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New Higgses at the Electroweak Scale and Differential $t\bar{t}$ Distributions

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Indications for new Higgs bosons at 95 GeV and 152 GeV with significance of $> 3\sigma$ and $> 4\sigma$, respectively, have been found. While the former mainly originates from the inclusive $\gamma\gamma$ channel, the latter is obtained by combining several modes of associated di-photon production, i.e. $\gamma\gamma + X$ with $X = \ell$, ℓb, MET, τ, etc. In particular, the Drell-Yan production $pp \to W^* \to H^0 H^\pm$, either in the ΔSM (the Standard Model extended by a real triplet) or a 2HDM can explain the 152 GeV excess. The former option offers a connection to $t\bar{t}$ differential distributions, which show strong tensions with the SM predictions, since the experimental signature is $WWb\bar{b}$: A simplified model with a new scalar H, produced via gluon fusion and decaying to two neutral Higgses S and S' with subsequent (dominant) decays to WW and $b\bar{b}$, respectively, leads to the same final state. Since WW is the dominant decay of a triplet Higgs with a mass around 152 GeV, this motivates that the anomalies might be connected. Furthermore, assuming that S' is an $SU(2)_L$ singlet, the resulting di-photon signal strength is compatible with the 95 GeV $\gamma\gamma$ measurements. A possible UV completion of this simplified model is the Δ2HDMS, i.e. a 2HDM supplemented with a singlet and a real triplet, which can successfully accommodate electroweak scale Baryogenesis.

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1. Introduction

The Standard Model (SM) cannot be the ultimate theory of physics as, among several shortcomings, it fails to explain the astrophysical observations of Dark Matter and cannot account for the non-vanishing neutrino masses required by neutrino oscillations. Furthermore, the minimality of its scalar sector with a single $SU(2)_L$ doublet Higgs giving rise to the mass of all (fundamental) fermions as well as the W and Z bosons is not guaranteed by any symmetry or consistency requirement.

While additional Higgs bosons must play a subleading role in the spontaneous breaking of the electroweak (EW) symmetry due to the constraints from SM Higgs signal strengths measurements and the global EW fit, the average of the W boson mass measurements even prefers a higher value than the SM prediction (3.7σ [1]). Furthermore, the multi-lepton anomalies at the LHC [2, 3], which appear in Higgs-like topologies in final states with at least two leptons, moderate missing energy and (b-)jets (see Refs. [4] for recent reviews),[1] can be explained by the production of a heavy scalar H decaying into Higgs-like scalars, S and S'. The mass range of S was determined to be in the range 150 ± 5 GeV [6, 7]. Furthermore, the excess in WWW [8] production compared to the one in $WW + b$-jet [9] suggest $m_{S'} < m_S$, such that S predominantly decays into WW and $\mathrm{Br}(S' \to WW) \ll \mathrm{Br}(S' \to bb)$. In this context, indications for new Higgs-like bosons with electroweak scale masses of 95 GeV and 152 GeV have emerged.

2. Hints for narrow resonances

Combining the CMS [10] and ATLAS analyses of $pp \to S' \to \gamma\gamma$ [11] a local significance of 2.9σ at 95 GeV is obtained [12]. While CMS finds a local excess of 3.1σ in $pp \to S' \to \tau\tau$ [13], the side-band of the corresponding SM Higgs ATLAS analysis [14] shows no indications of a signal at 95 GeV, which reduces the CMS significance by a factor $\sqrt{2}$ (assuming that the ATLAS and CMS analyses have similar sensitivity). Furthermore, the CMS analysis of b-associated τ pair production even sees a slight deficit. Recasting the SM Higgs analyses of $pp \to S' \to WW^*$ [15], a preference of $\approx 2.6\sigma$ for a non-vanishing cross section at 95 GeV is found. Finally, LEP reported an excess in $e^+e^- \to Z^* \to (S' \to bb) + Z$ with a local significance of 2.3σ at ≈ 98 GeV [16]. Using the latter to reduce the search window to 93 GeV $< m_{S'} <$ 103 GeV (but not including it directly in the significance calculation) and combining $S' \to \gamma\gamma$, $S' \to WW^*$ and $S' \to \tau\tau$ with three degrees of freedom, gives a global significance (including the trails-factor) of 3.4σ [17] (see left side of Fig. 1).[2]

2.1 152 GeV (S)

For the 152 GeV excess, no dedicated new physics (NP) searches exist such that we rely on the sidebands of SM Higgs analyses. While an $\approx 2\sigma$ excess in the inclusive di-photon channel exists at ≈ 152 GeV [18], the most significant excesses appear in $\gamma\gamma + X$ [19, 20], i.e. the associated production of di-photons with $X = \ell$, MET, ℓb, τ, ... Combining these channels in a simplified

[1] These proceedings are an updated and shortened version of my Moriond 2024 proceedings [5].

