Interpretation of the diphoton events in Left-Right models

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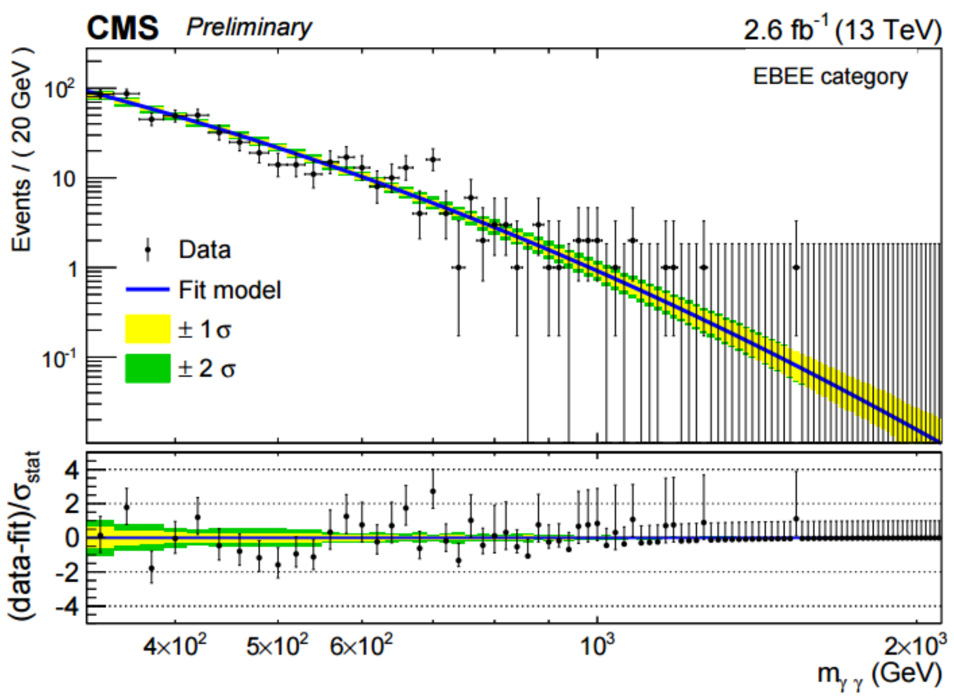
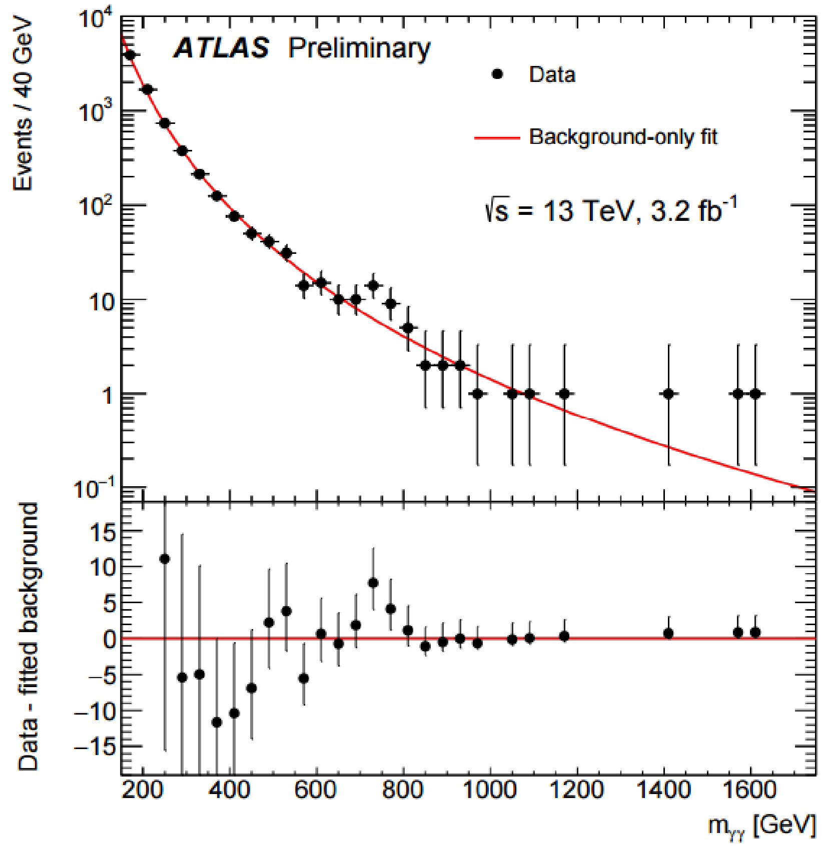
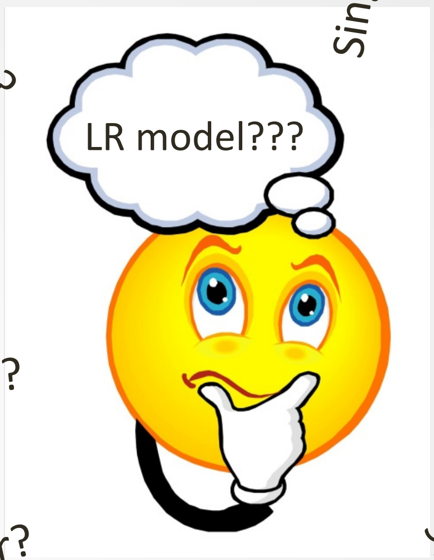
Based on
Bhupal Dev, Mohapatra & YCZ, 1512.08507
Curtin, Katz, Ramsey-Musolf, Bhupal Dev, Mohapatra & YCZ, 160x.xxxxx
Bhupal Dev, Mohapatra & YCZ, 160x.xxxxx
Bhupal Dev, Mohapatra & YCZ, 160y.yyyyy(?)

