

## Measuring the Diphoton Coupling of a 750 GeV Resonance

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A slight excess has been observed in the first data of photon-photon events at the 13 TeV Large Hadron Collider that might be interpreted as a hint of physics beyond the standard model. We show that a completely model-independent measurement of the photon-photon coupling of a putative 750 GeV resonance is possible using the forward proton detectors scheduled at ATLAS and CMS.

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**Introduction.**—The Large Hadron Collider (LHC) is currently performing collisions at the unprecedented center-of-mass energy of 13 TeV. Its primary goal is the search for physics beyond the standard model (SM) of particle physics. The most spectacular finding would be the observation of resonant production of new particles that show up as a bump in the invariant mass spectrum of certain observed final states.

The ATLAS and CMS collaborations have recently reported a small excess over the expected diphoton mass spectrum, in the first 13 TeV collisions recorded at the LHC [1,2]. The excess lies at an invariant mass of approximately  $\sim 750$  GeV, with a decay width estimated to  $\Gamma^{\text{tot}} \leq 45$  GeV by the experimental analyses [3,4]. While it is too early at this stage to know whether this excess is real or if it is due to statistical fluctuations, it is important to discuss which particle beyond the SM might explain the excess and how to test such hypotheses further. Many suggestions have been recently proposed; see Refs. [5–124].

In this Letter we work under the assumption that the excess is due to a spin-0 resonance that we denote by  $\phi$ . The next step is to pin down its properties, in particular, how it couples to SM fields. One possibility is to investigate other potential decay channels, in particular, decays into  $ZZ$ ,  $Z\gamma$ , and  $W^+W^-$  are generically expected [26,102]. On the other hand, as with the SM Higgs boson, a lot of information could be obtained if one were able to tag individual production modes. Most of the recent literature has been focusing on gluon fusion (GGF) or quark fusion (see, e.g., [13]). Given that the resonance has to have sizable couplings to photons, another possibility is photon fusion [26,27,97,112]. These production modes are dominantly inelastic, as the protons are destroyed in the collision, as depicted in Fig. 1.

In this Letter we propose to measure directly the coupling of the resonance to photons in the elastic scattering process  $pp \rightarrow pp\gamma\gamma$ , in which the colliding protons

remain intact. For this we have to consider the two diagrams in Fig. 2. The first one is photon fusion, the second one is gluon fusion with an additional gluon exchange to ensure that no color is extracted from the proton. As is shown below, for any set of parameters explaining the diphoton excess at 750 GeV, the second process has too small a cross section. In turn, using the former process, namely, elastic photon fusion, it is possible to directly measure the photon coupling to the resonance with a precision that allows us to access the theoretically interesting parameter space. The experimental strategy to suppress the dominant inelastic processes and thereby allow us to observe the elastic photon fusion process is to demand the detection of intact protons in forward detectors. In this way, a very clean sample of exclusive diphoton production can be obtained, and requesting a good matching between the diphoton kinematical properties (mass and rapidity) as measured in the central CMS or

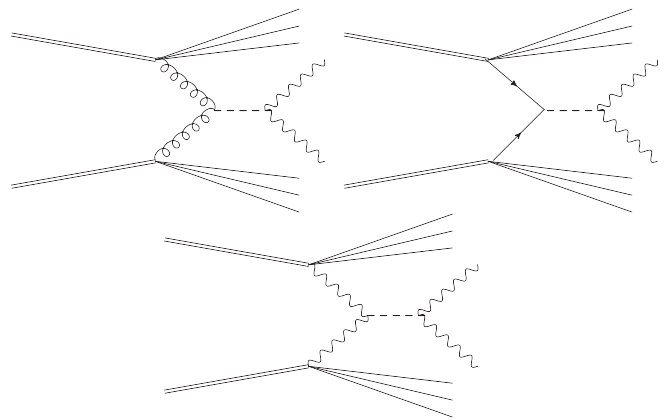


FIG. 1. Schematic representation of the resonant inelastic process  $pp \rightarrow \gamma\gamma X$  with gluon and quark fusion (above) and photon fusion (below).

