

130 GeV gamma-ray line and enhancement of $h \rightarrow \gamma\gamma$

in the Higgs triplet model plus a scalar dark matter

(L W, Xiao-Fang Han, arXiv:1209.0376)

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Outline:

- **Introduction**
- **Dark matter (DM) relic density and direct detection**
- **Gamma-ray lines from $SS \rightarrow \gamma\gamma, SS \rightarrow \gamma Z$**
- **LHC diphoton Higgs rate**
- **Conclusions**

Both ATLAS and CMS see diphoton excess

ATLAS 4.5σ at 126.5 GeV, $R_{\gamma\gamma} = 1.9 \pm 0.5$ ATLAS, PLB716,1-29,(2012)

CMS 4.1σ at 125 GeV, $R_{\gamma\gamma} = 1.56 \pm 0.43$ CMS, PLB716,30-61,(2012)

Fermi LAT data seems to have a line spectral feature at $E_\gamma = 130$ GeV

C. Weniger, arXiv:1204.2797, 3.3σ
T. Bringmann et al., arXiv:1203.1312, 3.1σ

If interpreted in terms of DM particles annihilating to a photon pair, the observation would imply

$$m_{DM} \square 130 \text{ GeV}, \langle \sigma v \rangle_{\gamma\gamma} \square 10^{-27} \text{ cm}^3 \text{s}^{-1}$$

Fermi LAT collaboration detected no spectral lines from 7 to 200 GeV, and sets an upper limit, Fermi LAT, arXiv:1205.2739

$$\langle \sigma v \rangle_{\gamma\gamma} < 1.4 \times 10^{-27} \text{ cm}^3 \text{s}^{-1} \text{ for } E_\gamma = 130 \text{ GeV}$$



The upper limits on the charged channels from the continuum spectrum:

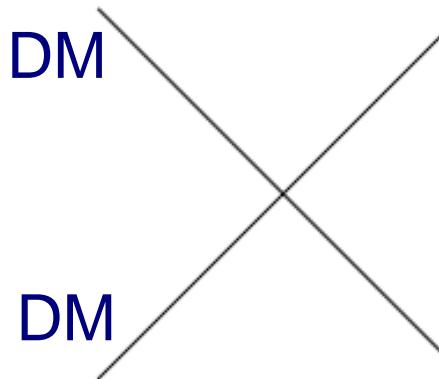
$$\langle \sigma v \rangle_{f\bar{f}, WW} < O(\text{few}) \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$$

M. Ackermann et al.,
PRL107,241302,(2011)

To generate to the observed relic density,

A. Geringer-Sameth et al.,
PRL107,241303,(2011)

$$\langle \sigma v \rangle \square 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$



$$\frac{\langle \sigma v \rangle_{tree}}{\langle \sigma v \rangle_\gamma} \square \left(\frac{\alpha}{\pi} \right)^2 \square 10^5$$

The charged particle mass should be larger than DM.

Higgs triplet model

Triplet and doublet fields:

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}, \quad \Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

Scalar potential:

$$\begin{aligned} V = & -m_\Phi^2 \Phi^\dagger \Phi + \frac{\lambda}{4} (\Phi^\dagger \Phi)^2 + M_\Delta^2 Tr(\Delta^\dagger \Delta) + \lambda_1 (\Phi^\dagger \Phi) Tr(\Delta^\dagger \Delta) \\ & + \lambda_2 (Tr \Delta^\dagger \Delta)^2 + \lambda_3 Tr(\Delta^\dagger \Delta)^2 + \lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi + [\mu (\Phi^T i\tau_2 \Delta^\dagger \Phi) + h.c.]. \end{aligned}$$

Vacuum expectation values:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_d \end{pmatrix}, \quad \langle \Delta \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ v_t & 0 \end{pmatrix} \quad v_{SM}^2 = v_d^2 + 4v_t^2 \approx (246 \text{ GeV})^2$$

Physical Higgs boson: h H A H^\pm $H^{\pm\pm}$

W. Konetschny et al., PLB70, 433 (1977);
J. Schechter et al. PRD 22, 2227 (1980);
T. P. Cheng, L.F. Li, PRD22, 2860 (1980).

For ν_t :

$\rho = m_W^2 / m_Z^2 \cos^2 \theta_W \square 1$ leads to the bound,

$$\nu_t < 8 \text{ GeV}$$

For $\nu_t < 10^{-4} \text{ GeV}$, $H^{\pm\pm} \rightarrow l^\pm l^\pm$ is the dominant decay mode,

CMS presents the bound, $m_{H^{\pm\pm}} > 383 \text{ GeV}$

CMS, arXiv:1207.2666

For $\nu_t > 10^{-4} \text{ GeV}$,

$H^{\pm\pm} \rightarrow W^\pm W^\pm$ and $H^{\pm\pm} \rightarrow H^\pm W^*$ are the dominant decay modes,

