ν-DARK MATTER MODELS

MODEL BUILDING

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Focus on

arXiv: arXiv:1308.3655 (JHEP), arXiv:1504.07892 (PRD), arXiv:1509.06313, arXiv:1511.01873, arXiv:1512.nnnnn.

In collaboration with

G. Palacio, F. von der Pahlen, D. Portillo, A. Rivera, M. Sánchez, O. Zapata (UdeA)

C. Arbeláez (USM), W. Tangarife (Tel Aviv U.), C. Yaguna (Heidelberg, Max Planck Inst.).

III Encuentro Nacional de Física de Sabores **Pesados**

December 12, Ibagué

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Review of SM

Boost in x

$$\{x^\mu\} = \begin{pmatrix} t \\ x \\ y \\ z \end{pmatrix} \to \begin{pmatrix} t' \\ x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} \frac{t+vx}{\sqrt{1-v^2}} \\ \frac{x+vt}{\sqrt{1-v^2}} \\ y \\ z \end{pmatrix} = \begin{pmatrix} \cosh\xi & \sinh\xi & 0 & 0 \\ \sinh\xi & \cosh\xi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} t \\ x \\ y \\ z \end{pmatrix}$$

$$x'^\mu \to x^\mu = \Lambda_x{}^\mu{}_\nu x^\nu \,,$$

where ($c = 1$)

$$\cosh\xi = \gamma \qquad \sinh\xi = v\gamma, \qquad \text{and} \qquad \gamma = \frac{1}{\sqrt{1-v^2}}.$$

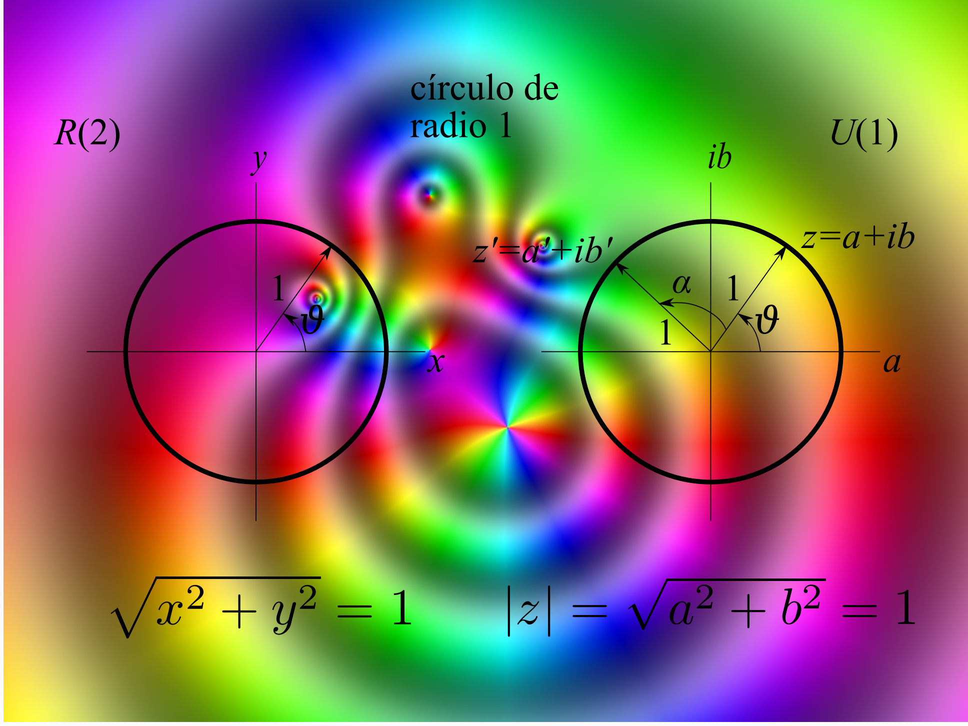
In general

$$\Lambda^\mu{}_\nu = \left[\exp\left(\boldsymbol{\xi}\cdot\mathsf{K} + i\boldsymbol{\theta}\cdot\mathsf{L}\right)\right]^\mu{}_\nu$$

$$x'\cdot y' = x'_\mu y'^\mu = x_\mu y^\mu \,, \qquad \text{if:} \qquad g_{\alpha\beta} = \Lambda^\mu{}_\alpha g_{\mu\nu} \Lambda^\nu{}_\beta \,.$$

For each continuous simetry there is at least one conserved charge.

Emmy Noether (1882-1935)


círculo de radio 1
R(2)
U(1)
y
x
ib
a
1
ϑ
α
z′=a′+ib′
z=a+ib
$\sqrt{x^2+y^2}=1$
$|z|=\sqrt{a^2+b^2}=1$

Lorentz+$U(1)$:

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi - \mu^2 \phi^* \phi - \lambda \left(\phi^* \phi\right)^2 \, . \tag{1}$$

$$\begin{aligned}
\phi(x) \to \phi'(x') =& \phi(\Lambda^{-1}x) && \text{Scalar field}\\
A^\mu(x) \to A'^\mu =& \Lambda^\mu{}_\nu A^\nu(\Lambda^{-1}x) && \text{Vector field}\\
\psi_\alpha(x) \to \psi'_\alpha(x) =& [S(\Lambda)]_\alpha{}^\beta \psi_\beta(\Lambda^{-1}x)\,, && \text{Left Weyl spinor}\\
(\psi_\alpha(x))^\dagger = \psi^\dagger_{\dot\alpha}(x) \to \psi'^\dagger_{\dot\alpha}(x) =& [S^*(\Lambda)]_{\dot\alpha}{}^{\dot\beta} \psi^\dagger_{\dot\beta}(\Lambda^{-1}x)\,, && \text{Right anti-Weyl spin}
\end{aligned}$$

With

$$S(\Lambda) = \exp\left(\boldsymbol{\xi} \cdot \frac{\boldsymbol{\sigma}}{2} + i\boldsymbol{\theta} \cdot \frac{\boldsymbol{\sigma}}{2}\right) \, ,$$

where $\boldsymbol{\sigma} = (\sigma_1, \sigma_2, \sigma_3)$ are the Pauli matrices. $\overline{\boldsymbol{\sigma}} \equiv -\boldsymbol{\sigma}$.

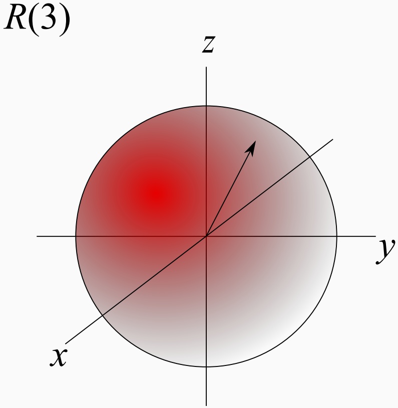
Electron field: *one in four*: Dreiner,... arXiv:0812.1594 (PR)

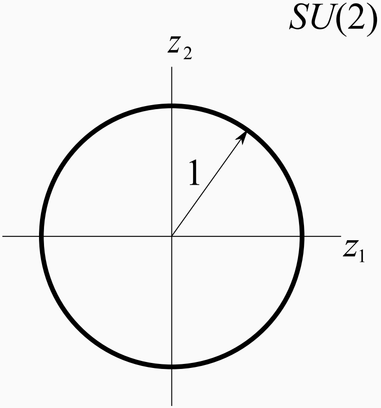
Scalar product: $\quad {}^{\alpha}{}_{\alpha} \quad$ and $\quad {}_{\dot{\alpha}}{}^{\dot{\alpha}}$.

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

$$\begin{aligned}\mathcal{L} =& i\xi^\dagger_{\dot{\alpha}}\overline{\sigma}^{\mu\,\dot{\alpha}\alpha}\partial_\mu\xi_\alpha + i\eta^\alpha\sigma^\mu_{\alpha\dot{\alpha}}\partial_\mu\eta^{\dagger\,\dot{\alpha}} - m\left(\eta^\alpha\xi_\alpha + \xi^\dagger_{\dot{\alpha}}\eta^{\dagger\,\dot{\alpha}}\right)\\ =& i\xi^\dagger\overline{\sigma}^\mu\partial_\mu\xi + i\eta\sigma^\mu\partial_\mu\eta^\dagger - m\left(\eta\xi + \xi^\dagger\eta^\dagger\right)\,. \end{aligned} \tag{2}$$

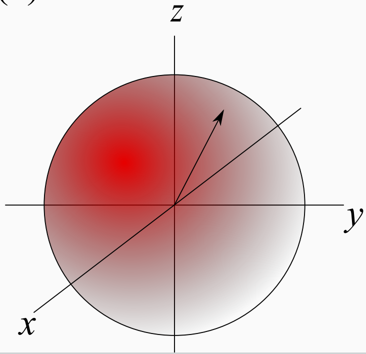
3 generadores



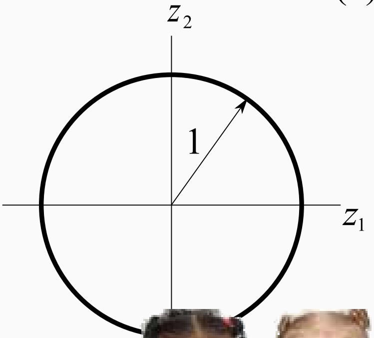


3 generadores

$R(3)$



$SU(2)$

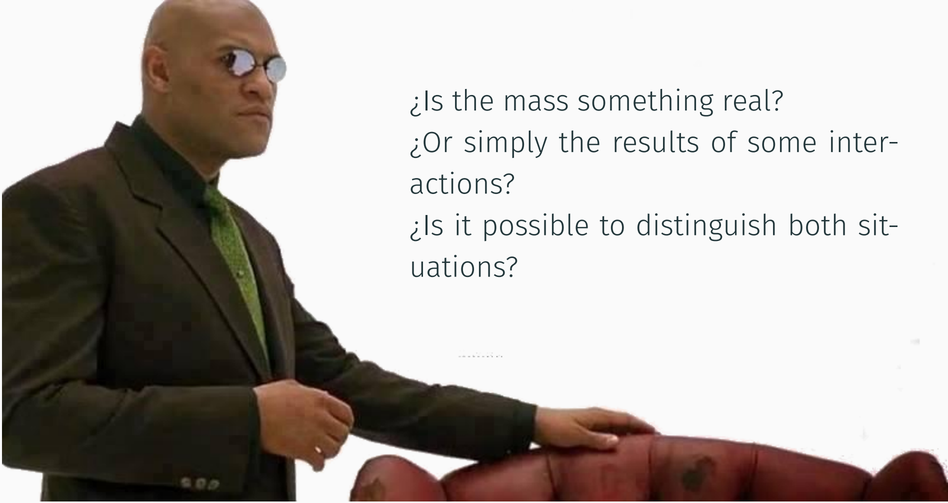


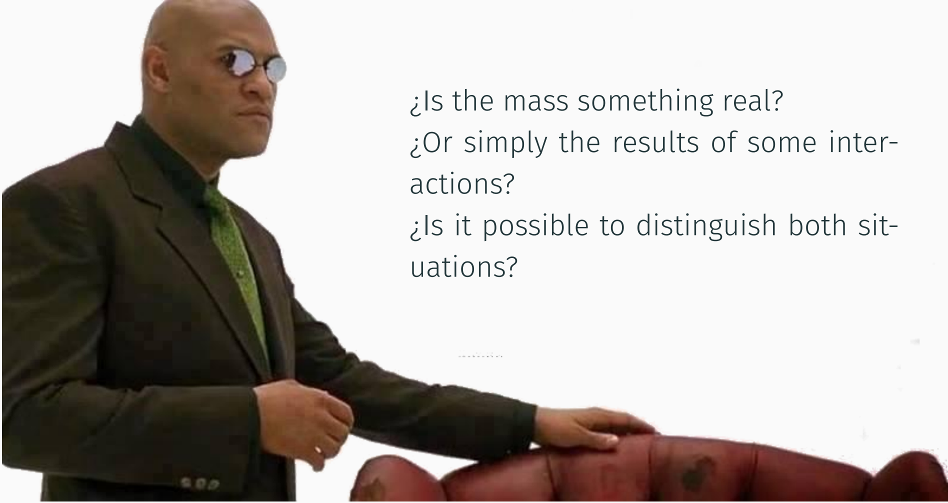
$SU(2)_L$ in an ideal Universe

$$L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad Q = \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

Massless states with same (hyper)charge!

¿Is the mass something real?
¿Or simply the results of some interactions?
¿Is it possible to distinguish both situations?

