The Unnatural Composite Higgs at the LHC

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Why unnaturalness?

- So far, no clear sign of new physics at the LHC
- Natural models to solve hierarchy problem starting to come under pressure
- In composite Higgs models fine-tuning $\Delta^{-1} \sim \frac{v^2}{f^2} \lesssim 10\%$

EWPT and flavour constraints also naively suggest $f \gtrsim 10$ TeV
(in absence of custodial symmetry and additional flavour structure)

How much fine-tuning is still "natural"? (10%, 1%, 0.1%, ...)

If we instead simply accept some fine-tuning, can we still place an upper-bound on the scale f?

Unnatural composite Higgs

Standard composite Higgs paradigm to address the "big hierarchy problem":

- Higgs is pNGB from new strong sector with global symmetry $\mathcal{G}$ spontaneously broken to $\mathcal{H}$ at scale f
- Explanation of Yukawa hierarchies via partial compositeness, ...

But...

- Accept fine tuning in the Higgs potential ($\lesssim 10^{-4}$)
- $f \gtrsim 10$ TeV to satisfy EWPT, flavour constraints
- Require gauge coupling unification, pNGB dark matter candidate

$\rightarrow f$ cannot be arbitrarily large!

Gauge Coupling Unification

Two features improve unification in composite Higgs models:

Agashe, Contino, Sundrum '05

- A fully composite t_R
- Embedding SM in a simple subgroup of strong sector's unbroken symmetry e.g. $SU(5) \subset H \subset G$

  → All composite objects come in complete GUT multiplets
  → Strong sector doesn't contribute to *differential* running (at LO)

But have additional light (composite) fermions from t_R GUT multiplet

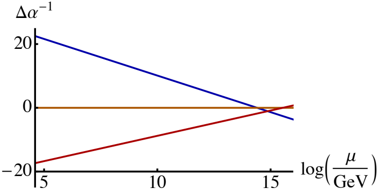
→ Need exotic elementary fermions to provide dirac partners
(and cancel anomalies)

$$\mathcal{L} \supset \lambda_\chi \mathcal{O}_t \chi \quad \Rightarrow \quad m_\chi \sim \lambda_\chi f \qquad \text{(top } \textit{companions}\text{)}$$

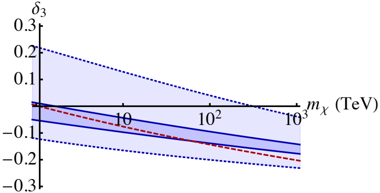
Gauge Coupling Unification

Differential running: $\alpha_i(\mu) - \alpha_j(\mu) = \text{SM} - \{H, t_R, \bar{t}_R\}$

Unification depends on mass of top companions:



$m_\chi = 20$ TeV



$\delta_3 \equiv [\alpha_3^{\text{th}}(M_Z) - \alpha_3^{\text{ex}}(M_Z)]/\alpha_3^{\text{ex}}(M_Z)$

Can obtain upper bound on $f \lesssim 100 - 1000$ TeV! $(\lambda_\chi \sim 1)$

Minimal Model

Require unbroken $SU(5)$ global symmetry and coset space containing

- Higgs multiplet
- Stabilised SM singlet (DM)

Minimal coset

$SU(7)/SU(6) \times U(1)$ Barnard, Gherghetta, Ray, Spray 1409.7391

Contains 12 pNGBs:

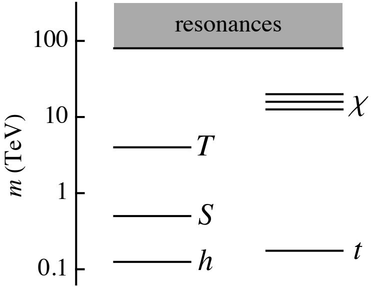
$\mathbf{5} = (T, H)$ and complex singlet, S, of $SU(5)$

colour-triplet: $T \sim (3,1)_{-1/3}$ singlet: $S \sim (1,1)_0$

Additional pNGBs give interesting LHC phenomenology

(Split) Spectrum

These models give rise to a split spectrum:



pNGB colour-triplet (and singlet) potentially *only* new states accessible at LHC (and future colliders).

