The future of (accelerator) neutrino physics
• Sorry for the far too ambitious title
• Most of the arguments already discussed by the previous speakers
• I will try to outline what is going to happen in the next 20 years (and it’s almost already fully decided)
• Very ambitious activities with a rich and valuable set of observables
• I will focus mostly in neutrino oscillations
... Apologies

... my record as crystal ball reader is just very poor

a) I worked full time in the 90’s in the Nomad experiment at CERN looking for $\nu_\mu - \nu_\tau$ oscillations at $\delta m^2 > 10$ eV$^2$ (4 orders of mag. higher the true one)

b) Early 2000’s I was convinced that to address leptonic CP violation a setup where a WC detector 20 times bigger of SK integrating 4MW beam for 10 years was needed.

At today both T2K and Nova have a 2σ indication of CP violation having integrated roughly 500 times less $\nu$ interactions (in terms of detector mass x run time x beam power).

What we missed?

- $\theta_{13}$ happened to be maximal
- T2K fits maximal values of $\delta_{\text{CP}}$
- Reactors expts. can precisely measure high $\theta_{13}$ values increasing the discovery potential of accelerator expts.

What lesson can we take?

- The parameters measured by neutrino experiments can significantly change their strategy along the way
- Synergies between different experiments can be very powerful
The importance of measuring $m_\nu$

- The only parameter measurable both by hep and cosmology
- A crucial test of consistency

Standard model of particle physics

- $v_0$
- $\theta_{13}$
- $m_\nu$
- $m_H$
- $\delta_{CP}$

Standard model of cosmology

- $H_0$
- $\Omega_m$
- $\Omega_B$
- $n_S$

Direct mass searches

- $m_\beta$ (eV)

Double beta decay

- $m_{\beta\beta}$ (eV)

Cosmology

- $\Sigma$ (eV)
A new portal to (non)standard particle and nuclear physics
... small but *multicolor*!

From E. Lisi opening talk
at Neutrino 2018

- new $\nu$ properties
- dark matter
- supernovae
- solar neutrinos
- sterile neutrinos
- nuclear form factors
- new interactions
- EW precision tests
- new detectors
Neutrino Mass Ordering

A degree of freedom in neutrino mass spectrum: neutrino masses can be ordered following the generations (normal hierarchy) or not (inverted hierarchy). Related to $\text{sign of } \Delta m^2_{31} = m_3^2 - m_1^2$

One of the key objectives in neutrino physics:
- Important phenomenological consequences in neutrino oscillations, supernova neutrinos, cosmology, neutrinoless double beta decays, ...
- Important consequences in neutrino theory: model building, symmetries etc.
Leptonic CP violation and its phase $\delta_{\text{CP}}$

- CP violation has not yet been observed in leptons
- $\delta_{\text{CP}}$ is a fundamental parameter of the standard model
- It is one of the few measurables that could shed some light into the baryon asymmetry of the Universe

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Leptogenesis and Low Energy CP Violation in Neutrino Physics

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Abstract

Taking into account the recent progress in the understanding of the lepton flavour effects in leptogenesis, we investigate in detail the possibility that the CP-violation necessary for the generation of the baryon asymmetry of the Universe is due exclusively to the Dirac and/or Majorana CP-violating phases in the PMNS neutrino mixing matrix $U$ and thus is directly related to the low energy CP-violation in the lepton sector (e.g., in neutrino oscillations, etc.). We first derive the conditions of CP-invariance of the neutrino Yukawa couplings.

