Neutrino Physics: theory and phenomenology

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Almost 2 decades of revolutionary neutrino experiments have revealed a new flavour sector, which does not quite fit in the Standard Model.

SuperKamiokande

KamLAND

MINOS, Opera

SNO

Borexino

T2K

...and more
After the discover the Brout-Englert-Higgs particle

Standard Model as healthy as ever...
What about neutrinos?

Neutrinos are massive -> there must be new dofs in the SM

\[ -\mathcal{L}_{\text{Dirac}} = \bar{\nu}_L m_\nu \nu_R + h.c. \leftrightarrow \bar{L} \tilde{\Phi} \lambda \nu_R + h.c. \]

\[
m_\nu \sim \lambda \nu
\]

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, ...) 
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

At least two \(\nu_R\)....
A neutrino experiment is an interferometer in flavour space, because neutrinos are so weakly interacting that can keep coherence over very long distances!

\[
P(\nu_\alpha \rightarrow \nu_\beta) = \sum_{ij} U_{\alpha i} U_{\beta i}^* U_{\alpha j}^* U_{\beta j} e^{-i \frac{(m_i^2 - m_j^2)L}{2E}}
\]

\[
L_{osc} \sim \frac{E}{m_i^2 - m_j^2}
\]
Two frequencies precisely measured

\[ \Delta m^2_{\text{sol}} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(100km)} \]

\[ |\Delta m^2_{\text{atm}}| \sim \frac{\mathcal{O}(GeV)}{\mathcal{O}(1000km)} \sim \frac{\mathcal{O}(MeV)}{\mathcal{O}(1km)} \]

Precision era has arrived: effects from the two frequencies sizeable
- different experiments need each other to fix their unknowns
SM+3 massive neutrinos: Global Fits

Marrone’s Parallel talk

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix} = U_{PMNS}(\theta_{12}, \theta_{23}, \theta_{13}, \delta, \ldots) 
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
\]

\[\Delta m^2_{13} > 0\]
\[\Delta m^2_{13} < 0\]

See also Capozzi et al, 1312.2878 and Forero et al, 1405.7540

Gonzalez-Garcia et al 1409.5439
Mass ordering degeneracy

\[ \Delta \chi^2 \leq 1 \sigma \]

No clear tendency: different data sets point in different directions....
$\Delta \chi^2 \leq 1.4 \ (1.0)\sigma$

Preference for non-maximal mixing: $\theta_{23} > 45^\circ$ IO, $\theta_{23} < 45^\circ$ NO

1) MINOS disappearance --> non-maximality
2) $\theta_{13}$(reactor) < $\theta_{13}$(T2K) relieved by non-maximality (depends on IO/NO and $\delta$)
3) Atmospheric data neutral for IO or adds positively for NO

Gonzalez-Garcia et al 1409.5439
Leptonic CP violation

Preference for $\delta > 180^\circ$ driven mostly by combination of reactor/T2K, atmospheric add positively
Absolute mass scale

Best constraints at present from cosmology
Absolute mass scale

Neutrinos as light as 0.1-1eV modify the large scale structure and CMB

Conservative limit:

\[
\begin{align*}
\sum m_\nu &< 0.23 \text{ eV} \\
\Omega_\nu h^2 &< 0.0025
\end{align*}
\]

\[95\%, \text{Planck TT+lowP+lensing+ext.}\]
What next?

A ambitious experimental program is underway to pin down the remaining unknowns and reach 1% precision in lepton flavour parameters

- Neutrino ordering
- Octant
- Majorana nature
- Leptonic CP violation

requires sensitivity to both osc. frequencies in the same experiment!

\[
P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta_{23} L}{2}\right) \equiv P_{\text{atmos}} \\
+ c_{23}^2 \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta_{12} L}{2}\right) \equiv P_{\text{solar}} \\
+ \tilde{J} \cos \left(\pm \delta - \frac{\Delta_{23} L}{2}\right) \frac{\Delta_{12} L}{2} \sin \left(\frac{\Delta_{23} L}{2}\right) \equiv P_{\text{inter}}
\]
What next?

