Minimal left right symmetric model Higgs phenomenology at the LHC for photon initiated processes

(in collaboration with Prof. Kaladi S. Babu)

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Sudip Jana

Oklahoma State University

❖ Outline

Brief Overview of the MLRSM

- Particle Spectrum
- Scalar Potential
- Physical Higgs States and Mass Spectrum

LHC Accessible Neutral Heavy Higgs phenomenology

- Four lepton resonance
- di-photon resonance
- di-Higgs Resonance

Doubly Charged Higgs Phenomenology

- Mass Limits
- Spectacular same sign di-lepton signal and LHC reach [based on K. S. Babu et al.(Phys.Rev. D95 (2017) no.5, 055020)]

Conclusion

- Initial guide to explore fermi-phobic Higgs at the LHC.
- Future Implications of photon initiated processes.

Why Left Right Symmetry ?

- Understanding the origin of the parity violation.
- Generates small neutrino mass via seesaw mechanism.
- These models place quarks and leptons on the same footing in the weak interactions.
- The gauge group is very simple extension of the SM gauge group. Provide a simple formula for the electric charge.

- Pati, Jogesh C. et al. Phys.Rev. D10 (1974) 275-289,
- Pati, Jogesh C. et al. Phys.Rev. D10 (1974) 275-289,
- Mohapatra, Rabindra N. et al. Phys.Rev. D11 (1975) 566-571
- Senjanovic, G. et al. Phys.Rev. D12 (1975) 1502

❖ Particle Spectrum of MLRSM

	$SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
Fermions	$Q_L = \begin{pmatrix} u \\ d \end{pmatrix}_L \sim (3,2,1,\frac{1}{3}), Q_R = \begin{pmatrix} u \\ d \end{pmatrix}_R \sim (3,1,2,\frac{1}{3})$ $\psi_L = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \sim (1,2,1,-1), \psi_R = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_R \sim (1,1,2,-1)$
Gauge	$G_{a,a=1-8}, A_{L_i,i=1-3}, A_{R_i,i=1-3}, B$
Higgs	$\phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \sim (1,2,2,0), \Delta_L = \begin{pmatrix} \frac{\delta_L^+}{\sqrt{2}} & \delta_L^{++} \\ \delta_L^0 & -\frac{\delta_L^+}{\sqrt{2}} \end{pmatrix} \sim (1,3,1,2),$ $\Delta_R = \begin{pmatrix} \frac{\delta_R^+}{\sqrt{2}} & \delta_R^{++} \\ \delta_R^0 & -\frac{\delta_R^+}{\sqrt{2}} \end{pmatrix} \sim (1,1,3,2)$

TABLE I. Matter, gauge and higgs contents of the model.

❖ MLRSM Higgs Potential

- Adding one extra soft breaking term, the most general renormalizable scalar potential is given by :

$$
\begin{aligned}
\mathcal{V}(\phi,\Delta_L,\Delta_R) &= -\mu_1^2 Tr(\phi^\dagger\phi) - \mu_2^2[Tr(\tilde{\phi}\phi^\dagger) + Tr(\tilde{\phi}^\dagger\phi)] - \mu_3^2[Tr(\Delta_L\Delta_L^\dagger) + Tr(\Delta_R\Delta_R^\dagger)] \\
&+\mu_4^2[\mathbf{Tr}(\mathbf{\Delta_R}\mathbf{\Delta_R^\dagger})] + \lambda_1[Tr(\phi^\dagger\phi)]^2 + \lambda_2[\{Tr(\tilde{\phi}\phi^\dagger)\}^2 + \{Tr(\tilde{\phi}^\dagger\phi)\}^2] + \lambda_3 Tr(\tilde{\phi}\phi^\dagger)Tr(\tilde{\phi}^\dagger\phi) \\
&+\lambda_4 Tr(\phi^\dagger\phi)[Tr(\tilde{\phi}\phi^\dagger) + Tr(\tilde{\phi}^\dagger\phi)] + \rho_1[\{Tr(\Delta_L\Delta_L^\dagger)\}^2 + \{Tr(\Delta_R\Delta_R^\dagger)\}^2] \\
&+\rho_2[Tr(\Delta_L\Delta_L)Tr(\Delta_L^\dagger\Delta_L^\dagger) + Tr(\Delta_R\Delta_R)Tr(\Delta_R^\dagger\Delta_R^\dagger)] + \rho_3 Tr(\Delta_L\Delta_L^\dagger)Tr(\Delta_R\Delta_R^\dagger) \\
&+\rho_4[Tr(\Delta_L\Delta_L)Tr(\Delta_R^\dagger\Delta_R^\dagger) + Tr(\Delta_R\Delta_R)Tr(\Delta_L^\dagger\Delta_L^\dagger)] + \alpha_1 Tr(\phi^\dagger\phi)[Tr(\Delta_L\Delta_L^\dagger) + Tr(\Delta_R\Delta_R^\dagger)] \\
&+\alpha_2[Tr(\tilde{\phi}\phi^\dagger)Tr(\Delta_L\Delta_L^\dagger) + Tr(\tilde{\phi}^\dagger\phi)Tr(\Delta_R\Delta_R^\dagger)] + \alpha_2^*[Tr(\phi\tilde{\phi}^\dagger)Tr(\Delta_L\Delta_L^\dagger) + Tr(\phi^\dagger\tilde{\phi})Tr(\Delta_R\Delta_R^\dagger)] \\
&+\alpha_3[Tr(\phi\phi^\dagger\Delta_L\Delta_L^\dagger) + Tr(\phi^\dagger\phi\Delta_R\Delta_R^\dagger)] + \beta_1[Tr(\phi\Delta_R\phi^\dagger\Delta_L^\dagger) + Tr(\phi^\dagger\Delta_L\phi\Delta_R^\dagger)] \\
&+\beta_2[Tr(\tilde{\phi}\Delta_R\phi^\dagger\Delta_L^\dagger) + Tr(\tilde{\phi}^\dagger\Delta_L\phi\Delta_R^\dagger)] + \beta_3[Tr(\phi\Delta_R\tilde{\phi}^\dagger\Delta_L^\dagger) + Tr(\phi^\dagger\Delta_L\tilde{\phi}\Delta_R^\dagger)]
\end{aligned}
$$

- Mohapatra, Rabindra N. et al. Phys.Rev. D23 (1981) 165
- Gunion, J.F. et al. Phys.Rev. D40 (1989) 1546
- Deshpande, N.G. et al. Phys.Rev. D44 (1991) 837-858

❖ Physical Higgs States and Mass Spectrum

Physical Higgs	Mass	State
h	$\frac{k}{\sqrt{2}}\left(4\lambda_1 - \frac{\alpha_1^2}{\rho_1}\right)^{1/2}$	Re $(\phi_1^0 + \xi e^{-i\alpha}\phi_2^0 - \theta_1\delta_R^0)$
H_1^0	$\sqrt{\frac{\alpha_3}{2}}v_R$	Re $(\phi_2^0 - \xi e^{i\alpha}\phi_1^0 + \theta_2\delta_R^0)$
H_2^0	$\left[\frac{(\rho_3-2\rho_1)}{2}v_R^2 - \mu_4^2\right]^{1/2}$	Re δ_L^0
$\mathbf{H_3^0}$	$\sqrt{2\rho_1}v_R$	Re $(\delta_R^0+\theta_1\phi_1^0 - \theta_2\phi_2^0)$
A_1^0	$\sqrt{\frac{\alpha_3}{2}}v_R$	Im $(\phi_2^0 - \xi e^{i\alpha}\phi_1^0)$
A_2^0	$\left[\frac{(\rho_3-2\rho_1)}{2}v_R^2 - \mu_4^2\right]^{1/2}$	Im δ_L^0
$H_1^\pm$	$\left[\frac{(\rho_3-2\rho_1)}{2}v_R^2 - \mu_4^2 + \frac{\alpha_3}{4}k^2\right]^{1/2}$	$\delta_L^\pm$
$H_2^\pm$	$\left[\frac{\alpha_3}{2}\left(v_R^2 + \frac{k^2}{2}\right)\right]^{1/2}$	$\phi_2^\pm + \xi e^{i\alpha}\phi_1^\pm + \frac{\epsilon}{2}\delta_R^\pm$
$H_1^{\pm\pm}$	$\left[\frac{(\rho_3-2\rho_1)}{2}v_R^2 - \mu_4^2 + \frac{\alpha_3}{2}k^2\right]^{1/2}$	$\delta_L^{\pm\pm}$
$H_2^{\pm\pm}$	$\left[4\rho_2 v_R^2 + \frac{\alpha_3}{2}k^2\right]^{1/2}$	$\delta_R^{\pm\pm}$

TABLE II. Physical Higgs states and mass spectrum at leading order in MLRSM. We assume $v_L \approx 0$ and keep only linear terms in $\epsilon = \frac{k}{v_R}$ and $\xi = \frac{k'}{k}$. Here mixing parameters are defined as $\theta_1 = \frac{\epsilon\alpha_1}{2\rho_1}$ and $\theta_2 = \frac{4\alpha_2\epsilon}{\alpha_3 - 4\rho_1}$.

Couplings	Values
H_3^0hh	$\frac{1}{2}\alpha_1 v_R$
$H_3^0H_1^{\pm\pm}H_1^{\mp\mp}$	$\rho_3 v_R$
$H_3^0H_2^{\pm\pm}H_2^{\mp\mp}$	$2(\rho_1 + 2\rho_2)v_R$
$H_3^0H_1^{\pm}H_1^{\mp}$	$\rho_3 v_R$
H_3^0NN	$\frac{M_N}{v_R}$
$H_3^0W_R^{\pm}W_R^{\mp}$	$g_R^2 v_R$
$H_3^0Z_RZ_R$	$\frac{g_R^2 v_R}{\cos^2\phi}$

TABLE III. The couplings relevant to H_3^0 production and decay at the LHC.

