

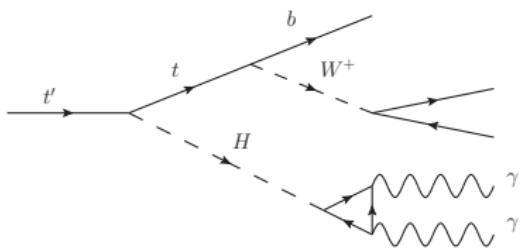
# Higgs boson production via vector-like top-partner decays and detection at the LHC

A. Azatov, O. Bondu, A. Falkowski, M. Felcini, S. Gascon-Shotkin,  
D. K. Ghosh, G. Moreau, A. Y. Rodríguez-Marrero, S. Sekmen

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GDR Terascale  
LPC Clermont

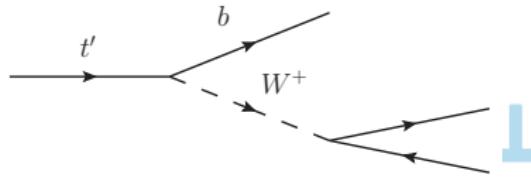
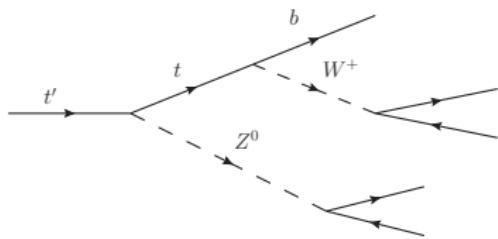


# Introduction (1)



## Idea

- Higgs production through decays of additional heavy colored particle
- Copious pair production of these at LHC via strong interactions



# Introduction (2)

## Motivation

- Extra quarks with vector-like couplings predicted by most alternatives to SUSY:
  - Little higgs: partners of the SM fields promoted to larger multiplets
  - Composite higgs/top: resonances of the SM-particles bounded states  
(R. Contino et al. 2003-2007, K. Agashe et al. 2005-2006, G. Burdman et al. 2007, C. T. Hill 1991)
  - Extra dimensional models with SM quarks in the bulk: KK excitations (H.-C. Cheng et al. 2000)
  - Gauge coupling unification theory: into  $SU(5)$  representations  
(C. Kilic et al. 2011)

## Documentation

Details in arXiv:hep-ph/1204.0455, started in 2011 Les Houches session

# Theoretical model (1)

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- Minimal scenario with only additional vector-like quark multiplets including  $t'$  components able to strongly suppress the gluon fusion:
  - First top-partner  $t'$  in a  $SU(2)_L$  doublet
  - Second top-partner  $t''$  in a gauge singlet
- For simplification, we do not consider the doublet including a  $b'$ , that would also be exchanged in the triangular loop
- We end up with the doublet  $(q_{5/3}, t')$ 
  - $q_{5/3}$  exotic quark w/ electric charge 5/3 and w/o self Yukawa coupling

$$\begin{aligned} \mathcal{L}_{\text{Yuk.}} = & Y \overline{\left( \begin{array}{c} t \\ b \end{array} \right)}_L H^\dagger t_R^c + Y' \overline{\left( \begin{array}{c} q_{5/3} \\ t' \end{array} \right)}_L H t_R^c + Y'' \overline{\left( \begin{array}{c} q_{5/3} \\ t' \end{array} \right)}_{L/R} H t_{R/L}'' + \tilde{Y} \overline{\left( \begin{array}{c} t \\ b \end{array} \right)}_L H^\dagger t_R'' \\ & + Y_b \overline{\left( \begin{array}{c} t \\ b \end{array} \right)}_L H b_R^c + m \bar{t}_L'' t_R^c + m' \overline{\left( \begin{array}{c} q_{5/3} \\ t' \end{array} \right)}_L \left( \begin{array}{c} q_{5/3} \\ t' \end{array} \right)_R + m'' \bar{t}_L'' t_R'' + \text{H.c.} \end{aligned}$$

## Theoretical model (2)

- By construction, the vector-like quarks have same quantum numbers and gauge group representations for the left- and right-handed states
- $t-t'-t''$  mixing dominates and CKM mixing angles are typically small
  - The first two quark generations are decoupled from  $b, t, t', t''$

### Notes

- Field redefinition rotating  $t_R^c$  and  $t_R''$  can eliminate the  $m$  term w/o loss of generality.
- $Y''$  term could be split in two w/ different chiralities and coupling constants.

