

On the Higgs triplet extension of the Standard Model

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- Introduction
- The Higgs triplet model
- Neutrino mass terms
- Cross sections
- Decay widths
- Conclusions

Introduction

Introduction: Unsolved problems of the SM

- The Standard Model of particle physics (SM) has to be extended due to unsolved problems like
 - Quantum gravity
 - baryon asymmetry
 - dark matter
 - hierarchy problem
 - strong CP-problem
 - neutrino masses
 - etc.

Introduction: Extension of the SM

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 - Introduction of a larger gauge group than $SU(3)_C \times SU(2)_L \times U(1)_Y$ like in Grand Unifying Theories
 - Assumption of extra dimensions like in string theories
 - etc.

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- Fundamental extensions:
 - Introduction of a larger gauge group than $SU(3)_C \times SU(2)_L \times U(1)_Y$ like in Grand Unifying Theories
 - Assumption of extra dimensions like in string theories
 - etc.
- Particular extensions:
 - Augmentation of a single sector of the SM like the scalar sector, etc.

Introduction: Extended scalar sector

- The scalar sector can be extended by introducing additional Higgs multiplets such as in
 - Two Higgs doublet models (SM + 2ϕ)
 - Zee model (SM + $2\phi + \eta^+$)
 - Zee-Babu model (SM + $\eta^+ + k^{++}$)
 - Higgs triplet model (SM + $\vec{\Phi} = (\phi^{++}, \phi^+, \phi^0)$)
 - etc.

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Introduction: Extended scalar sector

- What is the motivation for extending the scalar sector?
- In the SM neutrinos stay massless due to the absence of right-handed neutrino fields
- But recent experiments have discovered the phenomenon of neutrino flavour oscillations, which is only possible if neutrinos have non-zero and different masses
- One possibility to introduce neutrino masses is the so-called type-II see-saw mechanism, in which a complex scalar triplet with $Y = 2$, the Higgs triplet, is added to the scalar sector

Introduction: Extended scalar sector

- The Lagrangian of the Yukawa sector is enhanced with a gauge invariant coupling \mathcal{L}_Δ between the Higgs triplet and the lepton doublets
- \mathcal{L}_Δ automatically leads to a Majorana Mass term for neutrinos at tree level proportional to v_\top (the vacuum expectation value of the neutral component of the Higgs triplet)

The Higgs triplet model

The Higgs triplet model: The idea

- The idea of adding a scalar triplet to the SM was first mentioned in a work of W. Konetschny and W. Kummer in 1977 [1]

[1] W. Konetschny and W. Kummer, Nonconservation of total lepton number with scalar bosons Phys. Lett. **70B** (1977) 433.

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- This idea of an additional a scalar triplet was also used by G.B Gelmini and M. Roncadelli in 1981 in order to introduce neutrino masses [2]

[1] W. Konetschny and W. Kummer, Nonconservation of total lepton number with scalar bosons Phys. Lett. **70B** (1977) 433.

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The Higgs triplet model: The Lagrangian

The Yukawa Lagrangian in the lepton sector is given by [3]

$$\mathcal{L}_Y = \sum_{\alpha, \beta} \left\{ -c_{\alpha\beta} \bar{\ell}_{\alpha R} \phi^\dagger L_{\beta L} + \frac{1}{2} f_{\alpha\beta} L_{\alpha L}^T C^{-1} i\tau_2 \Delta L_{\beta L} \right\} + \text{H.c.}$$

- α, β flavour indices
- $L_{\alpha L} = (\nu_\alpha, \ell_{\alpha L})$ left-handed lepton doublets
- $\ell_{\alpha R}$ right-handed lepton singlets
- ϕ Higgs doublet
- Δ 2×2 representation of the Higgs triplet
- C charge conjugation matrix
- τ_2 second pauli matrix
- $c_{\alpha\beta}, f_{\alpha\beta}$ coupling matrices, f symmetric, i.e $f_{\alpha\beta} = f_{\beta\alpha}$

[3] W.Grimus, R.Pfeiffer and T.Schwetz, A 4-neutrino model with a Higgs triplet, Eur. Phys. J. C **13** (2000) 125 [arXiv:hep-ph/9905320]

The Higgs triplet model: The multiplets

- The multiplets transform under $U \in SU(2)$ as

$$L_{\alpha L} \rightarrow UL_{\alpha L}, \quad \ell_{\alpha R} \rightarrow \ell_{\alpha R}, \quad \phi \rightarrow U\phi, \quad \Delta \rightarrow U\Delta U^\dagger$$

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- The $U(1)$ transformation properties are determined by their hypercharges:

| | $L_{\alpha L}$ | $\ell_{\alpha R}$ | ϕ | Δ |
|---|----------------|-------------------|--------|----------|
| Y | -1 | -2 | 1 | 2 |

The Higgs triplet model: The 2×2 representation

- The relation between the triplet and the 2×2 representation is given by

$$\Delta = \vec{\Phi} \cdot \vec{\tau} = \begin{pmatrix} H^+ & \sqrt{2}H^{++} \\ \sqrt{2}H^0 & -H^+ \end{pmatrix} \quad \text{with} \quad \vec{\Phi} = \begin{pmatrix} \frac{1}{\sqrt{2}}(H^0 + H^{++}) \\ \frac{1}{\sqrt{2}}(H^0 - H^{++}) \\ H^+ \end{pmatrix}$$

