The fate of the Littlest Higgs Model with T-parity under 13 TeV LHC Data

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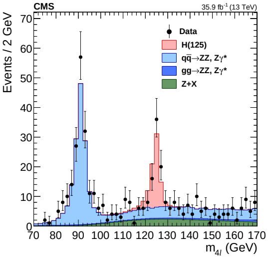
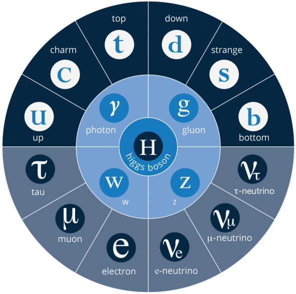
Based on [1801.06499] with D. Dercks, G. Moortgat-Pick and J. Reuter

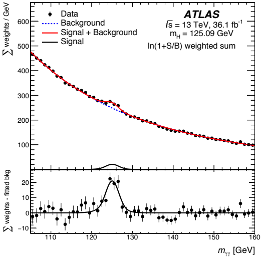
Outline

1. 125GeV Higgs boson
   - Hierarchy Problem
   - Higgs as a pseudo-Nambu Goldstone boson
   - Little Higgs mechanism
2. Little Higgs models
   - Littlest Higgs model
   - with T-parity
   - T-parity violation
   - Model parameters
   - Benchmark scenarios
3. LHC analyses
   - Fermion universal case
   - Heavy q_H case
   - EWPO; 4-fermion operators

Standard Model







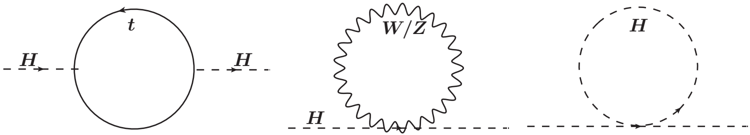
SM

- $M_H \sim 125$ GeV
- Couplings to gauge bosons and fermions are consistent with that of SM predictions.

Hierarchy Problem

Quadratic divergence

- Naturally, Higgs boson mass $M_H \sim \mathcal{O}(\Lambda^2)$
  $M^2(Q) = M^2(\mu) + \delta M^2$, where $\delta M^2 = \sum_i g_i (-1)^{2S_i} \frac{\lambda_i^2 M_i^2}{32\pi^2} \log(\frac{Q^2}{\pi^2})$



$\sim \Lambda^2$

$$M_H^2 = M_0^2 + \Lambda^2 \times \text{(loop-factor)}$$

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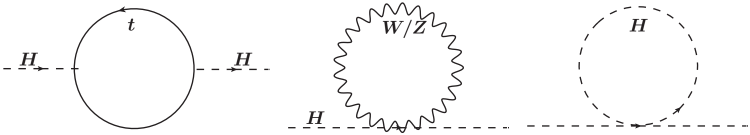


$\sim \Lambda^2$

$\sim \mathcal{O}$(TeV)

$$M_H^2 = M_0^2 + \Lambda^2 \times \text{(loop-factor)}$$

$$\gg (125\text{GeV})^2$$

Nambu-Goldstone Theorem

For each spontaneously broken global symmetry generator there is a massless boson in the spectrum.

Higgs as a pseudo-Nambu Goldstone boson

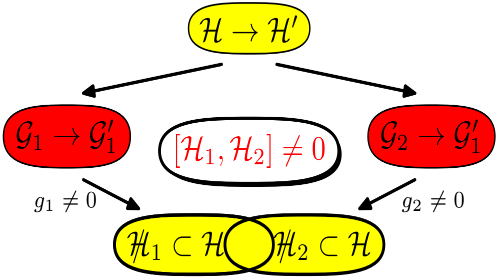
- NGB fields arising when G/H at a scale f [Georgi/Pais, '75; Georgi/Kaplan, '84]
- Large enough G
- $G \supset SU(2)_L \times U(1)_Y \equiv G_{\text{SM}}$

Little Higgs mechanism

Two assumptions

Collective Symmetry Breaking

- $G \supset \mathcal{H}_1 \times \mathcal{H}_2$
- One of $\mathcal{H}_1, \mathcal{H}_2$ is unbroken $\Rightarrow$ The Higgs remains massless.
- Quadratically divergent contributions to M_H vanish at one-loop.

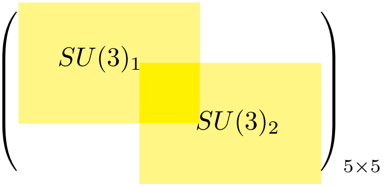


Littlest Higgs model

Arkani-Hamed/Cohen/Katz/Nelson, [hep-ph/0206021]

•Global symmetry and •Gauge symmetry

- $SU(5)/SO(5)$ symmetry breaking triggered by $\langle\Sigma\rangle = \begin{pmatrix} & & \mathbf{1} \\ & 1 & \\ \mathbf{1} & & \end{pmatrix}$
- $\Sigma(x) = e^{2i\Pi^a(x)X^a/f}\langle\Sigma\rangle$ where $\Pi^a X^a = \frac{1}{\sqrt{2}}\begin{pmatrix} & H^\dagger & \\ H & & H^* \\ & H^T & \end{pmatrix} + \frac{1}{2}\begin{pmatrix} & & \Phi^\dagger \\ & & \\ \Phi & & \end{pmatrix}$
- $(SU(2)_1 \times U(1)_1 \times SU(2)_2 \times U(1)_2)\,/\,(SU(2)_L \times U(1)_Y)$
- $W^a_{1\mu}, W^a_{2\mu}, B_{1\mu}, B_{2\mu} \;\Rightarrow W^\pm_H, Z_H, A_H$ and $W^\pm_\mu, Z_\mu, B_\mu$



- $SU(5) \supset SU(3)_1 \times SU(3)_2$
- 14 Broken generators X^a
- breaking scale f
- SM-like Higgs H
- $M_\Phi \sim \mathcal{O}$(TeV)

Cancellation of radiative corrections

- Heavy gauge bosons : $W^\pm_H,\ Z_H$
- Heavy fermions : top-partner T_+

Littlest Higgs model; top partner

Perelstein, hep-ph/0512128

- a pair of weak-singlet Weyl fermion U_L and U_R with electric charge $+2/3$ is introduced additionally.
- couple to the third generation quark doublet $q_{3L} = (t_L, b_L)^T$ and to the singlet t_R

$$\mathcal{L}_{\text{top}} = -\frac{\lambda_1}{2} f \chi^{\dagger}_{L_i} {}_{ijkmn} \Sigma_{jm} \Sigma_{kn} t_R - \lambda_2 f U_L^{\dagger} U_R + \text{h.c.},$$

where

$$\chi_L = \begin{pmatrix} \sigma_2 q_{3L} \\ U_L \end{pmatrix}$$

is the $SU(3)$ triplet.

Littlest Higgs model; top partner

Perelstein, hep-ph/0512128

- Σ_{jm} refers to the 3×2 upper-right block of the Σ
- Expanding the Σ field, after the spontaneous symmetry breaking at the scale f, but without the mixing by EWSB, their mass eigenstates are given by

$$t_L = u_L, \qquad t_R = \frac{\lambda_2 u_{3R} - \lambda_1 U_R}{\sqrt{\lambda_1^2 + \lambda_2^2}},$$

$$T_L = U_L, \qquad T_R = \frac{\lambda_1 u_{3R} + \lambda_2 U_R}{\sqrt{\lambda_1^2 + \lambda_2^2}}.$$

$$M_T = \sqrt{\lambda_1^2 + \lambda_2^2} f$$

Littlest Higgs model; top partner

Perelstein, hep-ph/0512128

$$\lambda_1 \left(\sqrt{2} q_L^\dagger \tilde{H} - \frac{1}{f} H^\dagger H U_L^\dagger \right) u_{3R} + \text{h.c.}$$

$$= \lambda_t q_L^\dagger \tilde{H} t_R + \lambda_T q_L^\dagger \tilde{H} T_R - \frac{1}{\sqrt{2} f} (H^\dagger H) T_L^\dagger (\lambda_T T_R + \lambda_t t_R) + \text{h.c.},$$

where $\tilde{H} = i\sigma^2 H$.

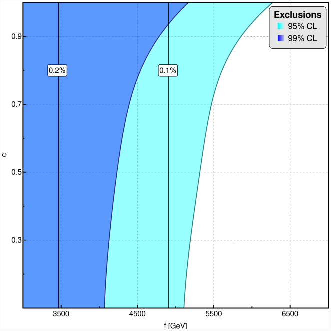
- The first term, $\lambda_t q_L^\dagger H t_R$, is the usual up-type Yukawa coupling.
- which becomes the top quark mass term after EWSB, as the Higgs field gets a *vev*.
- The SM top quarks mass is given with the definition of λ_t and λ_T as

$$M_t = \lambda_t v, \text{ where } \quad \lambda_t = \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}}, \qquad \lambda_T = \frac{\lambda_1^2}{\sqrt{\lambda_1^2 + \lambda_2^2}}.$$

T-parity: a discrete symmetry

Cheng/Low, [hep-ph/0308199], [hep-ph/0405243]

Littlest Higgs

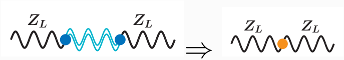


- Large contributions to EWPO

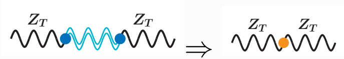
Hewett/Petriello/Rizzo, [hep-ph/0211124];

Csáki/Hubisz/Kribs/Meade/Terning, [hep-ph/0211218];

Kilian/Reuter, [hep-ph/0311095]



$\Delta T \sim \Delta\rho \sim \Delta M_Z^2 \, Z \cdot Z$



$\Delta S \sim W^0_{\mu\nu} B^{\mu\nu}, \quad \Delta U \sim W^0_{\mu\nu} W^{0\mu\nu}$

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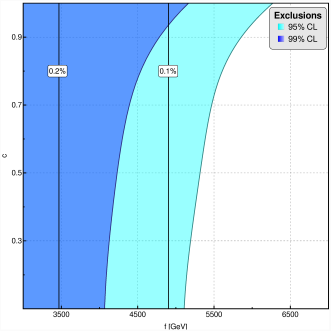
Littlest Higgs



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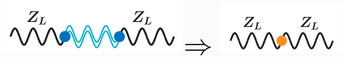

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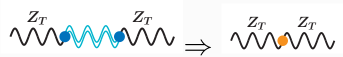


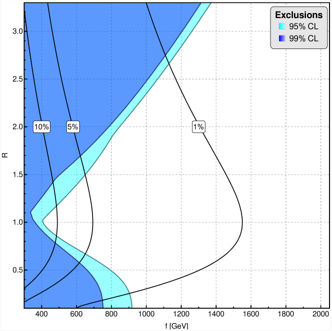
$\Delta S \sim W^0_{\mu\nu} B^{\mu\nu}, \quad \Delta U \sim W^0_{\mu\nu} W^{0\mu\nu}$

- $T: \quad \Pi \to -\Omega\Pi\Omega$ where $\Omega = \text{diag}(1,1,-1,1,1)$
- $T: \quad T^a \to T^a, \quad X^a \to -X^a$
- $T: \quad W^a_{2\mu} \leftrightarrow W^a_{1\mu}, \; B_{1\mu} \leftrightarrow B_{2\mu}$

T-parity: a discrete symmetry

Cheng/Low, [hep-ph/0308199], [hep-ph/0405243]

