HEP computer tools

from SARAH and beyond

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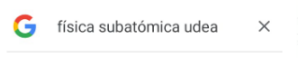
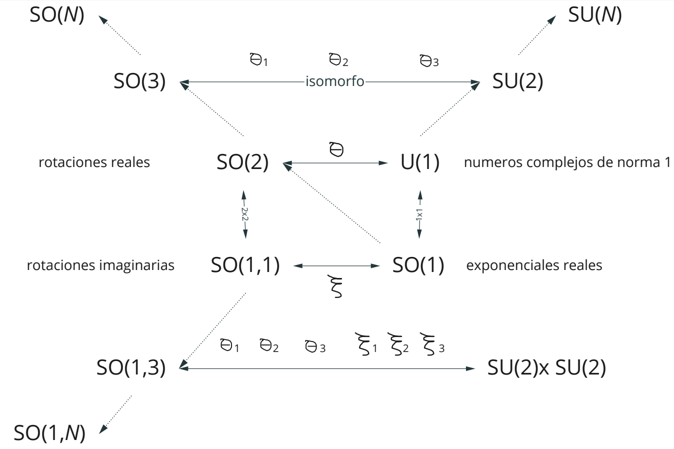
SO(3) **scalar product**

$$L = \frac{1}{2} m \boldsymbol{v} \cdot \boldsymbol{v} - V(|\boldsymbol{r}|).$$

Lie groups →



física subatómica udea



SO(N)

SU(N)

θ_1 θ_2 θ_3

SO(3)

isomorfo

SU(2)

rotaciones reales

SO(2)

θ

U(1)

numeros complejos de norma 1

2x2

1x1

rotaciones imaginarias

SO(1,1)

SO(1)

exponenciales reales

ξ

θ_1 θ_2 θ_3 ξ_1 ξ_2 ξ_3

SO(1,3)

SU(2)x SU(2)

SO(1,N)

$$U = \exp\left(i\sum_j T_j\theta^j\right), \tag{1}$$

where θ^j are the parameters of the transformation and T_j are the generators.

SO(1)

Consider the 1×1

$$K = -i\,, \tag{2}$$

which generates an element of dilaton group , SO(1), $R(\xi)$

$$\lambda(\xi) = \mathrm{e}^{\xi}\,, \tag{3}$$

which are just the group of the real exponentials. Such a number can be transformed as

$$x \rightarrow x' = \mathrm{e}^{\xi}\,x\,, \tag{4}$$

that corresponds to a boost by e^{ξ}. We can define the invariant scalar product just as the division of real numbers, such that

$$x \cdot y \rightarrow x' \cdot y' \equiv \frac{x'}{y'} = \frac{\mathrm{e}^{\xi}\,x}{\mathrm{e}^{\xi}\,y} = \frac{x}{y} = x \cdot y\,. \tag{5}$$

SO$(1,1)$

We want to obtain a 2×2 representation of the algebra

$$K = \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \to K^2 = -\mathbf{1}\,, \tag{6}$$

which can generates an element of the group SO$(1,1)$ with *parameter* ξ

$$\Lambda = \exp\left(i\xi K\right) = \begin{pmatrix} \cosh\xi & \sinh\xi \\ \sinh\xi & \cosh\xi \end{pmatrix}, \,. \tag{7}$$

The transformation of a timelike and a spacelike coordiantes, are $(c = 1)$

$$\begin{pmatrix} t \\ x \end{pmatrix} = \begin{pmatrix} x^0 \\ x^1 \end{pmatrix} \to \begin{pmatrix} x'^0 \\ x'^1 \end{pmatrix} = \begin{pmatrix} \cosh\xi & \sinh\xi \\ \sinh\xi & \cosh\xi \end{pmatrix} \begin{pmatrix} x^0 \\ x^1 \end{pmatrix}$$

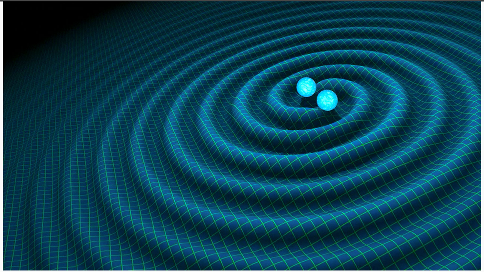
$$x'^\mu = \Lambda^\mu{}_\nu x^\nu\,, \qquad \mu = 0, 1\,.$$

$$\cosh \xi = \gamma = \frac{1}{\sqrt{1 - v^2}}$$

Special: parameter ξ or v is constant, e.g, inertial system invariance: *Global* conservation of E and $\boldsymbol{p}$ (still action at a distance!)

General: parameter $\xi(t, \boldsymbol{x})$ or $v(t, \boldsymbol{x})$ is local, e.g, accelerated system invariance: *Local* conservation of E and $\boldsymbol{p}$

Inestability of binary particle systems



Gravitational wave discovery by LIGO

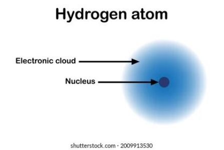
New

UNIVERSIDAD DE ANTIOQUIA

credits: science.org

Noether's paradigm → Lagrangian formulation of classical field theory

U(1): From special θ to general $\theta(t, \boldsymbol{x})$



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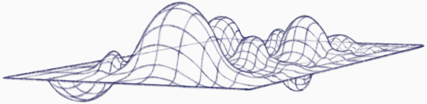
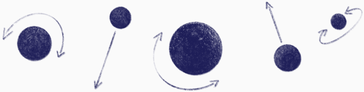
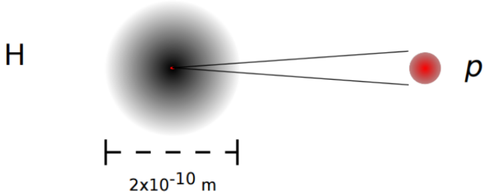
What is a ~~particle~~ *wavicle*? `https://www.quantamagazine.org/what-is-a-particle-20201112/`

Is a "Quantum Excitation of a Field"



Is a "Irreducible Representation of a Group"



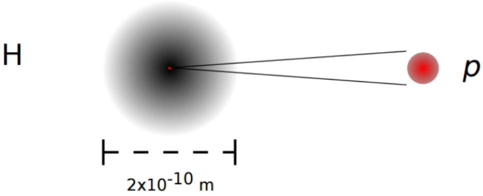

H
p
2x10^{-10} m

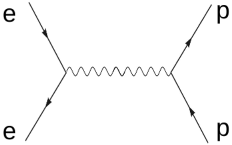
Interacción → Fuerza = Δ**p**/Δt

Introducción

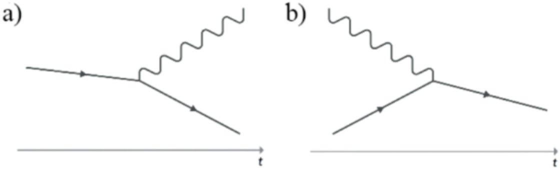
Campos de materia $\longrightarrow$

Campos de radiación 〰〰〰





doi:10.1088/1742-6596/1287/1/012045



Emisión

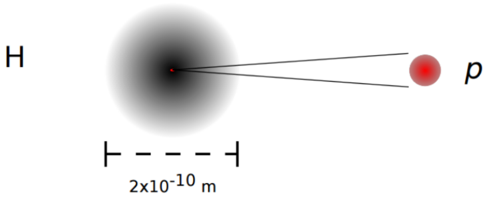
absorción

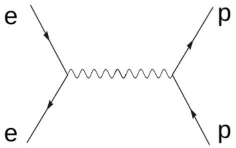
Interacción → Fuerza = Δ**p**/Δt

Introducción

Campos de materia


Campos de radiación



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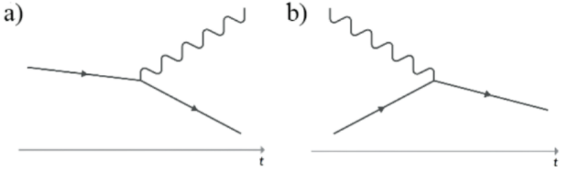
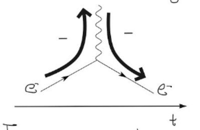


Emisión absorción

$$e^- \rightarrow e^{-iEt}$$

$$e^+ \rightarrow e^{-iE(-t)}$$

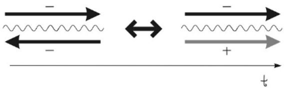
Single charge

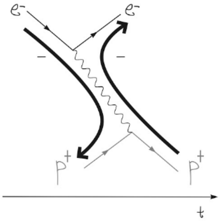


Fuerza $\frac{\Delta\vec{p}}{\Delta t} \neq 0$

$(e^-)^* = e^+$

 fotón neutro





Under a general Lorentz transformation we have for a pure upperscript 4-vector

$$A^\mu(x) \to A'^\mu(x) = \Lambda^\mu{}_\nu A^\nu(\Lambda^{-1}x), \tag{8}$$

where $\mu = 0, 1, 2, 3$. A pure underscript 4-vector is

$$\partial_\mu = \frac{\partial}{\partial x^\mu} = \left(\frac{\partial}{\partial t}, \frac{\partial}{\partial x}, \frac{\partial}{\partial y}, \frac{\partial}{\partial z}\right) = (\partial_0, \boldsymbol{\nabla}). \tag{9}$$

From $x'^\mu = \Lambda^\mu{}_\nu x^\nu$

$$\frac{1}{x'^\mu} = \left(\Lambda^{-1}\right)^\nu{}_\mu \frac{1}{x^\nu}\,, \tag{10}$$

the tranformation properties for a $\partial_\mu = \partial/\partial x^\mu$, are

$$\partial'_\mu = \partial_\nu \left(\Lambda^{-1}\right)^\nu{}_\mu\,. \tag{11}$$

In this way, the invariant scalar product between the 4-vector field and the four-gradient is just

$$\partial_\mu A^\mu \to \partial'_\mu A'^\mu = \partial_\mu A^\mu\,. \tag{12}$$

Photon: Representation of the Poincaré Groupwhich transform as a vector under $\mathrm{SO}(1,3)$

Name	Symbol	$\mathrm{SO}(1,3)$
Photon	A^μ	$\Lambda^\mu{}_\nu A^\nu$
4-gradient	∂_μ	$\partial_\nu \left(\Lambda^{-1}\right)^\nu{}_\mu$

Table 1: Scalar products: $\partial_\mu A^\mu\,, \quad A^\nu A_\nu\,, \quad \partial_\mu \partial^\mu$

Name	Symbol	SU(N)
scalar N-plet	Ψ	$U\Psi$
scalar anti-N-plet	$\Psi^\dagger$	$\Psi^\dagger U^\dagger$

Table 2: Scalar products: $\Psi^\dagger \Psi$

Photon: $\hat{\boldsymbol{p}} \oplus \mathrm{SO}(1,3) = i\partial^\mu \oplus \mathrm{SO}(1,3) \to i D^\mu \oplus \mathrm{SO}(1,3)$

Name	Symbol	SO(1, 3)
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Table 2: Scalar products: $\Psi^\dagger \Psi$

Name	Symbol	SL(2, C)	$U(1)_Q$
e_L: electron left	ξ_α	$S_\alpha{}^\beta\xi_\beta$	$e^{i\theta}\xi_\alpha$
$(e_L)^\dagger$: positron right	$(\xi_\alpha)^\dagger = \xi^\dagger_{\dot\alpha}$	$\xi^\dagger_{\dot\beta}\left[S^\dagger\right]^{\dot\beta}{}_{\dot\alpha}$	$\xi^\dagger_{\dot\alpha}e^{-i\theta}$
e_R: electron right	$(\eta^\alpha)^\dagger = \eta^{\dagger\,\dot\alpha}$	$\left[\left(S^{-1}\right)^\dagger\right]^{\dot\alpha}{}_{\dot\beta}\eta^{\dagger\,\dot\beta}$	$e^{i\theta}\eta^{\dagger\,\dot\alpha}$
$(e_R)^\dagger$: positron left	η^α	$\eta^\beta\left[S^{-1}\right]_\beta{}^\alpha$	$e^{-i\theta}\eta^\alpha$

Table 3: electron left: SL(2, C) × $U(1)_Q$ (subscript) and positron left: SL(2, C) × $U(1)_Q$ (superscript)

Scalar products

- ~~U(1)~~ Majorana scalars: $\xi^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\xi^{\dagger\dot\alpha}$, $\eta^\alpha\eta_\alpha + \eta^\dagger_{\dot\alpha}\eta^{\dagger\dot\alpha}$.
- Dirac scalar: $\eta^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\eta^{\dagger\,\dot\alpha}$.
- Tensor under subgroup SL(2, C) but vector under SO(1, 3): $S^{\dagger\dot\alpha}{}_{\dot\beta}\overline{\sigma}^{\mu\,\dot\beta\beta}S_\beta{}^\alpha = \Lambda^\mu{}_\nu\overline{\sigma}^{\nu\,\dot\alpha\alpha}$

$$\sigma^0 = \mathbb{1}\,, \qquad \overline{\sigma}^\mu = (\sigma^0, -\boldsymbol{\sigma}), \qquad \sigma^\mu = (\sigma^0, \boldsymbol{\sigma}).$$

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Table 4: electron left: SL(2, C) × $U(1)_Q$ (subscript) and positron left: SL(2, C) × $U(1)_Q$ (superscript)

General theory: QED → $D_\mu = i\partial_\mu - ieA_\mu$, $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

$$\xi_\alpha \to \xi'_\alpha = e^{i\theta(x)}\xi_\alpha \qquad \eta^\alpha \to \eta'^\alpha = e^{-i\theta(x)}\eta^\alpha$$

$$D_\mu\xi_\alpha \to (D_\mu\xi_\alpha)' = e^{i\theta(x)}D_\mu\xi_\alpha \qquad D_\mu\eta^\alpha \to (D_\mu\eta^\alpha)' = e^{-i\theta(x)}D_\mu\eta^\alpha$$

$$\mathcal{L} = i\xi^\dagger_{\dot\alpha}\bar\sigma^{\mu\,\dot\alpha\alpha}D_\mu\xi_\alpha + i\eta^\alpha\sigma^\mu_{\alpha\dot\alpha}D_\mu\eta^{\dagger\,\dot\alpha} - m\left[\eta^\alpha\xi_\alpha + \xi^\dagger_{\dot\alpha}\eta^{\dagger\,\dot\alpha}\right] - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

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$$\mathcal{L} = i\xi^\dagger\bar{\sigma} \quad D_\mu\xi \ + i\eta \ \sigma^\mu \ D_\mu\eta^\dagger \ - m\left[\eta \ \xi \ + \xi^\dagger\eta^\dagger \ \right] - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}$$

$$\mathcal{L} = i\overline{\psi}\gamma^\mu D_\mu\psi - m\overline{\psi}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\,.$$

Dirac spinor

$$\psi = \begin{pmatrix} e_L \\ e_R \end{pmatrix} = \begin{pmatrix} \xi \\ \eta^\dagger \end{pmatrix}$$

$$\gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \overline{\sigma}^\mu & 0 \end{pmatrix}$$

$$\overline{\psi} = \psi^\dagger\gamma^0\,.$$

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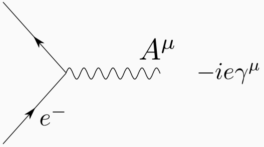
Dirac spinor



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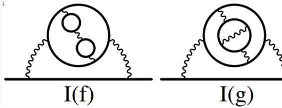
Dirac spinor

non-bare

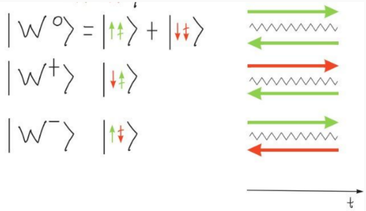


SU(2)$_L$ $\rightarrow D_\mu = \mathbf{1}\partial_\mu - ig_2\frac{\tau_i}{2}W^i_\mu$: 17 years later... (stages of grief $<$ 1967)

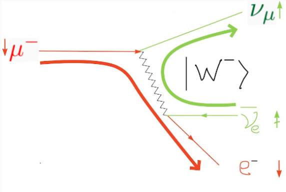
Not mass,

Field	Lorentz	SU(2)$_L$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	**2**

Denial



$$\mathcal{L} = i(L)^\dagger\,\overline{\sigma}^\mu D_\mu L - \frac{1}{4}W^i_{\mu\nu}W_i^{\mu\nu}$$

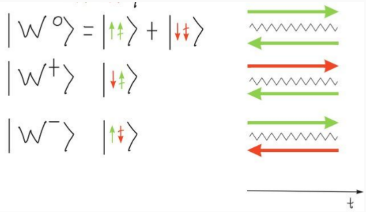


$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to D_\mu = 1\partial_\mu - ig_2\frac{\tau_i}{2}W^i_\mu - ig_1 B_\mu$: 17 years later... (stages of grief $<$ 1967)

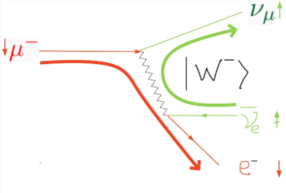
Not mass, hypercharge,

Field	Lorentz	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	**2**	$-1/2$

Denial



$$\mathcal{L} = i(L)^\dagger \bar{\sigma}^\mu D_\mu L - \frac{1}{4}W^i_{\mu\nu}W_i^{\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu}$$

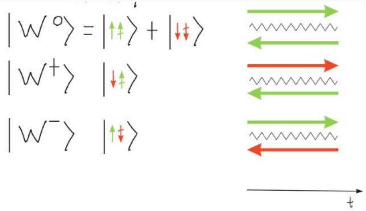


$SU(2)_L \times U(1)_Y \to D_\mu = \mathbb{1}\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$: 17 years later... (stages of grief < 1967)

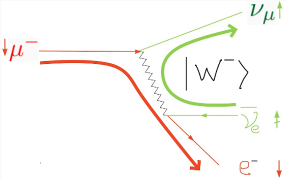
Not mass, hypercharge, not Dirac

Field	Lorentz	$SU(2)_L$	$U(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	**2**	$-1/2$
$(e_R)^\dagger$	η^α	**1**	-1

Denial



$$\mathcal{L} = i(L)^\dagger \bar{\sigma}^\mu D_\mu L - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R$$

