Abstract. The discovery of the Standard Model Higgs boson performed by the CMS and ATLAS collaborations during the LHC Run 1 has been an important success. This document is a short review of the search for the Higgs boson performed by the CMS collaboration during the LHC Run 1 and Run 2. In the first part, after a brief description of the Higgs boson production and decay channels, the Run-1 results are presented emphasizing the possible hints of New Physics. The main part of this document is devoted to the search for the Higgs boson with the 13-TeV data collected by the CMS experiment in 2015 and 2016, including the Standard Model searches as well as the Beyond Standard Model searches, such as the search for additional Higgs bosons and for resonant and non-resonant double Higgs boson production.

1. The Standard Model Higgs boson

1.1. Production and decay channels

In proton-proton colliders, the Standard Model (SM) Higgs boson can be produced through several production channels. The cross section of each channel depends on the center-of-mass energy \( \sqrt{s} \) and on the Higgs boson mass. In the Run 2, since the LHC increased \( \sqrt{s} \) from 8 TeV to 13 TeV, the 125-GeV SM Higgs boson cross section has increased in all the main production channels: gluon-gluon fusion (ggF, 19.3 pb \( \rightarrow \) 43.9 pb), vector-boson fusion (VBF, 1.57 pb \( \rightarrow \) 3.75 pb), vector-boson associated production (VH, 1.12 pb \( \rightarrow \) 2.25 pb), and top-quark pair associated production (ttH, 0.13 pb \( \rightarrow \) 0.51 pb) [1].

The branching ratios predicted by the SM for the main Higgs boson decay channels are \( H \rightarrow bb \) (58%), \( H \rightarrow WW \) (21%), \( H \rightarrow \tau \tau \) (6.3%), \( H \rightarrow ZZ \) (2.6%), and \( H \rightarrow \gamma \gamma \) (0.23%) [1].

2. Run 1 results

2.1. Higgs production and decay

In the Run 1, the Higgs boson was searched in many different final states with the CMS detector [2]. Figure 1 shows the signal strength \( \mu = \sigma/\sigma_{\tiny\text{SM}} \) measured in each analysis.

The analyses were combined according to the Higgs boson production channels, and the fitted values are shown in Fig. 2. All the results are compatible with the SM prediction within one standard deviation except for the \( ttH \) production channel \( \mu = 2.90^{+1.08}_{-0.94} \).

As shown in Fig. 3, the slight \( ttH \) excess was mainly driven by the same-sign two-leptons final-state analysis \( \mu = +5.3^{+2.1}_{-1.8} \), especially in the same-sign two-muons final states \( \mu = +8.5^{+3.3}_{-2.7} \) [4]. All the other measurements are in agreement with the SM expectation in 1.5 standard deviations.
The Higgs boson searches were also combined to measure the signal strength of the different decay channels. The results are shown in Fig. 4: the signal strengths are compatible with SM for all decay channels. The corresponding observed (expected) significances are

- \( H \rightarrow ZZ : 6.5 (6.3) \);
- \( H \rightarrow \gamma\gamma : 5.6 (5.3) \);
- \( H \rightarrow WW : 4.7 (5.4) \);
- \( H \rightarrow \tau\tau : 3.8 (3.9) \);
- \( H \rightarrow bb : 2.0 (2.6) \);
- \( H \rightarrow \mu\mu : < 0.1 (0.4) \) [3].

2.2. Higgs couplings

The Higgs boson searches were eventually combined to search for deviations from the SM in the Higgs boson couplings. Figure 5 shows the measured Higgs boson couplings to the fundamental particles with respect to the SM expectations. All the results are in agreement with the SM expectation.

2.3. Higgs mass

The Higgs mass was measured using the \( H \rightarrow \gamma\gamma \) and \( H \rightarrow ZZ \) channels and the combination of the two channels is shown in Figure 6. A slight tension of 1.6\( \sigma \) was reported between the two...
Figure 4. Run-1 signal strengths by decay channels [3].

