HEP computer tools

from SARAH and beyond

UNIVERSIDAD DE ANTIOQUIA
1803

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XXIX CONGRESO NACIONAL DE FÍSICA
vigesimonoveno

Least Action

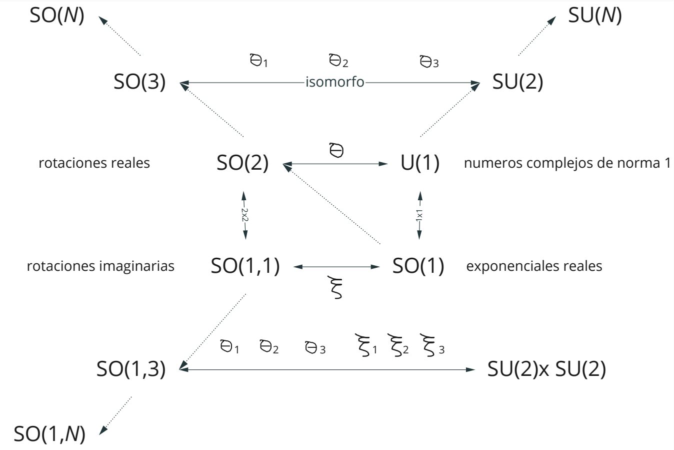
SO(3) scalar product

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

SO(3) **scalar product**

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

Lie groups



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

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

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

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

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

SO(1, 1)

Queremos obtener una representación 2×2 del álgebra

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

que genera un elemento del grupo SO(1, 1) con *parámetro ξ*

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

La transformación de una coordenada temporaloide y otra espacialoide ($c = 1$)

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

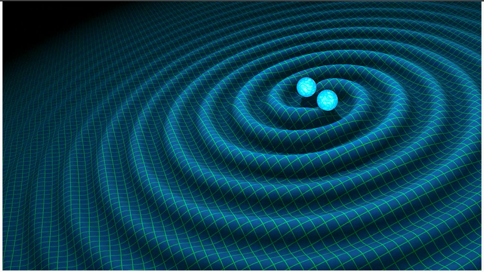
$$x'^\mu = \Lambda^\mu{}_\nu x^\nu\,, \qquad \mu = 0, 1\,.$$

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

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

Inestability of binary particle systems



Gravitational wave discovery by LIGO

New

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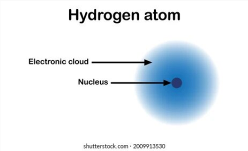
credits: science.org

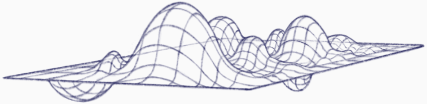
Noether's paradigm $\rightarrow$ Lagrangian formulation of classical field theory

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

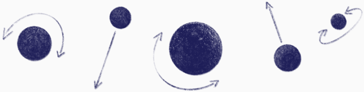


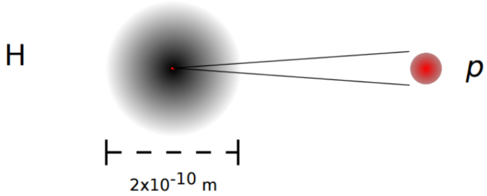
What is a ~~particle~~ *wavicle*? `https://www.quantamagazine.org/what-is-a-particle-20201112/`

Is a "Quantum Excitation of a Field"



Is a "Irreducible Representation of a Group"



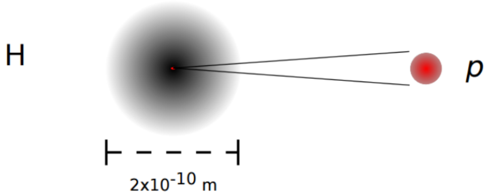

H
p
2x10-10 m

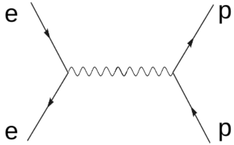
Interacción → Fuerza = $\Delta \mathbf{p}/\Delta t$

Introducción

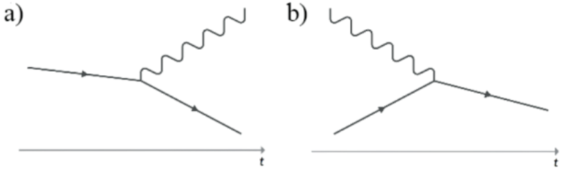
Campos de materia

Campos de radiación





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



Emisión absorción

Interacción → Fuerza = $\Delta \mathbf{p}/\Delta t$

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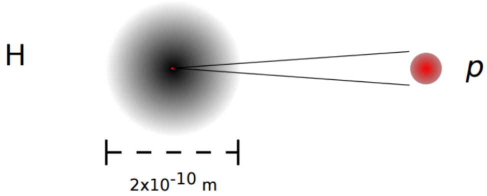
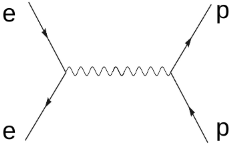
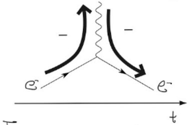