Littlest Higgs with T-parity

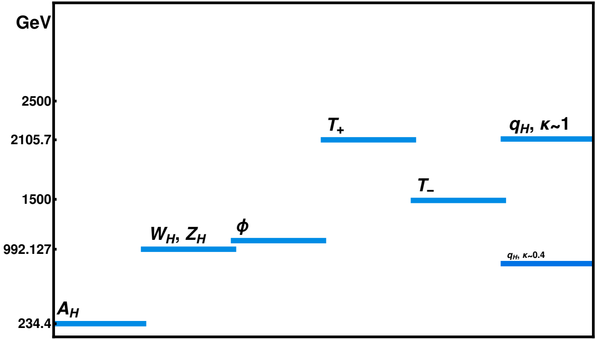


T-parity conservation

- eliminates tree-level contributions to EWPO.
- makes bounds relaxed on parameter space.
- allows only pair production of T-odd particles at colliders.
- Lightest T-odd particle is stable.
  $\rightarrow$Dark Matter candidate

- $T: \quad \Pi \to -\Omega\Pi\Omega$ where $\Omega = \mathrm{diag}(1,1,-1,1,1)$
  $T: \quad T^a \to T^a, \quad X^a \to -X^a$
- SM particles : T-parity *even*
- Heavy new particles : T-parity *odd* except for top-partner, T_+

T-parity; Particle Mass plot



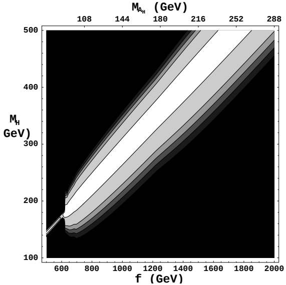
$f = 1500$GeV, $R = 1$

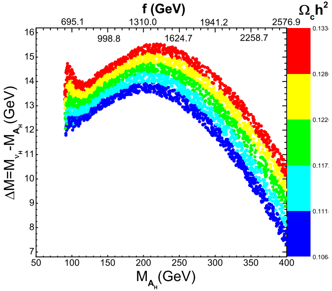
New particles

- Heavy Gauge bosons, A_H, W_H , Z_H
- top-partners, T_+, T_-
- T-parity odd fermion partners, q_H, ℓ_H; u_H, d_H, ..., t_H, ...

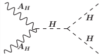
T-parity; Dark Matter candidates

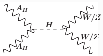
the Lightest T-odd particle: A_H





- Hubiz/Meade, [hep-ph/04111264]
- Dominant decay via s-channel Higgs exchange;





- Constraints from overclosure of universe

- Yang/Wang/Zhu, [1307.7780]; Wu/Yang/Zhang, [1607.06355]
- Severe constraints from direct detection

T-parity; Dark Matter candidates

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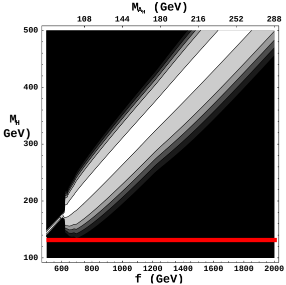

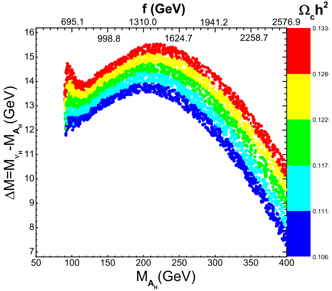

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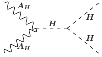

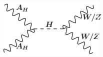

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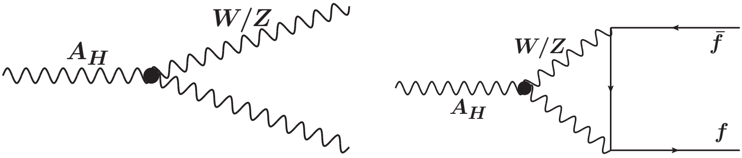
- Severe constraints from direct detection

T-parity violation

- Wess-Zumino-Witten anomaly in UV sector
  Hill and Hill, [0705.0697]; Freitas, Schwaller, and Wyler [0806.3674]
- $A_H \to WW, ZZ$ and $A_H \to ff$.



- $\Gamma(A_H \to ZZ) = \frac{1}{2\pi}\left(\frac{Ng'}{40\sqrt{3}\pi^2}\right)^2 \frac{M_{A_H}^3 m_Z^2}{f^4}\left(1 - \frac{4m_Z^2}{M_{A_H}^2}\right)^{\frac{5}{2}}$
- $\Gamma(A_H \to WW) = \frac{1}{\pi}\left(\frac{Ng'}{40\sqrt{3}\pi^2}\right)^2 \frac{M_{A_H}^3 m_W^2}{f^4}\left(1 - \frac{4m_W^2}{M_{A_H}^2}\right)^{\frac{5}{2}}$
- $\Gamma(A_H \to ff) = \frac{N_{C_f} M_{A_H}}{48\pi}\sqrt{1 - \frac{4m_f^2}{M_{A_H}^2}}\left(c_-^2\left(1 - \frac{4m_f^2}{M_{A_H}^2}\right) + c_+^2\left(1 + \frac{2m_f^2}{M_{A_H}^2}\right)\right)$

T-parity violation

- Wess-Zumino-Witten anomaly in UV sector
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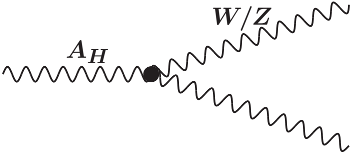
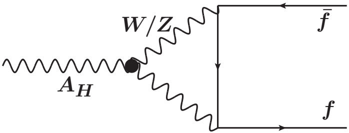
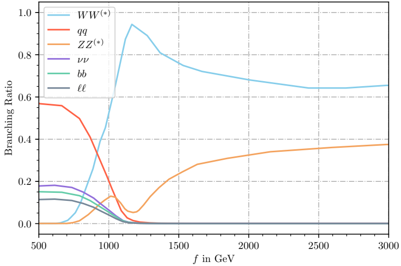






- $f \sim 1200\ \mathrm{GeV}$, threshold of the on-shell decay $A_H \to WW$
- In on-shell region $A_H \to WW$ has the largest branching ratio,
  in off-shell region the loop-induced decays become important.

Model parameters

New particles

- Heavy gauge bosons : $W_H^{\pm},\ Z_H,\ A_H$
- Heavy fermions : $u_H,\ d_H,\ \cdots,\ t_H\ , e_H,\ \ell_H\ \cdots$, top-partner T_+, T_-

Heavy gauge boson mass terms

- $M_{W_H} = gf$
- $M_{Z_H} = gf$
- $M_{A_H} = \frac{g' f}{\sqrt{5}}$

Scan parameters

$\{\ f\ \ \}$

- f: the symmetry breaking scale
-

Model parameters

New particles

- Heavy gauge bosons : $W_H^{\pm},\ Z_H,\ A_H$
- Heavy fermions : $u_H,\ d_H,\ \cdots,\ t_H$, $e_H,\ \ell_H\ \cdots$, top-partner T_+, T_-

T-odd fermion mass terms

- $M_{u_H} = \sqrt{2}\kappa_q f \left(1 - \frac{1}{8}\frac{v^2}{f^2}\right)$
- $M_{d_H} = \sqrt{2}\kappa_q f$
- $M_{\ell_H,\nu_H} = \sqrt{2}\kappa_\ell f$

Scan parameters

$\{\ f\ ,\ \kappa_q\ ,\ \kappa_\ell\ \}$

- f: the symmetry breaking scale
- κ_q, κ_ℓ: Yukawa coupling constant of T-odd fermions

Model parameters

New particles

- Heavy gauge bosons : $W_H^{\pm},\ Z_H,\ A_H$
- Heavy fermions : $u_H,\ d_H,\ \cdots,\ t_H,\ e_H,\ \ell_H\ \cdots$, top-partner T_+, T_-

Top and top-partner mass terms

- $M_t = \frac{\lambda_1 \lambda_2}{\lambda_1^2+\lambda_2^2} v = \frac{\lambda_2 R}{\sqrt{1+R^2}} v$
- $M_{T_-} = \lambda_2 f = \frac{M_t}{v} \frac{f\sqrt{1+R^2}}{R}$
- $M_{T_+} = \frac{M_t}{v} \frac{f(1+R^2)}{R}$
  $= M_{T_-} \sqrt{1+R^2}$

Scan parameters

$\{\ f\ ,\ R = \frac{\lambda_1}{\lambda_2}\ \}$

- f: the symmetry breaking scale
-
- R: the ratio of top Yukawa coupling constants

Model parameters

New particles

- Heavy gauge bosons : $W_H^\pm,\ Z_H,\ A_H$
- Heavy fermions : $u_H,\ d_H,\ \cdots,\ t_H$, $e_H,\ \ell_H\ \cdots$, top-partner T_+, T_-

Particle mass terms

- $M_t = \frac{\lambda_1\lambda_2}{\lambda_1^2+\lambda_2^2}v = \frac{\lambda_2 R}{\sqrt{1+R^2}}v$
- $M_{T_-} = \lambda_2 f = \frac{M_t}{v}\frac{f\sqrt{1+R^2}}{R}$
- $M_{T_+} = \frac{M_t}{v}\frac{f(1+R^2)}{R}$
  $= M_{T_-}\sqrt{1+R^2}$
- $M_{u_H} = \sqrt{2}\kappa_q f\left(1-\frac{1}{8}\frac{v^2}{f^2}\right)$
- $M_{d_H} = \sqrt{2}\kappa_q f$
- $M_{\ell_H,\nu_H} = \sqrt{2}\kappa_\ell f$
- $M_{W_H} = gf$
- $M_{Z_H} = gf$
- $M_{A_H} = \frac{g' f}{\sqrt{5}}$

Scan parameters

$\{\ f\ ,\ \kappa_q\ ,\ \kappa_\ell\ ,\ R = \frac{\lambda_1}{\lambda_2}\ \}$

- f: the symmetry breaking scale
- κ_q, κ_ℓ: Yukawa coupling constant of T-odd fermions
- R: the ratio of top Yukawa coupling constants

Benchmark scenarios

production processes

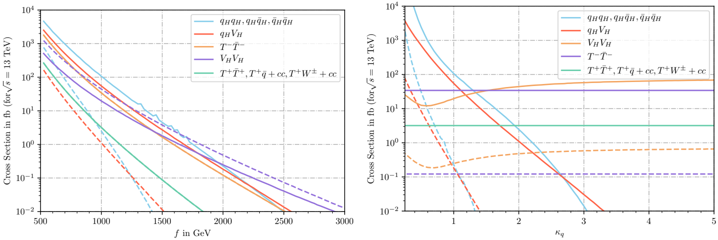
1. $pp \to q_H q_H, q_H \bar{q}_H, \bar{q}_H \bar{q}_H,$
2. $pp \to q_H V_H,$
3. $pp \to \ell_H \bar{\ell}_H$
4. $pp \to V_H V_H,$
5. $pp \to T_+ T_+, T_- T_-$
6. $pp \to T_+ \bar{q}, \bar{T}_+ q, T_+ W^\pm, \bar{T}_+ W^\pm$

- $q_H := \{u_H, d_H, s_H, c_H, b_H, t_H\}$
- $\ell_H := \{e_H, \mu_H\, \tau_H, \nu_{e_H}, \nu_{\mu_H}, \nu_{\tau_H}\}$
- $V_H := \{W_H, Z_H, A_H\}$

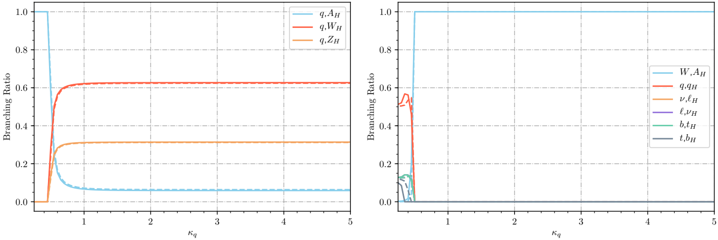
Sector	Model	Constraint	Phenomenology	Considered Topology
f_H	*Fermion Universality*	$\kappa_\ell = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible	Exclude process 3
	Heavy q_H	$\kappa_q = 4.0$	• q_H decoupled • ℓ_H production relevant	Exclude processes 1, 2
	Light ℓ_H	$\kappa_\ell = 0.2$	• ℓ_H very light • V_H branching ratios change	Exclude process 3
$T^\pm$	*Light* $T^\pm$	$R = 1.0$	• $T^\pm$ are light/accessible	Include process 4, 5
	Heavy $T^\pm$	$R = 0.2$	• $T^\pm$ are heavy/inaccessible	Exclude process 4, 5
A_H	*TPC*	No TPV	• A_H is stable and invisible	A_H stable
	TPV	With TPV	• A_H is unstable	$A_H \to VV$ decays

Productions and decays at the LHC

Fermion Universality model

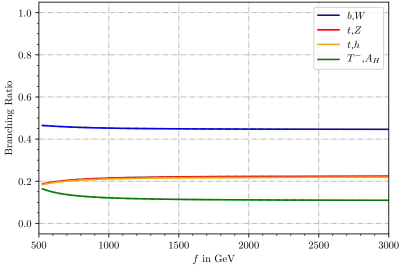


Left: for fixed $\kappa = 1.0$(solid), $\kappa = 2.0$ (dashed).
Right:for fixed $f = 1$ TeV (solid), $f = 2$ TeV (dashed).

