Light composite scalars at FCC-ee and FCC-hh

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Based on 2210.01826 in collaboration with Giacomo Cacciapaglia, Thomas Flacke, Manuel Kunkel and Werner Porod

Contents

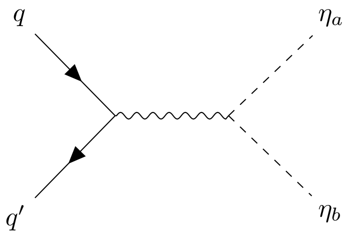
- Composite Higgs
- Production of composite scalars
- Analysis of the model M5
- Generic feature: Broken U(1)

Composite Higgs - Basics

- UV theory of hyperquarks, for example ψ, χ
- Breaking of global symmetry: $\mathcal{G} \to \mathcal{H} \supset G_{\text{SM}}$
- Induced by bilinear condensates $\langle \psi\psi \rangle \sim f_\psi^3 \Sigma_{0,\psi}$
- 3-hyperquark bound states with top-quark quantum numbers
- $\Rightarrow$ Top partners
- Linear mixing with the top: Explain large Yukawa coupling
- $\Rightarrow$ Partial Compositness

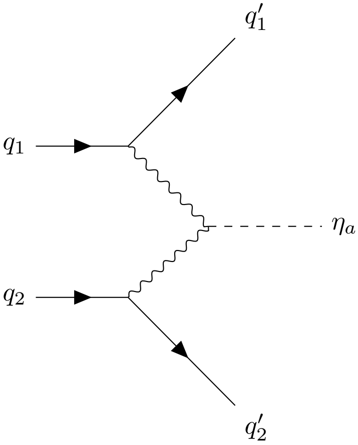
Composite Higgs - Composite Scalars

- A rich scalar sector emerges from the symmetry breaking
- Embed SM gauge groups into the broken group $\mathcal{H}$
- $\Rightarrow$ yields gauge couplings of the form $\mathcal{L}_{kin} \supset \kappa_{ij}^{B_k}(\eta_i \partial_\mu \eta_j - \partial_\mu \eta_i \eta_j) B_k^\mu$
- Gauging parts of $\mathcal{H} \subset \mathcal{G}$ explicitly breaks the global symmetry $\Rightarrow$ Mass contribution
- Couplings give rise to production channels of the pNGBs (Drell-Yan)



Composite Higgs - Anomaly

- Each hyperquark multiplet contributes a U(1) to the global symmetry
- $\Rightarrow$ broken, anomaly-free U(1) + anomalous U(1) generating an ABJ anomaly
- $\Rightarrow$ induces couplings $\mathcal{L}_{\text{anom.}} = \kappa_{\eta_i}^{A_j, A_k} \eta_i A_{j,\mu\nu} \tilde{A}_k^{\mu\nu}$

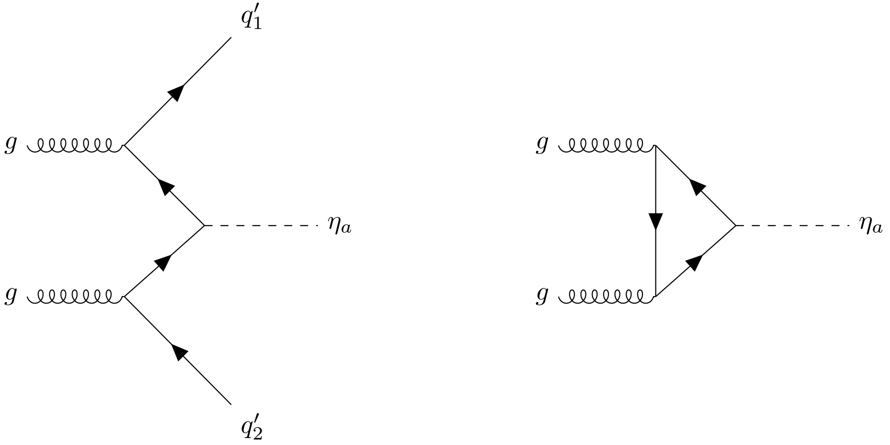


Composite Higgs - Fermions

- Partial compositness $\rightarrow$ couplings to top partners induce couplings to (3rd generation) SM quarks
- Need to embed SM quarks into global group
- Embeddings form an incomplete representation of global group
- $\Rightarrow$ Explicit breaking of global symmetry
- Couplings of the order $\kappa_t^\eta \sim m_t$, $\kappa_{tb}^\eta \sim m_t$, $\kappa_b^\eta \sim m_b$

