Composite Higgs models, LHC bounds and challenges for automatisation

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Overview

Motivations for composite Higgs models

Composite Higgs, basic idea

Models beyond the minimal one

LHC phenomenology
    Model independent bounds
    Bounds in a specific model

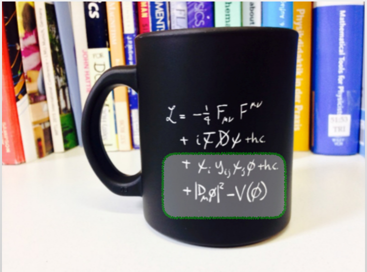
Challenges for automatisation

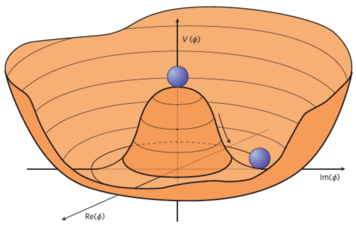
Conclusions & outlook

Jobs of the SM-Higgs Multiplet

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

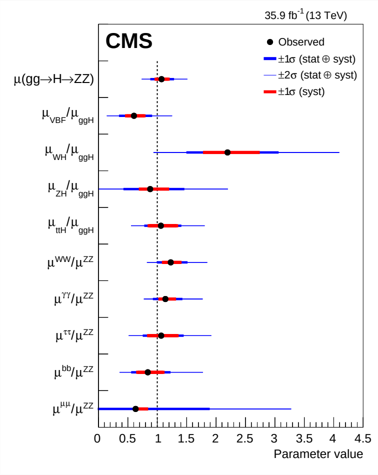
- its non-zero vacuum expectation value v spontaneously breaks the electroweak gauge group $SU(2)_L \times U(1)_Y$ to $U(1)_{em}$
- gives masses to $W^\pm, Z$
- gives masses to the fermions
- bonus: provides one physical scalar h ('the Higgs boson')



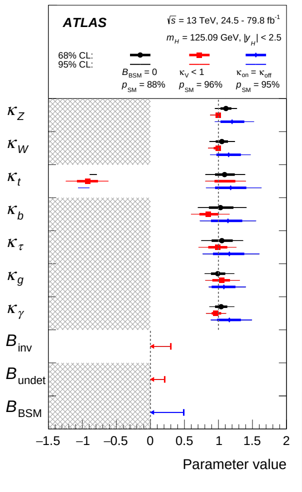


Motivation

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)

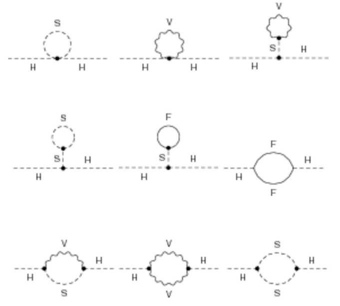


ATLAS coll., PRD **101**, 012002 (2020)

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

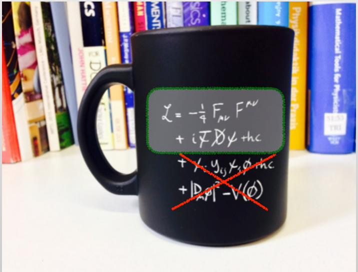


$$\frac{\delta v^2}{v^2} = \sum_i \pm \frac{g_i^2}{16\pi^2} \frac{M_i^2}{v^2} \gg 1$$

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

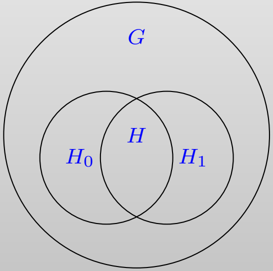
Model-Builder

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)

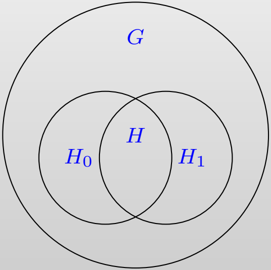
H_1: global symmetry group in confined phase
below scale f

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 Σ

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

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

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

yield after electroweak symmetry breaking

$$\begin{aligned}\mathcal{L}^V_{\rm eff} &= \frac{f^2}{8}\left(\frac{v+h}{f}\right)^2 \left(W^i_\mu W^{i\mu} - 2W^3_\mu B^\mu + B_\mu B^\mu\right) + \ldots \\ &= \left(1 + 2\sqrt{1-\xi}\frac{h}{v} + (1-2\xi)\frac{h^2}{v^2} + \ldots\right)\left(m_W^2 W^+_\mu W^{-\mu} + \frac{m_Z^2}{2} Z_\mu Z^\mu\right) + \ldots\end{aligned}$$

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

Minimal Composite Higgs Model

Fermion masses and couplings: partial compositeness

Higgs transforms non-linearly under G.
$\Rightarrow$ no Yukawa interaction if fermion are elementary (transform linearly).