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- The charge eigenfields are given by

$$H^{++} = \frac{1}{\sqrt{2}}(H_1 - iH_2), \quad H^+ = H_3, \quad H^0 = \frac{1}{\sqrt{2}}(H_1 + iH_2)$$

The Higgs triplet model: VEVs

- The VEVs of the Higgs multiplets consistent with electric charge conservation are given by

$$\langle \phi \rangle_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{and} \quad \langle \Delta \rangle_0 = \begin{pmatrix} 0 & 0 \\ v_T & 0 \end{pmatrix}$$

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- We have set $\langle H^0 \rangle_0 = \frac{v_T}{\sqrt{2}}$
- We expect $|v_T| \ll v$, since a larger triplet VEV would destroy the tree-level relation $M_W = M_Z \cos(\theta_w)$ between the gauge boson masses and the Weinberg angle and precision measurements place a stringent bound on v_T [4]

[4] J.Erler and P.Langacker, Constraints on extended neutral gauge structures, Phys.Lett. B **456** (1999) 68 [arXiv:hep-ph/9903476]

The Higgs triplet model: The potential

- The most general Higgs potential involving ϕ and Δ is given by

$$\begin{aligned} V(\phi, \Delta) = & a\phi^\dagger\phi + \frac{b}{2}\text{Tr}(\Delta\Delta^\dagger) + c(\phi^\dagger\phi)^2 + \frac{d}{4}(\text{Tr}(\Delta\Delta^\dagger))^2 \\ & + \frac{e-h}{2}\phi^\dagger\phi\text{Tr}(\Delta\Delta^\dagger) + \frac{f}{4}\text{Tr}(\Delta^\dagger\Delta^\dagger)\text{Tr}(\Delta\Delta) \\ & + h\phi^\dagger\Delta^\dagger\Delta\phi + (t\phi^\dagger\Delta\tilde{\phi} + \text{H.c.}) \end{aligned}$$

with $\tilde{\phi} = i\tau_2\phi^*$

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- All parameters of the potential are real, except t which is complex in general, i.e. $t = |t|e^{i\omega}$
- The doublet VEV v can be chosen real, by a performing global U(1) transformation
- Because of the t-term we do not have a second global symmetry, the lepton number to make v_T real therefore we can write $v_T = w e^{i\gamma}$ with $w = |v_T|$

The Higgs triplet model: The potential

- Following orders of magnitude for the parameters of the potential are assumed:

$$a, b \sim v^2; \quad c, d, e, f, h \sim 1; \quad |t| \ll v$$

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- Following orders of magnitude for the parameters of the potential are assumed:

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- The potential as function of the VEVs is given by

$$V(\langle\phi\rangle_0, \langle\Delta\rangle_0) = \frac{1}{2}av^2 + \frac{1}{2}bw^2 + \frac{1}{4}cv^4 + \frac{1}{2}dw^4 \\ + \frac{e-h}{4}v^2w^2 + v^2w|t|\cos(\omega + \gamma)$$

- It has to be minimized with respect to v , w and γ in order to obtain relations between parameters of the potential

The Higgs triplet model: Minimum conditions

- Minimization with respect to γ , the phase of v_T , gives $\omega + \gamma = \pi$ or

$$v_T = -w e^{-i\omega} \quad \text{and} \quad v_T t = -w |t|$$

- With this relation the other two minimum conditions are

$$a + c v^2 + \frac{e - h}{2} w^2 + 2 |t| w = 0$$

$$b + d w^2 + \frac{e - h}{2} v^2 + \frac{|t|}{w} v^2 = 0$$

- We find the approximate solution

$$v^2 \cong \frac{a^2}{c} \quad \text{and} \quad w \cong |t| \frac{v^2}{b + (e - h)v^2/2}$$

The Higgs triplet model: Minimum conditions

- We see that $w \sim |t|$, the triplet VEV is of the order of the parameter $|t|$ in the potential
- The fine-tuning to get a small triplet is therefore simply given by $|t| \ll v$
- Alternatively, one could use $b \gg v^2$ to get a small triplet VEV

The Higgs triplet model: Mass terms

- Mass terms for charged leptons and neutrinos are induced by \mathcal{L}_Y and the VEVs $\langle\phi\rangle_0, \langle\Delta\rangle_0$:

$$-\left(\bar{\ell}_R \mathcal{M}_\ell \ell_L + \text{H.c.}\right) \quad \text{with} \quad \mathcal{M}_\ell = \frac{v}{\sqrt{2}} (c_{\alpha\beta})$$

$$\frac{1}{2} \nu_L^T C^{-1} \mathcal{M}_\nu \nu_L + \text{H.c.} \quad \text{with} \quad \mathcal{M}_\nu = v_T (f_{\alpha\beta})$$