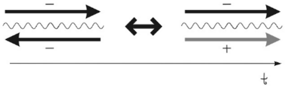
Single charge



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

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

fotón neutro



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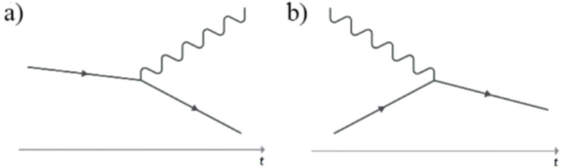
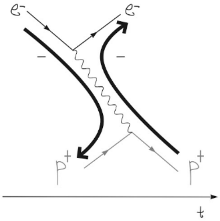


Emisión absorción

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

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



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)
Photon	A^μ	$\Lambda^\mu{}_\nu A^\nu$
4-gradient	∂_μ	$\partial_\nu \left(\Lambda^{-1}\right)^\nu{}_\mu$

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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	$(\eta^\alpha)^\dagger = \eta^{\dagger\,\dot\alpha}$	$\left[\left(S^{-1}\right)^\dagger\right]^{\dot\alpha}{}_{\dot\beta}\eta^{\dagger\,\dot\beta}$	$e^{i\theta}\eta^{\dagger\,\dot\alpha}$
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Table 3: electron left: SL(2, C) $\times$ $U(1)$ inferior and positron left: SL(2, C) $\times$ $U(1)$ superior

Scalar products

- $\cancel{\text{U(1)}}$ 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) $\times$ $U(1)$ inferior and positron left: SL(2, C) $\times$ $U(1)$ superior

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

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

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

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

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

Dirac spinor

$$\psi = \begin{pmatrix} e_L \\ e_R \end{pmatrix}$$

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

$$\bar\psi = \psi^\dagger\gamma^0\,.$$

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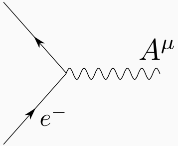
Dirac spinor



$-ie\gamma^\mu$

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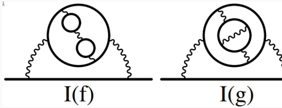
$$\mathcal{L} = i\overline{\psi}\gamma^\mu D_\mu\psi - m\overline{\psi}\psi - \frac{1}{4}F^{\mu\nu}F_{\mu\nu}\,. \to e\overline{\psi}\gamma^\mu\psi\, A_\mu$$

Dirac spinor

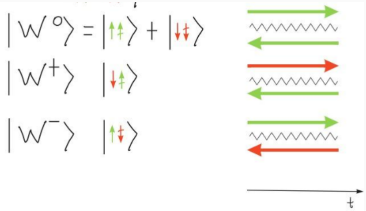
non-bare



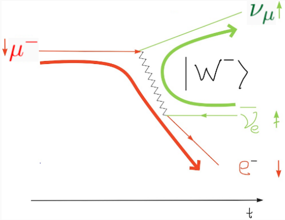
Not mass, not charge

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

Denial



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



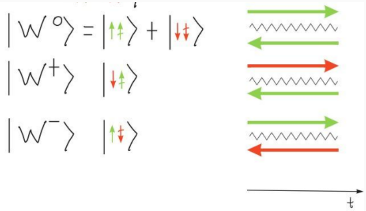
$SU(2)_L \times U(1)_Y \to D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$: 17 years later... (stages of grief $\to$ 1967)

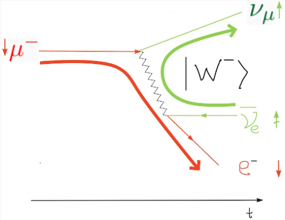
Not mass, hypercharge,

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

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

Denial

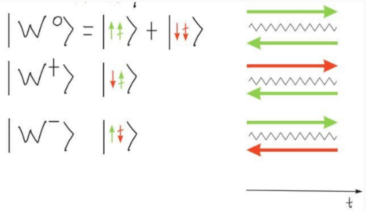




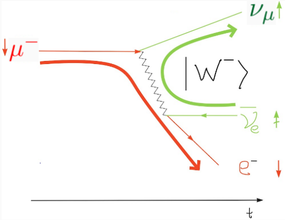
Not mass, hypercharge, not Dirac

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



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

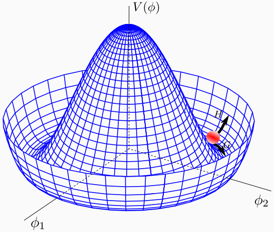


$SU(2)_L \times U(1)_Y \to D_\mu = \mathbf{1}\partial_\mu - ig_2 \frac{\tau_i}{2} W^i_\mu - ig_1 B_\mu$: 17 years later... (stages of grief → 1967)