Figure 5. Higgs boson coupling modifiers fitted in the Run 1 [3].

measurements, as shown by the log-likelihood scan of $m_{\gamma\gamma} - m_{4\ell}$ in Fig. 7. The best-fit mass is

$$m_H = 125.03^{+0.26}_{-0.27} \text{(stat.)}^{+0.14}_{-0.13} \text{(syst.)} \text{GeV}.$$

The measurement is dominated by the statistical uncertainty, and hence we expect to largely improve the measurement in the LHC Run 2.

Figure 6. Log-likelihood scan of the Higgs boson mass for the Run-1 $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$, and their combination [3].

Figure 7. Log-likelihood scan for the difference between the Higgs boson mass measured in the Run-1 $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ$ [3].

2.4. Higgs spin and parity

The high purity of the $H \rightarrow ZZ \rightarrow 4\ell$ channel allows to test the validity of many spin and parity models. Figure 8 shows the probability distributions of the likelihood ratio between the $0^+$ and $0^-$ hypotheses, for the two hypotheses: the experimental result excludes the $0^-$ parity hypothesis with 3.3 standard deviations. Likewise, many other spin/parity models were tested and the results are collected in Fig. 9. All results found are compatible with the SM within 2 standard deviations.
2.5. Higgs width

At $m_H = 125$ GeV, the width of Higgs boson predicted by the SM is of few MeV, but the experimental Higgs mass resolution is of few GeV. However, it can be measured indirectly exploiting the off-shell production of the Higgs boson, assuming that all properties of the Higgs boson are those predicted by the SM except for the Higgs boson width ($\Gamma_H$). Figure 11 compares the four-leptons invariant mass distribution expected for $\Gamma_H = \Gamma_{H,SM}$ and $\Gamma_H = 25 \times \Gamma_{H,SM}$. The likelihood scan of $\Gamma_H$ measured by the CMS collaboration after the LHC Run 1 is shown in Fig. 12. It sets an observed (expected) upper limit of 22 MeV (33 MeV) at a 95% CL corresponding to 5.4 (8.0) times the SM value.

2.6. Higgs differential cross section

The large statistic of the Run-2 will allow to measure precisely the differential cross section of the production of the Higgs boson. The first preliminary results were obtained in Run 1 for the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ \rightarrow 4\ell$. Figure 13 and 14 show, respectively, the $p_T(H)$ and $y(H)$
Figure 11. Four lepton mass distribution for $\Gamma = \Gamma_{SM}$ and $\Gamma = 25 \times \Gamma_{SM}$, in the $H \rightarrow ZZ$ channel [7].

differential cross section measured for the $H \rightarrow \gamma\gamma$ channel. Similarly, Figure 15 and 16 are for the $H \rightarrow ZZ \rightarrow 4\ell$ channel.

Figure 13. Differential cross section as a function of the Higgs boson momentum measured using the $H \rightarrow \gamma\gamma$ with 2012 data [8].

Figure 14. Differential cross section as a function of the Higgs boson rapidity measured using the $H \rightarrow \gamma\gamma$ with 2012 data [8].

2.7. Beyond Standard Model searches

Many Beyond Standard Model (BSM) Higgs boson searches were performed using the Run-1 dataset. Among them, a slight excess (2.5$\sigma$) was reported in the lepton flavour violation search $H \rightarrow \mu\tau$. The excess was equivalent to a $\text{BR}(H \rightarrow \mu\tau) = 0.89^{+0.40}_{-0.37}$%, as shown in Fig. 17. Figure 18 shows the $\tau\mu$ invariant mass distribution for the category with the decay $\tau \rightarrow e\nu\nu_\tau$, and one jet in the final state, assuming that the neutrinos have the same direction of the electron.
Figure 15. Differential cross section as a function of the Higgs boson momentum measured using the $H \to ZZ \to 4\ell$ with 2012 data [9].

Figure 16. Differential cross section as a function of the Higgs boson rapidity measured using the $H \to ZZ \to 4\ell$ with 2012 data [9].

Figure 17. Branching ratio of $H \to \mu\tau$, obtained using the 2012 dataset [10].