Colour-triplet decays

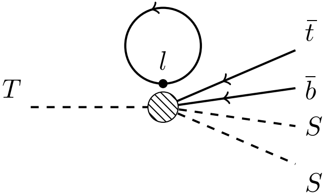
$\mathbb{Z}_3$ symmetry related to baryon number ensures DM stability

Also requires T to decay to the singlet, S:

$$T \to u^c d^c S S \qquad (t^c, b^c \text{ dominates})$$

Corresponding dimension-6 operator forbidden by accidental symmetries

Decay generated by *dimension-10* operator after closing elementary lepton loop



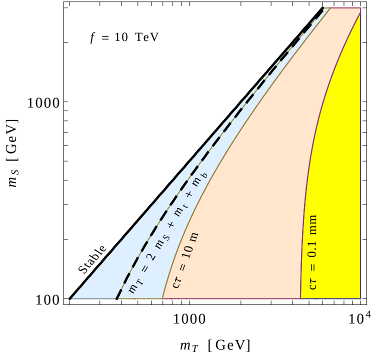
Colour-triplet decays

Long-lived colour-triplet scalar is a generic prediction of unnatural composite Higgs models containing $SU(5)$ (or $SO(10)$)

$$c\tau \simeq 0.6 \text{ mm} \left(\frac{1}{c_3^T}\right)^2 \left(\frac{8}{g_\rho}\right)^3 \left(\frac{3 \text{ TeV}}{m_T}\right)^5 \left(\frac{f}{10 \text{ TeV}}\right)^4$$

Need multiple searches strategies:

- collider stable
- displaced
- prompt



R-hadrons

Long-lived coloured objects will hadronise to form *R-hadrons*:

- More commonly considered in SUSY e.g. split-SUSY, RPV
- Colour-triplet scalar, T, has same quantum numbers as a sbottom
  $\rightarrow$ can take advantage of existing SUSY tools and searches!

ATLAS and CMS have searches for *collider stable* R-hadrons

- *escaping*, stopped
- Directly apply to our model

Also dedicated searches for *displaced* decays

- More model dependent
- Challenging to reinterpret

R-hadron (collider stable) searches

Heavy (charged) R-hadrons have $\beta = v/c \lesssim 0.9$ and can be identified by:

- Longer time-of-flight
- Increased ionisation energy-loss in the tracker

Searches virtually background free (< 1 event expected in Run 1 dataset)

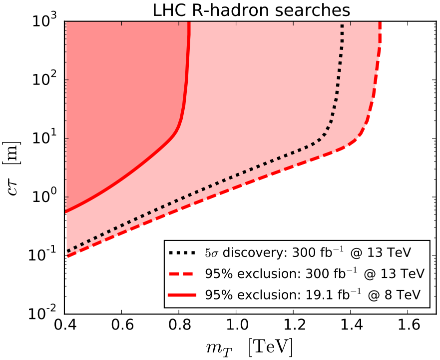
Re-interpret analysis for meta-stable R-hadrons:

- Simulate pair production of R-hadrons in `PYTHIA`
- Discard R-hadrons with $E < 20\,\text{GeV}$ which are likely stopped by detector
- Weight events by survival factor $p(r_{\text{decay}} > r_{\text{detector}}) = e^{-\beta_T r_{\text{detector}} \Gamma/\gamma}$
- Apply signal acceptance × efficiency ($\sim 8\%$)

R-hadron results

Current bound: $m_T > 845\,\text{GeV}$

5σ discovery reach up to *1.4 TeV* at $\sqrt{s} = 13\,\text{TeV}$



Results are model independent, apply to generic colour-triplet scalar

Displaced-vertex searches

R-hadron searches lose sensitivity for $c\tau \lesssim 10\,\mathrm{m}$
→ Dedicated displaced searches import to probe full parameter space

Strongest constraints from ATLAS displaced-vertex search: (1504.05162)

- Search for multitrack displaced-vertex, $4\,\mathrm{mm} < r_{DV} < 300\,\mathrm{mm}$
- In addition to high-p_T muon, electron, *jets* or $\not{E}_T$

DV+jets	≥ 4 jets ($p_T > 90$ GeV) or ≥ 5 jets ($p_T > 65$ GeV) or ≥ 6 jets ($p_T > 55$ GeV) and $\lvert\eta\rvert < 2.8$
DV+$\not{E}_T$	$\not{E}_T > 180$ GeV

But, displaced searches challenging to reinterpret:

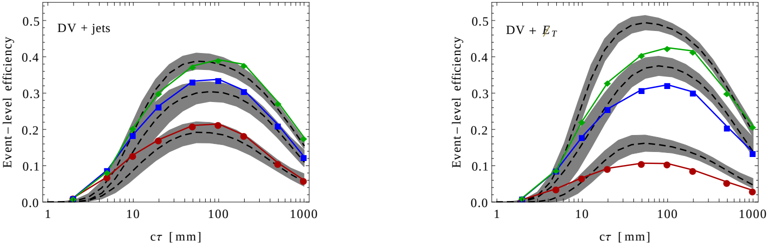
- Details of final-state important (model-dependent)
- Full detector simulation required to model interactions with detector and detailed object reconstruction
- Limited information on (tracking) efficiencies

