On the Higgs triplet extension of the Standard Model

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4th of October 2012, Vienna

Outline

- 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
  - Assumtion of extra dimensions like in string theories
  - etc.

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  - 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 + 2ϕ + η^{+})
  - Zee-Babu model (SM + η^{+} + k^{++})
  - Higgs triplet model (SM + $\overrightarrow{\Phi} = (\phi^{++}, \phi^{+}, \phi^{0})$)
  - etc.

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- 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 $\mathcal{L}_{\Delta}$ between the Higgs triplet and the lepton doublets
- $\mathcal{L}_{\Delta}$ automatically leads to a Majorana Mass term for neutrinos at tree level proportional to v_T (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]

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The Higgs triplet model: The Lagrangian

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

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

- 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 symmentric, 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
  $$L_{\alpha L} \to UL_{\alpha L},\ \ell_{\alpha R} \to \ell_{\alpha R},\ \phi \to U\phi,\ \Delta \to U\Delta U^{\dagger}$$

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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

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

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- The charge eigenfields are given by

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

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

$$V(\phi,\Delta) = a\phi^\dagger\phi + \frac{b}{2}\mathrm{Tr}\left(\Delta\Delta^\dagger\right) + c(\phi^\dagger\phi)^2 + \frac{d}{4}\left(\mathrm{Tr}\left(\Delta\Delta^\dagger\right)\right)^2$$
$$+ \frac{e-h}{2}\phi^\dagger\phi\mathrm{Tr}\left(\Delta\Delta^\dagger\right) + \frac{f}{4}\mathrm{Tr}\left(\Delta^\dagger\Delta^\dagger\right)\mathrm{Tr}(\Delta\Delta)$$
$$+\ h\phi^\dagger\Delta^\dagger\Delta\phi + (t\phi^\dagger\Delta\tilde{\phi} + \mathrm{H.c.})$$

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

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- 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 assumend:

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

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- The potential as function of the VEVs is given by

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

- 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

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

- With this relation the other two minimum conditions are

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

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

- We find the approximate soloution

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

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 $\langle\phi\rangle_0$, $\langle\Delta\rangle_0$:

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

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

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]:

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

- $\mathcal{M}$ is an arbitrary $n \times n$ mass matrix
- $\widehat{m}$ is a diagonal and positive mass matrix with the bidiagonalization $U_R{}^{\dagger} \mathcal{M} U_L = \widehat{m}$
- 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 ≠ 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

$$U_{PMNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13} e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13} e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & -s_{12} & 0 \\ -s_{12} & c_{23} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

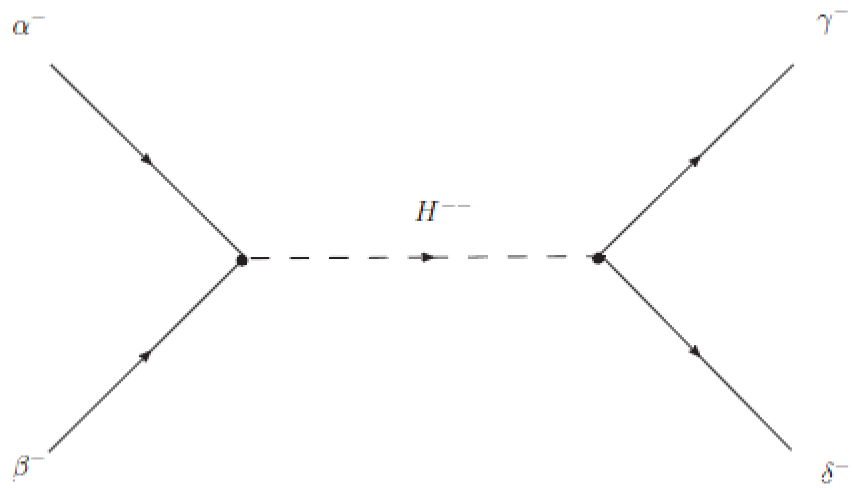
$$\times \begin{pmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

