

# $\nu$ -Dark matter models

## Model building



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September 11, 2016

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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

# Table of Contents

1. Scotogenic models
2. General framework
3. Proposal:  $pp \rightarrow l^+l^- + \cancel{E_T}$
4. Lepton flavor dependence
5. Recast at the LHC Run-I (wino-like scenario)
6. Conclusions
7. Beyond the standard model
8. Dark matter and unification

## Scotogenic models

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## General framework

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## $\nu$ -DM models

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

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

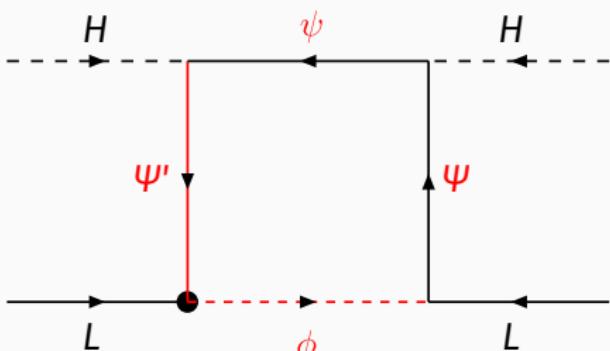
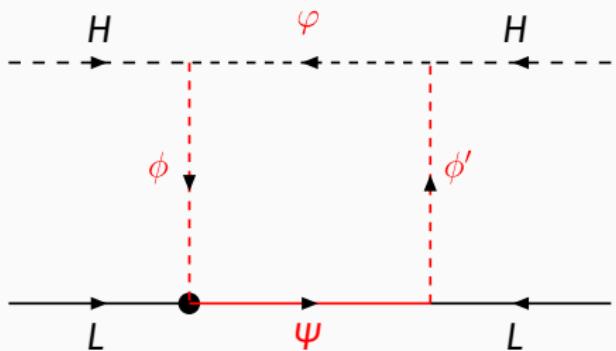
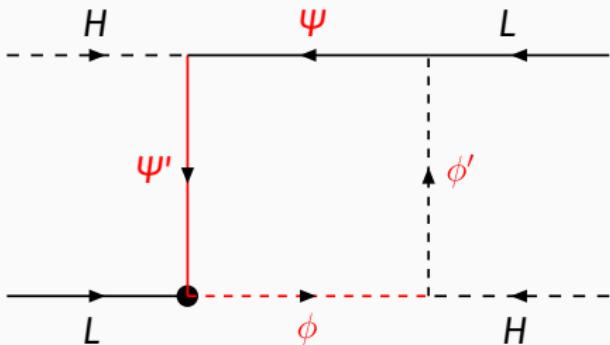
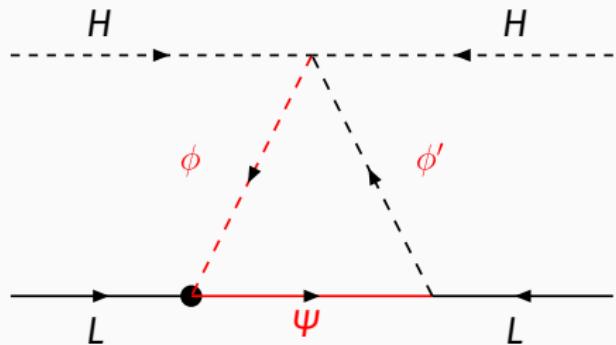
In this direction, models with one-loop radiative neutrino masses and viable dark matter candidates have now a complete classification given in

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.

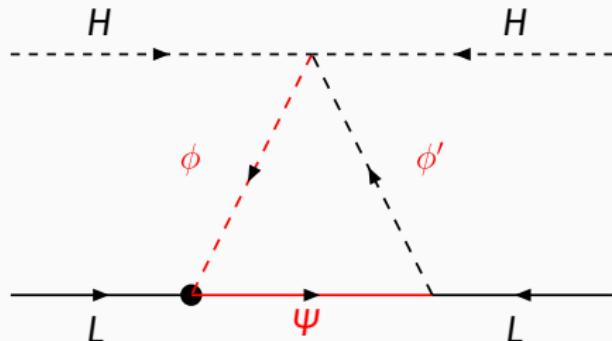
# Weinberg operator at one-loop

( $Z_2$ -odd fields)

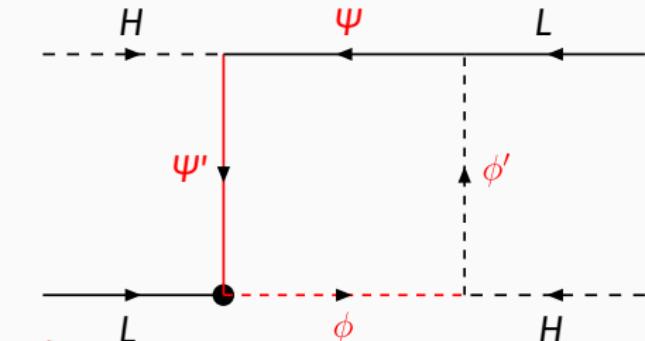


# Weinberg operator at one-loop

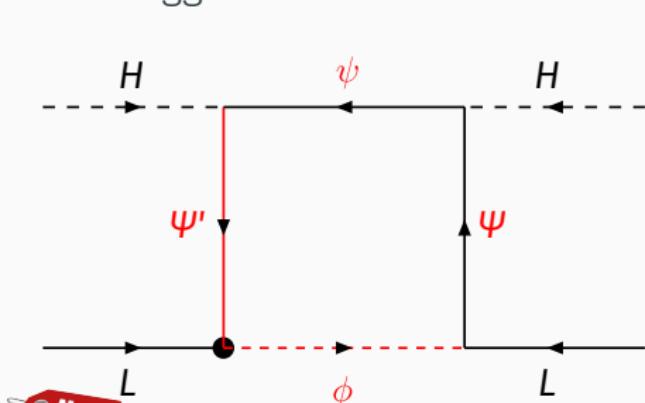
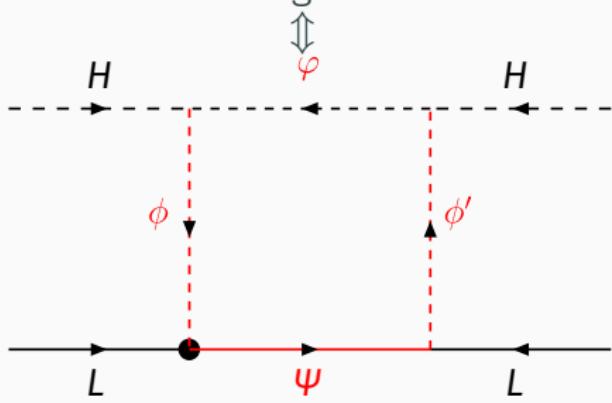
( $Z_2$ -odd fields)



Wino-like scotogenic model



Higgsino-like Zee model



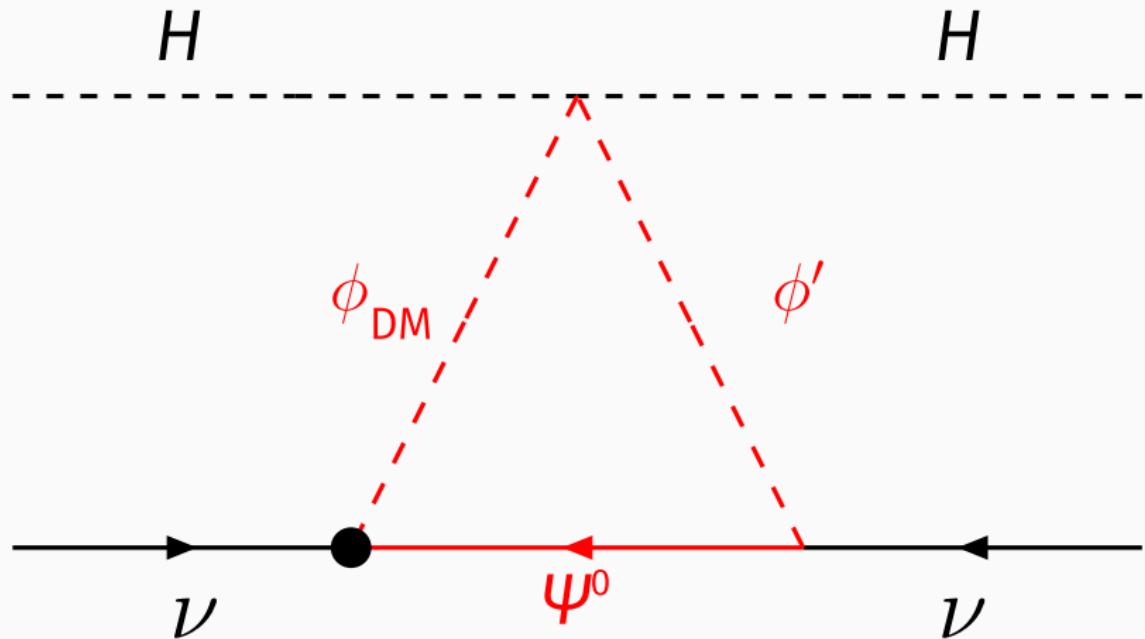
Higgsino-like scotogenic model

## Specific examples

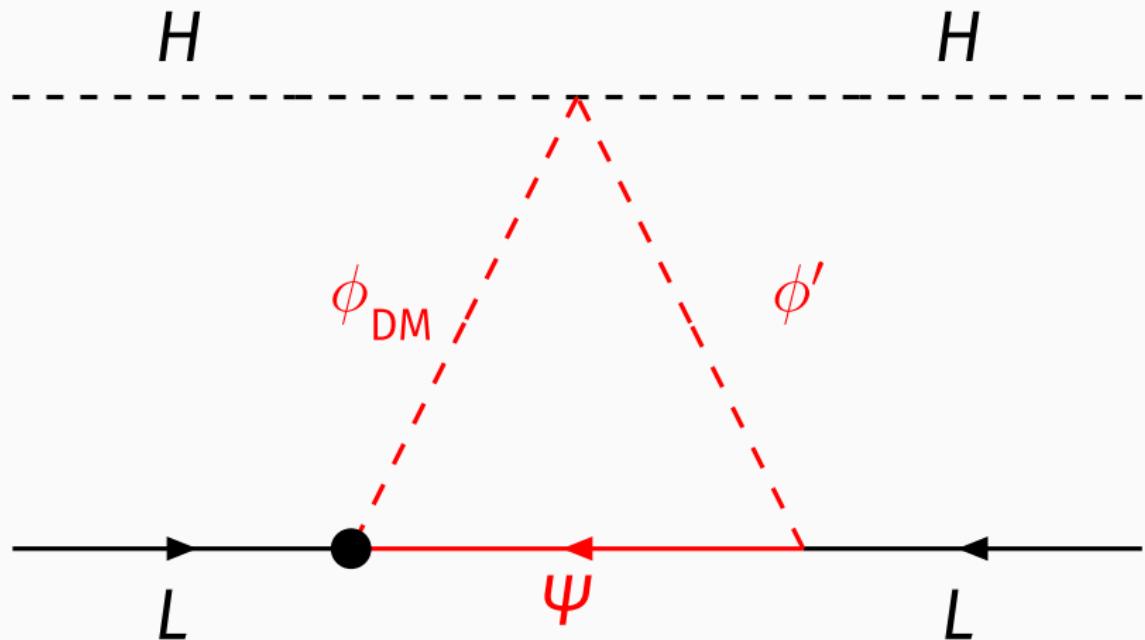
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- RSIII
- T13A
- RSII
- Inert Zee

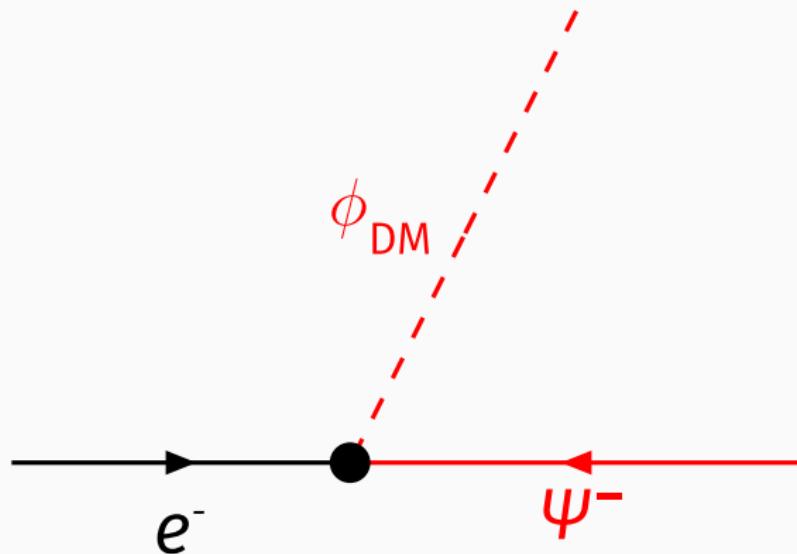
## Typical radiative neutrino mass diagram.



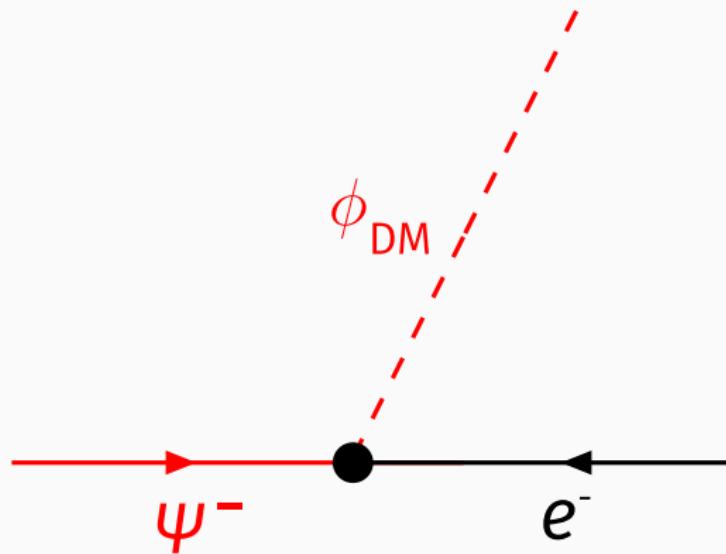
In term of general  $SU(2)_L$  multiplets,



may be also charged particles,



which may decay into the dark matter particle.

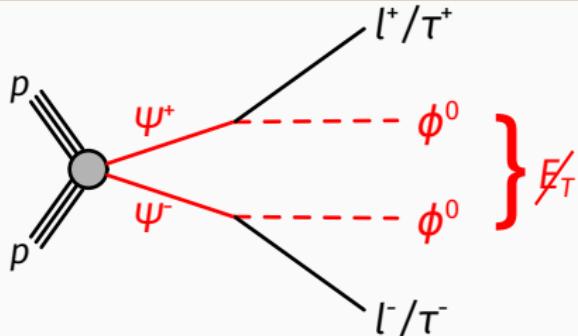


**Proposal:**  $pp \rightarrow l^+l^- + E_T$

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Benchmark: Resonance and 100 GeV Charged scalar

# Dilepton plus transverse missing energy signal

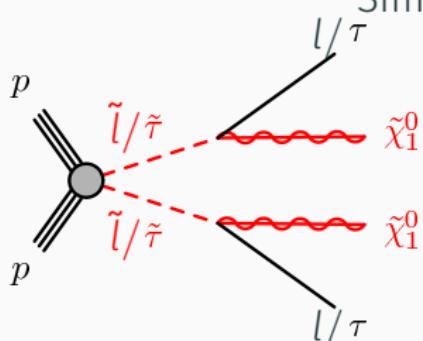


SU(2)<sub>L</sub> assignments:

$$\Psi = 1, 2, 3,$$

$$\Phi = 1, 2, \text{ with } m_{\text{DM}} \sim m_h/2.$$

Simplified SUSY models



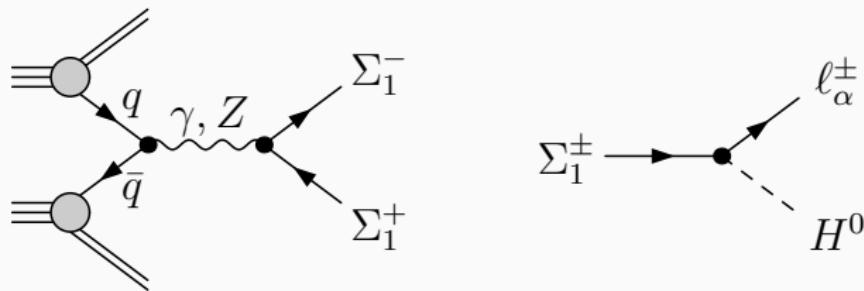
Smaller cross sections.

