ν-Dark matter models

Model building

UNIVERSIDAD DE ANTIOQUIA
1 8 0 3

Diego Restrepo

September 12, 2016

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

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

Table of Contents

Scotogenic models

General framework

ν-DM models

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.

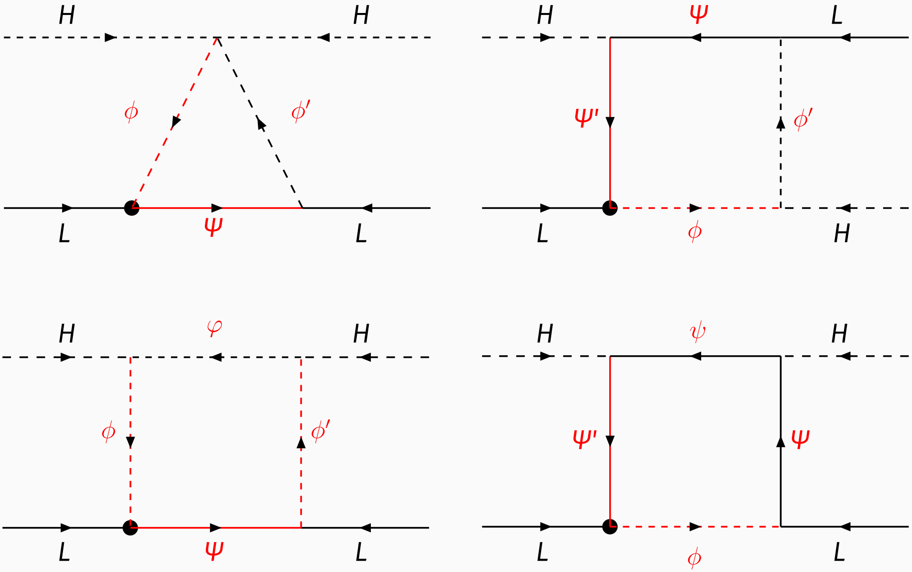
In this direction, models with one-loop radiative neutrino masses and viable dark matter candidates have now a complete classification given in

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.

Weinberg operator at one-loop

(Z_2-odd fields)



Weinberg operator at one-loop

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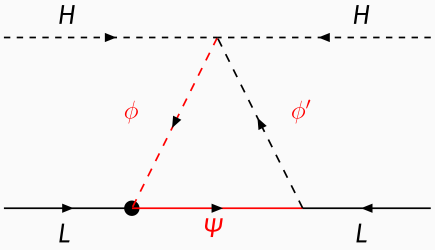
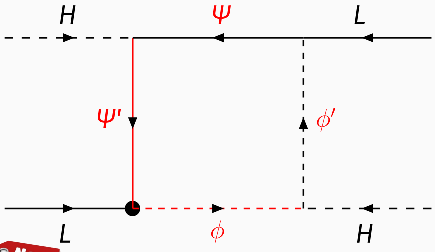
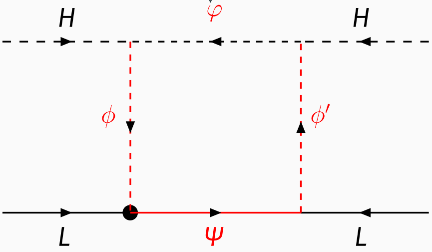


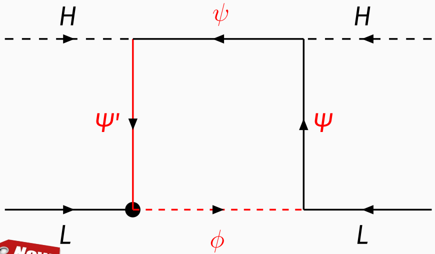
Wino-like scotogenic model



Higgsino-like Zee model

$\Updownarrow$



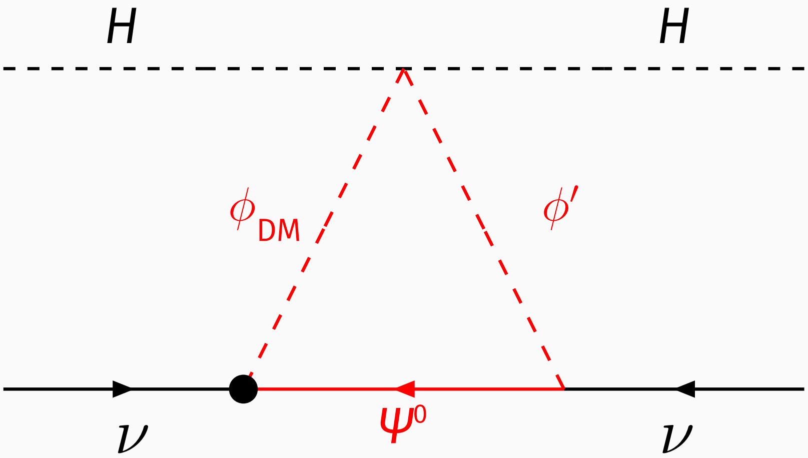


Higgsino-like scotogenic model

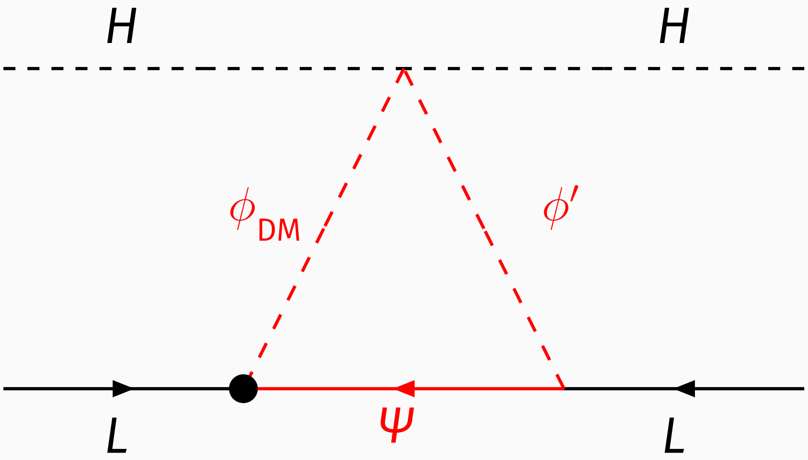
Specific examples

- RSIII
- T13A
- RSII
- Inert Zee

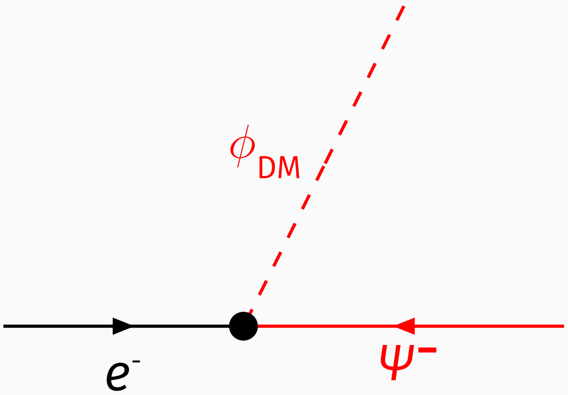
Typical radiative neutrino mass diagram.



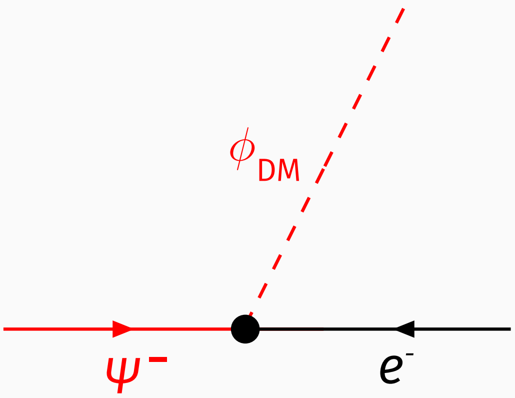
In term of general SU(2)$_L$ multiplets,



may be also charged particles,



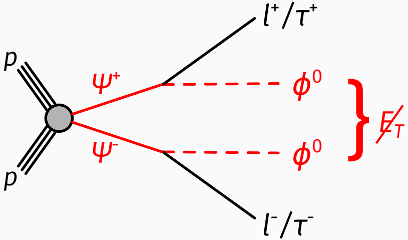
which may decay into the dark matter particle.



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

Benchmark: Resonance and 100 GeV Charged scalar

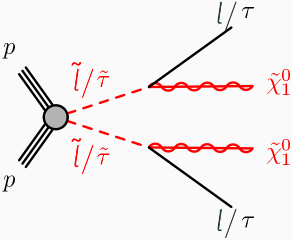
Dilepton plus transverse missing energy signal

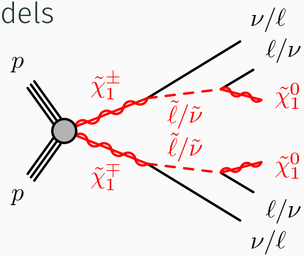


SU(2)$_L$ assignments:

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

Simplified SUSY models



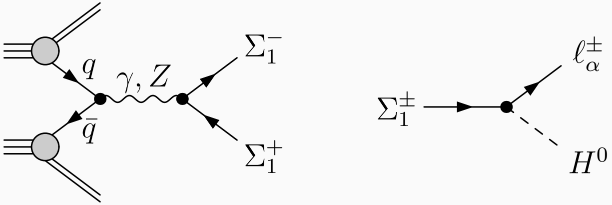


Smaller cross sections. Intermediate states and smaller lepton $\not{p}_T$

Specific examples

Radiative Type-III See-saw

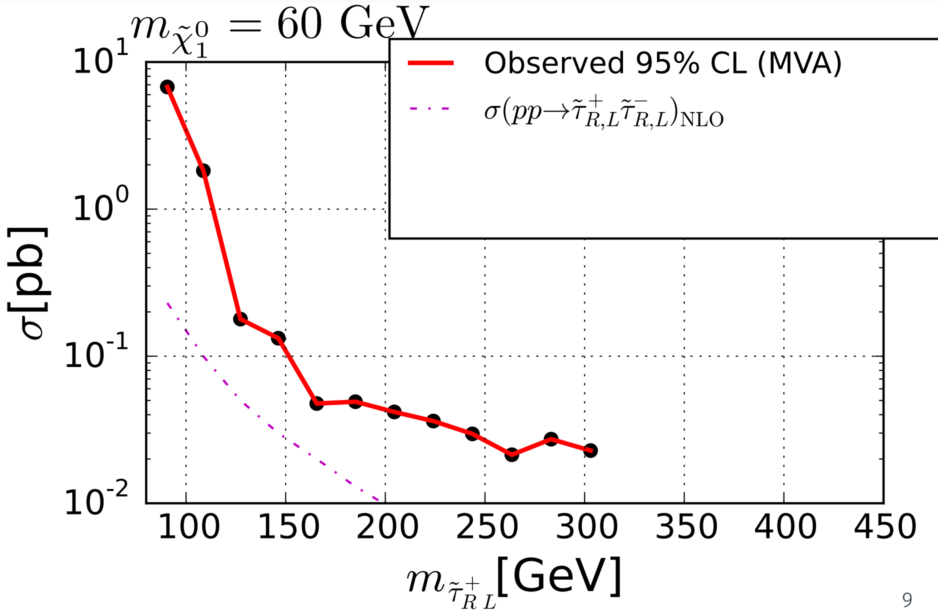
Radiative Type-II See-saw Wino-like production



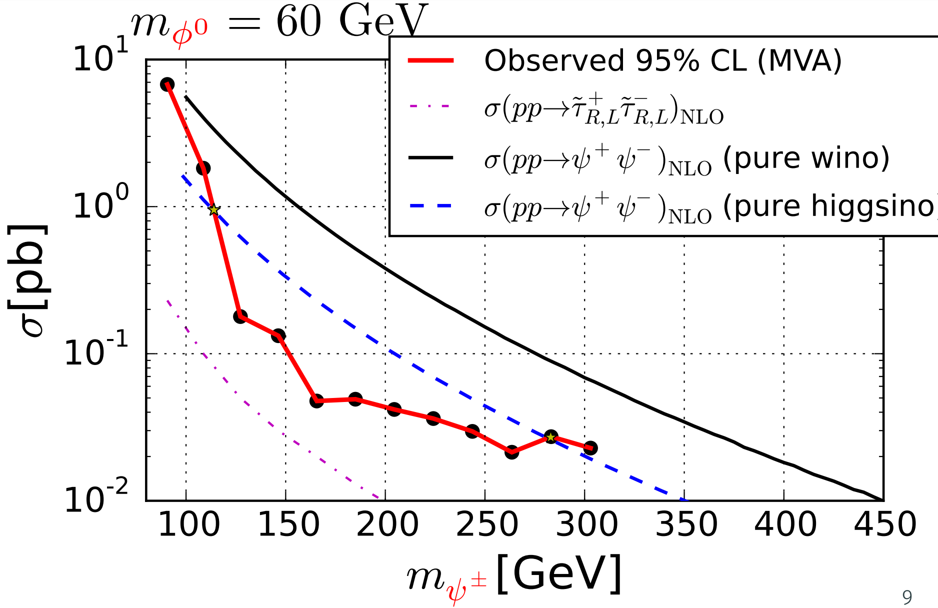
Higgsino-like

For example if $\ell_3^\pm = \tau^\pm$

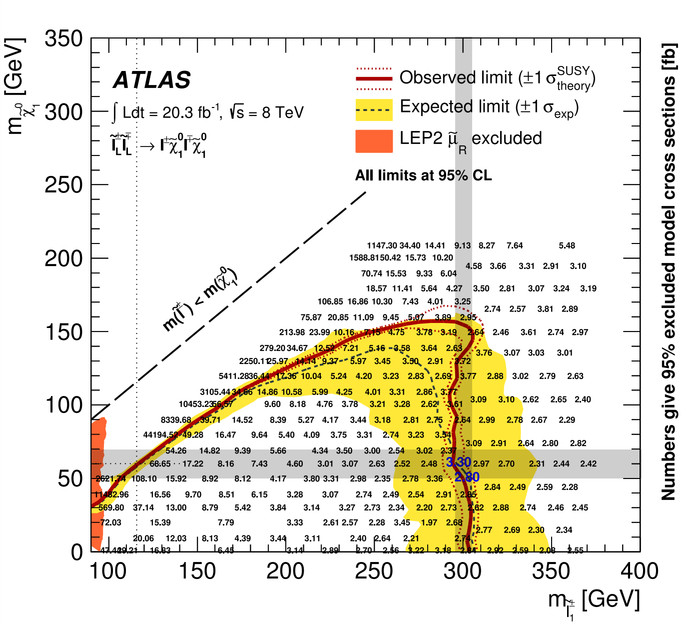
ATLAS arXiv:1509.07152, $X^+X^- \to 2 \times \tau\,\phi_{\mathrm{DM}}$: $X^+ = \psi^+, \tilde{\tau}^+_{R,L}$ (MVA)