❖ Higgs Mass and Couplings

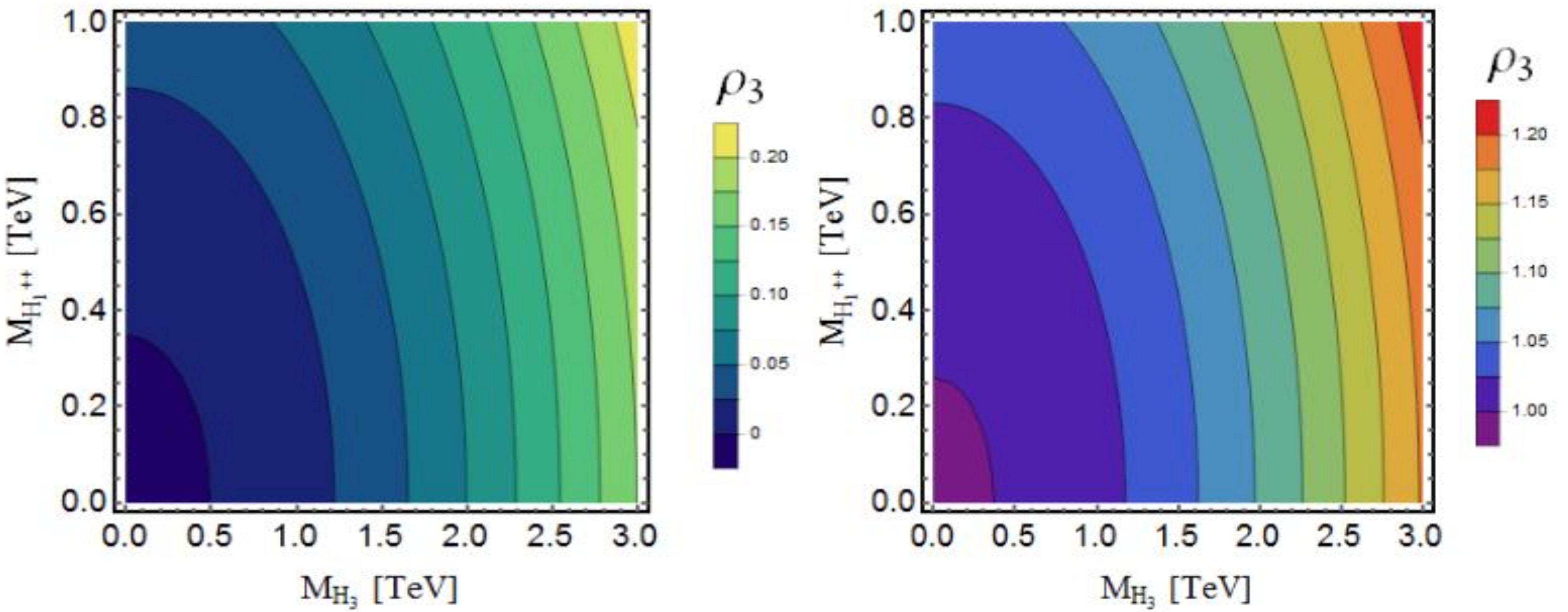


FIG. 1. Left : Contourplot of ρ_3 in $M_{H_3^0} - M_{H_1^{++}}$ plane before insertion of soft breaking term in the Higgs potential. Right : Contourplot of ρ_3 in $M_{H_3^0} - M_{H_1^{++}}$ plane after insertion of soft breaking term μ_4 in the Higgs potential. Scaling of ρ_3 is shown in right side of the each figure. Here we assume M_{W_R}= 4.45 TeV and μ_4 = 5 TeV.

❖ Higgs Mass and Couplings

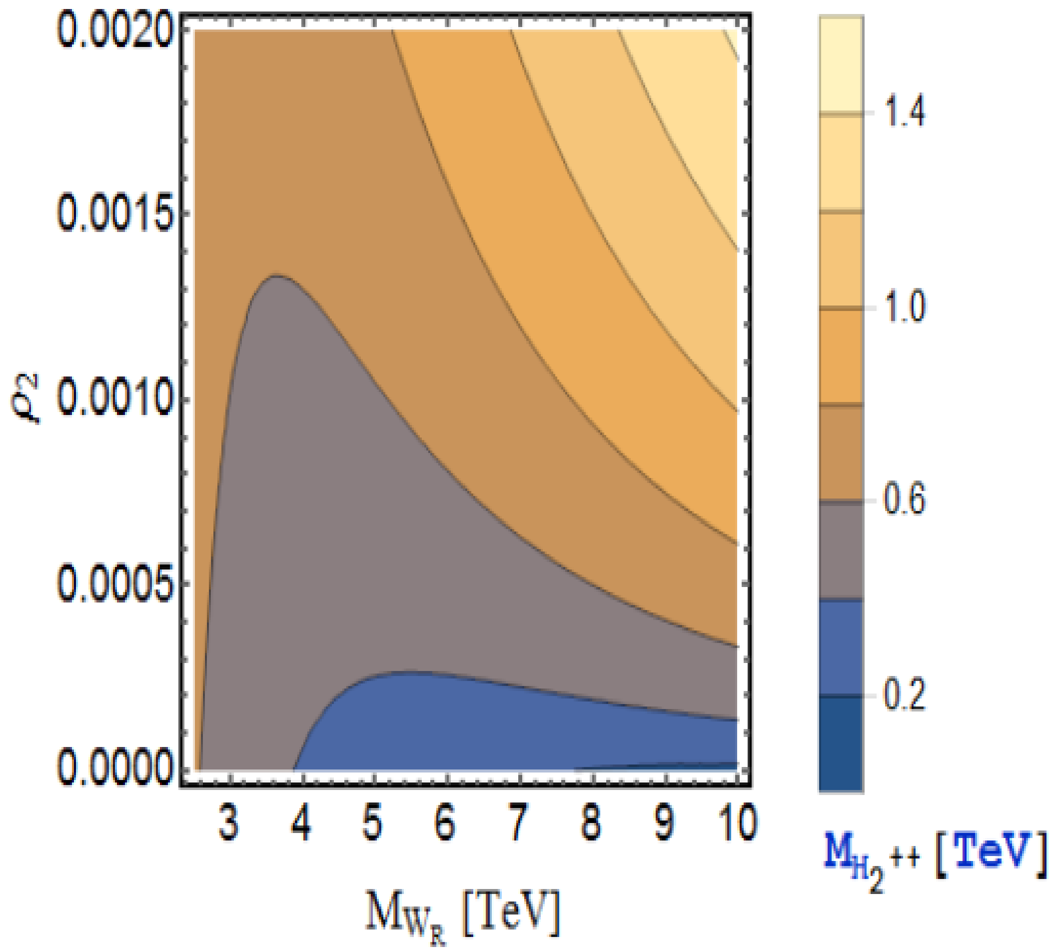


FIG. 2. Contourplot of $M_{H_2^{++}}$ in $\rho_2 - M_{W_R}$ plane. Scaling (shown in right side) is done in TeV scale.

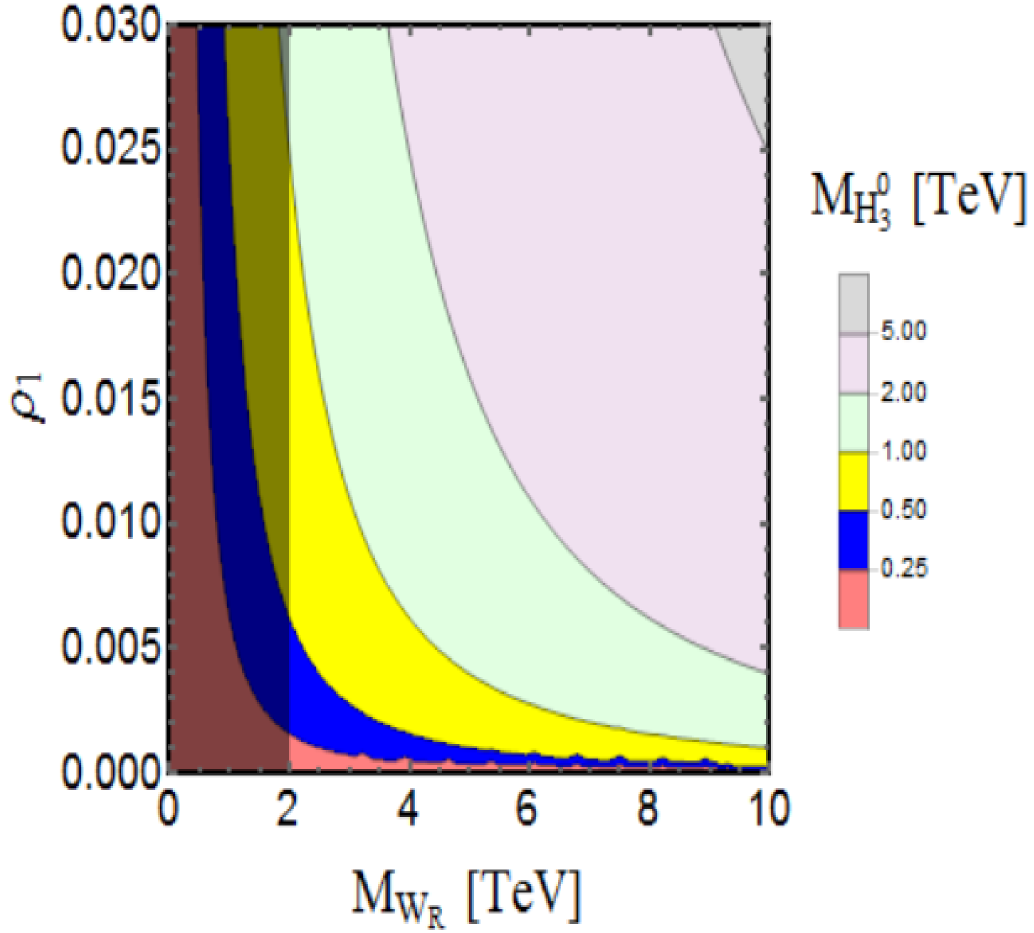


FIG. 3. $\rho_1 - M_{W_R}$ plane for different mass values of $M_{H_3^0}$. Scaling (shown in right side) is done in TeV scale. Black shaded zone is excluded from current experimental limit on M_{W_R}.

