Phenomenology at the future FCCee: detector sensitivity to exotic long-lived particles

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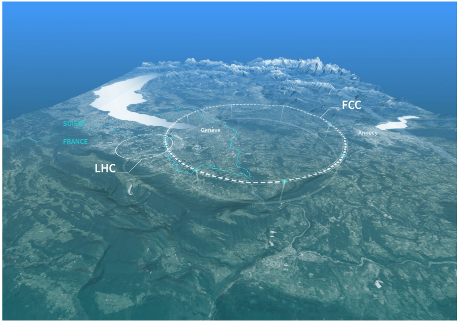
Summary

- **Context**
- **Building the theoretical model of heavy neutrinos**
- **Study of the heavy-neutrinos phenomenology at FCC-ee**
- **Signature of a long-lived heavy neutrino in the CLD detector**
- **Conclusion**

Context: FCCee

- FCCee: electron–positron Future Circular Collider
- Circumference: 90.7 km
- First phase at the Z pole-mass: $\sqrt{s} = 91$ GeV with $L_{int} \approx 50\ ab^{-1}$
- Schedule:
  - Feasability study: 2020 - 2025
  - Operational around 2040

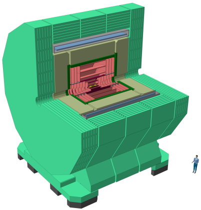


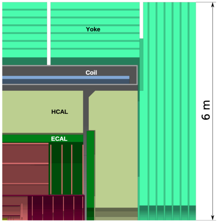
Context: CLD detector

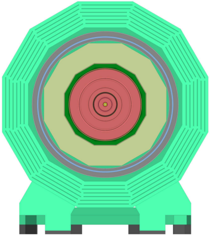
CLD (CLIC Like Detector) = a detector concept for the FCCee.

Focus on the silicon pixel vertex detector and the silicon tracker.

Involvement of the PICSEL team at IPHC.







Context: Long-lived particles

- **One axis of the FCCee research program:** producing hypothetical heavy particles which travel a distance from 1 cm until 1 m inside the detector before decaying.
- **Motivations for long-lived particles:**
  - Few long-lived particles in the Standard Model.
  - Reconstruction algorithms and analyses are traditionnaly designed for prompt particles $\rightarrow$ new challenges.
  - There is still the possibility to tune the geometry of the detector for improving its sensibility to this kind of exotic signature.
- **Chosen theoretical model:** Standard Model extended by the introduction of a Heavy Neutral Lepton (called usually heavy neutrino).
- **Goals of the internship:**
  - Determining the region of parameter-space consistent with long-lived heavy neutrinos.
  - Estimating the sensibility of the CLD detector to long-lived particles signature.

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Reminder of the Standard Model:
$\mathcal{L}$ corresponding to a free massless electron and neutrino:

$$\mathcal{L}_{fermion} = \overline{L} i\gamma^{\mu} D_{\mu} L + \overline{e}_R i\gamma^{\mu} D_{\mu} e_R$$

with $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$, $\overline{L} = \begin{pmatrix} \overline{\nu}_L & \overline{e}_L \end{pmatrix}$ and D_{μ} the (gauge) covariant derivative

Adding a (massless) sterile neutrino:
Introduction of N_R: right-handed chirality singlet with no charge.

$$\mathcal{L}_{N_R} = \overline{N}_R i\gamma^{\mu} D_{\mu} N_R$$

No charge $\Rightarrow D_{\mu} = \partial_{\mu} \Rightarrow$ no interaction

Type-I Seesaw Model

The most general mass term for neutrinos can be expressed as:

$$\begin{aligned} -\mathcal{L}_{\nu\ mass} = & - m_D(\overline{N}_R \nu_L + \overline{\nu}_L N_R) & \text{Dirac} \\ & - \frac{m_L}{2}(\overline{\nu}^c_L \nu_L + \overline{\nu}_L \nu^c_L) & \text{Majorana for } \nu_L \\ & - \frac{m_R}{2}(\overline{N}^c_R N_R + \overline{N}_R N^c_R) & \text{Majorana for } N_R \end{aligned}$$