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



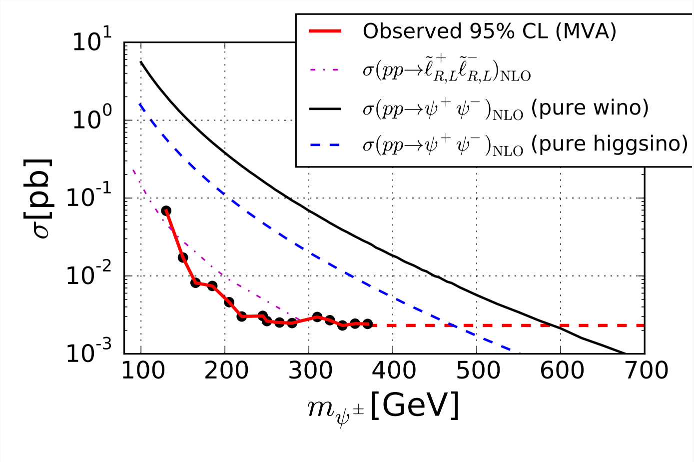
ATLAS arXiv:1403.5294 (JHEP)



CMS $\gtrsim$ 260 GeV

arXiv:1405.7570

Scalar dark matter mass 60 GeV



Lepton flavor dependence

Neutrino masses

$$(\mathcal{M}_\nu)_{\alpha\beta} \sum_{k=1}^{n_\Sigma} \left[Y^T \Lambda Y\right]_{\alpha\beta} \ , \qquad \alpha, \beta = 1, 2, 3 \, ,$$

From neutrino oscillation data, we can get a set of Y choosing the angles for R, an arbitrary orthogonal matrix

$$Y = \sqrt{\Lambda}^{-1} R \, \mathrm{diag}(\sqrt{m_{\nu_1}}, \sqrt{m_{\nu_2}}, \sqrt{m_{\nu_3}}) U^\dagger_{\mathrm{PMNS}} \, , \tag{1}$$

$$\hat{Y}_\alpha \equiv \hat{Y}_{1\alpha} = Y_{1\alpha} \Big/ \sqrt{\sum_{\alpha=e,\mu,\tau} |Y_{1\alpha}|^2} \quad \mathcal{B}_\alpha \equiv \mathrm{Br}(\Sigma_1^\pm \to \ell_\alpha H^0) = |\hat{Y}_\alpha|^2 \, .$$

Exploration of flavor space

Wino-like scotogenic 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^-, $\mu^+\mu^-$, $e^\pm\mu^\mp$.

`SARAH/FeynRules`

$\Downarrow$

`micrOMEGAS` (Experimental and theoretical constraints)

$\Downarrow$

`MadGraph`

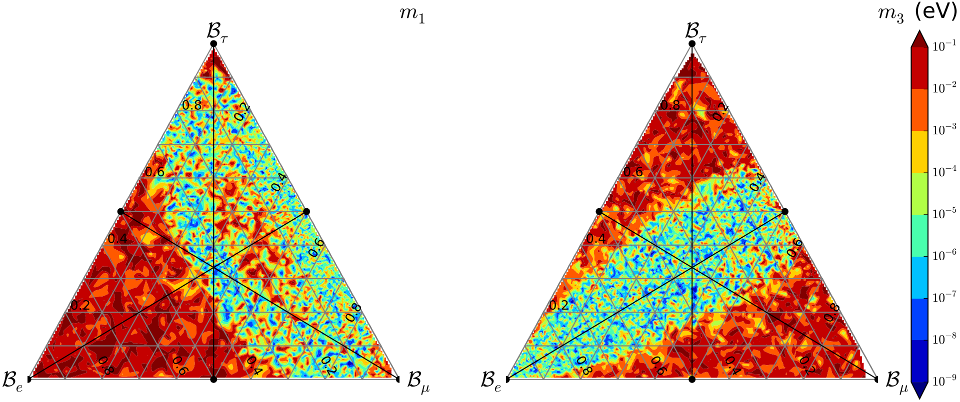
$\Downarrow$

`Pythia 6` (`hep` format)

$\Downarrow$

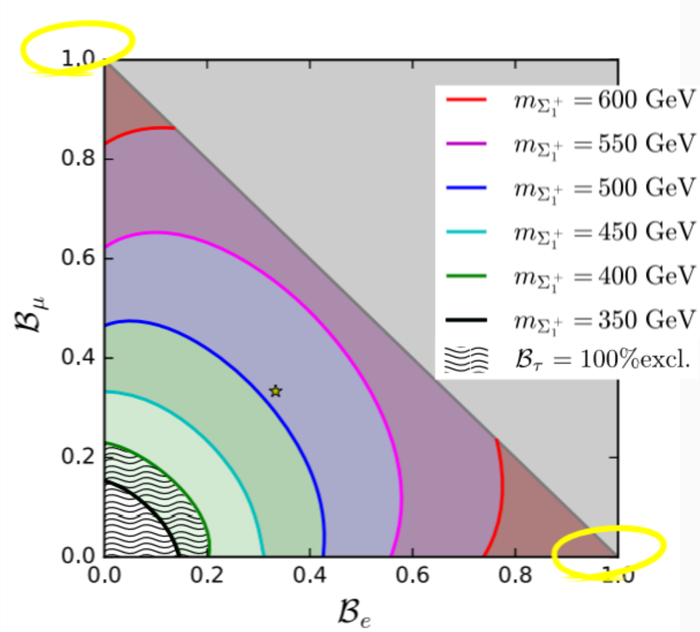
`checkMATE` (CL-calcutation)

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

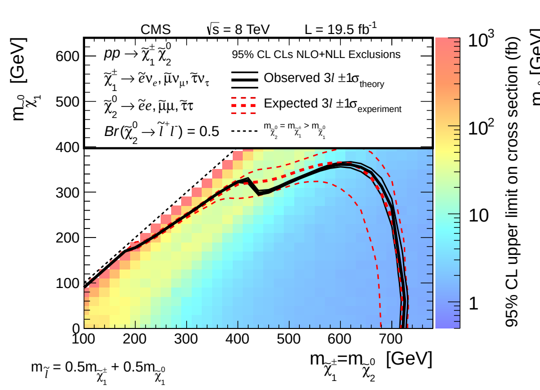


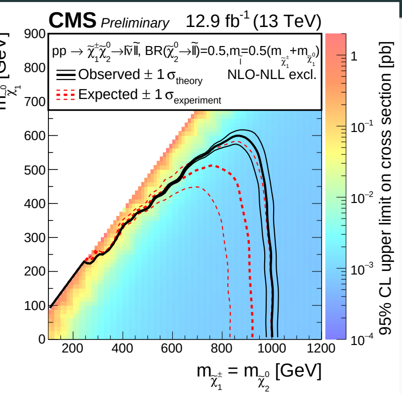
$$\mathcal{B}_l = \mathcal{B}\left(\psi^\pm \to l H^0\right)$$

Combination



Golden EW SUSY channel: trilepton and $\not{E}_T$





Improvement by a factor of 1.4

For a similar improvement in the wino-like sctogenic model, we could expect exclusions at the level of 900 GeV.

700 GeV in Higgsino-like scotogenic models.

Conclusions

To use of scotogenic models to interpret dilepton plus missing energy searches allows larger sensitivity and full flavor exploration

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

Exploration of flavor space

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`

$\Downarrow$

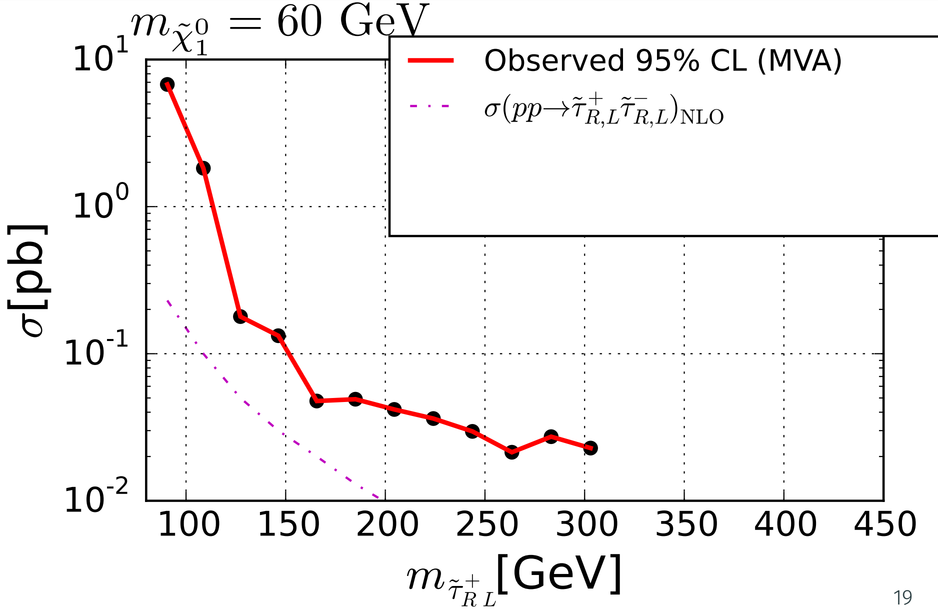
`Pythia 6` (`hep` format)

$\Downarrow$

`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)



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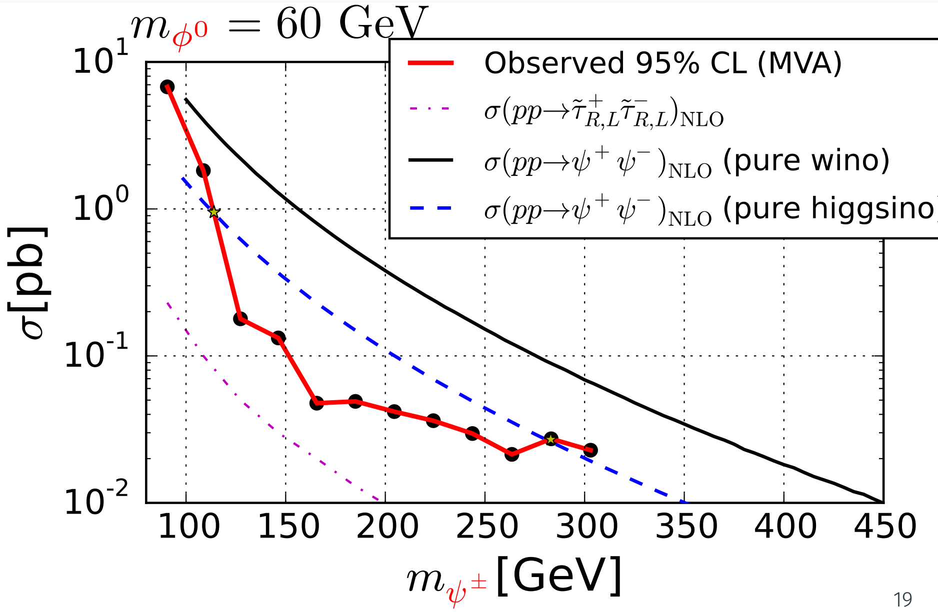
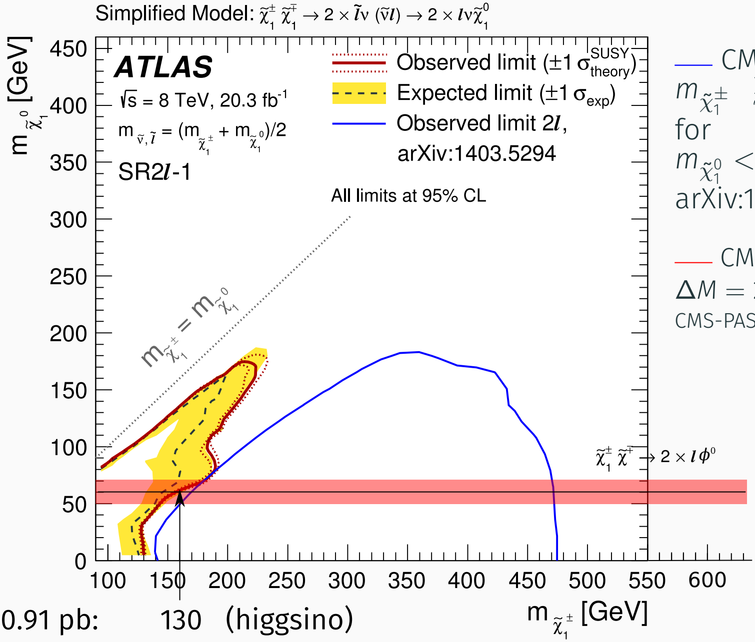


wino production to dilepton plus missing energy (ISR)

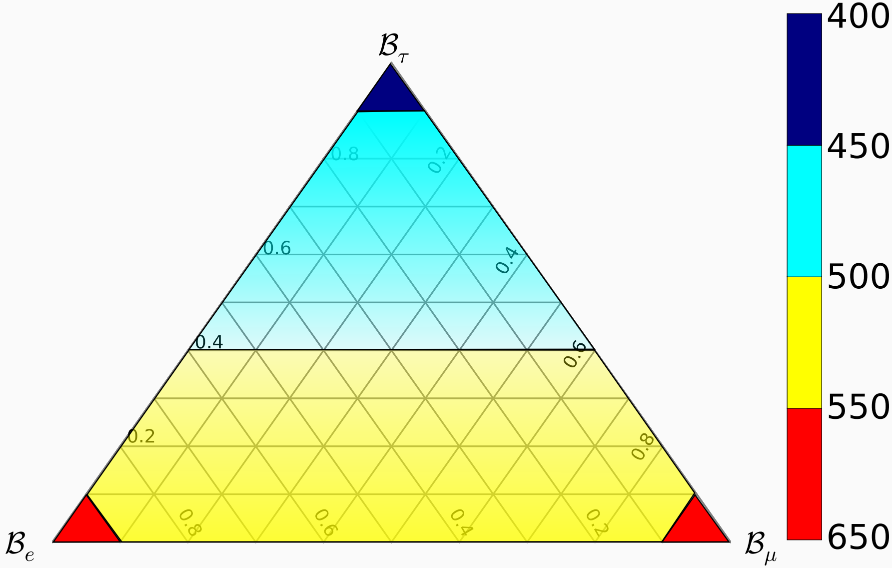


0.91 pb: 130 (higgsino)

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

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×(60 GeV DM.)

