NEUTRINOS

P. HERNÁNDEZ

(IFIC U. VALENCIA-CSIC)
LECTURE II

• The standard $3\nu$ scenario and its unknowns: status and prospects

• Neutrinos and beyond the Standard Model physics
Standard $3\nu$ scenario

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

\[\theta_{12} \sim 34^\circ\]
\[\theta_{23} \sim 42^\circ \text{ or } 48^\circ\]
\[\theta_{13} \sim 8.5^\circ\]
\[\delta \sim ?\]
SM+3 massive neutrinos: Global Fits

+T2K ‘18 +NoVA ‘18+ Daya Bay ‘18 + RENO ’18 (+ SK ’18 $\chi^2$ table)

Esteban, González-García, Hernández-Gabezudo, Maltoni, Schwetz ‘18

(see also Cappozzi et al ‘18, de Salas et al ‘18)
The big open questions

What is the **neutrino ordering** normal or inverted?

Is there **leptonic CP violation**?

**Absolute mass scale:** minimum $m_\nu$

Are neutrinos **Majorana** and if so, what **new physics** lies behind this fact?
2018 2σ-views

2σ hint for NO

\[ \sin^2 \theta_{13} = 0.0219 \pm 0.0012 \]

2σ hint of CP violation

2σ hint of octant

DATA FIT with reactor constraint

F&C 2σ confidence intervals
T2K Run1-9c Preliminary

T2K

-2\Delta \ln(\mathcal{L})

\delta_{CP}

NOvA FD

8.85 \times 10^{20} \text{ POT equiv } \nu + 6.9 \times 10^{20} \text{ POT } \bar{\nu}
Hierarchy through MSW @Earth

Spectacular MSW effect at O(6GeV) and very long baselines: no need for spectral info nor two channels

Mikheev, Smirnov; Wolfenstein
Neutrino ordering from MSW

\[ \Delta m_{12}^2 \cos 2\theta_{12} = 2\sqrt{2}G_F E N_e \]

Solar density, \( E_{\text{res}} \sim \) few MeV!

\[ \Delta m_{23}^2 \cos 2\theta_{13} = \pm 2\sqrt{2}G_F E N_e \]

Earth density, \( E_{\text{res}} \sim \) few GeV!

Atmospheric resonance

Solar resonance
Hierarchy from atmospherics? the hard way...

$\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu$

Atmospheric data contain the golden signal but hard to dig...

neutrino telescopes (PINGU, ORCA) or improved atmospheric detectors (HyperK, INO)
Hierarchy from reactor $\nu$'s

Petcov, Piai; Choubey et al; Learned et al

$L = 50 \text{ km}$

JUNO experiment is planning to do this measurement
Leptonic CP violation

CP violation shows up in a difference between

\[ P(\nu_\alpha \rightarrow \nu_\beta) \neq P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta) \quad \alpha \neq \beta \]

Golden channel:

\[
P_{\nu_e \nu_\mu (\bar{\nu}_e \bar{\nu}_\mu)} = s_{23}^2 \sin^2 2\theta_{13} \sin^2 \left( \frac{\Delta_{23} L}{2} \right) \equiv P_{\text{atmos}}
\]

\[+ c_{23}^2 \sin^2 2\theta_{12} \sin^2 \left( \frac{\Delta_{12} L}{2} \right) \equiv P_{\text{solar}} \]

\[+ \tilde{J} \cos \left( \pm \delta - \frac{\Delta_{23} L}{2} \right) \frac{\Delta_{12} L}{2} \sin \left( \frac{\Delta_{23} L}{2} \right) \equiv P_{\text{inter}} \]

\[\tilde{J} \equiv c_{13} \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23}\]

simultaneous sensitivity to both splittings is needed
Hierarchy + CP in one go...
superbeams + superdectectors

Japan Hyper-Kamiokande: 230km

USA DUNE: 1300km
Hierarchy + CP in one go... superbeams+superdetectors

DUNE CDR:

CP Violation

Hyper Kamiokande (10y)
Outliers: SBL anomalies

LSND

Reactors

+Gallium anomaly...
SBL anomalies: 4\textsuperscript{th} neutrino ?