Given that $s_{13} |\sin \delta| \lesssim 0.2$, the lower bound in this inequality can be satisfied only for $M_1 \gtrsim 2.9 \times 10^{11}$ GeV. Recalling that the flavour effects in leptogenesis of interest are fully developed for $M_1 \lesssim 5 \times 10^{11}$ GeV, we obtain a lower bound on the values of $|s_{13} \sin \delta|$ and $s_{13}$ for which we can have successful leptogenesis in the case considered:

$$|\sin \theta_{13} \sin \delta| \gtrsim 0.11, \quad \sin \theta_{13} \gtrsim 0.11.$$

(93)
Where we are

- All the oscillation parameters have a central value and errors!!!
- Absolute masses are not known
- Still wondering about the possibility that neutrinos are Majorana particles

<table>
<thead>
<tr>
<th>parameter</th>
<th>best fit $\pm$ 1σ</th>
<th>3σ range</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta m_{21}^2 [10^{-5}\text{eV}^2]$</td>
<td>$7.55^{+0.20}_{-0.16}$</td>
<td>7.05–8.14</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{31}^2</td>
<td>[10^{-3}\text{eV}^2]$ (NO)</td>
</tr>
<tr>
<td>$</td>
<td>\Delta m_{31}^2</td>
<td>[10^{-3}\text{eV}^2]$ (IO)</td>
</tr>
<tr>
<td>$\sin^2 \theta_{12}/10^{-1}$</td>
<td>$3.20^{+0.20}_{-0.16}$</td>
<td>2.73–3.79</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}/10^{-1}$ (NO)</td>
<td>$5.47^{+0.20}_{-0.30}$</td>
<td>4.45–5.99</td>
</tr>
<tr>
<td>$\sin^2 \theta_{23}/10^{-1}$ (IO)</td>
<td>$5.51^{+0.18}_{-0.30}$</td>
<td>4.53–5.98</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}/10^{-2}$ (NO)</td>
<td>$2.160^{+0.083}_{-0.069}$</td>
<td>1.96–2.41</td>
</tr>
<tr>
<td>$\sin^2 \theta_{13}/10^{-2}$ (IO)</td>
<td>$2.220^{+0.074}_{-0.076}$</td>
<td>1.99–2.44</td>
</tr>
<tr>
<td>$\delta/\pi$ (NO)</td>
<td>$1.32^{+0.21}_{-0.15}$</td>
<td>0.87–1.94</td>
</tr>
<tr>
<td>$\delta/\pi$ (IO)</td>
<td>$1.56^{+0.13}_{-0.15}$</td>
<td>1.12–1.94</td>
</tr>
</tbody>
</table>

https://globalfit.astroparticles.es/
deSalas et al, 1708.01186 (May 2018)
Status of CP and MO

- Global fits exclude CP conservation at 2σ
- SK, T2K and Nova favor NO at 2σ
- Global fits favor NO at 3σ
Running experiments CP sensitivity projection

- by 2024:
  > 2σ sensitivity on CP violation at max CP violation (π/2 & 3π/2)

- by 2026 (20×10^{21} POT):
  > 3σ sensitivity on CP violation
"Short term" sensitivities in MO

**ORCA**
Adrian-Martinez et al, 1601.07459

**NOvA**
Neutrino 2018

- by 2023: 3σ determination of MO (similar results for PINGU)
- by 2024: 3σ sensitivity for 30/50% of δ

**JUNO**
⇒ 3σ sensitivity on mass ordering after 6 years

Measuring CP violation

- Not the most elegant or compact parametrization
- But all the contributions are explicit

\[ p(\nu_\mu \rightarrow \nu_e) = 4c_{13}^2 s_{13}^2 s_{23}^2 \sin^2 \frac{\Delta m_{13}^2 L}{4E} \times \left[ 1 \pm \frac{2a}{\Delta m_{13}^2} (1 - 2s_{13}^2) \right] \theta_{13} \ \text{drive} \]

\[ + 8c_{13}^2 s_{12} s_{13}^2 s_{23} (c_{12} c_{23} \cos \delta - s_{12} s_{13} s_{23}) \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \ \text{CP-even} \]

\[ + 8c_{13}^2 c_{12} c_{23} s_{12} s_{13}^2 s_{23} \sin \delta \sin \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \sin \frac{\Delta m_{12}^2 L}{4E} \ \text{CP-odd} \]

