Exotic Higgs decays at the HL-LHC

(with a focus on Higgs $\rightarrow$ invisible)

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partially based on work with T. Stefaniak
(HL/HE Yellow Report, to appear)

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Beyond the Standard Model: Where do we go from here ?

24.8.18

Introduction and motivation: Higgs discovery and the Nobel Prize

As you all know, **extraordinary success** of particle physics in recent years

$\Rightarrow$ **Discovery of "a" Higgs boson** $\Leftarrow$

(by ATLAS and CMS, Phys.Lett. B716 (2012))

... leading to the **Nobel Prize** for Higgs/ Englert

$\Rightarrow$ **!! Particle physics is more exciting than ever !!** $\Leftarrow$

After Higgs discovery: Open questions

Higgs discovery in 2012 ⇒ last building block discovered

? Any remaining questions ?

- Why is the SM the way it is ??
  ⇒ search for **underlying principles/ symmetries**
- find **explanations for observations not described by the SM**
  ⇒ e.g. dark matter, flavour structure, ...
- ad hoc approach: Test **which other models still comply with experimental and theoretical precision**

for all: **Search for Physics beyond the SM (BSM)**

Current community efforts

Currently: **many community efforts** (⇒ European Strategy report)

- FCC-xx, CLIC, HL-LHC, HE-LHC, ...
- focus here:

HL-LHC

$$\sqrt{s} = 14\,\mathrm{TeV},\ \int\mathcal{L} = 3\,\mathrm{ab}^{-1}$$

- WG twiki:

  https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop

Role of Higgs couplings (I)

one way to search: **direct searches**

⇒ HL-LHC: can profit from enhanced statistics (cross sections identical to 14 TeV run)

other ways: **indirect constraints**

⇒ prominent example: Higgs couplings

study of Higgs couplings at HL-LHC combine direct searches with indirect constraints

Role of Higgs couplings (II)

- **direct Higgs channels:** e.g. $H \to$ invisible, $H \to$ exotics, ...
- **indirect constraints: modifications of SM decays**, via
  - a) suppression of rates (through new decay channels)
  - b) modification of relative BRs (new physics contributions)
- b): especially for loop-induced processes

$$H \to \gamma\gamma,\ H \to gg$$

Higgs to invisible

and interpretation within portal models

(in collaboration with T. Stefaniak)

Higgs to invisible: general setup

Higgs decay to invisible:

- typical realization in models with dark matter candidates

$$H \rightarrow \mathrm{DM}\,\mathrm{DM}$$

- in the SM: $H \rightarrow \nu\,\nu\,\bar{\nu}\,\bar{\nu} \leq 0.1\%$

  $\Longrightarrow$ **any (measurable) deviation: new physics** $\Longleftarrow$

- double effect:
  $\Rightarrow$ suppression of SM rates
  $\Rightarrow$ direct measurement

Discussion in the literature

- Widely discussed in the literature

  [e.g. Kanemura, Matsumoto, Nabeshima, Okada, Phys.Rev.D82 (2010); Djouadi, Lebedev, Mambrini, Quevillon, Phys. Lett. B709 (2012)]

- **typically considered:**
  portal coupling to scalar/ vector/ fermion DM candidates

$$\mathcal{L} \supset \qquad \lambda H^\dagger H\, S^2,\; \lambda H^\dagger H\, V_\mu V^\mu,\; \frac{\lambda}{\Lambda} H^\dagger H\, \overline{\chi}\chi$$

$\Rightarrow$ **nice feature:**
can be related to dark matter direct detection
(same coupling !!)

General parametrization

one step back... [next couple of slides stolen from T. Stefaniak]

Coupling scale factor (κ) parametrization

For many BSM theories, the 125 GeV Higgs collider pheno can be parametrized in terms of κ scale factors, [LHC HXSWG: YR3, '13]

$$\frac{\Gamma(H \to XX)}{\Gamma(H \to XX)_{\mathrm{SM}}} = \kappa_X^2 \quad (X = W, Z, g, \gamma, b, \tau, \ldots)$$

$$\frac{\sigma(gg \to H)}{\sigma(gg \to H)_{\mathrm{SM}}} = \kappa_g^2, \quad \frac{\sigma(qq \to VH)}{\sigma(qq \to VH)_{\mathrm{SM}}} = \kappa_V^2 \quad (V = W, Z), \text{ etc.}$$

and a rate for additional *new physics* (NP) Higgs decays, $\mathrm{BR}(H \to \mathrm{NP})$.

