Interplay between collider and dark matter searches in composite Higgs models

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Based on MC, Gröber, Spannowsky, *1801.06537.*

The Standard Model is very strong, but it cannot explain all observations

Planck scale

valid up to

TeV scale

Non-minimal composite Higgs models

(very good candidates for new physics)

- No hierarchy problem because the Higgs is a bound state,
- This is lighter than the new physics scale (presumably slightly above the TeV) because is a goldstone of $\mathcal{G}/\mathcal{H}$,
- Fermion masses are induced by non-hierarchical couplings in the UV,
- Extra (neutral) scalars can be dark matter candidates,
- Very predictive with respect to elementary counterpart; On the other side, reacher heavy-fermion phenomenology.

The composite Higgs paradigm

(a high-energy copy of QCD)

UV

GeV scale

IR

$$L \sim m_q \, \overline{q_L} q_R + SU(2)_L \times SU(2)_R$$

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quark condensate

$$p, n, \Delta, \Sigma, \cdots$$

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$$\downarrow$$

$$SU(2)_V$$

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$$\pi^0, \pi^\pm$$

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$$L \sim \lambda[\Lambda_{UV}]\overline{q_i}\mathcal{O}_F^{d_i} + \text{ new global } \mathcal{G}$$

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$$L \sim \lambda[\text{TeV}]\overline{q_i}Q^i$$

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$$\mathcal{H} \supset \mathcal{G}_{SM}$$

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parton condensate

$$L \sim \lambda[\text{TeV}]\overline{q_i}Q^i \qquad m_\rho = g_\rho f$$

$$h, S, \sim \frac{N_c m_\rho}{4\pi} \qquad \mathcal{H} \supset \mathcal{G}_{SM}$$

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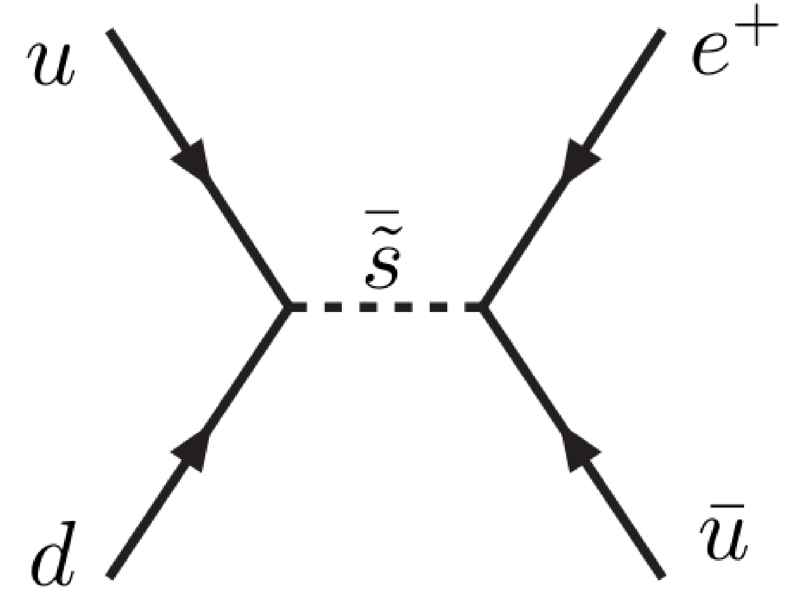
potential DM

$$h, S, \cdots \qquad \mathcal{H} \supset \mathcal{G}_{SM}$$

A comparison with R-parity in SUSY

(motivation relies *also* on dark matter)

Avoiding proton decay



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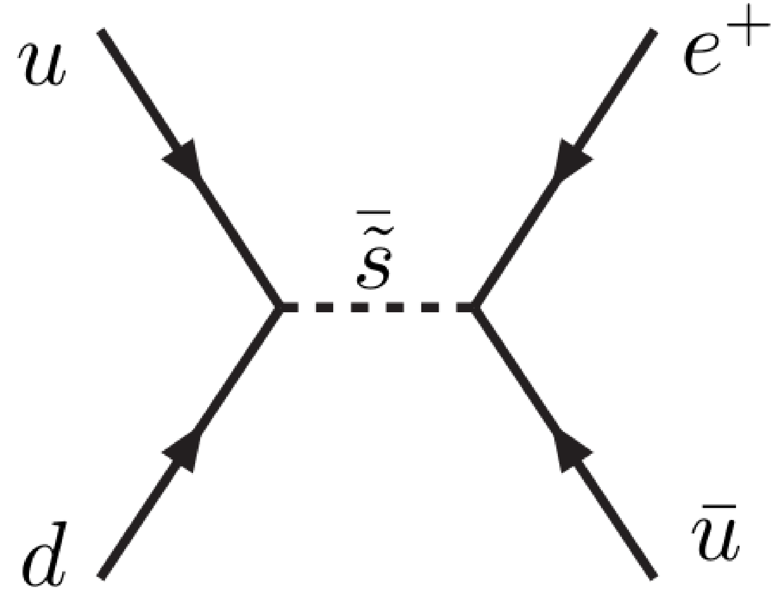
Avoiding proton decay

