

HEP computer tools

from SARAH and beyond



Diego Restrepo

VII Uniandes Particle Physics School

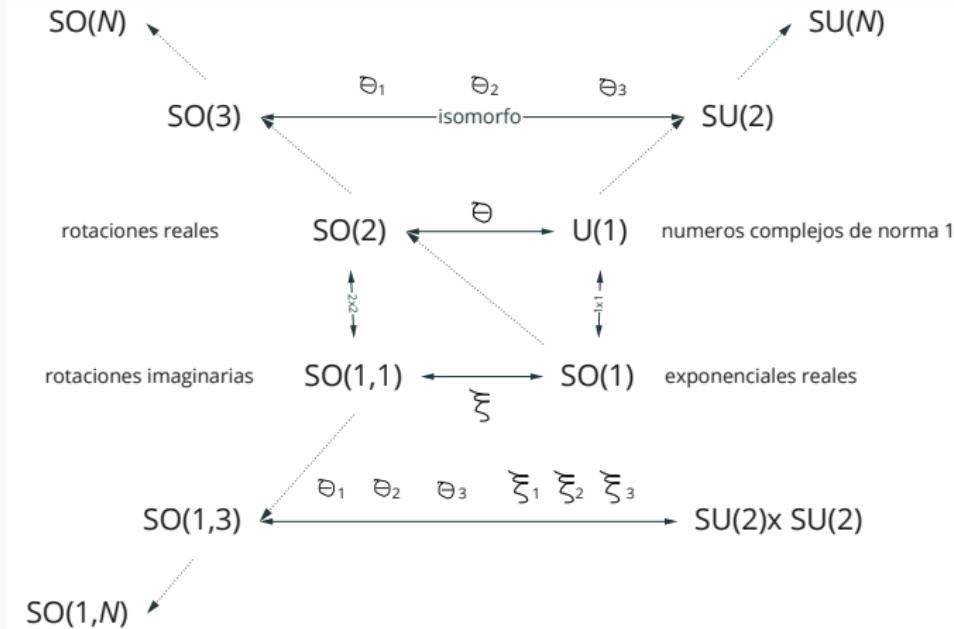
Instituto de Física
Universidad de Antioquia
Phenomenology Group
<http://gfif.udea.edu.co>



SO(3) scalar product

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

Lie groups



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

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

Consider the 1×1

$$K = -i, \quad (2)$$

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

$$\lambda(\xi) = e^\xi, \quad (3)$$

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

$$x \rightarrow x' = e^\xi x, \quad (4)$$

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

$$x \cdot y \rightarrow x' \cdot y' \equiv \frac{x'}{y'} = \frac{e^\xi x}{e^\xi y} = \frac{x}{y} = x \cdot y. \quad (5)$$

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

$$K = \begin{pmatrix} 0 & -i \\ -i & 0 \end{pmatrix} \rightarrow K^2 = -\mathbf{1}, \quad (6)$$

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

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

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

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

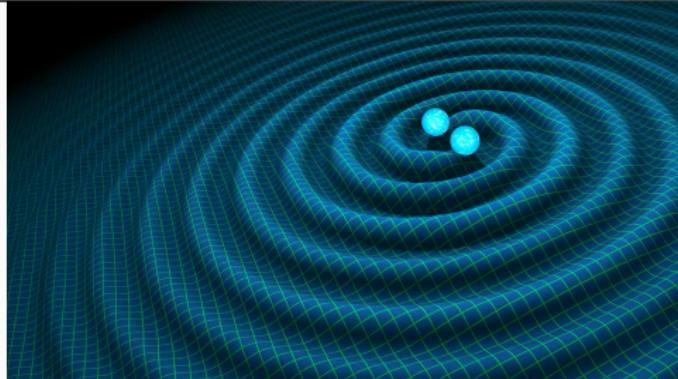
$$x'^{\mu} = \Lambda^{\mu}_{\nu} x^{\nu}, \quad \mu = 0, 1.$$

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

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

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

Inestability of binary particle systems



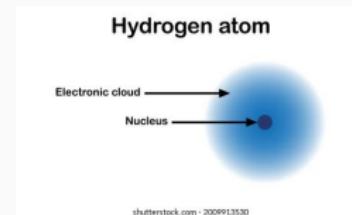
Gravitational wave discovery by LIGO



credits: science.org

Noether's paradigm → Lagrangian formulation of classical field theory

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



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

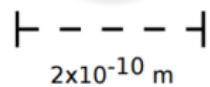
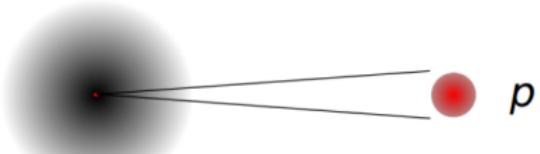
Is a “Quantum Excitation of a Field”



Is a “Irreducible Representation of a Group”