## Theoretical model (3)

The Lagragian gives rise, after EWSB, to the top mass matrix:

$$\mathcal{L}_{\text{mass}} = \overline{\begin{pmatrix} t \\ t' \\ t'' \end{pmatrix}}_L \begin{pmatrix} Yv & 0 & \tilde{Y}v \\ Y'v & m' & Y''v \\ m & Y''v & m'' \end{pmatrix} \begin{pmatrix} t^c \\ t' \\ t'' \end{pmatrix}_R + \text{H.c.} \quad (1)$$

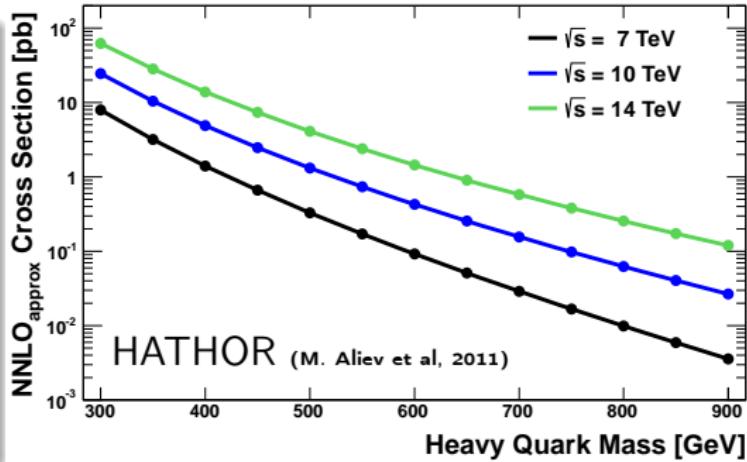
### Notes

- Vector-like fermions do not require EWSB to acquire mass
- Non trivial consequence of the  $t'$ ,  $t''$  charge assignment choice is Yukawa terms in the block diagonal matrix associated to the top-partners
  - Allows strong suppressions of the gluon fusion mechanism
  - The top-partner ( $t'$ ,  $t''$ ) Yukawa coupling ( $Y''$ ) sign can be chosen independently of the top ( $t$ ) Yukawa coupling ( $Y$ ) sign to generate destructive interferences between the top and top-partner loops

# Phenomenology

## Notations

- $t'$  and  $t''$ : states in the interaction basis
- $t_1$ ,  $t_2$  and  $t_3$  mass eigenstates
- $m_{t_3} > m_{t_2} > m_{t_1}$
- $t_1$  is the standard top,  $m_{t_1}$  its physical mass

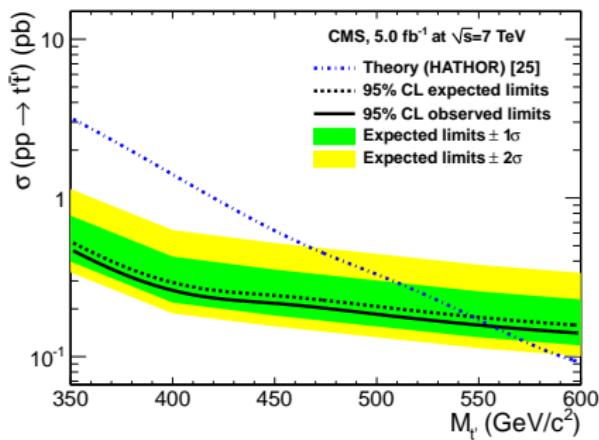


- Here only considering phenomenology of  $t_2$  (minimal  $t'$  model, compatible with actual direct and indirect experimental constraints)
- Allow enhancing or decreasing Higgs boson cross-section
- Production:  $pp \rightarrow t_2\bar{t}_2$
- Decay:  $t_2 \rightarrow th$ ,  $t_2 \rightarrow tZ$ ,  $t_2 \rightarrow bW$

# Experimental constraints on heavy top

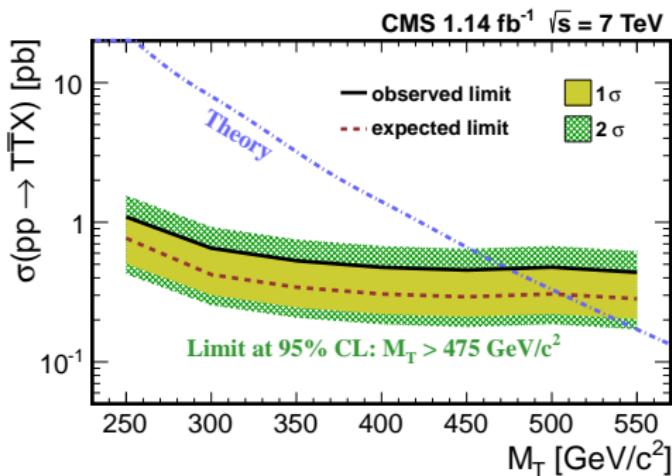
- Upper limits for exclusive  $t_2$  decays:  $\sigma(t_2\bar{t}_2)B^2(t_2 \rightarrow bW || t_2 \rightarrow tZ)$