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 meaningfull 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 $\alpha^-\beta^- \to \gamma^-\delta^-$ (for $\alpha, \beta, \gamma, \delta = e, \mu, \tau$)



Cross sections and decay widths

- The cross section was calculated as [6]

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

- 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^{--}

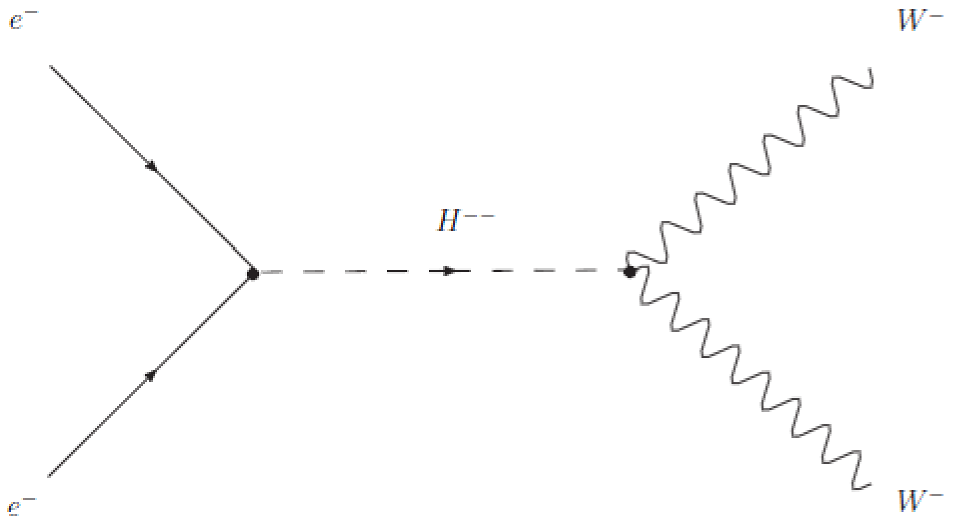
[6] W. Rodejohann and H. Zhang, Higgs triplets at like-sign linear colliders and neutrino mixing, Phys. Rev. D **83** (2011) 073005 [arXiv:1011.3606 [hep-ph]].

