

Higgs in Perspective III: concrete BSM

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The concrete BSM way... (not longer just top-down)

Which BSM ?

In the "good old days", we had a grand scheme:



EW Hierarchy problem ?

An enormous brain effort has been devoted to solving this problem, ie. understanding the separation between $M_{Higgs} << M_{Planck}$



New states at TeV, top quark special

LHC EW hierarchy razor

ATLAS SUSY Searches* - 95% CL Lower Limits

March 2019 $\sqrt{s} = 13 \text{ TeV}$ Signature $\int \mathcal{L} dt \, [fb^{-1}]$ Model Reference Mass limit 0 e.u 2-6 iets $\tilde{q}\tilde{q}, \tilde{q} \rightarrow q\tilde{\chi}_1^0$ Fmiss 36.1 [2x, 8x Degen 1.55 m(x10)<100 GeV 1712.02332 E_T^{T} mono-jet 1-3 jets 36.1 Ity 8y Degen 0.43 0.71 $m(\tilde{q})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ 1711.03301 Searches 2-6 jets E_T^{miss} 36.1 1712.02332 $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\bar{q}\tilde{\chi}_{1}^{0}$ 0.e.11 2.0 m(\$\tilde{\chi}_1)<200 GeV 0.95-1.6 m(x1)=900 GeV 1712.02332 4 jets m(𝑥̃⁰)<800 GeV $\tilde{g}\tilde{g}, \tilde{g} \rightarrow q\tilde{q}(\ell\ell)\tilde{\chi}_1^0$ 3 e, µ 36.1 1.85 1706.03731 ee, µµ 2 jets E_T^{miss} 36.1 1.2 $m(\bar{g})-m(\bar{\chi}_{1}^{0})=50 \text{ GeV}$ 1805.11381 Inclusive 7-11 jets $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qqWZ\tilde{\chi}_1^0$ 0 e, µ E_T^{miss} 36.1 1.8 $m(\tilde{\chi}_{1}^{0}) < 400 \text{ GeV}$ 1708.02794 3 e, µ 4 jets 0.98 m(g)-m(x10)=200 GeV 1706.03731 36.1 0-1 e, µ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow t\tilde{t}\tilde{\chi}_{1}^{0}$ 3h E_T^{miss} 79.8 2.25 $m(\tilde{\chi}_1^0)$ <200 GeV ATLAS-CONE-2018-041 1.25 3 e, µ 4 jets 36.1 m(g)-m(x10)=300 GeV 1706.03731 $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_1^0 / t \tilde{\chi}_1^{\pm}$ Multiple 1708.09266, 1711.03301 36.1 Forbidden 0.9 $m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=1$ Multiple Forbidden 0.58-0.82 $m(\tilde{\chi}_{1}^{0})=300 \text{ GeV}, BR(b\tilde{\chi}_{1}^{0})=BR(t\tilde{\chi}_{1}^{\pm})=0.5$ 1708.09266 36.1 Multiple 36.1 Forbidden 0.7 $m(\tilde{\chi}_{1}^{0})=200 \text{ GeV}, m(\tilde{\chi}_{1}^{\pm})=300 \text{ GeV}, BR(t\tilde{\chi}_{1}^{\pm})=1$ 1706.03731 ĥ. $\tilde{b}_1 \tilde{b}_1, \tilde{b}_1 \rightarrow b \tilde{\chi}_2^0 \rightarrow b h \tilde{\chi}_1^0$ E_T^{miss} $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}$ SUSV-2018-31 0 e. µ 6 b 139 \tilde{b}_1 Forbidden 0.23-1.35 0.23-0.48 $\Delta m(\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{0}) = 130 \text{ GeV}, m(\tilde{\chi}_{1}^{0}) = 0 \text{ GeV}$ SUSY-2018-31 0-2 e, µ 0-2 jets/1-2 b ET 1506.08616, 1709.04183, 1711.11520 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow W b \tilde{\chi}_1^0 \text{ or } t \tilde{\chi}_1^0$ 36.1 10 m(\$\vec{x}_1^0)=1 GeV T₁T₁, Well-Tempered LSP 0.48-0.84 1709.04183, 1711.11520 Multiple 36.1 $m(\tilde{\chi}_{1}^{0})=150 \text{ GeV}, m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=5 \text{ GeV}, \tilde{t}_{1} \approx \tilde{t}_{L}$ ĩı $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow \tilde{\tau}_1 bv, \tilde{\tau}_1 \rightarrow \tau \tilde{G}$ $1 \tau + 1 e, \mu, \tau$ 2 jets/1 b E_T^{miss} 36.1 m(~~1)=800 GeV 1803.10178 1.16 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow c \tilde{\chi}_1^0 / \tilde{c} \tilde{c}, \tilde{c} \rightarrow c \tilde{\chi}_1^0$ 0 e, µ 2 c E_T^{miss} 36.1 0.85 m(\$\tilde{X}_1^0)=0 GeV 1805.01649 0.46 m(t1,c)-m(x10)=50 GeV 1805.01649 0 e, µ mono-jet E_T^{miss} 36.1 0.43 $m(\tilde{t}_1, \tilde{c}) - m(\tilde{\chi}_1^0) = 5 \text{ GeV}$ 1711.03301 1-2 e, µ E_T^{miss} 36.1 0.32-0.88 $\tilde{t}_2 \tilde{t}_2, \tilde{t}_2 \rightarrow \tilde{t}_1 + h$ 4 b $m(\tilde{\chi}_{1}^{0})=0$ GeV, $m(\tilde{t}_{1})-m(\tilde{\chi}_{1}^{0})=180$ GeV 1706 03986 E_T^{miss} E_T^{miss} 1403.5294, 1806.02293 $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^0$ via WZ 2-3 e, µ 36.1 $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.6 $m(\tilde{\chi}_{1}^{0})=0$ ≥ 1 36.1 0.17 1712.08119 ee, µµ $m(\tilde{\chi}_{1}^{\pm})-m(\tilde{\chi}_{1}^{0})=10 \text{ GeV}$ $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}$ via WW 2 e, µ Fmiss 139 $\tilde{\chi}_1^{\pm}$ 0.42 $m(\tilde{\chi}_1^0)=0$ ATLAS-CONF-2019-008 $\tilde{\chi}_{1}^{\pm} \tilde{\chi}_{2}^{0}$ via Wh0-1 e, µ E_T^{miss} 2 b 36.1 $\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0$ 0.68 $m(\tilde{\chi}_{1}^{0})=0$ 1812.09432 $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}$ via $\tilde{\ell}_{L}/\tilde{\nu}$ 2 e, µ E_T^{miss} 139 $m(\tilde{\ell}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ ATLAS-CONE-2019-008 $\tilde{\chi}_{1}^{\pm}$ 1.0 E_T^{miss} 36.1 $\tilde{\chi}_1^{\pm} / \tilde{\chi}_2^0$ $\tilde{\chi}_1^{\pm} / \tilde{\chi}_2^0$ 0.76 1708.07875 $\tilde{\Sigma}$ $\tilde{\chi}_{1}^{\pm}\tilde{\chi}_{1}^{\mp}/\tilde{\chi}_{2}^{0}, \tilde{\chi}_{1}^{+} \rightarrow \tilde{\tau}_{1}\nu(\tau\tilde{\nu}), \tilde{\chi}_{2}^{0} \rightarrow \tilde{\tau}_{1}\tau(\nu\tilde{\nu})$ 2 7 $m(\tilde{\chi}_{1}^{0})=0, m(\tilde{\tau}, \tilde{\nu})=0.5(m(\tilde{\chi}_{1}^{\pm})+m(\tilde{\chi}_{1}^{0}))$ 1708.07875 0.22 $m(\tilde{\chi}_{1}^{\pm}) \cdot m(\tilde{\chi}_{1}^{0}) = 100 \text{ GeV}, m(\tilde{\tau}, \tilde{\nu}) = 0.5(m(\tilde{\chi}_{1}^{\pm}) + m(\tilde{\chi}_{1}^{0}))$ 0 jets E_T^{miss} E_T^{miss} ATLAS-CONF-2019-008 $\tilde{\ell}_{L,R}\tilde{\ell}_{L,R}, \tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$ 2 e, µ 139 0.7 $m(\tilde{\chi}_{1}^{0})=0$ 2 e. µ ≥ 1 36.1 0.18 $m(\tilde{\ell})-m(\tilde{\chi}_1^0)=5 \text{ GeV}$ 1712.08119 $\tilde{H}\tilde{H}, \tilde{H} \rightarrow h\tilde{G}/Z\tilde{G}$ 0 e, µ $\geq 3 b$ E_T^{miss} E_T^{miss} 36.1 0.13-0.23 0.29-0.88 $BR(\tilde{\chi}_{1}^{0} \rightarrow h\tilde{G})=1$ 1806.04030 4 e, µ 0 jets 36.1 $BR(\bar{\chi}_1^0 \rightarrow Z\bar{G})=1$ 1804.03602 0.3 E_T^{miss} 0.46 Direct $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ prod., long-lived $\tilde{\chi}_1^\pm$ Disapp. trk 1 jet 36.1 Pure Wind 1712 02118 Pure Higgsino $\tilde{\chi}_{1}^{\pm}$ 0.15 ATL-PHYS-PUB-2017-019 Stable g R-hadron Multiple 1902.01636,1808.04095 36.1 2.0 Metastable \tilde{g} R-hadron, $\tilde{g} \rightarrow q a \tilde{\chi}_1^0$ Multiple 36.1 $\tau(\tilde{g}) = 10 \text{ ns. } 0.2 \text{ ns}$ 2.05 2.4 m(x10)=100 GeV 1710.04901,1808.04095 LFV $pp \rightarrow \tilde{v}_{\tau} + X, \tilde{v}_{\tau} \rightarrow e\mu/e\tau/\mu\tau$ $\lambda'_{311}=0.11, \lambda_{132/133/233}=0.07$ еµ,ет,µт 3.2 1.9 1607.08079 $\tilde{\chi}_1^{\pm} \tilde{\chi}_1^{\mp} / \tilde{\chi}_2^0 \rightarrow WW/Z\ell\ell\ell\ell\nu\nu$ 0 jets E_T^{miss} 0.82 1.33 m(x10)=100 GeV 1804.03602 4 e, µ 36.1 $|\tilde{\chi}_{2}^{0} = [\lambda_{i33} \neq 0, \lambda_{12k} \neq 0]$ $\tilde{g}\tilde{g}, \tilde{g} \rightarrow qq\tilde{\chi}_1^0, \tilde{\chi}_1^0 \rightarrow qqq$ 4-5 large-R jets 36.1 Large $\lambda_{112}^{\prime\prime}$ 1804.03568 ")=200 GeV, 1100 GeV] =2e-4, 2e-5] 1.3 1.9 1.05 ATLAS-CONF-2018-003 Multiple 36.1 2.0 m(X10)=200 GeV, bino-like P P $\tilde{t}\tilde{t}, \tilde{t} \rightarrow t \tilde{\chi}_{1}^{0}, \tilde{\chi}_{1}^{0} \rightarrow tbs$ Multiple 36.1 1.05 $m(\tilde{\chi}_1^0)=200$ GeV, bino-like ATLAS-CONF-2018-003 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow bs$ 2 jets + 2 b 36.7 0.61 1710.07171 $\tilde{t}_1 \tilde{t}_1, \tilde{t}_1 \rightarrow q\ell$ 2 e, µ 2 b 36.1 0.4-1.45 $BR(\tilde{t}_1 \rightarrow be/b\mu) > 20\%$ 1710.05544 1μ DV 1e-10< l' <1e-8, 3e-10< $BR(\tilde{t}_1 \rightarrow q\mu) = 100\%$, $\cos\theta_r = 1$ ATLAS-CONF-2019-006 136 1.6

