Phenomenology of unusual top partners in composite Higgs models

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Particle physics seminar at TP2

February 10, 2022

arXiv:2112.00019v1 [hep-ph] 30 Nov 2021

Phenomenology of unusual top partners in composite Higgs models

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Outline

- Motivation
- Composite Higgs models with fermionic UV completions
- The model M5
- Phenomenology and bounds
- Conclusion and future work

Motivation

SM does not explain neutrino masses or dark matter

$\Rightarrow$ should be viewed as effective theory that is valid up to Λ_{SM}

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Naturalness problem:

$$m_h^2 = \delta_{\text{SM}} m_h^2 + \delta_{\text{BSM}} m_h^2$$

We know SM contribution:

$$\frac{\delta_{\text{SM}} m_h^2}{m_h^2} \simeq \left(\frac{\Lambda_{\text{SM}}}{450 \text{ GeV}} \right)^2$$

Need *unnatural* fine tuning $\delta_{\text{SM}} m_h^2 \simeq -\delta_{\text{BSM}} m_h^2$

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Possible solution: If Higgs is composite particle, then corrections to m_h^2 are naturally cut off around the compositeness scale

Low-energy QCD

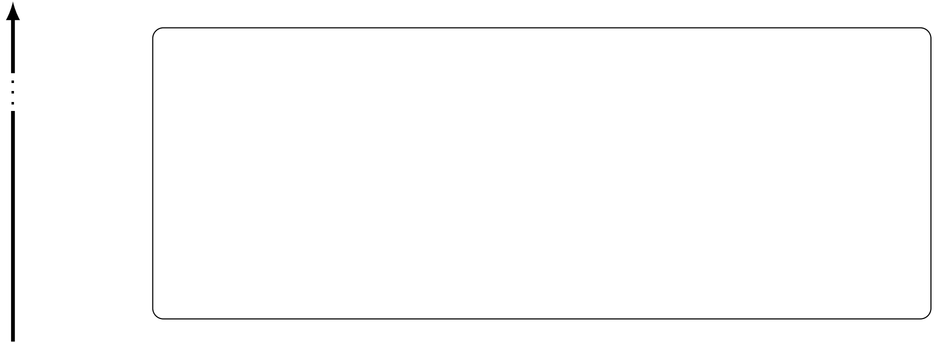
Two-flavor QCD with $m_u = m_d = 0$:

$\Lambda \gg$ GeV: global symmetry $\mathcal{G} = \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$

GeV: $\langle \bar{q}_R q_L \rangle \sim \mathbb{1}_2 \Rightarrow \mathcal{G} \to \mathcal{H} = \mathrm{SU}(2)_D$

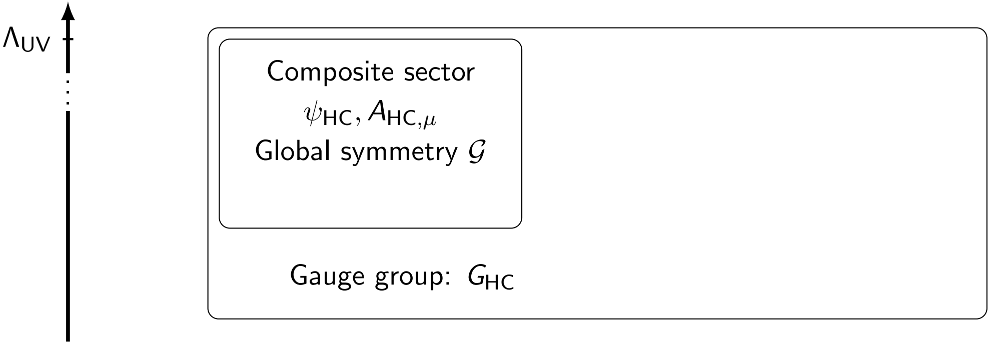
Nambu-Goldstone bosons (NGBs): pions $\pi^\pm, \pi^0 \in \mathcal{G}/\mathcal{H}$

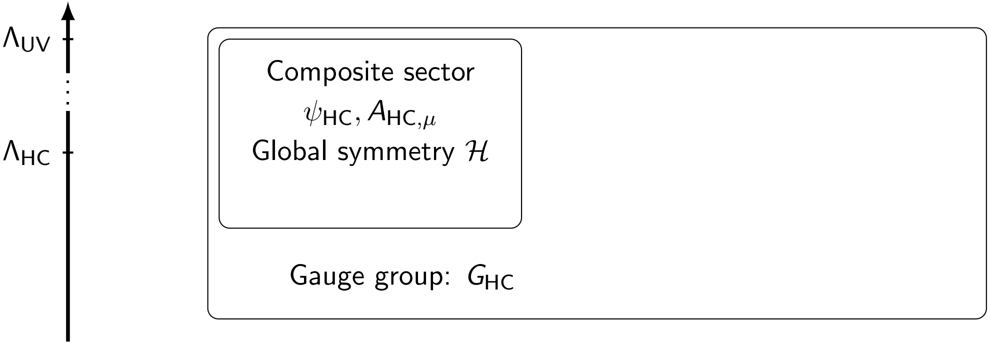
Pion decay constant $f_\pi = 93$ MeV, $4\pi f_\pi \sim 1$ GeV $\sim m_p$