\[ + 4s_{12}^2 c_{13}^2 \left( c_{13}^2 c_{23}^2 + s_{12}^2 s_{23}^2 s_{13}^2 - 2c_{12} c_{23} s_{12} s_{23} s_{13} \cos \delta \right) \sin^2 \frac{\Delta m_{12}^2 L}{4E} \ \text{solar drive} \]

\[ \mp 8c_{12}^2 s_{13}^2 s_{23}^2 \cos \frac{\Delta m_{23}^2 L}{4E} \sin \frac{\Delta m_{13}^2 L}{4E} \frac{aL}{4E} (1 - 2s_{13}^2) \ \text{matter effect (CP odd)} \]

- All the oscillation parameters matter
- Synergy between different experiments necessary
Third generation Long Baseline Experiments

Gigantic detectors with three liquids are under way:

- Liquid scintillator: **Juno** and **SNO+** are in construction
- Water: **Hyper-Kamiokande** selected as top project by Mext. And also **IceCube Gen 2, Km3net/Orca**
- Liquid Argon: **Dune** is approved and partially funded

Such a big effort and investment by thousands of physicists and several major funding agencies is the right recognition of the splendid results and great perspectives of neutrino physics
Hyper-Kamiokande

✓ Gigantic neutrino and nucleon decay detector
  ✓ 186 kton fiducial mass : ~10 × Super-K
  ✓ × 2 higher photon sensitivity than Super-K
  ✓ Superb detector capability, technology still evolving
  ✓ 2\textsuperscript{nd} oscillation maximum by 2\textsuperscript{nd} tank in Korea under study

✓ MW-class world-leading v-beam by upgraded J-PARC

✓ Project now is a priority project by MEXT’s Roadmap
  ✓ Aiming to start construction in FY2019, operation in FY2026
- 4 10-kt (fiducial) liquid argon TPC modules
- **Single-** and dual-phase detector designs (1\textsuperscript{st} module will be single phase)
- Integrated photon detection
- Modules will not be identical

Single phase: modular wire-plane readout

Single phase: 10 kt module
- 384,000 readout wires
- 150 “APAs” (2.3 m x 6 m)
- 12 m high
- 15.5 m wide
- 58 m long
Dune and HK CP Sensitivity

CP Violation

Simultaneous measurement of neutrino mixing angles and $\delta_{CP}$

$\sin\delta_{CP}=0$ exclusion

$\delta_{CP}$ 1σ error

1.3MW beam
1 year = $10^7$s

$\delta_{CP}=90^\circ$
$\delta_{CP}=0^\circ$
• **Central detector**
  - Acrylic sphere with liquid scintillator
  - PMTs in water buffer
  - 78% PMT coverage

• **Water Cherenkov muon veto**
  - 2000 20” PMTs
  - 35 ktons ultra-pure water
  - Efficiency > 95%
  - Radon control → less than 0.2 Bq/m³

• **Compensation coils**
  - Earth magnetic field <10%
  - Necessary for 20” PMTs

• **Top tracker**
  - Precision muon tracking
  - 3 plastic scintillator layers
  - Covering half of the top area
- $3\sigma$ MO
- Provided that energy res. <3%
- $4\sigma$ with an external input of $\Delta m_{ee}<1$
- Precision measurement of other 3 neutrino osc. parameters

| Dominant experiment | $\Delta m^2_{21}$ | $\sin^2\theta_{12}$ | $|\Delta m^2_{31}|$ | $\sin^2\theta_{13}$ | $\sin^2\theta_{23}$ |
|---------------------|-------------------|---------------------|---------------------|---------------------|---------------------|
| KamLAND             |                   |                     |                     |                     |                     |
| SNO                 |                   |                     |                     |                     |                     |
| T2K & NOvA/Daya Bay |                   |                     |                     |                     |                     |
| Daya Bay            |                   |                     |                     |                     |                     |
| T2K                 |                   |                     |                     |                     |                     |
| Individual 1σ       | 2.4%              | 6.7%                | 3.2%/3.5%           | 4.0%                | 9.8%                |
| Global 1σ *         | 2.2%              | 3.9%                | 1.2%                | 3.4%                | 5%                  |
| JUNO expected 1σ    | 0.6%              | 0.7%                | 0.4%                | ~15%                | -                   |
Complementarity

