# *Constraining Inert Triplet Dark Matter by the LHC and FermiLAT*

***By: Seyed Yaser Ayazi***
School of Particles and Accelerators, IPM , Tehran

*arXiv:1408.0654 by S. Y. Ayazi and S. Mahdi Firouzabadi*, JCAP11(2014)005

## *Outline:*

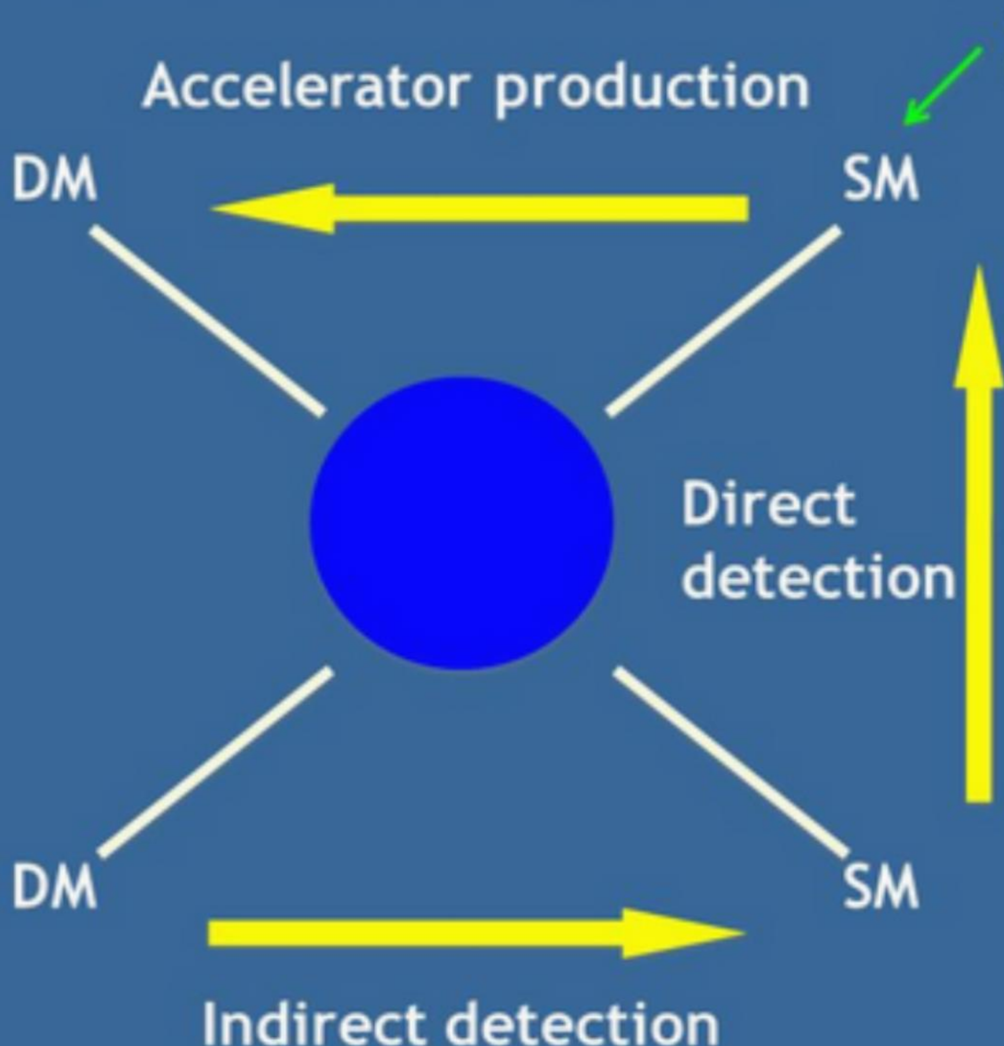
- Inert Triplet Model
- Direct Detection
- Collider Phenomenology of Dark Matter(DM)
- Indirect search for DM
- Conclusions

- SM extensions with singlet scalar or fermion fields are simplest model for DM.

- In the WIMP scenario, DM candidate can produce required relic density which is measured by PLANCK satellite. It is shown that allowed region for parameters space of singlet scalar and fermionic DM are strictly limited by relic density constraints.

- The one of simplest candidate for DM is SU(2)L scalar triplet field. The lightest component of triplet field is neutral and provides suitable candidate for DM.