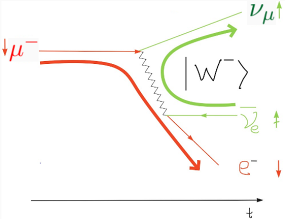
Higgs mechanism: tachyonic mass $\mu^2 < 0$, and condensate

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

Contempt



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



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

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

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
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	**2**	$1/2$

Contempt

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

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

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

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

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

Z and W phenomenology and 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
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	$\mathbf{2}$	$1/2$

Bargaining

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

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

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

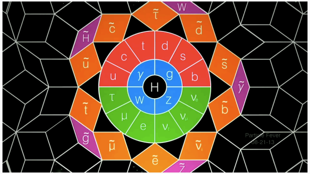
$$-\frac{1}{2} m_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu -} W^+_\mu + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right)\left(1 + 2\frac{H}{v} + \frac{H^2}{v^2}\right) + \frac{m_e}{v}\overline{\psi}\psi H$$

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

Hierarchy problem

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
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	$\mathbf{2}$	$1/2$

Depression



credit: quantumdiaries.org

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

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

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

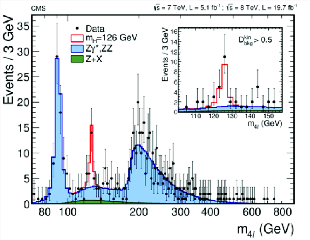
$$-\frac{1}{2} m_H^2 H^2 \left(1 + \frac{H}{v} + \frac{H^2}{4v^2}\right) + \left(m_W^2 W^{\mu -} W^+_\mu + \frac{1}{2} m_Z^2 Z^\mu Z_\mu\right)\left(1 + 2\frac{H}{v} + \frac{H^2}{v^2}\right) + \frac{m_e}{v}\overline{\psi}\psi H$$

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

Higgs discovery!

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
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x)+v}{\sqrt{2}}\right] \exp\left[i\frac{\tau^i}{2} G_i(x)\right]$	-	**2**	$1/2$

Acceptance



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

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

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

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

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};
```

$$B \to B_\mu,\ \widetilde{B} \qquad \Longrightarrow \mathrm{VB}\,,\ \mathrm{FB}$$

	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}};
```

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

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

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

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

Chuck Norris fact of the day

Chuck Norris lost his virginity before his dad

From A. Vicente

```
(* 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}};
```

./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

$$u^c \cdot H \cdot q = \delta^{\beta}_{\alpha} \epsilon_{ab}\, u^c_{\alpha} H^a q^{\beta b}$$
$$= \overline{\mathbf{3}} \times \mathbf{3} \otimes \mathbf{2} \times \mathbf{2}\,.$$

```
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
```

File Edit Options Buffers Tools Help

Save Undo

```
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
```

-:--- LesHouches.in.SSDM   Top L16   (Fundamental)

menu-bar options menu-set-font

File Edit Options Buffers Tools Help

Save Undo

```
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
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 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
```

-:--- 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
```

File Edit Options Buffers Tools Help

Save Undo

```
# 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

File Edit Options Buffers Tools Help

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```
  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)
```

$$M_S = 28 \text{ GeV}$$

```
-:---  SPheno.spc.SSDM    9% L75    (Fundamental)
```

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```
        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
```

-:--- SPheno.spc.SSDM   22% L186   (Fundamental)

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Save Undo

```
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
```

File Edit Options Buffers Tools Help

Save Undo

```
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 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)
```

File Edit Options Buffers Tools Help

Save Undo

```
 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 )
```

-:--- SPheno.spc.SSDM 80% L558 (Fundamental)

File Edit Options Buffers Tools Help

Save Undo

```
     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 )
```

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

-:--- **SPheno.spc.SSDM**   93% L632   (Fundamental)