Another important way to search for new physics is the measurement of the effective couplings of the Higgs boson with gluons ($\kappa_g$) and photons ($\kappa_\gamma$), since BSM particles might modify these loop interactions. The effective couplings were measured combining all the SM Higgs boson searches and assuming the SM prediction for the couplings with the other fundamental particles. Figure 19 shows the 68%, 95%, and 99.7% CL limits measured for the coupling modifiers $\kappa_g$ and $\kappa_\gamma$. The result is compatible with the SM expectation within one standard deviation and therefore no hint of New Physics was observed in the loops of the Higgs-gluon and Higgs-photon interactions.

3. Run 2 - SM Higgs
3.1. $H \to \gamma\gamma$

The di-photon Higgs decay was one of the main discovery channels in the Run 1. In the Run 2, the analysis has been performed splitting it into eight categories with different event topology...
Figure 19. Confidence regions for modifier Higgs couplings with photons ($\kappa_\gamma$) and gluons ($\kappa_g$), obtained using the Run-1 dataset [3].

(VBF, ttH, untagged) and signal-to-background ratio. The latter separation has been obtained using a Boosted Decision Tree (BDT) that exploits the most discriminating variables, with the exception of $m_{\gamma\gamma}$ and correlated variables. The definition of the four categories with the untagged topology is shown in Fig. 20. The signal has been extracted fitting simultaneously the $m_{\gamma\gamma}$ distribution in each category, looking for the Higgs peak on top of a smooth falling background distribution. Figure 21 shows the $m_{\gamma\gamma}$ distribution combining all categories and weighting each of them according to its purity ($S/(S + B)$). The result of each category is shown in Fig. 22. The measured combined signal strength is $\mu = 0.95^{+0.21}_{-0.18}$. The background-only hypothesis is excluded with 6.2 standard deviations. Figure 23 shows the Higgs boson cross section measured as a function of the center-of-mass energy, along with the SM prediction.

3.2. $H \rightarrow ZZ \rightarrow 4\ell$

In the Run-1, the other main channel of the Higgs boson discovery was the $H \rightarrow ZZ \rightarrow 4\ell$. The Run-2 analysis has been divided into three final states ($4\mu$, $4e$, $2e2\mu$) and in six event categories,
aiming to separate the different production channels (VBF-1jet, VBF-2jet, VH-leptonic, VH-hadronic, ttH, untagged). The signal composition of each event category is shown in Fig. 24. The overall four-leptons invariant mass distribution is shown Fig. 25. A matrix element discriminant ($D_{\text{kin}}$) has been exploited in order to increase the signal to background separation. The signal is extracted fitting the 2D distribution of ($m_4\ell,D_{\text{kin}}$) in 18 categories (3 final states $\times$ 6 event categories). Figure 26 is a superimposition of the 2D distributions of the 18 categories used in the final fit. The fitted global signal strength is $\mu = 0.99_{-0.26}^{+0.35}$ at $m_H = 125.09$ GeV, corresponding to an observation of the $H \rightarrow ZZ \rightarrow 4\ell$ with 6.2$\sigma$, as shown in Fig. 27. Figure 28 is the measurement of the Higgs boson cross section as a function of the center-of-mass energy. Likewise the Run 1, the $H \rightarrow ZZ \rightarrow 4\ell$ channel has been used to measure also the differential cross-section, the mass, and the width. Figure 29 shows the Higgs boson cross section as a function of $p_T(H)$. The best fit of the Higgs boson mass using the 13-TeV dataset is $m_H = 124.50_{-0.48}^{+0.48}$. The observed (expected) 95% CL upper limit on the Higgs boson width is 41 MeV (32 MeV), as shown in Fig. 30.

3.3. $ttH$ (multilepton)

In the multilepton $ttH$ analysis, the Higgs boson has been searched in the $ttH$ topology with at least two same-sign leptons in the final state. The signal includes the $H \rightarrow WW, ZZ, \tau\tau$ decays. The main backgrounds of this search are the $ttW$ and $ttZ$ productions: two BDTs have been trained in order to reject these backgrounds and are used in the final signal extraction. Other
backgrounds are the fake lepton identification from multijet events and the charge misidentified electrons. Figure 31 and 32 show the BDT distribution in the two and three leptons categories. The fitted combined signal strength is $\mu = 2.0^{+0.8}_{-0.7}$. The observed (expected) 95% CL upper limit is 3.4 (1.3) time the standard model cross section.