Neutrino mass terms

Neutrino mass terms: Dirac vs. Majorana neutrinos

- Majorana Fermions are their own anti-particles
- The equation for Majorana field is the same as for Dirac fields:

$$(i\gamma^\mu \partial_\mu - m)\psi = 0$$

- The Majorana nature is hidden in the Majorana condition:

$$\psi = \psi^C = C\gamma_0^T \psi^*$$

- Most of the SM extensions suggest that neutrinos have Majorana Nature
- In consequence of the smallness of the neutrino masses, it is difficult to distinguish between Dirac and Majorana neutrinos
- Neutrinoless $\beta\beta$ -decay to be the only prospective road so far

Neutrino mass terms: Dirac mass term

- With two independent chiral 4-spinor fields $\nu_{L,R}$ one can construct a Dirac mass term by writing a *Lorentz-invariant* bilinear for Dirac fields [5]:

$$\bar{\nu}_R \mathcal{M} \nu_L + \text{H.c.} = \bar{\nu}' \hat{m} \nu'$$

- \mathcal{M} is an arbitrary $n \times n$ mass matrix
- \hat{m} is a diagonal and positive mass matrix with the bidiagonalization $U_R^\dagger \mathcal{M} U_L = \hat{m}$
- The physical Dirac fields are given by

$$\nu' = \nu'_L + \nu'_R \text{ with } \nu_{L,R} = U_{L,R} \nu'_{L,R}$$

[5] W.Grimus, *Neutrino physics: Theory*, Lect. Notes Phys. **629** (2004) 169 [arXiv:hep-ph/0307149].

Neutrino mass terms: Majorana mass term

- With only one chiral 4-spinor field ν_L a *Lorentz-invariant* bilinear can still be constructed with the help of the charge conjugation matrix C . This bilinear is the so called Majorana mass term [5]:

$$\frac{1}{2} \nu_L^T C^{-1} \mathcal{M} \nu_L + \text{H.c.} = -\frac{1}{2} \bar{\nu}' \hat{m} \nu'$$

- \mathcal{M} is now a complex and symmetric $n \times n$ mass matrix
- \hat{m} is a diagonal and positive mass matrix with the diagonalization $U_L^T \mathcal{M} U_L = \hat{m}$
- The physical Majorana fields are given by

$$\nu' = \nu'_L + (\nu'_L)^c \text{ with } \nu_L = U_L \nu'_L$$

- The Majorana mass term violates not only the individual lepton family numbers just as the Dirac mass term, but it also violates the total lepton number $L = \sum_{\alpha} L_{\alpha}$

[5] W.Grimus, *Neutrino physics: Theory, Lect. Notes Phys.* **629** (2004) 169 [arXiv:hep-ph/0307149].

Neutrino mass terms: The mixing matrix U_{PMNS}

- Situation in the lepton sector analogue to the quark sector:
Flavour eigenfields \neq mass eigenfields
- Neutrino mixing given by

$$\nu_{\alpha L} = \sum_j U_{\alpha j} \nu_{jL}$$

- The lepton mixing matrix U_{PMNS} (Pontecorvo-Maki-Nakagawa-Sakata-matrix) is given as

$$U = U_L^{(\ell)\dagger} U_L^{(\nu)}$$

where $U_L^{(\ell)\dagger}$ and $U_L^{(\nu)}$ are the matrices which (bi)diagonalize the charged lepton/neutrino mass matrices

Neutrino mass terms: The mixing matrix U_{PMNS}

- The lepton mixing matrix is usually parametrized as

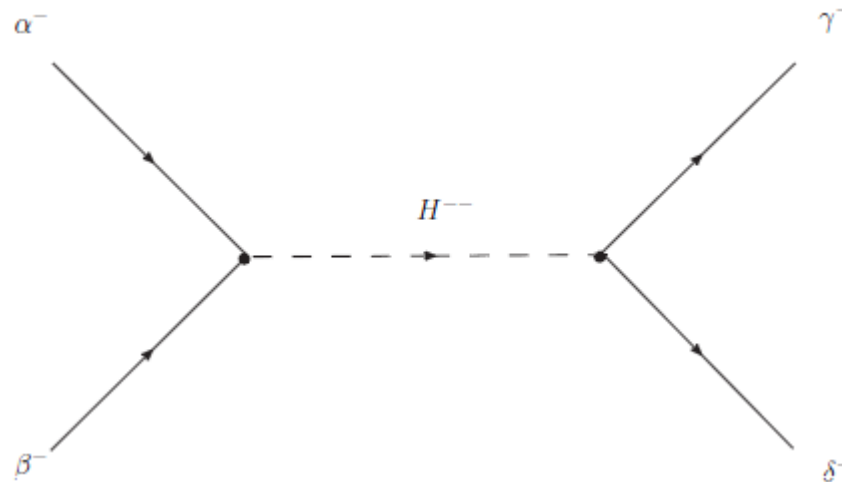
$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$
$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & -s_{12} & 0 \\ -s_{12} & c_{23} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$
$$\times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

with $c_{ij} = \cos(\theta_{ij})$, $s_{ij} = \sin(\theta_{ij})$, δ is non-zero only if neutrino oscillations violate CP symmetry. α_1, α_2 are physically meaningful if neutrinos have Majorana nature.