m_D is the Dirac mass whereas m_L and m_R are respectively the Majorana mass for the standard and the new neutrinos. Theses masses can be combined into a neutrino mass matrix as:

$$-\mathcal{L}_{\nu\ mass} = \frac{1}{2}\begin{pmatrix} \overline{\nu}^c_L & \overline{N_R} \end{pmatrix} \mathcal{M}_\nu \begin{pmatrix} \nu_L \\ N^c_R \end{pmatrix} + h.c \quad \text{with} \quad \mathcal{M}_\nu = \begin{pmatrix} m_L & m_D \\ m_D & M_R \end{pmatrix}$$

Type-I Seesaw Model

We obtain the final mass term by diagonalizing $\mathcal{M}_\nu$: $\mathcal{M}_\nu = V\mathcal{D}_\nu V^T$ with V a real direct orthogonal matrix which can be interpreted as a planar rotation of angle θ. After diagonalizing:

$$\mathcal{D}_\nu = \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix} \quad \text{and} \quad V = \begin{pmatrix} \cos\theta_N & \sin\theta_N \\ -\sin\theta_N & \cos\theta_N \end{pmatrix}$$

After diagonalization, for the situation $m_L = 0 =$ and $m_R \gg m_D$, the neutrino masses are :

$$m \approx \frac{m_D^2}{m_R} \qquad \text{and} \qquad M \approx m_R$$

These two masses correspond to the masses of the SM neutrino and the HNL respectively.

Lagrangian interaction density

New interactions appear when we move from the interaction states to mass states by the rotation matrix:

$$
\begin{aligned}
\mathcal{L}_{NInt} = & - \frac{g_W}{\sqrt{2}} \sin\theta_N \cdot W_\mu^- \overline{N}^c \gamma^\mu P_L \ell + h.c \\
& - \frac{g_W}{2\cos\theta_W} \sin\theta_N \cdot Z_\mu \overline{N}^c \gamma^\mu P_L \nu_\ell + h.c \\
& - \frac{g_W m_N}{2M_W} \sin\theta_N \cdot h\overline{N}^c P_L \nu_\ell + h.c
\end{aligned}
$$

The model depends on 2 parameters:

- $\sin\theta_N$ the mixing parameter, noted V in the following.
- m_N the mass of the heavy neutrino.

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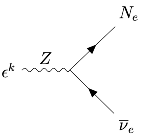
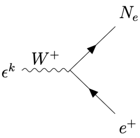
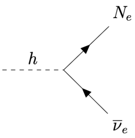
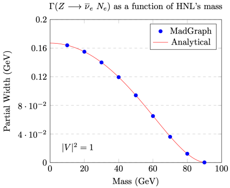
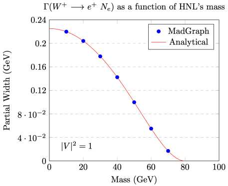
Indirect production of the heavy neutrinos

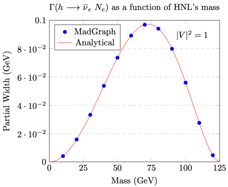












$$\Gamma(Z \longrightarrow N_e\, \overline{\nu}_e) = \frac{g_Z^2\, |V|^2\, m_Z}{192\, \pi} \left(\left(1 - \frac{m_N^2}{m_Z^2}\right)^2 + \left(1 - \frac{m_N^2}{m_Z^2}\right)\left(1 - \frac{m_N^4}{m_Z^4}\right) \right)$$