\[ P(\nu_\mu \to \nu_e) = O(|U_{e4}|^2 |U_{\mu4}|^2) \]

\[ P(\nu_e \to \nu_e) = O(|U_{e4}|^2) \]

\[ P(\nu_\mu \to \nu_\mu) = O(|U_{\mu4}|^2) \]

Oscillations at @meters for MeV neutrinos
MiniBOONE + LSND excess

In summary, the MiniBooNE experiment observes a 6σ discrepancy with SM!
New SBL reactor strategies: L-dep of signal

Stereo

DANSS

NEOS

Prospect

NEUTRINO-4

$\Delta m^2 = 1.4 \text{ eV}^2$, $\sin^2(2\theta) = 0.05$

$\Delta m^2 = 7.22 \text{ eV}^2$, $\sin^2(2\theta) = 0.35$

$\chi^2/\text{DoF} = 18.84/25$, GoF = 0.80

Unity

$\chi^2/\text{DoF} = 30.15/27$, GoF = 0.31
O(eV) sterile neutrinos?

No evidence for the involvement of muons:

1) Neutrino muons must disappear also but they don’t

Minos, Minos+
O(eV) sterile neutrinos?

No evidence for the involvement of muons:

2) Atmospheric neutrinos must resonate into steriles when crossing the nucleus of the Earth

\[ E_{\nu}^{\text{res}} \equiv \frac{\Delta m^2 \cos 2\theta}{2\sqrt{2}G_FN_e} \sim O(\text{TeV}) \]

Chizhov, Petcov; Nunokawa et al; Barger et al; Esmaili et al;
O(eV) 4th neutrino is not a good fit (all things considered...)

Dentler et al, 1803.10661

More exotic BSM posibilities...
Absolute $\nu$ mass scale

Best constraints at present from cosmology

$\sum m_\nu < 0.12 \text{ eV}$

(95%, Planck TT, TE, EE + lowE + lensing + BAO.)
Cosmological neutrinos

Neutrinos have left many traces in the history of the Universe

Galaxy distribution (LSS)

Nucleosynthesis

Rosenfeld’s lecture

CMB
Absolute $\nu$ mass scale

Neutrinos as light as 0.1-1eV modify the large scale structure and CMB
Why are neutrinos so much lighter?
Neutral vs charged hierarchy?
Why so different mixing?

CKM

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

PMNS

\[
|U|_{\text{PMNS}}^{\text{LID}} = \begin{pmatrix}
0.798 \rightarrow 0.843 & 0.517 \rightarrow 0.584 & 0.137 \rightarrow 0.158 \\
0.232 \rightarrow 0.520 & 0.445 \rightarrow 0.697 & 0.617 \rightarrow 0.789 \\
0.249 \rightarrow 0.529 & 0.462 \rightarrow 0.708 & 0.597 \rightarrow 0.773
\end{pmatrix}
\]

PDG

NuFIT 2016
Why so different mixing?

CKM

\[ V_{CKM} \simeq \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \]

PMNS

\[ |V_{PMNS}| \simeq \begin{pmatrix} \sqrt{\frac{2}{3}} & \sqrt{\frac{1}{3}} & 0 \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \\ \sqrt{\frac{1}{6}} & \sqrt{\frac{1}{3}} & \sqrt{\frac{1}{2}} \end{pmatrix} \]

Harrison, Perkins, Scott
Where the large mixing comes from?

Anarchy for leptons

Discrete or continuous symmetries

Lepton-quark flavour connection in GUTs?
Neutrinos have tiny masses -> a new physics scale, what?

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

Scale at which new particles will show up
What originates the neutrino mass?

Could be $\Lambda \gg v$... the standard lore (theoretical prejudice?)

$\Lambda = M_{\text{GUT}}$

$\lambda \sim \mathcal{O}(1)$

$\left\{ \begin{array}{l}
\Lambda = M_{\text{GUT}} \\
\lambda \sim \mathcal{O}(1) \\
\end{array} \right.$

$\mathcal{O}(1)$

Hierarchy problem

$\left\{ \begin{array}{l}
\Lambda^2 \\
m^2_H \propto \Lambda^2 \\
\end{array} \right.$

Vissani

not natural in the absence of SUSY/other solution to the hierarchy problem
The Standard Model is healthy as far as we can see...