$m_{H^{\pm\pm}}$ could be much light

A. G. Akeroyd et al., PRD72, 035011 (2005).

$\nu_t = 0.1 \text{ GeV}$ is fixed

For v_t is very small:

CP-even sector mixing angle: $\sin \alpha \square 2v_t / v_d$

Charged Higgs sector mixing angle: $\sin \beta' \square \sqrt{2}v_t / v_d$

$$m_h^2 \simeq \frac{\lambda}{2}v_d^2, \quad \text{---> from doublet field}$$

$$m_H^2 \simeq M_\Delta^2 + \left(\frac{\lambda_1}{2} + \frac{\lambda_4}{2}\right)v_d^2 + 3(\lambda_2 + \lambda_3)v_t^2,$$

$$m_A^2 \simeq M_\Delta^2 + \left(\frac{\lambda_1}{2} + \frac{\lambda_4}{2}\right)v_d^2 + (\lambda_2 + \lambda_3)v_t^2,$$

$$m_{H^\pm}^2 = M_\Delta^2 + \left(\frac{\lambda_1}{2} + \frac{\lambda_4}{4}\right)v_d^2 + (\lambda_2 + \sqrt{2}\lambda_3)v_t^2,$$

$$m_{H^{\pm\pm}}^2 = M_\Delta^2 + \frac{\lambda_1}{2}v_d^2 + \lambda_2v_t^2.$$

$$m_H = m_A = m_{H^\pm} = m_{H^\pm} \text{ for } \lambda_4 = 0$$

from
triplet field

h is taken as the SM-like Higgs boson, $m_h = 125$ GeV

\mathcal{H}	$\tilde{g}_{\mathcal{H}\bar{u}u}$	$\tilde{g}_{\mathcal{H}\bar{d}d}$	$\tilde{g}_{\mathcal{H}W^+W^-}$
h	$c_\alpha/c_{\beta'}$	$c_\alpha/c_{\beta'}$	$+e(c_\alpha v_d + 2s_\alpha v_t)/(2s_W m_W)$
H	$-s_\alpha/c_{\beta'}$	$-s_\alpha/c_{\beta'}$	$-e(s_\alpha v_d - 2c_\alpha v_t)/(2s_W m_W)$

suppression

$$g_{h^0 H^{++} H^{--}} = -\{2\lambda_2 v_t s_\alpha + \lambda_1 v_d c_\alpha\} \approx -\lambda_1 v_d,$$

$$\begin{aligned} g_{h^0 H^+ H^-} &= -\frac{1}{2} \left\{ \{4v_t(\lambda_2 + \lambda_3)c_{\beta'}^2 + 2v_t\lambda_1 s_{\beta'}^2 - \sqrt{2}\lambda_4 v_d c_{\beta'} s_{\beta'}\} s_\alpha \right. \\ &\quad \left. + \{\lambda v_d s_{\beta'}^2 + (2\lambda_1 + \lambda_4)v_d c_{\beta'}^2 + (4\mu - \sqrt{2}\lambda_4 v_t)c_{\beta'} s_{\beta'}\} c_\alpha \right\} \\ &\approx -(\lambda_1 + \frac{\lambda_4}{2})v_d \end{aligned}$$

$$g_{H^0 H^{++} H^{--}} = g_{h^0 H^{++} H^{--}} [c_\alpha \rightarrow -s_\alpha, s_\alpha \rightarrow c_\alpha]$$

$$g_{H^0 H^+ H^-} = g_{h^0 H^+ H^-} [c_\alpha \rightarrow -s_\alpha, s_\alpha \rightarrow c_\alpha]$$

suppression

Introducing a scalar dark matter S

A discrete symmetry : $S \rightarrow -S$

$$\mathcal{L}_S = \frac{1}{2} \partial^\mu S \partial_\mu S - \frac{m_0^2}{2} SS - \frac{\kappa_1}{2} \Phi^\dagger \Phi SS - \kappa_2 Tr(\Delta^\dagger \Delta) SS - \frac{\kappa_s}{4} S^4.$$

$$m_S = (m_0^2 + \frac{1}{2} \kappa_1 v_d^2 + \kappa_2 v_t^2)^{1/2} = 130 \text{ GeV}$$