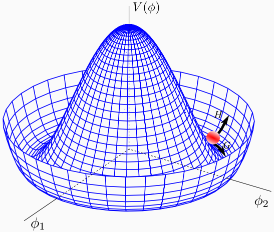


$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to D_\mu = 1\partial_\mu - i g_2 \frac{\tau_i}{2} W^i_\mu - i g_1 B_\mu$: 17 years later... (stages of grief > 1967)

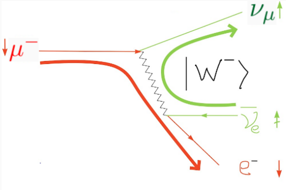
Higgs mechanism: tachyonic mass $\mu^2 < 0$, and condensate

Field	Lorentz	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	**2**	$-1/2$
$(e_R)^\dagger$	η^α	**1**	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	**2**	$1/2$

Contempt



$$\mathcal{L} = i(L)^\dagger \overline{\sigma}^\mu D_\mu L - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + h(e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2$$



$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$: 17 years later... (stages of grief → 1967)

Higgs mechanism: tachyonic mass $\mu^2 < 0$, and condensate

Field	Lorentz	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	**2**	$-1/2$
$(e_R)^\dagger$	η^α	**1**	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	**2**	$1/2$

Contempt

$$\begin{pmatrix} W^3_\mu \\ B_\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix},$$

$$\mathcal{L} = i(L)^\dagger \overline{\sigma}^\mu D_\mu L - \tfrac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \tfrac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + h(e_R)^\dagger \Phi^\dagger L - (D^\mu\Phi)^\dagger D_\mu\Phi - \mu^2 \Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2$$

$$\Phi \to \Phi' = \exp\left[i\frac{\tau^i}{2}\theta_i(x)\right]\Phi = \frac{1}{\sqrt{2}}[H(x) + v]$$

$$\mathcal{L} = i\overline{\psi}\gamma^\mu \partial\psi - m_e\overline{\psi}\psi - i(\nu_L)^\dagger \overline{\sigma}^\mu \partial_\mu \nu_L + \tfrac{1}{2}\partial^\mu H \partial_\mu H + \frac{e}{\cos\theta_W \sin\theta_W}\overline{\nu_L}\nu_L Z_\mu + \cdots$$

$$-\frac{1}{2} m_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu-} W^+_\mu + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right)\left(1 + 2\frac{H}{v} + \frac{H^2}{v^2}\right) + \frac{m_e}{v}\overline{\psi}\psi H$$

$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to D_\mu = 1\partial_\mu - i g_2 \frac{\tau_i}{2} W^i_\mu - i g_1 B_\mu$: 21 years later... (stages of grief → 1971)

Z and W phenomenology and discovery

Field	Lorentz	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	**2**	$-1/2$
$(e_R)^\dagger$	η^α	**1**	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	**2**	$1/2$

Bargaining

$$\mathcal{L} = i(L)^\dagger \bar{\sigma}^\mu D_\mu L - \frac{1}{4} W^i_{\mu\nu} W^{\mu\nu}_i - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + h(e_R)^\dagger \Phi^\dagger L - (D^\mu\Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger\Phi - \lambda\left(\Phi^\dagger\Phi\right)^2$$

$$\Phi \to \Phi' = \exp\left[i\frac{\tau^i}{2}\theta_i(x)\right]\Phi = \frac{1}{\sqrt{2}}[H(x) + v]$$

$$\mathcal{L} = i\bar{\psi}\gamma^\mu \partial\psi - m_e \bar{\psi}\psi - i(\nu_L)^\dagger \bar{\sigma}^\mu \partial_\mu \nu_L + \frac{1}{2}\partial^\mu H \partial_\mu H + \frac{e}{\cos\theta_W \sin\theta_W} \overline{\nu_L}\nu_L Z_\mu + \cdots$$

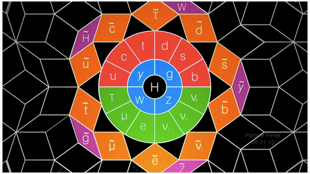
$$-\frac{1}{2} m_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu -} W^+_\mu + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right)\left(1 + 2\frac{H}{v} + \frac{H^2}{v^2}\right) + \frac{m_e}{v}\bar{\psi}\psi H$$

$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to D_\mu = 1\partial_\mu - ig_2\frac{\tau_i}{2}W^i_\mu - ig_1 B_\mu$: 32 years later... (stages of grief → 1982)

Hierarchy problem

Field	Lorentz	$\mathrm{SU}(2)_L$	$\mathrm{U}(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	**2**	$-1/2$
$(e_R)^\dagger$	η^α	**1**	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2}G_i(x)\right]$	-	**2**	$1/2$

Depression



credit: quantumdiaries.org

$$\mathcal{L} = i(L)^\dagger \bar{\sigma}^\mu D_\mu L - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + h(e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2$$

$$\Phi \to \Phi' = \exp\left[i\frac{\tau^i}{2}\theta_i(x)\right]\Phi = \frac{1}{\sqrt{2}}[H(x)+v]$$

$$\mathcal{L} = i\bar{\psi}\gamma^\mu\partial\psi - m_e\bar{\psi}\psi - i(\nu_L)^\dagger\bar{\sigma}^\mu\partial_\mu\nu_L + \frac{1}{2}\partial^\mu H\partial_\mu H + \frac{e}{\cos\theta_W \sin\theta_W}\overline{\nu_L}\nu_L Z_\mu + \cdots$$

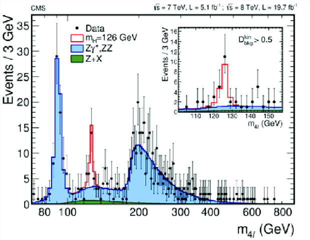
$$-\frac{1}{2}m_H^2 H^2\left(1+\frac{H}{v}+\frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu-}W^+_\mu + \frac{1}{2}m_Z^2 Z^\mu Z_\mu\right)\left(1+2\frac{H}{v}+\frac{H^2}{v^2}\right) + \frac{m_e}{v}\bar{\psi}\psi H$$

$SU(2)_L \times U(1)_Y \to D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$: 62 years later... (stages of grief → 2012)

Higgs discovery!

Field	Lorentz	$SU(2)_L$	$U(1)_Y$
$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	ξ_α	$\mathbf{2}$	$-1/2$
$(e_R)^\dagger$	η^α	$\mathbf{1}$	-1
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	$\mathbf{2}$	$1/2$

Acceptance



$$\mathcal{L} = i(L)^\dagger \bar{\sigma}^\mu D_\mu L - \frac{1}{4} W^i_{\mu\nu} W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + h(e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

$$\Phi \to \Phi' = \exp\left[i\frac{\tau^i}{2}\theta_i(x)\right] \Phi = \frac{1}{\sqrt{2}}[H(x) + v]$$

$$\mathcal{L} = i\bar{\psi}\gamma^\mu \partial\psi - m_e \bar{\psi}\psi - i(\nu_L)^\dagger \bar{\sigma}^\mu \partial_\mu \nu_L + \frac{1}{2}\partial^\mu H \partial_\mu H + \frac{e}{\cos\theta_W \sin\theta_W} \overline{\nu_L} \nu_L Z_\mu + \cdots$$

$$- \frac{1}{2} m_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu -} W^+_\mu + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right) \left(1 + 2\frac{H}{v} + \frac{H^2}{v^2}\right) + \frac{m_e}{v} \bar{\psi}\psi H$$

First generation of Standard Model (SM)

Field	Lorentz	SU(3)$_C$	SU(2)$_L$	U(1)$_Y$
Q	ξ^1_α	$\mathbf{3}$	$\mathbf{2}$	$1/6$
L	ξ^2_α	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
$\left(u_R^-\right)^\dagger$	η_1^α	$\overline{\mathbf{3}}$	$\mathbf{1}$	$-2/3$
$\left(d_R^-\right)^\dagger$	η_2^α	$\overline{\mathbf{3}}$	$\mathbf{1}$	$1/3$
$\left(e_R^-\right)^\dagger$	η_3^α	$\mathbf{1}$	$\mathbf{1}$	1
Φ	-	$\mathbf{1}$	$\mathbf{2}$	$1/2$

Table 5: Fundamental Fields of SM

Kircchoff's law

$$\widetilde{\Phi} = i\sigma_2\Phi^* = \begin{pmatrix} \phi^{0*} & -\phi^- \end{pmatrix}^\mathsf{T} \qquad L = \begin{pmatrix} \nu_L & e_L \end{pmatrix}^\mathsf{T} \tag{13}$$

$$(e_R)^\dagger \Phi^\dagger L = (e_R)^\dagger \Phi^\dagger L = (e_R)^\dagger \epsilon_{ab} \widetilde{\Phi}^a L^b \,, \tag{14}$$

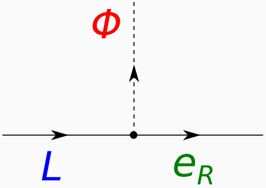
$$-Y_R - Y_\Phi + Y_L = 0$$

Kircchoff's law

$$\widetilde{\Phi} = i\sigma_2 \Phi^* = \begin{pmatrix} \phi^{0*} & -\phi^- \end{pmatrix}^{\mathsf{T}} \qquad L = \begin{pmatrix} \nu_L & e_L \end{pmatrix}^{\mathsf{T}} \tag{13}$$

$$(e_R)^\dagger \widetilde{\Phi} \cdot L\,, \tag{14}$$

Which can be represented as the Kircchoff's law:



$$\begin{aligned} -Y_R - Y_\Phi + Y_L &= 0 \\ Y_L &= Y_\Phi + Y_R \end{aligned}$$

BSM-Submodules

Install compilers:

```
sudo apt install build-essential gfortran feynmf
```

Download all the HEP-tools in one step:

```
git clone --recursive https://github.com/restrepo/BSM-Submodules.git
cd BSM-Submodules/
emacs SARAH/Models/SSDM/SSDM.m
```

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times Z_2$$

$$\begin{aligned} \mathcal{D}_\mu = \partial_\mu &- i g_1 Y B_\mu \\ &- i g_2 T W^B_\mu \\ &- i g_3 \Lambda G_\mu \,. \end{aligned}$$

```
Off[General::spell]

Model`Name = "SSDM";
Model`NameLaTeX ="Singlet scalar Dark Matter";
Model`Authors = "Diego Restrepo ...";
Model`Date = "2015-11-16";

(* 2013-01-24: ...)

(* Global Symmetries *)

Global[[1]] = {Z[2], Z2};

(* Gauge Groups *)

Gauge[[1]]={B,   U[1], hypercharge, g1,False,1};
Gauge[[2]]={WB, SU[2], left,        g2,True,1};
Gauge[[3]]={G,  SU[3], color,       g3,False,1};
```

$$B \rightarrow B_\mu,\ \widetilde{B} \qquad \Longrightarrow \texttt{VB}\,,\ \texttt{FB}$$

	N_F	Lorentz	Y	$SU(2)_L$	$SU(3)_c$	Z_2
Q	3	$\xi_{1\alpha} : (u_L \ d_L)^T$	$1/6$	$\mathbf{2}$	$\mathbf{3}$	$+$
L	3	$\xi_{2\alpha} : (\nu_L \ e_L)^T$	$-1/2$	$\mathbf{2}$	$\mathbf{1}$	$+$
d^c	3	$\eta_1^\alpha : (d_R)^\dagger$	$1/3$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$+$
u^c	3	$\eta_2^\alpha : (u_R)^\dagger$	$-2/3$	$\mathbf{1}$	$\overline{\mathbf{3}}$	$+$
e^c	3	$\eta_3^\alpha (e_R)^\dagger$	1	$\mathbf{1}$	$\mathbf{1}$	$+$
H	1	$(H^+ \ H^0)$	$1/2$	$\mathbf{2}$	$\mathbf{1}$	$+$
S	1	s	0	$\mathbf{1}$	$\mathbf{1}$	$-$

$$\texttt{conj[H]} = \widetilde{H} = \begin{pmatrix} H^{0*} \\ -H^- \end{pmatrix}$$

$$\mathcal{L} = (\mathcal{L}_C + \text{h.c}) \\ + \mathcal{L}_R ,$$

$$\mathcal{L}_C = - Y_e e^c \widetilde{H} \cdot L - Y_d d^c \widetilde{H} \cdot Q - Y_u u^c H \cdot Q ,$$

$$\mathcal{L}_R = - \mu^2 \widetilde{H} \cdot H - \lambda_1 (\widetilde{H} \cdot H)^2 \\ - M_S^2 S^2 - \lambda_{SH} S^2 \widetilde{H} \cdot H - \lambda_S S^4 .$$

$$Y_e \to N_F \times N_F, \cdots$$

```
(* Matter Fields *)

FermionFields[[1]] = {q, 3, {uL, dL},     1/6, 2,  3,1};
FermionFields[[2]] = {l, 3, {vL, eL},    -1/2, 2,  1,1};
FermionFields[[3]] = {dc, 3, conj[dR],    1/3, 1, -3,1};
FermionFields[[4]] = {uc, 3, conj[uR],   -2/3, 1, -3,1};
FermionFields[[5]] = {ec, 3, conj[eR],      1, 1,  1,1};

ScalarFields[[1]] =  {H, 1, {Hp, H0},     1/2, 2,  1,1};
ScalarFields[[2]] =  {S, 1, ss,             0, 1,  1,-1};
RealScalars = {S};

(*----------------------------------------------*)
(*   DEFINITION                                 *)
(*----------------------------------------------*)

NameOfStates={GaugeES, EWSB};

(* ----- Before EWSB ----- *)

DEFINITION[GaugeES][LagrangianInput]= {
  {LagHC, {AddHC->True}},
  {LagNoHC,{AddHC->False}}
};


LagHC =    -(Ye ec.conj[H].l + Yd dc.conj[H].q + Yu uc.H.q);

LagNoHC = -(mu2 conj[H].H + Lambda1/2 conj[H].H.conj[H].H
          + MS2/2 S.S + LamSH S.S.conj[H].H  + LamS/2 S.S.S.S);
```

$$\begin{pmatrix} B^\mu \\ W_3^\mu \end{pmatrix} = Z^{\gamma Z} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$$

$$H^0 = \frac{iA + (h + v)}{\sqrt{2}} \,.$$

$$\boldsymbol{d}_L = V_d \boldsymbol{D}_L \,, \qquad (\boldsymbol{d}_R)^\dagger = \boldsymbol{D}_R^c U_d \,,$$

$$V_d \to N_F \times N_F, \cdots$$

$$\Psi_d = \begin{pmatrix} \xi_{1\alpha} \\ (\eta_1^\alpha)^\dagger \end{pmatrix} = \begin{pmatrix} D_L \\ D_R \end{pmatrix}$$

```
(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector] =
{
  {{VB,VWB[3]},{VP,VZ},ZZ},
  {{VWB[1],VWB[2]},{VWp,conj[VWp]},ZW}
};

(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
{{H0,{v,1/Sqrt[2]}, {Ah,\[ImaginaryI]/Sqrt[2]},{hh,1/Sqrt[2]}} };


DEFINITION[EWSB][MatterSector]=
    {{{{dL}, {conj[dR]}}, {{DL,Vd}, {DRc,Ud}}},
     {{{uL}, {conj[uR]}}, {{UL,Vu}, {URc,Uu}}},
     {{{eL}, {conj[eR]}}, {{EL,Ve}, {ERc,Ue}}}};

(*------------------------------------------------------*)
(* Dirac-Spinors *)
(*------------------------------------------------------*)

DEFINITION[EWSB][DiracSpinors]={
 Fd ->{  DL, conj[DRc]},
 Fe ->{  EL, conj[ERc]},
 Fu ->{  UL, conj[URc]},
 Fv ->{  vL, 0}};
```

$$\begin{pmatrix} B^\mu \\ W_3^\mu \end{pmatrix} = Z^{\gamma Z} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix} = \begin{pmatrix} \cos\theta_W & \sin\theta_W \\ -\sin\theta_W & \cos\theta_W \end{pmatrix} \begin{pmatrix} A^\mu \\ Z^\mu \end{pmatrix}$$

$$H^0 = \frac{iA + (h + v)}{\sqrt{2}} \, .$$

$$\boldsymbol{d}_L = V_d \boldsymbol{D}_L \, , \qquad (\boldsymbol{d}_R)^\dagger = \boldsymbol{D}_R^c U_d \, ,$$

$$V_d \to N_F \times N_F, \cdots$$

```
(* Gauge Sector *)

DEFINITION[EWSB][GaugeSector] =
{
 {{VB,VWB[3]},{VP,VZ},ZZ},
 {{VWB[1],VWB[2]},{VWp,conj[VWp]},ZW}
};

(* ----- VEVs ---- *)

DEFINITION[EWSB][VEVs]=
{{H0,{v,1/Sqrt[2]}, {Ah,\[ImaginaryI]/Sqrt[2]},{hh,1/Sqrt[2]}} };


DEFINITION[EWSB][MatterSector]=
    {{{{dL}, {conj[dR]}}, {{DL,Vd}, {DRc,Ud}}},
     {{{uL}, {conj[uR]}}, {{UL,Vu}, {URc,Uu}}},
     {{{eL}, {conj[eR]}}, {{EL,Ve}, {ERc,Ue}}}};

(*------------------------------------------------------*)
(* Dirac-Spinors *)
(*------------------------------------------------------*)

DEFINITION[EWSB][DiracSpinors]={
 Fd ->{  DL, conj[DRc]},
 Fe ->{  EL, conj[ERc]},
 Fu ->{  UL, conj[URc]},
 Fv ->{  vL, 0}};
```

Chuck Norris fact of the day

Chuck Norris lost his virginity before his dad

From A. Vicente

./parameters.m

```
    ...
{g1,        { Description -> "Hypercharge-Coupling"}},
{g2,        { Description -> "Left-Coupling"}},
{g3,        { Description -> "Strong-Coupling"}},
...
{v,          { Description -> "EW-VEV",
               DependenceNum -> Sqrt[4*Mass[VWp]^2/(g2^2)],
               DependenceSPheno -> None  }},

{ThetaW,    { Description -> "Weinberg-Angle",
              DependenceNum -> ArcSin[Sqrt[1 - Mass[VWp]^2/Mass[VZ]^2]]}},

{ZZ, {Description -> "Photon-Z Mixing Matrix"}},

    ...
```