H

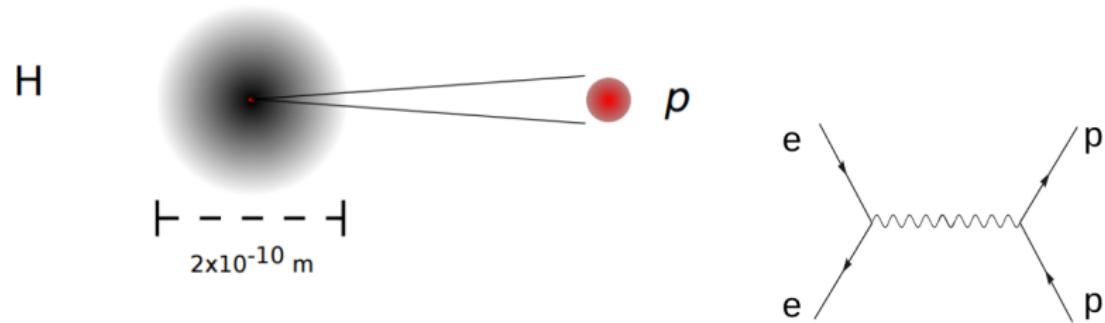


Interacción → Fuerza = $\Delta p/\Delta t$

Introducción

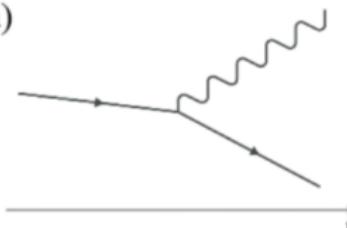
Campos de materia →

Campos de radiación ~~~~~



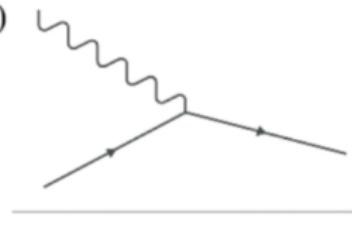
[doi:10.1088/1742-6596/1287/1/012045](https://doi.org/10.1088/1742-6596/1287/1/012045)

a)



Emisión

b)



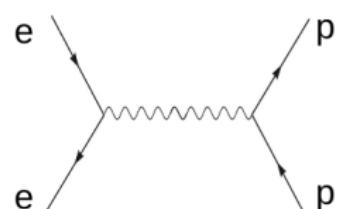
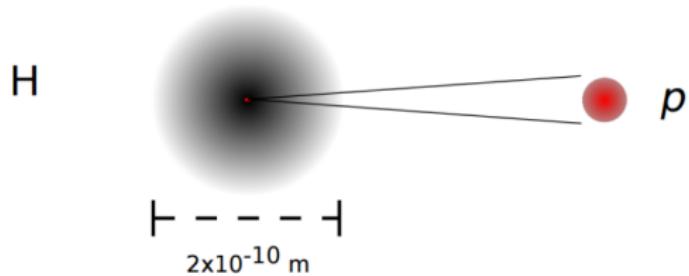
absorción

Interacción → Fuerza = $\Delta p/\Delta t$

Introducción

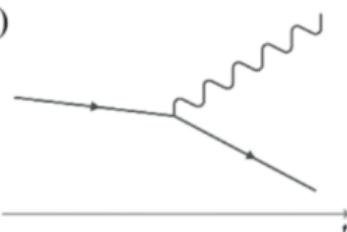
Campos de materia →

Campos de radiación ↗

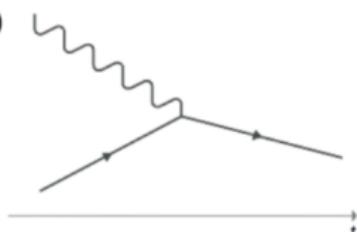


[doi:10.1088/1742-6596/1287/1/012045](https://doi.org/10.1088/1742-6596/1287/1/012045)

a)



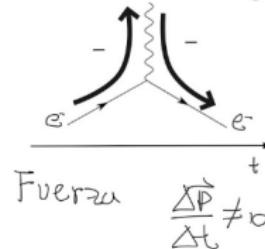
b)



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

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

Single charge

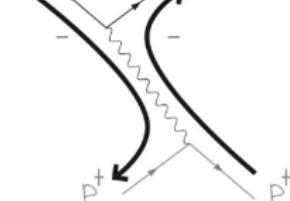


$$(e^-)^* = e^+$$

↗ fotón neutro



e^-



Emisión

absorción

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

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

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

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

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

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

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

$$\partial'_\mu = \partial_\nu (\Lambda^{-1})^\nu{}_\mu. \quad (11)$$

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

$$\partial_\mu A^\mu \rightarrow \partial'_\mu A'^\mu = \partial_\mu A^\mu. \quad (12)$$

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

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

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

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

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

Photon: $\hat{p} \oplus \text{SO}(1, 3) = i\partial^\mu \oplus \text{SO}(1, 3) \rightarrow iD^\mu \oplus \text{SO}(1, 3)$

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

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

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

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	$(\xi_\alpha)^\dagger = \xi_{\dot{\alpha}}^\dagger$	$\xi_{\dot{\beta}}^\dagger [S^\dagger]_{\dot{\alpha}}^{\dot{\beta}}$	$\xi_{\dot{\alpha}}^\dagger e^{-i\theta}$
e_R : electron right	$(\eta^\alpha)^\dagger = \eta^\dagger{}^{\dot{\alpha}}$	$[(S^{-1})^\dagger]_{\dot{\beta}}^{\dot{\alpha}} \eta^\dagger{}^{\dot{\beta}}$	$e^{i\theta} \eta^\dagger{}^{\dot{\alpha}}$
$(e_R)^\dagger$: positron left	η^α	$\eta^\beta [S^{-1}]_\beta^\alpha$	$e^{-i\theta} \eta^\alpha$

Table 3: electron **left**: $SL(2, C) \times U(1)$ inferior and positron **left**: $SL(2, C) \times U(1)$ superior

Scalar products

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

$$\sigma^0 = \mathbb{1},$$

$$\bar{\sigma}^\mu = (\sigma^0, -\boldsymbol{\sigma}),$$

$$\sigma^\mu = (\sigma^0, \boldsymbol{\sigma}).$$

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

Table 4: electron **left**: $\text{SL}(2, C) \times U(1)$ inferior and positron **left**: $\text{SL}(2, C) \times U(1)$ superior

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



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

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

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

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

Table 4: electron **left**: $\text{SL}(2, C) \times U(1)$ inferior and positron **left**: $\text{SL}(2, C) \times U(1)$ superior