# Strategies: search for Dark Matter




- Production in accelarators (LHC)
- Indirect detection:
  - search for annihilation/decay products of $\chi$'s (self-antiparticle)
- Direct detection:
  - $\chi$-nucleus elastic scattering

# Inert Triplet Model

- The Inert Triplet model (ITM) is an extension of the SM that can provide DM particle. In this model, apart from the SM Higgs doublet, we add a SU(2)L triplet scalar with Y = 0 or Y = 2.

- In addition, we impose Z2 symmetry condition under which the triplet is odd and all the SM fields are even. The Z2 symmetry is not spontaneously broken since the triplet does not develop a vacuum expectation value. The triplet for Y = 0 can be parameterized as:

$$T = \begin{pmatrix} \frac{1}{\sqrt{2}}T^0 & -T^+ \\ -T^- & -\frac{1}{\sqrt{2}}T^0 \end{pmatrix}, \qquad \langle T^0 \rangle = 0.$$

- The relevant scalar potential which is allowed by Z2 symmetry can be written as:

$$V = m^2|H|^2 + M^2\mathrm{tr}[T^2] + \lambda_1|H|^4 + \lambda_2(\mathrm{tr}[T^2])^2 + \lambda_3|H|^2\mathrm{tr}[T^2].$$

$$\langle H\rangle = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v \end{pmatrix}, \quad v = 246\ \mathrm{GeV}.$$

$m^2 < 0,\ v^2 = -m^2/2\lambda_1$ $\qquad$ $2M^2 + \lambda_3 v^2 > 0$

- The triplet masses can be written by two parameters $\lambda_3$ and $M$:

$$m^2_{T^0} = m^2_{T^\pm} = M^2 + \frac{1}{2}\lambda_3 v^2.$$

- At tree level, as it is seen in the above relation, all the components of T own the same mass, but at loop level the charged components are slightly heavier than T0.

Note that the Z2 symmetry ensures the stability of the lightest component to act as a cold DM candidate.

In case $Y = 2$ the $SU(2)_L$ triplet can be parameterized as:

$$T = \begin{pmatrix} \frac{1}{\sqrt{2}}T^{+} & T^{++} \\ T_r^0 + iT_i^0 & -\frac{1}{\sqrt{2}}T^{+} \end{pmatrix}$$

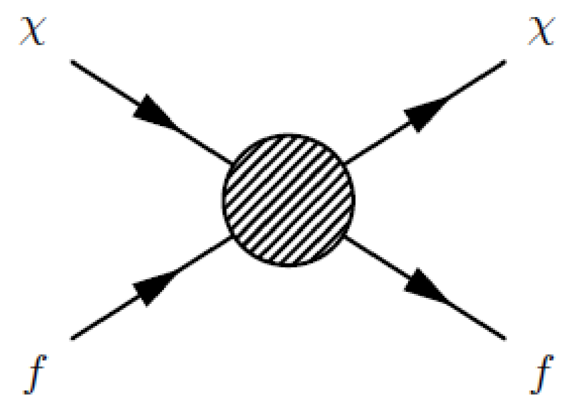
- In Y = 2 case, the T0r or T0i are playing the role of DM particle. Due to gauge coupling of Z to T0r,i the DM-nucleon cross section is 10^38 cm2 and much larger than upper limits by XENON100 experiment. This excludes all the regions of parameter space for this case.

# WIMP Direct Detection

DM can interact with nucleon by exchanging Higgs boson. The spin independent cross section of DM-nucleon is given by

$$\sigma_{SI} = \frac{\lambda_3^2 f_n^2 m_N^2}{4\pi} \frac{\mu^2 m_N^2}{m_{T^0}^2 m_h^4},$$

$$\mu = m_N m_{T^0}/(m_N + m_{T^0})$$




There are several experiments to detect DM particles directly through the elastic DM-nucleon scattering. The strict bounds on the DM-nucleon cross section obtained from XENON100 and LUX experiments. The minimum upper limits on the spin independent cross section are:

$$\text{XENON100} : \sigma_{SI} \leq 2 \times 10^{-45}\text{cm}^2$$

$$\text{LUX} : \sigma_{SI} \leq 7.6 \times 10^{-46}\text{cm}^2.$$

# Experimental Constraints on Inert Triplet Dark Matter

- *Relic Density*

In context of ITM, in mass regimes lower than 7 TeV, relic density conditions are satisfied. Since direct detection constraints are weak for large masses (mDM > 1TeV) henceforward, we assume mDM < 1 TeV and evaluate other experimental constraints on parameters space for low mass DM. [arXiv:1102.4906]