Conclusions ii

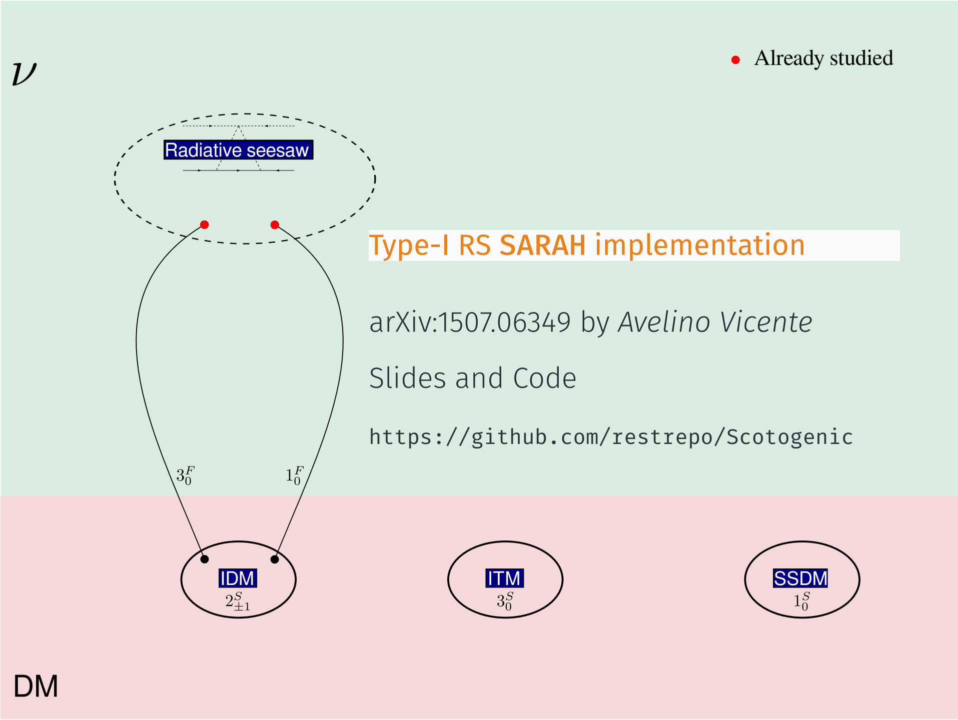
The wino-like scotogenic model (*radiative type-III seesaw*) with $\mathcal{B}(\psi^+ \to l_i\phi^0) = 1$ is a a good simplified model for the interpretation of experimental results at the LHC.

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

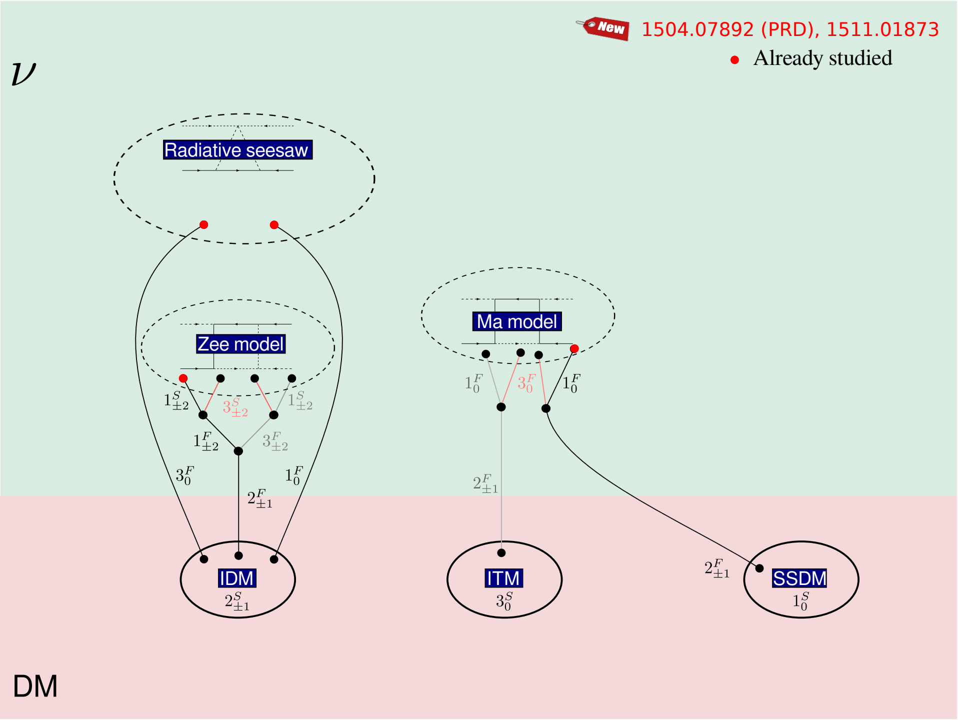
Including the compressed-spectra region

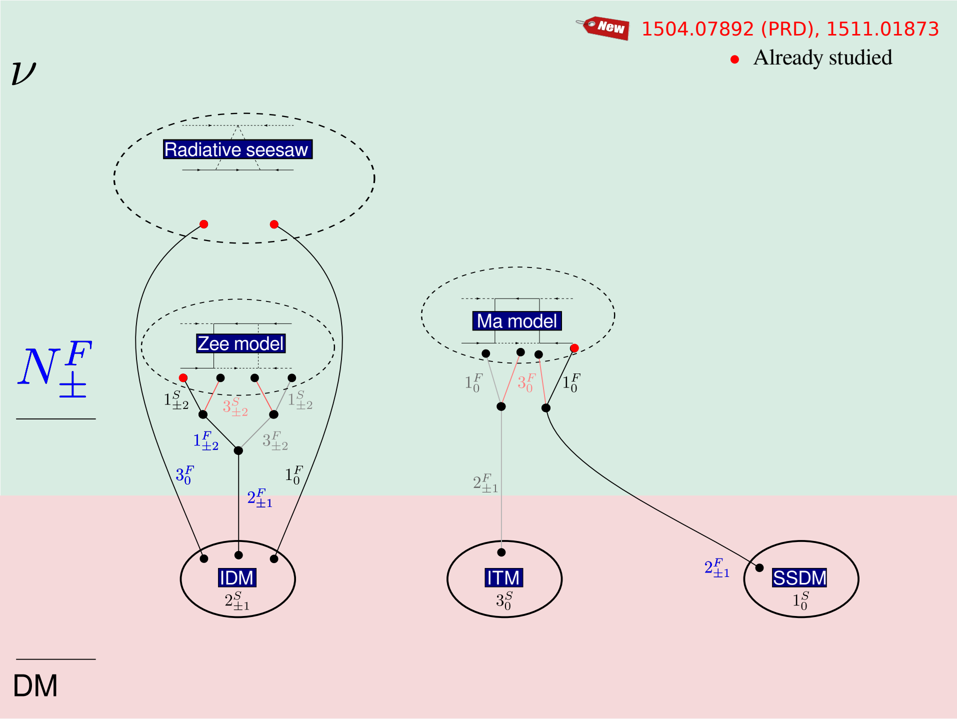
TODO: Higgsino-like case

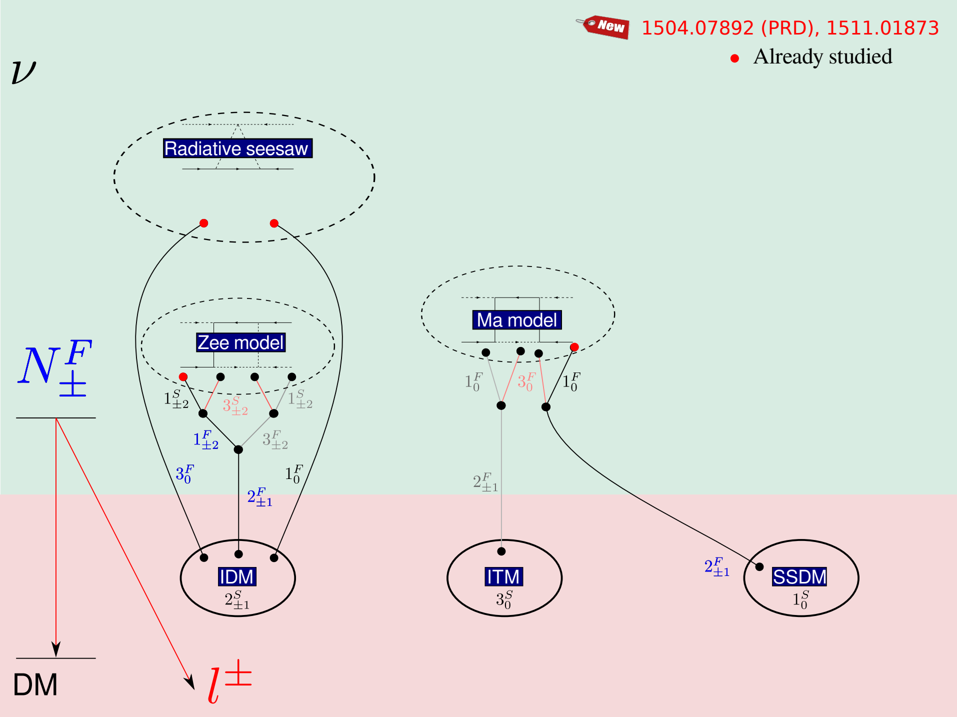
Thanks!



ν
Already studied
Radiative seesaw
Type-I RS SARAH implementation
arXiv:1507.06349 by *Avelino Vicente*
Slides and Code
https://github.com/restrepo/Scotogenic
3_0^F
1_0^F
IDM
$2_{\pm 1}^S$
ITM
3_0^S
SSDM
1_0^S
DM


New
1504.07892 (PRD), 1511.01873
Already studied
ν
Radiative seesaw
Zee model
Ma model
$1^S_{\pm2}$
$3^S_{\pm2}$
$1^S_{\pm2}$
$1^F_{\pm2}$
$3^F_{\pm2}$
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


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



New
1504.07892 (PRD), 1511.01873
Already studied
ν
Radiative seesaw
Zee model
Ma model
$N^F_\pm$
DM
$l^\pm$
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$3^S_{\pm2}$
$1^S_{\pm2}$
$1^F_{\pm2}$
$3^F_{\pm2}$
3^F_0
1^F_0
$2^F_{\pm1}$
1^F_0
3^F_0
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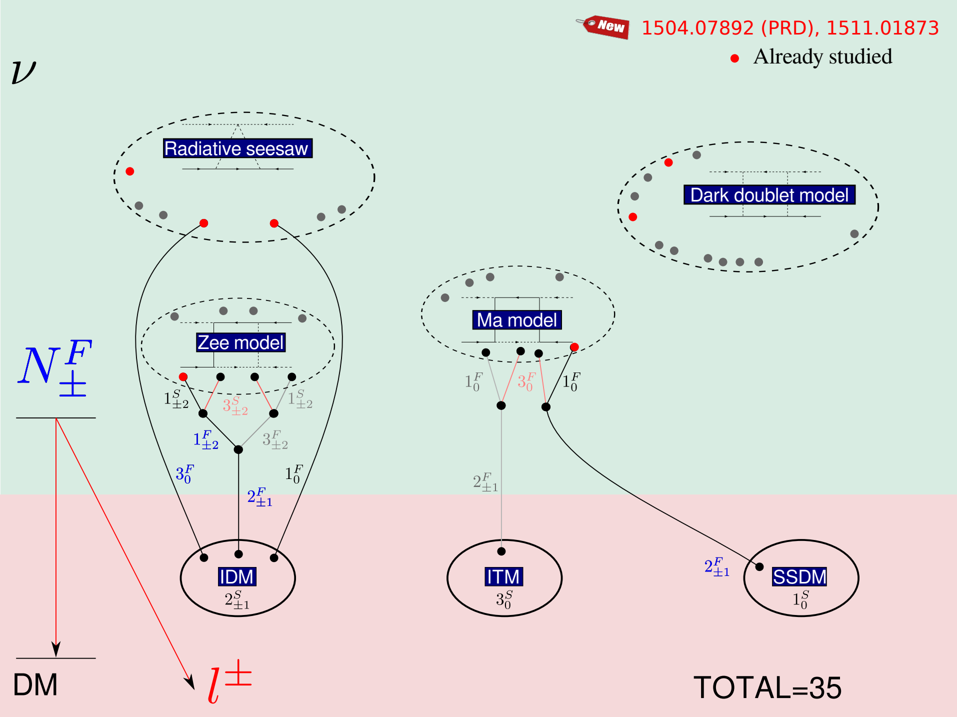
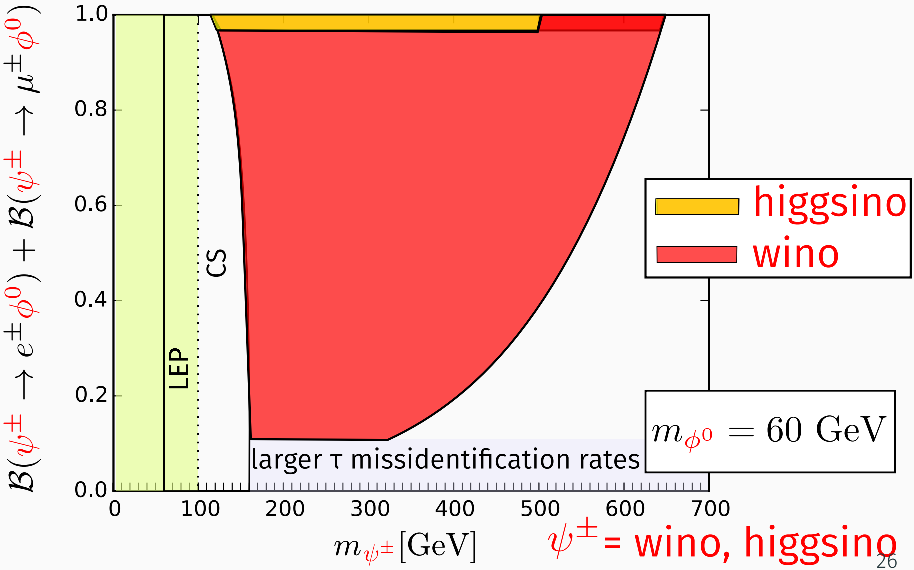
3^S_0
SSDM
1^S_0