Possible solution: mix elementary fermions with composite resonances.

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

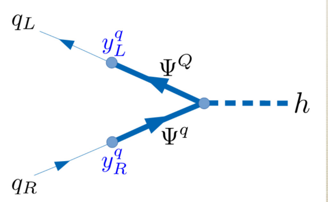
$$q_L = \frac{1}{\sqrt{2}}(\mathrm{i}d_L, d_L, \mathrm{i}u_L, -u_L, 0)^T$$

$$q_R = (0, 0, 0, 0, u_R)^T$$

Composite fermions ($SO(4)$) rep.)

$$\Psi^Q = \frac{1}{\sqrt{2}} \begin{pmatrix} \mathrm{i}\,B - \mathrm{i}\,X_{5/3} \\ B + X_{5/3} \\ \mathrm{i}\,T + \mathrm{i}\,X_{2/3} \\ -T + X_{2/3} \end{pmatrix}, \; \Psi^q = \tilde{T}$$

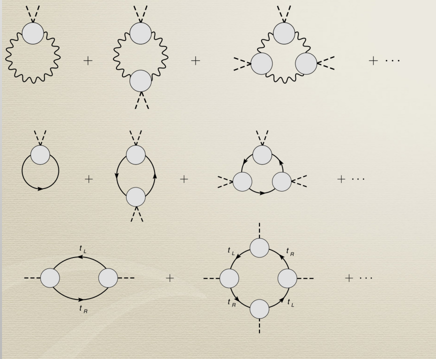
'dress' them to get $SO(5)$ rep.



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

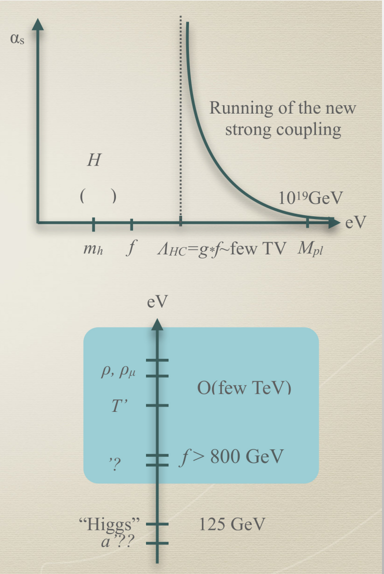
Possible solution to hierarchy problem

- 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 Λ_{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

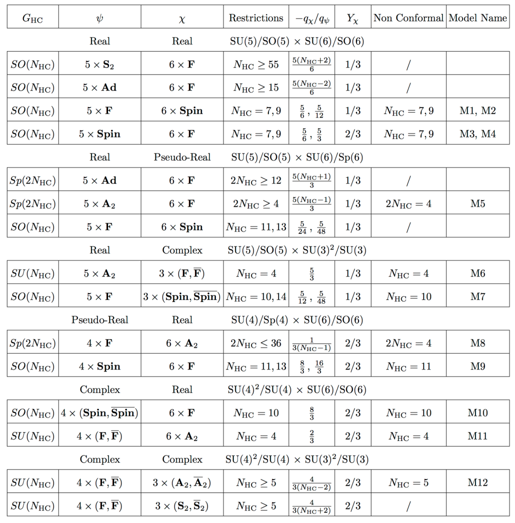
Underlying models of a composite Higgs should

- 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



$G_{\rm HC}$	ψ	χ	Restrictions	$-q_\chi/q_\psi$	Y_χ	Non Conformal	Model Name
	Real	Real	SU(5)/SO(5) × 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	SU(5)/SO(5) × 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	SU(5)/SO(5) × 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	SU(4)/Sp(4) × 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	SU(4)^2/SU(4) × 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	SU(4)^2/SU(4) × 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