- *Electroweak precision*

It is shown that contribution of ITM on oblique parameters S and T is negligibly small. [arXiv:1102.4906]

# Z boson decay width

The most constraining observable for ITM parameters is the Z boson decay width. The Z boson decay width was measured to be:

$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$

$$\Gamma(Z \to T^{\mp}T^{\pm})) = \frac{g^2 c_W^2 m_Z}{\pi}(1 - \frac{4m_{T^\pm}^2}{m_Z^2})^{3/2},$$

- Since $Z \to T^{\mp}T^{\pm}$ is suppressed for $m_{T^\pm} < m_Z/2$ , we assume that

$$m_{T^0}, m_{T^\pm} > 45.5 \text{ GeV}$$

# Invisible Higgs decays

Invisible Higgs decays provide chance for exploring possible DM-Higgs boson coupling. Nevertheless, invisible Higgs boson decays are not sensitive to DM coupling when mT0 > mh/2.

Any components of triplet scalar lighter than SM higgs boson can contribute to the invisible decay mode of higgs boson.

$$Br(h \to \text{Invisible}) = \frac{\Gamma(h \to \text{Inv})_{\text{SM}} + \Gamma(\text{h} \to 2\text{T}^0)}{\Gamma(h)_{\text{ITM}}},$$

*Where*

$$\Gamma(h)_{\text{ITM}} = \Gamma(h)_{\text{SM}} + \sum_{\chi = T^0, T^{\pm}, \gamma} \Gamma(h \to 2\chi).$$

- *Total width of higgs boson in SM is 4.15 MeV and the partial width for h→ 2T0 is given by:*

$$\Gamma(h \to 2T^0) = \frac{\lambda_3^2 v_0^2}{4\pi m_h} \sqrt{1 - \frac{4m_{T^0}^2}{m_h^2}}.$$

The SM prediction for branching ratio of the Higgs boson decaying to invisible particles is :

$$Br(h \to ZZ^* \to 4\nu) = 1.2 \times 10^{-3}$$

Recently, ATLAS Collaboration has performed a search of the SM higgs boson in its invisible decay mode and obtained an upper limit of 75%, at a mass of 125.5 GeV for Br(h → Invisible).

# Rγγ constraints on dark matter

- ITM also contribute to partial width of $h \rightarrow \gamma\gamma$ The partial decay rate for this process has not been measured at the LHC but the ratio of the diphoton rate of the observed Higgs to the SM prediction have been measured recently by CMS and ATLAS collaborations:

$$\text{CMS}: R_{\gamma\gamma} = \frac{\sigma_{\text{measured}}}{\sigma_{SM}} = 1.14^{+0.26}_{-0.23},$$

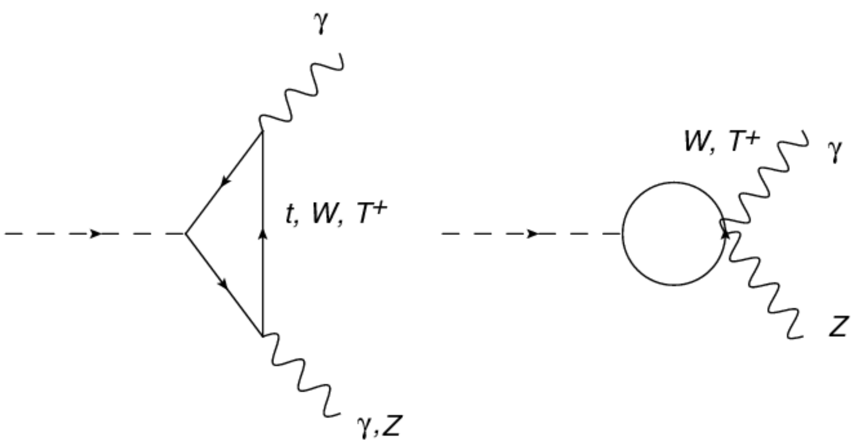
$$\text{ATLAS}: R_{\gamma\gamma} = \frac{\sigma_{\text{measured}}}{\sigma_{SM}} = 1.17 \pm 0.27$$