VUB, Jan 28, 2016

A TRUE signal of new physics at 750 GeV ???







Singlet scalar(s)?

Radion?

Composite models?

Heavy axion?

Spin-2 particle?

Neutrino models?

Effective theory?

Connection to dark matter?

From stirng theory?

Dilaton?

SUSY particle?

Left-Right interpretation

- LR models are natural UV completion scenarios beyond SM
- Natural solution to the following mysteries:
  Parity restoration, neutrino masses, strong CP problem, DM
- Can originate from GUT theories
- Testable at the LHC Run II and/or future 100 TeV collider FCC-hh or SppC
- Also testable at the next-generation high-intensity low-energy experiments, i.e. mu to e gamma

- More than one matter content realizations of the LR gauge symmetry

$$G_{LR} \equiv SU(2)_L \times SU(2)_R \times U(1)_{B-L}$$

“canonical” LR model

- Matter content

$$Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad Q_R \equiv \begin{pmatrix} u_R \\ d_R \end{pmatrix},$$

$$\psi_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \psi_R \equiv \begin{pmatrix} \nu_R \\ e_R \end{pmatrix},$$

- Scalar sector

$$\phi \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$$

$$\Delta_L \equiv \begin{pmatrix} \Delta_L^+/\sqrt{2} & \Delta_L^{++} \\ \Delta_L^0 & -\Delta_L^+/\sqrt{2} \end{pmatrix}, \quad \Delta_R \equiv \begin{pmatrix} \Delta_R^+/\sqrt{2} & \Delta_R^{++} \\ \Delta_R^0 & -\Delta_R^+/\sqrt{2} \end{pmatrix}$$