$pp \rightarrow t_2\bar{t}_2, t_2 \rightarrow bW$



CERN-PH-EP-2012-081  
CMS-EXO-11-050

$pp \rightarrow t_2\bar{t}_2, t_2 \rightarrow tZ$

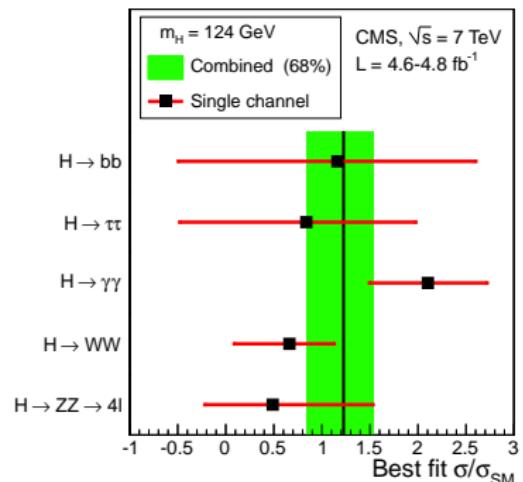
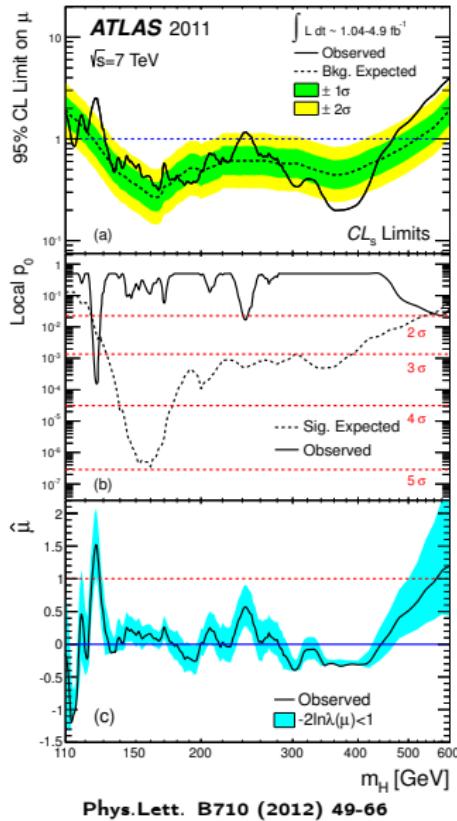


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- In our case we consider  $B_{t_2 \rightarrow th}$ ,  $B_{t_2 \rightarrow tZ}$ ,  $B_{t_2 \rightarrow bW}$

# Experimental constraints from higgs searches



Phys. Lett. B710 (2012) 26-48

- Exclusion or discovery of SM should happen this year's 8 TeV data
- BSM Higgs? BSM Higgs production?
- EWK fit constraints taken into account

# Choice of benchmark points

Parameter Set	A1	A2	B	C	D
$Y / \bar{Y}$	-1.43 / 2	1.02 / -0.1	1.15 / 0.4	1.12 / -0.5	1.05 / -0.3
$Y' / Y''$	1.85 / -1	1 / 0.55	-1.5 / 1.6	1.1 / 1.65	1.7 / 1.9
$m / m' (\text{GeV})$	0 / 370	0 / 675	0 / 770	0 / 810	80 / 1100
$m'' (\text{GeV})$	510	645	980	850	1100
$m_{t_3} (\text{GeV})$	722	804	1181	1125	1454
$m_{t_2} (\text{GeV})$	403	599	626	572	788
$m_h (\text{GeV})$	125	125	255	320	540
$\sigma_{gg \rightarrow h}^{\text{SM}} (\text{pb}) @ 7 \text{ TeV}$	15.31	15.31	3.18	2.25	0.58
$\sigma_{gg \rightarrow h}^{\text{SM}} (\text{pb}) @ 14 \text{ TeV}$	49.85	49.85	13.50	10.59	3.85
$\sigma_{gg \rightarrow h}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}}$	1.27	1.31	0.45	0.40	0.65
$\sigma_{\tilde{t}_1 \tilde{t}_1 h}^{t'} (\text{pb}) @ 7 \text{ TeV}$	0.0194	0.076	0.0037	0.0016	$7 \cdot 10^{-4}$
$\sigma_{\tilde{t}_1 \tilde{t}_1 h}^{t'} (\text{pb}) @ 14 \text{ TeV}$	0.138	0.0760	0.036	0.021	0.015
$\sigma_{\tilde{t}_2 \tilde{t}_2} (\text{pb}) @ 7 \text{ TeV}$	1.361	0.0936	0.0709	0.136	0.0115
$\sigma_{\tilde{t}_2 \tilde{t}_2} (\text{pb}) @ 14 \text{ TeV}$	13.53	1.465	1.164	1.975	0.284
$B_{t_2 \rightarrow t_1 h} (\%)$	62.6	82.1	60.8	13.5	43.0
$B_{t_2 \rightarrow t_1 Z} (\%)$	28.6	14.7	25.0	46.1	40.3
$B_{t_2 \rightarrow bW} (\%)$	8.8	3.2	14.2	40.4	16.6
$\Gamma_{t_2} (\text{GeV})$	4.4	3.5	19.8	6.5	8.8
$\sigma_{\tilde{t}_2 \tilde{t}_2} B_{t_2 \rightarrow bW}^2 (\text{pb})$	0.01	$1.5 \cdot 10^{-}$	0.001	0.022	0.000(3)
LHC bound (CMS)	< 0.26	< 0.14	< 0.14	< 0.16	×
$\sigma_{\tilde{t}_2 \tilde{t}_2} B_{t_2 \rightarrow t_1 Z}^2 (\text{pb})$	0.11	0.002	0.004	0.029	0.002
LHC bound (CMS)	< 0.5	< 0.4	< 0.4	< 0.4	×
$S / T$	0.05 / 0.05	0.03 / 0.03	-0.01 / 0.23	-0.01 / 0.30	-0.01 / 0.28