Our strategy:

Perform global fit to HL-LHC Higgs rates in two parametrizations

1. κ (common scale factor), $\mathrm{BR}(H \to NP)$;
2. κ (common for tree-level couplings), κ_g, κ_γ, $\mathrm{BR}(H \to NP)$;

Assume $\kappa_V \; (= \kappa) \leq 1$, but no further assumptions on $\mathrm{BR}(H \to NP)$ in fit.

Experimental input

Future HL-LHC limits from invisible Higgs searches

Official HL-LHC projections found in literature:

$\mu_{\mathsf{VBF}} \cdot \mathrm{BR}(H \to \mathrm{inv}) \leq 5.6\%$ (CMS, S2+ scenario) [CMS PAS FTR-16-002]

$\mu_{VH} \cdot \mathrm{BR}(H \to \mathrm{inv}) \leq 8.0\%$ (ATLAS, "realistic" scenario)

(with $\mu_i = \sigma_i / \sigma_{i,\mathsf{SM}}$) [ATL-PHYS-PUB-2013-014]

more studies are under way. . . (?)

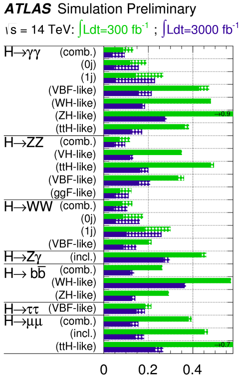
Let's make a tentative assumption:
"ATLAS (CMS) performs equally well as CMS (ATLAS) in missing channel!"

(Naive) combination of VBF and VH channels from ATLAS and CMS:

$$\Rightarrow \quad \mu_{\mathsf{VBF},VH} \cdot \mathrm{BR}(H \to \mathrm{inv}) \lesssim 3.5\% \quad (\text{ATLAS} \oplus \text{CMS})$$

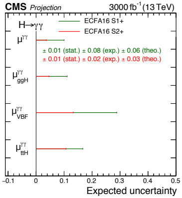
Experimental input

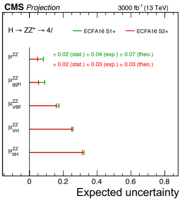
Future HL-LHC Higgs rate measurements



[ATL-PHYS-PUB-2014-016]

CMS ECFA 2016 report: [CMS PAS FTR-16-002]





CMS Snowmass report: [CMS, 1307.7135]

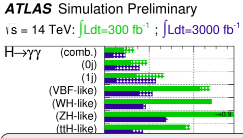
$\Delta\mu_{H\to WW} = 4\%$ $\quad$ $\Delta\mu_{H\to Z\gamma} = 20\%$

$\Delta\mu_{H\to bb} = 5\%$ $\quad$ $\Delta\mu_{H\to \mu\mu} = 20\%$

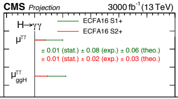
$\Delta\mu_{H\to \tau\tau} = 5\%$ $\quad$ (*Scenario 2*)

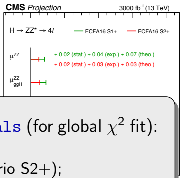
Experimental input

Future HL-LHC Higgs rate measurements



CMS ECFA 2016 report: [CMS PAS FTR-16-002]





Implementation of HL-LHC observables in HiggsSignals (for global χ^2 fit):

- Assume theory uncertainties are halved ($\simeq$ CMS scenario S2+);
- Correlations of theory/parametric uncertainties included in χ^2 calculation;
- Assume signal (i.e. production mode) compositions similar to current measurements.

$\Rightarrow$ Get a rough estimate of the combined ATLAS $\oplus$ CMS reach with $3000\ \mathrm{fb}^{-1}$.