- Baryon parity



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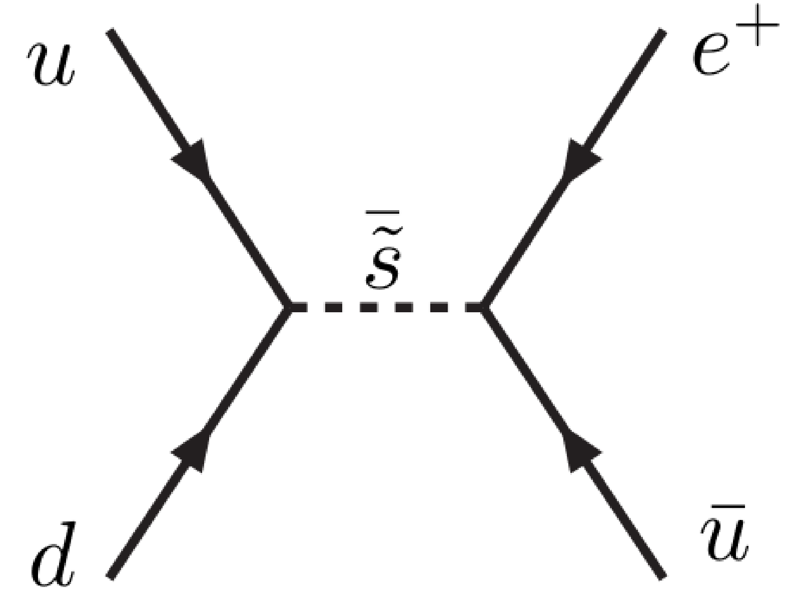
Avoiding proton decay

- Baryon parity
- Lepton parity



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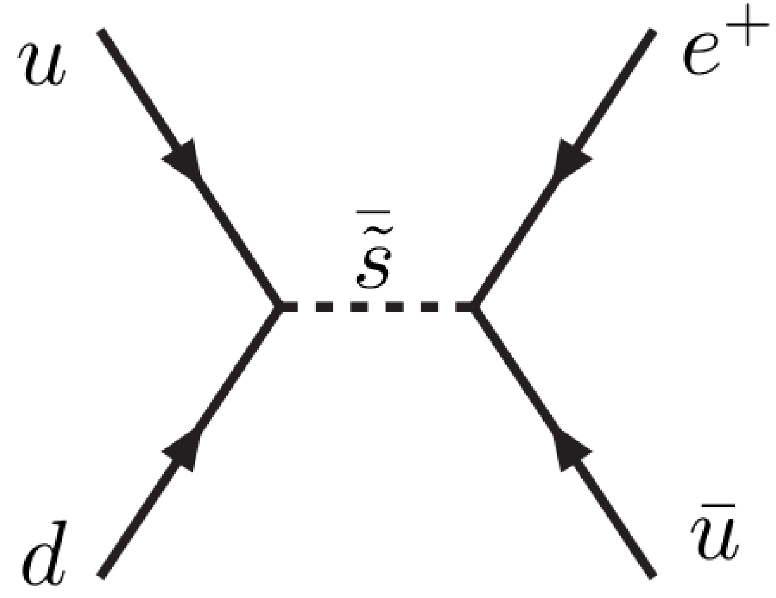
Avoiding proton decay

- Baryon parity
- Lepton parity
- Many others, see *e.g.* Smirnov and Visani, *9601387*. None prefered by GUT



A comparison with R-parity in SUSY

(motivation relies *also* on dark matter)

- Dark matter in SUSY does not really arise as a result of solving a *different* problem
- As SUSY, composite dark matter provides a rationale for the WIMP to be at the electroweak scale

Composite models are much more predictive!