# Sensitivity study

## Process

- LHC at  $\sqrt{s} = 14 \text{ TeV}$
- Production:  $pp \rightarrow t_2 \bar{t}_2$
- Decay:  $t_2 \rightarrow th$ ,  $t_2 \rightarrow tZ$  or  $t_2 \rightarrow bW$
- $thbW$ ,  $thtZ$ ,  $thth$  final states

## Search channels

Best sensitivity and measurement of Higgs mass:

- $h \rightarrow ZZ$  for  $m_h > 200 \text{ GeV}$   
(points B C D)
- $h \rightarrow \gamma\gamma$  for  $m_h = 125 \text{ GeV}$   
(points A1 A2)

## Analysis chain

- Signal model:
  - implemented in FeynRules (N. D. Christensen et al. 2009)
  - interfaced with MadGRAPH for MC generation (M. Herquet et al. 2008)
  - PYTHIA for hadronization (T. Sjostrand et al. 2006)
  - DELPHES for fastsim of LHC detector (CMS) (S. Ovyn et al. 2009)
- Backgrounds: ALPGEN (M. L. Mangano et al. 2003) → PYTHIA → DELPHES

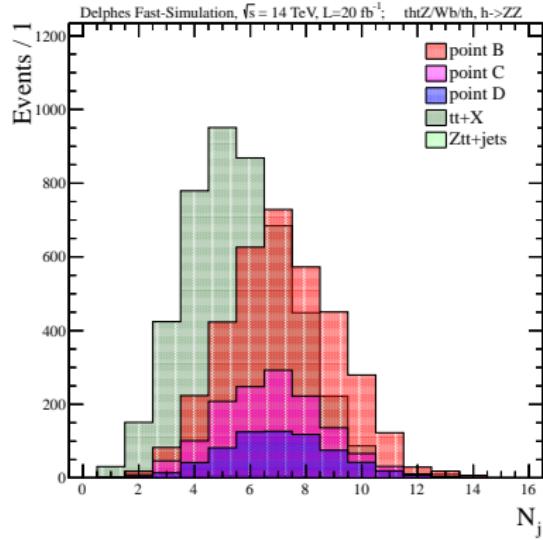
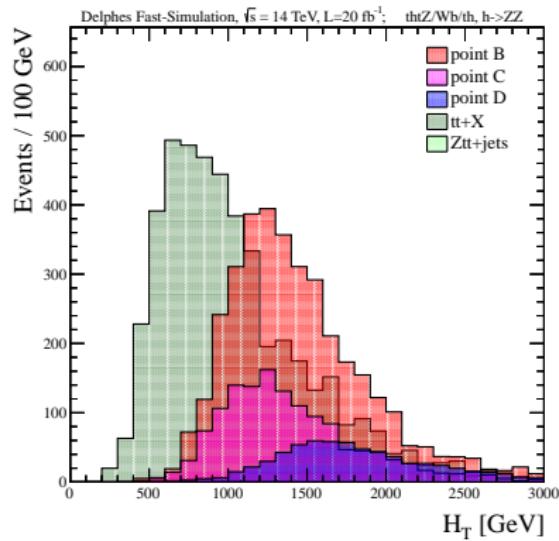
# Four leptons + multijets channel (1)

Parameter set	$m_{t_2}$ (GeV)	$m_h$ (GeV)	$\sigma_{t_2 t_2}$ (fb)	$B_{t_2 \rightarrow th}$	$B_{t_2 \rightarrow tZ}$	$B_{t_2 \rightarrow bW}$	$B_{h \rightarrow VV}^{SM}$	$f_{h \rightarrow VV}^{t'/SM}$	$\Upsilon_S(h \rightarrow VV)(fb)$		
									$tbhW$	$thtZ$	$thth$
Point A1	403	125	$1.353 \cdot 10^4$	0.626	0.286	0.088	$2.29 \cdot 10^{-3}$	0.91	3.11	10.1	22.1
Point A2	599	125	$1.465 \cdot 10^3$	0.821	0.147	0.032	$2.29 \cdot 10^{-3}$	0.90	0.159	0.729	4.07
Point B	626	255	$1.164 \cdot 10^3$	0.608	0.250	0.142	0.298	1.00	59.9	105	256
Point C	572	320	$1.975 \cdot 10^3$	0.135	0.461	0.404	0.309	1.00	66.6	76.0	22.2
Point D	788	540	$0.284 \cdot 10^3$	0.430	0.403	0.166	0.265	1.06	11.4	27.6	29.5

$h \rightarrow ZZ \rightarrow 4l + \text{jets}$  (B C D)

