The Search for Physics Beyond the Standard Model A Theorist Perspective





- Gustavo Burdman
- University of São Paulo, Brazil
 - TeVPA 2023, Napoli



- •The standard model of particle physics: the good
- The SM of particle physics: the bad and the ugly
- •What do BSM searches imply ?
- BSM without New Particles: the transition from energy to precision
- Testing the Higgs sector at the LHC and beyond
- Making connections: the Higgs, Dark Matter and beyond
- Conclusions and Outlook

Outline

 g_3

Strong

<u>The SM is a gauge theory</u>

with O(1) dimensionless couplings

- Built with the input from experimental observations
- Some fermions feel the strong interactions (quarks). I.e. they transform under SU(3)
- All SM fermions transform under the electroweak gauge group $SU(2)_L \times U(1)_Y$
- It describes all the (gauge) interactions of all elementary particles Gauge interactions tested with great precision at LEP, Tevatron, LHC, ...







The Higgs Sector of the Standard Model

- •Gauge invariance in the \mathscr{L}_{SM} forbids mass terms ! \Rightarrow Massless gauge bosons and fermions!
- Masses in \mathscr{L}_{SM} break gauge invariance explicitly
- Introduce a scalar sector to spontaneously break the electroweak symmetry

 $SU(2)_L \times U(1)_Y \longrightarrow U(1)_{\rm EM} \qquad M_{W^{\pm}}, M_{Z^0} \neq 0 \quad M_{\gamma} = 0$ Experimentally $m_h \simeq 125 \text{ GeV}, v \simeq 246 \text{ GeV}$

 $\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \text{ scalar } SU(2)_L \text{ doublet with } Y_\Phi = \frac{1}{2} \text{ Higgs doublet}$ Non-trivial minimum of $V(\Phi^{\dagger}\Phi) = -m^2 (\Phi^{\dagger}\Phi) + \lambda (\Phi^{\dagger}\Phi)^2 \implies m_h = \sqrt{2}m = \sqrt{2\lambda} v$

 $\Rightarrow \begin{array}{l} m\simeq 89 \,\, {\rm GeV} & {\rm is the one and only energy scale in all of } \mathscr{L}_{\rm SM} \, ! \\ \\ \mbox{(Only scale in fundamental physics together with } M_{\rm P} \, {\rm and } \, \Lambda_{\rm CC}) \end{array}$

Higgs Couplings

To fermions

 $\lambda_f \bar{\psi}_L \psi_R + \text{h.c.}$

with $\lambda_f = \frac{\sqrt{2} m_f}{m_f}$

• λ_t enters in production through ggF loop



- λ_b ggF+VH+ $t\bar{t}h$
- λ_{τ} VH+VBF+ggF
- λ_{μ} ggF+VBF

To gauge bosons



- Triple coupling tested in Higgs decays to both $\gamma\gamma$ and VV^* at the LHC
- *9hhVV* accessible in double Higgs production