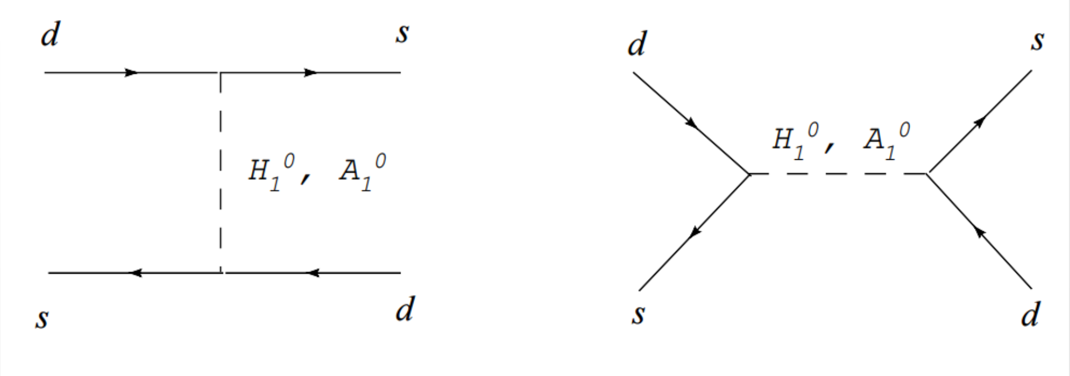
- Symmetry breaking chain

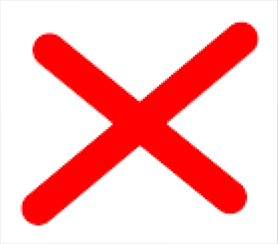
$$G_{LR} \xrightarrow{\Delta_R} G_{SM} \xrightarrow{\phi} U(1)_{\rm EM}$$

Scalar candidates: bifundamental

- FCNC constraints push these scalars far above the TeV scale

$$M_H \gtrsim 10\,\mathrm{TeV}$$



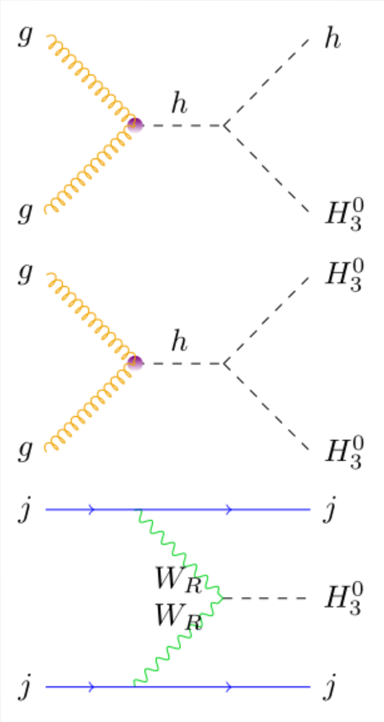


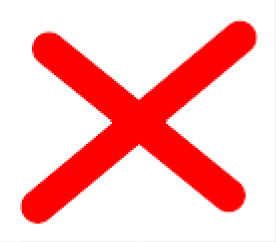
Scalar candidate: Leptophilic

Both production cross section & effective coupling to diphoton too small

Table 4. The couplings relevant for H_3^0 production and decay at 100 TeV hadron collider.

couplings	values
H_3^0hh	$\frac{1}{\sqrt{2}}\alpha_1 v_R$
$H_3^0hH_1^0$	$2\sqrt{2}\alpha_2 v_R$
$hH_3^0H_3^0$	$-\sqrt{2}\alpha_1\kappa\left[1-\frac{\alpha_1}{2\rho_1}+\frac{8\alpha_2^2}{\alpha_1(\alpha_3-4\rho_1)}\right]$
$H_1^0H_3^0H_3^0$	$-2\sqrt{2}\alpha_2\kappa\left[1-\frac{\alpha_1}{2\rho_1}+\frac{4\alpha_1+\alpha_3}{2(\alpha_3-4\rho_1)}\right]$
$H_3^0H_1^0H_1^0$	$\frac{1}{\sqrt{2}}(\alpha_1+\alpha_3)v_R$
$H_3^0A_1^0A_1^0$	$\frac{1}{\sqrt{2}}(\alpha_1+\alpha_3)v_R$
$H_3^0H_3^0H_3^0$	$\sqrt{2}\rho_1 v_R$
$H_3^0H_1^+H_1^-$	$\sqrt{2}(\alpha_1+\alpha_3)v_R$
$H_3^0H_2^{++}H_2^{--}$	$2\sqrt{2}(\rho_1+2\rho_2)v_R$
$H_3^0\bar{t}t$	$\frac{m_t}{\sqrt{2}\kappa}\frac{\alpha_1\epsilon}{2\rho_1}$
$H_3^0\bar{b}b$	$-\frac{m_t}{\sqrt{2}\kappa}\frac{4\alpha_2\epsilon}{\alpha_3-4\rho_1}$
H_3^0NN	$\frac{M_N}{\sqrt{2}v_R}$
$H_3^0W_R^+W_R^-$	$\sqrt{2}g_R^2 v_R$
$H_3^0Z_RZ_R$	$\frac{\sqrt{2}g_R^2 v_R}{\cos^2\phi}$





