Exploring extended Higgs sectors via pair production at the LHC

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G. Cacciapaglia, T. Flacke, M. Kunkel, W. Porod [JHEP 02 (2022) 208]

A. Banerjee et al. (Snowmass contribution) [2203.07270]

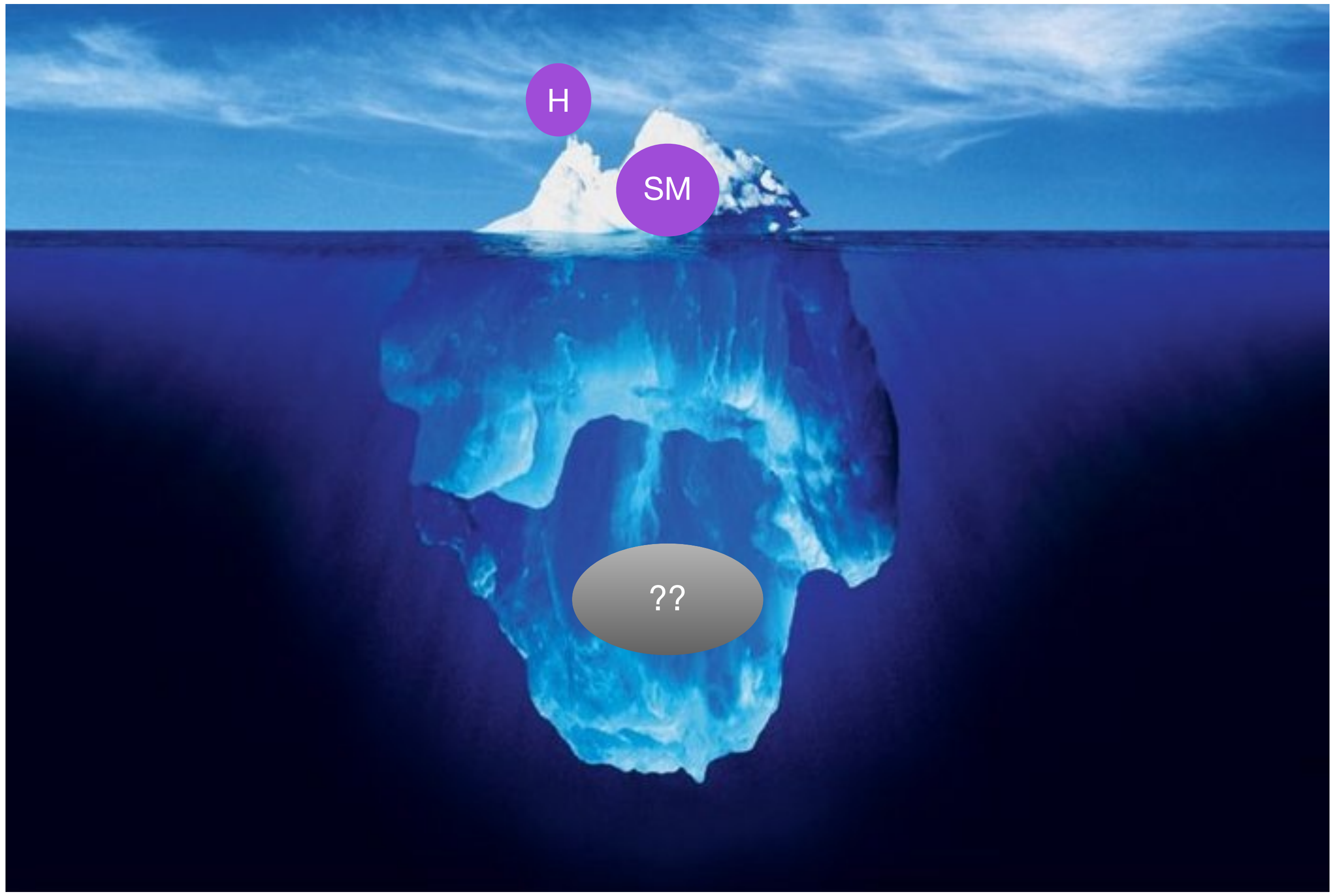
G. Cacciapaglia, T. Flacke, M. Kunkel, W. Porod, L. Schwarze [2210.01826]

G. Cacciapaglia, T. Flacke, Jeong Han Kim, Pyungwon Ko, W. Porod, et al. [in preparation]

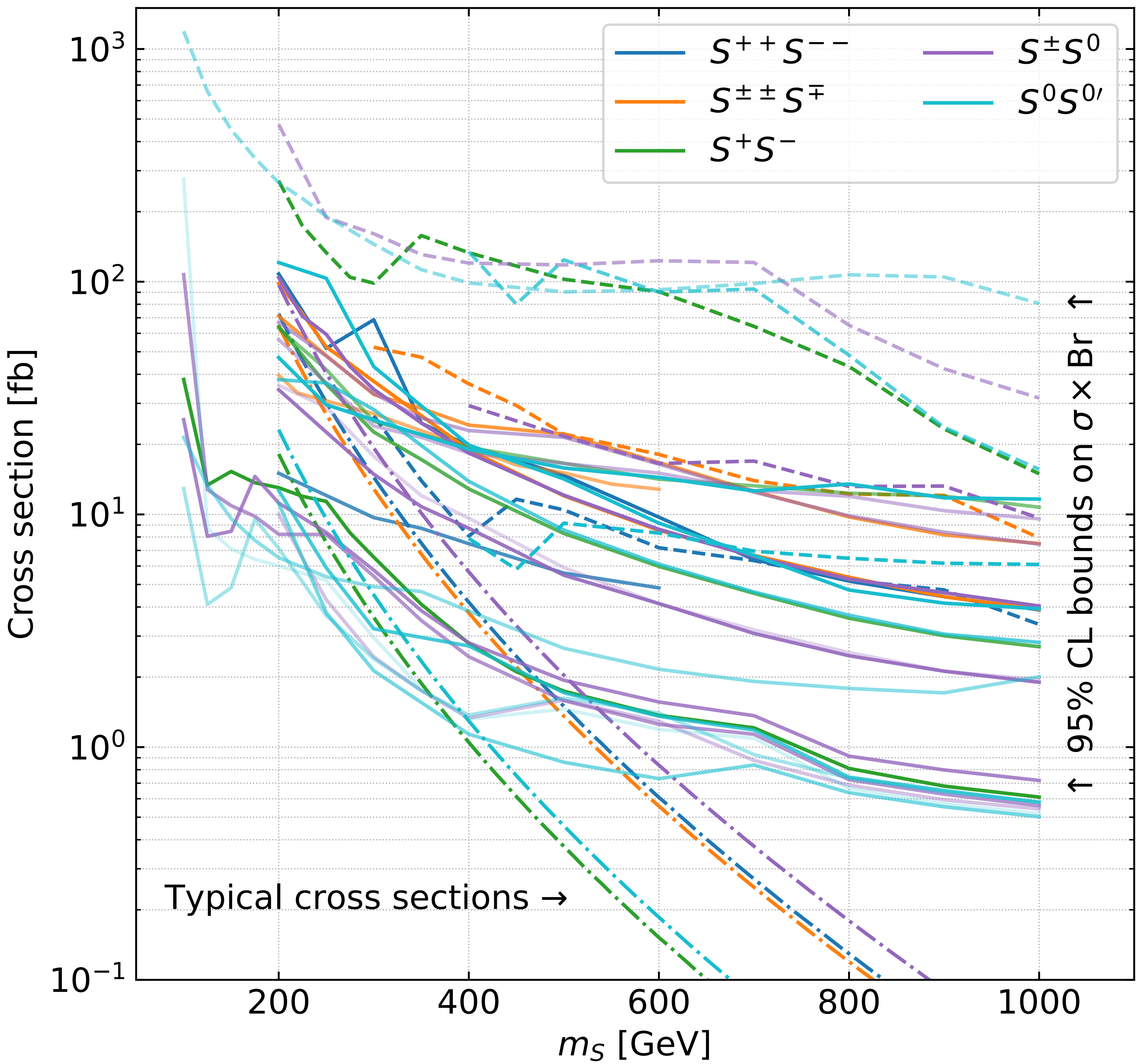
IBS-PNU Joint Workshop on Particle Physics and Cosmology, Busan, 2022/12/07

Outline

- Motivation 0: the talk in one plot
- Motivation I: Why is scalar pair production interesting?
- A simplified model for scalar pair production
- Bounds from existing recast searches (channel-by-channel)
- Motivation II: Underlying model with light BSM scalars — composite Higgs models
- Application of simplified model bounds to a full underlying model.
- Searching for exotic scalar pair production final states at the LHC.
- Conclusions & Outlook



The talk in one plot



Summary plot

Drell-Yan pair produced scalars: production cross sections for LHC@13 TeV and bounds from recasts of existing searches.

- dash-dotted: production cross sections σ
- solid: bounds on $\sigma \times BR(S) \times BR(S')$ for decays into EW bosons
- dashed: bounds on $\sigma \times BR(S) \times BR(S')$ from recasts for decays into 3rd generation quarks

Motivation

Why is BSM di-scalar production interesting?

- Many SM extensions which address the hierarchy problem have an extended Higgs sector with additional scalars which come in SU(2) multiplets.
- Single-production of BSM scalar interactions is highly model-dependent: arising from
  - Yukawa-type interactions,
  - the scalar kinetic term (if the scalar has a VEV),
  - the potential (via mixing with the Higgs),
  - or generated at loop-level.

  Pair-production is “less model-dependent”:
  The scalar kinetic term yields an SS’V interaction which depends only on the SU(2) x U(1) quantum numbers of the scalar multiplet which guarantees SS’ production through the Drell-Yan process. Mass mixing between different SU(2) multiplets can “re-shuffle” pair-production cross sections, but not tune all pair production cross sections small.

- Final states of scalar single-production are very explicitly targeted by the LHC search program (“resonance searches”). Final states in scalar pair-production (with $m_S \neq m_H$) are not.

Simplified model

A simplified model approach to obtain bounds from existing searches:

- We implement a simplified model in FeynRules which features:
  - pseudo- scalars with charge 2, 1, and a scalar and pseudo-scalar with charge 0
  - scalar pair production via Drell-Yan
  - scalar decay into two EW gauge bosons or into 3rd gen. quarks, respecting NWA
- We simulate signal events for each combination of decay channels of two scalars with MadGraph5,
- and determine bounds on production cross section times branching ratio into each channel combination by matching simulated events against all searches and measurements available in MadAnalysis5, CheckMATE and Contur.

- …our list of decay channels is not complete; you might not like our model parametrization. The simulation package we put together (“ScanGen”) is available upon request and will be made public “soon”. With it, adding channels and using other models is straight forward (by just replacing the FeynRules implementation / UFO).

Simplified model Lagrangian

$$\mathcal{L}_{\rm int} = \mathcal{L}_{SSV} + \mathcal{L}_{SVV} + \mathcal{L}_{ffS}$$

Production:
(and cascade decays)

$$\mathcal{L}_{SSV} = \frac{ie}{s_W} W^{-\mu} \left(K_W^{S^0 S^+} S^0 \overleftrightarrow{\partial_\mu} S^+ + K_W^{S^{0\prime} S^+} S^{0\prime} \overleftrightarrow{\partial_\mu} S^+ + K_W^{S^- S^{++}} S^- \overleftrightarrow{\partial_\mu} S^{++} \right) + \text{h.c.}$$
$$+ \frac{ie}{s_W c_W} Z^\mu \left(K_Z^{S^0 S^{0\prime}} S^0 \overleftrightarrow{\partial_\mu} S^{0\prime} + K_Z^{S^+ S^-} S^+ \overleftrightarrow{\partial_\mu} S^- + K_Z^{S^{++} S^{--}} S^{++} \overleftrightarrow{\partial_\mu} S^{--} \right)$$
$$- ieA^\mu \left(S^+ \overleftrightarrow{\partial_\mu} S^- + 2 S^{++} \overleftrightarrow{\partial_\mu} S^{--} \right) ,$$

decay
to gauge bosons:

$$\mathcal{L}_{SVV} = \frac{e^2}{16\pi^2 v} \Bigg[S^0 \left(\tilde{K}_{\gamma\gamma}^{S^0} F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{2}{s_W c_W} \tilde{K}_{\gamma Z}^{S^0} F_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{1}{s_W^2 c_W^2} \tilde{K}_{ZZ}^{S^0} Z_{\mu\nu} \tilde{Z}^{\mu\nu} + \frac{2}{s_W^2} \tilde{K}_{WW}^{S^0} W^+_{\mu\nu} \tilde{W}^{-\mu\nu} \right)$$
$$+ S^{0\prime} \left(K_{\gamma\gamma}^{S^{0\prime}} F_{\mu\nu} F^{\mu\nu} + \frac{2}{s_W c_W} K_{\gamma Z}^{S^{0\prime}} F_{\mu\nu} Z^{\mu\nu} + \frac{1}{s_W^2 c_W^2} K_{ZZ}^{S^{0\prime}} Z_{\mu\nu} Z^{\mu\nu} + \frac{2}{s_W^2} K_{WW}^{S^{0\prime}} W^+_{\mu\nu} W^{-\mu\nu} \right)$$
$$+ \left(S^+ \left(\frac{2}{s_W} \tilde{K}_{\gamma W}^{S^+} F_{\mu\nu} \tilde{W}^{-\mu\nu} + \frac{2}{s_W^2 c_W} \tilde{K}_{ZW}^{S^+} Z_{\mu\nu} \tilde{W}^{-\mu\nu} \right) + \text{h.c.} \right)$$
$$+ S^{++} \frac{1}{s_W^2} \tilde{K}_{W^- W^-}^{S^{++}} W^-_{\mu\nu} \tilde{W}^{-\mu\nu} + \text{h.c.} \Bigg] .$$

