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Higgs sector : What we would like to know

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Some key properties of the Higgs boson, such as its mass and couplings to electroweak bosons and third-generation fermions have by now been well established with multiple measurements by the ATLAS and CMS Collaborations. This note will instead review the status of the current "unknowns": the Higgs boson self-coupling, and Higgs boson rare and exotic decays, including those to second-generation fermions or to new light scalars.

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1. The Higgs boson self-coupling

The discovery of a Higgs-like boson by the ATLAS [1] and CMS [2] Collaborations in 2012 [3–5] has started a rich program of characterizing the boson and assessing its compatibility with the standard model (SM) predictions. One key property of the boson, essential for its role in electroweak symmetry breaking, is the Higgs boson self-interaction. The quadratic and quartic terms in the potential of the Higgs field yield, after symmetry breaking, the Higgs boson mass term and cubic and quartic self-interactions for the Higgs boson field. The cubic interaction, corresponding in the Feynman diagram picture to a vertex with three Higgs boson legs, can be probed at the LHC both directly by searching for double Higgs boson production (HH) or indirectly through the effects it has at next-to-leading order (NLO) on single Higgs boson observables. Results are normally interpreted in the formalism of coupling modifiers κ, introducing one for the trilinear coupling $\kappa_\lambda := \lambda/\lambda^{\mathrm{SM}}$.

The dominant HH production mode at LHC is gluon fusion, which receives both contributions from amplitudes involving the self-coupling and from amplitudes that depend only on Higgs boson couplings to fermions. These two kinds of amplitudes interfere destructively, yielding a cross section of 31 fb at $\sqrt{s} = 13$ TeV for the SM ($\kappa_\lambda = 1$), which grows by a factor 2.09 in the absence of self-coupling ($\kappa_\lambda = 0$). The state of the art for HH searches is still given by the combination of searches performed with the early LHC Run 2 data [6, 7], yielding sensitivities to cross sections around ten times the SM prediction, driven by the $\mathrm{b\bar{b}}\,\tau\tau$, $\mathrm{b\bar{b}}\,\gamma\gamma$ and $\mathrm{b\bar{b}}\,\mathrm{b\bar{b}}$ decay modes. A search for HH has also been performed on the full LHC Run 2 dataset by ATLAS targeting the $\mathrm{b\bar{b}}\,\mathrm{WW}^*$ decay mode in the fully leptonic final state [8], setting observed (expected) upper limits HH at 40 (29) $\times$ SM, improving the sensitivity by a factor 8 (3) compared to previous ATLAS (CMS) searches in that final state.

Searches for HH production have also been performed in the vector boson fusion (VBF) production mode. The most interesting aspect of VBF HH production is the destructive interference occurring between amplitudes involving two vertices coupling the Higgs boson to electroweak gauge bosons and those involving a single quartic vertex with two gauge bosons and two Higgs bosons. In the κ formalism, the first kind of vertices is associated to κ_{V} and the second to $\kappa_{2\mathrm{V}}$, and the cancellation occurs whenever the Higgs boson is part of a SU(2) doublet leading to $\kappa_{2\mathrm{V}} = \kappa_{\mathrm{V}}^2$. In scenarios where the cancellation is spoiled, a very large increase in cross section is expected, accompanied by a much harder kinematic of the signal. These two features have been considered in the first search for VBF HH production at LHC, performed by ATLAS in the $\mathrm{b\bar{b}}\,\mathrm{b\bar{b}}$ final state [9]. After a tight selection for VBF requiring a dijet pair with $m_{\mathrm{jj}} \geq 1$ TeV and $|\Delta\eta_{\mathrm{jj}}| > 5$, the analysis relies on the methods established in the earlier HH $\to \mathrm{b\bar{b}}\,\mathrm{b\bar{b}}$ search performed on the 36 fb^{-1} dataset [10]. The analysis is optimized for the scenario $\kappa_{2\mathrm{V}} \neq 1$ with $\kappa_{\mathrm{V}} = \kappa_\lambda = 1$, and can set constraints $-0.56 < \kappa_{2\mathrm{V}} < 2.89$ at the 95% confidence level (CL).

Constraints on the Higgs boson self-coupling from precision measurements of single Higgs boson observables have also been set by ATLAS [11] and CMS [12]. The constraints are set in the κ formalism, assuming that only κ_λ may deviate from unity. In the ATLAS case a combination of H and HH analyses has also been performed, allowing for a more general fit with the other κ_i constrained from the single Higgs measurements. The results are summarized in Table 1: a comparable constraining power is achieved for the two approaches. There are some caveats in these interpretations, as they rely on the κ framework with a mix of leading order and NLO predictions.