Intermediate states and smaller lepton  $p_T$

## Specific examples

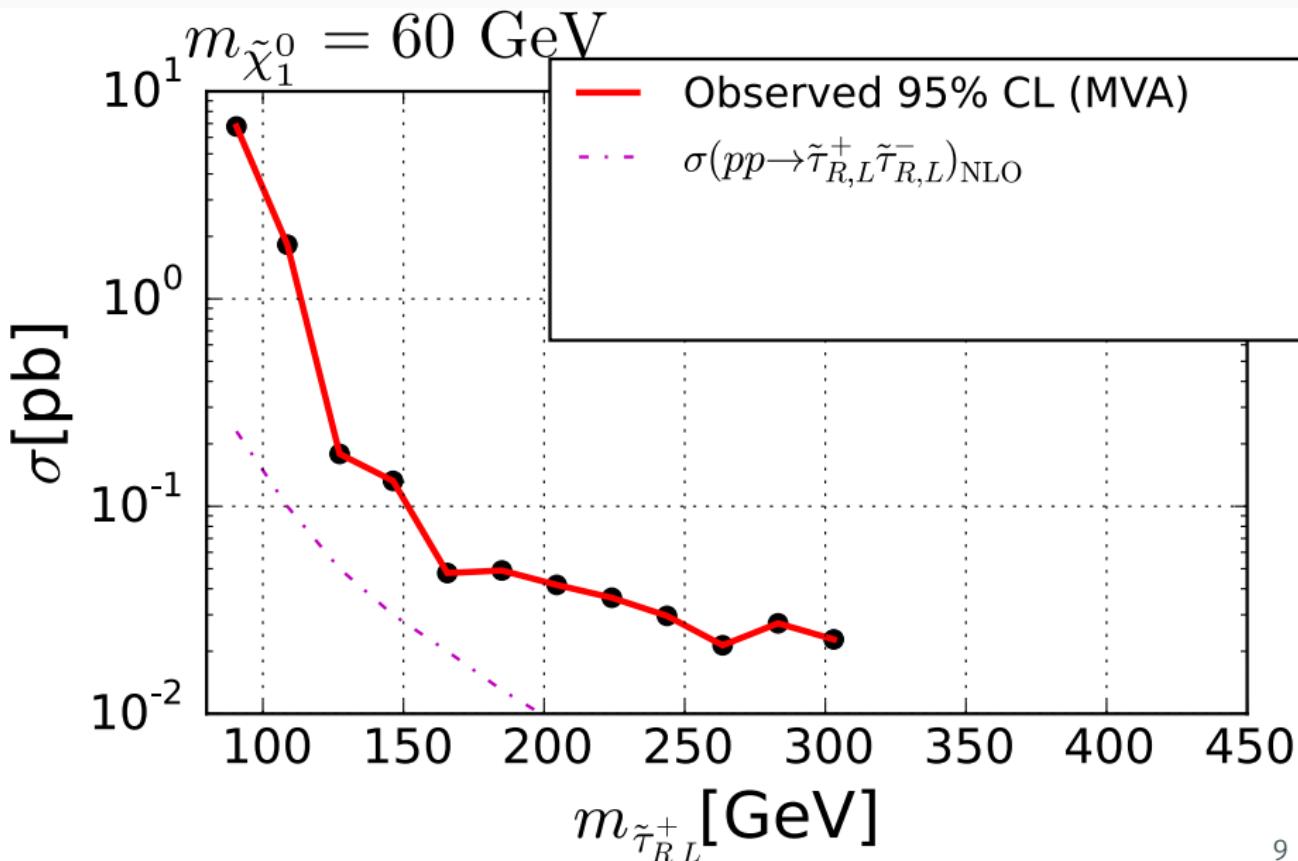
Radiative Type-III See-saw

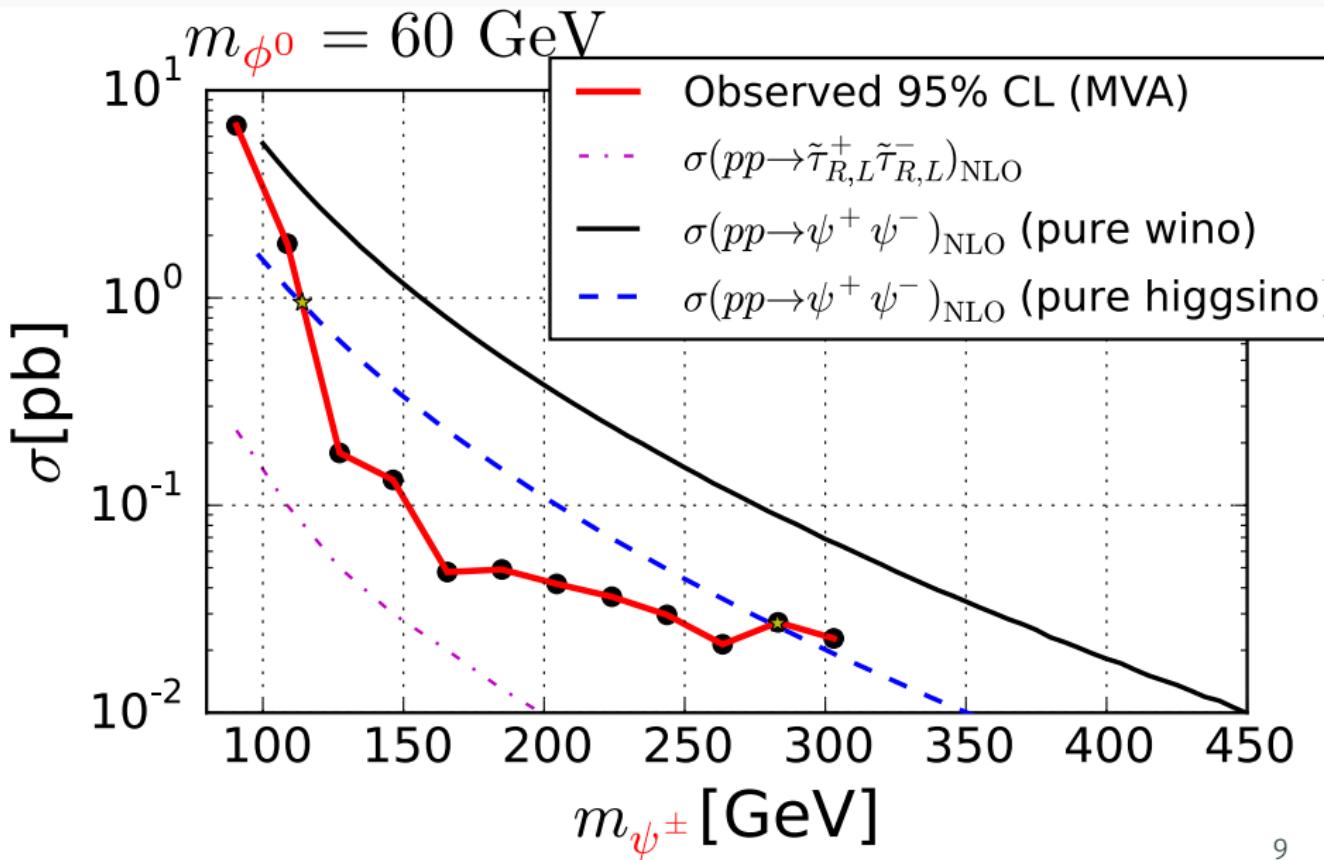
Radiative Type-II See-saw Wino-like production

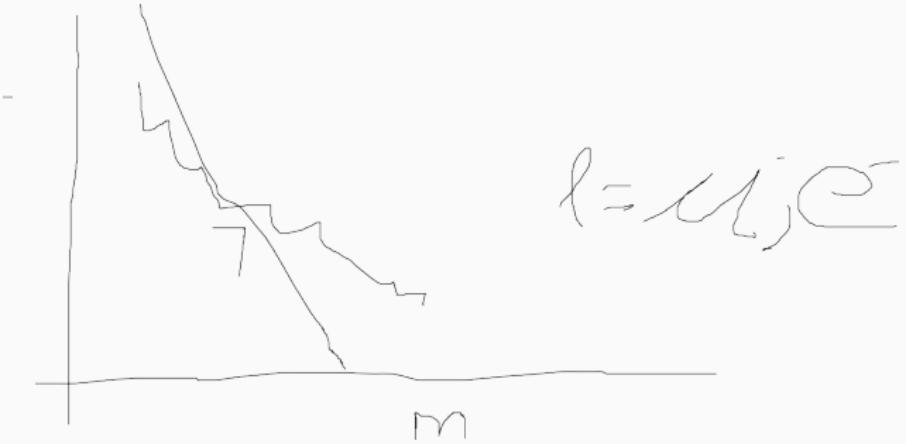


Higgsino-like

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







## Lepton flavor dependence

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## Neutrino masses

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

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

$$Y = \sqrt{\Lambda}^{-1} R \text{diag}(\sqrt{m_{\nu_1}}, \sqrt{m_{\nu_2}}, \sqrt{m_{\nu_3}}) U_{\text{PMNS}}^\dagger , \quad (1)$$

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

# 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  
~~E~~T with  $e^+e^-$ ,  $\mu^+\mu^-$ ,  $e^\pm\mu^\mp$ .

SARAH/FeynRules



micrOMEGAS (Experimental and theoretical constraints)



MadGraph



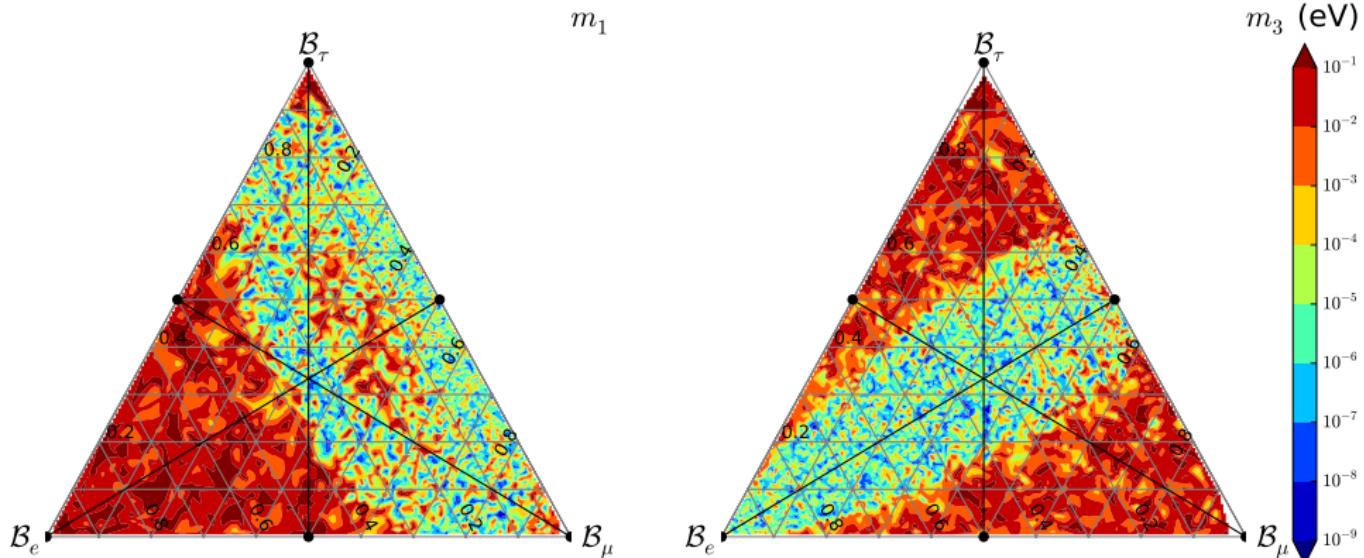
Pythia 6 (hep format)



checkMATE (CL-calculation)

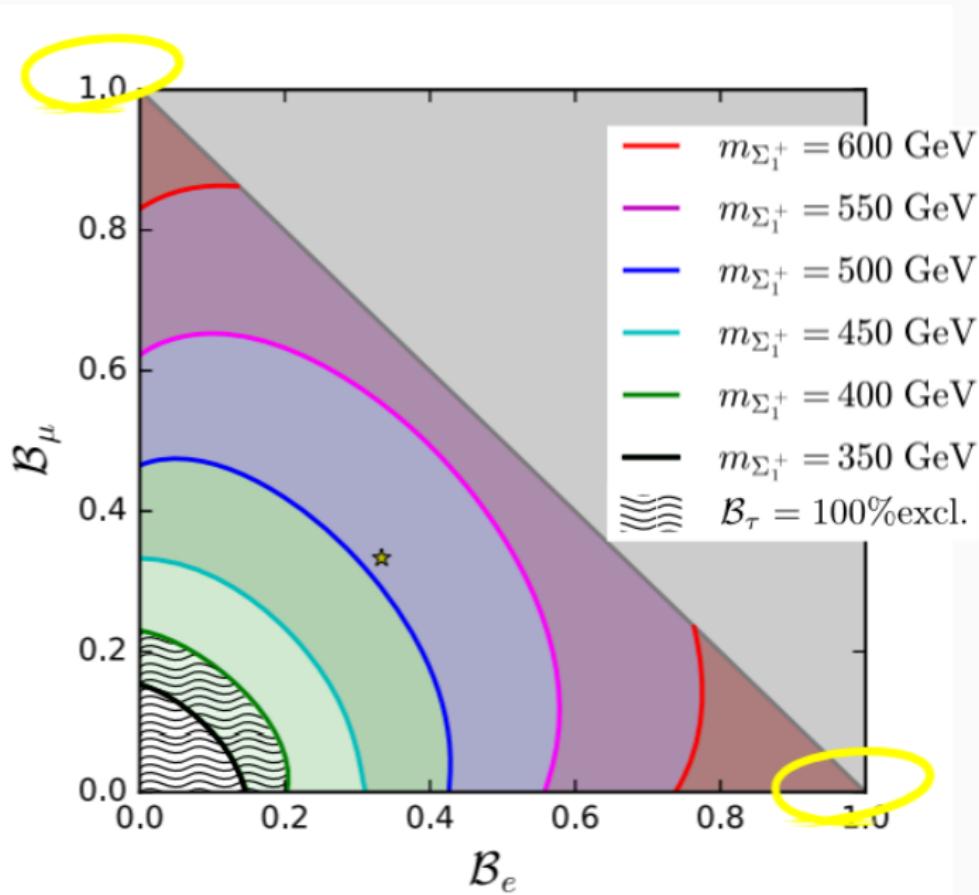
# Casas-Ibarra parametrization

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



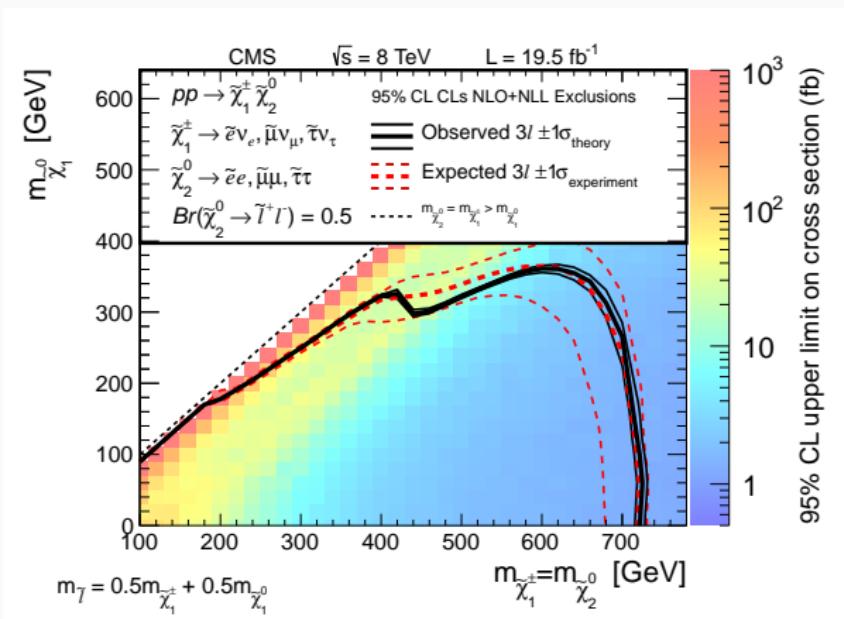
$$\mathcal{B}_l = \mathcal{B} (\psi^\pm \rightarrow l H^0)$$

# Combination



# CMS 1405.7570: Best SUSY simplified model:

Largest Wino-production to three leptons and MET



Interpretation of the results of the three-lepton search in the flavor-democratic signal model with slepton mass parameter  $\xi_{\tilde{l}} = 0.5$

Simplified SUSY to dileptons and MET: slepton pair production  
(see below)

## Conclusions

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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)

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# Exploration of flavor space

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

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Start with Signal regions as in ATLAS-arXiv:1403.5294 for  
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FeynRules



micrOMEGAS (Experimental and theoretical constraints)



MadGraph

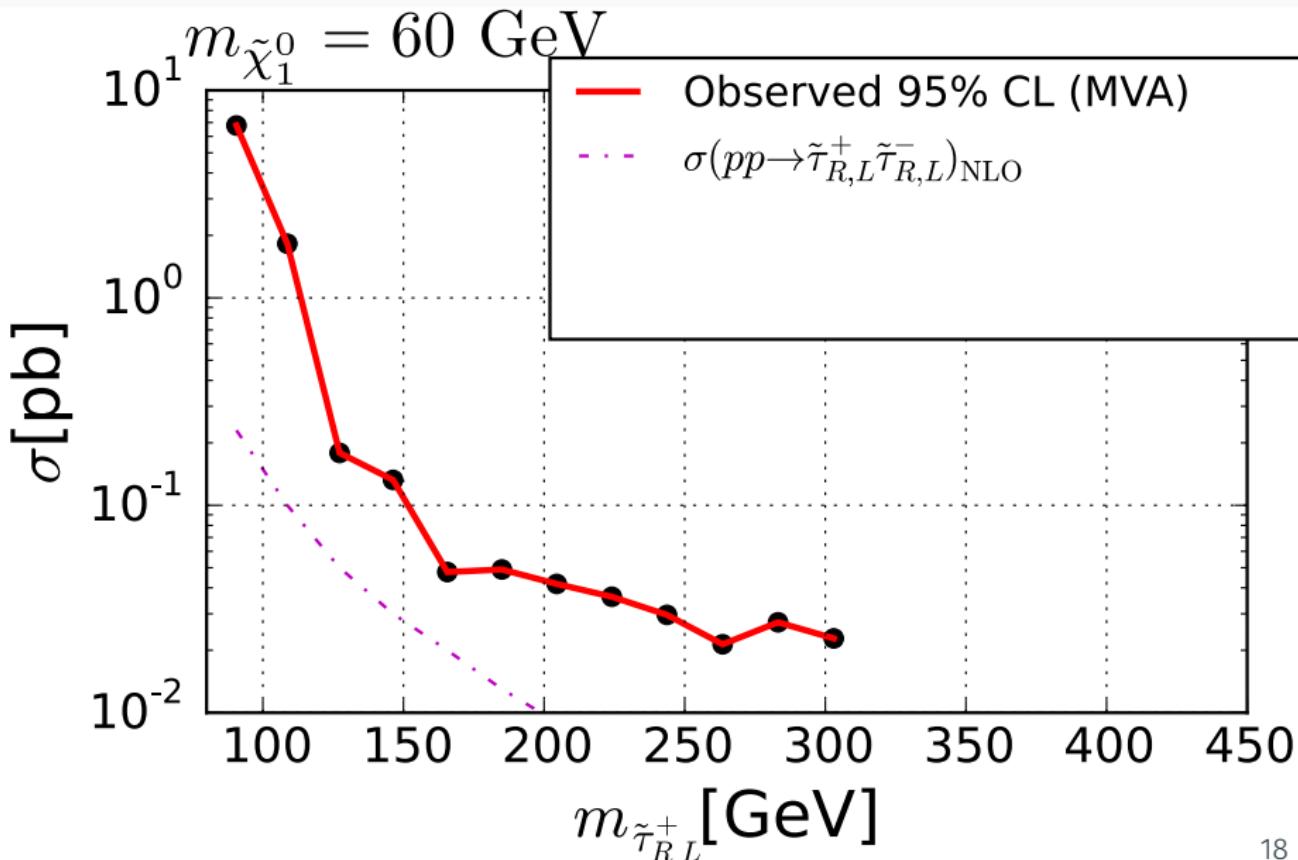


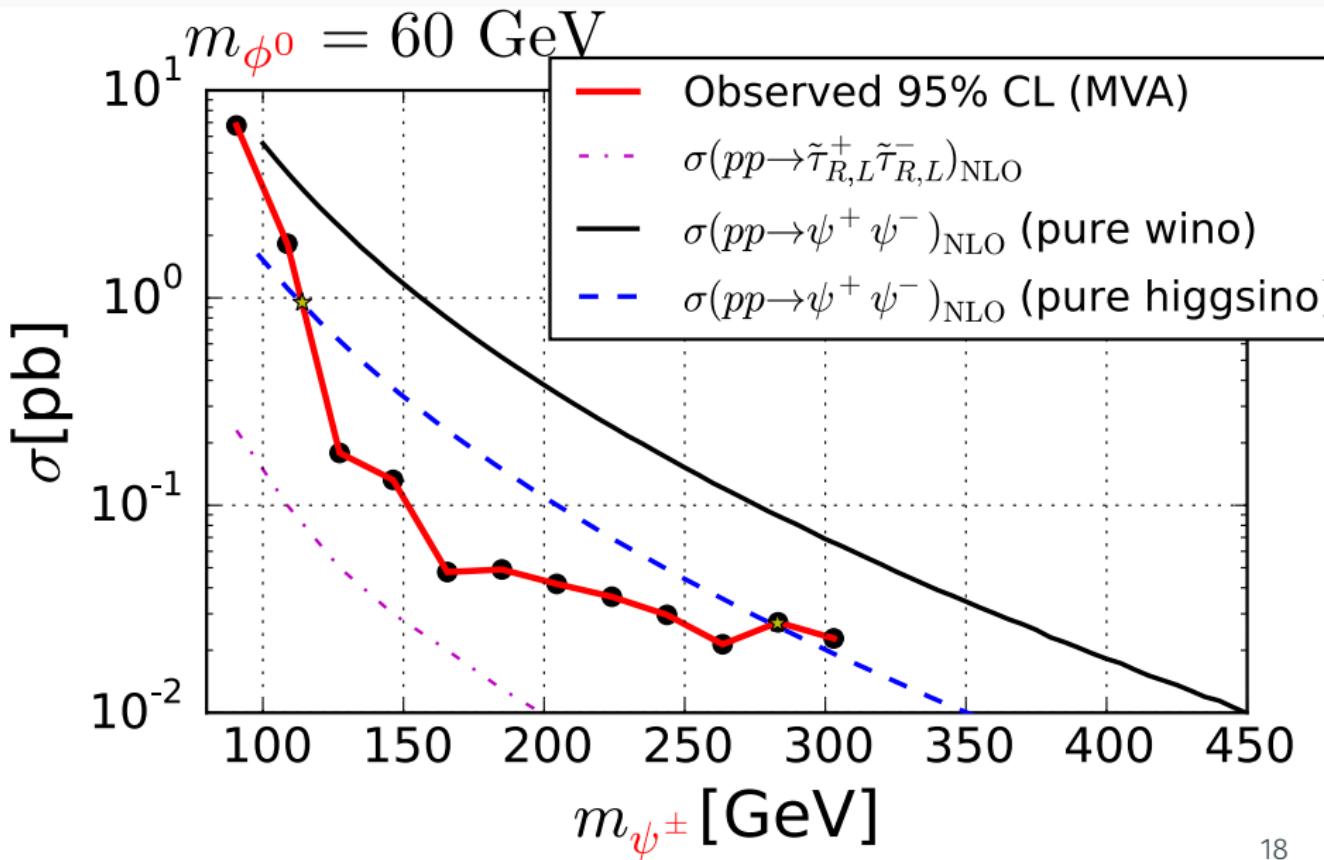
Pythia 6 (hep format)