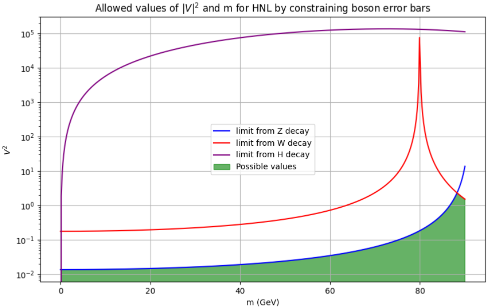
$$\Gamma(W^+ \longrightarrow N_e\, e^+) = \frac{g_W^2\, |V|^2 m_W}{92\, \pi} \left(\left(1 - \frac{m_N^2}{m_W^2}\right)^2 + \left(1 - \frac{m_N^2}{m_W^2}\right)\left(1 - \frac{m_N^4}{m_W^4}\right) \right)$$

$$\Gamma(h \longrightarrow N_e\, \overline{\nu}_e) = \frac{g_W^2\, |V|^2}{64\, \pi\, m_W^2}\, m_N^2 m_h \left(1 - \frac{m_N^2}{m_h^2}\right)^2$$

Limit on the heavy neutrino mass and mixing term

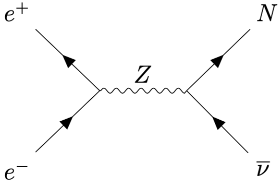
Those decays have never be observed. It suggests that these partial decay widths are smaller than the experimental uncertainty on the estimation of the total decay widths of these bosons. PDG values are:

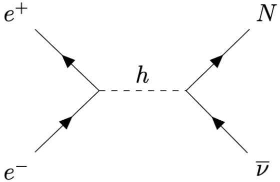
- $\Gamma_Z = (2.4955 \pm 0.0023)\ \mathrm{GeV}$
- $\Gamma_W = (2.085 \pm 0.042)\ \mathrm{GeV}$
- $\Gamma_H = 3.7^{+1.9}_{-1.4}\ \mathrm{MeV}$

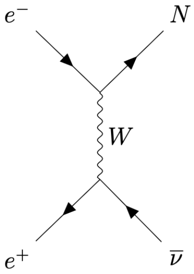


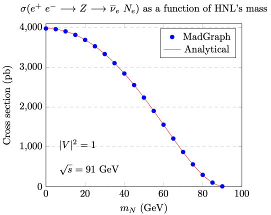
For masses under 70 GeV: $|V|^2 < 10^{-1}$

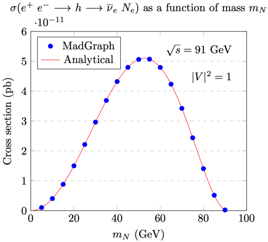
Direct production of the heavy neutrinos











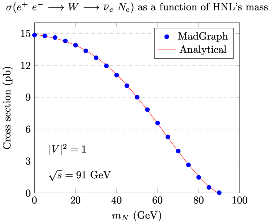
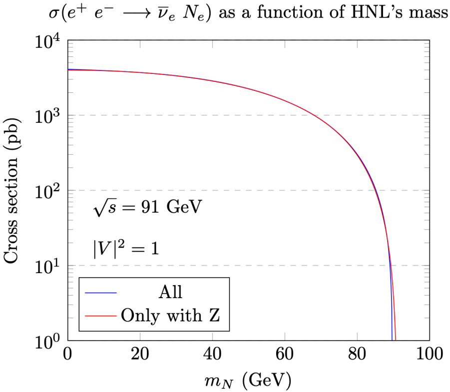


Diagram contribution via Z boson

$$\sigma_{tot} = \sigma_Z + \sigma_W + \sigma_h + \text{interference terms}$$

$$\sigma_{tot} \approx \sigma_Z$$



$$\sigma_Z = \frac{e^4 |V|^2 ((c_L^e)^2 + (c_R^e)^2)\, s}{1536\,\pi\, \cos^4\theta_W \sin^4\theta_W \left((s - m_Z^2)^2 + (m_Z\Gamma_Z)^2\right)} \left(\frac{m_N^2}{s} + 2\right)\left(1 - \frac{m_N^2}{s}\right)^2$$