k_1 determines the couplings $hhSS, hSS$

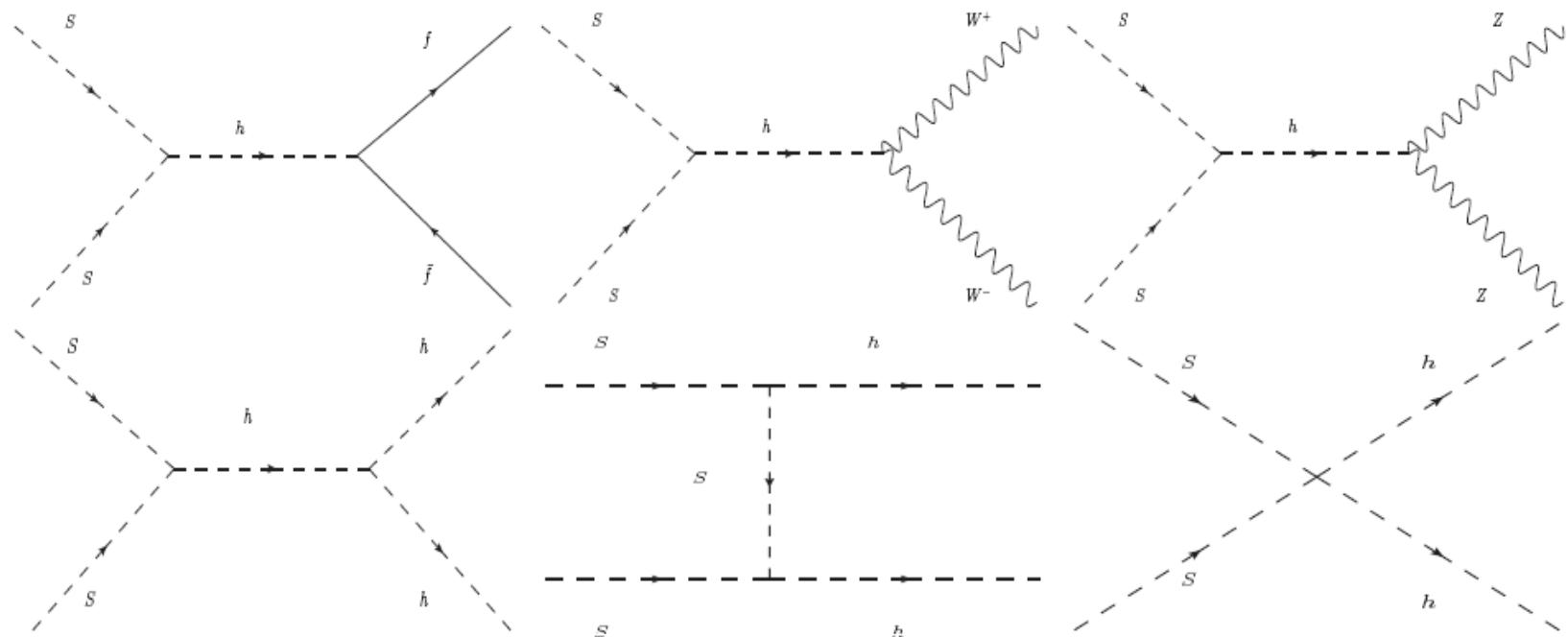
k_2 determines the couplings $H^{++}H^{--}SS, H^+H^-SS, HHSS, HSS$

HSS is suppressed by v_t

DM relic density

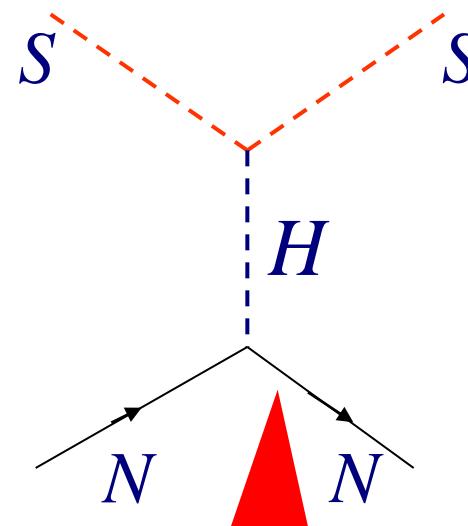
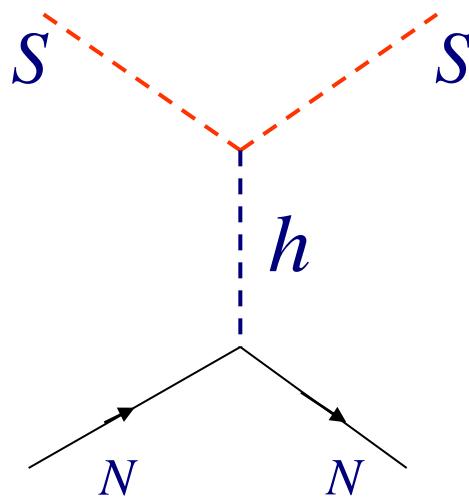
$SS \rightarrow HH, AA, H^{++}H^{--}, H^+H^-$ are forbidden for these scalar masses are much larger than S .

