Particles of SM

In the SM neutrinos do not appear in the right-handed state. By construction neutrinos are massless. Neutrino oscillations are evidence for physics beyond the SM!
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By construction neutrino are massless.

Neutrino oscillations are evidence for physics beyond the SM!
Extending the SM

A lazy person solution is to add the right-handed neutrinos in:

\[
\begin{array}{c}
\text{SM} \\
\begin{array}{c|c|c}
\text{Quarks} & \text{Leptons} \\
\hline
\text{Left} & \text{Right} & \text{Left} & \text{Right} \\
\hline
\text{up} & \text{charm} & \text{top} & \\
\text{down} & \text{strange} & \text{bottom} & \\
\hline
\text{e} & \text{mu} & \text{tau} & \\
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\text{nuMSM} \\
\begin{array}{c|c|c}
\text{Quarks} & \text{Leptons} \\
\hline
\text{Left} & \text{Right} & \text{Left} & \text{Right} \\
\hline
\text{up} & \text{charm} & \text{top} & \\
\text{down} & \text{strange} & \text{bottom} & \\
\hline
\text{electron} & \text{mu} & \text{tau} & \\
\end{array}
\end{array}
\]

\[
\begin{array}{c}
\text{mass} \\
\text{charge} \\
\text{name} \\
\end{array}
\begin{array}{c|c|c|c}
\hline
\text{u} & \text{c} & \text{t} & \\
\frac{2}{3} & \frac{2}{3} & \frac{2}{3} & \\
\text{d} & \text{s} & \text{b} & \\
\text{e} & \text{mu} & \tau & \\
\text{left} & \text{left} & \text{left} & \\
\text{right} & \text{right} & \text{right} & \\
\text{left} & \text{left} & \text{left} & \\
\end{array}
\]
A lazy person solution is to add the right-handed neutrinos in:

\[ \text{SM} \]

\[ \text{nuMSM} \]

⇒ But where are they?

arXiv::hep-ph/0605047, M. Shaposhnikov
Seesaw mechanism

\[ \mathcal{L} = \mathcal{L}_{SM} + \bar{\ell}_L F \nu_R \epsilon \Phi^* - \frac{1}{2} \bar{\nu}_R M_M \nu_R + \text{H.c.} \]

\[ \Rightarrow \text{After the EWSB:} \]

\[ \frac{1}{2} \left( \bar{\nu}_L \bar{\nu}_R ^c \right) \mathcal{M} \left( \nu_L \nu_R ^c \right)^T \]

\[ \Rightarrow \text{In the vanilla seesaw:} \]

\[ \mathcal{M} = \begin{pmatrix} 0 & M_D \\ M_D & M_M \end{pmatrix} \Rightarrow \lambda_+ \sim M_D, \quad \lambda_- \sim -\frac{M_M^2}{M_D} \]
Seesaw mechanism

\[ \mathcal{L} = \mathcal{L}_{SM} + \bar{\ell}_L F \nu_R e \Phi^* - \frac{1}{2} \bar{\nu}_R M_M \nu_R + H.c. \]

⇒ After the EWSB:

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⇒ In the vanilla seesaw:

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⇒ In reality:

\[ \mathcal{M} = \begin{pmatrix} \delta m_\nu^{1\text{loop}} & M_D \\ M_D^T & M_M + \delta M_N^{1\text{loop}} \end{pmatrix} \]
Seesaw mechanism

\[ U = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta^\dagger) & \cos(\theta^\dagger) \end{pmatrix} \begin{pmatrix} U_\nu & U_N^* \end{pmatrix} \]

\[ U^\dagger M U^* = \begin{pmatrix} m_\nu^{\text{diag}} & M_N^{\text{diag}} \end{pmatrix} \]

with

\[ M_N^{\text{diag}} = U_N^T M_N U_N = \text{diag}(M_1, M_2, M_3) \]

\[ m_\nu^{\text{diag}} = U_\nu^\dagger m_\nu U_\nu^* = \text{diag}(m_1, m_2, m_3). \]

For small mixings:

\[ U = \left[ \begin{pmatrix} I - \frac{1}{2} \theta \theta^\dagger & \theta \\ -\theta^\dagger & I - \frac{1}{2} \theta^\dagger \theta \end{pmatrix} + \mathcal{O}(\theta^3) \right] \begin{pmatrix} U_\nu & U_N^* \end{pmatrix}, \]
Correction to SM processes