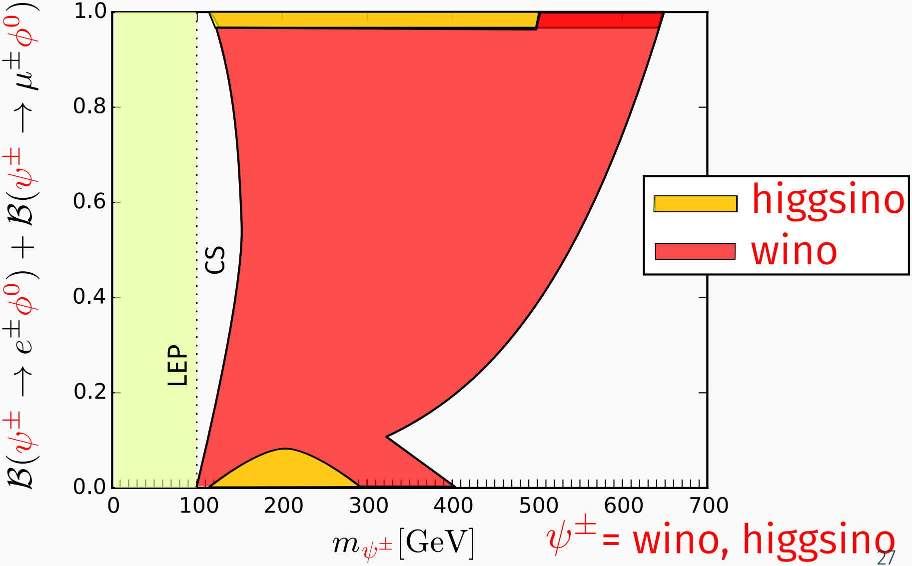

New
1504.07892 (PRD), 1511.01873
Already studied
ν
Radiative seesaw
Dark doublet model
Zee model
Ma model
$N^F_\pm$
$1^S_{\pm2}$
$3^S_{\pm2}$
$1^S_{\pm2}$
$1^F_{\pm2}$
$3^F_{\pm2}$
3^F_0
1^F_0
$2^F_{\pm1}$
1^F_0
3^F_0
1^F_0
$2^F_{\pm1}$
$2^F_{\pm1}$
IDM
$2^S_{\pm1}$
ITM
3^S_0
SSDM
1^S_0
DM
$l^\pm$
TOTAL=35

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



$\psi^{\pm}$= 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

Beyond the standard model

Recover fundamental masses ☹

Singlet scalar dark matter

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

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

Singlet fermion: Seesaw

$$\begin{aligned} \mathcal{L} =& \mathcal{L}_{\rm SM} + iN^\dagger \overline{\sigma}^\mu \partial_\mu N + \left(h_\nu L\cdot \Phi N - M\, NN + \text{h.c}\right)\,, \\ m_1 \sim& \frac{h_\nu v^2}{\sqrt{2}M}\,, \qquad\qquad m_2 \sim M\,. \end{aligned}$$

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

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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- Automatic generation of model files through LHA `SPheno` output for
    - `CalcHEP`
    - `micrOMEGAS`
    - `MadGRAPH`
    - `...`

SARAH implementation

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  - `CalcHEP`
  - `micrOMEGAS`
  - `MadGRAPH`
  - `...`
- **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};
  ```
  ```

