(Part 1: BSM Neutrino Physics and Dark Matter)

Searches for Low Mass Dark Matter

Light dark matter produced at the accelerator (meson decays)

Production

Elastic scattering

Fermionic DM $\chi$, $\alpha_D = 0.5$, $M_V = 3M_\chi$

Fermionic DM $\chi$, $\alpha_D = 0.5$, $M_\chi = 20$ MeV

$Y \equiv \varepsilon^2 \alpha_D \left( \frac{M_\chi}{M_V} \right)^4$

$\Omega_\chi = \Omega_{\text{obs}}$

$\Omega_\chi = \Omega_{\text{obs}}$
Neutrinos @ the LHC: Examples

Searches for right-handed neutrinos at the LHC

\( \nu_{\text{MSM}} \) (Neutrino Minimal Standard Model)

SND@LHC and FASER-\( \nu \) are 400m forward of the IPs and can study TeV-neutrinos with emulsion detectors
Neutrinos @ the LHC: SND@LHC

SND is 400m forward of the IPs and can Study TeV-neutrinos with emulsion and tracking+muon/calo detectors

SND = Scattering and neutrino detector
First Observed neutrinos in FASER-ν

These are the first ever directly observed neutrinos at the LHC!!

Neutrino interaction candidates

Highlights the potential of the forward LHC location for neutrino physics!
SUMMARY: Neutrinos

- Neutrinos studies is a vibrant field of research, and has still many open questions! Right-handed partners? Strong CP violation? More than 3 neutrinos? NS Interactions? Are neutrinos their own anti-particle?
- Now comes the age of neutrino precision physics with DUNE & T2HK and neutrino astronomy: look inside the sun, understand supernovae explosions, multi-messenger astronomy…
- Detailed study of PMNS oscillation parameters by experiments is key to the understanding
- Large experiments are really “observatories”
- The history of neutrino research showed many surprises. What surprise is waiting for us next??
Backup
Neutrinos from cosmic rays

Neutrinos are also produced in the atmosphere
NP07: The T2K ND280 Upgrade

CERN involved in the HA TPCs and SuperFGD

Much of the assembly done at CERN as we speak..

Transport CERN -> Tokai early next year
A Multi-Frontier Problem

Collider Probes of the origin of neutrino mass

- Neutrino oscillation experiments
  - Mass differences, mixings...
  - Hierarchy, CP violation...
  - Light sterile neutrinos?

- Absolute neutrino mass searches
  (KATRIN etc.)

- Neutrinoless double $\beta$ decay:
  - Dirac or Majorana?

- Fixed target experiments
  (SHiP, NA62, ...)

CMB and LSS: absolute neutrino mass

CMB and BBN: light sterile neutrinos?

IceCube
  - "Neutrino astronomy"

Cosmic Neutrino Background

Leptogenesis?

Sterile Neutrino Dark Matter?
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arXiv:1806.03310

arXiv:1907.08311

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- On-axis
- PRISM - 24 m
- LDMX - Phase1

LSND/MB DM

Fermionic DM $\chi$, $\alpha_D = 0.5$, $M_{\chi} = 20$ MeV

$\Omega_\chi = \Omega_{\text{obs}}$

BaBar

LSND/MB DM

Beam Dump

$\Omega_\chi = \Omega_{\text{obs}}$