decay
to fermions:

$$\mathcal{L}_{ffS} = S^0 \left[\bar{t} \left(\kappa_t^{S^0} + i \tilde{\kappa}_t^{S^0} \gamma_5 \right) t + \bar{b} \left(\kappa_b^{S^0} + i \tilde{\kappa}_b^{S^0} \gamma_5 \right) b \right] + (S^0 \to S^{0\prime})$$
$$+ S^+ \, \bar{t} \left(\kappa_{tb,L}^{S^+} P_L + \kappa_{tb,R}^{S^+} P_R \right) b + \text{h.c.} ,$$

pair decay channels (fermion-phobic scenario)

fermiophobic	$S^{++}S^{--}$	$S^{\pm\pm}S^{\mp}$	$S^{+}S^{-}$	$S^{\pm}S^{0(\prime)}$	$S^{0}S^{0\prime}/S^{0\prime}S^{0}$
$WWWW$	$W^+W^+W^-W^-$	-	-	-	$W^+W^-W^+W^-$
$WWW\gamma$	-	$W^\pm W^\pm W^\mp \gamma$	-	$W^\pm \gamma W^+W^-$	-
$WWWZ$	-	$W^\pm W^\pm W^\mp Z$	-	$W^\pm Z W^+W^-$	-
$WW\gamma\gamma$	-	-	$W^+\gamma W^-\gamma$	-	$W^+W^-\gamma\gamma$
$WWZ\gamma$	-	-	$W^\pm\gamma W^\mp Z$	-	$W^+W^-\gamma Z$
$WWZZ$	-	-	W^+ZW^-Z	-	W^+W^-ZZ
$W\gamma\gamma\gamma$	-	-	-	$W^\pm\gamma\gamma\gamma$	-
$WZ\gamma\gamma$	-	-	-	$W^\pm\{Z\gamma\}\gamma$	-
$WZZ\gamma$	-	-	-	$W^\pm\{Z\gamma\}Z$	-
$WZZZ$	-	-	-	$W^\pm ZZZ$	-
$\gamma\gamma\gamma\gamma$	-	-	-	-	$\gamma\gamma\gamma\gamma$
$Z\gamma\gamma\gamma$	-	-	-	-	$Z\gamma\gamma\gamma$
$ZZ\gamma\gamma$	-	-	-	-	$Z\{Z\gamma\}\gamma$
$ZZZ\gamma$	-	-	-	-	$ZZZ\gamma$
$ZZZZ$	-	-	-	-	$ZZZZ$

Table 1: Classification of the 24 di-scalar channels in terms of the 5 pair production cases (columns) and the 15 combinations of gauge bosons (rows) from decays. In the channels, the first two and second two bosons are resonantly produced. The notation $\{Z\gamma\} = Z\gamma + \gamma Z$ indicates the two permutations. Charge-conjugated states belong to the same di-scalar channel.

pair decay channels (fermion-phobic scenario)

fermiophilic	$S^{++}S^{--}$	$S^{++}S^{-}$	$S^{+}S^{-}$	$S^{+}S^{0(\prime)}$	$S^{0}S^{0\prime}/S^{0\prime}S^{0}$
$tttt$	-	-	-	-	$t\bar{t}t\bar{t}$
$tttb$	-	-	-	$t\bar{b}t\bar{t}$	-
$ttbb$	-	-	$t\bar{b}b\bar{t}$	-	$t\bar{t}b\bar{b}$
$tbbb$	-	-	-	$t\bar{b}b\bar{b}$	-
$bbbb$	-	-	-	-	$b\bar{b}b\bar{b}$
$Wttbb$	-	$W^{+}t\bar{b}b\bar{t}$	-	-	-
$WWttbb$	$W^{+}t\bar{b}W^{-}b\bar{t}$	-	-	-	-

Table 2: Classification of the 8 di-scalar channels in terms of the 5 pair production cases (columns) and the 5 combinations of top and bottom from decays (rows). In cases with one or two doubly charged scalars, one always obtains $ttbb$ with one or two additional W's, respectively. The charge-conjugated states are not shown.

…just for orientation

Typical Drell-Yan production cross sections (in SU(5)→SO(5) models):

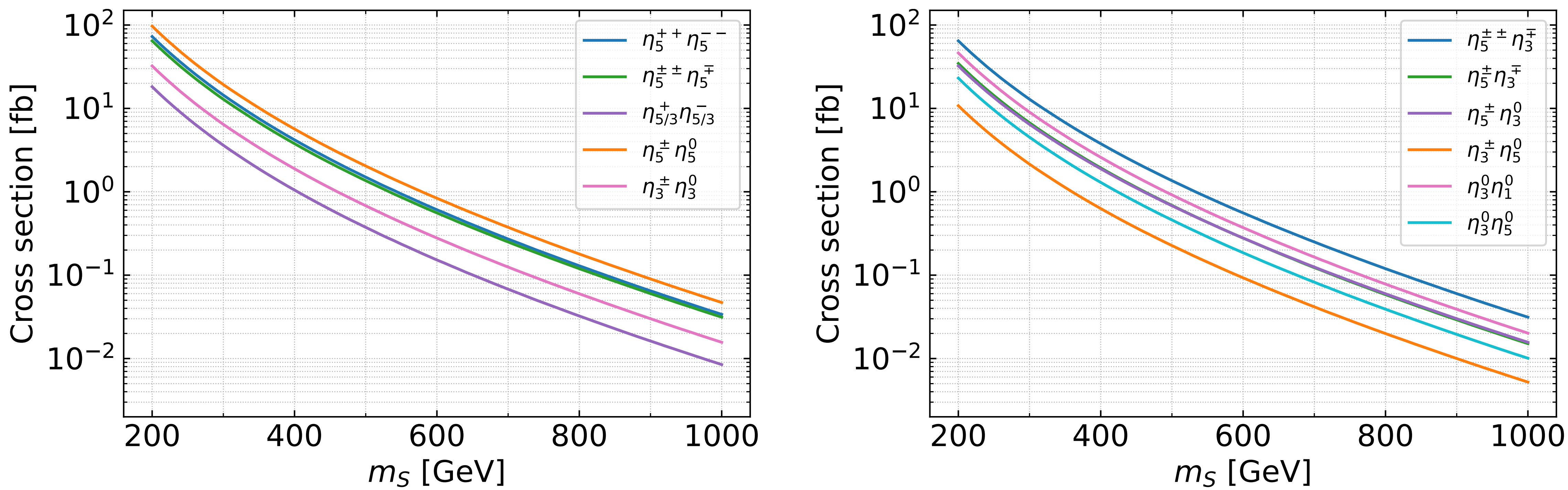
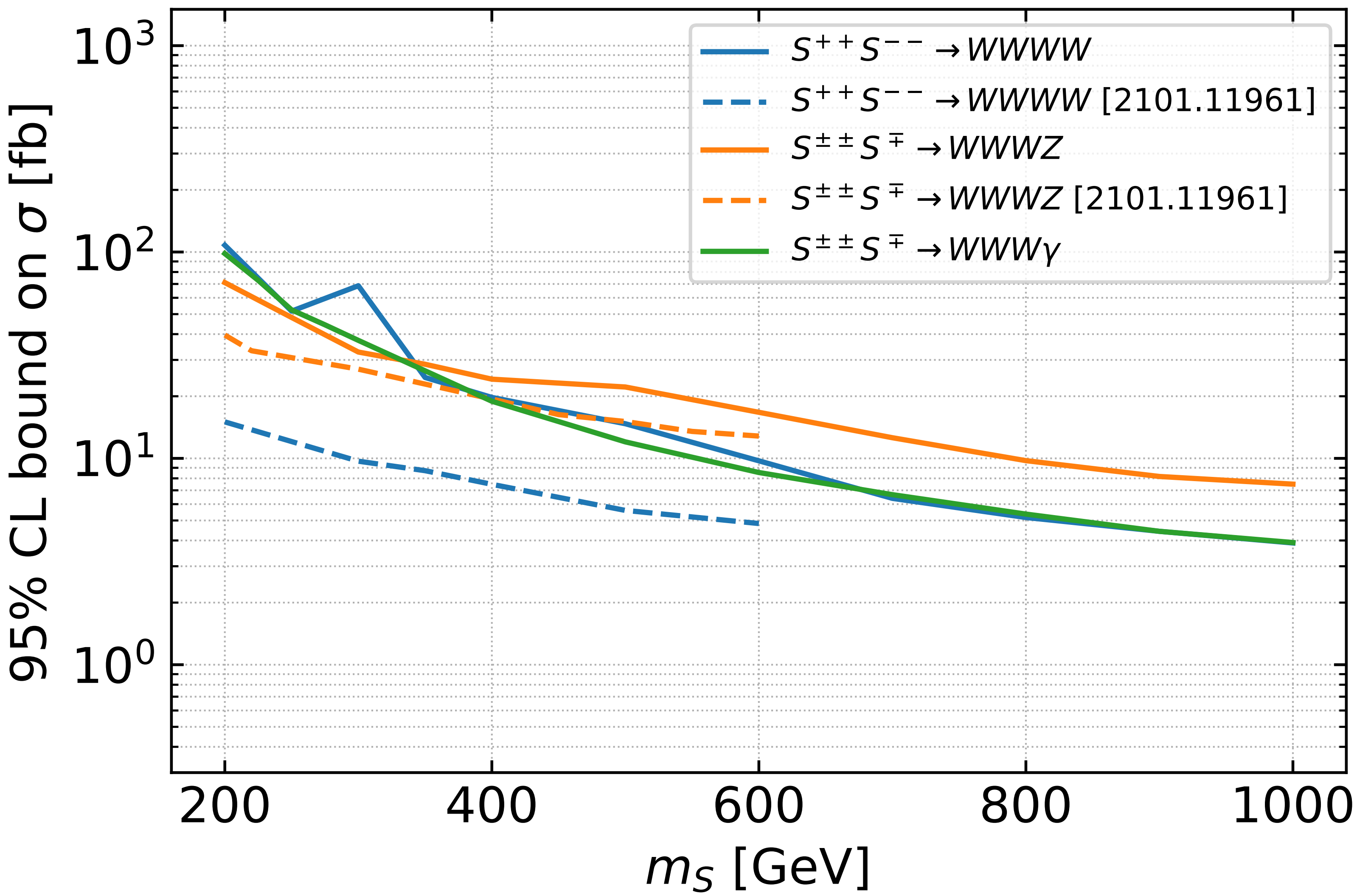


Figure 3: Cross sections for the Drell-Yan production of SU(5)/SO(5) pNGBs at the LHC with $\sqrt{s} = 13\,\text{TeV}$, assuming the same mass for all states of the custodial singlet, triplet, and quintuplet. Note that the $\eta_1^0\eta_5^0$ combination is not allowed as they are both parity-odd.