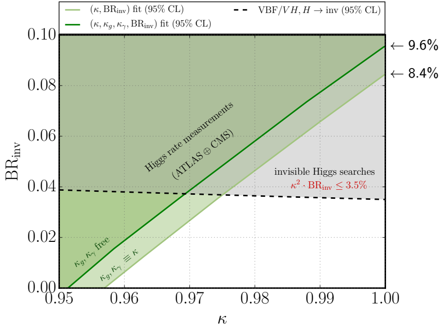
for more details, see [Bechtle, Heinemeyer, Stål, TS, Weiglein, 1403.1582]

[A

Simple fit: results

Result of combination: $\mathrm{BR}_{\mathrm{inv}} \leq 3.5\%$

HL-LHC prospects: κ parametrization

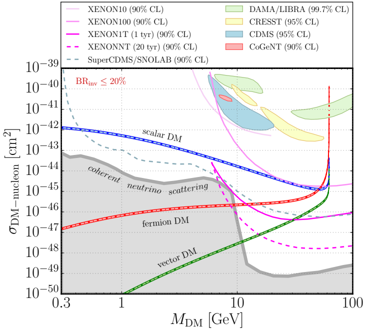


$\Longrightarrow$ can be interpreted in many models !! $\Longleftarrow$

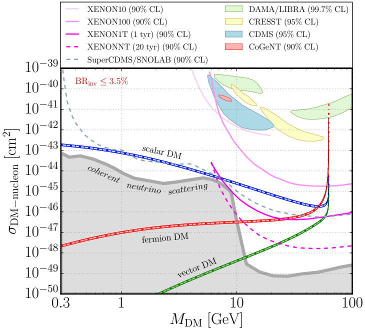
Higgs couplings in portal models

- remember: **relation between BR_{inv} and direct detection**

$\Rightarrow$ can translate limits



now



future

Higgs portal: a more concrete model

$\Rightarrow$ study a more concrete model to investigate complementarity

$\Rightarrow$ here: Higgs singlet:

2 scalar states h, H with mixing angle α

with singlet coupling to **scalar dark matter candidate X**

- important parameters

$$\underbrace{M_h,\ \cos\alpha,\ v_s}_{\text{as in "standard" singlet}}\ ,\ \underbrace{M_X,\lambda_{SXX}}_{\text{new}}$$

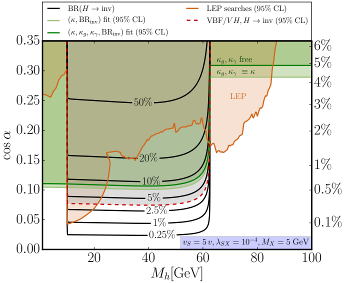
M_i new masses, λ new couplings, v_s singlet vev

(e.g. Englert, Plehn, Zerwas^2, Phys.Lett. B703 (2011))

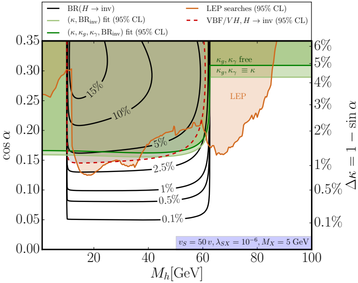
(Singlet: e.g. TR, T. Stefaniak, Eur.Phys.J. C75 (2015), Eur.Phys.J. C76 (2016))

Concrete model: results

Channels : $(a) H_{125} \rightarrow X\,X$ $(b) H_{125} \rightarrow h\,h \rightarrow 4X$



(b) enhanced



(b) suppressed

$\Rightarrow$ for certain regions, LEP direct searches always strongest constraints

$\Rightarrow$ for (b): direct limit better than fit

Higgs to invisible: summary

- simple fit in κ framework:

  large improvement wrt current status ✓
- dominance of fit or direct measurement depends on parameter point
- "simple" portal models:

interesting complementarity to direct detection experiments

⇒ for low DM masses, important probe !!

⇒ in general, improve by an order of magnitude

- for concrete model: **depends a lot in parameter space !**

⇒ large regions can be tested at HL-LHC

? Is this a physics case ?

Other exotic decays

(more a discussion)

Other exotic decays (excerpts)

⇒ (nearly) complete list: **D. Curtin ea, Phys.Rev. D90 (2014)**

- nice examples:

$$H_{125} \rightarrow SM(SM)\not{E}_T \qquad (1)$$

(example: Inert Doublet Model)

⇒ **can be largely constrained by $H \rightarrow$ invisible**

- would need searches/ search improvements for (1)

⇒ **searches often in specific models ! others might escape detection**

http://exotichiggs.physics.sunysb.edu

Exotic Higgs Decays
Working Group

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Theories Producing Exotic Higgs Decays

Here we summarize the phenomenology of exotic higgs decays generated by some well-motivated models, both simplified and more complete. This list is not meant to be exhaustive — for many decay channels we mention additional models which motivate that signature.