❖ H_3^0 Production at the LHC

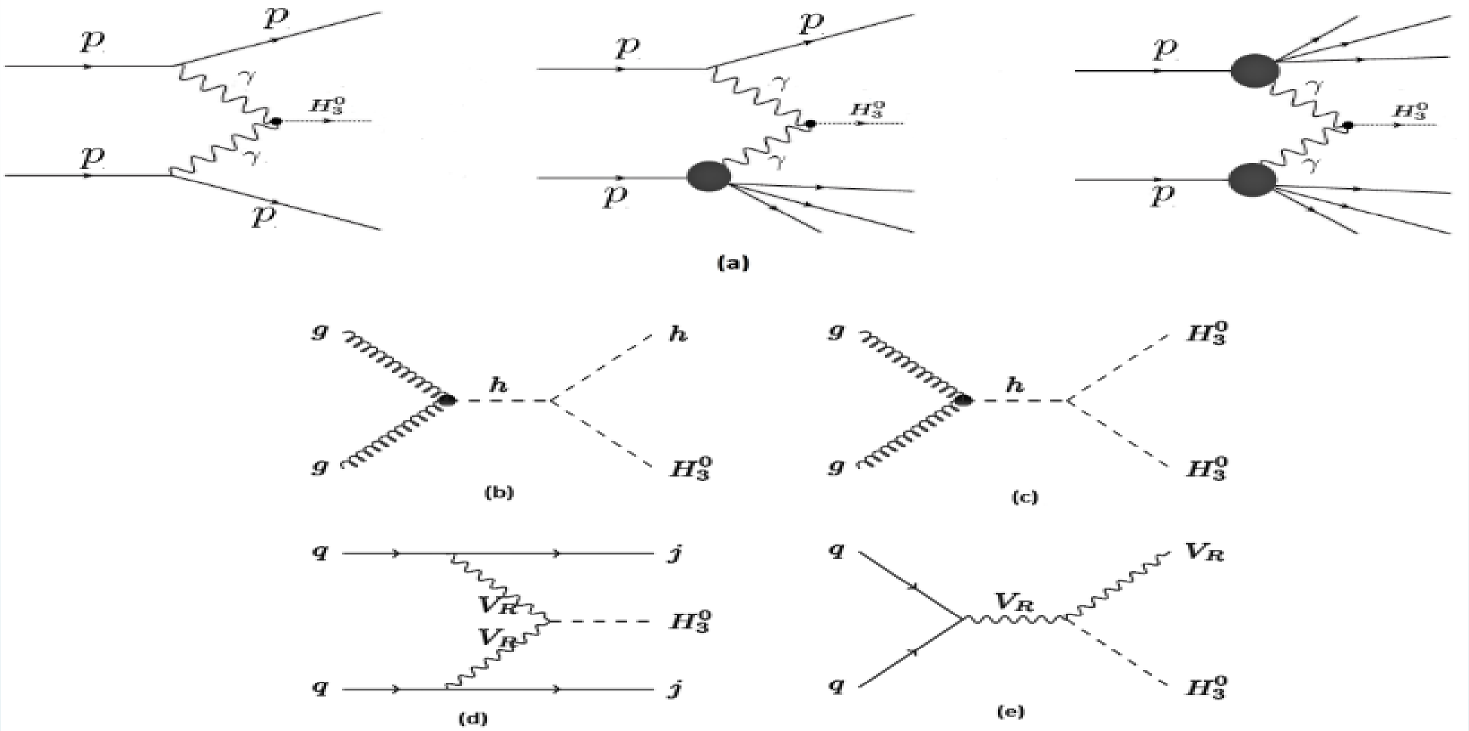
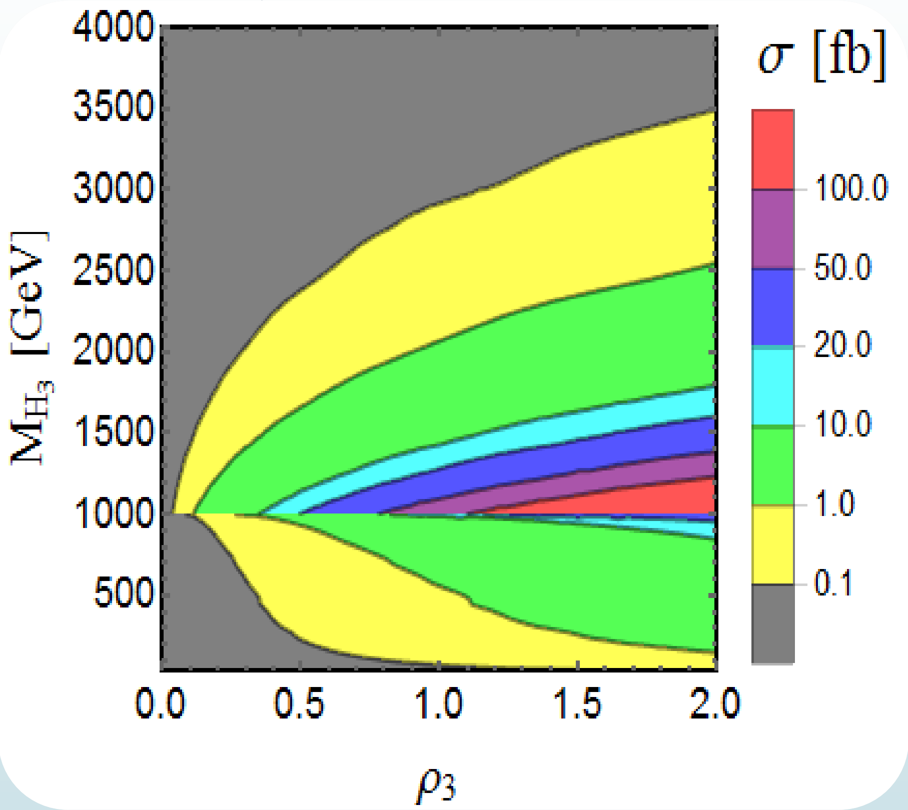
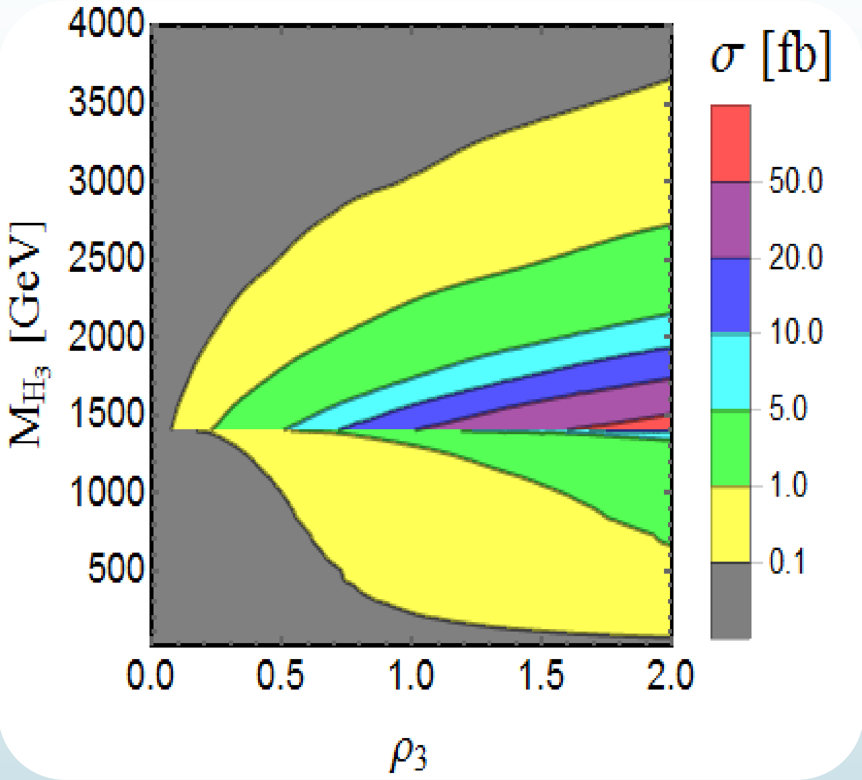


FIG. 4. The Feynman diagrams for the production processes of H_3^0. (a) the resonance production via photon-photon fusion process (elastic, semi-elastic and inelastic scattering subprocesses from left to right in top panel); (b) the associated production with the SM Higgs; (c) pair production; (d) Vector Boson Fusion (VBF) mediated by a pair of $V_R = (W_R, Z_R)$ in the t-channel; (e) Higgsstrahlung process ($V_R = W_R, Z_R$). In (a), the LO effective $H_3^0\gamma\gamma$ vertex is from the doubly and singly charged Higgs ($H_1^{++}, H_2^{++}, H_1^+$) loop induced coupling. In (b) and (c), the LO effective hgg vertex is predominantly from the top-quark loop induced SM coupling.

