1. Standardissimo?
2. Constraints on new physics: MSSM
3. Further probe of the Higgs sector
4. High precision measurements: Dγγ?
5. Conclusion
1. Standardissimo?

The Higgs discovery in July 2012: a triumph for high-energy physics.

A very non-trivial check of the SM: test at the quantum/permile level:
- constraints from data: \( M_H = 92^{+34}_{-26} \text{ GeV} \lesssim 160 \text{ GeV at 95\% CL} \)
- experimentally found to be: \( M_H = 125.1 \pm 0.24 \text{ GeV} \) (ie within 1\(\sigma\).)

In addition, it looks as it has the properties of the SM Higgs state:

The triumph of the SM model of particle physics or Standarissimo?!
1. Standardissimo?

We have a theory for the strong+electroweak forces, the SM, that is:
- a relativistic quantum field theory based on a gauge symmetry,
- renormalisable as proved by ’t Hooft and Veltman for sEWSB,
- unitary as we have now a Higgs and its mass is rather small,
- perturbative up to the Planck scale as again the Higgs is light,
- leads to a (meta)stable electroweak vacuum up to high scales,
- compatible with (almost) all precision data available to date...

Is SM the “theory of everything” and should we be satisfied with it?
No! Low energy manifestation of a fundamental theory that solves:
- “Esthetical” problems with eg multiple and arbitrary parameters; gauge coupling unification: $3 \neq g_i$ which do not meet a high scale.
- “Experimental” problems as it does not explain all seen phenomena: \( \nu \) masses/mixing, dark matter, baryon asymmetry in the universe ....

Note: $SO(10)$ at intermediate $Q = 10^{11}$ GeV and axions cure these pbs.
- “Theory” (or consistency) problem: the hierarchy/naturalness pbs. $\Delta M^2_H \propto \Lambda^2 \approx (10^{18} \text{ GeV})^2$: $M_H$ not stable against high scales.

All these indicate that there is beyond the Standard Model!
1. Standardissimo?

Three main avenues for solving the hierarchy or naturalness problems

I. Compositeness/substructure:
   All particles are composite: Technicolor
   \[ \Rightarrow \text{H bound state of two fermions} \]
   (no more spin–0 fundamental state).

II. Extra space–time dimensions
   where at least s=2 gravitons propagate.
   \[ \Rightarrow \text{effective gravity scale } \Lambda \approx 1 \text{ TeV}. \]
   EWSB mechanism needed: H or not H!

III. Supersymmetry: doubling the world.
   – links s=\( \frac{1}{2} \) fermions to s=1 bosons,
   – links internal/space-time symmetries,
   – if made local, provides link to gravity,
   – natural \( \mu^2 < 0 \): radiative EWSB,
   \[ \Rightarrow \text{sparticle loops cancel } \Lambda^2 \text{ behavior} \]
   extend EWSB sector: at least 2 doublets.
1. Standardissimo?

The problem is that:

A) we observe a Higgs with a mass of 125 GeV and no other Higgs:

\[ \sigma \times BR \text{ rates compatible with those expected in the SM} \]

Fit of all LHC Higgs data \( \Rightarrow \) agreement at 15–30% level

Results from the LHC 7–8 TeV campaign already give us:

\[ \mu_{\text{ATLAS}}^{\text{tot}} = 1.18 \pm 0.15 \]
\[ \mu_{\text{CMS}}^{\text{tot}} = 1.00 \pm 0.14 \]

B) we do not observe any particle beyond those of SM with Higgs:

profound implications for most discussed BSM scenarios; they are in:

- “Mortuary”: Higgsless, 4th generation, fermio or gauge-phobic..
- “Hospital”: Technicolor, composite models (but some loopholes) ....
- “Trouble” and strongly constrained: extra-dimensions, SUSY, ...

As an example, let us see what it implies for SUSY and the MSSM.

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Higgs physics at LHC – A. Djouadi – p.5/24
2. Constraints on new physics: MSSM

In the MSSM we need 2 doublets of complex scalar fields $H_1$, $H_2$ (it is a 2HDM of type II but with SUSY constraints).

After EWSB, 3 dof for $W_L^\pm$, $Z_L \Rightarrow 5$ physical states: $h$, $H$, $A$, $H^\pm$.

