Collider signals of new quarks and vector bosons

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and J. Santiago. Based on 1305.1940 and 1411.1771.
Outline

Going beyond the Standard Model: CHMs

Collider phenomenology of new quarks

Collider phenomenology of new gluons
The Standard Model is very strong

Planck scale

valid up to

Renormalizable
Stable vacuum
Degrassi et al., 1205.6497

...
The SM works extremely well, but...

\[ \mathcal{L}_S = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu_h^2 \phi^\dagger \phi - \lambda_h (\phi^\dagger \phi)^2 \]

- Puzzling hierarchy

- Instability

- Neutrino masses?
To big solutions to the hierarchy problem

Elementary scalar particles are unnatural in QFT...

Supersymmetry

CHMs
The Higgs boson, $h$, is a **bound state** of a new strongly interacting sector. The Higgs boson mass is protected by its finite size.
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$SM \subset H \subset G$
The Higgs boson, $h$, is a pNG boson of a new strongly interacting sector.

The Higgs boson mass is protected by its finite size.

It is naturally light.
In the MCHM, the scalar sector is well described by a non-linear sigma model based on the coset $G/H = SO(5)/SO(4)$.

$$\mathcal{L} = \frac{1}{2} \partial_\mu h \partial^\mu h + \frac{g^2}{4} f^2 \sin^2 \left( \frac{h}{f} \right) W_\mu^+ W_\mu^- + \frac{g^2}{8 c_W^2} f^2 \sin^2 \left( \frac{h}{f} \right) Z_\mu Z^\mu$$

$$\rightarrow \frac{1}{2} \partial_\mu h \partial^\mu h + \frac{g^2}{4} \left[ v^2 + 2v \sqrt{1 - \xi h} + (1 - 2\xi) h^2 \right] \left[ W_\mu^+ W_\mu^- + \frac{1}{2 c_W^2} Z_\mu Z^\mu \right]$$

**Departures from SM couplings of order** $\xi = \frac{v^2}{f^2}$
Generation of the quark mass hierarchy

(the top quark interacts stronger with the new sector)

UV scale

\[ \mathcal{L} \sim \lambda [\Lambda_{UV}] \bar{q}_i O^d_i + \text{h.c.} \]

Confinement scale \( \sim \text{TeV} \)

\[ \mathcal{L} \sim \lambda [\text{TeV}] \bar{q}_i Q^i + \text{h.c.} \]

elementary-composite mixing

Electroweak scale

\[ y_q \sim \frac{\lambda}{m_Q} \]
Phenomenological implications

- Low-energy physics: $S$ and $T$ parameters, corrections to the $Zbb$ vertex, etc. (can be controlled by symmetries)
- Higgs phenomenology: modified couplings.
- Unavoidable new fermionic resonances.

\[ \mathcal{L} \sim \mathcal{L}_{SM} + \sum_{i,j} \left\{ \overline{Q}_i \not{\!\!} D Q_i + [\Delta_{ij} \overline{Q}_i q_j + \text{h.c.}] \right\} \]
General properties of top/bottom partners

- **Rather light** (TeV scale), large fine tuning otherwise.
- Charged under SU(3), and hence copiously produced.
- Top (bottom) partners decay **only** into tZ, th, Wb (bZ, bh, Wt). BRs dictated by the linear mixings.

.Dictated by QCD: model-independent
Model-independent limits on $m_T < 750$ GeV and $m_B < 600$ GeV.

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Other searches for heavy quarks

- Searches in single production can shed light over the mixing structure.

- Searches for resonances of the light quarks can give rise to very interesting topologies: double Higgs production, ...

\[ \gamma^\mu \frac{q^\nu}{2m_{T(B)}} \lambda_{T(B)} \]

\[ b(t) \rightarrow W^- \rightarrow q \bar{q} \]

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\[ \text{arXiv:1207.0830} \]

\[ \text{arXiv:1302.0270} \]

\[ \text{ATLAS-CONF-2012-137} \]
Vector resonances can be also present

- Dramatic implications if $G^*$ decays also into heavy fermion partners: much **heavier width, different final states**.

