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11 Jato the multi TeV scale with a Uigge valder using 11 $\frac{1}{12}$ Into the multi-TeV scale with a Higgs golden ratio

13 78 $\frac{1}{14}$ Abdelhak Djouadi^a, Jeremie Quevillon ^b, Roberto Vega-Morales and a more contained by the state of the

15 80 ^a *Laboratoire de Physique Théorique, Université Paris–Sud and CNRS, F-91405 Orsay, France*

16 by Theoretical Particle Physics & Cosmology, Department of Physics, King's College London, London, WC2R 2LS, United Kingdom 61 17 \sim

¹⁹ ARTICLE INFO ABSTRACT ⁸⁴

20 and the state of *Article history:* Received 10 October 2015 Received in revised form 29 March 2016 Accepted 6 April 2016 Available online xxxx Editor: G.F. Giudice

²¹ Article history: **Article history:** The State of the upgrade of the LHC, the couplings of the observed Higgs particle to fermions and gauge bosons ⁸⁶ 22 87 will be measured with a much higher experimental accuracy than current measurements, but will still 23 Betterved in revised by in 29 March 2016 **by an order 10% theoretical uncertainty.** In this paper, we re-emphasize the fact that the ratio 88 24 89 of Higgs signal rates into two photons and four leptons, *^Dγγ* = *σ(pp* → *^H* → *γγ)/σ(pp* → *^H* → *Z Z*[∗] → 25 90 4±*)* can be made free of these ambiguities. Its measurement would be limited only by the statistical and ₂₆ 26 26 2015 2016 2016 101 Systematic errors, which can in principle be reduced to the percent level at a high-luminosity LHC. This decay ratio would then provide a powerful probe of new physics effects in addition to high precision ₉₂ 28
quarks and vector bosons can be constrained at the percent level and that new Higgs or supersymmetric 29 94 particles that contribute to the H*γγ* loop can be probed up to masses in the multi-TeV range and possibly 30 95 larger than those accessible directly. electroweak observables or the muon $g - 2$. As an example, we show that the Higgs couplings to top

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1. Introduction

₃₉ The newly begun LHC run will allow for a more thorough prob- these two channels have been measured with an accuracy at the ₁₀₄ $_{40}$ ing of the electroweak symmetry breaking (EWSB) scale and search level of 15% if only the statistical and systematic errors are taken $_{105}$ 41 for physics beyond the Standard Model (SM). Most beyond the SM antional account [\[5–7\].](#page-7-0) At a HL-LHC, one expects that the statistical er-42 scenarios that address the so-called hierarchy problem such as su- for, which is presently of $\mathcal{O}(10\%)$, will drop by more than an order $_{107}$ $_{43}$ persymmetry, extra space–time dimensions, or composite models, of magnitude. The systematic errors could also be significantly re- $_{44}$ predict the existence of new particles with masses at the TeV scale duced. Hence, an experimental accuracy at the percent level could $_{109}$ 45 or below [\[1\].](#page-7-0) The search for these new particles can of course be in principle be achieved for these two channels at a HL-LHC. Un-46 done by directly producing them and with the increase in cen-
tortunately, this precision will be spoiled by the large theoretical and the indefical and the large theoretical $\frac{1}{111}$ $_{47}$ ter of mass energy by almost a factor of two, the LHC will indeed uncertainties that affect the two channels, which are expected to $_{112}$ 48 by probe higher mass scales than currently. The search could also be $O(10)\%$ [2,3]. The newly begun LHC run will allow for a more thorough probfor physics beyond the Standard Model (SM). Most beyond the SM events than collected so far.

36 101 37 **1. Introduction** 4ℓ (with $\ell = e, \mu$) decay modes. In fact, already at the previous run 102 $\frac{1}{38}$ 103
38 103 with $\sqrt{s} = 7-8$ TeV and ≈ 25 fb⁻¹ data, the signal strengths for $\frac{1}{102}$ level of 15% if only the statistical and systematic errors are taken ror, which is presently of $O(10%)$, will drop by more than an order of magnitude. The systematic errors could also be significantly reduced. Hence, an experimental accuracy at the percent level could in principle be achieved for these two channels at a HL-LHC. Unfortunately, this precision will be spoiled by the large theoretical uncertainties that affect the two channels, which are expected to be O*(*10*)*% [\[2,3\].](#page-7-0)

49 done indirectly by performing more precise measurements of the let has been advocated in many instances, in particular in 114 $_{50}$ observed Higgs boson couplings, as they are sensitive to the virtual Refs. [8,9], that the theoretical uncertainties can be eliminated by $_{115}$ $_{51}$ effects of the new particles. These precision measurements will be performing ratios of signal rates when considering the same Higgs $_{116}$ ₅₂ allowed by the large increase in statistics that will be due not only production mode (choosing exactly the same kinematical configu-₅₃ to the upgrade in energy [\[2,3\]](#page-7-0) but also by the expected upgrade ration) but different final state decay channels. This is particularly 118 54 of the integrated luminosity. This will be particularly the case at the case for the ratio $D_{\gamma\gamma} = \sigma(pp \to H \to \gamma\gamma)/\sigma(pp \to H \to \gamma\gamma)$ 55 a high-luminosity LHC (HL-LHC) in which one expects to collect $ZZ^*\to 4\ell^{\pm}$) which will simply be given by the partial decay width 120 56 a few ab⁻¹ data [\[4\],](#page-7-0) some two orders of magnitude more Higgs into the very clean $H\to\gamma\gamma$ and $H\to 4\ell^\pm$ modes that have neg-121 57 122 ligible theoretical uncertainty. In fact, even some systematic errors 58 The indirect search for new physics effects will be particularly such as the one due to the luminosity measurement, will cancel 123 59 124 efficient in two very clean channels, the *^H* → *γγ* and *^H* → *Z Z*[∗] → 60 125 cal) uncertainties will be left implying that the decay ratio *Dγγ* 61 126 126 126 2010 Could be measured at the percent level at a HL-LHC, as also in-62 E-mail address: jeremie.quevillon@kcl.ac.uk (J. Quevillon). (a) dicated in Ref. [\[4\].](#page-7-0) This opens up an interesting possibility as this 127 It has been advocated in many instances, in particular in Refs. $[8,9]$, that the theoretical uncertainties can be eliminated by performing ratios of signal rates when considering the same Higgs production mode (choosing exactly the same kinematical configuration) but different final state decay channels. This is particularly the case for the ratio $D_{\gamma\gamma} = \sigma(pp \to H \to \gamma\gamma)/\sigma(pp \to H \to$ $ZZ^* \rightarrow 4\ell^{\pm}$) which will simply be given by the partial decay width into the very clean $H \to \gamma \gamma$ and $H \to 4\ell^{\pm}$ modes that have negsuch as the one due to the luminosity measurement, will cancel out in the ratio. Hence, only some experimental (mainly statisti-

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E-mail address: jeremie.quevillon@kcl.ac.uk (J. Quevillon).

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Table 1

The inclusive signal strengths in the two search channels $H \rightarrow \gamma \gamma$ and *ZZ* as mea-sured by ATLAS [\[5\]](#page-7-0) and CMS [\[6\]](#page-7-0) with the statistical and systematic (theoretical and experimental) errors indicated. The theoretical uncertainty alone is shown in parentheses.

Channel	ATI AS	CMS
$\mu_{\nu\nu}$	$1.17_{-0.23}^{+0.23}{}_{-0.11}^{+0.16}{}_{-0.08}^{+0.12}$	$1.14 + 0.21 + 0.16 + 0.09$ $-0.21 - 0.10 + 0.05$
μ_{ZZ}	$1.46^{+0.35}_{-0.31}$ $^{+0.19}_{-0.13}$ $(^{+0.18}_{-0.11})$	0.93 +0.26 +0.13 -0.23 -0.09

accuracy will be comparable to the expected size of effects from TeV scale new particles that could alter Higgs couplings and, in particular, the *Hγγ* loop induced vertex [\[10,11\].](#page-7-0) This would make *Dγγ* a comparable probe of new physics as some high-precision electroweak observables such as the *W* boson mass M_W or the electroweak mixing angle $\sin^2 \theta_W$ as well as the muon anomalous magnetic moment $(g - 2)$ _μ [\[12\].](#page-7-0)

18 and the emphasize in this necessation of the inclusion of the total theory uncertainty indeed closer to \approx 10%. We emphasize in this note that a 1% measurement of *Dγγ* would allow to probe new physics scales above a TeV, in some cases higher than those accessible in direct searches for new particles. To illustrate this point, we examine various specific cases including the Minimal Supersymmetric Standard Model (MSSM) [\[10,](#page-7-0) [11\],](#page-7-0) anomalous effective Higgs couplings to SM particles, and composite Higgs models. Before exploring these possibilities, we first discuss the signal strengths in the $H \rightarrow \gamma \gamma$, ZZ^* search channels and their ratio $D_{\gamma\gamma}$ as well as the present and expected precision at the LHC.