LR seesaw model

- Matter content

$$\text{SM fermions}: \quad Q_{L,R} = \begin{pmatrix} u \\ d \end{pmatrix}_{L,R}; \ \psi_{L,R} = \begin{pmatrix} \nu \\ e \end{pmatrix}_{L,R};$$

$$\text{Vectorlike fermions}: \quad P\left(3,1,1,+\frac{4}{3}\right), \ N\left(3,1,1,-\frac{2}{3}\right), \ E(1,1,1-2)$$

- Yukawa coupling

$$\begin{aligned} -\mathcal{L}_Y \quad = \quad & y_u \bar{Q}_L \tilde{\chi}_L P_R + y_d \bar{Q}_L \chi_L N_R + y_e \bar{L} \chi_L E_R + (L \leftrightarrow R) \\ & + f_u \bar{P}_L \mathbf{S} P_R + f_d \bar{N}_L \mathbf{S} N_R + f_e \bar{E}_L \mathbf{S} E_R + \text{H.c.} \end{aligned}$$

- The singlet scalar
  - Generate heavy VL quark and lepton masses to implement the the seesaw mechanism
  - The 750 GeV resonance for the diphoton events
  - Trigger the inflation or BAU at HE scale??? *(open question)*

Universal seesaw

- Given VEVs of the doublets and singlet, we have the seesaw form for the SM fermions

$$\mathcal{M}_q = \begin{pmatrix} 0 & \frac{1}{\sqrt{2}} y_q v_L \\ \frac{1}{\sqrt{2}} y_q v_R & f_q v_S \end{pmatrix}$$

leading to the suppressed fermion masses and alleviated Yukawa couplings

$$m_q \simeq \frac{y_q^2 v_L v_R}{2 f_q v_S}$$

- Typical energy scale:

$$\begin{aligned} v_L &: \quad 246 \text{ GeV}\,, \\ v_R &: \quad \text{multi-TeV scale}\,[M_{W_R} = g_R v_R]\,, \\ v_S &: \quad 1 \text{ TeV scale}\,, \end{aligned}$$

Scalar potential

- Scalar potential:

$$V = -\mu_L^2 \chi_L^\dagger \chi_L - \mu_R^2 \chi_R^\dagger \chi_R - \frac{1}{2}\mu_S^2 S^2 + \lambda_1 \left[(\chi_L^\dagger \chi_L)^2 + (\chi_R^\dagger \chi_R)^2\right]$$
$$+\lambda_2 (\chi_L^\dagger \chi_L)(\chi_R^\dagger \chi_R) + \lambda_S S^4 + \lambda_3 S^2 (\chi_L^\dagger \chi_L + \chi_R^\dagger \chi_R)$$

- Mass matrix square

$$\mathcal{M}^2_{\text{scalar}} = \begin{pmatrix} -\mu_L^2 + 3\lambda_1 v_L^2 & \lambda_2 v_L v_R & 2\lambda_3 v_L v_S \\ \lambda_2 v_L v_R & -\mu_R^2 + 3\lambda_1 v_R^2 & 2\lambda_3 v_R v_S \\ 2\lambda_3 v_L v_S & 2\lambda_3 v_R v_S & -\mu_S^2 + 6\lambda_S v_S^2 \end{pmatrix}$$

- To simplify the model as much as possible, we turn off the coupling of S to the doublets
  - Coupling to the SM Higgs h can induce decaying of S into hh
  - Mixing to the heavy doublet H can induce decaying of S into hh, WW, ZZ and tt.

production

- Dominate production channel for the singlet S @ LHC: gluon-gluon fusion mediated by the TeV-scale VL fermions.
- Naturally large numbers [3G] of heavy fermions: enhance the production cross section by a factor of N_f^2 [$N_f \approx 5$ (**not 6!**)].
- Production cross section can be obtained by simply rescaling the SM one by the ratio

$$\sigma_{\rm SM}^{13\ \rm TeV}(gg \to h) = 850\,\rm fb$$

$$r = \left| \frac{f_T \sin\alpha_L^t \sin\alpha_R^t}{M_t/v_{EW}} + \sum_{i=P,N} \frac{f_i v_{EW}}{M_i} \frac{A_{1/2}(\tau_i)}{A_{1/2}(\tau_t)} \right|^2 \simeq \left| \sum_{i=P,N,\ne T} \frac{f_i v_{EW}}{M_i} \frac{A_{1/2}(\tau_i)}{A_{1/2}(\tau_t)} \right|^2$$