../parameters.m

```
    ...
{{Description -> "Photon-Z Mixing Matrix",
       Dependence ->  {{Cos[ThetaW],-Sin[ThetaW]},
                       {Sin[ThetaW],Cos[ThetaW]}},
       Real ->True,
       LaTeX -> "Z^{\\gamma Z}",
       LesHouches -> None,
       OutputName -> ZZ }},
    ...
```

./particles.m

```
  ...
ParticleDefinitions[EWSB] = {

  {hh   ,  {  Description -> "Higgs",
              PDG -> {25},
              PDG.IX -> {101000001},
              Mass -> LesHouches,
              FeynArtsNr -> 1,
              LaTeX -> "h",
              ElectricCharge -> 0,
              LHPC -> {1},
              OutputName -> "h"  }},

  {ss   , {  Description -> "Singlet",
             PDG -> {6666635},
             PDG.IX -> {101000002},
             FeynArtsNr -> 10,
             Mass -> LesHouches,
             LaTeX -> "S",
             ElectricCharge -> 0,
             LHPC -> {"gold"},
             OutputName -> "Ss" }},
         ...
       }
  ...
```

./SPheno.m

```
OnlyLowEnergySPheno = True;

MINPAR={{1,Lambda1IN},
        {2,LamSHIN},
        {3,LamSIN},
        {4,MSinput}
        };
 ...
ListDecayParticles = {Fu,Fe,Fd,hh};
ListDecayParticles3B = {{Fu,"Fu.f90"},{Fe,"Fe.f90"},{Fd,"Fd.f90"}};


....

DefaultInputValues ={Lambda1IN -> 0.28, LamSHIN -> 0.01, LamSIN -> 0,
                     MSinput -> 200};
```

Implicit files without editors

```
cat << EOF > kk.txt
Hello world
EOF
```

Listing 1: Creates `kk.txt` file

```
math << EOF
2+2
EOF
```

Listing 2: commands expecting input files

```
Mathematica 11.0.0 for Linux x86 (64-bit)
Copyright 1988-2016 Wolfram Research, Inc.

In[1]:=
Out[1]= 4

In[2]:=
```

Automatic index contraction

Verifying Index Contractions

$$
\begin{aligned}
u^c \cdot H \cdot q &= \delta_{\alpha}^{\beta} \epsilon_{ab}\, u^c_{\alpha} H^a q^{\beta b} \\
&= \bar{\mathbf{3}} \times \mathbf{3} \otimes \mathbf{2} \times \mathbf{2}\,.
\end{aligned}
$$

```
math<<EOF
<<./SARAH/SARAH.m
Start["SSDM"]
MakeIndexStructure[{u, H, q}] (* uc.H.q *)
EOF
 ...
Out[3]: Delta[col1, col3] epsTensor[lef2, lef3]
```

Explicit index contraction in `SSDM.m`

```
   Delta[col1, col3] epsTensor[lef2, lef3]  uc.H.q
```

See `https://gitlab.in2p3.fr/goodsell/sarah/wikis/Automatic_index_contraction`

Check SARAH

```
math << EOF
<<./SARAH/SARAH.m
Start["SSDM"]
MakeSPheno[]
EOF
```

```
Mathematica 11.0.0 for Linux x86 (64-bit)
...
In[1]:= SARAH 4.14.1
by Florian Staub, 2018
...
In[2]:= Preparing arrays
 ...
Model files loaded
  Model     : SSDM
  Author(s): Diego Restrepo (based on SM model by F.Staub)
  Date      : 2015-11-16
*******************************************************
Loading Susyno functions for the handling of Lie Groups
Based on Susyno v.2.0 by Renato Fonseca (1106.5016)
webpage: web.ist.utl.pt/renato.fonseca/susyno.html
*******************************************************
...
Finished! SPheno code generated in 170.872s
....
The following steps are now necessary to implement the model in SPheno:
```

Check SPheno

```
cp -r SARAH/Output/SSDM/EWSB/SPheno SPheno/SSDM
cd SPheno
make Model=SSDM # Be sure that Makefile use gfortran!
```

```
cd SSDM ; make F90=gfortran version=400.00
make[1]: Entering directory '****/BSM-Submodules/SPHENO/SSDM'
.
.
.
make[2]: Leaving directory '****/BSM-Submodules/SPHENO/SSDM'
gfortran -o SPhenoSSDM -g   SPhenoSSDM.o ../lib/libSPhenoSSDM.a ../lib/libSPheno.a
mv SPhenoSSDM ../bin
rm SPhenoSSDM.o
make[1]: Leaving directory '****/BSM-Submodules/SPHENO/SSDM'
```

```
# Return to parent directory: BSM-Submodules
cd ../
```

Check micrOMEGAs

```
cd micromegas
make # Recompile everything!
make # twice
```

```
make -C CalcHEP_src  MICROMEGAS=MICROMEGAS
...
#--------------------------------------------------------
# CalcHEP has compiled successfuly and can be started.
# The manual can be found on the CalcHEP website:
#      http://theory.sinp.msu.ru/~pukhov/calchep.html
# The next step is typically to run
#      ./mkWORKdir  <new_dir>
# where <new_dir> is the new directory where you will do
# your calculations.  After creating this directory, you
# should cd into it and run calchep or calchep_batch.
# Please see the manual for further details.
#---------------------------------------------------------"
...
make[1]: Leaving directory '****/BSM-Submodules/micromegas/sources'
```

Build micrOMEGAs model

```
./newProject SSDM
cd .. # return to parent directory
```

Check micrOMEGAs II

```
math << EOF
<<./SARAH/SARAH.m
Start["SSDM"]
MakeCHep[]
EOF
```

```
Mathematica 11.0.0 for Linux x86 (64-bit)
...
Write main file for MicrOmegas
Done. Model files generated in 31.044s
Output is saved in ****/BSM-Submodules/SARAH/Output/SSDM/EWSB/CHep/
```

```
cp SARAH/Output/SSDM/EWSB/CHep/* micromegas/SSDM/work/models/
cd micromegas/SSDM/
cp work/models/*.cpp .
# check your micrOMEGAs version
make main=CalcOmega_with_DDetection_MOv5.cpp
```

```
make -C work
...
g++      -g -fPIC  -o CalcOmega_with_DDetection_MOv5 CalcOmega_with_DDetection_MOv5.cpp ... -lpthread
cd ../../ #Return to parent directory
```

Check Madgraph

```
math << EOF
<<./SARAH/SARAH.m
Start["SSDM"]
MakeUFO[]
EOF
```

```
Mathematica 11.0.0 for Linux x86 (64-bit)
...
Writing effective diphoton and digluon vertices

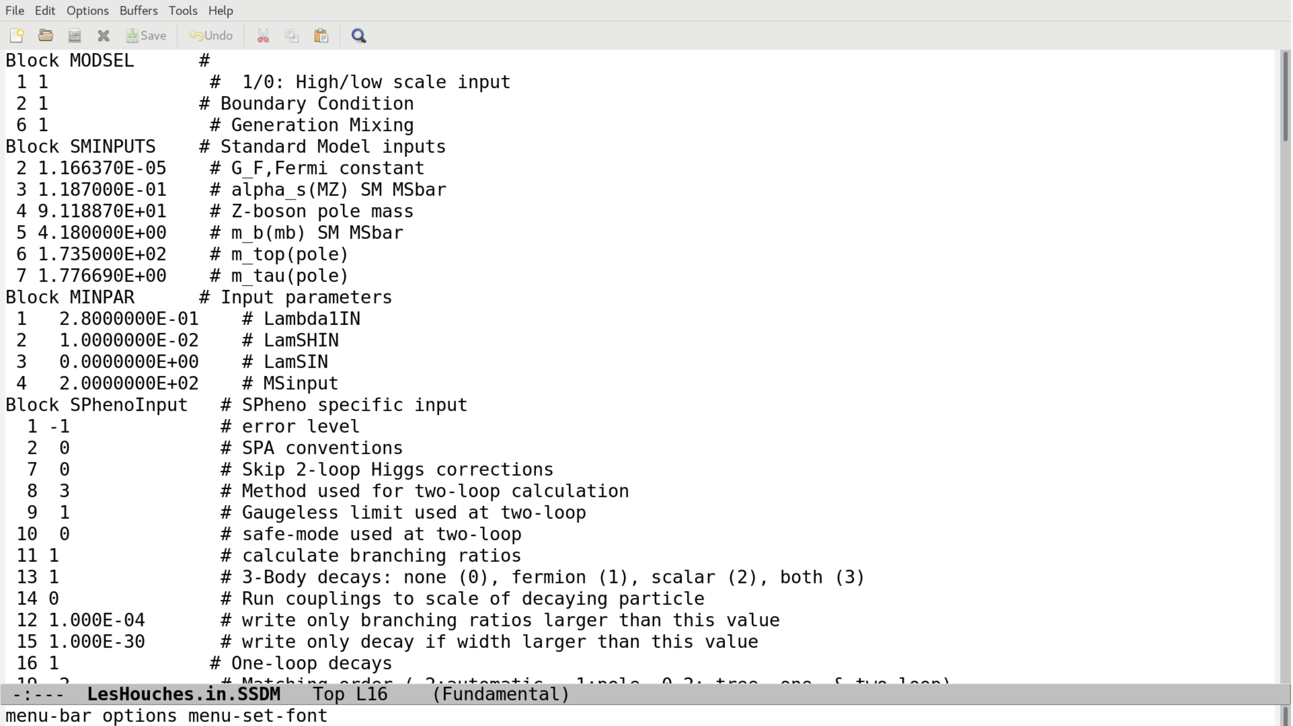
Done. UFO files generated in 30.716s
Output is saved in ****/BSM-Submodules/SARAH/Output/SSDM/EWSB/UFO/
```

```
cp -r SARAH/Output/SSDM/EWSB/UFO/ madgraph/models/SSDM
madgraph/bin/mg5_aMC << EOF
import model SSDM
check u u~ > mu+ mu-
EOF
```

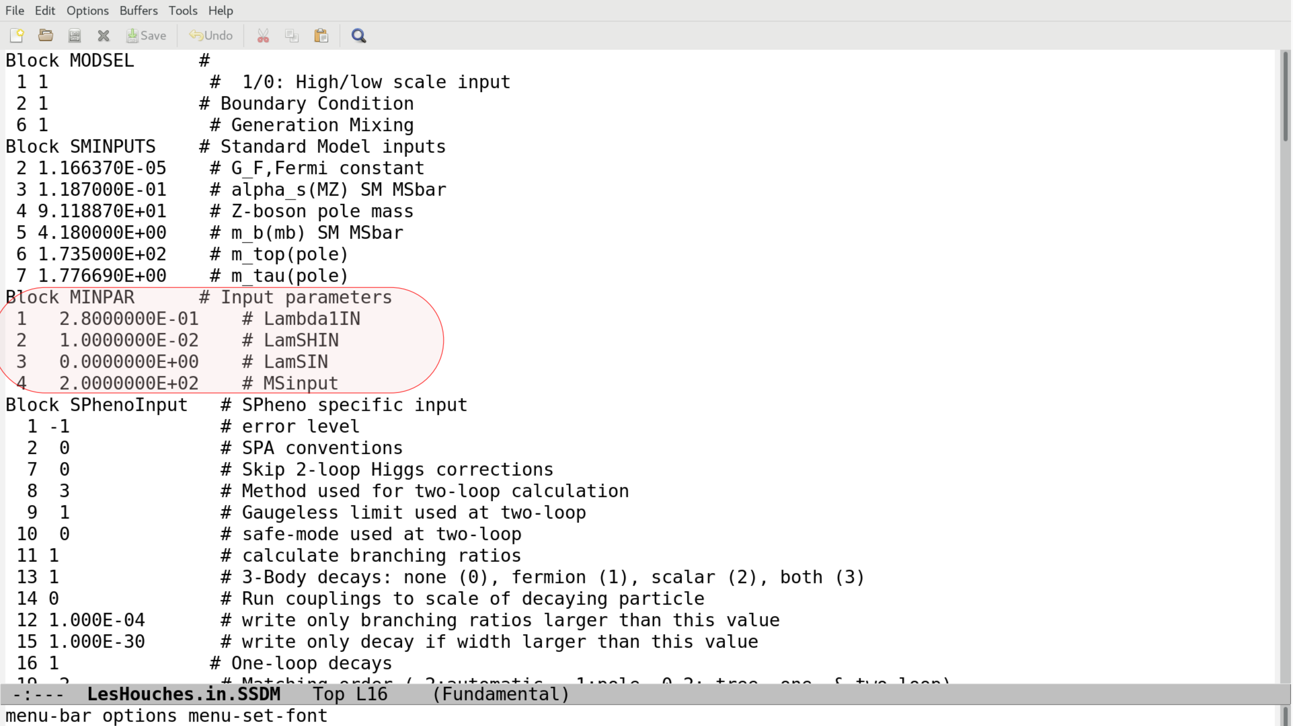
```
Process          Min element      Max element      Relative diff.    Result
u u~ > mu+ mu-   4.9949890843e-03 4.9949890843e-03 5.2093911919e-15  Passed
Summary: 1/1 passed, 0/1 failed
```

Benchmark point

```
cp SPheno/SSDM/Input_Files/LesHouches.in.SSDM .
emacs LesHouches.in.SSDM
```



```
Block MODSEL      #
 1 1               #  1/0: High/low scale input
 2 1              # Boundary Condition
 6 1               # Generation Mixing
Block SMINPUTS    # Standard Model inputs
 2 1.166370E-05    # G_F,Fermi constant
 3 1.187000E-01    # alpha_s(MZ) SM MSbar
 4 9.118870E+01    # Z-boson pole mass
 5 4.180000E+00    # m_b(mb) SM MSbar
 6 1.735000E+02    # m_top(pole)
 7 1.776690E+00    # m_tau(pole)
Block MINPAR      # Input parameters
 1   2.8000000E-01    # Lambda1IN
 2   1.0000000E-02    # LamSHIN
 3   0.0000000E+00    # LamSIN
 4   2.0000000E+02    # MSinput
Block SPhenoInput   # SPheno specific input
  1 -1              # error level
  2  0              # SPA conventions
  7  0              # Skip 2-loop Higgs corrections
  8  3              # Method used for two-loop calculation
  9  1              # Gaugeless limit used at two-loop
 10  0              # safe-mode used at two-loop
 11 1               # calculate branching ratios
 13 1               # 3-Body decays: none (0), fermion (1), scalar (2), both (3)
 14 0               # Run couplings to scale of decaying particle
 12 1.000E-04       # write only branching ratios larger than this value
 15 1.000E-30       # write only decay if width larger than this value
 16 1              # One-loop decays
 19  2              # Matching order ( 2:automatic,  1:pole, 0 2: tree, one- & two-loop)
-:---  LesHouches.in.SSDM   Top L16    (Fundamental)
menu-bar options menu-set-font
```



```
Block MODSEL       #
 1 1                # 1/0: High/low scale input
 2 1               # Boundary Condition
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Block SMINPUTS     # Standard Model inputs
 2 1.166370E-05     # G_F,Fermi constant
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Block MINPAR       # Input parameters
 1   2.8000000E-01    # Lambda1IN
 2   1.0000000E-02    # LamSHIN
 3   0.0000000E+00    # LamSIN
 4   2.0000000E+02    # MSinput
Block SPhenoInput   # SPheno specific input
  1 -1              # error level
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  8  3              # Method used for two-loop calculation
  9  1              # Gaugeless limit used at two-loop
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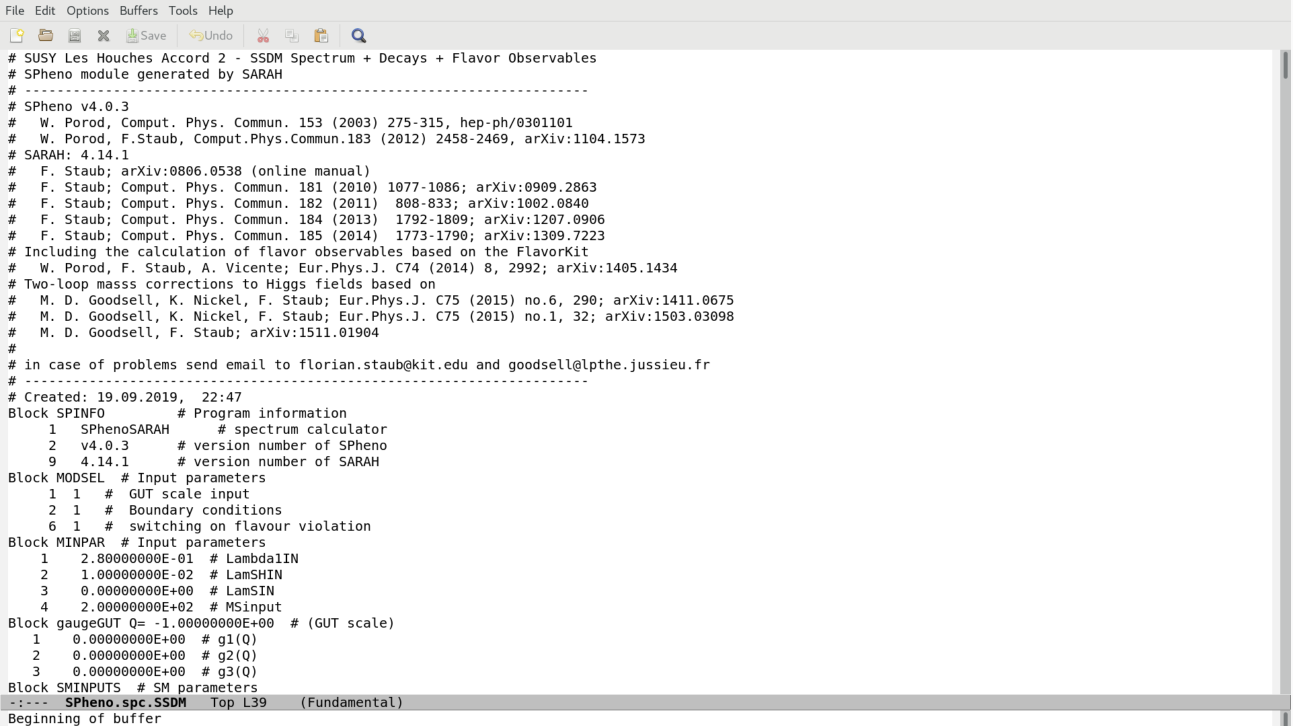
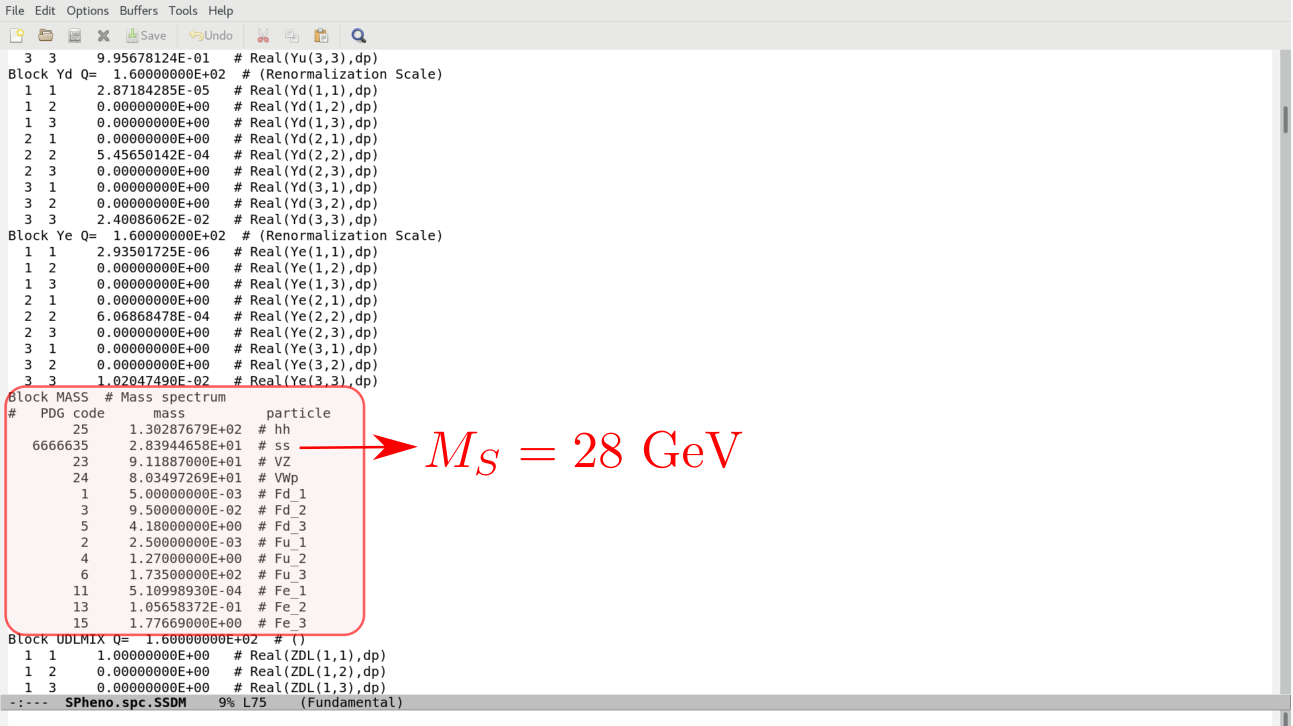
 13 1               # 3-Body decays: none (0), fermion (1), scalar (2), both (3)
 14 0               # Run couplings to scale of decaying particle
 12 1.000E-04       # write only branching ratios larger than this value
 15 1.000E-30       # write only decay if width larger than this value
 16 1              # One-loop decays
-:---  LesHouches.in.SSDM   Top L16    (Fundamental)
menu-bar options menu-set-font
```