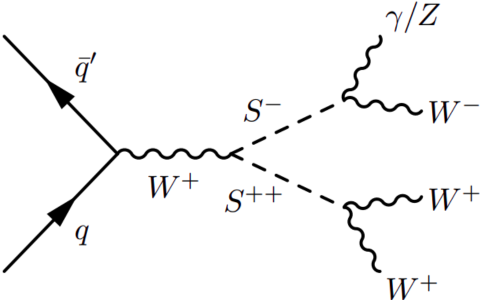
Composite Higgs - Fermions

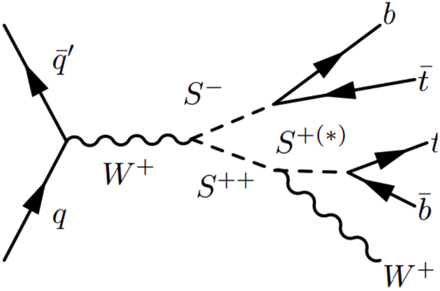
Couplings to fermions give rise to new production and decay channels



Bounds on various channels

Consider purely EW scalars up to charge 2





(2210.01826)

Bounds on various channels

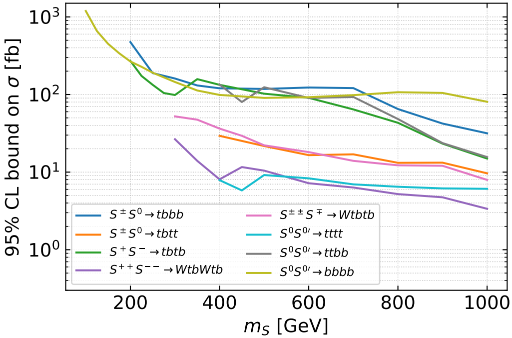
fermiophobic	$S^{++}S^{--}$	$S^{\pm\pm}S^{\mp}$	$S^{+}S^{-}$	$S^{\pm}S^{0(\prime)}$	$S^{0}S^{0\prime}/S^{0\prime}S^{0}$
$WWWW$	$W^{+}W^{+}W^{-}W^{-}$	-	-	-	$W^{+}W^{-}W^{+}W^{-}$
$WWW\gamma$	-	$W^{\pm}W^{\pm}W^{\mp}\gamma$	-	$W^{\pm}\gamma W^{+}W^{-}$	-
$WWWZ$	-	$W^{\pm}W^{\pm}W^{\mp}Z$	-	$W^{\pm}ZW^{+}W^{-}$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

Bounds on various channels

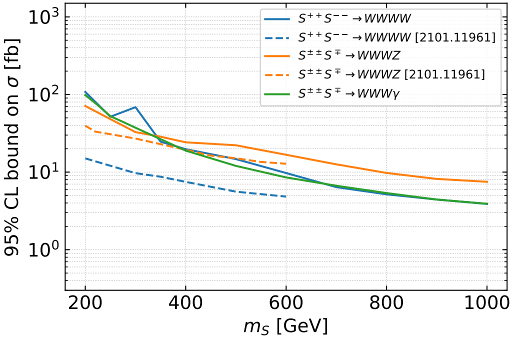
fermiophilic	$S^{++}S^{--}$	$S^{++}S^{-}$	$S^{+}S^{-}$	$S^{+}S^{0(\prime)}$	$S^{0}S^{0\prime}/S^{0\prime}S^{0}$
$tttt$	-	-	-	-	$t\bar{t}t\bar{t}$
$tttb$	-	-	-	$t\bar{b}t\bar{t}$	-
$ttbb$	-	-	$t\bar{b}b\bar{t}$	-	$t\bar{t}b\bar{b}$
$tbbb$	-	-	-	$t\bar{b}b\bar{b}$	-
$bbbb$	-	-	-	-	$b\bar{b}b\bar{b}$
$Wttbb$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

Bounds on various channels

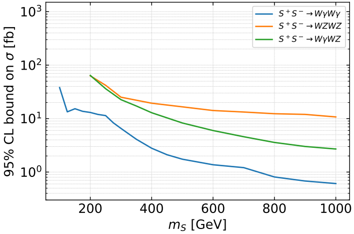
We simulated channels using MadGraph5_aMC@NLO and determined bounds from analyses available in rivet/contur, MadAnalysis and CheckMATE.



