Status of LHC measurements

Higgs coupling/SM expectation

ATLAS Preliminary

$\sqrt{s} = 13$ TeV, 36.1 - 79.8 fb$^{-1}$

$m_H = 125.09$ GeV, $|y_H| < 2.5$

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$B_{BSM} = 0$

$|\kappa_V| \leq 1$

$B_{BSM} \geq 0$

lack of CP violation, hierarchy, .... Where’s the new physics?
Status of LHC measurements

lack of CP violation, hierarchy,... Where’s the new physics?

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[ATLAS Preliminary]

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$B_{BSM} = 0$

$|\kappa_V| \leq 1$

$B_{BSM} \geq 0$

Higgs self-coupling missing...

$\kappa_Z$

$\kappa_W$

$\kappa_t$

$\kappa_b$

$\kappa_\tau$

$\kappa_g$

$\kappa_\gamma$

$B_{BSM}$

[ATLAS '18]
Higgs physics as a probe of (B)SM physics

- Can Higgs phenomenology pinpoint BSM solutions?
  
  Why have we not seen them yet? 
  What can be learned at 3/ab? 
  What about beyond the LHC?
Higgs physics as a probe of (B)SM physics

- Can Higgs phenomenology pinpoint BSM solutions?

1. Precision of Higgs coupling extraction
2. Sensitivity of rare final states (e.g., di-Higgs) and exotics
3. Sensitivity to weakly-coupled BSM

LHC can investigate this in three directions:

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- Higgs coupling extraction is made difficult by “blind directions”
- one of the most prominent and relevant for Higgs physics
Higgs coupling extraction is made difficult by “blind directions”

one of the most prominent an relevant for Higgs physics

contact ggH interactions mask top Yukawa measurements

way out: resolve loop for $p_T(H) \gtrsim m_t$ with one or more jets
way out: resolve loop for $p_T(H) \gtrsim m_t$ with one or more jets

[Banfi, Martin, Sanz `13] [Grojean, Salvioni, Schlaffer, Weiler `13]
[Schlaffer et al’ 14] [Buschmann et al. `14] [Buschmann et al. `14]...
neural network learns regions that are sensitive to uncertainty.

more kinematic information for H+2j, which is particularly promising, unfortunately $m_t=\infty$ SM limit accidentally good

$[\text{Del Duca et al.} \ '01]$

$\rightarrow$ S. Forte's talk

$[\text{CE, Galler, Harris, Spannowsky} \ '18]$
SM couplings

- more kinematic information for H+2j, which is particularly promising, unfortunately \(m_t=\infty\) SM limit accidentally good


\[
pp \rightarrow Hjj
\]

observables: \(p_T^{j,1}, \sigma_{hjj}\)

\[
c_g = -0.6 \quad c_t = 0.27
\]

... and can learn to avoid them \(\rightarrow\) robustness at highest sensitivity

see also [Goodfellow et al. ’14] [Louppe, Kagan, Cranmer ’16] ...
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The goal of this paper is to provide a comparative study and to offer concrete results of the search for di-Higgs boson production, with particular emphasis on the possible production of the Higgs boson pair (HH) and the measurement of the Higgs self-coupling. The CMS upgraded detector is studied with a parametric simulation.

Figure 9: Upper limit at the 95% CL on the HH production cross section as a function of the Higgs self-coupling. The red band corresponds to the range of the measurement.

A. General Remarks

The CMS Phase-2 project aims to collect 3000 fb\(^{-1}\) at 14 TeV, focusing on rare final states, which are crucial for obtaining large statistics. The study includes an analysis of the self-coupling of the Higgs boson, particularly in the context of its production in association with top quark pairs (ttH or t\(\bar{t}\)HH). The analysis is performed for the five decay channels investigated and their combination. The red band approximately represents the one standard deviation limits on the HH production cross section.

II. HIGGS PAIR PRODUCTION AT THE LHC

We begin with a discussion of some general aspects of the CMS detector's upgrade. The focus is on extending the analysis techniques, which are expected to improve the sensitivity to the Higgs self-coupling and other parameters.