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

Dirac spinor

$$\begin{aligned}
 \xi_\alpha &\rightarrow \xi'_\alpha = e^{i\theta(x)} \xi_\alpha & \eta^\alpha &\rightarrow \eta'^\alpha = e^{-i\theta(x)} \eta^\alpha \\
 D_\mu \xi_\alpha &\rightarrow (D_\mu \xi_\alpha)' = e^{i\theta(x)} D_\mu \xi_\alpha & D_\mu \eta^\alpha &\rightarrow (D_\mu \eta^\alpha)' = e^{-i\theta(x)} D_\mu \eta^\alpha \\
 \mathcal{L} &= i\xi_{\dot{\alpha}}^\dagger \bar{\sigma}^\mu{}^{\dot{\alpha}\alpha} D_\mu \xi_\alpha + i\eta^\alpha \sigma^\mu_{\alpha\dot{\alpha}} D_\mu \eta^\dagger{}^{\dot{\alpha}} - m \left(\eta^\alpha \xi_\alpha + \xi_{\dot{\alpha}}^\dagger \eta^\dagger{}^{\dot{\alpha}} \right) - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \\
 \mathcal{L} &= i\bar{\psi} \gamma^\mu D_\mu \psi - m \bar{\psi} \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu}.
 \end{aligned}$$

$$\begin{aligned}
 \psi &= \begin{pmatrix} e_L \\ e_R \end{pmatrix} \\
 \gamma^\mu &= \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix} \\
 \bar{\psi} &= \psi^\dagger \gamma^0.
 \end{aligned}$$

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

Table 4: electron **left**: $\text{SL}(2, C) \times U(1)$ inferior and positron **left**: $\text{SL}(2, C) \times U(1)$ superior

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

$$\xi_\alpha \rightarrow \xi'_\alpha = e^{i\theta(x)} \xi_\alpha$$

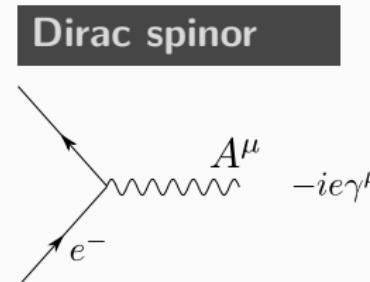
$$\eta^\alpha \rightarrow \eta'^\alpha = e^{-i\theta(x)} \eta^\alpha$$

$$D_\mu \xi_\alpha \rightarrow (D_\mu \xi_\alpha)' = e^{i\theta(x)} D_\mu \xi_\alpha$$

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

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

$$\mathcal{L} = \bar{\psi} \gamma^\mu D_\mu \psi - m \bar{\psi} \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \rightarrow e \bar{\psi} \gamma^\mu \psi A_\mu$$



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

Table 4: electron **left**: $\text{SL}(2, C) \times U(1)$ inferior and positron **left**: $\text{SL}(2, C) \times U(1)$ superior

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

$$\xi_\alpha \rightarrow \xi'_\alpha = e^{i\theta(x)} \xi_\alpha$$

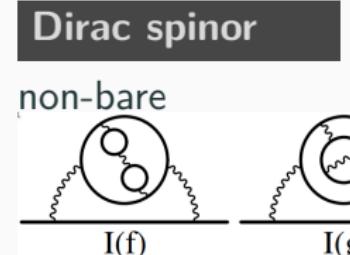
$$\eta^\alpha \rightarrow \eta'^\alpha = e^{-i\theta(x)} \eta^\alpha$$

$$D_\mu \xi_\alpha \rightarrow (D_\mu \xi_\alpha)' = e^{i\theta(x)} D_\mu \xi_\alpha$$

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

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

$$\mathcal{L} = \bar{n} \bar{\psi} \gamma^\mu D_\mu \psi - m \bar{\psi} \psi - \frac{1}{4} F^{\mu\nu} F_{\mu\nu} \rightarrow e \bar{\psi} \gamma^\mu \psi A_\mu$$



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

Not mass, not charge

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

Denial

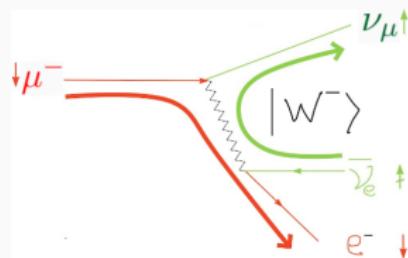
$$|W^0\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle \quad \begin{array}{l} \nearrow \text{green} \\ \searrow \text{green} \end{array}$$

$$|W^+\rangle \quad |\downarrow\uparrow\rangle \quad \begin{array}{l} \nearrow \text{red} \\ \searrow \text{green} \end{array}$$

$$|W^-\rangle \quad |\uparrow\downarrow\rangle \quad \begin{array}{l} \nearrow \text{green} \\ \searrow \text{red} \end{array}$$

$\rightarrow t$

$$\mathcal{L} = i(L)^\dagger \bar{\sigma}^\mu D_\mu L - \tfrac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu}$$

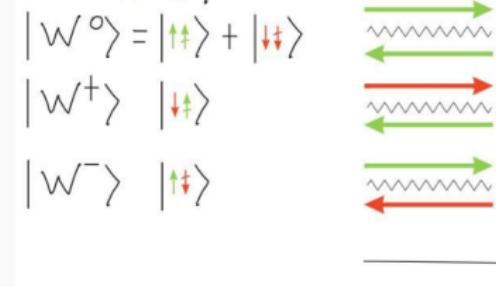


$SU(2)_L \times U(1)_Y \rightarrow D_\mu = \mathbf{1} \partial_\mu - ig_2 \frac{\tau_i}{2} W_\mu^i - ig_1 B_\mu : 17$ years later... (stages of grief $\rightarrow 1967$)

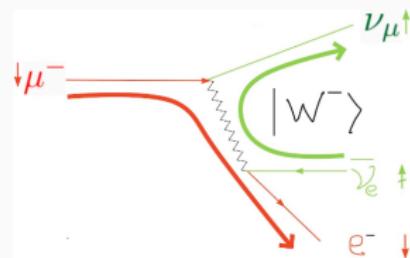
Not mass, hypercharge,

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

Denial



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

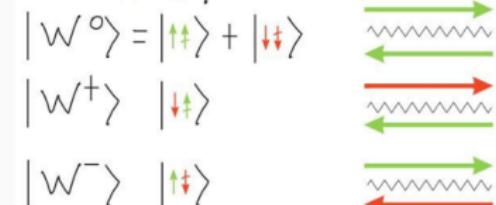


$SU(2)_L \times U(1)_Y \rightarrow D_\mu = \mathbf{1} \partial_\mu - ig_2 \frac{\tau_i}{2} W_\mu^i - ig_1 B_\mu$: 17 years later... (stages of grief \rightarrow 1967)