EW scalar pairs: bounds from the LHC

Model agnostic bounds: (**can be used for ANY model with dominant DY production**)

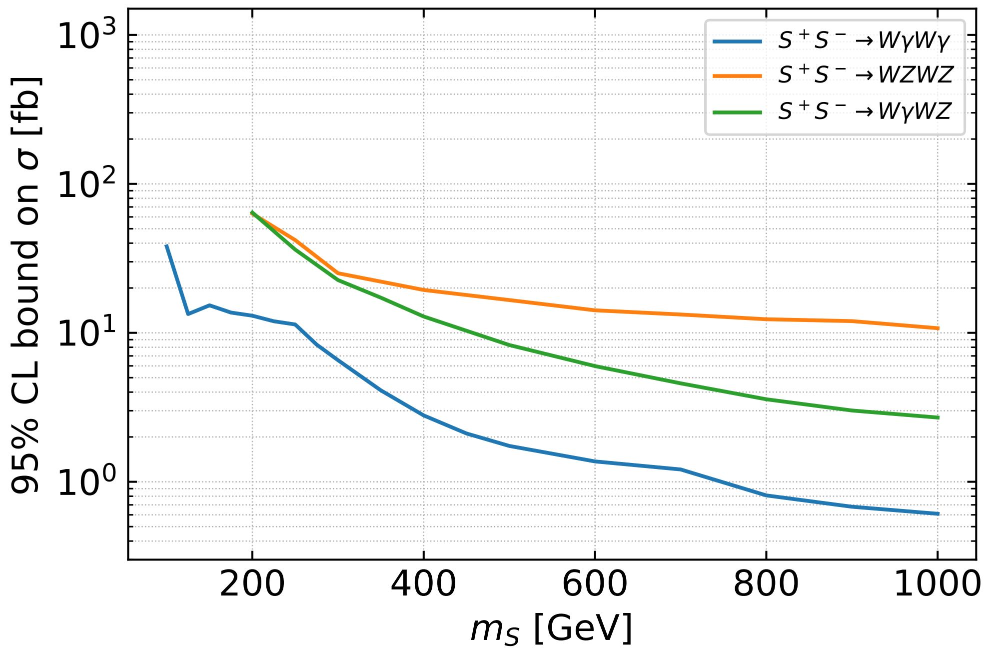
We simulate Drell-Yan pair production of EW pNGBs and decays into various decay channels and determine bounds from searches available in event-recast data bases.
(Simulaton chain: Feynrules → Madgraph5 → Pythia8 → (→ Delphes →) MadAnalysis5/CheckMATE/Contur)



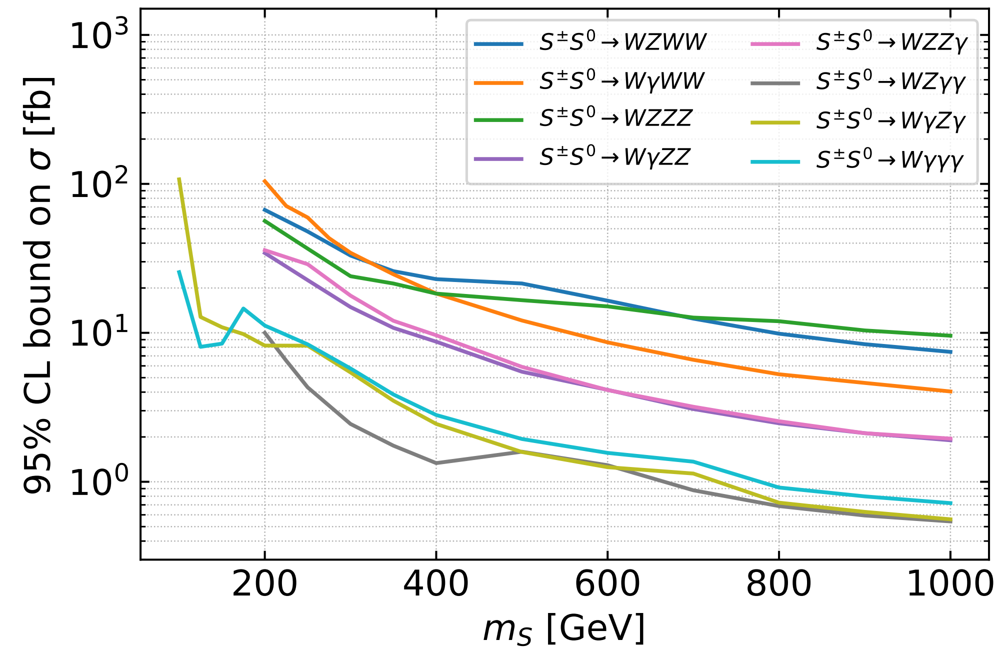
(b) $S^{++}S^{--}$ and $S^{\pm\pm}S^{\mp}$ with di-boson decays

EW scalar pairs: bounds from the LHC

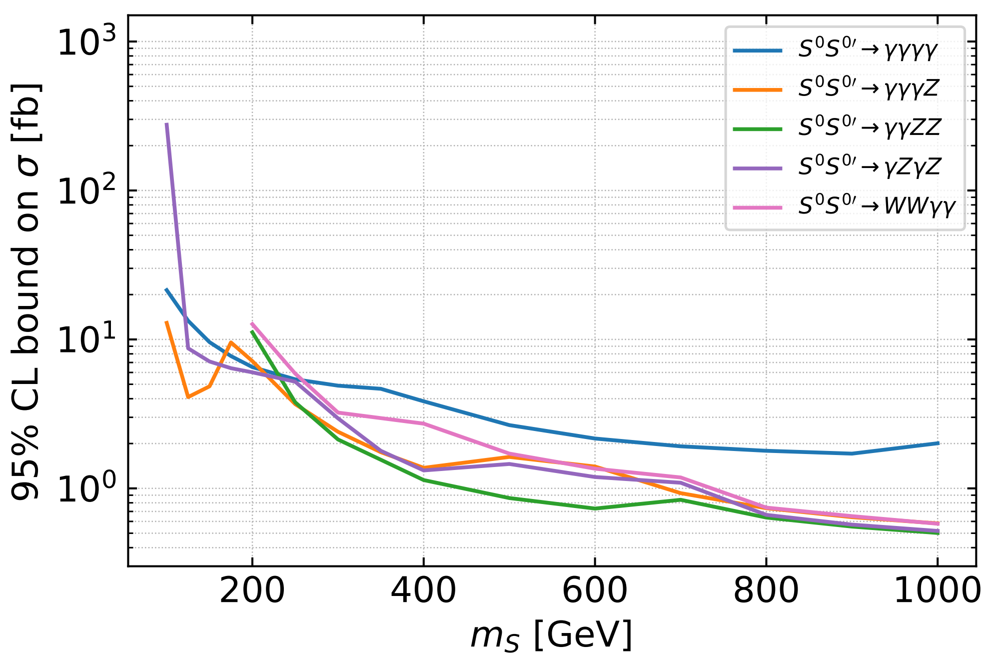
Model agnostic bounds: (**can be used for ANY model with dominant DY production**)



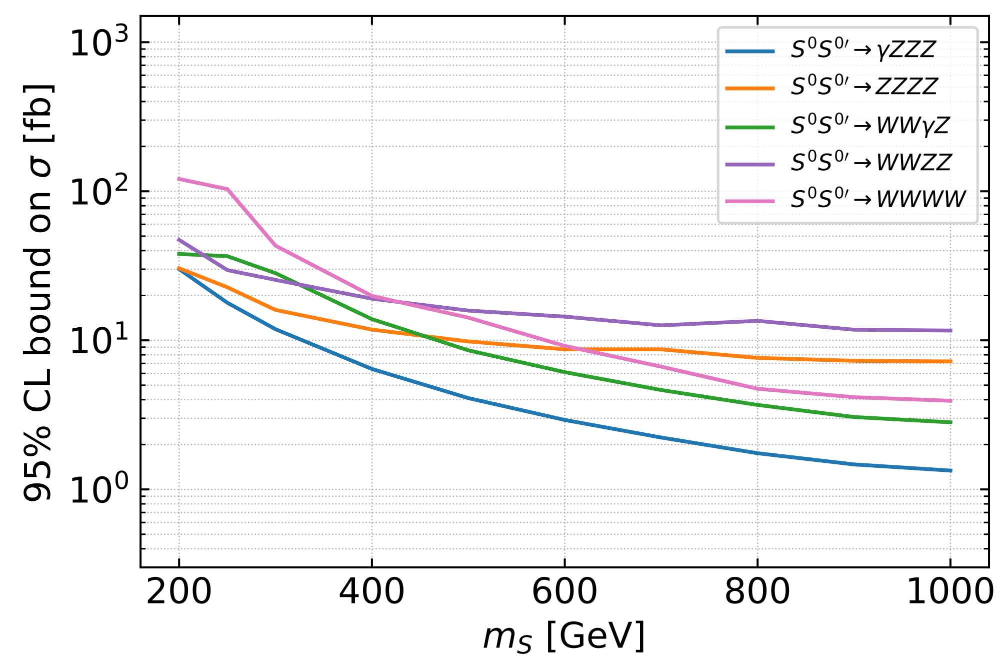
(c) S^+S^- with di-boson decays



(d) $S^\pm S^0$ with di-boson decays



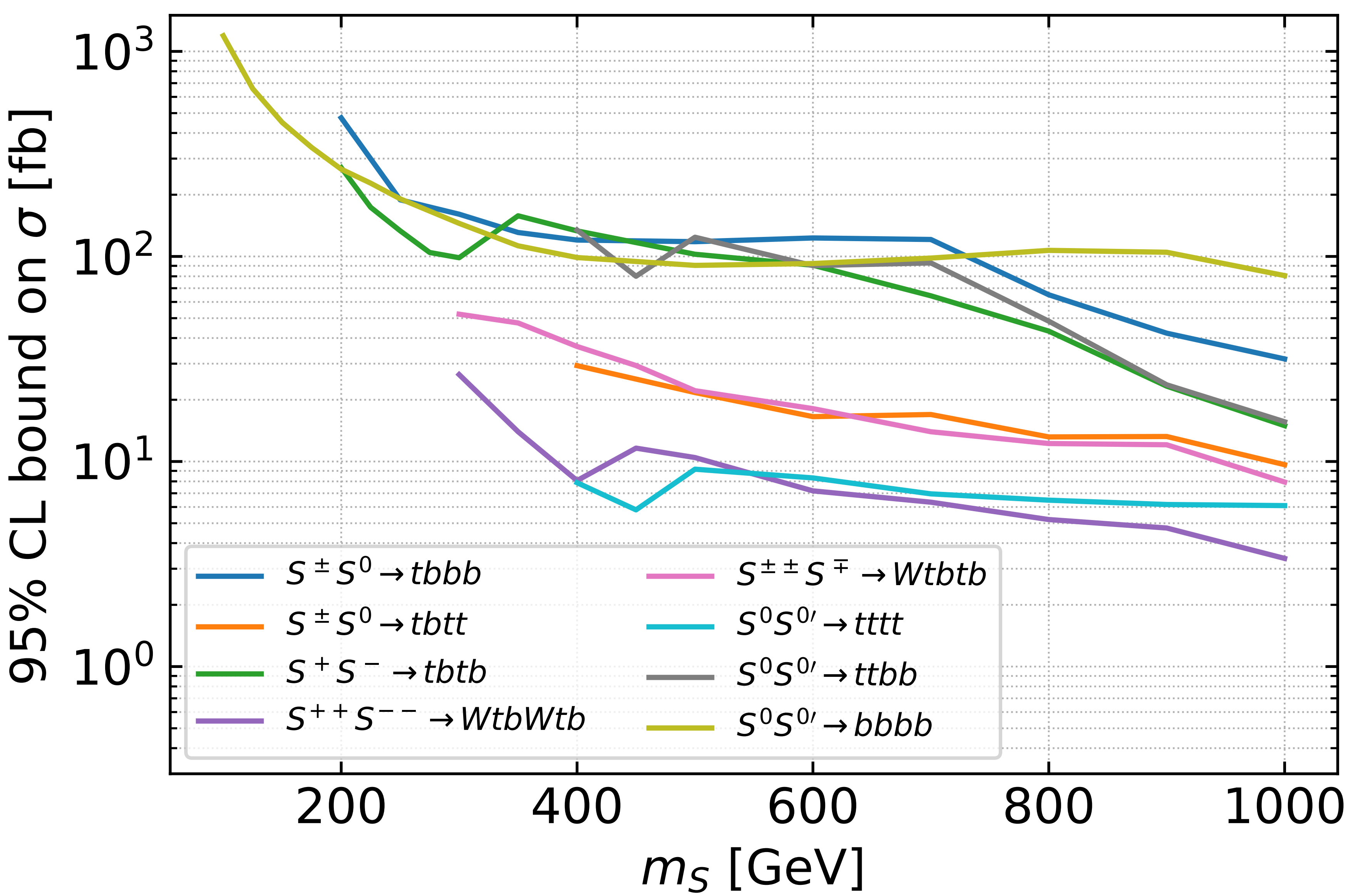
(e) $S^0S^{0\prime}$ with di-boson decays with ≥ 2 photons



(f) $S^0S^{0\prime}$ with di-boson decays with ≤ 1 photons

EW scalar pairs: bounds from the LHC

Model agnostic bounds: (**can be used for ANY model with dominant DY production**)