Cross sections and decay widths

- The gauge coupling

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

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



Cross sections and decay widths

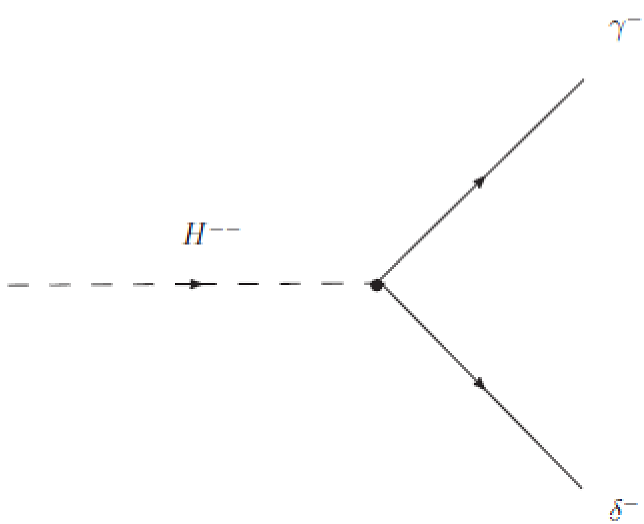
- The cross section was calculated as

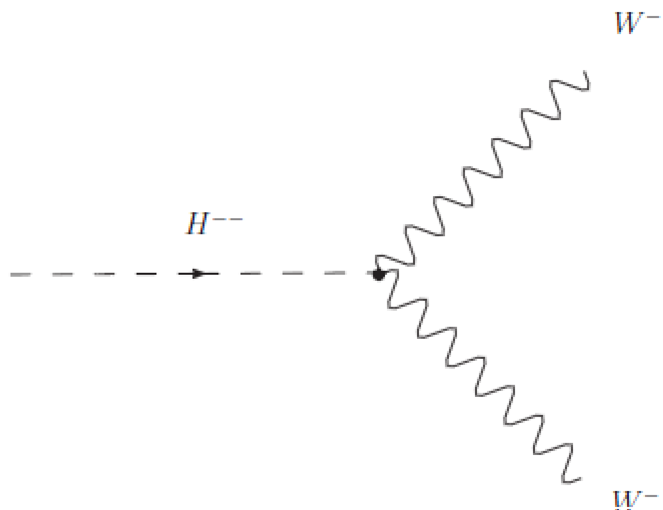
$$\sigma(e^- e^- \to W^- W^-) = \frac{G_F |f_{ee}|^2 |v_T|^2}{4\pi} \frac{(s - 2{m_W}^2)^2 + 8{m_W}^4}{(s-m)^2 + m^2\Gamma^2} \sqrt{1 - \frac{{m_W}^2}{m^2}}$$

- 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

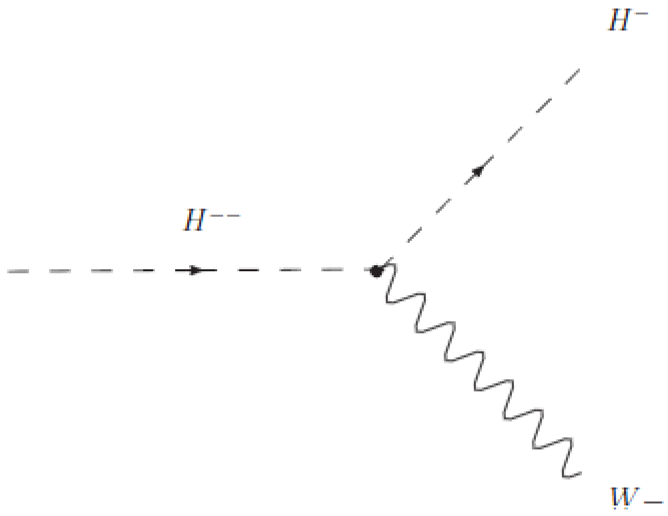
- Lets take a look at some decays of H^{--}
- $\Gamma(H^{--} \to \gamma^- \, \delta^-) = \frac{|f_{\gamma\delta}|^2}{4\pi(1+\delta_{\gamma\delta})} m$
- $\Gamma\,(H^{--} \to W^- \, W^-) = \frac{g^4|v_T|^2}{32\pi\, m} \frac{(s-2m_W{}^2)^2+8m_W{}^4}{m_W{}^4} \sqrt{1-\frac{m_W{}^2}{m^2}}$