2 free parameters at tree-level to describe Higgs pheno: $\tan \beta$, $M_A$:

$M_{h,H}^2 = \frac{1}{2} \left\{ M_A^2 + M_Z^2 \mp \left[ (M_A^2 + M_Z^2)^2 - 4M_A^2 M_Z^2 \cos^2 2\beta \right]^{1/2} \right\}$

$M_{H^\pm}^2 = M_A^2 + M_W^2$

$\tan 2\alpha = \frac{-(M_A^2 + M_Z^2) \sin 2\beta}{(M_Z^2 - M_A^2) \cos 2\beta} = \tan 2\beta \frac{M_A^2 + M_Z^2}{M_A^2 - M_Z^2} \left( -\frac{\pi}{2} \leq \alpha \leq 0 \right)$

$M_h \lesssim M_Z |\cos 2\beta| + RC \lesssim 130$ GeV, $M_H \approx M_A \approx M_{H^\pm} \lesssim M_{\text{EWSB}}$.

- Couplings of $h$, $H$ to $VV$ are suppressed; no $AVV$ couplings (CP).
- For $\tan \beta \gg 1$: couplings to $b$ ($t$) quarks enhanced (suppressed).

\[
\begin{array}{llll}
\Phi & g_\Phi \bar{uu} & g_\Phi \bar{dd} & g_\Phi VV \\
h & \frac{\cos \alpha}{\sin \beta} \rightarrow 1 & \frac{\sin \alpha}{\cos \beta} \rightarrow 1 & \sin(\beta - \alpha) \rightarrow 1 \\
H & \frac{\sin \alpha}{\sin \beta} \rightarrow 1/\tan \beta & \frac{\cos \alpha}{\cos \beta} \rightarrow \tan \beta & \cos(\beta - \alpha) \rightarrow 0 \\
A & 1/\tan \beta & \tan \beta & 0 \\
\end{array}
\]

Decoupling limit: MSSM Higgs sector reduces to SM with a light $h$. 

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Higgs physics at LHC – A. Djouadi – p.6/24
2. Constraints on new physics: MSSM

There is first direct implication from the measurement $M_h = 125$ GeV

$$M_h^2 \xrightarrow{M_A \gg M_Z} M_Z^2 \cos^2 2\beta + \frac{3 \bar{m}_t^4}{2 \pi^2 v^2 \sin^2 \beta} \left[ \log \frac{M_S^2}{\bar{m}_t^2} + \frac{X_t^2}{M_S^2} \left( 1 - \frac{X_t^2}{12M_S^2} \right) \right] \simeq (125)^2$$

Arbey, Battaglia, AD, Mahmoudi, Quevillon (2012)

$M_{SUSY} \gtrsim 1$ TeV in general MSSM and higher in constrained models.

Shanghai 02/07/2017    Higgs physics at LHC    – A. Djouadi    – p.7/24
2. Constraints on new physics: MSSM

This is backed up by direct searches of SUSY particles at the LHC: the SUSY scale $M_{SUSY} \gtrsim \mathcal{O}(1 \text{ TeV})$ in most experimental searches.

⇒ ATLAS/CMS depressing tables ....

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Higgs physics at LHC — A. Djouadi — p.8/24
2. Constraints on new physics: MSSM

Also backed up indirectly by measurement of Higgs properties:
fits of the h couplings \( \Rightarrow \) constraints on MSSM \([M_A, \tan\beta]\) space:

\[
\text{hMSSM: } g_{h\bar{t}t} = \cos\alpha/\sin\beta, \quad g_{h\bar{b}b} = \cos\alpha/\sin\beta, \quad g_{hVV} = \sin(\beta - \alpha)
\]

AD, Quevillon, Maiani... 2013

Direct search for pp\(\rightarrow\)H,A

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3. Further probe of the Higgs sector

So is Particle Physics “closed” and we should all go home? No!

1) Fully probe the TeV scale that is relevant for hierarchy problem ⇒ continue to search for heavier Higgs bosons (and superparticles).
3. Further probe of the Higgs sector

Continue searches for exotic particles in all possible channels.