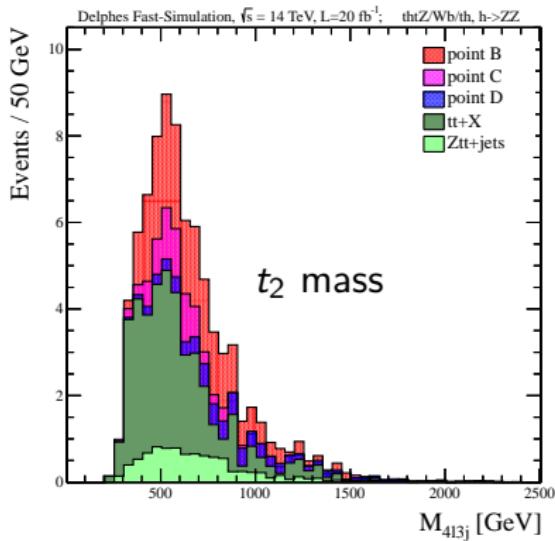
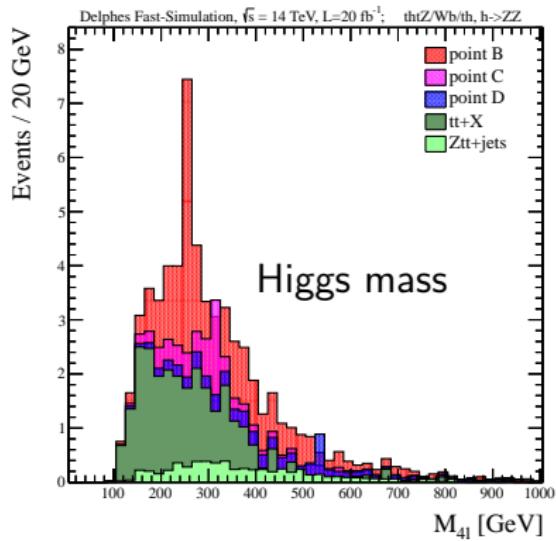
- $N_l > 4$ , with  $p_T^l > 20$  GeV and  $|\eta^l| < 2.4(2.5)$  muons (electrons)
- Two lepton pairs of same flavour and opposite charge leptons
- $M_{2l}^{lead} = M_Z \pm 15$  GeV and  $M_{2l}^{trail} > 12$  GeV

# Four leptons + multijets channel (2)



- $H_T > 1000 \text{ GeV}$  and  $N_j > 5$ 
  - $H_T$  scalar sum of the transverse momenta of identified leptons, photons, jets, and the missing energy
  - $N_j$  number of hadronic jets with  $p_T > 30 \text{ GeV}$  and  $|\eta| < 2.4$
- At least two b-tagged jets in the event.

# Four leptons + multijets channel (3)



Parameter set	Signal: $\text{thbW}/\text{thtZ}/\text{thth}, h \rightarrow \text{ZZ}$				Total signal $S, M_{4l}(\text{GeV})$ cut			
	$Y_S (\text{fb})$	$N_{4l}$	$N_{N_l, H_T}$	$N_{2b}$	no $M_{4l}$ cut	$M_{4l} > 200$	$> 300$	$> 500$
Point B	59.9 / 105 / 256	8.1 / 23.7 / 37.8	5.5 / 18.0 / 28.9	3.52 / 11.5 / 18.5	33.4	30.4	17.0	4.9
Point C	66.6 / 76.0 / 22.2	7.7 / 15.8 / 3.1	4.8 / 11.3 / 2.2	3.07 / 7.23 / 1.41	11.7	10.7	7.4	2.0
Point D	11.4 / 27.6 / 29.5	1.5 / 6.6 / 4.7	1.1 / 5.3 / 3.9	0.70 / 3.40 / 2.50	6.6	6.2	5.1	2.7
Background								
Process	$\sigma (\text{fb})$	$N_{4l}$	$N_{N_l, H_T}$	$N_{2b}$	Total background $B, M_{4l}(\text{GeV})$ cut			
$t\bar{t} + \text{jets}$	$9.19 \cdot 10^5$	4680	1480	27.5	no $M_{4l}$ cut	$M_{4l} > 200$	$> 300$	$> 500$
$t\bar{t}b\bar{b} + \text{jets}$	$2.50 \cdot 10^3$	5.60	3.10	2.0	35.5	23.5	13.2	6.8
$t\bar{t}W + \text{jets}$	$1.99 \cdot 10^2$	1.20	0.40	0.036	Statistical $\Delta B, M_{4l}(\text{GeV})$ cut			
$t\bar{t}Z + \text{jets}$	97.3	25.0	9.5	6.0	no $M_{4l}$ cut	$M_{4l} > 200$	$> 300$	$> 500$
					6.0	4.9	3.6	2.6

