# Phenomenology of unusual top partners in Composite Higgs Models

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# Overview

Motivations for composite Higgs models

Composite Higgs, basic idea

Models beyond the minimal one

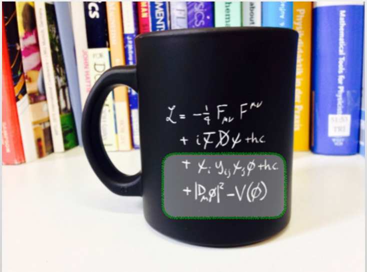
Phenomenological aspects for LHC

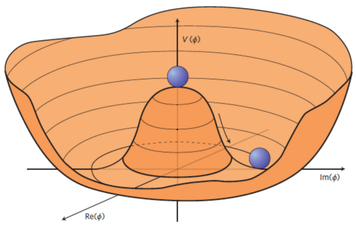
Conclusions & outlook

# Jobs of the SM-Higgs Multiplet

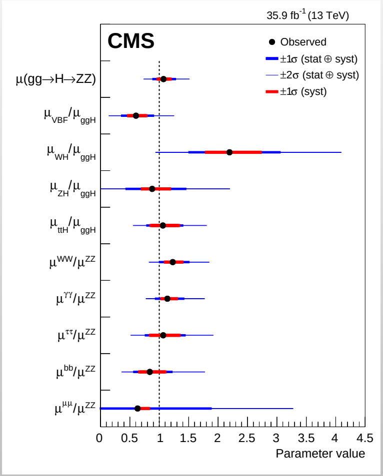
$$\phi(x) = \frac{1}{\sqrt{2}} e^{i\tau^a \chi^a(x)/v} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

- its non-zero vacuum expectation value $v$ spontaneously breaks the electroweak gauge group $SU(2)_L \times U(1)_Y$ to $U(1)_{em}$
- gives masses to $W^\pm$, $Z$
- gives masses to the fermions
- bonus: provides one physical scalar $h$ ('the Higgs boson')

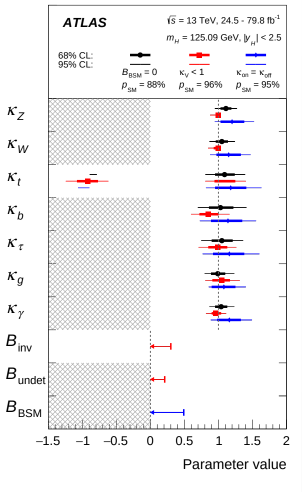




By now, many of the Higgs properties are properties are being tested.
With the HL-LHC run, we enter the Higgs precision area.



CMS coll., EPJC **79**, 421 (2019)

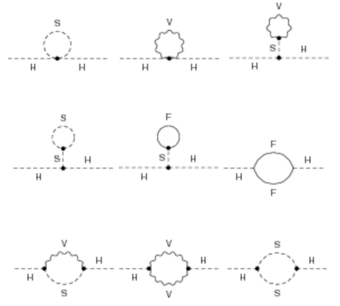


ATLAS coll., PRD **101**, 012002 (2020)

Note: So far, Higgs self-couplings are not experimentally verified
⇒ the Higgs potential is thus not measured, yet.

# Hierarchy problem

In the absence of new symmetries/dynamics: Higgs condensate and Higgs mass are unstable to quantum corrections & dragged-up to very large energy scales

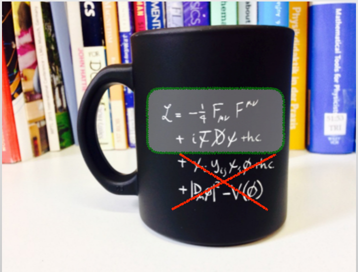


$$\frac{\delta v^2}{v^2} = \sum_i \pm \frac{g_i^2}{16\pi^2}\frac{M_i^2}{v^2} \gg 1$$

$M_i$: proxy for unknown heavy mass scales (flavour, GUTs, gravity, . . . )

# What if there were no Higgs?

QCD breaks electroweak symmetry! just wrongly



Gauge group: $SU(3)_C \times SU(2)_L \times U(1)_Y$

$1^{st}$ family quarks: $q_L, u_R$ and $d_R$

Global symmetry: $SU(2)_l \times SU(2)_r$
(of QCD sector)