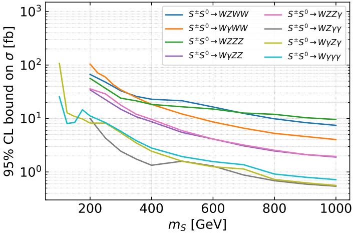
(a) Scalar pair with decays to quarks



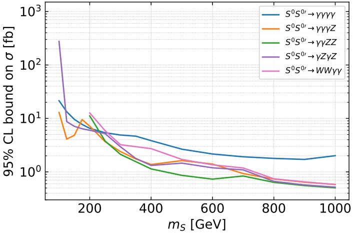
(b) $S^{++}S^{--}$ and $S^{\pm\pm}S^{\mp}$ with di-boson decays



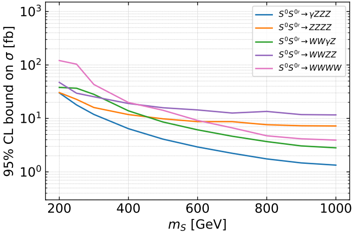
(a) S^+S^- with di-boson decays



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



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



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

Contributing Analyses

- 2101.11961: S^{++}/S^{--}, S^{++}/S^{-} direct search
- 1811.11028/2203.00480: $S^0/S^{0\prime}$, different kinematics
- di-Higgs production analyses mostly focus on masses of 125 GeV

Contributing Analyses

Fermiophilic scenario

- 2106.09609: Search for R-Parity violating SUSY, Most dominant for multi-top final states
- 2101.01629, 1807.07447, 1908.03122, MS PAS SUS-19-006, 1704.07781: Various SUSY searches, Most dominant for multi-bottom final states

Contributing Analyses

Fermiophobic scenario

- $WWW\gamma$: $Z\gamma$ production cross section measurement
- $WWWW/WWWZ$: Multi-lepton final states
- $W\gamma W\gamma$: Strongest bounds, search for gauge-mediated supersymmetry in final states containing photons and jets
- ...
- Full list in 2210.01826
- Numerical values of the limits are available at `https://github.com/manuelkunkel/scalarbounds`

Full model

Including full multiplets yields stronger bounds

- Example: Model M5 (1312.5330, 1610.06591)
- Gauge group: Sp(4)
- $5 \times \psi \in \mathbf{A_2}$
- $6 \times \chi \in \mathbf{F}$
- $\Rightarrow$ Coset is $\frac{SU(6)\times SU(5)\times U(1)}{Sp(6)\times SO(5)}$
- $Sp(6) \supset SU(3)_C \times U(1)_X$
- $SO(5) \supset SU(2)_L \times SU(2)_R \supset SU(2)_L \times U(1)_Y$
- In addition, there is a U(1) giving rise to an ABJ anomaly