- Current constraints together with naturalness arguments suggest that this is actually the case.
A *reductio ad absurdum* argument

Assume that heavy gluons do not decay into heavy fermion partners. Then use **constraints from top-antitop resonant searches**: 

![Graph](image1.png) 

![Graph](image2.png)

**TU Dortmund, January 19th 2016**

arXiv:1505.07018 

arXiv:1309.2030
A *reductio ad absurdum* argument

Assume that heavy gluons do not decay into heavy fermion partners. Then use *constraints from top-antitop resonant searches*:

The heavy gluon mass is bounded to be $>2$ TeV. On the other hand, the top partners are required to be (typically) $<1$ TeV. So at least two of the next three channels are expected to be also open:
Something related to non-Higgs channels

The decays of Bs into Z bosons give very clear signatures
New Higgs production mechanism

- We concentrate on **final states with a Higgs boson**.
- In practice, we have very few free parameters.
- We set $M_G = 2M_Q$ to avoid double production.
A benchmark point: $g_c = 3$, $s_q R = 0.6$

For the plots below we fix the mass of the heavy quark to 1 TeV.
Resonances of the $t$ quark

- Consider $h$ decay into $b\bar{b}$ and leptonic top decays.
- Large cross sections and very distinctive kinematics.
- Main backgrounds given by $t\bar{t}$ and $ttbb$.
- Analyses at 14 TeV can benefit from boosted techniques.

Large $S_T$

$$S_T \equiv \sum_{i=1}^{n_j+n_\ell} p_T^i + E_T^{\text{miss}}$$
Detailed set of cuts for 7 and 8 TeV

- At least four jets, at least three must be $b$-tagged.
- At least one isolated charged lepton.
- $S_T > 0.9, 1.1, 1.5$ TeV for $M_G = 1.5, 2, > 2.5$ TeV.

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Results for fixed $g_c = 3$
Resonances of the $b$ quark

- $4b$ quarks in the final state (SUSY searches are sensitive).
- Heavy quark and heavy gluon can be reconstructed.
- Example of new physics where **small departures** on current analyses drastically **increase the sensitivity**.
- Large decay of $B$ into $hb$.
- 4$b$ quarks in the final state (SUSY searches are sensitive).
- Heavy quark and heavy gluon can be reconstructed.
- Example of new physics where small departures on current analyses drastically increase the sensitivity.
Most probably, the decay into two heavy fermions is also open

Implications on searches for pair-produced heavy quarks:

arXiv:1507.06628 (similar conclusions in 1505.01506)
Implications for ttbar resonance searches

MC, Juknevich, Pérez, Santiago

1411.1771
Implications for ttbar resonance searches
Implications for ttbar resonance searches

A difference of 400 GeV
Testing heavy masses with EWPD
Running from the new physics scale down to the electroweak scale

\[ c_{\phi q}^{(1),(3)} \sim \frac{N_c y_t^2}{16\pi^2} c_{qt}^{(1)} \log \frac{\Lambda}{\nu} \]

It translates into constraints on the new scale of order TeV for couplings of order 1
\[
\begin{array}{c|c|c}
\text{Operator} & \text{Notation} & \text{Operator} \\
\frac{1}{2} (\bar{l}_L \gamma_\mu l_L) & \mathcal{O}_{ll}^{(1)} & \frac{1}{2} (\bar{q}_L \gamma_\mu T_A q_L) \\
\frac{1}{2} (\bar{q}_L \gamma_\mu q_L) (\bar{q}_L \gamma_\mu q_L) & \mathcal{O}_{qq}^{(1)} & \frac{1}{2} (\bar{l}_L \gamma_\mu \sigma_\alpha l_L) (\bar{q}_L \gamma_\mu \sigma_\alpha q_L) \\
(\bar{l}_L \gamma_\mu l_L) & \mathcal{O}_{lq}^{(1)} & \end{array}
\]

\[
\begin{array}{c|c|c}
\text{Operator} & \text{Notation} & \text{Operator} \\
\frac{1}{2} (\bar{e}_R \gamma_\mu e_R) & \mathcal{O}_{ee}^{(1)} & \frac{1}{2} (\bar{d}_R \gamma_\mu d_R) (\bar{d}_R \gamma_\mu d_R) \\
\frac{1}{2} (\bar{u}_R \gamma_\mu u_R) (\bar{u}_R \gamma_\mu u_R) & \mathcal{O}_{uu}^{(1)} & (\bar{u}_R \gamma_\mu T_A u_R) (\bar{d}_R \gamma_\mu T_A d_R) \\
(\bar{u}_R \gamma_\mu u_R) (\bar{d}_R \gamma_\mu d_R) & \mathcal{O}_{ud}^{(1)} & (\bar{e}_R \gamma_\mu e_R) (\bar{d}_R \gamma_\mu d_R) \\
(\bar{e}_R \gamma_\mu e_R) (\bar{u}_R \gamma_\mu u_R) & \mathcal{O}_{eu}^{(1)} & \end{array}
\]