Kaplan, Georgi (1984); Kaplan, Georgi, Dimopoulos (1984); Dugan, Georgi, Kaplan (1985)

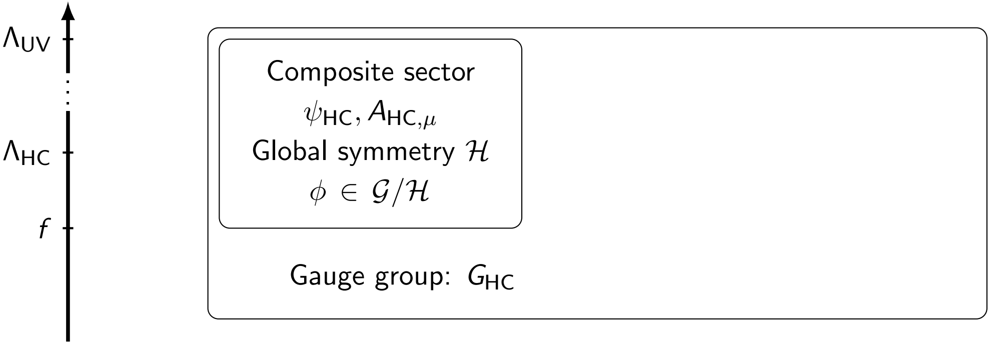
Composite Higgs Models



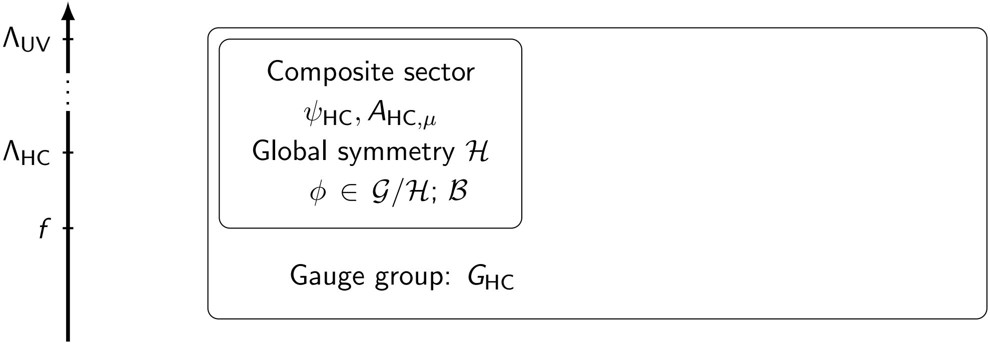


$$\left\langle \psi^i_{\mathrm{HC}} \psi^j_{\mathrm{HC}} \right\rangle \sim \Lambda^3_{\mathrm{HC}} \Sigma_0^{ij} \quad \Rightarrow \quad \text{breaks global symmetry } \mathcal{G} \to \mathcal{H} \supset G_{\mathrm{SM}}$$

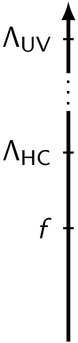
Composite Higgs Models



Composite states: NGBs $\phi \sim \psi_{HC}\psi_{HC}$, with decay constant $f \approx \Lambda_{HC}/(4\pi)$



Composite states: NGBs $\phi \sim \psi_{HC}\psi_{HC}$, hyper-baryons $\mathcal{B} \sim \psi_{HC}\psi_{HC}\psi_{HC}$