For more details, please refer to Section 1.3 of our Survey of Exotic Higgs Decays, arxiv:1312.4992

Standard Model plus a Singlet Scalar

Two-Higgs-Doublets Plus a Singlet

Standard Model plus a Singlet Fermion

Standard Model plus Two Singlet Fermions

Standard Model plus a Singlet Vector

MSSM

NMSSM with exotic Higgs decay to scalars

NMSSM with exotic Higgs decays to fermions

Little Higgs

Hidden Valleys

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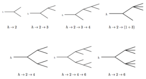
Decay Channels

We organize exotic Higgs decays by decay topology. This is well-adapted to a large number of specific models in the literature, allowing us to map easily between these models and our list.

In our discussion of exotic decays we will make three simplifying assumptions.

1. **The observed Higgs at 125 GeV is principally responsible for breaking the electroweak symmetry**. This amounts to taking something close to the decoupling limit in non-minimal Higgs theories, and assuming SM production.
2. **The Higgs decays to new particles beyond the SM.**
3. **The initial exotic Higgs decay is two-body.**



The exotic Higgs decay topologies we consider. Intermediate lines represent an *on-shell, neutral* particle, which is either a Z-boson or a BSM particle.

- $h \to 2$
  1. $h \to$ *invisible* (MET)
- $h \to 2 \to 3$
  1. $h \to \gamma$+MET.
  2. $h \to (b\bar{b})$ + MET.
  3. $h \to (\tau^+\tau^-)$ + MET.
  4. $h \to (\gamma\gamma)$ + MET.
  5. $h \to (ll)$ + MET (collimated leptons).
- $h \to 2 \to 3 \to 4$
  1. $(b\bar{b})$ + MET.
  2. $(\tau^+\tau^-)$ + MET.
  3. $(\gamma\gamma)$ + MET.
  4. $(l^+ l^-)$ + MET (isolated, collimated)
- $h \to 2 \to (1+3)$
  1. $l^+ l^-$ + MET (isolated)
- $h \to 2 \to 4$
  1. $(b\bar{b})(b\bar{b})$
  2. $(b\bar{b})$ $(\tau^+ \tau^-)$
  3. $(b\bar{b})$ $(\mu^+ \mu^-)$
  4. $(\tau^+ \tau^-)$ $(\tau^+ \tau^-)$
  5. $(\tau^+ \tau^-)$ $(\mu^+\mu^-)$
  6. (jj)(jj)
  7. (jj) $(\gamma\gamma)$
  8. (l^+l^-) (l^+l^-) ($h \to Z Z_D$, $h \to Z_D Z_D$, collimated leptons)
  9. $(\gamma\gamma)$ $(\gamma\gamma)$
  10. $\gamma\gamma$+ MET (no $\gamma\gamma$-resonance)
- $h \to 2 \to 4 \to 6$
  1. $h \to 2(ll)$ + MET (isolated, collimated).
  2. $h \to (ll)$ +MET +X (isolated, collimated)
- $h \to 2 \to 6$
  1. $h \to 2l$+ MET + X.
  2. $h \to 4l$+ MET.

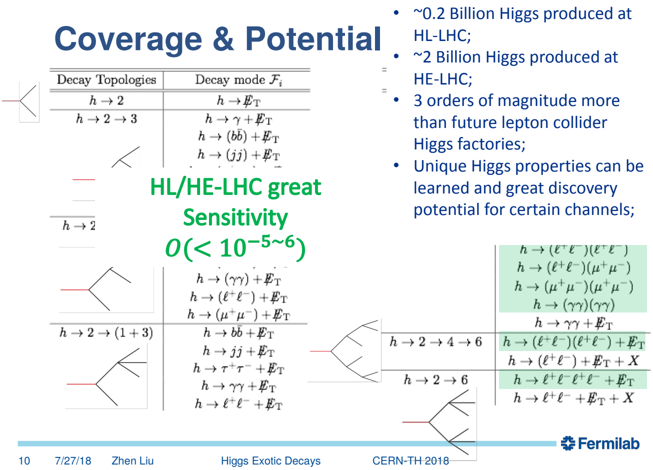
At the moment we only consider prompt decays with relatively low-multiplicity final states. Exploring displaced or h→ many decays will be the subject of future investigation.