“There are two possible outcomes: if the result confirms the hypothesis then you’ve made a measurement. If the result is contrary to the hypothesis then you’ve made a discovery”, Enrico Fermi.

• Without complementarity and redundancy HK and Dune risk to produce “boring” yet powerful measurements.
• With they increase their discovery potential
• HK and Dune nicely complement their physics reach in neutrino oscillations (see f.i. arXiv:1501.03918)
• Juno can improve their sensitivity in precisely measuring solar parameters while HK and Dune can measure $\Delta m_{ee}^2$ for Juno
• The three liquids really complement each other in detecting SN neutrinos, proton decays, solar neutrinos, indirect DM searches, ...
To fully exploit the physics potential of your experiment you have to wish all the best to your «competitors», the flow chart here below illustrates a possible real case at best.

Talk by S. Raut at NuFact 2017

Summary: A flowchart for the future?

- Expt data consistent with standard osc?
  - YES
    - Degeneracy?
      - YES (Octant degen)
        - More work needed
      - NO
        - YES (Hierarchy degen)
          - Large matter effects: LBL or atmospheric
          - Run in nu+antinu modes
        - Boring, but easy
        - Low energy, eg. second osc max
  - NO (Sterile, NSI, etc)

Sushant Raut | NuFact 2017, Uppsala
Tension between solar and KamLAND

⇒ 2σ tension between preferred value of Δm^2_{21} from KamLAND and solar data

• Δm^2_{21} preferred by KamLAND predicts steep upturn at solar spectrum and smaller D/N asymmetry

• More precise measurements of Δm^2_{21} by reactor (JUNO,RENO-50) and solar experiments may help.

• NSI (ε ~ 0.3) can reconcile solar and KL data

⇒ flatter spectrum at intermediate E-region
⇒ larger D/N asymmetries can be expected

Escrihuela et al, PRD80 (2009)
Coloma et al, PRD96 (2017)
Maltoni & Smirnov, EPJ 2015
Complementarity: measure $L/E$ at different $E$

Any subleading non-oscillatory effect would violate $L/E$ scaling
Ultimate Goal: Not Measure Parameters but Test the Formalism (Over-Constrain Parameter Space)
At full statistics Dune and HK, will be dominated by systematic errors. Detectors can’t be improved very much and any significant progress of sensitivities can only be achieved through neutrino beams.

The focus of next to next generation of Long Baseline experiments are new concepts in neutrino beams.

**What Next**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>$\nu_e + \bar{\nu}_e$</th>
<th>$1/\sqrt{N}$</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>T2K (current)</td>
<td>74 + 7</td>
<td>12% + 40%</td>
<td>2.2x10^{21} POT</td>
</tr>
<tr>
<td>NOvA (current)</td>
<td>33</td>
<td>17%</td>
<td>FERMILAB-PUB-17-065-ND</td>
</tr>
<tr>
<td>NOvA (projected)</td>
<td>110 + 50</td>
<td>10% + 14%</td>
<td>arXiv:1409.7469 [hep-ex]</td>
</tr>
<tr>
<td>T2K-I (projected)</td>
<td>150 + 50</td>
<td>8% + 14%</td>
<td>7.8x10^{21} POT, arXiv:1409.7469 [hep-ex]</td>
</tr>
<tr>
<td>T2K-II</td>
<td>470 + 130</td>
<td>5% + 9%</td>
<td>2x10^{21} POT, arXiv:1607.08004 [hep-ex]</td>
</tr>
<tr>
<td>Hyper-K</td>
<td>2900 + 2700</td>
<td>2% + 2%</td>
<td>10 yrs 2-tank staged KEK Preprint 2016-21</td>
</tr>
<tr>
<td>DUNE</td>
<td>1200 + 350</td>
<td>3% + 5%</td>
<td>3.5+3.5 yrs x 40kt @ 1.07 MW, arXiv:1512.06148 [physics.ins-det]</td>
</tr>
</tbody>
</table>