At QCD scale: condensation

$$\langle \bar{q}_L q_R \rangle = -f_\pi B_0 \simeq (200 \text{ MeV})^3$$

$SU(2)_l \times SU(2)_r \to SU(2) \Rightarrow$ 3 Nambu-Goldstone bosons: $\pi^{0,+,-}$

# Problems

- $m_W = m_Z \simeq$ O(100 MeV)
- no Higgs d.o.f. at the scale of $m_{W,Z}$
- $U(1)_{em} = U(1)_Y$
- a priori no masses for quarks and leptons (but could be induced via 4-Fermi operators, (as in Nambu-Jona-Lasinio model (NJL-model))

. . . but the hierarchy problem would be solved!


Experimentalist


Phenomenologist

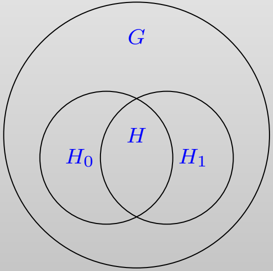

Model-Builder


Formal Theorist

# Minimal Composite Higgs Model

K. Agashe, R. Contino and A. Pomarol, NPB **719** (2005), 165
R. Contino, TASI lectures 2009

Assumes there is an additional strong force, often called hyper-color, and new ‘quarks’



$G$: global symmetry of the strong sector (at energy above confinement)

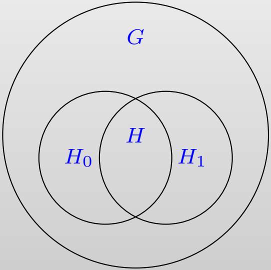
$H_1$: global symmetry group in confined phase below scale $f$

$H_0$: SM electroweak gauge group

$H$: unbroken gauge group

What are the smallest groups which can
give electroweak symmetry breaking and a Higgs?

# Minimal Composite Higgs Model



$G$: $SO(5) \times U(1)_X$

$H_1$: $SO(4) \times U(1)_X \sim SU(2)_L \times SU(2)_R \times U(1)_X$

$H_0$: $SU(2)_L \times U(1)_Y$

$H$: $U(1)_{em}$

- $SO(5) \to SO(4)$ breaking $\Rightarrow$ 4 Nambu-Goldstone bosons in $(2,2)$ of $SU(2)_L \times SU(2)_R$
- $Y = T^{3R} + X$, $U(1)_X$ needed to get correctly the hypercharges of the fermions

# Minimal Composite Higgs Model

The Nambu-Goldstone boson sector (aka Higgs multiplet) can be parameterized as a pNGB field $\Sigma$

$$\Sigma(x) = \mathrm{e}^{\Pi(x)/f}\Sigma_0\,, \qquad \Sigma_0 = (0,0,0,0,f)^T\,, \qquad \Pi(x) = -\mathrm{i}\sum_{\hat{a}} T^{\hat{a}} h^{\hat{a}}(x)$$

$$\Sigma = \frac{f\sin(h/f)}{h}\left(h^1, h^2, h^3, h^4, h\cot(h/f)\right)^T\,, \qquad h \equiv \sqrt{(h^{\hat{a}})^2}$$

The gauge interaction pf $\Sigma$ are given by $\mathcal{L}_\Sigma = \frac{1}{2}(D_\mu\Sigma)^T D^\mu\Sigma$

yield after electroweak symmetry breaking

$$\mathcal{L}^V_{\mathrm{eff}} = \frac{f^2}{8}\left(\frac{v+h}{f}\right)\left(W^i_\mu W^{i\mu} - 2W^3_\mu B^\mu + B_\mu B^\mu\right) + \dots$$

$$= \left(1 + 2\sqrt{1-\xi}\frac{h}{v} + (1-2\xi)\frac{h^2}{v^2} + \dots\right)\left(m^2_W W^+_\mu W^{-\mu} + \frac{m^2_Z}{2} Z_\mu Z^\mu\right) + \dots$$

where $\xi = \dfrac{v^2}{f^2}$

# Minimal Composite Higgs Model

Fermion masses and couplings: partial compositeness

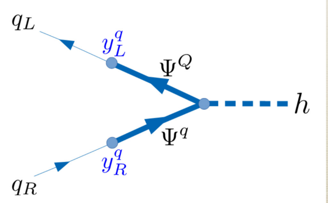
Higgs transforms non-linearly under $G$.
⇒ no Yukawa interaction if fermion are elementary (transform linearly).
Possible solution: mix elementary fermions with composite resonances.

