Challenging the Littlest Higgs by LHC 13 TeV data

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November 28, 2017

in collaboration with
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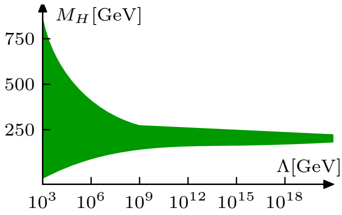
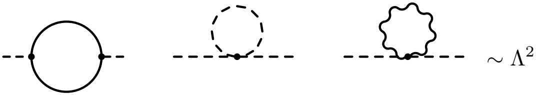
Outline

1. Littlest Higgs model
   - with T-parity (NOT Time-Reversal)
   - with broken T-parity
2. LHC analyses with CheckMATE
3. Results
   - Fermion universal case
   - Heavy q_H case

Hierarchy Problem





Heavy Higgs?

Naturally, $m_h \sim \mathcal{O}(\Lambda^2)$

$m_h^2 = m_0^2 + \Lambda^2 \times$(loop factors)

Light Higgs!

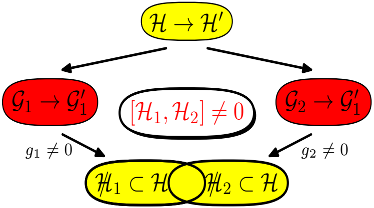
By EW precision observables, Higgs mass was favoured as $m_h < 0.5\ \mathrm{TeV}$

Hierarchy Problem

$m_h \ll \Lambda \Leftrightarrow$ Fine-Tuning!

Collective Symmetry Breaking

2 different global symmetries;
If one of them was unbroken, Higgs exact Goldstone boson and massless.
CSB breaks both symmetries at the same time: Higgs naturally light.



Littlest Higgs model group structure

$$SU(5)/SO(5)$$
$$\left(SU(2)_i \otimes U(1)_i\right)^2 / \left(SU(2)_W \otimes U(1)_Y\right)$$
$$W^a_{1\mu},\ W^a_{2\mu} \ \Rightarrow\ W^a_H, W^a_L$$
$$B_{1\mu},\ B_{2\mu}, \ \Rightarrow\ B_H, B_L$$

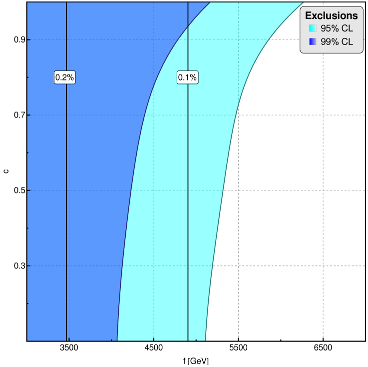
Higgs as a pseudo-Nambu Goldstone boson

14 NGBs from symmetry breaking $SU(5)/SO(5)$ at scale f

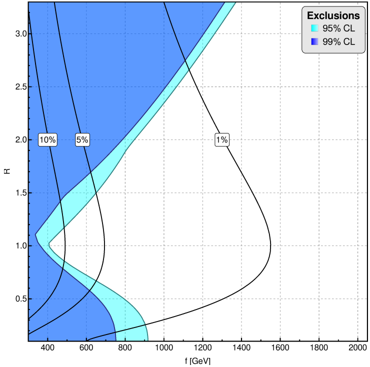
$$\Rightarrow \quad 1_0 \oplus 3_0 \oplus 2_{\pm\frac{1}{2}} \oplus 3_{\pm 1}$$

T-parity

Littlest Higgs



Littlest Higgs with T-parity



Z_2 symmetry acting on TeV scale particles

$$W^a_{2\mu} \leftrightarrow W^a_{1\mu},\ B_{1\mu} \leftrightarrow B_{2\mu};$$

Similar to R-parity in SUSY and KK-parity in extra dimension

T-parity prevents large corrections to the EWPO to happen
$\rightarrow$ Bound on f weaker $\rightarrow$ the model is less fine tuned.