Several models with composite WIMPs

(we will consider only singlets)

$$\frac{SO(6)}{SO(5)}$$

0902.1483, 1204.2808

$$\frac{SU(5)}{SO(5)} \times \frac{[SU(2) \times U(1)]^2}{SU(2) \times U(1)}$$

1707.09980

$$\frac{SO(7)}{SO(5)}$$

$$\frac{SO(7)}{SO(6)}$$

1605.08663, 1707.07685

$$\frac{SO(5) \times U(1)}{SO(4)}$$

1605.09647

$$\frac{SO(7)}{G_2}$$

1210.6208, 1704.07388

$$\frac{SU(5)}{SO(5)}$$

1304.4579

$$\frac{SO(6)}{SO(4)}$$

$$\frac{SO(6)}{SO(4) \times U(1)}$$

1105.5403

Simple yet broad parameterization

(several CHMs captured)

- H and S stand for the Higgs doublet and the DM singlet, respectively. We neglect the last term in our analysis

$$L = |D_\mu H|^2 \left[1 - a_1 \frac{S^2}{f^2}\right] + \frac{a_2}{f^2} \partial_\mu |H|^2 (S \partial_\mu S) + \frac{1}{2} (\partial_\mu S)^2 \left[1 - 2a_3 \frac{|H|^2}{f^2}\right]$$

$$-m_\rho^2 f^2 \frac{N_c y_t^2}{(4\pi)^2} \left[-\alpha \frac{|H|^2}{f^2} + \beta \frac{|H|^4}{f^4} + \gamma \frac{S^2}{f^2} + \delta \frac{S^2 |H|^2}{f^4}\right] + \left[i\epsilon \frac{y_t}{f^2} S^2 \overline{q_L} H t_R + \text{h.c.}\right]$$

The coset $SO(7)/G_2$

(first studied in *1210.6208*)

$$L \sim \frac{1}{2}\left[(\partial h)^2 + (\partial S)^2\right] + \frac{1}{2f^2}h^2(\partial h)^2 + \frac{1}{2f^2}hS(\partial h)(\partial S) + \cdots$$

$$+\, y_q \bar{q} q h \left[1 - \frac{h^2}{2f^2} - \frac{S^2}{2f^2}\right] + \cdots$$

$$\sim \frac{4m_S^2}{f^2}$$

$\mathcal{G}/\mathcal{H}$	$q_L + t_R$	a_1	a_2	a_3	γ	δ
$SO(6)/SO(5)$	$\mathbf{6}+\mathbf{1}$ $\mathbf{6}+\mathbf{15}$ $\mathbf{15}+\mathbf{15}$ $\mathbf{20}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$ $\ll 1$ $\ll 1$ $1/4$	$-$ $\ll 1$ $\ll 1$ $1/5$
$SO(7)/SO(6)$	$\mathbf{7}+\mathbf{1}$ $\mathbf{7}+\mathbf{7}$ $\mathbf{27}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$ $-$ $\leq 1/4$	$-$ $-$ $\leq 1/5$
$SO(7)/G_2$	$\mathbf{8}+\mathbf{8}$ $\mathbf{35}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$ $1/4$	$-$ $1/5$
$SO(6)/SO(4)$	$\mathbf{6}+\mathbf{6}$	0	$1/6$	$1/3$	$-$	$-$
$SO(5)\times U(1)/SO(4)$	$\mathbf{5}+\mathbf{5}$	0	0	0	$\ll 1$	$\ll 1$
$SO(7)/SO(5)$	$\mathbf{7}+\mathbf{7}$	$< 1/3$	$< 1/3$	$1/3$	$-$	$-$
$SO(7)/SO(6)$ [complex case]	$\mathbf{27}+\mathbf{1}$	~ 0.3	~ 0.3	~ 0.3	$\sim 1/4$	$\sim \sqrt{2}/5$

LHC constraints on VLQs

(non-SM decays also present)

- In all our cases of interest, there is always a custodial fourplet of VLQs and/or a VLQ decaying 100 % into St
- $m < 1.2$ TeV (expected 1.7 TeV for 3/ab), *[1705.03013]*

$$\mathrm{BR}(T, X_{2/3} \to ht) \sim \mathrm{BR}(T, X_{2/3} \to Zt) \sim 0.5$$

$$\mathrm{BR}(B \to W^- t) \sim \mathrm{BR}(X_{5/3} \to W^+ t) \sim \mathrm{BR}(T' \to St) \sim 1$$