2. The $\gamma \gamma$ and $4\ell^{\pm}$ signal strengths and $D_{\gamma \gamma}$ decay ratio

Among the Higgs signal strengths in the various search channels at the LHC, defined as

$$
\mu_{XX} = \sigma(pp \to H \to XX)/\sigma(pp \to H \to XX)|_{SM},\tag{1}
$$

³⁵ two have been precisely measured by the ATLAS and CMS Collab- of a 125 GeV Higgs boson. The uncertainties in the partial de- 100 36 orations: $\mu_{\gamma\gamma}$ and μ_{ZZ} , corresponding to the very clean $H \to \gamma\gamma$ cay widths in all the non-hadronic decay channels such as $H \to 101$ 37 and $H \to ZZ^* \to 4\ell^{\pm}$ (with $\ell = e, \mu$) final states. The latest re-
 $\gamma \gamma$, ZZ are in turn completely negligible. Hence, even if the the-38 sults quoted by the two experiments [\[5,6\]](#page-7-0) with the \approx 25 fb⁻¹ data oretical knowledge of the various components that make the $\mu_{\gamma\gamma}$ 103 39 collected at \sqrt{s} = 7 + 8 TeV are shown in Table 1, including the and μ_{ZZ} signal strengths improve by the time of a HL-LHC, the 104 40 105 statistical (first) and the systematic (second) errors. The latter in-41 106 volve systematic experimental errors, including ≈ 2*.*5% error due to 42 the luminosity measurement, as well as the theoretical uncertainty **Or** course all these problems disappear at once if we consider 107 43 due to scale variation (to account for missing higher orders) and the ratio of the $H\to\gamma\gamma$ and $H\to ZZ^*$ signal strengths for a given to 108 ⁴⁴ the errors in the parametrization of the parton distribution func- production channel, 109 45 tions (PDFs) and the measurement of the strong coupling constant σ (nn $(H \setminus W)$) σ (nn $(H) \setminus BP(H \setminus W)$) $(10^{10} \sigma)^{110}$ 46 (α_s). These errors are all then combined in quadrature (instead $D_{\gamma\gamma} = \frac{\alpha_{\gamma}P}{\gamma_{\gamma}} = \frac{1}{\gamma_{\gamma}} \frac{1}{\gamma_{\gamma}} = \frac{1}{\gamma_{\gamma$ 47 of linearly as advocated in [\[2,3\]\)](#page-7-0). The impact of the theoretical $O(pp \rightarrow H \rightarrow ZZ)$ $O(pp \rightarrow H) \times BC(H \rightarrow ZZ)$ ⁴⁸ uncertainties alone as assumed by ATLAS and CMS is shown in $\Gamma(H \to \gamma \gamma)$ c_{ν}^2 49 parentheses. $\qquad \qquad = \frac{1}{\Gamma(U_1 - 773)} \propto -\frac{1}{2}$. (2) 114 two have been precisely measured by the ATLAS and CMS Collabcollected at \sqrt{s} = 7 + 8 TeV are shown in Table 1, including the parentheses.

50 As can be seen in Table 1, the largest source of uncertainty at $\frac{15}{2}$ As can be seen in Table 1, the largest source of uncertainty at 51 present is of statistical nature and amounts to \approx 20% for $\mu_{\gamma\gamma}$ and If the same kinematical configuration for the Higgs production 116 52 ≈ 30% for $μ_{ZZ}$. This error will be drastically reduced at the next mechanism is adopted for both $H \to γγ$ and $H \to ZZ^*$, then the 117 53 LHC run as the Higgs data sample in these channels will be sig-
118 fiducial production cross section cancels in the ratio. One is then in the ratio. One is then in ⁵⁴ nificantly increased. In the main Higgs production process $gg \to H$ left not only with the ratio of the branching ratios but with the 119 ⁵⁵ which generates more than 85% of the total Higgs cross section ratio of the partial Higgs decay widths, as the total Higgs width can-
 ⁵⁶ even before kinematical cuts are applied, the cross section will cels out in the ratio. The two partial widths are affected by very ¹²¹ 57 increase by a factor $\simeq 2.5$ when moving from a center of mass small theoretical uncertainties, presently below 1% [16]. In fact, to 122 58 energy of 8 TeV to 14 TeV. Assuming 3000 fb⁻¹ at a HL-LHC, one first approximation and up to some kinematical factors and small 123 ⁵⁹ would have 300 times more events than what has been collected radiative corrections that are known with sufficient precision (in t²⁴ 60 125 so far. This sample will allow the reduction of the statistical er-61 rors quoted in Table 1 by a factor \approx 20, leading to an expected $\frac{1}{1}$ Note that the therminal uncertainties in the unter base fusion (10F) shaped 62 precision of $O(1-2\%)$ for $\mu_{\gamma\gamma}$ and μ_{ZZ} . The systematic uncer-
are much smaller for the inclusive cross section $\leq 5\%$ [2] However the rate is $\frac{63}{28}$ tainties listed above are dominated by the theoretical ones as the $\frac{63}{28}$ in erganization conduction and the finally theoretical ones as the $\frac{63}{28}$ in erganization conduction and the finally theoreti ⁶⁴ experimental errors are rather small in these two cleanly measured applied, increasing the statistical error to $\mathcal{O}(5\%)$. In addition, it was recently shown 65 channels. Channels are larger for the cross section with the VBF cuts [\[15\].](#page-7-0) ¹³⁰ \approx 30% for μ_{ZZ} . This error will be drastically reduced at the next LHC run as the Higgs data sample in these channels will be significantly increased. In the main Higgs production process $gg \rightarrow H$ which generates more than 85% of the total Higgs cross section channels.

¹ Table 1 and the systematic uncer- $\frac{66}{1}$ and $\frac{86}{1}$ and $\frac{$ 2 The inclusive signal strengths in the two search channels $H\to\gamma\gamma$ and ZZ as mea-**can trainties, one would be left only with the theoretical uncertain-** 67 3 Sured by ALLAS [5] and CMS [6] With the statistical and systematic (theoretical and the statistic mainly due to the unknown higher QCD orders 68 4 these the extraction of the contraction of the contraction of the contraction of the contraction of the control of the controller controller controller controller controller controller controller controller controller co $\frac{1}{2}$ $\frac{1}{2}$ 6 **Example 1** and which the ATLAS and CMS Col- $\mu_{\gamma\gamma}$ 1.17 -0.23 -0.11 (-0.08) 1.14 -0.21 -0.10 (-0.05) laborations assume to be of order ± 10 %. In fact, at the time the 72 8 μ_{ZZ} 1.46 $^{+0.33}_{-0.31}$ $^{+0.13}_{-0.11}$ ($^{+0.10}_{-0.11}$) 0.93 $^{+0.23}_{-0.23}$ $^{+0.19}_{-0.09}$ measurement was made, this uncertainty was larger as the scale 73 9 and PDF + α_s uncertainties in $gg \rightarrow H$ were both about $\pm 7.5\%$ 74 10 accuracy will be comparable to the expected size of effects from $\frac{1}{2}$ for a $M_H = 125$ GeV Higgs at $\sqrt{s} = 8$ TeV (they stay at the same 75 accuracy will be comparable to the expected size of effects from
Tevel at $\sqrt{s} = 14$ TeV). According to Refs. [\[2,3\],](#page-7-0) as they are of the-
TeV scale new particles that could alter Higgs couplings and, in $\frac{12}{12}$ retical is the Have lowed with $\frac{12}{10}$ $\frac{11}{10}$ This would make the control nature, these two uncertainties should not be treated as 77 13 **13** Find the showledge that the state of the total theoretical uncer- 78 14 $\frac{p}{p}$ a comparable probe of new physics as some mgn precision tainty should then be $\approx \pm 15\%$ and hence larger than in Table 1. 79 $\frac{15}{15}$ shortcover with $\frac{1}{2}$ and $\frac{1}{2}$ a 16 Becombing and the corrections of the corrections increase the cross section 16
magnetic \approx 10.111 $\frac{17}{17}$ in the scale dependence to less than 3%, $\frac{82}{17}$ only slightly, they reduce the scale dependence to less than 3%, $\frac{82}{17}$