Composite sector

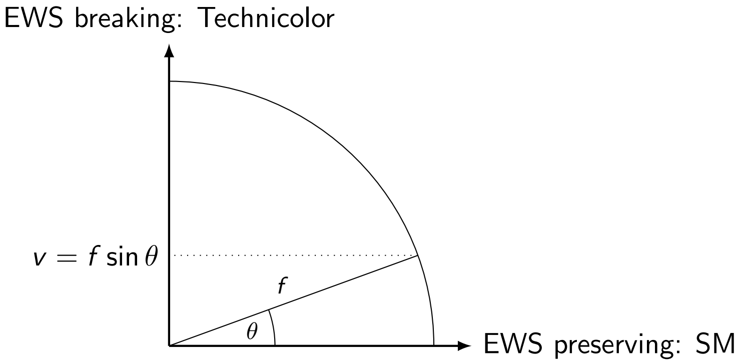
$\psi_{\rm HC}, A_{{\rm HC},\mu}$

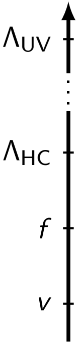
Global symmetry $\mathcal{H}$

$H, \phi \in \mathcal{G}/\mathcal{H}; \mathcal{B}$

Gauge group: $G_{\rm HC}$

Vacuum misalignment





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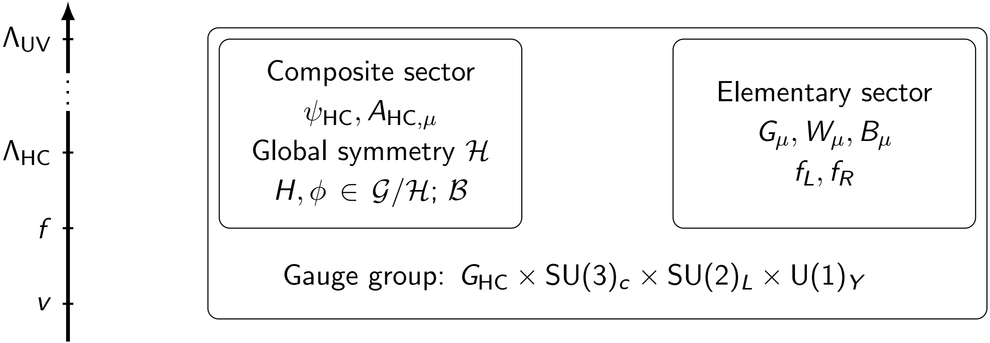
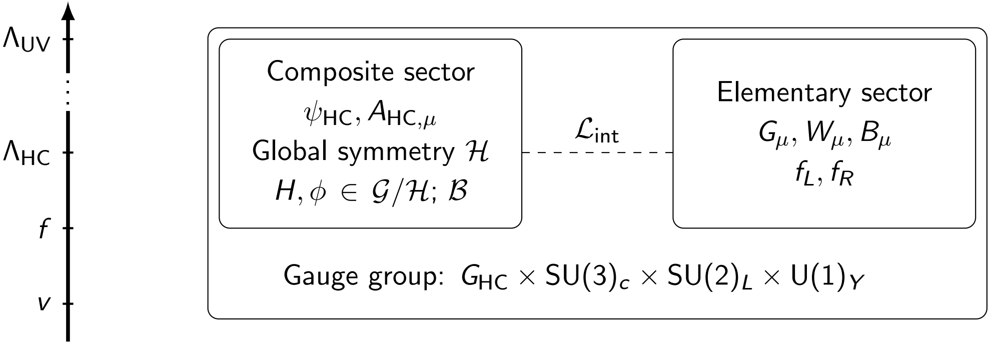
Gauge group: G_{HC}

$$\frac{v}{f} = \sin\theta \ll 1$$



Λ_{UV}
Λ_{HC}
f
v
Composite sector
$\psi_{\mathrm{HC}}, A_{\mathrm{HC},\mu}$
Global symmetry $\mathcal{H}$
$H, \phi \in \mathcal{G}/\mathcal{H}$; $\mathcal{B}$
Elementary sector
G_μ, W_μ, B_μ
f_L, f_R
Gauge group: $G_{\mathrm{HC}} \times \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$

Composite Higgs Models



Elementary-composite interactions: gauging G_{SM}, mixing of t with $\mathcal{B}$

$\Rightarrow$ explicitly breaks $\mathcal{H} \Rightarrow$ generates scalar potential: EWSB

No elementary Higgs: have to generate Yukawa couplings dynamically

Postulate top partners $Q \in (\mathbf{3}, \mathbf{2})_{1/6}$, $T \in (\mathbf{3}, \mathbf{1})_{2/3}$ among the hyper-baryons

Partial compositeness Kaplan (1991)

No elementary Higgs: have to generate Yukawa couplings dynamically

Postulate top partners $Q \in (\mathbf{3}, \mathbf{2})_{1/6}$, $T \in (\mathbf{3}, \mathbf{1})_{2/3}$ among the hyper-baryons

$$\mathcal{L}_{\mathrm{mass}} = -M \left(\bar{Q} Q + \bar{T} T \right) - \left(\lambda_L \bar{q}_L Q + \lambda_R \bar{t}_R T + \mathrm{h.c.} \right)$$

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Diagonalize mass matrix:

$$\begin{pmatrix} t_R \\ T \end{pmatrix} \to \begin{pmatrix} \hat{T}_1 \\ \hat{T}_2 \end{pmatrix} = \begin{pmatrix} \cos\varphi_R & \sin\varphi_R \\ -\sin\varphi_R & \cos\varphi_R \end{pmatrix} \begin{pmatrix} t_R \\ T \end{pmatrix}, \qquad \sin\varphi_R = \frac{\lambda_R}{\sqrt{M^2+\lambda_R^2}},$$

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Top Yukawa:

$$\mathcal{L}_{\text{comp}} \supset -g_* \bar{Q} T \tilde{H} + \text{h.c.} \supset -g_* \sin\varphi_L \bar{\hat{Q}}_1 \sin\varphi_R \hat{T}_1 \tilde{H} + \text{h.c.}$$

$$\Rightarrow y_t = g_* \sin\varphi_L \sin\varphi_R$$

Navigating the space of models

Assumptions and requirements [Ferretti et al, 1312.5330, 1604.06467, 1610.06591]:

- Two species of hyperquarks in distinct irreps of G_{HC}: ψ (EW) and χ (color)
- Consider only simple G_{HC}
- Consider only lowest-dimensional irrep for each reality
- Require $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_X \subset \mathcal{H}$ where $Y = T_R^3 + X$, presence of top partners and custodial Higgs bidoublet
- Consider only lowest possible number of flavors: minimal cosets
  - EW: SU(5)/SO(5), SU(4)/Sp(4), SU(4) $\times$ SU(4)/SU(4)
  - Color: SU(6)/SO(6), SU(6)/Sp(6), SU(3) $\times$ SU(3)/SU(3)

Cosets

- Real irrep: $\mathrm{SU}(n)/\mathrm{SO}(n)$
- Pseudoreal irrep: $\mathrm{SU}(2n)/\mathrm{Sp}(2n)$
- Complex irrep: $\mathrm{SU}(n) \times \mathrm{SU}(n)/\mathrm{SU}(n)$

Minimal models

Name	G_{HC}	ψ	χ	Coset	Top Partners
M1	SO(7)	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	(R, R)	$\chi\psi\chi$
M2	SO(9)	$5 \times \mathbf{F}$	$6 \times \mathbf{Spin}$	(R, R)	$\chi\psi\chi$
M3	SO(7)	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	(R, R)	$\psi\chi\psi$
M4	SO(9)	$5 \times \mathbf{Spin}$	$6 \times \mathbf{F}$	(R, R)	$\psi\chi\psi$
M5	Sp(4)	$5 \times \mathbf{A}_2$	$6 \times \mathbf{F}$	(R, PR)	$\chi\psi\chi$
⋮	⋮	⋮	⋮	⋮	⋮
M12	SU(5)	$4 \times (\mathbf{F}, \bar{\mathbf{F}})$	$3 \times (\mathbf{A}_2, \bar{\mathbf{A}}_2)$	(C, C)	$\psi\chi\psi$

Ferretti et al, 1312.5330, 1604.06467, 1610.06591

The model M5

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⋮	⋮	⋮	⋮	⋮	⋮

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$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$

Global symmetry:

$$\mathrm{SU}(5) \rightarrow \mathrm{SO}(5)$$

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$$\mathrm{SU}(5) \times \mathrm{SU}(6) \qquad \rightarrow \mathrm{SO}(5) \times \mathrm{Sp}(6)$$

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Embedding:

$$\text{SU}(2)_L \times \text{SU}(2)_R \subset \text{SO}(5), \quad \text{SU}(3)_c \times \text{U}(1)_X \subset \text{Sp}(6)$$

BSM particle content

Scalars

$$\mathrm{SU}(6)/\mathrm{Sp}(6): \quad 35 - 21 = 14 \text{ pNGBs in the } \mathbf{14}_{\mathrm{Sp}(6)}$$

Decompose $\mathrm{Sp}(6) \to \mathrm{SU}(3)_c \times \mathrm{U}(1)_{\mathrm{em}}$:

$$\mathbf{14}_{\mathrm{Sp}(6)} \to \mathbf{8}_0 + \mathbf{3}_{2/3} + \bar{\mathbf{3}}_{-2/3} \equiv \pi_8 + \pi_3 + \pi_3^*$$

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Top partners

$$\psi\chi\chi \in (\mathbf{5}, \mathbf{6} \times \mathbf{6}) = (\mathbf{5}, \mathbf{15}) + (\mathbf{5}, \mathbf{21}) \qquad \text{of } \mathrm{SU}(5) \times \mathrm{SU}(6)$$

$$\to (\mathbf{5}, \mathbf{14}) + (\mathbf{5}, \mathbf{1}) + (\mathbf{5}, \mathbf{21}) \qquad \text{of } \mathrm{SO}(5) \times \mathrm{Sp}(6)$$

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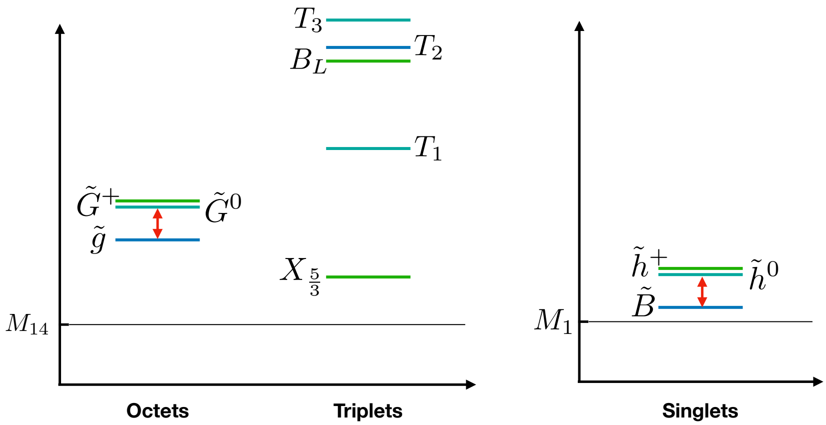
BSM particle content of M5