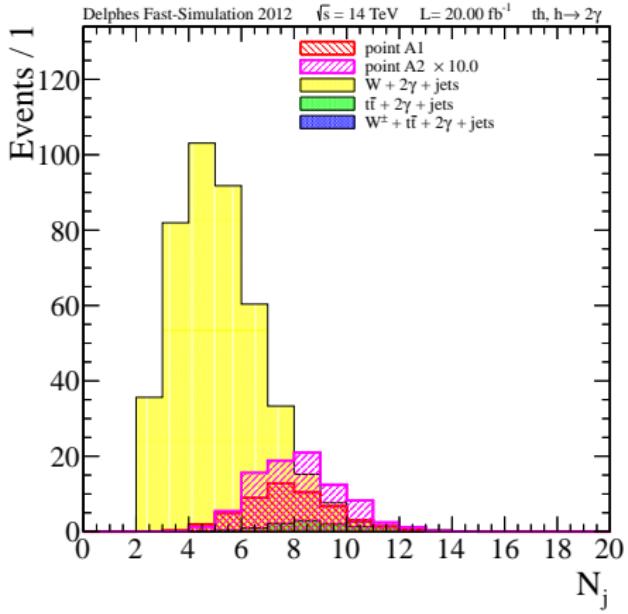
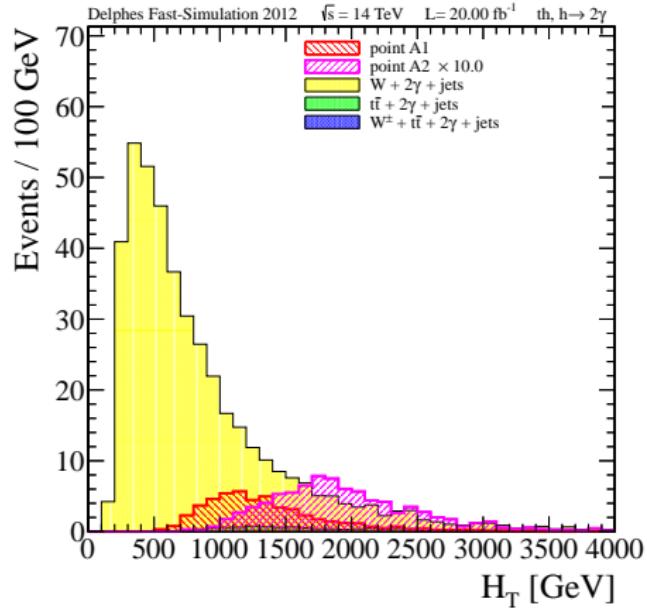
# Diphoton + multijets channel (1)

Parameter set	$m_{t_2}$ (GeV)	$m_h$ (GeV)	$\sigma_{t_2 t_2}$ (fb)	$B_{t_2 \rightarrow th}$	$B_{t_2 \rightarrow tZ}$	$B_{t_2 \rightarrow bW}$	$B_{h \rightarrow VV}^{SM}$	$f_{h \rightarrow VV}^{t'/SM}$	$\mathcal{Y}_S(h \rightarrow VV)(fb)$		
									$thbW$	$thtZ$	$thth$
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Point B	626	255	$1.164 \cdot 10^3$	0.608	0.250	0.142	0.298	1.00	59.9	105	256
Point C	572	320	$1.975 \cdot 10^3$	0.135	0.461	0.404	0.309	1.00	66.6	76.0	22.2
Point D	788	540	$0.284 \cdot 10^3$	0.430	0.403	0.166	0.265	1.06	11.4	27.6	29.5

$h \rightarrow \gamma\gamma + \text{jets}$  (A1 A2)

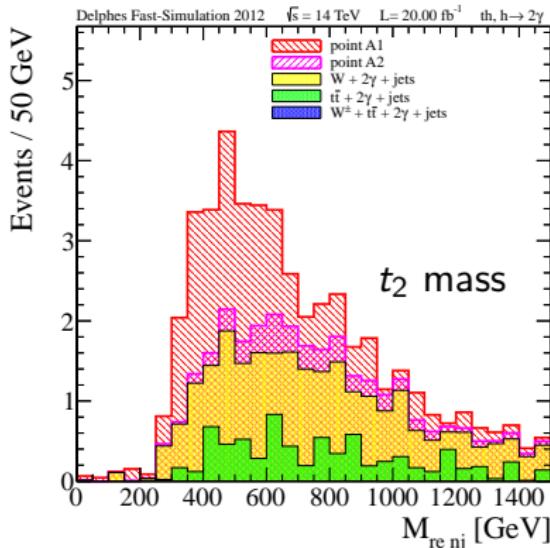
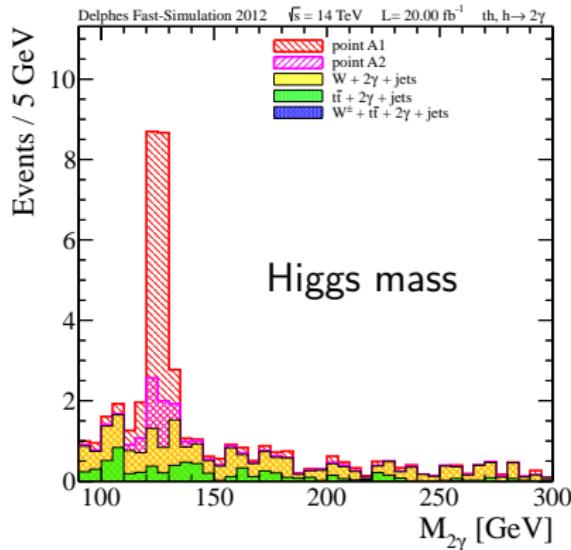
- $|\eta^\gamma| < 2.5$ ,  $p_T^{\gamma, \text{lead}} > 45 \text{ GeV}$ ,  $p_T^{\gamma, \text{trail}} > 30 \text{ GeV}$
- Combined tracker, ecal, hcal isolation
- $M_{2\gamma} > 90 \text{ GeV}$
- Hadronic jets with  $p_T^j > 30 \text{ GeV}$  and  $|\eta^j| < 2.4$