Number of N_e produced at FCC-ee

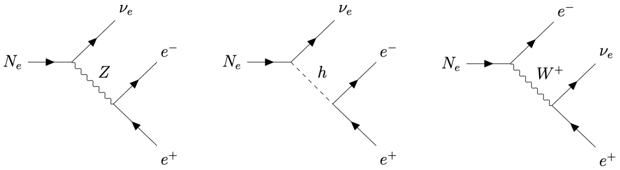
Number of N_e produced $= \sigma \times L_{int}$

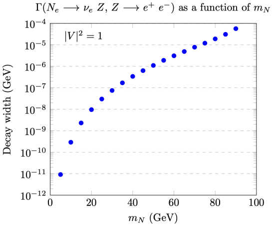
For $m_N = 50$ GeV, $\sqrt{s} = 91$ GeV, and $|V|^2 = 1$:
$\sigma(e^+ e^- \longrightarrow \overline{\nu}_e N_e) \approx 2240$ pb

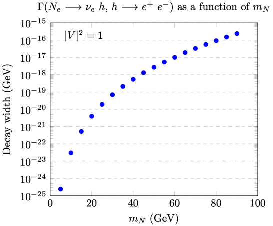
and for $L_{int} \approx 50\text{ab}^{-1} = 50 \cdot 10^6\text{pb}^{-1}$

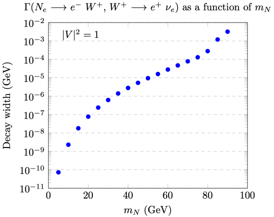
$\|V\|^2$	**Cross-section σ [pb]**	**Expected events at 50 ab^{-1}**
10^{-2}	2.24×10^1	1.12×10^9
10^{-3}	2.24	1.12×10^8
10^{-4}	2.24×10^{-1}	1.12×10^7
10^{-5}	2.24×10^{-2}	1.12×10^6
10^{-6}	2.24×10^{-3}	1.12×10^5
10^{-7}	2.24×10^{-4}	1.12×10^4
10^{-8}	2.24×10^{-5}	1.12×10^3
10^{-9}	2.24×10^{-6}	1.12×10^2
10^{-10}	2.24×10^{-7}	1.12×10^1

Feynman diagrams leading to the decay of the heavy neutrino to the final state $\nu_e\, e^+\, e^-$:









Flight distance of the heavy neutrinos at FCC-ee

The lifetime τ is linked to the total decay width Γ of the particle by the formula:

$$\tau = \frac{\hbar}{\Gamma}$$

The mean distance $< d >$ traveled by the particle in the laboratory frame can be calculated by the formula:

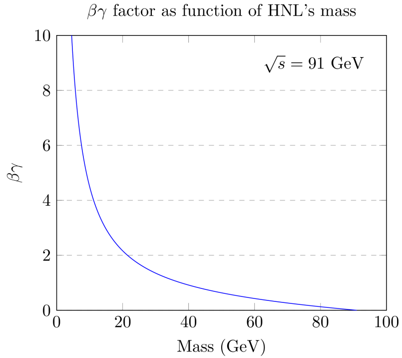
$$< d >= \beta\gamma c\tau$$

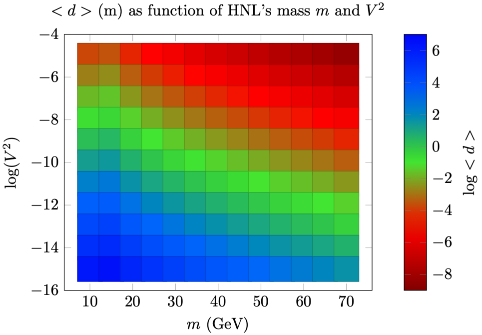
where $\beta = v/c$ and $\gamma = 1/\sqrt{1-\beta^2}$
If we consider the scenario of direct production of the heavy neutrino, their product can be derived:

$$\beta\gamma = \frac{p_N}{m_N} = \frac{s - m_N^2}{2m_N\sqrt{s}}$$

Flight distance of the heavy neutrinos at FCC-ee

We see a region where $< d >$ is larger to 1 cm and can reach 1 m. FCCee is sensible to this range. It corresponds to the green zone on the figure.