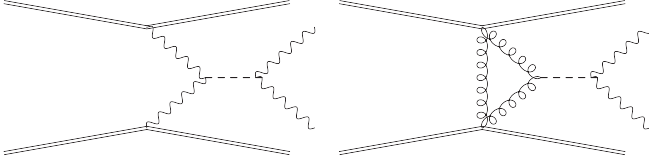


FIG. 2. Schematic representation of the resonant elastic process  $pp \rightarrow \gamma\gamma pp$ . The elastic gluon fusion (EGGF) process requires an additional exchange of a virtual gluon.

ATLAS detectors and the intact protons measured in CT-PPS or AFP removes almost completely the background [125,126].

We stress that in our proposal to measure the coupling of the resonance to photons we do not make any *a priori* assumption about which of the three production modes in Fig. 1 is mainly responsible for the observed excess. The reason is that the forward tagging allows one to suppress all of these production modes equally, and one is just left with the first diagram of Fig. 2.

*Effective couplings and experimental constraints.*—In this section we give a brief overview of the possible production modes for the 750 GeV resonance and their implications for the strength of the coupling to photons. For concreteness we consider two typical values for the total width  $\Gamma^{\text{tot}} = 0.5$  and 45 GeV.

Let us parametrize the most general linear couplings of the 750 GeV resonance  $\phi$  to the SM gauge fields and quarks by the effective Lagrangian of Ref. [127],

$$\mathcal{L} = \phi \left[ \frac{1}{f_g} (G_{\mu\nu})^2 + \frac{1}{f_B} (B_{\mu\nu})^2 + \frac{1}{f_W} (W_{\mu\nu})^2 + \frac{1}{f_H} |D_\mu H|^2 - \frac{1}{f_u} Y_{ij}^u H \bar{q}_L^i u_R^j - \frac{1}{f_d} Y_{ij}^d H \bar{q}_L^i d_R^j + \text{H.c.} \right], \quad (1)$$

where  $G$ ,  $W$ , and  $B$  denote the SM gauge field,  $H$  the Higgs boson, and  $q^i$ ,  $d^i$ , and  $u^i$  the quarks. The matrices  $Y^{u,d}$  are the SM Yukawa couplings [128]. The operator  $\phi |D_\mu H|^2$  can generate couplings to longitudinal gauge bosons and the Higgs boson, but not to photons. It is neglected in what follows, as its only effect for our purposes is a contribution to the width of  $\phi$ .

After electroweak (EW) symmetry breaking, the coupling to photons  $\mathcal{L}_{\phi\gamma\gamma} = f_\gamma^{-1} \phi (F_{\mu\nu})^2$  is given by

$$f_\gamma^{-1} = c_w^2 f_B^{-1} + s_w^2 f_W^{-1}. \quad (2)$$

The expected strength of the coupling  $f_\gamma^{-1}$  depends on the various production modes of  $\phi$ . For  $f_{g,u,d}^{-1}$  very small or 0, pure (inelastic) photon fusion dominates. In this case one can robustly translate the measured excess as [26]

$$\begin{aligned} f_\gamma &\approx 13.4 \text{ TeV} & (\Gamma^{\text{tot}} = 0.5 \text{ GeV}) \\ f_\gamma &\approx 4.4 \text{ TeV} & (\Gamma^{\text{tot}} = 45 \text{ GeV}), \end{aligned} \quad (3)$$

with 68% credible region of 3.9–4.9 TeV and 12.9–15.1 TeV, respectively.

Once the coupling  $f_g^{-1}$  is increased, gluon fusion starts to dominate over photon fusion. The allowed region in the plane  $f_g - f_\gamma$  is depicted in Fig. 3. The decay width into electroweak bosons and gluons  $\Gamma_{\text{EW}} + \Gamma_{gg}$  is required not to exceed the observed total width. The electroweak width is given by  $\Gamma_{\text{EW}} = \Gamma_{\gamma\gamma} + \Gamma_{\gamma Z} + \Gamma_{ZZ} + \Gamma_{WW}$  and satisfies  $1.64 < \Gamma_{\text{EW}}/\Gamma_{\gamma\gamma} < 53.9$  from theoretical and experimental constraints (see Ref. [26] and Fig. 5).