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- Neutrino ordering
- Octant
- Majorana nature
- Leptonic CP violation

requires sensitivity to both osc. frequencies in the same experiment!

See next talks...
Outliers

LSND

\[
P(\nu_\mu \rightarrow \nu_e) = O(|U_{ei}|^2 |U_{\mu i}|^2)
\]

Reactors

\[
P(\nu_e \rightarrow \nu_e) = O(|U_{ei}|^2)
\]

T. A. Mueller et al; P. Huber

+Gallium anomaly+ MiniBOONE low-energy excess...
Neutrino anomalies

Tension remains because no signal in \( P(\nu_\mu \rightarrow \nu_\mu) = O(|U_{\mu i}|^2) \)

MINOS+ parallel talk

Giunti’s parallel talk

Hopefully clarified in the next few years!

See next talks
Why are neutrinos so much lighter?
Neutral vs charged hierarchy?

\[ m_f \sim \lambda \nu \]

(large angle MSW)
Why so different mixing?

**CKM**

\[
|V|_{\text{CKM}} = \begin{pmatrix}
0.97427 \pm 0.00015 & 0.22534 \pm 0.0065 & (3.51 \pm 0.15) \times 10^{-3} \\
0.2252 \pm 0.00065 & 0.97344 \pm 0.00016 & (41.2^{+1.1}_{-5}) \times 10^{-3} \\
(8.67^{+0.29}_{-0.31}) \times 10^{-3} & (40.4^{+1.1}_{-0.5}) \times 10^{-3} & 0.999146^{+0.000021}_{-0.000046}
\end{pmatrix}
\]

**PMNS**

\[
|U| = \begin{pmatrix}
0.801 \rightarrow 0.845 & 0.514 \rightarrow 0.580 & 0.137 \rightarrow 0.158 \\
0.225 \rightarrow 0.517 & 0.441 \rightarrow 0.699 & 0.614 \rightarrow 0.793 \\
0.246 \rightarrow 0.529 & 0.464 \rightarrow 0.713 & 0.590 \rightarrow 0.776
\end{pmatrix}
\]
A new physics scale

Neutrinos have tiny masses \( \rightarrow \) a new physics scale

\[
-\mathcal{L}_{\text{Majorana}} = \bar{\nu}_L m_\nu \nu^c_L + h.c. \leftrightarrow \bar{L} \tilde{\Phi} \alpha \tilde{\Phi} L^c + h.c.
\]

\[
[\alpha] = -1
\]

\[
\alpha = \frac{Y_\nu}{\Lambda}
\]

\[
m_\nu = Y \frac{\nu^2}{\Lambda}
\]
Massive Majorana neutrinos & SSB?

If $\Lambda \gg v$ natural explanation for the smallness of neutrino mass

\begin{align*}
    m_f (\text{charged}) &\sim Y v, \\
    m_\nu &\sim Y \frac{\nu^2}{\Lambda}
\end{align*}
Fermi-era of neutrino physics

\[ G_F \sim \frac{1}{M_W^2} \]

Data-driven BSM: such that gives the Weinberg operator!

\( \nu_{i} \rightarrow \nu_{j}^c \)

\( \lambda_{ij} \)

\( \frac{\Lambda}{\Lambda} \)

\( \nu_{SM} \)

?
Resolving Weinberg’s operator at tree level

**Type I see-saw:**
a heavy singlet scalar

\[ m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N \]

Minkowski; Yanagida;
Glashow;
Gell-Mann, Ramond Slansky;
Mohapatra, Senjanovic...

**Type II see-saw:**
a heavy triplet scalar

\[ m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Delta \frac{\mu_\Delta}{M_\Delta^2} v^2 \]

Konetschny, Kummer;
Cheng, Li;
Lazarides, Shafi, Wetterich...

**Type III see-saw:**
a heavy triplet fermion

\[ m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_\Sigma^T \frac{v^2}{M_\Sigma} Y_\Sigma \]

Foot et al; Ma;
Bajc, Senjanovic...

Resolved at one and even two loops! Aristizabal’s parallel talk
How does the \(\nu\) scale relates to the EW scale?