SSDM in SARAH- ii

- ...

```
NameOfStates={GaugeES, EWSB};

DEFINITION[GaugeES][LagrangianInput]= {
{LagHC, {AddHC->True}},
{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]}, ...
  ```
  ```

Dark matter and unification

Unification: $SO(10)$

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

Not-susy SO(10) $\to SU(5) \to \mathrm{SU}(3)_C \times SU(2)_L \times \mathrm{U}(1)_Y \times Z_2$

Standard Model: Z_2-even

Fermions: $\mathbf{16}_F$

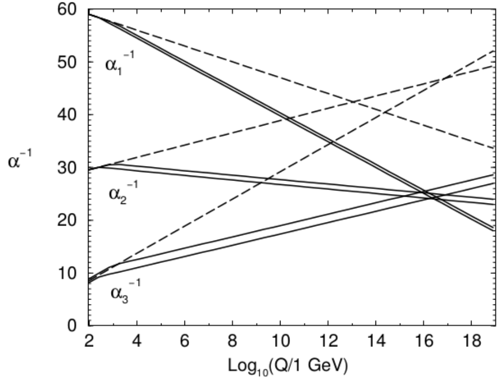
Scalars: $\mathbf{10}_H, \mathbf{45}_H \cdots$

New Z_2-odd particles

$\mathbf{10}_F, \mathbf{45}_F, \cdots$

$\mathbf{16}_H, \cdots$

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



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**

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

	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**

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

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

$SU(3)_C$: **3** (T), **6**, $\boxed{\mathbf{8}\ (\Lambda)}$

Split-SUSY like

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

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**

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

	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
$2_{\pm 1/2}$ $2^S_{1/2}$	10, 120, 126, 210, 210′	16, 144
3_0	45, 54, 210	144

$SU(3)_C$: **3** (T), **6**, **8** (Λ)

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

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**

Fermions: 16_F | $10_F, 45_F, \cdots$

Scalars: $10_H, 45_H \cdots$ | $16_H, \cdots$

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

	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
$2_{\pm 1/2}$ $2^S_{1/2}$	10, 120, 126, 210, 210′	16, 144
3_0	45, 54, 210	144

$SU(3)_C$: 3 (T), 6, 8 (Λ)

1509.06313

SUSY-like spectrum: bino-higgsino-wino

+ ↓

$10'_H$ with fermion DM or $16_H, \cdots$ 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

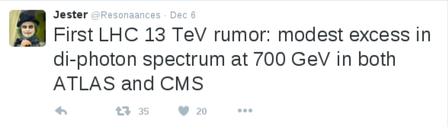
$$-\mathcal{L} \supset Y 10_F 45_F 10_H + M_{45_F} 45_F 45_F + M_{10_F} 10_F 10_F + \mathcal{L}(10_\Phi \qquad).$$

Basis

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

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

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



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

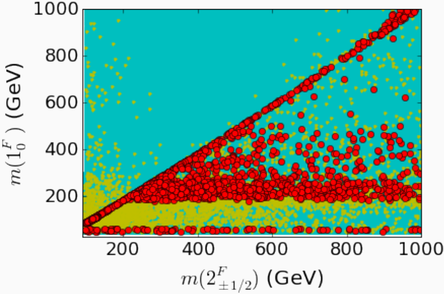
$$-\mathcal{L} \supset Y 10_F 45_F 10_H + M_{45_F} 45_F 45_F + M_{10_F} 10_F 10_F + \mathcal{L}(10_\Phi \text{ or } 16_\Phi).$$

Basis

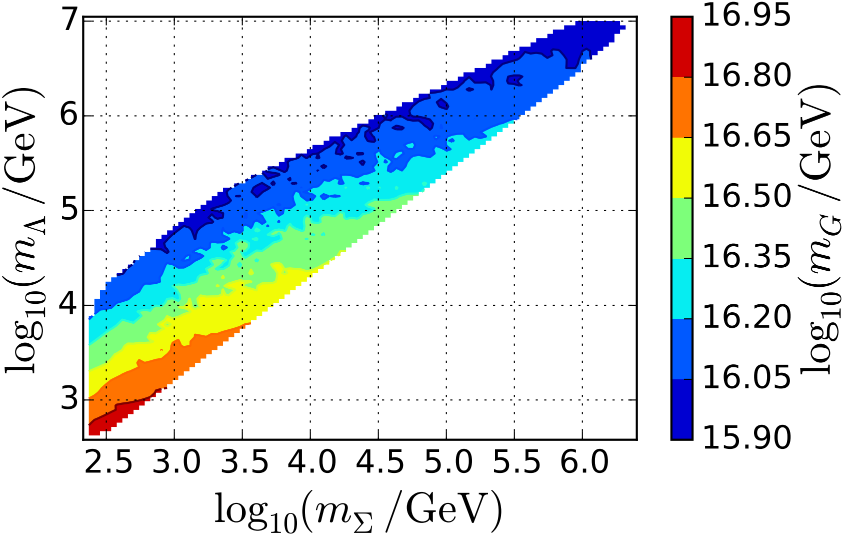
$$\psi^0 = \left(N, \Sigma^0, \psi_L^0, (\psi_R^0)^\dagger\right)^T$$

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

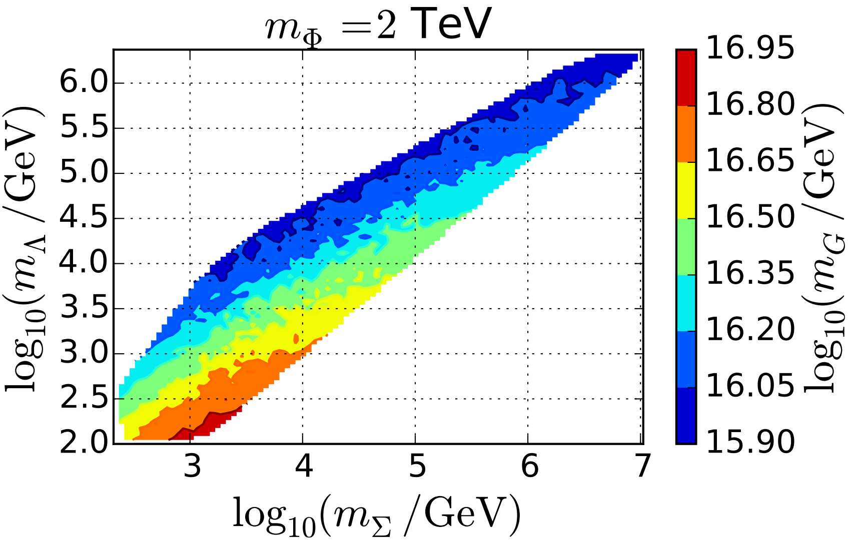
$$\begin{pmatrix} M_N & 0 & -y c_\beta v/\sqrt{2} & y s_\beta v/\sqrt{2} \\ 0 & M_\Sigma & f c_{\beta'} v/\sqrt{2} & -f s_{\beta'} v/\sqrt{2} \\ -y c_\beta v/\sqrt{2} & f c_{\beta'} v/\sqrt{2} & 0 & -M_D \\ y s_\beta v/\sqrt{2} & -f s_{\beta'} v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$



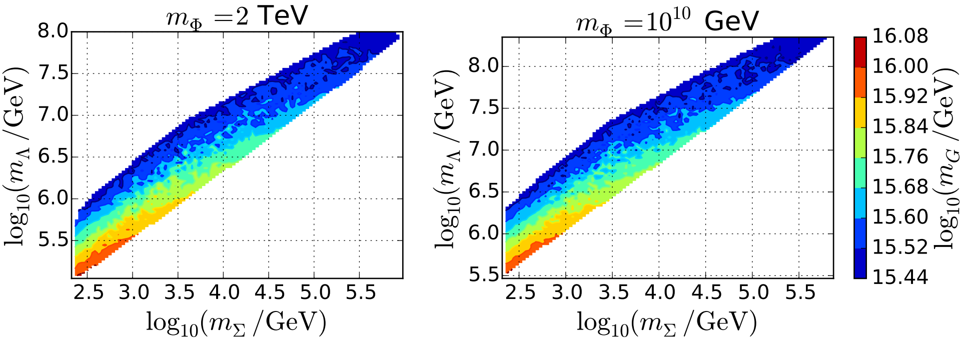
Split-SUSY like



Partial split-SUSY like



SUSY like



$m_\Phi = 2$ TeV
$\log_{10}(m_\Lambda/\mathrm{GeV})$
$\log_{10}(m_\Sigma/\mathrm{GeV})$
8.0
7.5
7.0
6.5
6.0
5.5
2.5 3.0 3.5 4.0 4.5 5.0 5.5
$m_\Phi = 10^{10}$ GeV
$\log_{10}(m_\Lambda/\mathrm{GeV})$
$\log_{10}(m_\Sigma/\mathrm{GeV})$
8.0
7.5
7.0
6.5
6.0
5.5
2.5 3.0 3.5 4.0 4.5 5.0 5.5
$\log_{10}(m_G/\mathrm{GeV})$
