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Particle Physics

Higgs Bosons Off the Shell

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The CMS Collaboration finds evidence for the contribution from off-shell Higgs bosons to the production of events with two *Z* bosons. This provides a measurement of the Higgs boson's width.

The Higgs boson is a particle like no other: it interacts with other particles with strengths proportional to their masses. If there were a massive particle that interacts only with the Higgs boson but not with any other particle, its effects may be invisible in particle physics experiments except for changes to the Higgs boson's production rates and decay branching fractions. Measurements of the products of these are consistent with standard model predictions[1,2]. However, a substantial contribution to the Higgs boson's decay width from modes with invisible or otherwise hard-to-detect particles cannot be excluded with existing data[3,4,5]. Therefore, it is important to measure the width of the Higgs boson to constrain such possible contributions. Now writing in *Nature Physics*[6], the CMS Collaboration reports just such a measurement by examining the production rate of *ZZ* events with invariant masses far above the Higgs boson mass of approximately 125 GeV, referred to as off shell, and comparing it to the on-shell case where the Higgs mass is close to its nominal value. This work yields strong constraints on the Higgs boson's decay width as well as evidence for the presence of off-shell contributions of the Higgs boson to the production rate of events with invariant masses above 220 GeV.

The width is inversely proportional to the lifetime, so that a longer lifetime implies a narrower width of the particle. Previously, the CMS Collaboration placed constraints on the lifetime by searching for Higgs bosons that travelled measurable distances before decaying[7]. However, the expected flight distances for the standard model Higgs boson are much smaller than the experimental resolution. With this method, an upper limit was set on the lifetime approximately nine orders of magnitude larger than that predicted by the standard model.

Another way to constrain the width of the Higgs boson is to measure the width of the distribution of the invariant mass reconstructed from its decay products. This sort of measurement works well for particles with decay widths that are larger than the experimental mass resolution. The Higgs boson's decay width is predicted to be approximately 4.1 MeV, and the measurement resolution on its mass is of the order of 1 GeV — almost three orders of magnitude larger. Thus, such a direct measurement will produce only weak constraints on the Higgs boson's width.

The most powerful way to measure this property — the method chosen by the CMS Collaboration[6] — is to measure the rate of off-shell or virtual Higgs boson interactions and compare it with the rate of on-shell interactions. The ratio of these two rates is sensitive to the width of the Higgs boson. The invariant mass of a particular Higgs boson decay event is computed from the total energies and the momenta of all of its decay products. The relationship between the energy, the momentum and the invariant mass is shown in Fig. 1. In the present analysis, events are used to measure the on-shell Higgs boson production rate if their invariant masses are between 105 GeV and 140 GeV, whereas events with invariant masses above 220 GeV are used to constrain the off-shell production rate.