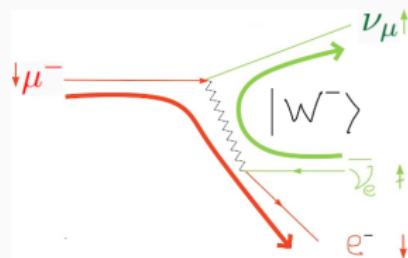
Not mass, hypercharge, not Dirac

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

Denial



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

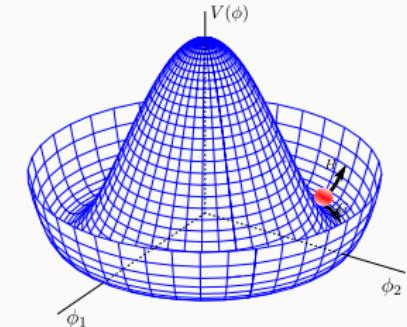


$SU(2)_L \times U(1)_Y \rightarrow D_\mu = \mathbf{1} \partial_\mu - ig_2 \frac{\tau_i}{2} W_\mu^i - ig_1 B_\mu : 17$ years later... (stages of grief $\rightarrow 1967$)

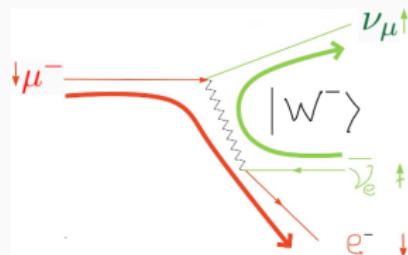
Higgs mechanism: tachyonic mass $\mu^2 < 0$, and condensate

Contempt

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	$1/2$



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



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

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

Field	Lorentz	$SU(2)_L$	$U(1)_Y$	Contempt
$L = \begin{pmatrix} \nu_L \\ e_L \\ (e_R)^\dagger \end{pmatrix}$	ξ_α	$\mathbf{2}$	$-1/2$	
$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \left[\frac{H(x) + v}{\sqrt{2}} \right] \exp \left[i \frac{\tau^i}{2} G_i(x) \right]$	η^α	$\mathbf{1}$	-1	$\begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix},$
	-	$\mathbf{2}$	$1/2$	

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

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

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

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

$SU(2)_L \times U(1)_Y \rightarrow D_\mu = 1\partial_\mu - ig_2 \frac{\tau_i}{2} W_\mu^i - ig_1 B_\mu$: 21 years later... (stages of grief \rightarrow 1971)

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	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



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

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

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

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

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

Hierarchy problem

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	$1/2$

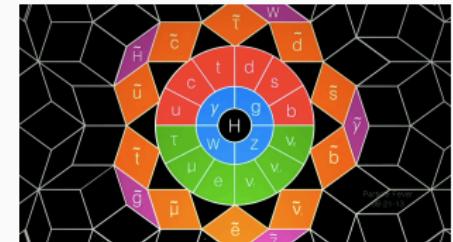
$$\mathcal{L} = i(L)^\dagger \bar{\sigma}^\mu D_\mu L - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + h(e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

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

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

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

Depression



credit: quantumdiaries.org

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

Higgs discovery!

Field

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$$

Lorentz

$$\xi_\alpha$$

$SU(2)_L$

$U(1)_Y$

$$(e_R)^\dagger \quad \eta^\alpha \quad \mathbf{1} \quad -1$$

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

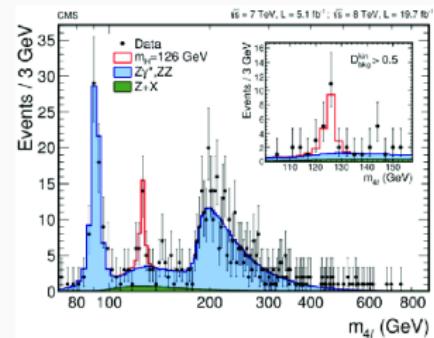
$$\mathcal{L} = i(L)^\dagger \bar{\sigma}^\mu D_\mu L - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - i(e_R)^\dagger \sigma^\mu D_\mu e_R + h(e_R)^\dagger \Phi^\dagger L - (D^\mu \Phi)^\dagger D_\mu \Phi - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2$$

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

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

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

Acceptance



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
```

$$\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \times \textcolor{red}{Z}_2$$

$$\begin{aligned}\mathcal{D}_\mu &= \partial_\mu - i\textcolor{red}{g}_1 Y B_\mu \\ &\quad - i\textcolor{red}{g}_2 T W_\mu^B \\ &\quad - i\textcolor{red}{g}_3 \Lambda G_\mu.\end{aligned}$$

$$B \rightarrow B_\mu, \tilde{B} \implies \mathrm{VB}, \mathrm{FB}$$

```

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};

```

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

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

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

$$+ \mathcal{L}_R,$$

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

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

$$Y_e \rightarrow N_F \times N_F, \dots$$

```
(* 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, HO},      1/2, 2, 1, 1};
ScalarFields[[2]] = {S, 1, ss,            0, 1, 1, -1};
RealScalars = {S};

(* ----- Before EWSB ----- *)
(* 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);
```

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

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

$$\begin{aligned} d_L &= V_d D_L, & (d_R)^\dagger &= D_R^c U_d, \\ V_d &\rightarrow N_F \times N_F, \dots \end{aligned}$$

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