Run SPheno

```
BSM-Submodules$ SPheno/bin/SPhenoSSDM  LesHouches.in.SSDM
Calculating branching ratios and decay widths
Calculating one loop decays
Loop masses not calculated: tree-level masses used for kinematics
Loop masses not calculated: no U-factors are applied
Calculating one-loop decays of Fu
Calculating one-loop decays of Fe
Calculating one-loop decays of Fd
Calculating one-loop decays of hh
Calculating low energy constraints
Calculating unitarity constraints
Writing output files
Finished!
BSM-Submodules$ emacs SPheno.spc.SSDM
```

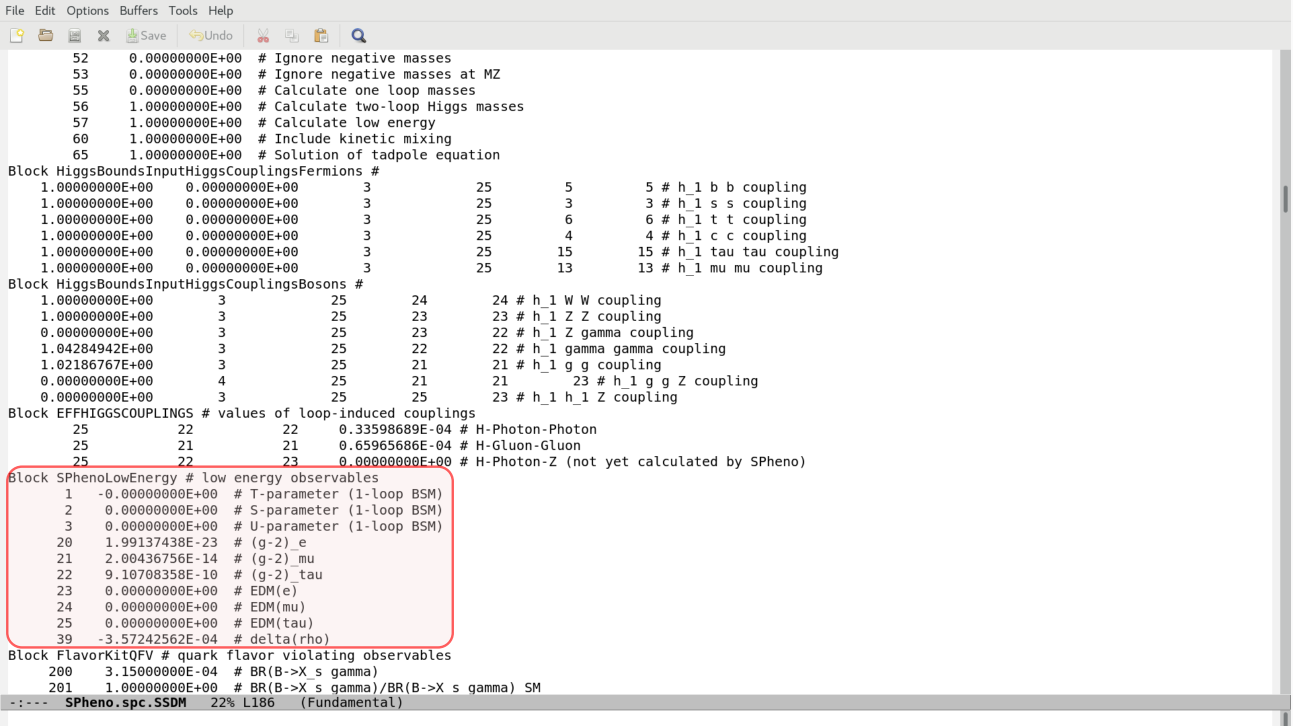


```
# SUSY Les Houches Accord 2 - SSDM Spectrum + Decays + Flavor Observables
# SPheno module generated by SARAH
# ----------------------------------------------------------------------
# SPheno v4.0.3
#   W. Porod, Comput. Phys. Commun. 153 (2003) 275-315, hep-ph/0301101
#   W. Porod, F.Staub, Comput.Phys.Commun.183 (2012) 2458-2469, arXiv:1104.1573
# SARAH: 4.14.1
#   F. Staub; arXiv:0806.0538 (online manual)
#   F. Staub; Comput. Phys. Commun. 181 (2010) 1077-1086; arXiv:0909.2863
#   F. Staub; Comput. Phys. Commun. 182 (2011)  808-833; arXiv:1002.0840
#   F. Staub; Comput. Phys. Commun. 184 (2013)  1792-1809; arXiv:1207.0906
#   F. Staub; Comput. Phys. Commun. 185 (2014)  1773-1790; arXiv:1309.7223
# Including the calculation of flavor observables based on the FlavorKit
#   W. Porod, F. Staub, A. Vicente; Eur.Phys.J. C74 (2014) 8, 2992; arXiv:1405.1434
# Two-loop masss corrections to Higgs fields based on
#   M. D. Goodsell, K. Nickel, F. Staub; Eur.Phys.J. C75 (2015) no.6, 290; arXiv:1411.0675
#   M. D. Goodsell, K. Nickel, F. Staub; Eur.Phys.J. C75 (2015) no.1, 32; arXiv:1503.03098
#   M. D. Goodsell, F. Staub; arXiv:1511.01904
#
# in case of problems send email to florian.staub@kit.edu and goodsell@lpthe.jussieu.fr
# ----------------------------------------------------------------------
# Created: 19.09.2019,  22:47
Block SPINFO         # Program information
     1   SPhenoSARAH      # spectrum calculator
     2   v4.0.3      # version number of SPheno
     9   4.14.1      # version number of SARAH
Block MODSEL  # Input parameters
     1  1   #  GUT scale input
     2  1   #  Boundary conditions
     6  1   #  switching on flavour violation
Block MINPAR  # Input parameters
    1    2.80000000E-01  # Lambda1IN
    2    1.00000000E-02  # LamSHIN
    3    0.00000000E+00  # LamSIN
    4    2.00000000E+02  # MSinput
Block gaugeGUT Q= -1.00000000E+00  # (GUT scale)
   1    0.00000000E+00  # g1(Q)
   2    0.00000000E+00  # g2(Q)
   3    0.00000000E+00  # g3(Q)
Block SMINPUTS  # SM parameters
-:---  SPheno.spc.SSDM   Top L39    (Fundamental)
Beginning of buffer
```

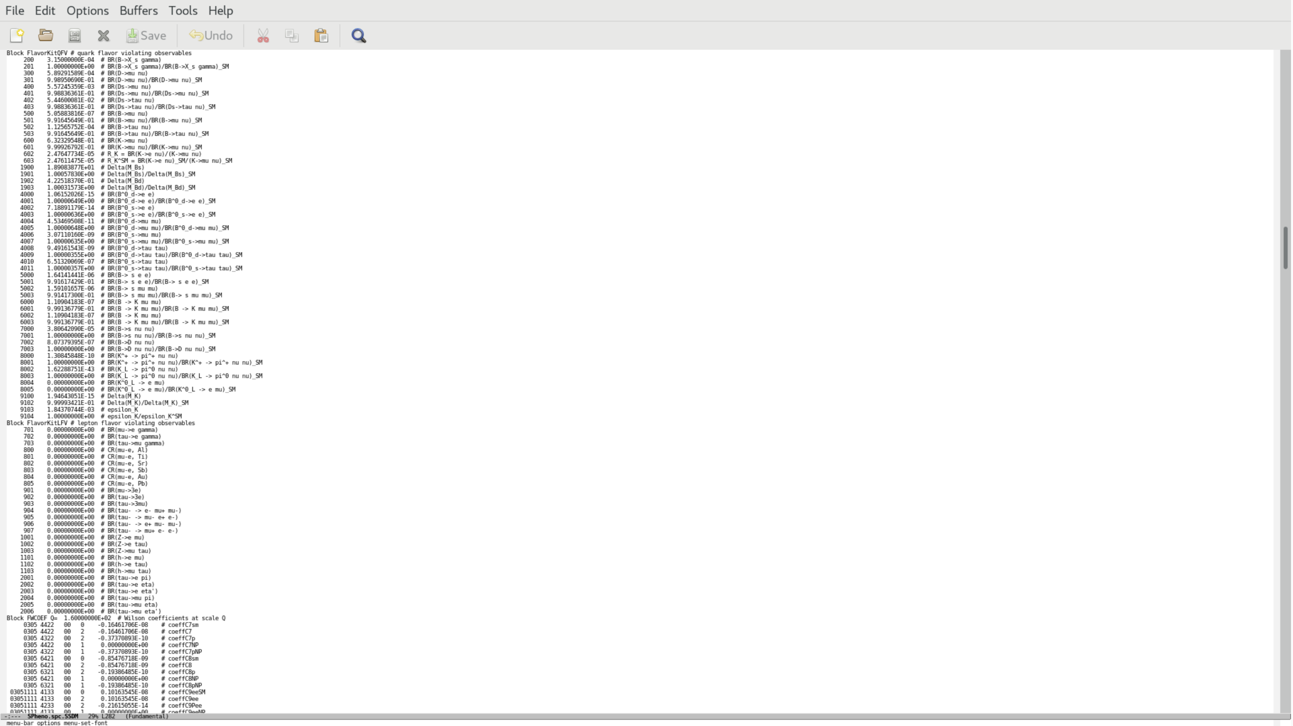


```
  3  3      9.95678124E-01   # Real(Yu(3,3),dp)
Block Yd Q=  1.60000000E+02  # (Renormalization Scale)
  1  1      2.87184285E-05   # Real(Yd(1,1),dp)
  1  2      0.00000000E+00   # Real(Yd(1,2),dp)
  1  3      0.00000000E+00   # Real(Yd(1,3),dp)
  2  1      0.00000000E+00   # Real(Yd(2,1),dp)
  2  2      5.45650142E-04   # Real(Yd(2,2),dp)
  2  3      0.00000000E+00   # Real(Yd(2,3),dp)
  3  1      0.00000000E+00   # Real(Yd(3,1),dp)
  3  2      0.00000000E+00   # Real(Yd(3,2),dp)
  3  3      2.40086062E-02   # Real(Yd(3,3),dp)
Block Ye Q=  1.60000000E+02  # (Renormalization Scale)
  1  1      2.93501725E-06   # Real(Ye(1,1),dp)
  1  2      0.00000000E+00   # Real(Ye(1,2),dp)
  1  3      0.00000000E+00   # Real(Ye(1,3),dp)
  2  1      0.00000000E+00   # Real(Ye(2,1),dp)
  2  2      6.06868478E-04   # Real(Ye(2,2),dp)
  2  3      0.00000000E+00   # Real(Ye(2,3),dp)
  3  1      0.00000000E+00   # Real(Ye(3,1),dp)
  3  2      0.00000000E+00   # Real(Ye(3,2),dp)
  3  3      1.02047490E-02   # Real(Ye(3,3),dp)
Block MASS  # Mass spectrum
#   PDG code      mass          particle
        25     1.30287679E+02  # hh
   6666635     2.83944658E+01  # ss
        23     9.11887000E+01  # VZ
        24     8.03497269E+01  # VWp
         1     5.00000000E-03  # Fd_1
         3     9.50000000E-02  # Fd_2
         5     4.18000000E+00  # Fd_3
         2     2.50000000E-03  # Fu_1
         4     1.27000000E+00  # Fu_2
         6     1.73500000E+02  # Fu_3
        11     5.10998930E-04  # Fe_1
        13     1.05658372E-01  # Fe_2
        15     1.77669000E+00  # Fe_3
Block UDLMIX Q=  1.60000000E+02  # ()
  1  1      1.00000000E+00   # Real(ZDL(1,1),dp)
  1  2      0.00000000E+00   # Real(ZDL(1,2),dp)
  1  3      0.00000000E+00   # Real(ZDL(1,3),dp)
-:---  SPheno.spc.SSDM    9% L75    (Fundamental)
```