Elementary fermions (in $SO(5)$) rep.)

$$q_L = \frac{1}{\sqrt{2}}(\mathrm{i}d_l, d_L, \mathrm{i}u_L, -u_L, 0)^T$$
$$q_R = (0,0,0,0,u_R)^T$$

Composite fermions (in $SO(5)$) rep.)

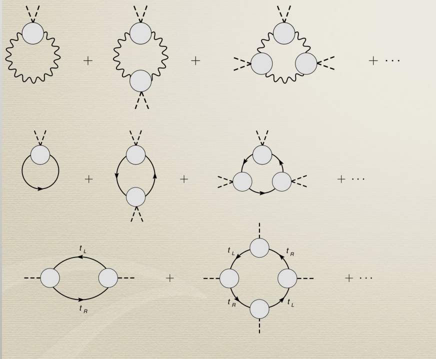
$$\Psi = \frac{1}{\sqrt{2}}\begin{pmatrix} \mathrm{i}D - \mathrm{i}X_{5/3} \\ D + X_{5/3} \\ \mathrm{i}U + \mathrm{i}X_{2/3} \\ -U + X_{2/3} \\ \sqrt{2}\tilde{U} \end{pmatrix}$$



# Minimal Composite Higgs Model

Up to now: Higgs als Nambu-Goldstone bosons, thus massless. But:

- Only the electroweak group is gauged, not the full $SO(5) \times U(1)_X$.
  $\Rightarrow$ global symmetry explicitly broken by electroweak gauge symmetries.
- Elementary fermions are embedded in incomplete $SO(5)$ reps.
  $\Rightarrow$ global symmetry explicitly broken by partial compositeness.



Explicit breaking induces a Higgs potential

$$V(h) \simeq \alpha \cos\left(\frac{h}{f}\right) - \beta \sin^2\left(\frac{h}{f}\right)$$

Minimum at

$$\xi = \sin^2\left(\frac{v}{f}\right) = 1 - \left(\frac{\alpha}{2\beta}\right)^2 \simeq \left(\frac{v}{f}\right)^2$$

# Generic Composite Higgs set-up

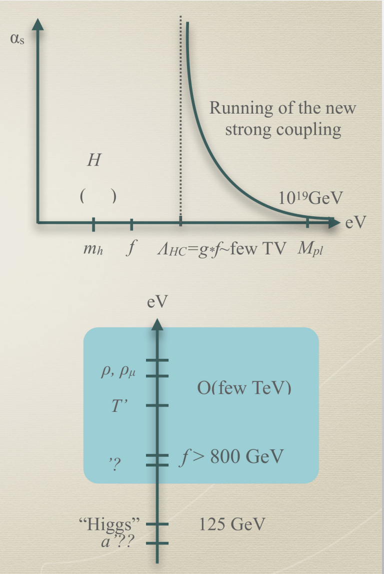
Possible solution to hierarchy problem

- Generate a scale $\Lambda_{HC} \ll M_{pl}$ through a new confining gauge group
- Interpret Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of the new strong sector

(Georgi, Kaplan, PLB **136** (1984), 136)

'Price' to pay

- additional resonances at the scale $\Lambda_{HC}$ (vectors, vector-like fermions, scalars)
- additional light pNGBs/ extended scalar sector
- deviations of the Higgs couplings from their SM values of O$(v/f)$



(thanks to T. Flacke)

# Towards underlying models

A wish list to construct and classify candidate models:
Gerghetta et al (2015), Ferretti et al. PLB (2014), PRD 94 (2016), JHEP 1701.094

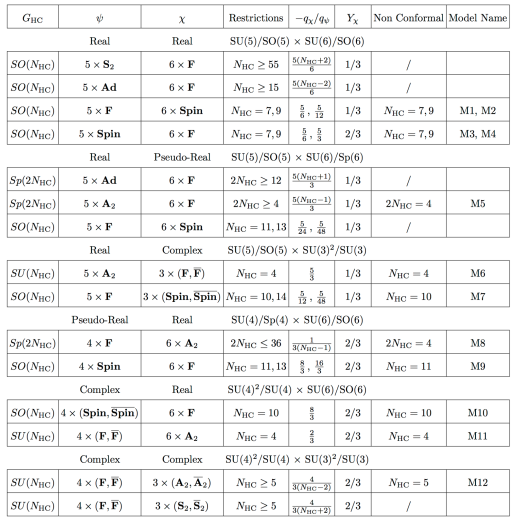
Underlying models of a composite Higgs should