Could be naturally $\Lambda \sim v$?

Yes! $\lambda$ in front of neutrino mass operator must be small...
Resolving the neutrino mass operator at tree level

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

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

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

\( \lambda \sim O(Y^2) \)

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

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

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

\( \lambda \sim O(Y \mu / M_\Delta) \)

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

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

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

\( \lambda \sim O(Y^2) \)
Where is the new scale?

Generic predictions

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

  model independent contribution from the neutrino mass 😊
Majorana nature: $\beta\beta 0\nu$

Plethora of experiments with different techniques/systematics: EXO, KAMLAND-ZEN, GERDA, CUORE, NEXT ...

$$m_{\beta\beta} = \sum_{i=1}^{3} [(U_{PMNS})_{ei}]^2 m_i$$

$\Sigma \equiv \sum_i m_i$

If $\Lambda > 100\text{MeV}$

Capozzi et al. '17
Where is the new scale?

Generic predictions:

- a matter-antimatter asymmetry if there is CP violation in the lepton sector via leptogenesis

model dependent...
Where is the new scale?

<table>
<thead>
<tr>
<th>new states accessible</th>
</tr>
</thead>
<tbody>
<tr>
<td>eV  keV  MeV  GeV  TeV</td>
</tr>
</tbody>
</table>

$M_{\text{Planck}}$  $M_N$

Generic predictions:

- there are other states out there at scale $\Lambda$: new physics beyond neutrino masses

  potential impact in cosmology, EW precision tests, collider, rare searches, $\beta\beta0\nu$, ...

model dependent... 😞
The EW scale is an interesting region: new physics underlying the matter-antimatter asymmetry could be predicted & tested!
Minimal model of neutrino masses:

**Type I seesaw:** SM+right-handed neutrinos

\[ \mathcal{L}_\nu = -\bar{l}Y \Phi N_R - \frac{1}{2} \bar{N}_R M N_R + h.c. \]

\[ m_\nu = \lambda \frac{\nu^2}{\Lambda} \equiv Y^T \frac{\nu^2}{M} Y \]

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

\[ n_R = 3 \]: 18 free parameters (6 masses + 6 angles + 6 phases)
out of which we have measured 2 masses and 3 angles...

\[ m_1, m_2, m_3, M_1, M_2, M_3 \]

Dirac \[ M_N \] Seesaw

\{ Light neutrinos \}
Type I seesaw models

Phenomenology (beyond neutrino masses) of these models depends on the heavy spectrum and the size of active-heavy mixing:

$$
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau
\end{pmatrix}
= U_{ll}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3
\end{pmatrix}
+ U_{lh}
\begin{pmatrix}
N_1 \\
N_2 \\
N_3
\end{pmatrix}
$$
Type I seesaw models

Strong correlation between active-heavy mixing and neutrino masses:

$$|U_{lh}|^2 \sim \frac{m_l}{M_N}$$

(but naive scaling too naive for $n_R > 1$...)

$R$: general orthogonal complex matrix (contains all the parameters we cannot measure in neutrino experiments)
Seesaw correlations:
flavour ratios of heavy lepton mixings strongly correlated with ordering, $U_{PMNS}$ matrix: $\delta, \phi_1$

$n_R=2$:

Caputo, PH, Lopez-Pavon, Salvado arxiv:1704.08721
Baryon asymmetry

The Universe seems to be made of matter

\[
\eta \equiv \frac{n_B - n_{\bar{B}}}{n_\gamma} = 6.21(16) \times 10^{-10}
\]
Baryon asymmetry

In the early Universe this implies

\[ \eta \equiv \frac{n_B - n_{\bar{B}}}{n_{\gamma}} = 6.21(16) \times 10^{-10} \]

WMAP
Baryon asymmetry

Can it arise from a symmetric initial condition with same matter & antimatter?

Sakharov’s necessary conditions for baryogenesis

- Baryon number violation (B+L violated in the Standard Model)
- C and CP violation (both violated in the SM)
- Deviation from thermal equilibrium (at least once: electroweak phase transition)

It does not seem to work in the SM with massless neutrinos ...