Testing the Higgs Couplings in the SM









Testing the Higgs Couplings in the SM

ATLAS Preliminary		Total Stat. Syst. SM
	1 02	Total Stat. Syst
	0.95	$\begin{array}{cccc} -0.11 & (-0.08, -0.07) \\ +0.11 & (+0.10, +0.04) \end{array}$
	1 13	-0.11 (-0.10 , $-0.03+0.13 (+0.06 +0.12$
	0.87	-0.12 (-0.06 , $-0.10+0.28 (+0.15 +0.23$
aaF+ttH uu	0.52	-0.25 (-0.15 , $-0.20+0.91 (+0.77 +0.49$
VBF γγ	1.47	-0.88 (-0.79 , $-0.38+0.27 (+0.21 +0.17$
VBF ZZ	1.31	+0.51 ($+0.50$ $+0.11$
VBFWW	1.09	+0.19 ($+0.15$ $+0.110.17 (-0.14 , -0.10$
VBF ττ	0.99	+0.20 $(+0.14 + 0.15)$ -0.14 $(-0.14 + 0.15)$ -0.12
VBF+ggF bb	0.98	+0.38 $(+0.31$ $+0.21-0.36$ $(-0.33$ $,-0.15$
VBF+VH μμ	2.33	+1.34 ($+1.32$ + 0.20 -1.26 (-1.24 , -0.23
VH γγ 🔁	1.33	$\begin{array}{c} +0.33 \\ -0.31 \end{array} \left(\begin{array}{c} +0.32 \\ -0.30 \end{array} \right) + 0.10 \\ -0.08 \end{array} \right)$
VH ZZ	1.51	$^{+1.17}_{-0.94}$ ($^{+1.14}_{-0.93}$, $^{+0.24}_{-0.16}$
VΗ ττ μαρι	0.98	$^{+0.59}_{-0.57}$ ($^{+0.49}_{-0.49}$, $^{+0.33}_{-0.29}$
WH bb	1.04	$^{+0.28}_{-0.26}$ ($^{+0.19}_{-0.19}$, $^{+0.20}_{-0.19}$
ZH bb	1.00	$^{+0.24}_{-0.22}$ ($^{+0.17}_{-0.17}$, $^{+0.17}_{-0.14}$
ttH+tH γγ	0.93	$ \begin{array}{c} +0.27 \\ -0.25 \end{array} \left(\begin{array}{c} +0.26 \\ -0.24 \end{array} \right) , \begin{array}{c} +0.08 \\ -0.06 \end{array} \right) $
ttH+tH WW	1.64	$^{+0.65}_{-0.61}$ ($^{+0.44}_{-0.43}$, $^{+0.48}_{-0.43}$
ttH+tH ZZ	1.69	$ \begin{array}{c} +1.69 \\ -1.10 \end{array} \left(\begin{array}{c} +1.65 \\ -1.09 \end{array} \right. \begin{array}{c} +0.37 \\ -0.16 \end{array} \right) $
ttH+tH ττ μ	1.39	$^{+0.86}_{-0.76}$ ($^{+0.66}_{-0.62}$, $^{+0.54}_{-0.44}$
ttH+tH bb 🖷	0.35	$^{+0.34}_{-0.33}$ ($^{+0.20}_{-0.20}$, $^{+0.28}_{-0.27}$
	<u> </u>	

 $\sigma \times B$ normalised to SM

Parameter	(a) $B_{i.} = B_{u.} = 0$	(b) $B_{i.}$ free, $B_{u.} \ge 0$, $\kappa_{W,Z} \le 1$
κ _Z	0.99 ± 0.06	$0.96 \begin{array}{c} + \ 0.04 \\ - \ 0.05 \end{array}$
κ _W	1.06 ± 0.06	$1.00 \begin{array}{c} + \ 0.00 \\ - \ 0.03 \end{array}$
Кb	0.87 ± 0.11	0.81 ± 0.08
κ _t	0.92 ± 0.10	0.90 ± 0.10
κ_{μ}	$1.07 \ ^{+}_{-} \ ^{0.25}_{0.30}$	$1.03 \begin{array}{c} + \ 0.23 \\ - \ 0.29 \end{array}$
$\kappa_{ au}$	0.92 ± 0.07	0.88 ± 0.06
κ_{γ}	1.04 ± 0.06	1.00 ± 0.05
$\kappa_{Z\gamma}$	$1.37 \ ^{+}_{-} \ ^{0.31}_{0.37}$	$1.33 \begin{array}{c} + 0.29 \\ - 0.35 \end{array}$
Кg	$0.92 \ ^{+ \ 0.07}_{- \ 0.06}$	$0.89 \begin{array}{c} + \ 0.07 \\ - \ 0.06 \end{array}$
$B_{i.}$	-	< 0.09 at 95% CL
B _{u.}	-	< 0.16 at 95% CL

The Trouble(s) with the Standard Model

The SM does not

- Have a candidate for Dark Matter. Is $m_{\rm DM}$ a new fundamental scale ?
- Explain the Baryon Asymmetry of the universe.
- Adequately account for neutrino masses. Mechanisms point to new physics scale.
- Explain the enormous range of Yukawa couplings (Flavor Puzzle). Why is $\lambda_t/\lambda_\mu \simeq 10^5$?
- Have any symmetry preventing CPV in the strong interactions, i.e. explaining $\theta < 10^{-10}$
- Explain the origin of its only energy scale $m \simeq 89$ GeV
- Provide any reason why the Higgs boson mass is so light compared to the SM cutoff

The Trouble(s) with the Standard Model

The SM does not

- TeV scale?