Cross sections and decay widths

Cross sections and decay widths

- The Lagrangian \mathcal{L}_Y permits lepton flavour violating processes $\alpha^- \beta^- \rightarrow \gamma^- \delta^-$ (for $\alpha, \beta, \gamma, \delta = e, \mu, \tau$)



Cross sections and decay widths

- The cross section was calculated as [6]

$$\sigma(\alpha^- \beta^- \rightarrow \gamma^- \delta^-) = \frac{|f_{\alpha\beta}|^2 |f_{\gamma\delta}|^2}{16\pi(1 + \delta_{\gamma\delta})} \frac{s}{(s - m^2)^2 + m^2\Gamma^2}$$

- f Yukawa coupling matrix
- $\delta_{\gamma\delta}$ Kronecker delta
- $s = (p_1 + p_2)^2$ Mandelstam variable
- m mass of H^{--}
- Γ total width of H^{--}

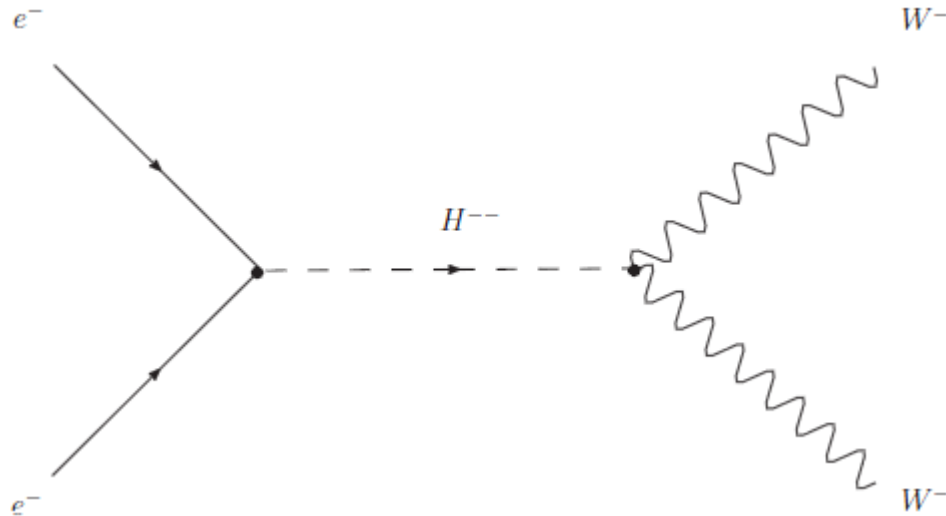
[6] W. Rodejohann and H. Zhang, Higgs triplets at like-sign linear colliders and neutrino mixing, Phys. Rev. D **83** (2011) 073005 [arXiv:1011.3606 [hep-ph]].

Cross sections and decay widths

- The gauge coupling

$$\mathcal{L}_{\Delta gauge} = \frac{1}{2} \text{Tr} \{ (D_\mu \Delta)^\dagger (D^\mu \Delta) \}$$

permits lepton number violating processes like $e^- e^- \rightarrow W^- W^-$



Cross sections and decay widths

- The cross section was calculated as

$$\begin{aligned} & \sigma(e^-e^- \rightarrow W^-W^-) \\ &= \frac{G_F |f_{ee}|^2 |v_T|^2 (s - 2m_W^2)^2 + 8m_W^4}{4\pi (s - m)^2 + m^2\Gamma^2} \sqrt{1 - \frac{m_W^2}{m^2}} \end{aligned}$$

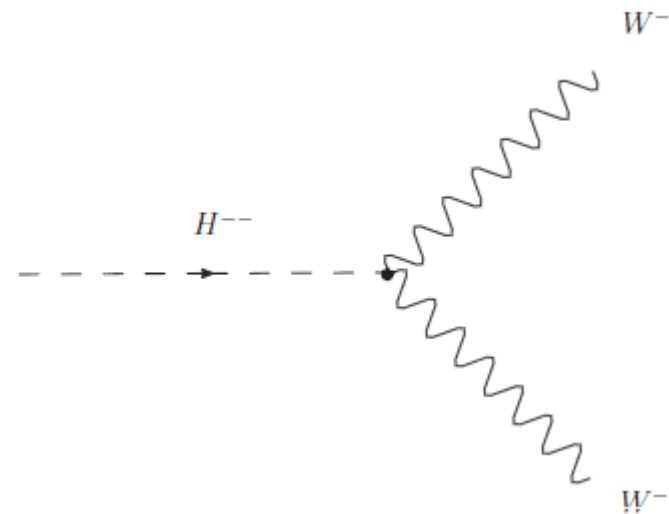
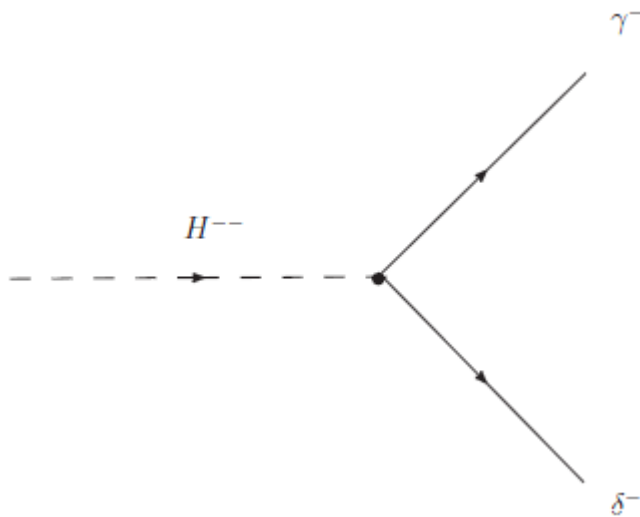
- G_F Fermi constant
- f Yukawa coupling matrix
- v_T triplet VEV
- m mass of H^{--}
- Γ total width of H^{--}
- m_W mass of the W-boson

