Doublet triplet fermion dark matter with neutrino masses

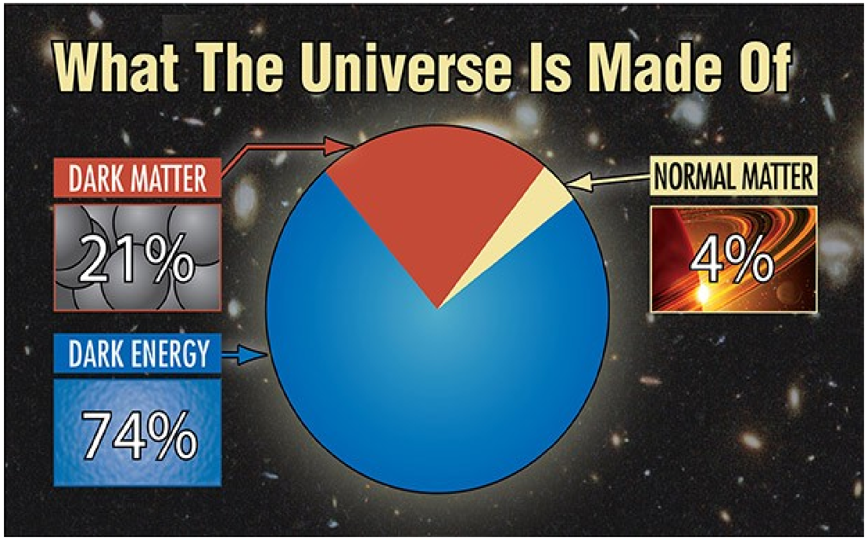
Robinson Longas Bedoya
In collaboration with A. Betancur, D. Restrepo and O. Zapata

XI SILAFAE-2016
Antigua, Guatemala

Outline

- Motivation and introduction
- The doublet triplet fermion dark matter (DTFDM) model
- The DTFDM with scalars
- Dark matter phenomenology
- Neutrino masses
- Conclusions

Motivation

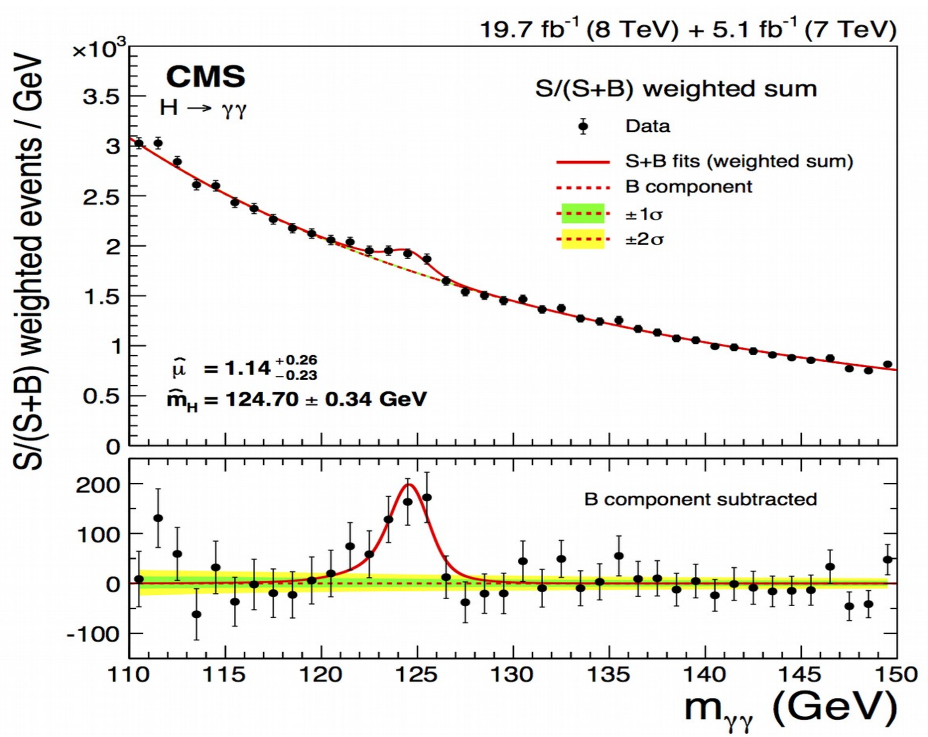


Dark matter

Neutrino Masses

Introduction

Eur.Phys.J. C74 (2014)



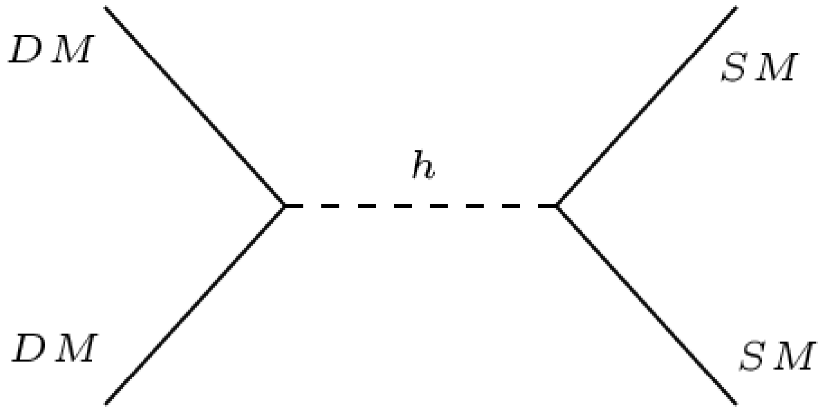
Higgs discovery

What then ?

Dark matter through Higgs portal?