Example: Type I seesaw model

\[
\mathcal{L} = \mathcal{L}_{SM} - \sum_{i=1}^{n_R} \bar{\ell}_L Y^\alpha i \tilde{\Phi} \nu_R^i - \sum_{i,j=1}^{n_R} \frac{1}{2} \bar{\nu}_R^{ic} M_{N}^{ij} \nu_R^j + h.c.
\]

\[m_\nu = \frac{\alpha v^2}{\Lambda} \equiv Y_N^T \frac{v^2}{M_N} Y_N\]

Minkowski; Yanagida; Glashow; Gell-Mann, Ramond Slansky; Mohapatra, Senjanovic...
Spectra of Type I seesaw models

18 free parameters (6 masses + 6 angles + 6 phases) out of which we have measured 2 masses and 3 angles...

\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U_{ll}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
+ U_{lh}
\begin{pmatrix}
N_1 \\
N_2 \\
N_3
\end{pmatrix}
\]

\[
U_{ll} \simeq U_{PMNS} + O\left(\frac{m}{M}\right)
\]

\[
U_{lh} \simeq iU_{PMNS}\sqrt{m_l}R\frac{1}{\sqrt{M_h}}
\]

\[
R^T R = 1
\]

Casas-Ibarra parametrization

Parameters we can know from neutrino experiments

\textbf{R:} contains all the parameters we cannot measure in neutrino experiments
Spectra of Type I seesaw models

The lower the seesaw scale $M_N$

- Lower kinematical threshold to produce new states
- Larger mixing with flavour states

**MANY NAMES:** right-handed neutrinos, sterile neutrinos, neutral heavy leptons, singlet fermions
Pinning down the new physics scale: naturalness

\[ M_N \leq \text{GUT} \]

\[ M_N = \text{TeV} \]
Pinning down the New physics scale: naturalness

The new scale is stable under radiative corrections due to Lepton Number symmetry but the EW is not!

\[ \delta m_H^2 = \frac{Y^+ Y}{4\pi^2} M_N^2 \log \frac{M_N}{\mu} \]

\[ M_N \gg m_H \]

not natural in the absence of SUSY
Pinning down the New physics scale: experiment

there is \textit{neutrinoless double beta} decay at some level ($M_N > 100\text{MeV}$)
Neutrinoless double-$\beta$ decay

\[ m_{\beta\beta} = \sum_{i=1}^{3} \left[ (U_{PMNS})_{ei} \right]^2 m_i + \sum_{i=j}^{3} U_{ej}^2 M_j \frac{M^{0\nu\beta\beta}(M_j)}{M^{0\nu\beta\beta}(0)} \]

\[ M_j \to \infty \quad \frac{M^{0\nu\beta\beta}(M_j)}{M^{0\nu\beta\beta}(0)} \propto \left( \frac{100 \text{ MeV}}{M_j} \right)^2 \]
Neutrinoless double-$\beta$ decay

$$m_{\beta\beta} = \sum_{i=1}^{3} [(U_{PMNS})_{ei}]^2 m_i + \sum_{i=j}^{3} U_{ej}^2 M_{ej} \frac{\lambda_{\beta\beta}(M_j)}{\lambda_{\beta\beta}(0)}$$

Light states

Heavy states

For $M_j >> 100$ MeV, amplitude dominated by light contribution

Vissani 2002, Fogli et al,
Updated by Gonzalez-Garcia et al, 2012
Neutrinoless double-β decay

\[ m_{\beta\beta} = \sum_{i=1}^{3} [(U_{PMNS})_{ei}]^2 m_i + \sum_{i=j}^{3} U_{ej}^2 M_j \frac{M_{0\beta\beta}^0(M_j)}{M_{0\beta\beta}^0(0)} \]

Heavy contributions might be naturally sizeable for \( M_j \) [100 MeV- few GeV]