16.08
16.00
15.92
15.84
15.76
15.68
15.60
15.52
15.44

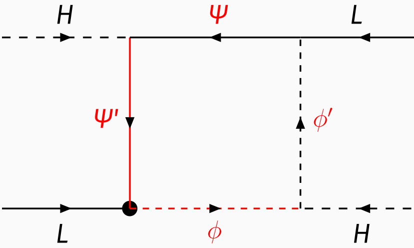
Notations

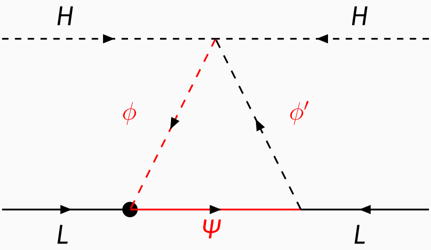
$$\mathrm{X}^{\mathcal{L}}{}_{\mathrm{Y}}$$

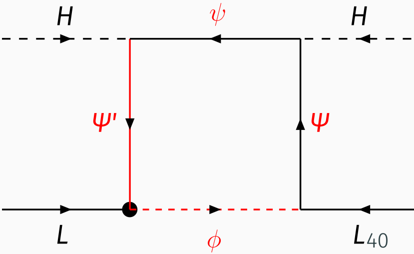
- $\mathcal{L}$ Lorentz nature: scalar (S) or fermion (F),
- $Y \equiv 2(Q - I_3)$ hypercharge: α arbitrary rational-number
- X $SU(2)$ nature: singlet 1, doublet 2, triplet 3
  - quadruplet 4, quintuplet 5, ...

Law, McDonald, arXiv:1305.6467

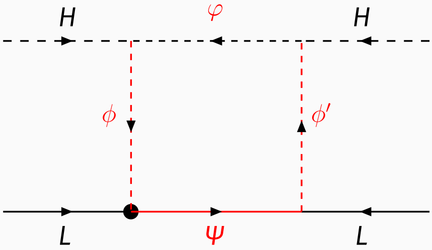
Weinberg operator at one-loop

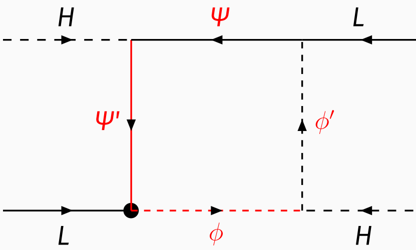


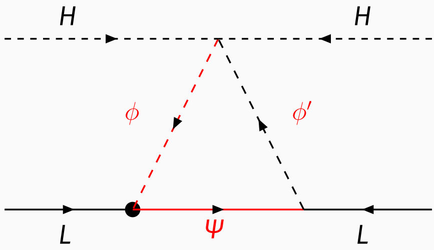


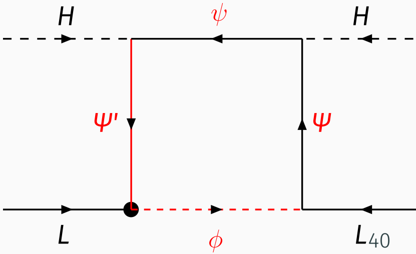


Weinberg operator at one-loop



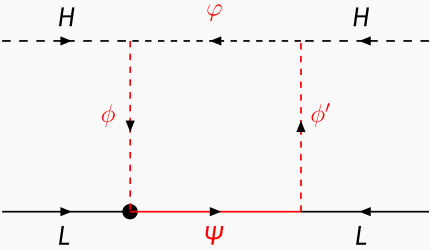


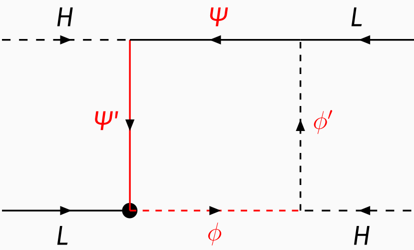


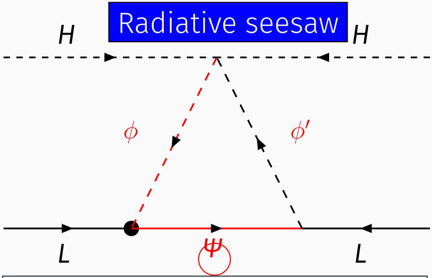


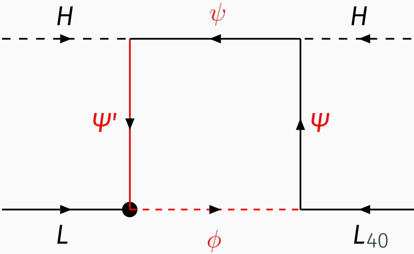
and reducible and divergent topol

Weinberg operator at one-loop



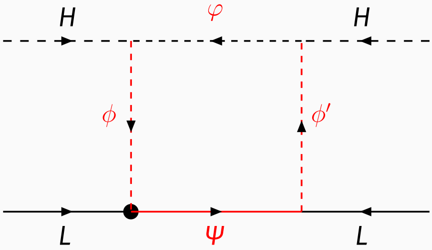


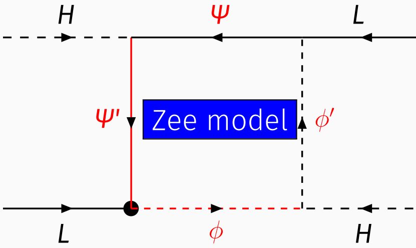


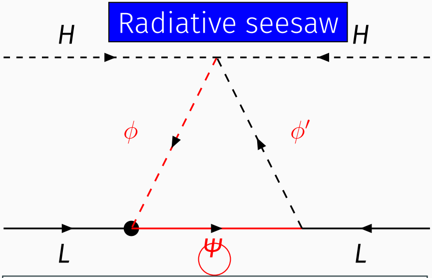


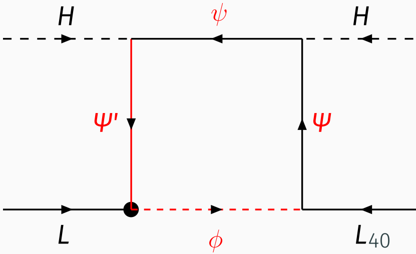
1^F 2^F 3^F 4^F 5^F

Weinberg operator at one-loop



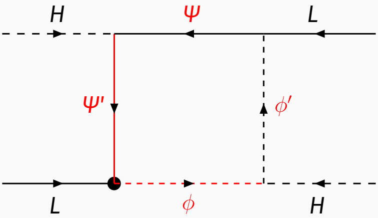






Generalized Zee model

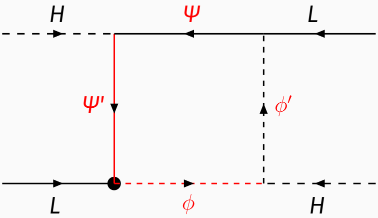
A. Zee, Phys.Lett.B93(1980)389 .



ψ	ϕ	ϕ'	ψ'	
2^F_1: $\overline{e_L}$	1^S_2: η^+	2^S_1: ϕ	1^F_2: $\overline{e_R}$	

Generalized Zee model

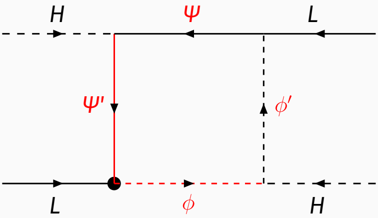
E. Ma, hep-ph/9805219 (PRL)



ψ	ϕ	ϕ'	ψ'
2^F_α	$1^S_{1+\alpha}$	2^S_α	$1^F_{1+\alpha}$
2^F_α	$3^S_{1+\alpha}$	2^S_α	$1^F_{1+\alpha}$
2^F_α	$3^S_{1+\alpha}$	2^S_α	$3^F_{1+\alpha}$
2^F_α	$1^S_{1+\alpha}$	2^S_α	$3^F_{1+\alpha}$

Generalized Zee model

(JHEP)

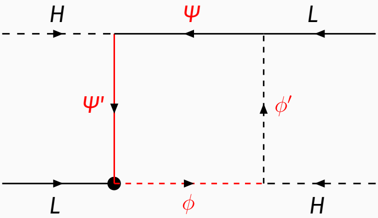


$$\alpha \to -\alpha - 1$$

ψ	ϕ	ϕ'	ψ'
1^F_α	$2^S_{1+\alpha}$	1^S_α	$2^F_{1+\alpha}$
2^F_α	$1^S_{1+\alpha}$	2^S_α	$1^F_{1+\alpha}$
1^F_α	$2^S_{1+\alpha}$	3^S_α	$2^F_{1+\alpha}$
2^F_α	$3^S_{1+\alpha}$	2^S_α	$1^F_{1+\alpha}$
2^F_α	$3^S_{1+\alpha}$	2^S_α	$3^F_{1+\alpha}$
3^F_α	$2^S_{1+\alpha}$	3^S_α	$2^F_{1+\alpha}$
2^F_α	$1^S_{1+\alpha}$	2^S_α	$3^F_{1+\alpha}$
3^F_α	$2^S_{1+\alpha}$	1^S_α	$2^F_{1+\alpha}$

Generalized Zee model

[?]

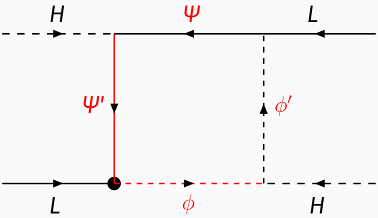


ψ	ϕ	ϕ'	ψ'
1^F_α	$2^S_{1+\alpha}$	1^S_α	$2^F_{1+\alpha}$
2^F_α	$1^S_{1+\alpha}$	2^S_α	$1^F_{1+\alpha}$
1^F_α	$2^S_{1+\alpha}$	3^S_α	$2^F_{1+\alpha}$
2^F_α	$3^S_{1+\alpha}$	2^S_α	$1^F_{1+\alpha}$
2^F_α	$3^S_{1+\alpha}$	2^S_α	$3^F_{1+\alpha}$
3^F_α	$2^S_{1+\alpha}$	3^S_α	$2^F_{1+\alpha}$
2^F_α	$1^S_{1+\alpha}$	2^S_α	$3^F_{1+\alpha}$
3^F_α	$2^S_{1+\alpha}$	1^S_α	$2^F_{1+\alpha}$

Larger $SU(2)_L$ multiplets

Generalized Zee model

D.R, Yagunga, Zapata, arXiv:1508.3655



Dark matter filter

- Impose Z_2 symmetry
  - SM particles are even
  - New particles are odd
- Lightest odd particle (LOP)
  - Color and electrically neutral
  - Consistent with direct detection constraints

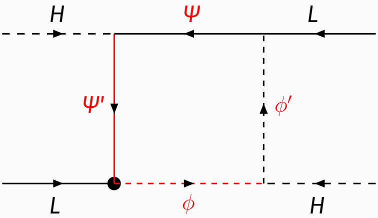
ψ	ϕ	ϕ'	ψ'	α
1^F_0	2^S_1	1^S_0	2^F_1	
2^F_{-1}	1^S_{-2}	2^S_{-1}	1^F_{-2}	
1^F_0	2^S_1	3^S_0	2^F_1	
2^F_{-1}	3^S_{-2}	2^S_{-1}	1^F_{-2}	
2^F_1	3^S_2	2^S_1	3^F_2	
3^F_0	2^S_{-1}	3^S_0	2^F_{-1}	
2^F_1	1^S_2	2^S_1	3^F_2	
3^F_0	2^S_{-1}	1^S_0	2^F_{-1}	

Larger $SU(2)_L$ multiplets

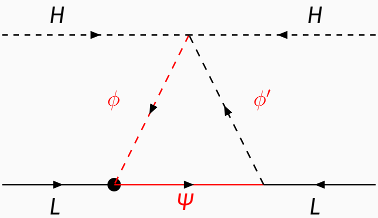
$Y = -2T_3$ for at least one particle

Generalized Zee model

D.R, Yagunga, Zapata, arXiv:1508.5655



Radiative type-I/III seesaw with additional contribution to neutrino masses.