Introduction

Higgs portal DM



- Singlet scalar: SM + a scalar singlet PLB161, 136 (1985)-PRD50, 3637 (1994) -NPB619, 709 (2001)
- Inert doublet model (IDM): SM + a scalar doublet PRD18, 2574 (1978)
- Higher scalar representations NPB753, 178 (2006)
- Doublet triplet fermion dark matter (DTFDM) PRD89, 115002 (2014)

We will focus on the DTFDM

The DTFDM model

The doublet triplet fermion dark matter enlarges the fermion sector of the SM by adding

$\mathrm{SU}(2)_L$ vectorlike doublet

$$\psi_L = \begin{pmatrix} \psi_L^0 \\ \psi_L^- \end{pmatrix}, \psi_R = \begin{pmatrix} \psi_R^0 \\ \psi_R^- \end{pmatrix}$$

$\mathrm{SU}(2)_L$ Majorana triplet

$$\Sigma_L \equiv \sqrt{2}\Sigma_L^i \tau^i = \begin{pmatrix} \Sigma_L^0/\sqrt{2} & \Sigma_L^+ \\ \Sigma_L^- & -\Sigma_L^0/\sqrt{2} \end{pmatrix}$$

The DTFDM model

The Yukawa Lagrangian contains the following terms

$$\mathcal{L}_Y = -y_1 H_1^\dagger \overline{\Sigma_L^c} \epsilon \psi_R^c + y_2 \overline{\psi_L^c} \epsilon \Sigma_L H_1 - \frac{1}{2}\mathrm{Tr}(\bar{\Sigma}_L^c M_\Sigma \Sigma_L) - M_\psi \bar{\psi}_R \psi_L + \mathrm{h.c.}$$

Neutralino-like mass matrix

$$\Xi^0 = (\Sigma_L^0, \psi_L^0, \psi_R^{0c})^T$$

$$\mathbf{M}_{\Xi^0} = \begin{pmatrix} M_\Sigma & \frac{1}{\sqrt{2}}y_1 v & \frac{1}{\sqrt{2}}y_2 v \\ \frac{1}{\sqrt{2}}y_1 v & 0 & M_\psi \\ \frac{1}{\sqrt{2}}y_2 v & M_\psi & 0 \end{pmatrix}$$

Chargino-like mass matrix

$$\Xi_R^- = (\Sigma_L^{+c}, \psi_R^-)^T \text{ and } \Xi_L^- = (\Sigma_L^-, \psi_L^-)^T$$

$$\mathbf{M}_{\Xi^\pm} = \begin{pmatrix} M_\Sigma & y_1 v \\ y_2 v & M_\psi \end{pmatrix}$$

Tree Majorana states: $\chi_1^0, \chi_2^0, \chi_3^0$

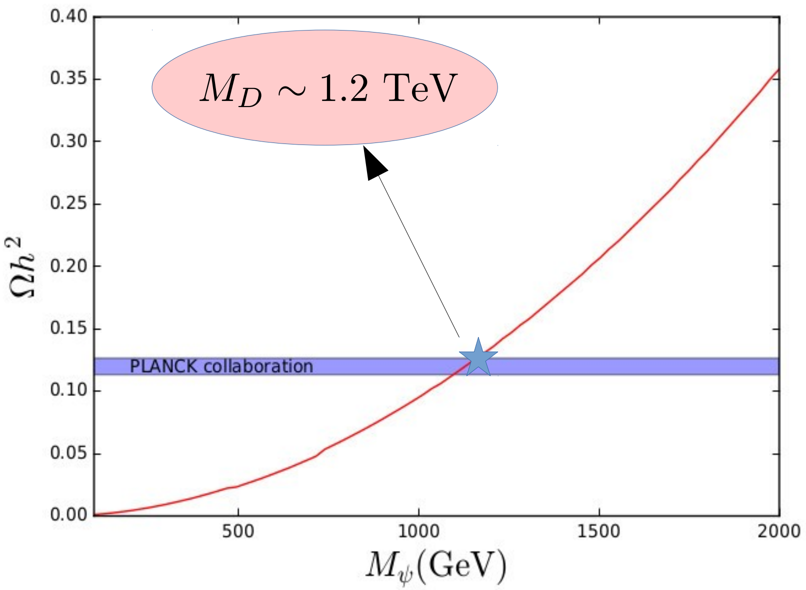
Two charged states: $\chi_1^\pm, \chi_2^\pm$

The conservation of the discrete symmetry renders the lightest state in the spectrum as a stable particle

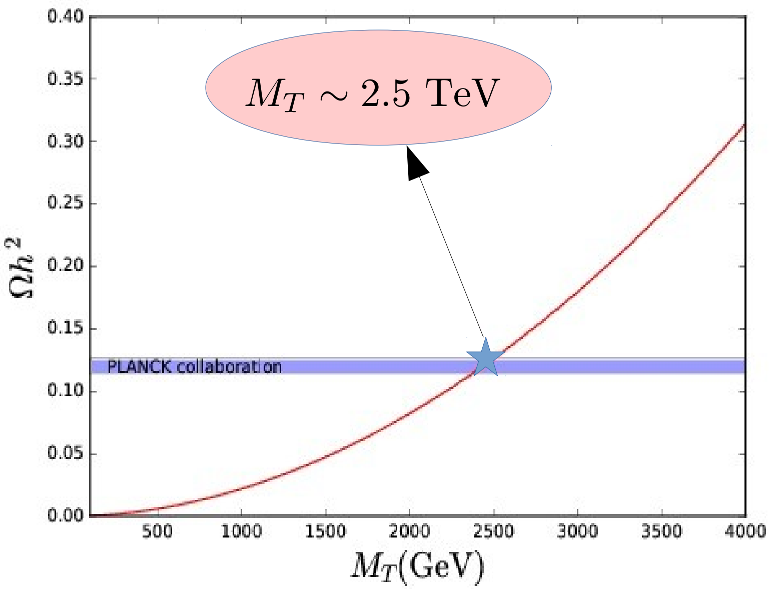
The DTFDM model

Dark matter abundance

Pure doublet case



Pure triplet case



The DTFDM model

- We are interested in the region $100 \lesssim \frac{M_\psi}{\mathrm{GeV}} \lesssim 300$