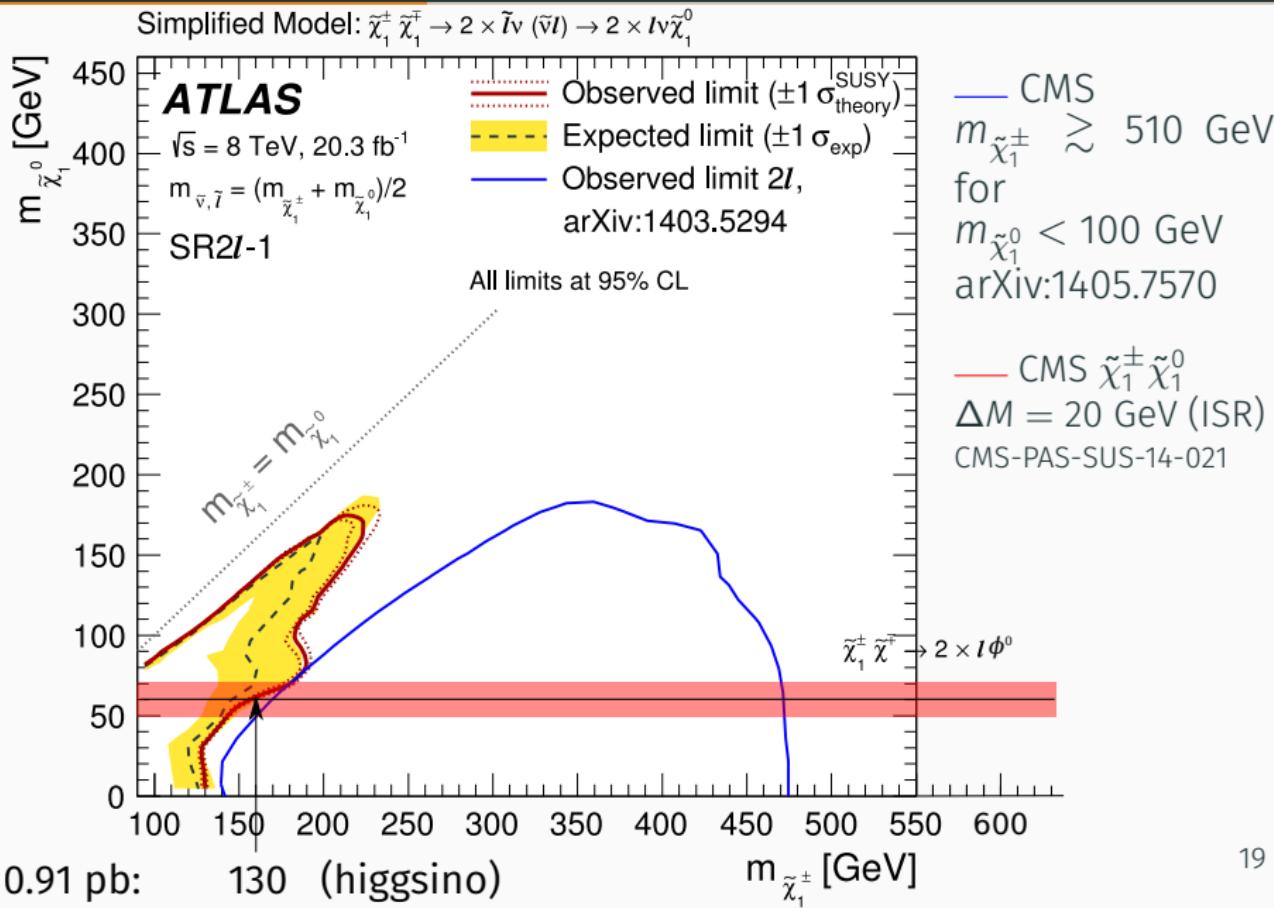
checkMATE (CL-calculation)

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

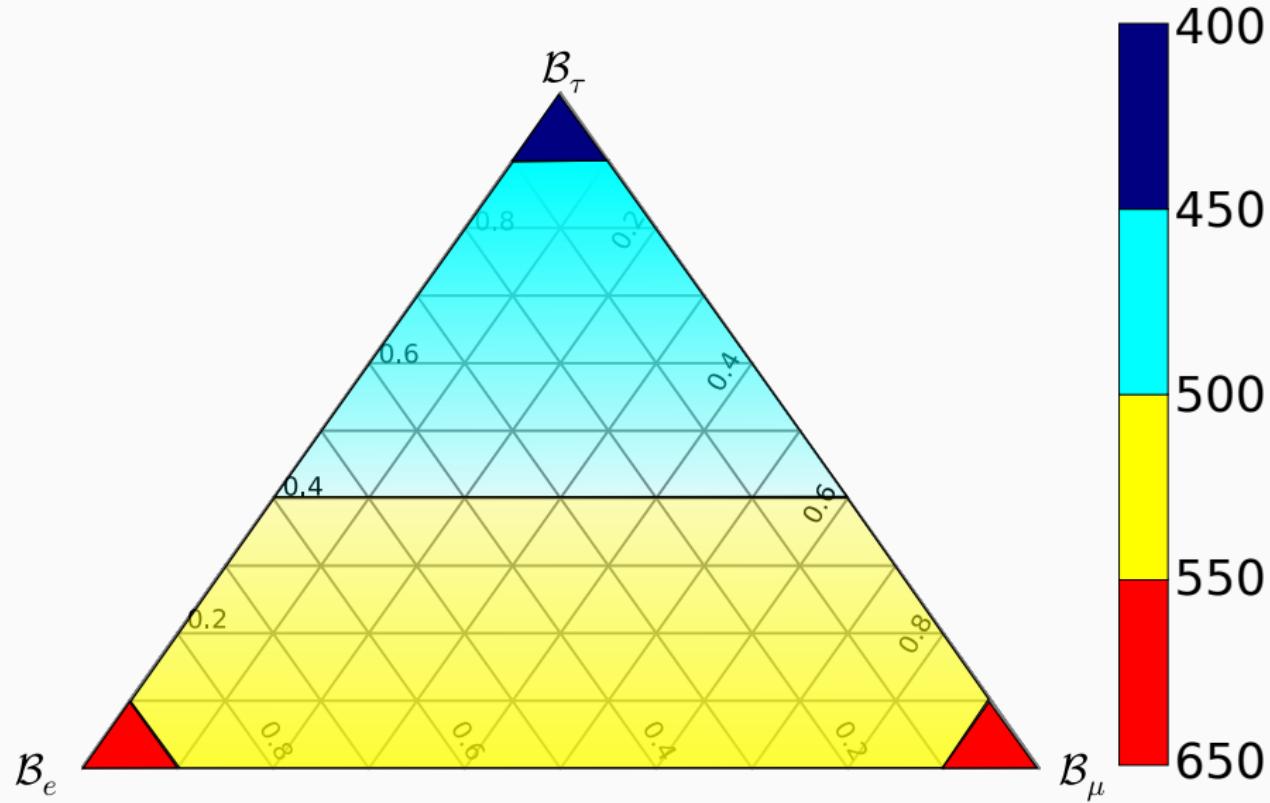




# wino production to dilepton plus missing energy (ISR)



# Wino-like exclusion from Run-I



## Conclusions

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## Conclusions i

After giving up the **hierarchy problem** (*heavy sfermion masses*), **dark matter** and **gauge coupling unification** is no longer associated to SUSY



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

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$Z_2$ -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  $2 \times (60 \text{ GeV DM.})$

## Conclusions ii

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The wino-like scotogenic model (*radiative type-III seesaw*) with  $\mathcal{B}(\psi^+ \rightarrow l_i \phi^0) = 1$  is 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  $\mathcal{B}(\psi^+ \rightarrow e^+ \phi^0) = 1$  ( $\mathcal{B}(\psi^+ \rightarrow \tau^+ \phi^0) = 1$ ),

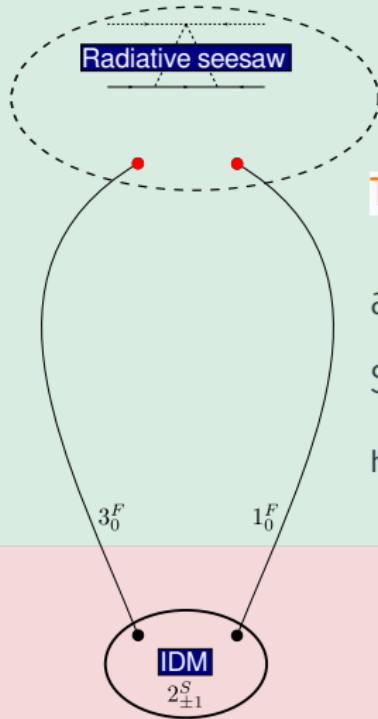
Including the compressed-spectra region

*TODO: Higgsino-like case*

Thanks!

$\nu$

- Already studied



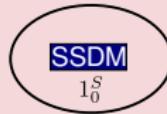
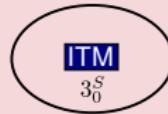
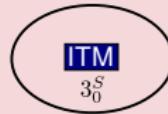
## Type-I RS SARAH implementation

arXiv:1507.06349 by Avelino Vicente

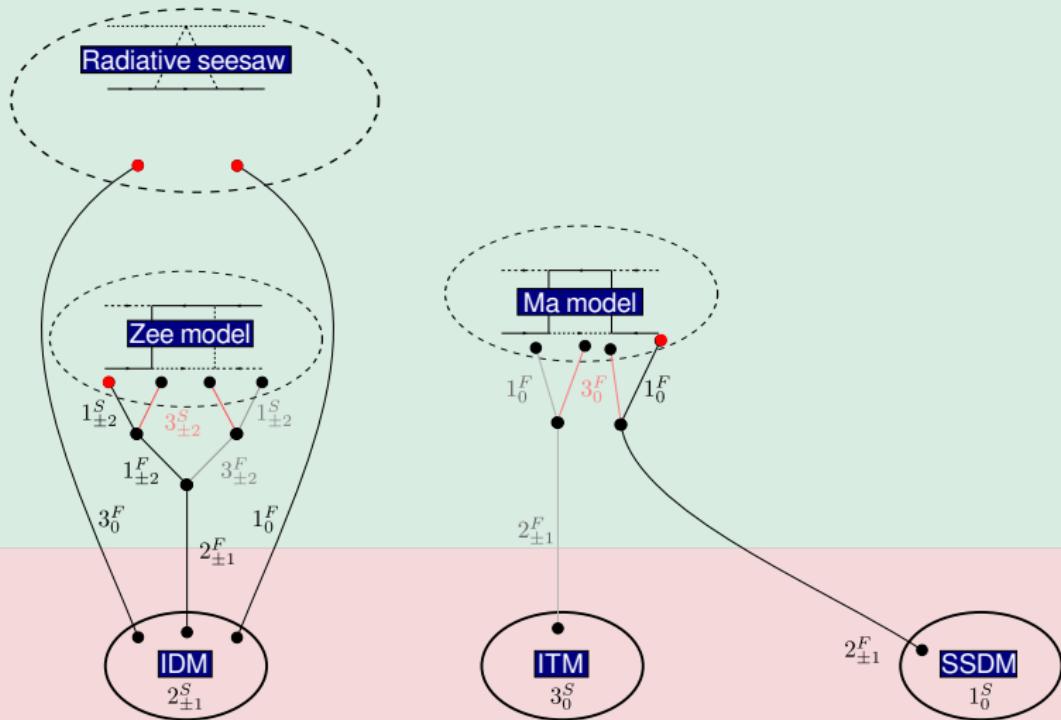
Slides and Code

<https://github.com/restrepo/Scotogenic>

DM

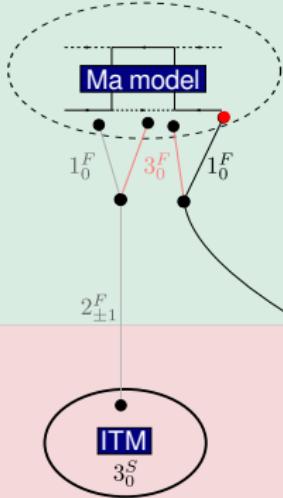
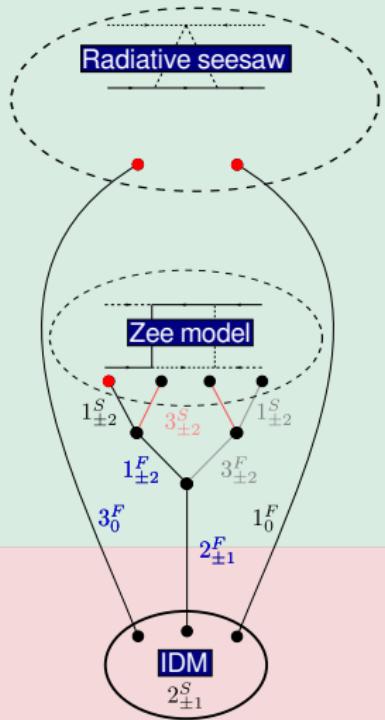


- Already studied

 $\nu$ 

DM

- Already studied

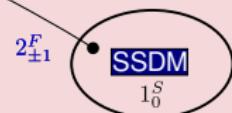
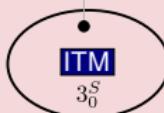
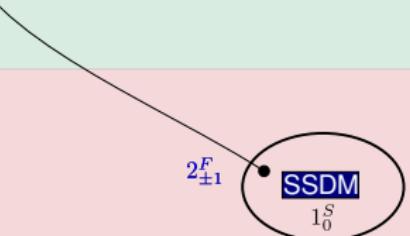
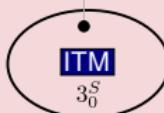
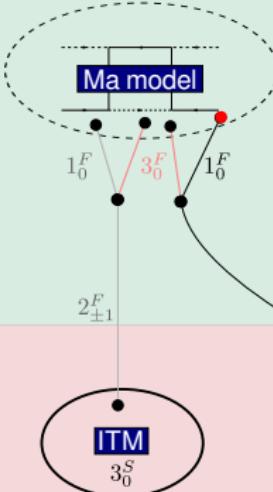
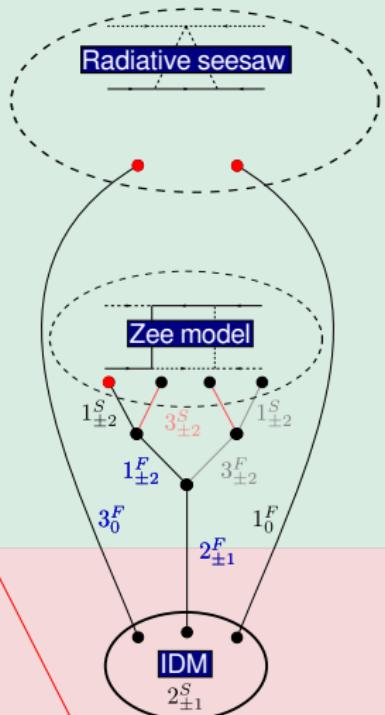
 $\nu$  $N_F^\pm$ 

DM

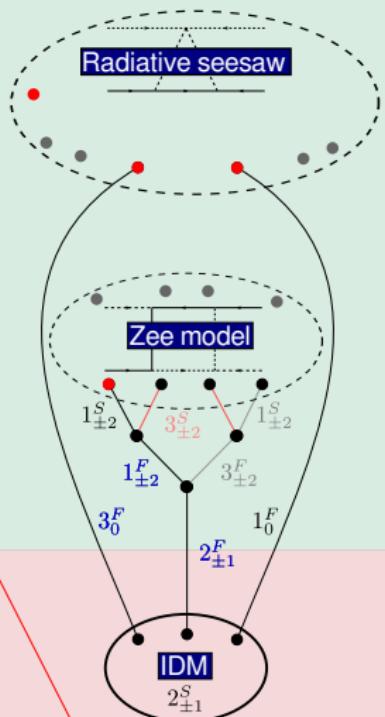
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 $\nu$  $N_F^\pm$ 