Displaced-vertex searches

Our analysis:

- Include d_0 dependence of tracking efficiencies in `DELPHES` detector sim.
- *Estimate* efficiencies from published results
- Simulate DV reconstruction algorithm
- Neglect R-hadron energy-loss in detector

Good agreement with ATLAS analysis:



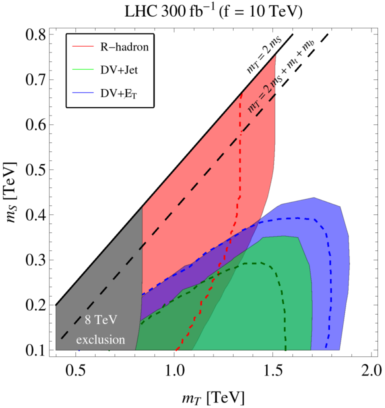
13 TeV 300 fb^{-1} projections

No constraint from Run-I DV search ($m_T > 845$ GeV from collider-stable)

Both R-hadron and DV searches important at $\sqrt{s} = 13$ TeV

DV search has higher signal eff.
(and less background)

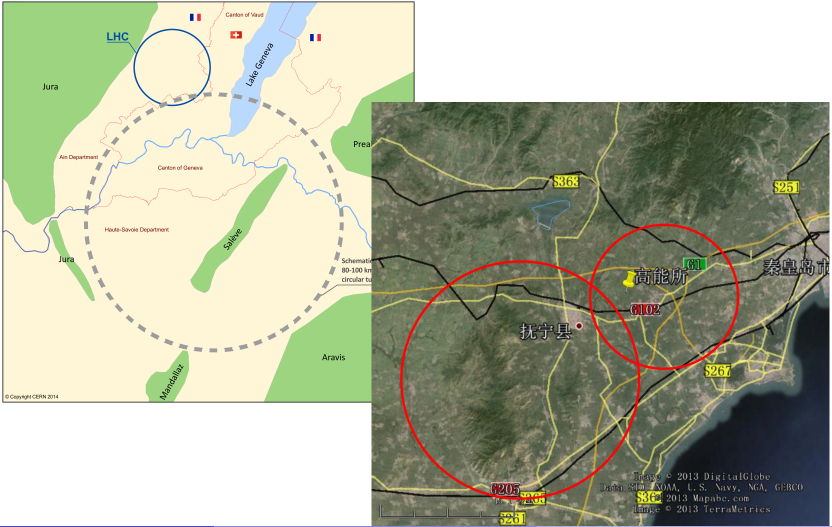
5σ discovery reach up to *1.8 TeV*



For larger $f \gtrsim 100$ TeV R-hadron searches provide only constraint

Future colliders

Now let's be hopeful...

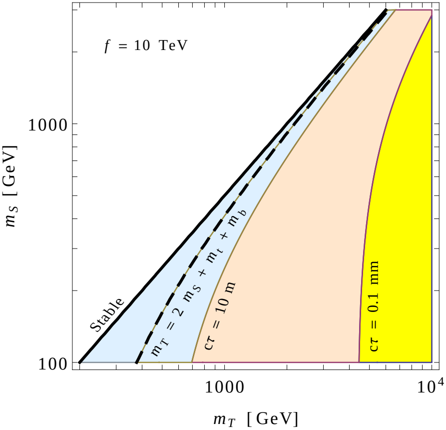


Colour-triplet decays

At 100 TeV can also probe region where T decays promptly

All 3 types of searches important:

- R-hadron/collider stable
- Displaced-vertex
- Prompt



Prompt searches

Take advantage of previous 100 TeV studies
→ use Snowmass detector and background Monte-Carlo (1308.1636)

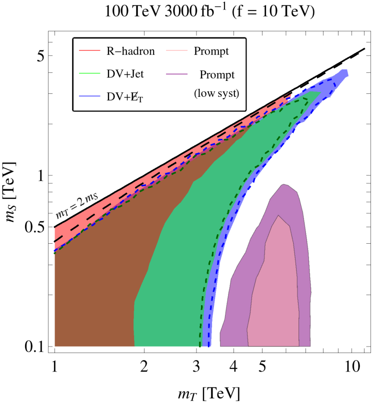
Final state is $t\bar{t}b\bar{b} + \not{E}_T \quad \Rightarrow$ dominant background is $t\bar{t}+$ jets.