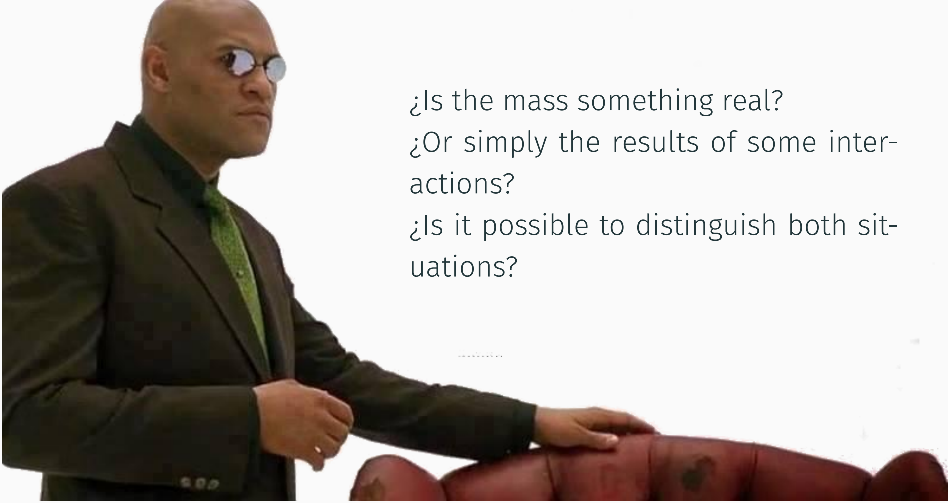




¿Is the mass something real?
¿Or simply the results of some interactions?
¿Is it possible to distinguish both situations?

Answer

- Prediction of charm quark (Bjorken-Glashow 1964)
- W and Z mass and SM Higgs boson



Answer

- Prediction of charm quark (Bjorken-Glashow 1964)
- W and Z mass and SM Higgs boson
- $m_{\text{proton}} \gg 2m_u + m_d$

Consider the left-quark up: u

$$\Psi_L^u = \begin{pmatrix} u_L \\ u_L \\ u_L \end{pmatrix}$$

Let $U(x) \in SU(N)$ and Ψ a multiplet of left spinors under $SU(N)$. We replace ∂_μ by the covariant derivative $\mathcal{D}_\mu$:

$$\Psi \to \Psi' = U\Psi\,, \qquad \Psi^\dagger \to \Psi'^\dagger = \Psi^\dagger U^\dagger\,,$$
$$\mathcal{D}_\mu\Psi \to (\mathcal{D}_\mu\Psi)' = U\left(\mathcal{D}_\mu\Psi\right)\,, \quad (\mathcal{D}_\mu\Psi)^\dagger \to (\mathcal{D}_\mu\Psi)'^\dagger = (\mathcal{D}_\mu\Psi)^\dagger\, U^\dagger\,,$$

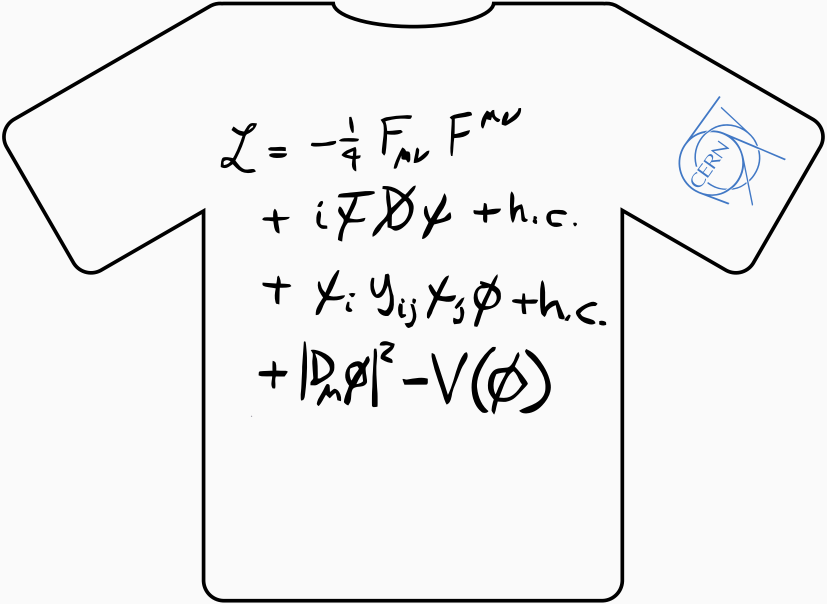
since the mass term is forbidden

$$\mathcal{L}_{SU(N)} = i\Psi\,\overline{\sigma}^\mu\mathcal{D}_\mu\Psi - \frac{1}{2}\operatorname{Tr}\left(G_{\mu\nu}G^{\mu\nu}\right)$$

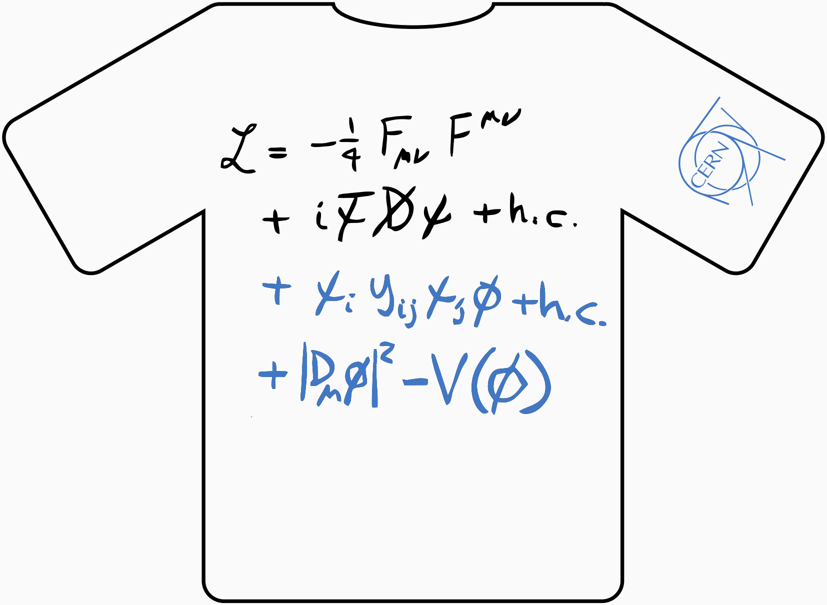
with the following $N\times N$ matrix equations ($\alpha_N \equiv g^2/4\pi$ is the $SU(N)$ coupling)

$$\mathcal{D}_\mu = \mathbf{1}\partial_\mu - igG_\mu\,, \qquad \widehat{G}_{\mu\nu} = \frac{i}{g}\left[\mathcal{D}_\mu, \mathcal{D}_\nu\right]$$

Details: `http://fisica.udea.edu.co`→`cursos`→ `Física Subatómica`


$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i \bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$
CERN

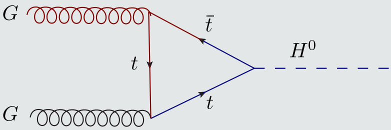
Standard Model Lagrangian (simplified version)



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c. + \psi_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Gluon fusion

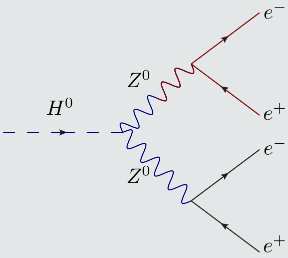
$i\bar{\psi}\not{D}\psi$



$\psi_i y_{ij} \psi_j \phi$

Golden channel

$|D_\mu \phi|^2$



$i\bar{\psi}\not{D}\psi$

$SU(3)_c$

$d_L^1 \quad d_L^2 \quad d_L^3$

$d_R^1 \quad d_R^2 \quad d_R^3$

$SU(3)_c$

$$\begin{array}{ccc} d_L^1 & d_L^2 & d_L^3 \\ u_L^1 & u_L^2 & u_L^3 \\ d_R^1 & d_R^2 & d_R^3 \\ u_R^1 & u_R^2 & u_R^3 \end{array}$$

Standard Model: particles

$SU(3)_c$

$$\begin{matrix} d_L^1 & d_L^2 & d_L^3 & s_L^1 & s_L^2 & s_L^3 & b_L^1 & b_L^2 & b_L^3 \\ u_L^1 & u_L^2 & u_L^3 & c_L^1 & c_L^2 & c_L^3 & t_L^1 & t_L^2 & t_L^3 \\ d_R^1 & d_R^2 & d_R^3 & s_R^1 & s_R^2 & s_R^3 & b_R^1 & b_R^2 & b_R^3 \\ u_R^1 & u_R^2 & u_R^3 & c_R^1 & c_R^2 & c_R^3 & t_R^1 & t_R^2 & t_R^3 \end{matrix}$$

$SU(3)_c$

$$
\begin{array}{l} G_1 \\ G_2 \\ \vdots \\ G_8 \end{array}
\left\{
\begin{array}{ccccccccccccc}
d_L^1 & d_L^2 & d_L^3 & s_L^1 & s_L^2 & s_L^3 & b_L^1 & b_L^2 & b_L^3 & \multirow{2}{*}{$\rightarrow$} & d_L^\alpha & s_L^\alpha & b_L^\alpha \\
u_L^1 & u_L^2 & u_L^3 & c_L^1 & c_L^2 & c_L^3 & t_L^1 & t_L^2 & t_L^3 & & u_L^\alpha & c_L^\alpha & t_L^\alpha \\
d_R^1 & d_R^2 & d_R^3 & s_R^1 & s_R^2 & s_R^3 & b_R^1 & b_R^2 & b_R^3 & \rightarrow & d_R^\alpha & s_R^\alpha & b_R^\alpha \\
u_R^1 & u_R^2 & u_R^3 & c_R^1 & c_R^2 & c_R^3 & t_R^1 & t_R^2 & t_R^3 & \rightarrow & u_R^\alpha & c_R^\alpha & t_R^\alpha
\end{array}
\right.
$$

$SU(3)_c$

$$
\begin{array}{llllllllllllll}
 & & & & & & & & & & & e_R & \mu_R & \tau_R \\
 & & & & & & & & & & & e_L & \mu_L & \tau_L \\
 & & & & & & & & & & & \nu_L^e & \nu_L^\mu & \nu_L^\tau \\
G_1 & \multirow{4}{*}{\Bigg\{} & d_L^1 & d_L^2 & d_L^3 & s_L^1 & s_L^2 & s_L^3 & b_L^1 & b_L^2 & b_L^3 & d_L^\alpha & s_L^\alpha & b_L^\alpha \\
G_2 & & u_L^1 & u_L^2 & u_L^3 & c_L^1 & c_L^2 & c_L^3 & t_L^1 & t_L^2 & t_L^3 \rightarrow & u_L^\alpha & c_L^\alpha & t_L^\alpha \\
\vdots & & d_R^1 & d_R^2 & d_R^3 & s_R^1 & s_R^2 & s_R^3 & b_R^1 & b_R^2 & b_R^3 \rightarrow & d_R^\alpha & s_R^\alpha & b_R^\alpha \\
G_8 & & u_R^1 & u_R^2 & u_R^3 & c_R^1 & c_R^2 & c_R^3 & t_R^1 & t_R^2 & t_R^3 \rightarrow & u_R^\alpha & c_R^\alpha & t_R^\alpha
\end{array}
$$

$$SU(3)_c \times SU(2)_L$$

$$
\begin{array}{llllllllllllllllll}
 & & & & & & & & & & & & e_R & \mu_R & \tau_R & & & \\
 & W^{\pm} & \Big\{ & & & & & & & & & & \left.\begin{matrix} e_L & \mu_L & \tau_L \\ \nu_L^e & \nu_L^\mu & \nu_L^\tau \end{matrix}\right\} & & & L_1 & L_2 & L_3 \\
G_1 & W^{\pm} & \left\{\begin{matrix} d_L^1 \\ u_L^1 \end{matrix}\right. & d_L^2 & d_L^3 & s_L^1 & s_L^2 & s_L^3 & b_L^1 & b_L^2 & b_L^3 & \to & \left.\begin{matrix} d_L^\alpha & s_L^\alpha & b_L^\alpha \\ u_L^\alpha & c_L^\alpha & t_L^\alpha \end{matrix}\right\} & & & Q_1^\alpha & Q_2^\alpha & Q_3^\alpha \\
G_2 & & & u_L^2 & u_L^3 & c_L^1 & c_L^2 & c_L^3 & t_L^1 & t_L^2 & t_L^3 & & & & & & & \\
\vdots & & d_R^1 & d_R^2 & d_R^3 & s_R^1 & s_R^2 & s_R^3 & b_R^1 & b_R^2 & b_R^3 & \to & d_R^\alpha & s_R^\alpha & b_R^\alpha & & & \\
G_8 & & u_R^1 & u_R^2 & u_R^3 & c_R^1 & c_R^2 & c_R^3 & t_R^1 & t_R^2 & t_R^3 & \to & u_R^\alpha & c_R^\alpha & t_R^\alpha & & &
\end{array}
$$