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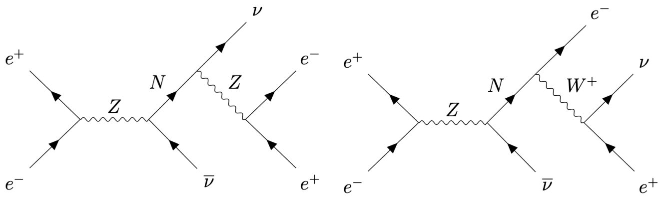
Signature of a long-lived heavy neutrino in the CLD detector

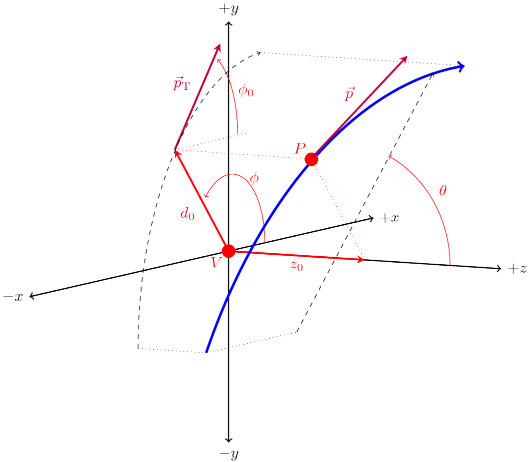
Feynman diagrams of HNL processes at electron-positrons collisions, with HNL production mediated with a Z boson, and HNL decays with a Z or W boson:



MC generation: MadGraph + Pythia + Delphes

Parametrisation of the reconstructed tracks

The perigee parametrisation of the track helix:



- d_0
- z_0 (d_z in DELPHES)
- ϕ
- θ
- ϕ_0

Influence of the model parameters on the reconstructed tracks

Mean values of $|d_0|$, in millimeters, as function of HNL mass and lifetime:

	$m = 10$ GeV	$m = 30$ GeV	$m = 50$ GeV
$c\tau = 1$ cm	0.85	0.55	0.29
$c\tau = 10$ cm	8.49	5.48	2.90
$c\tau = 100$ cm	69.54	52.27	29.03

Mean values of $|d_z|$, in millimeters, as function of HNL mass and lifetime:

	$m = 10$ GeV	$m = 30$ GeV	$m = 50$ GeV
$c\tau = 1$ cm	1.37	0.79	0.42
$c\tau = 10$ cm	13.56	7.87	4.21
$c\tau = 100$ cm	156.00	92.48	41.25