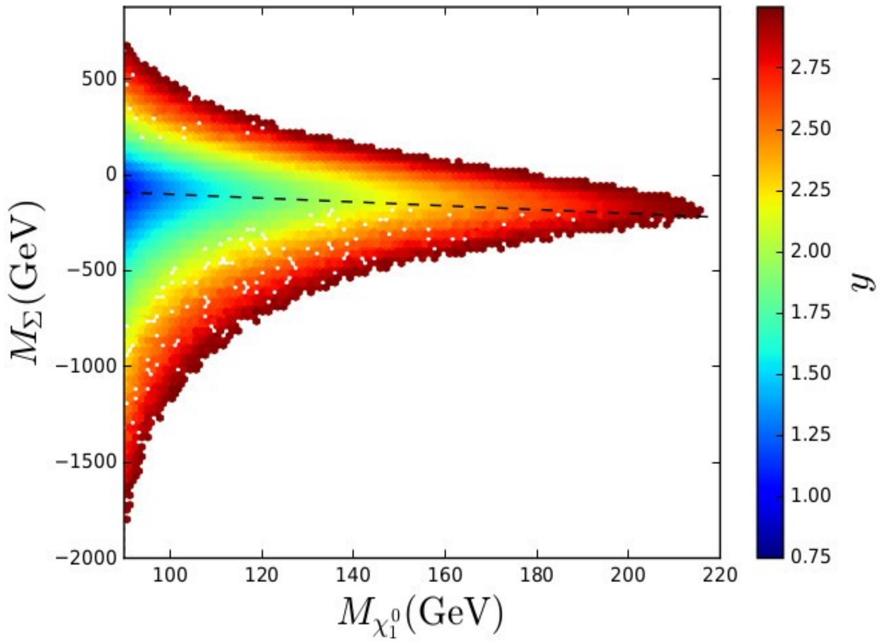
In the blind spot $y_1 = y_2 = y$

$$M_{\chi_1^0} = -M_\psi$$

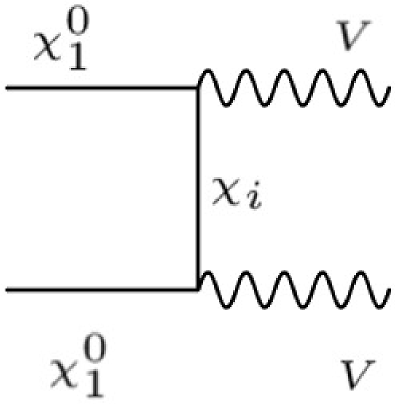
$$M_{\chi_2^0} = M_{\chi_1^\pm}$$

$$M_{\chi_3^0} = M_{\chi_2^\pm}$$

Dark matter abundance



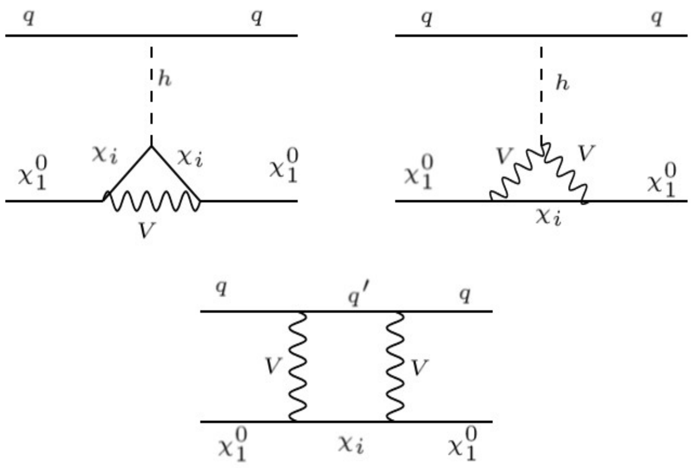
Only gauge interactions



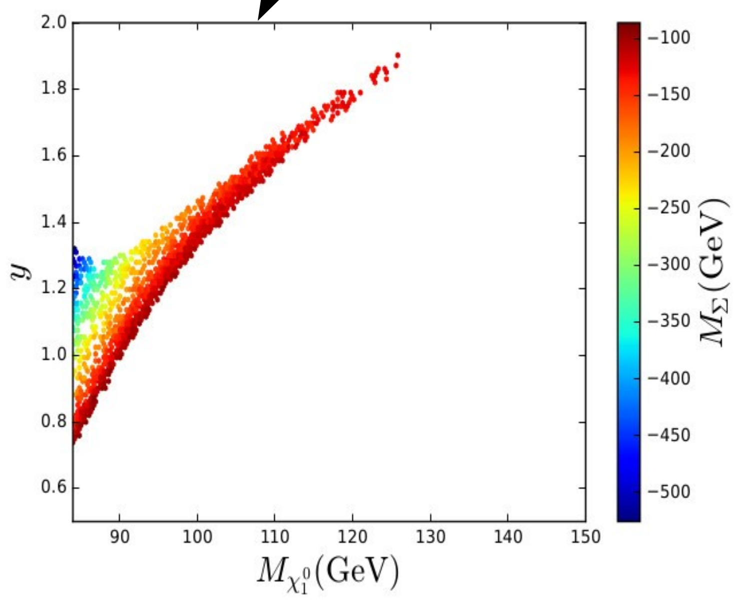
The DTFDM model

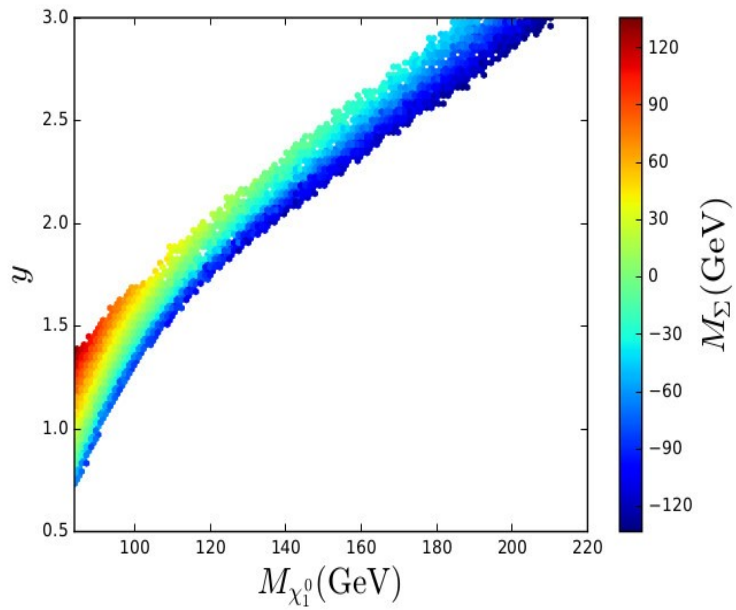
Direct detection at one loop

JHEP 09, 015 (2015)