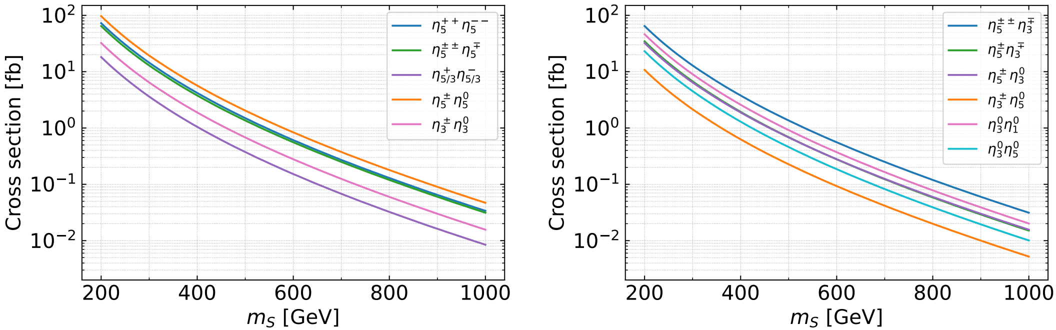
Full Model - Particle Content

pNGBs of M5, additional to the Higgs

Coset	Custodial Group	SM Gauge Group	Particle Content
U(1)	-	-	a
SU(5)/SO(5)	$\mathrm{SU}(2)_L \times \mathrm{SU}(2)_R$	$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$	$\eta + \eta_1 + \eta_3 + \eta_5$
	$(\mathbf{1},\mathbf{1}) + (\mathbf{3},\mathbf{3})$	$\mathbf{1}' + \mathbf{1} + \mathbf{3} + \mathbf{5}$	
SU(6)/Sp(6)	$\mathrm{SU}(3)_c \times \mathrm{U}(1)_X$	$\mathrm{SU}(3)_c$	$\Pi_{\mathbf{3}} + \Pi_{\bar{\mathbf{3}}} + \Pi_{\mathbf{8}}$
	$\mathbf{3}_{-2x} + \bar{\mathbf{3}}_{2x} + \mathbf{8}_0$		

Full Model - Particle Content

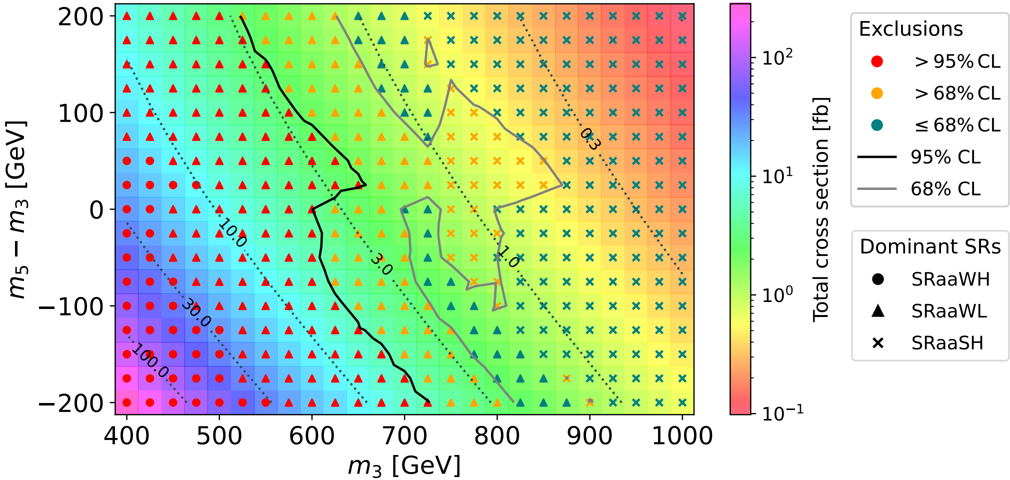
DY production cross section assuming equal masses at the LHC



Full Model - Simplified Scenarios

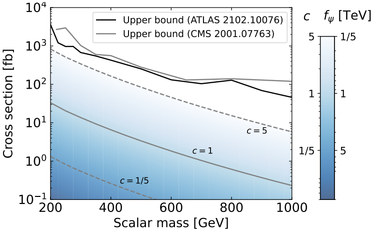
- Investigate fermiophobic and fermiophilic scenarios since the exact branching ratios are not known
- The NGB potential contains enough freedom for all possible hierarchies between the multiplet masses
- In the following, we treat states within the same multiplet as mass-degenerate
- Mass parameters: m_1, m_3, m_5
- For simplicity, consider scenarios where only two multiplets are present (the third one may be considered as heavy)

Full model results - fermiophobic example

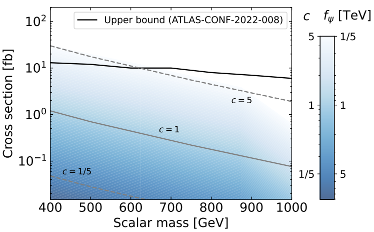


1802.03158 [Search for photonic signatures of gauge-mediated supersymmetry in 13 TeV pp collisions with the ATLAS detector]

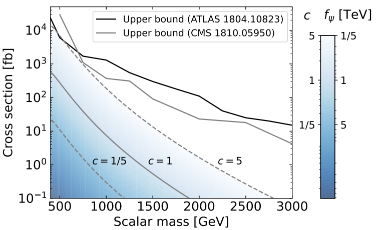
Full model results - fermiophilic examples



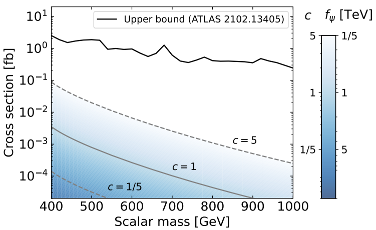
(a) $S^+tb \to tbtb$



(b) $S^0tt \to tttt$



(c) $S^0 \to tt$

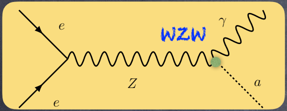


(d) $S^0 \to \gamma\gamma$

The broken U(1)