- Huitu, K. et al. Nucl.Phys. B487 (1997) 27-42
- Dutta, Bhaskar et al. Phys.Rev. D90 (2014) 055015
- Bambhaniya, G. et al. Phys.Rev. D92 (2015) no.1, 015016
- Babu, K.S. et al. Phys.Rev. D88 (2013) 055006
- Dev, P. S. Bhupal et al. JHEP 1605 (2016) 174

❖ H_3^0 Production at the LHC through photon initiated processes

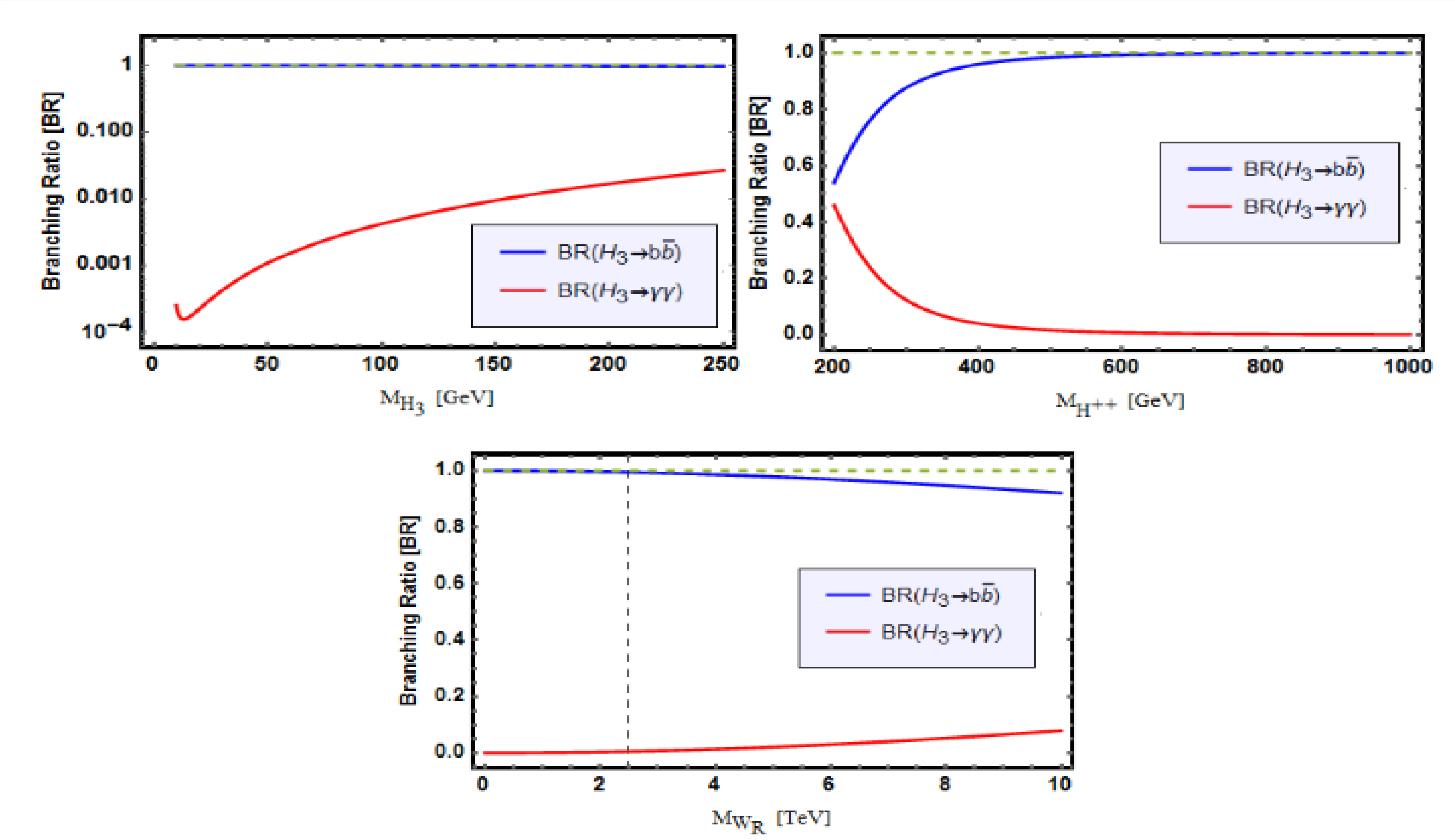




- NNPDF Collaboration (Ball, Richard D. et al.) JHEP 1504 (2015) 040

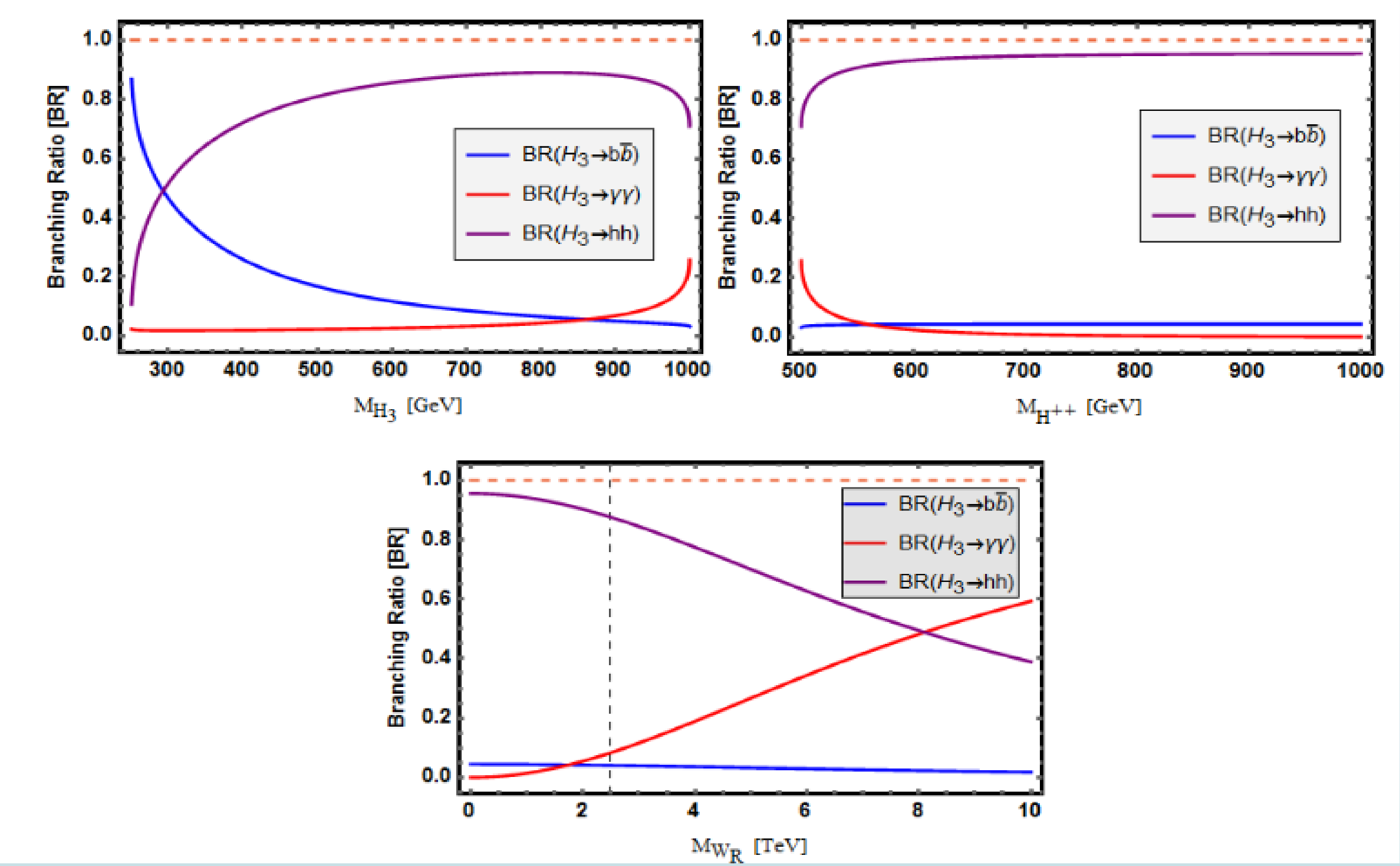
❖ Decay modes of H_3^0 :

➢ Region 1 : $M_{H_3^0} \leq 2M_h$



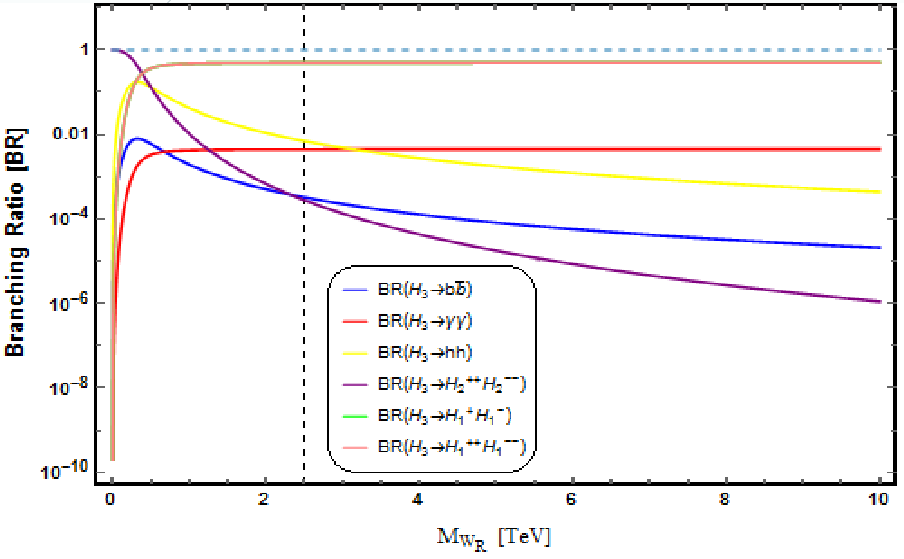
❖ Decay modes of H_3^0 :