- Explain the Baryon Asymmetry of the universe. Maybe some signals in HDV. Not guaranteed.
- Have a candidate for Dark Matter. Is m_{DM} a new fundamental scale ? Searches for DM particle(s). •Adequately account for neutrino masses. Mechanisms point to new physics scale. ν experiments. • Explain the enormous range of Yukawa couplings (Flavor Puzzle). Why is $\lambda_t / \lambda_u \simeq 10^5$? Flavor physics. • Have any symmetry preventing CPV in the strong interactions, i.e. explaining $\theta < 10^{-10}$ Axions. • Explain the origin of its only energy scale $m \simeq 89$ GeV Provide any reason why the Higgs boson mass is so light compared to the SM cutoff





The (In)Stability of the Electroweak Scale

Quantum corrections to the Higgs mass $\stackrel{h}{----} \longrightarrow \Delta m_h^2 \simeq \frac{c}{16\pi^2} \Lambda^2$

And Λ is a high energy scale, the highest considered in the loops Not a problem in QFT. Yes, the renormalization condition condition is highly tuned $(m_h^2)_{\rm phys.} = \Delta m_h^2 + \delta m_h^2$ But after removing Λ dependence by RC, $m_h^2(\mu)$ runs logarithmically

<u>However</u>, if heavy states of mass M couple to the Higgs with coupling yThey result in large threshold corrections

Motivation to have new physics either at Λ or M scales not too far above the electroweak scale

The energy scale in the potential $V(\Phi^{\dagger}\Phi) = -m^2 (\Phi^{\dagger}\Phi) + \lambda (\Phi^{\dagger}\Phi)^2$ has a large UV sensitivity

 $\Delta m_h^2 \simeq {y^2 \over 16\pi^2} \, M^2$ we recover the hierarchy problem



Searches for Physics Beyond the SM

New Particles enter in the quantum corrections so as to diminish the UV sensitivity of m_h^2