\[
\begin{array}{c|c|c}
\text{Operator} & \text{Notation} \\
(\bar{l}_L \gamma_\mu l_L) (\bar{e}_R \gamma_\mu e_R) & \mathcal{O}_{lc} \\
(\bar{l}_L \gamma_\mu l_L) (\bar{u}_R \gamma_\mu u_R) & \mathcal{O}_{lu} \\
(\bar{q}_L \gamma_\mu q_L) (\bar{u}_R \gamma_\mu u_R) & \mathcal{O}_{qu}^{(1)} \\
(\bar{q}_L \gamma_\mu q_L) (\bar{d}_R \gamma_\mu d_R) & \mathcal{O}_{qd}^{(1)} \\
(\bar{l}_E R) (\bar{d}_R q_L) & \mathcal{O}_{ledq} \\
(\bar{q}_L u_R) i \sigma_2 (\bar{q}_L d_R)^T & \mathcal{O}_{quad}^{(1)} \\
(\bar{l}_E R) i \sigma_2 (\bar{q}_L u_R)^T & \mathcal{O}_{lequ} \\
\end{array}
\]

\[
\begin{array}{c|c|c}
(\bar{q}_q)(\bar{t}t) & \mathcal{O}_{ll}^{(1)} \\
1008.3562, & \mathcal{O}_{ll}^{(3)} \\
1506.08845, & \mathcal{O}_{ll} \\
\end{array}
\]

\[
(\bar{q}_q)(\bar{q}_q) & \mathcal{O}_{ee}^{(1)} \\
1201.6510, & \mathcal{O}_{ee} \\
\text{low luminosity, flavor symmetry, no radiation/detector effects, ...} & \end{array}
\]

In preparation with J. Blas and J. Santiago
\[ \sigma = \sigma_{SM} + \frac{\alpha_1}{\Lambda^2} A_1 + \cdots + \frac{\alpha_N}{\Lambda^2} A_N \]
\[ + \frac{\alpha_1^2}{\Lambda^4} A_{11} + \cdots + \frac{\alpha_N^2}{\Lambda^4} A_{NN} \]
\[ + \frac{\alpha_1 \alpha_2}{\Lambda^4} A_{12} + \cdots + \frac{\alpha_{N-1} \alpha_N}{\Lambda^4} A_{NN-1} \]
At any rate, altogether show (minimal) composite Higgs models are in tension

- Constraints on large heavy quark masses (even more if heavy gluon are present) from the LHC.
- Constraints on v/f from Higgs measurements.
- Large constraints on v/f from EWPD.

\[ f \gg v, \text{ reintroduces fine-tuning} \]
Some plausible solutions

- Considering non-minimal CHMS: $\text{SO}(6)/\text{SO}(5)$ [0902.1483], $\text{SO}(7)/\text{G2}$ [1210.6208], $\text{SO}(6)/\text{SO}(4) \times \text{SO}(2)$ [1105.5403], ...

- New decays into the new scalar particles [1506.05110], less constrained than previous ones.

- Considering realistic lepton sector [1410.8555]: higher vector-like masses are naturally allowed.
Conclusions
• CHMs are an appealing solution to the hierarchy problem (including the quark mass puzzle).

• The goldstone symmetry of the Higgs boson is broken by the linear mixings between elementary and composite fermions.

• The mixing is larger for heavy fermions (top and bottoms), so their associated resonances are light (TeV).

• Model independent bounds on T partners around 750 GeV.

• The phenomenology is drastically different if heavy vectors are present in the spectrum.
Decays into fermionic resonances are expected to occur, which modifies the width of G and its final states.

Current searches for (realistic) heavy gluons give rise to limits around 500 GeV smaller than expected in simpler scenarios.

Future limits on vector resonances mediating Higgs production in CHMs are around 4 TeV.

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Thank you for your attention!