In the following: Excerpts from Z. Lius talk, CERN-TH Institute, 07/18

possible final states

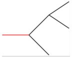
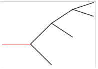
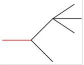
- $\ell^+ \ell^- \ell^+ \ell^- \; (+ \not{E}_T)$
  realized e.g. in models with dark gauge bosons Z_D, hidden valleys, additional scalars, SUSY, IDM, ...
- $\gamma\gamma\gamma\gamma$
  singlet, NMSSM, ...
- $b\bar{b}\tau^+\tau-$, $b\bar{b}b\bar{b}$
  extra scalars, NMSSM, little Higgs models
- ...
  (long list of final state signatures)

Excerpts from Z. Lius talk, CERN-TH Institute, 07/18



Excerpts from Z. Lius talk, CERN-TH Institute, 07/18

Coverage & Potential

Decay Topologies	Decay mode $\mathcal{F}_i$
$h \to 2$	$h \to \not{E}_T$
$h \to 2 \to 3$	$h \to \gamma + \not{E}_T$
	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
$h \to 2 \to 3 \to 4$	$h \to (b\bar{b}) + \not{E}_T$
	$h \to (jj) + \not{E}_T$
	$h \to (\tau^+\tau^-) + \not{E}_T$
	$h \to (\gamma\gamma) + \not{E}_T$
	$h \to (\ell^+\ell^-) + \not{E}_T$
	$h \to (\mu^+\mu^-) + \not{E}_T$
$h \to 2 \to (1+3)$	$h \to b\bar{b} + \not{E}_T$
	$h \to jj + \not{E}_T$
	$h \to \tau^+\tau^- + \not{E}_T$
	$h \to \gamma\gamma + \not{E}_T$
	$h \to \ell^+\ell^- + \not{E}_T$

Still a lot of uncharted territory for new searches!

Can be conquered using HL-LHC and future colliders with advanced analysis tools and new detectors.

For existing searches, new possibilities such as unequal masses (in progress) , etc.

See also nice crosstalk by A. Thamm and C. Caillol yesterday on Higgs->ALPs

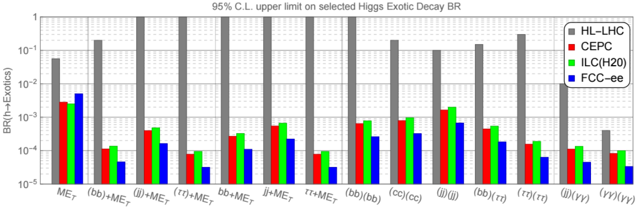
Decay mode $\mathcal{F}_i$
$h \to (b\bar{b})(b\bar{b})$
$h \to (b\bar{b})(\tau^+\tau^-)$
$h \to (b\bar{b})(\mu^+\mu^-)$
$h \to (\tau^+\tau^-)(\tau^+\tau^-)$
$h \to (\tau^+\tau^-)(\mu^+\mu^-)$
$h \to (jj)(jj)$
$h \to (jj)(\gamma\gamma)$
$h \to (jj)(\mu^+\mu^-)$
$h \to (\ell^+\ell^-)(\ell^+\ell^-)$
$h \to (\ell^+\ell^-)(\mu^+\mu^-)$
$h \to (\mu^+\mu^-)(\mu^+\mu^-)$
$h \to (\gamma\gamma)(\gamma\gamma)$
$h \to \gamma\gamma + \not{E}_T$
$h \to (\ell^+\ell^-)(\ell^+\ell^-) + \not{E}_T$
$h \to (\ell^+\ell^-) + \not{E}_T + X$
$h \to \ell^+\ell^-\ell^+\ell^- + \not{E}_T$
$h \to \ell^+\ell^- + \not{E}_T + X$

16 7/27/18 Zhen Liu Higgs Exotic Decays CERN-TH 2018 Fermilab

Excerpts from Z. Lius talk, CERN-TH Institute, 07/18

Coverage & Potential (FCC/CEPC/ILC/CLIC…)

ZL, L.-T. Wang, H. Zhang **1612.09284**



For these hard channels at the LHC:

- Lepton colliders show great advantage for decays that are very challenging at the LHC, such as Higgs decays into jets and Higgs decays with missing energy
- Hadron colliders and lepton colliders are complementary in probing Higgs exotic decays and could together provide a much more coherent picture for discovery

Fermilab

13 7/27/18 Zhen Liu Higgs Exotic Decays CERN-TH 2018

What about EFT setup ?