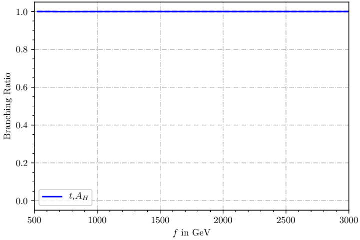


- d_H, $\quad M_{d_H} = \sqrt{2}\kappa_q f$
- W_H, $\quad M_{W_H} = g f$

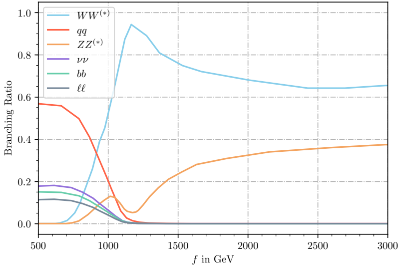
More Branching Ratio plots



- T_+



- T_-

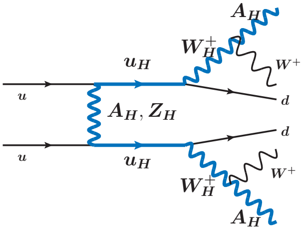


- A_H

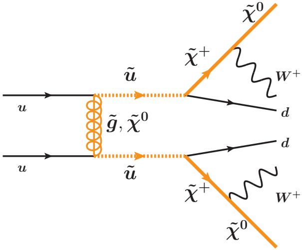
Tool chain for event simulation and recasting

- Steering program and Recasting tool
  - CheckMATE
    [Dercks/Desai/Kim/Rolbiecki/Tattersall/Weber, '16]
- Partonic events
  - MG_aMC@NLO
    [Alwall et al., '10]
  - WHIZARD v2.5
    [Kilian/Ohl/JRR, '10]
- Parton shower and hadronization
  - Pythia v.8.2
    [Sjöstrand/Mrenna/Skands, '08]
- Fast detector simulation
  - Delphes v3.2
    [de Favereau et al., '14]
- Clustering, jet selection
  - FastJet v3.3
    [Cacciari/Salam/Soyez, '11]

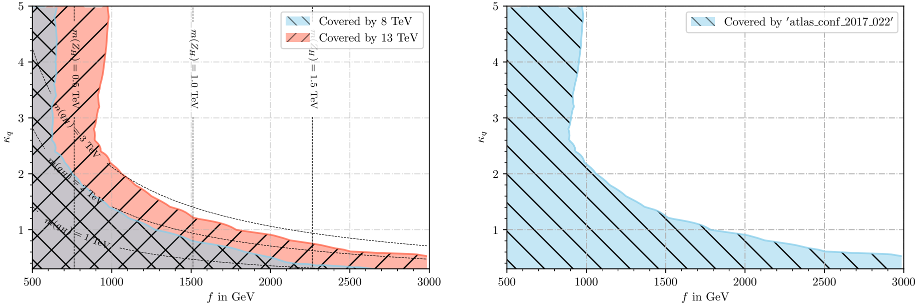
- q_H decay in LHT model



- squark decay in SUSY



Fermion universal case



Fermion Universality × Heavy $T^{\pm}$ × TPC

Sector	Model	Constraint	Phenomenology	Considered Topology
f_H	*Fermion Universality*	$\kappa_\ell = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible	Exclude process 3
	Heavy q_H	$\kappa_q = 4.0$	• q_H decoupled • ℓ_H production relevant	Exclude processes 1, 2
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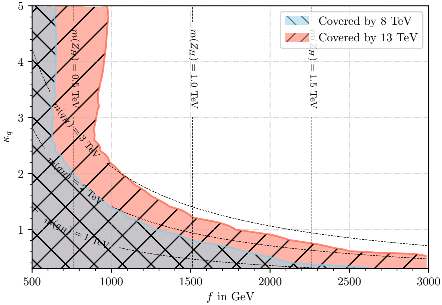
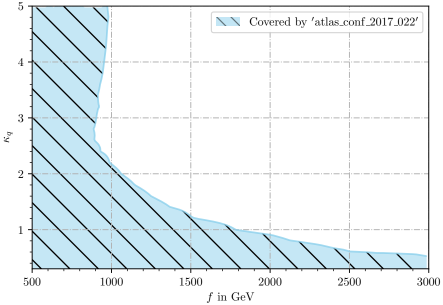
Fermion universal case





Fermion Universality $\times$ **Heavy** $T^{\pm}$ $\times$ **TPC**

- For high f, bounds run along M_{q_H} isocontour, $f\kappa < f\kappa_{\text{max}} \sim 2$ TeV for Run 2.
- $pp \to q_H q_H \to jjA_H A_H + X$
- For low f, κ -independent bound, because q_H too heavy to be produced, V_H production effects

- atlas_conf_2016_054: 1 lepton + jets + $\not{E}_T$
- atlas_conf_2016_096: 2-3 leptons + $\not{E}_T$
- **atlas_conf_2017_022: squarks and gluinos, 0ℓ, 2-6 jets + $\not{E}_T$**
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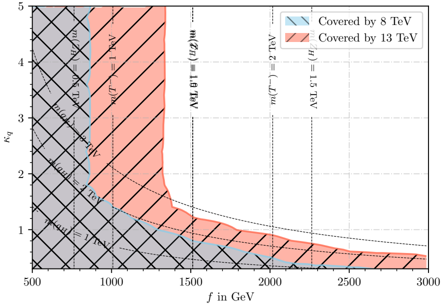
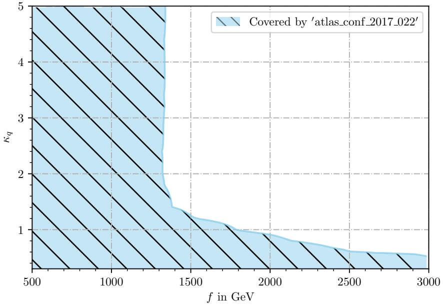
Fermion universal case





Fermion Universality × Light $T^{\pm}$ × TPC

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A_H	*TPC*	No TPV	• A_H is stable and invisible	A_H stable
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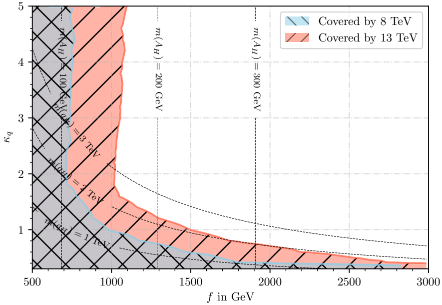
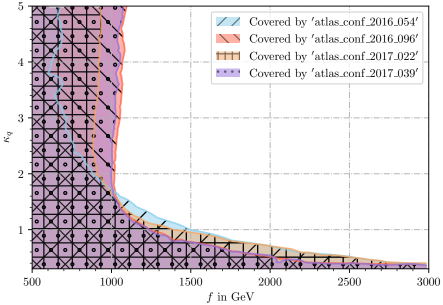
Fermion universal case





Fermion Universality $\times$ **Heavy** $T^{\pm}$ $\times$ **TPV**

Sector	Model	Constraint	Phenomenology	Considered Topology
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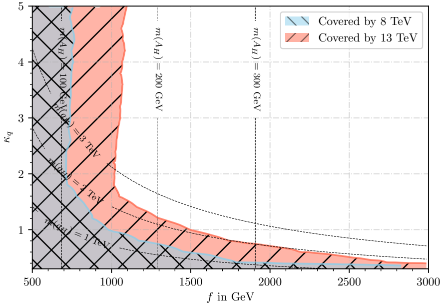
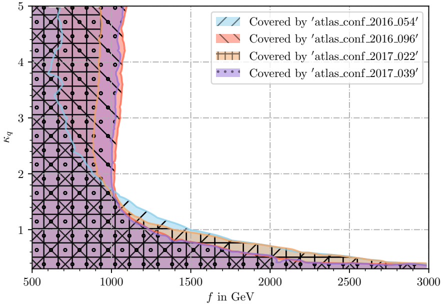
Fermion universal case





Fermion Universality $\times$ `Heavy` $T^{\pm}$ $\times$ `TPV`

- For high f, bounds run along M_{q_H} isocontour, $f\kappa < f\kappa_{\text{max}} \sim 2$ TeV for Run 2.
- For low f, κ -independent bound, because q_H too heavy to be produced, V_H production effects
- M_{q_H} isocontour bounds - slightly weakened and f-bound -improved. because more vector bosons are produced by TPV.

