VLQs at future colliders and implications for CHMs

Mikael Chala (IPPP)

With R. Grober and M. Spannowsky. *To appear soon*

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

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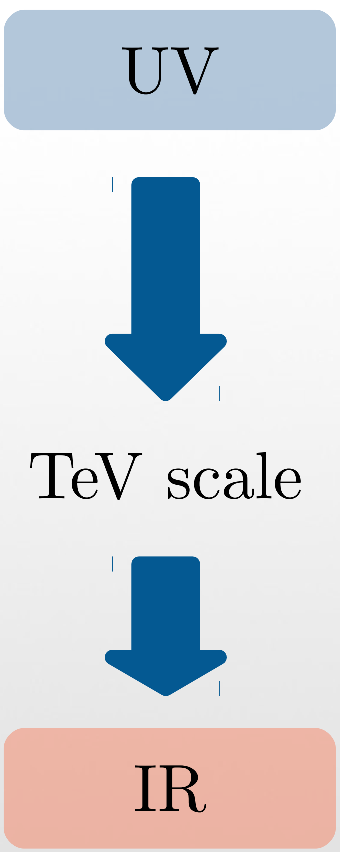

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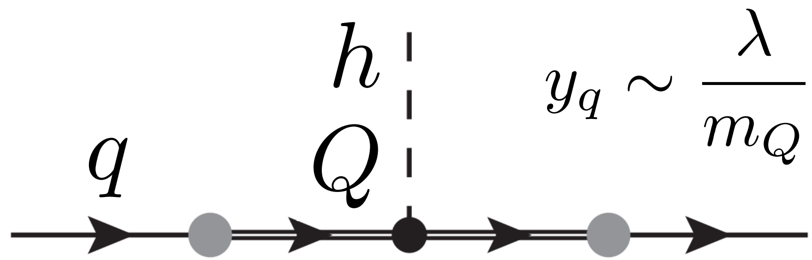

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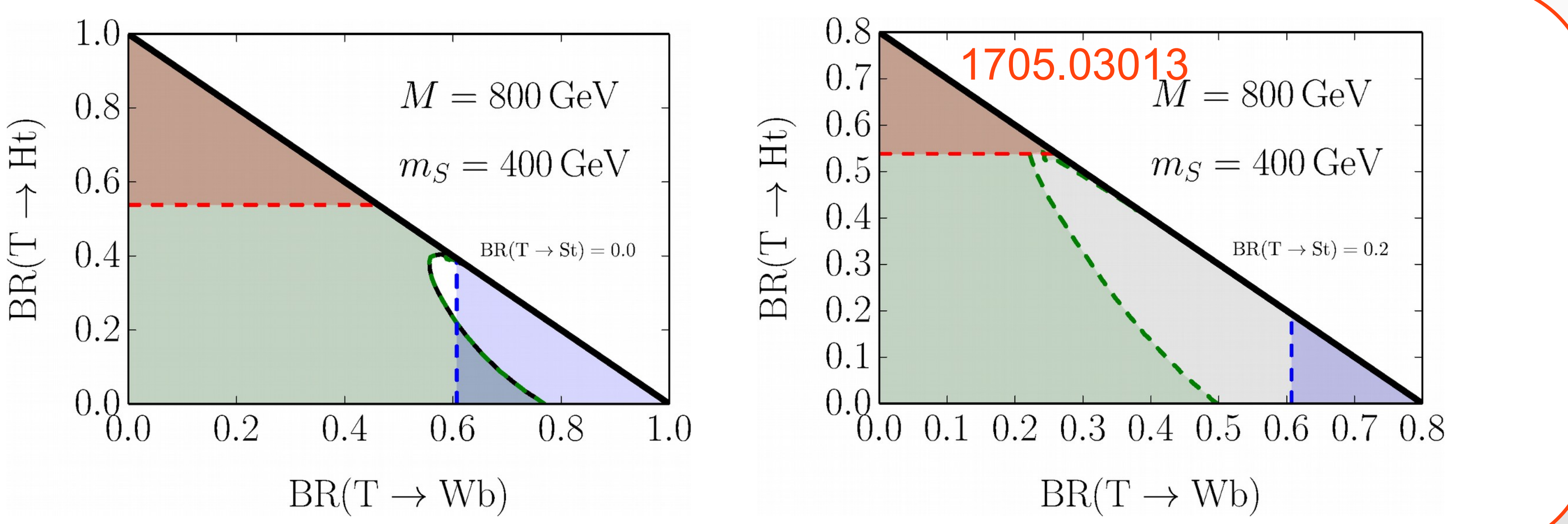

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- Upper bounds ranged from 1–1.5 TeV *[0612048]* to $<$ 1 TeV *[1204.6333, 1205.0232, 1205.0770, 1205.6434, 1210.7114]*. Ref. *[1210.7114]* showed that masses around 2 TeV are compatible with tuning of order 100 in some CHMs

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NB: Tuning gives only a (rough) order of magnitude!