Littlest Higgs with T-parity model contents

Particles

- Heavy Gauge bosons;
  $W^{\pm}_{H,-}$, $Z_{H,-}$ and $A_{H,-}$
- Heavy fermions;
  $u_{H,-}$, $d_{H,-}$, $\cdots$
  $e_{H,-}$, $\ell_{H,-}$, $\cdots$
- vectorlike top quark;
  $T_{\pm}$; a cancellon for the divergence of Higgs-top loop interaction

Mass

- Heavy Gauge bosons;
  $\sim gf$
  where f is symmetry breaking scale
- Heavy fermions;
  $m_{u_H} \sim m_{d_H} \sim \kappa_q f$,
  $m_{e_H} \sim m_{\ell_H} \sim \kappa_\ell f$,
  where κ is Yukawa coupling parameter of T-parity odd fermions
- vectorlike top quark;
  $m_{T_+} \sim f\sqrt{\lambda_1^2 + \lambda_2^2}$

If T-parity is conserved,

Heavy photon A_H cannot decay
because it is the lightest T-parity odd particle.

Broken T-parity

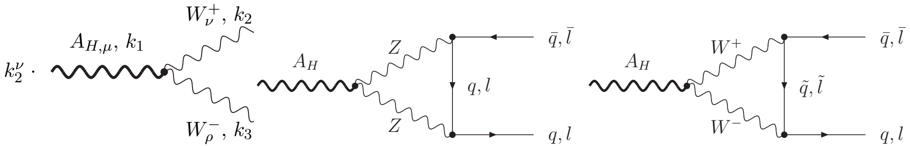
Wess-Zumino-Witten term

`Christopher T. Hill, Richard J. Hill [arXiv:0705.0697]`

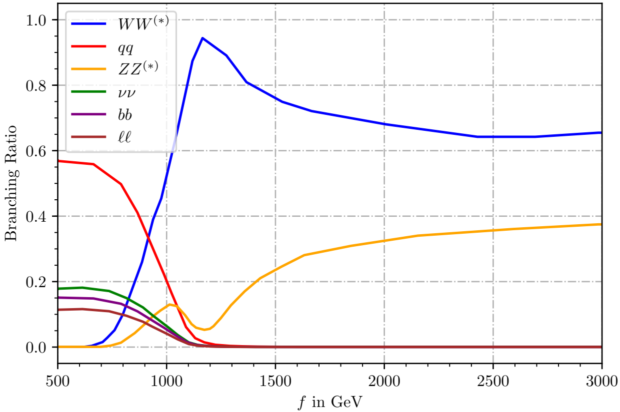
`A. Freitas, P. Schwaller and D. Wyler [arXiv:0806.3674]`

Because of the nontrivial vacuum structure

$$\Gamma_{WZW} = \frac{N}{48\pi^2}(\Gamma_0(\Sigma) + \Gamma(\Sigma, A_l, A_r))$$



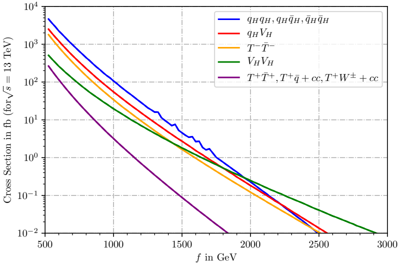
Broken T-parity

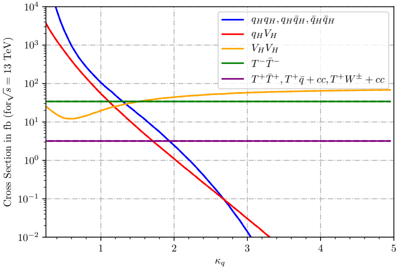


Branching Ratio of A_H

- $f \sim 1200$ 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.