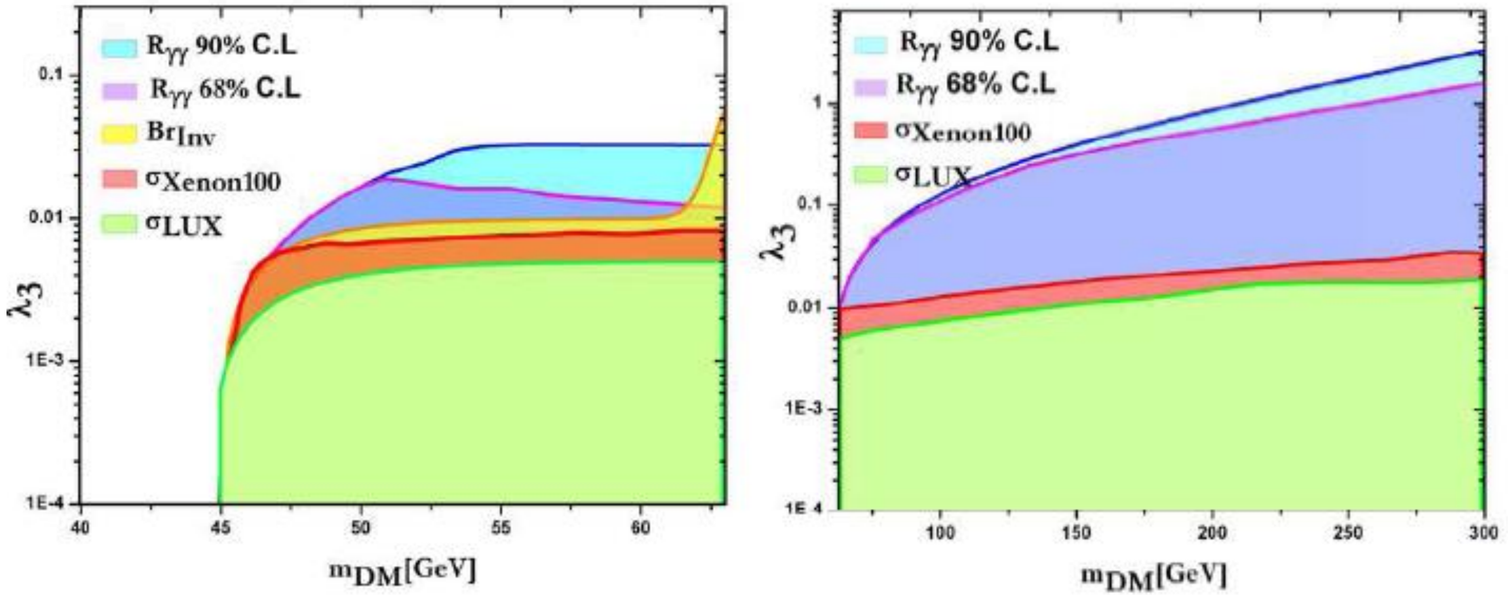
- The diphoton cross section normalized to SM prediction has been defined in the ITM as follow:

$$R_{\gamma\gamma} = \frac{\sigma(pp \to h \to \gamma\gamma)_{\text{ITM}}}{\sigma(pp \to h \to \gamma\gamma)_{\text{SM}}} \simeq \frac{\Gamma(h \to \gamma\gamma)_{\text{ITM}} \times \Gamma(h)_{\text{SM}}}{\Gamma(h \to \gamma\gamma)_{\text{SM}} \times \Gamma(h)_{\text{ITM}}}$$

We have used the fact that cross section of Higgs production in ITM is similar to SM. In ITM, for mZ/2 < mT0 < mh/2, there are two sources of deviation from R = 1.

- First is partial decay rate (h → $\gamma\gamma$ ) caused by charged scalar in loop level.
- Second is possible decay h →T0T0 and h → T+T+ which contribute to total decay rate of Higgs boson in ITM.






(a) (b)

Figure 1: Shaded areas depict ranges of parameter space in mass of DM and $\lambda_3$ coupling plane which are consistent with experimental measurements of $R_{\gamma\gamma}$ with 90% and 68% C.L, upper limit on $Br(h \to \text{Invisible})$ with 95% C.L, upper limit on $\sigma_{\text{Xenon100}}$ and $\sigma_{\text{LUX}}$ with 90% C.L. a) for $45.1 < m_{DM} < 62.5$, b) for $62.5 < m_{DM}$.

Since invisible higgs decay is forbidden kinematically for mD > mh/2, we study Br(h → Invisible) separately in Fig. 1-a. We suppose mZ/2 < mT0 < mh/2 and show valid area in mass of DM and λ3 coupling plane which is consistent with experimental upper limit on Br(h→Invisible).

