Right-Handed neutrino searches at FCC-(ee)

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On behalf of the FCC-ee physics group
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The FCC

- International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the Geneva area

- Ultimate goal: ≥100 TeV pp-collider (FCC-hh)

  - defining infrastructure requirements

  - Few possible first steps:
    - $e^+e^-$ collider (FCC-ee)
      High Lumi, $E_{CM} = 90-500$ GeV
    - HE-LHC 16T ⇒ 27 TeV in LEP/LHC tunnel
    - Low energy FCC <50TeV (after ESPPU)
    - Possible addition:
      - p-e (FCC-he) option
    - This is the center of discussions for the European Strategy Update

The way by FCC-ee is the fastest and cheapest way to 100 TeV, also produces the most physics. Preferred scenario presented in the CDR. [https://cerncourier.com/cern-thinks-bigger/](https://cerncourier.com/cern-thinks-bigger/)

It’s also a good start for a μμC!
Z peak $E_{cm} : 91 \text{ GeV}$

WW threshold $E_{cm} : 161 \text{ GeV}$

ZH threshold $E_{cm} : 240 \text{ GeV}$

$t\bar{t}$ threshold $E_{cm} : 350 \text{ GeV}$

$Z (91.2 \text{ GeV}) : 4.6 \times 10^{36} \text{ cm}^2\text{s}^{-1}$

$W^+W^- (161 \text{ GeV}) : 5.6 \times 10^{35} \text{ cm}^2\text{s}^{-1}$

$Z (240 \text{ GeV}) : 1.7 \times 10^{35} \text{ cm}^2\text{s}^{-1}$

$t\bar{t} (350 \text{ GeV}) : 3.8 \times 10^{34} \text{ cm}^2\text{s}^{-1}$

$H (250 \text{ GeV}) : 1.5 \times 10^{34} \text{ cm}^2\text{s}^{-1}$

$\sqrt{s} [\text{GeV}]$
FCC-ee running scenario

From FCC CDR Volume 2

Table 2.1: Run plan for FCC-ee in its baseline configuration with two experiments. The number of WW events is given for the entirety of the FCC-ee running at and above the WW threshold.

<table>
<thead>
<tr>
<th>Phase</th>
<th>Run duration (years)</th>
<th>Center-of-mass Energies (GeV)</th>
<th>Integrated Luminosity (ab$^{-1}$)</th>
<th>Event Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC-ee-Z</td>
<td>4</td>
<td>88-95</td>
<td>150</td>
<td>$3 \times 10^{12}$ visible Z decays</td>
</tr>
<tr>
<td>FCC-ee-W</td>
<td>2</td>
<td>158-162</td>
<td>12</td>
<td>$10^8$ WW events</td>
</tr>
<tr>
<td>FCC-ee-H</td>
<td>3</td>
<td>240</td>
<td>5</td>
<td>$10^6$ ZH events</td>
</tr>
<tr>
<td>FCC-ee-tt</td>
<td>5</td>
<td>345-365</td>
<td>1.5</td>
<td>$10^6$ t$\bar{t}$ events</td>
</tr>
</tbody>
</table>
FCC-ee discovery potential

Today we do not know how nature will surprise us. A few things that FCC-ee could do

- **Explore**
  - ~20-50 (stat 400…) fold improved precision on many EW quantities
    - x 5-7 in mass $m_Z$, $m_W$, $m_{top}$, $\sin^2\theta_W^{\text{eff}}$, $R_b$, $\alpha_{\text{QED}}(m_Z)$, $\alpha_s(m_Z,m_W,m_t)$, top quark couplings
  - Model-independent Higgs width and couplings measurements at percent-permil level
  - 10-100 TeV energy scale (and beyond) with Precision Measurements (through EFT)
  - ~3σ of effect of Higgs self-coupling from Vertex corrections (also maybe directly with FCC-ee 500GeV)
  - Only machine with possible investigation of $\nu$ coupling at $\sqrt{s} = m_H$

- **Discover**
  - Violation of flavour conservation or universality and unitarity of PMNS @10^{-5}
  - FCNC ($Z \rightarrow \mu\tau$, $e\tau$) in $5 \times 10^{12}$ Z decays and $\tau$ BR in $2 \times 10^{11}$ $Z \rightarrow \tau\tau$ (also FCNC in top decays with $10^6$ tops)
  - Flavour physics with $10^{12}$ $b\bar{b}$ events ($B \rightarrow s\tau\tau$ etc..)
  - Dark matter as «invisible decay» of H or Z (or in LHC loopholes)

- **Direct Discovery**
  - Very weakly coupled particle in 5-100 GeV energy scale such as: Right-Handed neutrinos, Dark Photons etc...