3.4. $ttH(bb)$

The $ttH(bb)$ analysis exploits the large branching ratio of $H \rightarrow bb$ (58%). The main background is top pairs production with additional jets. The analysis has been split into single and double lepton channels, and in categories depending on the number of jets and b-jets. A BDT has been trained to further split the categories into two parts (high and low S/B). Figure 33 shows the distribution of the BDT used to split one of the single-lepton categories. A Matrix Element Method (MEM) is used for the signal extraction, using the likelihood ratio of the event to be signal ($tt+H$) or background ($tt+bb$) as a discriminant. Figure 34 shows the MEM distribution for one of the single categories before and after the final fit. A background under-fluctuation has been reported: the fitted signal strength is $\mu = -0.19^{+0.80}_{-0.81}$ (stat.) $^{+0.66}_{-0.68}$ (syst.). The fitted upper limits obtained in the fully leptonic and semi-leptonic categories are shown, respectively, in Fig. 35 and 36. The combination of all categories gives a 95% CL observed (expected) upper limit of
1.5 (1.7) times the standard model cross section. Figure 38 shows a combination of the final BDT distributions from all categories, as a function of the signal-to-background ratio.

3.5. VBF H(bb)
The $H \rightarrow bb$ has been searched also in VBF production. This signal topology is made of two b-jets from the Higgs boson decay and two forward/backward jets from the vector-boson fusion. As shown in Fig. 39, the di-jet invariant mass resolution has been improved using a b-jet energy regression. A BDT has been trained in order to split the analysis into several categories with a different signal-to-background ratio. The BDT distribution is shown in Fig. 40. The signal is extracted fitting the $m_{bb}$ distribution in each category. Figure 41 shows the fit for the most sensitive category. A background under-fluctuation has been reported, as shown in Fig. 42 where the likelihood scan of the signal strength of the 13 TeV, 8 TeV, and the combination are reported. The 95% CL observed (expected) upper limit is 3.0 (5.0) times the SM cross-section.
Figure 33. BDT distribution in the \( \geq 6 \) jets and \( \geq 4 \) b jets region. The signal median is used to split the region into two categories [14].

Figure 34. MEM discriminant before and after the final fit, in the \( \geq 6 \) jets and \( \geq 4 \) b jets region [14].

Figure 35. Upper limit for the fully-leptonic \( ttH(bb) \) categories and their combination [14].

Figure 36. Upper limit for the semi-leptonic \( ttH(bb) \) categories and their combination [14].

Figure 37. Signal strength of the fully-leptonic, semi-leptonic \( ttH(bb) \), and their combination [14].

Figure 38. Combination of the \( ttH(bb) \) MEM distributions in S/B bins [14].

4. Run 2 - Higgs pair production
The search for the double Higgs boson production - and hence the measurement of the self Higgs boson couplings - is one important target of the High Luminosity LHC. However, new Physics
might enhance this process or produce new particles decaying into a Higgs boson pair, making this process visible even at a lower luminosity. Therefore, the double Higgs boson production has been searched in the Run 2 in both the resonant and non-resonant final states.

4.1. $HH \rightarrow \gamma\gamma bb$

One possible way to search for the double Higgs boson production is the resonant $pp \rightarrow X \rightarrow HH \rightarrow \gamma\gamma bb$, exploiting both the $H \rightarrow \gamma\gamma$ to reduce QCD background and the $H \rightarrow bb$ in the attempt to have the largest possible signal yield. This channel is characterized by a very high purity but a low statistic. The 95% CL upper limit is shown in Fig. 43 as a function of the resonance mass.

The $pp \rightarrow HH \rightarrow \gamma\gamma bb$ has been also searched also in the non-resonant final states. The upper limit is shown in Fig. 44 and it corresponds roughly to 90 times the SM cross section.