[2] Note that the LEP combination includes all measured decay channels assuming the Higgs is SM-like, not only the $b\bar{b}$ channel, even though this has the biggest impact on the fit.

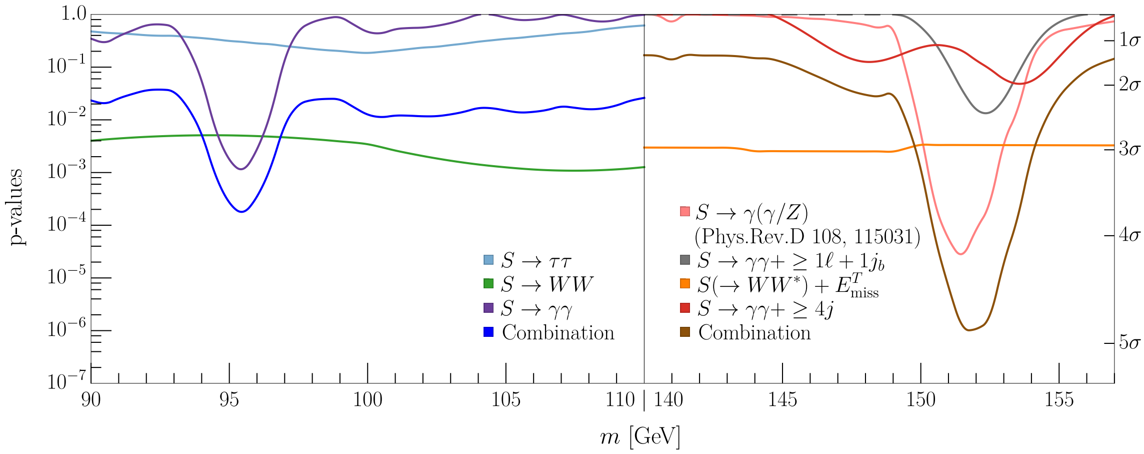

Figure 1: Indications for narrow resonances at the EW scale. While for the low-mass region containing the 95 GeV excess one relies on inclusive searches, the higher mass region with the 152 GeV excess has the most significant hints in associated production channels. For the latter, the combination is obtained within the simplified model $H \to SS^*$ with H produced via gluon fusion from a top-quark loop and the decay channels $S \to WW$, $b\bar{b}$, MET, $\gamma\gamma$ as motivated by the multi-lepton anomalies.

model with $pp \to H \to SS^*$ ($m_H \approx 270\,$GeV) and $S \to WW$, $b\bar{b}$, MET, $\gamma\gamma$, as motivated by the the multi-lepton anomalies [2, 3], a combined significance of 4.7σ is obtained [17] (see right plot of Fig. 1).[3]

Going beyond a simplified model, one can consider the $SU(2)_L$ triplet Higgs with hypercharge 0 which contains a neutral component Δ^0 and a charged component $\Delta^\pm$ (approximately degenerate in mass). This model predicts a positive shift in the W mass and leads to $\gamma\gamma + X$ signatures via the Drell-Yan process $pp \to W^* \to \Delta^\pm\Delta^0$ [21] with a cross-section entirely governed by the EW gauge couplings of around half a picobarn. Furthermore, since the decay rates of $\Delta^\pm$ depend to a good approximation only on its mass, WZ is dominant for 152 GeV followed by tb and $\tau\nu$, and one can combine all channels with a single degree of freedom (the branching ratio of Δ^0 to photons) for a given mass. Including in addition to Ref. [19] the $\gamma\gamma + \tau$ channel presented at Moriond EW [20] a combined significance of $\approx 4\sigma$ is obtained [22].