VLQs could be well out of the LHC reach

(this is expected in CHMs with DM!)

- Similarity of WIMP and EW scales explained
- Naturally small portal couplings
- DM annihilates then via derivative interations
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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

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

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

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$$V = \frac{i}{f^2}\left[-2N_c\delta\frac{m_\rho^2}{(4\pi)^2} + 2a_1(p_1\cdot p_2) + 2a_3(p_3\cdot p_4) - a_2(p_1+p_2)(p_3+p_4)\right]$$

$$= \frac{2i}{f^2}\left[(2a_1+2a_2+a_3)m_S^2 - N_c\delta\frac{m_\rho^2}{(4\pi)^2}\right] \sim \frac{2iN_c m_\rho^2}{(4\pi)^2 f^2}\left[2(2a_1+2a_2+a_3)\gamma-\delta\right]$$

Matching to concrete models

(with one stable pNGB singlet)

- a coefficients fixed by the sigma model. Others depend on fermionic representations. *e.g.* $SO(6)/SO(5)$ with **20+1**:

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$$V = c_1\left[2f^2|H|^2 - \frac{16}{3}|H|^4 - \frac{8}{3}S^2|H|^2\right] + c_2\left[-\frac{7}{2}f^2|H|^2\right.$$

1703.10624

$$\left.\frac{19}{3}|H|^4 - 2S^2 + \frac{23}{6}S^2|H|^2\right]$$

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$$L = |D_\mu H|^2 \left[1 - \frac{S^2}{3f^2}\right] + \frac{1}{3f^2}\partial_\mu |H|^2 (S\partial_\mu S) + \frac{1}{2}(\partial_\mu S)^2 \left[1 - 2\frac{|H|^2}{3f^2}\right]$$

$$- \left[\frac{1}{3} f^2 \lambda_H S^2 + \frac{5}{18}\lambda_H S^2 |H|^2\right]$$

$\mathcal{G}/\mathcal{H}$	$q_L + t_R$	a_1	a_2	a_3	γ	δ
$SO(6)/SO(5)$ 1204.2808	$\mathbf{6}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$	$-$
	$\mathbf{6}+\mathbf{15}$				$\ll 1$	$-$
	$\mathbf{15}+\mathbf{15}$				$\ll 1$	$-$
	$\mathbf{20}+\mathbf{1}$				$1/4$	$1/5$
$SO(7)/SO(6)$	$\mathbf{7}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$	$-$
	$\mathbf{7}+\mathbf{7}$				$-$	$-$
	$\mathbf{27}+\mathbf{1}$				$\leq 1/4$	$\leq 1/5$
$SO(7)/G_2$	$\mathbf{8}+\mathbf{8}$	$1/3$	$1/3$	$1/3$	$-$	$-$
	$\mathbf{35}+\mathbf{1}$				$1/4$	$1/5$
$SO(6)/SO(4)$	$\mathbf{6}+\mathbf{6}$	$1/3$	$1/6$	0	$-$	$-$
$SO(5)\times U(1)/SO(4)$	$\mathbf{5}+\mathbf{5}$	0	0	0	$\ll 1$	$\ll 1$
$SO(7)/SO(5)$	$\mathbf{7}+\mathbf{7}$	$1/3$	$< 1/3$	$< 1/3$	$\ll 1$	$\ll 1$
$SO(7)/SO(6)$ [complex case]	$\mathbf{27}+\mathbf{1}$	$\sim 1/4$	$\sim 1/4$	$\sim 1/4$	$\sim 1/4$	$\sim \sqrt{2}/5$

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$SO(7)/SO(6)$	$\mathbf{7}+\mathbf{1}$ $\mathbf{7}+\mathbf{7}$ $\mathbf{27}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$ $-$ $\leq 1/4$	$-$ $-$ $\leq 1/5$
$SO(7)/G_2$ 1704.07388	$\mathbf{8}+\mathbf{8}$ $\mathbf{35}+\mathbf{1}$	$1/3$	$1/3$	$1/3$	$-$ $1/4$	$-$ $1/5$
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$SO(7)/SO(6)$ 1707.07685 [complex case]	$\mathbf{27}+\mathbf{1}$	$\sim 1/4$	$\sim 1/4$	$\sim 1/4$	$\sim 1/4$	$\sim \sqrt{2}/5$

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 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: $ttVV$, $tttt$, $ttV + jets$.