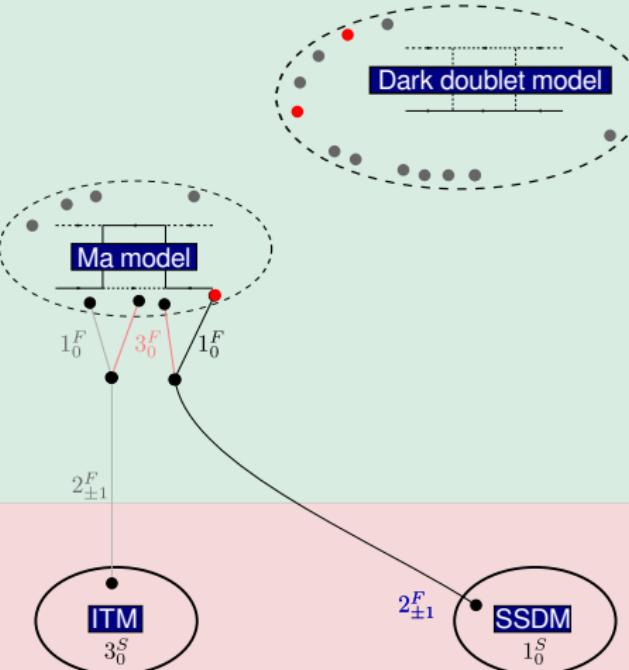
DM  
 $\downarrow$   
 $l^\pm$



- Already studied

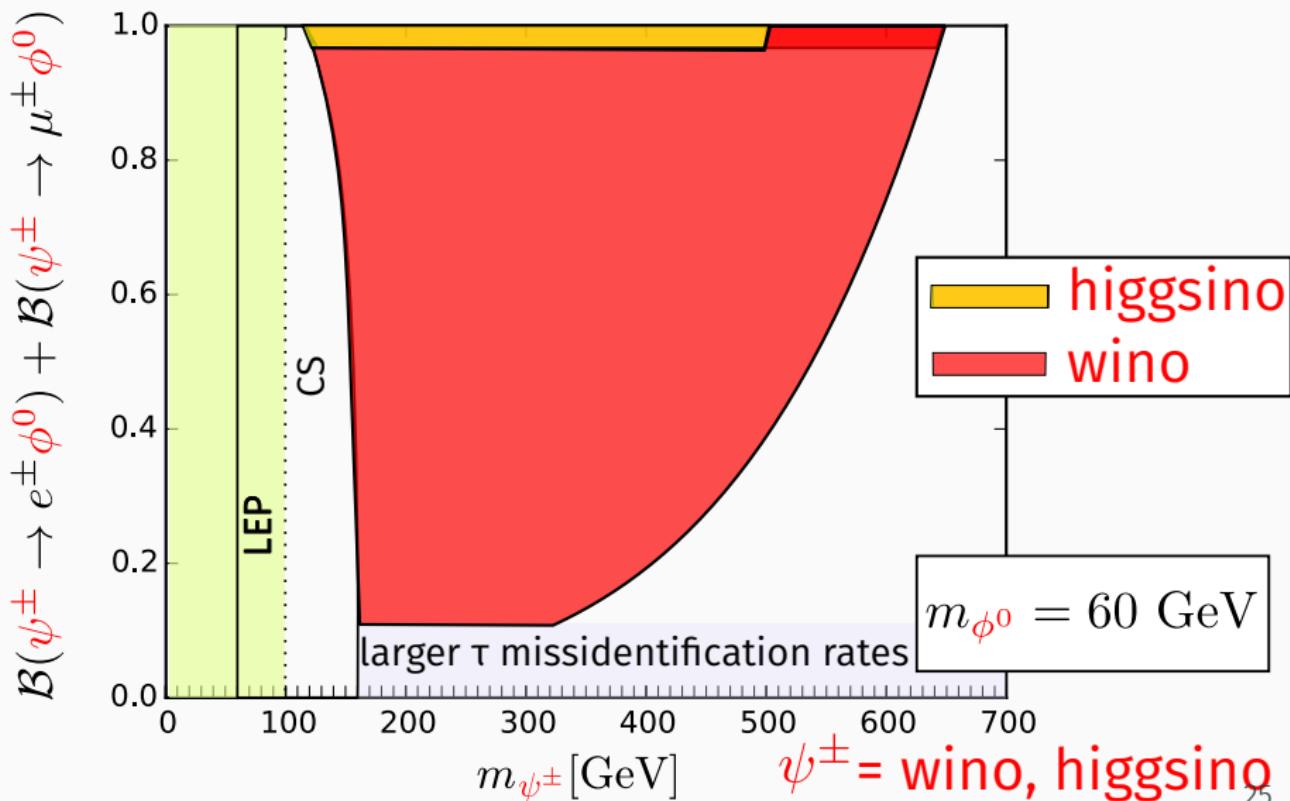
 $\nu$  $N_F^\pm$ 

DM

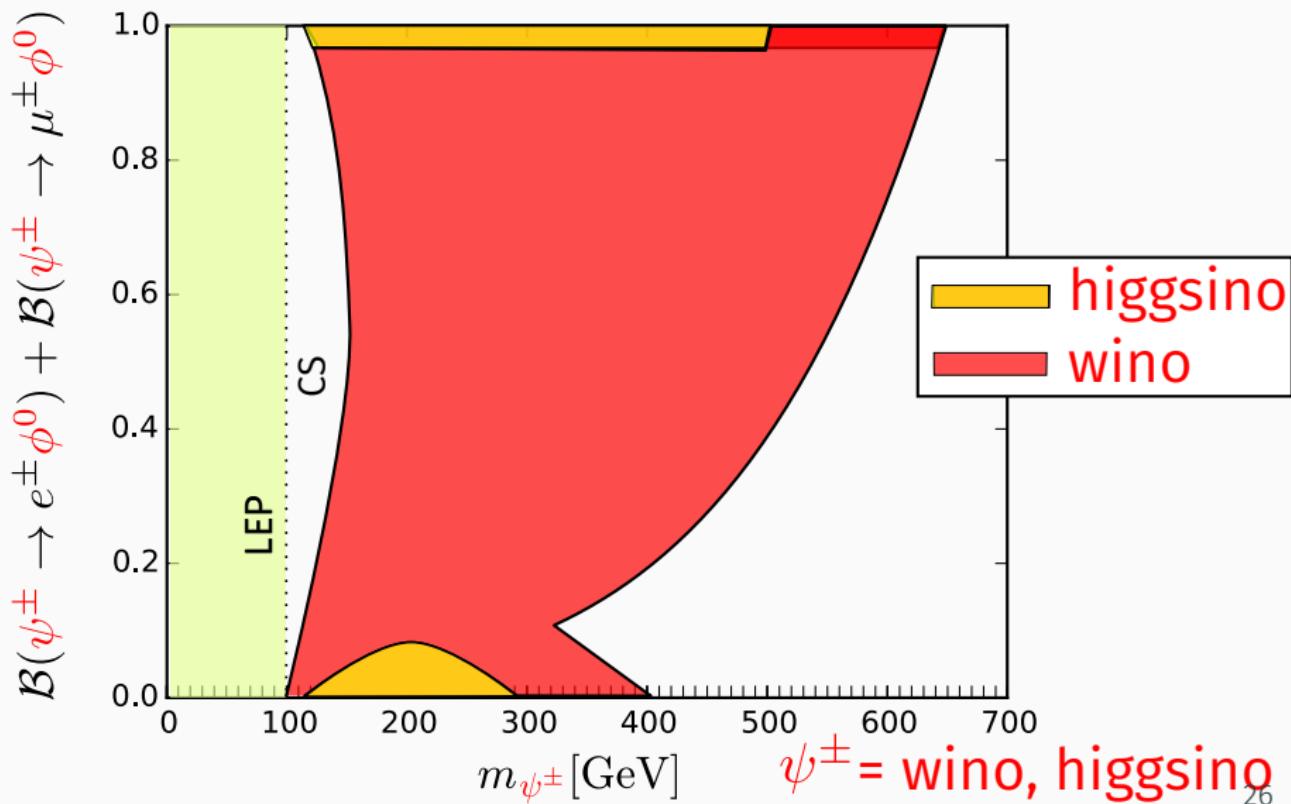
 $l^\pm$ 

TOTAL=35

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



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



## Beyond the standard model

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## Recover fundamental masses ☺

Singlet scalar dark matter

$$Z_2 : \quad \mathcal{L}_{\text{SM}} \rightarrow \mathcal{L}_{\text{SM}}, \quad S \rightarrow -S.$$

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

Singlet fermion: Seesaw

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

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

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

# 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  $S \rightarrow \gamma\gamma, GG$ )
  - LFV observables
  - LHA output

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

# SARAH implementation

- Automatic generation of Fortran-90 **SPheno** code and interaction-basis Les-Houches Accord (**LHA**) input file, for calculation of:
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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, Hθ}, 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

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# Unification: $SO(10)$

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



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

Standard Model:  $Z_2$ -even

Fermions:  $16_F$

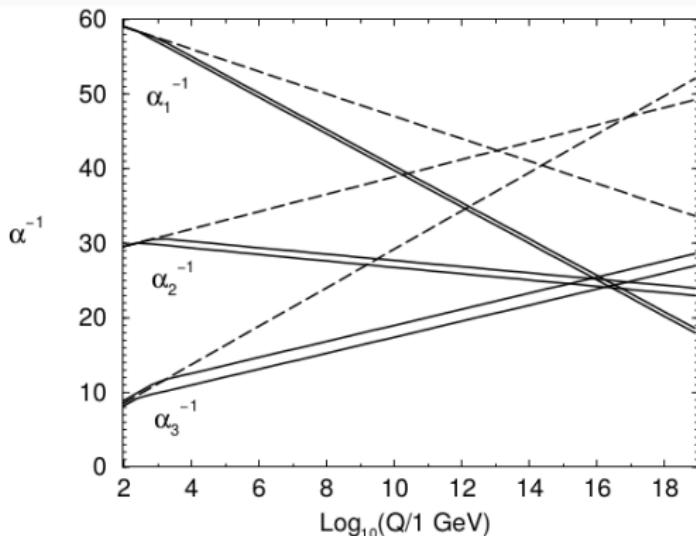
Scalars:  $10_H, 45_H \dots$

New  $Z_2$ -odd particles

$10_F, 45_F, \dots$

$16_H, \dots$

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



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

Standard Model:  $Z_2$ -even

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$16_H, \dots$

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

$SU(2)_L \times U(1)_Y$ representation	fermions even $SO(10)$ representations	scalars 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
$SU(3)_C : 3 (T), 6, 8 (\Lambda)$		

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

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

Standard Model:  $Z_2$ -even

Fermions:  $16_F$

Scalars:  $10_H, 45_H \dots$

New  $Z_2$ -odd particles

$10_F, 45_F, \dots$

$16_H, \dots$

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

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

$SU(3)_C : 3 (T), 6, 8 (\Lambda)$

Split-SUSY like

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

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

Standard Model:  $Z_2$ -even

Fermions:  $16_F$

New  $Z_2$ -odd particles

$10_F, 45_F, \dots$

Scalars:  $10_H, 45_H, \dots$

$16_H, \dots$

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

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

$SU(3)_C : 3 (T), 6, 8 (\Lambda)$

Radiative hybrid seesaw (Parida 1106.4137) or 1509.06313

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

+

↓

$10'$ , with fermion DM or

$16_H, \dots$ , with scalar DM

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

Standard Model:  $Z_2$ -even

Fermions:  $16_F$

Scalars:  $10_H, 45_H \dots$

New  $Z_2$ -odd particles

$10_F, 45_F, \dots$

$16_H, \dots$

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

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

$SU(3)_C$ :  $3(T)$  6,  $8(\Lambda)$

1509.06313

SUSY-like spectrum: bino-higgsino-wino

+

↓

$10'$  with fermion DM or

$16'$  ... with scalar DM

# Singlet-Doublet-Triplet fermion dark-matter

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

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

Basis

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

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

$$\begin{pmatrix} M_N & 0 & -yc_\beta v/\sqrt{2} & ys_\beta v/\sqrt{2} \\ 0 & M_\Sigma & fc_\beta v/\sqrt{2} & -fs_\beta v/\sqrt{2} \\ -yc_\beta v/\sqrt{2} & fc_\beta v/\sqrt{2} & 0 & -M_D \\ ys_\beta v/\sqrt{2} & -fs_\beta v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$

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

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

Basis

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

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

$$\begin{pmatrix} M_N & 0 & -yc_\beta v/\sqrt{2} & ys_\beta v/\sqrt{2} \\ 0 & M_\Sigma & fc_\beta' v/\sqrt{2} & -fs_\beta' v/\sqrt{2} \\ -yc_\beta v/\sqrt{2} & fc_\beta' v/\sqrt{2} & 0 & -M_D \\ ys_\beta v/\sqrt{2} & -fs_\beta' v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$



Jester @Resonaances · Dec 6

First LHC 13 TeV rumor: modest excess in di-photon spectrum at 700 GeV in both ATLAS and CMS



35



20

...

# Singlet-Doublet-Triplet fermion dark-matter

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

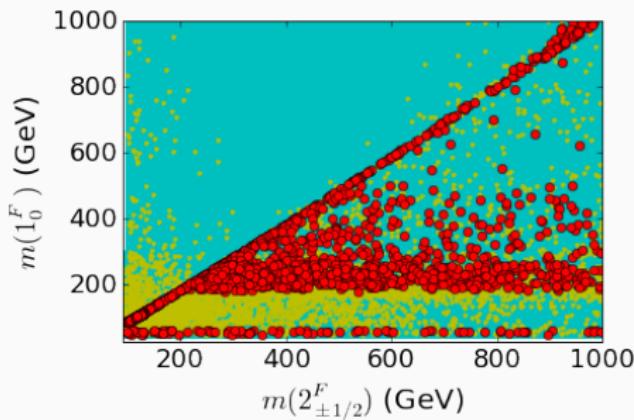
$$-\mathcal{L} \supset Y \mathbf{10}_F \mathbf{45}_F \mathbf{10}_H + M_{\mathbf{45}_F} \mathbf{45}_F \mathbf{45}_F + M_{\mathbf{10}_F} \mathbf{10}_F \mathbf{10}_F + \mathcal{L}(\mathbf{10}_\Phi \text{ or } \mathbf{16}_\Phi).$$

Basis

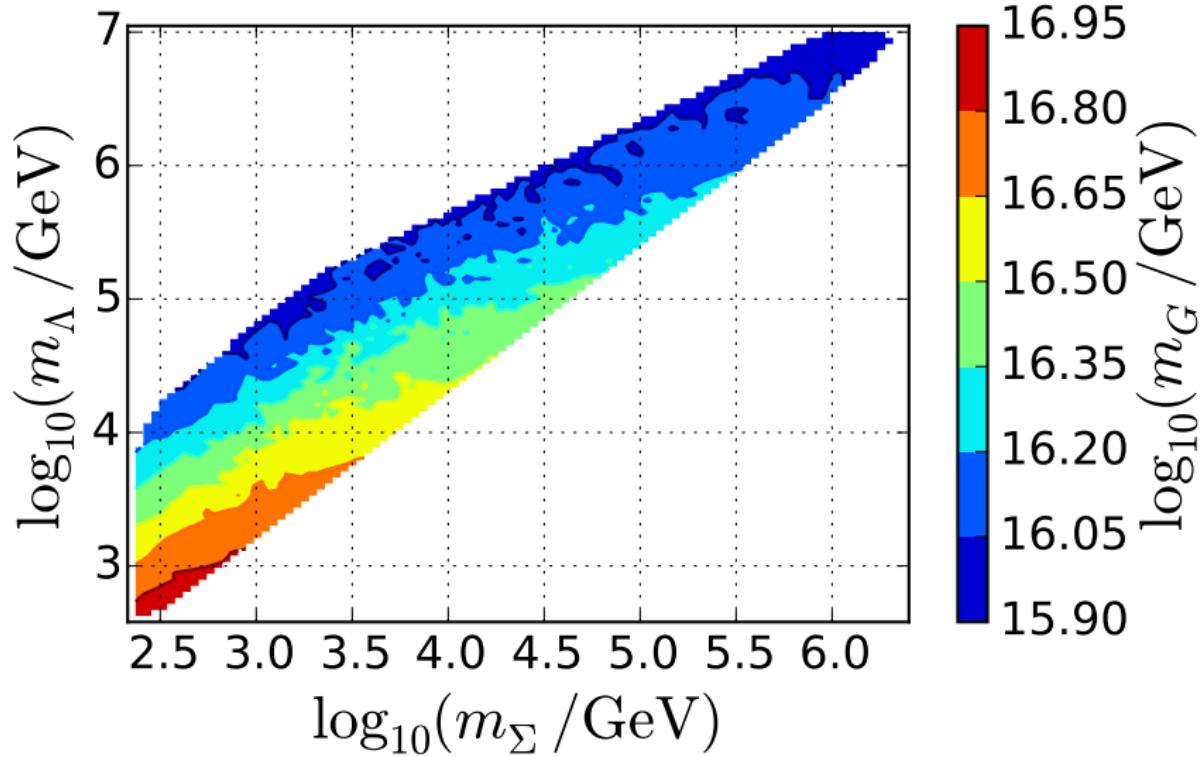
$$\psi^0 = \left( N, \Sigma^0, \psi_L^0, (\psi_R^0)^\dagger \right)^T$$

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

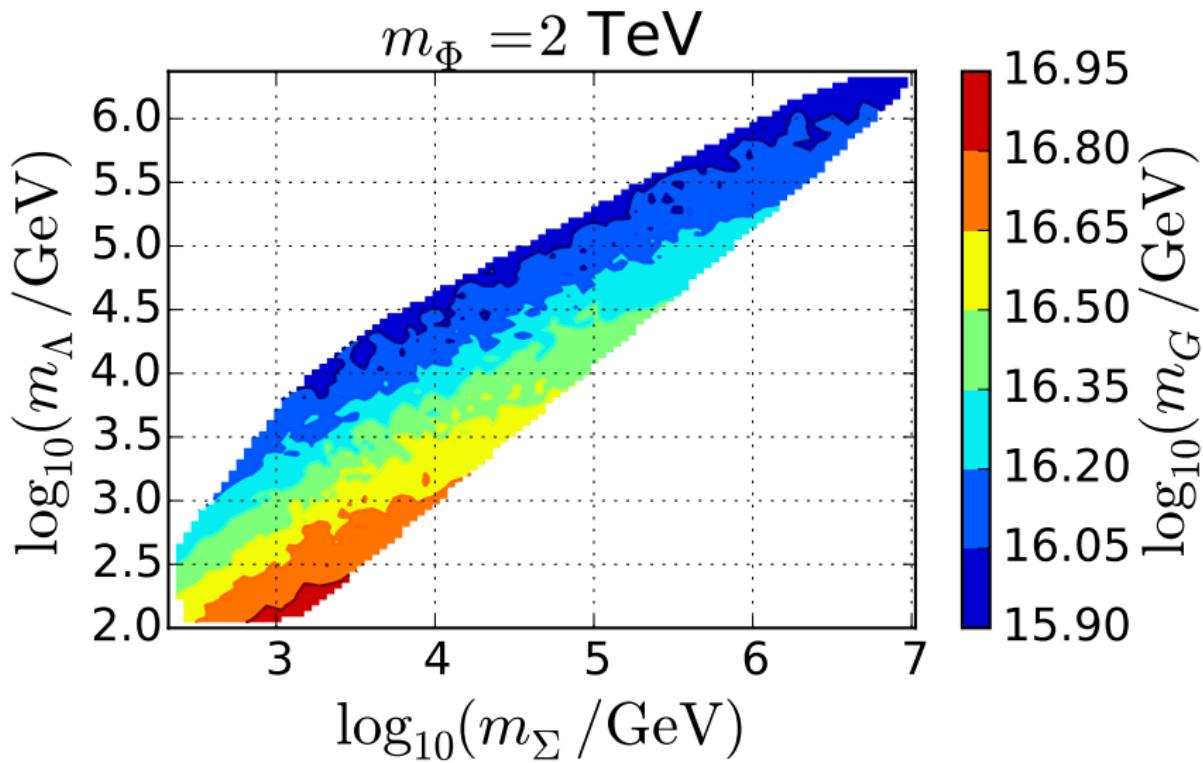
$$\begin{pmatrix} M_N & 0 & -yc_\beta v/\sqrt{2} & ys_\beta v/\sqrt{2} \\ 0 & M_\Sigma & fc_\beta v/\sqrt{2} & -fs_\beta v/\sqrt{2} \\ -yc_\beta v/\sqrt{2} & fc_\beta v/\sqrt{2} & 0 & -M_D \\ ys_\beta v/\sqrt{2} & -fs_\beta v/\sqrt{2} & -M_D & 0 \end{pmatrix},$$