The dominant annihilation processes:

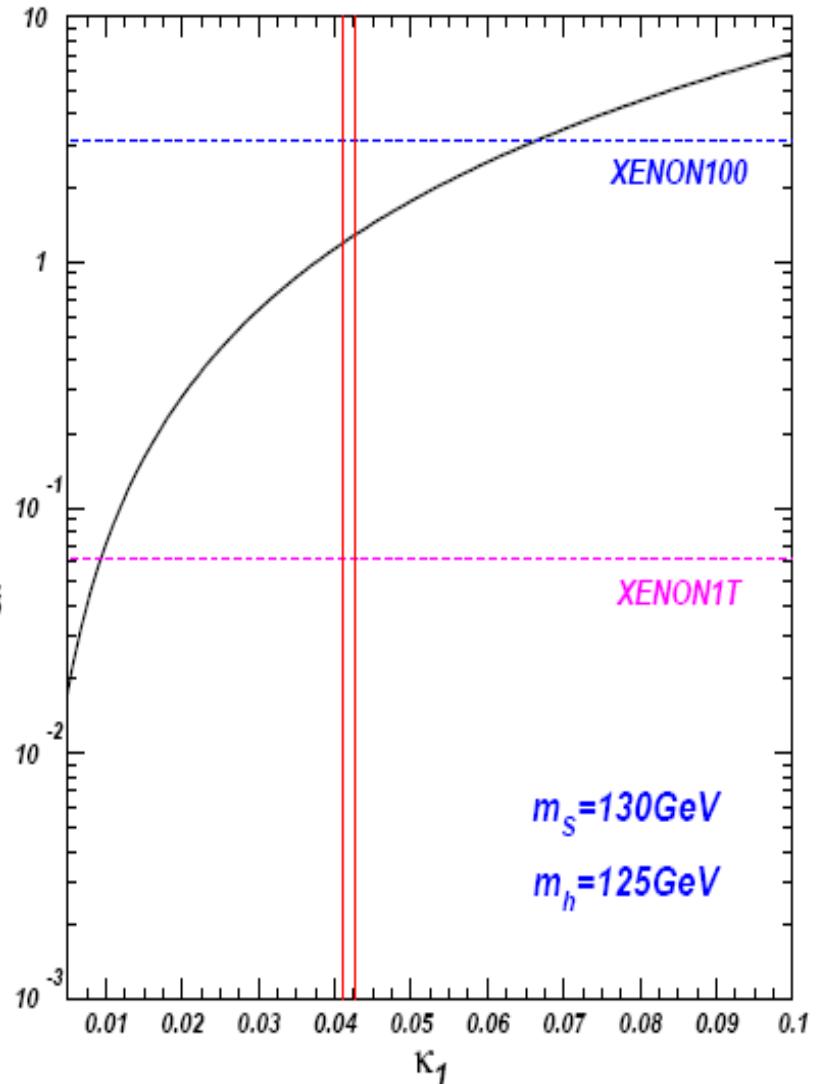
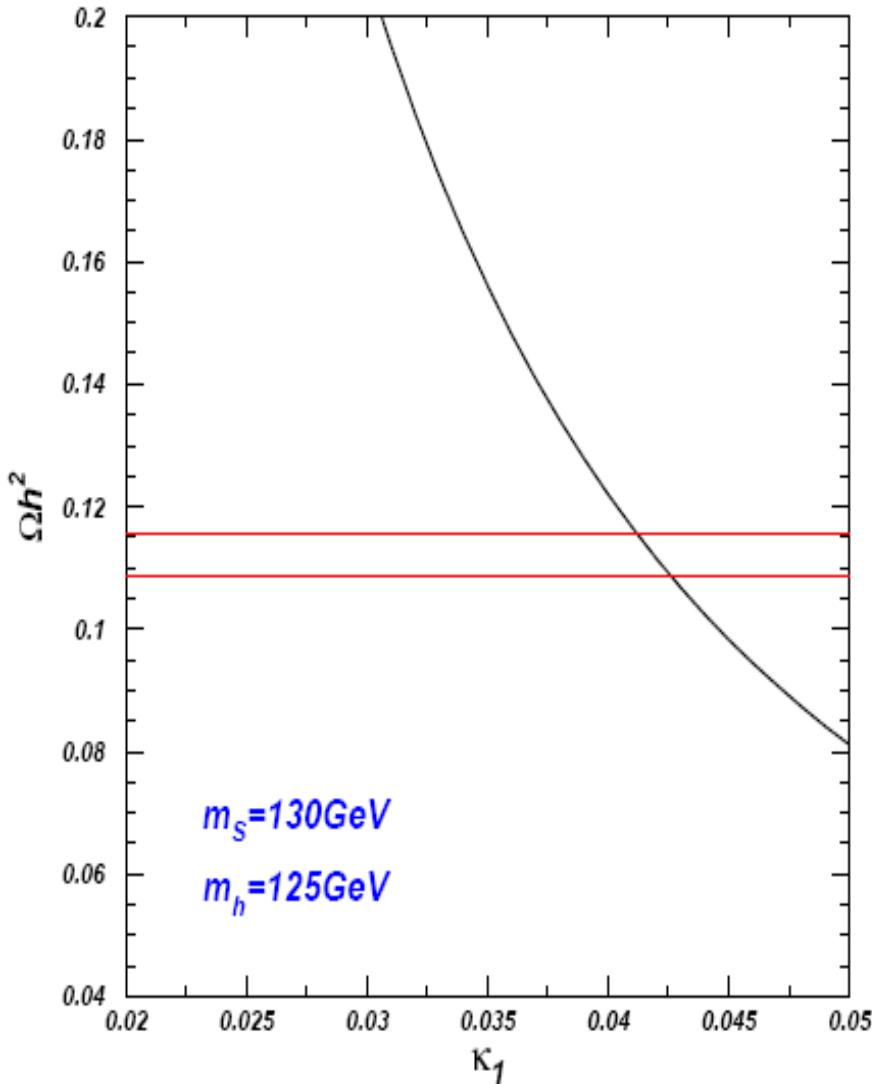
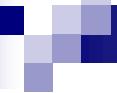