$$m_i = 0$$

$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$
\begin{array}{c}
Z^0 \\ \gamma
\end{array}
\left\{
\begin{array}{l}
\begin{array}{cc}
W^{\pm} & \left\{ \begin{array}{c} \\ \\ \\ \end{array} \right.
\end{array} \\
\begin{array}{c} G_1 \\ G_2 \\ \vdots \\ G_8 \end{array}
\left\{
\begin{array}{l}
W^{\pm} \left\{ \begin{array}{ccccccccc}
d_L^1 & d_L^2 & d_L^3 & s_L^1 & s_L^2 & s_L^3 & b_L^1 & b_L^2 & b_L^3 \\
u_L^1 & u_L^2 & u_L^3 & c_L^1 & c_L^2 & c_L^3 & t_L^1 & t_L^2 & t_L^3
\end{array} \right. \\
\qquad\;\; \begin{array}{ccccccccc}
d_R^1 & d_R^2 & d_R^3 & s_R^1 & s_R^2 & s_R^3 & b_R^1 & b_R^2 & b_R^3 \\
u_R^1 & u_R^2 & u_R^3 & c_R^1 & c_R^2 & c_R^3 & t_R^1 & t_R^2 & t_R^3
\end{array}
\end{array}
\right.
\end{array}
\right.
\begin{array}{c}
\\ \\ \\ \\ \rightarrow \\ \rightarrow \\ \rightarrow
\end{array}
\begin{array}{l}
\begin{array}{ccc} e_R & \mu_R & \tau_R \end{array} \\
\left.\begin{array}{ccc} e_L & \mu_L & \tau_L \\ \nu_L^e & \nu_L^\mu & \nu_L^\tau \end{array}\right\} \quad L_1 \quad L_2 \quad L_3 \\
\left.\begin{array}{ccc} d_L^\alpha & s_L^\alpha & b_L^\alpha \\ u_L^\alpha & c_L^\alpha & t_L^\alpha \end{array}\right\} \quad Q_1^\alpha \quad Q_2^\alpha \quad Q_3^\alpha \\
\begin{array}{ccc} d_R^\alpha & s_R^\alpha & b_R^\alpha \\ u_R^\alpha & c_R^\alpha & t_R^\alpha \end{array}
\end{array}
$$

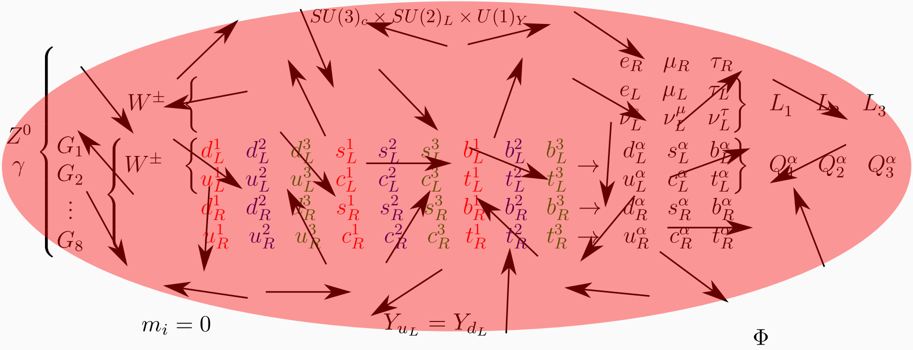
$$m_i = 0 \qquad\qquad Y_{u_L} = Y_{d_L}$$

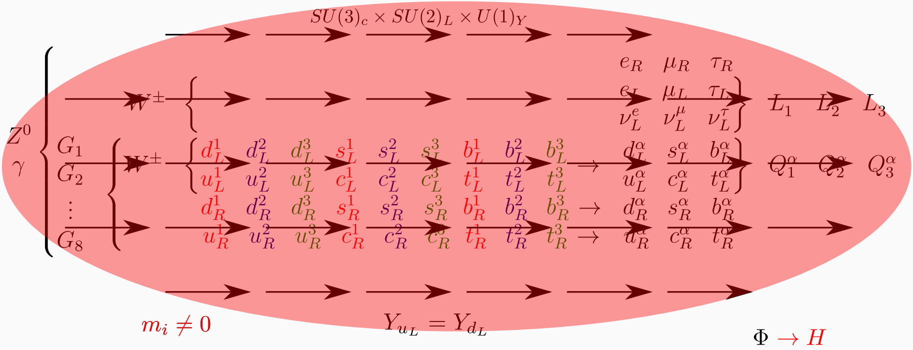
Standard Model: particles

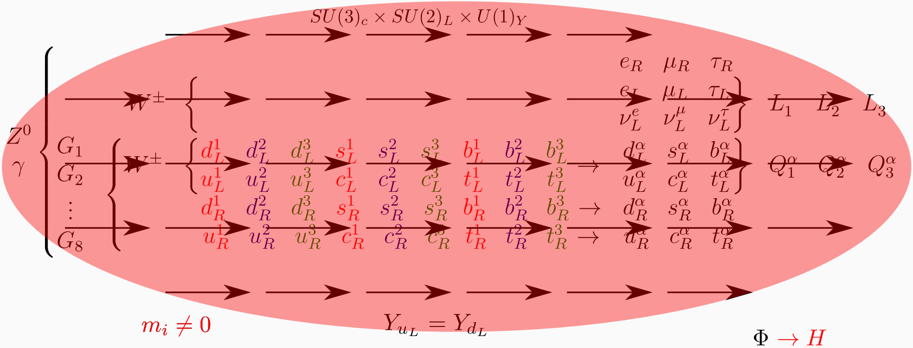
$$SU(3)_c \times SU(2)_L \times U(1)_Y$$

$$
\begin{array}{cccccccccccccccccccc}
 & & & & & & & & & & & & & e_R & \mu_R & \tau_R & & & & 3 \\
 & & W^{\pm} & \left\{ \begin{array}{c} \\ \\ \end{array} \right. & & & & & & & & & & \left. \begin{array}{c} e_L \\ \nu_L^e \end{array} \right. & \begin{array}{c} \mu_L \\ \nu_L^{\mu} \end{array} & \left. \begin{array}{c} \tau_L \\ \nu_L^{\tau} \end{array} \right\} & L_1 & L_2 & L_3 & 3 \\
Z^0 & \left\{ \begin{array}{c} G_1 \\ G_2 \\ \vdots \\ G_8 \end{array} \right. & \left\{ W^{\pm} \right. & \left\{ \begin{array}{c} d_L^1 \\ u_L^1 \end{array} \right. & \begin{array}{c} d_L^2 \\ u_L^2 \end{array} & \begin{array}{c} d_L^3 \\ u_L^3 \end{array} & \begin{array}{c} s_L^1 \\ c_L^1 \end{array} & \begin{array}{c} s_L^2 \\ c_L^2 \end{array} & \begin{array}{c} s_L^3 \\ c_L^3 \end{array} & \begin{array}{c} b_L^1 \\ t_L^1 \end{array} & \begin{array}{c} b_L^2 \\ t_L^2 \end{array} & \begin{array}{c} b_L^3 \\ t_L^3 \end{array} & \rightarrow & \begin{array}{c} d_L^{\alpha} \\ u_L^{\alpha} \end{array} & \begin{array}{c} s_L^{\alpha} \\ c_L^{\alpha} \end{array} & \left. \begin{array}{c} b_L^{\alpha} \\ t_L^{\alpha} \end{array} \right\} & Q_1^{\alpha} & Q_2^{\alpha} & Q_3^{\alpha} & 3 \\
\gamma & & & d_R^1 & d_R^2 & d_R^3 & s_R^1 & s_R^2 & s_R^3 & b_R^1 & b_R^2 & b_R^3 & \rightarrow & d_R^{\alpha} & s_R^{\alpha} & b_R^{\alpha} & & & & 3 \\
 & & & u_R^1 & u_R^2 & u_R^3 & c_R^1 & c_R^2 & c_R^3 & t_R^1 & t_R^2 & t_R^3 & \rightarrow & u_R^{\alpha} & c_R^{\alpha} & t_R^{\alpha} & & & & 3 \\
\hline
2 & 8 & 2=12 & & & & & & & & & & & & & & & & & 15
\end{array}
$$

$$m_i = 0 \qquad\qquad Y_{u_L} = Y_{d_L}$$


$SU(3)_c \times SU(2)_L \times U(1)_Y$
$e_R \quad \mu_R \quad \tau_R$
$e_L \quad \mu_L \quad \tau_L$
$\nu_L^e \quad \nu_L^\mu \quad \nu_L^\tau$
$L_1 \quad L_2 \quad L_3$
Z^0
γ
$W^\pm$
$W^\pm$
G_1
G_2
$\vdots$
G_8
$d_L^1 \quad d_L^2 \quad d_L^3 \quad s_L^1 \quad s_L^2 \quad s_L^3 \quad b_L^1 \quad b_L^2 \quad b_L^3 \to d_L^\alpha \quad s_L^\alpha \quad b_L^\alpha$
$u_L^1 \quad u_L^2 \quad u_L^3 \quad c_L^1 \quad c_L^2 \quad c_L^3 \quad t_L^1 \quad t_L^2 \quad t_L^3 \to u_L^\alpha \quad c_L^\alpha \quad t_L^\alpha$
$Q_1^\alpha \quad Q_2^\alpha \quad Q_3^\alpha$
$d_R^1 \quad d_R^2 \quad d_R^3 \quad s_R^1 \quad s_R^2 \quad s_R^3 \quad b_R^1 \quad b_R^2 \quad b_R^3 \to d_R^\alpha \quad s_R^\alpha \quad b_R^\alpha$
$u_R^1 \quad u_R^2 \quad u_R^3 \quad c_R^1 \quad c_R^2 \quad c_R^3 \quad t_R^1 \quad t_R^2 \quad t_R^3 \to u_R^\alpha \quad c_R^\alpha \quad t_R^\alpha$
$m_i = 0$
$Y_{u_L} = Y_{d_L}$
Φ


$SU(3)_c \times SU(2)_L \times U(1)_Y$
Z^0
γ
$W^\pm$
$W^\pm$
G_1
G_2
$\vdots$
G_8
e_R μ_R τ_R
e_L μ_L τ_L
ν_L^e ν_L^μ ν_L^τ
L_1 L_2 L_3
d_L^1 d_L^2 d_L^3 s_L^1 s_L^2 s_L^3 b_L^1 b_L^2 b_L^3 $\Rightarrow$ d_L^α s_L^α b_L^α
u_L^1 u_L^2 u_L^3 c_L^1 c_L^2 c_L^3 t_L^1 t_L^2 t_L^3 u_L^α c_L^α t_L^α
Q_1^α Q_2^α Q_3^α
d_R^1 d_R^2 d_R^3 s_R^1 s_R^2 s_R^3 b_R^1 b_R^2 b_R^3 $\rightarrow$ d_R^α s_R^α b_R^α
u_R^1 u_R^2 u_R^3 c_R^1 c_R^2 c_R^3 t_R^1 t_R^2 t_R^3 $\rightarrow$ u_R^α c_R^α t_R^α
$m_i \neq 0$
$Y_{u_L} = Y_{d_L}$
$\Phi \rightarrow H$



SM fields + Gauge + Lorentz Invariance→*Lagrangian*

Electroweak superconductor (*Higgs condensate*) with emergent masses which allows

- confined baryons (nuclear physics)
- atoms (chemistry)