```

(* 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}};

```

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

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

$$\begin{aligned} d_L &= V_d D_L, & (d_R)^\dagger &= D_R^c U_d, \\ V_d &\rightarrow N_F \times N_F, \dots \end{aligned}$$

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]=
{{HO,{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"}},
...
```

```
...
{{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

$$u^c \cdot H \cdot q = \delta_{\alpha}^{\beta} \epsilon_{ab} u_{\alpha}^c H^a q^{\beta b}$$
$$= \bar{3} \times 3 \otimes 2 \times 2.$$

```
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  MICROMEGRAS=MICROMEGRAS  
...  
#-----  
# CalcHEP has compiled successfully 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_M0v5.cpp
```

```
make -C work
...
g++      -g -fPIC  -o CalcOmega_with_DDetection_M0v5 CalcOmega_with_DDetection_M0v5.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

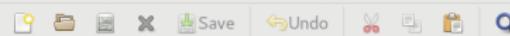
Done. UFO files generated in 30.716s
Output is saved in ****/BSM-Submodules/SARAH/Output/SSDM/EWSB/UFO/
```

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

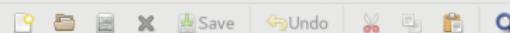
Process	Min element	Max element	Relative diff.	Result
u u~ > mu+ mu-	4.9949890843e-03	4.9949890843e-03	5.2093911919e-15	Passed
Summary:	1/1 passed,	0/1 failed		

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 # LambdaLIN
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 / ?; automatic, 1-loop, 0.2, tree, one, 5-loop
:-... LesHouches.in.SSDM  Top L16  (Fundamental)
```



```
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 # LambdaLIN
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-loop, 0.2; tree, one, or two loop
:-... LesHouches.in.SSDM  Top L16  (Fundamental)
```

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
```



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 2.8000000E-01 # Lambda1IN
  2 1.0000000E-02 # LamSHIN
  3 0.0000000E+00 # LamSIN
  4 2.0000000E+02 # MSinput
Block gaugeGUT Q= -1.0000000E+00 # (GUT scale)
  1 0.0000000E+00 # g1(Q)
  2 0.0000000E+00 # g2(Q)
  3 0.0000000E+00 # g3(Q)
Block SMINPUTS # SM parameters
----- SPheno.spc.SSDM Top L39 (Fundamental)
Beginning of buffer
```



Save Undo

```
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 # ()

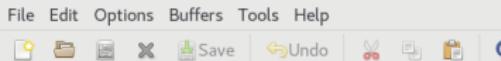
```
1 1 1.00000000E+00 # Real(ZDL(1,1),dp)
1 2 0.00000000E+00 # Real(ZDL(1,2),dp)
1 3 0.00000000E+00 # Real(ZDL(1,3),dp)
```

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

File Edit Options Buffers Tools Help

Save Undo

```
52 0.0000000E+00 # Ignore negative masses
53 0.0000000E+00 # Ignore negative masses at MZ
55 0.0000000E+00 # Calculate one loop masses
56 1.0000000E+00 # Calculate two-loop Higgs masses
57 1.0000000E+00 # Calculate low energy
60 1.0000000E+00 # Include kinetic mixing
65 1.0000000E+00 # Solution of tadpole equation
Block HiggsBoundsInputHiggsCouplingsFermions #
 1.0000000E+00 0.0000000E+00 3 25 5 5 # h_1 b b coupling
 1.0000000E+00 0.0000000E+00 3 25 3 3 # h_1 s s coupling
 1.0000000E+00 0.0000000E+00 3 25 6 6 # h_1 t t coupling
 1.0000000E+00 0.0000000E+00 3 25 4 4 # h_1 c c coupling
 1.0000000E+00 0.0000000E+00 3 25 15 15 # h_1 tau tau coupling
 1.0000000E+00 0.0000000E+00 3 25 13 13 # h_1 mu mu coupling
Block HiggsBoundsInputHiggsCouplingsBosons #
 1.0000000E+00 3 25 24 24 # h_1 W W coupling
 1.0000000E+00 3 25 23 23 # h_1 Z Z coupling
 0.0000000E+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
 0.0000000E+00 4 25 21 21 23 # h_1 g g Z coupling
 0.0000000E+00 3 25 25 23 # h_1 h_1 Z coupling
Block EFFHIGGSCOUPLEDINGS # 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 0.0000000E+00 # H-Photon-Z (not yet calculated by SPheno)
Block SPhenoLowEnergy # low energy observables
 1 -0.0000000E+00 # T-parameter (1-loop BSM)
 2 0.0000000E+00 # S-parameter (1-loop BSM)
 3 0.0000000E+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 0.0000000E+00 # EDM(e)
 24 0.0000000E+00 # EDM(mu)
 25 0.0000000E+00 # EDM(tau)
 39 -3.57242562E-04 # delta(rho)
Block FlavorKitQFV # quark flavor violating observables
 200 3.1500000E-04 # BR(B->X_s gamma)
 201 1.0000000E+00 # BR(B->X_s gamma)/BR(B->X_s gamma) SM
-:--- SPheno.spc.SSDM 22% L186 (Fundamental)
```