In Sec. II D, we present the results of studying the potential sensitivity at the parton-level to the Higgs self-coupling, applying contemporary simulation and effective theory. Decay modes such as ttH and t\(\bar{t}\)H are compared to other channels beyond b\(\bar{b}\) andZZ*(4l).

The sensitivity towards the Higgs self-coupling is assessed within the context of radiative corrections, with the assumption that the calculation of the matrix element is straightforwardly interfaced to parton showers. The nature of the SM Higgs boson is constrained via the relative contribution of trilinear and quartic interactions to the integrated cross section. Note that the e\(\tau\) channel is less effective than the t\(\bar{t}\) channel.

In principle, allowing the Higgs self-coupling to change the nature of the SM Higgs boson would not significantly change the results, as the operators in Eq. (3) have different suppression than other e\(\tau\) modes. The sensitivity is assessed by comparing the results of Refs. [14–17].

For the five decay channels investigated and their combination, the red band approximately represents the one standard deviation limits on the HH production cross section.
**CMS Phase-2**

3000 fb\(^{-1}\) (14 TeV)

**Simulation Preliminary**

Assumes no HH signal

95\% CL upper limits - Median expected

- b\overline{b}b\overline{b}
- b\overline{b}\tau\tau
- b\overline{b}VV(l\nu l\nu)
- b\overline{b}\gamma\gamma
- b\overline{b}ZZ\( (++4l)\)
- Combination

**Theoretical prediction**

---

**di-Higgs final states**

rare final states = large statistics

---

we are in the domain of large (end-of-lifetime) LHC luminosity
Figure 9: Upper limit at the 95% CL on the HH production cross section as a function of the Higgs self-coupling ($\kappa_\lambda$) expectation, assuming no HH signal. The limits are shown for different decay channels of the HH system: $b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}VV$, $b\bar{b}\gamma\gamma$, and $b\bar{b}ZZ^{(*)}(4l)$. The combination of these channels yields the median expected limit. The red band represents the theoretical prediction. The CMS-PAS-FTR-18-019 Ref. indicates that we are in the domain of large (end-of-lifetime) LHC luminosity.
The lower panel shows the ratio with respect to the central value, and it can be seen that the scale uncertainty, evaluated by varying independently the above scales in the range \( \mu \), is only achievable with a statistical precision of the order of \( 10\% \). Other final states, namely those containing leptons, can also lead to a measurement of the SM signal, although in these cases the expected significance is lower than in the di-Higgs final states containing top quarks.

- easy to arrange ad-hoc EFT in a way to get spectacular rates, but can doubt physical relevance of such limits (\( \rightarrow \) matching)
di-Higgs final states

\[ g \rightarrow \bar{t}h + h \]

\[ g \rightarrow t + h + h \]

di-Higgs anatomy at 3/\text{ab}

corr. with on-shell Higgs phenomenology

\[ \sim \bar{t}th^2/\Lambda, \ldots \]

- easy to arrange ad-hoc EFT in a way to get spectacular rates, but can doubt physical relevance of such limits (→ matching)

- use concrete Higgs sector extensions (C2HDM/CxSM/…)
  - extrapolate 125 GeV signal strengths
  - extrapolate exotic Higgs searches
  - more constraints (electron EDMs, flavor, perturbativity, strong PS, CP viol.)

What’s left for di-Higgs?

---

[Basler, Dawson, CE, Mülleitner `18]
In the following, we will use the quantity SM-like Higgs boson the production of a SM-like Higgs pair with subsequent their prominent decays into top-quark pairs.

Thus there exist Higgs spectra with heavy Higgs bosons whose production remains below 3 in the 4\( \times \)10\(^2\) points, but at the rate below 2 in the 2\( \times \)10\(^2\) points would be excluded. This is because the T2 sample allowed by the luminosity of about 36 fb\(^{-1}\) leads to the lack of a dedicated experimental analysis for this.

As can be inferred from the figures in the C2HDM T1, SM-like measurements can show a plethora resonant anomalies due to the small enhancement in the di-Higgs final states important for BSM discovery.