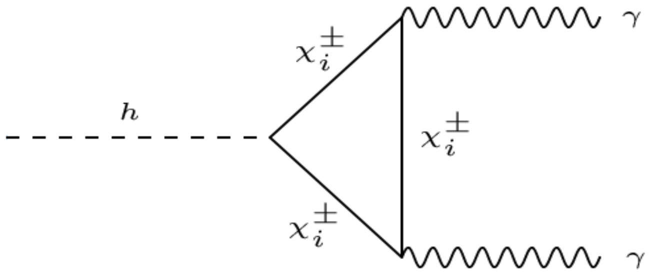
With LUX2016 arXiv:1608.07648





The DTFDM model

What is the problem?

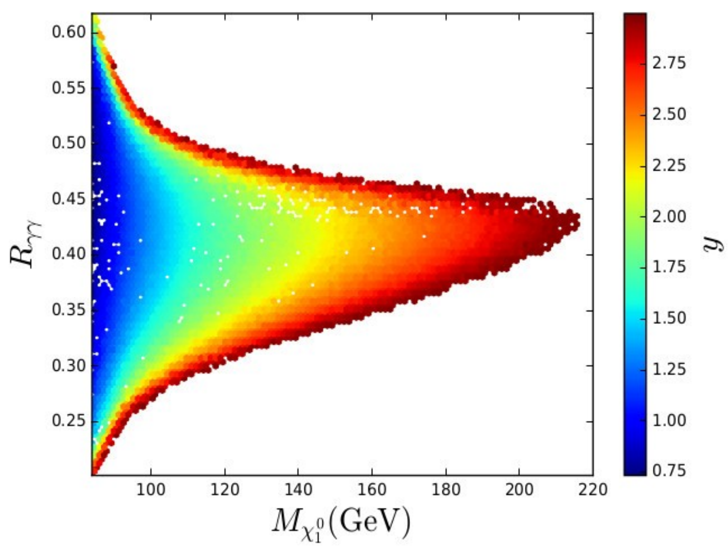


$$\tau_i = \frac{m_h^2}{4M_{\chi_i^{\pm}}} \qquad A_{SM} \sim -6.5$$

JHEP 09, 015 (2015)

$$R_{\gamma\gamma} = \frac{\Gamma(h \to \gamma\gamma)}{\Gamma(h \to \gamma\gamma)_{\mathrm{SM}}} = \left| 1 + \frac{1}{A_{\mathrm{SM}}} \sum_{i=1,2} \frac{y\, v}{M_{\chi_i^+}} A_{\frac{1}{2}}(\tau_i) \right|^2$$

CMS-PAS-HIG-16-020 $0.95^{+0.21}_{-0.18}$ ATLAS-CONF-2016-067 $0.85^{+0.22}_{-0.20}$



Conclusion

- Higgs diphoton decay excludes the DTFDM at low energy !

SILAFAE 2016 14-18/11/2016

The DTFDM model plus scalars

What should we do?

We demand that the scalars do not develop a vev in order to preserve the discrete symmetry

Inert scalar doublet

Inert scalar triplet

$$H_2 = \begin{pmatrix} H^+ \\ \frac{H^0 + iA^0}{\sqrt{2}} \end{pmatrix} \qquad \Delta = \frac{1}{2}\begin{pmatrix} \Delta_0 & \sqrt{2}\,\Delta^+ \\ \sqrt{2}\,\Delta^- & -\Delta_0 \end{pmatrix}$$

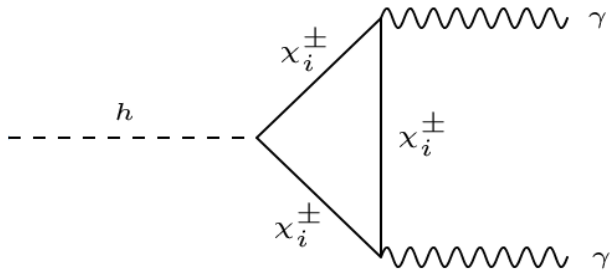
$$\mathcal{V} \supset \lambda_3 |H_1|^2 |H_2|^2 + \lambda_3' (H_1^\dagger H_1)\mathrm{Tr}[\Delta^2] + \left[\frac{\lambda_5}{2}\left(H_1^\dagger H_2\right)^2 + \mu H_1^\dagger \Delta H_2 + \mathrm{h.c.}\right]$$

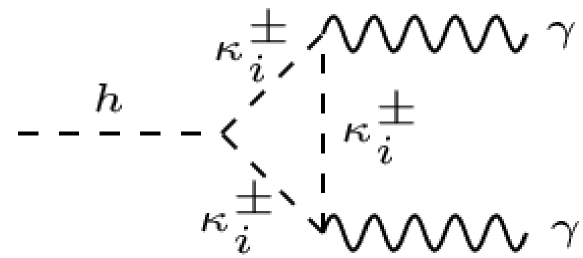
Two neutral CP-even states: η_1^0, η_2^0 through: $\sin(2\alpha) = \frac{\mu v}{m^2_{\eta_2^0} - m^2_{\eta_1^0}}$

A neutral CP-odd states: A^0

Two charged states: $\kappa_1^\pm, \kappa_2^\pm$ through: $\sin(2\beta) = \frac{\mu v}{m^2_{\kappa_2^\pm} - m^2_{\kappa_1^\pm}}$