# Diphoton + multijets channel (2)



- No  $H_T$  cut in this case
- $N_j > 6(8)$  at preselection (final selection)

# Diphoton + multijets channel (3)



Parameter set	Signal: $thbW/thtZ/thth, h \rightarrow \gamma\gamma$				Total signal $S, M_{2\gamma}(\text{GeV})$ cut	
	$Y_S (\text{fb})$	$N_{2\gamma}$	$N_{N_l > 6}$	$N_{N_l > 8}$	$M_{2\gamma} > 90$	$M_{2\gamma} = [115, 135]$
Point A1	3.1 / 10.1 / 22.1	5.4 / 15.4 / 30.4	4.1 / 12.7 / 27.1	1.4 / 6.2 / 14.5	22.1	17.7
Point A2	0.16 / 0.73 / 4.1	0.34 / 1.35 / 6.98	0.27 / 1.17 / 6.6	0.10 / 0.62 / 3.8	4.5	3.2
Background						Total background $B, M_{2\gamma}(\text{GeV})$ cut
Process	$\sigma(\text{fb})$	$N_{M_{2\gamma} > 90}$	$N_{N_l > 6}$	$N_{N_l > 8}$	$M_{2\gamma} > 90$	$M_{2\gamma} = [115, 135]$
$W\gamma\gamma + \text{jets}$	450	422	110	19.6	27.8	4.38
$t\bar{t}\gamma\gamma + \text{jets}$	15.5	11.8	11.3	8.18	Statistical $\Delta B, M_{2\gamma}(\text{GeV})$ cut	
$t\bar{t}W\gamma\gamma + \text{jets}$	0.0678	0.0577	0.0515	0.0272	$M_{2\gamma} > 90$	$M_{2\gamma} = [115, 135]$
					5.3	2.1

# Results

For an integrated luminosity of  $20 \text{ fb}^{-1}$ :

- Signal for point A1 detectable with  $S/\Delta B \sim 9$ 
  - With  $B_{t_2 \rightarrow th} \sim 0.6$ , then  $S/\Delta B \gtrsim 5$  if  $B_{t_2 \rightarrow th} \gtrsim 0.3$
- Signal for point A2 expected  $S/\Delta B \sim 1.5$ 
  - For  $S/\Delta B \gtrsim 5$ : at least  $10\times$  luminosity, or better background rejection
- Signal for point B detectable with  $S/\Delta B \sim 6$ 
  - With  $B_{t_2 \rightarrow th} \sim 0.6$ , then  $S/\Delta B \gtrsim 5$  if  $B_{t_2 \rightarrow th} \gtrsim 0.5$
- Signal for point C expected  $S/\Delta B \sim 2$ 
  - With  $B_{t_2 \rightarrow th} \sim 0.1$ , then  $S/\Delta B \gtrsim 5$  if  $B_{t_2 \rightarrow th} \gtrsim 0.25$
- Signal for point D expected  $S/\Delta B \sim 1.4$ 
  - For  $S/\Delta B \gtrsim 5$ : at least  $10\times$  luminosity, or better background rejection