Talk on systematics by D. Hadley at Nufact ‘17
New concepts in neutrino beams

Few well known considerations

The high value of $\theta_{13}$ made possible to design powerful setups to look for leptonic CP violation based on conventional neutrino beams.

Conventional neutrino beams have severe limitations:

- Intrinsic $\nu_e$ contamination
- Neutrino parents are secondary particles and their production is not entirely described (next talk)
- The strong correlation among flux and cross section uncertainty makes very difficult to keep systematic errors below 4-5%

Solutions:

- Short term(*): Better and better close detectors, hadroproduction and ancillary experiments
- Long term: New concepts in neutrino beams, where neutrino parents are under control and intrinsic backgrounds smaller

(*) In neutrino physics metrics short term could be 20 years ...
Conventional neutrino beams

1) Proton Beam
2) Interaction target
3) Pion and Kaon hadroproduction
4) Magnetic Horn(s): Charge and momentum selection of hadrons
5) Decay tunnel
6) Mostly muons and neutrinos
7) Beam dump:
8) Neutrino Beam Mostly $\nu_\mu$
New concepts for $\nu$ beams

• More powerful proton driver, breaking the MW wall: ESSnuSB

• Different concepts:
  – $\pi$-DAR neutrinos: DAE$\delta$ALUS (first stage: IsoDAR)
  – Neutrinos from muon decays: Nufact (first stage: nuSTORM) and Moment (first stage: EMuS)
  – Not discussed here: pure $\nu_e$ ($\bar{\nu}_e$) beams from accelerated radioactive ions: Beta Beams (but see O.Titov, Poster #118)
The European Spallation Source Linac

- The ESS will be a copious source of spallation neutrons.
- **5 MW** average beam power.
- **125 MW** peak power.
- **14 Hz** repetition rate (2.86 ms pulse duration, $10^{15}$ protons).
- Duty cycle **4%**.
- **2.0 GeV** protons
  - up to **3.5 GeV** with linac upgrades
- >$2.7 \times 10^{23}$ p.o.t/year.
The neutron program must not be affected modifications.

**Linac**: double the pulse rate (14 Hz→ 28 Hz), from 4% duty cycle to 8%.

**Accumulator** (C~400 m) needed to compress to few μs the 2.86 ms proton pulses, affordable by the magnetic horn (350 kA)

- H⁻ source (instead of protons),
- space charge problems in the accumulator ring to be solved.

**Target station** (studied in EUROν).

**Underground detector** (WC à la Hyper-K studied in LAGUNA).

Short pulses (~μs) will also allow DAR experiments (as those proposed for SNS) using the neutron target.
The DAEδALUS concept

• $\pi$-DAR neutrino beams are free from $\bar{\nu}_e$
• Powerful searches for CP violation can be performed looking for $\bar{\nu}_\mu - \bar{\nu}_e$ oscillations at different distances ...
• ... requiring LS or GD-doped WC detectors
• First stage of DAEδALUS is IsoDAR
The IsoDAR (Isotope Decay-A-Rest) experiment is a high-intensity neutrino factory paired with a kiloton scale detector, that is able to make a **definitive statement about the existence of light sterile neutrinos**.