The DTFDM model plus scalars





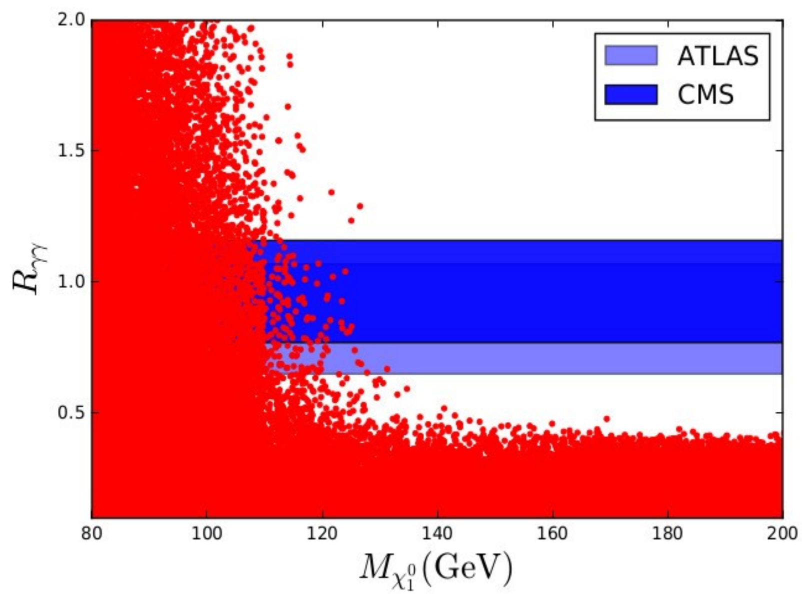
$$R_{\gamma\gamma} = \left| 1 + \frac{1}{A_{\rm SM}} \sum_{i=1,2} \frac{y\, v}{M_{\chi_i^+}} A_{\frac{1}{2}}(\tau_i) + \frac{1}{A_{SM}} \frac{\lambda_3}{4m^2_{\kappa_1^\pm}} A_0\left(\frac{m_h^2}{4m^2_{\kappa_1^\pm}}\right) + \frac{1}{A_{SM}} \frac{\lambda_3'}{4m^2_{\kappa_2^\pm}} A_0\left(\frac{m_h^2}{4m^2_{\kappa_2^\pm}}\right) \right|^2$$

$$\tau_i = \frac{m_h^2}{4M_{\chi_i^\pm}} \quad A_{SM} \sim -6.5$$

$$-2 < \lambda_3 \,, \lambda_3' < 4\pi$$

$$1.2 < \frac{m_{\kappa_1^\pm}}{M_D} < 3 \quad 1.2 < \frac{m_{\kappa_2^\pm}}{M_D} < 3$$

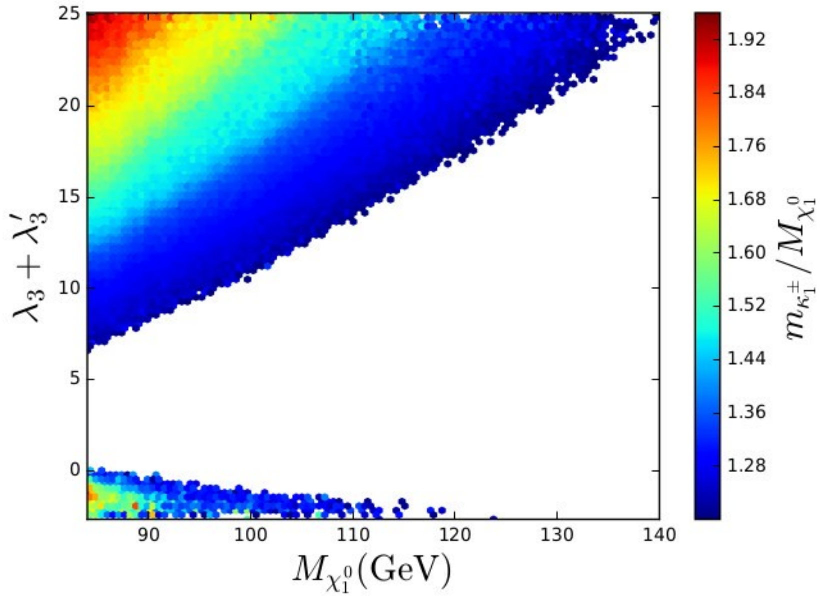
$$\frac{m_{H^0}}{M_D} > 1.2 \quad \frac{m_{A^0}}{M_D} > 1.2$$

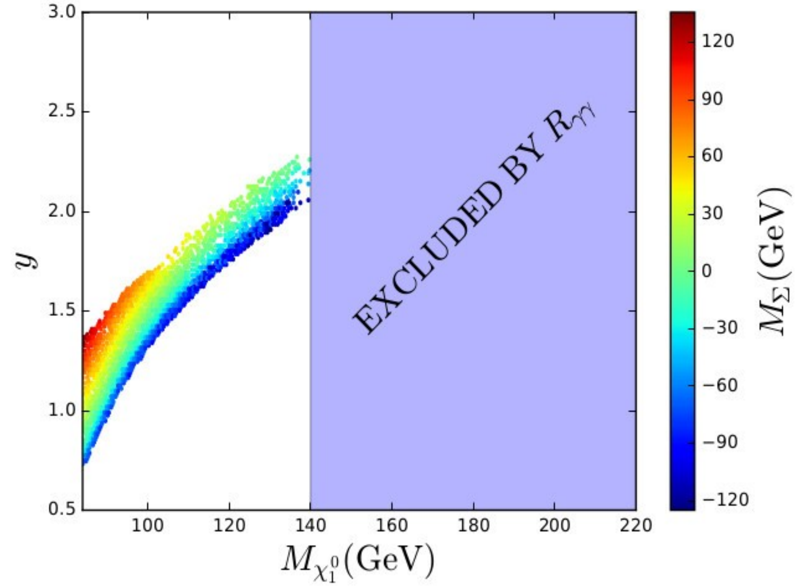


No coannnihilations between fermion DM and new scalar states

The DTFDM model plus scalars

$$R_{\gamma\gamma} = \left| 1 + \frac{1}{A_{\rm SM}} \sum_{i=1,2} \frac{y\,v}{M_{\chi_i^+}} A_{\frac{1}{2}}(\tau_i) + \frac{1}{A_{SM}} \frac{\lambda_3}{4m^2_{\kappa_1^\pm}} A_0\left(\frac{m_h^2}{4m^2_{\kappa_1^\pm}}\right) + \frac{1}{A_{SM}} \frac{\lambda_3'}{4m^2_{\kappa_2^\pm}} A_0\left(\frac{m_h^2}{4m^2_{\kappa_2^\pm}}\right) \right|^2$$