19 19 10000 bights that the second proposal in the second of the second proposal in 20 also to illustrate this point we available various considered so far, the one due to the use of an effective 85 $\frac{21}{100}$ shows the Minimal Cuneral metric Candard Model (MCCM) $\frac{10}{10}$ field theory (EFT) approach to calculate some corrections beyond 86 22 87 and 22 23 approximate the subleading the substitution of the subject of the subleading *b*-quark loop contri- 88 24 Butles Frances are the contribution when it interferes with the 89
discuss the signal strengths in the $H \to \nu \nu Z Z^*$ search channels $\frac{25}{100}$ and their principles in the masses of the masses of the properties t -loop and which is currently known only to NLO accuracy $[14]$. ⁹⁰ 26 at the UIC state $2\gamma\gamma$ as well as the present and expected precision. Depending on how conservative one is, this uncertainty is expected $\frac{91}{20}$ to be in the range 4% [\[2\]](#page-7-0) to 7% [\[3\],](#page-7-0) bringing us back to the $\approx 15\%$ 32 28 93

29 94 Furthermore, uncertainties in Higgs decay branching ratios, 30 Among the Higgs signal strengths in the various search chan-
 $\mathcal{O}(5\%)$ for both the $H \to \gamma\gamma$ and ZZ^* decays [\[16\],](#page-7-0) 95 31 31 Final strategies in the various search chan
Should be taken into account. In fact, this uncertainty is solely 32 due to the QCD ambiguities that affect the $H \rightarrow bb$ partial width 97 33 $\mu = \tau$ (np $H \times Y \times (\tau(m) \times H \times Y)$) (mainly the parametric uncertainties due to the inputs *b*-quark 98 α_s μ_{XX} = σ (p p \rightarrow n \rightarrow λ λ)/ σ (p p \rightarrow n \rightarrow λ λ)/ σ (p p \rightarrow n \rightarrow λ λ)/ σ cay widths in all the non-hadronic decay channels such as $H \rightarrow$ *γγ , Z Z* are in turn completely negligible. Hence, even if the theoretical knowledge of the various components that make the $\mu_{\gamma\gamma}$ theoretical uncertainties will stay of order 10%, thus limiting the power to probe TeV scale physics.

> Of course all these problems disappear at once if we consider the ratio of the $H \rightarrow \gamma \gamma$ and $H \rightarrow ZZ^*$ signal strengths for a given production channel,

$$
D_{\gamma\gamma} = \frac{\sigma(pp \to H \to \gamma\gamma)}{\sigma(m \to H \to ZZ^*)} = \frac{\sigma(pp \to H) \times BR(H \to \gamma\gamma)}{\sigma(m \to H) \times BR(H \to ZZ^*)}
$$

$$
D' \gamma \gamma = \frac{}{\sigma(pp \to H \to ZZ^*)} = \frac{}{\sigma(pp \to H) \times BR(H \to ZZ^*)}
$$

$$
=\frac{\Gamma(H\to\gamma\gamma)}{\Gamma(H\to ZZ^*)}\propto\frac{c_\gamma^2}{c_Z^2}.\tag{2}
$$

If the same kinematical configuration for the Higgs production cels out in the ratio. The two partial widths are affected by very small theoretical uncertainties, presently below 1% [\[16\].](#page-7-0) In fact, to first approximation and up to some kinematical factors and small radiative corrections that are known with sufficient precision (in

 $^{\rm 1}$ Note that the theoretical uncertainties in the vector boson fusion (VBF) channel are much smaller for the inclusive cross section, $\leq 5\%$ [\[2\].](#page-7-0) However, the rate is an order of magnitude smaller than for gluon fusion even before the VBF cuts are applied, increasing the statistical error to $\mathcal{O}(5%)$. In addition, it was recently shown

TICI E IN

EVALUATE: 1. Contours of $D_{YY} + \Delta D_{YY}$ in the [c_V, c_t] (left) and [c_t/c_V, c_t/c_V] (right) planes assuming $D_{YY} = 1$ and $\Delta D_{YY} = 1$ % (black), 2% (red), 3% (blue). (For interpretation of a 20 and the contract of the con the references to color in this figure legend, the reader is referred to the web version of this article.)

²¹ particular when *M_H* will be more precisely measured), *D_{γγ}* will the *Hγγ* vertex as $M_H^2/M_{\rm NP}^2$. Nevertheless, if their coupling to the $\frac{86}{87}$ be simply given by the ratio of the squared "reduced" Higgs cou-
be simply given by the ratio of the squared "reduced" Higgs cou-
 $\frac{1}{2}$ Higgs is $\mathcal{O}(\alpha_W)$, contributions of order 1% could be achieved for pling to photons and massive gauge bosons,² $D_{\gamma\gamma} \propto c_{\gamma}^2/c_{V}^2$ where masses $M_{\rm NP} \gtrsim 1$ TeV. $\frac{24}{3}$ pm, to photomorphic massive gauge bosons, $\frac{24}{3}$ y $\frac{24}{3}$ where $\frac{24}{3}$ mass $\frac{24}{3}$ particular when M_H will be more precisely measured), $D_{\gamma\gamma}$ will $c_X \equiv g_{HXX}/g_{HXX}^{SM}$.

26 Another interesting aspect of this ratio is that systematic un-
26 Another interesting aspect of this ratio is that systematic un- $_{27}$ certainties common to both channels, such as the one due to higgs-photon interactions generated via higher dimensional opera- $_{28}$ the luminosity, will also cancel out leaving only the statistical the source neavy particles have been integrated out of in composite $_{93}$ 29 errors. Combining $Δμ_{γγ}$ and $Δμ_{ZZ}$ in quadrature gives a sta-**Allages** scenarios. The relevant terms in the effective Lagrangian can 30 tistical uncertainty of $\Delta D_{\gamma\gamma} \approx 2\%$ at the HL-LHC. In fact, the solution as $V = 246$ GeV), $_{31}$ recently released ATLAS + CMS combined analysis of the Higgs H (2003 μ +11 μ 2 = π 11 μ = π 2 = π 11 π = π 2 = π 32 properties gives a statistical (equivalent to total) uncertainty of $\mathcal{L} = \frac{1}{\pi} (c_V (2 M_W^2 W_W^{-\mu} + M_Z^2 Z_\mu Z^\mu) - m_t t (c_t + i c_t \gamma^3) t$ $\Delta_{\text{Run1}}^{\text{comb}} D_{\gamma\gamma} = +26\%$ [\[7\]](#page-7-0) which would then lead to an expected accu-
98 $\frac{34}{4}$ racy of Δ_{FU-LHC} $D_{\gamma\gamma} \approx \frac{+1.5\%}{-1.2\%}$. Such a high level of accuracy in Higgs $+ \frac{c_{\gamma\gamma}}{4} F^{\mu\nu} F_{\mu\nu} + \frac{c_{\gamma\gamma}}{4} F^{\mu\nu} F_{\mu\nu}$ (3) 99 35 physics, $\approx \pm 1\%$, was envisaged only in the case of observables to $\frac{4}{1}$ $\frac{4}{1}$ $\frac{4}{1}$ ³⁶ be measured in the "cleaner" environment of future e^+e^- collid-
 $\frac{1}{2}$ where we have allowed for both CP even (c_X) and CP odd (\tilde{c}_X) be measured in the "cleaner" environment of future *e*⁺*e*[−] colliders.³

38 With this level of expected precision, the ratio $D_{\gamma\gamma}$ may pro-
At *tree level* in the SM we have $c_V = c_t = 1$ and $c_{\gamma\gamma} = \tilde{c}_t = \tilde{c}_{\gamma\gamma} = 0$ 103 ³⁹ vide a high precision electroweak observable at the LHC. And be- while at one-loop a contribution $c_{\nu\nu}\approx -0.008$ is generated. 104 40 cause it involves the loop induced $H \to \gamma \gamma$ channel in which The loop W, t loop contributions and the effective $H\gamma\gamma$ inter-⁴¹ many charged particles could contribute, the decay ratio would al- action enter into $D_{\nu\nu}$ as 42 107 low us to probe more deeply the TeV scale as will be discussed With this level of expected precision, the ratio *Dγγ* may pro-

⁵⁵ 120
-- heavy (as their coupling to the Higgs is proportional to the mass), Focusing first on deviations which enter through the top and W

Higgs is $\mathcal{O}(\alpha_W)$, contributions of order 1% could be achieved for masses $M_{\rm NP}$ \gtrsim 1 TeV.