4.2. $HH \rightarrow bbbb$

The search for the double Higgs in the fully hadronic final state exploits the high $H \rightarrow bb$ branching ratio (58%), but it is characterized by a large multijet background. In the resonant search, the signal has been extracted looking for a peak in the smooth di-Higgs invariant mass
Figure 43. Upper limit for the search for resonant \( pp \rightarrow X \rightarrow HH \rightarrow bb\gamma \) [16].

Figure 44. Upper limit for the search for non-resonant \( pp \rightarrow HH \rightarrow bb\gamma \) [16].

distribution, as shown in Fig. 45 and 46. As shown if Fig. 47, a kinematic fit has been used in order to improve the resolution on the di-Higgs mass, exploiting the Higgs mass constraint. The results are shown in Fig. 48: no excess has been found. The \( pp \rightarrow X \rightarrow HH \rightarrow bbbb \) is the analysis with the highest sensitivity at high resonance mass.

Figure 45. Four b jet invariant mass distribution in the low mass \( pp \rightarrow X \rightarrow HH \rightarrow bbbb \) signal region [17].

Figure 46. Four b jet invariant mass distribution in the high mass \( pp \rightarrow X \rightarrow HH \rightarrow bbbb \) signal region [17].

The search of non-resonant \( pp \rightarrow HH \rightarrow bbbb \) has been performed using a BDT, to select a signal-like phase-space, and a 2D fit of the mass of the two Higgs boson candidates, to perform the final signal extraction. Figure 49 shows the BDT distribution and Figure 50 show the unrolled 2D-mass fit. The background has been estimated in a fully data-driven way. The observed (expected) upper limit is \( 3.88 \text{ pb}^{-1} \) (\( 3.49 \text{ pb}^{-1} \)), corresponding to roughly 340 times the standard model cross section.

4.3. \( HH \rightarrow bb\ell\ell \)

The search for \( HH \rightarrow bb\ell\ell \) includes both the \( HH \rightarrow bbW(\ell\nu)W(\ell\nu) \) and \( HH \rightarrow bbZ(\ell\ell)Z(\nu\nu) \) signals: in both cases, the presence of two neutrinos in the final state degrades the invariant mass resolution on the Higgs boson decaying to leptons. The main background is the top-pair production decaying fully leptonically.

In the resonant search, two BDTs have been trained to separate the signals \( (m_X = 400 \text{ GeV}, 650 \text{ GeV}) \) from the background, as shown in Fig. 51. The phase space has been then
Figure 47. Four b-jet invariant mass resolution before and after the kinematic fit [17].

Figure 48. Upper limit of the search for resonant $pp \rightarrow X \rightarrow HH \rightarrow bbbb$ [17].

Figure 49. Signal and background BDT distribution in the search for non-resonant $pp \rightarrow HH \rightarrow bbbb$ [18].

Figure 50. Signal and background BDT distribution in the search for non-resonant $pp \rightarrow HH \rightarrow bbbb$ [18].

Figure 51. 2.3 fb$^{-1}$ (13 TeV)

 CMS Preliminary

 Expected Upper Limit

 Expected 1 σ

 Expected 2 σ

 Observed Upper Limit

 KK-Gluon, mt=30, k_{M}=0.1

2.3 fb$^{-1}$ (13 TeV)

 Expected Upper Limit

 Expected 1 σ

 Expected 2 σ

 Observed Upper Limit

 KK-Gluon, mt=30, k_{M}=0.1

 The 95% upper limits are shown in Fig. 52 as a function of the resonance mass.

The nonresonant search has been performed splitting the di-jet $m_{bb}$ invariant mass, shown in Fig. 53, in three parts and then fitting the BDT distribution in each of these regions, as shown in Fig. 54. The 95% CL upper limit is about $\sigma < 400\sigma_{SM}$.

4.4. $HH \rightarrow bb\tau\tau$

The $pp \rightarrow HH \rightarrow bb\tau\tau$ search has been divided into three sub-channels $\tau(\mu\nu\nu)\tau(\text{hadr.}\nu)$, $\tau(e\nu\nu)\tau(\text{hadr.}\nu)$, $\tau(\text{hadr.}\nu)\tau(\text{hadr.}\nu)$. A kinematic fit has been used in order to improve the $m_{\tau\tau bb}$ resolution - degraded by the presence of neutrinos in the final state. The main backgrounds are $t\bar{t}$, Drell-Yan, and the multijet events.