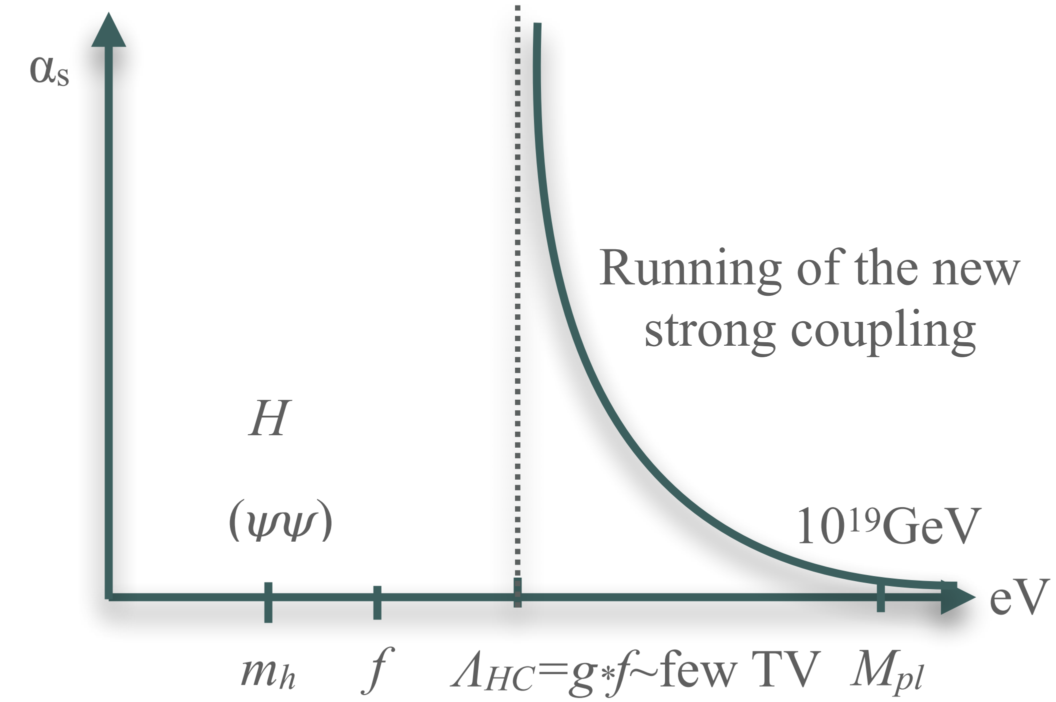


(a) Scalar pair with decays to quarks

Motivation for a composite Higgs

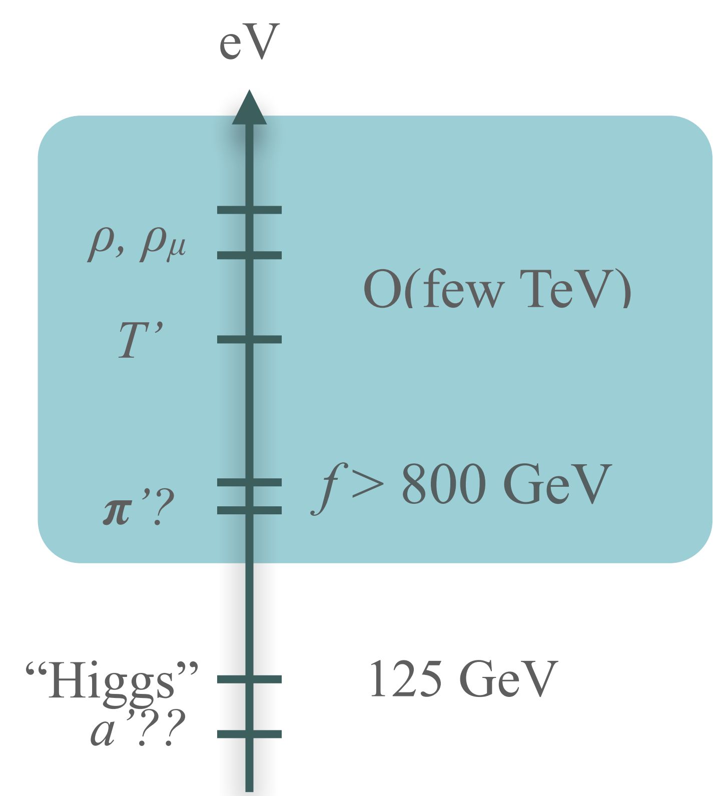
An alternative solution to the hierarchy problem:

- Generate a scale $\Lambda_{HC} << M_{pl}$ through a new confining gauge group.
- Interpret the Higgs as a pseudo-Nambu-Goldstone boson (pNGB) of a spontaneously broken global symmetry of the new strong sector.
  [Georgi, Kaplan (1984)]



The price to pay:

- additional resonances around Λ_{HC} (vectors, vector-like fermions, scalars),
- additional pNGBs / an extended scalar sector.
- deviations of the Higgs couplings from their SM values of O(v/f).



Composite Higgs Models: Towards underlying models

A wish list to construct and classify candidate models:

Underlying models of a composite Higgs should

Gherghetta etal (2015), Ferretti etal (2014), PRD 94 (2016) no 1, 015004, JHEP 1701, 094

- contain no elementary scalars (to not re-introduce 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),

The resulting models have several common features:

- All models contain two types of underlying fermions.
- All models predict SM neutral, electroweak and colored pNGBs beyond the Higgs multiplet.

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	/	

M5: (Todays model) [JHEP 2202, 208]

M6: [Ferretti (2014)]

M8: [JHEP1511,201]

M11: [Vecchi (2015)]

Additional model: SU(3) with 8x(F,F) [Appelquist,Ingoldby,Piai (2021)]

[JHEP1701,094]

CH: EW pNGBs - bounds from the LHC

EW sector: SU(5)→SO(5)

- 14 pNGBs in a (3,3), a (2,2) and a (1,1) of $SU(2)_L$ x $SU(2)_R$
  an EW singlet, the Higgs, and $(\mathbf{3},\mathbf{3}) \to \mathbf{5}+\mathbf{3}+\mathbf{1} \equiv \eta_5+\eta_3+\eta_1$,
  $$\eta_5 = (\eta_5^{++}, \eta_5^{+}, \eta_5^{0}, \eta_5^{-}, \eta_5^{--}), \quad \eta_3 = (\eta_3^{+}, \eta_3^{0}, \eta_3^{-}), \quad \eta_1 = \eta_1^0$$
- Couplings:
  SS'V: gauge interactions (fixed; relevant for production; or cascade decays)
  SVV': WZW interactions (tiny; relevant for decay)
  Sff': explicit symmetry breaking terms (tiny; relevant for decay)
- Single-production of EW pNGBs is strongly suppressed.
- Pair-production is generically dominated by Drell-Yan pair production.
- For a given model, the WZW coefficients are fixed, and thus branching fractions of pNGB decays to EW gauge bosons are determined.
- Decays to 3rd generation quarks arise from a different source.
- Typically dominant pNGB decay channels:

fermiophilic scenario

$$\eta_5^{++} \to W^+ t\bar{b}$$
$$\eta_{3,5}^{+} \to t\bar{b}$$
$$\eta_{1,3,5}^{0} \to t\bar{t},\, b\bar{b}$$

fermiophobic scenario

$$\eta_5^{++} \to W^+W^+$$
$$\eta_{3,5}^{+} \to W^+\gamma,\, W^+Z$$
$$\eta_{1,5}^{0} \to \gamma\gamma,\, \gamma Z,\, ZZ$$
$$\eta_3^0 \to W^+W^-\gamma,\, W^+W^-Z \quad \text{via } \eta_{3,5}^{\pm(*)}$$
$$\eta_3^0 \to Z\gamma\gamma,\, ZZ\gamma,\, ZZZ \quad \text{via } \eta_{1,5}^{0(*)}$$

CH: EW pNGBs - bounds from the LHC

Production cross sections in SU(5)→SO(5) models:

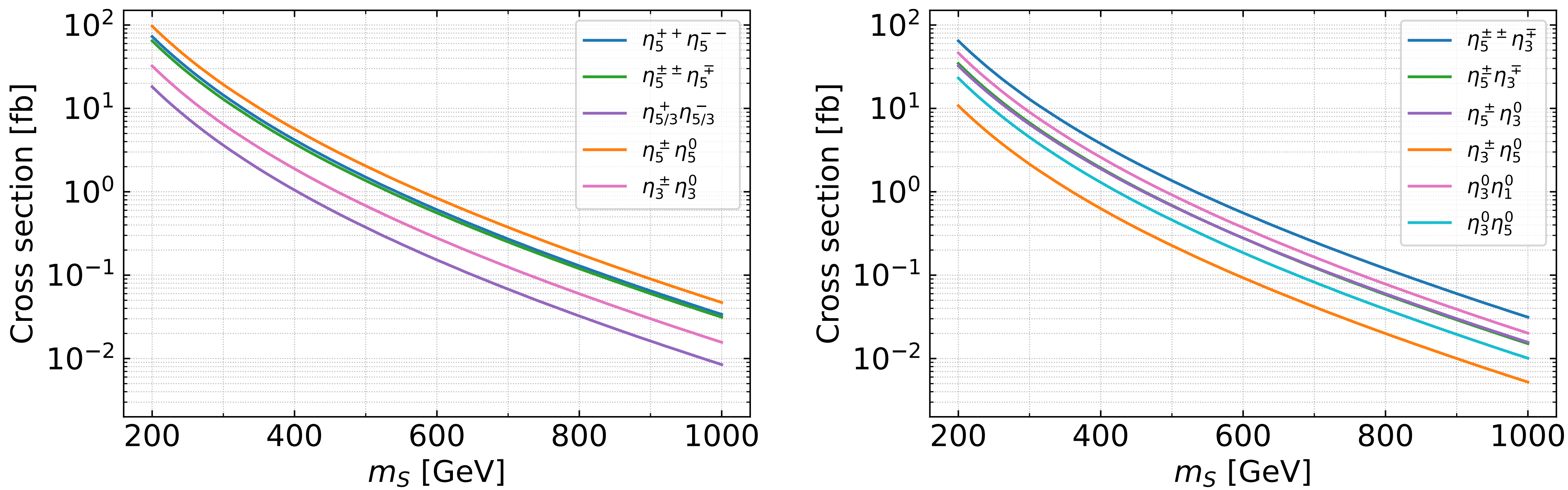
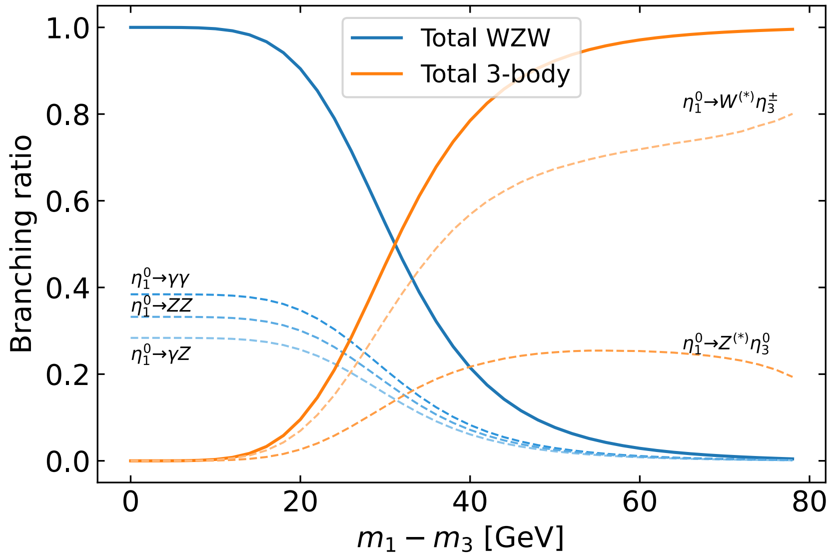


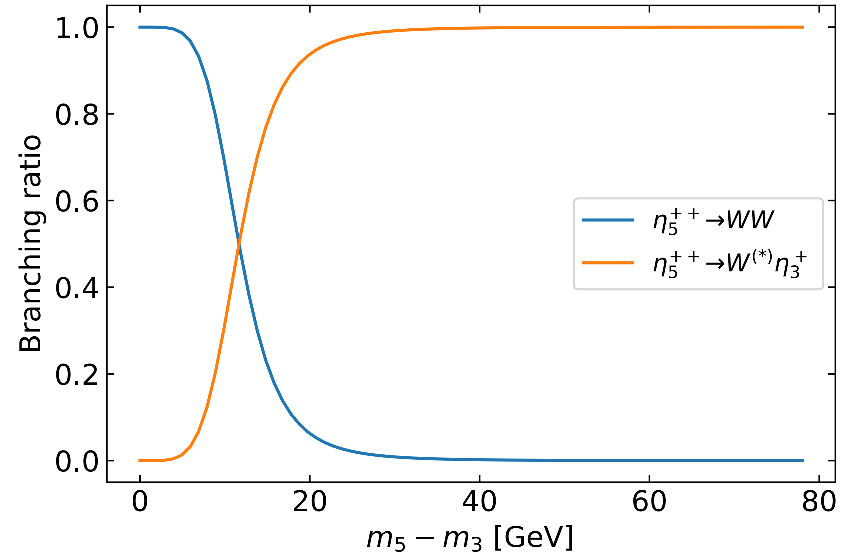
Figure 3: Cross sections for the Drell-Yan production of SU(5)/SO(5) pNGBs at the LHC with $\sqrt{s} = 13\,\text{TeV}$, assuming the same mass for all states of the custodial singlet, triplet, and quintuplet. Note that the $\eta_1^0\eta_5^0$ combination is not allowed as they are both parity-odd.