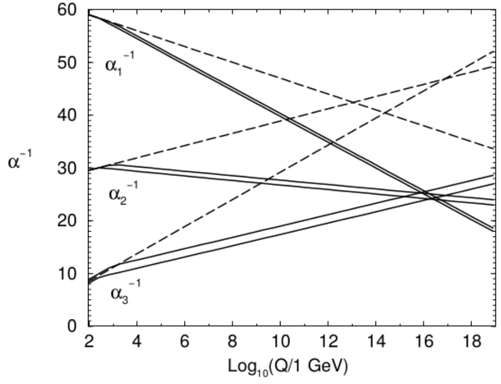
Dark matter and unification

Unification: $SO(10)$

$$16_{F_i} = \begin{pmatrix} {u_R}^\dagger \\ {u_R}^\dagger \\ {u_R}^\dagger \\ u_L \\ u_L \\ u_L \\ d_L \\ d_L \\ d_L \\ {d_R}^\dagger \\ {d_R}^\dagger \\ {d_R}^\dagger \\ \nu_L \\ e_L \\ {e_R}^\dagger \\ N \end{pmatrix}_i \qquad \Rightarrow \mathcal{L}_{SM} \supset h\, \mathbf{16}_F \times \mathbf{16}_F \times \mathbf{10}_S + \text{h.c}$$

Standard Model: Z_2-even	New Z_2-odd particles
Fermions: $\mathbf{16}_F$	$\mathbf{10}_F, \mathbf{45}_F, \cdots$
Scalars: $\mathbf{10}_H, \mathbf{45}_H \cdots$	$\mathbf{16}_H, \cdots$

Lightest Odd Particle (LOP) may be a suitable dark matter candidate, and can improve gauge coupling unification



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	fermions	scalars
$SU(2)_L \times U(1)_Y$ representation	even $SO(10)$ representations	odd $SO(10)$ representations
1_0	45, 54, 126, 210	16, 144
$2_{\pm 1/2}$	10, 120, 126, 210, 210′	16, 144
3_0	45, 54, 210	144

$SU(3)_C$: 3 (T), 6, 8 (Λ)

$$m_{3_0} = 2.7\text{ TeV}, \qquad m_\Lambda \sim 10^{10}\text{ TeV}, \qquad m_{\text{GUT}} \sim 10^{16}\text{ GeV}.$$

arXiv:0912.1545 (Frigerio-Hambye)

NOT-SUSY SO(10) $\to SU(5) \to$ SU(3)$_C \times SU(2)_L \times$ U(1)$_Y \times Z_2$

Standard Model: Z_2-even	New Z_2-odd particles
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Split-SUSY like

arXiv:1509.06313 (C. Arbelaez, R. Longas, D.R, O. Zapata)

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Radiative hybrid seesaw (Parida 1106.4137) or 1509.06313

Partial Split-SUSY-like spectrum: bino-higgsino-wino

+ $\downarrow$

$\mathbf{10}'_H$ with fermion DM or, $\mathbf{16}_H, \cdots$ with scalar DM

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$SU(3)_C$: 3 (T), 6, 8 (Λ)

1509.06313

SUSY-like spectrum: bino-higgsino-wino

+ $\downarrow$

$\mathbf{10}'_H$ with fermion DM or, $\mathbf{16}_H, \cdots$ with scalar DM

Singlet-Doublet-Triplet fermion dark-matter

The most general SO(10) invariant Lagrangian contains the following Yukawa terms

$$-\mathcal{L} \supset Y\mathbf{10}_F\mathbf{45}_F\mathbf{10}_H + M_{\mathbf{45}_F}\mathbf{45}_F\mathbf{45}_F + M_{\mathbf{10}_F}\mathbf{10}_F\mathbf{10}_F$$

Basis

$$\boldsymbol{\psi}^0 = \left(N, \Sigma^0, \psi_L^0, (\psi_R^0)^\dagger\right)^T$$

$$\mathcal{M}_{\boldsymbol{\psi}^0} =$$

$$\begin{pmatrix} M_N & 0 & -y\,c_\beta v/\sqrt{2} & y\,s_\beta v/\sqrt{2} \\ 0 & M_\Sigma & f\,c_{\beta'} v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} \\ -y\,c_\beta v/\sqrt{2} & f\,c_{\beta'} v/\sqrt{2} & 0 & -M_D \\ y\,s_\beta v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$

Model used for the Nimatron proposal: arXiv:1511.06495

Physics Opportunities of a 100 TeV Proton-Proton Collider

Nima Arkani-Hamed, T. Han, M. Mangano, LT Wang.

Singlet-Doublet-Triplet fermion dark-matter

The most general SO(10) invariant Lagrangian contains the following Yukawa terms

$$-\mathcal{L} \supset Y 10_F 45_F 10_H + M_{45_F} 45_F 45_F + M_{10_F} 10_F 10_F + \mathcal{L}(10_\Phi \quad).$$

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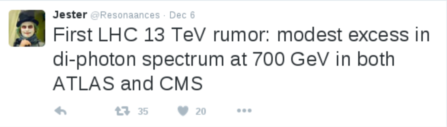
$$\psi^0 = \left(N, \Sigma^0, \psi_L^0, (\psi_R^0)^\dagger\right)^T$$

$$\mathcal{M}_{\psi^0} = \begin{pmatrix} M_N & 0 & -y\,c_\beta v/\sqrt{2} & y\,s_\beta v/\sqrt{2} \\ 0 & M_\Sigma & f\,c_{\beta'} v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} \\ -y\,c_\beta v/\sqrt{2} & f\,c_{\beta'} v/\sqrt{2} & 0 & -M_D \\ y\,s_\beta v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$



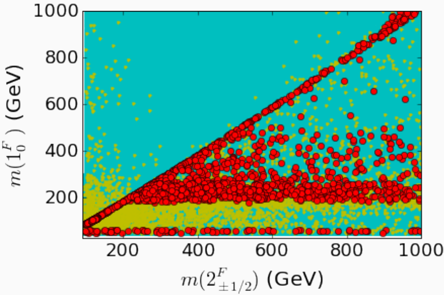
The most general SO(10) invariant Lagrangian contains the following Yukawa terms

$$-\mathcal{L} \supset Y 10_F 45_F 10_H + M_{45_F} 45_F 45_F + M_{10_F} 10_F 10_F + \mathcal{L}(10_\Phi \text{ or } 16_\Phi).$$

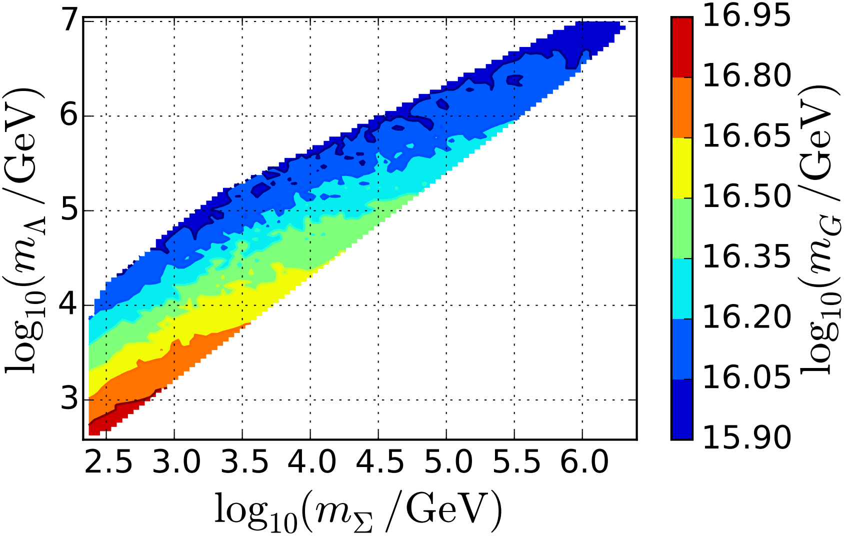
Basis

$$\psi^0 = \left(N, \Sigma^0, \psi_L^0, (\psi_R^0)^\dagger\right)^T$$

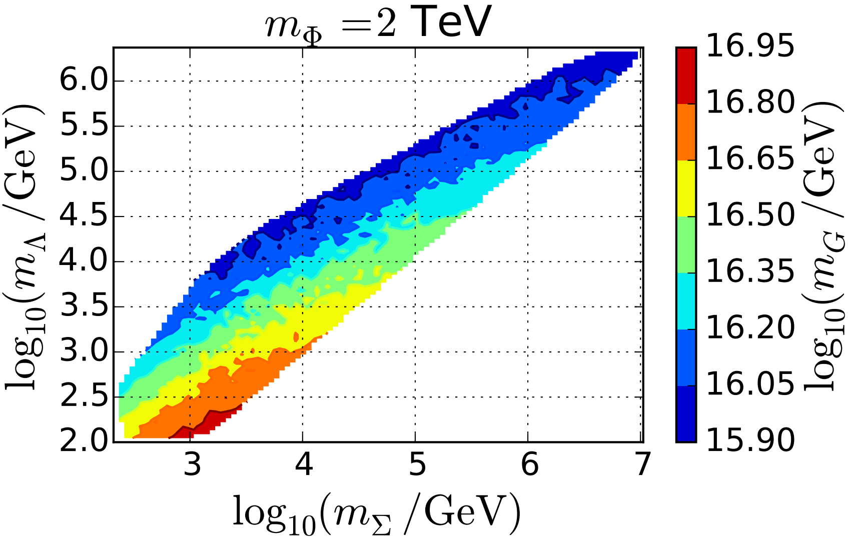
$$\mathcal{M}_{\psi^0} = \begin{pmatrix} M_N & 0 & -y\,c_\beta v/\sqrt{2} & y\,s_\beta v/\sqrt{2} \\ 0 & M_\Sigma & f\,c_{\beta'} v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} \\ -y\,c_\beta v/\sqrt{2} & f\,c_{\beta'} v/\sqrt{2} & 0 & -M_D \\ y\,s_\beta v/\sqrt{2} & -f\,s_{\beta'} v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$

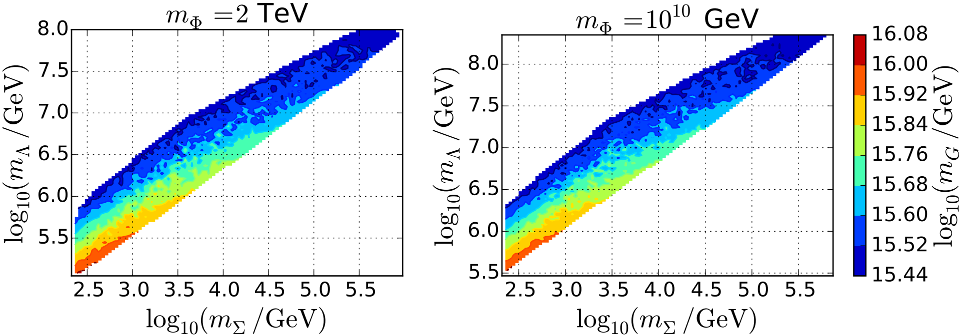


Split-SUSY like



Partial split-SUSY like





m_Φ =2 TeV
m_Φ $=10^{10}$ GeV
$\log_{10}(m_\Lambda\,/\mathrm{GeV})$
$\log_{10}(m_\Sigma\,/\mathrm{GeV})$
$\log_{10}(m_G\,/\mathrm{GeV})$
16.08
16.00
15.92
15.84
15.76
15.68
15.60
15.52
15.44

Beyond the standard model

Singlet scalar dark matter

$$Z_2: \qquad \mathcal{L}_{SM} \to \mathcal{L}_{SM}\,, \qquad S \to -S\,.$$

$$\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{1}{4}\lambda S^4 + \lambda_{SH}\Phi^\dagger \Phi S^2.$$

Singlet fermion: Seesaw

$$\mathcal{L} = \mathcal{L}_{SM} + i N^\dagger \overline{\sigma}^\mu \partial_\mu N + \left(h_\nu L \cdot \Phi N - M\, NN + \text{h.c}\right)\,,$$

$$m_1 \sim \frac{h_\nu v^2}{\sqrt{2} M}\,, \qquad m_2 \sim M\,.$$

$$M \gg h_\nu v/\sqrt{2}$$

SARAH implementation

- Automatic generation of `Fortran-90` SPheno code and interaction-basis Les-Houches Accord (LHA) input file, for calculation of:
  - 1-loop spectrum
  - Decay branching (including generic one loop $S \to \gamma\gamma, GG$)
  - LFV observables
  - LHA output

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    - `CalcHEP`
    - `micrOMEGAS`
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    - `...`

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  - `...`
- **Hint**: Use `SARAH Toolbox` toolkit:

  `https://sarah.hepforge.org/Toolbox.html`

```
$  ./butler SSDM #Your model name
```