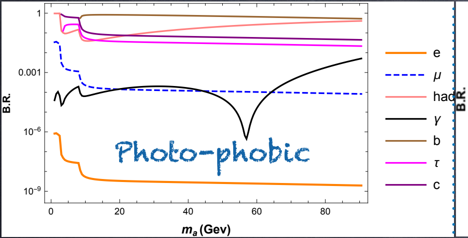
- Common for all CHMs: broken U(1) giving rise to pNGB a
- a is gauge singlet but has anomalous couplings
- In particular, $aZ\gamma$ vertex may exist
- a is expected to be light
- $\Rightarrow$ Light composite scalar, can be produced in FCC-ee and can probe the composite sector of Composite Higgs models

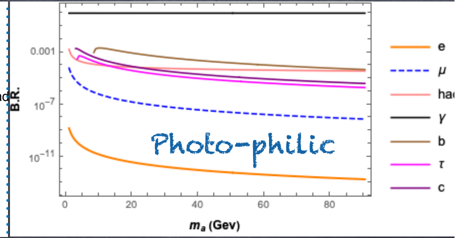
Tera-Z portal to compositeness (via ALPs)



G.Cacciapaglia et al. 2104.11064

This process is always associated with a monochromatic photon.





No leading order coupling to Photons (WZW interaction is Zero!!)

eg. SU(4)/SP(4), SU(4)xSU(4)/SU(4)

WZW interaction to photons (like the pion)

eg. SU(5)/SO(5), SU(6)/SO(6)

Phenomenology-Prompt Decays

Photo-philic

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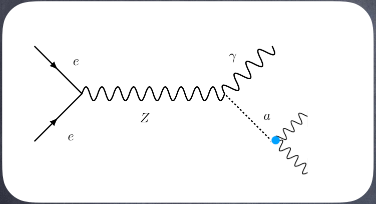
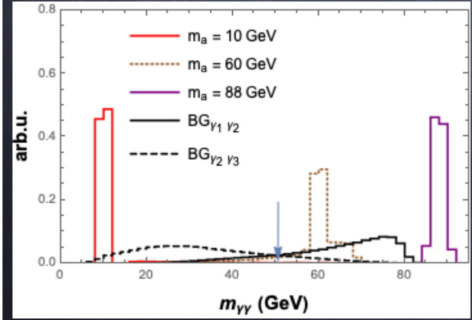
2104.11064



- Three isolated photons

$BR(Z \to 3\gamma)_{\text{LEP}} < 2.2 \cdot 10^{-6}$



Discriminating variable:
invariant mass

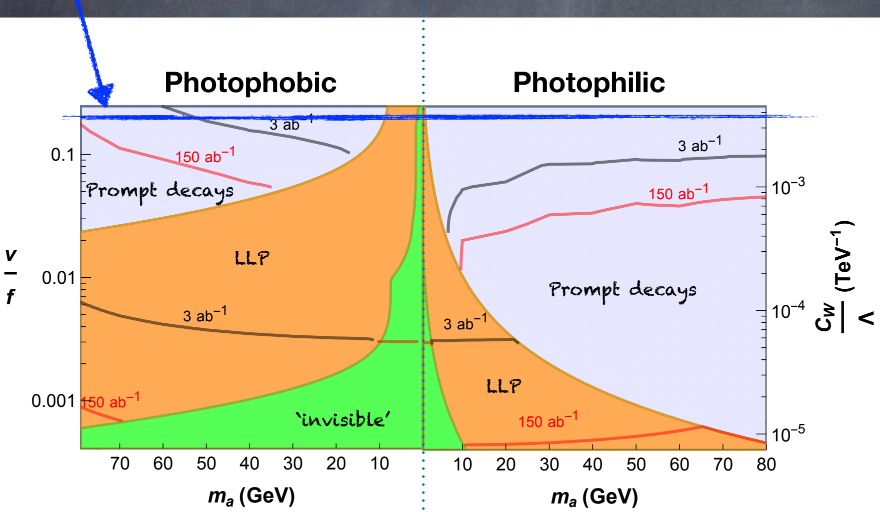
Photon ordering changes
at inv. mass 50 GeV

Bins above 80 GeV
populated by fakes:
hard to estimate!