The weak coupling region ( $f_\gamma$  large) requires large couplings to gluons to compensate the small branching fraction into photons. This region can be probed with dijet searches. One can see that the expected strength of the photon coupling varies roughly between

$$\begin{aligned} f_\gamma &\approx 14 \dots 248 \text{ TeV} & (\Gamma^{\text{tot}} = 0.5 \text{ GeV}) \\ f_\gamma &\approx 4.7 \dots 80 \text{ TeV} & (\Gamma^{\text{tot}} = 45 \text{ GeV}) \end{aligned} \quad (4)$$

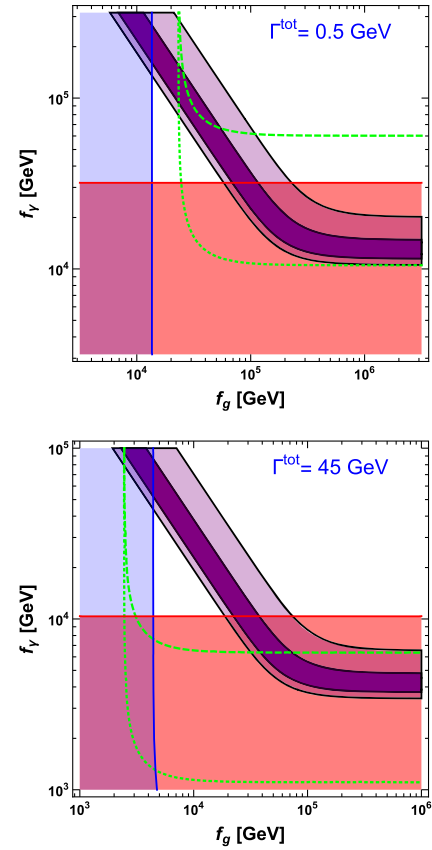


FIG. 3. Bounds and sensitivities in the  $f_\gamma - f_g$  plane, in case of production via photon and gluon fusion. Purple: 68% and 95% C.L. credible regions corresponding to the observed diphoton event rate. Green lines: Limit of the region above which  $\Gamma_{\text{EW}} + \Gamma_{gg} \leq \Gamma^{\text{tot}}$ . Dotted (dashed) lines correspond to  $\Gamma_{\text{EW}}/\Gamma_{\gamma\gamma} = 1.64$  (53.9), respectively. Blue: Excluded region from run 1 dijet searches [129,130]. Red: Sensitivity region from the potential measurement of  $pp \rightarrow \gamma\gamma pp$  using forward proton detectors, for  $300 \text{ fb}^{-1}$  of integrated luminosity; see Eq. (10).

at 68% C.L. Our method is able to probe the strong coupling region ( $f_\gamma$  small) that is insensitive to dijet searches.

*Experimental setup.*—The strategy we propose to measure elastic diphoton production (see Fig. 2) relies on the observation of intact protons in the final state using the AFP and CT-PPS forward proton detectors. Simultaneously, the two photons are measured in the central CMS and ATLAS detectors. The forward detectors are located symmetrically at about 210 m from the main interaction point and cover the range  $0.015 < \xi < 0.15$ , where  $\xi$  is the proton fractional momentum loss, for the standard LHC lattice used at high luminosity. For  $a \sim 750$  GeV resonance produced in 13 TeV collisions, one expects  $\xi \sim 0.06$ . At the LHC, a large number of interactions (called pileup) occur within the same bunch crossing in order to obtain a large luminosity. Given the fact that the SM exclusive production cross section of two photons is very small [125], the main background originates from pileup, i.e., the production of two photons superimposed with an elastic soft event producing two intact protons. The proton tagging allows us to require a good matching between the proton and diphoton kinematical properties, which in turn reduces the pileup background to a small amount estimated to

$$\sigma_{\gamma\gamma pp}^{\text{bkd}} = 3 \times 10^{-4} \text{ fb} \quad (5)$$

in [125,126]. In addition, the time of flight of the scattered proton could be measured with a precision of  $\sim 10$ – $15$  ps that provides a reconstruction of the interaction point of the protons within 2.1 mm inside ATLAS and CMS. Checking if the proton and photon scattering points are the same provides another way of suppressing the pileup background [131].