CP violation in quark sector far to small, EW phase transition too weak...
Leptogenesis

Models with massive neutrinos generically lead to generation of lepton and therefore baryon asymmetries

Standard leptogenesis in out-of-equilibrium decay $M_N > 10^7$GeV

Fukuyita, Yanagida
Leptogenesis

Resonant leptogenesis $M > 100$ GeV

Pilaftsis...
Leptogenesis

Leptogenesis from neutrino oscillations
$0.1\text{GeV} < M < 100\text{GeV}$

Akhmedov, Rubakov, Smirnov;
Asaka, Shaposhnikov,...
Sakharov conditions

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

\[ Y = U_{PMNS}^* \sqrt{m_\nu} R \sqrt{M_h} \frac{\sqrt{2}}{v} \]

(R: 3 complex angles + $U_{PMNS}$: 3 phases)

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

+ $L$ (high-scales)
+ $L\alpha$ (high and low scales)

Out of equilibrium: different for low and high scales
High–scale leptogenesis

New sources of CP violation and L violation in the neutrino sector can induce CP asymmetries in decays of heavy Majorana $\nu$

Fukuyita, Yanagida

$$\epsilon_1 = \frac{\Gamma(N \to \Phi l) - \Gamma(N \to \Phi \bar{l})}{\Gamma(N \to \Phi l) + \Gamma(N \to \Phi \bar{l})}$$

$$Y_B = 4 \times 10^{-3} \quad \text{CP–asym eff. factor}$$

Generic and robust feature of see-saw models for large enough scales $M_N > 10^7-10^9 \text{GeV}$ (unless an extreme degeneracy exits)
Low-scale Leptogenesis

Akhmedov, Rubakov, Smirnov

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

\[
L_\alpha \rightarrow L_\beta \neq \bar{L}_\alpha \rightarrow \bar{L}_\beta
\]

\[
Y_B \propto \sum_\alpha \Delta_{CP}^\alpha \eta_\alpha
\]

\[
\sum_\alpha \Delta_{CP}^\alpha = 0
\]

Different flavours different efficiency in transferring it to the baryons
High-scale leptogenesis
(larger Y)

\[ Y \]

\[ Y_N \]

\[ Y_N^* \]

\[ Y_2 - Y_N \]

\[ T^{-1} \]

\[ \Gamma_N \leq H(M_N) \]

(decay rate < hubble expansion)

Low-scale leptogenesis
(smaller Y)

\[ T_{EW} \]

\[ \Gamma_s(T_{EW}) \leq H(T_{EW}) \]

(scattering rate < hubble expansion)
Testability/predictivity?

- $Y_B$ cannot be determined from neutrino masses and mixings only

- More information from the heavy sector is needed:
  
  High-scale scenarios: very difficult for $M_N > 10^7$ GeV

  Low-scale scenarios: N’s can be produced in the lab and could be in principle detectable!
In the minimal model with just \( n_R = 2 \) neutrinos (IH)

Colored regions: posterior probabilities of successful \( Y_B \)

PH, Kekic, Lopez-Pavon, Racker, Salvado

Colored regions: posterior probabilities of successful \( Y_B \)
In the minimal model with just $n_R=2$ neutrinos (IH)

Rare meson decays searches
Eg: @SHIP

Displaced vertex searches in $Z$ decays
Eg: @FCC-ee
Predicting $Y_B$ in the minimal model $n_R=2$ ?

Assume a point within SHIP reach that gives the right baryon asymmetry

- SHIP measurement could provide (if states not too degenerate)
  
  \[ M_1, M_2, |U_{e1}|^2, |U_{\mu_1}|^2, |U_{e2}|^2, |U_{\mu_2}|^2 \]

- Future neutrino oscillations: $\delta$ phase in the $U_{\text{PMNS}}$
Predicting $Y_B$ in the minimal model $n_R=2$ (IH)

<table>
<thead>
<tr>
<th>$m_{\beta\beta}$ (eV)</th>
<th>$Y_B (10^{-11})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs. $Y_B = 8.6 \times 10^{-11}$</td>
<td></td>
</tr>
</tbody>
</table>

$\Delta|U|^2 = 1\%$, $\Delta M = 0.1\%$, $\Delta \delta = 17$ rad

PH, Kekic, Lopez-Pavon, Racker, Salvado
Predicting $Y_B$ in the minimal model $n_R=2$

Heavy states also contribute to the $\beta\beta 0\nu$ amplitude...