CH: EW pNGBs - bounds from the LHC

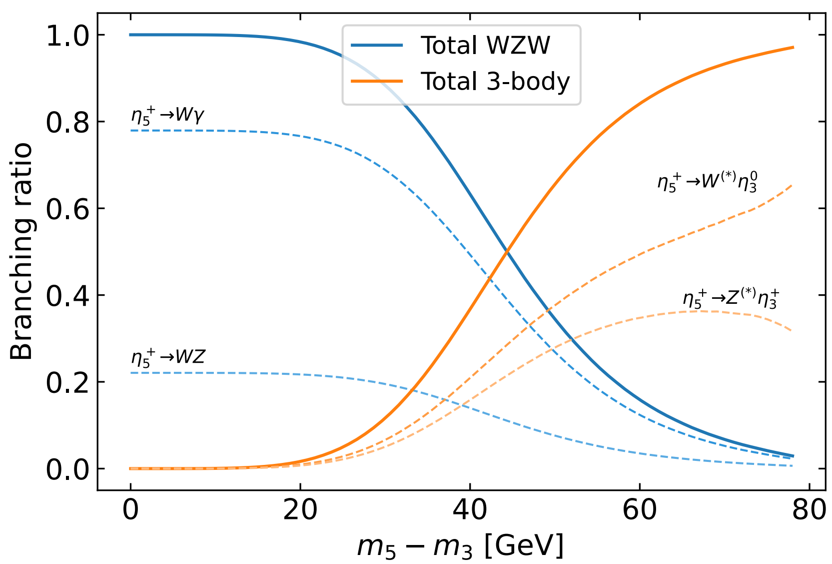
Branching fractions in SU(5)→SO(5) models (fermio-phobic scenario):



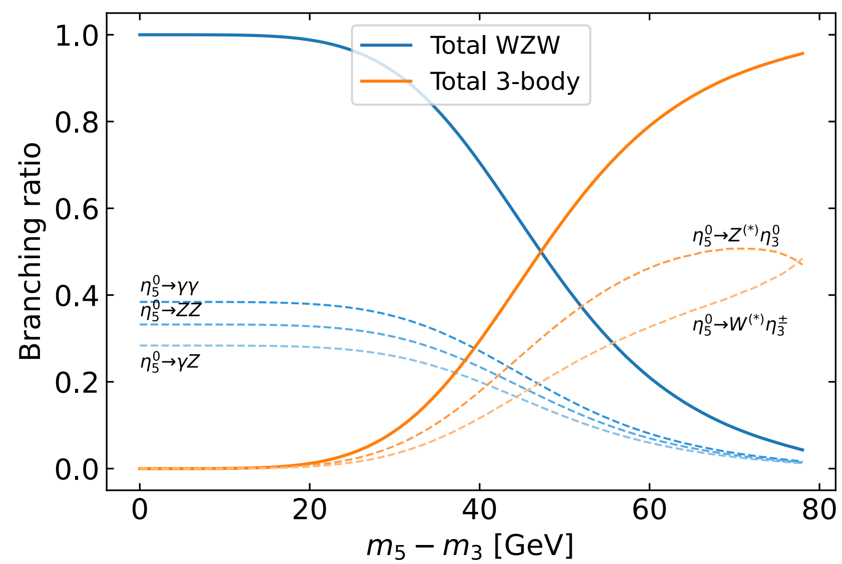
(a) Decays of η_1^0 for $m_1 = 600$ GeV $> m_3$



(b) Decays of η_5^{++} for $m_5 = 600$ GeV $> m_3$



(c) Decays of η_5^+ for $m_5 = 600$ GeV $> m_3$

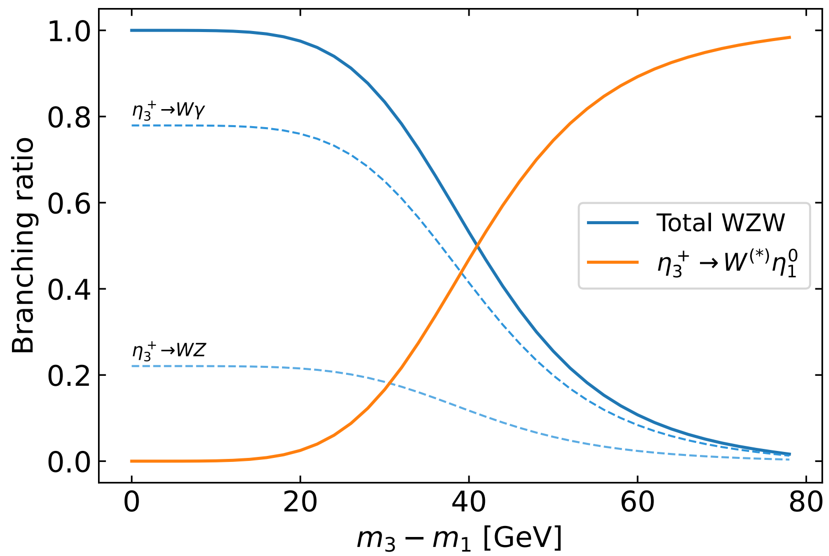


(d) Decays of η_5^0 for $m_5 = 600$ GeV $> m_3$

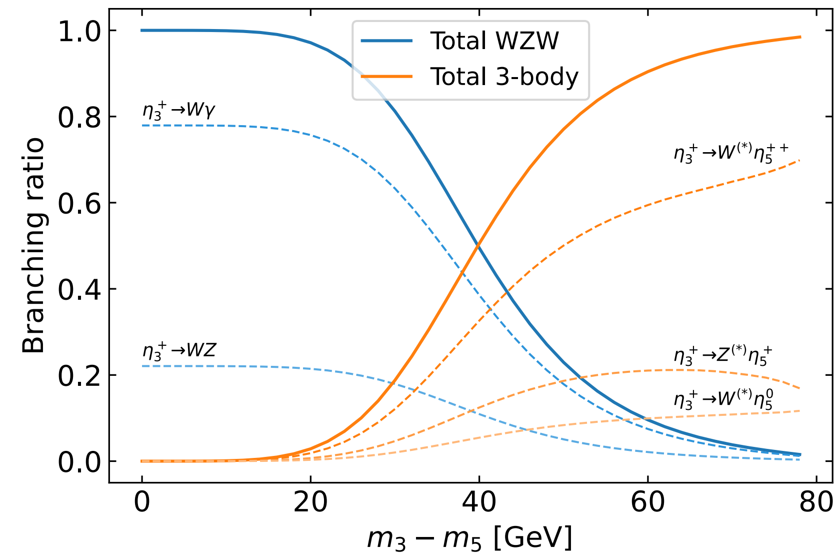
Figure 5: Overview of the pNGB decays in the fermiophobic case. The mass of the decaying particles is set to 600 GeV. The heavier state decays either via the anomaly into di-boson final states or via an (off-shell) gauge boson into a lighter pNGB.

CH: EW pNGBs - bounds from the LHC

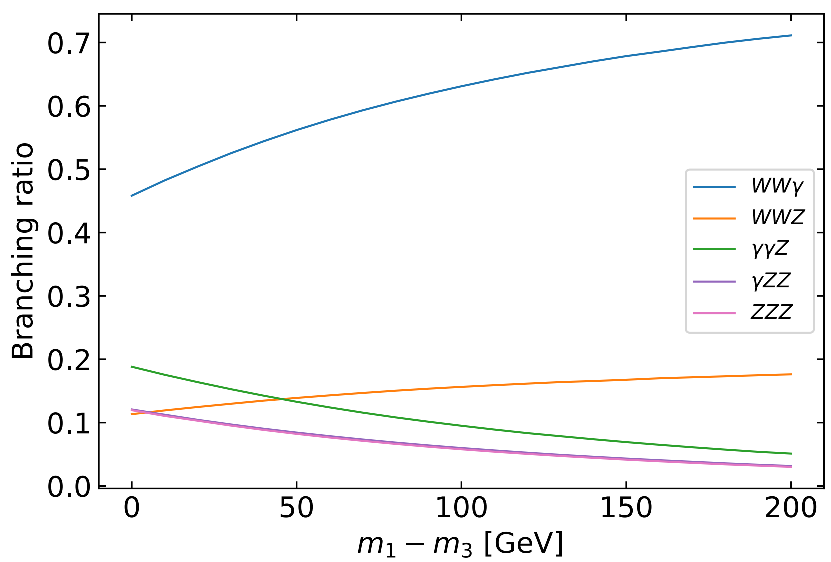
Branching fractions in SU(5)→SO(5) models (fermio-phobic scenario):



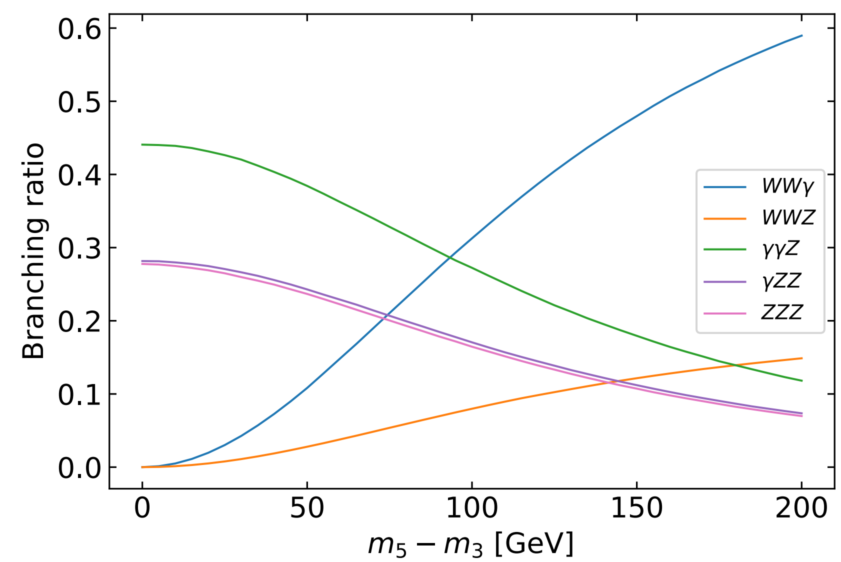
(a) Decays of η_3^+ for $m_5 \gg m_3 = 600$ GeV $> m_1$



(b) Decays of η_3^+ for $m_1 \gg m_3 = 600$ GeV $> m_5$



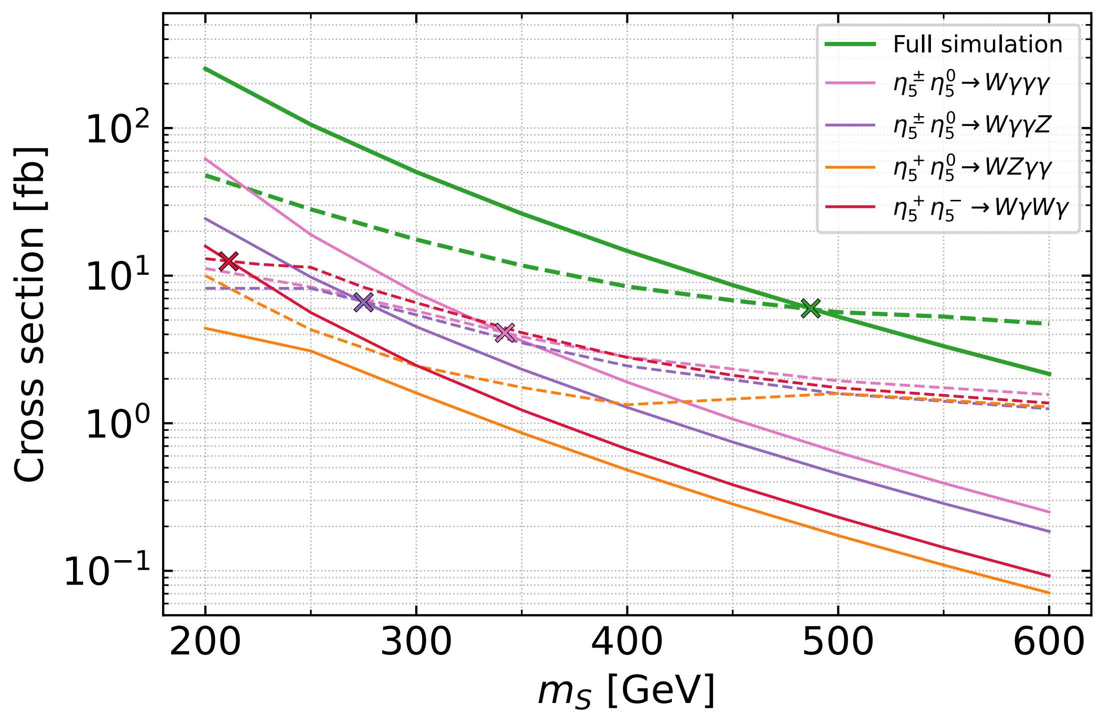
(c) Decays of η_3^0 for $m_5 \gg m_1 > m_3 = 600$ GeV



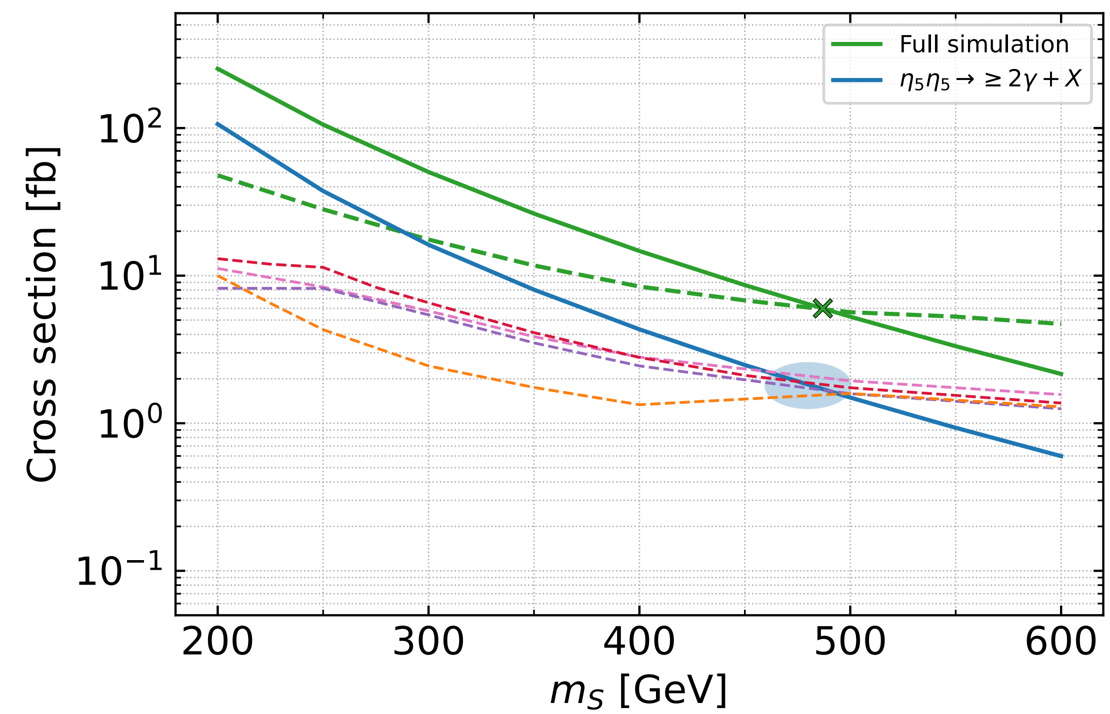
(d) Decays of η_3^0 for $m_1 \gg m_5 > m_3 = 600$ GeV

Figure 6: Overview of the pNGB decays in the fermiophobic case (continued from Fig. 5). The neutral triplet component decays into three gauge bosons, as it does not couple to the anomaly.