Top and top partner loops

- Top quark contribution is suppressed by the LH t-T mixing

$$\sin\alpha_L^t \simeq \frac{y_t v_{\rm EW}}{\sqrt{2} f_T v_S} \sim 0.03, \left[y_t = \sqrt{\frac{2 M_t M_T}{v_{\rm EW} v_R}} \right]$$

- Top partner gains its mass mostly from v_R, due to the large RH t-T mixing,

$$M_T^2 = \frac{1}{2} y_t^2 (v_R^2 + v_{\rm EW}^2) + f_T^2 v_S^2 - M_t^2 \simeq 2.5\,{\rm TeV}, \begin{bmatrix} v_R = 3\,{\rm TeV} \\ v_S = 1\,{\rm TeV} \end{bmatrix}$$

- The effective No. of heavy VL fermions **is 5 not 6**,

$$\sigma(pp \to S) \propto M_F^{-2}$$

decay

- Dominate decay widths

$$\Gamma_{t\bar{t}} = \frac{3y_{St\bar{t}}^2 M_S}{16\pi}\left(1-\frac{4M_t^2}{M_S^2}\right)^{3/2},$$

$$\Gamma_{gg} = \frac{\alpha_s^2 M_S^3}{128\pi^3}\left|\sum_{i=t,\,P,\,N}\frac{f_i}{M_i}A_{1/2}(\tau_i)\right|^2\left(1+k_{gg}\frac{\alpha_s}{\pi}\right),$$

$$\Gamma_{\gamma\gamma} = \frac{\alpha^2 M_S^3}{256\pi^3}\left|\sum_{i=t,\,P,\,N,\,E}\frac{f_i}{M_i}N_{Ci}Q_i^2 A_{1/2}(\tau_i)\right|^2,$$

$$\Gamma_{\gamma Z} \simeq \frac{\alpha^2 M_S^3}{128\pi^3 s_w^2 c_w^2}\left|\sum_{i=t,\,P,\,N,\,E}\frac{f_i}{M_i}N_{Ci}Q_i\left(\frac{1}{2}I_{3i}-Q_i s_w^2\right)A_{1/2}(\tau_i)\right|^2,$$

$$\Gamma_{ZZ} \simeq \frac{\alpha^2 M_S^3}{256\pi^3 s_w^4 c_w^4}\left|\sum_{i=t,\,P,\,N,\,E}\frac{f_i}{M_i}N_{Ci}\left(\frac{1}{2}I_{3i}-Q_i s_w^2\right)^2 A_{1/2}(\tau_i)\right|^2.$$