 $c_X = g_{HXX}/g_{HXX}^{SM}$. The new physics contributions to $D_{\gamma\gamma}$ can enter either via deviations in the *W* and top couplings to the Higgs or through 'contact' Higgs–photon interactions generated via higher dimensional operators once heavy particles have been integrated out or in composite Higgs scenarios. The relevant terms in the effective Lagrangian can be written as ($v = 246$ GeV),

$$
\mathcal{L} = \frac{H}{v} \Big(c_V (2M_W^2 W_\mu^+ W^{-\mu} + M_Z^2 Z_\mu Z^\mu) - m_t \bar{t} (c_t + i \tilde{c}_t \gamma^5) t
$$

$$
c_{\gamma \gamma \mu \nu \tau} \bar{c}_{\gamma \gamma \bar{\nu} \mu \nu \tau} \Big)
$$
 (3)

$$
+\frac{c_{\gamma\gamma}}{4}F^{\mu\nu}F_{\mu\nu}+\frac{\tilde{c}_{\gamma\gamma}}{4}\tilde{F}^{\mu\nu}F_{\mu\nu}\Big) \tag{3}
$$

 37 ers.³ couplings and assumed custodial symmetry to set $c_Z = c_W = c_V$. ¹⁰² while at one-loop a contribution $c_{\gamma\gamma}$ ≈ −0.008 is generated.

The loop *W ,t* loop contributions and the effective *Hγγ* interaction enter into *Dγγ* as

with some examples below.

\n
$$
D_{\gamma\gamma} \equiv \mu_{\gamma\gamma}/\mu_{ZZ} = \left| 1.28 - 0.28 \left(c_t/c_V \right) + \left(c_{\gamma\gamma}/c_V \right) \right|^2
$$
\n
$$
+ \left| 0.43 \left(\tilde{c}_t/c_V \right) + \left(\tilde{c}_{\gamma\gamma}/c_V \right) \right|^2
$$
\n44

\n3. Probing effective couplings and a composite Higgs

\n(4)

46 111 where the numerical values correspond to the *W* and top loop ⁴⁷ The ratio $D_{\gamma\gamma}$ measures the magnitude of the *Hγγ* loop ver-
tunctions [10,11] for $M_H = 125$ GeV. As is clear, $D_{\gamma\gamma}$ is only sen-⁴⁸ tex normalized to the *HVV* coupling. In the SM, the former is sitive to the ratios of couplings c_v/c_v , \tilde{c}_v/c_v and not the absolute ⁴⁹ generated by contributions from the *W* boson and the heavy top magnitude of the couplings. Note also that *D_{ine}* cannot lift degen- $\frac{50}{2}$ quark (neglecting smaller contributions such as from the *b*-quark) eracies such as when $c_v \rightarrow -c_v$ and is not directly sensitive to CP $\frac{1}{51}$ which interfere destructively. In beyond the SM scenarios, any par-
wilation which requires interference between the CP even and CP 52 ticle that is electrically charged and couples to the Higgs boson $\frac{117}{\text{odd}}$ couplings.⁴ Below we examine new physics possibilities which 53 118 will contribute to the *Hγγ* loop. However, contrary to SM parti- $\frac{54}{2}$ cles which leave their imprint in the loop even if they are very countings. functions [\[10,11\]](#page-7-0) for $M_H = 125$ GeV. As is clear, $D_{\gamma\gamma}$ is only sensitive to the ratios of couplings c_X/c_V , \tilde{c}_X/c_V and not the absolute magnitude of the couplings. Note also that *Dγγ* cannot lift degeneracies such as when $c_X \rightarrow -c_X$ and is not directly sensitive to CP violation which requires interference between the CP even and CP odd couplings. 4 Below we examine new physics possibilities which can enter into *Dγγ* via *W* and top couplings or effective *Hγγ* couplings.

⁵⁶ 121
heavy new physics (NP) particles will generically decouple from couplings, we take $C_{yy} = \tilde{C}_{yy} = 0$ and study how well the C_{xy} and 57 ineavy new physics (NP) particles will generically decouple from couplings, we take $c_{\gamma\gamma} = \tilde{c}_{\gamma\gamma} = 0$ and study how well the c_V and 122 c_t , \tilde{c}_t couplings can be constrained with $D_{\gamma\gamma}$. We show in Fig. 1 $_{123}$ ⁵⁹ ² Here, we assume $c_W = c_Z$ as is the case in the SM and most of its extensions. In *fright*) planes assuming $D_{\gamma\gamma} = 1$ and $\Delta D_{\gamma\gamma} = 1\%$. 2% and 3%. In Focusing first on deviations which enter through the top and *W* contours of $D_{\gamma\gamma} \pm \Delta D_{\gamma\gamma}$ in the [*c_V , c_t*] (left) and [*c_t*/*c_V* , \tilde{c}_t /*c_V*] (right) planes assuming $D_{\gamma\gamma} = 1$ and $\Delta D_{\gamma\gamma} = 1\%$, 2% and 3%. In the $[c_V, c_t]$ plane, focusing on the region around the SM point

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⁶⁰ fact, the ratio c_W/c_Z measures the breaking of custodial symmetry and is related to the fact of province of the ratio $\frac{25}{100}$ and $\frac{1}{25}$ and $\frac{1}{25}$ and $\frac{1}{25}$ and $\frac{1}{25}$ and $\frac{1}{25}$ and $\frac{1}{2$ 61 the ρ parameter, $\rho \equiv M_W^2/(\cos^2 \theta_W M_Z^2) = c_W^2/c_Z^2$ which is very close to unity [\[12\].](#page-7-0) The [CV, Ct] plane, focusing on the region around the Sivi point 126 62 One can combine the results for $H \rightarrow ZZ$ and $H \rightarrow WW$ to increase the statistical accuracy if the systematics in the latter mode could also be made very small.

⁶⁴ colliders was considered with the motivation that it would allow for a measurement study of differential distributions as in *H* → 4*l*, 2*lγ* or *H* → *γγ* where the photons ³ In the past, the possibility to turn linear e^+e^- machines into high-energy *γγ* colliders was considered with the motivation that it would allow for a measurement

⁶³ 128 ⁴ To be sensitive to such effects requires combination with other channels or the 65 of the *Hγγ* coupling at the few percent level [\[11\].](#page-7-0) The state of the detector, see Refs. [18]. The of the *Hγγ* coupling at the few percent level [11]. The state of the detector; see Refs. [18]. convert in the detector; see Refs. [\[18\].](#page-7-0)

19 **Fig. 2.** Left: As in [Fig. 1,](#page-3-0) but in the $[c_{\gamma\gamma}, \tilde{c}_{\gamma\gamma}]$ plane. Right: Same as left except now in the [[g_{NP}], M_{NP}] plane where we have rescaled the effective coupling as $c_{\gamma\gamma} \rightarrow a$ $\frac{1}{20}$ $(\alpha/4\pi)(g_{NP}v/M_{NP})^2$. We also show contours of $\Delta D_{\gamma\gamma} = 1\%$ and 10% for the CP odd coupling (dashed lines), similarly rescaled as $\tilde{c}_{\gamma\gamma} \to (\alpha/4\pi)(\tilde{g}_{NP}v/M_{NP})^2$ (see text).