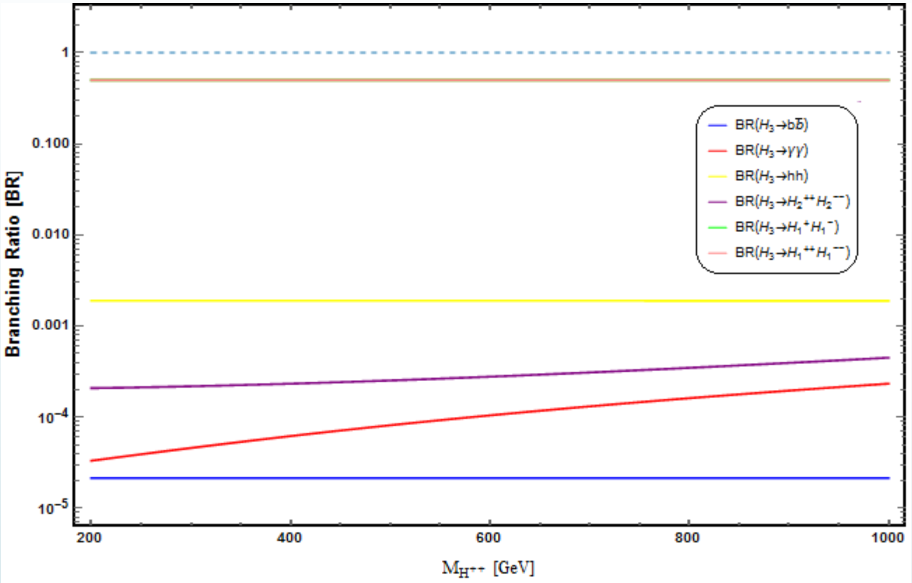
➢ Region 2 : $2M_h \leq M_{H_3^0} \leq 2M_{H_{1,2}^{\pm\pm}}$

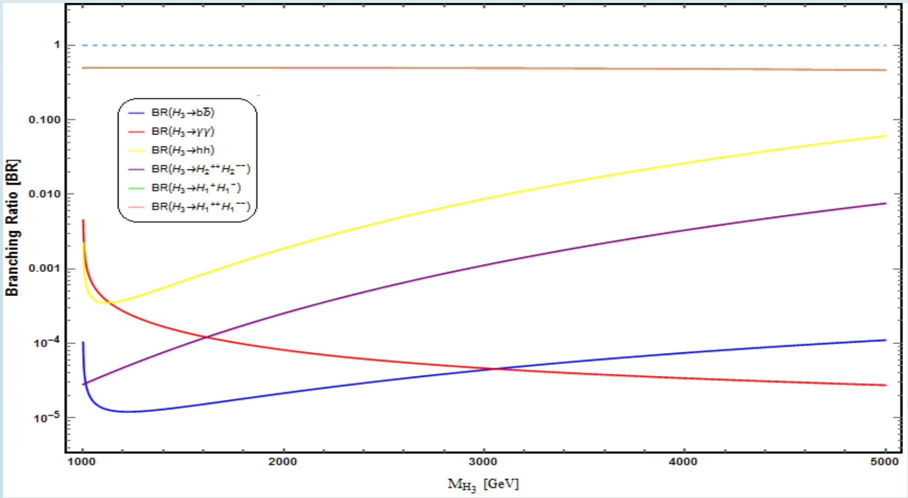


❖ Decay modes of H_3^0 :

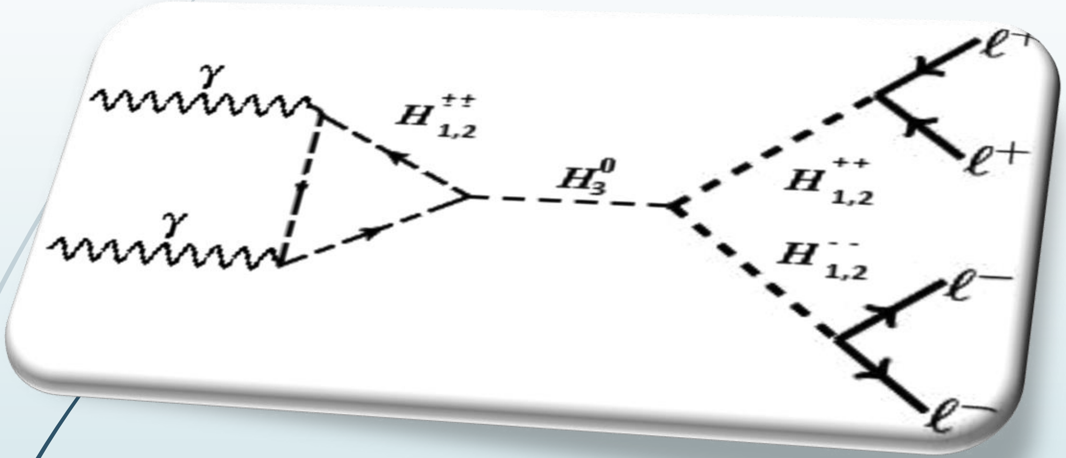
➢ Region 3 : $M_{H_3^0} \geq 2M_{H_1^{\pm\pm}}, 2M_h$

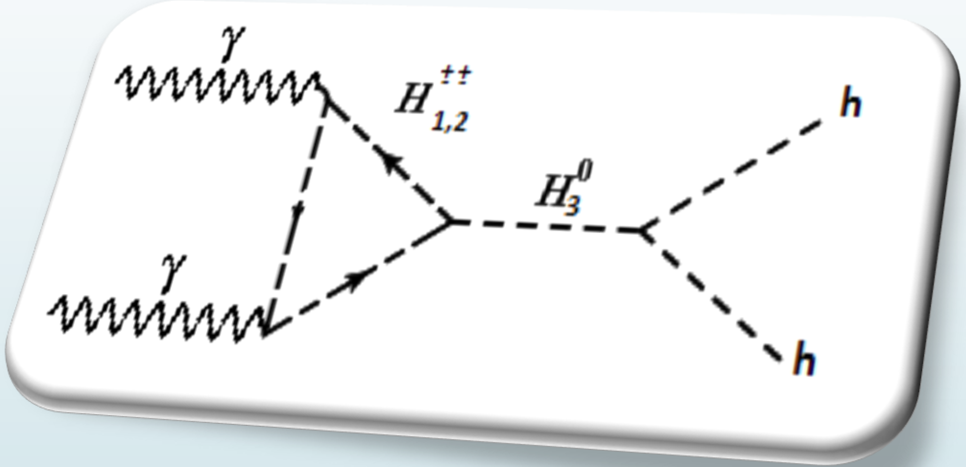


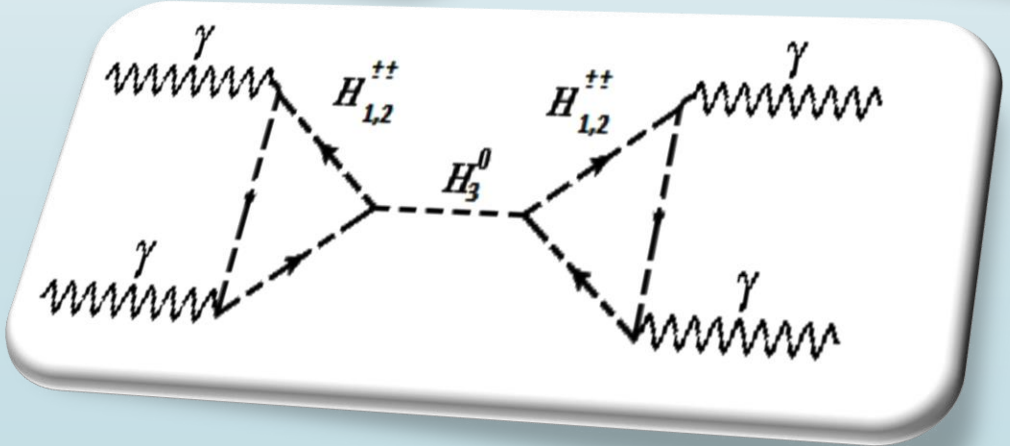




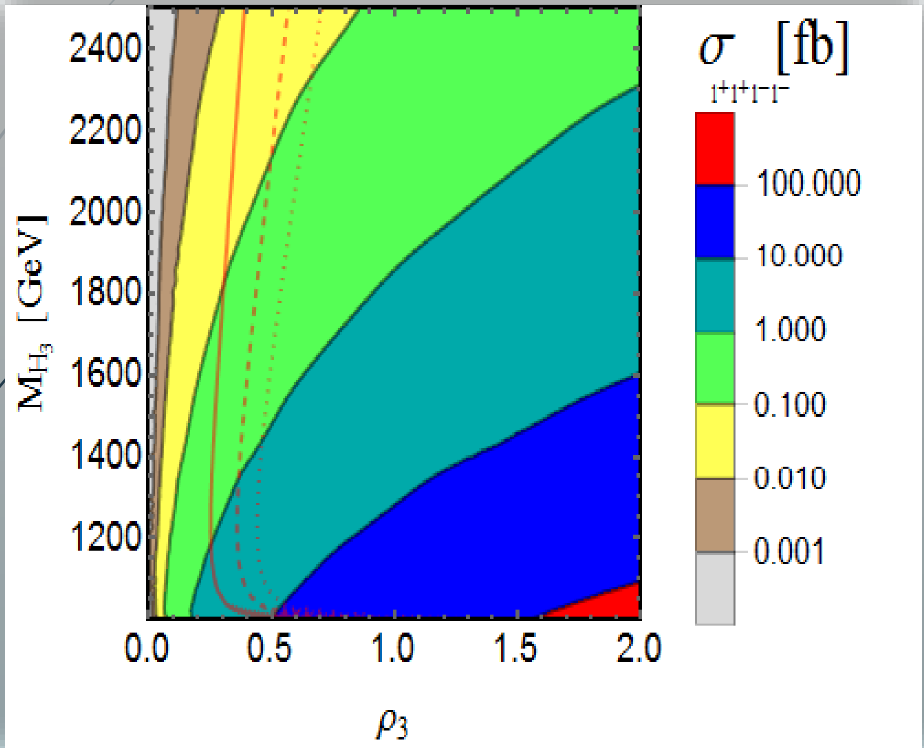
❖ Potential discovery signals of H_3^0 at LHC :