$$y_{St\bar{t}} = \sqrt{2}f_T \sin\alpha_L^t \sin\alpha_R^t\,,$$

$$k_{gg} = \frac{95}{4}-\frac{7N_f}{6} = 16.75\ [N_f = 6]$$

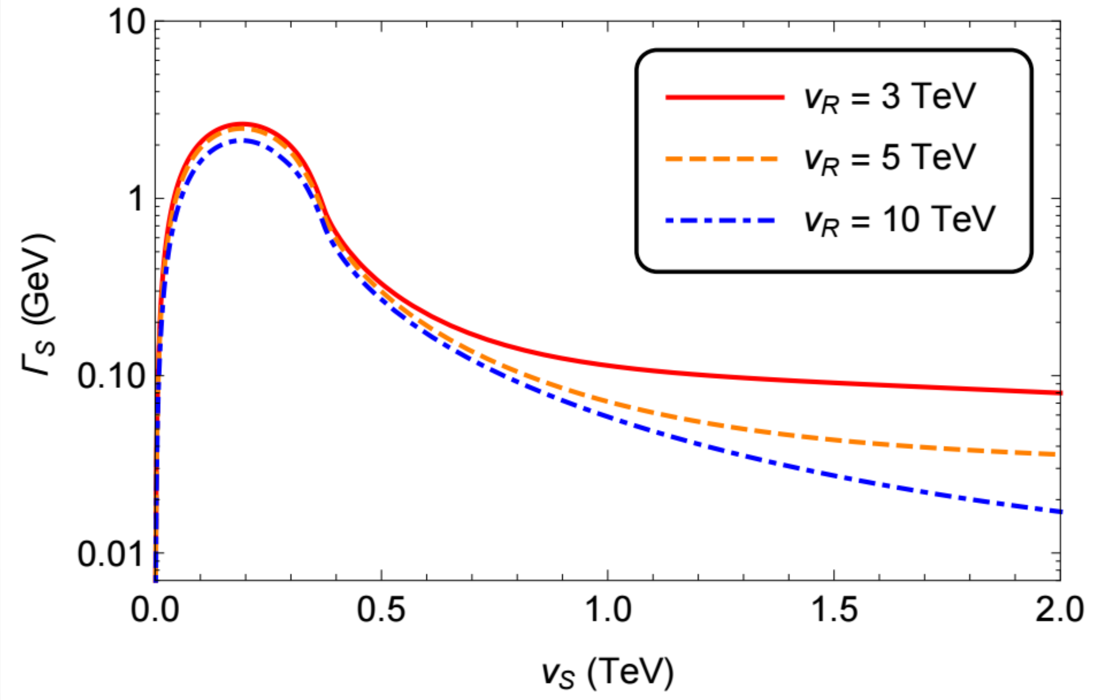
Gauge symmetry

- The WW decay channel is induced by the top quark loop and thus highly suppressed by the LH t-T mixing…
- For the γγ, γZ and ZZ channels, in the limit of $M_S >> M_Z$,

$$g_{\gamma F\bar{F}} = Q_F$$
$$g_{ZF\bar{F}} = Q_F \tan^2\theta_w$$

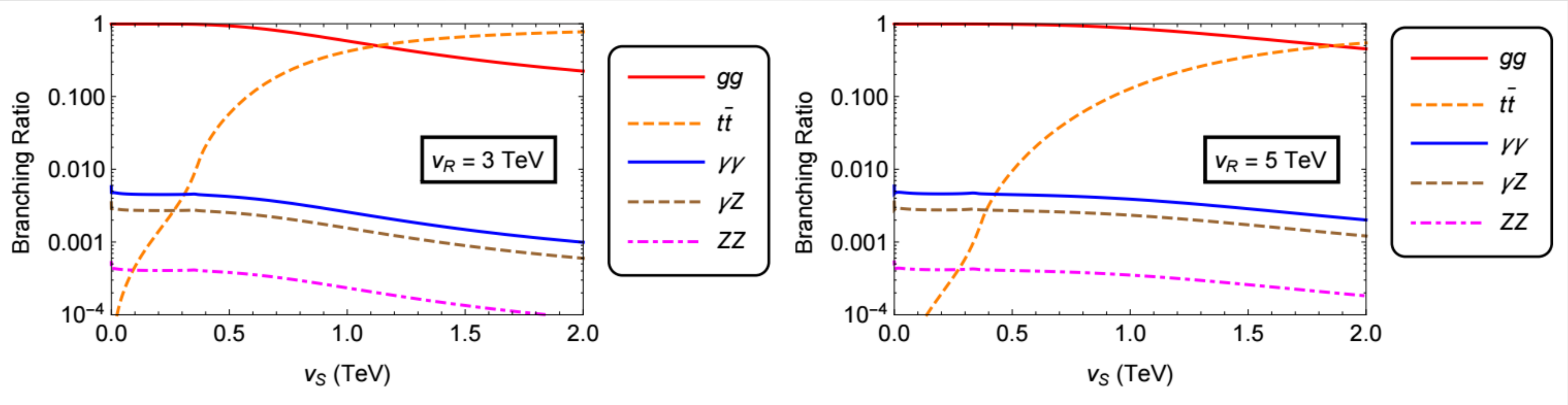
$$\Gamma_{\gamma\gamma} : \Gamma_{Z\gamma} : \Gamma_{ZZ} = 1 : 2\tan^2\theta_w : \tan^4\theta_w$$

Narrow width



- Only the universal Yukawa coupling f_F and the VEV v_S are input by hand, apart from the RH scale vR.
- In the plot $f_F = 1$.
- Width is suppressed either by the small t-T mixing or the loop factor, thus it is narrow.