1. Produce and inject $\text{H}_2^+$ into a compact cyclotron.
2. Accelerate and extract 5 mA of $\text{H}_2^+$ at 60 MeV/amu.
3. Impinge $\text{H}_2^+$ on a $^9\text{Be}$ target to produce neutrons
4. Capture neutrons : $^7\text{Li}+n \rightarrow ^8\text{Li} \rightarrow ^8\text{Be} + e^- + \bar{\nu}_e$
5. Measure the $\bar{\nu}_e$ disappearance via IBD within a kiloton scale detector like KamLAND.
Probe the 3+1 global allowed region:
- 5σ in 4 months

Distinguish between different sterile models.
- 3+1 versus 3+2
- sterile neutrino decay

Collect the worlds largest sample of low energy $\bar{\nu}_e$ - $e^-$ elastic scattering events.

IsoDAR makes innovations in:
- High current cyclotrons
- Axial injection into cyclotrons
- Ion source development
- Medical isotope production

**Expected sensitivity of IsoDAR**

Collin et al. 1602.00671
Dentler et al. 1803.10661

**IsoDAR@KamLAND**
• $\nu$ parents ($\mu$) have all the same energy, same direction and are well counted
• $\nu$ beam known at % level (before any close detector constrain)
• Signal events are wrong sign muons
• The first stage of a Muon Collider ...
• ... but still very expensive (and challenging)
MICE is a single particle experiment where single muons are selected upstream of the absorber and formed into ensembles to represent a muon beam.

$R_{AMP}>1$ indicates cooling.
1. %-level ($\nu eN$) cross sections
   • Double differential

2. Sterile neutrino search
   • Beyond Fermilab SBN

Precise neutrino flux:
   - Normalisation: < 1%
   - Energy (and flavour) precise

$\pi \rightarrow \mu$ injection pass:
   - “Flash” of muon neutrinos

nuSTORM: neutrinos from stored muons

Fast extraction at >~ 100 GeV

Conventional pion production and capture (horn)
Quadrupole pion-transport channel to decay ring

Fast extraction at >~ 100 GeV

Conventional pion production and capture (horn)
Quadrupole pion-transport channel to decay ring
CCQE at nuSTORM:

- Six-fold improvement in systematic uncertainty compared with “state of the art”
- Electron-neutrino cross section measurement **unique**
- Require to demonstrate: 
  \(~<1\%\) precision on flux
• Concept: fire Juno with an accelerator neutrino beam
• Use a CW proton Linac: 15 MW, 1.5 GeV
• Derived from China-ADS Linac development
• Fluidized target in high-field SC solenoid
• Muon transport and decay channel
• Other possibilities: p-decayed beam and DAR neutrinos
Conclusions

• Neutrino physics had an enormous progress since the discovery of neutrino oscillations in 1998
• New fundamental measurements are at hand in the next years
• This convinced thousands of physicists and funding agencies to invest in future experiments
• Complementarity and redundancy are necessary to strengthen the foreseen measurements and allow unexpected discoveries.
• In the long term new technologies will be needed, particularly to develop neutrino beams of new concept
• This requires full support to their R&D since now
Short term: Sterile Neutrinos

Sterile Neutrinos

- Short Baseline at FNAL
  - LAr1ND
  - MicroBooNE
  - Icarus

- Long Baseline
  - Daya Bay
  - T2K
  - Nova

- Reactors
  - DANSS
  - NEOS
  - nuLat
  - Neutrino4
  - PROSPECT
  - SoLid
  - Chandler
  - Stereo

- Cosmology

- DAR ν beams
  - JSNS\(^2\)
  - Isodar (?)

- ν generators
  - CeSOX
  - Katrin
  - Best (?)
Excess of $\nu_e$-like events in a $\nu$ beam from $\pi$ decays at rest

$\pi$ DAR
- JSNS$^2$

JSNS$^2$ TDR: arXiv:1705.08629
90%CL sensitivity for 1MW x 3 years x 1 detector