Prospects for 100 TeV

(VLQs with SM decays)

- The most important cuts we impose are shown below. The most important backgrounds are then: $ttVV$, $tttt$, $ttV + jets$.

$$3\ell, |\eta_\ell| < 2.5, p_{T,\ell_1} > 250\ \text{GeV}, p_{T,\ell_2} > 100\ \text{GeV},$$

$$4j, p_{T,j} > 40\ \text{GeV}, |\eta_j| < 5, n_b = 2$$

$$H_T = \sum_{\text{leptons}} p_{T,\ell} + \sum_{\text{jets}} p_{T,j} + E_{T,miss} > 6\ \text{TeV}$$

Prospects for 100 TeV

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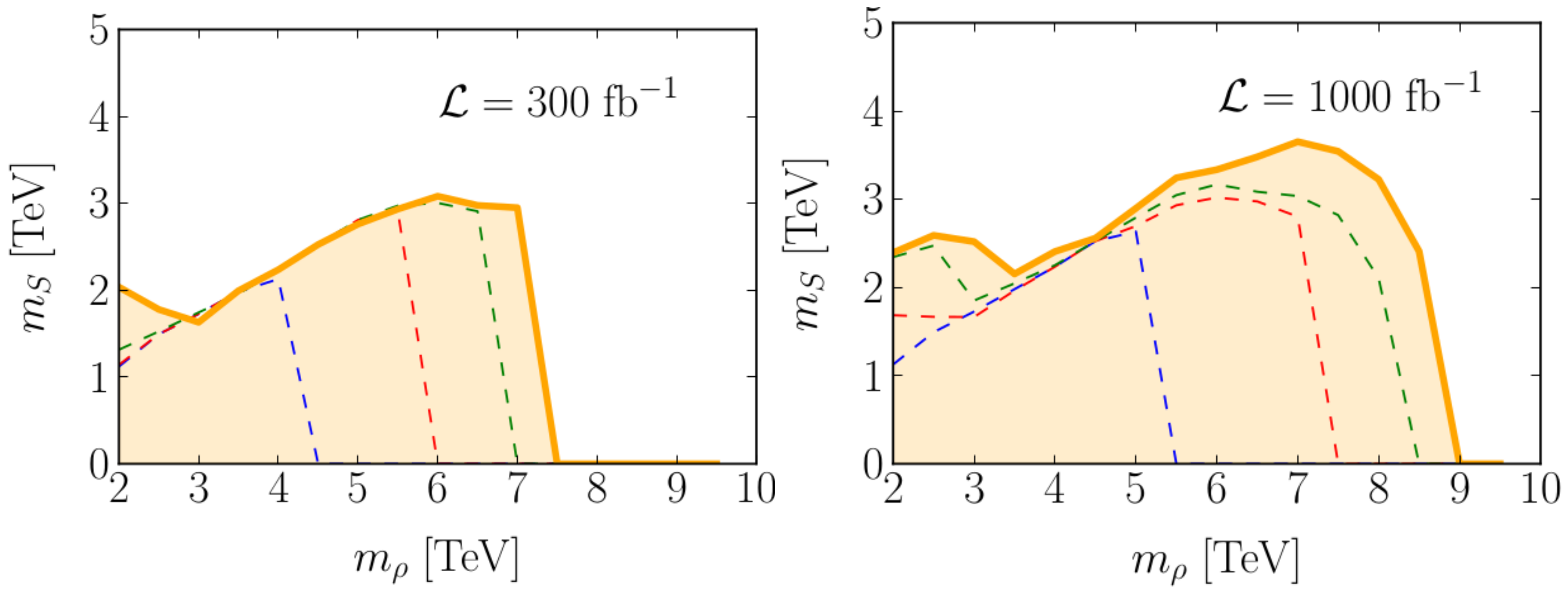
$$m_\rho \lesssim 6.4 \text{ TeV}$$

Prospects for 100 TeV

(VLQs with exotic decay)