Spin independent cross section between S and nucleon

The dominant processes:



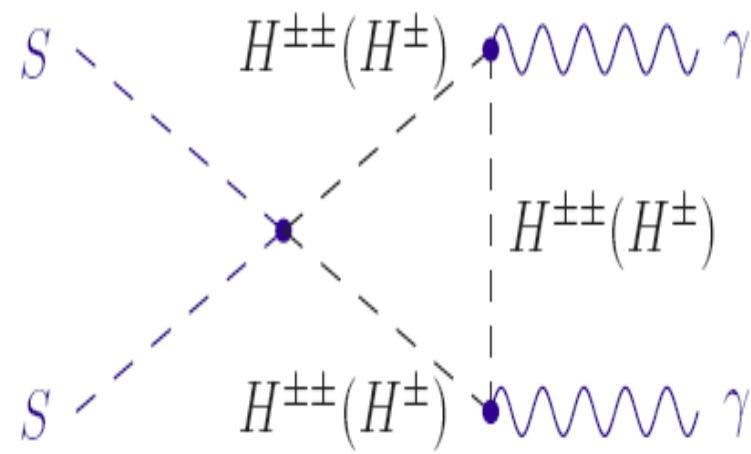
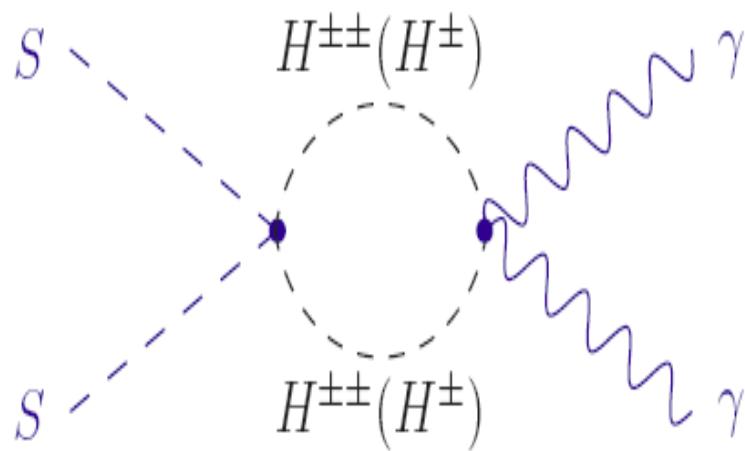
suppression



WMAP, *Astrophys. J. Suppl.* 192, 18 (2011); XENON100, *PRL* 107, 131302 (2011)