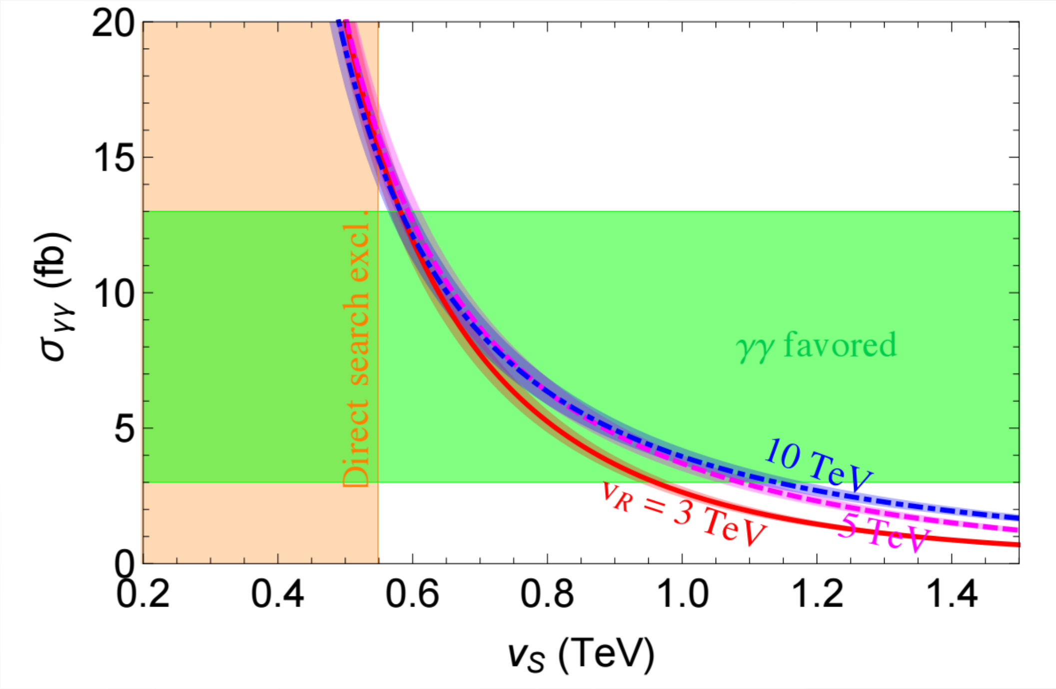
Branching ratios



Dominate channel: tt and gg, followed by γγ, γZ and ZZ.

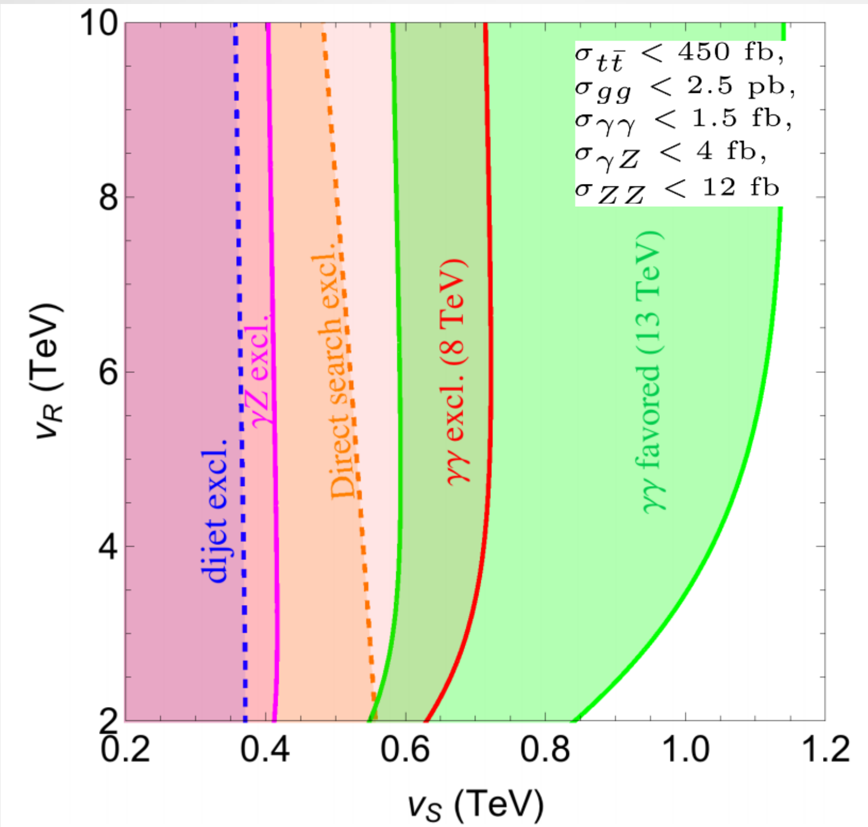
- In most of the parameter space of interest, gg is the dominate decay channel.
- Larger v_S, larger LH t-T mixing, larger top ratio.
- Gauge boson channels at the per mil level, suppressed by $\alpha^2/\alpha s^2$ or loop factors.