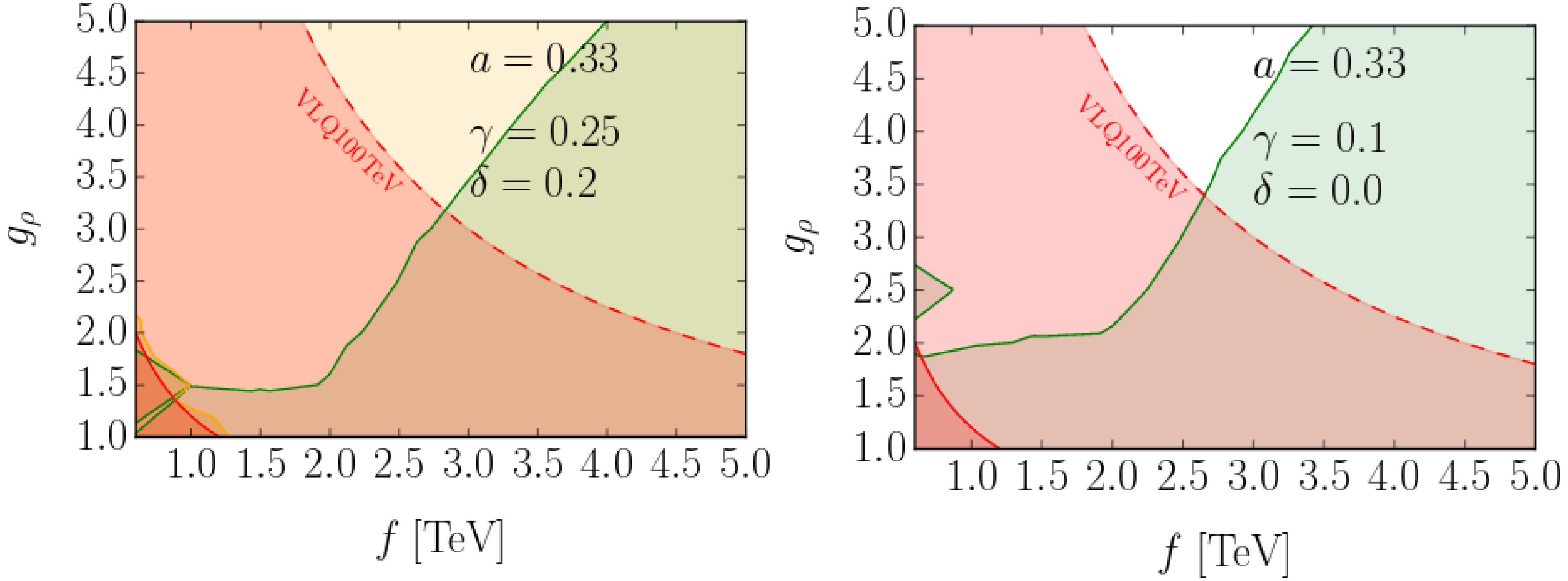
- Searches for pair-produced stops decaying into neutralino apply, *[1406.4512]*



Prospects for 100 TeV

(VLQs with exotic decay)

- Having all together: LHC (solid red), solid orange (LUX), relic (green), dashed red (100 TeV), dashed orange (LZ)



Conclusions

- In CHMs with DM, one single mechanism explains why the electroweak (EW) and the DM scales are of the same order, as suggested by the WIMP paradigm

- The Higgs has small portal couplings to the pNGB DM, while the observed relic density can be produced by effective derivative couplings

- Many of the (few) models are described by very few parameters. In some, the stability of DM after EWSB is *predicted*

- The amount of relic density requires $f < 2\text{-}3$ TeV. While resonances at this scale are out of the reach of the LHC, a future 100 TeV collider can observe them

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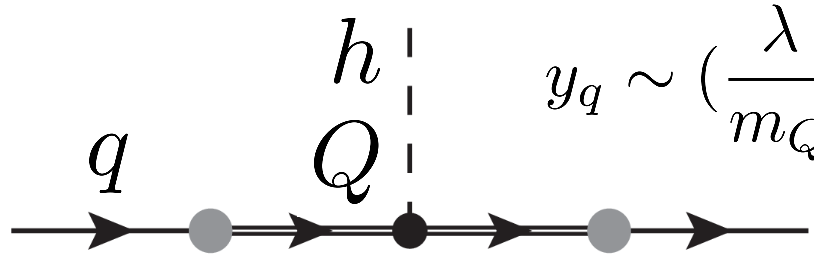

$$y_q \sim \left(\frac{\lambda}{m_Q}\right)^2$$

$$\mathcal{H} \supset \mathcal{G}_{SM}$$