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Features in the Standard Model diphoton background

Kyrylo Bondarenko,[1] Alexey Boyarsky,[1] Oleg Ruchayskiy,[2] and Mikhail Shaposhnikov[3]

[1] *Instituut-Lorentz for Theoretical Physics, Universiteit Leiden, Niels Bohrweg 2, Leiden, The Netherlands*
[2] *Discovery Center, Niels Bohr Institute, Blegdamsvej 17, DK-2100 Copenhagen, Denmark*
[3] *Ecole Polytechnique Fédérale de Lausanne, FSB/IPHYS/LPPC, BSP 720, CH-1015, Lausanne, Switzerland*

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We argue that the electromagnetic decays of energetic unflavoured neutral mesons, notably η, mis-identified as single photons due to granularity of the electromagnetic calorimeter might create bump-like features in the diphoton invariant mass spectrum at different energies, including 750 GeV. We discuss what kind of additional analysis can exclude or confirm this hypothesis.

I. INTRODUCTION

Recent reports of excess in the diphoton invariant mass spectrum at energies about 750 GeV [1–3] have generated a lot of interest in the community [4, 5]. Most of the works concentrated on interpretations of the excess as coming from some new particle, while few explored also the statistical significance of the signal [6–8].

The "data-driven" background fits lead to smooth functions at energies of interest [1, 2] (see also [9] in context of Higgs $\to \gamma\gamma$ searches). While the functional form of the backgrounds used for the analysis was challenged in [6], the diphoton *Standard Model background* is expected to be *monotonic* across the energies of interest (the recent work [10] discussed top-quark threshold effects at lower energies $m_{\gamma\gamma} \sim 2m_{top}$). Studies of the direct (prompt) diphoton production confirm this expectation [11–16].

This paper scrutinizes the assumption of the smoothness of the background. Our main idea is the following: while the physical background is indeed smooth, due to a finite granularity of the electromagnetic calorimeter, sufficiently boosted neutral mesons (such as π^0 or η), decaying electromagnetically, cannot be distinguished from a single photon, travelling in the direction of the meson and carrying all its energy[1]. The probability of such a misinterpretation sharply increases with energy of the incoming neutral meson, while the overall number of mesons drops fast with energy. The convolution of growing and decaying functions leads to a bump-like feature in the energy distribution of photons and, correspondingly, propagates to the diphoton spectrum. The position of this feature depends on three main factors: energy of incoming particle, size of the calorimeter's granularity, and the type of the incident neutral meson. Going straight to our main result, we find that the bumps which may result from $\eta \to 3\pi^0 \to 6\gamma$ decays in the ATLAS detector can indeed appear around 750 GeV (see Fig. 1).

[1] Such decays are well known as one of the main non-prompt backgrounds for photon detection at ATLAS [17] and CMS [18]. A lot of work has been done to analyze this background, in particular in the domain of energies of the Standard Model Higgs.

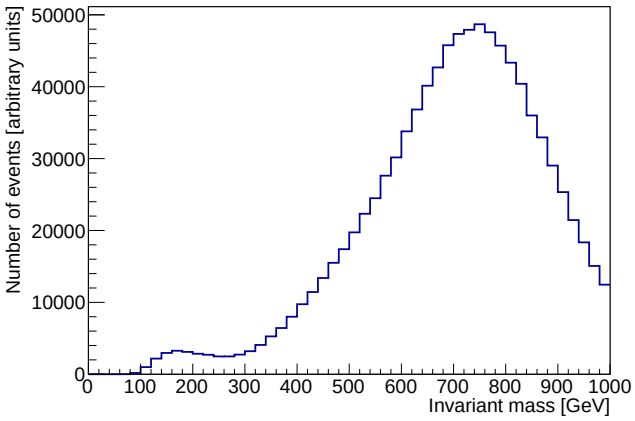

FIG. 1: Invariant mass of two η-mesons mis-identified as photons with the ATLAS detector for the $\eta \to 3\pi^0 \to 6\gamma$ decay process. See text for details.

The idea that some hypothetical neutral particles, decaying to two photons can be mis-interpreted as a single photon had been previously invoked in the context of $H \to \gamma\gamma$ process [19–26] or 750 GeV excess [27–33]. However, to the best of our knowledge the question of $\eta \to 3\pi^0 \to 6\gamma$ decays contributing to the diphoton spectrum has not been analysed either theoretically or by using Monte Carlo simulations combined with the simulated detector responses.