Cross sections and decay widths

- Lets take a look at some decays of H^{--}

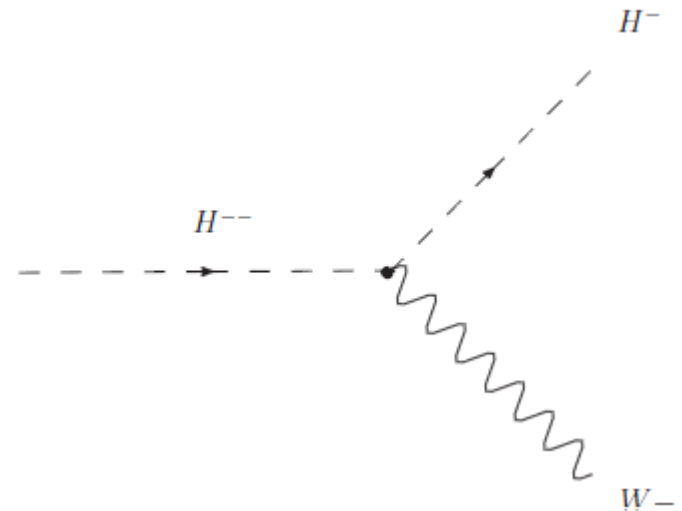
- $\Gamma(H^{--} \rightarrow \gamma^- \delta^-) = \frac{|f_{\nu\delta}|^2}{4\pi(1+\delta_{\gamma\delta})} m$

- $\Gamma(H^{--} \rightarrow W^- W^-) = \frac{g^4 |v_T|^2}{32\pi m} \frac{(s-2m_W^2)^2 + 8m_W^4}{m_W^4} \sqrt{1 - \frac{m_W^2}{m^2}}$