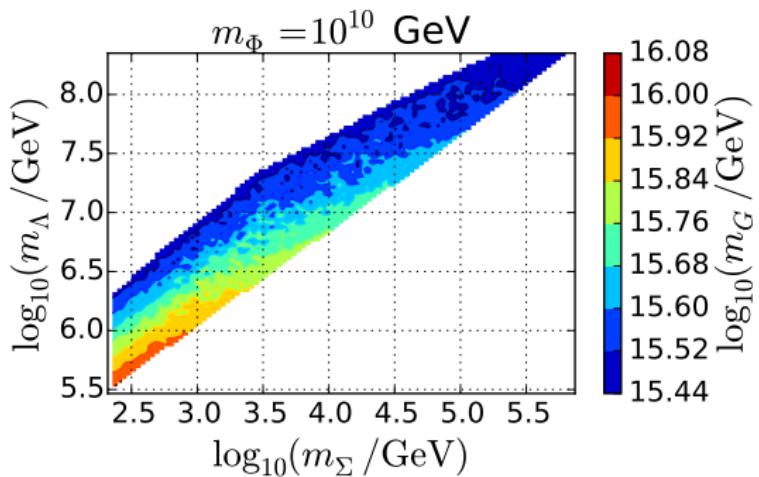
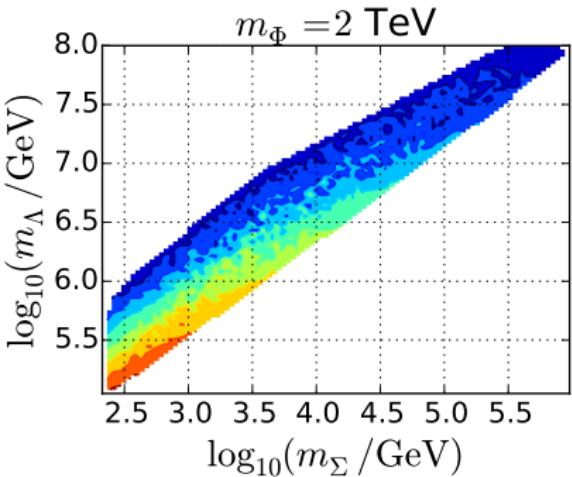


# Split-SUSY like



# Partial split-SUSY like





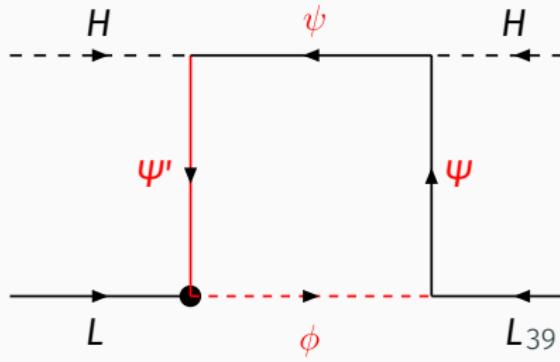
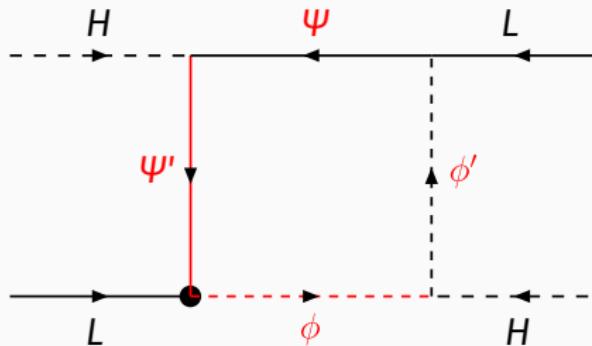
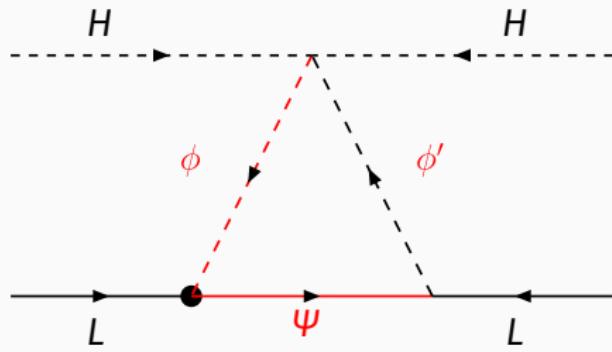
## Notations

$$X^{\mathcal{L}}_Y$$

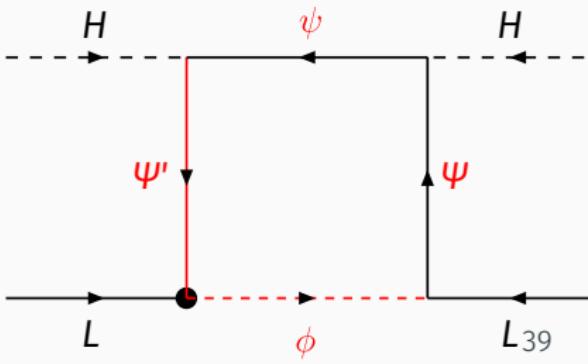
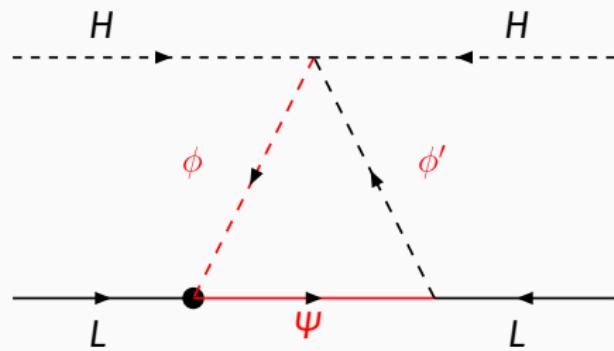
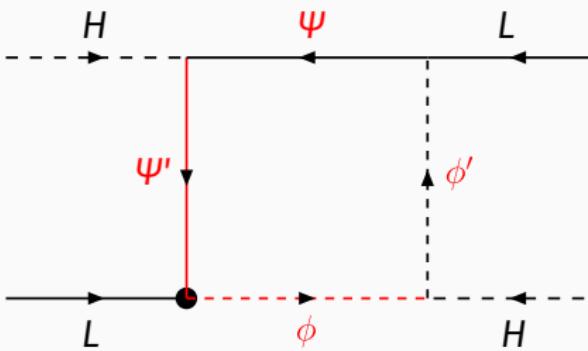
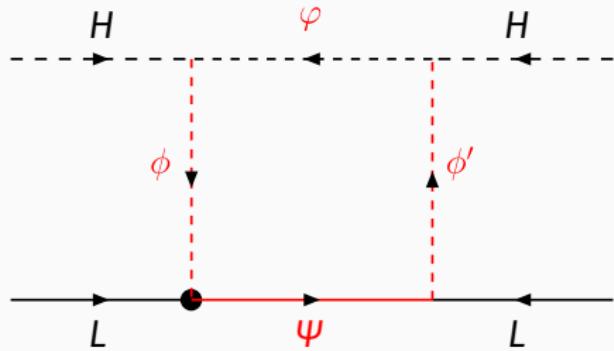
- $\mathcal{L}$  Lorentz nature: scalar ( $S$ ) or fermion ( $F$ ),
- $Y \equiv 2(Q - I_3)$  hypercharge:  $\alpha$  arbitrary rational-number
- $X$   $SU(2)$  nature: singlet  $1$ , doublet  $2$ , triplet  $3$ 
  - quadruplet  $4$ , quintuplet  $5$ , ...

Law, McDonald, arXiv:1305.6467

# Weinberg operator at one-loop

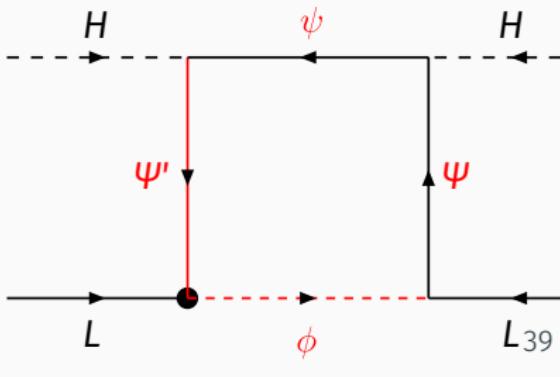
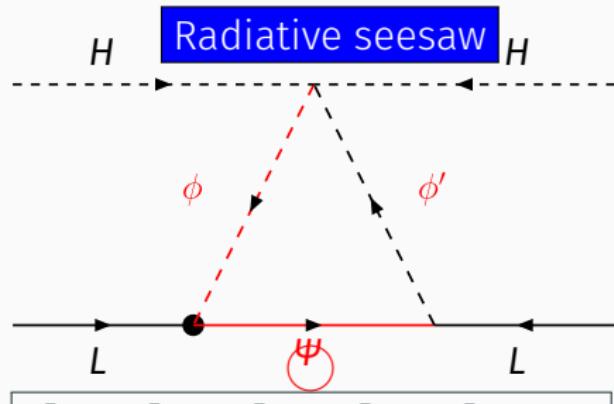
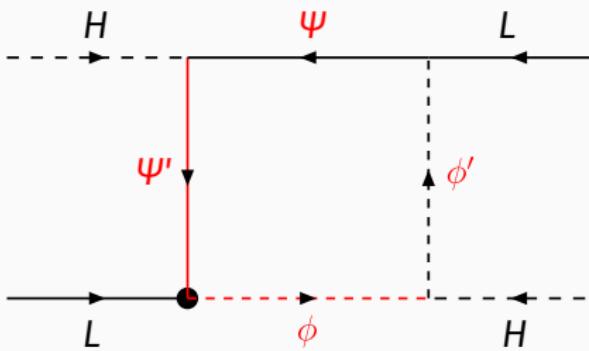
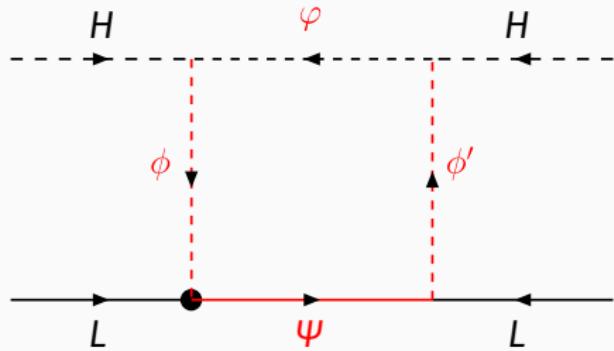


# Weinberg operator at one-loop

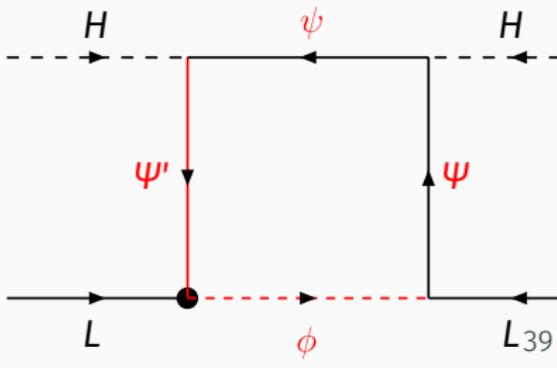
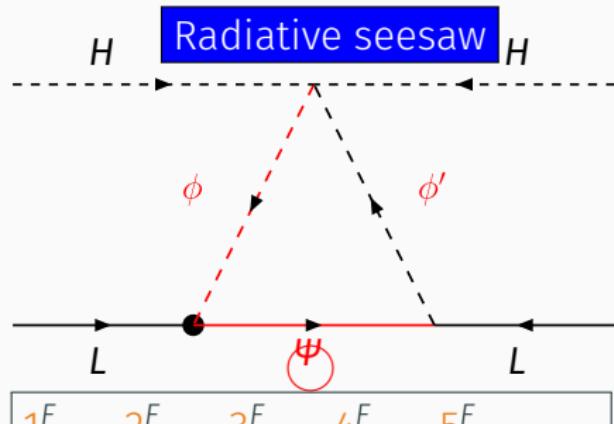
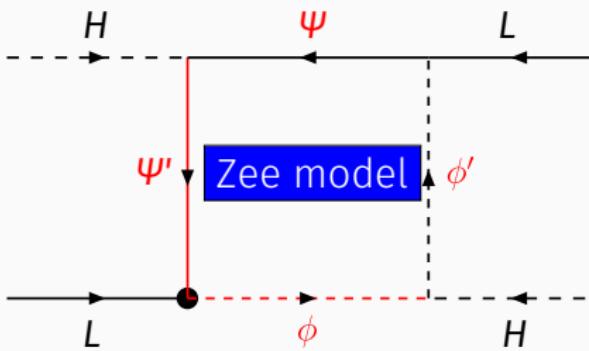
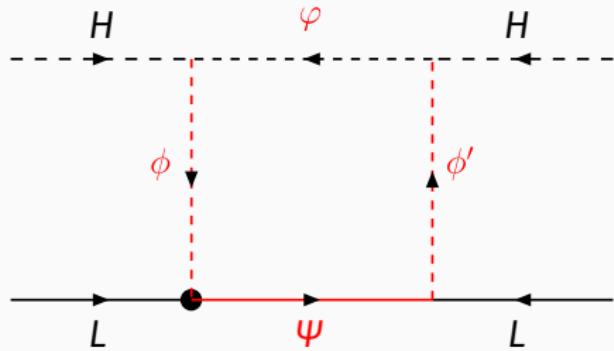


and reducible and divergent topologies

# Weinberg operator at one-loop

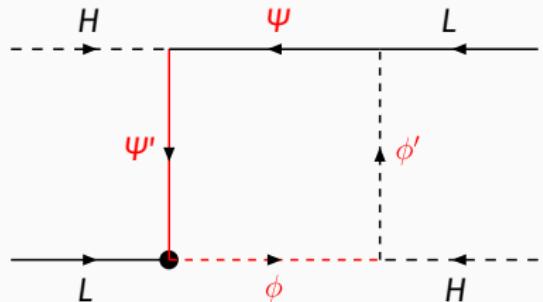


# Weinberg operator at one-loop



# Generalized Zee model

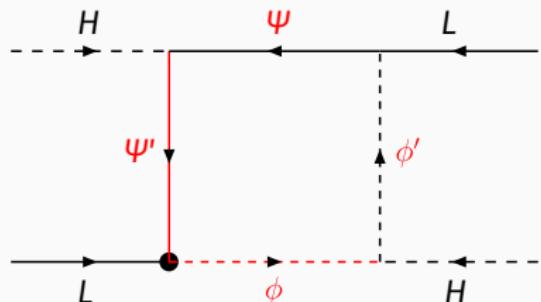
A. Zee, Phys. Lett. B 655 (2007) 587.



$\psi$	$\phi$	$\phi'$	$\psi'$
$2_1^F: \bar{e}_L$	$1_2^S: \eta^+$	$2_1^S: \phi$	$1_2^F: \bar{e}_R$

# Generalized Zee model

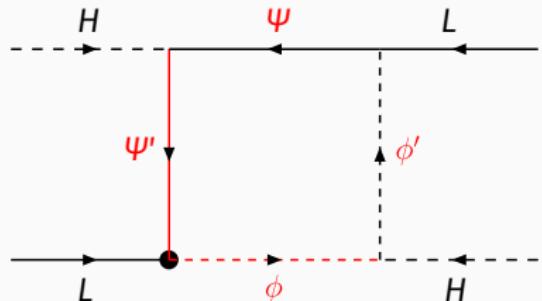
L. Ma, hep-ph/2005217 (FRL)



$\psi$	$\phi$	$\phi'$	$\psi'$
$2^F_\alpha$	$1^S_{1+\alpha}$	$2^S_\alpha$	$1^F_{1+\alpha}$
$2^F_\alpha$	$3^S_{1+\alpha}$	$2^S_\alpha$	$1^F_{1+\alpha}$
$2^F_\alpha$	$3^S_{1+\alpha}$	$2^S_\alpha$	$3^F_{1+\alpha}$
$2^F_\alpha$	$1^S_{1+\alpha}$	$2^S_\alpha$	$3^F_{1+\alpha}$

# Generalized Zee model

(UNESP)

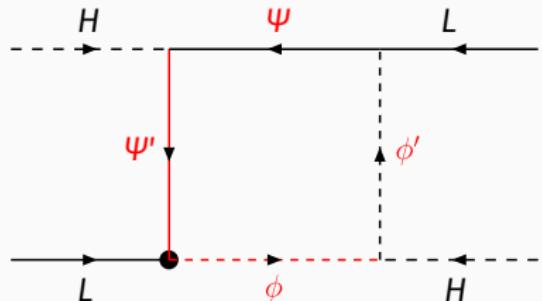


$$\alpha \rightarrow -\alpha - 1$$

$\psi$	$\phi$	$\phi'$	$\psi'$
$1^F_\alpha$	$2^S_{1+\alpha}$	$1^S_\alpha$	$2^F_{1+\alpha}$
$2^F_\alpha$	$1^S_{1+\alpha}$	$2^S_\alpha$	$1^F_{1+\alpha}$
$1^F_\alpha$	$2^S_{1+\alpha}$	$3^S_\alpha$	$2^F_{1+\alpha}$
$2^F_\alpha$	$3^S_{1+\alpha}$	$2^S_\alpha$	$1^F_{1+\alpha}$
$2^F_\alpha$	$3^S_{1+\alpha}$	$2^S_\alpha$	$3^F_{1+\alpha}$
$3^F_\alpha$	$2^S_{1+\alpha}$	$3^S_\alpha$	$2^F_{1+\alpha}$
$2^F_\alpha$	$1^S_{1+\alpha}$	$2^S_\alpha$	$3^F_{1+\alpha}$
$3^F_\alpha$	$2^S_{1+\alpha}$	$1^S_\alpha$	$2^F_{1+\alpha}$

# Generalized Zee model

[1:1]

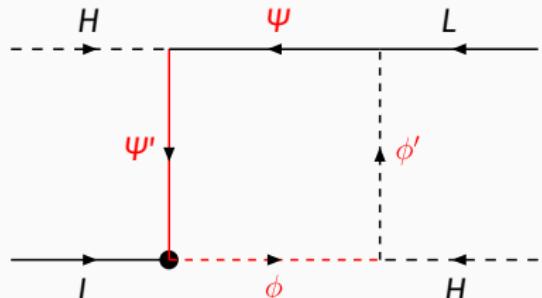


$\psi$	$\phi$	$\phi'$	$\psi'$
$1^F_\alpha$	$2^S_{1+\alpha}$	$1^S_\alpha$	$2^F_{1+\alpha}$
$2^F_\alpha$	$1^S_{1+\alpha}$	$2^S_\alpha$	$1^F_{1+\alpha}$
$1^F_\alpha$	$2^S_{1+\alpha}$	$3^S_\alpha$	$2^F_{1+\alpha}$
$2^F_\alpha$	$3^S_{1+\alpha}$	$2^S_\alpha$	$1^F_{1+\alpha}$
$2^F_\alpha$	$3^S_{1+\alpha}$	$2^S_\alpha$	$3^F_{1+\alpha}$
$3^F_\alpha$	$2^S_{1+\alpha}$	$3^S_\alpha$	$2^F_{1+\alpha}$
$2^F_\alpha$	$1^S_{1+\alpha}$	$2^S_\alpha$	$3^F_{1+\alpha}$
$3^F_\alpha$	$2^S_{1+\alpha}$	$1^S_\alpha$	$2^F_{1+\alpha}$