LHC Phemonenology





Considered LHC 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. $pp \to f_H \bar{f}_H$
4. $pp \to V_H V_H\,,$
5. $pp \to T_+ T_+, T_- T_-$
6. $pp \to T_+ \bar{q}, \bar{T}_+ q, T_+ W^\pm, \bar{T}_+ W^\pm$

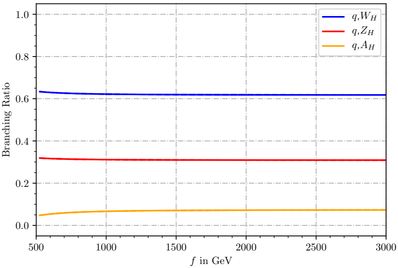
Scan parameters

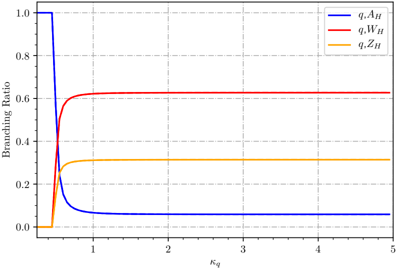
$\{\ f\ ,\ \kappa_q\ ,\ \kappa_\ell\ \}$

- All cross sections drop with f because all masses increase with f .
- Heavy fermions' mass terms depend on κ but other particles do not.
  $\Rightarrow$ Bound will depend on both f and κ

LHC Phemonenology

q_H branching ratio





Decay examples

- $W_H \;\rightarrow\; W \; A_H$
- $Z_H \;\rightarrow\; H \; A_H$

- $pp \rightarrow q_H q_H \rightarrow qq A_H A_H$
  $pp \rightarrow V_H V_H \rightarrow WW A_H A_H$
- For broken T-parity cases, A_H decays and produces even more final state particles with less $\not{E}_T$

Benchmark Scenarios

- with conserved T-parity
  1. $\kappa_q \;=\; \kappa_\ell$: Fermion Universality
  2. $\kappa_q \;=\; 4.0$: Heavy q_H
- with T-parity violation
  1. $\kappa_q \;=\; \kappa_\ell$: Fermion Universality
  2. $\kappa_q \;=\; 4.0$: Heavy q_H

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 TeVand 14 TeV available

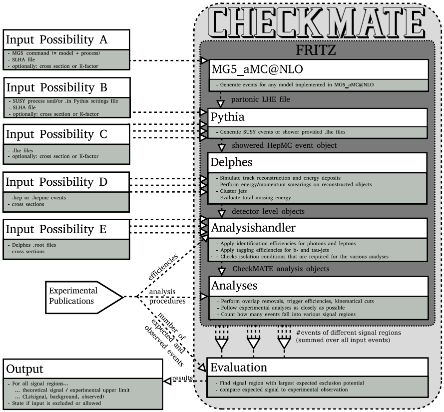
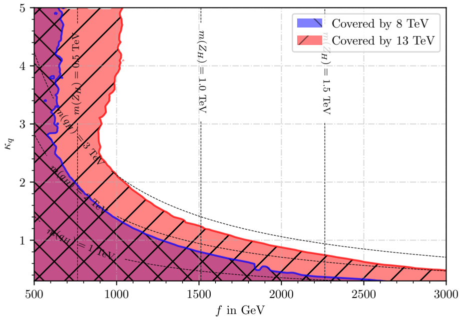
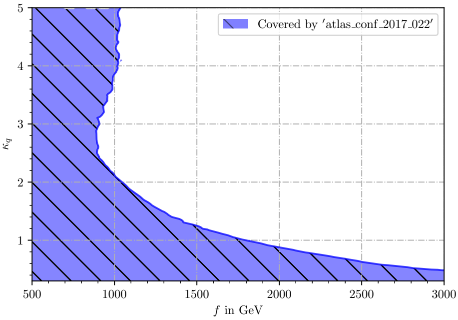


Figure 1: Flow chart to demonstrate the chain of data processing within `CheckMATE`.

