Phenomenology of an unusual Composite Higgs Model

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Based on G. Cacciapaglia, T. Flacke, M. Kunkel and WP, JHEP **02** (2022), 208 (arXiv:2112.00019)
G. Cacciapaglia, T. Flacke, M. Kunkel, WP and L. Schwarze, JHEP **12** (2022), 087 (arXiv:2210.01826)

10 June 2024

Generic Composite Higgs set-up

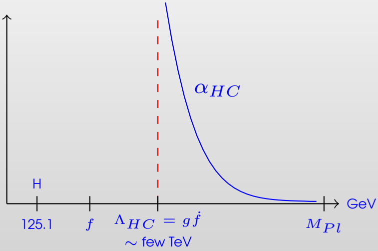
Possible solution to hierarchy problem

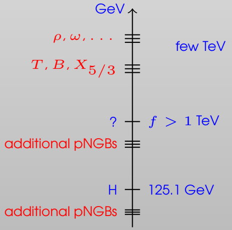
- Generate a scale $\Lambda_{HC} \ll M_{pl}$ through a new confining gauge group
- Interpret Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of the new strong sector

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

'Price' to pay

- additional resonances at the scale Λ_{HC} (spin-1 resonances, vector-like fermions, scalars)
- additional light pNGBs/ extended scalar sector
- deviations of the Higgs couplings from their SM values of O(v/f)





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 of the bound states
- 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

can be extended to include neutrino masses and dark matter, e.g. G. Cacciapaglia, M. Rosenlyst, JHEP **09** (2021), 167

List of "minimal" CHM UV embeddings

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

G. Ferretti, JHEP **06** (2016), 107; A. Belyaev et al. JHEP **01** (2017), 094

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)	$\eta, H, \eta_1^0, \eta_3^{+,0,-}, \eta_5^{++,+,0,-,--}$
			$(S_i^0 = \eta, \eta^0_{1,3,5},\ S_i^+ = \eta^+_{3,5},\ S^{++} = \eta_5^{++})$
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

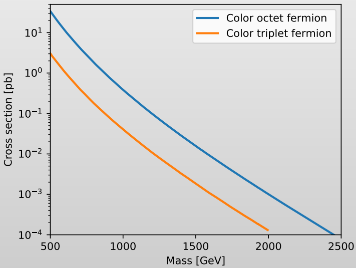
fermionic bound states:

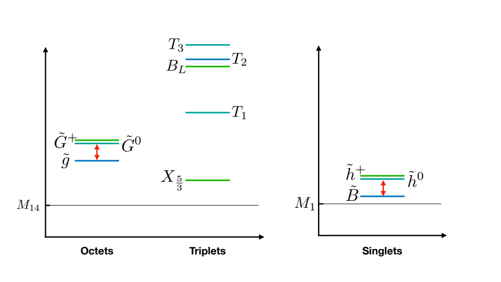
$SO(5) \times Sp(6)$	$SU(3)_L \times SU(2)_L \times U(1)_Y$ / names				
$(\mathbf{5}, \mathbf{14})$	$(3,2)_{7/6}$	$(3,2)_{1/6}$	$(8,2)_{1/2}$	$(3,1)_{2/3}$	$(8,1)_0$
	$(X_{5/3}, X_{3,2})$	(T_L, B_L)	$(\tilde{G}^+, \tilde{G}^0)$	T_R	$\tilde{g}$
$(\mathbf{5}, \mathbf{1})$	$(1,2)_{1/2}$	$(1,1)_0$			
	$(\tilde{H}^+,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

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

accidental global symmetry: 'baryon' number

Hyper-baryons (top-partners)





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

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

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

Possible decays:

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

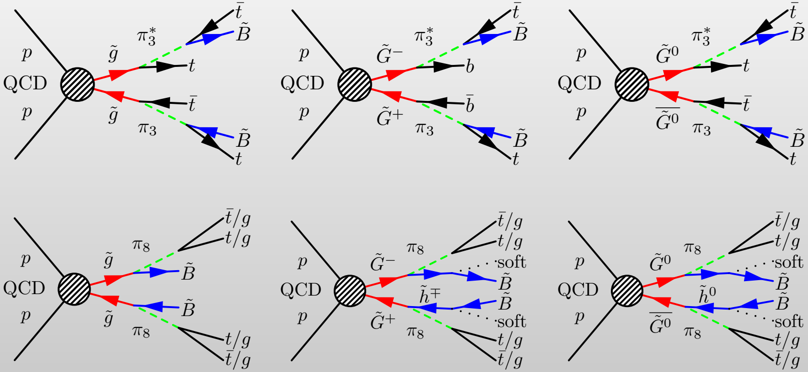
$\tilde{H}^+ \to \pi^+\tilde{B}$, $\tilde{H}^0 \to \pi^0\tilde{B}$ with very soft pions