$M_S = 28$ GeV

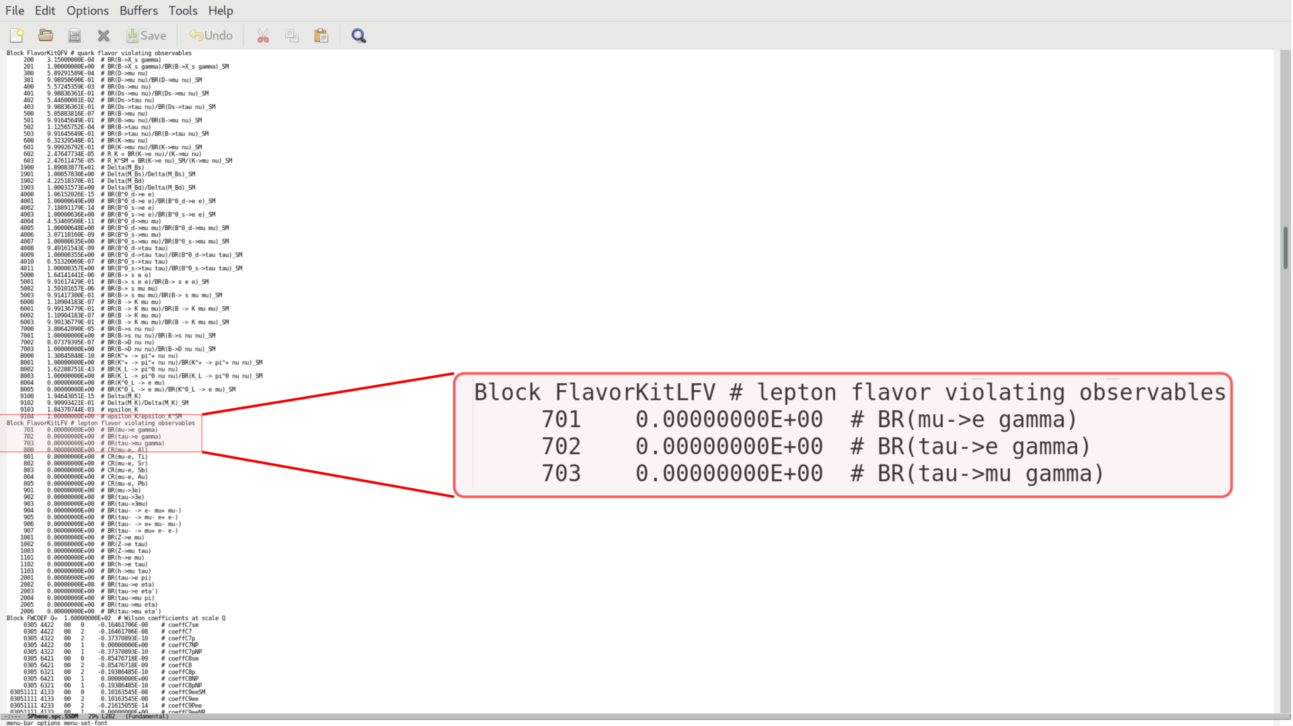


```
        52     0.00000000E+00  # Ignore negative masses
        53     0.00000000E+00  # Ignore negative masses at MZ
        55     0.00000000E+00  # Calculate one loop masses
        56     1.00000000E+00  # Calculate two-loop Higgs masses
        57     1.00000000E+00  # Calculate low energy
        60     1.00000000E+00  # Include kinetic mixing
        65     1.00000000E+00  # Solution of tadpole equation
Block HiggsBoundsInputHiggsCouplingsFermions #
    1.00000000E+00    0.00000000E+00        3             25          5          5 # h_1 b b coupling
    1.00000000E+00    0.00000000E+00        3             25          3          3 # h_1 s s coupling
    1.00000000E+00    0.00000000E+00        3             25          6          6 # h_1 t t coupling
    1.00000000E+00    0.00000000E+00        3             25          4          4 # h_1 c c coupling
    1.00000000E+00    0.00000000E+00        3             25         15         15 # h_1 tau tau coupling
    1.00000000E+00    0.00000000E+00        3             25         13         13 # h_1 mu mu coupling
Block HiggsBoundsInputHiggsCouplingsBosons #
    1.00000000E+00        3             25        24        24 # h_1 W W coupling
    1.00000000E+00        3             25        23        23 # h_1 Z Z coupling
    0.00000000E+00        3             25        23        22 # h_1 Z gamma coupling
    1.04284942E+00        3             25        22        22 # h_1 gamma gamma coupling
    1.02186767E+00        3             25        21        21 # h_1 g g coupling
    0.00000000E+00        4             25        21        21        23 # h_1 g g Z coupling
    0.00000000E+00        3             25        25        23 # h_1 h_1 Z coupling
Block EFFHIGGSCOUPLINGS # values of loop-induced couplings
        25           22           22     0.33598689E-04 # H-Photon-Photon
        25           21           21     0.65965686E-04 # H-Gluon-Gluon
        25           22           23     0.00000000E+00 # H-Photon-Z (not yet calculated by SPheno)
Block SPhenoLowEnergy # low energy observables
       1   -0.00000000E+00  # T-parameter (1-loop BSM)
       2    0.00000000E+00  # S-parameter (1-loop BSM)
       3    0.00000000E+00  # U-parameter (1-loop BSM)
      20    1.99137438E-23  # (g-2)_e
      21    2.00436756E-14  # (g-2)_mu
      22    9.10708358E-10  # (g-2)_tau
      23    0.00000000E+00  # EDM(e)
      24    0.00000000E+00  # EDM(mu)
      25    0.00000000E+00  # EDM(tau)
      39   -3.57242562E-04  # delta(rho)
Block FlavorKitQFV # quark flavor violating observables
     200    3.15000000E-04  # BR(B->X_s gamma)
     201    1.00000000E+00  # BR(B->X_s gamma)/BR(B->X_s gamma)_SM
```



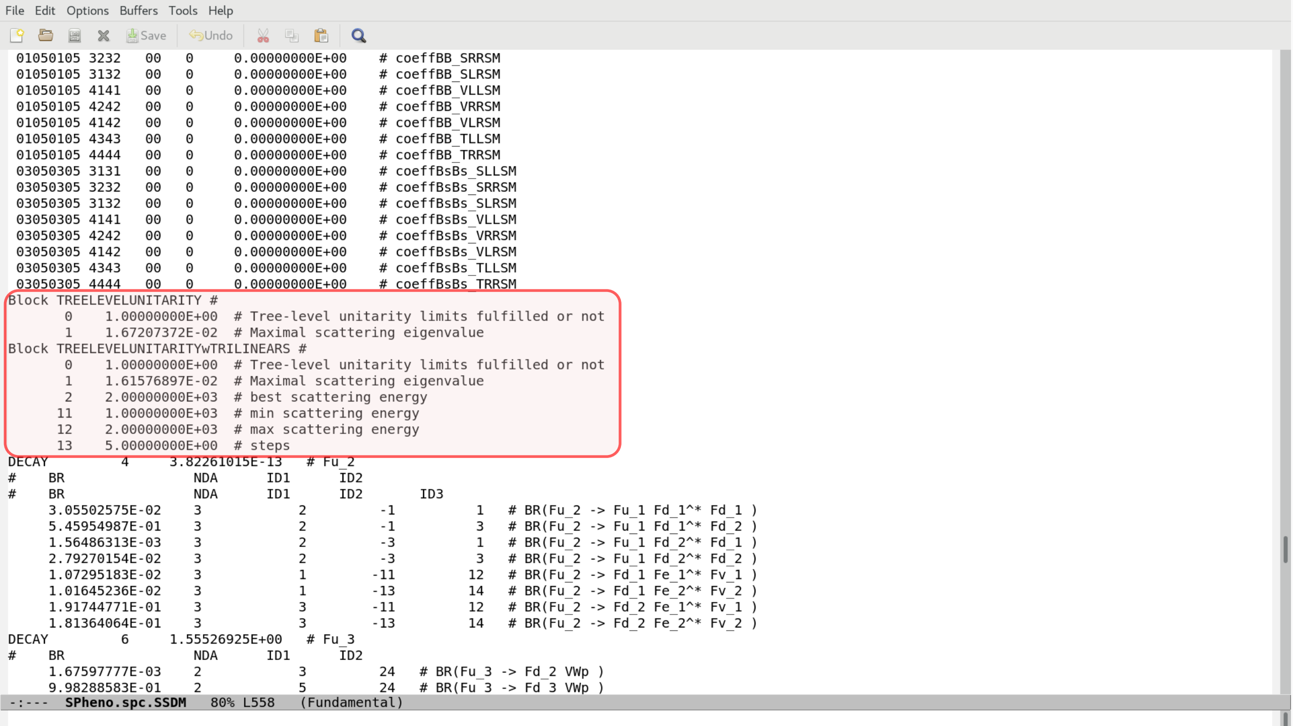
```
Block FlavorKitQFV # quark flavor violating observables
     200    3.15000000E-04  # BR(B->X_s gamma)
     201    1.00000000E+00  # BR(B->X_s gamma)/BR(B->X_s gamma)_SM
     300    5.89291589E-04  # BR(D->mu nu)
     301    9.98950690E-01  # BR(D->mu nu)/BR(D->mu nu)_SM
     400    5.57245359E-03  # BR(Ds->mu nu)
     401    9.98836361E-01  # BR(Ds->mu nu)/BR(Ds->mu nu)_SM
     402    5.44600081E-02  # BR(Ds->tau nu)
     403    9.98836361E-01  # BR(Ds->tau nu)/BR(Ds->tau nu)_SM
     500    5.05883816E-07  # BR(B->mu nu)
     501    9.91645649E-01  # BR(B->mu nu)/BR(B->mu nu)_SM
     502    1.12565752E-04  # BR(B->tau nu)
     503    9.91645649E-01  # BR(B->tau nu)/BR(B->tau nu)_SM
     600    6.32329548E-01  # BR(K->mu nu)
     601    9.99926792E-01  # BR(K->mu nu)/BR(K->mu nu)_SM
     602    2.47647734E-05  # R_K = BR(K->e nu)/(K->mu nu)
     603    2.47611475E-05  # R_K^SM = BR(K->e nu)_SM/(K->mu nu)_SM
    1900    1.89083877E+01  # Delta(M_Bs)
    1901    1.00057830E+00  # Delta(M_Bs)/Delta(M_Bs)_SM
    1902    4.22518370E-01  # Delta(M_Bd)
    1903    1.00031573E+00  # Delta(M_Bd)/Delta(M_Bd)_SM
    4000    1.06152026E-15  # BR(B^0_d->e e)
    4001    1.00000649E+00  # BR(B^0_d->e e)/BR(B^0_d->e e)_SM
    4002    7.18891179E-14  # BR(B^0_s->e e)
    4003    1.00000636E+00  # BR(B^0_s->e e)/BR(B^0_s->e e)_SM
    4004    4.53469508E-11  # BR(B^0_d->mu mu)
    4005    1.00000648E+00  # BR(B^0_d->mu mu)/BR(B^0_d->mu mu)_SM
    4006    3.07110160E-09  # BR(B^0_s->mu mu)
    4007    1.00000635E+00  # BR(B^0_s->mu mu)/BR(B^0_s->mu mu)_SM
    4008    9.49161543E-09  # BR(B^0_d->tau tau)
    4009    1.00000355E+00  # BR(B^0_d->tau tau)/BR(B^0_d->tau tau)_SM
    4010    6.51320069E-07  # BR(B^0_s->tau tau)
    4011    1.00000357E+00  # BR(B^0_s->tau tau)/BR(B^0_s->tau tau)_SM
    5000    1.64141441E-06  # BR(B-> s e e)
    5001    9.91617429E-01  # BR(B-> s e e)/BR(B-> s e e)_SM
    5002    1.59101657E-06  # BR(B-> s mu mu)
    5003    9.91417300E-01  # BR(B-> s mu mu)/BR(B-> s mu mu)_SM
    6000    1.10904183E-07  # BR(B -> K mu mu)
    6001    9.99136779E-01  # BR(B -> K mu mu)/BR(B -> K mu mu)_SM
    6002    1.10904183E-07  # BR(B -> K mu mu)
    6003    9.99136779E-01  # BR(B -> K mu mu)/BR(B -> K mu mu)_SM
    7000    3.80642090E-05  # BR(B->s nu nu)
    7001    1.00000000E+00  # BR(B->s nu nu)/BR(B->s nu nu)_SM
    7002    8.07379395E-07  # BR(B->D nu nu)
    7003    1.00000000E+00  # BR(B->D nu nu)/BR(B->D nu nu)_SM
    8000    1.30845848E-10  # BR(K^+ -> pi^+ nu nu)
    8001    1.00000000E+00  # BR(K^+ -> pi^+ nu nu)/BR(K^+ -> pi^+ nu nu)_SM
    8002    1.62288751E-43  # BR(K_L -> pi^0 nu nu)
    8003    1.00000000E+00  # BR(K_L -> pi^0 nu nu)/BR(K_L -> pi^0 nu nu)_SM
    8004    0.00000000E+00  # BR(K^0_L -> e mu)
    8005    0.00000000E+00  # BR(K^0_L -> e mu)/BR(K^0_L -> e mu)_SM
    9100    1.94643051E-15  # Delta(M_K)
    9102    9.99993421E-01  # Delta(M_K)/Delta(M_K)_SM
    9103    1.84370744E-03  # epsilon_K
    9104    1.00000000E+00  # epsilon_K/epsilon_K^SM
Block FlavorKitLFV # lepton flavor violating observables
     701    0.00000000E+00  # BR(mu->e gamma)
     702    0.00000000E+00  # BR(tau->e gamma)
     703    0.00000000E+00  # BR(tau->mu gamma)
     800    0.00000000E+00  # CR(mu-e, Al)
     801    0.00000000E+00  # CR(mu-e, Ti)
     802    0.00000000E+00  # CR(mu-e, Sr)
     803    0.00000000E+00  # CR(mu-e, Sb)
     804    0.00000000E+00  # CR(mu-e, Au)
     805    0.00000000E+00  # CR(mu-e, Pb)
     901    0.00000000E+00  # BR(mu->3e)
     902    0.00000000E+00  # BR(tau->3e)
     903    0.00000000E+00  # BR(tau->3mu)
     904    0.00000000E+00  # BR(tau- -> e- mu+ mu-)
     905    0.00000000E+00  # BR(tau- -> mu- e+ e-)
     906    0.00000000E+00  # BR(tau- -> e+ mu- mu-)
     907    0.00000000E+00  # BR(tau- -> mu+ e- e-)
    1001    0.00000000E+00  # BR(Z->e mu)
    1002    0.00000000E+00  # BR(Z->e tau)
    1003    0.00000000E+00  # BR(Z->mu tau)
    1101    0.00000000E+00  # BR(h->e mu)
    1102    0.00000000E+00  # BR(h->e tau)
    1103    0.00000000E+00  # BR(h->mu tau)
    2001    0.00000000E+00  # BR(tau->e pi)
    2002    0.00000000E+00  # BR(tau->e eta)
    2003    0.00000000E+00  # BR(tau->e eta')
    2004    0.00000000E+00  # BR(tau->mu pi)
    2005    0.00000000E+00  # BR(tau->mu eta)
    2006    0.00000000E+00  # BR(tau->mu eta')
Block FWCOEF Q=  1.60000000E+02  # Wilson coefficients at scale Q
     0305 4422   00   0    -0.16461706E-08    # coeffC7sm
     0305 4422   00   2    -0.16461706E-08    # coeffC7
     0305 4322   00   2    -0.37370893E-10    # coeffC7p
     0305 4422   00   1     0.00000000E+00    # coeffC7NP
     0305 4322   00   1    -0.37370893E-10    # coeffC7pNP
     0305 6421   00   0    -0.85476718E-09    # coeffC8sm
     0305 6421   00   2    -0.85476718E-09    # coeffC8
     0305 6321   00   2    -0.19386485E-10    # coeffC8p
     0305 6421   00   1     0.00000000E+00    # coeffC8NP
     0305 6321   00   1    -0.19386485E-10    # coeffC8pNP
 03051111 4133   00   0     0.10163545E-08    # coeffC9eeSM
 03051111 4133   00   2     0.10163545E-08    # coeffC9ee
 03051111 4233   00   2    -0.21615055E-14    # coeffC9Pee
 03051111 4133   00   1     0.00000000E+00    # coeffC9eeNP
```

```
-:---  SPheno.spc.SSDM   29% L282   (Fundamental)
menu-bar options menu-set-font
```