- contain no elementary scalars (otherwise there would be again a hierarchy problem)
- have a simple hyper-color group
- have a Higgs candidate amongst the pNGBs
- have a top-partner amongst its bound states (for top mass via partial compositeness)
- satisfy further 'standard' consistency conditions (asymptotic freedom, no gauge anomalies)

The resulting models have several common features:

- All models predict pNGBs beyond the Higgs multiplet
- All models contain several top partner multiplets

## List of "minimal" CHM UV embeddings



| $G_{\rm HC}$ | $\psi$ | $\chi$ | Restrictions | $-q_\chi/q_\psi$ | $Y_\chi$ | Non Conformal | Model Name |
|---|---|---|---|---|---|---|---|
| | Real | Real | $\mathrm{SU(5)/SO(5)} \times \mathrm{SU(6)/SO(6)}$ | | | | |
| $SO(N_{\rm HC})$ | $5 \times \mathbf{S}_2$ | $6 \times \mathbf{F}$ | $N_{\rm HC} \geq 55$ | $\frac{5(N_{\rm HC}+2)}{6}$ | $1/3$ | / | |
| $SO(N_{\rm HC})$ | $5 \times \mathbf{Ad}$ | $6 \times \mathbf{F}$ | $N_{\rm HC} \geq 15$ | $\frac{5(N_{\rm HC}-2)}{6}$ | $1/3$ | / | |
| $SO(N_{\rm HC})$ | $5 \times \mathbf{F}$ | $6 \times \mathbf{Spin}$ | $N_{\rm HC} = 7, 9$ | $\frac{5}{6}, \frac{5}{12}$ | $1/3$ | $N_{\rm HC} = 7, 9$ | M1, M2 |
| $SO(N_{\rm HC})$ | $5 \times \mathbf{Spin}$ | $6 \times \mathbf{F}$ | $N_{\rm HC} = 7, 9$ | $\frac{5}{6}, \frac{5}{3}$ | $2/3$ | $N_{\rm HC} = 7, 9$ | M3, M4 |
| | Real | Pseudo-Real | $\mathrm{SU(5)/SO(5)} \times \mathrm{SU(6)/Sp(6)}$ | | | | |
| $Sp(2N_{\rm HC})$ | $5 \times \mathbf{Ad}$ | $6 \times \mathbf{F}$ | $2N_{\rm HC} \geq 12$ | $\frac{5(N_{\rm HC}+1)}{3}$ | $1/3$ | / | |
| $Sp(2N_{\rm HC})$ | $5 \times \mathbf{A}_2$ | $6 \times \mathbf{F}$ | $2N_{\rm HC} \geq 4$ | $\frac{5(N_{\rm HC}-1)}{3}$ | $1/3$ | $2N_{\rm HC} = 4$ | M5 |
| $SO(N_{\rm HC})$ | $5 \times \mathbf{F}$ | $6 \times \mathbf{Spin}$ | $N_{\rm HC} = 11, 13$ | $\frac{5}{24}, \frac{5}{48}$ | $1/3$ | / | |
| | Real | Complex | $\mathrm{SU(5)/SO(5)} \times \mathrm{SU(3)^2/SU(3)}$ | | | | |
| $SU(N_{\rm HC})$ | $5 \times \mathbf{A}_2$ | $3 \times (\mathbf{F}, \overline{\mathbf{F}})$ | $N_{\rm HC} = 4$ | $\frac{5}{3}$ | $1/3$ | $N_{\rm HC} = 4$ | M6 |
| $SO(N_{\rm HC})$ | $5 \times \mathbf{F}$ | $3 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$ | $N_{\rm HC} = 10, 14$ | $\frac{5}{12}, \frac{5}{48}$ | $1/3$ | $N_{\rm HC} = 10$ | M7 |
| | Pseudo-Real | Real | $\mathrm{SU(4)/Sp(4)} \times \mathrm{SU(6)/SO(6)}$ | | | | |
| $Sp(2N_{\rm HC})$ | $4 \times \mathbf{F}$ | $6 \times \mathbf{A}_2$ | $2N_{\rm HC} \leq 36$ | $\frac{1}{3(N_{\rm HC}-1)}$ | $2/3$ | $2N_{\rm HC} = 4$ | M8 |
| $SO(N_{\rm HC})$ | $4 \times \mathbf{Spin}$ | $6 \times \mathbf{F}$ | $N_{\rm HC} = 11, 13$ | $\frac{8}{3}, \frac{16}{3}$ | $2/3$ | $N_{\rm HC} = 11$ | M9 |
| | Complex | Real | $\mathrm{SU(4)^2/SU(4)} \times \mathrm{SU(6)/SO(6)}$ | | | | |
| $SO(N_{\rm HC})$ | $4 \times (\mathbf{Spin}, \overline{\mathbf{Spin}})$ | $6 \times \mathbf{F}$ | $N_{\rm HC} = 10$ | $\frac{8}{3}$ | $2/3$ | $N_{\rm HC} = 10$ | M10 |
| $SU(N_{\rm HC})$ | $4 \times (\mathbf{F}, \overline{\mathbf{F}})$ | $6 \times \mathbf{A}_2$ | $N_{\rm HC} = 4$ | $\frac{2}{3}$ | $2/3$ | $N_{\rm HC} = 4$ | M11 |
| | Complex | Complex | $\mathrm{SU(4)^2/SU(4)} \times \mathrm{SU(3)^2/SU(3)}$ | | | | |
| $SU(N_{\rm HC})$ | $4 \times (\mathbf{F}, \overline{\mathbf{F}})$ | $3 \times (\mathbf{A}_2, \overline{\mathbf{A}}_2)$ | $N_{\rm HC} \geq 5$ | $\frac{4}{3(N_{\rm HC}-2)}$ | $2/3$ | $N_{\rm HC} = 5$ | M12 |
| $SU(N_{\rm HC})$ | $4 \times (\mathbf{F}, \overline{\mathbf{F}})$ | $3 \times (\mathbf{S}_2, \overline{\mathbf{S}}_2)$ | $N_{\rm HC} \geq 5$ | $\frac{4}{3(N_{\rm HC}+2)}$ | $2/3$ | / | |