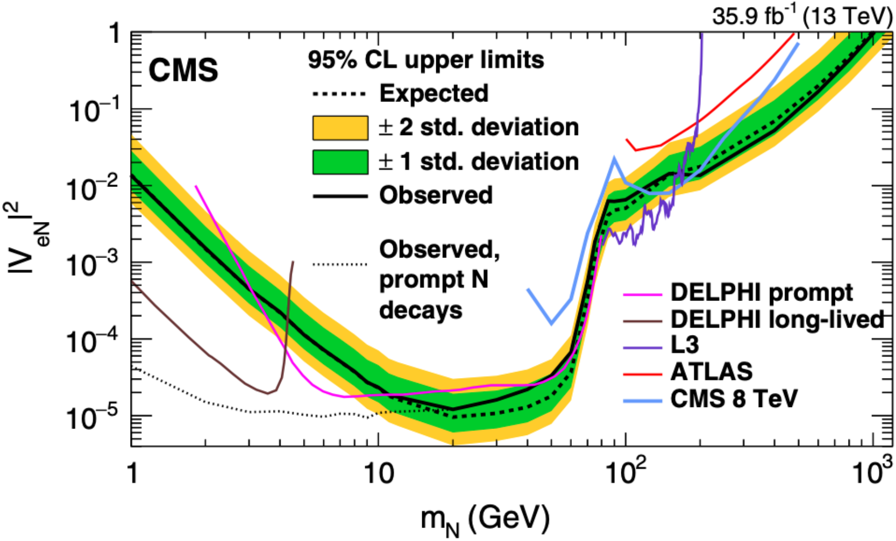
Conclusion

- **Objective of the internship**: determining the CLD detector sensitivity to hypothetical heavy long-lived neutrinos.
- The work has split in several steps:
  - Building the theoretical model and deriving the Feynman rules.
    $\Rightarrow$ the model depends on 2 parameters: the mixing angle and the heavy neutrino mass.
  - Studying the different ways to produce the heavy neutrino at FCCee and the different decay channels.
    $\Rightarrow$ Calculation of cross-section and decay widths by hand + validation of the MadGraph model implementation.
    $\Rightarrow$ We highlight the region of the parameter-space for which the heavy neutrino have a flight distance between 1 cm and 1 m.
  - Generation of Monte-Carlo samples including the CLD simulation.
    $\Rightarrow$ We showed the impact of the life-time and the mass of the HNL on the parameters of the reconstructed tracks such as the d_0 and the d_z.

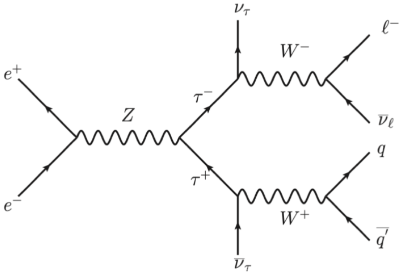
Perspective

- The objective of the internship has not been reached by lack of time.
- To-do list:
  - Studying the efficiency and the resolution of the reconstructed tracks.
  - Studying the detector performance to reconstruct the displaced secondary vertices with the tracks.
  - Taking into account the potential background sources.

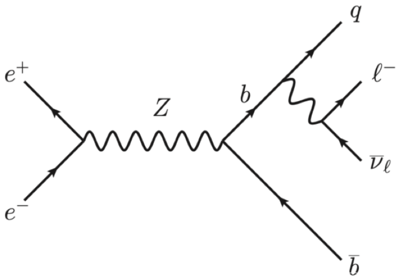
Exclusion region from other experiments



Possible background



(a) 4-body



(b) Z → bb

Chirality and helicity analysis

Contribution in % to the partial decay width of the Z boson of the fermion helicity combinations (left) and of the fermion chirality combinations (right):

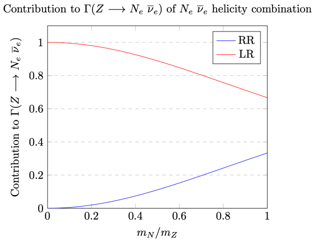
For Helicity:

N_e	$\bar{\nu}_e$	%
R	R	$\frac{x^2}{2+x^2}$
R	L	0
L	R	$\frac{2}{2+x^2}$
L	L	0

For Chirality:

N_e	$\bar{\nu}_e$	%
R	R	0
R	L	0
L	R	100
L	L	0

In the equation x corresponds with the ratio m_N/m_Z.



Chirality and helicity analysis

Contribution in % to the partial decay width of the Higgs boson of the fermion helicity combinations (left) and of the fermion chirality combinations (right):

For Helicity:

N_e	$\bar{\nu}_e$	%
R	R	100
R	L	0
L	R	0
L	L	0

For Chirality:

N_e	$\bar{\nu}_e$	%
R	R	100
R	L	0
L	R	0
L	L	0

Trace identities

- $Tr\left[\left(\not{p}_1 + m_1\right)\gamma^\mu \left(\not{p}_2 + m_2\right)\gamma^\nu\right]$
$= 4\left[p_1^\mu p_2^\nu + p_1^\nu p_2^\mu - (p_1 \cdot p_2)\eta^{\mu\nu} + m_1 m_2 \eta^{\mu\nu}\right]$
- $Tr\left[\left(\not{p}_1 + m_1\right)\gamma^\mu \left(\not{p}_2 + m_2\right)\gamma^\nu P_\pm\right]$
$= 2\left[p_1^\mu p_2^\nu + p_1^\nu p_2^\mu - (p_1 \cdot p_2)\eta^{\mu\nu} + 2m_1 m_2 \eta^{\mu\nu} \pm i p_{1\alpha} p_{2\beta} \epsilon^{\alpha\beta\mu\nu}\right]$
- $Tr\left[\left(\not{p}_1 + m_1\right)\gamma^\mu \left(\not{p}_2 + m_2\right)\gamma^\nu\right] Tr\left[\left(\not{p}_3 + m_3\right)\gamma_\mu \left(\not{p}_4 + m_4\right)\gamma_\nu\right]$
$= 32\left[(p_1 \cdot p_3)(p_2 \cdot p_4) + (p_1 \cdot p_4)(p_3 \cdot p_2)\right.$
$\left. - m_3 m_4 (p_1 \cdot p_2) - m_1 m_2 (p_3 \cdot p_4) + 2 m_1 m_2 m_3 m_4\right]$
- $Tr\left[\left(\not{p}_1 + m_1\right)\gamma^\mu \left(\not{p}_2 + m_2\right)\gamma^\nu\right] Tr\left[\left(\not{p}_3 + m_3\right)\gamma^\mu \left(\not{p}_4 + m_4\right)\gamma^\nu P_\pm\right]$
$= 16\left[(p_1 \cdot p_3)(p_2 \cdot p_4) + (p_1 \cdot p_4)(p_3 \cdot p_2) - m_1 m_2 (p_3 \cdot p_4) - m_3 m_4 (p_1 \cdot p_2) + 2 m_1 m_2 m_3 m_4\right]$
- $Tr\left[\left(\not{p}_1 + m_1\right)\gamma^\mu \left(\not{p}_2 + m_2\right)\gamma^\nu P_\pm\right] Tr\left[\left(\not{p}_3 + m_3\right)\gamma^\mu \left(\not{p}_4 + m_4\right)\gamma^\nu P_\pm\right]$
$= Tr\left[\left(\not{p}_1 + m_1\right)\gamma^\mu \left(\not{p}_2 + m_2\right)\gamma^\nu P_\pm\right] Tr\left[\left(\not{p}_3 + m_3\right)\gamma^\mu \left(\not{p}_4 + m_4\right)\gamma^\nu P_\mp\right]$
$= 8\left[2(p_1 \cdot p_3)(p_2 \cdot p_4) - m_1 m_2 (p_3 \cdot p_4) - m_3 m_4 (p_1 \cdot p_2) + 2 m_1 m_2 m_3 m_4\right]$

Reminder of the electroweak SM

The electron is the sum of the two possible chiralities :

$$e = P_L e + P_R e = e_L + e_R \quad \text{and} \quad \overline{e} = e^\dagger \gamma^0 = \overline{e} P_R + \overline{e} P_L = \overline{e}_R + \overline{e}_L$$

The Lagrangian density corresponding to free massless electron and neutrino can be expressed as:

$$\mathcal{L}_{fermion} = \overline{L} i \gamma^\mu \partial_\mu L + \overline{e}_R i \gamma^\mu \partial_\mu e_R$$

by writing $L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$ and $\overline{L} = \begin{pmatrix} \overline{\nu}_L & \overline{e}_L \end{pmatrix}$

The Higgs field Φ is a complex scalar field doublet defined by:

$$\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

For adding a mass to the electron, we implementing the Yukawa interaction term:

$$\mathcal{L}_{Yukawa} = -\frac{y_e}{\sqrt{2}} \overline{e}_R (\Phi^\dagger L_e) + h.c$$