CH: EW pNGBs - bounds from the LHC



(a) Bounds from individual channels

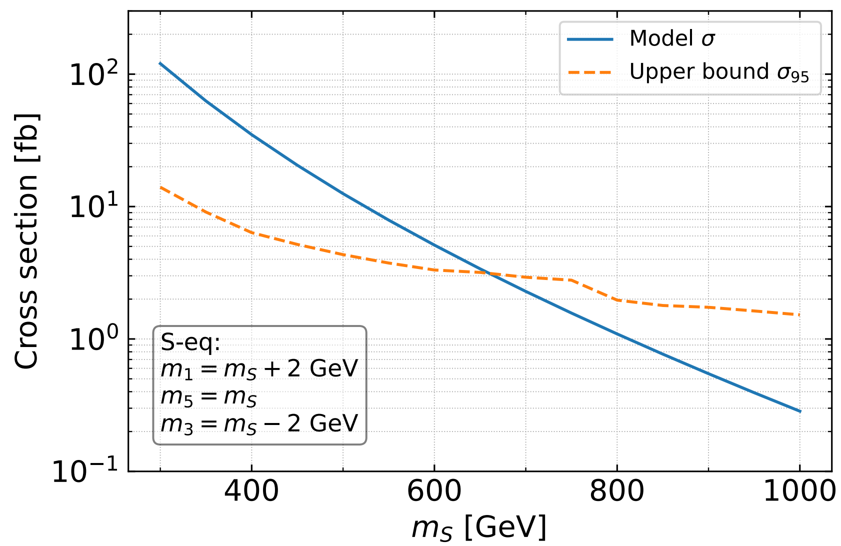


(b) Bounds from sum of multiphoton channels

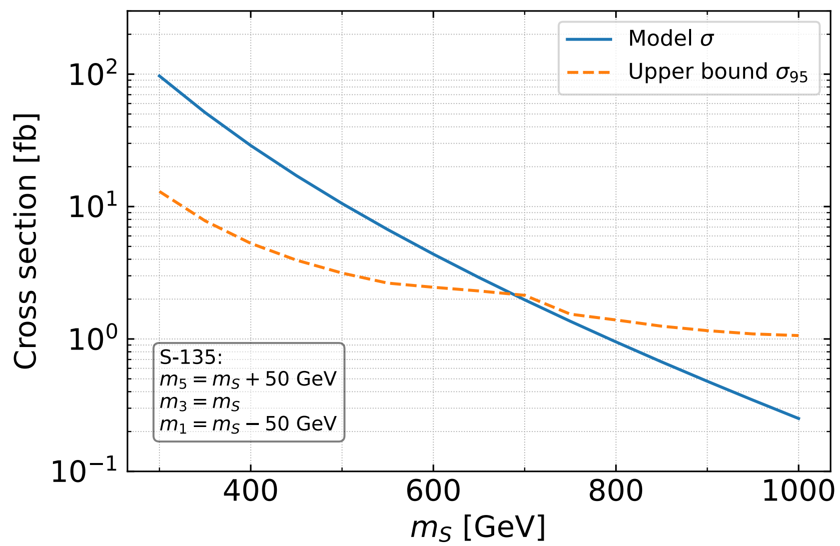
Figure 7: Application of the model-independent bounds to a specific model, the custodial quintuplet η_5 from the SU(5)/SO(5) coset. In (a) we determine the bounds from the dominant individual channels by comparing the cross section time branching ratio from the model (solid) with the upper limits from Fig. 2 (dashed). In green we show the results of a full simulation. The blue line in (b) is the sum of the individual multi-photon cross sections shown in (a). Further details are given in the text.

CH: EW pNGBs - bounds from the LHC

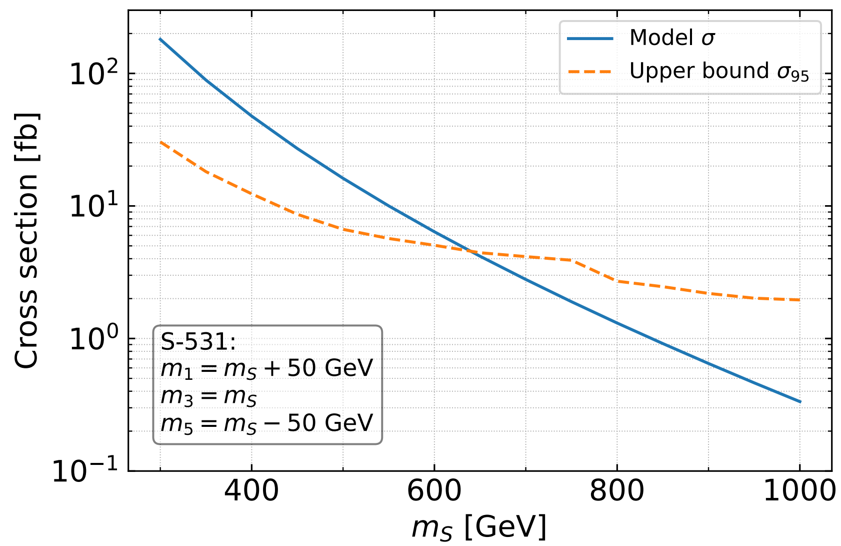
Resulting bounds in full SU(5)→SO(5) model scenarios



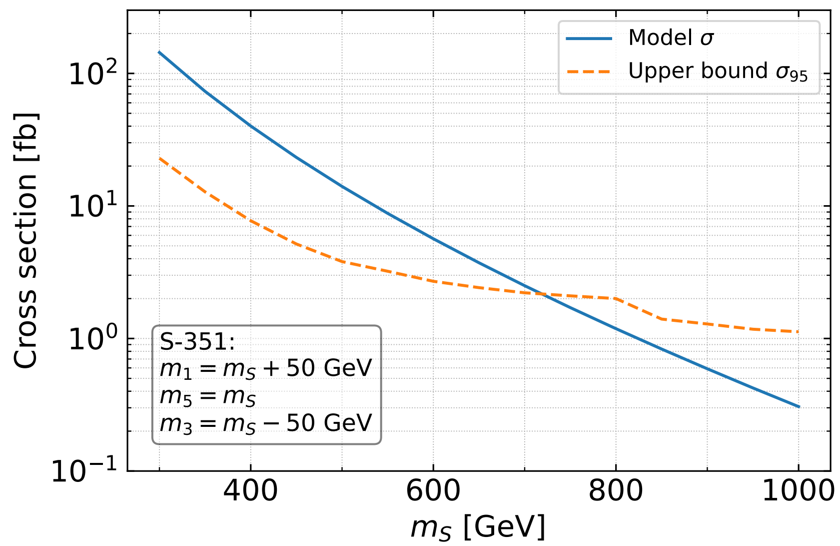
(a) Scenario S-eq



(b) Scenario S-135



(c) Scenario S-531



(d) Scenario S-351

Figure 8: Bounds on the pNGB masses for the Drell-Yan production of the full bi-triplet for multiple benchmark mass spectra defined in Eq. (3.12). In (a), all masses are approximately equal. In the remaining panels, there is a 50 GeV mass split between the multiplets.

CH: EW pNGBs - bounds from the LHC

Resulting bounds in full SU(5)→SO(5) model scenarios

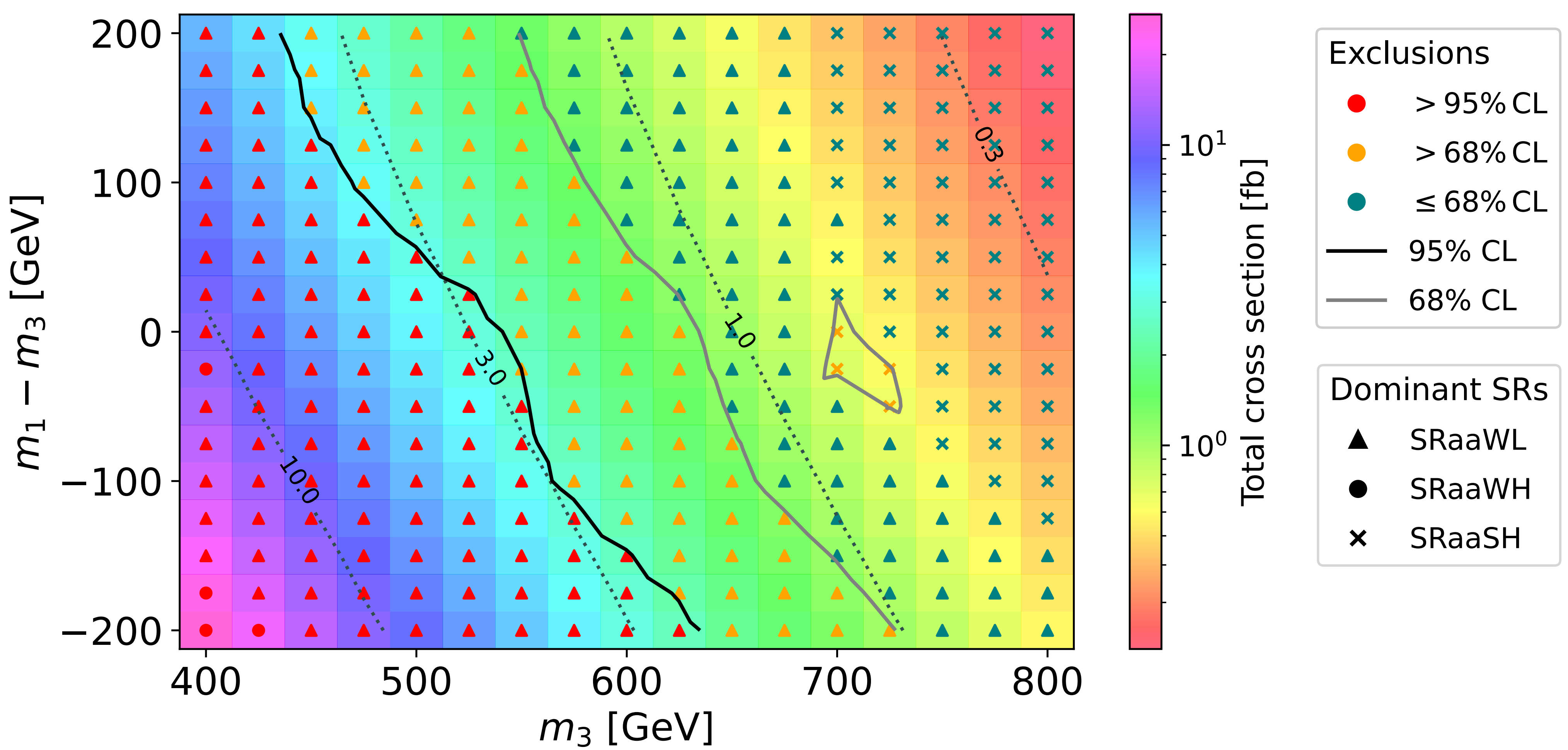


Figure 9: Bounds on the pNGB masses for the Drell-Yan production of the custodial triplet η_3 and singlet η_1 with the quintuplet η_5 decoupled (scenario S-31). Depending

CH: EW pNGBs - bounds from the LHC

Resulting bounds in full SU(5)→SO(5) model scenarios (fermio-philic scenario)