Above a few GeV large cancellation between tree and 1 loop ν mass

Lopez-Pavon, Molinaro, Petcov 1506.05296
Pinning down the New physics scale

Sterile neutrinos below 100 MeV can strongly modify

- Big-Bang Nucleosynthesis
- Cosmic Microwave background
- Large Scale structure

Either they contribute too much radiation or too much matter, modifying in unacceptable ways the expansion history and/or growth of perturbations.
Seesaw scale vs cosmology

Type I seesaw $N = 3$ that explains neutrino masses

$m_{\text{lightest}} > 3.2 \times 10^{-3}$ eV

PH, M. Kekic, J. López-Pavon 1311.2614;1406.2961
Type I seesaw $N=3$ that explains neutrino masses

$m_{\text{lightest}} < 3.2 \times 10^{-3} \text{ eV}$

PH, M. Kekic, J. López-Pavon 1311.2614;1406.2961
Warm Dark Matter?

Dodelson, Widrow
Fuller et al...
Shaposhnikov et al

7 keV neutrino?

Bulbul et al 1402.2301; Boyarsky 1402.4119

Hierarchy problem or SUSY?

Intense debate: Jeltema et al; M Carlson et al; Boyarsky et al; Bulbul et al

Caveat: huge lepton asymmetries are necessary, otherwise cannot produce sufficient DM!
EW Leptogenesis

Resonant Leptogenesis $M > 100 \text{GeV}$

Pilaftsis

Leptogenesis via oscillations $M = 0.1 - 10 \text{GeV}$

Akhmedov, Smirnov; Shaposnikov et al
EW Leptogenesis

Sakharov conditions:

✔ CP violation (up to 6 new CP phases in the lepton sector)

✔ B+L violation from sphalerons $T > T_{EW}$

✔ Out of equilibrium: at least one of the sterile states does not reach thermal equilibrium before $T_{EW}$

(in contrast with standard leptogenesis in the decay of the heavy states: the violation of L from Majorana masses is not relevant $M/T << 1$)

“Flavoured” CP asymmetries arise in production of sterile states via the interference of CP-odd phases and CP-even phases from oscillations

Assumptions: $y_3 << y_1, y_2$, $M_i [0.1, 100]$ GeV
GeV Leptogenesis

In model with only two sterile neutrinos

Canetti, Drewes, Frossard, Shaposhnikov 12084607

exploration of three neutrino underway...

Is EW leptogenesis testable?
Other states out there EW scale?

Can be produced in flavoured via CC, NC, Higgs interactions:

\[| (U_{lh})_{\alpha i} |^2 \propto \frac{m_\nu}{M_N}\]

too small couplings unless....
Seesaw models + approx Lepton number

Wyler, Wolfenstein; Mohapatra, Valle; Branco, Grimus, Lavoura, Malinsky, Romao; Kersten, Smirnov; Abada et al; Gavela et al....many others

\[
\begin{pmatrix}
0 & Yv & 0 \\
Yv & 0 & M_N \\
0 & M_N & \mu \\
\end{pmatrix}
\]

\[
\begin{pmatrix}
0 & Yv & 0 \\
Yv & 0 & M_N \\
0 & M_N & \mu \\
\end{pmatrix}
\]

They are all a subclass of type I seesaw models (different choices of R)
Charged/neutral hierarchy in seesaw

\[ M_N = \text{TeV} \]

\[ M_N \leq \text{TeV} + \text{aprox. } U(1)_L \]

\[ \nu \text{ Yukawa} \]

\[ \nu \text{ Yukawa} \]

Eg: Inverse seesaw/direct seesaw

Generically degenerate heavy neutrinos: pseudo-dirac pairs
Rich phenomenology of low-scale models with U(1)

Direct production in meson decays, beam dump experiments, electroweak precision tests: sensitive to active-sterile mixings and heavy masses

Reviews Atre, Han, Pascoli, Zhang; Gorbunov, Shaposhnikov; Ruchayskiy, Ivashko

From 1504.04855

Parallel talks: De Romeri, M. Drewes J. Hernandez
LHC Searches

\[ \sigma \times B_R > 10^{-3} \text{ pb} \]

\[ 19.7 \text{ fb}^{-1} (8 \text{ TeV}) \]

CMS

CMS 1501.05566

ATLAS 1506.06020
LFV decays \[ \mu \rightarrow e \gamma \quad \mu \rightarrow e e e \quad \mu \rightarrow e \text{ conversion} \]

Recent analysis Alonso, et al; Dinh et al

Very strong constraints and extremely good prospects!
It is possible to attain singlet fermion mass in the 100 GeV range with Dirac Yukawa. Clearly, which charged lepton appears will depend on the flavor structure of the interactions of Re($h$).