- Note that allowed region of Br(h →Invisible) and direct detection experiments are very similar for $m_Z/2 < m_{T0} < m_h/2$.

- As it is seen, for $m_Z/2 < m_{T0} < m_h/2$ allowed region is not much different from other measurements.

# Rzγ constraints on ITM dark matter

We pursue our analysis on ITM phenomenology by calculating the h →Zγ decay.

$$R_{Z\gamma} = \frac{\sigma(pp \to h \to Z\gamma)_{\rm ITM}}{\sigma(pp \to h \to Z\gamma)_{\rm SM}} = \frac{\sigma(gg \to h)_{\rm ITM} \times Br(h \to Z\gamma)_{\rm ITM}}{\sigma(gg \to h)_{\rm SM} \times Br(h \to Z\gamma)_{\rm SM}}$$

The decay rate for h→Zγ can be expressed by:

$$\begin{aligned}\Gamma(h \to Z\gamma) &= \frac{G_f \alpha^2 M_h^3}{16\sqrt{2}\pi^3}(1 - \frac{M_Z^2}{M_h^2})^3 |\mathcal{A}_t(x_i, y_i) + \mathcal{A}_W(x_i, y_i) \\ &+ \mathcal{A}_{T^+}(x_i, y_i)|^2\end{aligned}$$

ATLAS and CMS collaborations have presented a search for the SM Higgs boson in the decay channel h→Zγ. Sensitivity of these measurements are far from SM prediction. For a Higgs boson mass of 125 GeV, the observed exclusion limits are between 7.3 and 22 times of the Standard Model prediction.

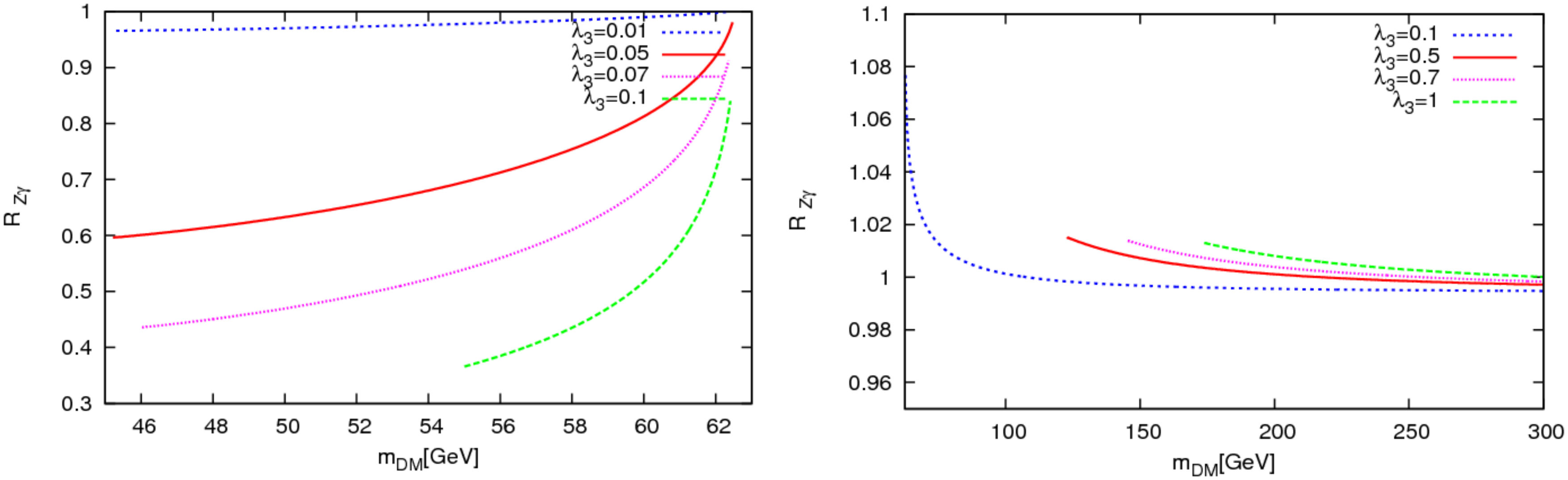



Figure 3: The $R_{\gamma Z}$ as a function of the DM mass for several values of $\lambda_3$. a) for $45.1 < m_{DM} < 62.5$, b) for $62.5 < m_{DM}$.