⇒ Charge currents:

\[ j_\mu^+ = \frac{g}{2} \theta_\alpha \bar{\ell}_\alpha \gamma_\mu N \]

⇒ Neutral currents:

\[ j_\mu^0 = \nu_\alpha \gamma_\mu \theta_\alpha N \]

⇒ The Yukawa couplings:

\[ \mathcal{L}_{Yukawa} = \mathcal{L}_{Yukawa}^{SM} \theta_\alpha \]
Since the RHN are modifying fundamental properties of SM they are hugely constrained:

- EW precision observables
- LFV, LNV
- Neutrinoless double beta decay
- Big Bang Nucleosynthesis
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**Indirect**
- EW precision observables
- LFV, LNV
- Neutrinoless double beta decay
- Big Bang Nucleosynthesis

**Direct**
- Fix target experiments
- Collider searches (LEP, LHC, etc.)
The direct searches are the strongest constraints where production cross sections are the largest.

arXiv::1908.02302
Indirect constraints

⇒ The indirect searches show power for high couplings:

⇒ Small excess is visible. Consistent with the fluctuation.
⇒ arXiv::1908.02302
What can happen in the future?
What can happen in the future?
International FCC collaboration with CERN as host lab to study:

- ~100 km tunnel infrastructure in Geneva area, linked to CERN
- $e^+e^-$ collider (FCC-ee), potential first step
- $pp$-collider (FCC-hh) long-term goal, defining infrastructure requirements

$\sim 16 \text{ T} \Rightarrow 100 \text{ TeV } pp \text{ in } 100 \text{ km}$

- HE-LHC with FCC-hh technology
- Ions and lepton-hadron options with hadron colliders
FCC-ee:

- ~20-50 fold improved precision on many EW quantities (equiv. to factor 5-7 in mass) \((m_Z, m_W, m_{\text{top}}, \sin^2 \theta_W^{\text{eff}}, R_b, \alpha_{\text{QED}} (m_z) \alpha_s (m_z, m_W, m_t)), \text{Higgs and top quark couplings})
- Exploring 10 - 100 TeV energy scale via couplings with precision measurements
  - Machine design for highest luminosities at Z, WW, ZH and ttbar working points

FCC-hh:

- Highest center of mass energy for direct production up to 20 - 30 TeV
- Huge rates for single and multiple production of SM bosons (H,W,Z) and quarks
  - Machine design for ~100 TeV c.m. energy & int. luminosity ~ 20 ab\(^{-1}\) in 25 years

HE-LHC:

- Doubling LHC collision energy with FCC-hh 16 T magnet technology
- c.m. energy ~ 27 TeV = 14 TeV x 16 T/8.33T, target luminosity ≥ 4 x HL-LHC
  - Machine design within constraints from LHC CE and using HL-LHC and FCC technn.
## FCCee Physics

<table>
<thead>
<tr>
<th>working point</th>
<th>assumed typical luminosity/IP [10^{34} cm^{-2}s^{-1}] = design value minus 15(10)%</th>
<th>total luminosity (2 IPs)/yr; half of typical luminosity assumed in 1st two years (Z) and 1st year (t\bar{t})</th>
<th>physics goal</th>
<th>run time [yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z first 2 years</td>
<td>100</td>
<td>26 ab^{-1}/year</td>
<td>150 ab^{-1}</td>
<td>4</td>
</tr>
<tr>
<td>Z later</td>
<td>200</td>
<td>48 ab^{-1}/year</td>
<td>10 ab^{-1}</td>
<td>1-2</td>
</tr>
<tr>
<td>W</td>
<td>25</td>
<td>6 ab^{-1}/year</td>
<td>5 ab^{-1}</td>
<td>3</td>
</tr>
<tr>
<td>H</td>
<td>7.0</td>
<td>1.7 ab^{-1}/year</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

machine modification for RF installation & rearrangement: 1 year

top 1st year (350 GeV) | 0.8 | 0.2 ab^{-1}/year | 0.2 ab^{-1} | 1

top later (365 GeV)    | 1.4 | 0.34 ab^{-1}/year | 1.5 ab^{-1} | 4

**total program duration**: 15 years – *incl. machine modifications*

**phase 1 (Z, W, H):** 9 years, **phase 2 (top):** 6 years
FCCee in context

⇒ The FCCee is the most efficient machine up to the $t\bar{t}$ threshold.