SSDM in SARAH- I

./SARAH/Models/SSDM/SSDM.m

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

  FermionFields[[1]] = {q, 3, {uL, dL},     1/6, 2,  3,1};
  FermionFields[[2]] = {l, 3, {vL, eL},    -1/2, 2,  1,1};
  FermionFields[[3]] = {d, 3, conj[dR],     1/3, 1, -3,1};
  FermionFields[[4]] = {u, 3, conj[uR],    -2/3, 1, -3,1};
  FermionFields[[5]] = {e, 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};
  ```
  ```

-
```
...
NameOfStates={GaugeES, EWSB};

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


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);
LagHC =  -(Yu H.u.q+Yd conj[H].d.q + Ye conj[H].e.l);
```

SSDM in SARAH- III

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

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

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

  DEFINITION[EWSB][DiracSpinors]={
   Fd ->{  DL, conj[DR]}, ...
  ```
  ```

General framework

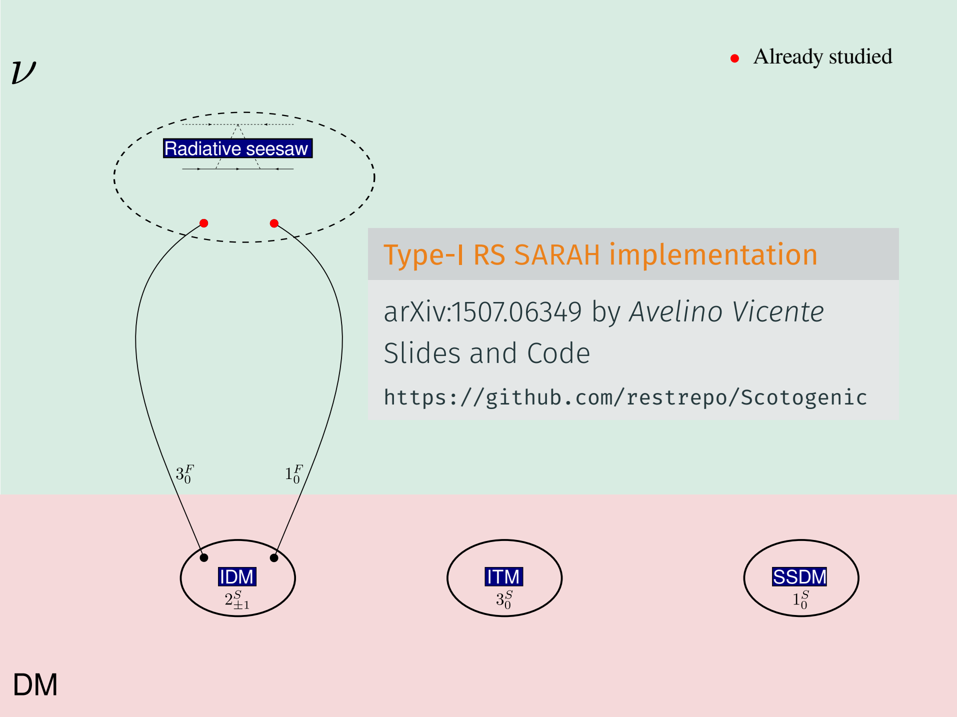
If neutrino masses arise radiatively it may originate from new physics at the TeV scale in join with dark matter (DM)

It may be, though, that they are related to each other.

In this direction, models with one-loop radiative neutrino masses and viable dark matter candidates have now a complete classification given in

R.D., Yaguna, C, Zapata, O, arXiv:1308.3655 (JHEP)

There, the new fields are odd under a Z_2 symmetry which ensures the stability of the DM particle, while the SM particles are even.

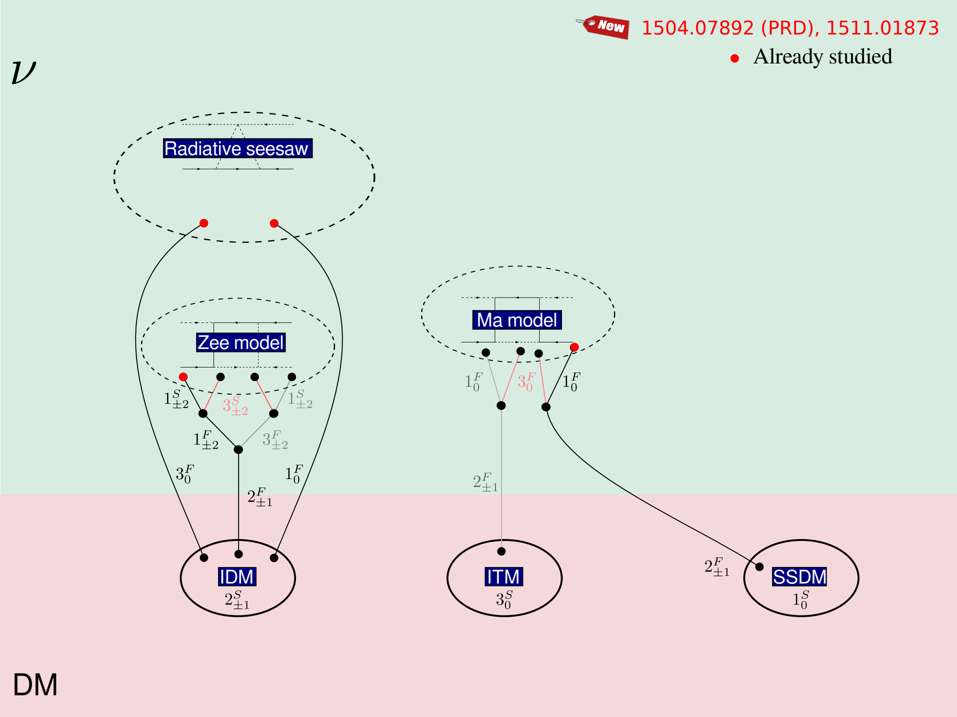


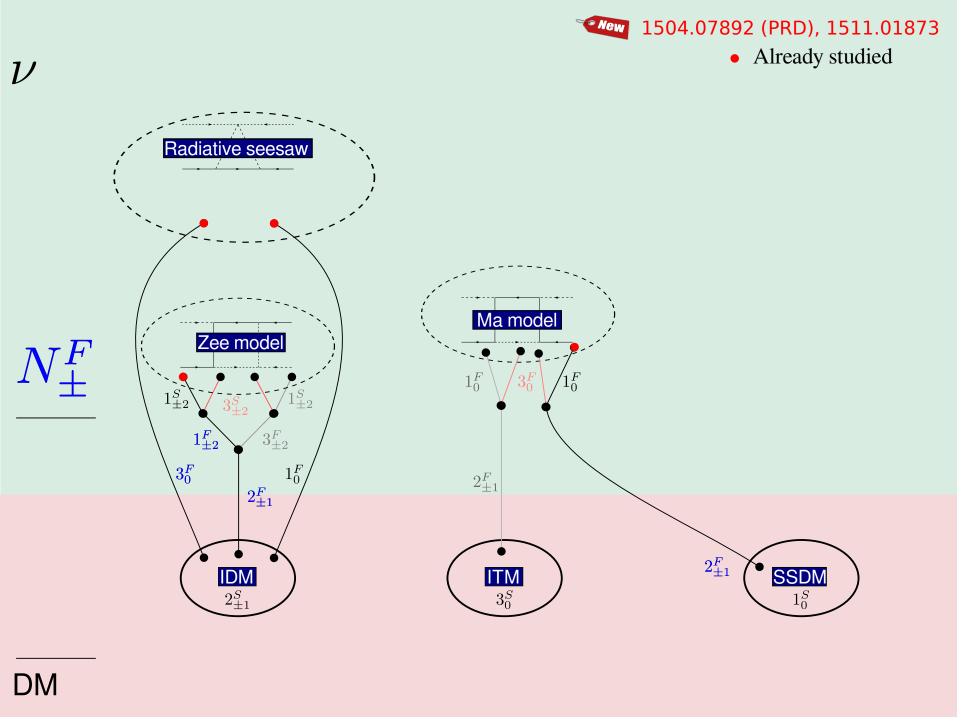
Type-I RS SARAH implementation

arXiv:1507.06349 by *Avelino Vicente*

Slides and Code

`https://github.com/restrepo/Scotogenic`


New
1504.07892 (PRD), 1511.01873
Already studied
ν
Radiative seesaw
Zee model
Ma model
$1^S_{\pm 2}$
$3^S_{\pm 2}$
$1^S_{\pm 2}$
$1^F_{\pm 2}$
$3^F_{\pm 2}$
3^F_0
1^F_0
$2^F_{\pm 1}$
1^F_0
3^F_0
1^F_0
$2^F_{\pm 1}$
$2^F_{\pm 1}$
IDM
$2^S_{\pm 1}$
ITM
3^S_0
SSDM
1^S_0
DM



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3^F_0
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1^F_0
1^F_0
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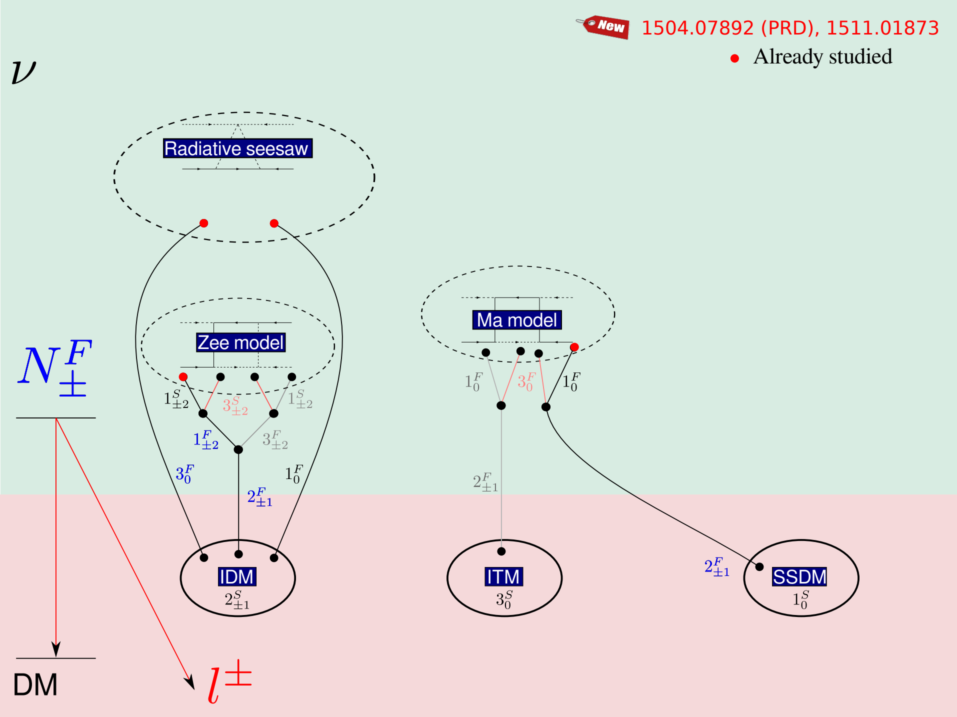
DM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ν
Radiative seesaw
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$N^F_{\pm}$
DM
$l^{\pm}$
$1^S_{\pm 2}$
$3^S_{\pm 2}$
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$1^F_{\pm 2}$
$3^F_{\pm 2}$
3^F_0
$2^F_{\pm 1}$
1^F_0
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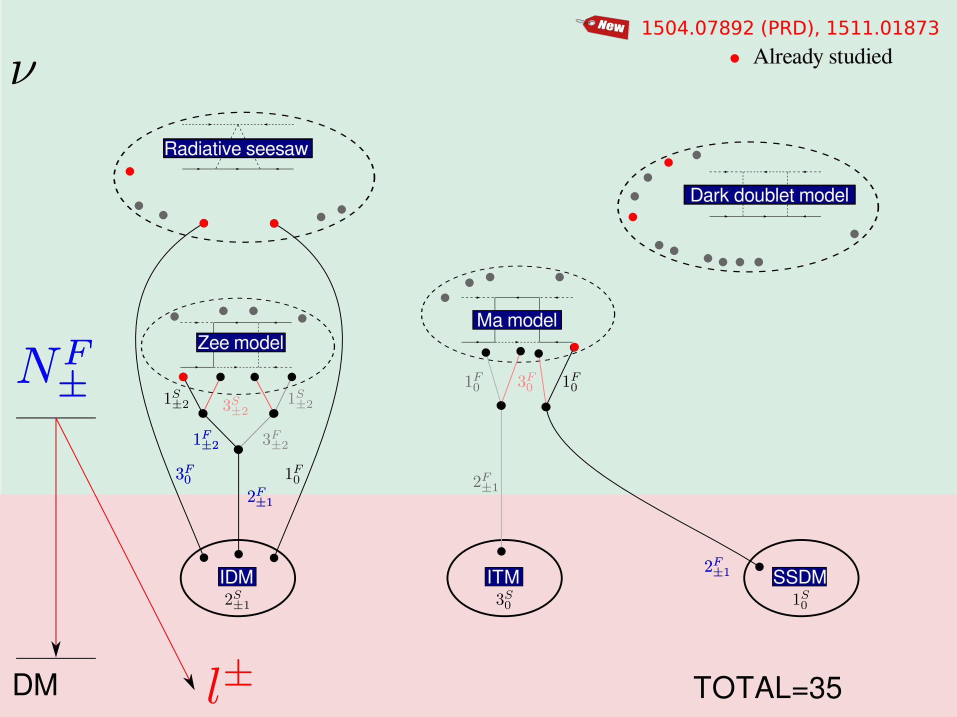
3^F_0
1^F_0
$2^F_{\pm 1}$
$2^F_{\pm 1}$
IDM
$2^S_{\pm 1}$
ITM
3^S_0
SSDM
1^S_0