II. PHOTONS FROM NEUTRAL MESON DECAYS

Consider neutral unflavoured mesons, π^0 and η, that decay to two photons (branching ratios: $Br_{\pi^0\to 2\gamma} \simeq 100\%$, $Br_{\eta\to 2\gamma} \approx 39.4\%$ [34]). The distribution of photons in the meson's rest frame is isotropic, therefore in the laboratory frame where the meson has Lorentz factor γ, the distribution in α – angle between two photons – has the form

$$\frac{dN_\gamma}{d\alpha} = \frac{1}{2\sqrt{\gamma^2-1}} \frac{\cos(\alpha/2)}{\sin^2(\alpha/2)} \frac{1}{\sqrt{\gamma^2 \sin^2(\alpha/2) - 1}}\,, \quad (1)$$

Layer	$\eta-$direction	$\phi-$direction	Comment
ATLAS			
1st layer	$\Delta\eta_A = 0.003 - 0.006$	$\Delta\phi_A = 0.1$	η-dependent
2nd layer	$\Delta\eta_A = 0.025$	$\Delta\phi_A = 0.025$	
CMS			
	$\Delta\eta_C = 0.0174$	$\Delta\phi_C = 0.0174$	

TABLE I: Granularities of ATLAS and CMS calorimeters.

where dN_γ is the number of photon pairs with the separation in the laboratory frame between α and $\alpha + d\alpha$ (see Fig. 2). The minimal angle between two photons is therefore

$$\alpha_{min} = 2\arcsin(\gamma^{-1}) \approx \frac{2}{\gamma} \quad \text{for} \quad \gamma \gg 1\,. \tag{2}$$

The distribution (1) is sharply peaked and 95% of all photons have angles $\alpha_{min} < \alpha < 3\alpha_{min}$.

In case of η-meson, there is another neutral decay mode: $\eta \to 3\pi^0$ ($Br \simeq 32.7\%$, [34]) with subsequent decay of each $\pi^0 \to 2\gamma$ (*for simplicity in what follows we call this mode* $\eta \to 6\gamma$). To simulate the distribution of resulting photons, we wrote a ROOT [35] program, that use TGenPhaseSpace utility to simulate n-body decays. In our analysis we assumed that the $3\pi^0$ angular distribution is isotropic in the η rest frame and did-not take into account the energy dependence of the corresponding matrix element [36].

Given that $m_\eta - 3m_\pi = 143\,\text{GeV}$, π^0 mesons, arising in the decay $\eta \to 3\pi^0$, are mildly- or non-relativistic in the η-meson's rest frame. Then one should have $\gamma_{\pi^0} \approx \gamma_\eta$ and could expect that 6 photons arrive collimated similarly to the 2 photon case. Nevertheless, as the average momentum of π^0 in the rest frame of the η mesons is $|\vec{p}_{\pi^0}| \sim 120\,\text{MeV}$, the total width of the photon distribution (maximal angle between a photon and the direction of η-meson) is wider, than in the two photon case (green vs. red curve in Fig. 2), but not surprisingly, most of the energy is contained in the photons, that are "closer than on average" to the direction of the original meson (in the rest frame of η-meson these photons are emitted closest to the direction of the boost), see dashed magenta line in Fig. 2, see also Fig. 4.

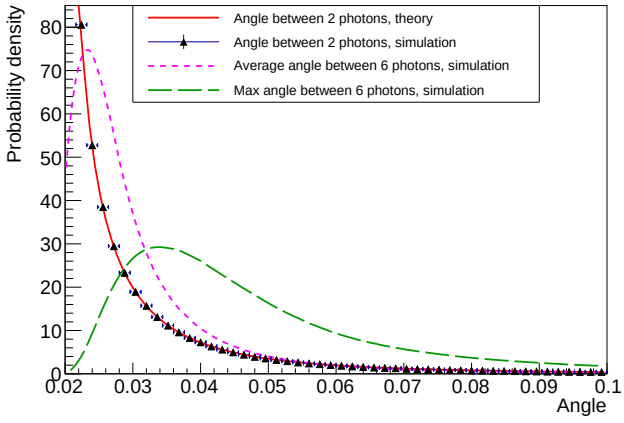

FIG. 2: Angular separation of photons from meson decay. Decays $\eta \to 2\gamma$: red line is Eq. (1) vs. blue (MC) point. Green line – *maximal* angle among 6 photons for $\eta \to 6\gamma$. Average angle between 6 photons and the direction of original η-meson is shown in magenta, short-dashed line.

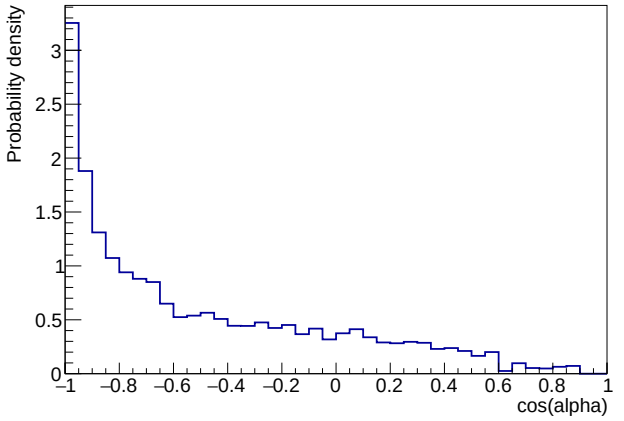

FIG. 3: Distribution of angles between two η-mesons. A peak at $\cos\alpha = 1$ (corresponding to two mesons in the same jet) is not shown.