<u>SUSY</u>





SUSY Searches

ATLAS SUSY Searches* - 95% CL Lower Limits August 2023								ATLAS Preliminary $\sqrt{s} = 13$ TeV				
	Model	S	ignature	e ∫.	<i>L dt</i> [fb ⁻	¹] M	ass limit					Reference
S	$\tilde{q}\tilde{q},\tilde{q}{ ightarrow}q\tilde{\chi}_{1}^{0}$	0 <i>e</i> ,μ mono-jet	2-6 jets 1-3 jets	$E_T^{ m miss}$ $E_T^{ m miss}$	140 140	<i>q̃</i> [1×, 8× Degen.] <i>q̃</i> [8× Degen.]		1.0 0.9	1.	.85	$m(\tilde{\chi}_1^0) < 400 \text{ GeV}$ $m(\tilde{a}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$	2010.14293 2102.10874
arche	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q \bar{q} \tilde{\chi}_1^0$	0 <i>e</i> , <i>µ</i>	2-6 jets	E_T^{miss}	140	ğ ĩg		Forbidden	1.15-	2.3	$m(\tilde{\chi}_1^0)=0 \text{ GeV}$ $m(\tilde{\chi}_1^0)=1000 \text{ GeV}$	2010.14293 2010.14293
Se	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}W\tilde{\chi}^0_1$	1 <i>e</i> , <i>µ</i>	2-6 jets		140	ĝ				2.2	$m(\tilde{\chi}_1^0)$ <600 GeV	2101.01629
lusive	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}(\ell\ell)\tilde{\chi}_1^0$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$	ee, μμ 0 e, μ SS e, μ	2 jets 7-11 jets 6 jets	E_T^{miss} E_T^{miss}	140 140 140	το το το το το		1	.15	2.2 1.97	$ \begin{array}{c} m(\tilde{\chi}_{1}^{\circ}) < 700 \text{ GeV} \\ m(\tilde{\chi}_{1}^{0}) < 600 \text{ GeV} \\ m(\tilde{\varrho}) - m(\tilde{\chi}_{1}^{0}) = 200 \text{ GeV} \end{array} $	2204.13072 2008.06032 2307.01094
lnc	$\tilde{g}\tilde{g}, \tilde{g} \rightarrow t t \tilde{\chi}_1^0$	0-1 <i>e</i> , μ SS <i>e</i> ,μ	3 <i>b</i> 6 jets	$E_T^{\rm miss}$	140 140	ĩ trấng trác trác trác trác trác trác trác trác			1.25	2.45	$m(\tilde{\chi}_{1}^{0}) < 500 \text{ GeV}$ $m(\tilde{g}) - m(\tilde{\chi}_{1}^{0}) = 300 \text{ GeV}$	2211.08028 1909.08457
	$ ilde{b}_1 ilde{b}_1$	0 <i>e</i> , <i>µ</i>	2 b	$E_T^{\rm miss}$	140	$egin{array}{c} ilde{b}_1 \ ilde{b}_1 \end{array}$		0.68	1.255		$m(ilde{\mathcal{X}}_1^0){<}400GeV$ 10 GeV ${<}\Deltam(ilde{b}_1, ilde{\mathcal{X}}_1^0){<}20GeV$	2101.12527 2101.12527
arks stion	$\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 {\rightarrow} b \tilde{\chi}_2^0 {\rightarrow} b h \tilde{\chi}_1^0$	0 <i>e</i> ,μ 2 τ	6 <i>b</i> 2 <i>b</i>	$E_T^{ m miss}$ $E_T^{ m miss}$	140 140	$ ilde{b}_1$ Forbidden $ ilde{b}_1$		0 0.13-0.85	.23-1.35	$\Delta m(ilde{\chi}_{2}^{2})$	$(\tilde{\chi}_1^0)$ =130 GeV, m $(\tilde{\chi}_1^0)$ =100 GeV $(\tilde{\chi}_2^0, \tilde{\chi}_1^0)$ =130 GeV, m $(\tilde{\chi}_1^0)$ =0 GeV	1908.03122 2103.08189
oduc squi	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0$	0-1 e,μ	≥ 1 jet 3 jets/1 <i>h</i>	E_T^{miss} E^{miss}	140 140	\tilde{t}_1	Forbiddon	1.05	1.25		$m(\tilde{\chi}_1^0)=1 \text{ GeV}$	2004.14060, 2012.03799 2012.03799 ATLAS-CONE-2023-043