As it is seen, for 45.1 < mDM < 62:5, due to dependency of Rzγ to h →2T0, destructive effect of ITM to Rzγ can be large. As a result, if forthcoming observed exclusion limit is in the range of SM prediction, ITM parameters can be constrained by this measurement.

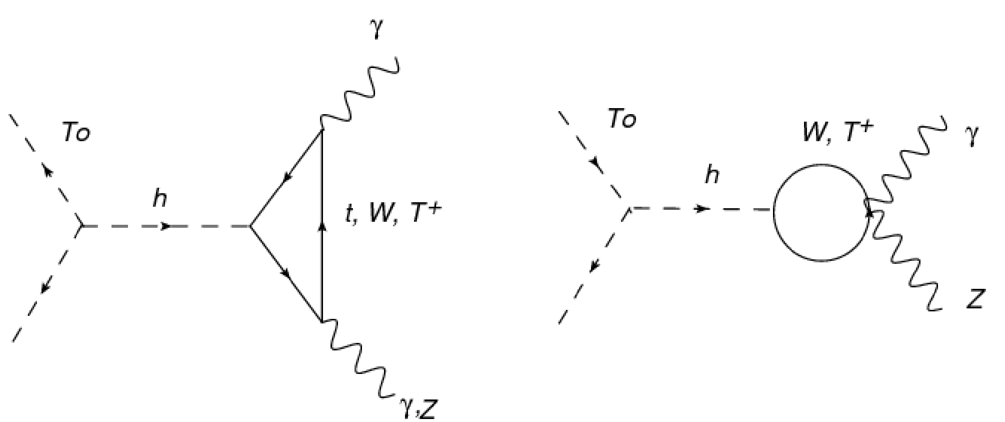
# Indirect Search

## Annihilation of Dark Matter into monochromatic photons

We calculate possible annihilation of DM candidate in ITM into 2γ and Zγ

The amplitude for 2T0-→2$\gamma$ can be written down as follows:

$$i|\mathcal{M}|_{2T^0\to 2\gamma} = \frac{i v_0 \lambda_3}{s - m_h^2 - i m_h \Gamma_h}\mathcal{M}_{h\to 2\gamma}$$



The cross section is given by:

$$\sigma v = \frac{1}{4\pi s}|\mathcal{M}|^2_{2T^0\to 2\gamma} = \frac{1}{(s-m_h^2)^2+m_h^2\Gamma_h^2} \times \frac{\alpha^2 g^2 v_0^2 \lambda_3^2 s}{512\pi^3 M_W^2}|\frac{4}{3}\mathcal{A}_{1/2}(x_i)$$
$$+ \mathcal{A}_1(x_i) + 2v_0\lambda_3\frac{M_W}{gM_{T^\pm}^2}\mathcal{A}_0(x_i)|^2,$$

The amplitude for 2T0→ Zγ can be expressed as follows:

$$i|\mathcal{M}|_{2T^0\to Z\gamma} = \frac{iv_0\lambda_3}{s-m_h^2-im_h\Gamma_h}\mathcal{M}_{h\to Z\gamma}$$

$$\sigma v = \frac{1}{8\pi s}(\sqrt{1-\frac{m_Z^2}{s}})|\mathcal{M}|^2_{2T^0\to Z\gamma} = \frac{\alpha^2 g^2 v_0^2 \lambda_3^2}{64\pi^3 c_W^2}(1-\frac{m_Z^2}{s})^{5/2}|\mathcal{A}_t(x_i,y_i)$$
$$+ \mathcal{A}_W(x_i,y_i) + \mathcal{A}_{T^+}(x_i,y_i)|^2 \times \frac{1}{(s-m_h^2)^2+m_h^2\Gamma_h^2}$$

FermiLAT collaboration has measured flux for diffuse gamma ray background and gamma-ray spectral lines from 7 to 300 GeV obtained from 3.7 years data.