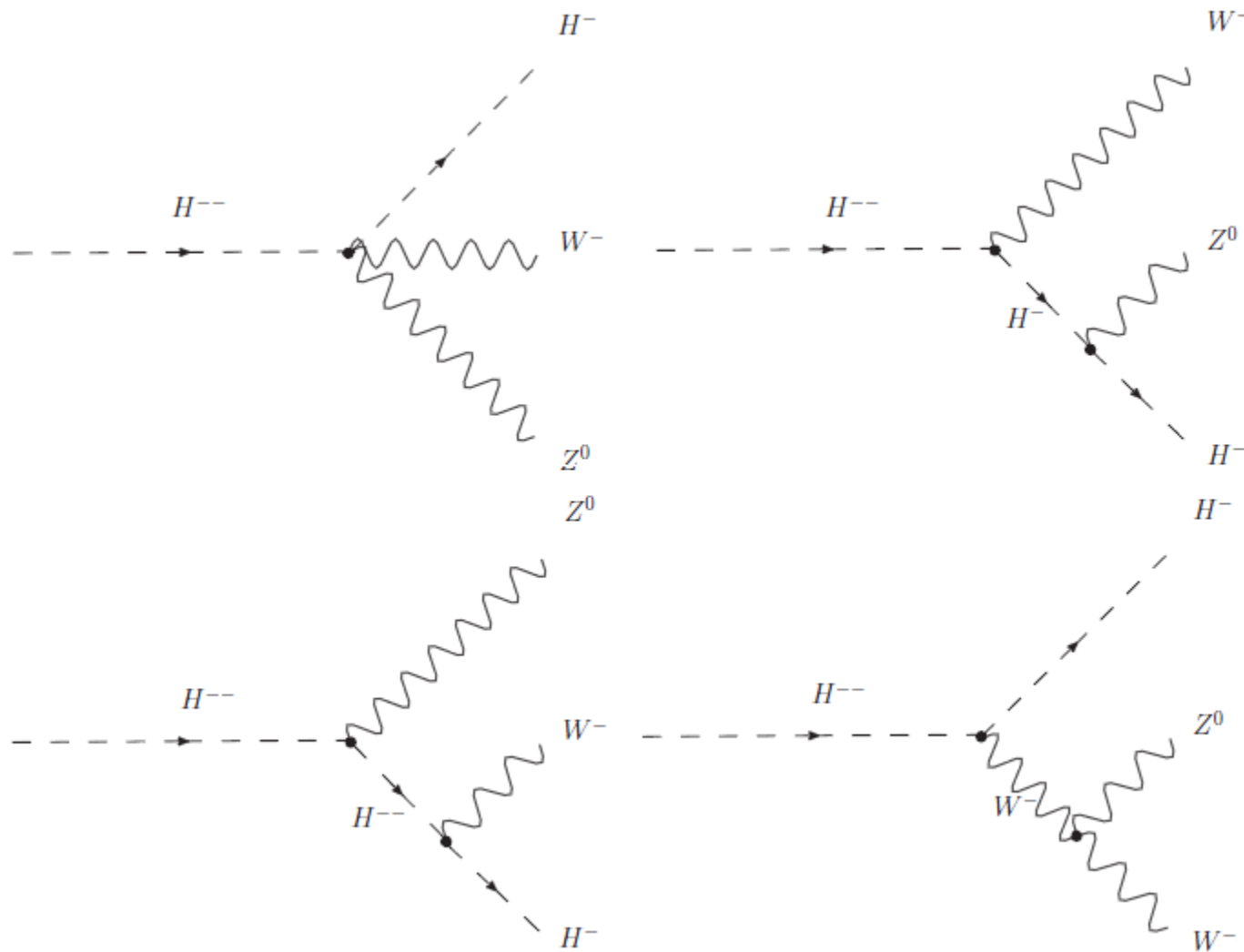
Cross sections and decay widths

- $\Gamma(H^{--} \rightarrow H^- W^-) = \frac{g^2}{16\pi m^3 m_W^2} [\lambda(m^2, m_-^2, m_W^2)]^{\frac{3}{2}}$
- m mass of H^{--}
- m_- mass of H^-
- m_W mass of the W-boson
- g coupling constant
- $\lambda(x, y, z) = x^2 + y^2 + z^2 - 2(xy + xz + yz)$



Cross sections and decay widths

- The 3-body decay $H^{--} \rightarrow H^- W^- Z^0$ has four contributions:



Cross sections and decay widths

- The squared amplitude $|\mathcal{M}|^2$ of this process consists of over a hundred terms
- Most of the terms contain H^- , H^{--} or W^- propagators
- The 3-body phase-space integral over the rational functions was not solvable analytically
- Therefore $\Gamma(H^{--} \rightarrow H^- W^- Z^0)$ was solved numerically with the FORTRAN program RAMBOC, based on “RAMBO” (random momenta beautifully organized)[7]
- “RAMBO” is based on the Monte Carlo algorithm. The integration over phase space is replaced by a number of random choices over the integration variable.

[7] R. Kleiss, W. J. Stirling and S. D. Ellis, A new Monte Carlo treatment of multiparticle phase space at high-energies, *Comput. Phys. Commun.* **40** (1986) 359.

Cross sections and decay widths

RAMBOTS

Rambo started with IC = 1000
 ET = 1000
 - XM(1) = 600
 - XM(2) = 80
 - XM(3) = 91

IC: 1000
 mh2_ET: 1000
 mh_XM(1): 600
 mw_XM(2): 80
 mz_XM(3): 91

Make it Rambo

Rambo started
 Rambofill (FORTRAN95) initialized
 GOT P, WT
 Rambofunctionsfill (FORTRAN95) initia...
 GOT MC
 GOT NH
 GOT NHZ
 GOT MAW
 GOT NBW
 GOT NCW
 GOT SUM6
 GOT EPICENDSUM
 Rambo stopped
 Calc V & U

V
 89361,7274963809

U
 59256,2041659774

Matrix P3

| kw | kh | kz |
|-------------------|-------------------|------------------|
| -140.964978688327 | 65.1051299369503 | 75.8598465175227 |
| -90.7558459408685 | -66.465655843134 | 197.21950796867 |
| 128.200329538449 | -112.913550462184 | -15.696901674447 |
| 636.036987304688 | 166.479415893955 | 197.483596801758 |

W:

| Column1 | Column1 | Column1 | Column1 |
|-------------------|-------------------|-------------------|------------------|
| 3.59920454291908 | 3.54450953856369 | -2.18231574945345 | 10.8270668228949 |
| 1.54409953856369 | 1.99464117527384 | -1.49501591716702 | 6.97066475456204 |
| -2.18231574945345 | -1.49501591716702 | 2.98470287329634 | -9.8466551589305 |
| 10.8270668228949 | 6.97066475456204 | -9.8466551589305 | 47.8519561912357 |

Z:

| Column1 | Column1 | Column1 | Column1 |
|-------------------|-------------------|-------------------|-------------------|
| 1.0261744240097 | 1.86353671024702 | -0.18593722703995 | -2.34079302236089 |
| 1.86353671024702 | 4.86218338940614 | -0.3853484441285 | -4.85129280078205 |
| -0.18593722703995 | -0.3853484441285 | 1.03844932804584 | 0.48404643652719 |
| -2.34079302236089 | -4.85129280078205 | 0.48404643652719 | 5.05371421964588 |