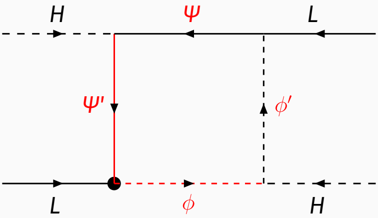


ψ	ϕ	ϕ'	ψ'	α
1^F_0	2^S_1	1^S_0	2^F_1	0
2^F_{-1}	1^S_{-2}	2^S_{-1}	1^F_{-2}	
1^F_0	2^S_1	3^S_0	2^F_1	0
2^F_{-1}	3^S_{-2}	2^S_{-1}	1^F_{-2}	
2^F_1	3^S_2	2^S_1	3^F_2	
3^F_0	2^S_{-1}	3^S_0	2^F_{-1}	−
2^F_1	1^S_2	2^S_1	3^F_2	
3^F_0	2^S_{-1}	1^S_0	2^F_{-1}	−

Larger $SU(2)_L$ multiplets

Generalized Zee model

D.R, Yagunga, Zapata, arXiv:1508.3655



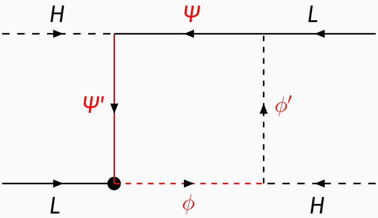
Inert doublet model with one-loop neutrino masses (susy-like)

ψ	ϕ	ϕ'	ψ'	α
1^F_0	2^S_1	1^S_0	2^F_1	0
2^F_{-1}	1^S_{-2}	2^S_{-1}	1^F_{-2}	$\boxed{-}$
1^F_0	2^S_1	3^S_0	2^F_1	0
2^F_{-1}	3^S_{-2}	2^S_{-1}	1^F_{-2}	$\boxed{-}$
2^F_1	3^S_2	2^S_1	3^F_2	$\boxed{1}$
3^F_0	2^S_{-1}	3^S_0	2^F_{-1}	$-$
2^F_1	1^S_2	2^S_1	3^F_2	$\boxed{1}$
3^F_0	2^S_{-1}	1^S_0	2^F_{-1}	$-$

Larger $SU(2)_L$ multiplets

Generalized Zee model

D.R, Yagunga, Zapata, arXiv:1308.3655

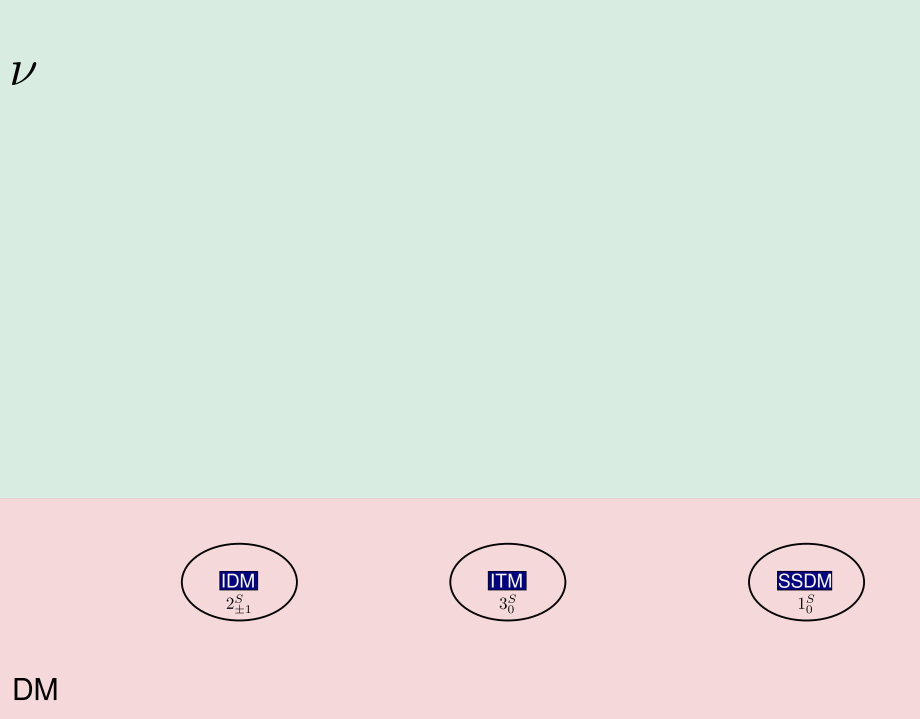


Inert doublet model with one-loop neutrino masses (susy-like)

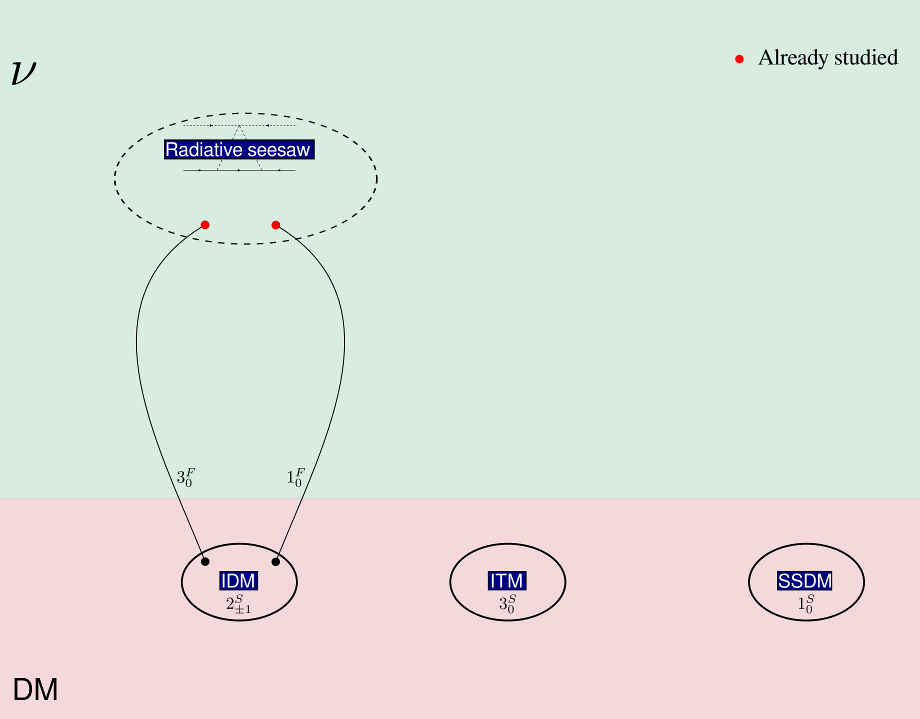
and exotic charges

ψ	ϕ	ϕ'	ψ'	α
1^F_0	2^S_1	1^S_0	2^F_1	0
2^F_{-1}	1^S_{-2}	2^S_{-1}	1^F_{-2}	$-$
1^F_0	2^S_1	3^S_0	2^F_1	0
2^F_{-1}	3^S_{-2}	2^S_{-1}	1^F_{-2}	$\boxed{-}$
2^F_1	3^S_2	2^S_1	3^F_2	$\boxed{1}$
3^F_0	2^S_{-1}	3^S_0	2^F_{-1}	$-$
2^F_1	1^S_2	2^S_1	3^F_2	$\boxed{1}$
3^F_0	2^S_{-1}	1^S_0	2^F_{-1}	$-$

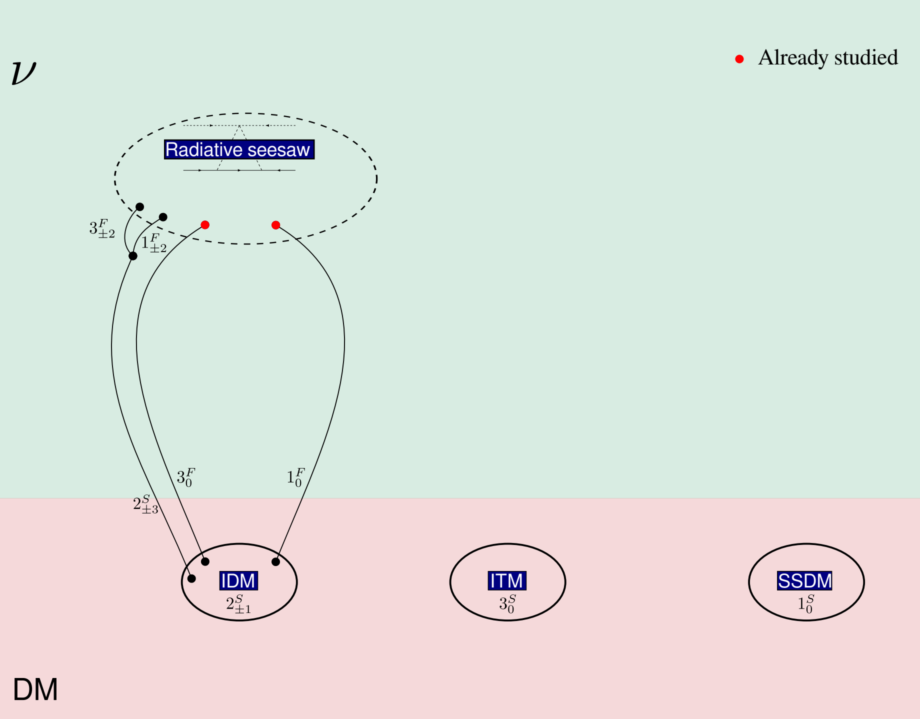
Larger $SU(2)_L$ multiplets



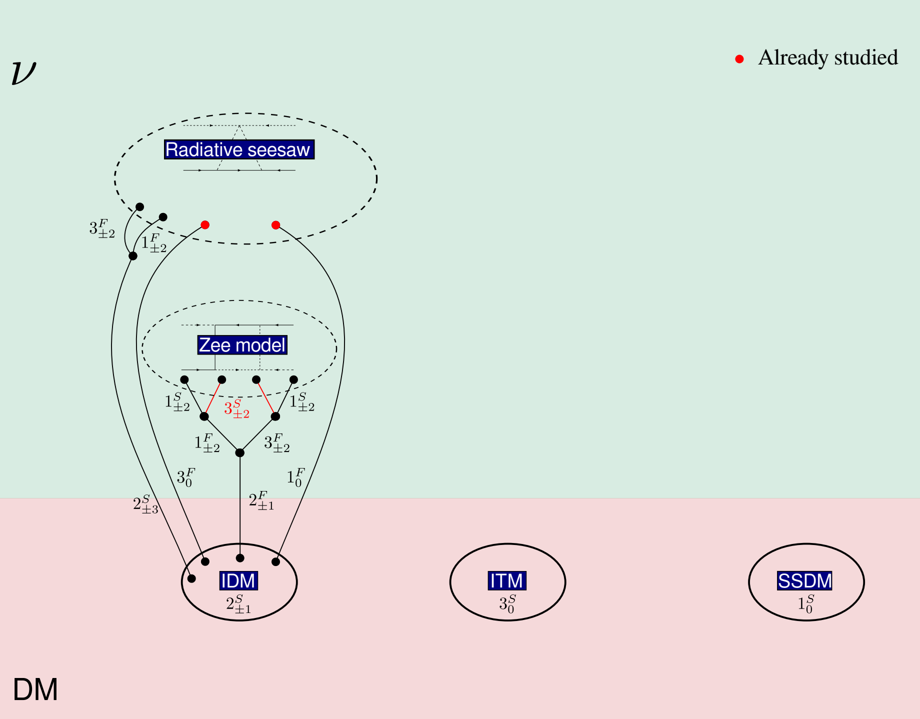
ν
IDM
$2^S_{\pm 1}$
ITM
3^S_0
SSDM
1^S_0
DM



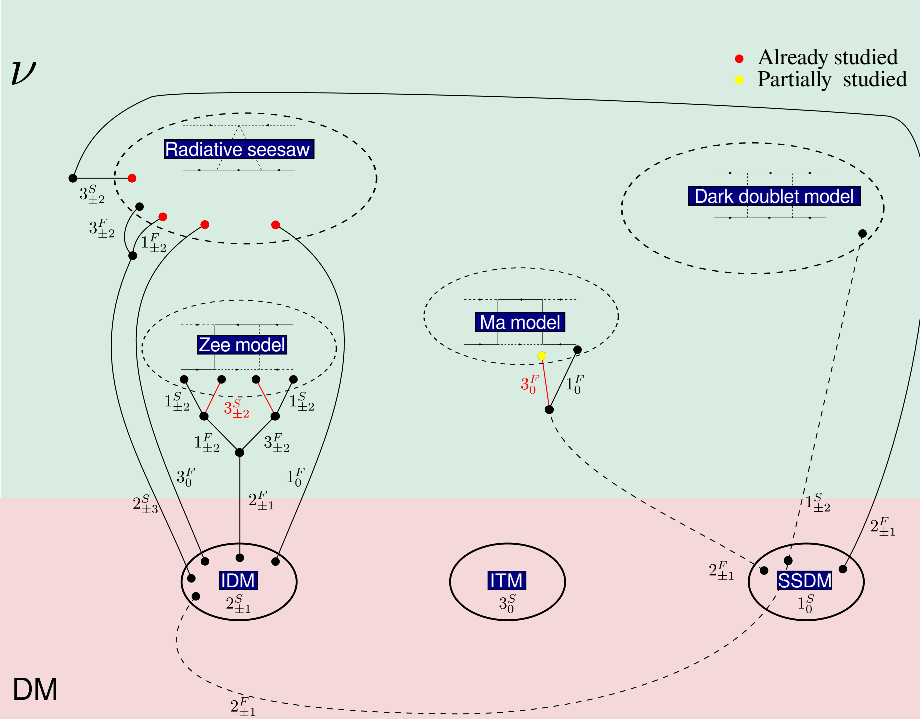
ν
Already studied
Radiative seesaw
3_0^F
1_0^F
IDM
$2_{\pm 1}^S$
ITM
3_0^S
SSDM
1_0^S
DM



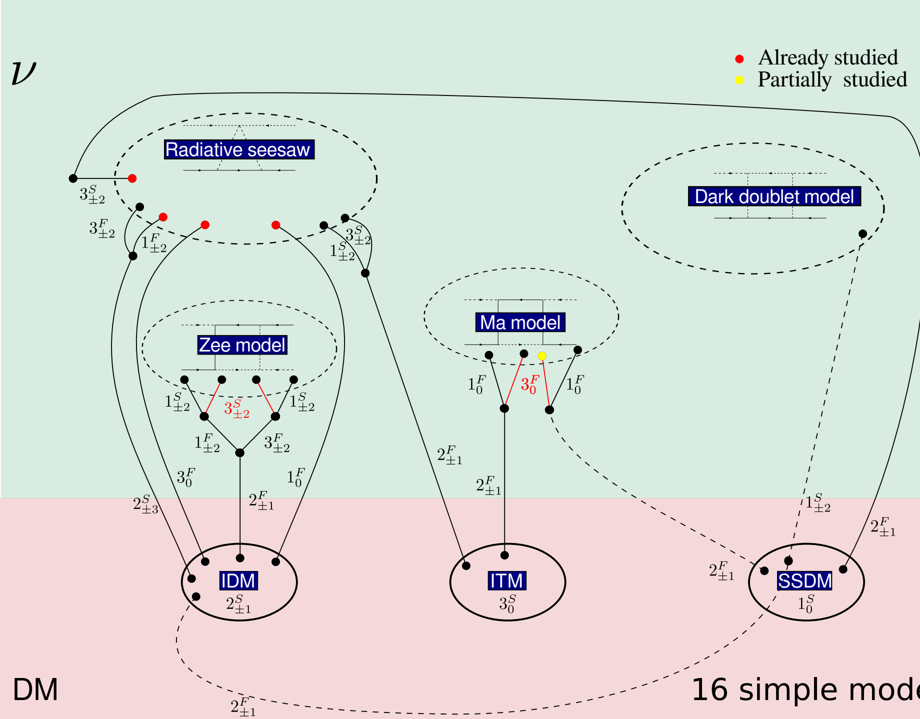
ν
Already studied
Radiative seesaw
$3^F_{\pm 2}$
$1^F_{\pm 2}$
3^F_0
1^F_0
$2^S_{\pm 3}$
IDM
$2^S_{\pm 1}$
ITM
3^S_0
SSDM
1^S_0
DM



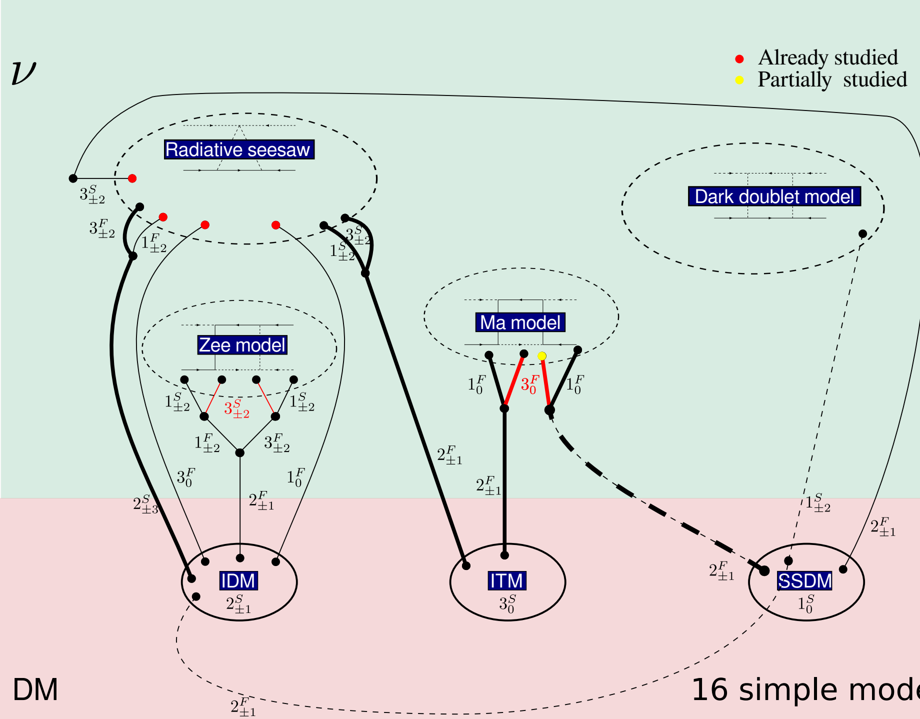
ν
Already studied
Radiative seesaw
Zee model
$3^F_{\pm2}$
$1^F_{\pm2}$
$1^S_{\pm2}$
$3^S_{\pm2}$
$1^S_{\pm2}$
$1^F_{\pm2}$
$3^F_{\pm2}$
3^F_0
1^F_0
$2^S_{\pm3}$
$2^F_{\pm1}$
IDM
$2^S_{\pm1}$
ITM
3^S_0
SSDM
1^S_0
DM



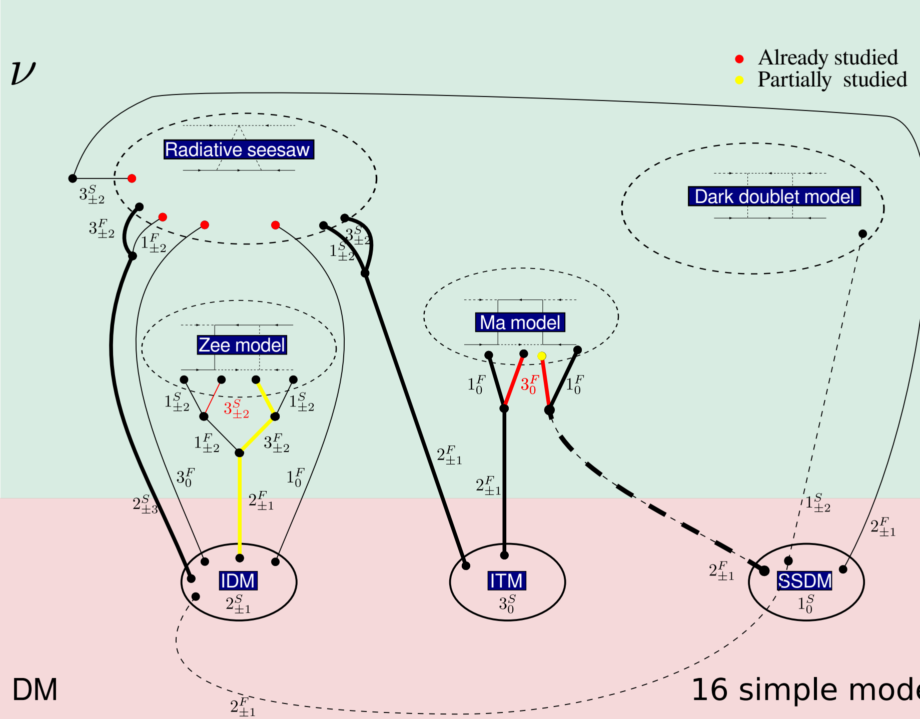
ν
Already studied
Partially studied
Radiative seesaw
Dark doublet model
Zee model
Ma model
$3^S_{\pm2}$
$3^F_{\pm2}$
$1^F_{\pm2}$
$1^S_{\pm2}$
$3^S_{\pm2}$
$1^S_{\pm2}$
$1^F_{\pm2}$
$3^F_{\pm2}$
3^F_0
1^F_0
$2^F_{\pm1}$
$2^S_{\pm3}$
3^F_0
1^F_0
$1^S_{\pm2}$
$2^F_{\pm1}$
$2^F_{\pm1}$
IDM
$2^S_{\pm1}$
ITM
3^S_0
SSDM
1^S_0
DM
$2^F_{\pm1}$



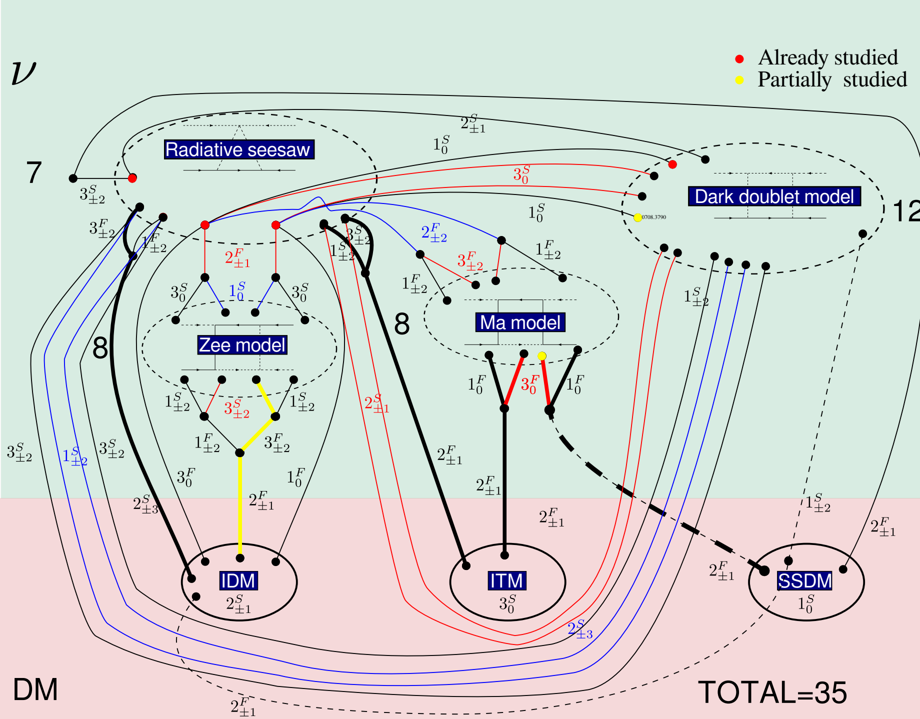
ν
Already studied
Partially studied
Radiative seesaw
Dark doublet model
Zee model
Ma model
$3^S_{\pm2}$
$3^F_{\pm2}$
$1^F_{\pm2}$
$1^S_{\pm2}$
$3^S_{\pm2}$
$1^S_{\pm2}$
$1^S_{\pm2}$
$1^F_{\pm2}$
$3^F_{\pm2}$
1^F_0
3^F_0
1^F_0
3^F_0
$2^F_{\pm1}$
$2^F_{\pm1}$
$2^F_{\pm1}$
$2^S_{\pm3}$
$1^S_{\pm2}$
$2^F_{\pm1}$
$2^F_{\pm1}$
IDM
$2^S_{\pm1}$
ITM
3^S_0
SSDM
1^S_0
$2^F_{\pm1}$
DM
16 simple mode



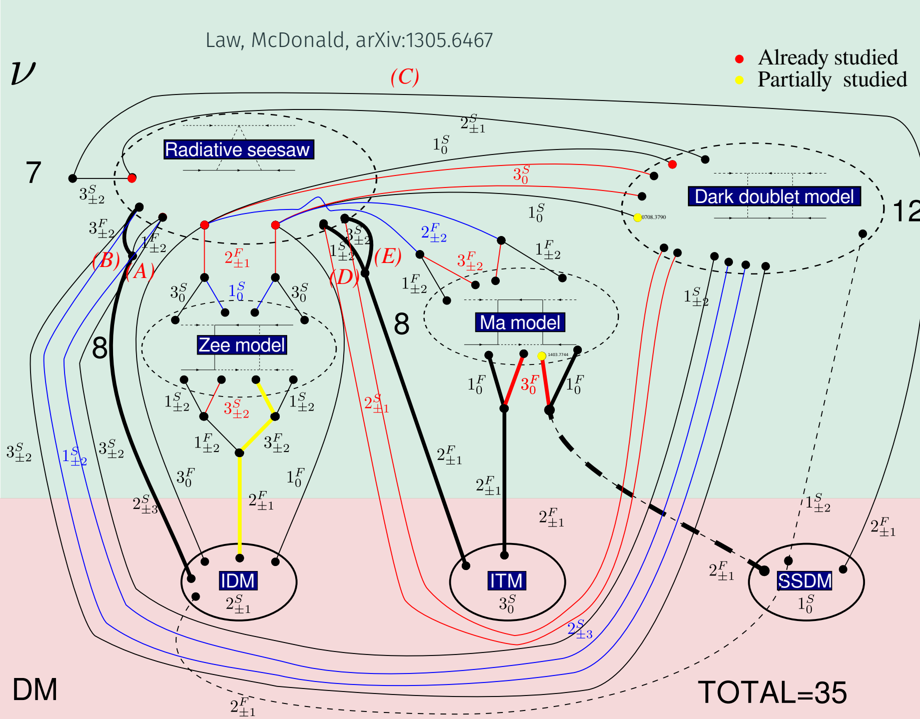
ν
Already studied
Partially studied
Radiative seesaw
Dark doublet model
Zee model
Ma model
IDM
ITM
SSDM
DM
16 simple mode



ν
Already studied
Partially studied
Radiative seesaw
Dark doublet model
Zee model
Ma model
IDM
ITM
SSDM
$3^S_{\pm2}$
$3^F_{\pm2}$
$1^F_{\pm2}$
$1^S_{\pm2}$
$2^F_{\pm1}$
1^F_0
3^F_0
$2^S_{\pm3}$
$2^S_{\pm1}$
3^S_0
1^S_0
DM
16 simple mode

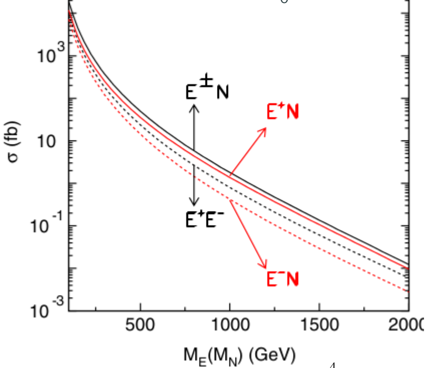


ν
Already studied
Partially studied
Radiative seesaw
Dark doublet model