However, SM-like resonance searches become sensitive to the lack of a dedicated experimental analysis for this. This shows the importance of experimental analyses in classification whether a Higgs boson has a sizable non-SM-like decay channel. The maximum allowed enhancement is due to the large di-Higgs production process with subsequent decay into a bottom quark pair. Applying our rough estimate on the exclusion power of the experiments for this process, based on the very few points in the 10\(^5\) range below the SM values.

Moreover, the maximum branching ratio into photons, however, the maximum allowed enhancement is due to the large di-Higgs production process with subsequent decay into a bottom quark pair. Applying our rough estimate on the exclusion power of the experiments for this process, based on the very few points in the 10\(^5\) range below the SM values.

Therefore, classifying whether a Higgs boson has a sizable non-SM-like decay channel is very important. The maximum branching ratio into photons, however, the maximum allowed enhancement is due to the large di-Higgs production process with subsequent decay into a bottom quark pair. Applying our rough estimate on the exclusion power of the experiments for this process, based on the very few points in the 10\(^5\) range below the SM values.

Thus, the exotic states can be dominantly discovered in diHiggs final states important for BSM discovery. Di Higgs final states quickly lose relevance when approaching EFT limit. Examples include C2HDM.
di-Higgs final states

- large interference effects of Higgs “signal” with QCD background

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

Parton level; before selection

\( m_A = 500 \text{ GeV}, \tan\beta = 0.68 \)

[ATLAS `17]

special role of tops

[Gaemers, Hoogeveen `84] [Dicus et al. `94]....
di-Higgs final states

- large interference effects of Higgs “signal” with QCD background

[Gaemers, Hoogeveen ’84] [Dicus et al. ’94]...

\[ \text{Events / 10 GeV} \]

\[ \sqrt{s} = 8 \text{ TeV}, 20.3 \text{ fb}^{-1} \]

\[ \text{Parton level; before selection} \]

\[ m_A = 500 \text{ GeV}, \tan \beta = 0.68 \]

\[ \text{ATLAS Simulation} \]

\[ m_{tt} \text{ [GeV]} \]

\[ \times 10^3 \]

\[ \text{S} \]

\[ \text{S+I} \]

\[ \text{top resonance searches in Higgs sector extensions with narrow width approximation is inadequate!} \]
special role of tops

- destructive interference in top final states can be correlated with excess in HH - how?

FIG. 2: Representative non-resonant “background” diagrams contributing to $pp \to t \bar{t}$ (a,b) and $pp \to hh$ (c) searches (diagram flows are understood implicitly). The $t \bar{t}$-shell $h$-induced background contribution derives from graphs shown in Fig. 1 with an $o$-shell running in the $s$-channel.

FIG. 3: Ratio of signal + interference cross section and OS cross-section for degenerate non-SM-like Higgs states. Points are pre-selected to have resonance cross sections of at least 170 fb at LO in the $t \bar{t}$ and 8 fb in the $hh$ channels. Left: 2HDM type 1, right: 2HDM, type 2.

When considered in relation to the on-shell signal definition can be very large, however in this case they have little phenomenological importance. We therefore filter our results with some minimum cross section requirements for both $pp \to t \bar{t}$ and $pp \to hh$. For $pp \to t \bar{t}$ we require at least 170 fb before the inclusion of $K$ factors, for $pp \to hh$ we demand at least 8 fb. This amounts to about $O(0.5 \text{pb})$\cite{83,84} when higher-order corrections are included for $t \bar{t}$ final states and $'16 \text{fb}$ for $hh$ production \cite{85–92}.

B. Results and Discussion

1. The C2HDM

In order to investigate the effects from interferences for the $hh$ and $t \bar{t}$ final states, we introduce the ratio of the signal plus interference cross section (defined in Eq. (20)) and the signal cross section $os$ (defined in Eq. (18)) for the requirement Eq. (19), i.e.