*Sensitivity to the diphoton coupling.*—We now estimate the sensitivity of the elastic scattering process to the diphoton coupling of the resonance. We implement all gluon and photon initiated processes in the forward physics Monte Carlo generator [132]. In the case of the two-photon  $pp$  events, we use the Budnev flux [133], which describes properly the coupling of the photon to the proton, taking into account the proton electromagnetic structure. The survival probability of the colliding protons is expected to be close to 1 [134]; here, we implement a factor of  $S^2 \sim 0.72$  [135]. The exclusive production via gluon exchanges is performed following the calculations by Khoze, Martin, *et al.* [134]. The forward and central detector acceptance and resolution have been taken into account using a simplified simulation of the detector [125,136], including realistic efficiencies for the central detector. The acceptance for the forward detectors is taken to be  $0.015 < \xi < 0.15$ , with 100% efficiency in this window.

We first argue that EGGF, i.e., the second diagram in Fig. 2, can always be neglected for the excess under consideration. The reason that this process is so small is due to the fact that the soft gluon emission in the gluon ladder has to be suppressed in order to get an exclusive diffractive event with intact protons. Technically, a Sudakov

form factor is introduced to suppress this emission that kills the cross section at high mass.

For a more quantitative estimate of this effect, consider the production cross section of a 750 GeV SM Higgs boson via the same mechanism,

$$\sigma_{\text{EGGF}}^h \approx 2 \times 10^{-3} \text{ fb}. \quad (6)$$

Moreover, we also know the inelastic gluon fusion cross section for a 750 GeV SM Higgs boson [137],

$$\sigma_{\text{GGF}}^h \approx 550 \text{ fb}. \quad (7)$$

We can now recast these cross sections in order to put a bound on the resonant production of  $\phi$  by EGGF. Since the total GGF production cross section of the scalar resonance cannot exceed the observed cross section of the 750 GeV resonance,  $\sigma_{\text{GGF}} \mathcal{B}_{\gamma\gamma} < 10$  fb, one can easily bound

$$\sigma_{\text{EGGF}} \mathcal{B}_{\gamma\gamma} = \frac{\sigma_{\text{EGGF}}^h}{\sigma_{\text{GGF}}^h} \sigma_{\text{GGF}} \mathcal{B}_{\gamma\gamma} < 3 \times 10^{-5} \text{ fb}. \quad (8)$$

It follows that the elastic gluon fusion process is extremely small. Therefore, only the process of elastic photon fusion remains. This process provides direct access to the photon coupling of the resonance, i.e., the quantity  $f_\gamma$  in Eq. (2).

We obtain a cross section of

$$\sigma_{pp \rightarrow \gamma\gamma pp} = (0.184 \text{ fb}) \left( \frac{5 \text{ TeV}}{f_\gamma} \right)^4 \left( \frac{45 \text{ GeV}}{\Gamma_{\text{tot}}} \right). \quad (9)$$

This cross section readily provides the sensitivity of the  $\gamma\gamma pp$  measurement to the diphoton coupling of the scalar resonance.

Assuming Poisson statistics and the background rate Eq. (5), one can readily infer the values of  $f_\gamma$  for given luminosity and number of observed events (see Fig. 4). One can also obtain the exclusion bound on  $f_\gamma$  in the absence of any events; we find

$$\begin{aligned} f_\gamma &> 41.4(31.9) \text{ TeV} & (\Gamma^{\text{tot}} = 0.5 \text{ GeV}) \\ f_\gamma &> 13.4(10.4) \text{ TeV} & (\Gamma^{\text{tot}} = 45 \text{ GeV}) \end{aligned} \quad (10)$$

at 68% (95%) C.L. and  $300 \text{ fb}^{-1}$ . We use the 95% C.L. bound as a definition for the sensitivity of our method and also show it in Fig. 3. For  $3000 \text{ fb}^{-1}$ , the sensitivity would reach  $f_\gamma > 61.4$  and  $19.9$  TeV, respectively, for the small and large width cases. One observes that this elastic measurement is complementary to dijet searches that typically probe the weak diphoton coupling regime. With enough luminosity, both measurements together should give access to the whole relevant parameter space (purple regions).