- Not only a «Higgs Factory», «Z factory» and «top» are important for ‘discovery potential’ (also QCD)
### Electroweak eigenstates

<table>
<thead>
<tr>
<th>( \begin{pmatrix} e \ v_e \end{pmatrix}<em>L \ \begin{pmatrix} \mu \ v</em>\mu \end{pmatrix}<em>L \ \begin{pmatrix} \tau \ v</em>\tau \end{pmatrix}_L )</th>
<th>( \begin{pmatrix} e_R \ v_e_R \end{pmatrix} \ \begin{pmatrix} \mu_R \ v_\mu_R \end{pmatrix} \ \begin{pmatrix} \tau_R \ v_\tau_R \end{pmatrix} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( l=1/2 )</td>
<td>( l=0 )</td>
</tr>
</tbody>
</table>

- We measure neutrino parameters, but:
  - No right-handed neutrinos in the SM
  - No mass matrix, no mixing of the neutrino flavour states

⇒ Neutrino oscillations are evidence for physics beyond the SM.

- Right handed neutrinos are singlets,
  - No weak interaction
  - No EM interaction
  - No strong interaction

- Can’t produce them, Can’t detect them
  - So why bother? (also called Sterile)
The Seesaw mechanism with RH neutrinos

• Economic extension by adding a number of Fermionic singlets
  • “Right-handed” or “sterile” neutrinos

• Two mass-differences
  • At least two sterile neutrinos
  • New mass scale, a priori unrelated to the known ones

• Many constraints from experiments on all energy scales

• May be connected to e.g. Dark Matter and Baryogenesis
The Big Picture

Neutrino Yukawa coupling $y_
u$

$Y_{\text{top}}$ $Y_e$

$10^{-3}$ $10^{-7}$ $10^{-9}$ $10^{-11}$

eV keV GeV PeV ZeV $M_{\text{GUT}}$ $M_{\text{Pl}}$

Sterile neutrino mass scale

$m^2 = \Delta m^2_{\text{atm}}$

$m^2 = \Delta m^2_{\text{sol}}$

$\Lambda_{\text{EW}}$

GUT

reactor & LSND anomaly

Right-Handed neutrino at FCC
Searches at FCC

Production

\[ W_a: \]

\[ X \rightarrow W \theta_a N \]

\[ Z_b: \]

\[ X \rightarrow Z \theta_c, \theta_\mu, \theta_\tau N \]

\[ h_1: \]

\[ X \rightarrow h \theta_c, \theta_\mu, \theta_\tau N \]

Decay

\[ \ell_\beta \bar{\nu} \]

\[ \theta_\beta \]

\[ W^\mp \]

Final States

\[ pp: \ell_\alpha \ell_\beta \bar{\nu} jj, \ell_\alpha \ell_\beta \ell_\gamma \bar{\nu} \]

\[ e^+ e^-, e^- p: Y \ell_\beta \ell_\gamma jj, Y \ell_\beta \ell_\gamma \bar{\nu} \]

\[ e^- e^+, pp: \nu \ell_\beta \ell_\gamma jj, \nu \ell_\beta \ell_\gamma \bar{\nu} \]

\[ pp: \ell_\alpha \nu jj, \ell_\alpha \ell_\beta \ell_\gamma \bar{\nu}, \ell_\alpha \nu \bar{\nu} \]

\[ e^- e^+, pp: \nu \ell_\beta \ell_\gamma jj, \nu \ell_\beta \ell_\gamma \bar{\nu} \]

\[ e^- e^+, pp: \nu \ell_\beta \ell_\gamma jj, \nu \ell_\beta \ell_\gamma \bar{\nu} \]

\[ pp: \ell_\alpha \nu jj, \ell_\alpha \nu \ell_\beta \ell_\gamma \bar{\nu}, \ell_\alpha \nu VV \]

\[ e^- e^+, pp: \nu \ell_\beta \ell_\gamma jj, \nu \ell_\beta \ell_\gamma \bar{\nu} \]

\[ e^- e^+, pp: \nu \ell_\beta \ell_\gamma jj, \nu \ell_\beta \ell_\gamma \bar{\nu} \]