Similarly, one can work in a 2HDM, where $H^\pm \to ZW$ is not allowed at tree-level, to obtain a fit to data which is even slightly better [23]. However, in this case, to obtain the sizable branching ratio to photons required by the fit, one has to use the term $\lambda_6 H_1^\dagger H_2 H_1^\dagger H_1$ which violates the usually applied Z_2 symmetry.

3. Differential top-quark distributions

The statistically most significant multi-lepton anomaly is encoded in the latest ATLAS analysis of the $t\bar{t}$ differential cross-sections [9], i.e. it appears in $e^\pm\mu^\mp + b-$jets final states. The di-lepton mass ($m^{e\mu}$) and the angle between the leptons ($\Delta\phi^{e\mu}$) are the most relevant observables. Several SM simulations, using different Monte Carlo generators and showering, were performed by ATLAS.

[3] Note that this does not include the $\gamma\gamma + \tau$ of Ref. [20].

However, all of them describe data so poorly that Ref. [9] concluded: "No model (SM simulation) can describe all measured distributions within their uncertainties."

Therefore, one should seriously consider the option of these differential distributions containing a NP contamination. In fact, the process $pp \to H \to SS'$ with $S \to WW$ and $S' \to bb$ has the same final state as $t\bar{t}$ production and decay in the SM but with different kinematics. If we fix $m_S = 152\,\text{GeV}$ and $m_{S'} = 95\,\text{GeV}$ from the hints for narrow resonances discussed in the last section, we can fit the cross section for $pp \to H \to SS' \to WWb\bar{b}$ to data for a given mass of H. Since we checked that the impact of varying m_H is small, we chose 270 GeV as a benchmark point and find that the NP hypothesis is preferred over the SM one by at least 5.8σ.

Allowing now m_S, to which the distributions are most sensitive among the new scalar masses, to vary, one finds that the range $\approx$ (144 GeV)-(157 GeV), which is compatible with $m_S \approx 152\,\text{GeV}$ obtained from the $\gamma\gamma + X$ excesses, explains the anomalies in the $t\bar{t}$ differential distributions. Furthermore, averaging the six different SM predictions the resulting best fit to $t\bar{t}$ data is obtained for $\sigma(pp \to H \to SS' \to WWb\bar{b}) \approx 9\text{pb}$. Assuming that S' has SM-like branching ratios (e.g. is an $SU(2)_L$ singlet), and thus decays to 86% to $b\bar{b}$, this results at the same time in a di-photon signal strength in agreement with the 95 GeV $\gamma\gamma$ excess. Similarly, S should decay dominantly to WW but only suppressed to ZZ (as there is no four-lepton excess at $\approx$152 GeV), which suggests that it could be the neutral component of an $SU(2)_L$ triplet, further strengthening the connection to the 152 GeV excess.

4. Conclusions and Outlook

Statistically significant indications for new narrow resonances with masses of 95 GeV and 152 GeV have been observed in LHC data. While the former appears in inclusive searches, the latter is most pronounced in associated production channels, i.e. $\gamma\gamma{+}X$ with $X = \ell$, MET, ℓb, τ, ... For the 95 GeV candidate a model-independent significance of $3.4\,\sigma$ is found, while combining the hints for associated di-photon production within the ΔSM, i.e. the SM supplemented by a Higgs triplet with $Y = 0$, or a second doublet, results in a $\approx 4\sigma$ excess at 152 GeV.

The Higgs triplet option not only predicts a positive shift in the W mass, as preferred by the current global EW fit, but also provides a possible connection to the multi-lepton anomalies. Since its neutral component decays dominantly to WW (for small mixing angles with the SM Higgs), it could be involved in the explanation of the discrepancies between the SM predictions and measurements of the differential top-quark distributions via the NP contamination $pp \to SS' \to WWb\bar{b}$. In fact, if one assumes that S is the neutral component of the triplet and S' a singlet, a 95 GeV di-photon signal strength in agreement with experimental data is obtained.

Recently, we proposed the Δ2HDMS, i.e. the SM extended by a singlet, a $Y = 0$ triplet and a second $Y = 1/2$ doublet, as a UV complete model that can account for the top-quark differential distributions and the 95 GeV and 152 GeV excesses [24]. Interestingly, this model was previously studied in a very different context; it was shown to give rise to EW scale Baryogenesis [25], i.e. explain the matter anti-matter asymmetry in the universe.

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