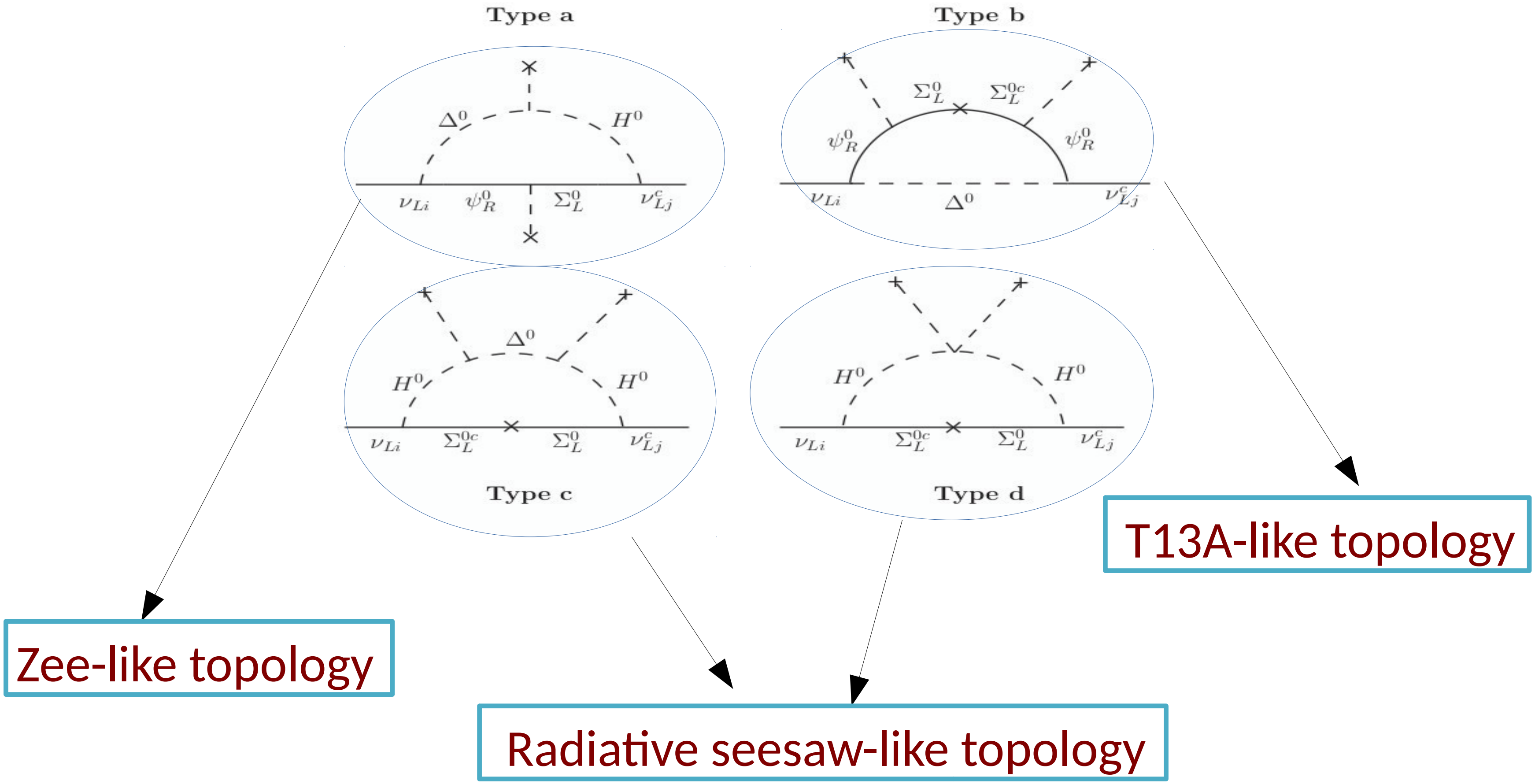


We recover the dark matter mass up to 140 GeV

Neutrino masses

New Yukawa Lagrangian

$$\mathcal{L} \supset -y_1 H_1^\dagger \overline{\Sigma_L^c} \epsilon \psi_R^c + y_2 \overline{\psi_L^c} \epsilon \Sigma_L H_1 - \zeta_i \bar{L}_i \Sigma_L^c \tilde{H}_2 - \rho_i \bar{\psi}_L H_2 e_{Ri} - f_i \overline{L_i} \Delta \psi_R + \text{h.c.}$$



Neutrino masses

$$M^{\nu} = \Lambda_{\zeta}\zeta_i\zeta_j + \Lambda_f f_i f_j + \Lambda_{f\zeta}(\zeta_i f_j + f_i\zeta_j)$$

$$\Lambda_{\zeta} = \frac{1}{32\pi^2}\frac{1}{2}\sum_{k=1}^{3} m_{\chi_k^0}\,(U_{1k})^2\left[c_\alpha^2 F_1(m_{\eta_1}^2, m_{\chi_k^0}^2) + s_\alpha^2 F_1(m_{\eta_2}^2, m_{\chi_k^0}^2) - F_1(m_{A^0}^2, m_{\chi_k^0}^2)\right]$$

$$\Lambda_f = \frac{1}{16\pi^2}\frac{1}{4}\sum_{k=1}^{3} m_{\chi_k^0}\,(U_{3k})^2\left[s_\alpha^2 F_2(m_{\eta_1}^2, m_{\chi_k^0}^2) + c_\alpha^2 F_2(m_{\eta_2}^2, m_{\chi_k^0}^2)\right]$$

$$\Lambda_{\zeta f} = \frac{1}{32\pi^2}\left[\frac{1}{2}s_\alpha c_\alpha\sum_{k=1}^{3} m_{\chi_k^0}\,U_{1k}U_{3k}\left[F_1(m_{\eta_2}^2, m_{\chi_k^0}^2) - F_1(m_{\eta_1}^2, m_{\chi_k^0}^2)\right]\right.$$
$$\left. + s_\beta c_\beta\sum_{k=1}^{2} m_{\chi_k^\pm}\,V_{1k}^L V_{2k}^{R*}\left[F_1(m_{\kappa_1}^2, m_{\chi_k^\pm}^2) - F_1(m_{\kappa_2}^2, m_{\chi_k^\pm}^2)\right]\right]$$