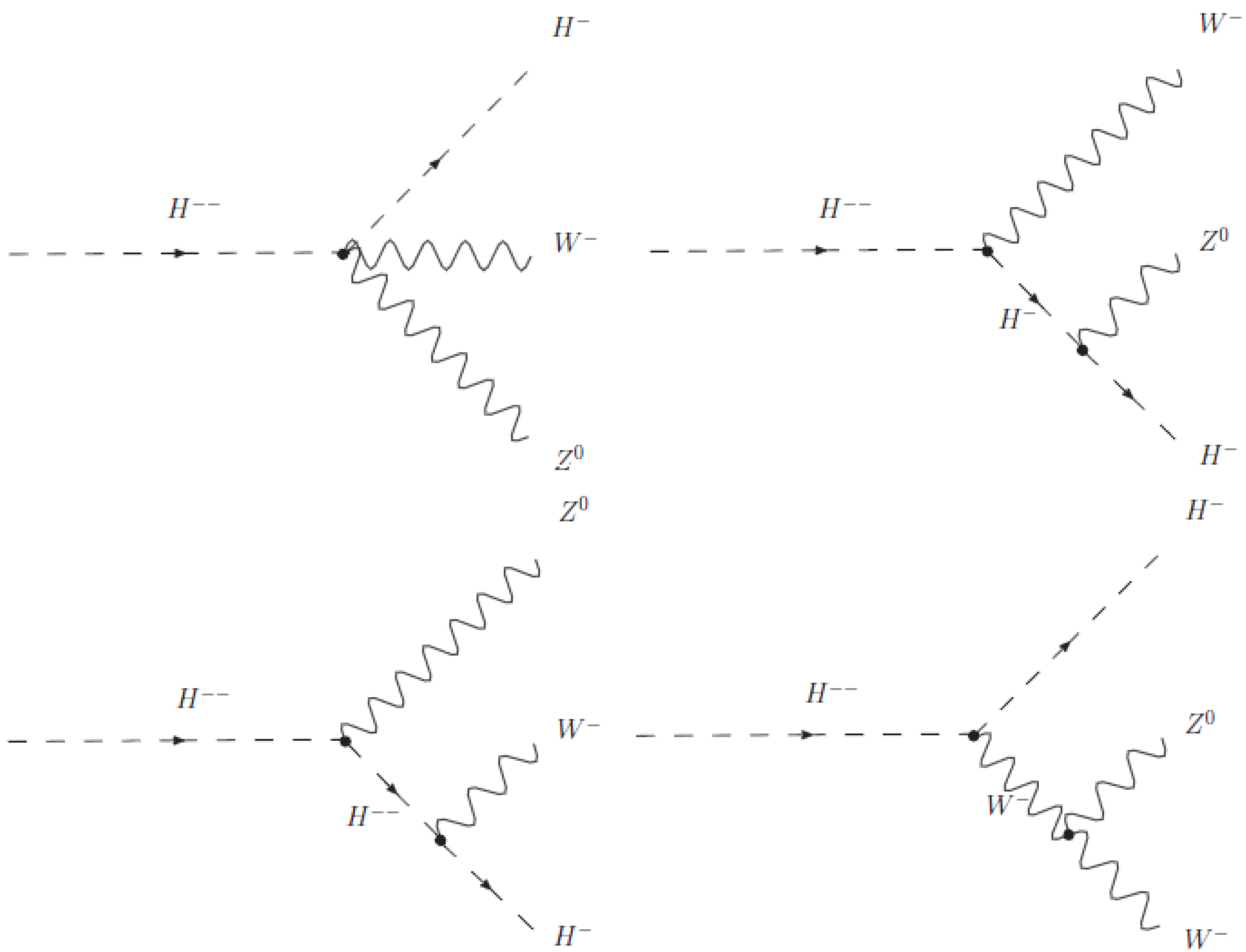
Cross sections and decay widths

- $\Gamma(H^{--} \to H^{-}\, W^{-}) = \frac{g^2}{16\pi\, m^3 m_w{}^2}\left[\lambda(m^2, m_-{}^2, m_W{}^2)\right]^{\frac{3}{2}}$
- m mass of H^{--}
- m_- mass of H^{-}
- m_W mass of the W-boson
- g coulpling 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:

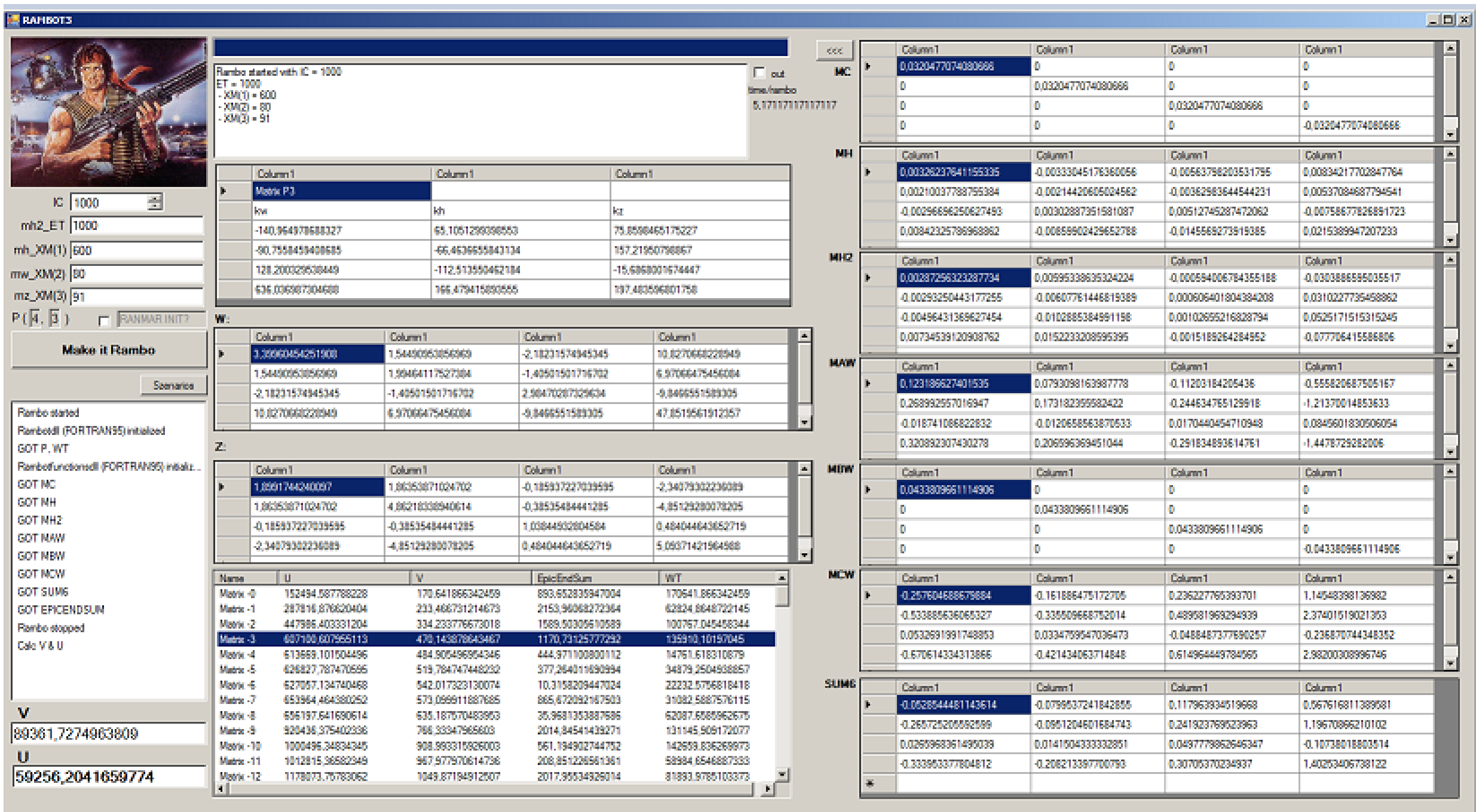


Cross sections and decay widths

- 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 $\Gamma(H^{--} \to H^- W^- Z^0)$ 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