Notation and procedure

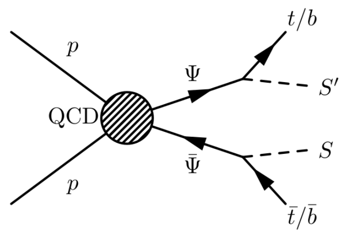
Fields	Spin	$SU(3)_c$	$U(1)_{\text{em}}$
S_i^0	0	$\mathbf{1}$	0
$S_i^\pm$	0	$\mathbf{1}$	±1
$S_i^{\pm\pm}$	0	$\mathbf{1}$	±2
π_r^q	0	$\mathbf{r}$	q
T	$1/2$	$\mathbf{3}$	$2/3$
B	$1/2$	$\mathbf{3}$	$-1/3$
X	$1/2$	$\mathbf{3}$	$5/3$

We use in the following

- generated events using `MadGraph5_aMC@NLO`, hadronized with `Pythia8`
- recast tools
    - `MadAnalysis5`, event reconstruction using `Delphes 3` and the anti-k_T algorithm implemented in `FastJet`
    - SM measurements implemented in `Rivet`, exclusions `Contur`

for details see A. Banerjee *et al.*, arXiv:2203.07270 (hep-ph)

Vector-like quarks



with

- $\Psi = B, T, X$
- $S, S' = S_i^0, S_i^\pm, S_i^{\pm\pm}, \pi_6^q, \pi_8$

'standard' signatures

$$X_{5/3} \to t\, W^+$$
$$T \to b\, W^+\,,\ t\, Z\,,\ t\, h$$
$$B \to t\, W^-$$

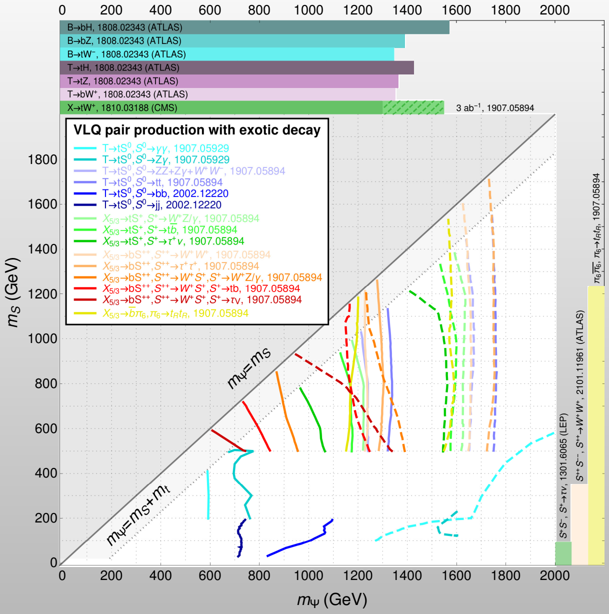
examples of 'new' signatures

$X_{5/3} \to \bar{t}\, S^{++} \to \bar{b}\, W^+\, W^+$ or $\bar{b}\,\bar{b}\, t\, W^+\, \gamma$

$T \to t\, S^0 \to t\, \gamma\, \gamma$ or $t\, \bar{t}\, t$

$B \to t\, S^- \to t\, W^-\, \gamma$ or $t\, \bar{t}\, b$

Model independent bounds



full lines: 95% CL limits in the $\{m_\Psi, m_S\}$ plane for VLQs decaying to new pNGBs using ~ 36 fb^{-1}

dashed lines: same but projections for HL-LHC

A. Banerjee *et al.*, arXiv:2203.07270 (hep-ph)

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

pNGBs:

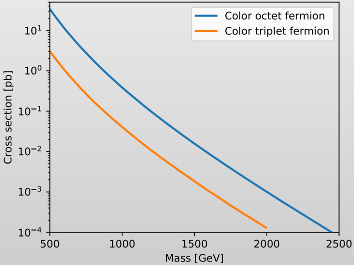
electroweak:	$SO(5)$	$SU(2)_L\times SU(2)_R$	states
	14	(1,1) + (2,2) + (3,3)	η, H, η_1^0, $\eta_3^{+,0,-}$, $\eta_3^{++,+,0,-,--}$
			$(S_i^0=\eta,\eta^0_{1,3,5},\ S_i^+=\eta^+_{3,5},\ S^{++}=\eta_5^{++})$
strong:	$Sp(6)$	$SU(3)_C\times U(1)_{em}$	states
	14	$3_{2/3}$ + $\overline{3}_{-2/3}$ + 8_0	π_3, π_3^*, π_8

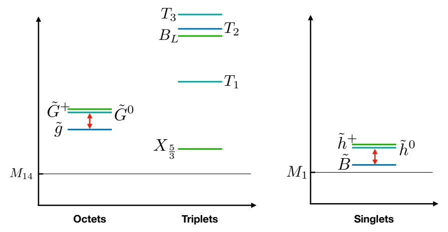
fermionic bound states:

$SO(5)\times Sp(6)$	$SU(3)_L\times SU(2)_L\times U(1)_Y$ / 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

Hyper-baryons (top-partners)





3 @ NLO, **8** @ NNLO$_{\text{approx}}$+NNLL
G. Cacciapaglia *et al.*,
arXiv:2112.00019

Bounds in a specific model

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:

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

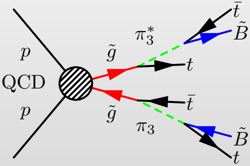
$\tilde{H}^+ \to \pi^+ \tilde{B}$, $\tilde{H}^0 \to \pi^0 \tilde{B}$ with very soft pions

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

Bounds on π_3: $\tilde{t}_R$ searches, $\simeq 1.3$ TeV[†]
π_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)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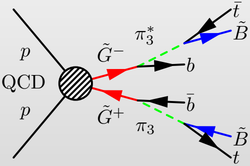
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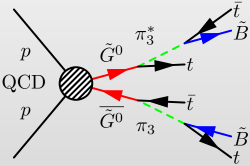
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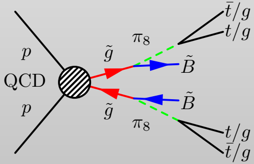
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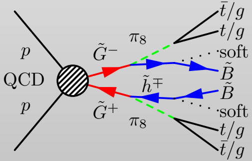
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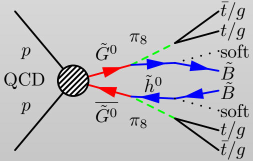
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t/g
soft
$\tilde{B}$
$\tilde{B}$
soft
t/g
$\bar{t}/g$

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)

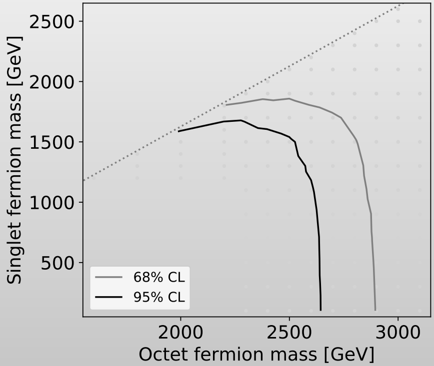
- MADANALYSIS 5, E. Conte and B. Fuks, arXiv:1808.00480 (hep-ph)
- CHECKMATE 2, D. Dercks et al.arXiv:1611.09856 (hep-ph)

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

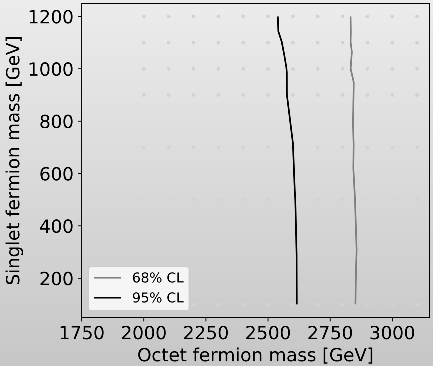
MADANALYSIS 5 gives in this particular case the stronger bounds