gen. ct pr	$t_1 t_1, t_1 \rightarrow w b x_1$ $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 b \nu, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$	1-2 τ	2 jets/1 <i>b</i>	E_T^{miss}	140	\tilde{t}_1 \tilde{t}_1	1 Urbidden	Forbidden	1.4		$m(\tilde{\tau}_1)=800 \text{ GeV}$ $m(\tilde{\tau}_1)=800 \text{ GeV}$	2108.07665
3 rd (dire	$\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$	0 e,μ 0 e,μ	2 c mono-jet	$E_T^{ m miss}$ $E_T^{ m miss}$	36.1 140	\tilde{c} \tilde{t}_1	0.55	0.85			$m(\widetilde{\chi}_1^0)$ =0 GeV $m(\widetilde{t}_1,\widetilde{c})$ - $m(\widetilde{\chi}_1^0)$ =5 GeV	1805.01649 2102.10874
	$ \tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow t \tilde{\chi}_2^0, \tilde{\chi}_2^0 \rightarrow Z/h \tilde{\chi}_1^0 \tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + Z $	1-2 <i>e</i> , μ 3 <i>e</i> ,μ	1-4 <i>b</i> 1 <i>b</i>	$E_T^{ m miss} \ E_T^{ m miss}$	140 140	$ ilde{t}_1 \\ ilde{t}_2$	Forbidden	0.067- 0.86	1.18	$m(\widetilde{\chi}_1^0)$ =	$m(\tilde{\chi}_{2}^{0})=$ 500 GeV =360 GeV, $m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0})=$ 40 GeV	2006.05880 2006.05880
	$ ilde{\chi}_1^{\pm} ilde{\chi}_2^0$ via WZ	Multiple ℓ /jet	s ≥ 1 jet	$E_T^{ m miss}$ $E_T^{ m miss}$	140 140			0.96			$\mathfrak{m}(\tilde{\chi}_1^0)=0, ext{ wino-bino } \mathfrak{m}(\tilde{\chi}_1^\pm)-\mathfrak{m}(\tilde{\chi}_1^0)=5 ext{ GeV, wino-bino }$	2106.01676, 2108.07586 1911.12606
	$\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{1}^{\mp}$ via WW	$2 e, \mu$	_	E_T^{miss}	140	$\tilde{\chi}_1^{\pm}$	0.42				$m(\tilde{\chi}_1^0)=0$, wino-bino	1908.08215
	$\chi_1^+\chi_2^+$ via Wh $\tilde{\chi}_1^+\tilde{\chi}_1^+$ via $\tilde{\ell}_L/\tilde{\chi}$	Multiple ℓ /jet	S	E_T^{miss} E_T^{miss}	140 140	$\chi_1^{\pm}/\chi_2^{\circ}$ Forbidden $\tilde{\chi}_1^{\pm}$		1.0	5		$m(\tilde{\chi}_1^0) = 70 \text{ GeV}, \text{ wino-bino}$ $m(\tilde{\ell}, \tilde{\chi}) = 0.5(m(\tilde{\chi}_1^{\pm}) + m(\tilde{\chi}_1^0))$	2004.10894, 2108.07586 1908 08215
W ect	$\tilde{\tau}\tilde{\tau}, \tilde{\tau} \rightarrow \tau \tilde{\chi}_1^0$	2τ		E_T^{miss}	140	$\tilde{\tau}$ [$\tilde{\tau}_{\mathrm{R}}, \tilde{\tau}_{\mathrm{R},\mathrm{L}}$]	0.34 0.48				$m(\tilde{\mathcal{X}}_1^0) = 0$	ATLAS-CONF-2023-029
<u>е</u> і ш	$\tilde{\ell}_{\mathrm{L,R}}\tilde{\ell}_{\mathrm{L,R}}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$	2 e,μ ee,μμ	0 jets ≥ 1 jet	$E_T^{ m miss}$ $E_T^{ m miss}$	140 140	${\scriptstyle \widetilde{\ell} \ \widetilde{\ell}}$ 0.26		0.7			$m(\widetilde{\ell})=0$ $m(\widetilde{\ell})-m(\widetilde{\chi}_1^0)=10~GeV$	1908.08215 1911.12606
	$\tilde{H}\tilde{H}, \tilde{H} { ightarrow} h\tilde{G}/Z\tilde{G}$	0 e,μ 4 e μ	$\geq 3 b$	$E_T^{ m miss}$	140 140	\tilde{H}	0.55	0.94			$BR(\tilde{\chi}_1^0 \to h\tilde{G}) = 1$ $RP(\tilde{\chi}_1^0 \to Z\tilde{G}) = 1$	To appear 2103 11684
		$0 e, \mu$	≥ 2 large jets	$E_{T_{i}}^{T_{i}}$	140	n Ĥ	0.55	0.45-0.93			$BR(\tilde{\chi}^0_1 \to Z\tilde{G})=1$	2108.07586