Neutrino masses

The Majorana neutrino mass has a zero determinant which implies only two massive neutrinos

Either the normal hierarchy or the inverted one

The flavor structure of the Majorana matrix allows to write the Yukawa coupling as a function of the mixing angles and the neutrino masses

In particular, for the normal hierarchy

$$f_i = \frac{(-1)^{k_x}}{\Lambda_f}\left(\sqrt{-\Lambda_f\Lambda_\zeta\zeta_i^2 + \Lambda_f m_2 e^{i\alpha/2} V_{i2}^{*2} + \Lambda_f m_3 V_{i3}^{*2} + \Lambda_{\zeta f}^2\zeta_i^2}\right) - \frac{\Lambda_{\zeta f}\zeta_i}{\Lambda_f}$$

$$\zeta_j = (-1)^{k_y}\left(\frac{\sqrt{\Lambda_f^2 e^{i\alpha/2} m_2 m_3(\Lambda_f\Lambda_\zeta - \Lambda_{\zeta f}^2)(V_{13}^*V_{j2}^* - V_{12}^*V_{j3}^*)^2(-\Lambda_f\Lambda_\zeta\zeta_1^2 + m_2 V_{12}^{*2}e^{i\alpha/2}\Lambda_f + m_3 V_{13}^{*2} + \Lambda_{\zeta f}^2\zeta_1^2)}}{(\Lambda_f^2\Lambda_\zeta - \Lambda_f\Lambda_{\zeta f}^2)(e^{i\alpha/2}m_2 V_{12}^{*2} + m_3 V_{13}^{*2})} + (-1)^{k_z}\frac{\left(e^{i\alpha/2}V_{12}^*V_{j2}^* + m_3 V_{13}^* V_{j3}^*\right)(\Lambda_f^2\Lambda_\zeta^2\zeta_1 - \Lambda_f\Lambda_{\zeta f}^2\zeta_1)}{(\Lambda_f^2\Lambda_\zeta - \Lambda_f a_3^2)(e^{i\alpha/2}m_2V_{12}^{*2} + m_3V_{13}^{*2})}\right)$$

$$k_x, k_y, k_z = 0, 1$$

Conclusions

- We have shown that the inclusion of the doublet and triplet scalar representations to the DTFDM model allow to recover the low mass region for the fermion dark matter up to around 140 GeV
- The couplings of the new charged scalars to the Higgs boson must be either large or negative in order to increase the Higgs diphoton decay

$$\lambda_3 + \lambda_3' \gtrsim 5 \quad \text{or} \quad -2 \lesssim \lambda_3 + \lambda_3' \lesssim 0$$

- The scalars have been used to generate Majorana neutrino masses at one loop through Zee-like and radiative seesaw-like topologies
- The Majorana mass matrix flavor structure allows to write the Yukawa couplings as functions of the neutrino masses and the mixing angles
- Only two massive neutrinos are allowed by the mass matrix flavor structure

Thanks!

Backup

In the blind spot

There is a global $SU(2)_R$ symmetry that protects the electroweak precision observable T and all the mass eigenstates have not diagonal couplings to the Z boson, i.e., $g_{\chi_i \chi_i Z} = 0$. Second, it is possible to have a pure doublet DM candidate ($|m_{\chi_1^0}| < |m_{\chi_2^0}|, |m_{\chi_3^0}|$) as long as the condition $M_\Sigma < (y^2 v^2 - 4M_\psi^2)/(4M_\psi)$ is fulfilled. As it can be seen from the structure of the O matrix, the χ_1^0 state is an equal mixture between the doublet components and has no triplet component, which entails that its diagonal coupling to the Higgs boson $g_{\chi_1 \chi_1 h}$ is also zero at tree level.

$$\mathbf{M}'_{\Xi^0} = O^T \mathbf{M}_{\Xi^0} O$$

$$\mathbf{M}'_{\Xi^0} = \begin{pmatrix} M_\Sigma & yv & 0 \\ yv & M_\psi & 0 \\ 0 & 0 & -M_\psi \end{pmatrix} \qquad O = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} \\ 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\mathbf{M}_{\Xi^\pm} = \begin{pmatrix} M_\Sigma & yv \\ yv & M_\psi \end{pmatrix}$$

$$m_{\chi_1^\pm, \chi_2^\pm} = \frac{1}{2}\left[M_\psi + M_\Sigma \mp \sqrt{(M_\psi - M_\Sigma)^2 + 2y^2 v^2} \right]$$

Backup

All the scalar potential is given by

$$\mathcal{V}= -\mu_1^2|H_1|^2 + \frac{\lambda_1}{2}|H_1|^4 + \mu_2^2|H_2|^2 + \frac{\lambda_2}{2}|H_2|^4 + \lambda_3|H_1|^2|H_2|^2 + \lambda_4|H_1^\dagger H_2|^2 + \frac{\lambda_5}{2}\left[(H_1^\dagger H_2)^2 + \text{h.c.}\right]$$
$$+\mu_\Delta^2[\Delta^2] + \frac{\lambda_\Delta}{2}\text{Tr}[\Delta^2]^2 + \lambda_3'(H_1^\dagger H_1)\text{Tr}[\Delta^2] + \lambda_{\Delta H_2}(H_2^\dagger H_2)\text{Tr}[\Delta^2] + \mu\left[\text{H}_1^\dagger \Delta \text{H}_2 + \text{h.c.}\right]$$

Vacuum stability and perturbativity impose

$$\lambda_3 + \sqrt{\lambda_1\lambda_2} > 0\,, \lambda_3 + \lambda_4 - |\lambda_5| + \sqrt{\lambda_1\lambda_2} > 0\,, \lambda_3' + \sqrt{\lambda_1\lambda_\Delta} > 0\,,$$
$$\lambda_{H_2\Delta} + \sqrt{\lambda_2\lambda_\Delta} > 0\,, \lambda_3 < 4\pi\,, \lambda_3' < 4\pi\,, \lambda_{2,\Delta} < \frac{4\pi}{3}.$$

Neutral and charged mass matrices

(H^0, Δ^0) $\qquad$ $(H^\pm, \Delta^\pm)$

$$M_{S^0} = \begin{pmatrix} \mu_2^2 + \lambda_L v^2 & \frac{1}{2}\mu v \\ \frac{1}{2}\mu v & \mu_\Delta^2 + \frac{1}{2}\lambda_{\Delta H_1} v^2 \end{pmatrix}, M_{S^\pm} = \begin{pmatrix} \mu_2^2 + \frac{1}{2}\lambda_3 v^2 & -\frac{1}{2}\mu v \\ -\frac{1}{2}\mu v & \mu_\Delta^2 + \frac{1}{2}\lambda_{\Delta H_1} v^2 \end{pmatrix}$$

Backup

In the blind spot →
No lepton contributions to STU

But, what about scalars?