New
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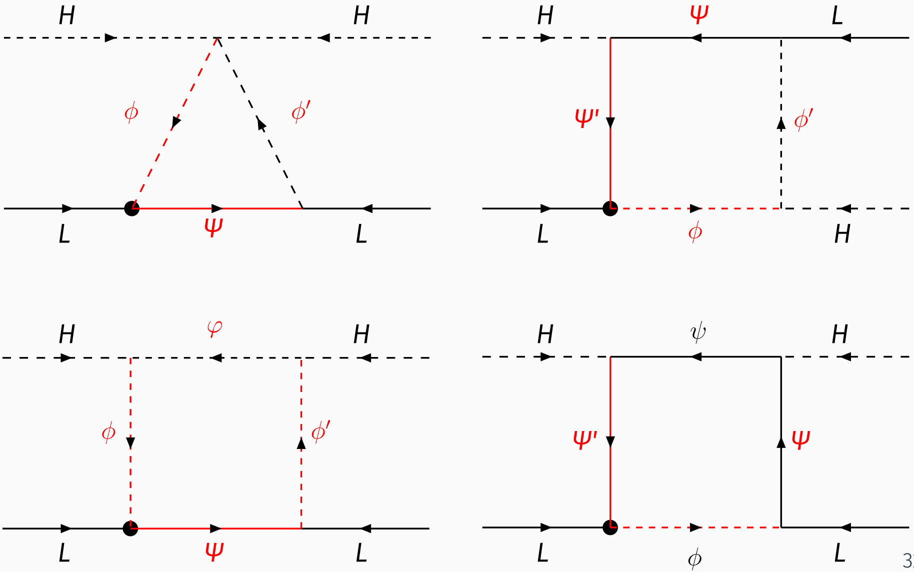
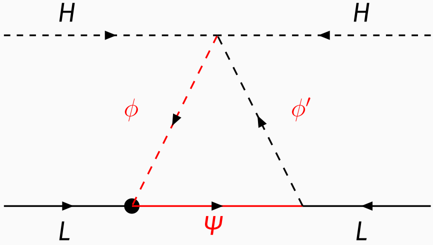
Already studied
ν
Radiative seesaw
Dark doublet model
Zee model
Ma model
$N^F_{\pm}$
$1^S_{\pm2}$
$3^S_{\pm2}$
$1^S_{\pm2}$
$1^F_{\pm2}$
$3^F_{\pm2}$
3^F_0
1^F_0
$2^F_{\pm1}$
1^F_0
3^F_0
1^F_0
$2^F_{\pm1}$
$2^F_{\pm1}$
IDM
$2^S_{\pm1}$
ITM
3^S_0
SSDM
1^S_0
DM
$l^{\pm}$
TOTAL=35

Weinberg operator at one-loop

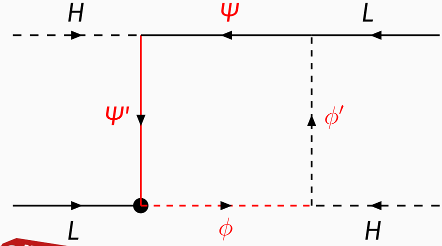
(Z_2-odd fields)



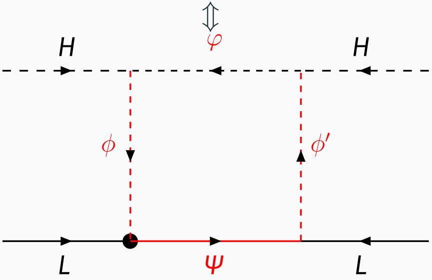
(Z_2-odd fields)

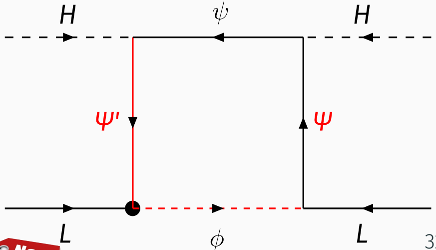


Wino-like scotogenic model



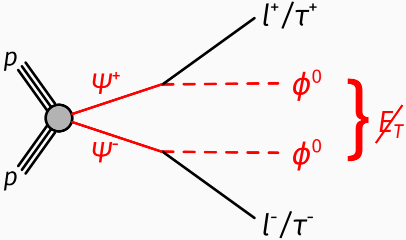
New Higgsino-like Zee model





New Higgsino-like scotogenic model

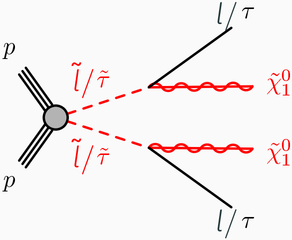
Proposal: $pp \to l^+ l^- + \not{E}_T$

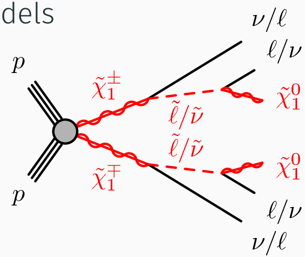


SU(2)$_L$ assignments:

$\Psi = 1, 2, 3\,, \qquad \Phi = 1, 2\,,$ with $m_{\rm DM} \sim m_h/2\,.$

Simplified SUSY models

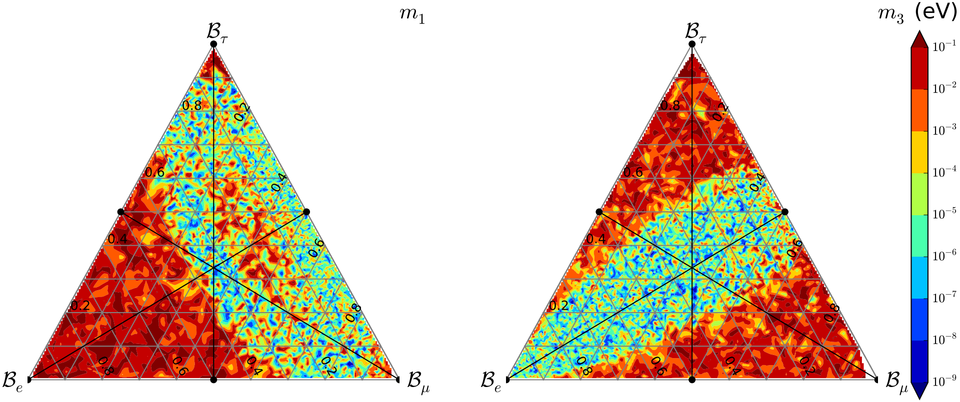




Smaller cross sections. Intermediate states and smaller lepton $\not{p}_T$

Lepton flavor dependence

In wino-like scotogenic model (may be in general)



$$\mathcal{B}_l = \mathcal{B}\left(\psi^{\pm} \to l H^0\right)$$

Recast at the LHC Run-I (wino-like scenario)

Wino-like escotogenic model: Recast for $B_\mu + B_e \gtrsim 0.1$ and

$$m_{H^0} < m_{\psi^\pm} = m_{\psi^0} < m_{A^0}, m_{H^\pm}$$

Start with Signal regions as in ATLAS-arXiv:1403.5294 for $\not{E}_T$ with e^+e^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$.

`FeynRules`

$\Downarrow$

`micrOMEGAS` (Experimental and theoretical constraints)

$\Downarrow$

`MadGraph`

$\Downarrow$

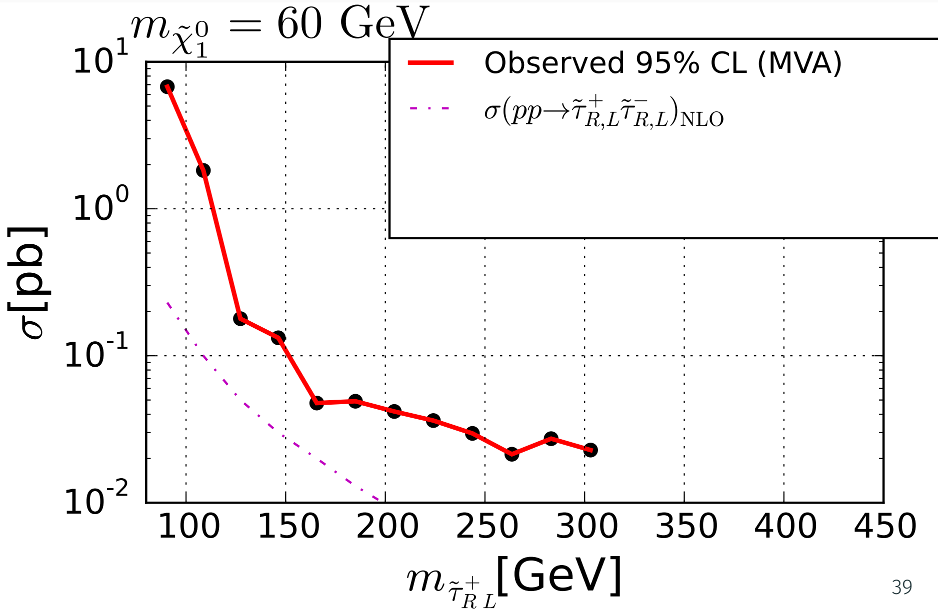
`Pythia 6` (`hep` format)

$\Downarrow$

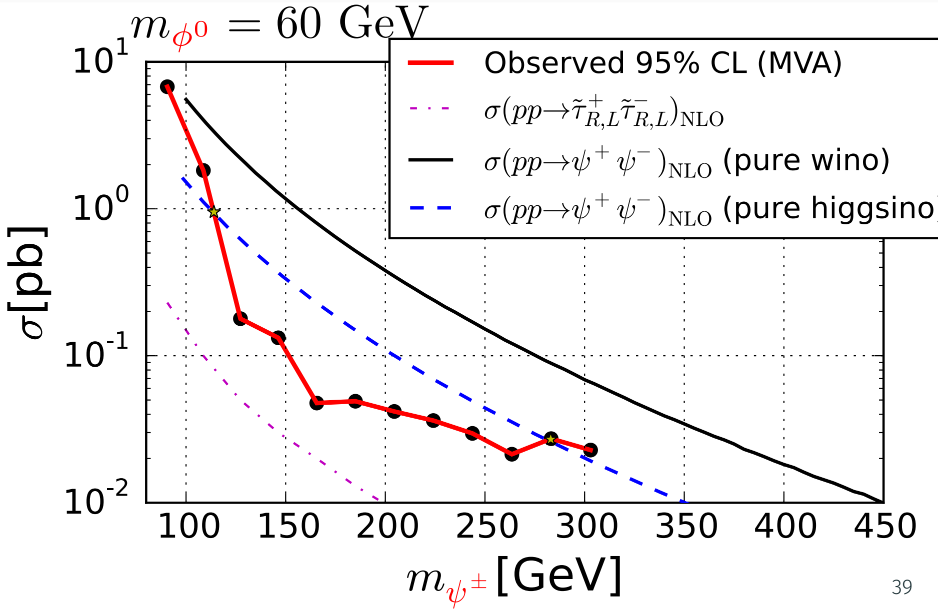
`checkMATE` (CL-calcutation)