Larger  $SU(2)_L$  multiplets

# Generalized Zee model

D.R. Tagungs, Zapata, arXiv:1508.0555



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

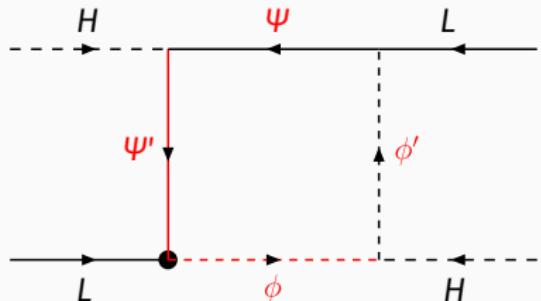
$\psi$	$\phi$	$\phi'$	$\psi'$	$\alpha$
$1^F_0$	$2^S_1$	$1^S_0$	$2^F_1$	
$2^F_{-1}$	$1^S_{-2}$	$2^S_{-1}$	$1^F_{-2}$	
$1^F_0$	$2^S_1$	$3^S_0$	$2^F_1$	
$2^F_{-1}$	$3^S_{-2}$	$2^S_{-1}$	$1^F_{-2}$	
$2^F_1$	$3^S_2$	$2^S_1$	$3^F_2$	
$3^F_0$	$2^S_{-1}$	$3^S_0$	$2^F_{-1}$	
$2^F_1$	$1^S_2$	$2^S_1$	$3^F_2$	
$3^F_0$	$2^S_{-1}$	$1^S_0$	$2^F_{-1}$	

Larger  $SU(2)_L$  multiplets

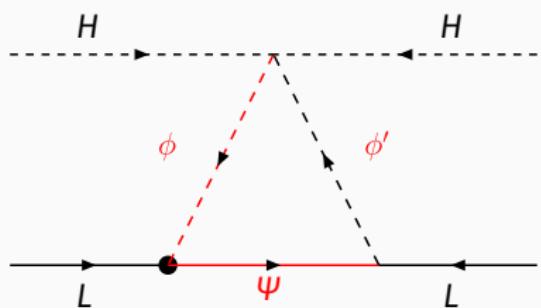
○  $Y = -2T_3$  for at least one particle

# Generalized Zee model

D.R. Tauranga, Zapata, arXiv:1708.0555



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

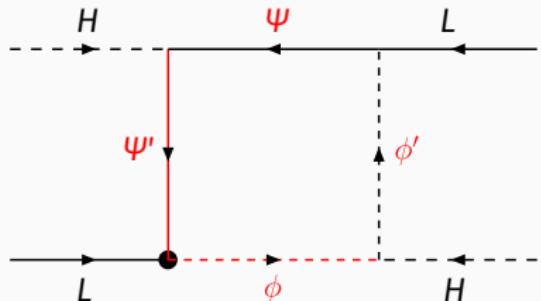


$\psi$	$\phi$	$\phi'$	$\psi'$	$\alpha$
$1^F_0$	$2^S_1$	$1^S_0$	$2^F_1$	0
$2^F_{-1}$	$1^S_{-2}$	$2^S_{-1}$	$1^F_{-2}$	0
$1^F_0$	$2^S_1$	$3^S_0$	$2^F_1$	0
$2^F_{-1}$	$3^S_{-2}$	$2^S_{-1}$	$1^F_{-2}$	0
$2^F_1$	$3^S_2$	$2^S_1$	$3^F_2$	-
$3^F_0$	$2^S_{-1}$	$3^S_0$	$2^F_{-1}$	-
$2^F_1$	$1^S_2$	$2^S_1$	$3^F_2$	-
$3^F_0$	$2^S_{-1}$	$1^S_0$	$2^F_{-1}$	-

Larger  $SU(2)_L$  multiplets

# Generalized Zee model

D.R. Tauranga, Zapata, arXiv:1508.0555



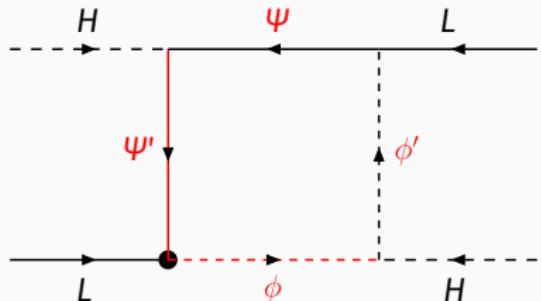
Inert doublet model with  
one-loop neutrino masses  
(susy-like)

$\psi$	$\phi$	$\phi'$	$\psi'$	$\alpha$
$1^F_0$	$2^S_1$	$1^S_0$	$2^F_1$	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
$2^F_{-1}$	$3^S_{-2}$	$2^S_{-1}$	$1^F_{-2}$	-
$2^F_1$	$3^S_2$	$2^S_1$	$3^F_2$	1
$3^F_0$	$2^S_{-1}$	$3^S_0$	$2^F_{-1}$	-
$2^F_1$	$1^S_2$	$2^S_1$	$3^F_2$	1
$3^F_0$	$2^S_{-1}$	$1^S_0$	$2^F_{-1}$	-

Larger  $SU(2)_L$  multiplets

# Generalized Zee model

D.R. Tauranga, Zapata, arXiv:1508.0555



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

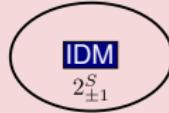
and exotic charges

$\psi$	$\phi$	$\phi'$	$\psi'$	$\alpha$
$1^F_0$	$2^S_1$	$1^S_0$	$2^F_1$	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
$2^F_{-1}$	$3^S_{-2}$	$2^S_{-1}$	$1^F_{-2}$	-
$2^F_1$	$3^S_2$	$2^S_1$	$3^F_2$	1
$3^F_0$	$2^S_{-1}$	$3^S_0$	$2^F_{-1}$	-
$2^F_1$	$1^S_2$	$2^S_1$	$3^F_2$	1
$3^F_0$	$2^S_{-1}$	$1^S_0$	$2^F_{-1}$	-

Larger  $SU(2)_L$  multiplets

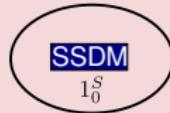
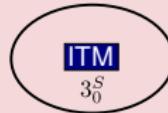
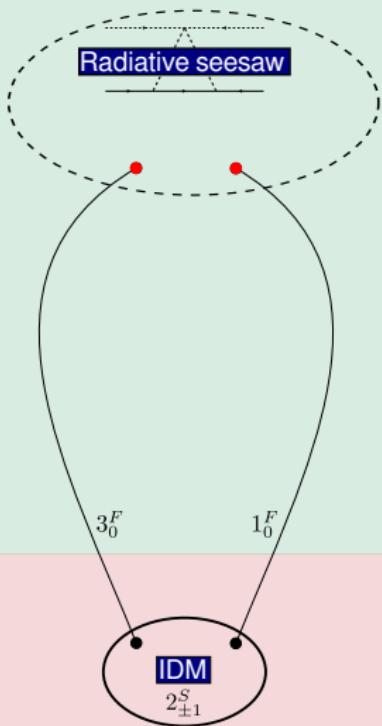
$\nu$

DM



$\nu$

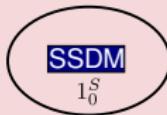
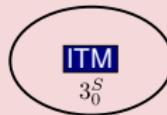
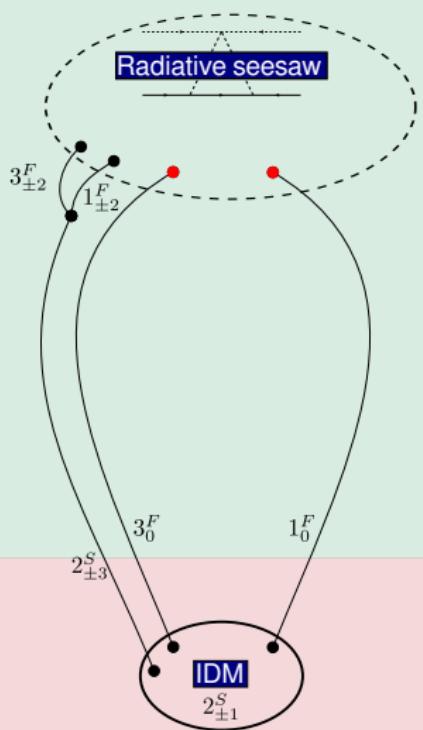
- Already studied



DM

$\nu$

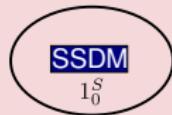
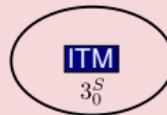
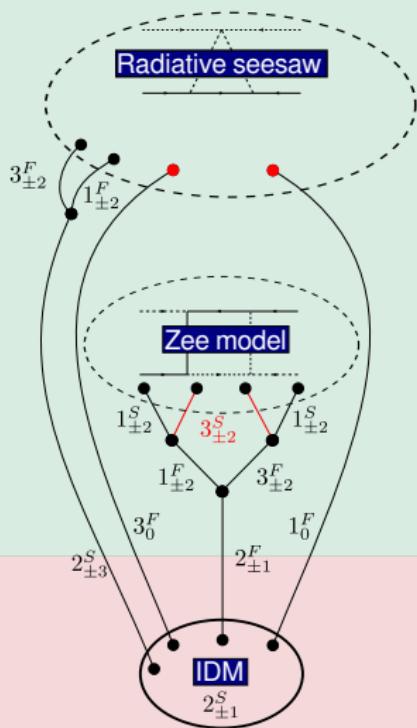
- Already studied