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A more solid interpretation from the theoretical point of view would however require a global fit at NLO in an effective field theory extension of the SM, for which substantial work is still needed from both theoretical and experimental sides.

Table 1: Summary of present constraints from ATLAS and CMS on the Higgs boson self coupling [6, 7, 11, 12].

inputs	**model**	**ATLAS**	*(expected)*	**CMS**	*(expected)*
H	only κ_λ	$-3.2, 11.9$	$-6.2, 14.4$	$-3.5, 14.5$	$-5.1, 13.7$
HH	only κ_λ	$-5.0, 12.0$	$-5.8, 12.0$	$-11.8, 18.8$	$-7.1, 13.6$
H + HH	only κ_λ	$-2.3, 10.3$	$-5.1, 11.2$		
H + HH	κ_i & κ_λ	$-3.7, 11.5$	$-6.2, 11.6$		

2. Rare, forbidden and beyond-SM

The Higgs boson couplings to second generation fermions are a natural target of research following the successful observation of all three couplings to third generation fermions. In this context, $\mathrm{H} \to \mu\mu$ is the most promising mode. The most recent result in this decay mode is from ATLAS on the full LHC Run 2 dataset [13], reporting a signal strength $\mu = 0.5 \pm 0.7$ and observed significance of 0.8σ (expected 1.5σ). Second generation couplings can also be probed in $\mathrm{H} \to \mathrm{c\bar{c}}$, for which the state of the art is the CMS result on partial Run 2 data [14], targeting VH associated production with $\mathrm{W} \to \ell\nu$, $\mathrm{Z} \to \ell\ell$ and $\mathrm{Z} \to \nu\nu$ and setting an upper limit at 70 times the SM prediction (expected: 37).

Higgs boson couplings to lighter quarks are not expected to be accessible in the SM, but they could be greatly enhanced in some flavour-inspired modifications of the SM, and could be probed via Higgs boson decays to mesons. CMS has performed a search for $\mathrm{H} \to \mathrm{Z}\,\rho$ and $\mathrm{H} \to \mathrm{Z}\,\phi$ [15], selecting the decays $\rho \to \pi^+\pi^-$ and $\phi \to \mathrm{K^+K^-}$ that can be cleanly reconstructed in the inner tracker. It is an inclusive search, relying on the invariant four-body mass to extract a resonant signal over the continuum background from Z + jets. Upper limits on the branching ratio are set in the 0.3–2% range depending on the meson and polarization scenario assumed, corresponding to 860–1350 × SM.

While Higgs boson decays to gauge boson pairs have all been observed since Run 1, the $\mathrm{H} \to \mathrm{Z}\gamma$ decay remains elusive due to a small branching fraction $\mathcal{B}(\mathrm{H} \to \mathrm{Z}\gamma \to \ell\ell\gamma) = 0.5 \cdot 10^{-4}$ and a large non-resonant background from $\mathrm{Z}\gamma$ production. In the SM or extensions of it where the Higgs boson is part of a $SU(2)_L$ doublet, the Higgs boson interactions to $\mathrm{Z}\gamma$, WW, ZZ, $\gamma\gamma$ are tied together, so that a simultaneous measurement of all four can provide a consistency test if any deviations are seen, or point to the need of more general BSM physics. The most recent result on this decay mode is from ATLAS [16] on $139\,\mathrm{fb}^{-1}$, reporting a signal strength of 2.0 ± 1.0 corresponding to a 2.2σ excess that may be the first hint of a signal.

Higgs boson decays can also be used to probe for new particles beyond the SM. In particular, in some models with an extended scalar sector, it is possible to have Higgs boson decays to new light pseudoscalar particles (a), as either $\mathrm{H} \to \mathrm{aa}$ or $\mathrm{H} \to \mathrm{Za}$. The first search for these decays on the full Run 2 dataset is from ATLAS, targeting $m_\mathrm{a} < 4\,\mathrm{GeV}$ and inclusive hadronic decays of the

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a particle [17]. Neural networks are used to separate the jets from $\mathrm{a} \to$ jet decays from the jets in the main Z + jets background, and regress the mass of the a particle. Sensitivity is better for lower masses, where a better discrimination is achieved. Upper limits are set on $\sigma \times \mathcal{B}(\mathrm{H} \to \mathrm{Za})$ ranging from about $30\% \times \sigma_{\mathrm{SM}}$ at $m_{\mathrm{a}} = 0.5\,\mathrm{GeV}$ to $\geq 100\% \times \sigma_{\mathrm{SM}}$ for $m_{\mathrm{a}} \geq 2.8\,\mathrm{GeV}$.