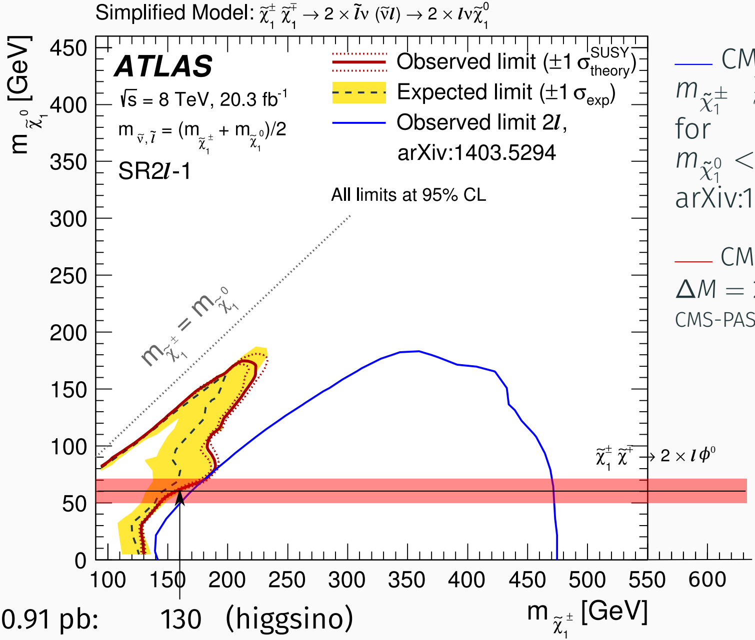
$$CL = CL^{ee} CL^{\mu\mu} CL^{\mu e}$$

ATLAS arXiv:1509.07152, $X^+X^- \to 2 \times \tau\,\phi_{\mathrm{DM}}$: $X^+ = \psi^+, \tilde{\tau}^+_{R,L}$ (MVA)



ATLAS arXiv:1509.07152, $X^+X^- \to 2\times\tau\,\phi_{\rm DM}$: $X^+ = \psi^+, \tilde{\tau}^+_{R,L}$ (MVA)



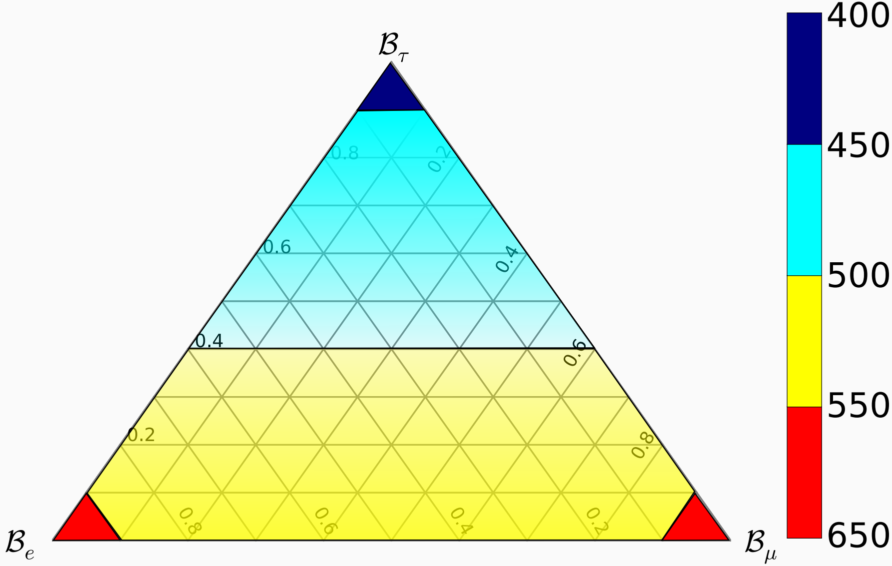


CMS
$m_{\tilde{\chi}_1^\pm} \gtrsim 510$ GeV for $m_{\tilde{\chi}_1^0} < 100$ GeV
arXiv:1405.7570

CMS $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$
$\Delta M = 20$ GeV (ISR)
CMS-PAS-SUS-14-021

0.91 pb: 130 (higgsino)

Wino-like exclusion from Run-I



Conclusions

Conclusions I

After give up the hierarchy problem (*heavy sfermion masses*), dark matter and gauge coupling unification is not longer associated to SUSY

$$\text{Bino-Higgsino-Wino} \quad \underbrace{\longrightarrow}_{\text{generic couplings}} \quad \text{Singlet-Doublet-Triplet}$$

But difficult to test at colliders, like radiative neutrino mass models

---

Z_2-odd: Fermion(Singlet-Doublet-Triplet)+Scalar(Singlet-Doublet)

- Radiative neutrino masses
- Rich lepton flavor structure at low and high-energy experiments
- Generic collider signal: dileptons plus $2\times$(60 GeV DM.)

Conclusions II

The wino-like scotogenic model (*radiative type-III seesaw*) with $\mathcal{B}(\psi^+ \to l_i\phi^0) = 1$ is a a good simplified model for the interpretation of experimental results at the LHC.

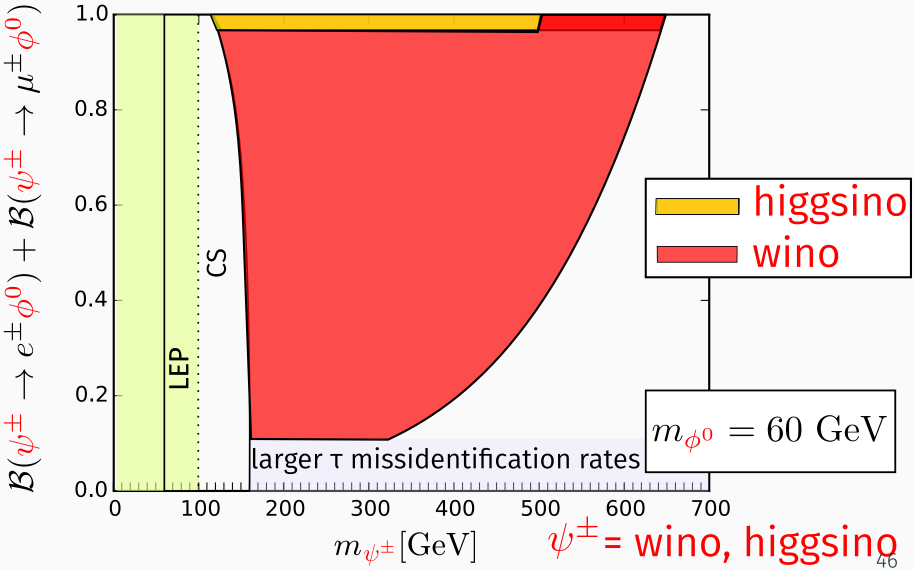
At Run-I, the charged fermion have been excluded until 630 GeV (400 GeV) for $\mathcal{B}(\psi^+ \to e^+\phi^0) = 1$ $\left(\mathcal{B}(\psi^+ \to \tau^+\phi^0) = 1\right)$,

Including the compressed-spectra region

TODO: Higgsino-like case

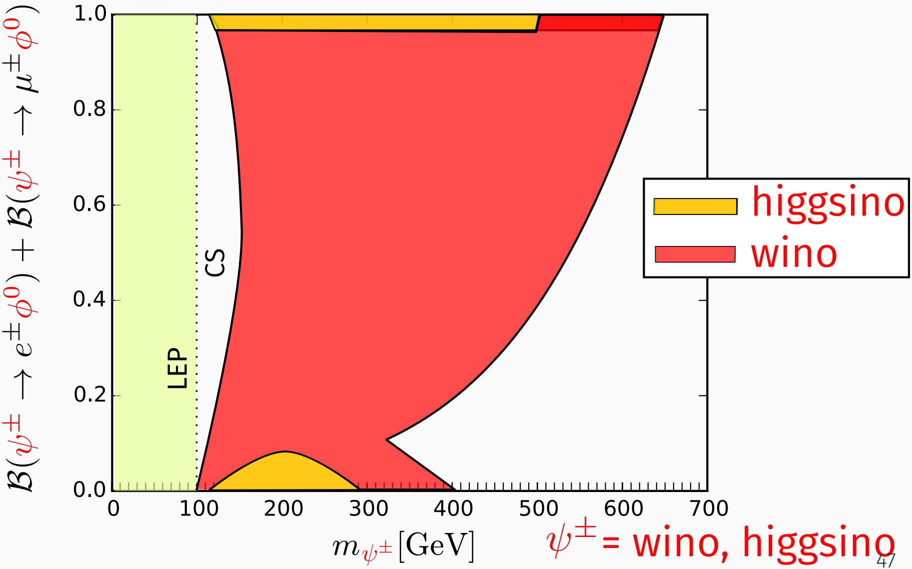
Thanks!

$$pp \to \psi^{\pm}\psi^{\mp} \to l_i^{\pm} l_j^{\mp} \phi^0 \phi^0 \quad l_i = e, \mu, \tau, \quad \phi^0 = H^0, S^0$$



$\psi^{\pm}$ = wino, higgsino

$$pp \to \psi^{\pm}\psi^{\mp} \to l_i^{\pm} l_j^{\mp} \phi^0 \phi^0 \quad l_i = e, \mu, \tau, \quad \phi^0 = H^0, S^0$$



$\psi^{\pm}$ = wino, higgsino

New simplified models

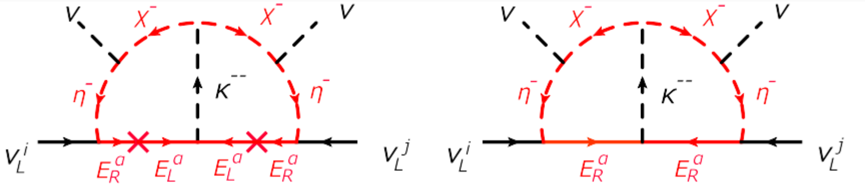
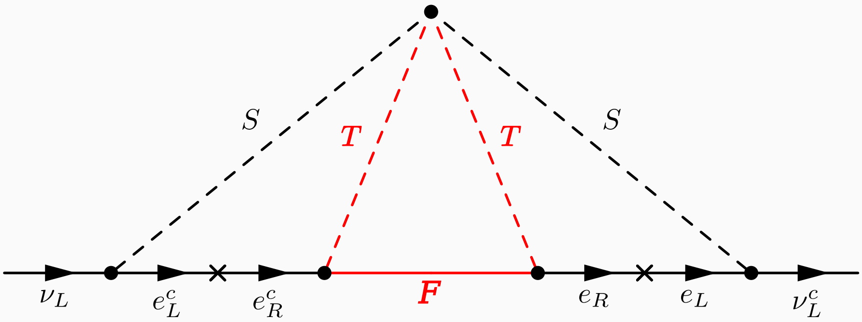
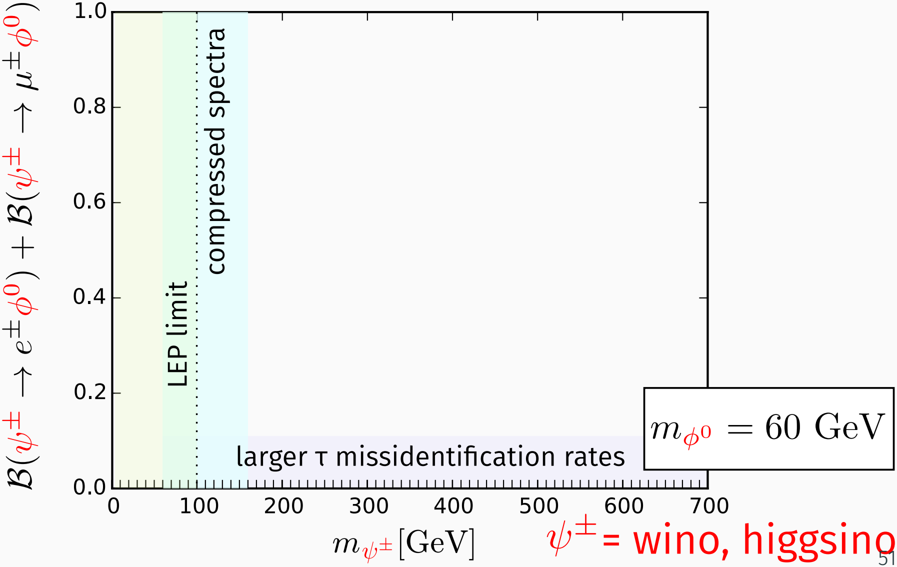


FIG. 2: Feynman diagrams for the neutrino mass generation at the two-loop level. Particles indicated by the red color have the Z_2 odd parity.