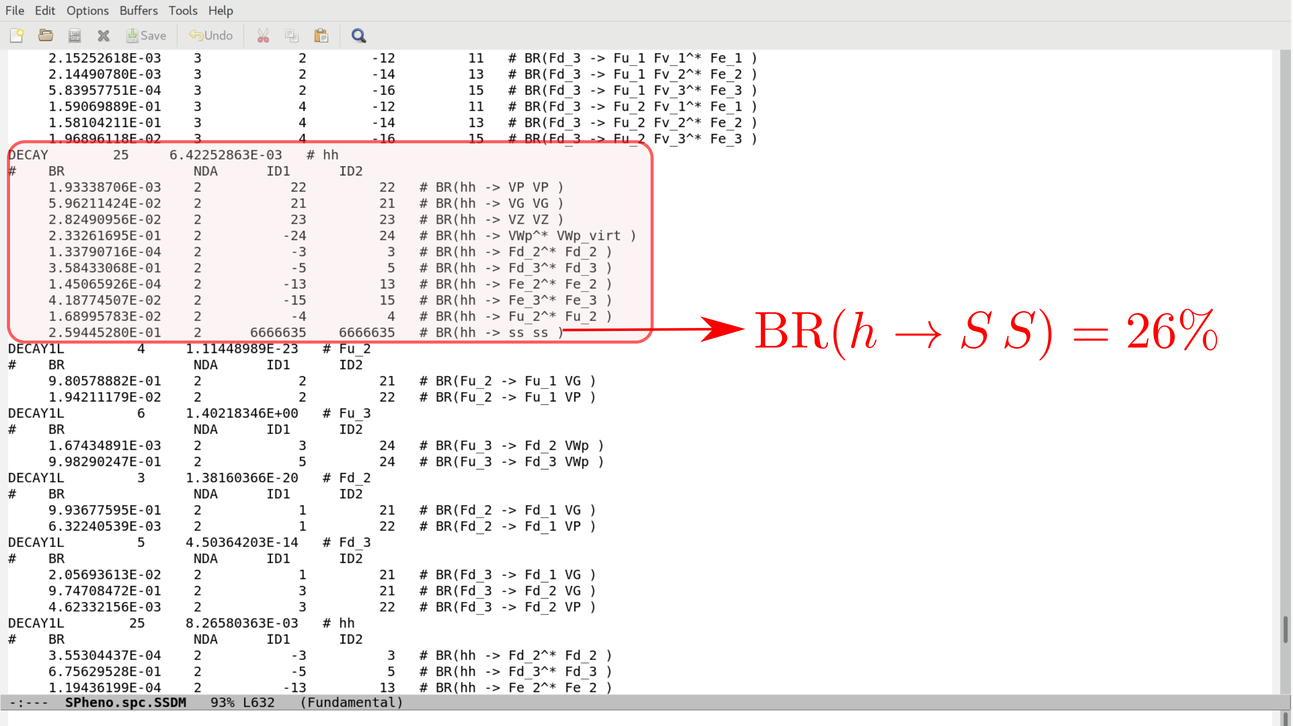


```
Block FlavorKitQFV # quark flavor violating observables
    200    3.15000000E-04  # BR(B->X_s gamma)
    201    1.00000000E+00  # BR(B->X_s gamma)/BR(B->X_s gamma)_SM
    300    5.89291589E-04  # BR(D->mu nu)
    301    9.98950690E-01  # BR(D->mu nu)/BR(D->mu nu)_SM
    400    5.57245359E-03  # BR(Ds->mu nu)
    401    9.98836361E-01  # BR(Ds->mu nu)/BR(Ds->mu nu)_SM
    402    5.44600081E-02  # BR(Ds->tau nu)
    403    9.98836361E-01  # BR(Ds->tau nu)/BR(Ds->tau nu)_SM
    500    5.05883816E-07  # BR(B->mu nu)
    501    9.91645649E-01  # BR(B->mu nu)/BR(B->mu nu)_SM
    502    1.12565752E-04  # BR(B->tau nu)
    503    9.91645649E-01  # BR(B->tau nu)/BR(B->tau nu)_SM
    600    6.32329548E-01  # BR(K->mu nu)
    601    9.99926792E-01  # BR(K->mu nu)/BR(K->mu nu)_SM
    602    2.47647734E-05  # R_K = BR(K->e nu)/(K->mu nu)
    603    2.47611475E-05  # R_K^SM = BR(K->e nu)_SM/(K->mu nu)_SM
   1900    1.89083877E+01  # Delta(M_Bs)
   1901    1.00057830E+00  # Delta(M_Bs)/Delta(M_Bs)_SM
   1902    4.22518370E-01  # Delta(M_Bd)
   1903    1.00031573E+00  # Delta(M_Bd)/Delta(M_Bd)_SM
   4000    1.06152026E-15  # BR(B^0_d->e e)
   4001    1.00000649E+00  # BR(B^0_d->e e)/BR(B^0_d->e e)_SM
   4002    7.18891179E-14  # BR(B^0_s->e e)
   4003    1.00000636E+00  # BR(B^0_s->e e)/BR(B^0_s->e e)_SM
   4004    4.53469508E-11  # BR(B^0_d->mu mu)
   4005    1.00000648E+00  # BR(B^0_d->mu mu)/BR(B^0_d->mu mu)_SM
   4006    3.07110160E-09  # BR(B^0_s->mu mu)
   4007    1.00000635E+00  # BR(B^0_s->mu mu)/BR(B^0_s->mu mu)_SM
   4008    9.49161543E-09  # BR(B^0_d->tau tau)
   4009    1.00000355E+00  # BR(B^0_d->tau tau)/BR(B^0_d->tau tau)_SM
   4010    6.51320069E-07  # BR(B^0_s->tau tau)
   4011    1.00000357E+00  # BR(B^0_s->tau tau)/BR(B^0_s->tau tau)_SM
   5000    1.64141441E-06  # BR(B-> s e e)
   5001    9.91617429E-01  # BR(B-> s e e)/BR(B-> s e e)_SM
   5002    1.59101657E-06  # BR(B-> s mu mu)
   5003    9.91417300E-01  # BR(B-> s mu mu)/BR(B-> s mu mu)_SM
   6000    1.10904183E-07  # BR(B -> K mu mu)
   6001    9.99136779E-01  # BR(B -> K mu mu)/BR(B -> K mu mu)_SM
   6002    1.10904183E-07  # BR(B -> K mu mu)
   6003    9.99136779E-01  # BR(B -> K mu mu)/BR(B -> K mu mu)_SM
   7000    3.80642090E-05  # BR(B->s nu nu)
   7001    1.00000000E+00  # BR(B->s nu nu)/BR(B->s nu nu)_SM
   7002    8.07379395E-07  # BR(B->D nu nu)
   7003    1.00000000E+00  # BR(B->D nu nu)/BR(B->D nu nu)_SM
   8000    1.30845848E-10  # BR(K^+ -> pi^+ nu nu)
   8001    1.00000000E+00  # BR(K^+ -> pi^+ nu nu)/BR(K^+ -> pi^+ nu nu)_SM
   8002    1.62288751E-43  # BR(K_L -> pi^0 nu nu)
   8003    1.00000000E+00  # BR(K_L -> pi^0 nu nu)/BR(K_L -> pi^0 nu nu)_SM
   8004    0.00000000E+00  # BR(K^0_L -> e mu)
   8005    0.00000000E+00  # BR(K^0_L -> e mu)/BR(K^0_L -> e mu)_SM
   9100    1.94643051E-15  # Delta(M_K)
   9102    9.99993421E-01  # Delta(M_K)/Delta(M_K)_SM
   9103    1.84370744E-03  # epsilon_K
   9104    1.00000000E+00  # epsilon_K/epsilon_K^SM
Block FlavorKitLFV # lepton flavor violating observables
    701    0.00000000E+00  # BR(mu->e gamma)
    702    0.00000000E+00  # BR(tau->e gamma)
    703    0.00000000E+00  # BR(tau->mu gamma)
    800    0.00000000E+00  # CR(mu-e, Al)
    801    0.00000000E+00  # CR(mu-e, Ti)
    802    0.00000000E+00  # CR(mu-e, Sr)
    803    0.00000000E+00  # CR(mu-e, Sb)
    804    0.00000000E+00  # CR(mu-e, Au)
    805    0.00000000E+00  # CR(mu-e, Pb)
    901    0.00000000E+00  # BR(mu->3e)
    902    0.00000000E+00  # BR(tau->3e)
    903    0.00000000E+00  # BR(tau->3mu)
    904    0.00000000E+00  # BR(tau-  -> e- mu+ mu-)
    905    0.00000000E+00  # BR(tau-  -> mu- e+ e-)
    906    0.00000000E+00  # BR(tau-  -> e+ mu- mu-)
    907    0.00000000E+00  # BR(tau-  -> mu+ e- e-)
   1001    0.00000000E+00  # BR(Z->e mu)
   1002    0.00000000E+00  # BR(Z->e tau)
   1003    0.00000000E+00  # BR(Z->mu tau)
   1101    0.00000000E+00  # BR(h->e mu)
   1102    0.00000000E+00  # BR(h->e tau)
   1103    0.00000000E+00  # BR(h->mu tau)
   2001    0.00000000E+00  # BR(tau->e pi)
   2002    0.00000000E+00  # BR(tau->e eta)
   2003    0.00000000E+00  # BR(tau->e eta')
   2004    0.00000000E+00  # BR(tau->mu pi)
   2005    0.00000000E+00  # BR(tau->mu eta)
   2006    0.00000000E+00  # BR(tau->mu eta')
Block FWCOEF Q=  1.60000000E+02  # Wilson coefficients at scale Q
    0305 4422   00   0    -0.16461706E-08    # coeffC7sm
    0305 4422   00   2    -0.16461706E-08    # coeffC7
    0305 4322   00   2    -0.37370893E-10    # coeffC7p
    0305 4422   00   1     0.00000000E+00    # coeffC7NP
    0305 4322   00   1    -0.37370893E-10    # coeffC7pNP
    0305 6421   00   0    -0.85476718E-09    # coeffC8sm
    0305 6421   00   2    -0.85476718E-09    # coeffC8
    0305 6321   00   2    -0.19386485E-10    # coeffC8p
    0305 6421   00   1     0.00000000E+00    # coeffC8NP
    0305 6321   00   1    -0.19386485E-10    # coeffC8pNP
 03051111 4133   00   0     0.10163545E-08    # coeffC9eeSM
 03051111 4133   00   2     0.10163545E-08    # coeffC9ee
 03051111 4233   00   2    -0.21615055E-14    # coeffC9Pee
 03051111 4133   00   1     0.00000000E+00    # coeffC9eeNP
```

```
Block FlavorKitLFV # lepton flavor violating observables
    701    0.00000000E+00  # BR(mu->e gamma)
    702    0.00000000E+00  # BR(tau->e gamma)
    703    0.00000000E+00  # BR(tau->mu gamma)
```



```
 01050105 3232   00   0     0.00000000E+00    # coeffBB_SRRSM
 01050105 3132   00   0     0.00000000E+00    # coeffBB_SLRSM
 01050105 4141   00   0     0.00000000E+00    # coeffBB_VLLSM
 01050105 4242   00   0     0.00000000E+00    # coeffBB_VRRSM
 01050105 4142   00   0     0.00000000E+00    # coeffBB_VLRSM
 01050105 4343   00   0     0.00000000E+00    # coeffBB_TLLSM
 01050105 4444   00   0     0.00000000E+00    # coeffBB_TRRSM
 03050305 3131   00   0     0.00000000E+00    # coeffBsBs_SLLSM
 03050305 3232   00   0     0.00000000E+00    # coeffBsBs_SRRSM
 03050305 3132   00   0     0.00000000E+00    # coeffBsBs_SLRSM
 03050305 4141   00   0     0.00000000E+00    # coeffBsBs_VLLSM
 03050305 4242   00   0     0.00000000E+00    # coeffBsBs_VRRSM
 03050305 4142   00   0     0.00000000E+00    # coeffBsBs_VLRSM
 03050305 4343   00   0     0.00000000E+00    # coeffBsBs_TLLSM
 03050305 4444   00   0     0.00000000E+00    # coeffBsBs_TRRSM
Block TREELEVELUNITARITY #
        0   1.00000000E+00  # Tree-level unitarity limits fulfilled or not
        1   1.67207372E-02  # Maximal scattering eigenvalue
Block TREELEVELUNITARITYwTRILINEARS #
        0   1.00000000E+00  # Tree-level unitarity limits fulfilled or not
        1   1.61576897E-02  # Maximal scattering eigenvalue
        2   2.00000000E+03  # best scattering energy
       11   1.00000000E+03  # min scattering energy
       12   2.00000000E+03  # max scattering energy
       13   5.00000000E+00  # steps
DECAY         4     3.82261015E-13   # Fu_2
#    BR                 NDA      ID1      ID2
#    BR                 NDA      ID1      ID2       ID3
     3.05502575E-02    3            2         -1           1   # BR(Fu_2 -> Fu_1 Fd_1^* Fd_1 )
     5.45954987E-01    3            2         -1           3   # BR(Fu_2 -> Fu_1 Fd_1^* Fd_2 )
     1.56486313E-03    3            2         -3           1   # BR(Fu_2 -> Fu_1 Fd_2^* Fd_1 )
     2.79270154E-02    3            2         -3           3   # BR(Fu_2 -> Fu_1 Fd_2^* Fd_2 )
     1.07295183E-02    3            1        -11          12   # BR(Fu_2 -> Fd_1 Fe_1^* Fv_1 )
     1.01645236E-02    3            1        -13          14   # BR(Fu_2 -> Fd_1 Fe_2^* Fv_2 )
     1.91744771E-01    3            3        -11          12   # BR(Fu_2 -> Fd_2 Fe_1^* Fv_1 )
     1.81364064E-01    3            3        -13          14   # BR(Fu_2 -> Fd_2 Fe_2^* Fv_2 )
DECAY         6     1.55526925E+00   # Fu_3
#    BR                 NDA      ID1      ID2
     1.67597777E-03    2            3         24   # BR(Fu_3 -> Fd_2 VWp )
     9.98288583E-01    2            5         24   # BR(Fu_3 -> Fd_3 VWp )
```



```
     2.15252618E-03    3           2         -12          11   # BR(Fd_3 -> Fu_1 Fv_1^* Fe_1 )
     2.14490780E-03    3           2         -14          13   # BR(Fd_3 -> Fu_1 Fv_2^* Fe_2 )
     5.83957751E-04    3           2         -16          15   # BR(Fd_3 -> Fu_1 Fv_3^* Fe_3 )
     1.59069889E-01    3           4         -12          11   # BR(Fd_3 -> Fu_2 Fv_1^* Fe_1 )
     1.58104211E-01    3           4         -14          13   # BR(Fd_3 -> Fu_2 Fv_2^* Fe_2 )
     1.96896118E-02    3           4         -16          15   # BR(Fd_3 -> Fu_2 Fv_3^* Fe_3 )
DECAY        25     6.42252863E-03   # hh
#    BR                NDA      ID1      ID2
     1.93338706E-03    2          22          22   # BR(hh -> VP VP )
     5.96211424E-02    2          21          21   # BR(hh -> VG VG )
     2.82490956E-02    2          23          23   # BR(hh -> VZ VZ )
     2.33261695E-01    2         -24          24   # BR(hh -> VWp^* VWp_virt )
     1.33790716E-04    2          -3           3   # BR(hh -> Fd_2^* Fd_2 )
     3.58433068E-01    2          -5           5   # BR(hh -> Fd_3^* Fd_3 )
     1.45065926E-04    2         -13          13   # BR(hh -> Fe_2^* Fe_2 )
     4.18774507E-02    2         -15          15   # BR(hh -> Fe_3^* Fe_3 )
     1.68995783E-02    2          -4           4   # BR(hh -> Fu_2^* Fu_2 )
     2.59445280E-01    2     6666635     6666635   # BR(hh -> ss ss )
DECAY1L       4     1.11448989E-23   # Fu_2
#    BR                NDA      ID1      ID2
     9.80578882E-01    2           2          21   # BR(Fu_2 -> Fu_1 VG )
     1.94211179E-02    2           2          22   # BR(Fu_2 -> Fu_1 VP )
DECAY1L       6     1.40218346E+00   # Fu_3
#    BR                NDA      ID1      ID2
     1.67434891E-03    2           3          24   # BR(Fu_3 -> Fd_2 VWp )
     9.98290247E-01    2           5          24   # BR(Fu_3 -> Fd_3 VWp )
DECAY1L       3     1.38160366E-20   # Fd_2
#    BR                NDA      ID1      ID2
     9.93677595E-01    2           1          21   # BR(Fd_2 -> Fd_1 VG )
     6.32240539E-03    2           1          22   # BR(Fd_2 -> Fd_1 VP )
DECAY1L       5     4.50364203E-14   # Fd_3
#    BR                NDA      ID1      ID2
     2.05693613E-02    2           1          21   # BR(Fd_3 -> Fd_1 VG )
     9.74708472E-01    2           3          21   # BR(Fd_3 -> Fd_2 VG )
     4.62332156E-03    2           3          22   # BR(Fd_3 -> Fd_2 VP )
DECAY1L      25     8.26580363E-03   # hh
#    BR                NDA      ID1      ID2
     3.55304437E-04    2          -3           3   # BR(hh -> Fd_2^* Fd_2 )
     6.75629528E-01    2          -5           5   # BR(hh -> Fd_3^* Fd_3 )
     1.19436199E-04    2         -13          13   # BR(hh -> Fe_2^* Fe_2 )
-:---  SPheno.spc.SSDM    93% L632    (Fundamental)
```

$$\mathrm{BR}(h \to S\,S) = 26\%$$

Run micrOMEGAs

```
micromegas/SSDM/CalcOmega_with_DDetection_MOv5 SPheno.spc.SSDM
```

```
Masses of odd sector Particles:
~Ss   : MSs    =    28.4 ||
PROCESS: ~Ss,~Ss->AllEven,1*x{h,g,A,Z,Wp,Wm,nu1,Nu1,nu2,Nu2,nu3,Nu3,d1,D1,d2,D2,d3,D3,u1,U1,u2,U2,u3,U3,e1,E1,e2,E2,e3,
     E3
Xf=1.64e+01 Omega h^2=2.28e+01

# Channels which contribute to 1/(omega) more than 1%.
# Relative contributions in % are displayed
   85% ~Ss ~Ss ->d3 D3
    8% ~Ss ~Ss ->e3 E3
    4% ~Ss ~Ss ->u2 U2
    2% ~Ss ~Ss ->g g

==== Calculation of CDM-nucleons amplitudes  =====
         TREE LEVEL
PROCESS: QUARKS,~Ss->QUARKS,~Ss{d1,D1,d2,D2,d3,D3,u1,U1,u2,U2,u3,U3
Delete diagrams with _S0_!=1,_V5_,A
....
CDM-nucleon cross sections[pb]:
 proton  SI 2.407E-09  SD 0.000E+00
 neutron SI 2.471E-09  SD 0.000E+00

======== Direct Detection ========
73Ge: Total number of events=1.29E-03 /day/kg
Number of events in 10 - 50 KeV region=4.19E-04 /day/kg
131Xe: Total number of events=2.66E-03 /day/kg
```

Automatic generation of scotogenic models

Python program: `minimal-lagrangians`

Simon May, `https://arxiv.org/pdf/2003.08037` [CPC]

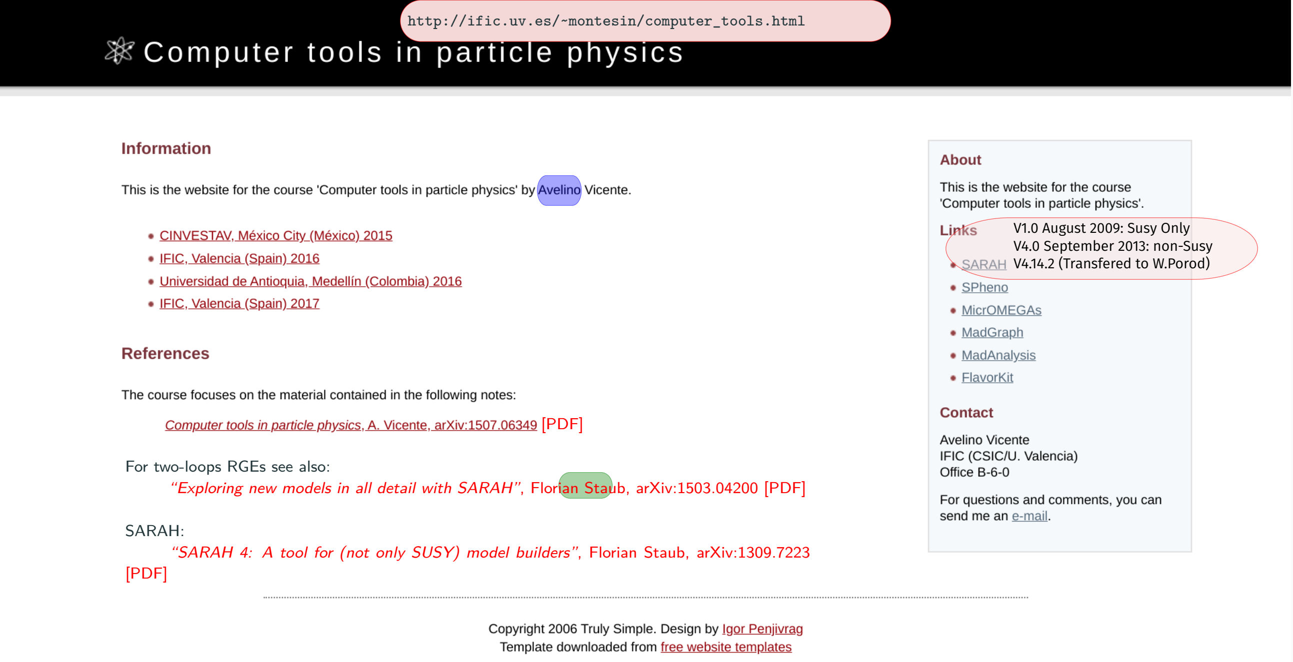
```
pip install minimal-lagrangians
```

- As the program was originally written for the study of minimal darkmatter models with radiative neutrino masses: D. Restrepo, O. Zapata, C. E. Yaguna, Models with radiative neutrinomasses and viable dark matter candidates, arXiv:1308.3655 [JHEP]
- Lagrangians for the individual models.
- Model files for SARAH can be constructed automaticallyfrom the specified field content, which can be tedious if done manually

Thus, minimal-lagrangians enables rapid phenomenological studies using `SARAH` and, successively, further tools like `SPheno`, and `micrOMEGAs` → Sec. 8: Outlook

```
BSMModel('T1-3-B', (
FermionField("Ψ",  1, Y= 0),
FermionField("Ψ'", 2, Y= 1),
ScalarField ("phi",  3, Y= 0),
FermionField("Ψ'",  2, Y=-1),6), (0, 2)), # = -2 is equivalent  to= 2
```

http://ific.uv.es/~montesin/computer_tools.html



Computer tools in particle physics

Information

This is the website for the course 'Computer tools in particle physics' by Avelino Vicente.