$$\pi_3 \to t\,\tilde{B} \qquad \pi_8 \to g\,g$$
$$(\to t\,\nu) \qquad \to t\,\bar{t}$$
$$(\to \bar{s}\,\bar{d}) \qquad (\to q\,\bar{q},\, q = u, d, s, c, b)$$

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)



for later use:

$$Q_8 = \{\tilde{g}, \tilde{G}^0, \tilde{G}^\pm\}$$

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

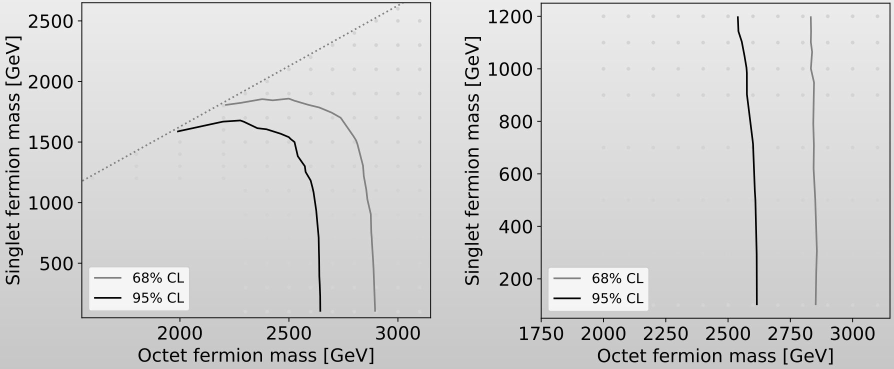
In all cases: additional soft pions possible.

We used here and in the following

- generated 10^5 events per data point using `MadGraph5_aMC@NLO`, hadronized with `Pythia8`
- recast tools
  - `MadAnalysis5`, mainly SUSY searches, E. Conte et al., arXiv:1206.1599, arXiv:1808.00480
  - `CheckMate`, SUSY searches, M. Drees et al., arXiv:1312.2591; D. Dercks et al., arXiv:1611.09856
  - `Contur`, based on SM measurements implemented in `Rivet`, J. Butterworth et al., arXiv:1606.05296, arXiv:1902.03067
- check for each data point which tool gives the best constraint

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

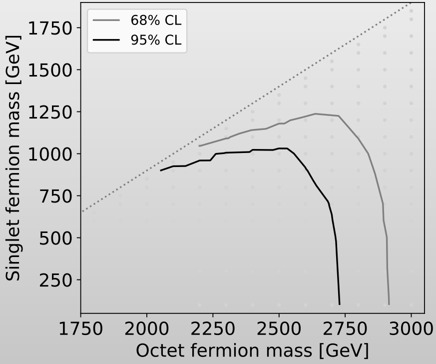
Octet decays with 100% decays into π_3



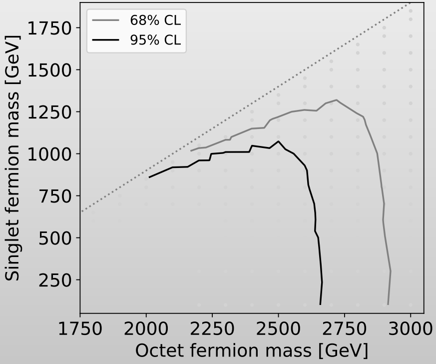
$m_{Q_8} - m_{\pi_3} = 200$ GeV $\qquad$ $m_{\pi_3} = 1.4$ TeV