*Prospects for elastic gauge boson production.*—It is clear from  $SU(2) \times U(1)_Y$  gauge invariance that the diphoton coupling of the resonance must be accompanied by a coupling to  $ZZ$ ,  $Z\gamma$ , and potentially  $W^+W^-$ . From the

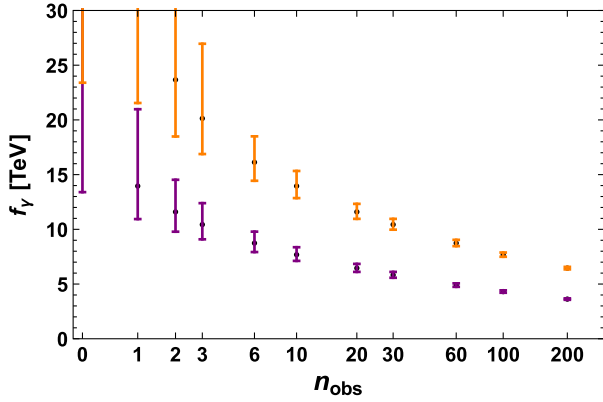


FIG. 4. Inferred value of  $f_\gamma$  (68% C.L.) as a function of the observed number of events for 300 (purple) and 3000  $\text{fb}^{-1}$  (orange) of data. We have assumed  $\Gamma^{\text{tot}} = 45$  GeV.

effective couplings of Eq. (1), there are two independent operators  $f_B^{-1}\phi(B_{\mu\nu})^2$ ,  $f_W^{-1}\phi(W_{\mu\nu})^2$ . The partial decay widths into weak bosons can be found in [26] and are shown in Fig. 5. The ratio  $\Gamma_{\text{EW}}/\Gamma_{\gamma\gamma}$  is bounded from above from diboson searches at LHC run 1 [138–141]. We show an exclusion bound in Fig. 5, obtained by taking the lowest 95% C.L. value  $\sigma_{pp \rightarrow \gamma\gamma X}^{13 \text{ TeV}} = 2.5$  fb and assuming a typical factor  $\sim 4$  with respect to the 8 TeV rate. The  $Z\gamma$  bound [138] from run 1 turns out to be the most stringent one, excluding the  $-0.87 < f_W/f_B < 0.005$  region, implying, in particular,  $\Gamma_{\text{EW}}/\Gamma_{\gamma\gamma} < 53.9$ .

The ratios of event rates  $\sigma_{pp \rightarrow VV'X}/\sigma_{pp \rightarrow \gamma\gamma X}$  in the case of production via gluon fusion and quark fusion are proportional to  $\Gamma_{VV'}/\Gamma_{\gamma\gamma}$ . This is also the case for elastic production, the  $W$  and  $Z$  fluxes from the proton being negligible [142]. Whenever this condition is true, the measurement of one of the  $ZZ$ ,  $Z\gamma$ ,  $WW$  rates readily provides access to the two couplings  $f_B^{-1}$ ,  $f_W^{-1}$ . Interestingly, the event rates into other gauge boson pairs

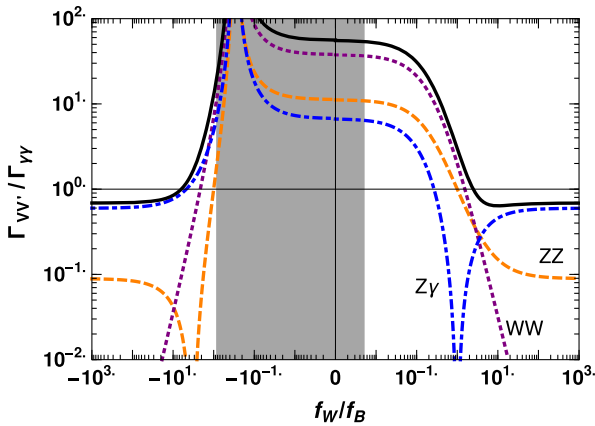


FIG. 5. Partial decay width for  $\phi \rightarrow ZZ$ ,  $Z\gamma$ ,  $W^+W^-$  normalized to the  $\phi \rightarrow \gamma\gamma$  width. The black line corresponds to  $\Gamma_{\text{EW}}/\Gamma_{\gamma\gamma}$ . The grey region is excluded at 95% C.L. by the  $Z\gamma$  search from run 1 [138].