		2 <i>e</i> ,µ	≥ 2 jets	E_T^{miss}	140	Ĥ		0.77		E	$R(\tilde{\chi}_1^0 \to Z\tilde{G}) = BR(\tilde{\chi}_1^0 \to h\tilde{G}) = 0.5$	2204.13072
D (0	Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$	Disapp. trk	1 jet	$E_T^{\rm miss}$	140	$ \tilde{\chi}_{1}^{\pm} \\ \tilde{\chi}_{1}^{\pm} $ 0.21		0.66			Pure Wino Pure higgsino	2201.02472 2201.02472
-live clea	Stable \tilde{g} R-hadron	pixel dE/dx		E_T^{miss}	140	ĝ				2.05	~0	2205.06013
ng- arti	Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow qq\chi_1^\circ$	pixei dE/dx Disnl len		E_T^{miss}	140 140	$g [\tau(g) = 10 \text{ ns}]$ \tilde{e}, \tilde{u}		0.7		2.2	$m(\chi_1^\circ)=100 \text{ GeV}$ $\tau(\tilde{\ell})=0.1 \text{ ns}$	2205.06013
р Го	$\iota, \iota \rightarrow \iota 0$	pixel dE/dx		E_T E_T^{miss}	140	τ, μ τ τ	0.34 0.36	0.7			$\tau(\tilde{\ell}) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 0.1 \text{ ns}$ $\tau(\tilde{\ell}) = 10 \text{ ns}$	2011.07812 2205.06013
	$\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_1^0, \tilde{\chi}_1^{\pm} \rightarrow Z\ell \rightarrow \ell\ell\ell$	3 <i>e</i> , µ	0 ista	rmiss	140	$\tilde{\chi}_1^{\mp}/\tilde{\chi}_1^0$ [BR($Z\tau$)=1, BR(Ze)=1]	0.6	525 1.05	1.55		Pure Wino	2011.10543
	$\chi_1^-\chi_1^-/\chi_2^- \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$ $\tilde{a}\tilde{a} \rightarrow aa\tilde{\chi}^0, \tilde{\chi}^0 \rightarrow aaa$	4 e,µ	>8 iets	E_T	140 140	$\begin{array}{ccc} \chi_1 / \chi_2 & [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0] \\ \tilde{\alpha} & [m(\tilde{\chi}^0) = 50 \text{ GeV} \ 1250 \text{ GeV}] \end{array}$		0.95	1.55	2.25	$m(\chi_1)=200 \text{ GeV}$ Large χ''_{12}	2103.11684 To appear
>	$\widetilde{t}\widetilde{t}, \widetilde{t} \rightarrow t\widetilde{\chi}_1^0, \widetilde{\chi}_1^0 \rightarrow tbs$		Multiple		36.1	$\tilde{t} = [\lambda''_{323} = 2e-4, 1e-2]$	0.55	1.05	5		$m(\tilde{\chi}_1^0)$ =200 GeV, bino-like	ATLAS-CONF-2018-003
ЧP	$\tilde{t}\tilde{t}, \tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^{\pm} \rightarrow bbs$		$\geq 4b$		140	ĩ	Forbidden	0.95			$m(\tilde{\chi}_1^{\pm})$ =500 GeV	2010.01015
	$\begin{array}{c} t_1 t_1, \ \overline{t}_1 \rightarrow bs \\ \overline{t}, \ \overline{t}_1, \ \overline{t}_1 \rightarrow c\ell \end{array}$	2011	2 jets + 2 b		36.7	$\begin{bmatrix} t_1 & [qq, bs] \\ \tilde{t}_1 \end{bmatrix}$	0.42 0.0	61	0 4 1 45		$BR(\tilde{t}, h_a/h_a) > 200/$	1710.07171
	·1·1, ·1 ·4·	1μ	DV		136	\tilde{t}_1 [1e-10< λ'_{23k} <1e-8, 3e-10< λ'_{23k}	′ <3e-9]	1.0	1.6		$BR(\tilde{t}_1 \to q\mu) = 100\%, \cos\theta_t = 1$	2003.11956
	$\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0/\tilde{\chi}_1^0, \tilde{\chi}_{1,2}^0 \rightarrow tbs, \tilde{\chi}_1^{\pm} \rightarrow bbs$	1-2 <i>e</i> , µ	≥6 jets		140	$\tilde{\chi}_{1}^{0}$ 0.2-0.	32				Pure higgsino	2106.09609