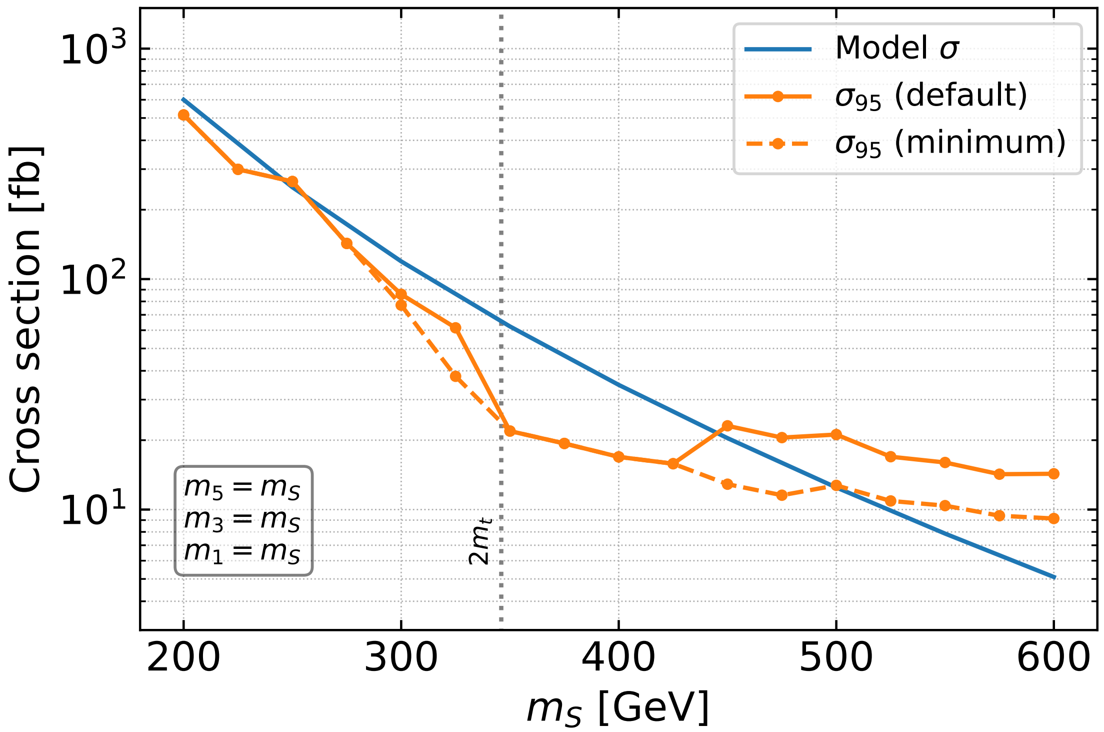
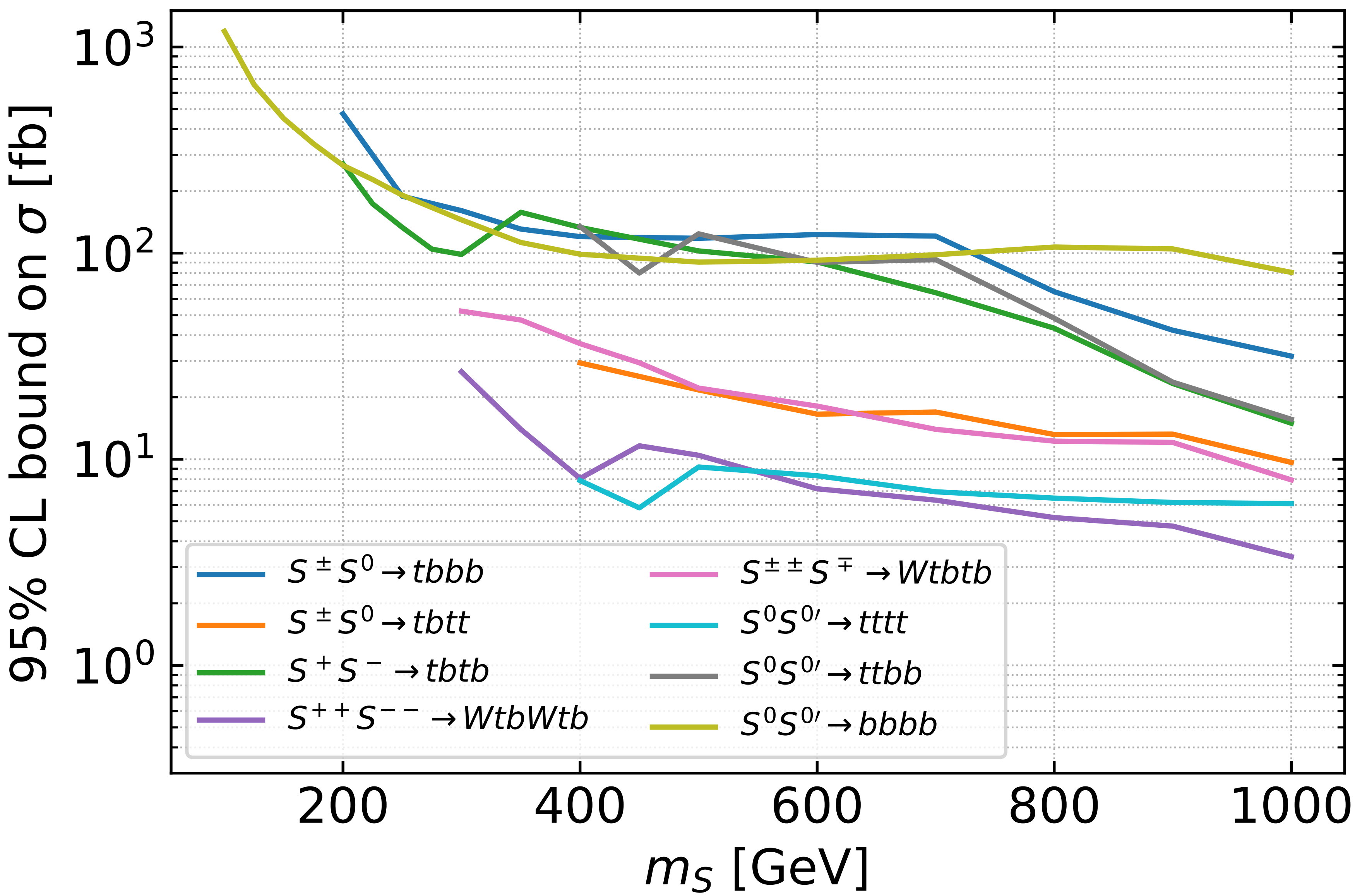


Figure 12: Bounds on the pNGB masses for the Drell-Yan production of the full bitriplet with decays to third-generation quarks.

Outlook:
There is a lot of room for improvement in many diboson channels



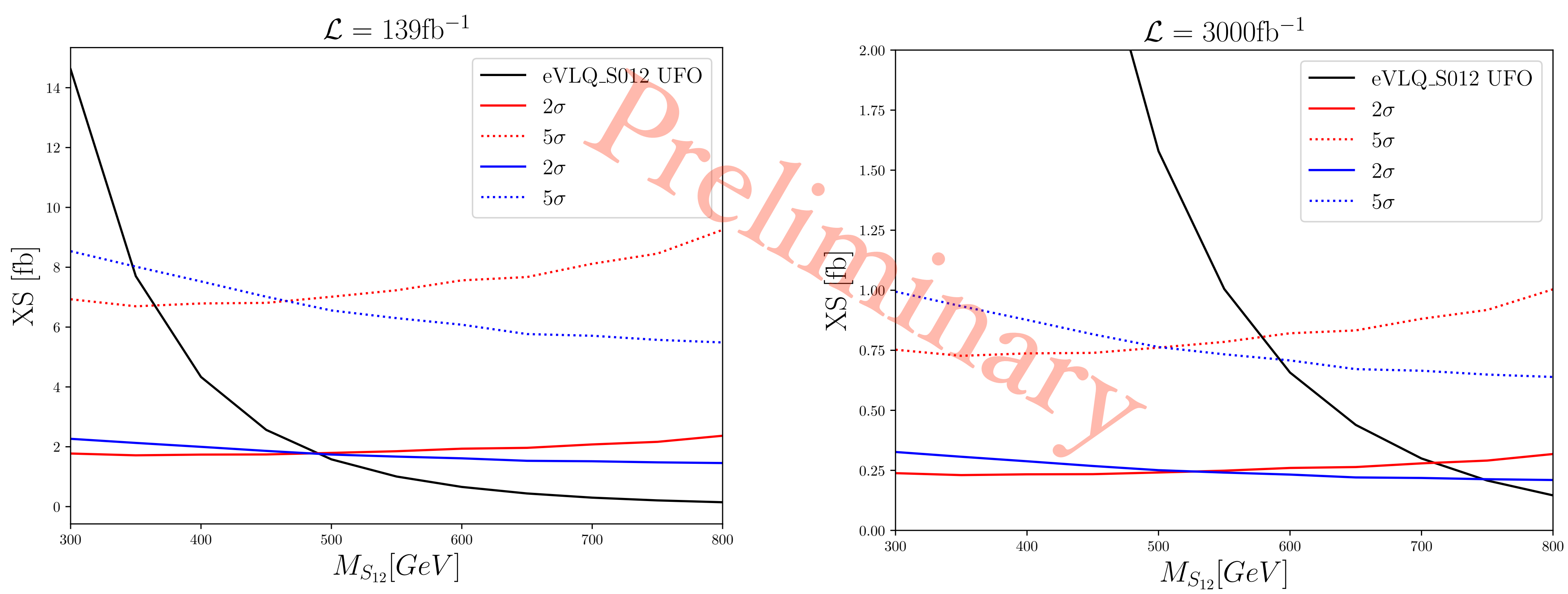
(a) Scalar pair with decays to quarks

Outlook:

Channel: $S^{++}S^{--} \to W^+ t\bar{b} W^- \bar{t} b$ in SSL + jets

[with Jeong Han Kim, Pyungwon Ko, Werner Porod, et al.]

Using CNN and jet images, sensitivity to doubly charged scalar production with fermio-philic decays can be substantially improved.



Summary & Outlook

- We presented a survey of current constraints on BSM di-scalar pair production through the Drell-Yan process in manifold decay channels.
- Very few of these di-boson channels are directly targeted by experimental searches.
- Constraints were obtained by using all recast LHC searches and measurements available in MadAnalysis5, CheckMATE and Contur.
- We applied constraints to a composite Higgs model with underlying fermionic field content, but results are presented "as model-independent as possible".
- While existing searches set some bounds to di-scalar pair production, dedicated searches can promise discovery potential in several di-boson decay channels, which deserve further investigation.

Backup

EW pNGBs (Snowmass)