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

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

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

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$$m_\rho \lesssim 5 \text{ TeV}$$

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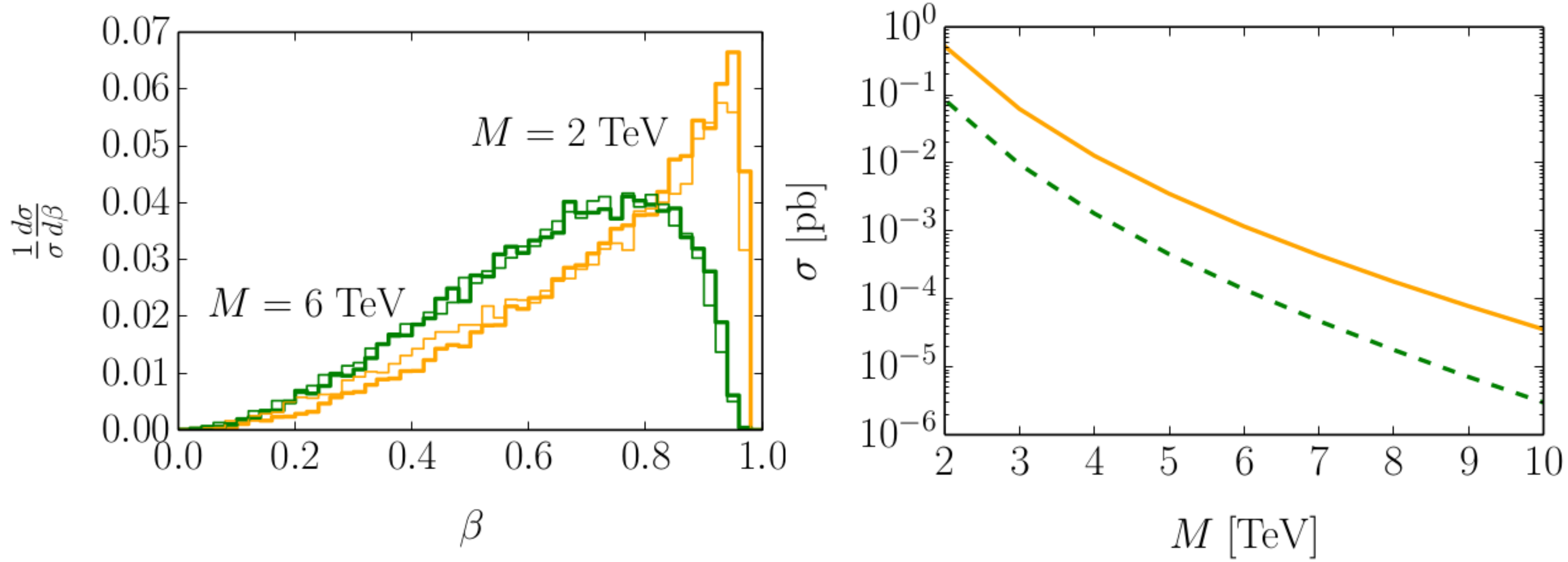
- Searches for pair-produced stops decaying into neutralino apply, *[1406.4512]*