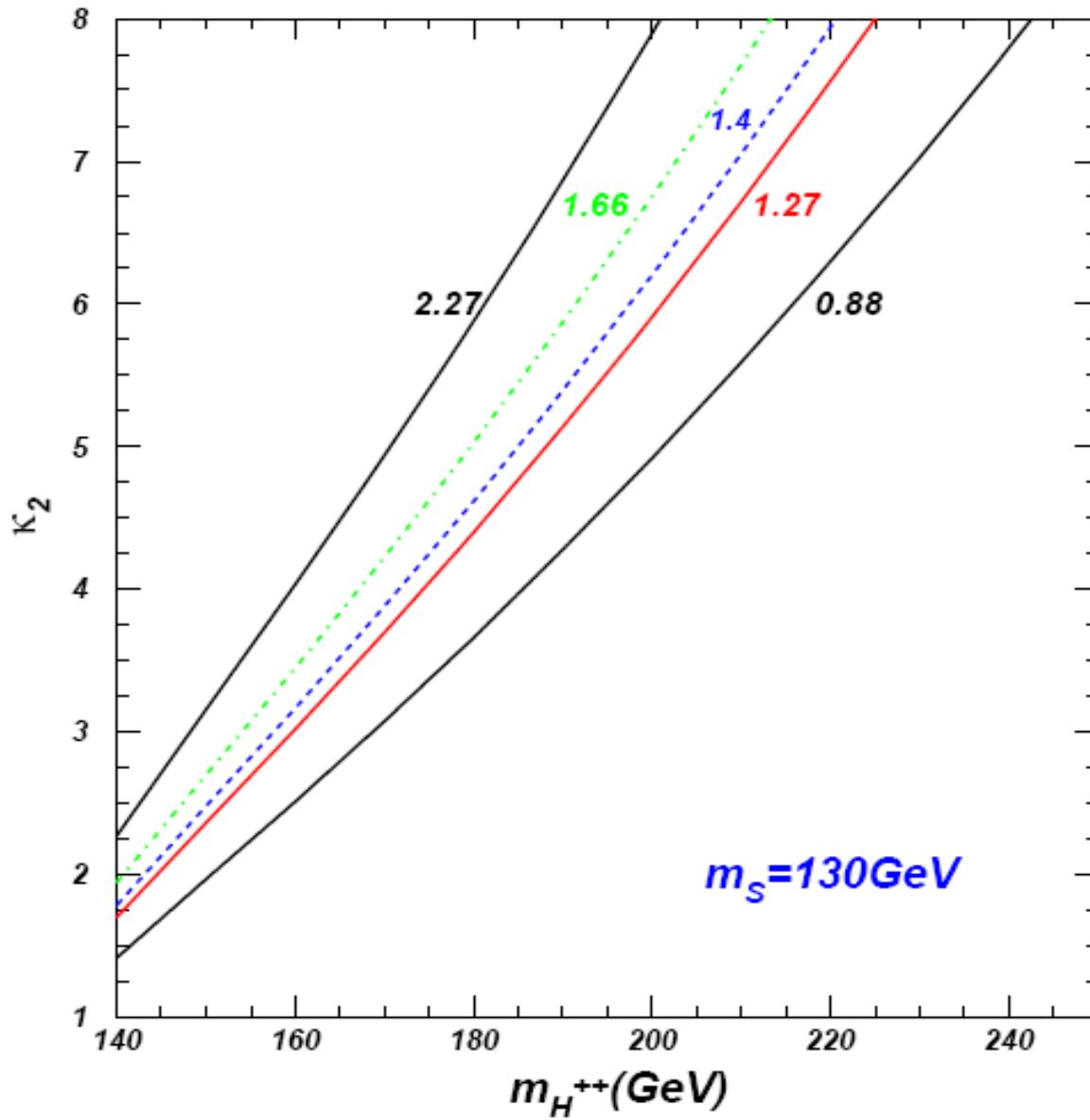
Gamma-ray line from $SS \rightarrow \gamma\gamma$

The dominant processes:



$$\langle \sigma v \rangle_{SS \rightarrow \gamma\gamma} \simeq \frac{\alpha^2 \kappa_2^2}{32\pi^3 m_S^2} \left| 4E(\tau_{H^{\pm\pm}}) + E(\tau_{H^\pm}) \right|^2 = \frac{25\alpha^2 \kappa_2^2}{32\pi^3 m_S^2} E(\tau_{H^{\pm\pm}})^2$$

$$E(\tau) = 1 - \tau [\sin^{-1}(1/\sqrt{\tau})]^2.$$



The numbers on the curves denote $\langle \sigma v \rangle_{SS \rightarrow \gamma\gamma} / 1.0 \times 10^{-27} \text{ cm}^3 \text{s}^{-1}$

Gamma-ray line from $SS \rightarrow \gamma Z$

$$\frac{<\sigma v>_{SS \rightarrow \gamma Z}}{<\sigma v>_{SS \rightarrow \gamma\gamma}} \simeq 2(\cot 2\theta_W)^2(1 - \frac{m_Z^2}{4m_S^2})^{1/2} = 0.76$$

$$E_\gamma = m_s - \frac{m_z^2}{4m_s} \square 114 \text{ GeV}$$

The current Fermi LAT upper limit:

$$<\sigma v>_{SS \rightarrow \gamma Z} < 2.6 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1} \text{ for } E_\gamma = 110 \text{ GeV}$$