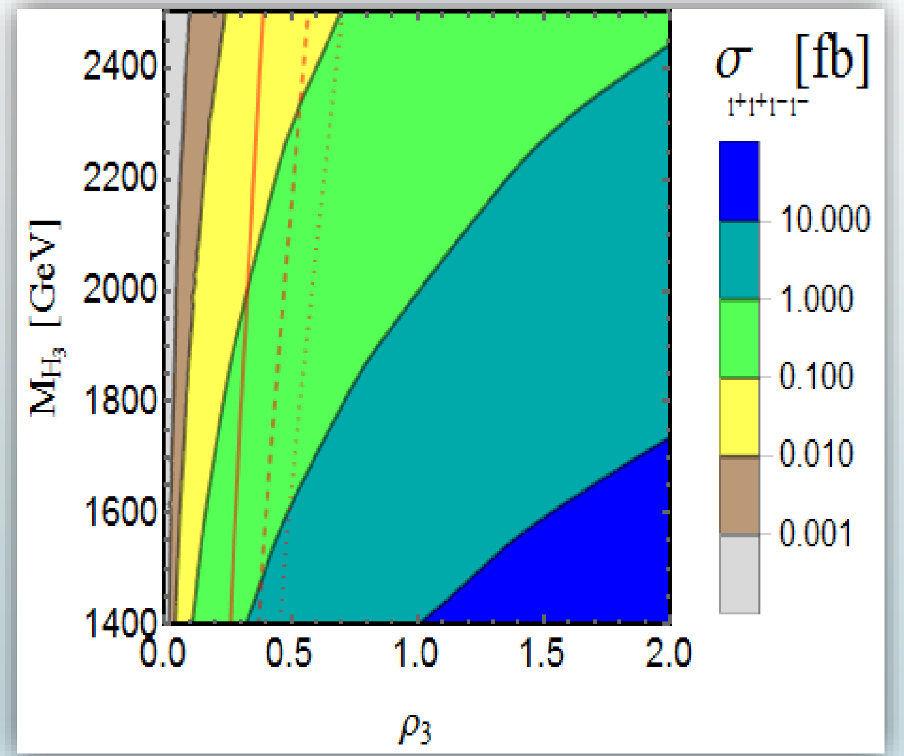




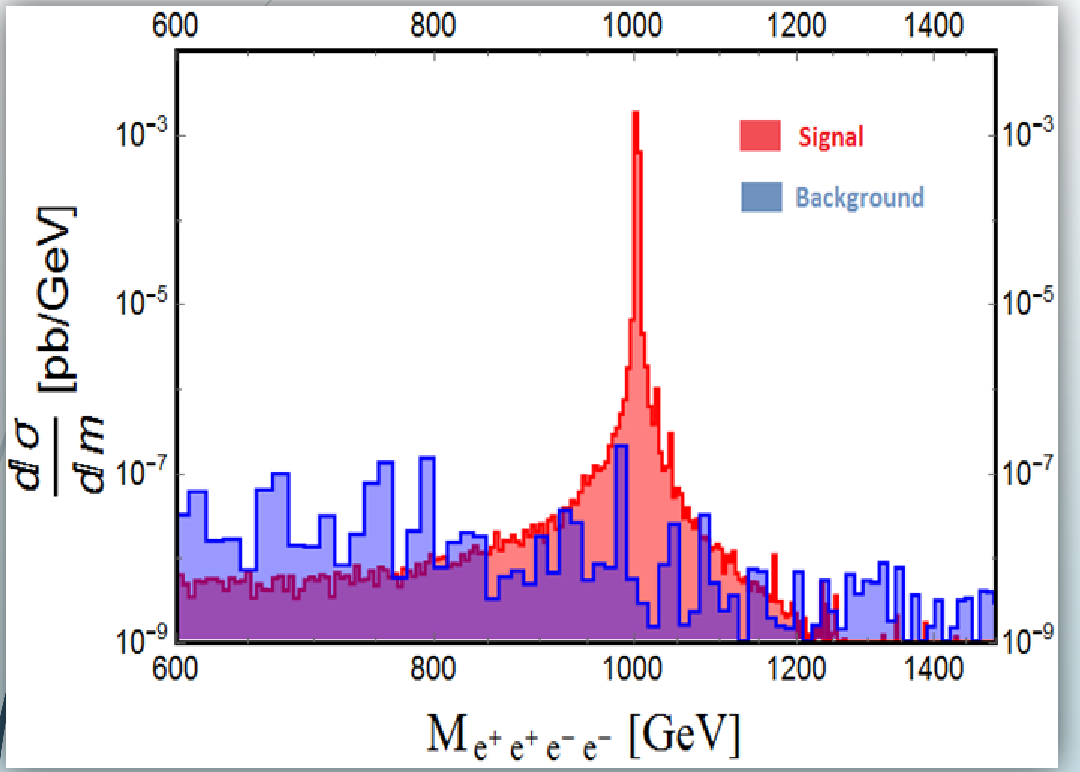


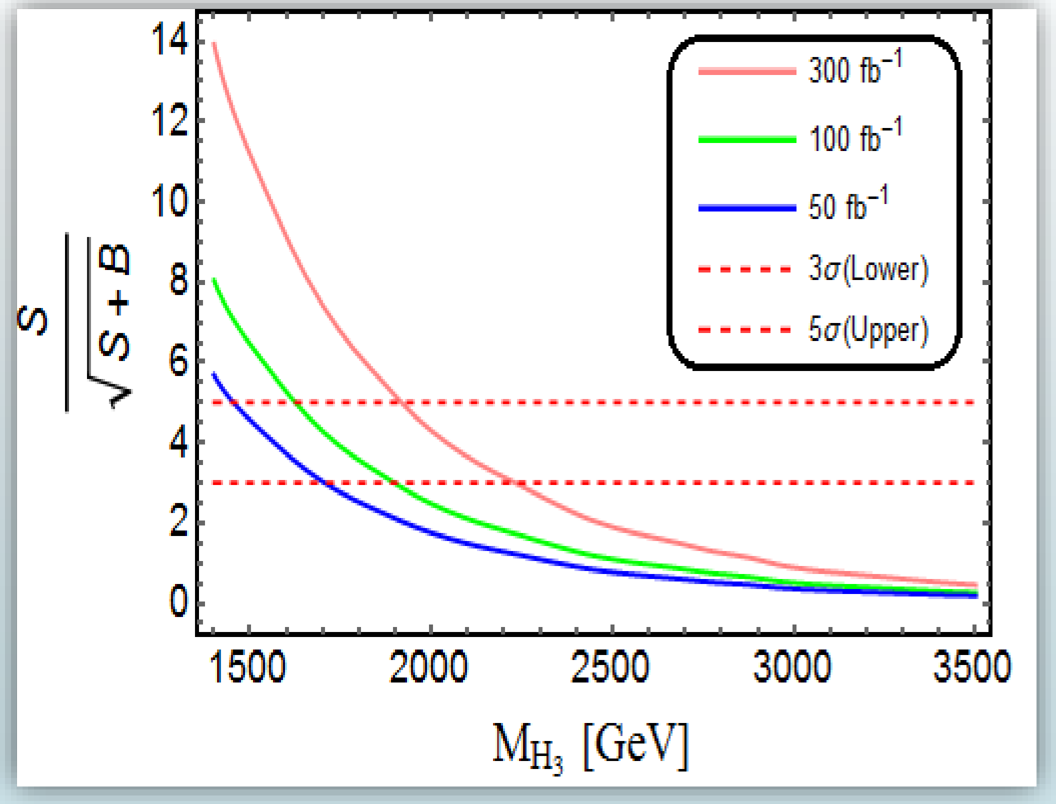
➢ H_3^0 as four lepton resonance at LHC:





➤ H_3^0 AS FOUR LEPTON RESONANCE AT LHC:



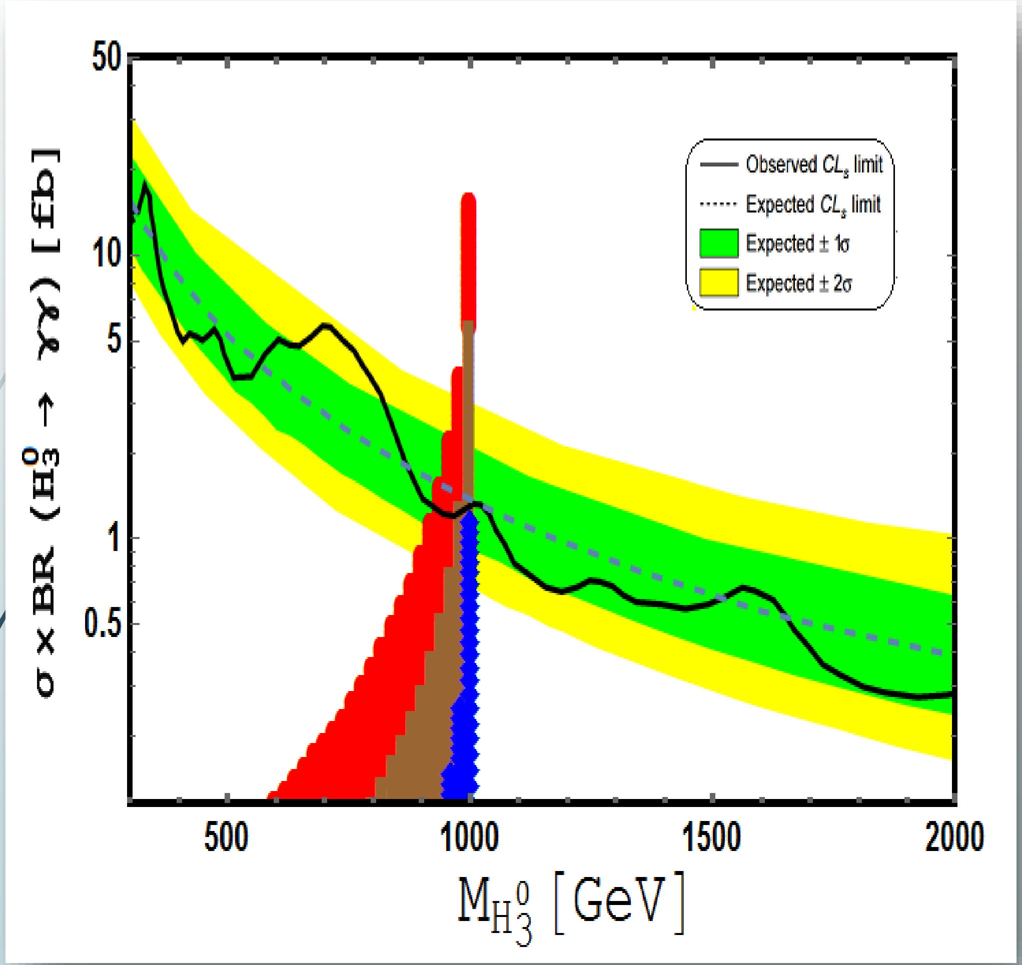


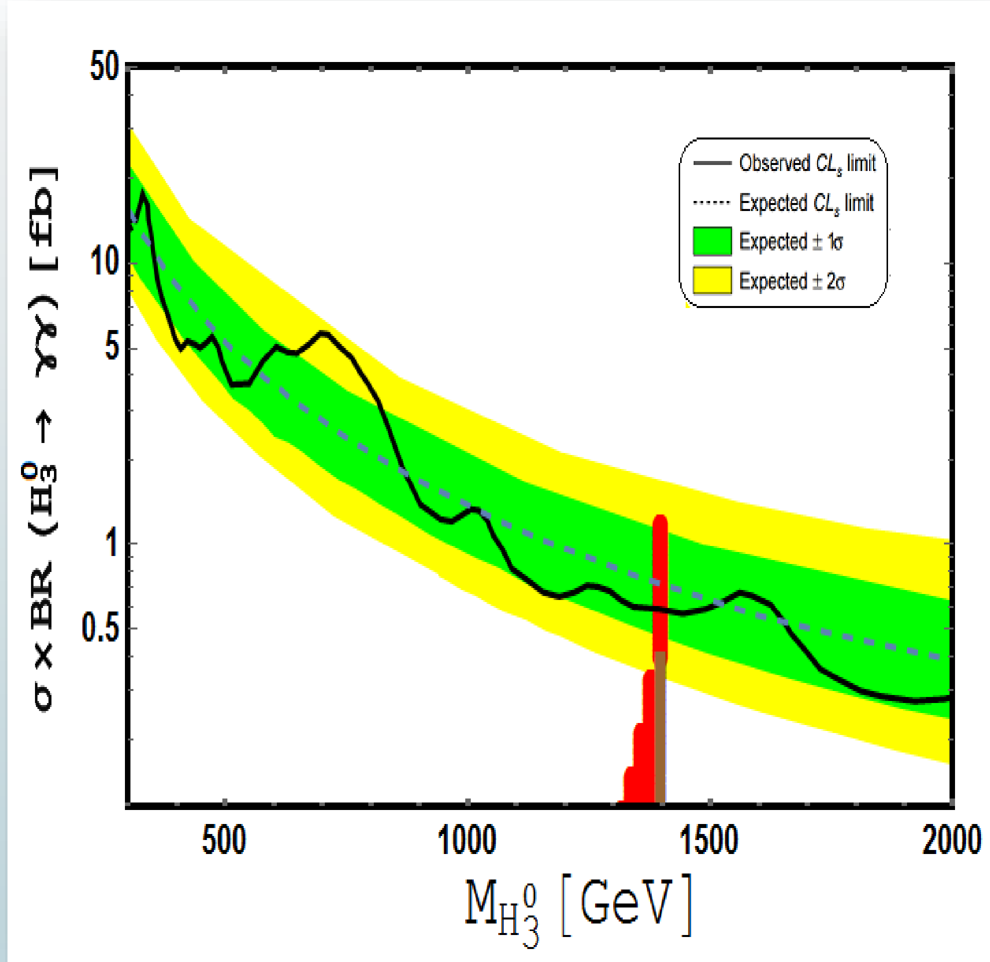
➢ H_3^0 AS FOUR LEPTON RESONANCE AT LHC:

Benchmark Point	$M_{H_3^0}$ [TeV] (3σ limit)	(5σ limit)
$l = 50\ fb^{-1}$	1.71	1.46
$l = 100\ fb^{-1}$	1.91	1.62
$l = 300\ fb^{-1}$	2.22	1.92

➨ Summary of H_3^0 mass reach at the 13 TeV LHC :

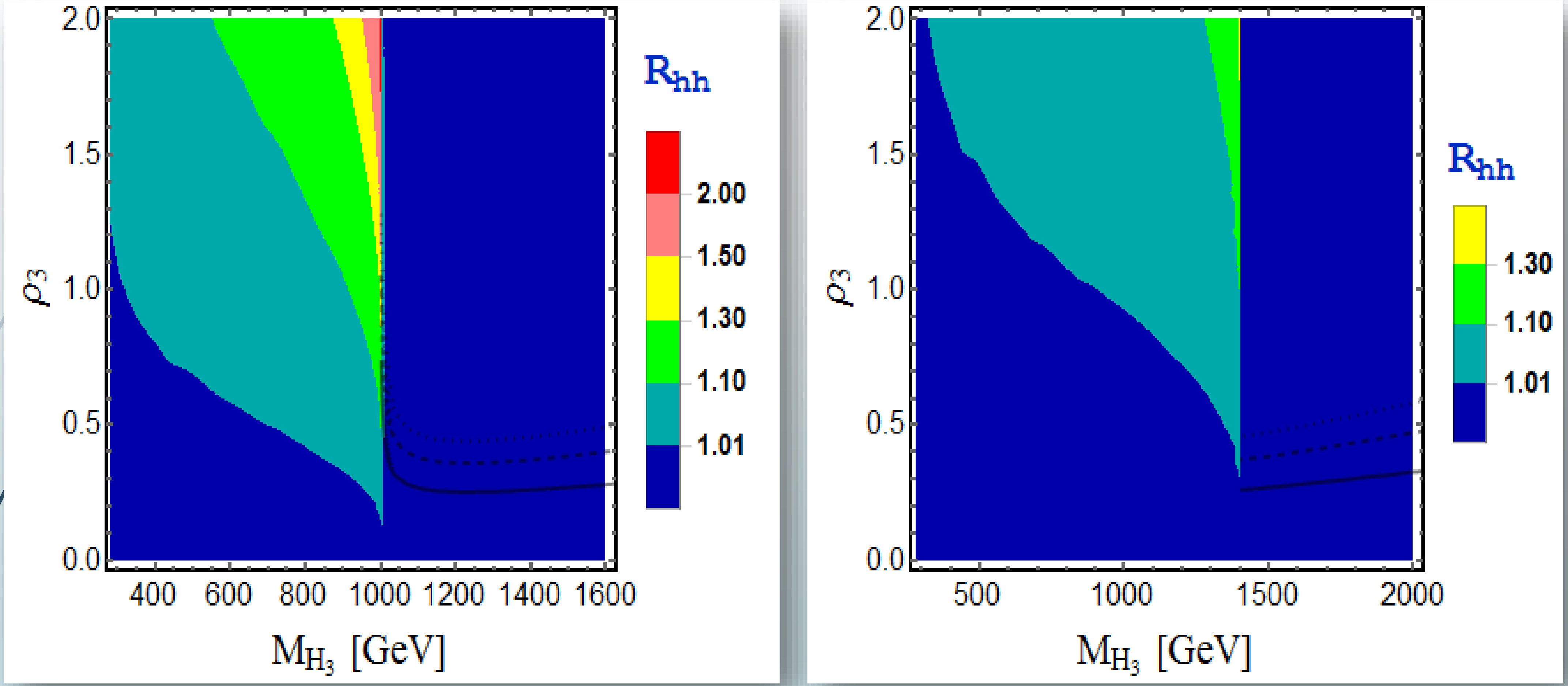
➢ H_3^0 as di-photon resonance at LHC:



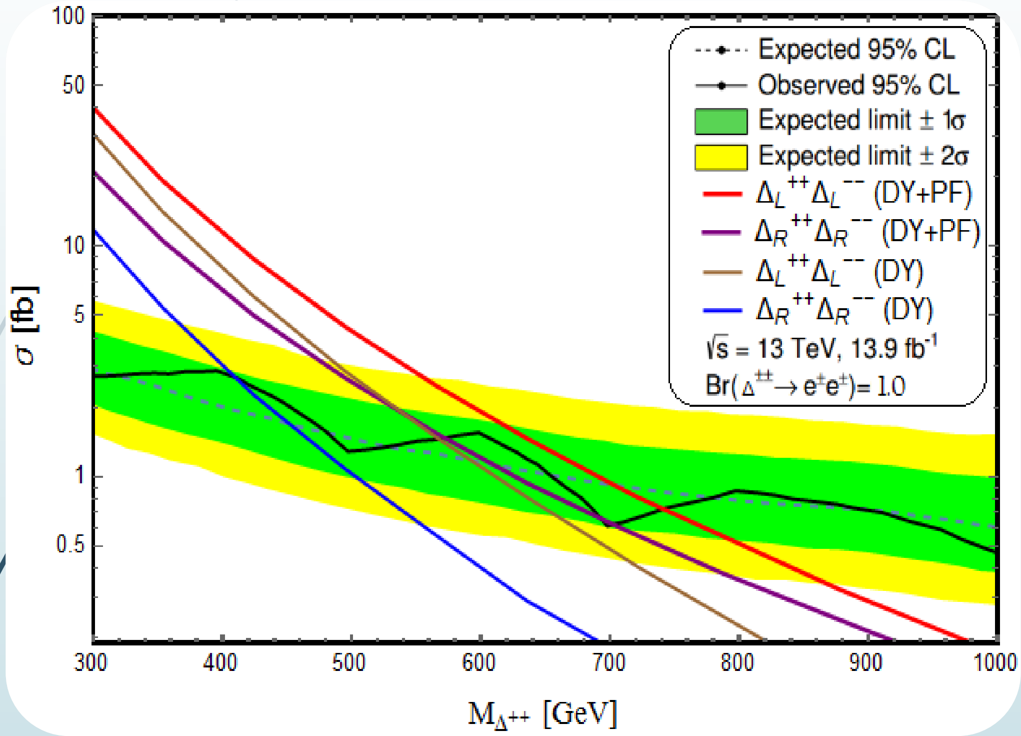


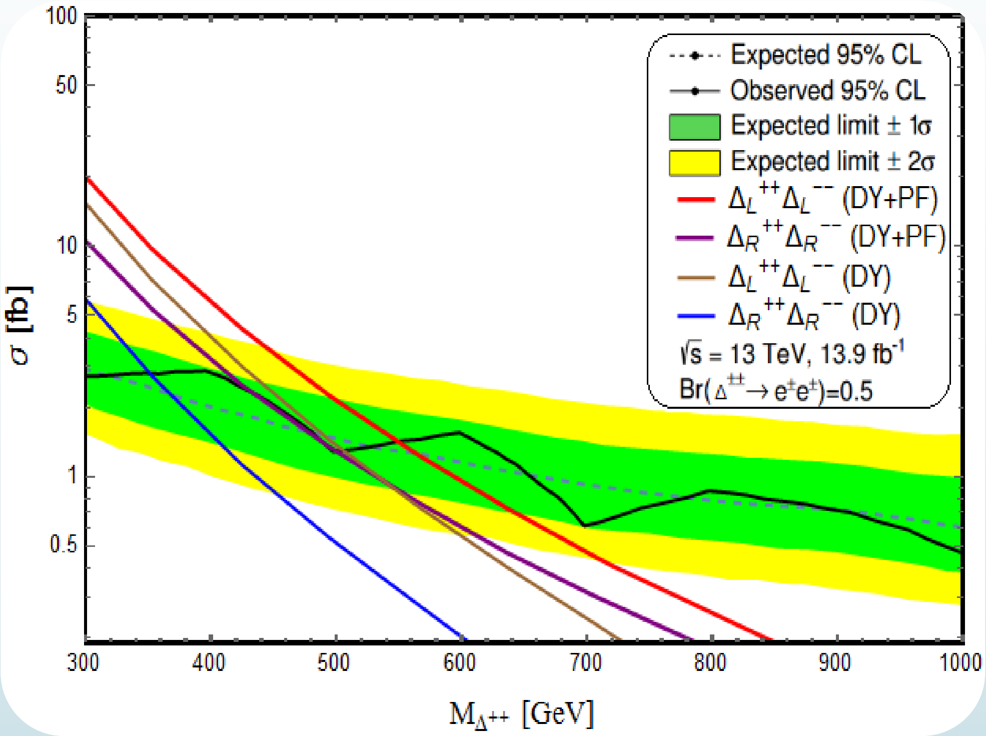
- ATLAS-CONF-2016-059
- CMS collaboration (Phys. Lett. B 767,147(2017))

➢ H_3^0 as di-Higgs resonance at LHC:



❖ Doubly Charged Higgs Phenomenology





- ATLAS-CONF-2016-051
- K. S. Babu et al.(Phys.Rev. D95 (2017) no.5, 055020)

Conclusion

1

- The photon fusion process, which has been neglected in the theoretical and experimental analyses thus far, could provide a new probe of the TeV scale left right models.

2

- The sensitivity reach for new hadrophobic neutral and doubly-charged Higgs bosons can go up to a few TeV depending on the RH scale and the couplings.

3

- The results presented here can be taken as an initial guide in the exploration of the heavy fermiphobic as well as hadrophobic Higgs at colliders via photon initiated process.


Thank you!

Back up Slides :

$$\Gamma(H_3^0 \to hh) \simeq \frac{\alpha_1^2 v_R^2}{32\pi M_{H_3^0}}\{1 - \frac{4M_h^2}{M_{H_3^0}^2}\}^{1/2} \quad (5.3)$$

$$\Gamma(H_3^0 \to H_1^{\pm\pm} H_1^{\mp\mp}) \simeq \frac{\rho_3^2 v_R^2}{16\pi M_{H_3^0}}\{1 - \frac{4M_{H_1^{\pm\pm}}^2}{M_{H_3^0}^2}\}^{1/2} \quad (5.4)$$

$$\Gamma(H_3^0 \to H_2^{\pm\pm} H_2^{\mp\mp}) \simeq \frac{(\rho_1 + 2\rho_2)^2 v_R^2}{4\pi M_{H_3^0}}\{1 - \frac{4M_{H_2^{\pm\pm}}^2}{M_{H_3^0}^2}\}^{1/2} \quad (5.5)$$

$$\Gamma(H_3^0 \to H_1^{\pm} H_1^{\mp}) \simeq \frac{\rho_3^2 v_R^2}{16\pi M_{H_3^0}}\{1 - \frac{4M_{H_1^{\pm}}^2}{M_{H_3^0}^2}\}^{1/2} \quad (5.6)$$

$$\Gamma(H_3^0 \to W_R^+ W_R^-) \simeq \frac{\sqrt{2\rho_1^3} v_R}{8\pi}\{1 - \frac{4M_{W_R}^2}{M_{H_3^0}^2}\}^{1/2}(1 - \frac{4M_{W_R}^2}{M_{H_3^0}^2} + \frac{12M_{W_R}^4}{M_{H_3^0}^4}) \quad (5.7)$$

$$\Gamma(H_3^0 \to Z_R Z_R) \simeq \frac{\rho_1^{3/2} v_R}{8\sqrt{2}\pi}\{1 - \frac{4M_{Z_R}^2}{M_{H_3^0}^2}\}^{1/2}(1 - \frac{4M_{Z_R}^2}{M_{H_3^0}^2} + \frac{12M_{Z_R}^4}{M_{H_3^0}^4}) \quad (5.8)$$

$$\Gamma(H_3^0 \to N_R N_R) \simeq \frac{3\rho_1^{1/2} f^2 v_R}{8\sqrt{2}\pi}\{1 - \frac{4M_{N_R}^2}{M_{H_3^0}^2}\}^{3/2}(1 + \frac{2M_{N_R}^2}{M_{H_3^0}^2 - 4M_{N_R}^2}) \quad (5.9)$$

$$\Gamma(H_3^0 \to b\bar{b}) \simeq \frac{3M_t^2 M_{H_3^0}}{16\pi k_1^2}\sin^2\theta_2\{1 - \frac{4M_b^2}{M_{H_3^0}^2}\}^{3/2} \quad (5.10)$$

$$\Gamma(H_3^0 \to \gamma\gamma) \simeq \frac{\alpha^2 M_{H_3^0}^3}{1024\pi^3} | \sum_{i=1}^{3} Q_i^2 \frac{\lambda_{H_3^0 H_i H_i}}{M_{H_i}^2} F_0(x_{H_3^0}) |^2 \quad (5.11)$$

where Q_i stands for the electric charge of $H_i(H_2^{++}, H_1^{++}, H_1^{+})$ in the loop. The loop factor is given by :

$$F_0(x_{H_3^0}) = \tau[1 - \tau f(\tau)]; \quad where\ \tau = \frac{4M_{H_i}^2}{M_{H_3^0}^2}; \quad (5.12)$$

$$f(\tau) = \begin{cases} [\sin^{-1}(\sqrt{\tau^{-1}})]^2 & if \ \ \tau \geq 1; \\ -\frac{1}{4}[\ln(\frac{\eta_+}{\eta_-}) - i\pi]^2 & if \ \ \tau < 1; \end{cases} \quad (5.13)$$

$$where \quad \eta_{\pm} = 1 \pm \sqrt{1 - \tau}. \quad (5.14)$$

Production Channel	Primary Production	Secondary Production	Potential Signal
a. $(pp \to H_3^0 \to H_1^{\pm\pm} H_1^{\mp\mp})$	$H_1^{\pm\pm} H_1^{\mp\mp}$	-	$l^\pm l^\pm l^\mp l^\mp$
		$H_1^\pm H_1^\pm H_1^\mp H_1^\mp$	See c
		$H_1^\pm W_i^\pm H_1^\mp W_j^\mp$	depends on W's decay modes and see c
		$W_i^\pm W_i^\pm W_j^\mp W_j^\mp$	depends on W's decay modes
b. $(pp \to H_3^0 \to H_2^{\pm\pm} H_2^{\mp\mp})$	$H_2^{\pm\pm} H_2^{\pm\pm}$	-	$l^\pm l^\pm l^\mp l^\mp$
		$H_1^\pm H_1^\pm H_1^\mp H_1^\mp$	See c
		$W_{iR}^\pm W_{iR}^\pm W_{jR}^\mp W_{jR}^\mp$	depends on W_R's decay modes
c. $(pp \to H_3^0 \to H_1^\pm H_1^\mp)$	$H_1^\pm H_1^\mp$	$l^\pm l^\mp \nu_L \nu_L$	$l^\pm l^\mp \bigoplus MET$
		$Z_i W_i^\pm Z_j W_j^\mp$	depends on W's and Z's decay modes
d. $(pp \to H_3^0 \to hh)$	hh	–	$4b/2b2\gamma$
e. $(pp \to H_3^0 \to b\bar{b})$	$b\bar{b}$	–	$2b$
f. $(pp \to H_3^0 \to \gamma\gamma)$	$\gamma\gamma$	–	2γ