ATLAS Exotics Searches - 95% CL Exclusion

<table>
<thead>
<tr>
<th>Model</th>
<th>$f$</th>
<th>$g$</th>
<th>Jets</th>
<th>$E_{miss}^{T}$</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADO $G_{a}$ + $g$, $q$</td>
<td>$f$</td>
<td>$g$</td>
<td>$q$, $u$</td>
<td>$b$, $v$</td>
<td>$t$, $j$</td>
</tr>
<tr>
<td>ADO non-resonant $f$</td>
<td>2.9</td>
<td>6.1</td>
<td>$Z_{bb}$</td>
<td>$Z_{bb}$</td>
<td>$b$, $b$</td>
</tr>
<tr>
<td>ADO OBR $f$</td>
<td>1.2</td>
<td>1.0</td>
<td>$Z_{bb}$</td>
<td>$Z_{bb}$</td>
<td>0.001</td>
</tr>
<tr>
<td>ADO $\rho$</td>
<td>1.2</td>
<td>1.0</td>
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<td>$Z_{bb}$</td>
<td>0.001</td>
</tr>
<tr>
<td>$\rho$ $\rightarrow$ $Z_{bb}$ multiplet</td>
<td>2.9</td>
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<td>$Z_{bb}$</td>
<td>$Z_{bb}$</td>
<td>0.001</td>
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<tr>
<td>Res $G_{a}$ $\rightarrow$ $f$</td>
<td>2.9</td>
<td>6.1</td>
<td>$Z_{bb}$</td>
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</tr>
<tr>
<td>Bulk $G_{a}$ $\rightarrow$ $W^{+}W^{-} \rightarrow q\bar{q}^{*}$</td>
<td>1.2</td>
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<tr>
<td>Bulk $G_{a}$ $\rightarrow$ $H^{+}H^{-} \rightarrow b\bar{b}$</td>
<td>4.9</td>
<td>13.3</td>
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<tr>
<td>ZUED / RPP</td>
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**ATLAS Preliminary**

$\int L \, dt = (3.2 - 20.3) \, fb^{-1}$

$\sqrt{s} = 8, 13 \, TeV$

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**ATLAS Preliminary**

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$\sqrt{s} = 8, 13 \, TeV$

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Higgs physics at LHC – A. Djouadi – p.11/24

*Only a selection of the available mass limits on new states or phenomena is shown. Lower bounds are specified only when explicitly not excluded.

†Small-radius (large radius) jets are denoted by the jet label (j).
3. Further probe of the Higgs sector

The next question is then: “is Particle Physics closed”? Answer is no!

2) Need to check that H is indeed responsible of EWSB (SM-like?)

⇒ measure its fundamental properties in the most precise way:

- its mass and total decay width (invisible width from dark matter?),
- its spin–parity quantum numbers (CP violation for baryogenesis?),
- its couplings to fermions and gauge bosons and check if they are only proportional to particle masses (no new physics contributions?),
- its self-couplings to reconstruct $V_S$ potential that makes EWSB.

Possible for $M_H \approx 125$ GeV as all production/decay channels useful.
3. Further probe of the Higgs sector

A check of spin–parity quantum numbers.

Spin: clear situation (no suspense) as the new state decays into $\gamma\gamma \Rightarrow$ not s=1 from Landau–Yang and s=2 (KK graviton?) unlikely..

CP numbers: CP-even, CP-odd, or mixture?

(more important issue: CPV in Higgs sector.) ATLAS and CMS MELA analyses for pure CP $\Rightarrow$ pure CP-even favored at $\gtrsim 3\sigma$ level.

But problems with this (too simple) picture: pure CP–odd does not couple to VV@tree-level; in $H \rightarrow ZZ^*$ only CP-even part is projected out.

- **Direct probe**: via production/decays in extensions like C2HDM: Ex: Undoubtable signs of CP-violation in Higgs decays at HL-LHC combined searches of $h_i \rightarrow h_j Z$ and $h_i \rightarrow ZZ$ with $i, j = 1, 2, 3$.

- **Indirect probe**: $g_{Hff}$ more democratic $\Rightarrow$ fermionic decays.

ex: spin-correlations in $q\bar{q} \rightarrow HZ \rightarrow b\bar{b}ll$, $q\bar{q}/gg \rightarrow Ht\bar{t} \rightarrow b\bar{b}t\bar{t}$.