Money plot

Typical EWPT bound

G.Cacciapaglia et al.
2104.11064



Conclusion

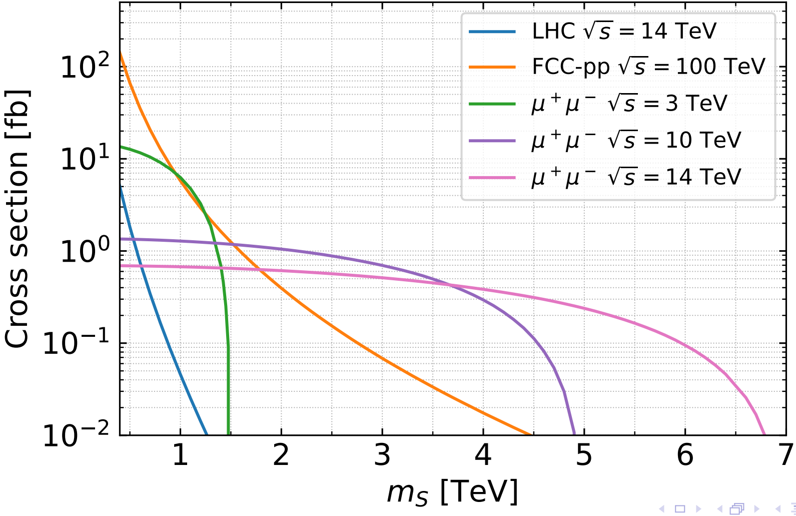
- Composite Higgs models come with composite scalar particles
- Electroweak pNGBs can have masses of a couple 100 GeV
- ALP a can be used to probe the composite sector
- FCC-ee may be used to probe neutral channels and FCC-hh for charged ones

Backup

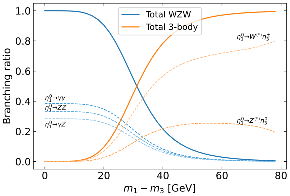
	G_{HC}	SM gauge group			global group		
	Sp(4)	$\mathrm{SU}(3)_C$	$\times\ \mathrm{SU}(2)_L$	$\times\ \mathrm{U}(1)_Y$	SU(5)	$\times$ SU(6)	$\times$ U(1)
$\psi_{1,2}$	$\mathbf{A_2}$	$\mathbf{1}$	$\mathbf{2}$	1/2			
$\psi_{3,4}$	$\mathbf{A_2}$	$\mathbf{1}$	$\mathbf{2}$	-1/2	$\mathbf{5}$	$\mathbf{1}$	$-\frac{3q_\chi}{5}$
ψ_5	$\mathbf{A_2}$	$\mathbf{1}$	$\mathbf{1}$	0			
$\chi_{1,2,3}$	$\mathbf{F}$	$\mathbf{3}$	$\mathbf{1}$	x	$\mathbf{1}$	$\mathbf{6}$	q_χ
$\chi_{4,5,6}$	$\mathbf{F}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-x$			

Backup

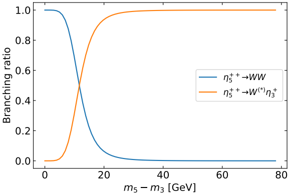
Cross sections of the doubly charged pair production at the HL-LHC and some proposed future colliders



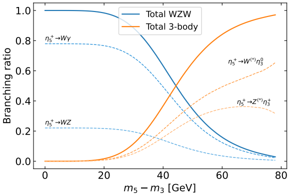
Backup



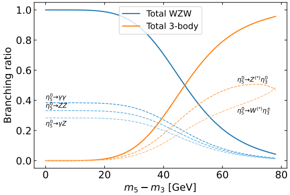
(a) Decays of η_1^0 for $m_1 = 600$ GeV $> m_3$