```

Block FlavorKit{F# quark flavor violating observables
  2.35200000E+00 # BR(B->s gamma)
  291. 0.00000000E+00 # BR(B->s gamma)/BR(B->s gamma)_SM
  301. 0.00000000E+00 # BR(B->s mu)/BR(B->s mu)_SM
  301. 0.00000000E+00 # BR(B->s mu)/BR(B->s mu)_SM
  301. 0.00000000E+00 # BR(B->s mu)/BR(B->s mu)_SM
  493. 5.72432536E-03 # BR(Ds->nu mu)
  493. 9.88359316E-01 # BR(Ds->nu mu)/BR(Ds->nu mu)_SM
  493. 9.88359316E-01 # BR(Ds->nu mu)/BR(Ds->nu mu)_SM
  493. 9.88359316E-01 # BR(Ds->nu mu)/BR(Ds->nu mu)_SM
  500. 5.85838126E-07 # BR(B->tau nu)
  500. 9.88359316E-01 # BR(B->tau nu)/BR(B->tau nu)_SM
  500. 1.12565735E-04 # BR(B->tau nu)/BR(B->tau nu)_SM
  503. 9.16456406E-01 # BR(B->tau mu)/BR(B->tau mu)_SM
  503. 9.99670267E-01 # BR(K->mu nu)/BR(K->mu nu)_SM
  661. 2.47647745E-01 # R = BR(K->mu nu)/(K->mu nu)
  661. 9.99670267E-01 # BR(K->mu nu)/BR(K->mu nu)_SM
  1996. 8.90838770E+01 # Delta(B)0/Delta(B)0
  1996. 8.90838770E+01 # Delta(B)0/Delta(B)0
  1996. 8.90838770E+01 # Delta(B)0/Delta(B)0
  1996. 8.90838770E+01 # Delta(B)0/Delta(B)0
  4000. 1.06152026E-15 # BR(B->d e e)
  4000. 1.06152026E-15 # BR(B->d e e)/BR(B->d -> e)_SM
  4002. 1.88801776E-14 # BR(B->d e e)/BR(B->d -> e)_SM
  4003. 1.06009362E-09 # BR(B->d e e)/BR(B->d -> e)_SM
  4005. 5.34959864E-11 # BR(B->d -> mu)
  4005. 1.06009362E-09 # BR(B->d -> mu)/BR(B->d -> mu)_SM
  3. 87118106E-09 # BR(B->d -> mu)/BR(B->d -> mu)_SM
  3. 87118106E-09 # BR(B->d -> mu)/BR(B->d -> mu)_SM
  1000. 1.06009352E-06 # BR(B->d -> tau)/BR(B->d -> tau)_SM
  1000. 1.06009352E-06 # BR(B->d -> tau)/BR(B->d -> tau)_SM
  1000. 1.06009352E-06 # BR(B->d -> tau)/BR(B->d -> tau)_SM
  1000. 5.1320996E-07 # BR(B->d -> tau tau)
  1000. 5.1320996E-07 # BR(B->d -> tau tau)
  1000. 5.1320996E-07 # BR(B->d -> tau tau)/BR(B->d -> tau tau)_SM
  1000. 6.6411441E-06 # BR(B->s e e)
  5001. 9.16172479E-01 # BR(B->s + e) / BR(B->s + e)_SM
  5001. 9.16172479E-01 # BR(B->s + e) / BR(B->s + e)_SM
  5003. 9.14717306E-01 # BR(B->s mu) / BR(B->s mu) _SM
  6000. 1.1694138E-07 # BR(B-> K mu) mu
  6000. 1.1694138E-07 # BR(B-> K mu) mu / BR(B-> K mu) _SM
  6002. 1.1998413E-07 # BR(B-> K mu) mu / BR(B-> K mu) _SM
  6003. 9.9913779E-01 # BR(B-> K mu) mu / BR(B-> K mu) _SM
  6003. 9.9913779E-01 # BR(B-> K mu) mu / BR(B-> K mu) _SM
  7001. 8.0642094E-06 # BR(B->s nu) / BR(B->s nu) _SM
  7001. 8.0642094E-06 # BR(B->s nu) / BR(B->s nu) _SM
  7002. 8.8737935E-07 # BR(B->s nu) / BR(B->s nu) _SM
  7003. 8.00000000E+00 # BR(B->s nu) / BR(B->s nu) _SM
  8000. 1.00000000E+00 # BR(B->s nu) / BR(B->s nu) _SM
  8001. 8.00000000E+00 # BR(K-> pi+ mu nu)/BR(K-> pi+ mu nu)
  8002. 6.2288751E-43 # BR(KL-> pi- mu nu)/BR(KL-> pi- mu nu)
  8003. 8.00000000E+00 # BR(KL-> pi- mu nu)/BR(KL-> pi- mu nu)
  8004. 8.00000000E+00 # BR(KL-> pi- mu nu)/BR(KL-> pi- mu nu)
  8005. 8.00000000E+00 # BR(KL-> pi- mu nu)/BR(KL-> pi- mu nu)

```

Block FlavorKitEV # lepton flavor violating observables

```

701 0.0000000E+00 # BR(mu->e gamma)
702 0.0000000E+00 # BR(tau->e gamma)
703 0.0000000E+00 # BR(tau->mu gamma)

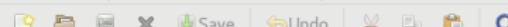
```

```

1001 0 0.00000000e+00 # BR(Z-> e-)
1002 0 0.00000000e+00 # BR(Z-> e+)
1101 0 0.00000000e+00 # BR(h-> mu-)
1102 0 0.00000000e+00 # BR(h-> mu+)
1103 0 0.00000000e+00 # BR(h-> tau-)
2001 0 0.00000000e+00 # BR(tau-> pi+)
2002 0 0.00000000e+00 # BR(tau-> pi0)
2003 0 0.00000000e+00 # BR(tau-> pi-)
2004 0 0.00000000e+00 # BR(tau-> eta)
2005 0 0.00000000e+00 # BR(tau-> eta')
Block PMCC = 1.00000000e+00 # Wilson coefficients at scale 0
0305 4422 0 0 -0.16470160 # cmtFCfcm
0305 4422 0 1 0.00000000 # cmtFCfcp
0305 4322 0 2 -0.37708923 # cmtFCTp
0305 4422 0 0 0.00000000e+00 # cmtFCf0
0305 4422 0 1 0.00000000e+00 # cmtFCf0p

```

0305	6421	00	00	-8.8547618E-09	#	confTCBall
0305	6421	00	2	-8.8547618E-09	#	confTCB8
0305	6321	00	2	-0.1930484E-10	#	confTCBp
0305	6421	00	1	-0.1930484E-10	#	confTCBpp
0305	6421	00	0	-0.3864968E-10	#	confTCBppP
03051111	4133	00	00	-8.1615354E-06	#	confTCBallSM
03051111	4133	00	2	-8.1615354E-06	#	confTCBee
03051111	4233	00	2	-2.2161505E-14	#	confTCBppEE
03051111	4133	00	1	-2.2161505E-14	#	confTCBppP