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

Octet decays with 100% decays into π_3



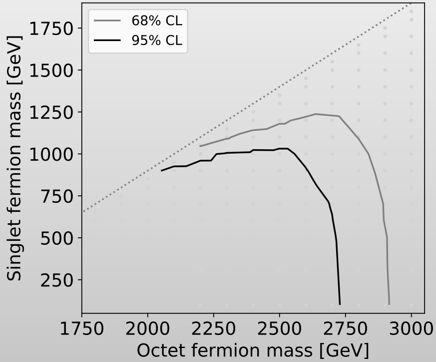
$m_{Q_8} - m_{\pi_3} = 200$ GeV



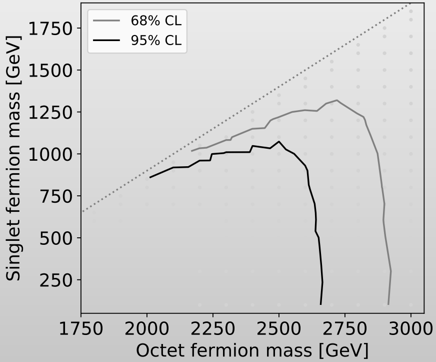
$m_{\pi_3} = 1.4$ TeV

G. Cacciapaglia *et al.*, arXiv:2112.00019

Octet decays with 100% decays into π_8



$\pi_8 \to gg, m_{\pi_8} = 1.1$ TeV



$\pi_8 \to t\bar{t}, m_{\pi_8} = 1.1$ TeV

G. Cacciapaglia *et al.*, arXiv:2112.00019

Challenges for automatisation

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

Field content of the underlying model

	$Sp(4)$	$SU(3)_C$	$SU(2)_L$	$U(1)_Y$	$SU(5)$	$SU(6)$	$U(1)$
$\psi_{1,2}$	$\begin{array}{c}\square\\\square\end{array}$	$\mathbf{1}$	$\mathbf{2}$	$1/2$	**5**	**1**	$-\frac{3q_\chi}{5(N_c-1)}$
$\psi_{3,4}$	$\begin{array}{c}\square\\\square\end{array}$	$\mathbf{1}$	$\mathbf{2}$	$-1/2$			
ψ_5	$\begin{array}{c}\square\\\square\end{array}$	$\mathbf{1}$	$\mathbf{1}$	0			
χ_1 χ_2 χ_3	$\square$	$\mathbf{3}$	$\mathbf{1}$	$-x$	**1**	**6**	q_χ
χ_4 χ_5 χ_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 χ to get $(3,2)_{1/6}$ and $(3,1)_{2/3}$

‘Dressing’ of operators I

- SM fermions form incomplete representations of G
- need Goldstone matrices to get interactions between SM-fermions ($\in G$) and hyper-baryons ($\in H$)

$$\Sigma_i(x) = e^{\Pi(x)/f_i}\Sigma_{0,i} \xrightarrow{G} g\,\Sigma_i\, h(g,\Pi)\,, \quad g\in G\,,\, h\in H$$

$$i=\psi \to G=SU(5)\,,\; H=SO(5) \quad \text{and} \quad i=\chi \to G=SU(6)\,,\; H=Sp(6)$$

Example

$$\Psi_{\mathbf{14}} = \begin{pmatrix} -Q_3^c & -\frac{1}{2\sqrt{2}}Q_8^a\,\lambda^a \\ \frac{1}{2\sqrt{2}}Q_8^a\,(\lambda^a)^T & -Q_3 \end{pmatrix}\,,$$

Each component Q_3 and Q_8 also transform as 5 of $SO(5)$:

$$Q_3 = (X_{5/3}, X_{2/3}, T_L, B_L, iT_R)^T\,,$$
$$Q_3^c = (B_L^c, -T_L^c, -X_{2/3}^c, X_{5/3}^c, -iT_R^c)^T\,,$$
$$Q_8 = (\tilde{G}_u^+, \tilde{G}_u^0, \tilde{G}_d^0, \tilde{G}_d^-, i\tilde{g})^T\,,$$

SM-quarks in $\bar{\mathbf{5}}$ of $SU(5)$

$$\zeta_L = (b_L, -t_L, 0, 0, 0)\,,$$
$$\zeta_R = (0, 0, 0, 0, -it_R^c)\,.$$

‘Dressing’ of operators II

embed SM-quarks in $\overline{\mathbf{15}}$ $(\bar{A})$ of $SU(6)$

$$\zeta_{L,\bar{A}} = \begin{pmatrix} \frac{1}{2}\epsilon_{ijk}\zeta_{L,k} & 0 \\ 0 & 0 \end{pmatrix} , \qquad \zeta_{R,\bar{A}} = \begin{pmatrix} 0 & 0 \\ 0 & \frac{1}{2}\epsilon^{ijk}\zeta_R^k \end{pmatrix} ,$$

and now hyper-baryons in $(\mathbf{5}, \mathbf{15})$ of $SU(5) \times SU(6)$

$$\mathcal{O}_{A,14} = \Sigma_\chi \left(\Sigma_\psi \cdot \Psi_{14}\right) \Sigma_\chi^T , \qquad \mathcal{O}_{A,1} = \left(U_\psi \cdot Q_1\right) \; U_\chi \cdot \Sigma_{\chi,0} \cdot U_\chi^T$$