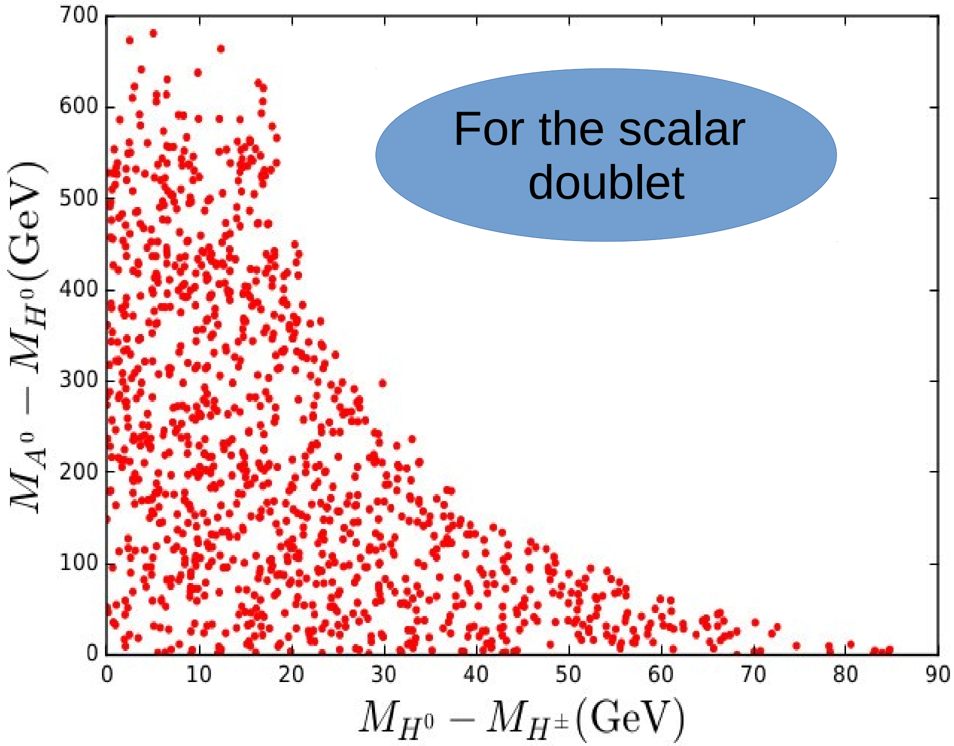
μ

Parameter gives big contributions

$\mu \sim 0.0001$

STU at 95% CL

Eur. Phys. J. C74 (2014) 3046

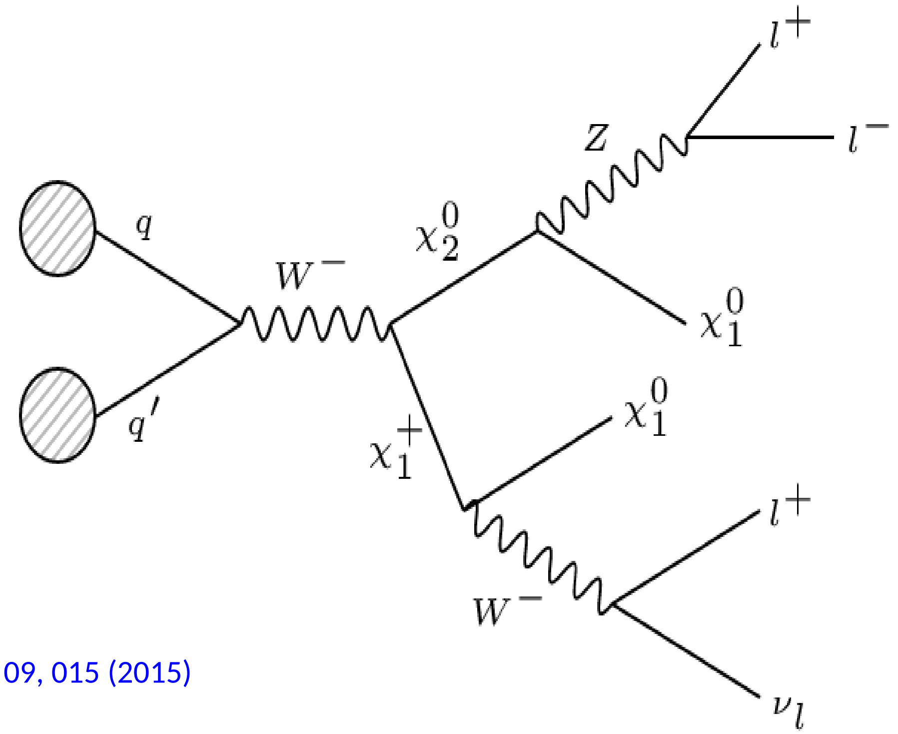


For the scalar doublet

Backup

Production at colliders

Trileptons plus missing energy searches in SUSY can give constraints on the leptons because of the phenomenological similarity of the model with the neutralino-chargino sector of the MSSM



No bounds at luminosity ~30 inverse fb and 13 center of mass energy (with heavy scalars)

JHEP 09, 015 (2015)

All the parameter space (100-300 GeV) will be excluded with 3000 inverse fb and 14 center of mass energy (with heavy scalars)

JHEP 09, 015 (2015)