```

01050105 3232 00 0 0.0000000E+00 # coeffBB_SRRSM
01050105 3132 00 0 0.0000000E+00 # coeffBB_SLRSM
01050105 4141 00 0 0.0000000E+00 # coeffBB_VLLSM
01050105 4242 00 0 0.0000000E+00 # coeffBB_VRRSM
01050105 4142 00 0 0.0000000E+00 # coeffBB_VLRSM
01050105 4343 00 0 0.0000000E+00 # coeffBB_TLLSM
01050105 4444 00 0 0.0000000E+00 # coeffBB_TRRSM
03050305 3131 00 0 0.0000000E+00 # coeffBsBs_SLLSM
03050305 3232 00 0 0.0000000E+00 # coeffBsBs_SRRSM
03050305 3132 00 0 0.0000000E+00 # coeffBsBs_SLRSM
03050305 4141 00 0 0.0000000E+00 # coeffBsBs_VLLSM
03050305 4242 00 0 0.0000000E+00 # coeffBsBs_VRRSM
03050305 4142 00 0 0.0000000E+00 # coeffBsBs_VLRSM
03050305 4343 00 0 0.0000000E+00 # coeffBsBs_TLLSM
03050305 4444 00 0 0.0000000E+00 # coeffBsBs_TRRSM

Block TREELEVELUNITARITY #
  0 1.0000000E+00 # Tree-level unitarity limits fulfilled or not
  1 1.67207372E-02 # Maximal scattering eigenvalue

Block TREELEVELUNITARITYwTRILINEARS #
  0 1.0000000E+00 # Tree-level unitarity limits fulfilled or not
  1 1.61576897E-02 # Maximal scattering eigenvalue
  2 2.0000000E+03 # best scattering energy
  11 1.0000000E+03 # min scattering energy
  12 2.0000000E+03 # max scattering energy
  13 5.0000000E+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
  1.6759777E-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 )

```

BR($h \rightarrow S S$) = 26%

- : --- SPheNo.spc.SSDM 93% L632 (Fundamental)

Run micrOMEGAs

```
micromegas/SSDM/CalcOmega_with_DDetection_M0v5 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.pdf> [CPC]

```
pip install minimal-lagrangians
```

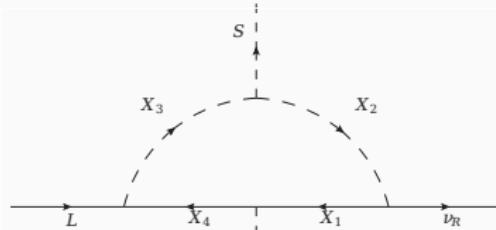
- As the program was originally written for the study of minimal darkmatter models with radiative neutrino masses: D. Restrepo, O. Zapata, C. E. Yaguna, Models with radiative neutrino masses and viable dark matter candidates, arXiv:1308.3655 [JHEP]
- Lagrangians for the individual models.
- Model files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

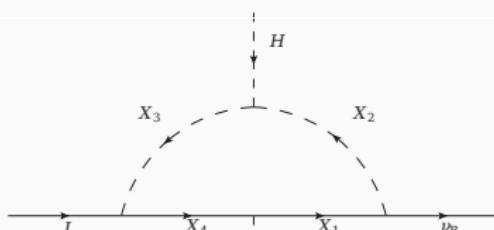
```
BSMModel('T1-3-B', (
    FermionField("Psi", 1, Y= 0),
    FermionField("Psi'", 2, Y= 1),
    ScalarField ("phi", 3, Y= 0),
    FermionField("Psi''", 2, Y=-1), 6), (0, 2)), # = -2 is equivalent to= 2
```

Dirac neutrino masses

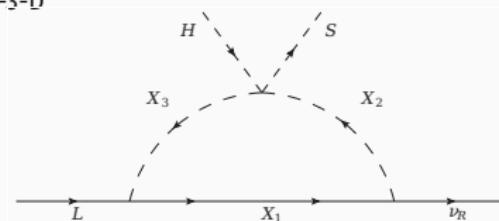
One loop topologies $U(1)_{B-L} \oplus Z_2 \oplus Z_2$



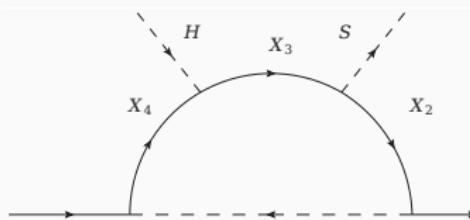
T1-3-D



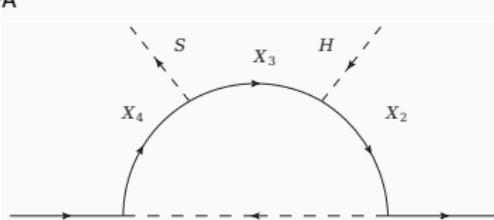
T1-3-E



T3-1-A



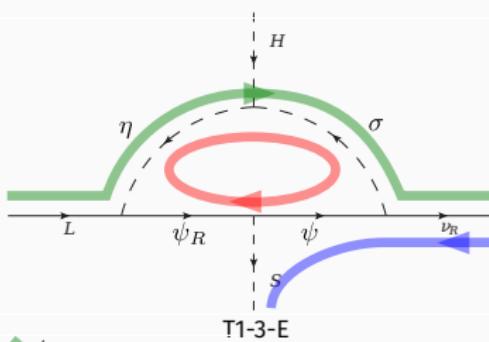
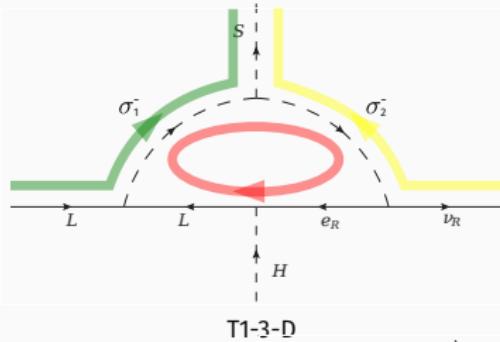
T1-2-A