(slides from C. Murphy, HE/HL LHC meeting, June '18)

20 COEFFICIENTS CONSIDERED 11

DIMENSION-6 OPERATORS IN WARSAW BASIS

$$\bar{C} \equiv \frac{v^2}{\Lambda^2} C$$

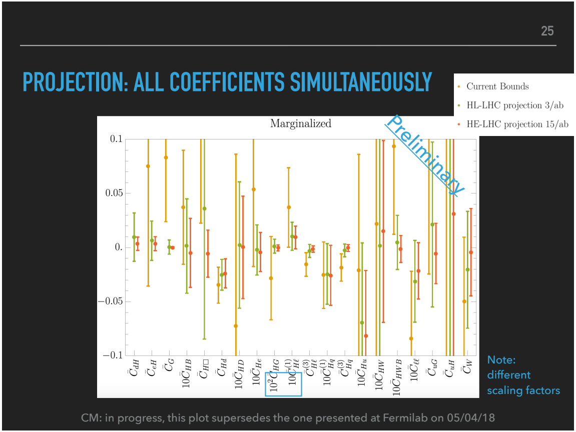
$$\begin{aligned}
\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset\ & \frac{\bar{C}_{Hl}^{(3)}}{v^2}(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{l}\tau^I\gamma^\mu l) + \frac{\bar{C}_{Hl}^{(1)}}{v^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{l}\gamma^\mu l) + \frac{\bar{C}_{ll}}{v^2}(\bar{l}\gamma_\mu l)(\bar{l}\gamma^\mu l) \\
& + \frac{\bar{C}_{HD}}{v^2}\left|H^\dagger D_\mu H\right|^2 + \frac{\bar{C}_{HWB}}{v^2} H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu} \\
& + \frac{\bar{C}_{He}}{v^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{e}\gamma^\mu e) + \frac{\bar{C}_{Hu}}{v^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{u}\gamma^\mu u) + \frac{\bar{C}_{Hd}}{v^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{d}\gamma^\mu d) \\
& + \frac{\bar{C}_{Hq}^{(3)}}{v^2}(H^\dagger i \overleftrightarrow{D}^I_\mu H)(\bar{q}\tau^I\gamma^\mu q) + \frac{\bar{C}_{Hq}^{(1)}}{v^2}(H^\dagger i \overleftrightarrow{D}_\mu H)(\bar{q}\gamma^\mu q) + \frac{\bar{C}_W}{v^2}\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_{\rm SMEFT}^{\rm Warsaw} \supset\ & \frac{\bar{C}_{eH}}{v^2} \boxed{y_e} (H^\dagger H)(\bar{l}eH) + \frac{\bar{C}_{dH}}{v^2} \boxed{y_d} (H^\dagger H)(\bar{q}dH) + \frac{\bar{C}_{uH}}{v^2} \boxed{y_u} (H^\dagger H)(\bar{q}u\widetilde{H}) \\
& + \frac{\bar{C}_G}{v^2} f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho + \frac{\bar{C}_{H\Box}}{v^2}(H^\dagger H)\Box(H^\dagger H) + \frac{\bar{C}_{uG}}{v^2} \boxed{y_u} (\bar{q}\sigma^{\mu\nu}T^A u)\widetilde{H}\, G^A_{\mu\nu} \\
& + \frac{\bar{C}_{HW}}{v^2} H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu} + \frac{\bar{C}_{HB}}{v^2} H^\dagger H\, B_{\mu\nu} B^{\mu\nu} + \frac{\bar{C}_{HG}}{v^2} H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}\,.
\end{aligned}$$

results of EMSY 1803.03252 expressed in both SILH and Warsaw bases

What about EFT setup ?