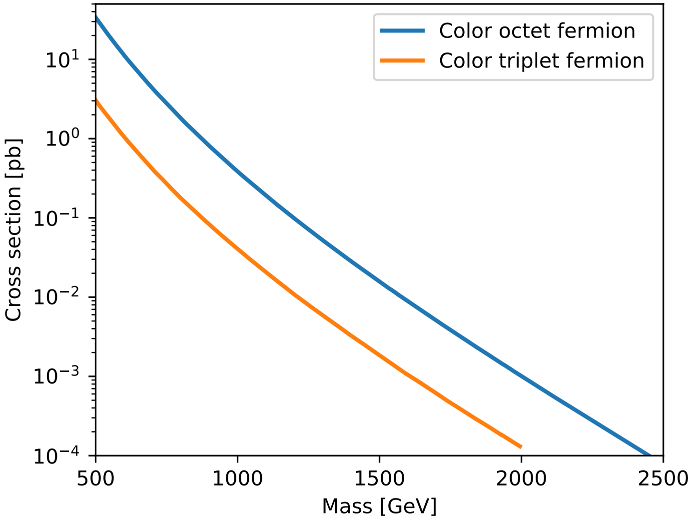
8	$\tilde{G}^+, \tilde{G}^0$	octoni	octet top partners Q_8
	$\tilde{g}$	gluoni	
3	$X_{5/3}$		triplet top partners Q_3
	$T_{1,2,3}$		
	B		
1	$\tilde{h}^+, \tilde{h}^0$	higgsoni	singlet top partners Q_1
	$\tilde{B}$	boni	

Spectrum



T_3
T_2
B_L
T_1
$\tilde{G}^+$
$\tilde{G}^0$
$\tilde{g}$
$X_{\frac{5}{3}}$
M_{14}
Octets
Triplets
$\tilde{h}^+$
$\tilde{h}^0$
$\tilde{B}$
M_1
Singlets

Spectrum



Color octet fermion
Color triplet fermion
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Cross section [pb]
500
1000
1500
2000
2500
Mass [GeV]

Phenomenology

$$\tilde{G}^+ \to \pi_8 \tilde{h}^+,\ \pi_3 \bar{b}, \qquad \tilde{G}^0 \to \pi_8 \tilde{h}^0,\ \pi_3 \bar{t}, \qquad \tilde{g} \to \pi_8 \tilde{B},\ \pi_3 \bar{t},\ \pi_3^* t$$

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$$\pi_8 \to t\bar{t};\ gg,\ g\gamma,\ gZ$$

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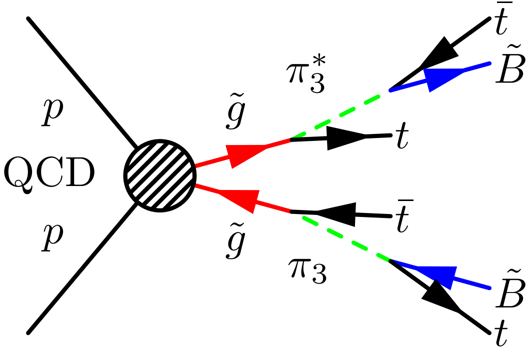
$$\pi_8 \to t\bar{t};\ gg,\ g\gamma,\ gZ$$

If $m_{\pi_3} > m_{\tilde{B}}$:

$$\pi_3 \to b\tilde{h}^+,\ t\tilde{h}^0,\ t\tilde{B}$$
$$\tilde{h}^{+,0} \to \tilde{B} + \text{soft}$$

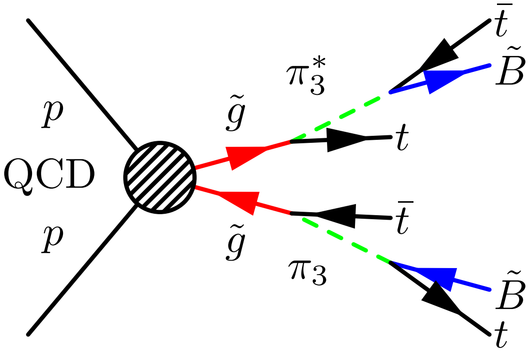
Phenomenology: $\tilde{g} \to t\pi_3 \to tt\tilde{B}$



Technical details

- Simplified models implemented in FeynRules
- Generate 10,000 events with MadGraph5
- PDF set NNPDF 3.0
- Showering with Pythia8
- Rescaling cross section to $\text{NNLO}_{\text{approx}}+\text{NNLL}$ from calculations for gluinos
- Calculate CL_s exclusions for recasted searches in MadAnalysis5 and CheckMATE