*Only a selection of the available mass limits on new states or phenomena is shown. Many of the limits are based on simplified models, c.f. refs. for the assumptions made.



Mass scale [TeV]

Difficult to avoid bounds on stops and sbottoms from reaching 600-700 GeV

This makes the SUSY solution to the UV sensitivity of m_h , fine tuned typically $\ll 1\%$.

However, this is what SUSY needs to get $m_h \simeq 125$ GeV correctly



Searches for Physics Beyond the SM

<u>Composite Higgs Models</u>

- Long history of non-elementary Higgs boson
 - Technicolor. Many problems. Plus: no Higgs! X
 - Topcolor. Main problem: heavier Higgs. X

- Modern CHMs: Higgs is a (pseudo) Nambu-Goldstone boson 🗸 K. Agashe, R. Contino, A. Pomarol, 2005 $m_{\pi} \ll \Lambda_{\rm hadronic} \simeq {\rm GeV}$ analogous to $m_h \ll \Lambda_{\rm BSM} \simeq {\rm TeV}$



<u>MCHM</u>: SO(5)/SO(4)

G is a global symmetry spontaneously broken at $f \Rightarrow$ massless Higgs SM interactions explicitly break $G \Rightarrow$ Generate V(H) and m_h Minimal model: just enough pNGBs to make a H doublet



Searches in CHMs

In CHMs vector and fermion resonances responsible for taming the UV sensitivity in m_h

Fermion resonances:



Resonance bounds are typically above 1 TeV. Similarly for vector resonances.

Still not as fined tuned as SUSY since H is a pNGB.





BSM without New Particles

- The energy frontier will stay at the LHC for some time. HL-LHC up to 2030s.
- Look for hidden/dark sectors: dark sector/DM searches at various energies
- Test the SM with precision, low(er) energies: Flavor Physics, Electroweak tests
- Precision Tests of the Higgs Sector: Higgs Couplings to everything

Higgs as a window to new dynamics BSM + Energy Frontier: at $\sqrt{s} \simeq 14$ TeV for a while



Understand Higgs couplings at the LHC/HL-LHC

Effective Field Theory Approach

•New physics encoded in expansion in local HDOs suppressed by a cutoff Λ

$$\mathcal{L}_{SM} + \sum_{i,n>4} \frac{c_i^{(n)}}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}$$

- Model Independent requires 59 operators up to dimension 6.
- Correlated constraints from EW and Higgs data.



• Contradicts expectation from m_h UV sensitivity.

Brivio and Trott (2019) SMEFT

The Higgs Potential

In the SM we have

$$V(\Phi^{\dagger}\Phi) = -m^2 \Phi^{\dagger}\Phi + \lambda (\Phi^{\dagger}\Phi)^2 \quad \text{a}$$

$$\mathcal{L}_h = -\frac{1}{2}m_h^2 h^2 - \frac{g_{h^3}}{3!} h^3 - \frac{g_{h^4}}{4!}$$

But HDOs could be present

$$V(\Phi^{\dagger}\Phi) = -m^2 (\Phi^{\dagger}\Phi) + \lambda (\Phi^{\dagger}\Phi)^2 + \frac{c}{\Lambda^2} (\Phi^{\dagger}\Phi)^3 + \frac{d}{\Lambda^4} (\Phi^{\dagger}\Phi)^4 + \cdots$$

Test the "shape" of the Higgs potential.

and using

$$v = \sqrt{\frac{m^2}{\lambda}}$$

from minimization



$$m_{h} = \sqrt{2\lambda} v$$

$$g_{h^{3}} = \frac{3m_{h}^{2}}{v}$$

$$g_{h^{4}} = \frac{3m_{h}^{2}}{v^{2}}$$



The Higgs Potential

Require experimental access to (at least) double Higgs production



Fundamental question: is the coupling extracted from the measurement of m_h really the Higgs self-coupling? We will begin attacking this question at the HL-LHC.

From $m_h \simeq 125 \,\mathrm{GeV}$ using $m_h = \chi$

We arrive at

Measurements of λ in multi-Higgs production directly test the shape of the Higgs potential



$$\sqrt{2\lambda} v$$
 and $v \simeq 246 \, {
m GeV}$
 $\lambda \simeq 0.13$

Higgs Self-Coupling from Di-Higgs Production







Searching for BSM through the Higgs

Higgs Couplings as a window to BSM physics

New physics can generate momentum dependence in couplings







Form factor in Higgs couplings Bellazzini, Csaki, et al. (2016)

Requires off shell momentum

Isidori, Trott (2014)

Gonçalves, Han, Mukhopadhyay (2018)

Off-Shell Higgs and BSM Effects

Model dependent approach

Matching with EFT may require operators of dim > 6 to capture full non-local features

- Higgs line
- Gauge boson line
- Fermion line

Pedro Bittar, GB, 2022

- Compute the Higgs form factors in a specific model full momentum dependence
- **Loose** generality, **Gain** in power of data to constrain specific BSM not directly accessible
- "Scan" over models so as to cover all signals : where is the momentum dependence coming from ?