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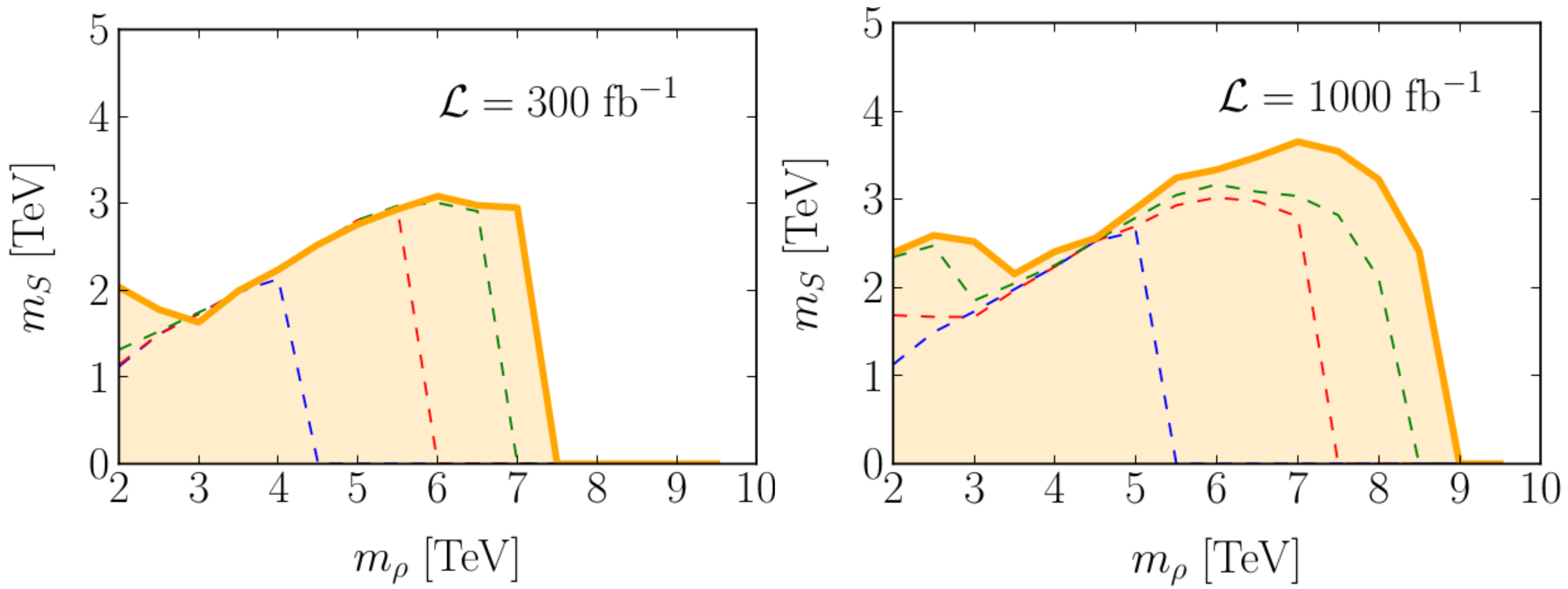

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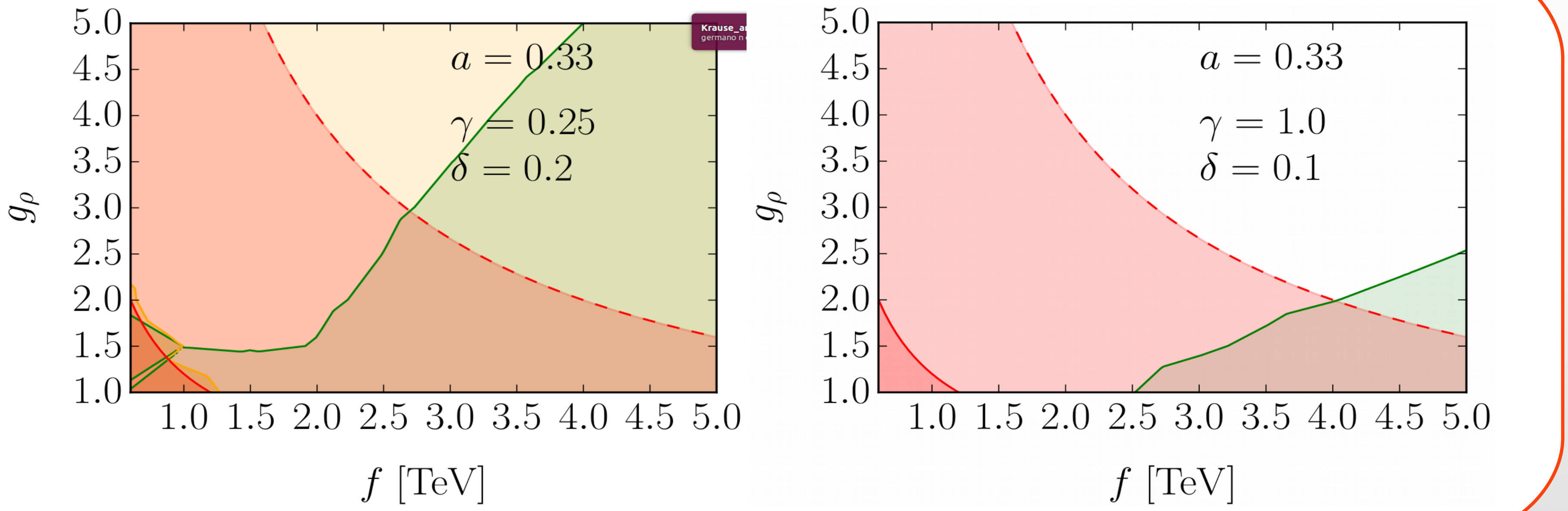
- Having all together (preliminary): LHC (solid red), solid orange (LUX), relic (green), dashed red (100 TeV)



Conclusions

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- Models of composite Higgs with DM (in which f is fixed by observation) suggest $m > 2$ TeV
- Searches for VLQs (in SM decays) at 100 TeV collider can test masses as large as 5 TeV. Searches for VLQs (in stop-like decay) can test even larger masses: 9 TeV
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