$$R(xx) = \frac{\sigma(xx)}{\sigma^{os}(xx)}, xx = hh, t \bar{t}. (21)$$

In Fig. 3(a) we show $R(hh)$ versus $R(t \bar{t})$ for the C2HDM type 1 for degenerate non-SM-like Higgs states, i.e. states whose masses differ by less than 10%. As can be inferred from the figure, there is a broad range of possible phenomenological outcomes. We can have a large enhancement or suppression of the $H_i \to t \bar{t}$ signal while the $hh$ rate can be either enhanced or reduced. Points with large constructive interference effects in the $t \bar{t}$ final state are likely to be constrained through $pp \to t \bar{t}$ measurements. We also obtain parameter points for which interference effects decrease the search potential in both the $t \bar{t}$ and $hh$ channels. Having simultaneous contributions from signal-signal (i.e. interference between the two $s$-channel $H_i \to h$ contributions) and signal-background interference for the resonance masses not too far away from each other, both effects contribute when we obtain a simultaneous enhancement in the $t \bar{t}$ and $hh$ rates.
special role of tops

- destructive interference in top final states can be correlated with excess in HH - how?
- phenomenologically viable regions exhibit compressed spectra: signal-signal interference

[Basler, Dawson, CE, Mühlleitner `19]
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3. sensitivity to weakly-coupled BSM
weakly-coupled BSM

- weakly coupled BSM: the $\mathbb{Z}_2$-symmetric Higgs portal
  \[ \mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} (\partial_\mu S)^2 - \frac{m_S^2}{2} S^2 - \lambda S^2 \left( \Phi^\dagger \Phi - v^2 / 2 \right) \]

- for $m_S > m_H / 2$ no direct SM Higgs decays

- Higgs physics modifications via loop- or kinematics-suppressed effects
weakly-coupled BSM

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- for $m_S > m_H/2$ no direct SM Higgs decays
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Trilinear Higgs coupling modifications

[H, Zhu '16]
[Voigt, Westhoff '17]
[CE, Jäckel '19]

Higgs precision studies at colliders

[CE, McCullough '13]
[Craig, CE, McCullough '13]
[Goncalves, Han, Mukhopadhyay '18]

off-shell production

[Craig, Lou. et al. '14]
[Ruhdorfer, Salvioni, Weiler '19]
The Coleman-Weinberg approximation for di-Higgs can be useful when we expect higher sensitivity than the electroweak potential unstable approximation for Higgs boson production (Higgs-strahlung) beyond just finding a deviation from the SM and fingerprint precision calculations at the time. That said, it is clear that such analyses are diHiggs @ FCC-hh [Contino et al. `17] needed to be contrasted with coherent destructive interference between the diagrams in Fig. 53. The red, orange and yellow regions correspond to a 1.7%, 1.06% and 0.5% measurement with respect to pair production of the new scalar weakly-coupled BSM boson, giving rise to a missing energy signal. These constraints do not depend on the energy produced via an on-shell Higgs, typically leading to miss-energy signals. The eventual sensitivity yield will obviously depend on the details of the machine itself as well as the status of SM physics. 

At hadron colliders, the Higgs portal interaction leads to di-Higgs @ LHC production. These constraints do not depend on the energy produced via an on-shell Higgs, typically leading to miss-energy signals. The eventual sensitivity yield will obviously depend on the details of the machine itself as well as the status of SM physics.

It is known that the associated weak corrections will be efficiently large statistics could enable us to go beyond just finding a deviation from the SM and fingerprint precision calculations at the time. That said, it is clear that such analyses are diHiggs @ FCC-hh [Contino et al. `17] needed to be contrasted with coherent destructive interference between the diagrams in Fig. 53. The red, orange and yellow regions correspond to a 1.7%, 1.06% and 0.5% measurement with respect to pair production of the new scalar weakly-coupled BSM boson, giving rise to a missing energy signal. These constraints do not depend on the energy produced via an on-shell Higgs, typically leading to miss-energy signals. The eventual sensitivity yield will obviously depend on the details of the machine itself as well as the status of SM physics.
Higgs physics sits at the heart of our BSM efforts

- enhancing theoretical predictions
- limit setting tailored to minimise systematics pollution
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Opportunity to link the Higgs sector to new physics

- cure SM shortcomings (CP violation...)
- multi-Higgs is a hard case for BSM sensitivity
- new collider concepts can maximise precision vs energy reach in complementary ways