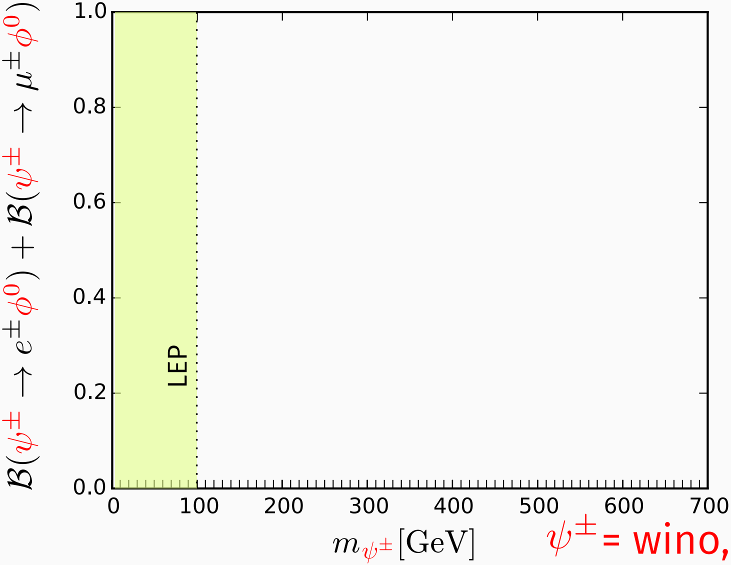
Three-loop diagram for neutrino mass. Here, $S \sim (1,1,2)$ and $T \sim (1,2n+1,2)$ are beyond-SM scalars while $F \sim (1,2n+1,0)$ is a beyond-SM fermion.

$$pp \to \psi^\pm \psi^\mp \to l_i^\pm l_j^\mp \phi^0 \phi^0 \quad l_i = e, \mu, \tau, \quad \phi^0 = H^0, S^0$$



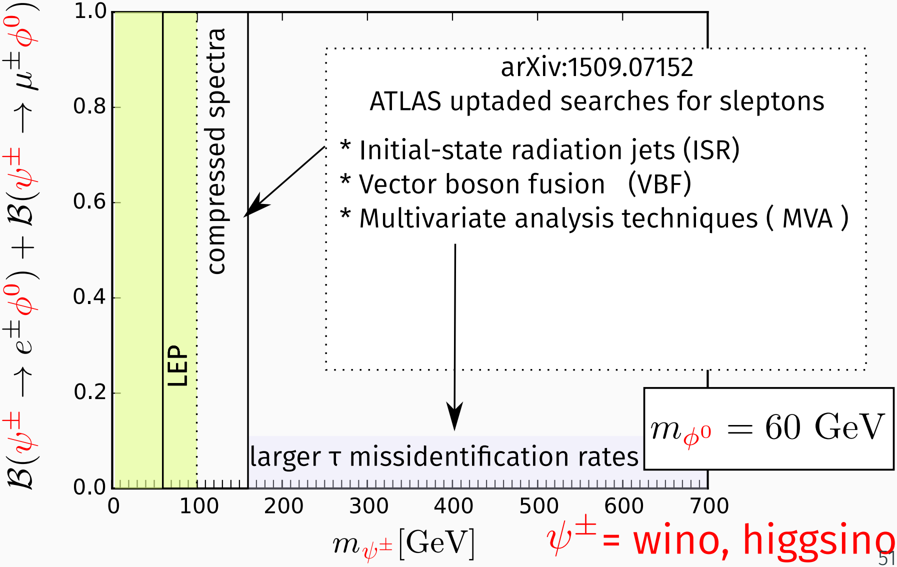
$\psi^\pm$ = wino, higgsino

$$pp \to \psi^{\pm}\psi^{\mp} \to l_i^{\pm} l_j^{\mp} \phi^0 \phi^0 \quad l_i = e, \mu, \tau, \quad \phi^0 = H^0, S^0$$



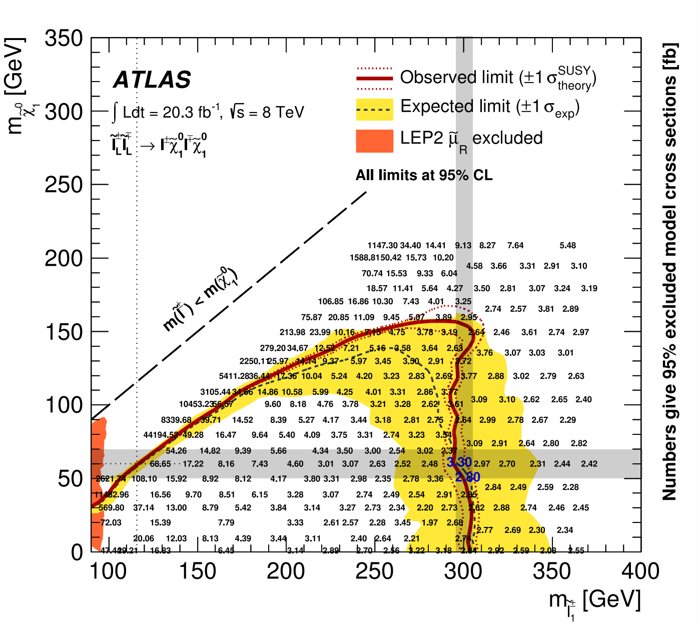
$\psi^{\pm}$= wino, higgsino

$$pp \to \psi^{\pm}\psi^{\mp} \to l_i^{\pm} l_j^{\mp} \phi^0 \phi^0 \quad l_i = e, \mu, \tau, \quad \phi^0 = H^0, S^0$$



$\psi^{\pm}$ = wino, higgsino

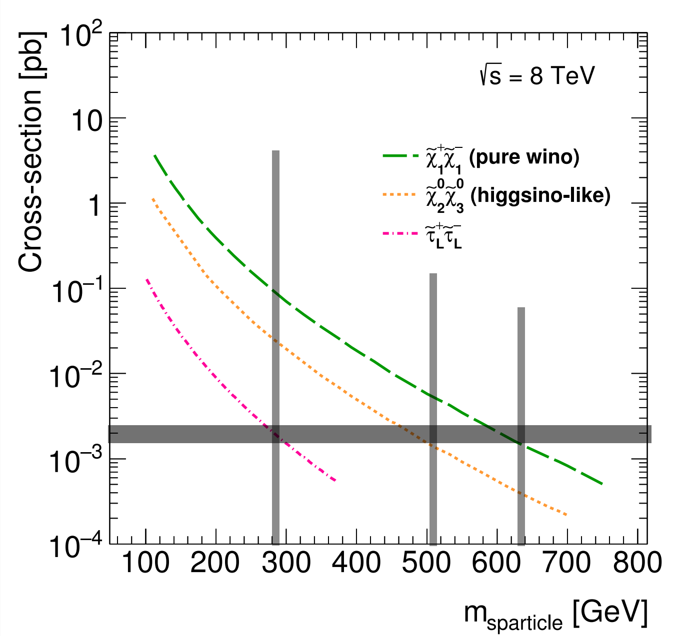
ATLAS arXiv:1403.5294 (JHEP)



CMS

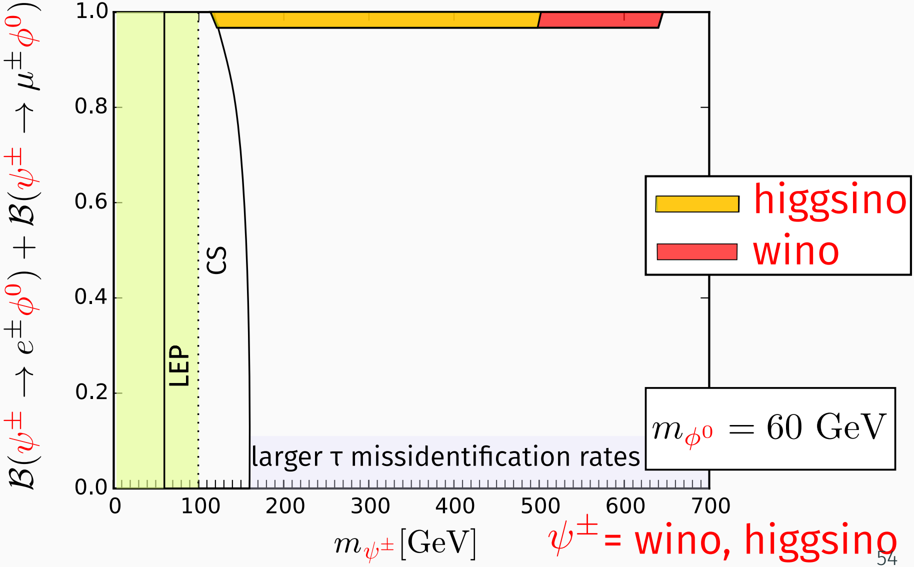
$\gtrsim$ 260 GeV

arXiv:1405.7570



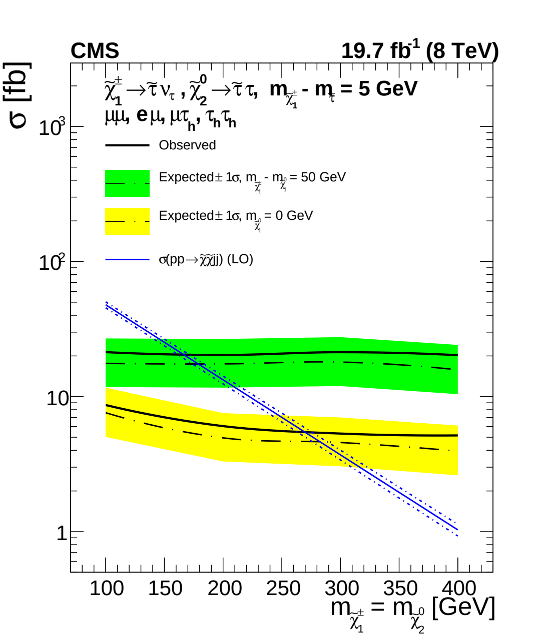
Cross-section [pb]
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
$\sqrt{s}$ = 8 TeV
$\tilde{\chi}_1^+\tilde{\chi}_1^-$ (pure wino)
$\tilde{\chi}_2^0\tilde{\chi}_3^0$ (higgsino-like)
$\tilde{\tau}_L^+\tilde{\tau}_L^-$
100 200 300 400 500 600 700 800
$m_{sparticle}$ [GeV]

$$pp \to \psi^\pm \psi^\mp \to l_i^\pm l_j^\mp \phi^0 \phi^0 \quad l_i = e, \mu, \tau, \quad \phi^0 = H^0, S^0$$



$\psi^\pm$ = wino, higgsino

CMS 1508.07628: DI-TAU PLUS MISSING ENERGY (VBF)

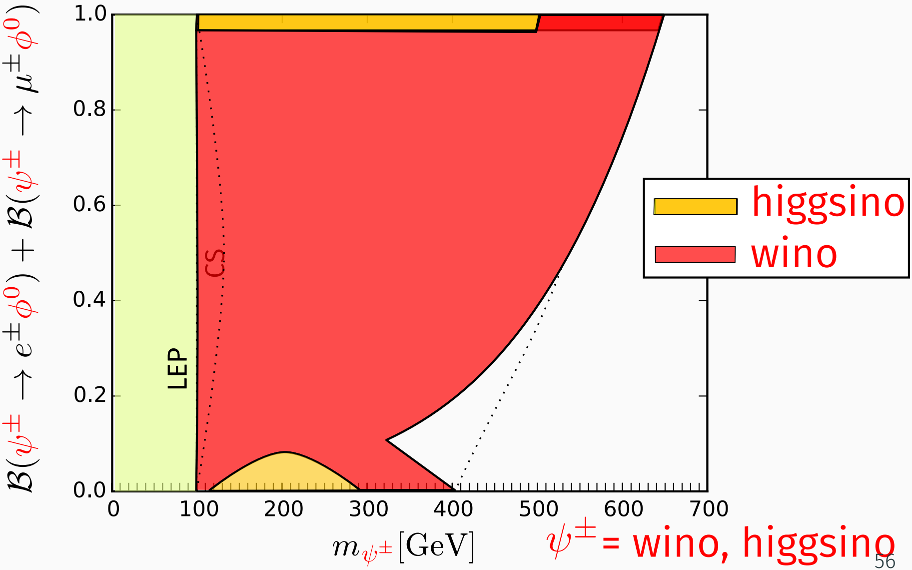


$\cancel{\psi^\pm\psi^0}$

$\psi^\pm\psi^\mp$

$\psi^\pm\psi^\pm$

$$pp \to \psi^{\pm}\psi^{\mp} \to l_i^{\pm} l_j^{\mp} \phi^0 \phi^0 \quad l_i = e, \mu, \tau, \quad \phi^0 = H^0, S^0$$



$\psi^{\pm}$= wino, higgsino