$\Rightarrow$ able to construct terms for Lagrangian

$$y_L \, \mathcal{O}_{A,14} \, \zeta_{L,\bar{A}} = y_L \left(\frac{1}{2} \, \zeta_{L,i} \cdot Q^c_{3,i} - \frac{\sqrt{2}i}{4 f_\chi} \, \pi^*_{3,i} \lambda^a_{ij} \, \zeta_{L,j} \cdot Q^a_8 - \frac{\sqrt{2}i}{4 f_\chi} \, \pi^a_8 \lambda^a_{ij} \, \zeta_{L,j} \cdot Q^c_{3,i} \right.$$
$$\left. + \mathcal{O}(\Pi^2_\chi) + \mathcal{O}(\Pi_\psi) \right) ,$$

$$y_R \, \mathcal{O}_{A,14} \, \zeta_{R,\bar{A}} = y_R \left(\frac{1}{2} \, \zeta_{R,i} \cdot Q_{3,i} - \frac{\sqrt{2}i}{4 f_\chi} \, \pi_{3,i} \lambda^a_{ij} \, \zeta_{R,j} \cdot Q^a_8 - \frac{\sqrt{2}i}{4 f_\chi} \, \pi^a_8 \lambda^a_{ij} \, \zeta_{R,j} \cdot Q_{3,i} \right.$$
$$\left. + \mathcal{O}(\Pi^2_\chi) + \mathcal{O}(\Pi_\psi) \right) ,$$

$SU(5)$ contractions

$$\zeta_L \cdot Q^c_3 = B^c_L b_L + T^c_L t_L , \quad \zeta_L \cdot Q_8 = \tilde{G}^+_u b_L - \tilde{G}^0_u t_L , \quad \zeta_R \cdot Q_3 = t^c_R T_R , \qquad \zeta_R \cdot Q_8 = t^c_R \tilde{g} ,$$

'Dressing' of operators III

alternative: embed SM-quarks in $\mathbf{35}$ (D) of $SU(6)$ and $\mathbf{5}$ (D) of $SU(5)$

$$\zeta_{L,D} = \begin{pmatrix} 0 & 0 \\ \frac{1}{2}\epsilon_{ijk}\zeta^c_{L,k} & 0 \end{pmatrix}, \qquad \zeta_{R,D} = \begin{pmatrix} 0 & -\frac{1}{2}\epsilon_{ijk}\zeta^c_{R,k} \\ 0 & 0 \end{pmatrix},$$
$$\zeta^c_L = (0, 0, t_L, b_L, 0), \quad \zeta^c_R = (0, 0, 0, 0, it^c_R).$$

and now hyper-baryons in $(\bar{\mathbf{5}}, \mathbf{35})$ of $SU(5) \times SU(6)$

$$\mathcal{O}_{D,14} = U_\chi(\Psi_{14} \cdot U^\dagger_\psi)U^\dagger_\chi, \qquad \mathcal{O}_{D,21} = U_\chi(\Psi_{21} \cdot U^\dagger_\psi)U^\dagger_\chi,$$

with

$$\Psi_{21} = \begin{pmatrix} -Q_6 & \frac{1}{2\sqrt{2}}Q'^a_8\,\lambda^a + Q'_1 \\ \frac{1}{2\sqrt{2}}Q'^a_8\,(\lambda^a)^T + Q'_1 & -Q^c_6 \end{pmatrix}.$$

⇒ terms for Lagrangian

$$y'_L\,\zeta_{L,D}\,\mathcal{O}_{D,14} = y'_L\left(\frac{1}{2}\,\zeta_{L,i}\cdot Q^c_{3,i} + \mathcal{O}(\Pi^2_\chi) + \mathcal{O}(\Pi_\psi)\right),$$
$$y'_R\,\zeta_{R,D}\mathcal{O}_{D,14} = y'_R\left(\frac{1}{2}\,\zeta_{R,i}\cdot Q_{3,i} + \mathcal{O}(\Pi^2_\chi) + \mathcal{O}(\Pi_\psi)\right),$$

challenge: octets and sextets do not have linear couplings to pNGBs
⇒ completely changed phenomenology, e.g. dominant octet decays like

$$\tilde{g} \to \pi_8\pi^*_3 t_R$$

Required parts

given

- G_{HC} gauge group of additional fermions χ, ψ
- G unbroken global group, H unbroken subgroup which contains SM gauge group as subgroup

required tasks

- determine SM quantum numbers of pNGBs & embedding of SM in H
- find G_{HC} singlets of $\chi\chi\psi$ combinations which can serve as top-partners
- embed SM-fermions in incomplete G representations
- determine Lagrangian including terms with dim > 4, include also anomaly terms
- extend SARAH to cope with terms with dim > 4
- extend tree-level decay routines to include the corresponding higher-dimensional coupling

group theory part: use `GroupMath` by R.M. Fonseca, arXiv:2011.01764 (hep-th)

generic problem with MC like MadGraph: 3-body (or even 4-body) decays or decays via higher-dimensional operators (e.g. anomaly terms)