Need to be lucky or is very challenging even at the HL–LHC...

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Higgs physics at LHC

A. Djouadi

p.13/24
3. Further probe of the Higgs sector

Perform a much more precise measurement of the Higgs couplings \( \Rightarrow \) would allow a better sensitivity to new physics virtual effects.

- **In standard production+decay channels as** \( gg \rightarrow H \rightarrow ZZ, WW, \gamma\gamma \)
  Presently sensitivity is low in many cases as 2HDM of type I and II: still large theoretical+experimental errors of about 15–20% each

  - Falkowski et al., 1611.01112

- **In very rare decays that allow additional/unknown information:**
  - \( H \rightarrow \mu^+\mu^- \) to probe second generation fermion couplings
  - \( H \rightarrow \Upsilon\gamma \) to probe the sign of some fermionic couplings (here b’s).
  - \( H \rightarrow Z\gamma \) with information that is complementary to \( H \rightarrow \gamma\gamma \)

But will this be sufficient to probe BSM physics? (see discussion later)
3. Further probe of the Higgs sector

- **Total width**: $\Gamma_H = 4\text{MeV}$, too small to be resolved experimentally.
  - very loose bound from interference $gg\rightarrow ZZ$ (factor 2–5 at most).
  - no way to access it indirectly (via production rates) precisely.

- **Invisible width**: more accessible

**Direct measurement of $H\rightarrow \text{inv}$**
$q\bar{q} \rightarrow HZ$ with $Z \rightarrow ll$, $H \rightarrow \text{inv}$
similar $E_T$ search in VBF mode and also in $gg\rightarrow \text{Higgs}+\text{jet}$...

**Combined $HZ+VBF$ in CMS**
$\text{BR}_{\text{inv}} \lesssim 50\% @ 95\% \text{CL}$
assuming a SM Higgs state
$10\% @ \text{HL-LHC}$ possible?

**Indirect measurement of $H\rightarrow \text{inv}$**
via Higgs BRs measurement: again accuracy of $O(10\%)$ at HL-LHC
but with TH assumptions: no other decays, SM-like Higgs, etc...

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**Higgs physics at LHC**  – A. Djouadi  – p.15/24
3. Further probe of the Higgs sector

**Important challenge:** measure Higgs self-couplings and access to $V_H$.

- $g_{H^3}$ from $pp \rightarrow HH + X \Rightarrow$
- $g_{H^4}$ from $pp \rightarrow 3H + X$, hopeless.

Various processes for HH prod:
- only $gg \rightarrow HHX$ relevant...

$\sqrt{s} = 14$ TeV, $M_H = 125$ GeV

$\sigma(pp \rightarrow HH + X)/\sigma_{SM}$

- $gg \rightarrow HH$
- $qq' \rightarrow HHqq'$
- $qq' \rightarrow WHH$
- $qq \rightarrow ZHH$

- $H \rightarrow b\bar{b}$ decay alone not clean
- $H \rightarrow \gamma\gamma$ decay very rare,
- $H \rightarrow \tau\tau$ would be possible?
- $H \rightarrow WW$ not useful?

$bb\tau\tau, bb\gamma\gamma$ viable? Maybe...
but needs very large luminosity.

Baglio et al., arXiv:1212.5581

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Higgs physics at LHC – A. Djouadi – p.16/24
3. Further probe of the Higgs sector

Very precise measurements mostly at $\sqrt{s} \lesssim 500$ GeV and mainly in $e^+e^- \to ZH$ (with $\sigma \propto 1/s$) and $ZHH$, $ttH$

| $g_{HWW}$ | $\pm 0.012$ |
| $g_{HZZ}$ | $\pm 0.012$ |
| $g_{Hbb}$ | $\pm 0.022$ |
| $g_{Hcc}$ | $\pm 0.037$ |
| $g_{H\tau\tau}$ | $\pm 0.033$ |
| $g_{Htt}$ | $\pm 0.030$ |
| $\lambda_{HHH}$ | $\pm 0.22$ |
| $M_H$ | $\pm 0.0004$ |
| $\Gamma_H$ | $\pm 0.061$ |
| $CP$ | $\pm 0.038$ |

$\Rightarrow$ best option for $\approx 125$ GeV Higgs (see C. Grojean)

But let’s get back to the near future: what can we do at HL-LHC?