- `atlas_conf_2016_054`: 1 lepton + jets + $\not{E}_T$
- `atlas_conf_2016_096`: 2-3 leptons + $\not{E}_T$
- `atlas_conf_2017_022`: squarks and gluinos, 0ℓ, 2-6 jets + $\not{E}_T$
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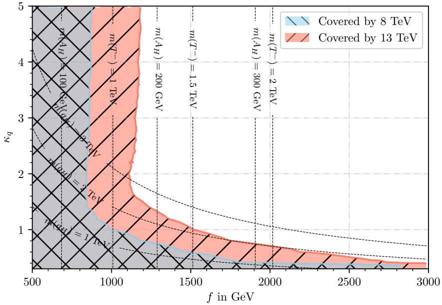
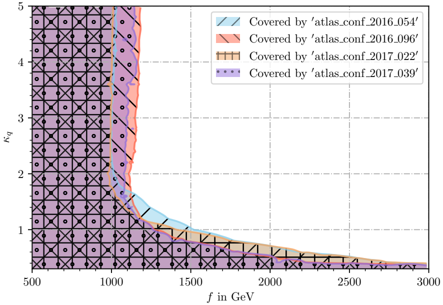
Fermion universal case





Fermion Universality $\times$ Light $T^{\pm}$ $\times$ TPV

Sector	Model	Constraint	Phenomenology	Considered Topology
f_H	*Fermion Universality*	$\kappa_\ell = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible	Exclude process 3
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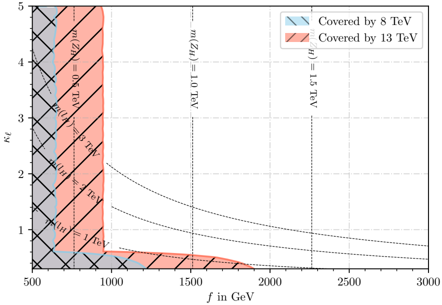
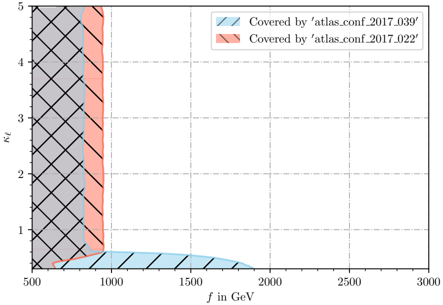
	TPV	With TPV	• A_H is unstable	$A_H \to VV$ decays

Heavy q_H case





Heavy q_H × Heavy $T^{\pm}$ × TPC

Sector	Model	Constraint	Phenomenology	Considered Topology
f_H	*Fermion Universality*	$\kappa_\ell = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible	Exclude process 3
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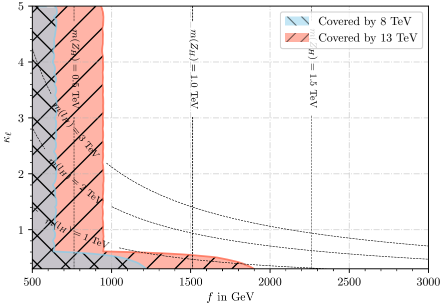
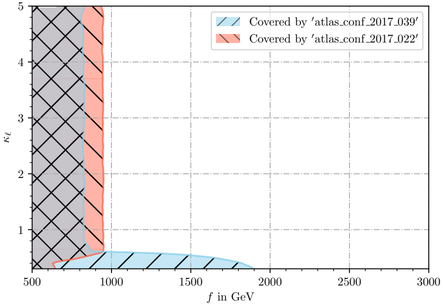
Heavy q_H case





Heavy q_H × Heavy $T^{\pm}$ × TPC

- Main decay topology changes from $q_H \to qV_H$ to $\ell_H \to \ell V_H$
- $\sigma_{(pp \to q_H q_H)} \gtrsim (2 \sim 3) \times \sigma_{(pp \to \ell_H \ell_H)}$
- For $\kappa_\ell \lesssim 0.5$, $V_H \to \ell \ell_H$

- `atlas_conf_2016_054`: 1 lepton + jets + $\not{E}_T$
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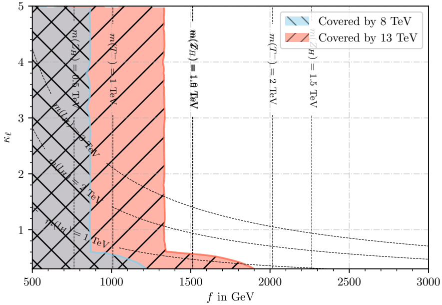
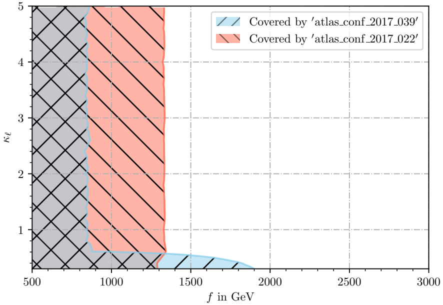
Heavy q_H case





Heavy q_H × Light $T^\pm$ × TPC

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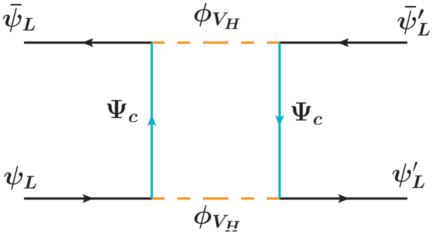
EWPO; 4-fermion operators

- low-energy bounds: flavor observables
- 4-fermion operators via box diagrams

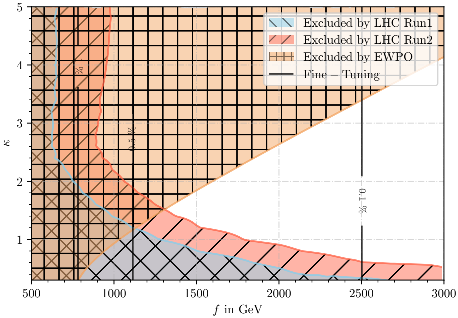
- ϕ_{V_H} : Goldstone boson of heavy gauge bosons
- Ψ_c : Mirror fermions

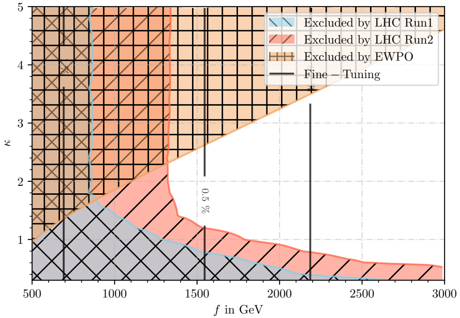


$$\mathcal{O}_{\text{4-fermion}} = -\frac{\kappa_{q,\ell}^2}{128\pi^2 f^2}\left(\bar{\psi}_L\gamma^\mu\psi_L\right)\left(\bar{\psi}'_L\gamma_\mu\psi'_L\right)$$

- constraints from LEP: $\Lambda\left[(\bar{e}e)(\bar{q}q)\right] \lesssim 26.4$ TeV
- LHC dijet bounds : $\Lambda\left[(\bar{q}q)(\bar{q}q)\right] \lesssim 15.7$ TeV

LHC Run 2 and EWPO





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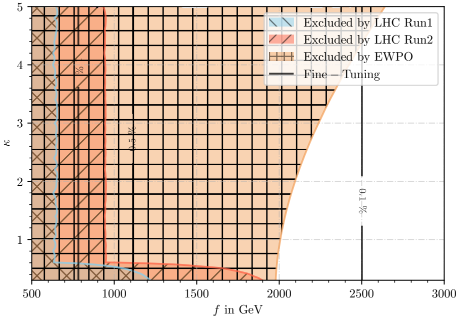

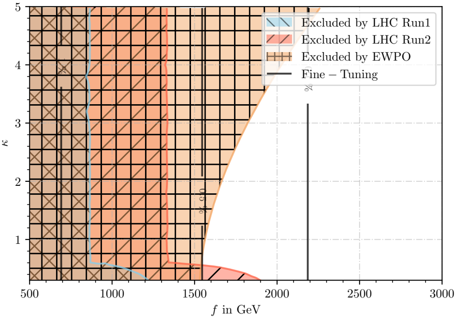

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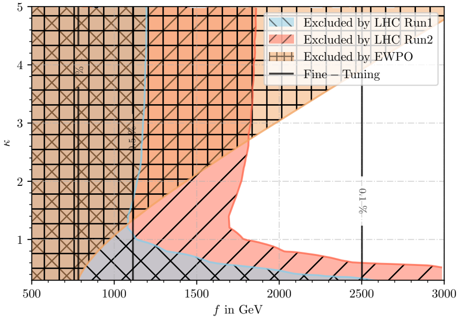

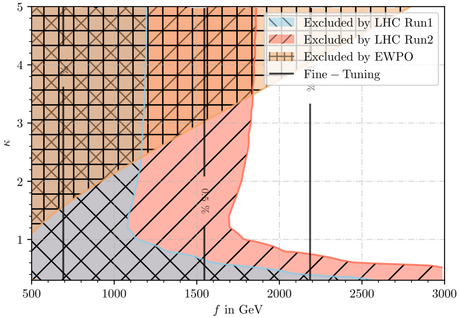

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Conclusion and Summary

- Little Higgs models provide a solution for the Hierarchy problem.
- T-parity is introduced for electroweak precision observables.
- New LHT particles($W_H, A_H, q_H, \ell_H \cdots$) decay similarly as Supersymmetric particles.
- By LHC Run 1 data at $\sqrt{s} = 8$ TeV, $f \gtrsim 600$ GeV
- By LHC Run 2 data at $\sqrt{s} = 13$ TeV, $f \gtrsim 1.3$ TeV
- 4-fermion operators set complimentary bounds.
- (Almost) no constraints from the Higgs measurement at the LHC $\Rightarrow$ **ILC**

Thank you

Littlest Higgs model

Lagrangian

$$\mathcal{L}_{eff} = \mathcal{L}_G + \mathcal{L}_F + \mathcal{L}_\Sigma + \mathcal{L}_Y - V_{CW}(\Sigma)$$

$$\mathcal{L}_G = -\frac{1}{4}\sum_{j=1}^{2}\left(W_{ja}^{\mu\nu}W_{j\mu\nu}^{a} + B_{ja}^{\mu\nu}B_{j\mu\nu}^{a}\right)$$

$$\mathcal{L}_F = \sum_f \bar{\psi}_f i\gamma^\mu D_\mu \psi_f, \text{ where } D_\mu = \partial_\mu - i\sum_{j=1}^{2}(g_j W_{j\mu} + g'_j B_{j\mu})$$

$$\mathcal{L}_\Sigma = \frac{1}{2}\frac{f^2}{4}\text{Tr}|\mathcal{D}_\mu\Sigma|^2, \text{ where } \mathcal{D}_\mu = \partial_\mu\Sigma - i\sum_{j=1}^{2}\left(g_j\left(W_j\Sigma + \Sigma W_j^T\right) + g'_j\left(B_j\Sigma + \Sigma B_j^T\right)\right)$$

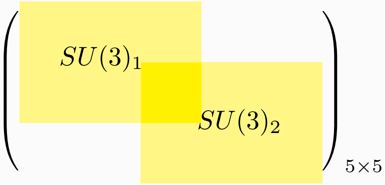
$$\mathcal{L}_Y = \frac{1}{2}\lambda_1 f\epsilon_{ijk}\epsilon_{xy}\chi_i\Sigma_{jx}\Sigma_{ky}u_3'^{\,c} + \lambda_2 f\tilde{t}\tilde{t}'^c + \text{h.c., where } \chi_i = (b_3, t_3, \tilde{t})$$

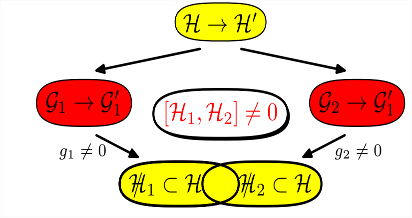
$$V_{CW} \supset \lambda_{\Phi^2} f^2\text{Tr}(\Phi^\dagger\Phi) + i\lambda_{h\Phi h} f\left(h\Phi^\dagger h^T - h^*\Phi h^\dagger\right) - \mu^2 hh^\dagger + \lambda_{h^4}(hh^\dagger)^2$$

Littlest Higgs model

[Arkani-Hamed/Cohen/Katz/Nelson, 2002]

Global symmetry





Gauge symmetry

$$Q_1^a = \frac{1}{2}\begin{pmatrix} \sigma^a & \\ & \end{pmatrix}, \qquad \Pi^a X^a = \frac{1}{\sqrt{2}}\begin{pmatrix} & H^\dagger & \\ H & & H^* \\ & H^T & \end{pmatrix}$$

$$Q_2^a = \frac{1}{2}\begin{pmatrix} & \\ & -\sigma^a \end{pmatrix} \qquad + \frac{1}{2}\begin{pmatrix} & \Phi^\dagger \\ \Phi & \end{pmatrix}$$

Nambu-Goldstone boson

What does NGB have to do with Little Higgs?