DM

$\nu$

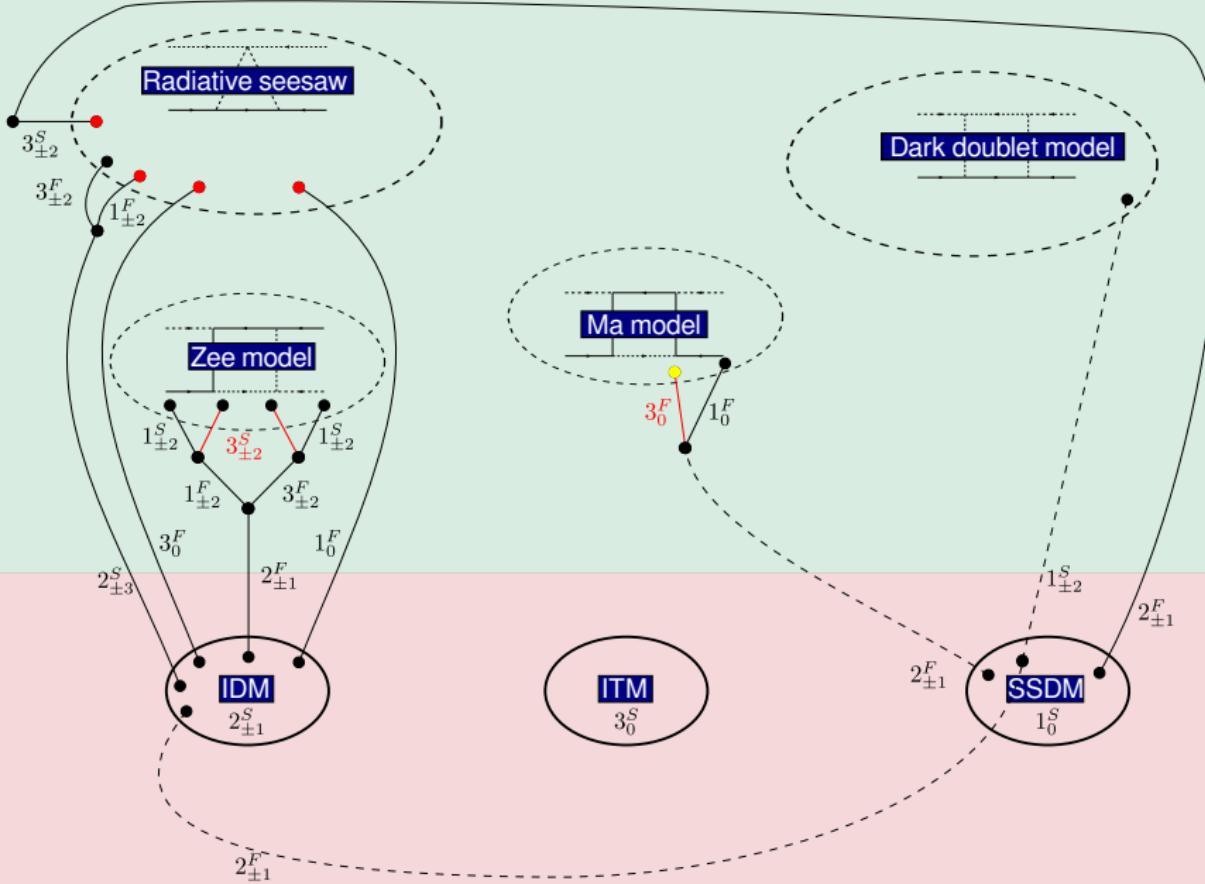
- Already studied



DM

$\nu$

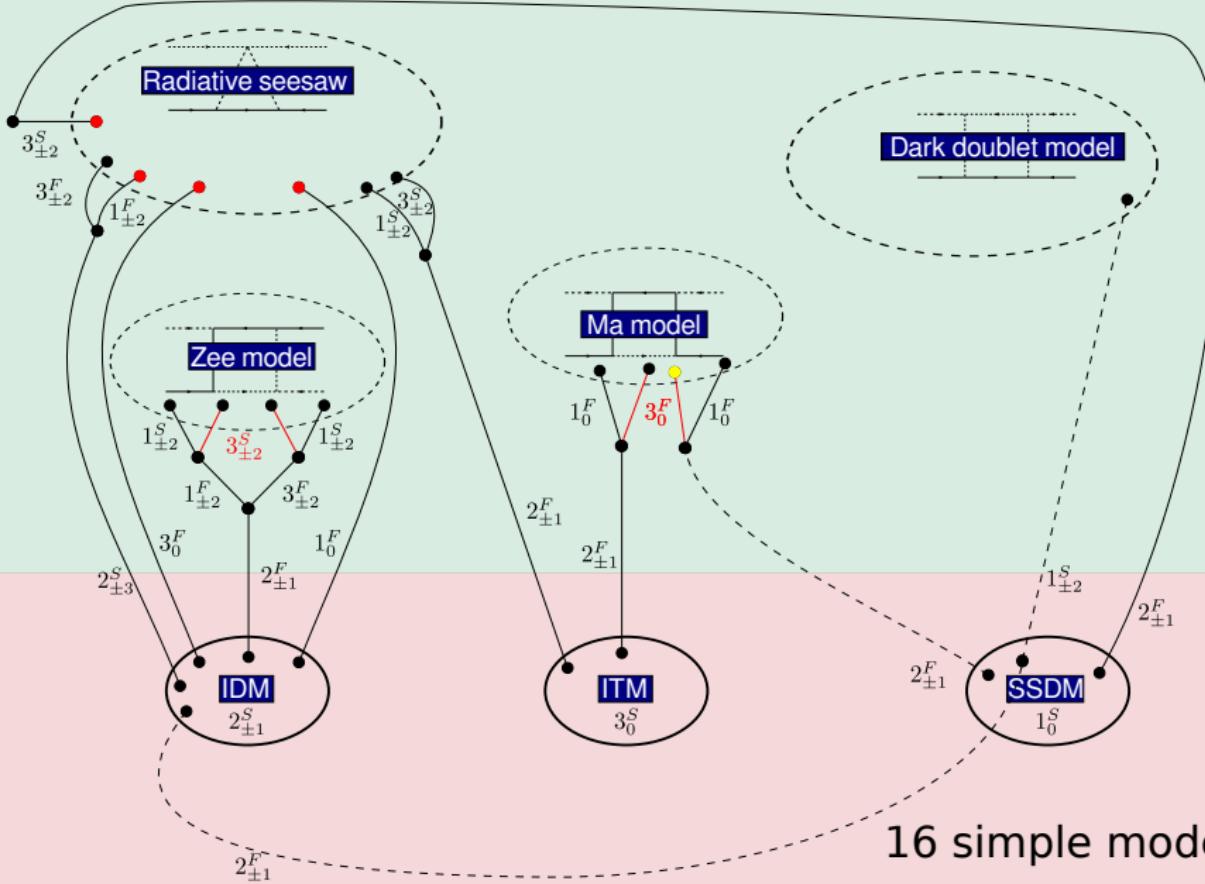
- Already studied
- Partially studied



DM

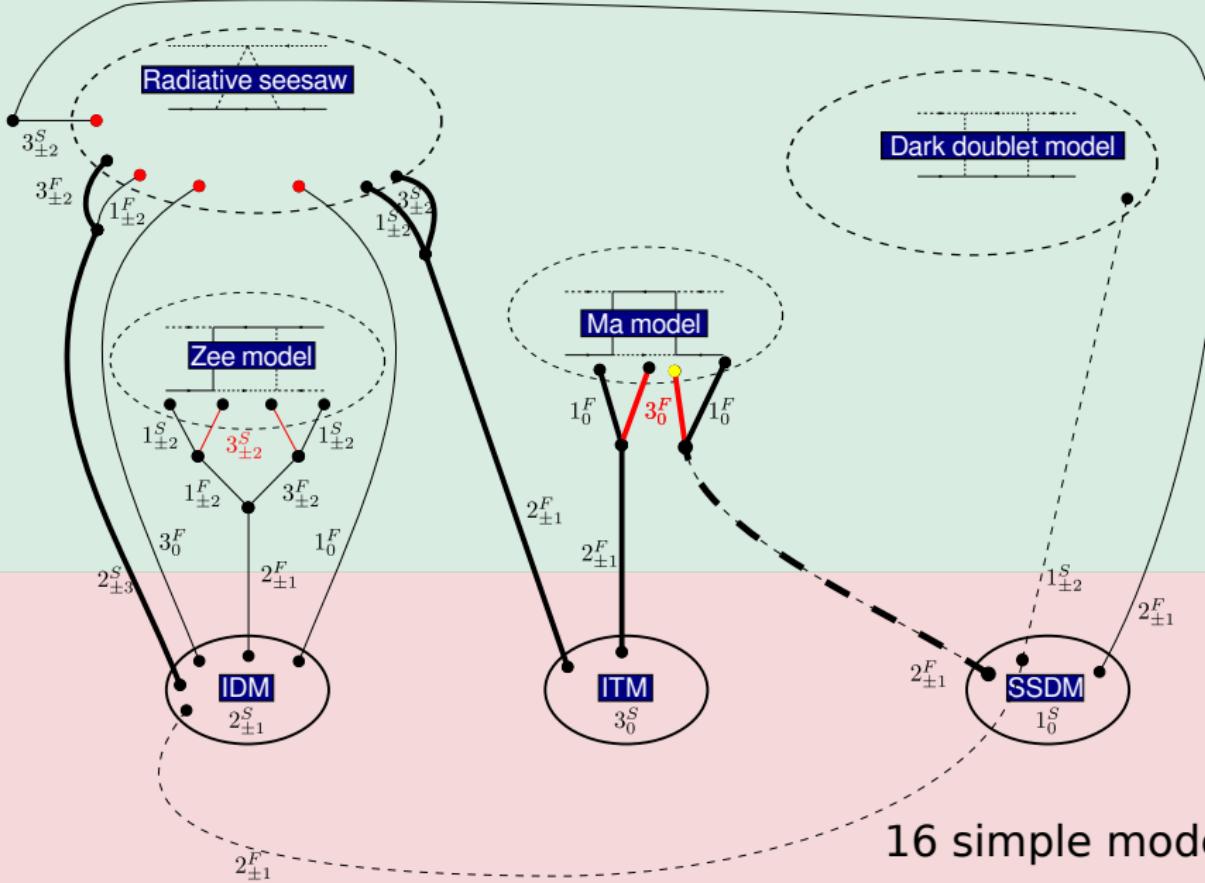
$\nu$

- Already studied
- Partially studied



$\nu$

- Already studied
- Partially studied

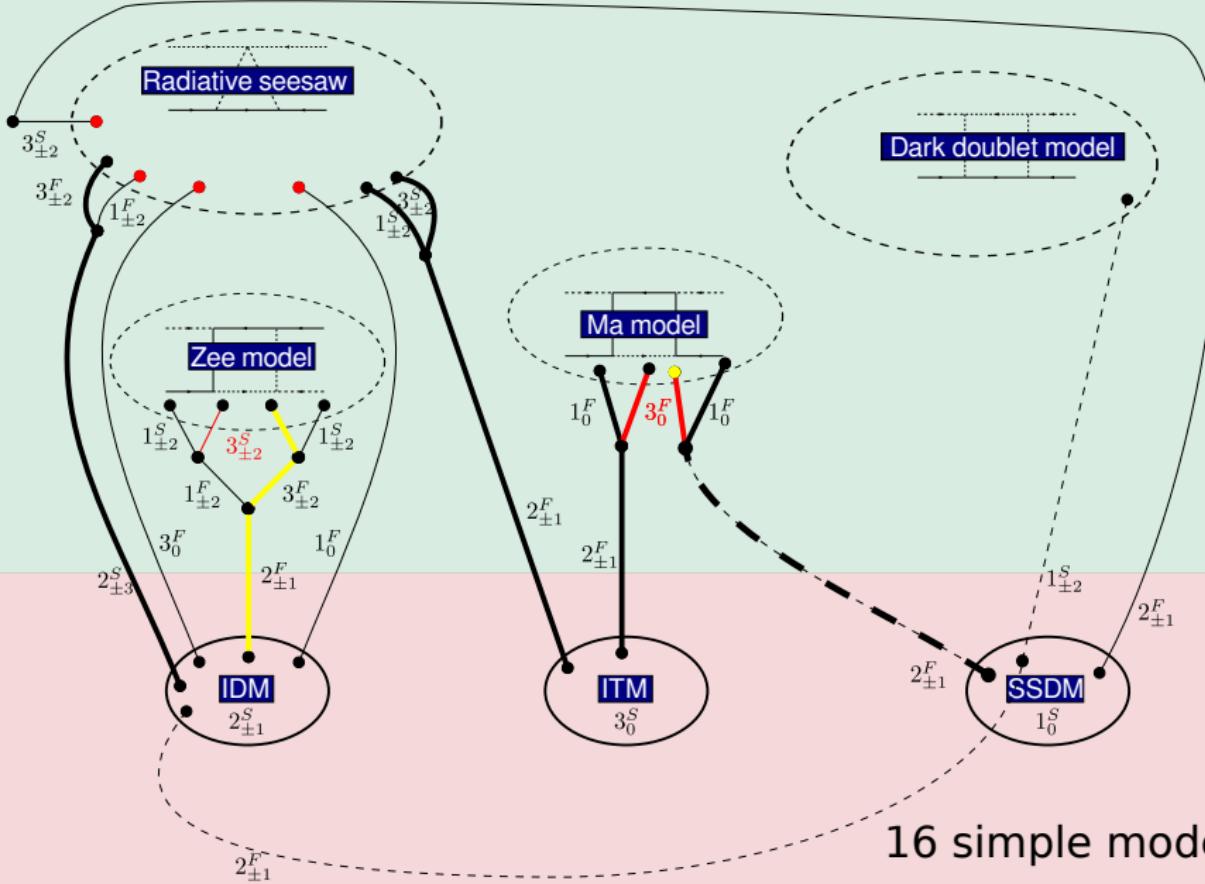


DM

16 simple mode

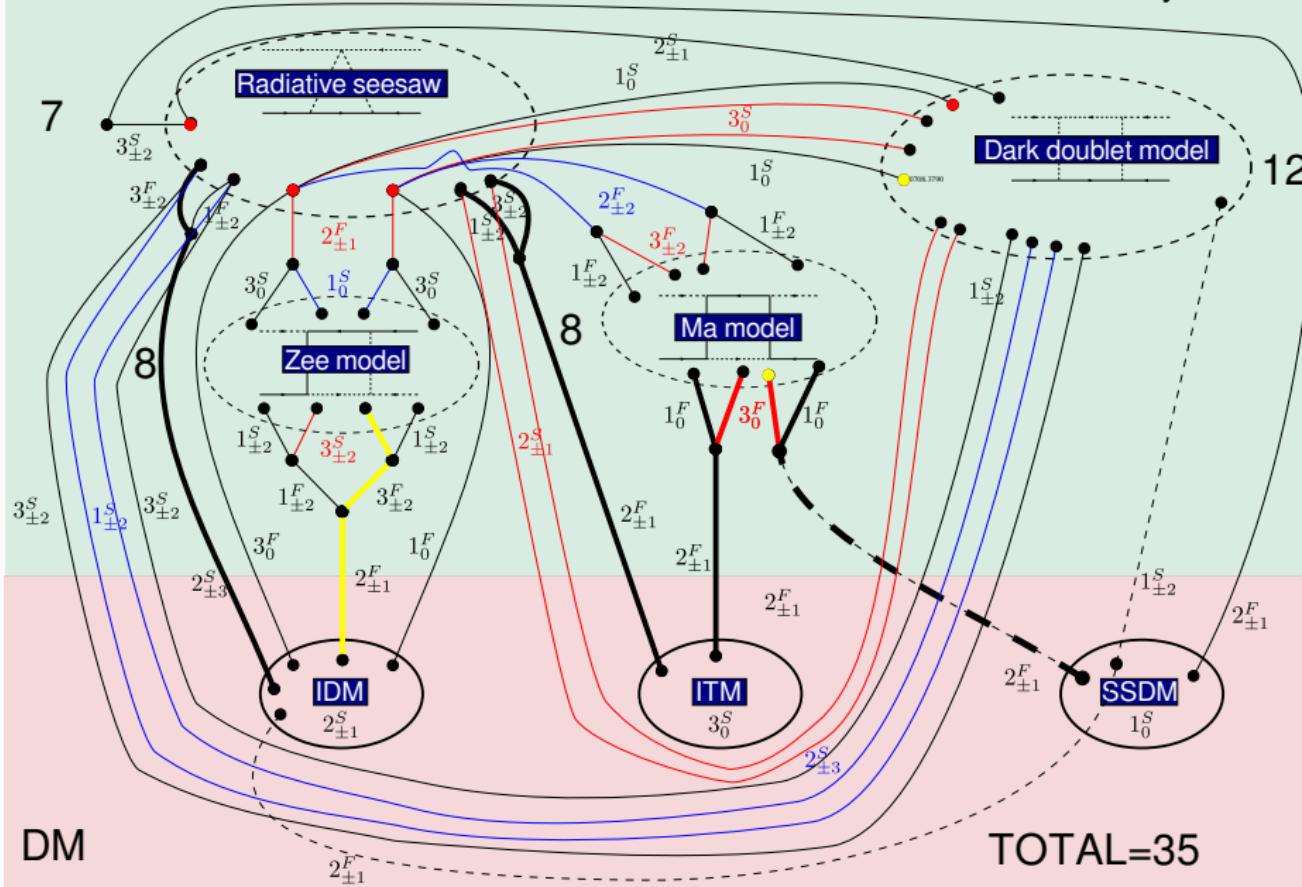
$\nu$

- Already studied
- Partially studied



v

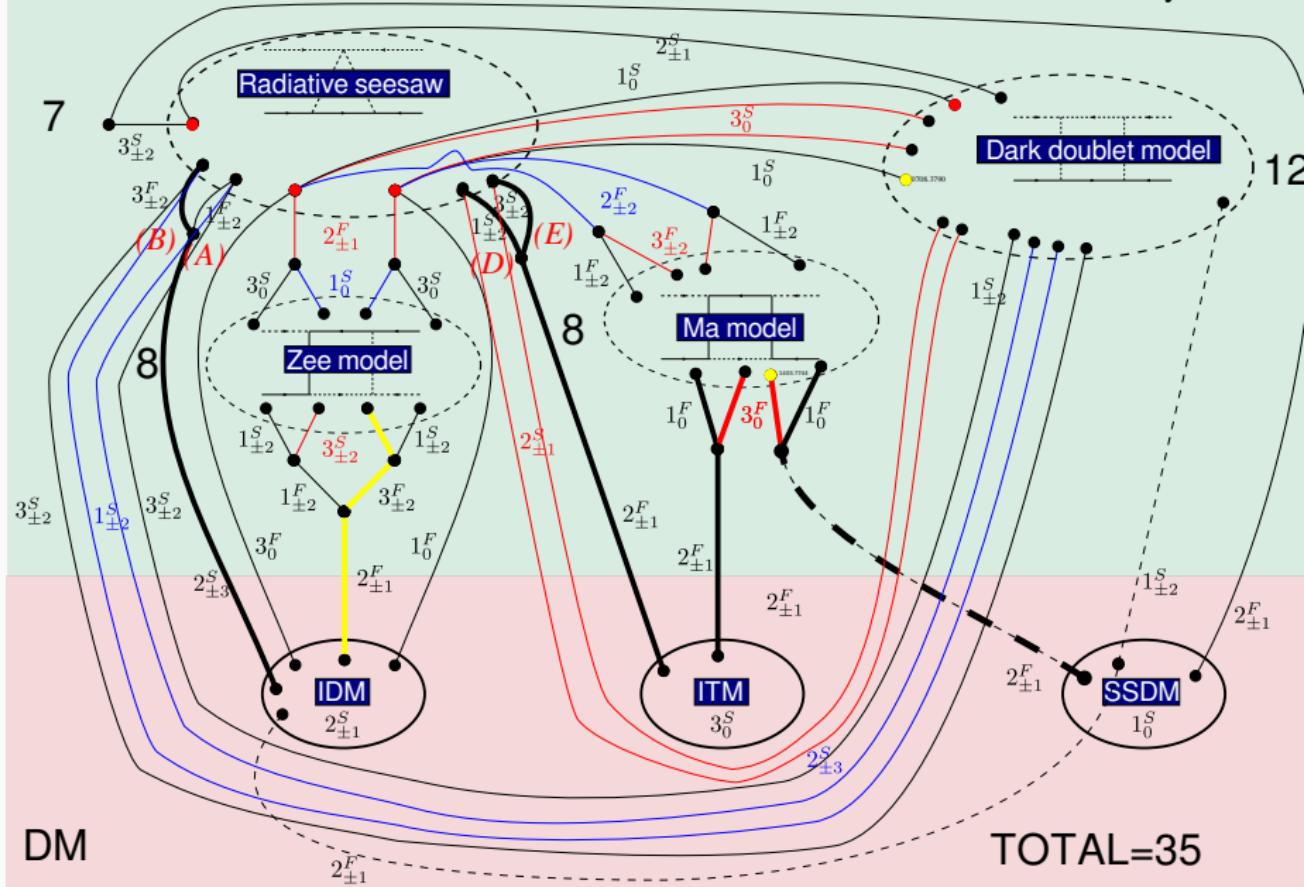
- Already studied
  - Partially studied

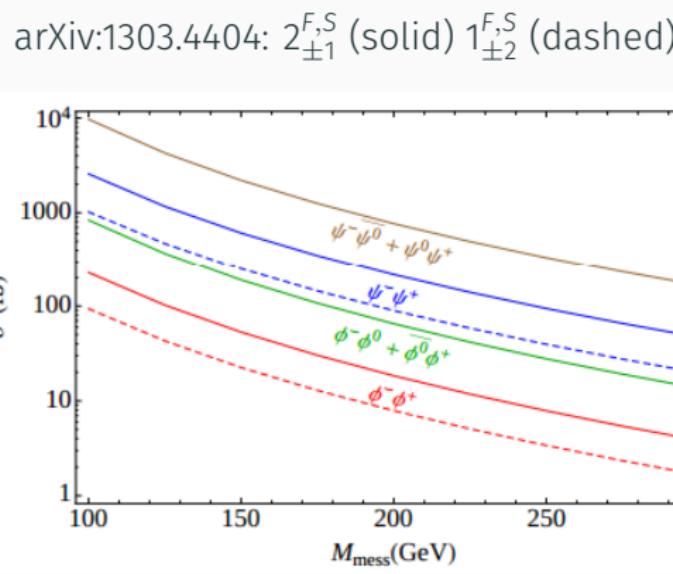
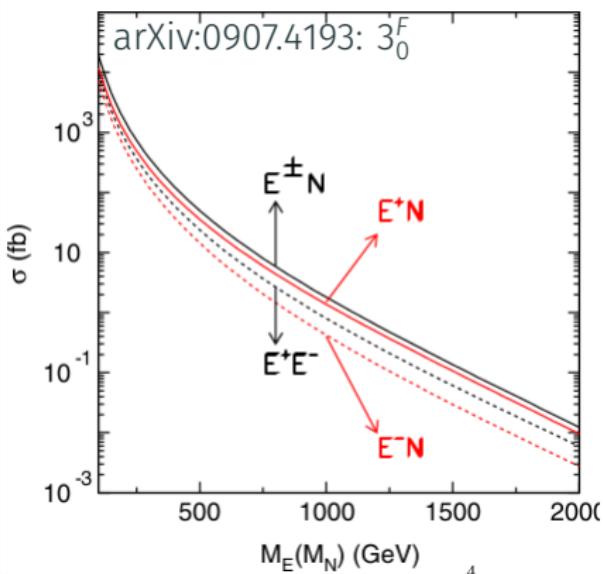


$\nu$ 

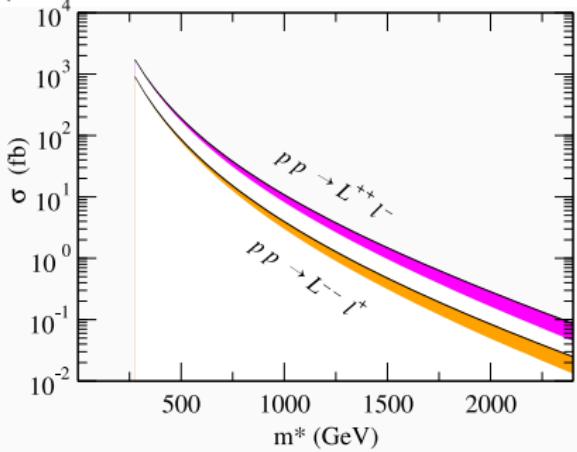
(C)

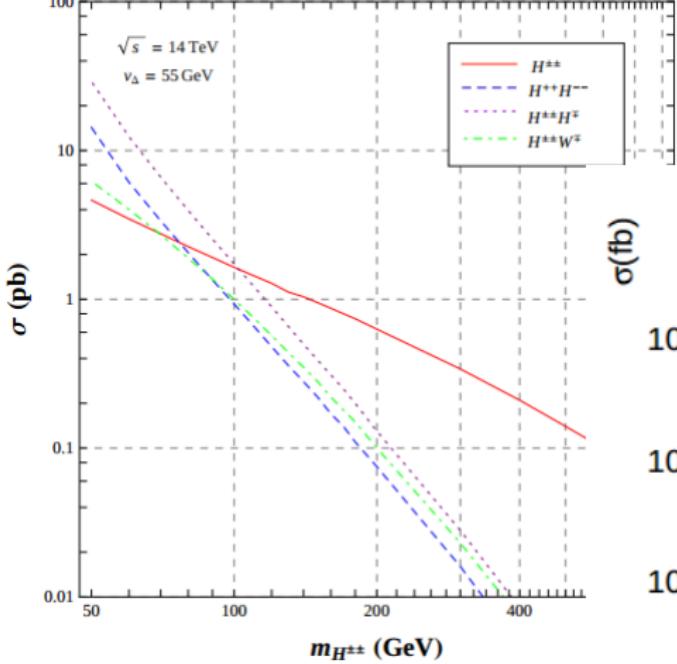
- Already studied
- Partially studied



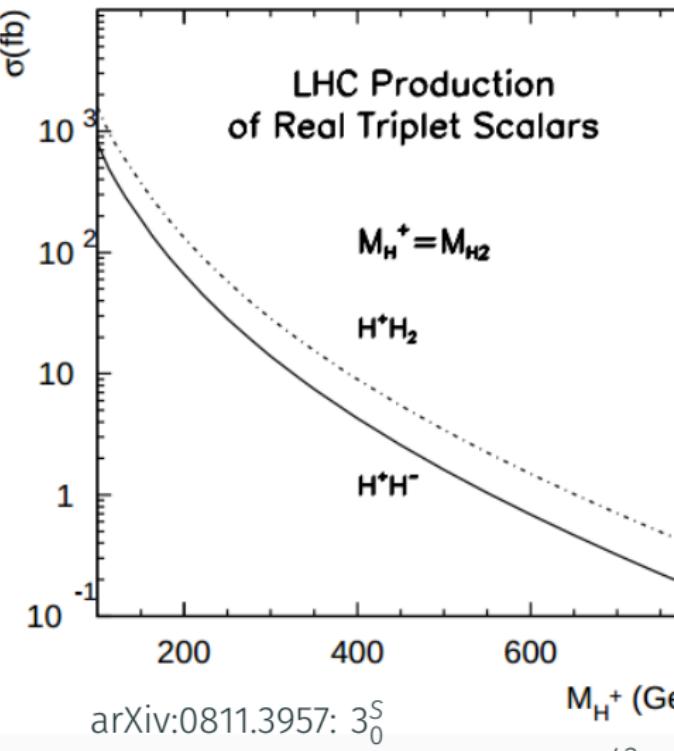


arXiv:1201.3764  $3_{\pm 2}^F$





arXiv:1202.2014:  $3_{\pm 2}^S$



arXiv:0811.3957:  $3_0^S$

$M_{H^+}$  (GeV)

## FeynRules/SARAH

micrOMEGAS (CalcHEP)  
DM

MadGraph(UFO)  
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

---

$$10 \times 16 = 16 + 144$$

$$\overline{16} \times 16 = 1 + \dots$$

$$\overline{144} \times 144 = 1 + \dots$$

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

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

and the singlet can be chosen real

## New simplified models

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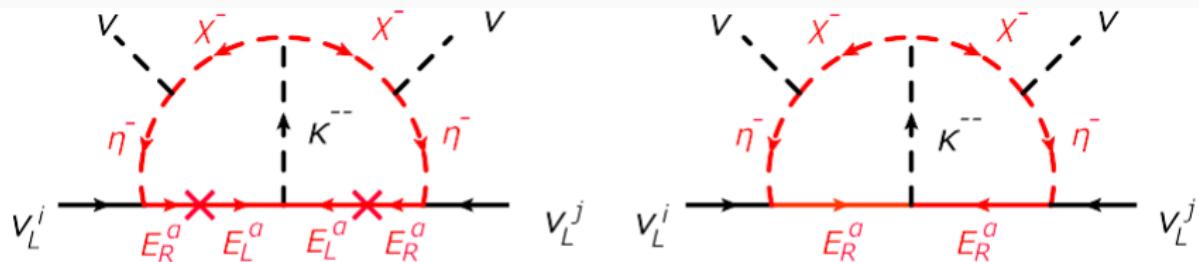
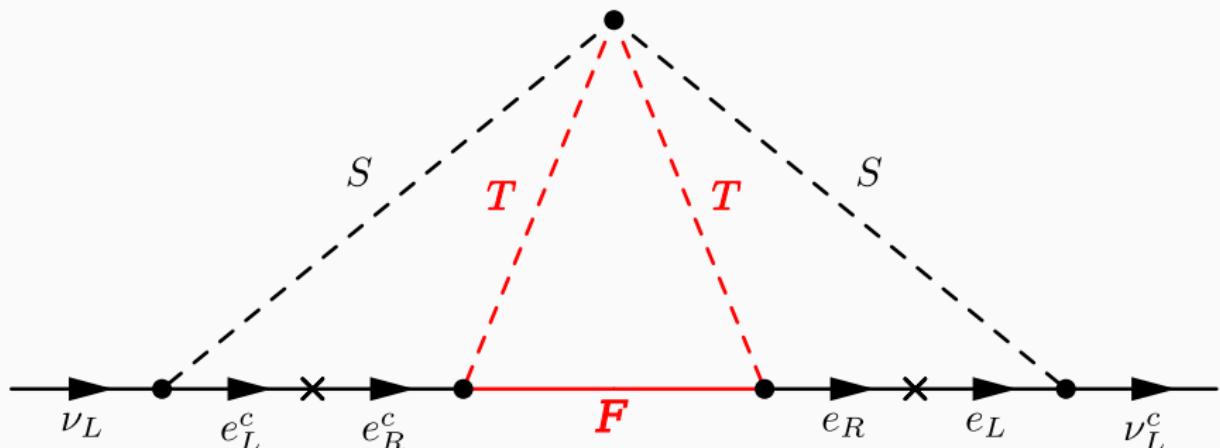


FIG. 2: Feynman diagrams for the neutrino mass generation at the two-loop level. Particles indicated by the red color have the  $Z_2$  odd parity.