In most models the $\mathrm{a} \to \mathrm{b\bar{b}}$ decay becomes dominant once it is kinematically accessible. A new dedicated search for $\mathrm{H} \to \mathrm{aa} \to \mathrm{b\bar{b}\,b\bar{b}}$ has been performed at ATLAS targeting $15 < m_{\mathrm{a}} <$ GeV [18], to complement previous searches optimized for larger m_{a}. The search is performed on the early $36\,\mathrm{fb}^{-1}$ dataset, and relies on ZH associated production with $\mathrm{Z} \to \ell\ell$ to provide a handle to select events at trigger level. Large-radius jets with substructure and b-tagging are used to reconstruct the $\mathrm{a} \to \mathrm{b\bar{b}}$ decays. Upper limits are set on $\sigma_{\mathrm{ZH}} \times \mathcal{B}(\mathrm{H} \to \mathrm{aa} \to \mathrm{b\bar{b}\,b\bar{b}})$, with the best sensitivity achieved around $m_{\mathrm{a}} = 20\,\mathrm{GeV}$ at $80\% \times \sigma_{\mathrm{ZH}}^{\mathrm{SM}}$ (expected 60%).

Leptonic decays of the a boson are also possible, and can offer a better purity. This is exploited in the CMS search for $\mathrm{H} \to \mathrm{aa} \to \mu\mu\,\tau\tau$ [19], where a dedicated reconstruction is used to handle the overlapping decay products of the two τ leptons. A two-dimensional fit is performed in the plane of $m(\mu\mu)$ and $m(\mu\mu\tau\tau)$, and upper limits are set on $\mathcal{B}(\mathrm{H} \to \mu\mu\tau\tau)$ in the 0.02–0.08% range for $3.6 < m_{\mathrm{a}} < 21\,\mathrm{GeV}$.

A different class of extensions of the SM can feature new vector particles that can couple universally to leptons, e.g. a dark sector $\mathrm{Z_D}$. Building on the existing $\mathrm{H} \to \mathrm{ZZ}^* \to 4\ell$, a search for $\mathrm{H} \to \mathrm{ZZ_D}$ and $\mathrm{H} \to \mathrm{Z_D Z_D}$ in the 4ℓ final state has been performed by CMS on the full $137\,\mathrm{fb}^{-1}$ dataset [20]. The four-lepton invariant mass is required to be compatible with that of a Higgs boson, and then for the two different topologies a different pairing criteria is used to identify the leptons from the $\mathrm{Z_D}$ candidates and a sliding window is used in the dilepton mass ($\mathrm{ZZ_D}$) or masses ($\mathrm{Z_D Z_D}$). Assuming flavour-democratic decays, upper limits of order 10^{-4} are set on $\mathcal{B}(\mathrm{H} \to \mathrm{ZZ_D}) \times \mathcal{B}(\mathrm{Z_D} \to \ell\ell)$ in the $4 < m_{\mathrm{Z_D}} < 35\,\mathrm{GeV}$ range, and around $2 \cdot 10^{-6}$ on $\mathcal{B}(\mathrm{H} \to \mathrm{ZZ_D}) \times \mathcal{B}(\mathrm{Z_D} \to \ell\ell)^2$ in the $4 < m_{\mathrm{Z_D}} < 60\,\mathrm{GeV}$ range.

While all the above searches were focused on light new particles, a search for heavy Higgs bosons in the context of the minimal supersymmetric extension of the SM (MSSM) has also been performed at ATLAS [21]. The search targets $\mathrm{H/A} \to \tau\tau$, the flagship MSSM mode at high $\tan(\beta)$ where the $\tau\tau$ branching fraction and the cross section for associated $\mathrm{b\bar{b}H}$ production are enhanced. Model-independent limits on the cross sections are set up to $m_{\mathrm{H}} = 2.5\,\mathrm{TeV}$, and the largest excess is found at a mass of around 400 GeV, with a local significance of about 2σ. Interpretations in several MSSM benchmark models are provided, reaching down to $\tan(\beta) < 8$ at a mass of 1 TeV.

3. Conclusions

The quest for the Higgs boson self-coupling goes on, improved analysis methods are being deployed and for the first time also the VBF production mode is being probed. A substantial improvement in sensitivity is expected to come when the analysis of the most sensitive decay modes using the full Run 2 dataset will be completed, and giving good prospects for the observation of HH production at the High Luminosity LHC.

Numerous searches have been performed using the Higgs boson to probe into the unknown, searching for decays into yet unobserved particles or rare decays that could be largely enhanced

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by new physics. Similarly to the case of HH production, the collaborations have only just started exploiting the full Run 2 dataset for these analyses, so many more results are expected in the future.

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