- CINVESTAV, México City (México) 2015
- IFIC, Valencia (Spain) 2016
- Universidad de Antioquia, Medellín (Colombia) 2016
- IFIC, Valencia (Spain) 2017

References

The course focuses on the material contained in the following notes:

Computer tools in particle physics, A. Vicente, arXiv:1507.06349 [PDF]

For two-loops RGEs see also:

"Exploring new models in all detail with SARAH", Florian Staub, arXiv:1503.04200 [PDF]

SARAH:

"SARAH 4: A tool for (not only SUSY) model builders", Florian Staub, arXiv:1309.7223 [PDF]

About

This is the website for the course 'Computer tools in particle physics'.

Links

- SARAH
- SPheno
- MicrOMEGAs
- MadGraph
- MadAnalysis
- FlavorKit

V1.0 August 2009: Susy Only
V4.0 September 2013: non-Susy
V4.14.2 (Transfered to W.Porod)

Contact

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Office B-6-0

For questions and comments, you can send me an e-mail.

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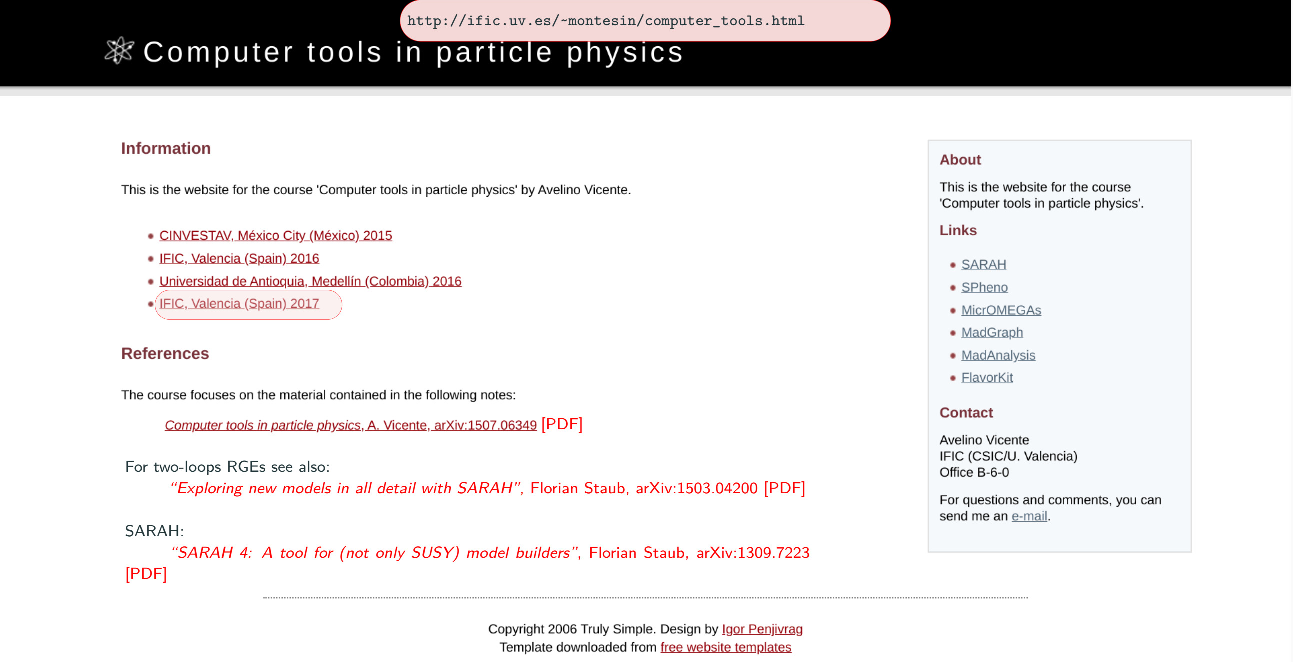
Template downloaded from free website templates

http://ific.uv.es/~montesin/computer_tools.html



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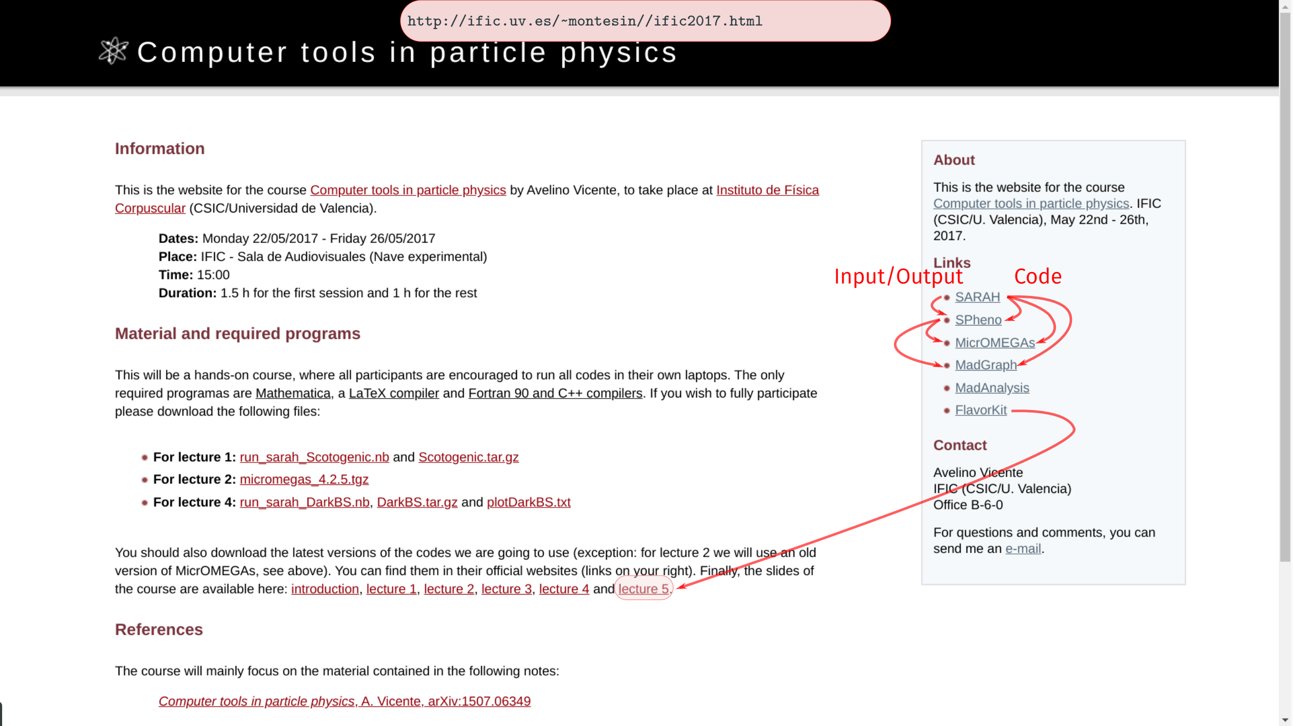

Computer tools in particle physics

Information

This is the website for the course Computer tools in particle physics by Avelino Vicente, to take place at Instituto de Física Corpuscular (CSIC/Universidad de Valencia).

Dates: Monday 22/05/2017 - Friday 26/05/2017
Place: IFIC - Sala de Audiovisuales (Nave experimental)
Time: 15:00
Duration: 1.5 h for the first session and 1 h for the rest

Material and required programs

This will be a hands-on course, where all participants are encouraged to run all codes in their own laptops. The only required programas are Mathematica, a LaTeX compiler and Fortran 90 and C++ compilers. If you wish to fully participate please download the following files:

- **For lecture 1:** run_sarah_Scotogenic.nb and Scotogenic.tar.gz
- **For lecture 2:** micromegas_4.2.5.tgz
- **For lecture 4:** run_sarah_DarkBS.nb, DarkBS.tar.gz and plotDarkBS.txt

You should also download the latest versions of the codes we are going to use (exception: for lecture 2 we will use an old version of MicrOMEGAs, see above). You can find them in their official websites (links on your right). Finally, the slides of the course are available here: introduction, lecture 1, lecture 2, lecture 3, lecture 4 and lecture 5.

References

The course will mainly focus on the material contained in the following notes:

Computer tools in particle physics, A. Vicente, arXiv:1507.06349

About

This is the website for the course Computer tools in particle physics. IFIC (CSIC/U. Valencia), May 22nd - 26th, 2017.

Links

- SARAH
- SPheno
- MicrOMEGAs
- MadGraph
- MadAnalysis
- FlavorKit

Contact

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Office B-6-0

For questions and comments, you can send me an e-mail.

Observables already in FlavorKit

Lepton flavor	**Quark flavor**
$\ell_\alpha \to \ell_\beta \gamma$	$B^0_{s,d} \to \ell^+ \ell^-$
$\ell_\alpha \to 3\,\ell_\beta$	$\bar{B} \to X_s \gamma$
$\mu - e$ conversion in nuclei	$\bar{B} \to X_s \ell^+ \ell^-$
$\tau \to P\,\ell$	$\bar{B} \to X_{d,s} \nu \bar{\nu}$
$h \to \ell_\alpha \ell_\beta$	$B \to K \ell^+ \ell^-$
$Z \to \ell_\alpha \ell_\beta$	$K \to \pi \nu \bar{\nu}$
	$\Delta M_{B_{s,d}}$
	ΔM_K and ε_K
	$P \to \ell \nu$

Ready to be computed in your favourite model!

Observables already in FlavorKit

Lepton flavor	**Quark flavor**
$\ell_\alpha \to \ell_\beta \gamma$	$B^0_{s,d} \to \ell^+ \ell^-$
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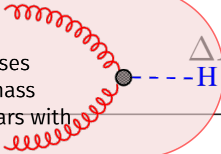
Also in SARAH

S,T,U

- One-loop corrections to All masses
- Two-loop corrections to Higgs mass
- Gluon fusion production of scalars with proper output for MadGraph



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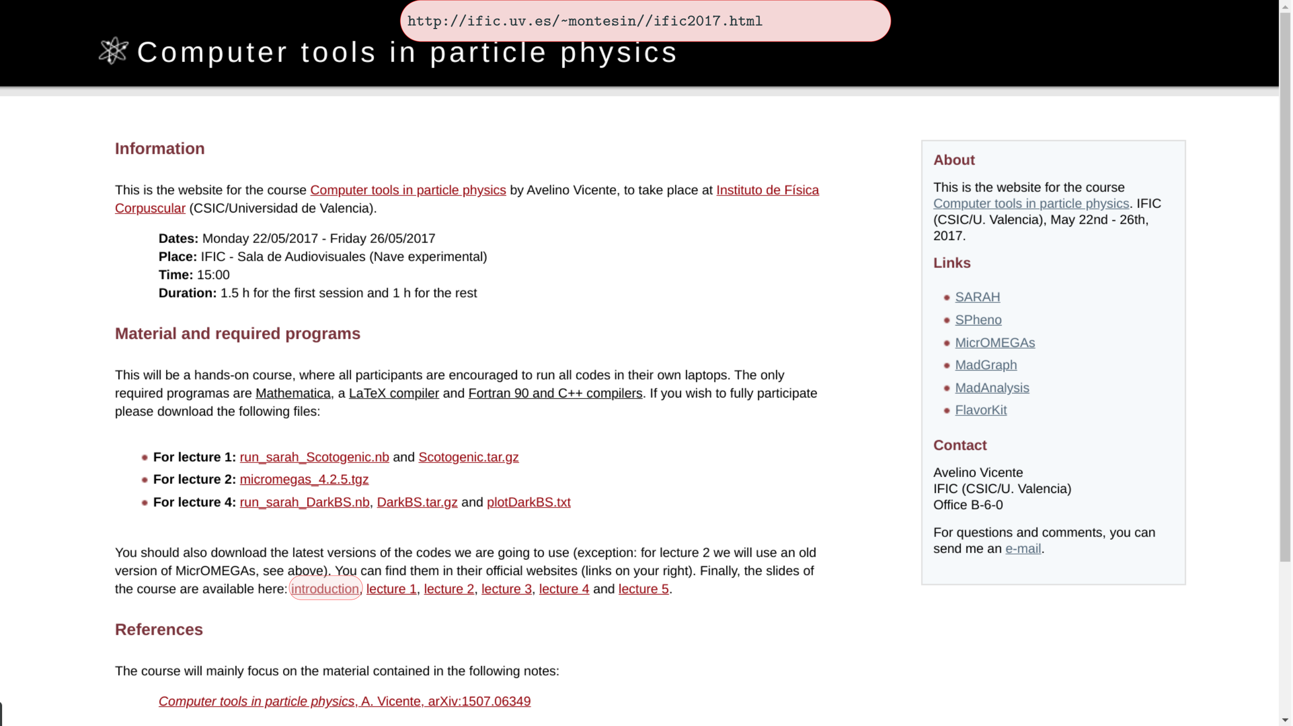

http://ific.uv.es/~montesin//ific2017.html

Computer tools in particle physics

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Links

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- MadAnalysis
- FlavorKit

Contact

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IFIC (CSIC/U. Valencia)
Office B-6-0

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Models already in SARAH

Supersymmetric Models

- MSSM [in several versions]
- NMSSM [in several versions]
- Near-to-minimal SSM (near-MSSM)
- General singlet extended SSM (SMSSM)
- DiracNMSSM
- Triplet extended MSSM/NMSSM
- Several models with R-parity violation
- Several U(1)-extended models
- Secluded MSSM
- Several B-L extended models
- Inverse and linear seesaws
- MSSM/NMSSM with Dirac Gauginos
- Minimal R-Symmetric SSM
- Minimal Dirac Gaugino SSM
- Seesaws I-II-III [SU(5) versions]
- Left-right symmetric model
- Quiver model
- Models with vector-like superfields

Non-Supersymmetric Models

- Standard Model
- Two Higgs doublet models (including inert)
- Singlet extensions
- Triplet extensions
- U(1) extensions
- SM extended by a scalar color octet
- Gauged Two Higgs doublet model
- Singlet extended SM
- Singlet Scalar DM
- Singlet-Doublet DM
- Models with vector-like fermions
- Model with a scalar SU(2) 7-plet
- Leptoquark models
- Left-right models
- 331 models (with and without exotics)
- Georgi-Machacek model

More info: http://sarah.hepforge.org/

Models already in SARAH

Always check any version of SARAH and SPheno with this one!

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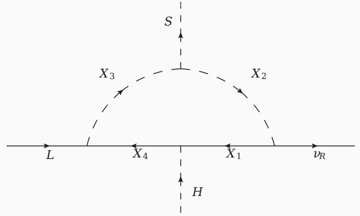
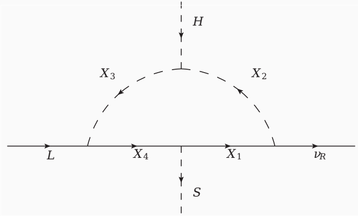
THANK YOU

Dirac neutrino masses

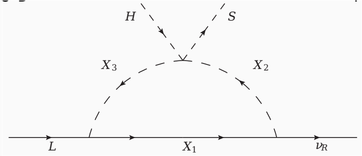
One loop topologies $\mathrm{U}(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

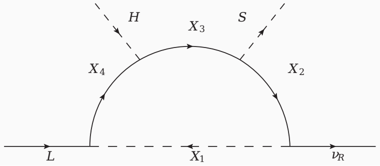


T1-3-E

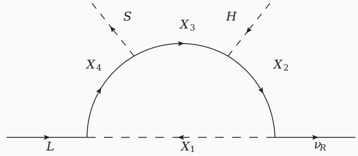


T3-1-A

Chang-Yuan Yao and Gui-Jun Ding, arXiv:1802.05231 [PRD]

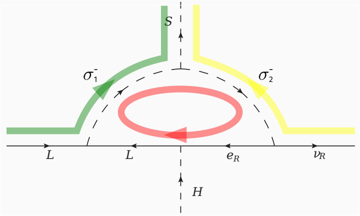


T1-2-A

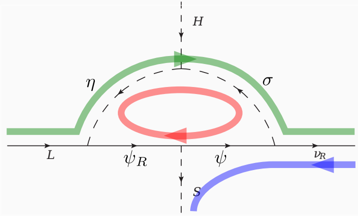


T1-2-B

One loop topologies $\mathrm{U}(1)_{B-L}$ only!