Displaced vertex searches at FCC-ee

- Test minimal type I seesaw hypothesis
- Together with $\Delta M$ also tests the compatibility with leptogenesis
- Long life time $\rightarrow$ detached vertex for $\sim < M_Z$
- Backgrounds: four fermions
  - $e^+e^- \rightarrow W^*W^*$, $e^+e^- \rightarrow Z^*(\text{nunu})(Z/\gamma)^*$

Parameter points consistent with baryogenesis

arXiv:1411.5230

Antusch et al. JHEP 1809 (2018) 124
Indirect searches in Higgs properties

• Additional mono-Higgs production mechanism

• New Higgs decay channels:
  • Modification of Higgs branching ratios
  • New exotic decay channels: \( h \to \nu N, N \to \text{SM} \)
  • New invisible decay channels

• \( N \) contribution to the triple Higgs coupling
Outlook for FCC-hh

• Z factory like FCC-ee offers a clean method for detection of Heavy Right-Handed neutrinos

• W bosons are less abundant at the lepton colliders
  • At the 100 TeV FCC-hh W is the dominant particle: Expect $10^{13}$ real W’s
  • There is a lot of pile-up/backgrounds/lifetime/trigger issues which need to be investigated

• But.... in the regime of long lived HNLs the simultaneous presence of
  • the initial lepton from W decays
  • the detached vertex with kinematically constrained decay
  • -> Would allow for a significant background reduction

• Could also served as a characterization both in flavour and charge of the produced neutrino
  • information of the flavour sensitive mixing angles
  • test of the fermion violating nature of the intermediate (Majorana) particle
Overview of sensitivities

- At one-sigma confidence level
- ep and pp at parton level

**Right-Handed neutrino at FCC**

- Best sensitivity from displaced vertex searches at FCC-ee
- EWPO sensitivity up to very high mass scales
- Good sensitivity reach from FCC-hh and FCC-eh

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*S. Antusch et al.; Int. J. Mod. Phys. A 32 (2017)*
Synergy and complementarity

• **FCC-ee**
  - Highest sensitivity in the low mass regime \((M<m_W)\)
    - test model predictions: seesaw, leptogenesis
  - SM precision tests have high sensitivity; mass independent
    - Test heavy neutrinos up to \(~60\text{TeV}\)
    - Not sensitive to the model details

• **FCC-hh and he**
  - Direct test of lepton-flavor and number violation
    - Number of heavy neutrino generations and their masses
  - Indirect test via measurement of Higgs potential
  - Sensitive to high mass regime
Conclusion

• The FCC design study is establishing the feasibility or the path to feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology.

• Both FCC-ee and FCC-hh have outstanding physics cases
  • each in their own right
  • the sequential implementation of FCC-ee, FCC-hh, would maximise the physics reach

• FCC has unique prospects of testing model predictions.

• Attractive scenarios of staging and implementation (budget!) cover more than 50 years of exploratory physics, taking full advantage of the synergies and complementarities

• Neutrino mass physics should be a benchmark for future collider studies!
A 100km circular collider as next the step

![Diagram showing collider steps]

The FCC design study is establishing the feasibility of an ambitious set of colliders after LEP/LHC, at the cutting edge of knowledge and technology.

Both FCC-ee and FCC-hh have outstanding physics cases.