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
    - bounds depend strongly on possible decay modes
- taking the so-called M5-model: color octets among the top-partners
  bounds of up to 2.7 TeV in case of simplified assumptions

Outlook:

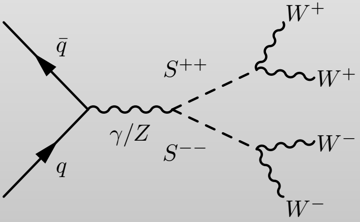
- write another module for SARAH to generate Lagrangian for Composite Higgs models
- extend (or rewrite) SARAH to treat higher dimensional operators in the Lagrangian
- extend library of (tree-level) decay functions

electroweak pNGBs

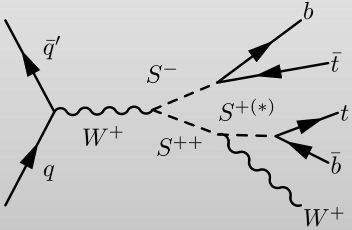
$$pp \to S_i^{\pm\pm} S_j^{\mp}\,,\ S_i^{\pm} S_j^{0}\,,\ S_i^{++} S_j^{--}\,,\ S_i^{+} S_j^{-}\,,\ S_i^{0} S_j^{0}$$

two limiting scenarios

fermiophoic

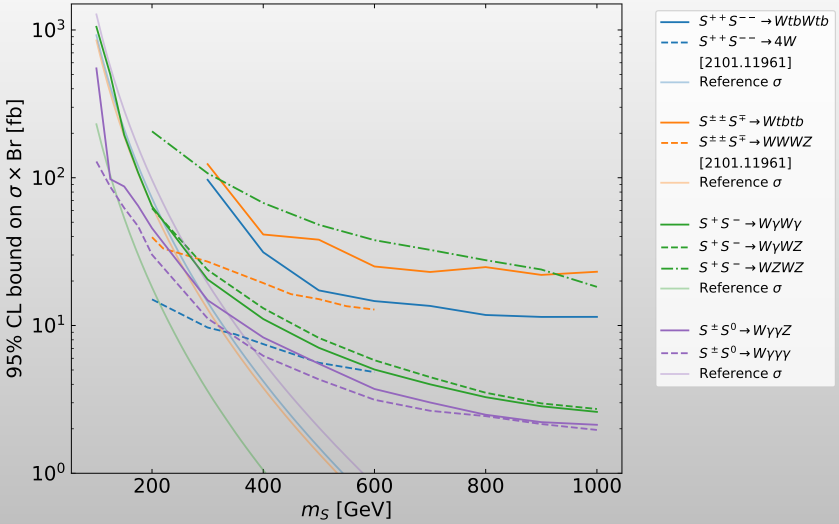


fermiophil



$$S_i^{++} \to W^+ W^+$$
$$S_i^{+} \to W^+ \gamma,\ W^+ Z$$
$$S_i^{0} \to W^+ W^-,\ \gamma\gamma,\ \gamma Z,\ ZZ.$$

$$S^{++} \to W^+ t\bar{b},$$
$$S^{+} \to t\bar{b},$$
$$S^{0} \to t\bar{t},\ b\bar{b}.$$



A. Banerjee *et al.*, arXiv:2203.07270 (hep-ph)

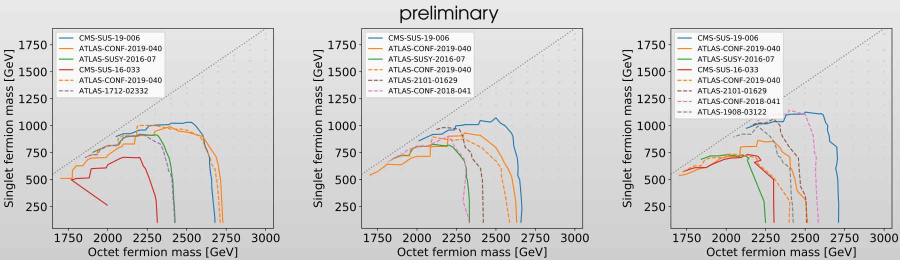
The reference cross sections σ for pair production are calculated for η_5 of M_5.