 $c_t = c_V = 1$ which is preferred by present data [\[12\],](#page-7-0) one sees $c_t/c_V = [1 - (1 + n)\xi]/((1 - \xi))$, $\tilde{c}_t = c_{\gamma\gamma} = \tilde{c}_{\gamma\gamma} = 0$, (5) ₈₇ $\frac{23}{23}$ that $D\gamma\gamma$ constraints of an is a positive integer dictated by the fermion representa- $_{24}$ ing $c_V = 1$, $D_{\gamma\gamma}$ could constrain the CP-even top coupling at the tion. In Fig. 3 (left), we display $D_{\gamma\gamma}$ as a function of the com- $\frac{25}{26}$ level of $t_f \approx 1-2/6$ for $\Delta D\gamma\gamma$ 5. Clearly for the [*t_t*/τ/τ/τ/τ/τ] positeness scale *f* for $n = 0, 1, 2$. One first notes that $D\gamma\gamma$ is not so $\frac{26}{12}$ plane, $D_{\gamma\gamma}$ alone is not enough to int the degeneracy winch exists
or when $\tilde{c}_t \rightarrow -\tilde{c}_t$ even for $c_V = 1$ However if one assumes that the $\frac{27}{100}$ when $\frac{1}{4}$ $\frac{1}{2}$ $\frac{1}{2}$ on *ξ* drops out. For the cases of *n* = 1 and *n* = 2, we see that with $\frac{92}{100}$ on *ξ* drops out. For the cases of *n* = 1 and *n* = 2, we see that with $\frac{92}{100}$ 28 Cr-0dd coupling $t_t \approx 0$ (as suggested by ineasurements of electric and 1% measurement of $D_{\gamma\gamma}$, compositeness scales of 2–3 TeV can 93 29 dipole moments for instance [\[19\]\)](#page-7-0), then $D_{\gamma\gamma}$ would constrain the **propertially be probed** that $D_{\gamma\gamma}$ constrains c_t and c_V to lie in a narrow band. Assumlevel of $c_t \approx 1-2\%$ for $\Delta D_{\gamma\gamma} \sim 1\%$. Clearly for the $[c_t/c_V, \tilde{c}_t/c_V]$ plane, $D_{\gamma\gamma}$ alone is not enough to lift the degeneracy which exists when $\tilde{c}_t \rightarrow -\tilde{c}_t$ even for $c_V = 1$. However, if one assumes that the CP-odd coupling $\tilde{c}_t \approx 0$ (as suggested by measurements of electric CP-even coupling ratio c_t/c_V to ~2% for $\Delta D_{\gamma\gamma} \sim 1\%$.

 31 because the Higgs state arises as a pseudo-Goldstone boson of sponta-
the Higgs state arises as a pseudo-Goldstone boson of sponta- 32 entrough the $7/2$ enective couplings while the $\frac{1}{2}$ of the disc of the direct invariance [\[22\].](#page-7-0) The dilaton again couples to $\frac{97}{2}$ 33 plugs have SM-like values $\zeta y = \zeta t = 1$. On the fermion shot sauge bosons and fermions but it also has a direct coupling to θ $\frac{34}{24}$ rig. 2, we display contours of $D_{\gamma\gamma} + \Delta D_{\gamma\gamma}$ in the $[\iota_{\gamma\gamma}, \iota_{\gamma\gamma}]$ plane botons which is generated by the trace anomaly. Since all these $\frac{99}{24}$ 35 again assuming $D_{\gamma\gamma} = 1$ and $\Delta D_{\gamma\gamma} = 1\%$, 2%, 3%. Here also, $D_{\gamma\gamma}$ couplings depend on *ξ* in the same way, $\propto \sqrt{\xi}$, the ratio of widths also alone cannot lift all degeneracies but for $\tilde{c}_{\text{env}} \approx 0.1$ 36 divide California and degeneratives but for $\chi_{\gamma} \approx 0$ [19], one can po-
top intially obtain persont lovel constraints on the ratio $\epsilon_{\gamma}/\epsilon_{\gamma}$ is not directly sensitive to the composite scale f. The cou-Next, we examine the case where new physics enters only through the *Hγγ* effective couplings while the *W* and top couplings have SM-like values $c_V = c_t = 1$. On the left hand side of Fig. 2, we display contours of $D_{\gamma\gamma} + \Delta D_{\gamma\gamma}$ in the $[c_{\gamma\gamma}, \tilde{c}_{\gamma\gamma}]$ plane again assuming $D_{\gamma\gamma} = 1$ and $\Delta D_{\gamma\gamma} = 1\%$, 2%, 3%. Here also, $D_{\gamma\gamma}$ alone cannot lift all degeneracies but for $\tilde{c}_{\gamma\gamma} \approx 0$ [\[19\],](#page-7-0) one can potentially obtain percent level constraints on the ratio *cγγ /cV* .

38 The effective couplings $c_{\gamma\gamma}$, $\tilde{c}_{\gamma\gamma}$ are implicitly associated to 39 some new physics scale M_{NP} and scale as v^2/M_{NP}^2 , which sup-
 $c_t/c_V = (1 + \gamma_t)$, 40 presses the dimension-6 operators in the unbroken $SU(2)_L \times U(1)_Y$ $G = (SU_1 - \alpha / (4\pi) \times (h^{EM} h^{EM})$ 41 invariant phase from which they arise. To visualize which scales $\epsilon_{\gamma\gamma}/\epsilon \nu = \alpha/(\frac{4\pi}{\gamma} \times (\nu_{IR} - \nu_{UV})$, 42 can be probed, we perform the rescaling $c_{\gamma\gamma} \to (\alpha/4\pi)(g_{NP}v)$ $\tilde{c}_t = \tilde{c}_{\gamma\gamma} = 0$, (6) 107 43 M_{NP} ² where g_{NP} and M_{NP} are some generic new physics cou-
 g_{NP} is the anomalous dimensions which masses which masses the sum of the spannalous dimensions which masses the sum 44 pling and scales respectively. We again plot contours of $D_{\gamma\gamma}$ (right γ is the alternative state in the plittuight (IB) be 45 in Fig. 2), but now in the $[|g_{NP}|, M_{NP}]$ plane. We see for example $\frac{p_{I}}{I}$ functionally due to the intaility in the dituationer (OV) be $\frac{110}{I}$ 46 that $\Delta D_{\gamma\gamma} \approx 1\%$ would potentially allow us to probe scales as high tween the elementary and composite states associated with the 111 47 as 1.2 TeV for strongly coupled theories. We also show similar con-48 tours for the CP odd coupling which has similarly been rescaled as μ by infigural (ID) due to the spatial which is first that the state of solid to t $\tilde{c}_{\gamma\gamma} \to (\alpha/4\pi)(\tilde{g}_{NP}v/M_{NP})^2$. Since it does not interfere with the the final eq (in) due to the contribution of composite neigs to the 114 50 115 dominant *W* -loop contribution, the sensitivity is less strong and 51 even for $O(4\pi)$ couplings, only scales \lesssim 200 GeV can be probed
 ΔP in the $\log (4\pi/6^{(EM)})$ $\frac{1}{2}$ $\frac{1}{2}$ plane assuming again at which point the EFT approximation begins to break down.

53 Finally, let us briefly discuss contributions to $D_{\gamma\gamma}$ in two $D_{\gamma\gamma}=1$ and the usual $\Delta D_{\gamma\gamma}$ precision of 1%, 2% and 3%. One 118 ⁵⁴ generic composite Higgs scenarios. The first case is when the Higgs can see that for $b_{\rm in}^{\rm (m)} - b_{\rm in}^{\rm (m)}}^{\rm (m)} \approx 0$, as in the SM [22], γ can be 119 55 boson arises as a pseudo-Goldstone boson of a spontaneously bro- constrained at the 1–2% level for $\Delta D_{VV} = 1$ %. As we approach this 120 ⁵⁶ ken approximate global symmetry in a strongly interacting sec- level of precision it will start to become possible to exclude nega- 121 ⁵⁷ tor [20]. In this class of models, the HVV couplings are given by tive values of γ*t* for any $b_{IR}^{(EM)} - b_{UV}^{(EM)}$. There is also a degenerate 122 $c_V = \sqrt{1-\xi}$ where $\xi = v^2/f^2$ with *f* the compositeness scale or second region at $\gamma_t \sim 7$ which is not displayed. 59 124 the decay constant of the pseudo-Goldstone Higgs boson. The cou-⁶⁰ plings to fermions depend not only on the scale f, but also on **4. Probing the heavy new particles of the MSSM** 125 ⁶¹ the representations of the SM fermions under the global symme- 62 try group of the strongly interacting sector for which there are $\hskip 1.6cm$ We now examine one-loop contributions to the Higgs decay to $\hskip 1mm$ 127 63 128 many possibilities [\[21\].](#page-7-0) For the minimal case based on the SO*(*5*)* ⁶⁴ global symmetry broken to SO(4) the fermion couplings take the known, the MSSM possesses a two Higgs doublet structure that ¹²⁹ Finally, let us briefly discuss contributions to *Dγγ* in two generic composite Higgs scenarios. The first case is when the Higgs boson arises as a pseudo-Goldstone boson of a spontaneously brotor [\[20\].](#page-7-0) In this class of models, the *HVV* couplings are given by form [\[21\],](#page-7-0)

$$
c_t = c_V = 1
$$
 which is preferred by present data [12], one sees $c_t/c_V = [1 - (1+n)\xi]/((1-\xi))$, $\tilde{c}_t = c_{\gamma\gamma} = \tilde{c}_{\gamma\gamma} = 0$, (5)

tion. In [Fig. 3](#page-5-0) (left), we display $D_{\gamma\gamma}$ as a function of the compotentially be probed.