A. Belyaev et al. JHEP **01** (2017), 094

# Example M5: HC = $Sp(4)$, $SU(5) \times SU(6)/SO(5) \times Sp(6)$

pNGBs:

| | | | |
|---|---|---|---|
| electroweak: | $SO(5)$ | $SU(2)_L \times SU(2)_R$ | states |
| | 14 | (1,1) + (2,2) + (3,3) | $S, H, \eta_1^0, \eta_3^{+,0,-}, \eta_3^{++,+,0,-,--}$ |
| strong: | $Sp(6)$ | $SU(3)_C \times U(1)_{em}$ | states |
| | 14 | $3_{2/3} + \overline{3}_{-2/3} + 8_0$ | $\pi_3, \pi_3^*, \pi_8$ |

fermionic bound states:

| $SO(5) \times Sp(6)$ | $SU(3)_L \times SU(2)_L \times U(1)_Y$ / names | | | | |
|---|---|---|---|---|---|
| $(\mathbf{5}, \mathbf{14})$ | $(3,2)_{7/6}$ | $(3,2)_{1/6}$ | $(8,2)_{1/2}$ | $(3,1)_{2/3}$ | $(8,1)_0$ |
| | $(X_{5/3}, X_{3,2})$ | $(T_L, B_L)$ | $(\tilde{G}^+, \tilde{G}^0)$ | $T_R$ | $\tilde{g}$ |
| $(\mathbf{5}, \mathbf{1})$ | $(1,2)_{1/2}$ | $(1,1)_0$ | | | |
| | $(\tilde{H}^+, \tilde{H}^0)$ | $\tilde{B}$ | | | |

$\tilde{g}$ and $\tilde{B}$ are Majorana fermions, all other are Dirac fermions

# Phenomenological aspects for LHC

Asssumption: 1) fermions within an $SO(5) \times Sp(6)$ muliplet have about the same mass
mass splitting due to SM gauge interactions

2) $\tilde{B}$ is stable

⇒ LHC: 1) fermionic color octets have largerst cross section
2) events with large missing $p_T$