Phenomenology: $\tilde{g} \to t\pi_3 \to tt\tilde{B}$



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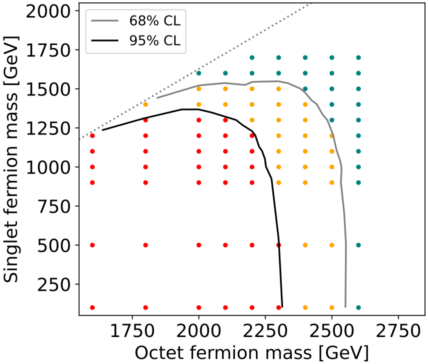
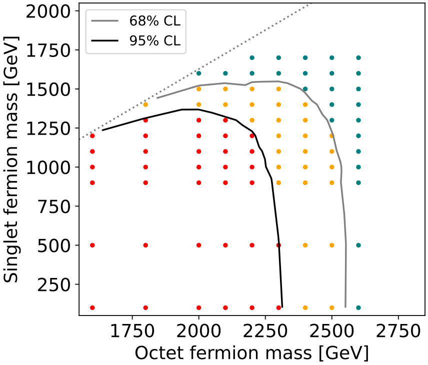
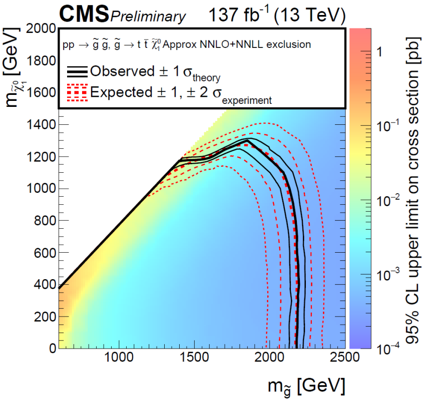


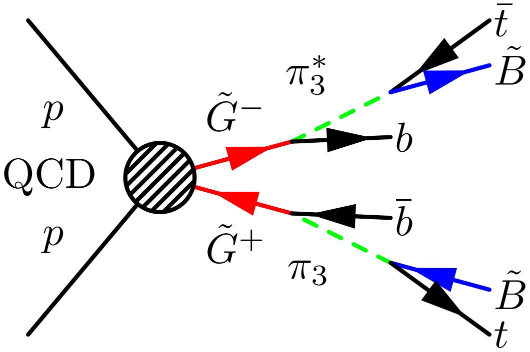
$m_{\tilde{g}} - m_{\pi_3} = 200$ GeV



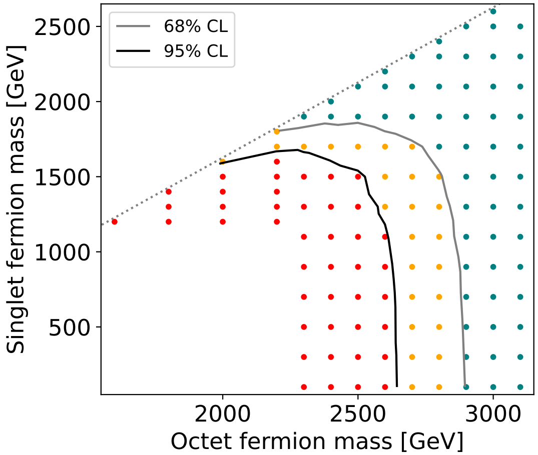


[CMS-PAS-SUS-19-006]

Phenomenology: $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$

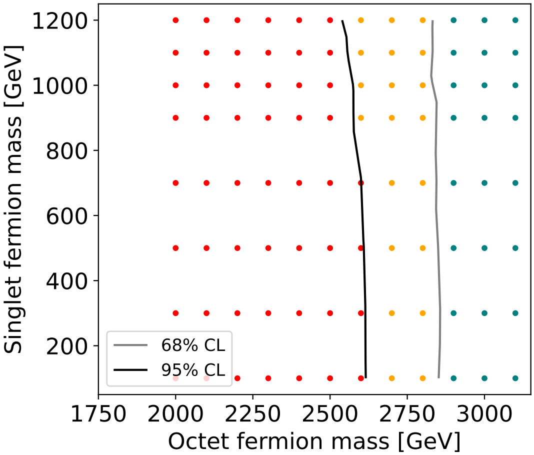


Phenomenology: $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$



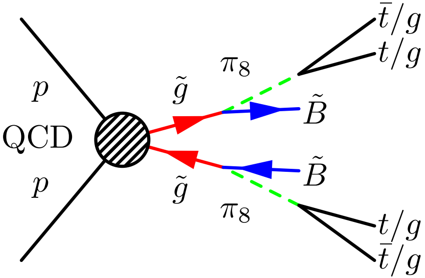
$m_{Q_8} - m_{\pi_3} = 200\ \text{GeV}$

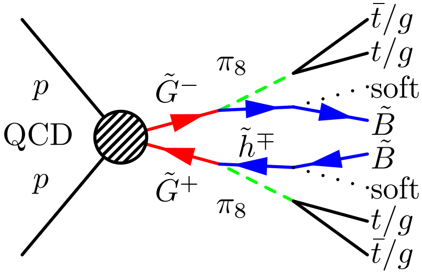
Phenomenology: $Q_8 \to \bar{q}\pi_3 \to \bar{q}t\tilde{B}$