LHC diphoton Higgs rate

A. Arhrib et al., arXiv:1112.5453;
A. G. Akeroyd et al., arXiv:1206.0535;
L. Wang, X.-F. Han, arXiv:1206.1673

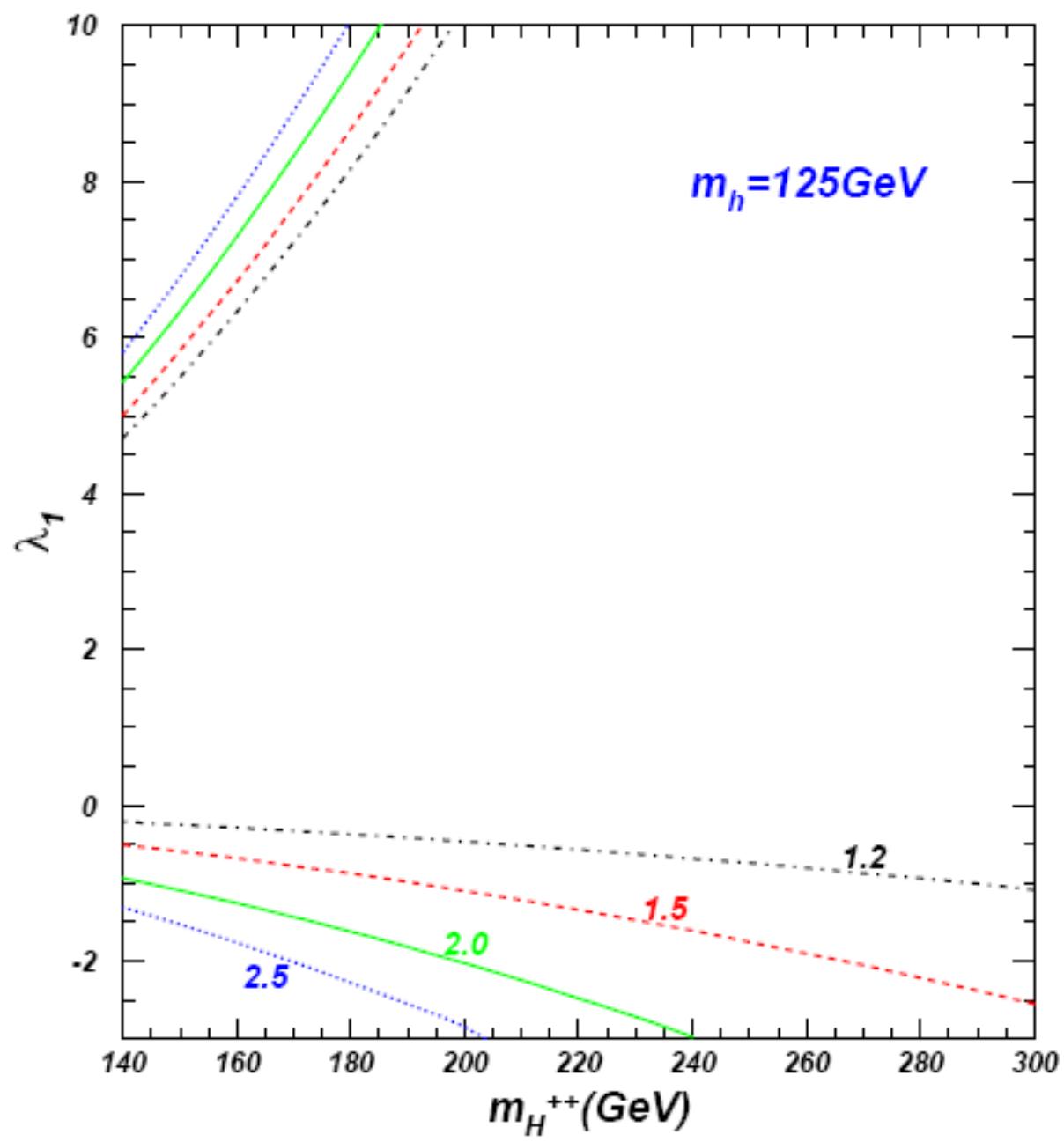
$h \rightarrow HH, AA, H^{++}H^{--}, H^+H^-$ are forbidden for the scalar masses are larger than h

Compared to SM, only $h \rightarrow \gamma\gamma$ are corrected for the model

$$\Gamma(h \rightarrow \gamma\gamma) = \frac{\alpha^2 m_h^3}{256\pi^3 v^2} \left| F_1(\tau_W) + \sum_i N_{cf} Q_f^2 F_{1/2}(\tau_f) + g_{H^\pm} F_0(\tau_{H^\pm}) + 4g_{H^{\pm\pm}} F_0(\tau_{H^{\pm\pm}}) \right|^2$$

$$R_{\gamma\gamma} = \frac{Br(h \rightarrow \gamma\gamma)}{Br(h \rightarrow \gamma\gamma)^{SM}} \simeq \frac{\Gamma(h \rightarrow \gamma\gamma)}{\Gamma(h \rightarrow \gamma\gamma)^{SM}}$$

$\lambda_4 = 0$ is fixed, $-3 < \lambda_1 < 10$ is allowed via tuning λ_2 and λ_3



Conclusions

1. We add a scalar to Higgs triplet model, which can be as a candidate of dark matter.
2. This model can satisfy the constraint from the WMAP 7-year result and Xenon100 data, and give a valid explanation for the claimed 130 GeV gamma-ray line signal and excess of LHC diphoton signal.

Thanks !

$$\sigma v = \sigma_{ff}v + \sigma_{WW}v + \sigma_{ZZ}v + \sigma_{hh}v,$$

$$\sigma_{ff}v = \sum_f \frac{\kappa_1^2}{4\pi} \frac{m_f^2}{(s - m_h^2)^2} (1 - \frac{4m_f^2}{s})^{3/2},$$

$$\sigma_{WW}v = \frac{\kappa_1^2}{8\pi} \frac{s}{(s - m_h^2)^2} \sqrt{1 - \frac{4m_W^2}{s}} \left(1 - \frac{4m_W^2}{s} + \frac{12m_W^4}{s^2} \right),$$