Shanghai 02/07/2017 Higgs physics at LHC – A. Djouadi – p.17/24
4. High precision measurements: $D_{\gamma\gamma}$?

Another way to search for New Physics: high precision measurements.
Example: Higgs couplings in cleanest channels: $H \rightarrow \gamma\gamma, H \rightarrow 4\ell^{\pm}$

<table>
<thead>
<tr>
<th>channel</th>
<th>atlas</th>
<th>cms</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu_{\gamma\gamma}$</td>
<td>1.17 $^{+0.23}<em>{-0.23}$ $^{+0.16}</em>{-0.11}$ ($^{+0.12}_{-0.08}$)</td>
<td>1.14 $^{+0.21}<em>{-0.21}$ $^{+0.16}</em>{-0.10}$ ($^{+0.09}_{-0.05}$)</td>
</tr>
<tr>
<td>$\mu_{\ell\ell}$</td>
<td>1.46 $^{+0.35}<em>{-0.31}$ $^{+0.19}</em>{-0.13}$ ($^{+0.18}_{-0.11}$)</td>
<td>0.93 $^{+0.26}<em>{-0.23}$ $^{+0.13}</em>{-0.09}$</td>
</tr>
</tbody>
</table>

Is this enough to probe effects of new physics or BSM?
Not in the case of weakly interacting theories like 2HDM, SUSY, etc...
expect effects at $\approx \frac{C_{\text{new}}\alpha_W}{\pi} \approx \frac{M_h^2}{M_{\text{new}}^2} \approx 1\%$;

Is 1% accuracy achievable at HL-LHC (3ab$^{-1}$)?

- Statistical error: $20\% / \sqrt{3 \times 100} \lesssim 1-2\%$ (projection OK with ATLAS+CMS combo)
- Systematical error: can be made $\lesssim 1\%$? some errors are common (luminosity, etc....).
- Theoretical uncertainty (if it is $\gg 1\%$): will be then by far the crucial/limiting issue!

⇒ How big is it? Can it be reduced? Removed?

Shanghai 02/07/2017   Higgs physics at LHC   – A. Djouadi – p.18/24
4. High precision measurements: $D_{\gamma\gamma}$?

Production cross sections

$gg \rightarrow H$ by far dominant process
$(\approx 85\%$ of the events before cuts$)$
$\Rightarrow O(10\%)$ total TH uncertainty ..... followed by cleaner VBF+VH modes:
only $\lesssim 15\%$ of rate before cuts...
smaller TH error only for inclusive...
$\Rightarrow O(10\%)$ for total uncertainty?


Decay branching ratios

Dominant decay $H \rightarrow b\bar{b} \approx 60\%$
Affected by QCD+parametric errors:
from $m_b$ and $\alpha_s$ only, a few $\%$ $\Rightarrow$
migrate to $O(5\%)$ error in other modes
such as $H \rightarrow \gamma\gamma, ZZ, WW, \tau\tau$
(partial widths very precise $\lesssim 1\%)$.
$\Rightarrow$ too large theory uncertainties
(even if reduced by a factor of 2)...
4. High precision measurements: $D_{\gamma\gamma}$?

Best way to eliminate theory uncertainty: use ratios of signal rates.

$H \rightarrow VV$ with $V \rightarrow \ell$ as reference and $H \rightarrow XX$ with $H$ produced in $p$:

$$D_{XX} = \frac{\sigma^p(pp \rightarrow H \rightarrow XX)}{\sigma^p(pp \rightarrow H \rightarrow VV)}$$

$$= \frac{\sigma^p(pp \rightarrow H) \times \text{BR}(H \rightarrow XX)}{\sigma^p(pp \rightarrow H) \times \text{BR}(H \rightarrow VV)}$$

$$= \frac{\text{BR}(H \rightarrow XX)}{\text{BR}(H \rightarrow VV)} = \frac{\Gamma(H \rightarrow XX)}{\Gamma(H \rightarrow VV)}$$

To first approximation: $D_{XX} = c_X^2/c_V^2$

Works only if one selects exactly same kinematical configuration (i.e. same ”fiducial cross sections”) for the two channels X and V!