$m_{\pi_3} = 1.4$ TeV

Phenomenology: $Q_8 \to \pi_8 Q_1 \to t\bar{t}\tilde{B}/gg\tilde{B}$ (+ soft)





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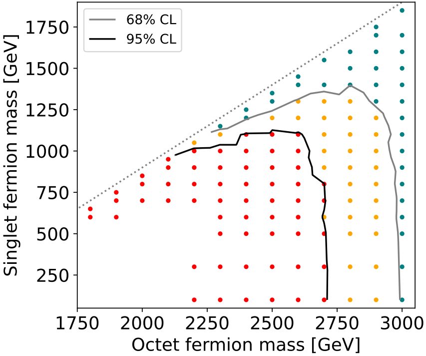
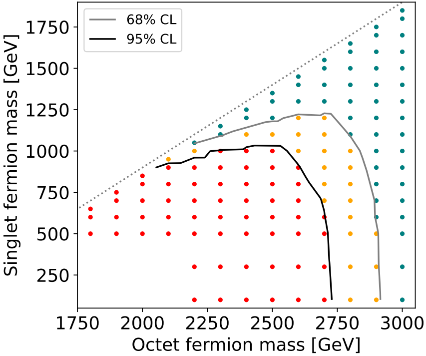
$\pi_8 \to t\bar{t}$



$\pi_8 \to gg$



$m_{\pi_8} = 1.1$ TeV

Conclusion

Summary

- Realistic composite Higgs models are complicated
- Model M5, based on SU(5) × SU(6) × U(1)/SO(5) × Sp(6), has especially rich phenomenology
- Color octet top partners excluded up to 2.7 TeV
- Bounds from pair production of vector-like quarks are negligible since $m_{Q_8} \approx m_{Q_3}$

Conclusion

Summary

- Realistic composite Higgs models are complicated
- Model M5, based on $SU(5) \times SU(6) \times U(1)/SO(5) \times Sp(6)$, has especially rich phenomenology
- Color octet top partners excluded up to 2.7 TeV
- Bounds from pair production of vector-like quarks are negligible since $m_{Q_8} \approx m_{Q_3}$

Future work

- Electroweak pNGBs in $SU(5)/SO(5)$
- Different mass hierarchy: $m_{\pi_3} < m_{\tilde{B}}$: lepton-number violating decays $\pi_3 \to b\tau^+, t\bar{\nu}_\tau$, neutrino masses via $\tilde{B}$
- Different top partner embedding: color sextet fermions, $Q_6 \to 5t + \text{MET}$

Backup

The Model M5: Microscopic Field Content

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$			
ψ_5	$\begin{array}{c}\square\\[-4pt]\square\end{array}$	$\mathbf{1}$	$\mathbf{1}$	0			
χ_1 χ_2 χ_3	$\square$	$\mathbf{3}$	$\mathbf{1}$	$-x$	$\mathbf{1}$	$\mathbf{6}$	q_χ
χ_4 χ_5 χ_6	$\square$	$\bar{\mathbf{3}}$	$\mathbf{1}$	x			

The Model M5: Spontaneous Symmetry Breaking

SSB pattern: SU(5) × SU(6) × U(1)/SO(5) × Sp(6)

We embed $SU(2)_L \times SU(2)_R \subset SO(5)$, $SU(3)_c \times U(1)_X \subset Sp(6)$ and $Y = X + T_R^3$

- EW pNGBs: under $SO(5) \to SU(2)_L \times SU(2)_R \to SU(2)_D$,

$$\begin{aligned} \mathbf{14}_{SO(5)} &\to (\mathbf{3}, \mathbf{3}) + (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1}) \\ &\to (\mathbf{5} + \mathbf{3} + \mathbf{1}) + (\mathbf{3} + \mathbf{1}) + \mathbf{1} \\ &\equiv \eta_5 + \eta_3 + \eta_1 + \phi + h + \eta \end{aligned}$$

- Colored pNGBs: under $Sp(6) \to SU(3)_c \times U(1)_{em}$,

$$\mathbf{14}_{Sp(6)} \to \mathbf{8}_0 + \mathbf{3}_{2x} + \bar{\mathbf{3}}_{-2x} \equiv \pi_8 + \pi_3 + \pi_3^*$$

The Model M5: Top Partners

Top partners must have same SM QN as $t_L \in (\mathbf{3}, \mathbf{2})_{1/6}$ and $t_R^c \in (\bar{\mathbf{3}}, \mathbf{2})_{-2/3}$