⇒ Check out the CDR: CERN-ACC-2018-0057
⇒ Also the theory report: arXiv:1905.05078
Schematizing sterile neutrino searches at FCC

Credit to S.Antusch, E.Cazzato, O.Fischer, arXiv::1612.02728

Marcin Chrzaszcz (CERN, IFJ)

Searches for heavy neutral leptons at the Future Circular Colliders
In the interesting region: \( m < m_W \) and \( \theta < 10^{-5} \)

Displacement: measurement of primary (production) vertex.

Secondary vertex with „large” displacement

\( ee \) he: A few times tracking resolution: \( \mathcal{O}(10) \mu m \),

\( hh \): Beyond background, detector noise, pileup: \( \mathcal{O}(10) \text{cm} \).

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FCCee indirect

⇒ Modification of the theory prediction of precision observables.
⇒ Also CKM unitarity, cLFV, LUV.
⇒ Currently still dominated by LEP!

Antusch, OF; JHEP 1410 (2014) 094

Exotic lepton flavor violating $Z$ boson decays

A. Abada et al.; JHEP04 (2015) 051
FCCee Higgs portal

⇒ Mono-Higgs production mechanism!
⇒ New Higgs decays:
  • Modification of Higgs Branching fractions.
  • New decays: $H \rightarrow N \nu$.
  • Invisible width modification.
⇒ Modification of triple Higgs coupling.

S. Antusch, OF; JHEP 1604 (2016) 189
Large Lorentz boost makes the displaced vertexes clearly visible.

Many final states to look at:

| Name          | Final State     | $|\theta_{\alpha}|$ Dependency | LFV |
|---------------|-----------------|-------------------------------|-----|
| lepton-trijet | $jjj\ell_\alpha^-$ | $\frac{|\theta_e \theta_{\alpha}|^2}{\theta^2}$ | ✓   |
| jet-dilepton  | $j\ell_\alpha^- \ell_\beta^+ \nu$ | $\frac{|\theta_e \theta_{\alpha}|^2}{\theta^2}$ | ✓   |
| trijet        | $jjj\nu$        | $|\theta_e|^2$               | ×   |
| monojet       | $j\nu\nu\nu$    | $|\theta_e|^2$               | ×   |
| dilepton-dijet| $\ell_\alpha^- \ell_\beta^+ v j j$ | $\frac{|\theta_e \theta_{\alpha}|^2}{\theta^2}$ | ✓   |
| trilepton     | $\ell_\alpha^- \ell_\beta^- \ell_\gamma^+ v v$ | $\frac{|\theta_e \theta_{\alpha}|^2}{\theta^2}$ | ✓   |
| quadrijet     | $jjjj\nu$       | $|\theta_e|^2$               | ×   |
| electron-di-b-jet | $e^- b\bar{b}\nu\nu$ | $|\theta_e|^2$ | ×   |
| dijet         | $jj\nu\nu\nu$   | $|\theta_e|^2$               | ×   |
| monojet       | $\ell_\alpha^- v\nu\nu\nu$ | $|\theta_e|^2$ | ×   |

Credit to S.Antusch, E.Cazzato, O.Fischer, arXiv::1612.02728.
LFV is the thing to look for!!!

The best final states: $\ell_\alpha^\pm \ell_\beta^\mp j j$, $\ell^\pm \ell^\mp \ell^\pm$

For ep machine the more sensitive ones are: $\mu j j j j$ and $\tau j j j j$.

Also LNU are there: $\mu^\pm \mu^\pm j$ (pp) and $e^+ j$ (ep).

Marcin Chrzaszcz (CERN, IFJ)
FCC in total

⇒ FCCee:
- Dominates the exclusion below the $m_W$ mass.
- Precision indirect constraints: EWPO, CKM, etc.

⇒ FCCeh, FCChh:
- Sensitivity in high mass region.
- Higgs potential.
- LFV, LNV.

Credit to S. Antusch, E. Cazzato, O. Fischer, arXiv::1612.02728
Summary

⇛ Hunting for RHN is very well motivated.
⇛ Neutrino program has to be considered a core of future colliders.
⇛ FCC has unique sensitivity for RHN!
⇛ Huge amount of measurements and constraints to be performed.
⇛ Complementarity between different colliders.

Credit to M. Drewers, [Slides]