# Conclusion

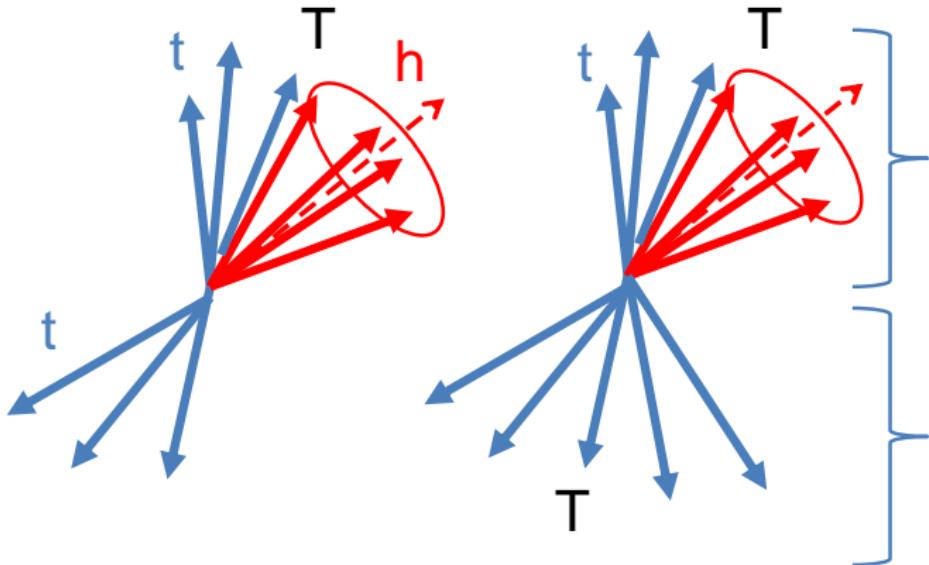
- There exist BSM parameter space allowed by present constraints for heavy vector-like top partner production, which may give rise to new Higgs production channel
- New possibilities to discover a Higgs boson and/or measure its properties
  - 14 TeV LHC with luminosities 20-200 fb-1
  - $pp \rightarrow t_2\bar{t}_2 \rightarrow tbW, thZ, thth$  with  $h \rightarrow \gamma\gamma$  and  $h \rightarrow ZZ \rightarrow 4l$  decays
- Investigate Higgs boson production over the whole mass range 120-600 GeV
- Measure Higgs and heavy top masses (+ other properties) with 200fb-1 or more
- Details in [arXiv:hep-ph/1204.0455](https://arxiv.org/abs/hep-ph/1204.0455)

# BACKUP

# Definition of T Hemispheres

 $pp \rightarrow Tt$  $pp \rightarrow TT$ 

<http://arxiv.org/abs/1204.0455>



«  $T \rightarrow h$  »  
hemisphere  
identified by the  
leptons or  
photons

Recoil T  
hemisphere  
contains  
recoiling  
jets

Kinematic fit shall test two different hypothesis: singly or pair produced T

# Choice of benchmark points (2)

[A1] ([A2])

$$\sigma_{\text{gg} \rightarrow h}^{\text{t}'} B_{h \rightarrow \gamma\gamma}^{\text{t}'} / \sigma_{\text{gg} \rightarrow h}^{\text{SM}} B_{h \rightarrow \gamma\gamma}^{\text{SM}} = 1.16 \text{ (1.19)} ; \quad \sigma_{\text{gg} \rightarrow h}^{\text{t}'} B_{h \rightarrow \text{WW}}^{\text{t}'} / \sigma_{\text{gg} \rightarrow h}^{\text{SM}} B_{h \rightarrow \text{WW}}^{\text{SM}} = 1.25 \text{ (1.28)}$$

$$\sigma_{\text{gg} \rightarrow h}^{\text{t}'} B_{h \rightarrow ZZ}^{\text{t}'} / \sigma_{\text{gg} \rightarrow h}^{\text{SM}} B_{h \rightarrow ZZ}^{\text{SM}} = 1.25 \text{ (1.28)} ; \quad \sigma_{\text{gg} \rightarrow h}^{\text{t}'} B_{h \rightarrow \tau\tau}^{\text{t}'} / \sigma_{\text{gg} \rightarrow h}^{\text{SM}} B_{h \rightarrow \tau\tau}^{\text{SM}} = 1.25 \text{ (1.28)}$$

$$\sigma_{\text{gg} \rightarrow h}^{\text{t}'} B_{h \rightarrow bb}^{\text{t}'} / \sigma_{\text{gg} \rightarrow h}^{\text{SM}} B_{h \rightarrow bb}^{\text{SM}} = 1.25 \text{ (1.28)}$$

The cross section for the Higgs production is enhanced,

$$\sigma_{\text{gg} \rightarrow h}^{\text{t}'} / \sigma_{\text{gg} \rightarrow h}^{\text{SM}} = 1.27 \text{ (1.31)},$$

due to the combination of two possible effects: the increase of the  $t_1$  Yukawa coupling and the constructive interferences between the  $t_1$  contribution and the  $t_2$ ,  $t_3$  ones. In contrast, the branching fraction for the decay channel into diphoton is slightly decreased,

$$B_{h \rightarrow \gamma\gamma}^{\text{t}'} / B_{h \rightarrow \gamma\gamma}^{\text{SM}} = 0.91 \text{ (0.90)}.$$

# Choice of benchmark points (3)

(B, C, D)

$$\sigma_{gg \rightarrow h}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}} = 0.45 \quad [B] ; \quad 0.40 \quad [C]$$

$$\sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow ZZ}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow ZZ}^{\text{SM}} = 0.69 \quad \sigma_{gg \rightarrow h}^{t'} B_{h \rightarrow WW}^{t'} / \sigma_{gg \rightarrow h}^{\text{SM}} B_{h \rightarrow WW}^{\text{SM}} = 0.69$$

where

$$B_{h \rightarrow ZZ}^{t'} / B_{h \rightarrow ZZ}^{\text{SM}} = 1.06 \quad B_{h \rightarrow WW}^{t'} / B_{h \rightarrow WW}^{\text{SM}} = 1.06 \quad [D].$$