- `Goldstone boson theorem` : spontaneous symmetry breaking $\rightarrow$ massless Goldstone boson

Little Higgs comparison - II

to Supersymmetric Standard Model

- Same spin vs spin shifted $1/2$

to Composite Higgs model

- Collective symmetry breaking

Coleman-Weinberg potential

- $V_{\text{CW}} = V_{\text{gauge}} + V_{\text{top}}$
  - $V_{\text{gauge}} \supset \frac{3}{64\pi^2} \text{Tr} M_V^4(\Sigma) \log \frac{M_V^2(\Sigma)}{\Lambda^2}$.
  - $V_{\text{top}} = -\frac{3}{16\pi^2} \text{Tr} \left(M_t(\Sigma) M_t^\dagger(\Sigma) \right)^2$
  - where $M_t(\Sigma)$ is the Σ-dependent top mass squared operator.
- $V = \mu_{\text{Higgs}} H^2 + \Lambda H^4$
  - $\mu_{\text{Higgs}} = \mu_{\text{gauge}} + \mu_{\text{top}}$
  - $\mu^2_{\text{gauge}}(H) = \frac{3}{64\pi^2} \left(3g^2 M^2_{W_H} \log \frac{\Lambda^2}{M^2_{W_H}} + g'^2 M^2_{B_H} \log \frac{\Lambda^2}{M^2_{B_H}} \right)$.
  - $\mu_t^2(H) = -\frac{3\lambda_t^2 M_T^2}{8\pi^2} \log \frac{\Lambda^2}{M_T^2}$.
  - This gives a negative contribution to the Higgs parameter μ.

Top partner

To realized the collective symmetry breaking for top sector, the interaction state of $SU(3)$ is in incomplete $SU(5)$ multiplets as

$$\Psi_{t1} = \begin{pmatrix} q_1 \\ T_{1L} \\ 0_{2\times 1} \end{pmatrix}, \qquad \Psi_{t2} = \begin{pmatrix} 0_{2\times 1} \\ T_{2L} \\ q_2 \end{pmatrix}. \tag{1}$$

For the quark doublets

$$q_i = -i\sigma_2 \begin{pmatrix} t_i \\ b_i \end{pmatrix} \tag{2}$$

where σ_2 is one of Pauli matrices. T_L is introduced as cancellon field. Under T-parity, they transform as following:

$$T : \begin{cases} \Psi_{t1} \leftrightarrow -\Psi_{t2} & (q_1 \leftrightarrow -q_2,\ T_{1L} \leftrightarrow -T_{2L}) \\ T_{1R} \leftrightarrow T_{1R} & \\ T_{2R} \leftrightarrow -T_{2R} & \end{cases} \tag{3}$$

Top partner

Including the $SU(5)$ multiplet, the T-parity invariant Yukawa-like Lagrangian is

$$\mathcal{L}_Y \supset \frac{\lambda_1 f}{2\sqrt{2}}{}_{ijk}{}^{xy} \left((\bar{\Psi}_{1t})_i \Sigma_{jx} \Sigma_{ky} - (\bar{\Psi}_{2t})_i \Sigma'_{jx} \Sigma'_{ky} \right) t_R$$
$$+ \lambda_2 f (\bar{T}_{1L} T_{1R} + \bar{T}_{2L} T_{2R}) + \text{h.c.} \quad (4)$$

where $\{i, j, k\}$ sum over {1,2,3} and $\{x, y\}$ sum over {4,5}. The SM top and top partner fields form T-parity eigenstates as

$$q_{L\pm} = \frac{(q_1 \mp q_2)}{\sqrt{2}}, \qquad T_{L\pm} = \frac{(T_{1L} \mp T_{2L})}{\sqrt{2}}, \quad \text{and} \quad T_{R\pm} = \frac{(T_{1R} \mp T_{2R})}{\sqrt{2}}, \quad (5)$$

where the states with subscripts $+$ are T-parity even states while those with subscript $-$ are T-odd eigenstates.

Top partner

the Lagrangian in terms of the T-parity eigenstates

$$\mathcal{L}_Y \supset \lambda_1 f \left(\frac{s_\Sigma}{\sqrt{2}} \bar{t}_{L+} t_{R+} + \frac{1 + c_\Sigma}{2} \bar{T}_{L+} t_{R+} \right) + \lambda_2 f (\bar{T}_{L+} T_{R+} + \bar{T}_{L-} T_{R-}) + \text{h.c} \tag{6}$$

and $s_\Sigma = \sin(\sqrt{2}h/f)$, $c_\Sigma = \cos(\sqrt{2}h/f)$, respectively. We obtain mass terms for T-odd top partner state $T_- \equiv (T_{L-}, T_{R-})$ as

$$M_{T-} = \lambda_2 f. \tag{7}$$

Top partner

For the mass of the T-even combination of the states, one gets

$$\mathcal{L}_Y \supset (\bar{t}_{L+}, \bar{T}_{L+}) \left(\begin{array}{c} t_R \\ T_{R+} \end{array} \right) + \text{h.c.} \quad \text{where} \quad = \left(\begin{array}{cc} \frac{\lambda_1 f}{\sqrt{2}} \sin\left(\frac{\sqrt{2}h}{f}\right) & 0 \\ \lambda_1 f \cos^2\left(\frac{h}{\sqrt{2}f}\right) & \lambda_2 f \end{array} \right) \tag{8}$$

Diagonalizing and expanding of Σ at leading order in v/f, one can find the mass spectrum for top quarks,

$$M_{t+} = M_{t_{SM}} = \frac{\lambda_1 \lambda_2}{\sqrt{\lambda_1^2 + \lambda_2^2}} v, \qquad M_{T+} = f\sqrt{\lambda_1^2 + \lambda_2^2}. \tag{9}$$

Top partner

The top partner and SM top quark mass term can be rewrite as functions of R, the ratio between the top Yukawa coupling constants λ_1/λ_2, as

$$M_t = \frac{\lambda_2 R}{\sqrt{1+R^2}} v, \tag{10}$$

$$M_{T^-} = \frac{M_t}{v} \frac{f\sqrt{1+R^2}}{R}, \tag{11}$$

$$M_{T^+} = \frac{M_t}{v} \frac{f(1+R^2)}{R} = M_{T^-}\sqrt{1+R^2}. \tag{12}$$

Lagrangian, kinetic terms

the kinetic terms of the non-linear sigma model:

$$\mathcal{L}_{kin} \;=\; \frac{f^2}{4}\mathrm{Tr}|D_\mu\Sigma|^2$$

where the scalar sigma field is given by

$$\Sigma \;=\; e^{i\Pi/f}\;\Sigma_0\;e^{i\Pi^T/f} \;=\; e^{2i\Pi/f}\;\Sigma_0$$

with the covariant derivative

$$D_\mu\Sigma \;=\; \partial_\mu\Sigma - i\sum_j[g_j W_j^a(Q_j^a\Sigma + \Sigma Q_j^{a^T}) + g_j' B_j(Y_j\Sigma + \Sigma Y_j)]$$

Lagrangian, mirror fermion

Top sector

$$\Psi = \begin{pmatrix} ib_L \\ -it_{1L} \\ t_{2L} \\ \mathbf{0}_{2\times 1} \end{pmatrix} = \begin{pmatrix} q_L \\ t_{2L} \\ \mathbf{0}_{2\times 1} \end{pmatrix}, \qquad \Psi' = \begin{pmatrix} \mathbf{0}_{2\times 1} \\ t'_{2L} \\ ib'_L \\ -it'_{1L} \end{pmatrix} = \begin{pmatrix} \mathbf{0}_{2\times 1} \\ t'_{2L} \\ q'_L \end{pmatrix},$$

$$\mathcal{L}_{\text{top}} \supset \frac{\lambda_1 f}{2\sqrt{2}} \epsilon_{ijk}\epsilon_{xy}(\bar{\Psi}_i \Sigma_{jx}\Sigma_{ky} - (\bar{\Psi}')_i \tilde{\Sigma}_{jx}\tilde{\Sigma}_{ky})t_{1R} + \lambda_2 f(\bar{t}_{2L}t_{2R} + \bar{t}'_{2L}t_{2R}) + h.c.$$

1st / 2nd generation quarks and leptons

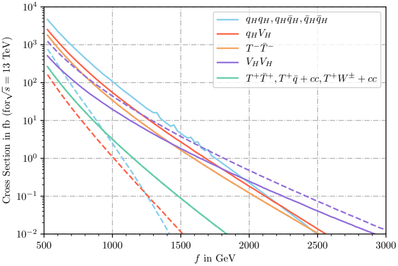
$$\mathcal{L}_Y \supset \frac{i\lambda_d f}{2\sqrt{2}} \epsilon_{ij}\epsilon_{xyz}(\overline{\Psi'}_x \Sigma_{jy}\Sigma_{jz}\Sigma_{33}^{\pm\frac{1}{4}} - (\overline{\Psi}\Sigma_0)_x \tilde{\Sigma}_{iy}\tilde{\Sigma}_{jz}\tilde{\Sigma}_{33}^{\pm\frac{1}{4}})d_R \quad .$$

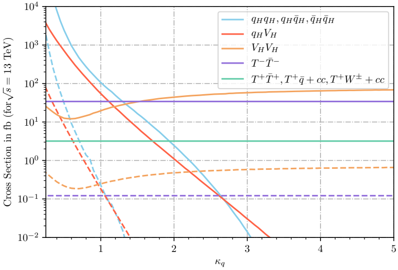
Mirror fermions intrudoced for generate T-odd fermion mass terms

$$\Psi_c = \left(id_c,\, -iu_c,\, \chi_c,\, i\tilde{d}_c,\, -i\tilde{u}_c\right)^T = (q_c,\, \chi_c,\, \tilde{q}_c)^T \ , \qquad \Psi_c \overset{T}{\longleftrightarrow} -\Psi_c \ .$$

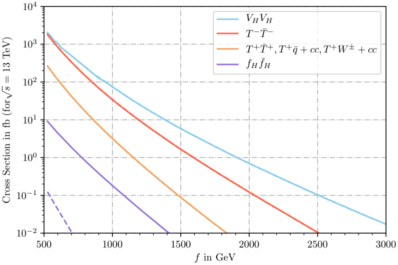
$$\mathcal{L}_\kappa = -\kappa f(\overline{\Psi'} e^{i\Pi^a X^a/f}\Psi_c + \overline{\Psi}\Sigma_0 \Omega e^{-i\Pi^a X^a/f}\Omega\Psi_c) + h.c. \quad .$$