$$\sigma_{ZZ}v = \frac{\kappa_1^2}{16\pi} \frac{s}{(s - m_h^2)^2} \sqrt{1 - \frac{4m_Z^2}{s}} \left(1 - \frac{4m_Z^2}{s} + \frac{12m_Z^4}{s^2} \right),$$

$$\begin{aligned} \sigma_{hh}v &= \frac{\kappa_1^2}{16\pi s} \sqrt{1 - \frac{4m_h^2}{s}} \left[\left(\frac{s + 2m_h^2}{s - m_h^2} \right)^2 - \frac{8\kappa_1 v^2}{s - 2m_h^2} \frac{s + 2m_h^2}{s - m_h^2} F(\xi) \right. \\ &\quad \left. + \frac{8\kappa_1^2 v^4}{(s - 2m_h^2)^2} \left(\frac{1}{1 - \xi^2} + F(\xi) \right) \right]. \end{aligned}$$

$$<\sigma v> = a + b < v^2> + {\cal O}(< v^4>) \simeq a + 6b {T \over m_S}$$

$$x_f=\ln\frac{0.038g m_{pl}m_S<\sigma v>}{g_*^{1/2}x_f^{1/2}}.$$

$$\Omega h^2\simeq \frac{1.07\times 10^9}{m_{pl}}\frac{x_f}{\sqrt{g_*}}\frac{1}{(a+3b/x_f)}.$$

$$\Omega_{DM}h^2=0.1123\pm0.0035.$$

$$\sigma_{Sp(n)}^{SI} = \frac{m_{p(n)}^2}{4\pi (m_S + m_{p(n)})^2} [f^{p(n)}]^2,$$

where

$$f^{p(n)} = \sum_{q=u,d,s} f_{T_q}^{p(n)} \mathcal{C}_{Sq} \frac{m_{p(n)}}{m_q} + \frac{2}{27} f_{T_g}^{p(n)} \sum_{q=c,b,t} \mathcal{C}_{Sq} \frac{m_{p(n)}}{m_q},$$

with $\mathcal{C}_{Sq} = \frac{\kappa_1 m_q}{m_h^2}$ [34],

$$f_{T_u}^{(p)} \approx 0.020, \quad f_{T_d}^{(p)} \approx 0.026, \quad f_{T_s}^{(p)} \approx 0.118, \quad f_{T_g}^{(p)} \approx 0.836,$$

$$f_{T_u}^{(n)} \approx 0.014, \quad f_{T_d}^{(n)} \approx 0.036, \quad f_{T_s}^{(n)} \approx 0.118, \quad f_{T_g}^{(n)} \approx 0.832.$$

$$\Gamma(h \rightarrow \gamma\gamma) = \frac{\alpha^2 m_h^3}{256\pi^3 v^2} \left| F_1(\tau_W) + \sum_i N_{cf} Q_f^2 F_{1/2}(\tau_f) + g_{H^\pm} F_0(\tau_{H^\pm}) + 4g_{H^{\pm\pm}} F_0(\tau_{H^{\pm\pm}}) \right|^2$$

$$\begin{aligned} \tau_W &= \frac{4m_W^2}{m_h^2}, & \tau_f &= \frac{4m_f^2}{m_h^2}, & \tau_{H^\pm} &= \frac{4m_{H^\pm}^2}{m_h^2}, & \tau_{H^{\pm\pm}} &= \frac{4m_{H^{\pm\pm}}^2}{m_h^2}, \\ g_{H^\pm} &= -\frac{v}{2m_{H^\pm}^2} g_{hH^+H^-}, & g_{H^{\pm\pm}} &= -\frac{v}{2m_{H^{\pm\pm}}^2} g_{hH^{++}H^{--}}. \end{aligned}$$

$$F_1 = 2 + 3\tau + 3\tau(2-\tau)f(\tau), \quad F_{1/2} = -2\tau[1 + (1-\tau)f(\tau)], \quad F_0 = \tau[1 - \tau f(\tau)],$$

with

$$f(\tau) = \begin{cases} [\sin^{-1}(1/\sqrt{\tau})]^2, & \tau \geq 1 \\ -\frac{1}{4}[\ln(\eta_+/\eta_-) - i\pi]^2, & \tau < 1 \end{cases}$$

where $\eta_\pm = 1 \pm \sqrt{1-\tau}$.

$$\rho \equiv 1 + \delta\rho = \frac{1 + 2x^2}{1 + 4x^2}.$$

$$\rho (= M_W^2/M_Z^2 \cos^2 \theta_W) \qquad x = v_\Delta/v$$

For $v_t < 10^{-4}$ GeV, $H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$ is the dominant decay mode of $H^{\pm\pm}$. Assuming $Br(H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm) = 1$, CMS presents the low bound 383 GeV on $m_{H^{\pm\pm}}$ from the searches for $H^{\pm\pm} \rightarrow \ell^\pm \ell^\pm$ via $q\bar{q} \rightarrow H^{\pm\pm} H^{\mp\mp}$ and $q\bar{q} \rightarrow H^{\pm\pm} H^\mp$ production processes [25]. However,