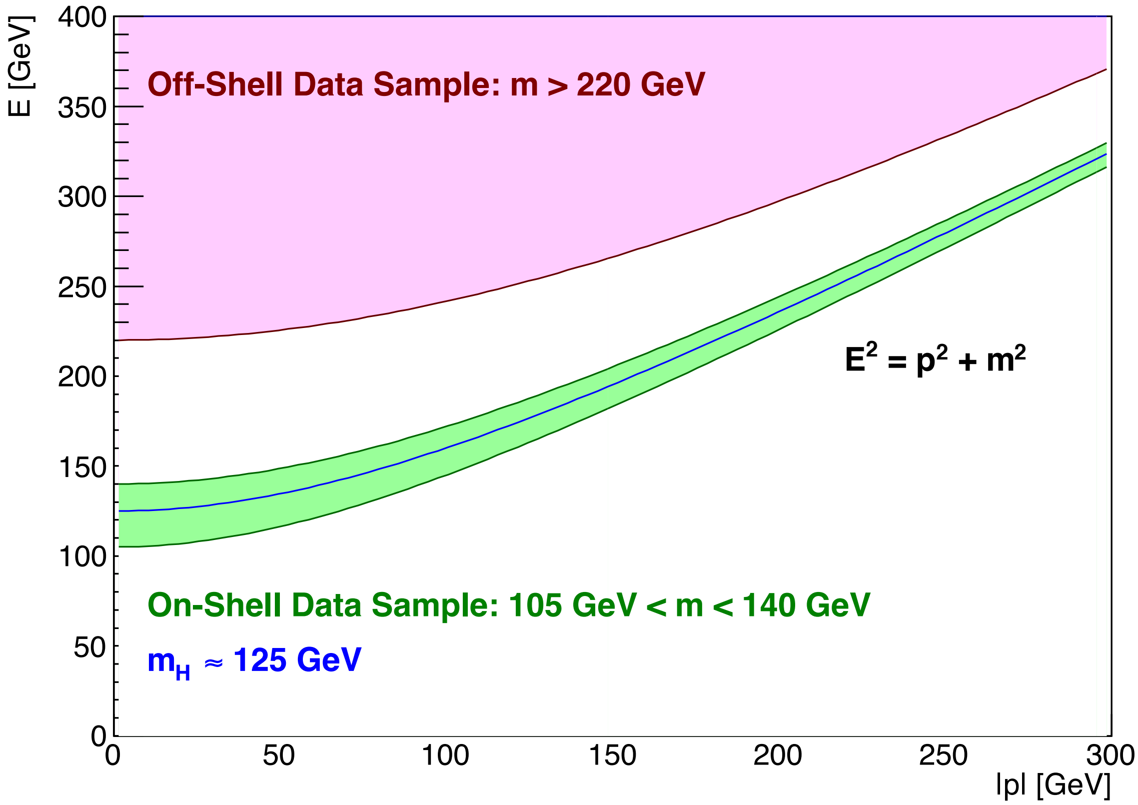

Fig. 1: On-shell and off-shell data regions. The relationship between the total energy, momentum, and invariant mass of the Higgs boson's decay products is illustrated. Regions used to measure the on-shell and off-shell production rates are depicted in green and pink, respectively. Events in which the Higgs boson has its nominal mass of 125 GeV lie on the blue solid line.

At high masses, off-shell Higgs boson production is enhanced by the fact that the two *Z* bosons can be resonant while on-shell Higgs boson decays to two *Z* bosons always involve at least one off-shell *Z* boson, and also due to resonating top quarks in one of the production processes[8].

An interesting wrinkle to the off-shell Higgs boson production process is that it interferes quantum mechanically with background processes that do not involve the Higgs boson, such as nonresonant *ZZ* production from two gluons, where the interference is destructive. The destructive interference terms are larger in absolute value than the Higgs boson production component by itself. Therefore, the net contribution of the off-shell Higgs boson process reduces the amount of *ZZ* events expected to be observed relative to a scenario without the Higgs boson's contribution[8]. Due to the small expected size of the effect of the Higgs boson's presence, highly accurate predictions of the rate of *ZZ* production are required and are used by the CMS Collaboration. The authors also use a data-driven approach to reduce the uncertainties in the predictions to the levels needed to make a strong statement about the Higgs boson's contribution.

Compared to an earlier study[9], this work makes use of a much larger sample of collision data and reconstructs the *ZZ* in an additional final state. This not only results in much stronger constraints on the width of the Higgs boson, but also excludes the scenario with no off-shell contributions with a p-value of 0.0003, which corresponds to 3.6 standard deviations. The measured value of the width of the Higgs boson is consistent with that predicted for the standard model Higgs boson.

The ratio of the on-shell to off-shell Higgs production rates is not only sensitive to the width of the Higgs boson. Exotic processes, such as those involving additional particles, could also contribute. They, however, may have a more complex impact on the Higgs boson's lineshape than can be summarized with one parameter, such as the width.

In the particle physics community, a significance corresponding to 3.6 standard deviations counts as evidence for the off-shell contribution of the Higgs boson to *ZZ* production. But the gold standard for discovery is five standard deviations. By all measures, the current result's sensitivity is limited by the size of the analysed data sample, which is only a few percent of the total size of the data the Large Hadron Collider is expected to provide as it continues running. This measurement promises to become more and more exciting as the constraints on the Higgs boson's lineshape tighten, allowing tests of exotic models that predict contributions to off-shell Higgs boson production.

Competing interests

The author declares no competing interests.

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