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
```

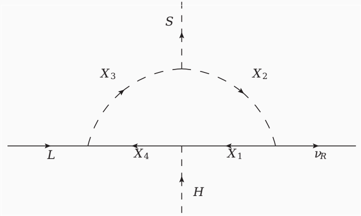
- As the program was originally written for the study of minimal darkmatter models with radiative neutrino masses: D. Restrepo, O. Zapata, C. E. Yaguna, Models with radiative neutrinomasses and viable dark matter candidates, arXiv:1308.3655 [JHEP]
- Lagrangians for the individual models.
- Model files 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

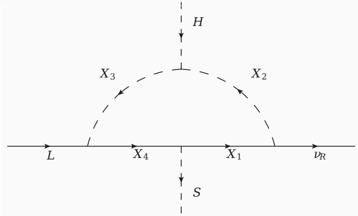
```
BSMModel('T1-3-B', (
FermionField("Ψ",  1, Y= 0),
FermionField("Ψ'", 2, Y= 1),
ScalarField ("phi",  3, Y= 0),
FermionField("Ψ'",  2, Y=-1),6), (0, 2)), # = -2 is equivalent to= 2
```

Dirac neutrino masses

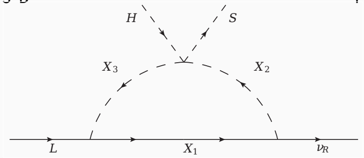
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



T1-3-D

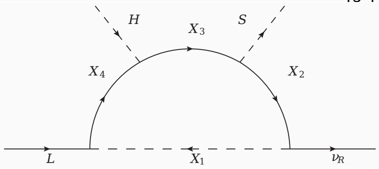


T1-3-E

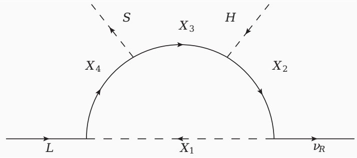


T3-1-A

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

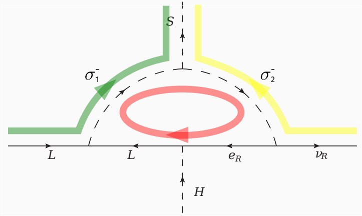


T1-2-A

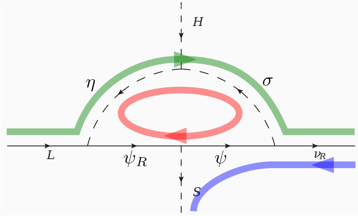


T1-2-B

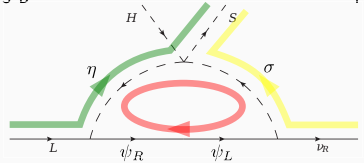
One loop topologies $U(1)_{B-L}$ only!



T1-3-D



T1-3-E

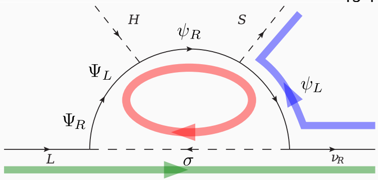


T3-1-A

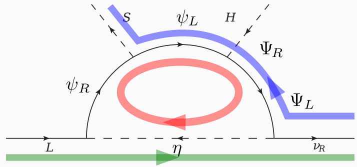
$\psi_{L,R} \to$ Singlet fermions (vector-like)

σ $\to$Singlet scalar

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

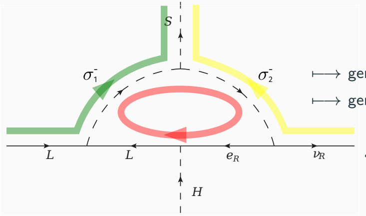


T1-2-A



T1-2-B

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

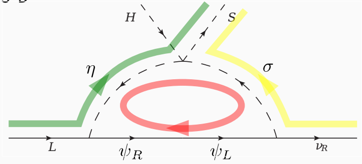


T1-3-D

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

$\longmapsto$ generalization to $U(1)_R$: *et al*, S. Saad arXiv:1904.07407

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



T3-1-A

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

$\sigma \to$Singlet scalar

Anomaly cancellation conditions

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

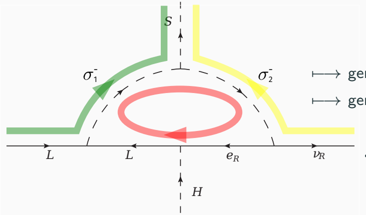
$$\sum_i \nu_{Ri}^3 = -3$$

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]

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

$\uparrow$

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

Anomaly cancellation conditions

σ $\to$Singlet scalar

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

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

Three-level cancellation conditions

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

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

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[]
EOF
```

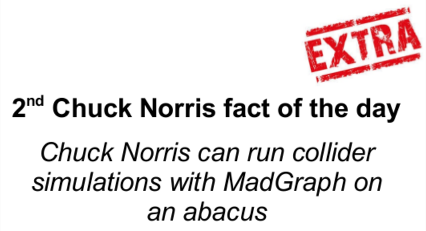
```
cp -r SARAH/Output/B-L-DZ/EWSB/SPheno SPheno/BLDZ
cd SPheno
make Model=BLDZ
cd .. # Return to parent directory
```

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

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

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
```



From A. Vicente

Backup slides

Preliminars

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

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

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

Contact

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

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

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

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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

Contact

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

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

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

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Input/Output Code

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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!

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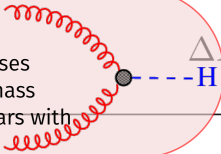
Also in SARAH

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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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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