Accumulating Evidence for the Associate Production of a Neutral Scalar with Mass around 151 GeV

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To establish the discovery of a new phenomenon (for example, a new particle or interaction) an experiment must reach a certain level of statistical significance. More precisely, the probability of deviations from the null hypothesis (in which the new particle or interaction is not present) equal or greater than the observed deviation must fall below a certain value. This probability is known as the p-value. In the particle physics literature, the p-value is often converted to a significance Z, defined as the number of standard deviations giving the same probability when integrating the standard Gaussian distribution from Z to ∞. Values of the p-value below 2.87×10^{-7} (corresponding to a 5σ significance) usually define a discovery.

Before collecting data, the ATLAS and CMS collaborations did not know *a priori* where an excess would appear in the invariant mass distributions of the $\gamma\gamma$ and other relevant search channels. Consequently, their statistical analyses had to account for the *look-elsewhere effect* (LEE), i.e. the fact that an excess of events anywhere in the search range can be interpreted as a signal [2]. Two approaches can be used to compute a significance for a resonance search. The *local* significance is calculated from the p-value found by fixing the mass of the resonance to the best-fit value. The *global* significance accounts for the LEE by multiplying the local p-value by a trial factor N_{trial} depending approximately on the invariant mass search range Δm and resolution σ_m of the experiment. The relationship between the global and local significances is then

$$Z_{\text{global}} = \Phi^{-1}(1 - N_{\text{trial}} + \Phi(Z_{\text{local}})N_{\text{trial}})\,, \tag{1}$$

where $\Phi(x)$ is the cumulative distribution function of the standard Gaussian distribution. Considering a single search channel, a rule of thumb estimate for the trial factor is

$$N_{\text{trial}} \approx \frac{1}{3}\frac{\Delta m}{\sigma_m} Z_{\text{local}}\,. \tag{2}$$

Increasing Δm or decreasing σ_m will thus increase N_{trial} and from Eq. (1) reduce Z_{global} with respect to Z_{local}. An experiment with a wide search range and high resolution is more susceptible to the LEE and the reduction in Z_{global} takes this into account. From the $\gamma\gamma$ and $ZZ^* \to 4\ell$ channels, the ATLAS (CMS) collaboration found a local significance of 5.8σ (5.0σ) for the 125 GeV excess. Adjusting for the search range of 110 GeV to 150 GeV (110 GeV to 145 GeV), a global significance of 5.3σ (4.5σ) was found. The combined results of ATLAS and CMS were sufficient to announce a discovery in July 2012.

The recent paper by Crivellin et al. [1] has re-examined the search channels used by ATLAS and CMS to detect and characterise the 125 GeV excess. The $\gamma\gamma$ channel was again considered, either inclusive of all other outgoing particles or accompanied specifically by missing transverse energy E^T_{miss}, b-jets or $W^\pm/Z$ bosons. Also included were $Z^*\gamma \to \ell^+\ell^-\gamma$ events with an associated charged lepton ℓ (not produced in the decay of the Z). Finally, $b\bar{b}$ events with missing transverse energy were incorporated. Motivated by the recent anomalies seen for multi-lepton final states, the energy range examined was 140 GeV to 155 GeV, the side band of the ATLAS and CMS searches. The results of the analysis, taking into account the combined channels, are shown in Fig. 1. To the left, an excess from the SM background at $m_S = 151$ GeV can be seen in the combined spectrum of (five of) the six channels. To the right, the local p-value of this excess can be seen to drop to 1.70×10^{-7} when all channels are included, translating to a local significance of 5.1σ. The authors compute a trial factor of $N_{\text{trial}} \approx 5$ giving a global significance of 4.8σ. Such significances lie at the threshold to claim the discovery of a new scalar boson of mass $m_S = 151$ GeV; we believe it unnecessary to state the impact such a discovery would have on the current landscape of particle physics.

The question now is this one: can we trust this claim? The study was not lauded by the scientific community as one might expect for such a discovery claim. According to the author of Ref. [3], two mistakes were made in the statistical analysis of Ref. [1] that must be corrected to obtain realistic results. The first concerns the combination of six search channels; the method used by the authors of Ref. [1] to calculate the local p-value is applicable only for a single channel and not six. Making this correction reduces the local significance from 5.1σ to 4.1σ. The second concerns the magnitude of the trial factor N_{trial}. The author of Ref. [3] finds a larger value of $N_{\text{trial}} \approx 12$ using

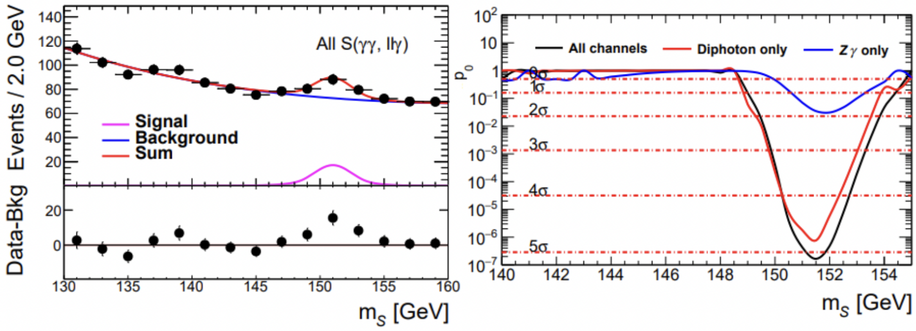

Figure 1: (Left) The combined spectrum of five of the six channels examined by Ref. [1]. The claimed 5.1σ (4.8σ) excess can be seen at 151 GeV. (Right) The local p-value of the excess as a function of the invariant mass, m_S, for: all channels (black solid line), only the $\gamma\gamma$ channel (red solid line), and only the $Z\gamma$ channel (blue solid line). Including all channels, the local p-value is claimed to fall below 2.87×10^{-7}, corresponding to a 5σ significance.

the well-established Monte Carlo method of Gross and Vitells [2]. This further reduces the global significance from 4.8σ to 3.5σ. Such values fail to reach the threshold of discovery, but could still constitute an anomaly in the data.

The next question is, therefore: can we be convinced that this anomaly will lead to further data supporting the aforementioned discovery? We cannot be sure at all. A notable example along these lines is the now-infamous 750 GeV excess. In December 2015 the ATLAS and CMS collaborations reported evidence (at 3.9σ and 3.4σ local significance respectively, combining to 4.4σ) of a resonance in the $\gamma\gamma$ channel suggesting a new particle of mass 750 GeV [4, 5]. The coincidence of hints at ATLAS and CMS aroused the enthusiasm of many in the theory community, as evidenced by the hundreds of papers written on the topic in the months following the announcement. After another year of data collection, however, analyses over the same energy range showed no appreciable anomalies; the resonance was just a statistical fluctuation and the global significance was estimated to be less than 1σ. This episode has warned many in the community not to use local significance as a metric of discovery.

The discovery of a new particle claimed by this paper is certainly something to keep an eye on. However, in the light of past episodes, e.g. the 750 GeV resonance, we cannot take this result for granted or as a hint until the appropriate statistical threshold is reached. Sometimes we are tempted to think that it is exaggerated or to forget that statistics can be very misleading for intuition if not considered carefully, and that is why cases like this should be kept in mind: as a popular saying goes, "even a broken clock tells the right time twice a day".

References

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