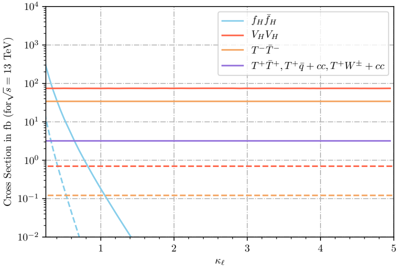
Production at the LHC





the *Fermion Universality* and *Light* ℓ_H model

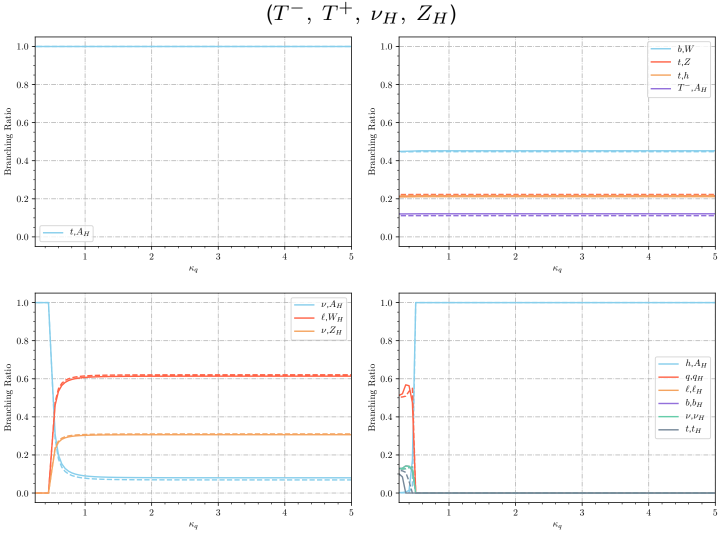




the *Heavy* q_H model

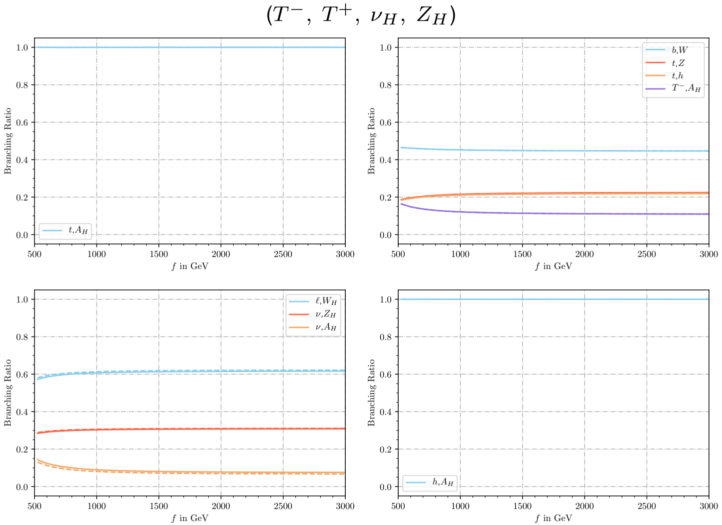
Fermion Universality

(κ, BR)



Fermion Universality

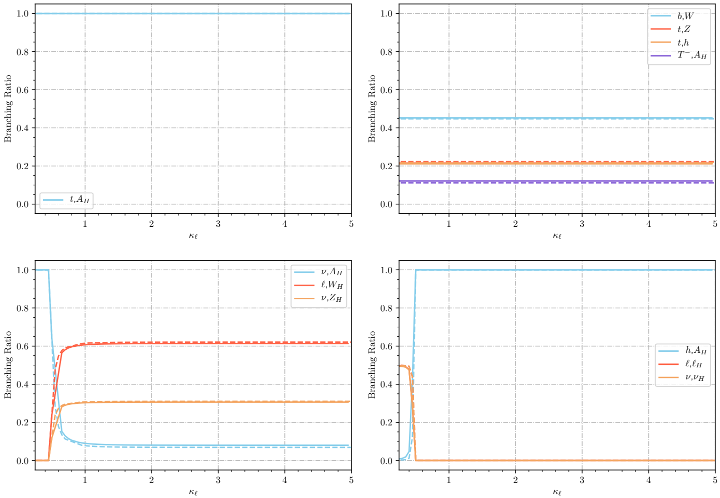
(f, BR)



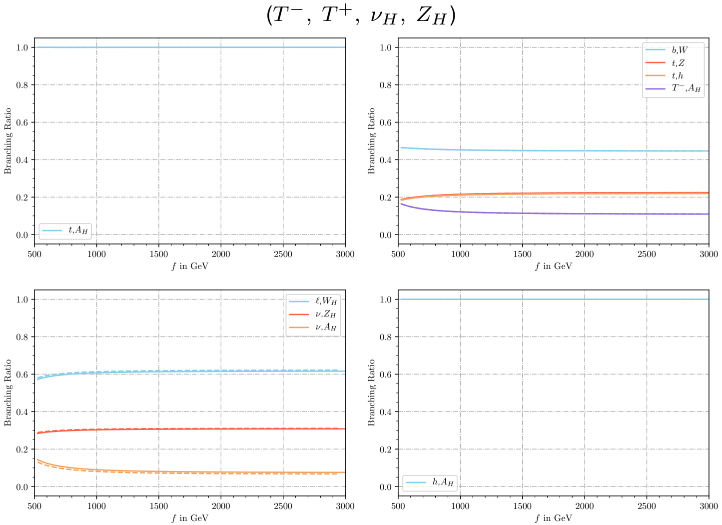
Heavy q_H

(κ, BR)

$(T^-,\ T^+,\ \nu_H,\ Z_H)$



Heavy q_H
(f, BR)

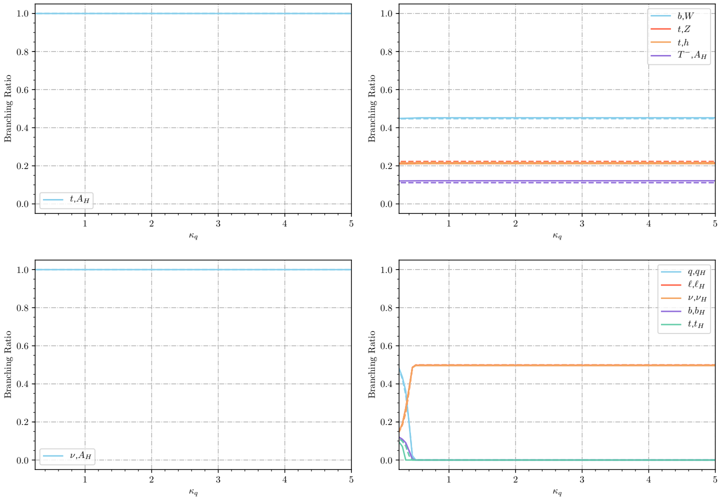


$(T^-,\ T^+,\ \nu_H,\ Z_H)$
Branching Ratio
f in GeV
t,A_H
b,W
t,Z
t,h
T^-,A_H
ℓ,W_H
ν,Z_H
ν,A_H
h,A_H

Light ℓ_H

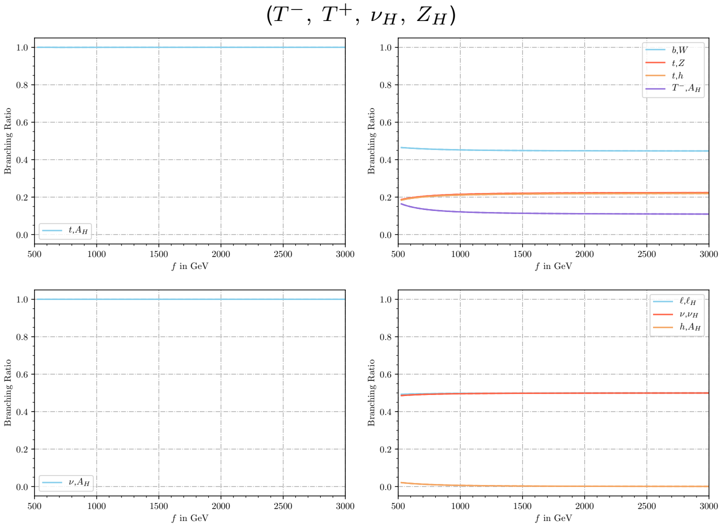
(κ, BR)

$(T^-,\ T^+,\ \nu_H,\ Z_H)$

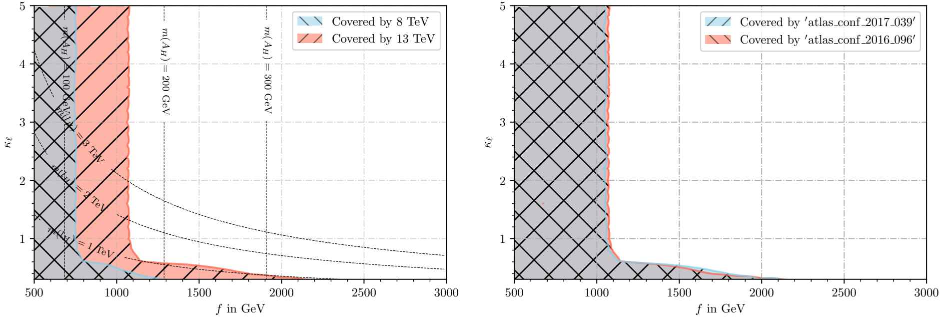


Light ℓ_H

(f, BR)



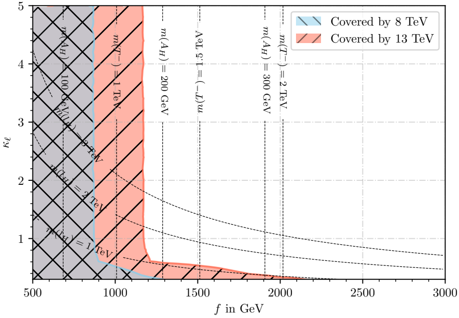
Heavy q_H case

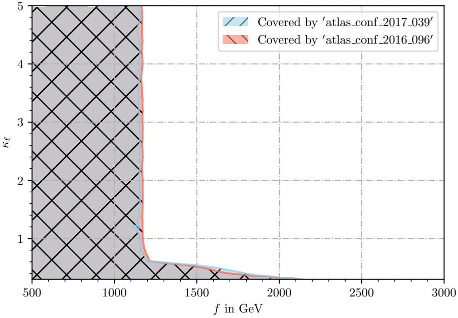


Heavy q_H × Heavy $T^{\pm}$ × TPV

Sector	Model	Constraint	Phenomenology	Considered Topology
f_H	*Fermion Universality*	$\kappa_\ell = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible	Exclude process 3
	Heavy q_H	$\kappa_q = 4.0$	• q_H decoupled • ℓ_H production relevant	Exclude processes 1, 2
	Light ℓ_H	$\kappa_\ell = 0.2$	• ℓ_H very light • V_H branching ratios change	Exclude process 3
$T^{\pm}$	*Light $T^{\pm}$*	$R = 1.0$	• $T^{\pm}$ are light/accessible	Include process 4, 5
	Heavy $T^{\pm}$	$R = 0.2$	• $T^{\pm}$ are heavy/inaccessible	Exclude process 4, 5
A_H	*TPC*	No TPV	• A_H is stable and invisible	A_H stable
	TPV	With TPV	• A_H is unstable	$A_H \to VV$ decays

Heavy q_H case





Heavy q_H × Light $T^\pm$ × TPV

Sector	Model	Constraint	Phenomenology	Considered Topology
f_H	*Fermion Universality*	$\kappa_\ell = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible	Exclude process 3
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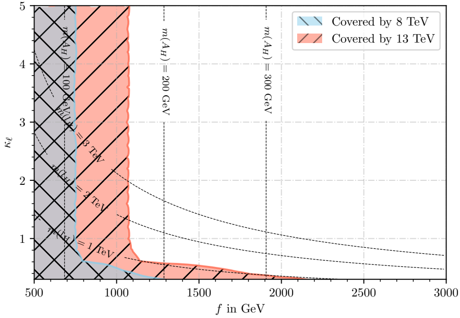
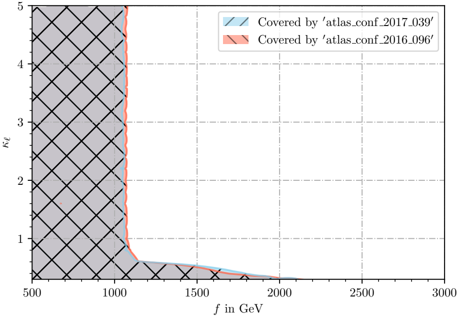
Heavy q_H case