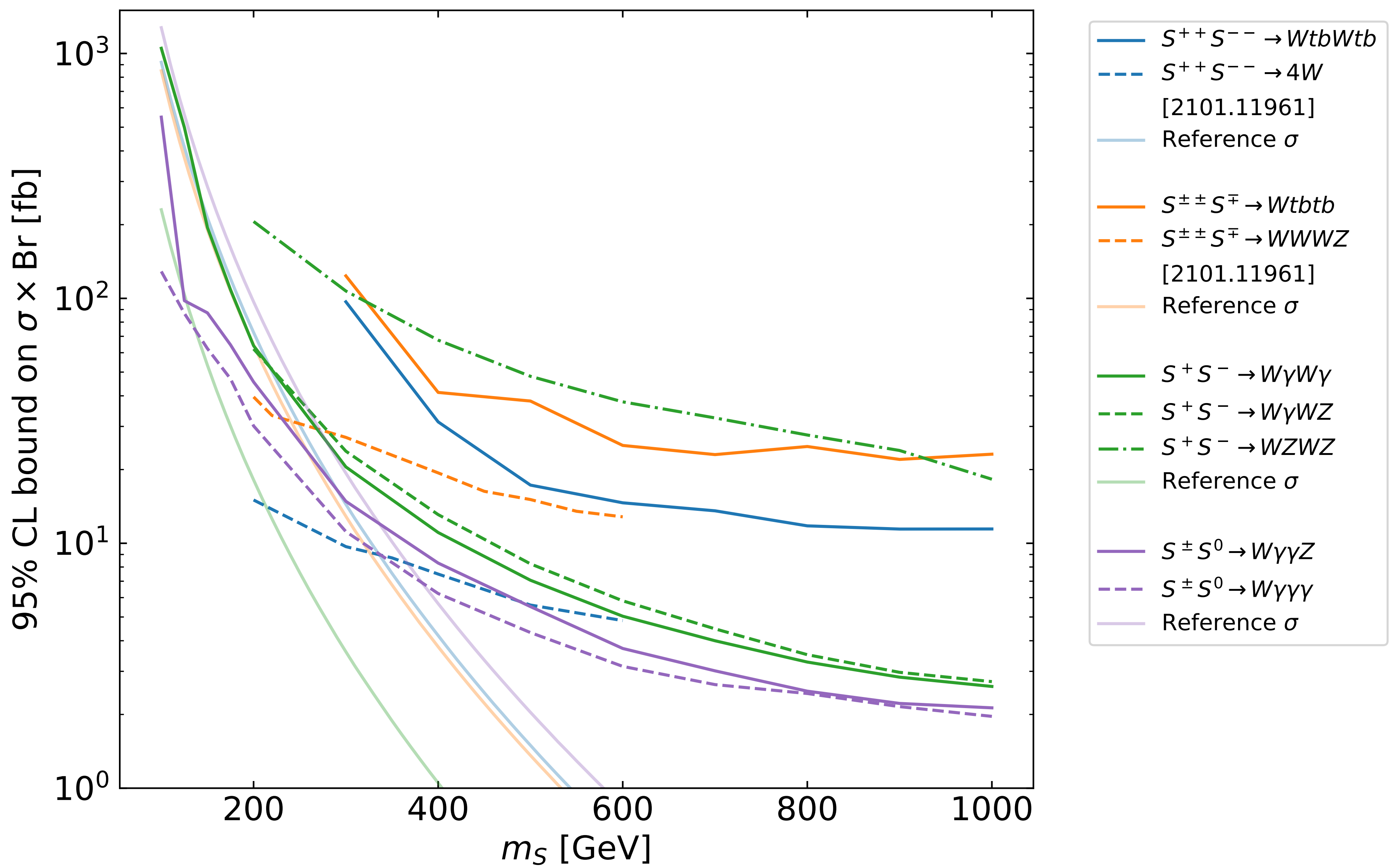
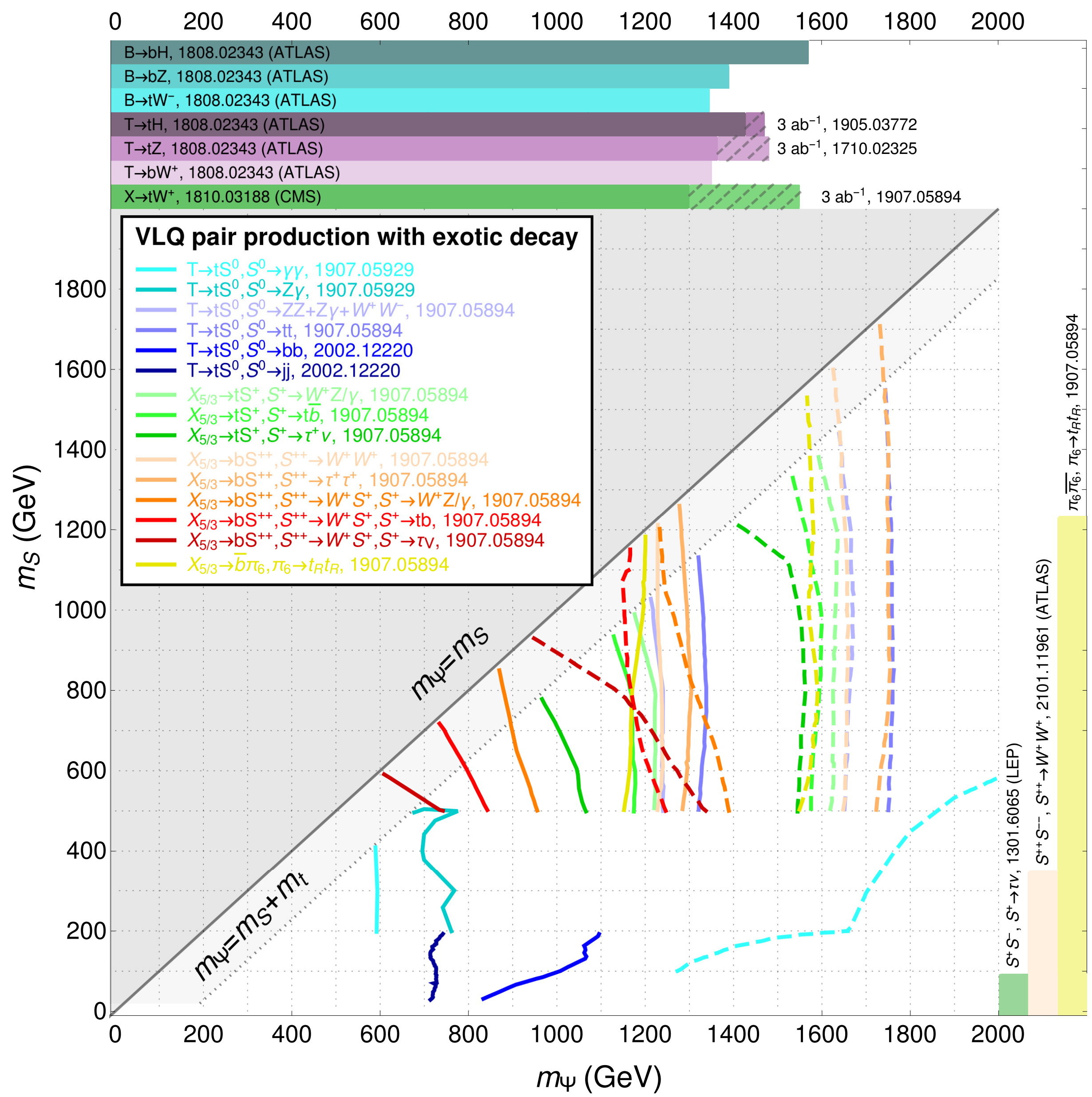


Figure 2: Upper limits on the cross section times branching ratio of the Drell-Yan production of electroweak pNGBs. The bounds are obtained from recasts implemented in `Contur` and `MadAnalysis5` except for the ones presented in [63]. The reference cross sections σ for pair production are calculated for a custodial quintuplet from a benchmark model that is discussed in detail in Sec. 4.

[2203.07270]

color triplet VLQs (Snowmass)



[2203.07270]

Figure 4: 95% CL limits in the $\{m_\Psi, m_S\}$ plane for VLQs decaying to new pNGBs. Current bounds (13 TeV, 36 fb^{-1}) are shown by the solid lines while the projections for the high luminosity LHC (3 ab^{-1}) are shown in dashed lines (for details, see corresponding references). Current experimental bounds on the masses of VLQs decaying to SM particles only and the masses of spin-0 states produced in pairs are provided as horizontal and vertical bars respectively. The hatched regions in the bars denote projections for 3 ab^{-1} luminosity.

Resulting bounds in full SU(5)→SO(5) model scenarios (fermio-philic scenario)

(Detailed view)

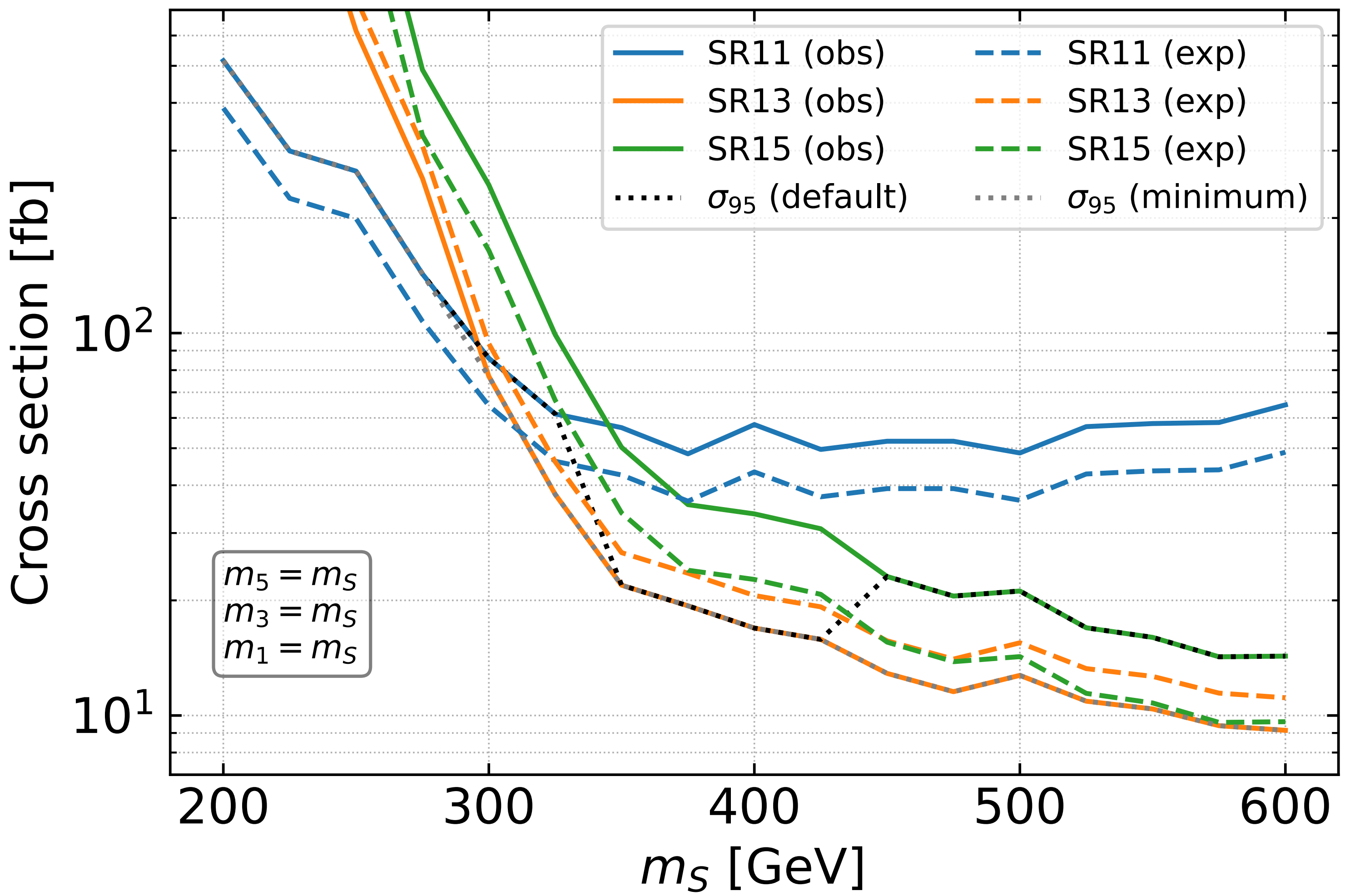


Figure 14: Bounds on the pNGB masses for the Drell-Yan production of the full bitriplet with decays to third-generation quarks.

Analysis	Description	Recast	
ATLAS JHEP [68] 139 fb^{-1}	$S^{++}S^{--} \to 4W$, $S^{++}S^{-} \to WWWZ$; 2, 3 or 4 leptons, MET and jets	–	
CMS PAS EXO-19-002 [69] 137 fb^{-1}	Type-III seesaw and light scalars; at least 3 charged leptons	`MadAnalysis5` `cms_exo_19_002`	
ATLAS PRD 97 [70] 36.1 fb^{-1}	Gauge mediated SUSY breaking; (multi)photon and jets	`CheckMATE` `atlas_1802_03158`	"many photons"
ATLAS JHEP [71] 139 fb^{-1}	Measurement of prompt photon-pair production	`Rivet/Contur` `ATLAS_2021_I1887997`	
ATLAS EPJ C 81 [72] 139 fb^{-1}	RPV SUSY; many jets, ≥ 1 leptons and 0 or ≥ 3 b-jets	`CheckMATE` `atlas_2106_09609`	"many tops"
ATLAS EPJ C 81 [73] 139 fb^{-1}	Squarks and gluinos; 1 lepton, jets and MET	`CheckMATE` `atlas_2101_01629`	
ATLAS EPJ C 79 [74] 3.2 fb^{-1}	General search for new phenomena	`CheckMATE` `atlas_1807_07447`	
ATLAS JHEP [75] 139 fb^{-1}	Bottom-squark pair production; no leptons, ≥ 3 b-jets and MET	`CheckMATE` `atlas_1908_03122`	"many bottoms"
CMS PAS SUS-19-006 [76] 137 fb^{-1}	Gluinos and squarks; no leptons, multiple jets and MET	`MadAnalysis5` `cms_sus_19_006`	
CMS-SUS-16-033 [77] 35.9 fb^{-1}	Gluinos and stops; no leptons, multiple jets and MET	`MadAnalysis5` `cms_sus_16_033`	
ATLAS JHEP [78] 139 fb^{-1}	Chargino-neutralino production; MET and $h \to \gamma\gamma$	`CheckMATE` `atlas_2004_10894`	
ATLAS JHEP [79] 139 fb^{-1}	Measurements of four-lepton differential cross sections	`Rivet/Contur` `ATLAS_2021_I1849535`	
ATLAS JHEP [80] 139 fb^{-1}	Measurement of the $Z(\to \ell^+\ell^-)\gamma$ production cross section	`Rivet/Contur` `ATLAS_2019_I1764342`	"$Z\gamma$"
ATLAS JHEP [81] 36.1 fb^{-1}	Measurement of the $Z(\to \nu\bar{\nu})\gamma$ production cross section	`Rivet/Contur` `ATLAS_2018_I1698006`	
ATLAS-CONF-2016-096 [82] 13.3 fb^{-1}	Electroweakino production; 2 to 3 leptons, MET and no jets	`CheckMATE` `atlas_conf_2016_096`	
CMS PAS SUS-16-039 [83] 35.9 fb^{-1}	Electroweakino production; ≥ 2 leptons and MET	`CheckMATE` `cms_sus_16_039`	

Table 3: Summary of the analyses that contribute to the simplified model bounds in Fig. 2.