Example: Mixing with an Unparticle Scalar Sector

Scalar unparticle operator $\phi(x)$ of dimension d

2-point function with IR cutoff μ

$$\Delta(p,\mu,d) = \int d^4x \langle 0|\mathcal{T}\phi(x)\phi^{\dagger}(0)|0\rangle = \frac{A_d}{2\pi} \int_{\mu^2}^{\infty} ds (s-\mu^2)^{d-2} \frac{i}{p^2 - s + i\epsilon},$$

Non-local action $S_{\rm NL} =$



d 1 < d < 2 Fox, Rajaraman, Shirman (2007) Cacciapaglia, Marandella, Terning (2008)

$$\int d^4x \left\{ \phi^{\dagger} (D^2 - \mu^2)^{2-d} \phi + \alpha |H|^2 \frac{|\phi|^2}{\Lambda^{2(d-1)}} \right\}$$



Form Factor from an Unparticle Scalar Sector

Results for $f_{hVV}(q^2)$ with off shell Higgs, on shell gauge bosons P. Bittar, G.B. 2022

> $\mu = 1 \text{ TeV}$ ---- d=1.01 — d=1.1 — d=1.2 — d=1.3 — d=1.4 — d=1.5



3.0









Another Example: the Twin Higgs

- The Higgs is a pNGB, just as in CHMs
- New states controlling the UV sensitivity in m_h are in an invisible (twin) sector
- In the Mirror Twin Higgs, two copies of the SM are related by a \mathbb{Z}_2 symmetry
- Exact Z_2 means f = v. Excluded by Higgs phenomenology (invisible decays, couplings)
- Need soft Z_2 breaking so that $\frac{f}{v} \gtrsim 3 \Rightarrow$ Twin particles somewhat heavier than SMs

All Higgs couplings to SM are suppressed by a factor of $\cos\left(\frac{v}{\sqrt{2}f}\right)$

Z. Chacko, H. Goh and R. Harnik, 2005



It is hard to constraint the MTH at the LHC



 \Rightarrow MTH to remain natural well into the HL-LHC

Future Berne dicte om Higgs

Other aspects of the Mirror Twin Higgs

Cosmology:

- Potentially large contribution to $\Delta N_{\rm eff.}$ from twin neutrinos and photon
- Many possible solutions: give twin ν 's large masses, asymmetric reheating, ...

Dark Matter:

- Mirror standard model playground for DM model building
- •Thermal relic, asymmetric DM, ...
- Details depend on twin matter content (e.g. Mirror vs. Fraternal), on Z_2 breaking, ...

Asymmetric Dark Matter in the Mirror Twin Higgs

ADM in the MTH naturally just around O(1) GeV Twin quarks heavier $\Rightarrow \tilde{\Lambda}_{\rm QCD} \gtrsim \Lambda_{\rm QCD} \Rightarrow m_{\rm DM} \simeq 1.4 \, m_N$



Pedro Bittar, G.B, Larissa Pastrello, 2023

Summary and Outlook

- No evidence for BSM in direct searches at the LHC, or in flavor physics.
- Next BSM frontier: precision measurements involving the Higgs boson
 - Energy frontier closing for sometime. HL-HLC \rightarrow 2030s-2040
- Future accelerators:
 - Higgs factory. FCC-ee great reach in precision, including 5% in λ . (Would start 2048!?)
 - FCC-hh 100 TeV (same tunnel as FCC-ee at CERN \Rightarrow 2070s !)
 - Muon Collider: 3 TeV, 10 TeV? (Off real axis right now, but ...)
- A lot of interesting correlations between DM searches and accelerator physics still happening This will continue throughout the HL-LHC lifetime.
 These include new experiments coming on line for highly displaced vertices: Dark Sectors, BAU, ...