Again, focus on fully hadronic final state due to larger BR
Final selection: $N_b \geq 4$, $\not{E}_T > 2.5$ TeV, $m_{\text{eff}} > 10$ TeV

Of course, many assumptions about future detector performance:
→ b-tagging has largest effect (assume 70-75% efficiency, 3% mis-tag rate)

100 TeV (f = 10 TeV)

5σ discovery reach for R-hadron/displaced searches
95% CLs exclusion for prompt searches

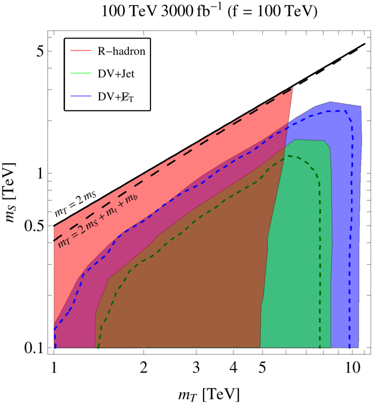


Search strategies complementary

→ but intermediate region potentially challenging

100 TeV (f = 100 TeV)

Triplet lifetime increases for $f = 100\,\text{TeV}$
→ prompt decays beyond reach of even 100 TeV machine



R-hadron and displaced searches provide good coverage up to $\sim 10\,TeV$

Summary

- Absence of new physics at the LHC *could* suggest Higgs potential is fine-tuned
- Unnatural (split) composite Higgs models provide precision unification, dark matter, explanation of fermion mass hierarchy *but* at the expense of tuning in Higgs sector
- The symmetry breaking scale, f, cannot be arbitrarily large ($\lesssim 500\,$TeV)
- Predict a colour-triplet scalar partner of the Higgs, which is often long-lived
- Current R-hadron limits imply $m_T > 845\,$GeV with discovery up to 1.8 TeV at 13 TeV LHC

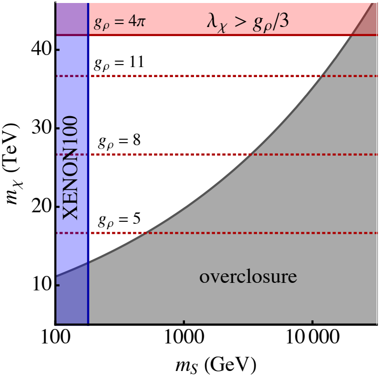
Backup slides

Dark Matter

Higgs portal coupling $V \supset \kappa |H|^2 |S|^2$

$$\kappa \sim 0.02 \left(\frac{m_\chi}{f}\right)^4$$

$$\gtrsim 3 \times 10^{-4} \left(\frac{m_S}{\text{GeV}}\right)$$ (overclosure)



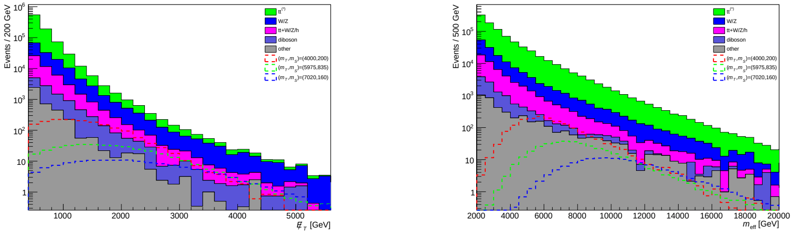
LUX bound $m_S \gtrsim 150$ GeV

For $f = 10$ TeV:

$$150 \text{ GeV} \lesssim m_S \lesssim 10 \text{ TeV} \qquad 10 \text{ TeV} \lesssim m_\chi \lesssim 40 \text{ TeV}.$$

Prompt searches

Initial selection: $N_j \geq 4$ ($p_T > 150, 50$ GeV), $N_b \geq 3$, $\not{E}_T > 400$ GeV, $m_{\text{eff}} > 2000$ GeV



Optimise cuts over (m_T, m_S) plane: $N_b \geq 4$, $\not{E}_T > 2.5$ TeV, $m_{\text{eff}} > 10$ TeV

	Preselection	Final selection
$(m_T, m_S) = (7020, 160)$	147	22
Total background	8.6×10^5	39

Assume systematic uncertainties:

- Background norm. (20%)
- Signal eff. (15%)
- PDF (5%)
- Luminosity (2.8%)