III. MESON-PHOTON MISIDENTIFICATION

Next we take into account that both ATLAS and CMS electromagnetic calorimeters (ECAL) have finite spatial resolution. The ATLAS calorimeter is lead-liquid argon sampling calorimeter with an accordion geometry (described in details e.g. in [37]). Its characteristics, relevant for our analysis are listed in Table I. The CMS ECAL is made of $PbWO_4$ crystals, with square cross-section (Table I).

By considering the 2 photon decay and requiring $\alpha_{min} \leq 0.003$ (minimal granularity in η-direction for ATLAS ECAL) we find that

$$E \geq \begin{cases} 87\,\text{GeV} & \text{for } \pi^0\text{-meson} \\ 354\,\text{GeV} & \text{for } \eta\text{-meson} \end{cases}\,. \tag{3}$$

This naive estimate suggests that for a sufficient number of isolated η-meson a feature at $E \gtrsim 350\,\text{GeV}$ should appear in single photon spectrum. Correspondingly, the diphoton invariant mass would have a similar feature at twice this energy. Of course realistic photon reconstruction at ATLAS/CMS is much more sophisticated [17, 18] and depends on the details of the detector. Below we take into account some of the factors: realistic energy and angular meson distribution; geometry of the ECAL pixels; all neutral decay modes of η meson.

A. Isolated neutral mesons

Using PYTHIA8 simulations [38] we find that the number of η-mesons at energies of interest is well approximated by the exponential

$$\frac{dN_\eta}{dE} \propto e^{-E/84\,\mathrm{GeV}} \,. \tag{4}$$

We also find that in events where two η-mesons do not belong to a single jet, they are mostly back-to-back. The distribution of angles between two η-mesons (excluding $\cos\alpha = 1$ bin) is shown in Fig. 3.

B. Realistic energy and angular distribution of photons

The above estimate (3) is modified by the fact that the realistic pixel has a different shape. Namely, for photons that arrive aligned along the ϕ-direction (where resolution is much lower) such probability is non-zero for low energies. In case of $\eta \to 6\gamma$ decay, the effect of all 6 photons aligned along the ϕ direction is drastically reduced and therefore one can think about the ATLAS pixel as having "square" form with both dimensions being $\Delta\eta_A$.

IV. RESULTS: FEATURE IN DI-MESON INVARIANT MASS SPECTRUM

Finally, we generate the invariant mass, $m_{\eta\eta}$ of two η-mesons misinterpreted as two photons. To this end we perform the following procedure:

(1) Use the function (4) as probability density function and draw from it two random energies of η-mesons, E_1 and E_2;
(2) Use distribution of cosines between two η mesons (Fig. 3) to generate random $\cos\alpha$;
(3) We calculate invariant mass $m_{2\eta}$ as

$$m_{2\eta} = \sqrt{E_1E_2 - p_1p_2\cos\alpha}, \qquad p_i = \sqrt{E_i^2 - m_\eta^2} \,. \tag{5}$$

The result for the ATLAS is shown in Fig. 1 where one can see that di-eta invariant mass spectrum has a peak at energy ~ 750 GeV. To make a definitive conclusion regarding the contribution of this effect to the di-photon feature [1–3], we need to determine the correct normalisation of the peak in Fig. 1, which one cannot do without realistic Monte Carlo simulations. The corresponding peak for CMS is located at about 5.8 times lower energies (the ratio of $\Delta\eta_C/\Delta\eta_A$, see Table I), curiously falling into the range of the Standard Model Higgs boson.

Discussion

A localized exsess in the diphoton invariant mass spectrum is one of the preferred ways to look for new particles due to its sufficiently low background. The searches for new particles with diphotons implicitly assume that the Standard Model background, as measured by the ATLAS or CMS detectors is *smooth* along the energies of interest.