 $\frac{30}{20}$ Cr-even coupling ratio $t_f/\sqrt{10} \approx 2.6$ in $\frac{20}{27}$ is extension. As a second scenario, we consider the case of a dilaton where $\frac{95}{20}$ 37 102 pling ratios entering *Dγγ* are explicitly given by [\[22\],](#page-7-0)

$$
c_t/c_V = (1 + \gamma_t), \qquad \qquad \text{10}
$$

$$
c_{\gamma\gamma}/c_V = \alpha/(4\pi) \times (b_{\rm IR}^{\rm EM} - b_{\rm UV}^{\rm EM}),
$$

$$
\tilde{c}_t = \tilde{c}_{\gamma\gamma} = 0,\tag{6}
$$

where γ_t is the anomalous dimensions which measures the explicit breaking due to the mixing in the ultraviolet (UV) between the elementary and composite states associated with the top quark. The β function coefficients, b_{UV}^{EM} and b_{IR}^{EM} , parameterize the explicit breaking of scale invariance in the ultraviolet and the infrared (IR) due to the contribution of composite fields to the running of the photon gauge coupling [\[22\].](#page-7-0)

52 at which point the EFT approximation begins to break down. $\Delta D_{\gamma\gamma}$ in the $[\alpha/4\pi (b_{IR}^{(EM)} - b_{UV}^{(EM)}), \gamma_t]$ plane assuming again 117 In the right-hand side of [Fig. 3,](#page-5-0) we show contours of $D_{\gamma\gamma}$ + can see that for $b_{\text{IR}}^{(\text{EM})} - b_{\text{UV}}^{(\text{EM})} \approx 0$, as in the SM [\[22\],](#page-7-0) γ_t can be constrained at the 1–2% level for $\Delta D_{\gamma\gamma} = 1$ %. As we approach this level of precision it will start to become possible to exclude negasecond region at $\gamma_t \sim$ 7 which is not displayed.

4. Probing the heavy new particles of the MSSM

⁶⁵ form [21], the spectrum with five Higgs states: two CP-even t³⁰ We now examine one-loop contributions to the Higgs decay to photons from new heavy charged particles in the MSSM. As is well known, the MSSM possesses a two Higgs doublet structure that

ICI E IN I

18 **Fig. 3.** Left: $D_{\gamma\gamma}$ vs. compositeness scale f for $n=0$ (blue), $n=1$ (orange) and $n=2$ (green) in minimal composite Higgs scenarios. Right: Contours of $D_{\gamma\gamma} + \Delta D_{\gamma\gamma}$ in the α $[\alpha/4\pi (b_{IR}^{(EM)} - b_{UV}^{(EM)}), \gamma_I]$ plane with $D_{\gamma\gamma} = 1$ and $\Delta D_{\gamma\gamma} = 1\%$ (black), 2% (red), 3% (blue). (For interpretation of the references to color in this figure legend, the reader is additionally 20 Processes and the Version of the anticipity of the control of the con referred to the web version of this article.)

h and *H* (with *h* being the observed one), a CP-odd *A* and two this sector: M_A and tan β , the ratio of vacuum expectation values when higher order corrections are included, provided that the constraint $M_h = 125$ GeV is used as in the hMSSM approach discussed when normalized to the SM Higgs couplings are simply given by

$$
c_V = \sin(\beta - \alpha), \ \ c_t = \cos\alpha/\sin\beta, \ \ c_b = -\sin\alpha/\cos\beta, \tag{7}
$$

33 with α the mixing angle in the CP-even Higgs sector which, in charged $H^{\pm\pm}$ states are present, the contributions to $D_{\gamma\gamma}$ can be s₉₈ $_{34}$ the *hMSSM, is simply given in terms of* M_A *, tan* β *, and* M_h *. When even larger [26]. In this case, values as large as* $M_{H^{++}}$ \approx *2.5 TeV* $_{99}$ 35 M_A \gg M_Z, one is in the decoupling regime in which $\alpha \approx \beta-\frac{\pi}{2}$ can be probed for $g_{hH^{++}H^{--}}$ ≈ 5 if an accuracy of ∆D_{YY} ≈ 1% is 100 36 and *h* has SM-like couplings, $c_t = c_b = c_V = 1$. In this decoupled achieved. $_{37}$ regime, which is also implied by the experimental data [\[12\],](#page-7-0) the Turning to the effects of the superpartners, we assume for sim-38 heavier charged Higgs states have mass $M_{H^{\pm}} = \sqrt{M_A^2 + M_W^2}$ while plicity that we are in the decoupling regime $M_A \gg M_Z$ with h 103 $\frac{39}{4}$ 1 and 4 bave comparable masses and couplings. with α the mixing angle in the CP-even Higgs sector which, in $M_A \gg M_Z$, one is in the decoupling regime in which $\alpha \approx \beta - \frac{\pi}{2}$ *H* and *A* have comparable masses and couplings.

 $\frac{1}{41}$ 106 $\frac{1}{41}$ 42 this case two effects are a the power the charged H^{\pm} state will by powers of M_{NP} . Three contributions can be important in the $_{107}$ 43 contribute to the hyperpolitude A_1 is A_2 is A_3 in A_4 is A_5 is A_6 is A_7 is A_8 is A_1 is A_2 is A_3 is A_4 is A_5 is A_6 is A_7 is A_8 is A_7 is A_8 is A_9 is A_9 is A_1 43 contribute to the *hγγ* amplitude, $M_H \pm \alpha - \frac{1}{3} g_{hH^+H^-} M_W^2 / M_H^2$.

A second contribution also essure at low M_L upluse as ano is the charginos [27], the tau slepton [28], and the stop squark, see 10g 45 0.1 Second contribution and 45 110 46 e.g. [\[29\].](#page-7-0) We discuss each of them in the phenomenological MSSM 110 $\frac{46}{10}$ and $\frac{48}{10}$ and $\frac{48}{10}$ in which all soft SUSY-breaking parameters are free but with $\frac{111}{111}$ We first consider MSSM contributions to the *hγγ* loop induced vertex 5 [24] in the limit where all superpartners are very heavy. In this case two effects are at play. First, the charged H^{\pm} state will A second contribution also occurs at low M_{H^\pm} values as one is outside the decoupling regime and the reduced Higgs couplings c_W and c_t are not SM-like, eq. (7).

48 tracted in the $\frac{1}{2}$ 113 $\frac{1}{2$ The simultaneous impact of these two contributions is illustrated in the $[M_{H^{\pm}}$, tan β] plane in [Fig. 4](#page-6-0) (left). As can be seen, especially at high tan β . This is due to the fact that the decoupling limit $c_V = c_t = 1$ is already reached for such a H^{\pm} mass and the fact that the *hH*+*H*− coupling is small in the MSSM. Indeed, at tree-level, it is given by ($c_W^2 = 1 - \sin^2 \theta_W \approx 3/4$),

$$
g_{hH^+H^+} = \sin(\beta - \alpha) + \cos 2\beta \sin(\beta + \alpha) / (2c_W^2)
$$

\n
$$
\stackrel{M_A \gg M_Z}{\rightarrow} 1 - \cos^2 2\beta / (2c_W^2),
$$
\n(8)