- the theoretical uncertainties from the cross sections drop out;
- the parametric uncertainties from the branching ratios drop out;
- the theoretical ambiguities in the Higgs total width also drop out;

$\Rightarrow D_{XX}$ measures only the ratio of partial decay widths.

- Extremely clean theoretically, although some information is lost.
- Maybe it has also some advantages from the experimental side?

Best probe by far is $D_{\gamma\gamma}$ which measures deviations of the $\gamma\gamma$ loop

$$D_{\gamma\gamma} = \frac{\sigma(pp \rightarrow H \rightarrow \gamma\gamma)}{\sigma(pp \rightarrow H \rightarrow VV)} = \frac{\Gamma(H \rightarrow \gamma\gamma)}{\Gamma(H \rightarrow VV)} = d_{\gamma\gamma} c_\gamma^2 / c_V^2$$

AD (2012)
4. High precision measurements: $D_{\gamma\gamma}$?

\[ \Gamma = \frac{G_\mu}{128 \sqrt{2}} \frac{\alpha^2 M_H^3}{\pi^3} \left| \sum_f N_c e_f^2 A_H^{\frac{1}{2}}(\tau_f) + A_1^H(\tau_W) \right|^2 \]

\[ A_{1/2}^H(\tau) = 2[\tau + (\tau - 1)f(\tau)] \tau^{-2} \]
\[ A_1^H(\tau) = -[2\tau^2 + 3\tau + 3(2\tau - 1)f(\tau)] \tau^{-2} \]

- Loop decay; SM: only $W$, top loops are relevant (others small).
- For $m_i \to \infty \Rightarrow A_{1/2} = \frac{4}{3}$ and $A_1 = -7$: $W$ loop dominating!

$\gamma\gamma$ width counts the number of charged particles coupling to Higgs!

Contribution $A_p^s$ of particle $p$ of spin $s$ with Higgs coupling $g_{Hpp}$:

\[ A_0^p = -\frac{1}{3} g_{Hpp}^2 / m_P^2, \quad A_{1/2}^p = +\frac{4}{3} g_{Hpp}^2 / m_P^2, \quad A_1^p = -7 g_{Hpp}^2 / m_P^2, \]

If $g_{Hpp} \propto m_P \Rightarrow A_0^p \to +\frac{1}{3}, A_{1/2}^p \to -\frac{4}{3}, A_1^p \to +7. $

Small/calculated QCD and EW corrections: of order of percent.

AD+Spira+Zerwas, Vicini et al., AD+Gambino, Actis et al., (ZZ: Denner et al.)

In SM with $W$, $t$ loops: $c_\gamma \approx 1.26 \times |c_W - 0.21c_t|$

Assuming custodial symmetry $g_{HZZ} = g_{HWW} = c_V$, $D_{\gamma\gamma} = c_\gamma^2 / c_V^2$ is

\[ c_\gamma^2 / c_V^2 \approx 6.5 \times |1 - \frac{1}{5} c_t / c_V|^2 \]

with $c_V = c_t = 1$ in SM. Any new physics effects will alter this value.
4. High precision measurements: $D_{\gamma\gamma}$?

Will $D_{\gamma\gamma}$ be the g-2 of the LHC? Yes, if measured at 1% level!

Examples in BSM: AD, Quevillon, Vega-Morales, 1509.03913

Model independent search through an effective Lagrangian approach.

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

$$\left. + \frac{c_{\gamma\gamma}}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\tilde{c}_{\gamma\gamma}}{4} \tilde{F}_{\mu\nu} \tilde{F}^{\mu\nu} \right)$$

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Higgs physics at LHC – A. Djouadi – p.22/24
4. High precision measurements: $D_{\gamma\gamma}$?

Will $D_{\gamma\gamma}$ be the g-2 of the LHC? Yes, if measured at 1% level!

Example in MSSM: AD, Ouevillon, Vega-Morales. 1509.03913
5. Conclusion

We need to continue to search for New Physics and falsify the SM:
• directly via new (heavy or light) particle searches with more data.
• indirectly via high precision measurements in H/W/Z/top sectors,

So let’s move forward: it is still action time!
(or as experimentalists usually say: stay tuned!)