From this case since in our model, the mass of Re($h$) is large enough) or in a global analysis of Higgs decay data \cite{1207.2756} for $\ell^+\ell^-$

THE LHC bounds from the observation of a Higgs-like particle at the rate of new phenomena in the region of phase space where the excesses are concentrated suggests that they are originated from the presence of additional decay modes in $\ell^+\ell^-$

The obtained bound for a fixed $\nu$ is large enough) or in a global analysis of Higgs decay data \cite{1207.2756} for $\ell^+\ell^-$

It follows from the above Lagrangian that if one of the singlet fermions has mass in the $100$ GeV range, it is possible to attain singlet fermion mass in the 100 GeV range with Dirac Yukawa. Clearly, which charged lepton appears will depend on the flavor structure of the interactions of Re($h$) so that neither the heavy gauge boson associated with (II) nor the pseudo-Dirac pair and lepton number is almost exactly conserved.

The presence of additional decay modes opens up a new mode for SM Higgs decay, i.e., $h\rightarrow \ell^+\ell^-$.

It is possible to attain singlet fermion mass in the 100 GeV range with Dirac Yukawa. Clearly, which charged lepton appears will depend on the flavor structure of the interactions of Re($h$). Almost exactly conserved.

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Lower mass: Displaced Vertices

Helo, Kovalenko, Hirsch 1312.2900

Gago, PH, Jones-Perez, M. Losada, A. Moreno 1505.05880
Weinberg’s operator from some more fundamental principle?

**Grand Unification e.g. SO(10)**
- Babu, Mohapatra; Fukuyama Okada; Bajc, Senjanovic, Vissani; Joshipura, Patel; Altarelli, Meloni;...

**Left-right symmetric models ...**
- Pati, Salam; Mohapatra, Pati; Mohapatra, Senjanovic...

These models as well, as type II, III, richer phenomenology because new states with gauge interactions (easier to produce)
What about mixing?

• Discrete symmetries: e.g. tri-bimaximal mixing
  not so much motivated with large $\theta_{13}$ -> understanding corrections
  -> + GUTs

• Anarchy for leptons?

  Murayama, Naba, De Gouvea

• Minimal flavour violation and dynamical origin of Yukawas

  R. Alonso, et al

Parallel talks: Meloni Titov
Conclusions

• The results of many beautiful experiments have demonstrated that $\nu$ are (for the time-being) the less standard of the SM particles.

• Many fundamental questions remain to be answered however: Majorana nature of neutrinos and scale of new physics? CP violation in the lepton sector? Source of the matter-antimatter asymmetry? Lepton vs quark flavour?

• A rich experimental neutrino programme lies ahead, that will answer some of these important questions.

• LHC, LFV, SHiP, future colliders... could provide essential information on the new physics underlying neutrino masses if it lies naturally close to the EW scale.
BACKUP
Neutrino anomalies explained by oscillations is in strong tension with cosmology.

Reconciling LSND and cosmology: suppress sterile neutrino production with exotic physics.

Foot, Volkas; Mirizzi, et al; Saviano et al; Hannestad, Tamborra, Tram; Dasgupta, Kopp; Hannestad, Hasen, Tram; Archidiacono, et al; Bringmann, Hasenkamp, Kersten.
Several updated analyses from ATLAS: Grancagnolo’s parallel talk

- Type III: \( m_{L^+} < 400 \) GeV

- LR Type I symmetric models:

\[
\begin{align*}
\sigma &\pm 95\% \text{ CL Expected limit} \\
R_W = m_{N_m} &
\end{align*}
\]

Full results for all mass points are in HepData
Their only escape: that they do not thermalize because of small mixing/extra exotic physics