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

Light states

Heavy states

\[
M_j \rightarrow \infty \quad \frac{M^{0\nu\beta\beta}(M_j)}{M^{0\nu\beta\beta}(0)} \propto \left( \frac{100 \text{ MeV}}{M_j} \right)^2
\]

the heavy contribution is sizeable for $M_i$ of O(GeV)

Blennow, Fernandez-Martinez, Lopez-Pavon, Menendez; Lopez-Pavon, Pascoli, Wong; Lopez-Pavon, Molinaro, Petcov

The non standard contributions bring essential information of some CP phases and other unknown parameters
Predicting $Y_B$ in the minimal seesaw model $M \sim \text{GeV}$

The GeV-miracle: the measurement of the mixing to $e/\mu$ of the sterile states, neutrinoless double-beta decay and $\delta$ in neutrino oscillations have a chance to give a prediction for $Y_B$
Exploring the EW region

Reviews Atre, Han, Pascoli, Zhang; Gorbunov, Shaposhnikov; Ruchayskiy, Ivashko; Deppisch, Dev, Pilaftsis
Bounds only interesting if \[ |U_{\alpha i}|^2 \gg \frac{m_\nu}{M_i} \leftrightarrow R \gg 1 \]

- In some cases \textbf{unnatural}:
  
  \textit{eg:} cancellation between tree level and 1 loop contribution to neutrino masses
  
  Lopez-Pavon, Pascoli, Wang

- But also technically natural textures:
  
  protected by an approximate global \textit{U}(1)$_L$

Example $n_R = 2$:

\[ L(N_1) = +1, \quad L(N_2) = -1 \]

\[ -\mathcal{L}_\nu \supset \bar{N}_1 M N_2^c + Y \bar{L} \bar{\Phi} N_1 + h.c. \]

Does not induce neutrino masses: $Y$ unbounded by them
Seesaw models + approx Lepton number

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

\[
\begin{pmatrix}
0 & Y_1 \nu & \epsilon Y_2 \nu \\
Y_1 \nu & \mu' & M_N \\
\epsilon Y_2 \nu & M_N & \mu
\end{pmatrix}
\]

They are all a subclass of type I seesaw models with the generic features:

- quasi-Dirac heavy states
- LNV (neutrino masses, same-sign W decays, etc) \( \sim O(\mu, \mu', \epsilon) \)
- Yukawa hierarchies

Look for LNC processes ! Can we test their Majorana nature ?
imposing the CMS selection criteria listed above. The corresponding number of signal events passing TeV LHC as a function of the lightest heavy neutrino mass neutrino mixing derived here can be treated as conservative bounds. 

finite result. Using a lower value of quarks in the for the SF case; for the FD case, the cross sections are enhanced by a factor of two. Note that for 14 TeV LHC as a function of the lightest heavy neutrino mass larger gluon content of the proton, as compared to the quark content [1]. The numerical values of the two-body final state diagrams involving quark-gluon fusion, such as those shown in Figure 2, which give rise to hard jets not contain any jets at the parton-level, but initial state radiation (ISR) e

selection cuts listed above turn out to be the most er
erent selection criteria than those used by the current CMS analysis is beyond the scope of this Nl

Note that there are additional contributions to the trilepton signal from FMMF [37], and NuTeV [39]. It is important to note here that in order to make a direct comparison of our signal events with the standard model background is observed. 

In summary, a search has been performed for a heavy neutral lepton N of Majorana nature produced in the decays of a W boson, with subsequent prompt decays of N to W

The CMS analysis [27] has given the number of observed events and the corresponding SM background expectation for various ranges of 

The limited statistical precision of the available MC samples leads to an additional uncertainty of 1–30%, depending on the process and search region. 