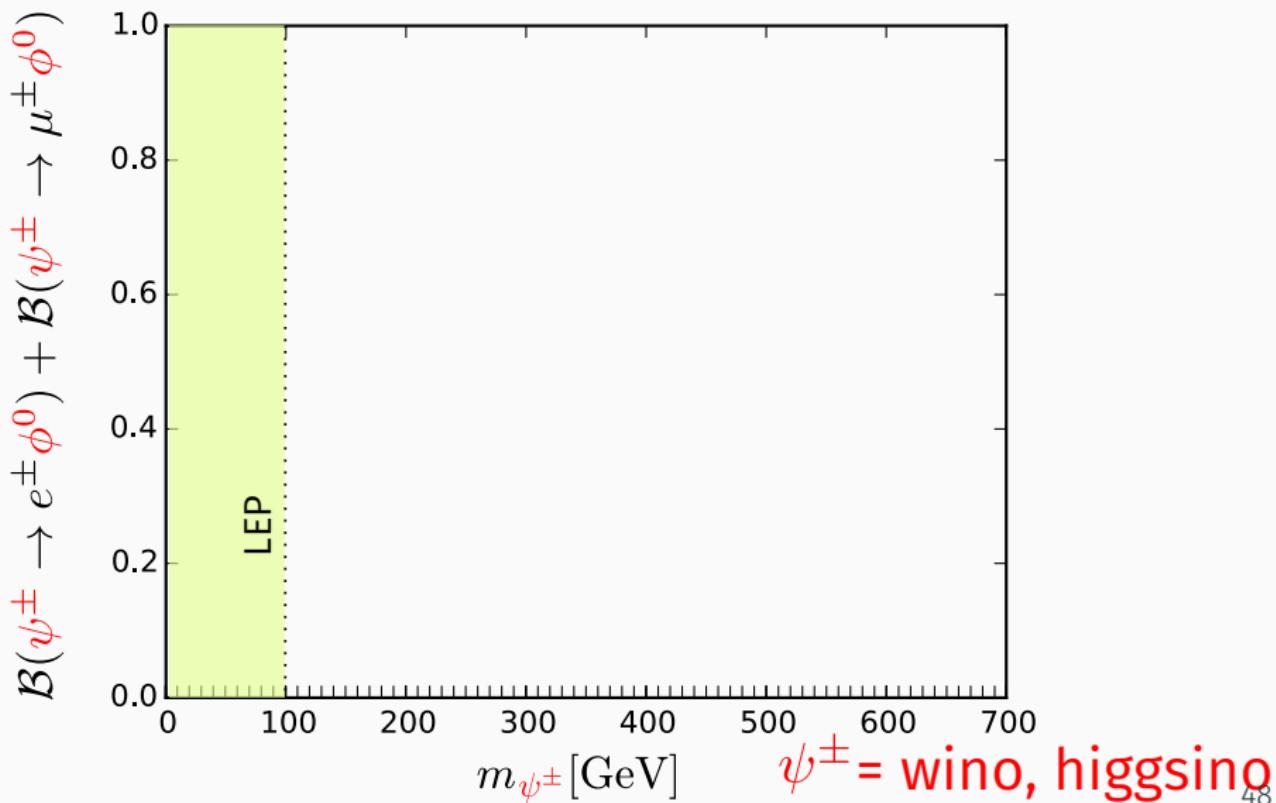


Three-loop diagram for neutrino mass. Here,  $S \sim (1, 1, 2)$  and  $T \sim (1, 2n + 1, 2)$  are beyond-SM scalars while  $F \sim (1, 2n + 1, 0)$  is a beyond-SM fermion.

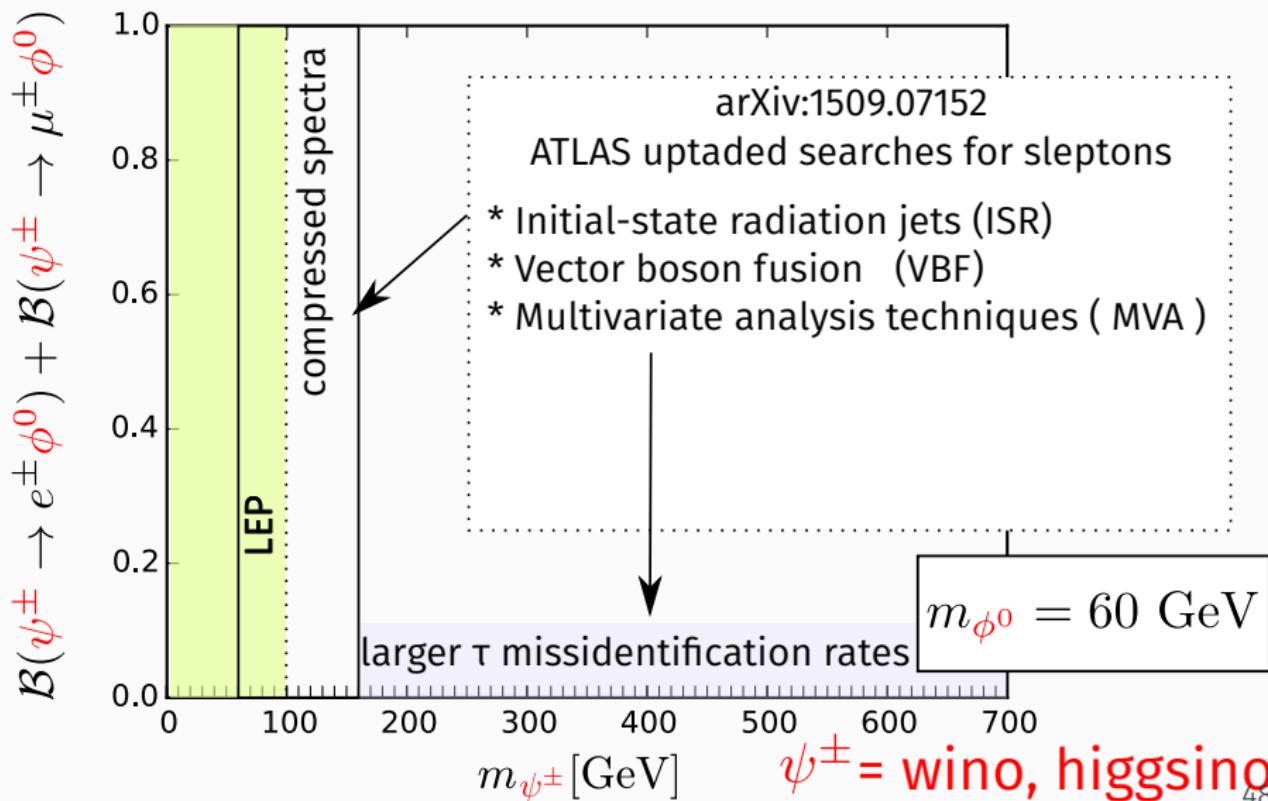
$$pp \rightarrow \psi^\pm \psi^\mp \rightarrow l_i^\pm l_j^\mp \phi^0 \phi^0 \quad l_i = e, \mu, \tau, \quad \phi^0 = H^0, S^0$$

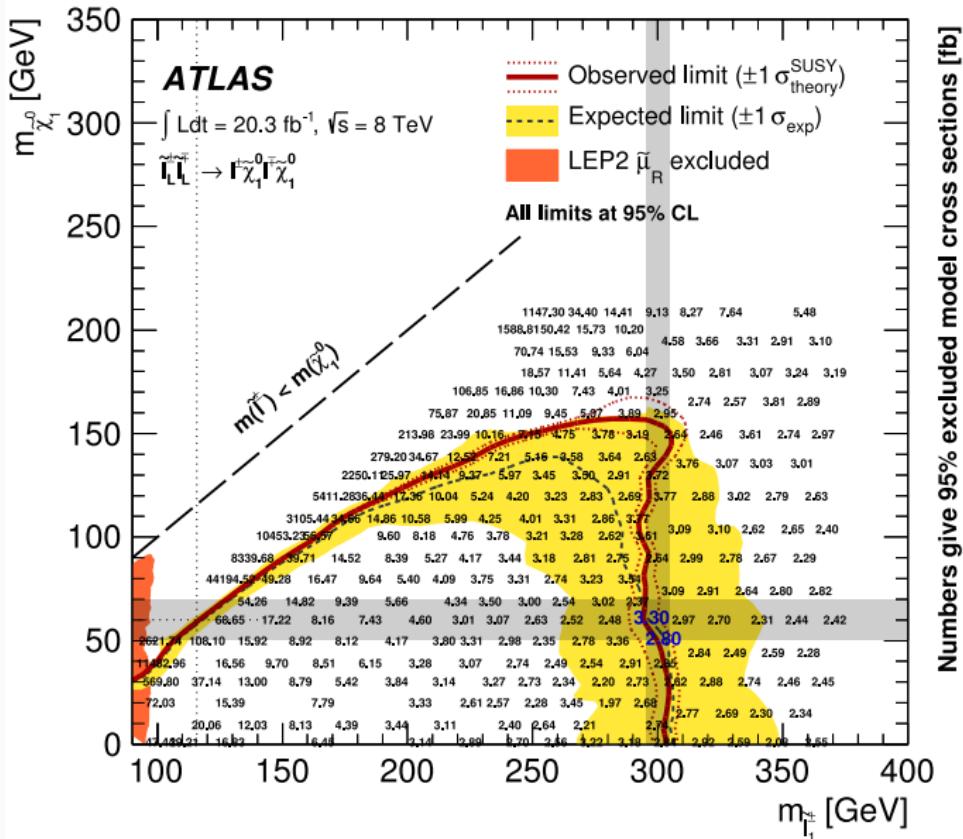
$\psi^\pm$  = wino, higgsino

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



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



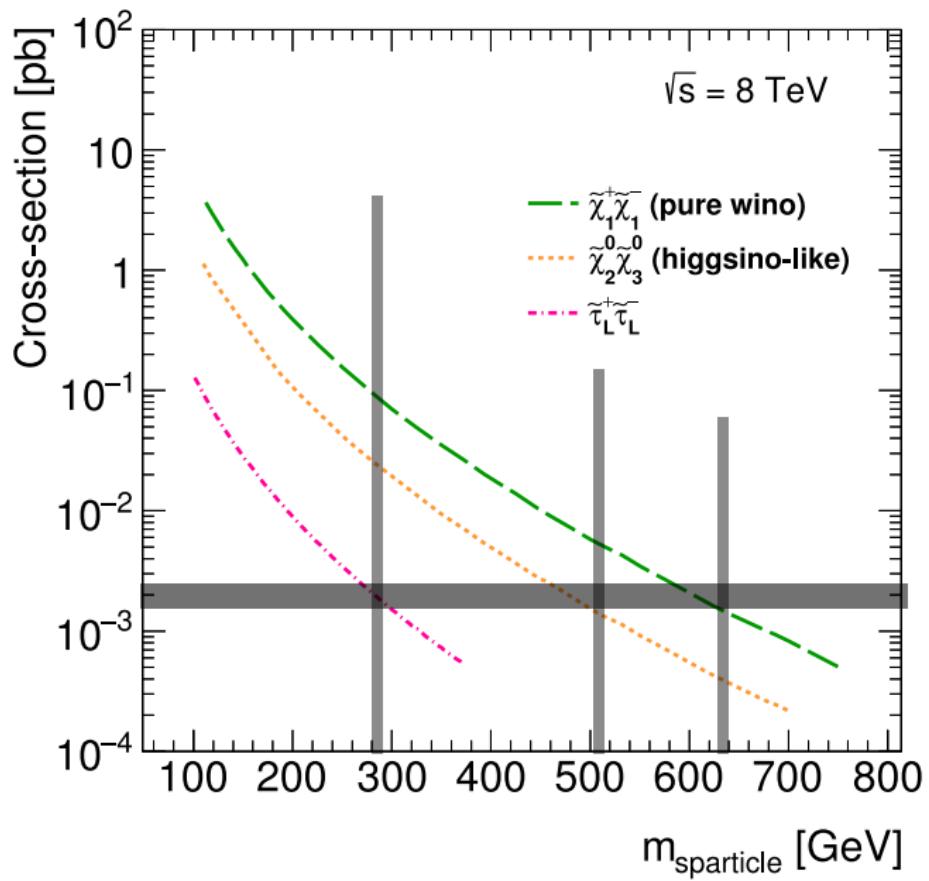


CMS

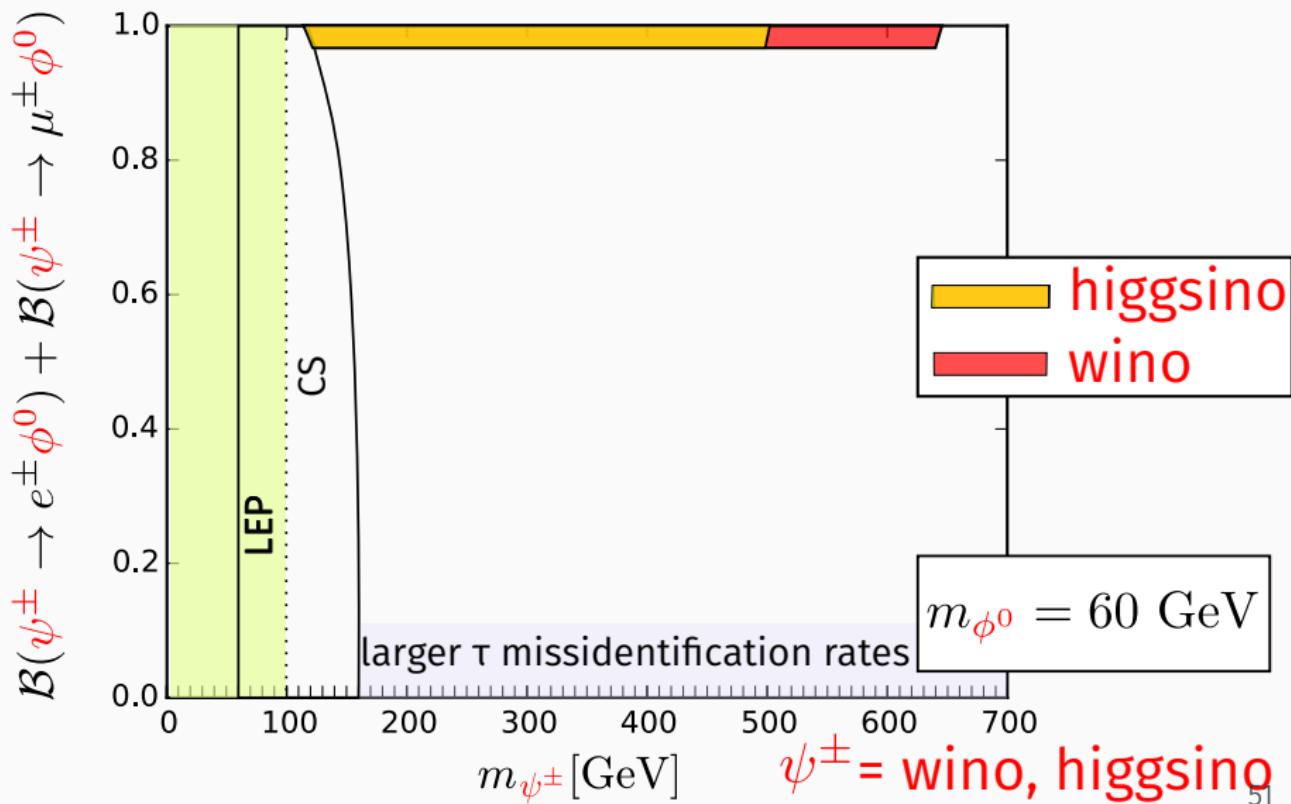
 $\gtrsim 260 \text{ GeV}$ 

arXiv:1405.7570

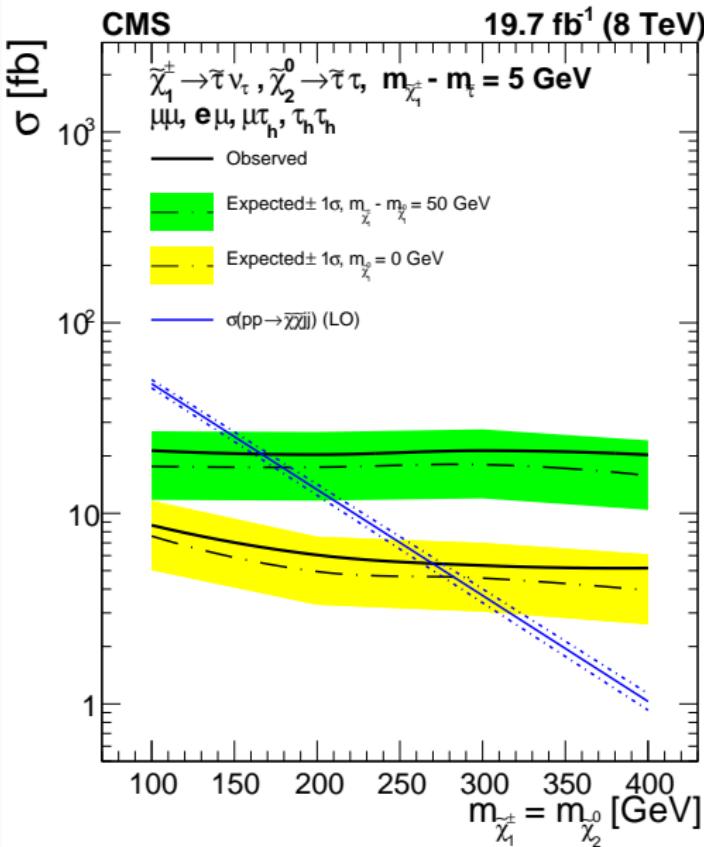
# Excluded cross section for higgsino and wino fermions



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



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



$$\psi^\pm \psi^0$$

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

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

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