We are preparing to move to the next step, as soon as possible (EPPSU)
Bonus
Right-Handed neutrino at FCC

With $5 \times 10^{12} Z$
Manifestation of Right-Handed neutrinos

One see saw family

\[ \theta \approx \left( \frac{m_D}{M} \right) \]

\[ m_\nu \approx \frac{m_D^2}{M} \]

\[ m_N \approx M \]

\[ |U|^2 \propto \theta^2 \approx \frac{m_\nu}{m_N} \]

- mixing with active neutrinos leads to various observable consequences
  - if very light (eV), possible effect on neutrino oscillations
  - if in keV region (dark matter), monochromatic photons from galaxies with E=mN/2
- possibly measurable effects at High Energy
  - If N is heavy it will decay in the detector (not invisible)
    - PMNS matrix unitarity violation and deficit in Z «invisible» width
    - Higgs, Z, W visible exotic decays H\(\rightarrow\) viNi and Z\(\rightarrow\) viNi, W\(\rightarrow\) li Ni
  - also in K, charm and b decays via W*\(\rightarrow\) li \(\pm\) N, N \(\rightarrow\) lj \(\pm\) with any of six sign and lepton flavour combination
    - violation of unitarity and lepton universality in Z, W or \(\tau\) decays
- Couplings are very small \(\left( \frac{m_\nu}{m_N} \right)\) (but *who knows?*) and generally seem out of reach at high energy colliders.

What is produced is W,Z decays is:

\[ \nu_L = \nu \cos \theta + N \sin \theta \]

\(\nu = \text{light mass eigenstate}\)

\(N = \text{heavy mass eigentstate}\)

\(\neq \nu_L\) active neutrino which couples to weak inter

\(\neq N_R\) which does not
(indirect) Effect of RH ν on EW precision obs.

- The relationship $|U|^2 \propto \theta^2 \approx m_\nu / m_N$ is valid for one family see-saw
- For two or three families the mixing can be larger
- *Shaposhnikov, Antush and Fisher*, have shown that a slight # in Majorana mass can generate larger mixing between the left- and right-handed neutrinos
- $\langle v_l \rangle = v \cos \theta + N \sin \theta \rightarrow (\cos \theta)^2$ becomes parametrized as $1 + \epsilon_{\alpha \beta}$ ($\epsilon_{\alpha \alpha}$ is negative) the coupling to light ‘normal’ neutrinos is typically reduced.
- In the $G_F, M_Z$ scheme, $G_F$ (extracted from $\mu \rightarrow e\nu e\nu \mu$) and $g$ should be increased.
- This leads to correlated variations of all predictions upon e or $\mu$ neutrino mixing.
- Only the ‘number of neutrinos’ ($R_{inv}^{\nu}$ and $\sigma_{peak}^{\nu}$) and the tau specific CC observables (tau decays) are sensitive to the tau-neutrino mixing.

<table>
<thead>
<tr>
<th>Prediction in MUV</th>
<th>Prediction in the SM</th>
<th>Experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{inv}^{\nu}$</td>
<td>20.744(11)</td>
<td>20.767(25)</td>
</tr>
<tr>
<td>$R_0$</td>
<td>0.21577(4)</td>
<td>0.21629(66)</td>
</tr>
<tr>
<td>$R_1$</td>
<td>0.17266(6)</td>
<td>0.1721(30)</td>
</tr>
<tr>
<td>$\sigma_{had}^{\nu}$</td>
<td>41.470(15) nb</td>
<td>41.541(37) nb</td>
</tr>
<tr>
<td>$M_W^{\nu}$</td>
<td>5.9723(10)</td>
<td>5.942(16)</td>
</tr>
<tr>
<td>$T^{\nu}$</td>
<td>80.359(11) GeV</td>
<td>80.385(15) GeV</td>
</tr>
<tr>
<td>$\epsilon_{had}^{\nu}$</td>
<td>83.966(12) MeV</td>
<td>83.983(86) MeV</td>
</tr>
<tr>
<td>$\epsilon_{lep}^{\nu}$</td>
<td>0.23150(1)</td>
<td>0.23113(21)</td>
</tr>
<tr>
<td>$\epsilon_{had}^{\nu}$</td>
<td>0.23150(1)</td>
<td>0.23222(27)</td>
</tr>
</tbody>
</table>