Hyperbaryons $\psi\chi\chi \in (\mathbf{5}, \mathbf{6} \times \mathbf{6}) = (\mathbf{5}, \mathbf{15}) + (\mathbf{5}, \mathbf{21}) \to (\mathbf{5}, \mathbf{14}) + (\mathbf{5}, \mathbf{1}) + (\mathbf{5}, \mathbf{21})$

Under $\mathrm{Sp}(6) \to \mathrm{SU}(3)_c \times \mathrm{U}(1)_X$:

$$\mathbf{14} \to \mathbf{8}_0 + \mathbf{3}_{2x} + \bar{\mathbf{3}}_{-2x}, \qquad \mathbf{21} \to \mathbf{8}_0 + \mathbf{6}_{-2x} + \bar{\mathbf{6}}_{2x} + \mathbf{1}_0$$

$\Rightarrow$ top partners in $\mathbf{14}_{\mathrm{Sp}(6)}$ for $x = 1/3$

EW sector: Under $\mathrm{SO}(5) \to \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$, $\mathbf{5} \to (\mathbf{2}, \mathbf{2}) + (\mathbf{1}, \mathbf{1})$

The Model M5: Top Partners

Let's look at the hyperbaryons in the antisymmetric $(\mathbf{5},\mathbf{15})_G$ under $SU(2)_L \times SU(2)_R \times SU(3)_c \times U(1)_X$:

$$\begin{aligned}
(\mathbf{5},\mathbf{14})_H &\to \left((\mathbf{2},\mathbf{2})+(\mathbf{1},\mathbf{1}),(\mathbf{8}_0+\mathbf{3}_{2/3}+\bar{\mathbf{3}}_{-2/3})\right)\\
&= (\mathbf{2},\mathbf{2};\mathbf{8}_0)+(\mathbf{2},\mathbf{2};\mathbf{3}_{2/3})+(\mathbf{2},\mathbf{2};\bar{\mathbf{3}}_{-2/3})+(\mathbf{1},\mathbf{1};\mathbf{8}_0)+(\mathbf{1},\mathbf{1};\mathbf{3}_{2/3})+(\mathbf{1},\mathbf{1};\bar{\mathbf{3}}_{-2/3})\\
&\equiv \quad \tilde{G}_2 \quad + Q_L \quad + Q_L^c \quad + \tilde{g} \quad + T_R \quad + T_R^c
\end{aligned}$$

$$(\mathbf{5},\mathbf{1})_H \to (\mathbf{2},\mathbf{2};\mathbf{1}_0)+(\mathbf{1},\mathbf{1};\mathbf{1}_0) \equiv \tilde{h}+\tilde{B}$$

Top partners: $Q_L = \left(\begin{pmatrix} X_{5/3} \\ X_{2/3} \end{pmatrix}, \begin{pmatrix} T \\ B \end{pmatrix}\right)$ and T_R^c

BSM particle content

	$\mathbf{8}_0$	$\mathbf{3}_{2/3}$	$\bar{\mathbf{3}}_{-2/3}$	$\mathbf{1}_0$
$\mathbf{5}$	Q_8	Q_3	Q_3^c	Q_1
$\downarrow$				
$(\mathbf{2},\mathbf{2})$	$\tilde{G}$	Q_L	Q_L^c	$\tilde{h}$
$+$				
$(\mathbf{1},\mathbf{1})$	$\tilde{g}$	T_R	T_R^c	$\tilde{B}$
		$\mathcal{B}_{14}$		$\mathcal{B}_1$

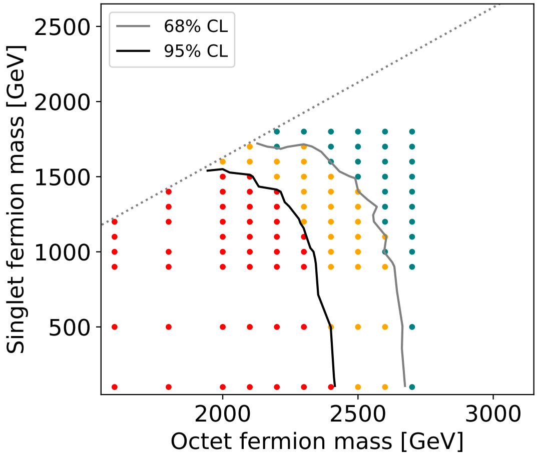
Top partners, $\mathcal{B}$

Mass splitting

$$r = \frac{2\Delta m^{\text{em}}}{m_p + m_n}$$

$$\frac{2(m_{\tilde{g}} - m_{X_{5/3}})}{m_{\tilde{g}} + m_{X_{5/3}}} = \frac{\alpha_S(\text{TeV})}{\alpha_{\text{em}}(\text{GeV})}\left(3 - \frac{4}{3}\right) r \sim 1.4\%$$

Phenomenology: $\tilde{G}^+ \to \bar{b}\pi_3 \to \bar{b}t\tilde{B}$



$m_{\tilde{G}^+} - m_{\pi_3} = 200$ GeV

Phenomenology: Mixed decays