Possible decays:

$$\begin{array}{ll|ll|ll} \tilde{g} & \to t\,\pi_3^* \,,\, \bar{t}\,\pi_3 & \tilde{G}^0 & \to \bar{t}\,\pi_3 & \tilde{G}^+ & \to \bar{b}\,\pi_3 \\ & \to \tilde{B}\,\pi_8 & & \to \tilde{H}^0\,\pi_8 & & \to \tilde{H}^+\,\pi_8 \end{array}$$

$\tilde{H}^+ \to \pi^+ \tilde{B}$, $\tilde{H}^0 \to \pi^0 \tilde{B}$ with very soft pions

$$\begin{array}{ll|ll} \pi_3 & \to t\,\tilde{B} & \pi_8 & \to g\,g \\ & (\to t\,\nu) & & \to t\,\bar{t} \\ & (\to \bar{s}\,\bar{d}) & & (\to q\,\bar{q}, q = u, d, s, c, b) \end{array}$$

Bounds on $\pi_3$: $\tilde{t}_R$ searches, $\simeq 1.3$ TeV$^\dagger$
$\pi_8$: $\simeq 1.1$ TeV$^*$

† (ATLAS, arXiv:2102.01444 (hep-ex); CMS, arXiv:2107.10892 (hep-ex))

* G. Cacciapaglia et al.,arXiv:2002.01474 (hep-ph)

# Recast of existing LHC analyses

LHC signatures:

- 4 $t$ + missing $p_T$
- 3 $t$ + $j$ + missing $p_T$
- 2 $t$ + 2 $j$ + missing $p_T$
- $t$ + 3 $j$ + missing $p_T$
- 4 $j$ + missing $p_T$

In all cases: additional soft pions possible.

Use existing recast tools for SUSY searches to get bounds on
$\tilde{g}, \tilde{G}^0, \tilde{G}^+$ ($= Q_8$ if summed over all states)

- MADANALYSIS 5, E. Conte and B. Fuks, arXiv:1808.00480 (hep-ph)
- CHECKMATE 2, D. Dercks et al.arXiv:1611.09856 (hep-ph)

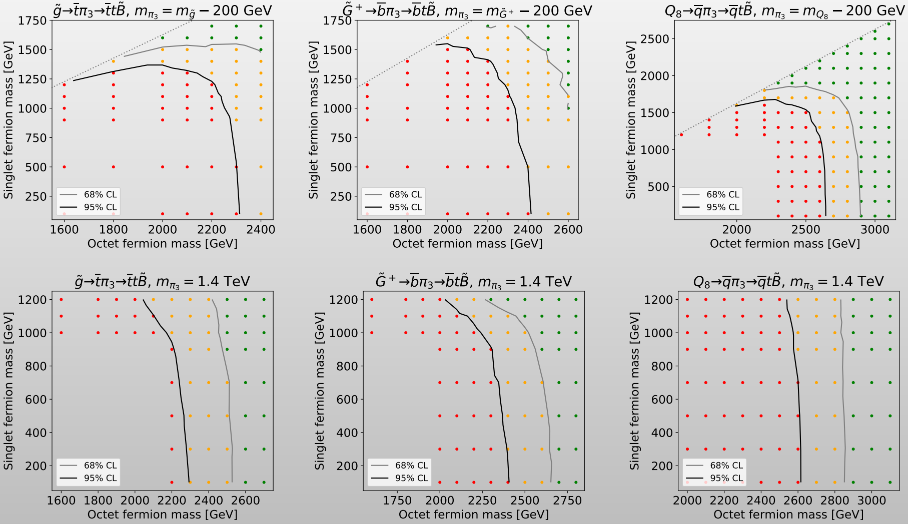
Have different analyses implemented, have one relevant in common with reasonable agreement

MADANALYSIS 5 gives in this particular case the stronger bounds

Cross sections: NNLOapprox + NNLL, from `https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections13TeVgluglu`