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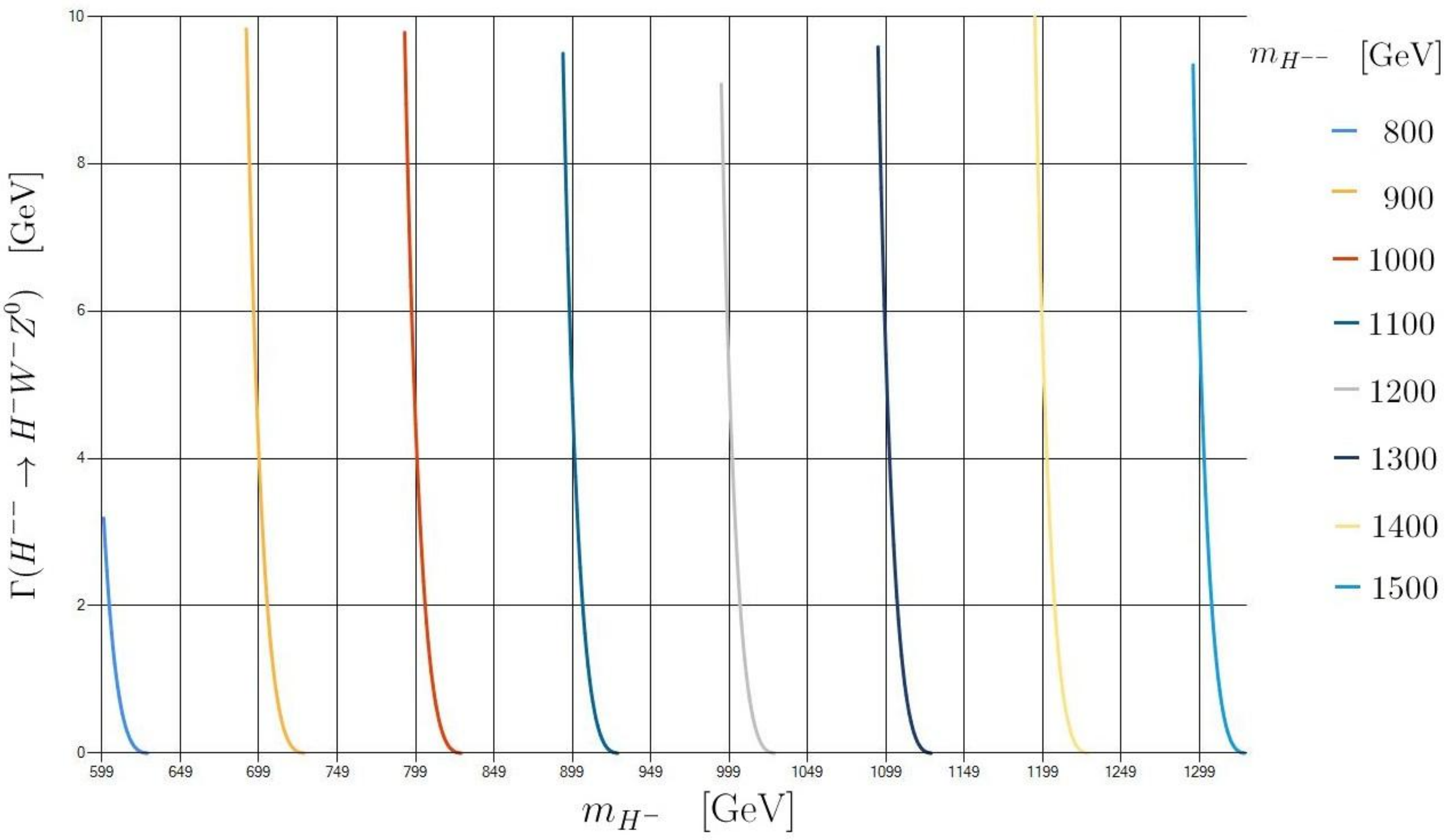

Conclusions

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- 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 $\frac{1}{2}{\nu_L}^T C^{-1}\mathcal{M}_\nu \nu_L$ + 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 ($t\phi^\dagger\Delta\tilde{\phi}$ + 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 $\alpha^-\beta^- \to \gamma^-\delta^-$, $e^-e^- \to W^-W^-$, $H^{--} \to H^-\,W^-$, $H^{--} \to H^-\,W^-Z^0$

Thank you for your attention!