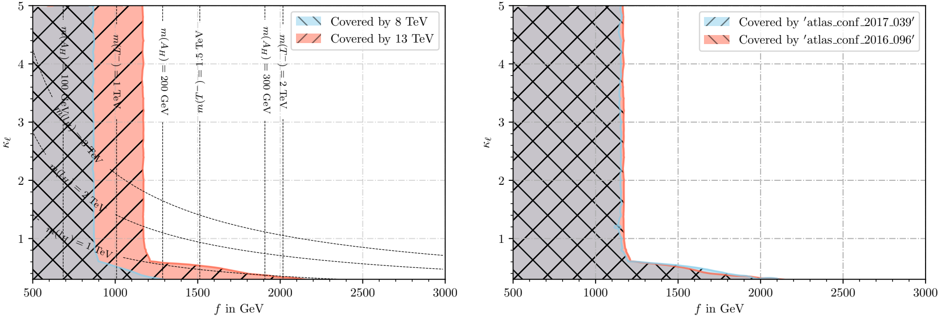


***Heavy* q_H $\times$ Heavy $T^\pm$ $\times$ TPV**

- Main decay topology changes from $q_H \to qV_H$ to $\ell_H \to \ell V_H$.
- $\sigma_{(pp \to q_H q_H)} \gtrsim (2 \sim 3) \times \sigma_{(pp \to \ell_H \ell_H)}$
- For $\kappa_\ell \lesssim 0.5$, $V_H \to \ell \ell_H$

- atlas_conf_2016_054: 1 lepton + jets + $\not{E}_T$
- atlas_conf_2016_096: 2-3 leptons + $\not{E}_T$
- atlas_conf_2017_039: chargino-neutralino pair; 2-3 leptons + $\not{E}_T$.
- atlas_conf_2017_022: squarks and gluinos, 0ℓ, 2-6 jets + $\not{E}_T$

Heavy q_H case



Heavy q_H × Light $T^{\pm}$ × TPV

- Main decay topology changes from $q_H \to qV_H$ to $\ell_H \to \ell V_H$.
- $\sigma_{(pp \to q_H q_H)} \gtrsim (2 \sim 3) \times \sigma_{(pp \to \ell_H \ell_H)}$
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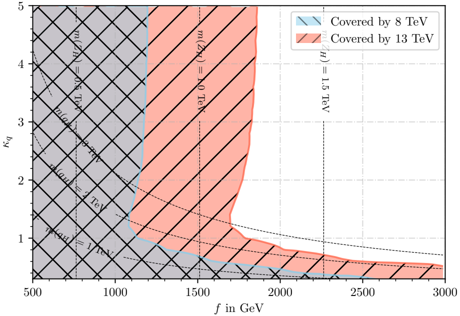
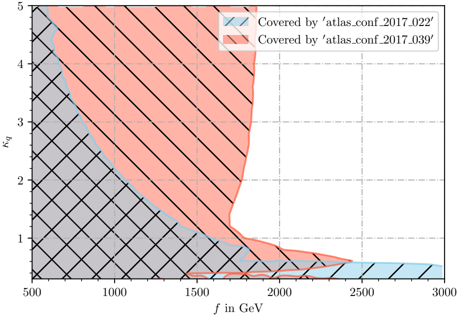
Light ℓ_H case





Light ℓ_H × Heavy $T^{\pm}$ × TPC

Sector	Model	Constraint	Phenomenology	Considered Topology
f_H	*Fermion Universality*	$\kappa_\ell = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible	Exclude process 3
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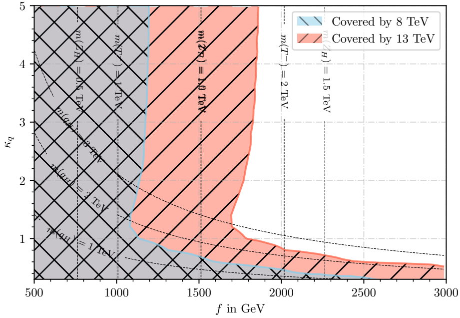
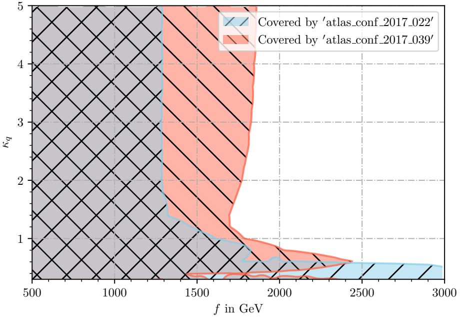
Light ℓ_H case





Light ℓ_H × Light $T^{\pm}$ × TPC

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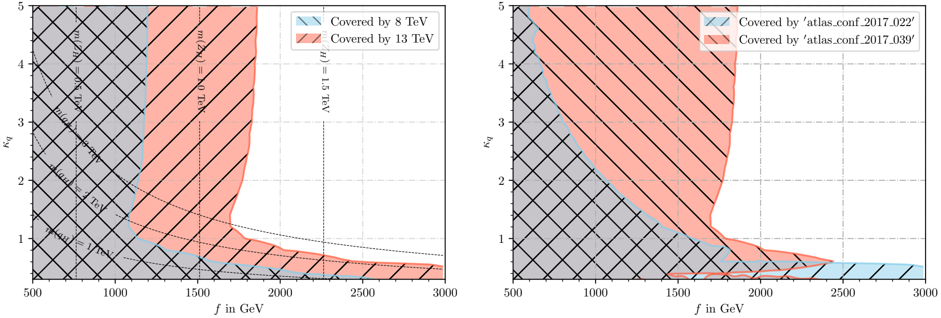
Light ℓ_H case



Light ℓ_H × Heavy $T^{\pm}$ × TPC

- For $\kappa_q > 0.5$, $pp \to jjV_HV_H \to jj\ell\ell\ell\ell A_HA_H$
- Large-κ bounds are stronger than other benchmark scenarios.
- For $\kappa_q < 0.5$, $V_H \to q_Hq$ $\Rightarrow$ multi-jet analysis

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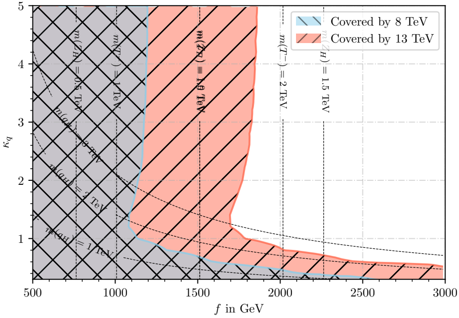
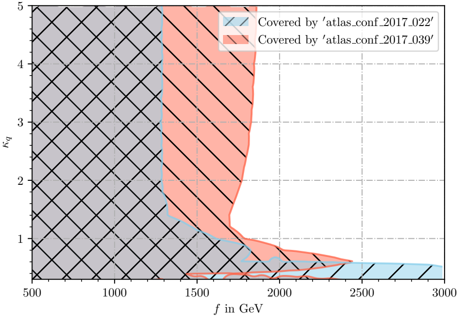
Light ℓ_H case





Light ℓ_H × Light $T^{\pm}$ × TPC

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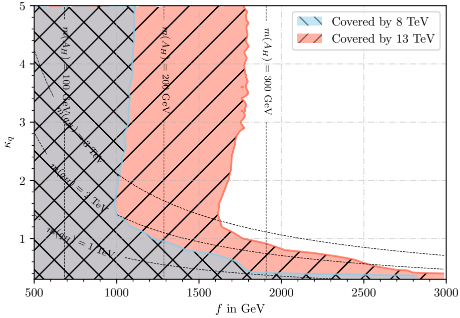
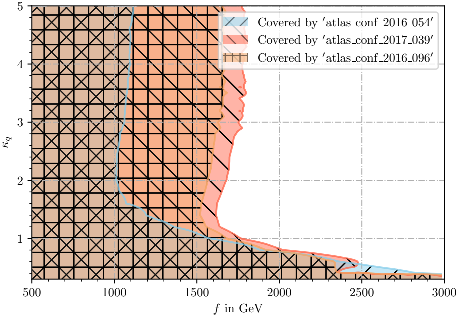
Light ℓ_H case





Light ℓ_H × Heavy $T^{\pm}$ × TPV

Sector	Model	Constraint	Phenomenology	Considered Topology
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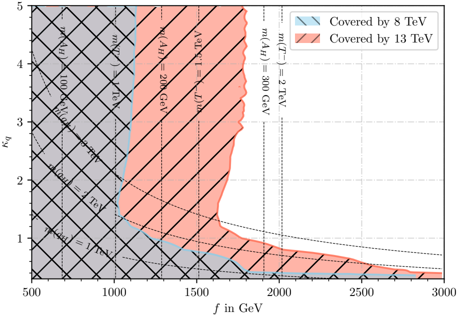
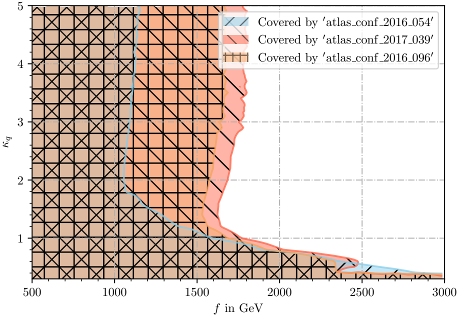
Light ℓ_H case

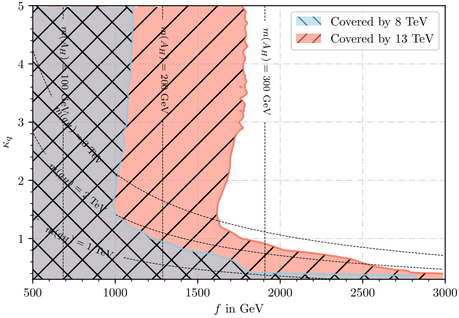


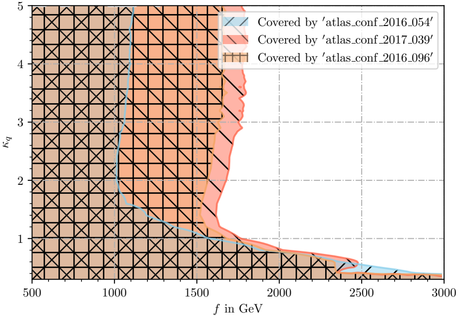


Light ℓ_H × Light $T^{\pm}$ × TPV

Sector	Model	Constraint	Phenomenology	Considered Topology
f_H	*Fermion Universality*	$\kappa_\ell = \kappa_q$	• mass degeneracy of q_H, ℓ_H • ℓ_H production negligible	Exclude process 3
	Heavy q_H	$\kappa_q = 4.0$	• q_H decoupled • ℓ_H production relevant	Exclude processes 1, 2
	Light ℓ_H	$\kappa_\ell = 0.2$	• ℓ_H very light • V_H branching ratios change	Exclude process 3
$T^{\pm}$	*Light $T^{\pm}$*	$R = 1.0$	• $T^{\pm}$ are light/accessible	Include process 4, 5
	Heavy $T^{\pm}$	$R = 0.2$	• $T^{\pm}$ are heavy/inaccessible	Exclude process 4, 5
A_H	*TPC*	No TPV	• A_H is stable and invisible	A_H stable
	TPV	With TPV	• A_H is unstable	$A_H \to VV$ decays