21 and the set of the s $_{22}$ *h* and *H* (with *h* being the observed one), a CP-odd *A* and two *which approaches* \approx 1/3 for tan $\beta \gg$ 1. The *D_{γγ}* sensitivity to ₈₇ $_{23}$ charged states H[±] [\[10,11\].](#page-7-0) Two parameters are needed to describe the H $^\pm$ states is only slightly improved for values of tan $\beta\approx1$ ₈₈ ₂₄ this sector: M_A and tan β , the ratio of vacuum expectation values when the coupling becomes of order unity. In contrast, in a gen- $_{25}$ of the two Higgs fields. This is true not only at tree-level but also eral two-Higgs doublet model (2HDM) [25], the coupling $g_{hH^+H^-}$ ₉₀ $_{26}$ when higher order corrections are included, provided that the con-parametally a free parameter and can be larger, leading to more $_{91}$ ₂₇ straint M_h = 125 GeV is used as in the hMSSM approach discussed significant contributions to D_{γγ} [\[10,25\].](#page-7-0) This is illustrated in the ₉₂ ₂₈ in Ref. [\[23\].](#page-7-0) The couplings of *h* to fermions and gauge bosons, cright-hand side of Fig. 4 where the H^{\pm} contribution is displayed $_{93}$ ₂₉ when normalized to the SM Higgs couplings are simply given by ∠ in the [M_H±, g_{hH+H}−] plane for a 2HDM in the "alignment" limit ₉₄ $\sin(\beta - \alpha) = 1$ which leads to $c_V = c_t = 1$. In this case H^{\pm} 31 $c_V = \sin(\beta - \alpha)$, $c_t = \cos\alpha/\sin\beta$, $c_b = -\sin\alpha/\cos\beta$, (7) masses close to the TeV scale can be probed for $g_{hH^+H^-} \gtrsim 5$ ago $\frac{1}{32}$ if $\Delta D_{\gamma\gamma} \approx 1$ %. Note that in triplet Higgs models where doubly $\frac{1}{97}$ the H^{\pm} states is only slightly improved for values of tan $\beta \approx 1$ eral two-Higgs doublet model (2HDM) [\[25\],](#page-7-0) the coupling $g_{hH^+H^-}$ right-hand side of [Fig. 4](#page-6-0) where the H^{\pm} contribution is displayed even larger [\[26\].](#page-7-0) In this case, values as large as $M_{H^{++}} \approx 2.5$ TeV achieved.

 μ and *n* avec comparator masses and couplings.
 μ loop. As the superpartner couplings to the *h* state are not $\frac{47}{112}$ the constraint that they are not CP or flavor violating. The program 112 Turning to the effects of the superpartners, we assume for simplicity that we are in the decoupling regime $M_A \gg M_Z$ with *h* MSSM (besides that from H^{\pm} discussed earlier) [\[24\]:](#page-7-0) those from the charginos $[27]$, the tau slepton $[28]$, and the stop squark, see

49 a 1% measurement of *D*_{γγ} probes only *H*[±] masses of *O*(200 GeV), and *a* and higgsino mass parameters *M*₂ and *μ* and by tan *β*, and *μ* 50 115 gaugino and higgsino mass parameters *M*² and *μ* and by tan *β*. 51 limit $c_V = c_t = 1$ is already reached for such a H^{\pm} mass and the If $M_2 \gg |\mu|$, the lightest chargino χ_1^{\pm} is a pure higgsino while 116 52 μ a pure gaugino; for *M*₂ \ll |*μ*| the situation is 117 and the heavier one χ_1^{\pm} a pure gaugino; for *M*₂ \ll |*μ*| the situation is 117 53 tree-level, it is given by $(c_W^2 = 1 - \sin^2 \theta_W \approx 3/4)$, reversed. In the limit $M_2 = |\mu| \gg M_W$, the two spin- $\frac{1}{2}$ chargino 54 $\frac{118}{120}$ $\frac{118}{120}$ states χ_i^{\pm} are equal mixtures of higgsinos and gauginos and are ⁵⁵
degenerate in mass so that their total contribution to the *hγγ* ver-
-- α _{*ν*} (*A* = *c*) + cos 2*8* sin(*B* + α)/(2c²,) 56 δhH^+H^+ = δhH^+H^- = δhH^+H^- = $\delta hH^ \delta hH^-$ = $\delta hH^ \delta hH^-$ 56 $\delta nH^+H^+ = 3m(p-1)$ (cos 2p sm(p + a)/(2c W)
57 *M*₄ $\gtrsim M^2$ *M*_{*X*⊥}[±] and is therefore small. The 122
57 *M*₄ $\gtrsim M^2$ 122 $\frac{58}{36}$ \rightarrow 1 \sim $\frac{29}{123}$ (20 $\frac{1}{23}$), \sim 123 \sim 59 11 $\text{Fig. 5 in the } [m_{\chi_1^\pm}, m_{\chi_2^\pm}]$ $\text{Fig. 5 in the } [m_{\chi_1^\pm}, m_{\chi_2^\pm}]$ $\text{Fig. 5 in the } [m_{\chi_1^\pm}, m_{\chi_2^\pm}]$ plane for fixed tan $\beta = 1$ (the sensitivity $\frac{124}{3}$ $\frac{1}{5}$ is lower for higher values of tan *β*). One sees that for $ΔD_{γγ} ≈ 1$ %, 125 *i*) Light charginos: the chargino system is described by the *chargino contribution to* $D_{\gamma\gamma}$ *is shown in the left-hand side of*

 $\frac{62}{127}$ $\frac{1}{127}$ $\frac{$ 63 ticle in the same configuration would be $A_2 = -1$ [10.11] Note that while spin-1 sleptons is negligible [\[24\]\)](#page-7-0): the stau system can be described with 128 64 and spin-0 states contribute like $1/M^2$, spin- $\frac{1}{2}$ fermions contribute as $1/M$ (modulo three parameters, the soft SUSY-breaking mass parameters $m_{\tilde{\tau}_L}$ and 129 65 couplings). $m_{\tilde{\tau}_R}$, and the mixing parameter $X_{\tau} = A_{\tau} - \mu \tan \beta$. In the de- 130

^{61 &}lt;sup>3</sup> In the limit where the loop particle is much heavier than the *h* state, the con-

stributions to the *h* \rightarrow *y* y vertex up to coupling and charge factors are *A*₁ = -7 for ⁵ In the limit where the loop particle is much heavier than the *h* state, the contributions to the *h* $\rightarrow \gamma \gamma$ vertex up to coupling and charge factors, are *A*₁ = −7 for spin-1 states and $A_{1/2} = +\frac{4}{3}$ for spin- $\frac{1}{2}$ fermions; the contribution of a spin-0 particle in the same configuration would be $A_0 = -\frac{1}{3}$ [\[10,11\].](#page-7-0) Note that while spin-1 and spin-0 states contribute like $1/M^2$, spin- $\frac{1}{2}$ fermions contribute as $1/M$ (modulo couplings).

JID:PLB AID:31879 /SCO Doctopic: Phenomenology [m5Gv1.3; v1.175; Prn:11/04/2016; 14:20] P.6 (1-8)

17 Fig. 4. Left: Contributions of the MSSM Higgs sector to $D_{\gamma\gamma}$ in the $[M_{H^{\pm}}$, $\tan\beta$ plane when all superparticles are heavy. Right: H \pm contributions to $D_{\gamma\gamma}$ in 2HDMs with 18 arbitrary *hH*⁺ *H*[−] coupling in the [*M_H*±, *g_{hH}*+ *H*[−]] plane in the "alignment" limit sin(*β* − *α*) = 1.

58 Fig. 5. Contours for the contributions of the charginos (left) and stau leptons (right) to $D_{\gamma\gamma}$ in the planes formed by the masses of two states. For charginos tan $\beta = 1$ is 103 39 assumed while for staus, we set tan $\beta = 60$, $X_\tau \le 0$ and assume $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R}$.

 40 $\frac{41}{4}$ coupling limit and assuming $m_{\tilde{t}_L} = m_{\tilde{t}_R}$, the Higgs–stau coupling two stop masses will split and t_1 will be much lighter than t_2 with 106 42 reads $g_{12} = \frac{1}{2} \cos 2\theta + \frac{m_t^2}{2} + \frac{m_t X_t}{2}$ When X_t is large and neg. Harge COUPHING to the *n* state, $g_{h_t^2, t_1}^2 \propto m_t X_t$. $\frac{42}{\pi}$ reads $g_{h\tilde{\tau}\tilde{\tau}} = -\frac{1}{4}\cos 2\beta + \frac{m_{\tilde{\tau}}^2}{2M_Z^2} + \frac{m_{\tilde{\tau}}X_{\tilde{\tau}}}{2M_Z^2}$. When X_{τ} is large and neg-