*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. ATLAS Preliminary

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Mass scale [TeV]

10⁻¹

LHC EW hierarchy razor



EW Hierarchy Problem ?

LHC has found no smoking gun for a solution to the big hierarchy problem and has enhanced the "Little hierarchy problem":

But O(10-100)TeV still an interesting scale to explore!

WIMP Dark Matter

Thermal relic (freeze-out):

neutral and stable Weakly Interacting Massive Particle related to the physics that solves the hierarchy problem (eg. SUSY LSP)

WIMP Dark Matter

Vanilla WIMP getting squeezed but a clear motivation to explore the [10GeV-100TeV] !

WIMP Dark Matter

Strong (and complementary) constraints from direct detection and colliders

Many ideas in the market to target the low mass region in direct detection

Several anomalies: DAMA-LIBRA, CDMS and also astrophysical 3.5keV, GeV excess...

What if solving the hierarchy problem is not the right lead ?

...we still need to understand data: DM, neutrino masses, Matter-antimatter asymmetry

Motivational Toolkit beyond EW hierarchy

I. Avoid hierarchy problem & improve testability

Models for the spotlight ?

Models for the spotlight ?

New spotlights for well motivated models

Motivational Toolkit beyond EW hierarchy

II. Occam's Razor

+ Origin of matter-antimatter asymmetry for $M_N > O(100)MeV$

BSM: Neutrino mass-Leptogenesis

New spotlights: beam dump and collider searches of neutral heavy leptons

The measurement of the mixing to e/μ of the sterile states, $\beta\beta$ ov and δ in neutrino oscillations have a chance to give a prediction for Y_B

BSM: Neutrino mass-Leptogenesis

New spotlights: beam dump and collider searches of neutral heavy leptons

Motivational Toolkit beyond EW hierarchy II. Occam's Razor

QCD axion:

 $m_A^2 f_A^2 \propto m_\pi^2 f_\pi^2$

Axion Dark Matter

$$\begin{split} \Omega_A^{\rm vr} h^2 &\approx 0.12 \, \left(\frac{f_A}{9\times 10^{11}~{\rm GeV}}\right)^{1.165} \, F \, \bar{\Theta}_{\rm i}^2 \\ &\approx 0.12 \, \left(\frac{6~\mu {\rm eV}}{m_A}\right)^{1.165} F \, \Theta_{\rm i}^2 \,, \end{split}$$

Axion Dark Matter

Bright prospect to explore the phase space of QCD axion models

Irastorza, Redondo '18

Motivational Toolkit beyond EW hierarchy

II. Occam's Razor

Alternative to QCD anomalous breaking:

 $m_a^2 f^2 \gg m_\pi^2 f_\pi^2$

ALPs searches

New spotlights: ALP searches @ colliders and beam dump experiments

Motivational Toolkit beyond EW hierarchy

II. Occam's Razor

Many models of this type to explain Dark Matter: FIMPs, SIMPs, Mirror worlds...

Motivational Toolkit beyond EW hierarchy

III. Searching for connections: towards a new grand scheme

The BSM Landscape

"Truth is ever to be found in simplicity, and not in the multiplicity and confusion of things"

I. Newton