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

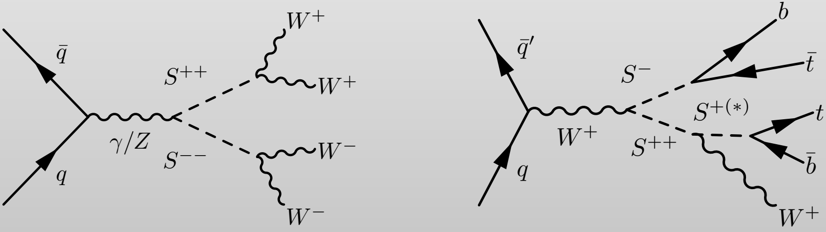
G. Cacciapaglia *et al.*, arXiv:2112.00019

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

fermiophobic — fermiophilic



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

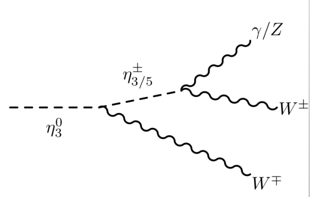
$$S^{++} \to W^+ t\bar{b},$$
$$S^{+} \to t\bar{b},$$
$$S^{0} \to t\bar{t},\, b\bar{b}.$$

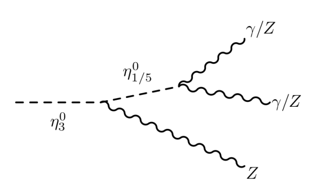
Electroweak pNGBs

fermiophilic scenario: only weak bounds in a very small region of parameter space

$\Rightarrow$ focus on fermiophobic 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

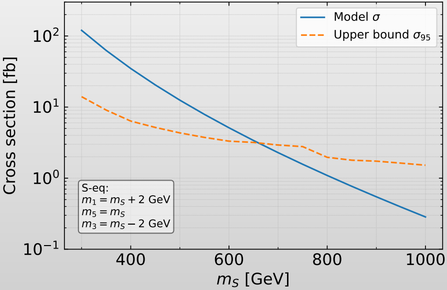


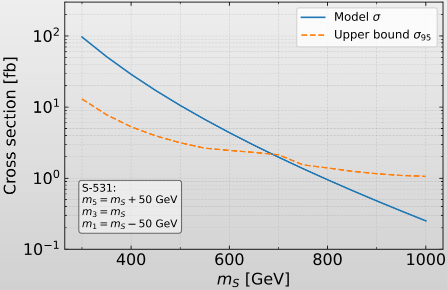


- for the heavier custodial multiplets: decays into (off-shell) vector bosons + lighter multiplet, e.g.

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

Bounds on η_1, η_3, η_5





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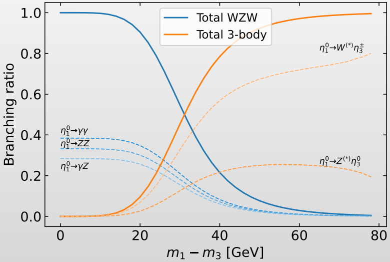
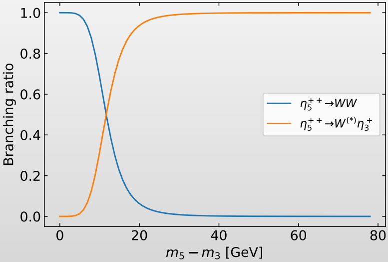
Conclusions:

- 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
- example, M5-model:
  - mass bounds on electroweak pNGBs:
    fermiophilic scenario: only very weak bounds in small part of parameter space
    fermiophobic scenario: $\sim$ 400-650 GeV depending on mass splittings
  - color octets among the top-partners: bounds of up to 2.8 TeV on their masses