relevant analyses for pNGBs in the fermiophiopc scenario

`Contur` pool	Description	final state(s)
`ATLAS-13-LL-GAMMA`	dilepton and ≥ 1 photon	$W\gamma W\gamma$,
`ATLAS-13-GAMMA`	inclusive multiphotons	$W\gamma W\gamma$, $W\gamma WZ$ $W\gamma\gamma\gamma$
`ATLAS-13-GAMMA-MET`	photon and MET	$W\gamma WZ$
`ATLAS-13-4L`	four leptons	$WZWZ$
`ATLAS-13-L1L2METJET`	unlike dilepton, MET and jets	$W\gamma W\gamma$, $WZWZ$
`ATLAS-13-MMJET`	$\mu^+\mu^-$ at the Z pole, plus optional jets	$WZWZ$
`CMS-13-EEJET`	e^+e^- at the Z pole, plus optional jets	$WZWZ$
`CMS-13-MMJET`	$\mu^+\mu^-$ at the Z pole, plus optional jets	$WZWZ$

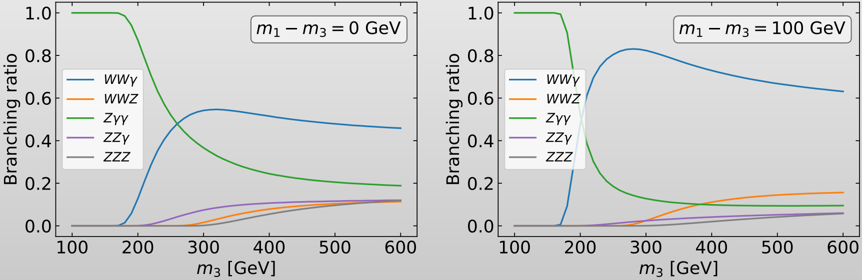
Backup

Contribution of different searches



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

Decays of η_3^0

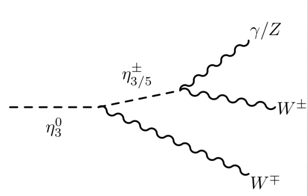


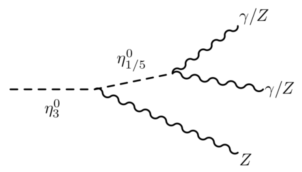
A. Banerjee *et al.*, arXiv:2203.07270 (hep-ph)

Electroweak pNGBs

focus on leptophobic scenario

- assume custodial multiplets are mass-degenerate
- lights multiplet decays only via anomaly terms, except η_3^0 which does not couple to the anomaly, but

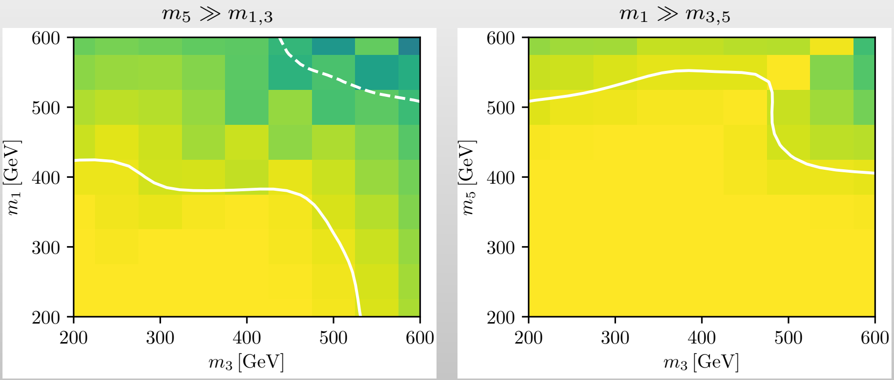




- for the heavier custodial multiplets: decays into (off-shell) vector bosons + lighter multiplet, e.g.

$$\eta_3^+ \to \eta_5^{++} W^{-(*)}\,,\ \eta_5^+ Z^{(*)}\,,\ \eta_5^0 W^{+(*)}\,,\ \eta_1^0 W^{+(*)}\,;$$
$$\eta_3^0 \to \eta_5^\pm W^{\mp(*)}\,,\ \eta_5^0 Z^{(*)}\,,\ \eta_1^0 Z^{(*)}\,.$$

Current bounds based on analyses in `Contur`



A. Banerjee *et al.*, arXiv:2203.07270 (hep-ph)

full (dashed) lines represent the 2-σ (1-σ) exclusion