Fitting the diphoton events



- Fitting the (8±5) fb data
- Mild dependence on v_R:
  from mixing of SM quarks and their heavy partners.
- Vertical orange region:
  direct searches of bottom partners @ LHC8 at the 95% CL.

LHC8 constraints

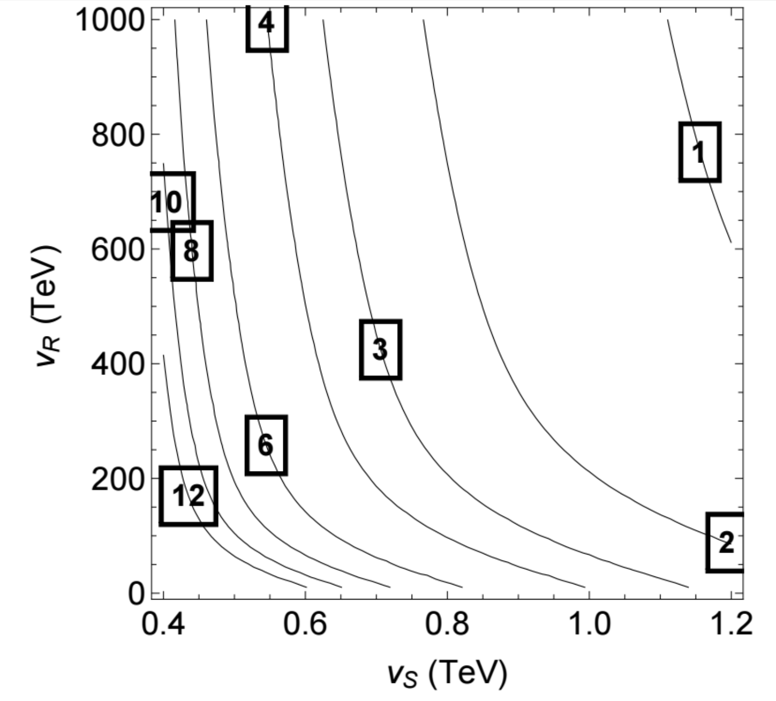


- Rescaling the cross section from the SM value:

$$\sigma_{\rm SM}^{8\ \rm TeV}(gg \to h) = 156.8\,\text{fb}$$

- The tt and ZZ limits exclude regions with smaller values of v_R and v_S, not shown in the plot.

Upper limits on RH scale



For fixed f_F and v_S, larger v_R leads to larger RH light-heavy mixing:

- Havy vector-like fermions are pushed to be heavier;
- Effective coupling of heavy fermions to S smaller,

For v_S = 1 TeV, v_R < 65 TeV [with $\sigma_{\gamma\gamma}$ > 3 fb].

Two sets of parameters

	$v_R = 3$ TeV	$v_R = 5$ TeV
f_F (input)	1	1
v_S [GeV] (input)	800	1000
$\sigma(gg \to S)$ [pb]	1.61	0.95
$\Gamma_{\text{total}}(S)$ [GeV]	0.21	0.071
signal cross section [fb]		
$t\bar{t}$	423	122
gg	1173	825
$\gamma\gamma$	5.3	3.7
γZ	3.2	2.3
ZZ	0.48	0.34

Takeaway points

- Looking forward to more 13/14 TeV data
- Minimal "canonical" model can NOT explain diphoton data.
- Narrow resonance of 750 GeV might come from LR seesaw model.
- (Large number of) vector-like heavy fermions at the TeV scale.
- W_R and parity restoration might appear at the few TeV scale.
- Connection to NP in the top sector [large t-T mixing].
- GUT completion of the LR model and vacuum stability up to the GUT/Planck scale.

- *More work in progress on both the two LR models…*

Thank you very much!!!