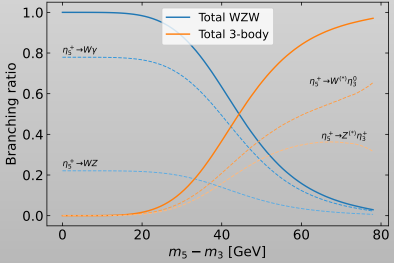
Branching ratios 1, M5-model



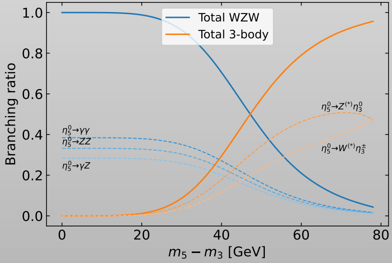
$\eta_1^0, m_1 = 600 \text{ GeV} > m_3$



$\eta_5^{++}, m_5 = 600 \text{ GeV} > m_3$

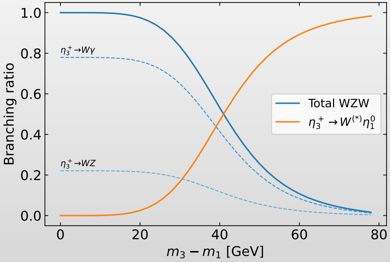


$\eta_5^+, m_5 = 600 \text{ GeV} > m_3$

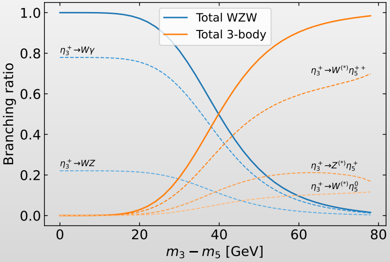


$\eta_5^0, m_5 = 600 \text{ GeV} > m_3$

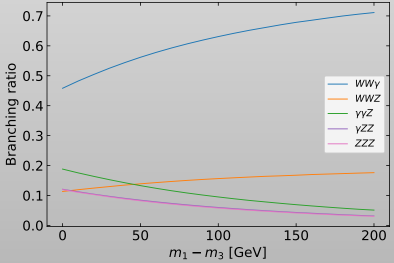
Branching ratios 2, M5-model



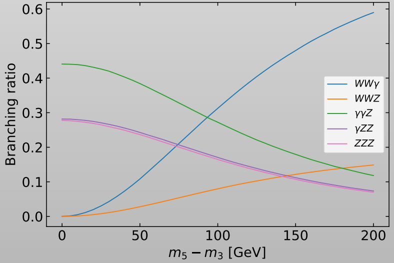
$\eta_3^+, m_5 \gg m_3 = 600$ GeV $> m_1$



$\eta_3^+, m_1 \gg m_3 = 600$ GeV $> m_5$



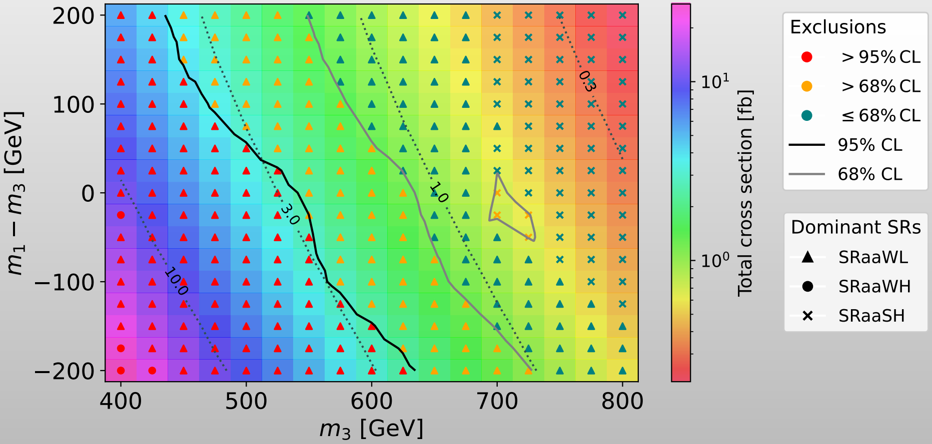
$\eta_3^0, m_5 \gg m_1 > m_3 = 600$ GeV



$\eta_3^0, m_1 \gg m_5 > m_3 = 600$ GeV

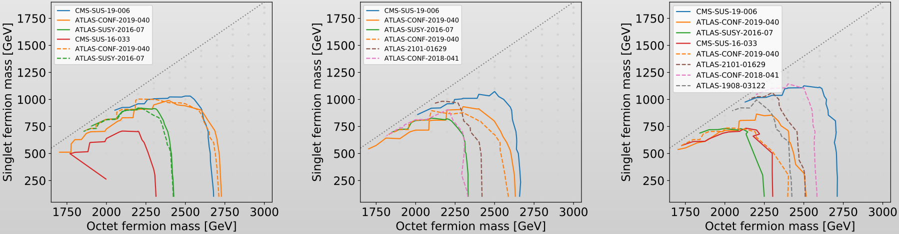
Bounds on η_1, η_3, η_5

$m_5 \gg m_1, m_3$



Contribution of different searches for color octets

preliminary



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