Name U V EpicEndSum WT

| | | | | |
|------------|------------------|------------------|------------------|-------------------|
| Matrix -0 | 152494.587788228 | 170.641866342459 | 893.652833947004 | 170641.866342459 |
| Matrix -1 | 287816.876620404 | 233.466731214673 | 2153.96068272364 | 62824.8648722145 |
| Matrix -2 | 447985.403331204 | 334.233776673018 | 1589.50305610589 | 100767.045458344 |
| Matrix -3 | 607100.607955113 | 470.143878643467 | 1170.73125777292 | 135910.10197045 |
| Matrix -4 | 813565.101504496 | 484.905456954346 | 444.571103001112 | 14761.618310879 |
| Matrix -5 | 628827.787470595 | 519.784747448202 | 377.264311680994 | 34879.2504588857 |
| Matrix -6 | 627057.134740468 | 542.017323130074 | 10.158209447034 | 2232.5776818418 |
| Matrix -7 | 653964.464380252 | 573.096911887685 | 865.672092167603 | 31882.5887676115 |
| Matrix -8 | 656197.641690614 | 635.187570483953 | 35.968135388789 | 62087.6585962675 |
| Matrix -9 | 920436.375402336 | 786.33547965603 | 2014.94541439271 | 131145.5091726077 |
| Matrix -10 | 1000496.34834345 | 908.993315926003 | 561.194902744752 | 148509.836269973 |
| Matrix -11 | 1012815.36582349 | 967.577970614736 | 208.851226561361 | 58994.6546887933 |
| Matrix -12 | 1178073.75783062 | 1049.87194912507 | 2017.95534926014 | 81893.9785103373 |

MC

| Column1 | Column1 | Column1 | Column1 |
|--------------------|--------------------|--------------------|---------------------|
| 0.0320477074080966 | 0 | 0 | 0 |
| 0 | 0.0320477074080966 | 0 | 0 |
| 0 | 0 | 0.0320477074080966 | 0 |
| 0 | 0 | 0 | -0.0320477074080966 |

MH

| Column1 | Column1 | Column1 | Column1 |
|----------------------|----------------------|----------------------|----------------------|
| 0.00326237641155335 | -0.00333045176360056 | -0.00563798203531795 | 0.00834217702847784 |
| 0.00210037788795384 | -0.00214420605024562 | -0.0036298364444231 | 0.00537084687794541 |
| -0.00296696250627493 | 0.00302897351581087 | 0.00512745287472062 | -0.00758677826891723 |
| 0.00842325789698862 | -0.00859502429652788 | -0.0145568273919385 | 0.0215389947207233 |

MHZ

| Column1 | Column1 | Column1 | Column1 |
|-----------------------|----------------------|-----------------------|--------------------|
| 0.00287256323287734 | 0.00959338635324224 | -0.000594006784355188 | -0.030388659035517 |
| -0.002953250443177255 | -0.00607761446819389 | 0.000606401804384208 | 0.0310227735458982 |
| -0.00496431369627454 | -0.0102885384991198 | 0.00102695216828794 | 0.052517151515245 |
| 0.00734539120908762 | 0.0152233203959395 | 0.00115189264284952 | -0.077766415586806 |

MAW

| Column1 | Column1 | Column1 | Column1 |
|-------------------|---------------------|--------------------|--------------------|
| 0.123186627401535 | 0.0793099163987778 | -0.11203184205436 | 0.555820687505167 |
| 0.26992557016947 | 0.173182395982422 | 0.244634755129918 | -1.21370014853633 |
| 0.018741068822832 | -0.0126658563870533 | 0.0170440454710948 | 0.0849601830506054 |
| 0.320893207430278 | 0.206996369451044 | 0.291834893614761 | -1.4478729282006 |

MHW

| Column1 | Column1 | Column1 | Column1 |
|--------------------|--------------------|--------------------|---------------------|
| 0.0433809661114906 | 0 | 0 | 0 |
| 0 | 0.0433809661114906 | 0 | 0 |
| 0 | 0 | 0.0433809661114906 | 0 |
| 0 | 0 | 0 | -0.0433809661114906 |