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

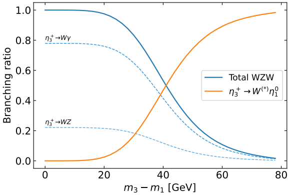


(c) Decays of η_5^+ for $m_5 = 600$ GeV $> m_3$

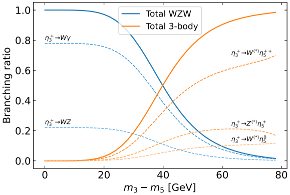


(d) Decays of η_5^0 for $m_5 = 600$ GeV $> m_3$

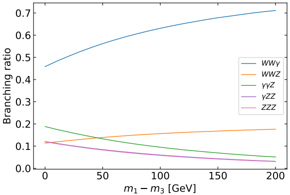
Backup



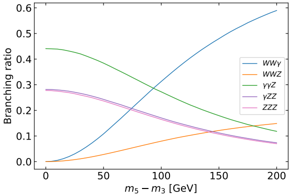
(a) Decays of η_3^+ for $m_5 \gg m_3 = 600$ GeV $> m_1$



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

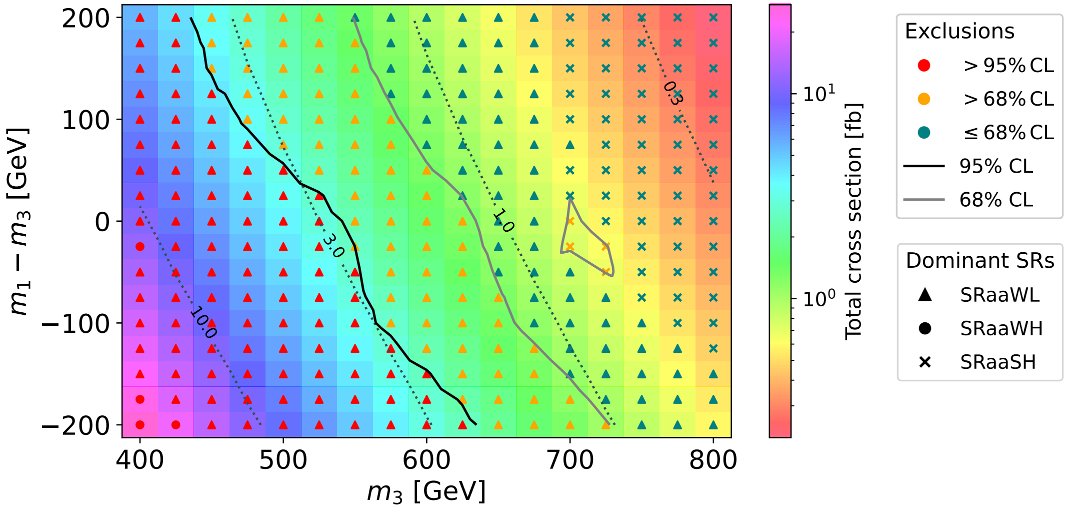


(c) Decays of η_3^0 for $m_5 \gg m_1 > m_3 = 600$ GeV



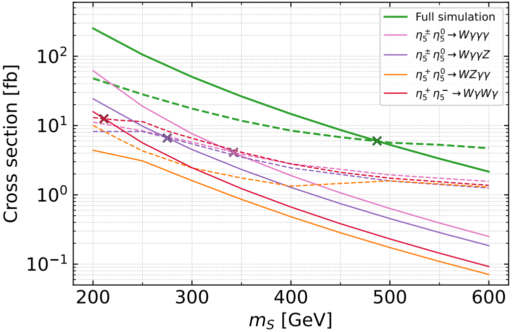
(d) Decays of η_3^0 for $m_1 \gg m_5 > m_3 = 600$ GeV

Backup

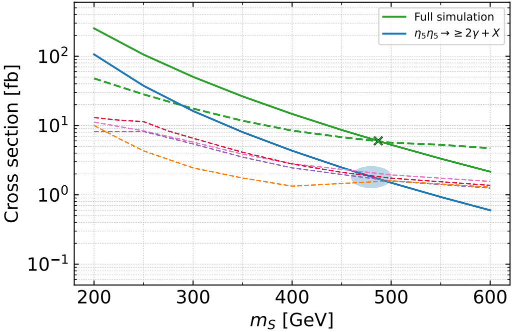


200
100
0
−100
−200
$m_1 - m_3$ [GeV]
400
500
600
700
800
m_3 [GeV]
10.0
3.0
1.0
0.3
10^1
10^0
Total cross section [fb]
Exclusions
> 95% CL
> 68% CL
≤ 68% CL
95% CL
68% CL
Dominant SRs
SRaaWL
SRaaWH
SRaaSH

Backup



(a) Bounds from individual channels



(b) Bounds from sum of multiphoton channels