Fermion universal case with conserved T-parity

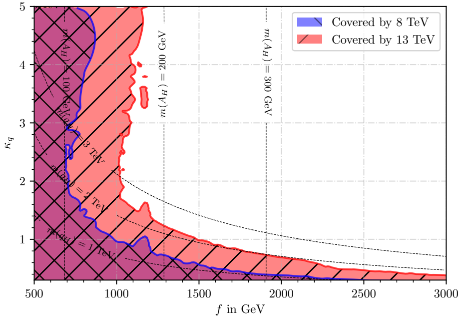


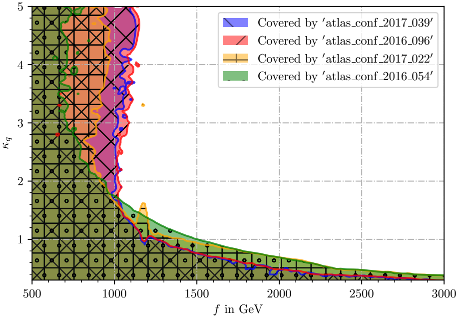


- $\kappa_q = \kappa_l$
- A_H does not decay.
- For $f < 1$ TeV, vector boson production produces κ -independent bound.
- For $f > 1$ TeV, heavy quarks produce κ -dependent bound.

- CheckMATE tests many analyses, this is the most sensitive for this model
- Search designed for squarks and gluinos, similar topology as q_H in our model
- atlas_conf_2017_022: squarks and gluinos; 0ℓ, 2-6 jets + $\not{E}_T$

Fermion universal case with broken T-parity

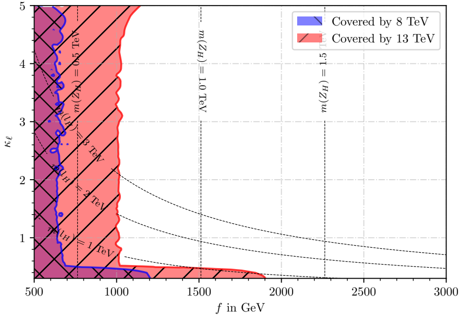


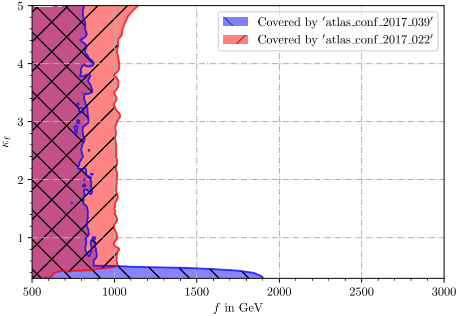


- A_H decays .
- At $f < 1.2$ TeV, off-shell decay happen and many possible final states appear
- CheckMATE determines many sensitive analyses in this region.

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

Heavy q_H case with conserved T-parity

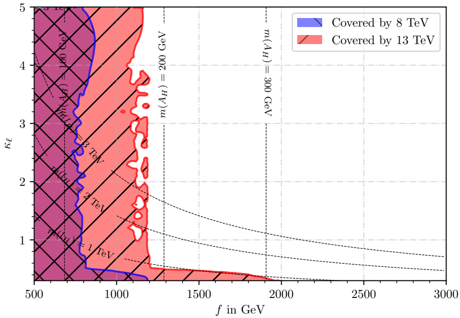


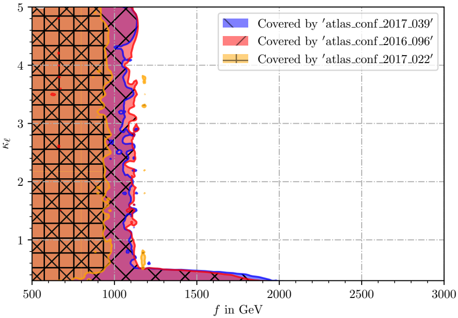


- $\kappa_q = 4.0$
- A_H does not decay.
- For $f < 1$ TeV, as before, vector boson production produces κ -independent bound.
- For $f > 1$ TeV, bound much weaker as q_H are decoupled and ℓ_H are much less produced.

- 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 with broken T-parity





- $\kappa_q = 4.0$
- A_H decays .

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- atlas_conf_2016_096:
  2-3 leptons + $\not{E}_T$
- atlas_conf_2017_022:
  squarks and gluinos, 0ℓ, 2-6 jets + $\not{E}_T$

Conclusion

- Little Higgs models suggest a solution for the Hierarchy problem.
- The additional particles($W_H, A_H, q_H, \ell_H \cdots$) decay similarly as in Supersymmetry.
- LHC really starts to exclude the remaining "not so fine tuned" region.
- This is the first analysis which takes the effect of T-parity violation into account.
- We analyse more benchmark cases in our publication.