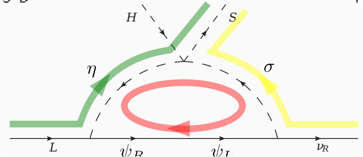
T1-3-D



T1-3-E

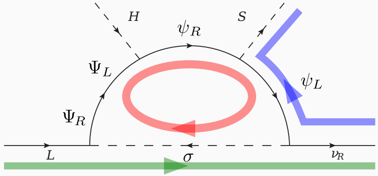
$\psi_{L,R}$ → Singlet fermions (vector-like)

σ →Singlet scalar

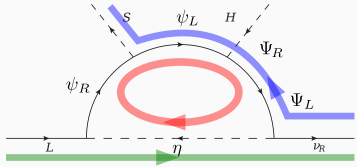


T3-1-A

with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



T1-2-A



T1-2-B

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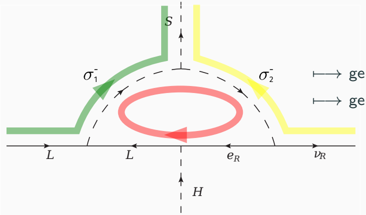


T1-3-D

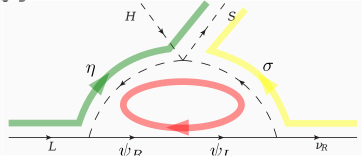
⟼ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]

⟼ generalization to $\mathrm{U}(1)_{\mathrm{R}}$: *et al*, S. Saad arXiv:1904.07407

Fields: f_i	L, e_R	ν_{R3}	ν_{R2}	ν_{R1}	S	H
$\mathrm{U}(1)_{B-L}$	-1	-4	-4	$+5$	$+3$	0

$\psi_{L,R}$ → Singlet fermions (vector-like)

σ →Singlet scalar



T3-1-A

Anomaly cancellation conditions

$$\sum_i \nu_{Ri} = -3$$

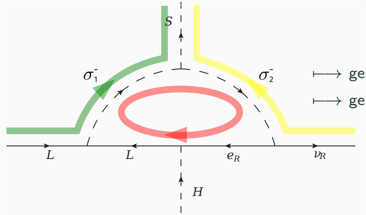
$$\sum_i \nu_{Ri}^3 = -3$$

Three-level cancellation conditions

$$\cancel{\nu_R \nu_R}$$

$$\cancel{(\nu_R)^\dagger L \cdot H}$$

One loop topologies $\mathrm{U}(1)_{B-L}$ only! with J. Calle, C. Yaguna, and O. Zapata, arXiv:1812.05523 [PRD]



T1-3-D

$\longmapsto$ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]

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$\uparrow$

Fields: f_i	L, e_R	ν_{R3}	ν_{R2}	ν_{R1}	σ_1^-	σ_2^-	S	H
$\mathrm{U}(1)_{B-L}$	-1	-4	-4	$+5$	-2	-5	$+3$	0

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Three-level cancellation conditions

$$\cancel{\nu_R \nu_R}$$

$$\cancel{(\nu_R)^\dagger L \cdot H}$$

σ $\rightarrow$Singlet scalar

Dirac Zee

```
cp -r BSM/SARAH/Models/B-L/ SARAH/Models/
math << EOF
<<./SARAH/SARAH.m
Start["B-L/DZ"]
MakeSPheno[]
EOF
```

```
cp -r SARAH/Output/B-L-DZ/EWSB/SPheno SPheno/BLDZ
cd SPheno
make Model=BLDZ
cd .. # Return to parent directory
```

```
cp BSM/Input_Files/LesHouches.in.BLDZ .
```

```
SPheno/bin/SPhenoBLDZ LesHouches.in.BLDZ
```

LesHouches.in.BLDZ: Fix options!

```
55 1        # Calculate loop corrected masses
50 0        # Majorana phases: use only positive masses
520 0       # Write effective Higgs couplings
```

Dirac Zee

```
cp -r BSM/SARAH/Models/B-L/ SARAH/Models/
math << EOF
<<./SARAH/SARAH.m
Start["B-L/DZ"]
MakeSPheno[]
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```
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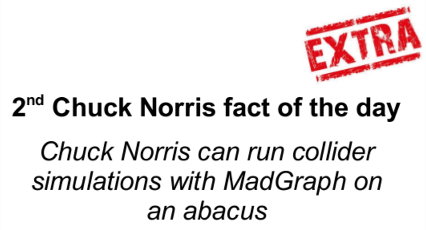
cd SPheno
make Model=BLDZ
cd .. # Return to parent directory
```

```
cp BSM/Input_Files/LesHouches.in.BLDZ .
```

```
SPheno/bin/SPhenoBLDZ  LesHouches.in.BLDZ
```

cat SPheno.spc.BLDZ

```
Block MASS  # Mass spectrum
#   PDG code       mass          particle
        25     1.24861947E+02  # hh_1
        35     1.71464282E+03  # hh_2
    900037     2.00000000E+03  # Hm_2
    900038     3.00000000E+03  # Hm_3
        22     0.00000000E+00  # VP
        23     9.11887000E+01  # VZ
        21     0.00000000E+00  # VG
        24     7.96796394E+01  # VWm
        31     2.57196423E+03  # VZp
         1     5.00000000E-03  # Fd_1
         .
         .
         .
        15     1.77669000E+00  # Fe_3
        12     0.00000000E+00  # Fv_1
        14    -1.61994502E-31  # Fv_2
        16     4.42048291E-14  # Fv_3
   8810012    -4.42048291E-14  # Fv_4
   8810014     2.08300541E-10  # Fv_5
   8810016    -2.08300541E-10  # Fv_6
```



EXTRA

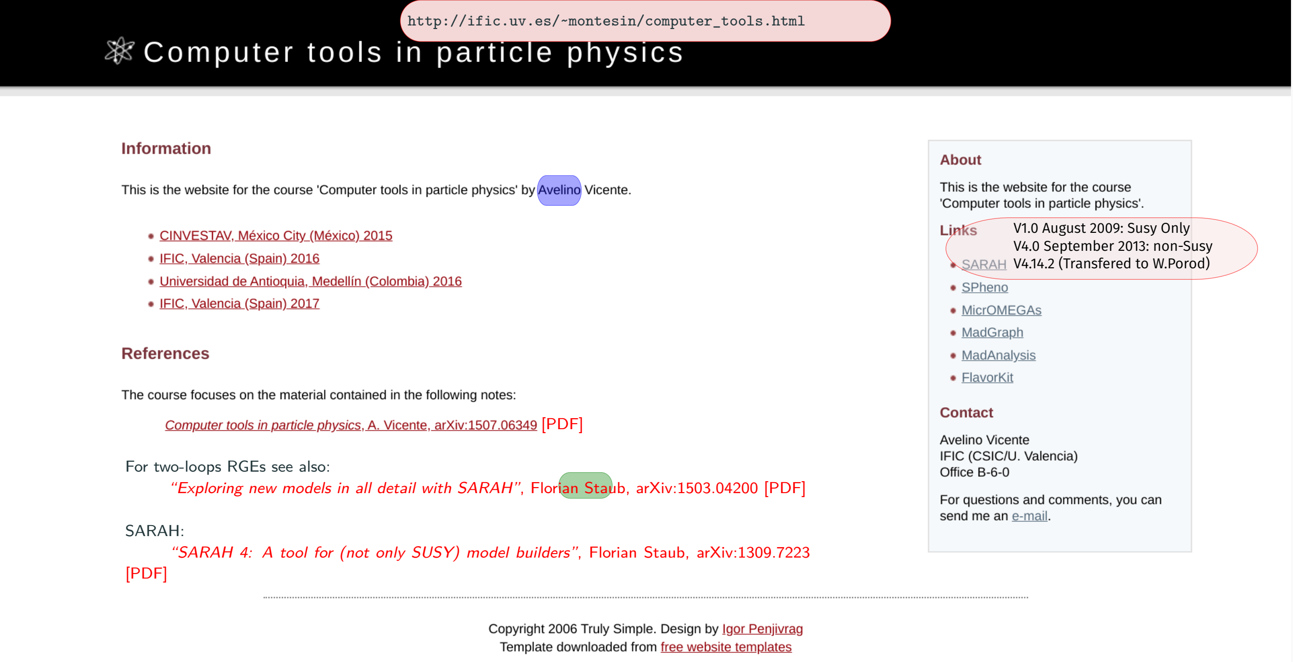
2nd Chuck Norris fact of the day

Chuck Norris can run collider simulations with MadGraph on an abacus

From A. Vicente

Backup slides

Preliminars



http://ific.uv.es/~montesin/computer_tools.html

Computer tools in particle physics

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- CINVESTAV, México City (México) 2015
- IFIC, Valencia (Spain) 2016
- Universidad de Antioquia, Medellín (Colombia) 2016
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SARAH:

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- MicrOMEGAs
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- FlavorKit

V1.0 August 2009: Susy Only
V4.0 September 2013: non-Susy
V4.14.2 (Transfered to W.Porod)

Contact

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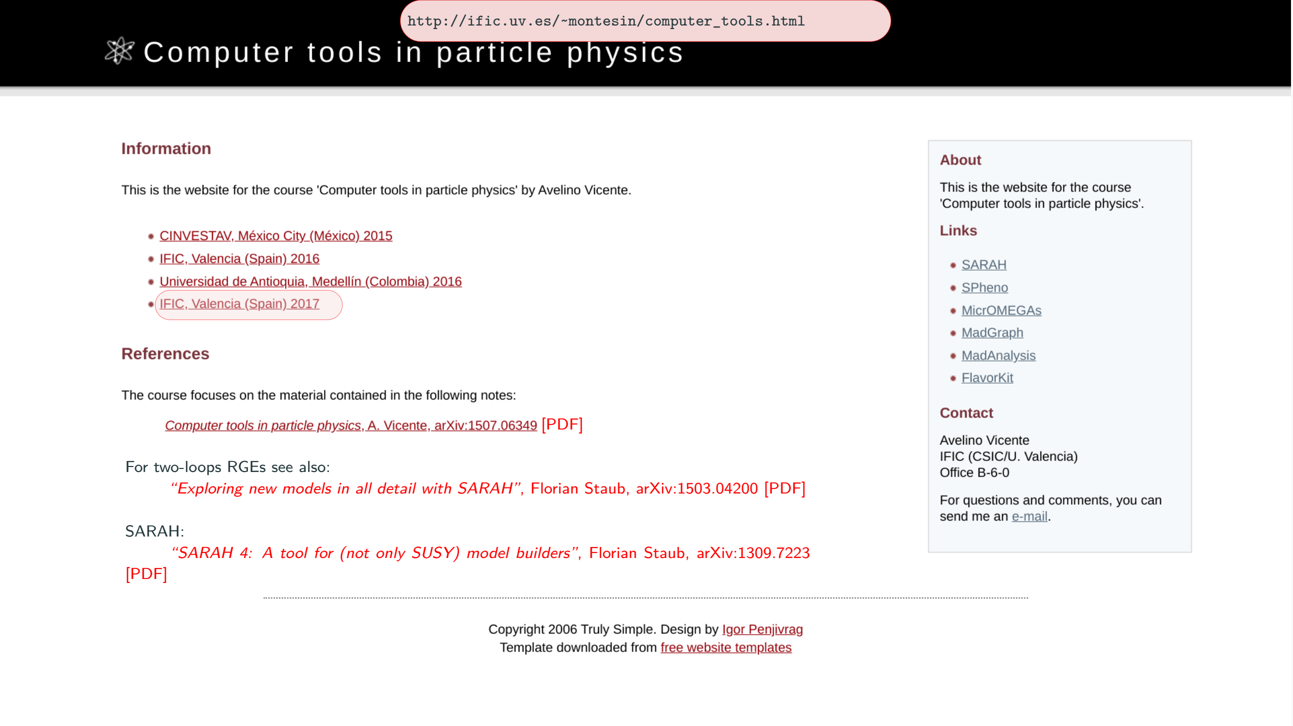

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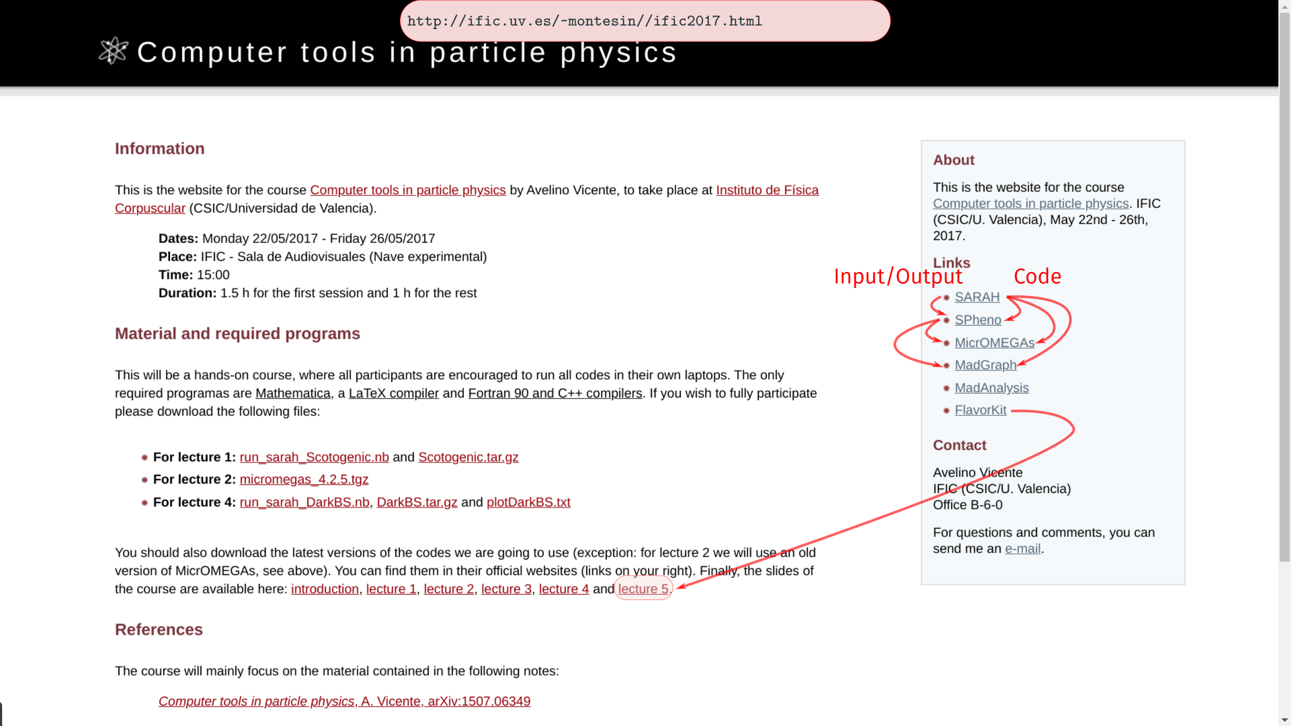

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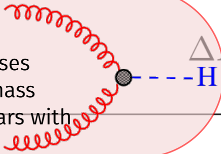

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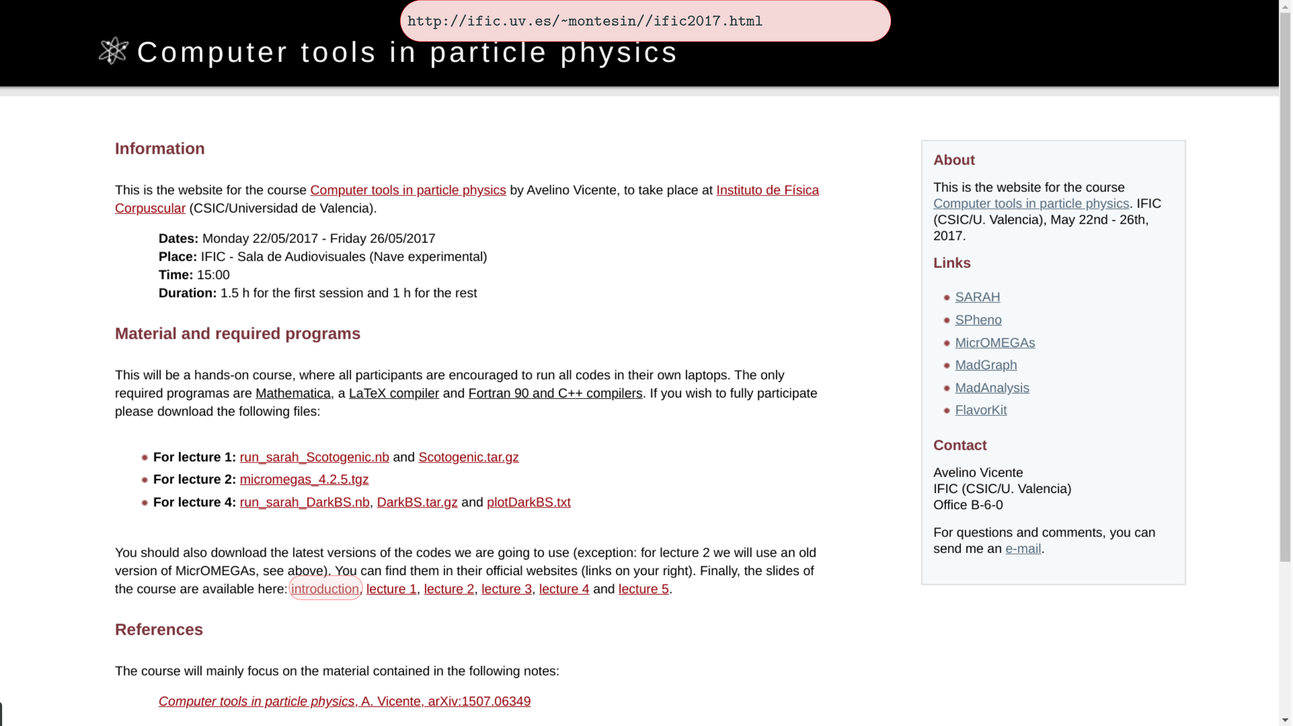

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- MicrOMEGAs
- MadGraph
- MadAnalysis
- FlavorKit

Contact

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For questions and comments, you can send me an e-mail.

Models already in SARAH

Supersymmetric Models

- MSSM [in several versions]
- NMSSM [in several versions]
- Near-to-minimal SSM (near-MSSM)
- General singlet extended SSM (SMSSM)
- DiracNMSSM
- Triplet extended MSSM/NMSSM
- Several models with R-parity violation
- Several U(1)-extended models
- Secluded MSSM
- Several B-L extended models
- Inverse and linear seesaws
- MSSM/NMSSM with Dirac Gauginos
- Minimal R-Symmetric SSM
- Minimal Dirac Gaugino SSM
- Seesaws I-II-III [SU(5) versions]
- Left-right symmetric model
- Quiver model
- Models with vector-like superfields

Non-Supersymmetric Models

- Standard Model
- Two Higgs doublet models (including inert)
- Singlet extensions
- Triplet extensions
- U(1) extensions
- SM extended by a scalar color octet
- Gauged Two Higgs doublet model
- Singlet extended SM
- Singlet Scalar DM
- Singlet-Doublet DM
- Models with vector-like fermions
- Model with a scalar SU(2) 7-plet
- Leptoquark models
- Left-right models
- 331 models (with and without exotics)
- Georgi-Machacek model

More info: http://sarah.hepforge.org/

Models already in SARAH

Always check any version of SARAH and SPheno with this one!

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