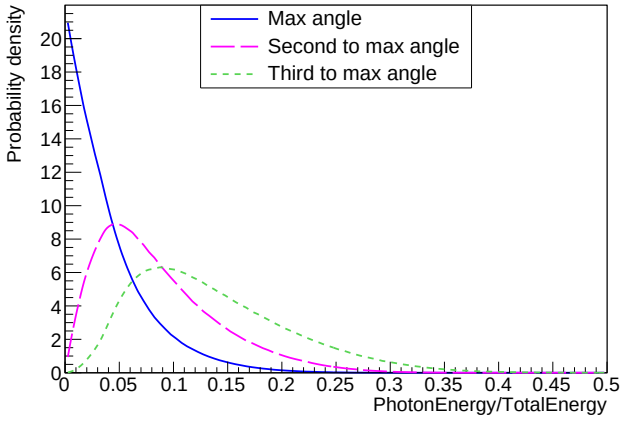

FIG. 4: Fraction of η-meson energy, carried by a photon that is maximally away from the original meson's direction, then second and third largest angles.

In this work we investigated this assumption and demonstrated that there are several potential factors that can produce bump-like features in the otherwise smooth spectrum of diphotons in the Standard Model. They are associated with calorimeter granularity, experimental cuts, and single photon misidentification. Of course, we cannot really claim that these bumps are indeed seen in experiment or even that they could be seen at LHC at all, as this would require to make a number a number of checks of our hypothesis, listed below.

1. As the neutral mesons are part of jets (probably carrying a large fraction of jet's p_T), making stronger photon isolation cuts should decrease the excess (while it should not affect the actual physical diphoton signal of course).

2. The region around $E \sim 350-400$GeV in single photon (photon + jet) spectrum may reveal a feature if our hypothesis is correct.

3. Finally, the best way to check this hypothesis is to perform the diphoton analysis over a Standard Model Monte Carlo simulations, using full detector simulation and applying the same types of cuts as in [1, 2],

Clearly, our results are rather qualitative, as the detector responses, in particular the isolation requirements used in the experimental analysis for suppression of jet background, were very crudely modeled in this work. First of all, to estimate the size of this effect (the total number of events in the "excess") we need to know the absolute number of isolated η-mesons at energies of interest. We understand that this number is tiny which

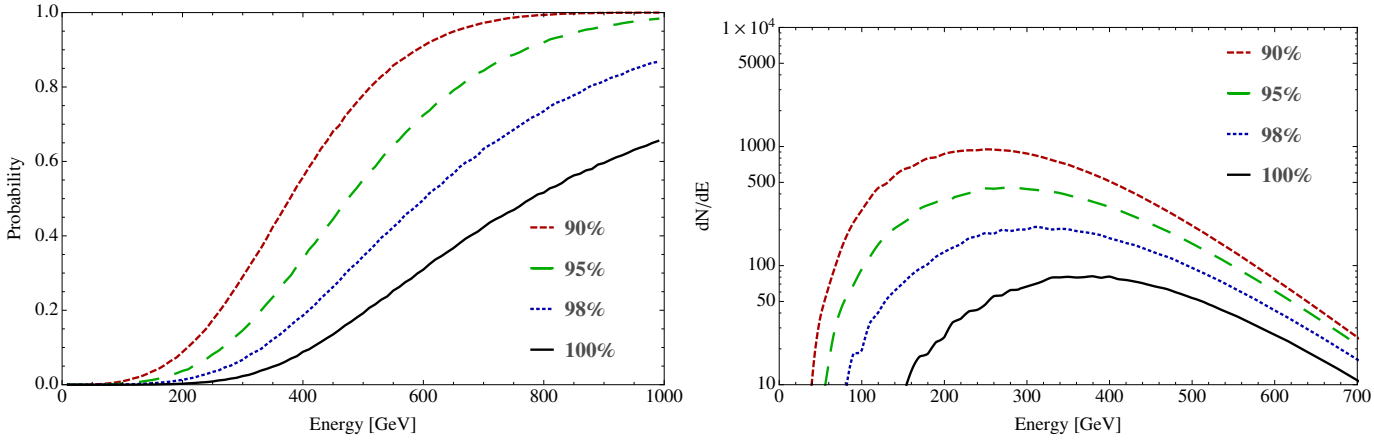

FIG. 5: *Left:* Probability that a fraction of the total energy carried by some of 6γ is deposited in a single pixel. *Right:* The same probability convoluted with Eq. (4).

makes it more difficult to estimate. Additional details of photon reconstruction also affect shape and position of the bump (and our Fig. 5 illustrates this).

Even if the 750 GeV excess will not be confirmed with more data or with refined analysis, it is important to understand whether the observed excess was the fluctuation or unaccounted background contribution as our note suggests. As the searches in the diphoton channel will continue, clarifying the exact shape of the Standard Model diphoton background will remain an important question.

A final remark. None of the authors of this paper is an expert in detector physics, nor do we have an access to details of the experimental analysis or to large scale Monte-Carlo simulations which can estimate the η production. Still, we find it quite curious that the appearing bump energy scale is in the interesting region around 750 GeV, and that the η decays (to the best of our knowledge) were not discussed in this connection. These considerations lead us to idea to make this note public.

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