# Phenomenological aspects for LHC

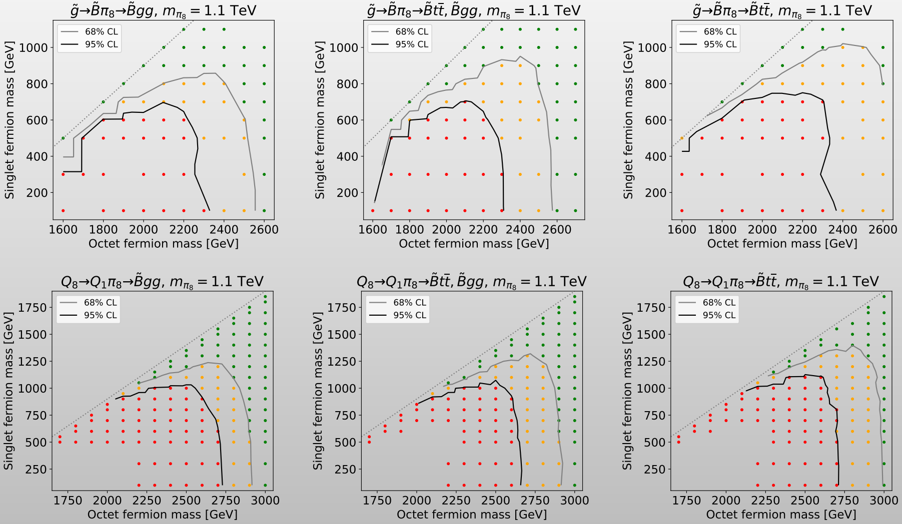
preliminary



black lines: 95% CL, gray lines 68% CL,

# Phenomenological aspects for LHC

preliminary



black lines: 95% CL, gray lines 68% CL,

## Conclusions & outlook

### Conclusions:

- Composite Higgs models provide a viable solution to the hierarchy problem but they still provide many challenges and room for exploration in theory and model-building.
- In general:
  - several pNGBs, also in the strongly interacting sector
  - fermionic bound states: not only color triplets, but also for example octets and singlets
- taking the so-called M5-model: color octets among the top-partners bounds of up to 2.8 TeV in case of simplified assumptions

### Outlook:

- assumption of equal top-partner masses is based on the assumption, that the hyper-quarks have equal masses ⇒ if not, triplets could be lighter than octets, also larger splittings between $\tilde{H}$ and $\tilde{B}$ possible: first investigations show that bounds change considerably.
- Somewhat more exotic signatures

$$X_{5/3} \to \eta_5^{++}\,\bar{b} \to W^+\,W^+\,\bar{b}$$
$$X_{5,3}, T_L \to \eta_5^{+}\,\bar{b} \to W^+\,\gamma\,\bar{b}$$

- include CONTUR package for scenarios where $\tilde{B}$ is unstable and/or heavier than $\pi_3$.

## Example M5: HC = $Sp(4)$, $SU(5) \times SU(6)/SO(5) \times Sp(6)$

Field content of the underlying model

| | $Sp(4)$ | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $SU(5)$ | $SU(6)$ | $U(1)$ |
|---|---|---|---|---|---|---|---|
| $\psi_{1,2}$ | $\begin{smallmatrix}\square\\\square\end{smallmatrix}$ | $\mathbf{1}$ | $\mathbf{2}$ | $1/2$ | **5** | **1** | $-\frac{3q_\chi}{5(N_c-1)}$ |
| $\psi_{3,4}$ | $\begin{smallmatrix}\square\\\square\end{smallmatrix}$ | $\mathbf{1}$ | $\mathbf{2}$ | $-1/2$ | | | |
| $\psi_5$ | $\begin{smallmatrix}\square\\\square\end{smallmatrix}$ | $\mathbf{1}$ | $\mathbf{1}$ | $0$ | | | |
| $\chi_1$<br>$\chi_2$<br>$\chi_3$ | $\square$ | $\mathbf{3}$ | $\mathbf{1}$ | $-x$ | **1** | **6** | $q_\chi$ |
| $\chi_4$<br>$\chi_5$<br>$\chi_6$ | $\square$ | $\bar{\mathbf{3}}$ | $\mathbf{1}$ | $x$ | | | |

pNGBs: electroweak $SU(5)/SO(5) : 14 \xrightarrow{SO(5) \supset SU(2)_L \times SU(2)_R} (1,1) + (2,2) + (3,3)$