The thermal average cross section is expressed by:

$$\langle\sigma v\rangle = \frac{1}{8m_{DM}^4 T_F K_2^2(m_{DM}/T_F)} \int_{4m_{DM}^2}^{\infty} ds\sigma(s)(s-4m_{DM}^2)\sqrt{s}K_1(\frac{\sqrt{s}}{T_F})$$

$$x_F = \ln(\frac{0.382 c m_{DM} M_{pl} g_{DM}}{\sqrt{g_* x_F}}\langle\sigma v\rangle)$$

$$x_F = m/T_F,\ c = \sqrt{2}-1 \text{ and } g_* = 91.5$$

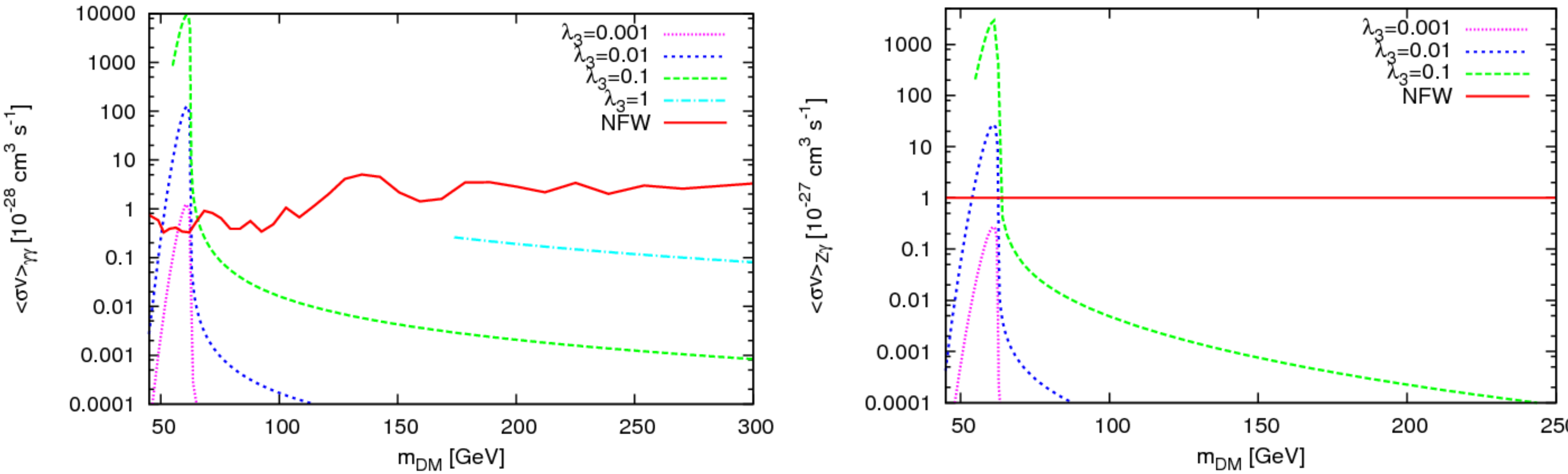



Figure 6: The thermal average annihilation cross-section of $T^0$ (DM) to (a) $\gamma\gamma$ and (b)$Z\gamma$ as a function of the DM mass for several values of $\lambda_3$.

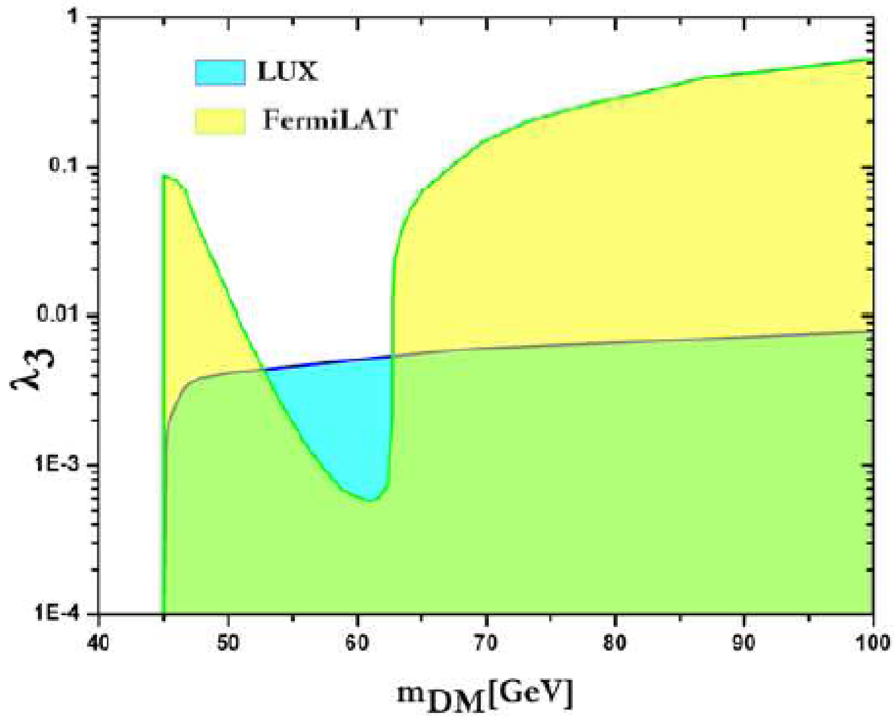



Figure 7: Shaded areas depict ranges of parameter space in mass of DM and $\lambda_3$ coupling plane which are consistent with upper limit on $\sigma_{\mathrm{FermiLAT}}$ with 95% C.L (indirect detection) and $\sigma_{\mathrm{LUX}}$ with 90% C.L (direct detection)