T1-2-B

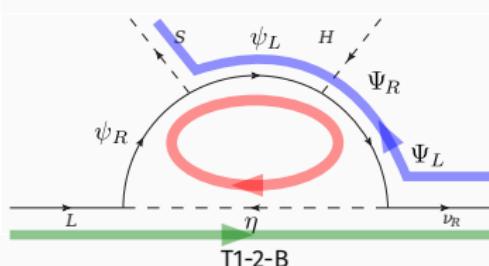
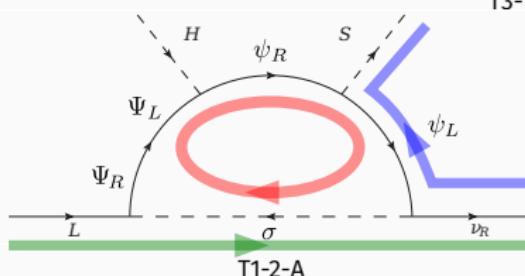
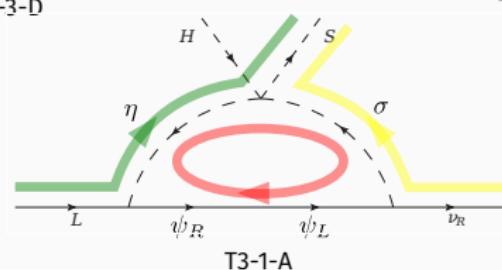
Chang-Yuan Yao and Gui-Jun Ding, arXiv:1802.05231 [PRD]

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

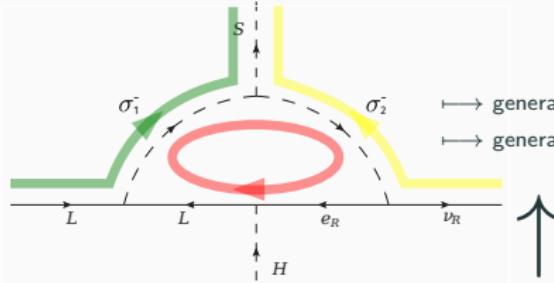


$\psi_{L,R} \rightarrow$ Singlet fermions (vector-like)
 $\sigma \rightarrow$ Singlet scalar

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



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

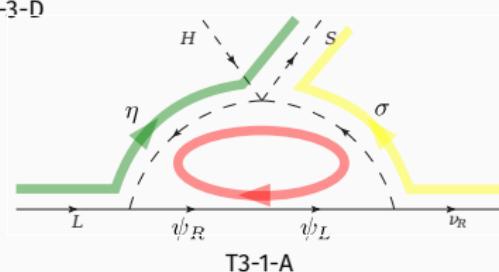


→ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]
 → generalization to $U(1)_R$: et al, S. Saad arXiv:1904.07407

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

T1-3-D

$\psi_{L,R} \rightarrow$ Singlet fermions (vector-like)
 $\sigma \rightarrow$ Singlet scalar



T3-1-A

Anomaly cancellation conditions

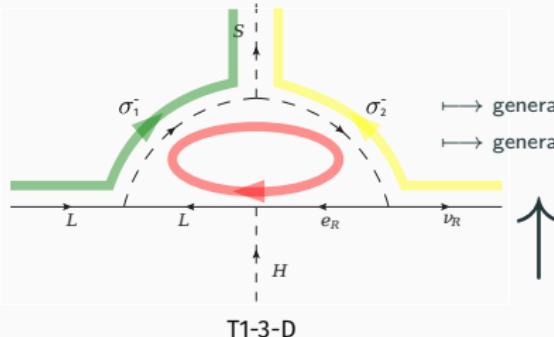
$$\sum_i \nu_{Ri} = -3$$

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

Three-level cancellation conditions

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

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



→ generalization to two and three loops: S. Saad arXiv:1902.07259 [NPB]
 → generalization to $U(1)_R$: et al, S. Saad arXiv:1904.07407

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

Anomaly cancellation conditions

$\sigma \rightarrow$ Singlet scalar

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

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

Three-level cancellation conditions

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

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 .
```

SP1/Run/SP1-BLDZ/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
```

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

✿ 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
 - [SARAH](#) V4.14.2 (Transferred to W.Porod)
 - [SPheno](#)
 - [MicrOMEGAS](#)
 - [MadGraph](#)
 - [MadAnalysis](#)
 - [FlavorKit](#)

Contact

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

For questions and comments, you can send me an [e-mail](#).

✿ 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](#)

Contact

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

For questions and comments, you can send me an [e-mail](#).

✿ 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 programs 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](#)

Input/Output

Code



Contact

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

For questions and comments, you can send me an [e-mail](#).

Observables already in FlavorKit

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

Ready to be computed in your favourite model!

Observables already in FlavorKit

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

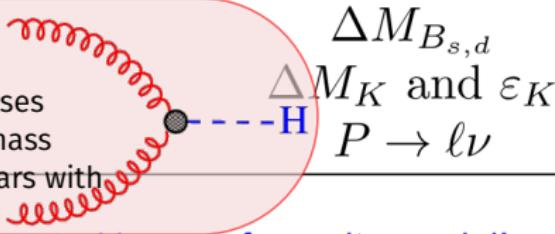
Also in SARAH

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



Ready to be computed in your favourite model!

✿ 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 programs 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

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

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

Supersymmetric Models

- Minimal supersymmetric SM
- NMSSM (in several versions)
- Minimal R-minimal SSM (near-MSM_{inv})
- General singlet extended SSM (GMSM)
- DiracNMSM
- 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

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

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

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/>