strong $SU(6)/Sp(6) : 14 \xrightarrow{Sp(6) \supset SU(3)_C} 3 + \bar{3} + 8$

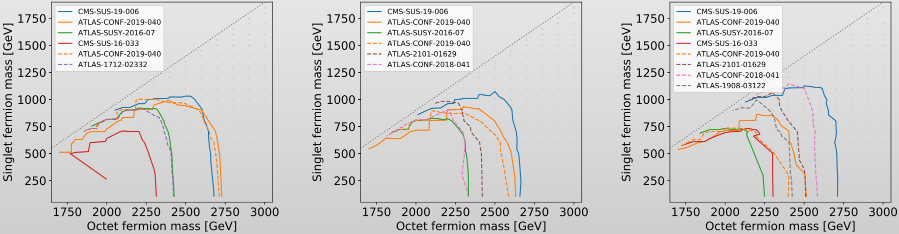
'baryonic' bound states of the model

| | $SU(5) \times SU(6)$ | $SO(5) \times Sp(6)$ | $SU(3)_C \times SU(2)_L \times U(1)_Y$ |
|---|---|---|---|
| $\psi\chi\chi$ | $(\mathbf{5},\mathbf{15})$ | $(\mathbf{5},\mathbf{14})$ | $(3,2)_{7/6}$, $(3,2)_{1/6}$, $(8,2)_{1/2}$, $(3,1)_{2/3}$, + h.c. + $(8,1)_0$ |
| | | $+(\mathbf{5},\mathbf{1})$ | $(1,2)_{1/2}$, $(1,2)_{-1/2}$, $(1,1)$ |
| | $(\mathbf{5},\mathbf{21})$ | $(\mathbf{5},\mathbf{21})$ | $(6,2)_{7/6}$, $(6,2)_{1/6}$, $(8,2)_{1/2}$, $(6,1)_{2/3}$, + h.c. + $(8,1)_0$ |
| $\psi\chi\bar{\chi}$ | $(\mathbf{5},\mathbf{35})$ | $(\mathbf{5},\mathbf{14})$ | ... |
| | | $+(\mathbf{5},\mathbf{21})$ | ... |
| | $(\mathbf{5},\mathbf{1})$ | $(\mathbf{5},\mathbf{1})$ | ... |

We fixed $\chi$ to get $(3,2)_{1/6}$ and $(3,1)_{2/3}$

## Contribution of different searches

preliminary



Comparison of the bounds at 95% CL obtained from different searches implemented in MadAnalysis 5 (solid lines) and CheckMATE 2 (dashed lines).

Generic features

- $m_S < m_{B,T} < M_V$
- new decay channels compared to standard LHC searches, e.g.

$$T \to S\,t$$

$$V \to T\bar{T} \to S\,t\,S^{(*)}\,\bar{t}$$

Example: model based on $Sp(14)$ gauge group with $5A_2$ and $6F$:

- contains a very light scalar $S$ with $m_S \ll m_h$ even for non-vanishing hyper-quark masses
- changes decay pattern of top-partner

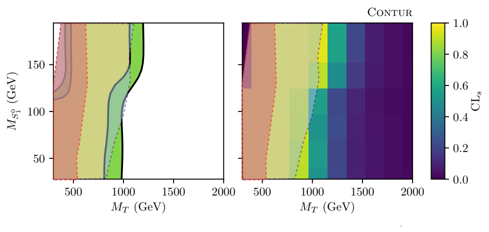
$$T \to S\,t \to \bar{b}\,b\,t \quad \text{or } T \to S\,t \to j\,j\,t$$

standard decay channels $T \to Wb$, $T \to tZ$, $T \to th$ subdominant

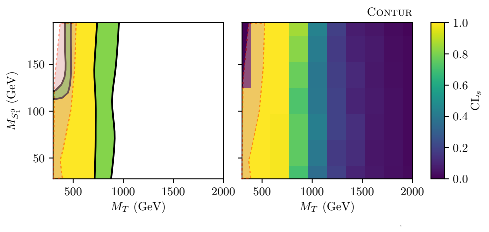
Standard channels lead to bounds on $M_T$ between 1 and 1.4 TeV
Impact investigated in G. Brooijmans et al., Les Houches 2019 Physics at TeV Colliders: New Physics Working Group Report, contri. by J. Butterworth, WP et al., arXiv:2002.12220 (hep-ph)

# Backup

$S \to \bar{b}b$



$S \to jj$



- left-hand: areas which are excluded at 1 (2) $\sigma$ level in green (yellow)
- right-hand: heatmap of the obtained $\mathrm{CL}_s$ values at each point
- For comparison, red and blue areas show 2 $\sigma$ exclusions as obtained in G. Cacciapaglia et al.,PLB **798** (2019), 135015