The contributions to $D_{\gamma\gamma}$ are shown in Fig. 6 in the plane 108 $\frac{44}{\pi}$ ative, the coupling simplifies to $g_h \tilde{\tau} \tilde{\tau} \propto m_\tau \lambda_\tau$ and is important $[m_{\tilde{t}_1}, m_{\tilde{t}_2}]$ for the value tan $\beta = 10$ while X_t^2 is fixed by the re-
only for large X, making the splitting between $\frac{45}{45}$ only for large Λ_{τ} , making the spitting between the two statis quirement that $M_h = 125$ GeV when only the stop dominant con-
also year, large This allows for one of them to be pather light. $_{46}$ also very large. This allows for one of them to be rather light tributions to the radiative corrections in the MSSM Higgs sector are the 47 Fendering maximal the impact of the τ_1 loop in the $n\gamma\gamma$ vertex, considered [\[11\].](#page-7-0) In this case the shift of the Higgs mass is given by 112 48 113 which interferes constructively with the *W* loop. When the mix-49 ing parameter is not negative enough, the Higgs-stau coupling is ΔM_1^2 l l $\sim 3m^4/(2\pi^2 v^2)$ [log(M_2^2/m^2) $+ X^2/M_2^2$ 50 115 then positive and its contribution interferes destructively with the 51 dominant one coming from the *W* boson. Nevertheless, as the con- $X_t^+(12M_S^{\dagger})$, (9) 116 ⁵² tribution of a spin-0 particle is small and damped by $g_{h\tilde{\tau}\tilde{\tau}}/m_{\tilde{\tau}}^2$, the which gives at maximum two solutions for X_f^2 . For a precision of $\frac{117}{118}$ 53 staus decouple quickly from the amplitude. This is exemplified in $\Delta D \approx 1\%$ one could probe the mass values in to $m_s \approx 0.5$ TeV ⁵⁴ Fig. 5 (right) where the contribution to *D_{γγ}*, assuming $m_{\tilde{\tau}_L} = m_{\tilde{\tau}_R}$ and $m_{\tilde{\tau}_2} \sim 3$ TeV for very large mass splitting between the two 198 55 is displayed in the plane from multiple on that stays of a fow and $m_{\tilde{t}_2} \sim 3$ TeV for very large mass splitting between the two 120⁵⁵ is displayed in the plane from multiple sees that stays of a fow 56 11 is displayed in the plane [$m_{\tilde{t}_1}$, $m_{\tilde{t}_2}$]. We see that staus of a few stops and $[m_{\tilde{t}_1}, m_{\tilde{t}_2}]$ ~ [1.5, 2] TeV for smaller mass splitting, when 121 57 **122** hundred GeV could still contribute by more than 1% to $D_{\gamma\gamma}$. One considering only the optimistic maximal solution for X_t^2 . These 122
122 **phorolant that there are closed undetectable at the UIC is direct** $_{58}$ should note that staus are almost undetectable at the LHC in diffect state mass values are significantly higher than those which can be $_{123}$ reads $g_{h\tilde{\tau}\tilde{\tau}} = -\frac{1}{4}\cos 2\beta + \frac{m_{\tilde{\tau}}^2}{M_Z^2} + \frac{m_{\tau}X_{\tau}}{2M_Z^2}$. When X_{τ} is large and negative, the coupling simplifies to $g_{h\tilde{\tau}\tilde{\tau}} \propto m_{\tau} X_{\tau}$ and is important only for large X_{τ} , making the splitting between the two staus also very large. This allows for one of them to be rather light rendering maximal the impact of the $\tilde{\tau}_1$ loop in the $h\gamma\gamma$ vertex, is displayed in the plane $[m_{\tilde{t}_1}, m_{\tilde{t}_2}]$. We see that staus of a few hundred GeV could still contribute by more than 1% to *Dγγ* . One should note that staus are almost undetectable at the LHC in direct searches [\[28\].](#page-7-0)

 $_{60}$ iii) Stop loops: they provide the largest contribution to the LSP neutralino is rather heavy [4]. $_{125}$ $h \rightarrow \gamma \gamma$ vertex. The stop sector, similarly to the stau sector, can be $h \rightarrow \gamma \gamma$ vertex. The stop sector, similarly to the stau sector, can be 62 parameterized by the three inputs $m_{\tilde{t}_L}$, $m_{\tilde{t}_R}$ and $X_t = A_t - \mu/\tan \beta$ 5. Conclusions 63 (the SUSY scale is defined as $M_S = \sqrt{m_{\tilde{t}_L} m_{\tilde{t}_R}}$ and should be of or-64 der 1 TeV for a mixing $X_t/M_S \approx 2$ in order to allow for an *h* boson In this letter, we have re-emphasized the fact that the decay ra-⁶⁵ mass of $M_h=125$ GeV [\[32\]\)](#page-8-0). If the mixing parameter is large, the tio $D_{\gamma\gamma}$ of Higgs signal rates into two photons and four charged ¹³⁰

two stop masses will split and \tilde{t}_1 will be much lighter than \tilde{t}_2 with

The contributions to *Dγγ* are shown in [Fig. 6](#page-7-0) in the plane

$$
\Delta M_h^2|_{1\text{loop}}^{t/\tilde{t}} \sim 3m_t^4/(2\pi^2 v^2)[\log(M_S^2/m_t^2) + X_t^2/M_S^2 - X_t^4/(12M_S^4)],\tag{9}
$$

 $_{59}$ searcnes [28]. The second set of the second in direct stop pair production at the LHC, especially if the $_{124}$ which gives at maximum two solutions for X_t^2 . For a precision of $\Delta D_{\gamma\gamma} \approx 1\%$ one could probe stop mass values up to $m_{\tilde{t}_1} \sim 0.5$ TeV LSP neutralino is rather heavy $[4]$.

5. Conclusions

In this letter, we have re-emphasized the fact that the decay ratio *Dγγ* of Higgs signal rates into two photons and four charged

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20 **Fig. 6.** Contours for the stop contributions to $D_{\gamma\gamma}$ in the $[m_{\tilde{t}_1}, m_{\tilde{t}_2}]$ plane for the maximal possible values of the mixing X_t . The plot on the left corresponds to a large mass as $_{21}$ splitting between the two stops and the one on the right corresponds to a moderate mass splitting.

₂₃ leptons is free of theoretical uncertainties which limit the preci- [10] J. Gunion, H. Haber, G. Kane, S. Dawson, The Higgs Hunter's Guide, Reading, ₈₈ 24 sion in other Higgs observables, but which cancel in the ratio. The $\frac{1990}{24}$, $\frac{1}{2}$ and $\frac{1}{2}$ 25 measurement of $D_{\gamma\gamma}$ would be then limited simply by the statisti-
25 measurement of $D_{\gamma\gamma}$ would be then limited simply by the statisti-
25 measurement of $D_{\gamma\gamma}$ would be then limited simply by the statisti-26 Carand Systemant errors, which can in principle be reduced to the 12 K. Olive, et al., Particle Data Group, Chin. Phys. C 38 (2014) 090001. 291 $_{27}$ level of one percent at a high-luminosity LHC. This allows us to $_{[13]}$ C. Anastasiou, Phys. Rev. Lett. 114 (21) (2015) 212001. 28 use this Higgs decay ratio as a probe of new physics effects which $[14]$ M. Spira, et al., Nucl. Phys. B 453 (1995) 17. zo is complementary to direct searches at the LTC and also other high (16) A. Denner, S. Heinemeyer, I. Puljak, D. Rebuzzi, M. Spira, Eur. Phys. J. C 71 94 cal and systematic errors, which can in principle be reduced to the is complementary to direct searches at the LHC and also other high

31 Stephen Lave discussed various examples, including anomalous of For an earlier analysis see A. Djouadi, M. Spira, P. Zerwas, Z. Phys. C 70 (1996) 96 $_{32}$ Higgs couplings to top quarks and vector bosons which can be $_{427}$. 33 constrained at the percent level, as well as composite Higgs mod-
33 Constrained at the percent level, as well as composite Higgs mod-
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J. Ellis, T. You, J. High Energy Phys. 1306 (2013) 103. 35 100 [18] Y. Chen, D. Stolarski, R. Vega-Morales, arXiv:1505.01168 [hep-ph]; $_{36}$ metric particles contributing to the HYY loop can be probed up $\,$ Y. Chen, R. Harnik, R. Vega-Morales, Phys. Rev. Lett. 113 (2014) 191801, arXiv: $\,$ $_{101}$ 37 102 Y. Chen, A. Falkowski, I. Low, R. Vega-Morales, Phys. Rev. D 90 (2014) 113006; $\frac{38}{28}$ 103 39 104 [19] D. McKeen, M. Pospelov, A. Ritz, Phys. Rev. D 86 (2012) 113004; $_{40}$ powerful tool to probe the multi-rev scale. We have discussed various examples, including anomalous els where we find that compositeness scales as high as 2–3 TeV can be probed. We have also shown that new Higgs or supersymmetric particles contributing to the H*γγ* loop can be probed up to masses of several TeV as is the case of top squarks for instance. These scales are comparable and in some cases even higher than those accessible directly at the LHC, making this golden ratio a powerful tool to probe the multi-TeV scale.

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