can be substantially larger than the photon-photon one, in particular, if the coupling to the  $(W_{\mu\nu})^2$  operator dominates.

Searches in inelastic channels are one evident method to pin down the  $f_B^{-1}$ ,  $f_W^{-1}$  couplings. However, just like for  $\gamma\gamma$ , the elastic  $VV'$  channels are also of interest because they contain information that is complementary from the inelastic ones. Let us briefly comment about such elastic searches.

(i)  $pp \rightarrow ZZpp$ : At least one  $Z$  decaying leptonically has to be required because of the huge QCD background. The other  $Z$  can be tagged as a large-radius jet. However, because of the small branching ratio ( $\sim 9\%$ ), and after taking into account selection efficiencies, this channel is hardly competitive with the diphoton one.

(ii)  $pp \rightarrow Z\gamma pp$ : The large-radius jet arising from the hadronic decay of the  $Z$  can be efficiently tagged using increasingly powerful jet substructure techniques. Using the full kinematic information provided by forward proton detection, i.e., matching the jet-photon system with the proton-proton system, an excellent background rejection is expected. It is expected to be slightly lower than in the diphoton case because of the worse resolution on the jet momentum. As the event rates can be up to 6.4 times larger than the  $\gamma\gamma$  case, this channel is potentially competitive with the diphoton channel. A full study including all pileup background is worth considering.

(iii)  $pp \rightarrow W^+W^-pp$ : Requesting a fully leptonic decay of the  $WW$  pair implies an overall branching ratio of  $\sim 10\%$ . This is potentially interesting as the  $WW$  rate can be up to  $\sim 37$  times larger than the  $\gamma\gamma$  rate. There is a background at the matrix element level, the main one being SM dilepton production via  $\gamma\gamma \rightarrow \ell\ell$ . This background can be completely removed by requiring nonback-to-back leptons, using a cut on the azimuthal angle between leptons [143,144]. Removing the pileup background requires the installation of precise timing detectors since the matching between the  $WW$  and proton informations lacks efficiency because of the presence of the two neutrinos. Although a detailed study is needed to evaluate the potential of this channel, one may expect that  $WW$  searches are potentially competitive with respect to the  $\gamma\gamma$  searches.

*Conclusion.*—We have demonstrated that the diphoton coupling  $f_\gamma^{-1}\phi(F_{\mu\nu})^2$  of a putative 750 GeV resonance  $\phi$  can be accurately determined in a completely model-independent way by tagging the elastic process  $pp \rightarrow \gamma\gamma pp$  with forward detectors, thereby obtaining a background-free sample of photon-induced processes. We find a sensitivity  $f_\gamma \approx 31.5$  TeV (10.2 TeV) at 300  $\text{fb}^{-1}$  for  $\Gamma^{\text{tot}} = 0.5$  (45) GeV, covering a large portion of the parameter space of models predicting a production of  $\phi$  in gluon or photon fusion. Notice that our method alone cannot exclude models with  $f_g \lesssim f_\gamma$ .

Provided that the total width is independently measured, the determination of  $f_\gamma$  provides indirect information about the dominant production mode. For instance, if  $\Gamma^{\text{tot}} \approx 45$  GeV,  $f_\gamma > 5$  TeV would exclude photon fusion

as the main production mechanism. Further techniques of how to disentangle the production mechanisms have recently been discussed in Ref. [112].

Furthermore, we have commented on the various other channels that one can probe with elastic measurements. Detecting the  $Z\gamma$  final state, as well as the  $WW$  final state, seems possible provided that timing detectors can be exploited.

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