Light ℓ_H case



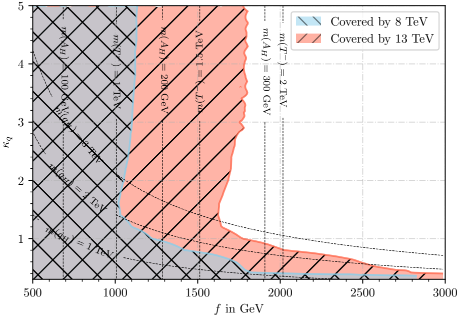


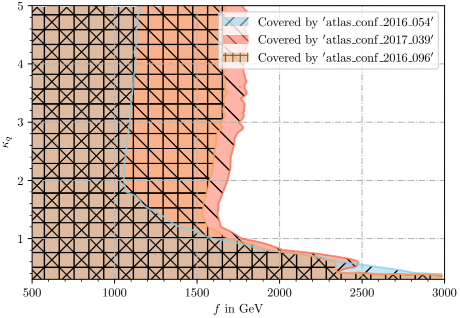
Light ℓ_H × Heavy $T^{\pm}$ × TPV

- For $\kappa_q > 0.5$, $pp \to jjV_HV_H \to jj\ell\ell\ell\ell A_HA_H$
- Large-κ bounds are stronger than other benchmark scenarios.
- For $\kappa_q < 0.5$, $V_H \to q_Hq$ $\Rightarrow$ multi-jet analysis

- atlas_conf_2016_054: 1 lepton + jets + $\not{E}_T$
- atlas_conf_2016_096: 2-3 leptons + $\not{E}_T$
- atlas_conf_2017_039: chargino-neutralino pair; 2-3 leptons + $\not{E}_T$.
- atlas_conf_2017_022: squarks and gluinos, 0ℓ, 2-6 jets + $\not{E}_T$

Light ℓ_H case





Light ℓ_H $\times$ Light $T^\pm$ $\times$ TPV

- For $\kappa_q > 0.5$, $pp \to jjV_H V_H \to jj\ell\ell\ell\ell A_H A_H$
- Large-κ bounds are stronger than other benchmark scenarios.
- For $\kappa_q < 0.5$, $V_H \to q_H q$ $\Rightarrow$ multi-jet analysis

- atlas_conf_2016_054: 1 lepton + jets + $\not{E}_T$
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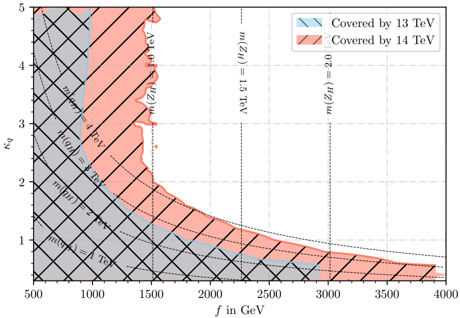
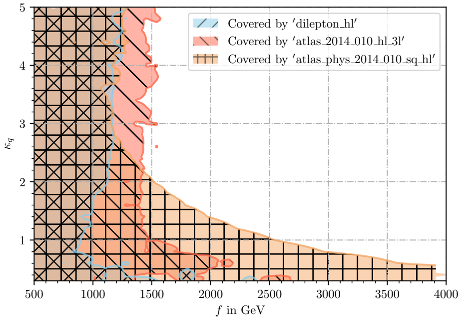
High-luminosity results, $\mathcal{L} = 3000\,\mathrm{fb}^{-1}$

Fermion Universality $\times$ Heavy $T^{\pm}$ $\times$ TPC

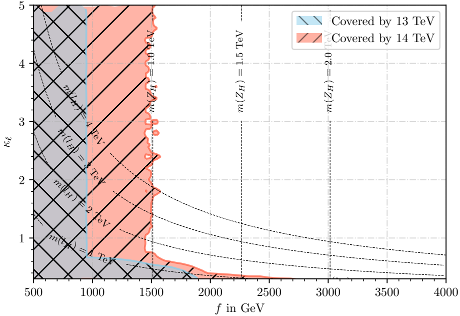


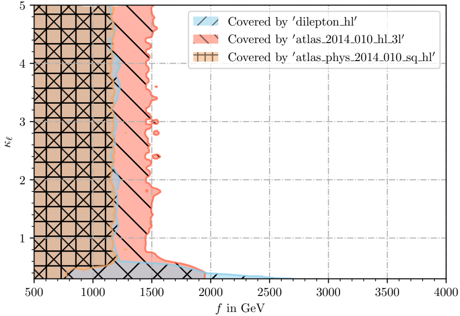


CM identifier	Final State	Designed for
atlas_2014_010_hl_3l	$\not\!\!E_T + 3\ell$	$\tilde{\chi}^{\pm}, \tilde{\chi}^{0}$
atlas_phys_2014_010_sq_hl	$\not\!\!E_T$+ 0 ℓ + 2-6 j	$\tilde{q}, \tilde{g}$
dilepton_hl	$\not\!\!E_T$ + 2 ℓ	$\tilde{\chi}^{\pm}, \tilde{\ell}$

High-luminosity results, $\mathcal{L} = 3000\,\mathrm{fb}^{-1}$

Heavy q_H $\times$ Heavy $T^{\pm}$ $\times$ TPC

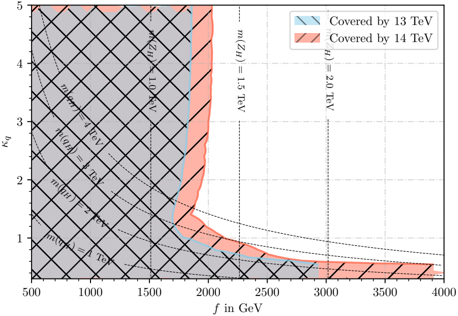


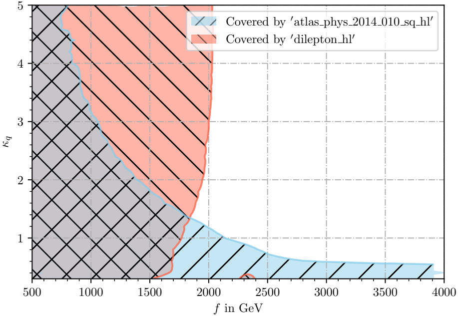


CM identifier	Final State	Designed for
atlas_2014_010_hl_3l	$\not{E}_T + 3\ell$	$\tilde{\chi}^{\pm}, \tilde{\chi}^0$
atlas_phys_2014_010_sq_hl	$\not{E}_T$+ 0 ℓ + 2-6 j	$\tilde{q}, \tilde{g}$
dilepton_hl	$\not{E}_T$ + 2 ℓ	$\tilde{\chi}^{\pm}, \tilde{\ell}$

High-luminosity results, $\mathcal{L} = 3000\,\mathrm{fb}^{-1}$

Light ℓ_H × Heavy $T^{\pm}$ × TPC





CM identifier	Final State	Designed for
`atlas_2014_010_hl_3l`	$\not{E}_T + 3\ell$	$\tilde{\chi}^{\pm}, \tilde{\chi}^0$
`atlas_phys_2014_010_sq_hl`	$\not{E}_T$+ 0 ℓ + 2-6 j	$\tilde{q}, \tilde{g}$
`dilepton_hl`	$\not{E}_T$ + 2 ℓ	$\tilde{\chi}^{\pm}, \tilde{\ell}$

LHT in ILC?

- heavy gauge bosons and T-odd leptons; mass and couplings
-

  Kato/Asano/Fujii/Matsumoto/Takubo/Yamamoto [1203.0762v1]

CheckMATE

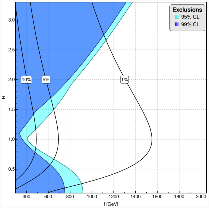
- `Daniel Dercks et al., CheckMATE2, [arXiv:1611.09856]`
- Automatized program for testing new physics at LHC
- Based on `root`, `MadGraph`, `Pythia 8`, `Delphes`

- Managing event generating, showering, hadronising by itself
- UFO model file is enough to run CheckMATE
- SUSY analyses for LHC 8 TeV, 13 $\mathrm{TeV}$and 14 TeV available

T-parity: a discrete symmetry

Cheng/Low, [hep-ph/0308199], [hep-ph/0405243]

Littlest Higgs with T-parity



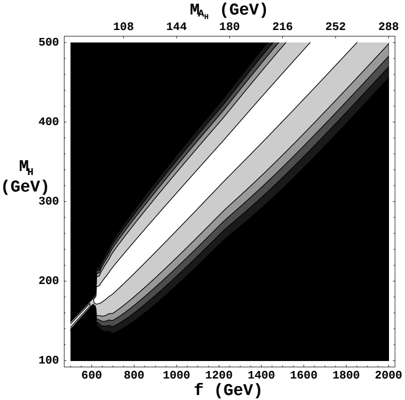
T-parity conservation

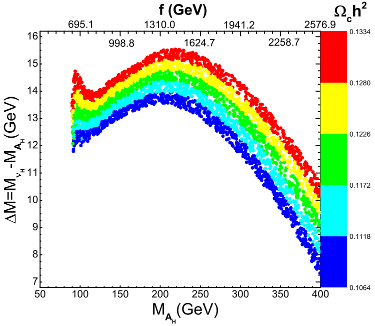
- eliminates tree-level contributions to EWPO.
- makes bounds relaxed on parameter space.
- allows only pair production of T-odd particles at colliders.

  Lightest T-odd particle is stable.
  $\rightarrow$Dark Matter candidate

Constrain for A_H as Dark Matter

relic density

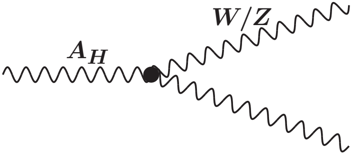


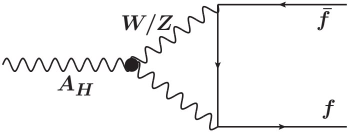


- Dominant decay via s-channel Higgs exchange $A_H A_H \to H \to WW, ZZ, HH$
  Hubiz/Meade, [hep-ph/04111264]
- Severe constraints from direct detection Yang/Wang/Shu, [1307.7780]; Wu/Yang/Zhang, [1607.06355]

T-parity violation

- Wess-Zumino-Witten anomaly in UV sector
  Hill and Hill, [0705.0697]; Freitas, Schwaller, and Wyler [0806.3674]
- $A_H \to WW, ZZ$ and $A_H \to ff$.
- $\Gamma(A_H \to ZZ) = \frac{1}{2\pi}\left(\frac{Ng'}{40\sqrt{3}\pi^2}\right)^2 \frac{M_{A_H}^3 m_Z^2}{f^4}\left(1 - \frac{4m_Z^2}{M_{A_H}^2}\right)^{\frac{5}{2}}$
- $\Gamma(A_H \to WW) = \frac{1}{\pi}\left(\frac{Ng'}{40\sqrt{3}\pi^2}\right)^2 \frac{M_{A_H}^3 m_W^2}{f^4}\left(1 - \frac{4m_W^2}{M_{A_H}^2}\right)^{\frac{5}{2}}$
- $\Gamma(A_H \to ff) = \frac{N_{C_f} M_{A_H}}{48\pi}\sqrt{1 - \frac{4m_f^2}{M_{A_H}^2}}\left(c_-^2\left(1 - \frac{4m_f^2}{M_{A_H}^2}\right) + c_+^2\left(1 + \frac{2m_f^2}{M_{A_H}^2}\right)\right)$





new DM candidates?

- in the context of stongly-interacting UV completion, Axion
- mesons

neutrino mass in Little Higgs model

- in Littlest Higgs scenario, the most satisfactory way of incorporating neutrino masses is to include a lepton-number violating interaction between the scalar triplet and lepton doublets.