Zee model
Ma model
IDM
ITM
SSDM
7
8
8
12
DM
TOTAL=35
$2^S_{\pm1}$
1^S_0
3^S_0
$3^S_{\pm2}$
$3^F_{\pm2}$
$1^F_{\pm2}$
$2^F_{\pm1}$
$2^F_{\pm2}$
3^F_0
1^F_0
$2^S_{\pm3}$
$1^S_{\pm2}$
0708.3790

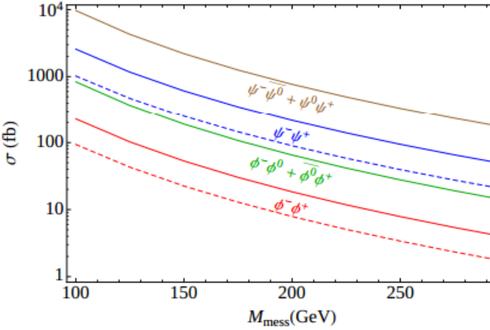


Law, McDonald, arXiv:1305.6467
ν
Already studied
Partially studied
(C)
Radiative seesaw
Dark doublet model
Zee model
Ma model
IDM
ITM
SSDM
7
8
8
12
(A)
(B)
(D)
(E)
$3^S_{\pm 2}$
$3^F_{\pm 2}$
$1^F_{\pm 2}$
$2^S_{\pm 1}$
1^S_0
3^S_0
$2^F_{\pm 1}$
$2^F_{\pm 2}$
1^F_0
3^F_0
$1^S_{\pm 2}$
$2^S_{\pm 3}$
$2^F_{\pm 1}$
DM
TOTAL=35

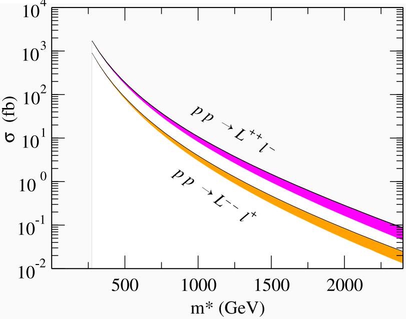
arXiv:0907.4193: 3_0^F

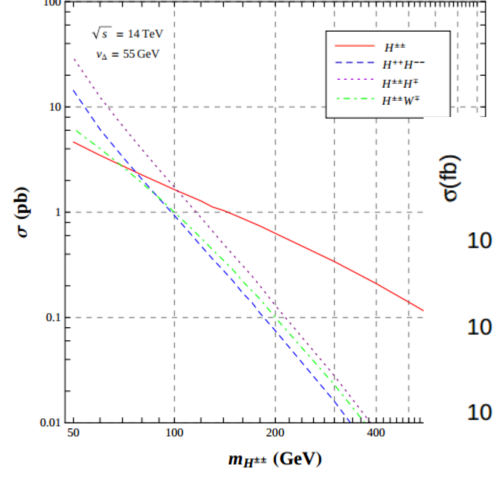


arXiv:1303.4404: $2_{\pm1}^{F,S}$ (solid) $1_{\pm2}^{F,S}$ (dashed)

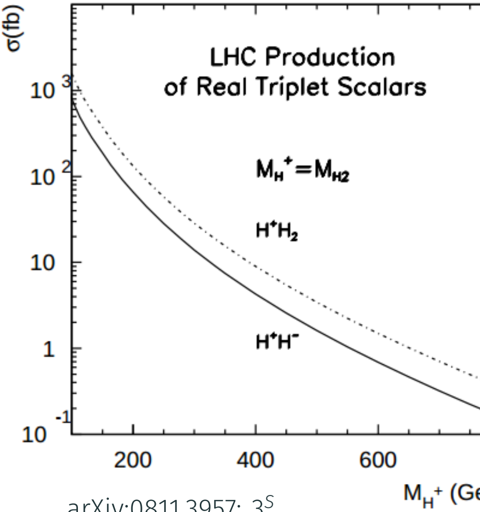


arXiv:1201.3764 $3_{\pm2}^F$





arXiv:1202.2014: $3^S_{\pm 2}$



arXiv:0811.3957: 3^S_0

Discussion

FeynRules/SARAH

micrOMEGAS (CalcHEP) — MadGraph(UFO)

DM — LHC

- The collider and dark matter phenomenology of many of these viable models have yet to be studied in detail.
- We have only qualitatively described the particle content and the dark matter candidates of each model. A more specific analysis of some of these models is certainly desirable.
- Some strategies to systematically search for this kind of models at colliders would be designed.
- New particles allowed to be even under Z_2 could give rise to new possibilities.

Higgsino-like radiative seesaw

$$
\begin{aligned}
10 \times 16 =& 16 + 144 \\
\overline{16} \times 16 =& 1 + \cdots \\
\overline{144} \times 144 =& 1 + \cdots
\end{aligned}
$$

The singlet comes from the following $SU(5)$ representation

$$\overline{144} \times 144 \supset 24 \times 24 = 1$$

and the singlet can be choosen real

New simplified models

H. Okada et. al, arXiv:1408.0961, Inert Zee-babu model

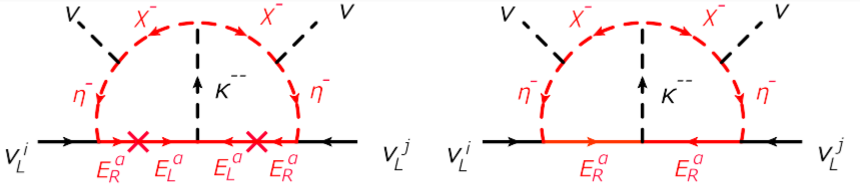
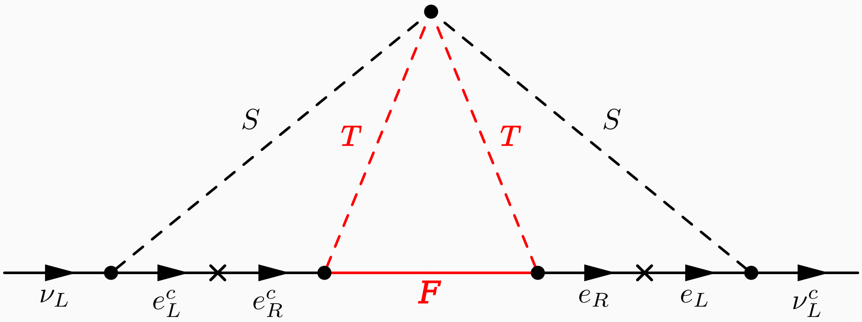


FIG. 2: Feynman diagrams for the neutrino mass generation at the two-loop level. Particles indicated by the red color have the Z_2 odd parity.

A. Ahriche, et. al, arXiv:1508.05881, three-loop ν-DM

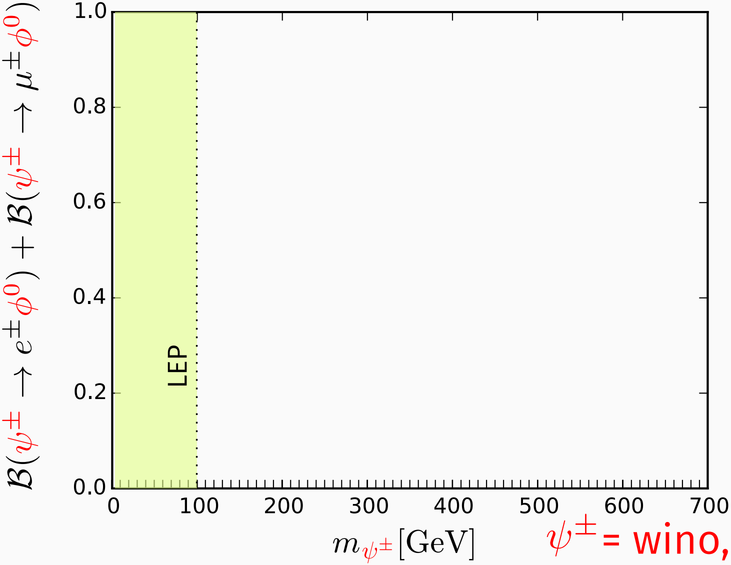


Three-loop diagram for neutrino mass. Here, $S \sim (1, 1, 2)$ and $T \sim (1, 2n+1, 2)$ are beyond-SM scalars while $F \sim (1, 2n+1, 0)$ is a beyond-SM fermion.

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

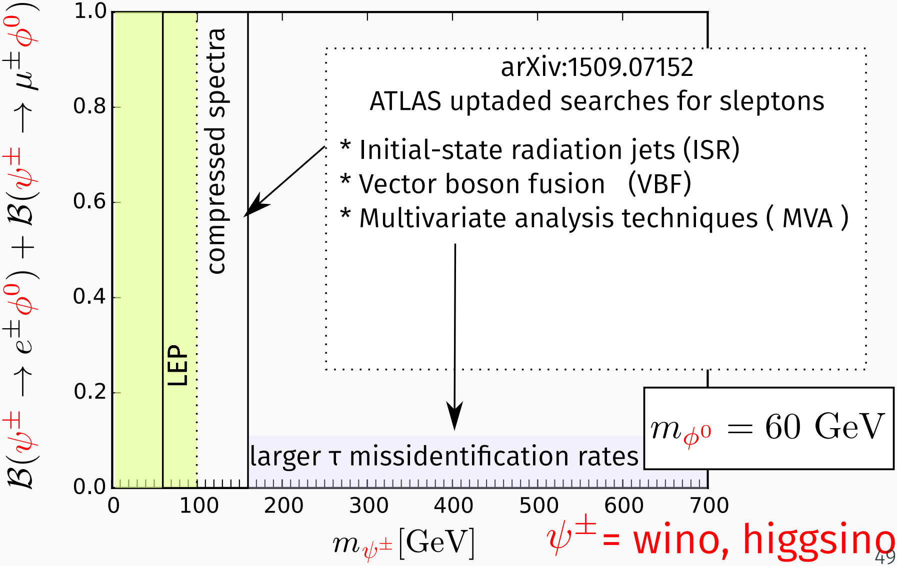
$\psi^{\pm}$= wino, higgsino

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



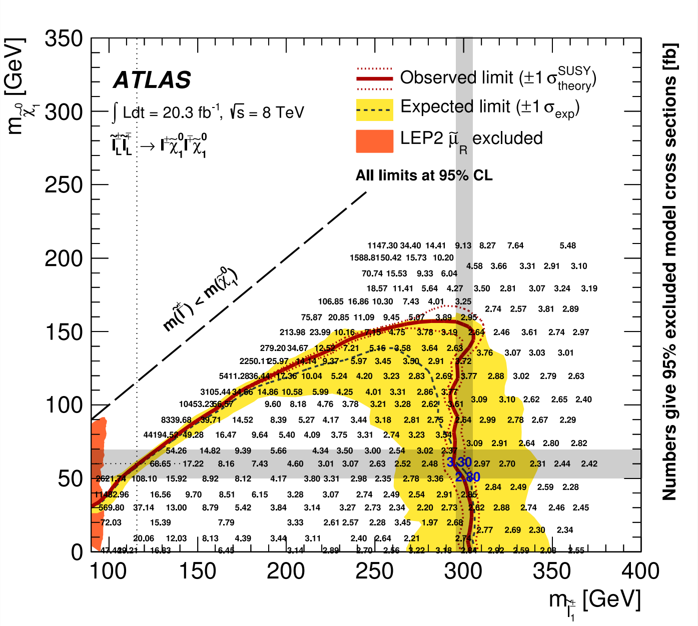
$\psi^{\pm}$= wino, higgsino

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



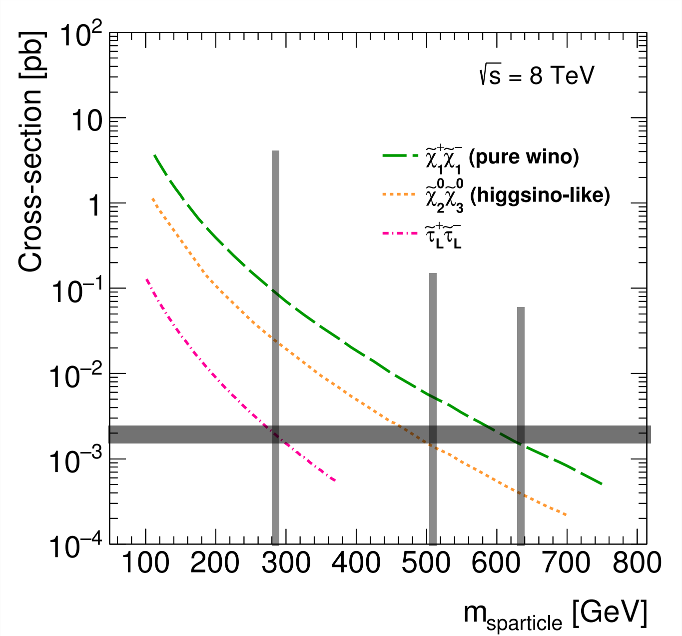
$\psi^{\pm}$ = wino, higgsino

ATLAS arXiv:1403.5294 (JHEP)

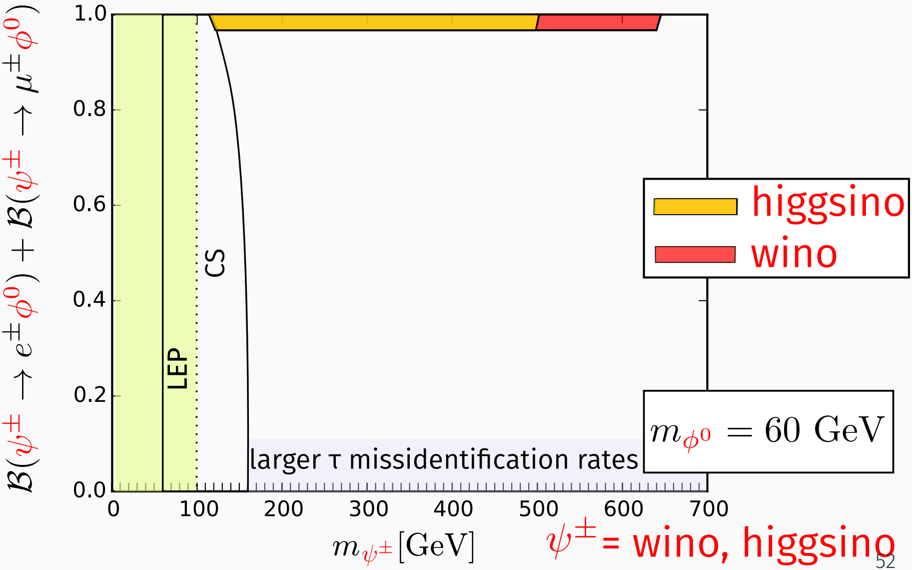


CMS $\gtrsim 260$ GeV arXiv:1405.7570

Excluded cross section for higgsino and wino fermions

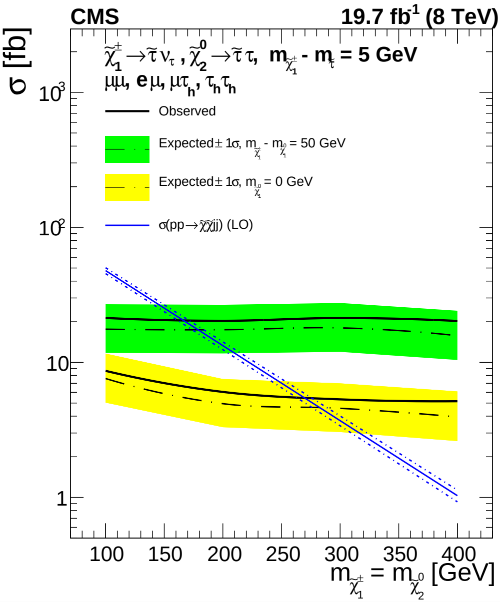


$$pp \to \psi^{\pm}\psi^{\mp} \to l_i^{\pm} l_j^{\mp} \phi^0 \phi^0 \quad l_i = e, \mu, \tau, \quad \phi^0 = H^0, S^0$$



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

CMS 1508.07628: di-tau plus missing energy (VBF)

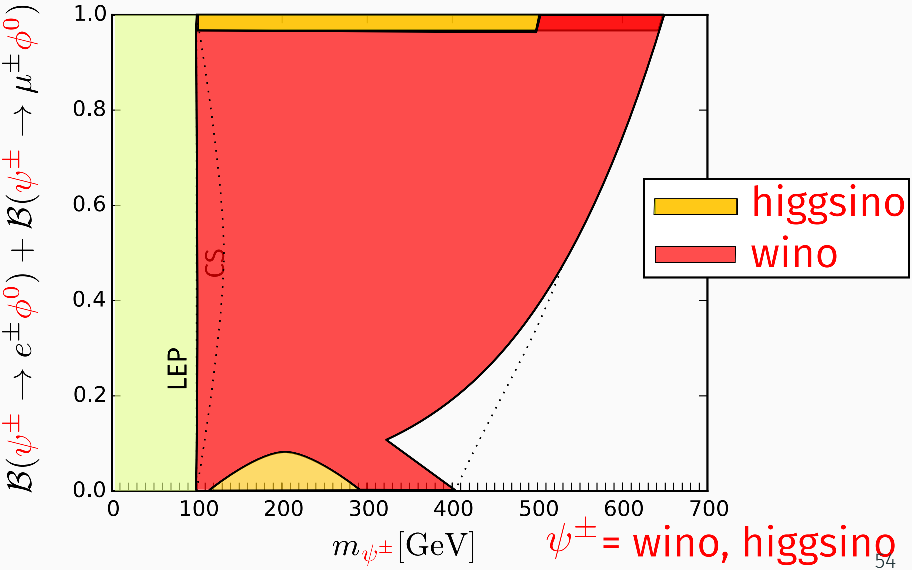


$\cancel{\psi^\pm \psi^0}$

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

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

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



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