(slides from C. Murphy, HE/HL LHC meeting, June '18)



Another example: dark photons

[M.Heikinheimo, WG3 HL-LH meeting, 05/18]

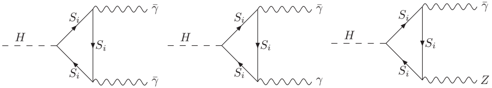
Dark Photons

- Dark photons appear in several beyond the Standard Model physics scenarios, where a new $U(1)$ gauge group is added to the SM.
- Massive dark photons can be dark matter candidates, while massless dark photons can appear in models of self-interacting dark matter. (Cusp-vs-core, missing satellites...)
- Unbroken $U(1)$ results in a massless dark photon. Motivated e.g. in a model for radiative origin of the SM Yukawa couplings. Gabrielli and Raidal: [arXiv:1310.1090 [hep-ph]]

Another example: dark photons
[M.Heikinheimo, WG3 HL-LH meeting, 05/18]

Coupling to the SM

Couplings to the Higgs can be generated via messenger particles charged under $U(1)' \times U(1)$.



Similar diagrams will also contribute to the $H \to \gamma\gamma$, $H \to ZZ$ decay widths.
Effective Lagrangian:

$$\mathcal{L}_{\mathrm{DP_H}} = \frac{\alpha}{\pi}\left(\frac{C_{\gamma\bar{\gamma}}}{v}\gamma^{\mu\nu}\bar{\gamma}_{\mu\nu}H + \frac{C_{Z\bar{\gamma}}}{v}Z^{\mu\nu}\bar{\gamma}_{\mu\nu}H + \frac{C_{\bar{\gamma}\bar{\gamma}}}{v}\bar{\gamma}^{\mu\nu}\bar{\gamma}_{\mu\nu}H\right)$$

Another example: dark photons

[M.Heikinheimo, WG3 HL-LH meeting, 05/18]

$H\gamma\bar{\gamma}$ Search; reach

Based on the two event selection criteria discussed above (the event selection adapted from the CMS analysis [1507.00359], and the jet veto), we estimate the reach for the $H \to \gamma\bar{\gamma}$ branching ratio (in %) in the HL-LHC and HE-LHC:

int. luminosity	3 ab^{-1}@14 TeV		15 ab^{-1}@27 TeV	
significance	2σ	5σ	2σ	5σ
CMS inspired	0.012	0.030	0.0052	0.013
jet veto in $\|\eta^j\| < 4.5$	0.020	0.051	0.021	0.053

These are our initial attempts to estimate the reach: A full detector simulation is required to better understand the QCD background.

Discussion

$\Rightarrow$ did not cover: **long lived particles**
(might also be interesting...)

- **in EFT: advantages of HL (and HE) LHC clear !**
- dark photon [very (!) optimistic cuts]:
  strong limits seem possible

$\Longrightarrow$ **in general: not enough studies [that I saw]** $\Longleftarrow$

- (maybe) missing **priority list** $\Rightarrow$ **needed ?**
- **also not seen: clear case for exotic decays at HL-LHC**
  (lepton colliders better in many cases)
- so far not covered (as far as I know) in YREP
  (maybe in single models)

Constraining BSM through SM

- another way: **determine $H_{125}^{3,(4)}$ couplings**
- **Status:**

HH analyses: HL-LHC

Two alternative approaches to sensitivity prediction of HH @ HL-LHC:

CMS
- Full analysis based on Delphes:
  - Phase-II CMS @HL-LHC
  - Better account for experimental effects + 14 TeV + detector upgrades
- $bbbb$, $bb\gamma\gamma$, $bb\tau\tau$, $bbVV$, $bbZZ$

ATLAS
- Based on extrapolation from run-II:
  - Studying systematics and triggers in HL-LHC environment
- $bbbb$, $bb\tau\tau$, $bb\gamma\gamma$

\+ Combination +

Channel	CMS	ATLAS
HH→ bbbb	$Z(\sigma_{HH}(SM))=0.39\ \sigma$	$-4.1 < \lambda_{HHH}/\lambda_{SM} < 8.7$ @95 % C.L.
HH→ bbττ	1.6 xSM	0.6 σ $-4.0 < \lambda_{HHH}/\lambda_{SM} < 12.0$ @95 % C.L.
HH→ bbγγ	1.43 σ	1.5 σ $0.2 < \lambda_{HHH}/\lambda_{SM} < 6.9$ @95 % C.L. (stat only)
HH→ WWbb	0.45 σ	

current projections: more info see ▸ Back-up

J.Langford | Higgs self coupling & HH | HL/HE-LHC Workshop 18 Jun. 2018 | 3 / 13

Conclusion

It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories, instead of theories to suit facts.

Sherlock Holmes, *A scandal in Bohemia* (A. C. Doyle)