# Conclusions:

- We have investigated an extension of SM which includes a SU(2)_L triplet scalar with hypercharge Y=0,2.

1. We have shown that the effect of ITM on invisible Higgs decay and **$R\gamma\gamma$** for low mass DM<63 GeV can be as large as constraints from LUX direct detection experiment .

2. We calculate the annihilation cross section of DM candidate into $\gamma\gamma$ and **Z**$\gamma$. The minimum upper limit on annihilation cross-section from FermiLAT have been employed to constraint parameters space of ITM. We also showed for 52<mDM<63 GeV, FermiLAT constraint is stronger than direct detection constraint for low mass DM.

# THANK YOU FOR ATTENTION

# • Interaction in Y=0 ITM:

The three-point gauge interactions:

- $2ig\left[(\partial^\mu T^+)W_\mu^- T^0 + (\partial^\mu T^0)W_\mu^+ T^-\right] + h.c.\ ,$
- $2ig(\partial^\mu T^+)(c_w Z_\mu + s_w A_\mu)T^- + h.c.\ ,$

four-point gauge interactions:

- $g^2\left[|W_\mu^- T^+ - W_\mu^+ T^-|^2 + 2|W_\mu^+ T^0|^2\right],$
- $2g^2(c_w Z_\mu + s_w A_\mu)^2|T^+|^2,$
- $2g^2(W_\mu^+ T^0)(c_w Z_\mu + s_w A_\mu)T^- + h.c.\ .$

$$
\begin{aligned}
\mathcal{A}_0(x_i) &= -[x_i + f(x_i)]x_i^{-2} \\
\mathcal{A}_{1/2}(x_i) &= 2[x_i + (x_i - 1)f(x_i)]x_i^{-2} \\
\mathcal{A}_1(x_i) &= -[3x_i + 2x_i^2 + 3(2x_i - 1)f(x_i)]x_i^{-2}
\end{aligned}
$$

$$
f(x) = \begin{cases} (\arcsin\sqrt{x})^2 & x \le 1 \\ -\frac{1}{4}\left[\log\frac{1+\sqrt{1-x^{-1}}}{1-\sqrt{1-x^{-1}}} - i\pi\right]^2 & x > 1 \end{cases}
$$

$$
\begin{aligned}
\mathcal{A}_{T^+}(x_{T^+}, y_{T^+}) &= \frac{2(2c_W^2 - 1)}{c_W^2} \frac{g M_W v_0 \lambda_3}{M_{T^+}^2} I_1(x_{T^+}, y_{T^+}) \\
\mathcal{A}_t(x_t, y_t) &= \frac{2 - (16/3) s_W^2}{s_W c_W} [I_1(x_t, y_t) - I_2(x_t, y_t)] \\
\mathcal{A}_W(x_W, y_W) &= \cot\theta_W \{4(3 - \tan\theta_W^2) I_2(x_W, y_W) \\
&+ [(1 + 2x_W)\tan\theta_W^2 - (5 + 2x_W)] I_1(x_W, y_W)\}
\end{aligned}
$$

$$
\begin{aligned}
I_1(x, y) &= \frac{-1}{2(x-y)} + \frac{1}{2(x-y)^2}[f(x) - f(y)] + \frac{y}{2(x-y)^2}[g(x) - g(y)] \\
I_2(x, y) &= \frac{1}{2(x-y)}[f(x) - f(y)],
\end{aligned}
$$

$$
g(x) = \begin{cases} \sqrt{x^{-1} - 1} \arcsin \sqrt{x} & x \le 1 \\ \frac{1}{2}\sqrt{1 - x^{-1}} \left[ \log \frac{1 + \sqrt{1 - x^{-1}}}{1 - \sqrt{1 - x^{-1}}} - i\pi \right]. & x > 1 \end{cases}
$$