The interpretation of the results is presented in Fig. 2. The N lifetime is inversely proportional to 

The dashed black curve is the expected upper limit, with one and two standard-deviation

grounds sources in each search region, are shown in Fig. 1. Tabulated results and enlarged ver-

sions of Fig. 1, with potential signals superimposed, are provided in Appendix A. We see no evidence for a significant excess in data beyond the expected SM background. We compute

LNC @LHC: trilepton + missing energy

Del Aguila, Aguilar-Saavedra; ...Chen,Dev; Izaaguirre, Shuve; Dib et al; many more

CMS ‘18

Reaching significantly lower mixings (& lower masses) via displaced decays

Helo, Kovalenko, Hirsch ; Gago, PH, Jonez-Perez, Losada, Moreno; Blondel, Graverini,Serra, Shaposhnikov;Antush, Cazzato, Ficher;...
The brown lines show the prompt trilepton reach with (dot-dashed) and (dashed) sensitivity at the displaced vertex might be too soft to allow for one coming from the displaced vertex, the hadronic activity at the displaced vertex and pseudorapidity constraints previously discussed.

In the trilepton final state with no opposite-sign, same-flavor lepton pair, CMS has set limits from searches that are greatly suppressed. In this framework, LEP has set direct limits on sterile neutrinos. In the LRSM the decay length can be written $\tau_{10}$ GeV.

For masses $10, 15$ and $20$ GeV, OSSF-0 bin with $0$ events. We find that, although the overall shape of the projections is not very different, the changes presented in this paper are significant. In the following, we plot the ratio of surviving events for each cut, indicated by the red dashed line, which was obtained by reconstructing to the same vertex (which was not the correct vertex). One of the jets is typically not from the correctly reconstructed decay products of the displaced lepton jet search at (dot-dashed) $10$ GeV with $300$ fb$^{-1}$ integrated luminosity of $300$ fb$^{-1}$.

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Majorana vs pseudo-Dirac @ e+e-

with the masses of the light neutrinos, so they can be safely neglected. The total unpolarized amplitude otherwise it represents an additional

\[ |U_{e4} - 2x \sigma_{d \bar{d}}| \, d\eta \, (pb) \]

Figure 2: The process

\[ \nu \]

\[ e^+ \]

\[ e^- \]

\[ W \]

\[ N_i \]

\[ \mu^- \]

\[ W^+ \]

\[ e^+ \]

\[ e^- \]

\[ W \]

\[ \mu^- \]

\[ W^+ \]

\[ \nu \]

\[ N_i \]

\[ (\text{neglecting the electron and light neutrino masses}) \]

\[ |M| \]

\[ \cos \theta \]

\[ \eta \]

\[ j \]

\[ k \]

\[ \eta \]

\[ \mu \]

\[ \nu \]

\[ \xi \]

\[ \mu \]

\[ \xi \]

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Majorana vs pseudo-Dirac \(e^+e^-\)

\[
A^\pm = \frac{N^\pm(\eta > 0) - N^\pm(\eta < 0)}{N_{\text{tot}}^\pm},
\]

\(PH, Jones-Pérez, Suárez-Navarro\)
Beyond the minimal model

Many possibilities:

Examples:  type I + extra Z’,
            type II, III
            left-right symmetric models
            GUTs, etc

Keung, Senjanovic; Pati, Salam, Mohapatra, Pati; Mohapatra, Senjanovic; Ferrari et al + many recent refs...

➢ Generically new gauge interactions can enhance the production in colliders: richer phenomenology

➢ But also make leptogenesis more challenging (out-of-equilibrium condition harder to meet)
New era of ν physics: neutrino astronomy, geology,…

Understand the Earth

Understand Astrophysical sources

Donini, Palomares-Ruiz, Salvado, 1803.05901

Whole new lecture!
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? $\beta\beta_0\nu$, CP violation in the lepton sector? Source of the matter-antimatter asymmetry?
- Lepton vs quark flavour?

A new scale $\Lambda$ could explain the smallness of neutrino and other mysteries such as the matter-antimatter asymmetry, DM, etc.

Complementarity of different experimental approaches: $\beta\beta_0\nu$, CP violation in neutrino oscillations, direct searches in meson decays, collider searches of displaced vertices, etc... holds in well motivated models with a low scale $\Lambda$ (GeV scale very interesting)
The νSM?