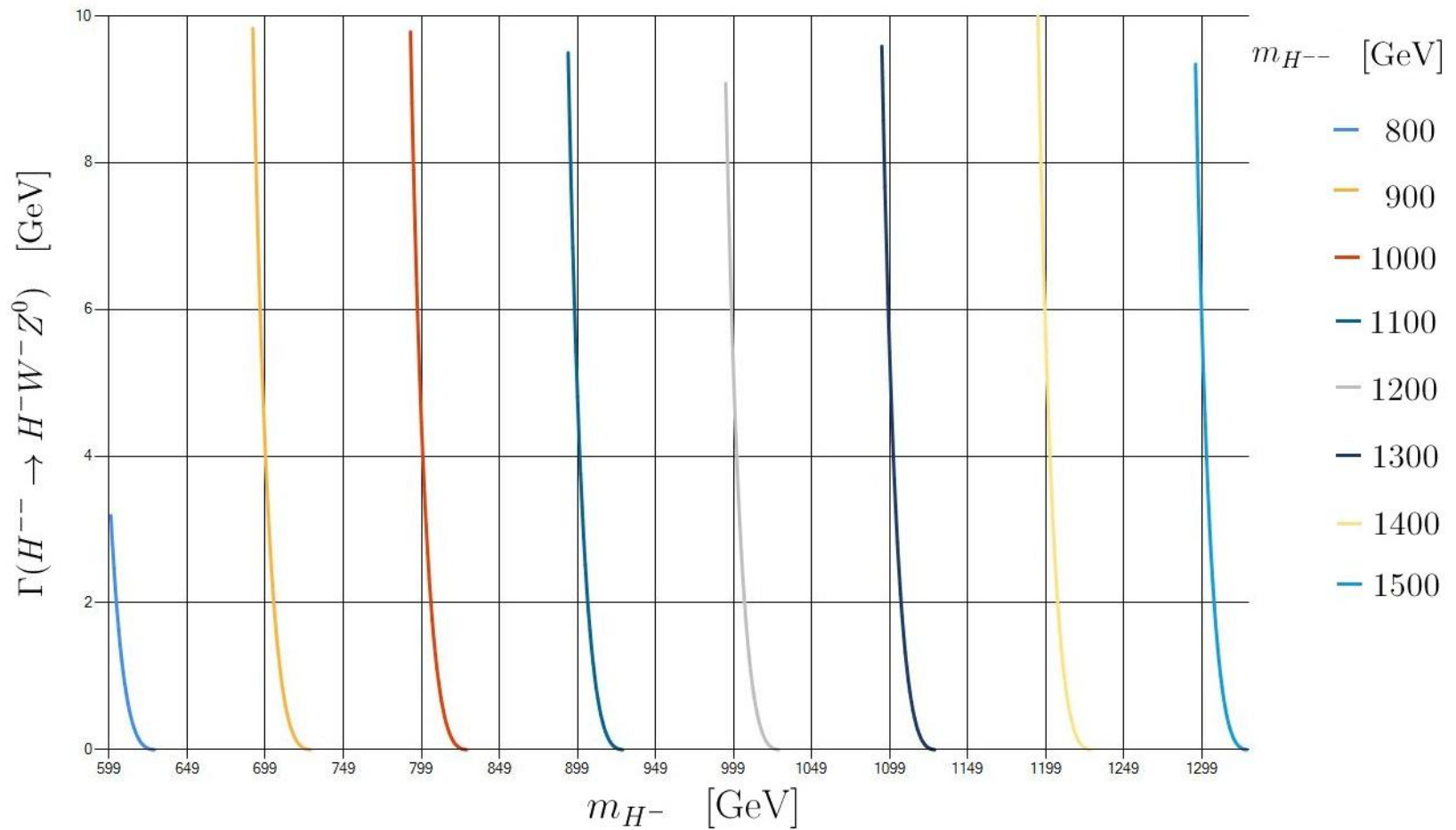
MCW

| Column1 | Column1 | Column1 | Column1 |
|---------------------|--------------------|---------------------|--------------------|
| -0.2576046588579884 | -0.161888475172705 | 0.236227765393701 | 1.14548398136982 |
| -0.533865636065327 | -0.335009668752014 | 0.493981963294939 | 2.37401519021353 |
| 0.052691991748953 | 0.0334799547036473 | -0.0488487377690257 | -0.236870744348352 |
| -0.670614343313866 | -0.421434063714848 | 0.614964449784095 | 2.8202030996746 |

SUM6

| Column1 | Column1 | Column1 | Column1 |
|---------------------|---------------------|-------------------|-------------------|
| -0.0628544481143614 | -0.0799637241842895 | 0.117963934519668 | 0.067616811389981 |
| -0.265725205582599 | -0.0951204601684743 | 0.241923769523963 | 1.19670866210102 |
| 0.0295968361495039 | 0.0141504333332851 | 0.049777982646347 | -0.10738018803514 |
| -0.33985377804812 | -0.208213397700793 | 0.30705370234937 | 1.40253406798122 |

Cross sections and decay widths



Conclusions

Conclusions

- The additional term in the Yukawa Lagrangian \mathcal{L}_Y induced a lepton number violating Majorana mass term for neutrinos at tree level, which was found as $\frac{1}{2} \nu_L^T C^{-1} \mathcal{M}_\nu \nu_L + \text{H.c.}$
- The mass matrix was given by $\mathcal{M}_\nu = v_T (f_{\alpha\beta})$
- The triplet VEV had to be very small, i.e. $|v_T| \ll v$, which was achieved by the fine-tuning $|t| \ll v$; t was the parameter of the lepton number violating term in the potential ($t\phi^\dagger \Delta\tilde{\phi} + \text{H.c.}$)
- Neutrinos can be Dirac or Majorana fermions, most SM extension suggest Majorana nature of the neutrino
- \mathcal{L}_Y permits interesting lepton flavour and lepton number violating processes like $\alpha^- \beta^- \rightarrow \gamma^- \delta^-$, $e^- e^- \rightarrow W^- W^-$, $H^{--} \rightarrow H^- W^-$, $H^{--} \rightarrow H^- W^- Z^0$

Thank you for your attention!