The resonant search is performed looking for a peak in the $m_{\tau\tau bb}$ distribution, as shown in Fig. 55. No significant excess have been found. The measured upper limits are shown in Fig. 56. In the non-resonant analysis, a BDT has been trained in order to increase the signal-to-
Figure 51. BDT distribution in the search for resonant $pp \to X \to HH \to bb\ell\ell$ [19].

Figure 52. Upper limits as a function of the resonant $pp \to X \to HH \to bb\ell\ell$ mass [19].

Figure 53. Di-jet invariant mass distribution in the search for non-resonant $pp \to HH \to bb\ell\ell$ [20].

Figure 54. Di-jet invariant mass distribution in the search for non-resonant $pp \to HH \to bb\ell\ell$ [20].

Figure 55. Invariant mass distribution, after the kinematic fit, of $X \to HH \to bb\tau\tau$ [21].

Figure 56. Upper limit for the search of $X \to HH \to bb\tau\tau$, as a function of the resonance mass [21].
background ratio. Figure 57 shows the BDT output distribution in one of the $\tau(\mu\nu)\tau(\text{had.}\nu)$ subchannel. The signal has been extracted fitting the di-Higgs mass distribution, as shown in Fig. 58. The results have been interpreted as 95% CL limits on the cross-section, as a function of the coupling modifier $\kappa_\lambda = \lambda_{HHH}/\lambda_{SM}^{HHH}$. They are shown in Fig. 59. For $\kappa_\lambda = 1$, the observed (expected) 95% CL upper limit is about 200 (170) $\sigma_{SM}$.

**Figure 57.** BDT distribution for the search of non-resonant $pp \rightarrow HH \rightarrow bb\tau\tau$ [22].

**Figure 58.** Higgs boson pair invariant mass distribution in the search of non-resonant $pp \rightarrow HH \rightarrow bb\tau\tau$ [22].

5. Run 2 - BSM Higgs

5.1. Higgs to invisible

If a massive weakly interacting particle couple with the Higgs boson, it would give the decay $H \rightarrow \text{invisible}$, if $m_H > 2m_X$. This decay has been searched in different Higgs production channels: VBF $H(\text{inv.})$, $Z(\ell\ell)H(\text{inv.})$, $Z(bb)H(\text{inv.})$, $V(jj)H(\text{inv.})$, $ggF\ H(\text{inv.}) + \text{jets}$.

Figure 60 shows the upper limit on the $H(\text{inv.})$ branching ratio, for all channels and their combination. Figure 61 shows the likelihood scan of the branching ratio of $H \rightarrow \text{inv.}$ for the Run 1 and Run 2 analyses, and their combination. The observed (expected) upper limit for the combination is 24% (23%).

**Figure 59.** Cross-section 95% upper limit as a function of $\kappa_\lambda$ obtained with the search for non-resonant $pp \rightarrow HH \rightarrow bb\tau\tau$ [22].
5.2. $tH(bb)$

The search for the Higgs boson produced in association with a single top quark is a powerful way to probe the sign of the top quark Yukawa coupling ($y_t$). Figure 62 shows the two leading diagrams that produce the $tH$ signal. In the SM, the interference of these two processes is destructive. Any alteration of $y_t$ or $y_W$ would increase the cross section: it increases of about a factor ten for $y_t = -1$.

The analysis is performed using two BDTs, where jets are assigned according to the $tH$ and $tt$ hypothesis. They are inputs of a final BDT, shown in Fig. 63, that is used for the signal extraction. The upper limit, as a function of $y_t$, is shown in Fig. 64. For $y_t = -1$, the observed (expected) upper limit is $\sigma < 6.0 \,(6.4)\sigma_{y_t=-1}$.

5.3. $H \rightarrow \tau\mu$ (lepton flavour violation)

In Run 1, a slight excess was reported in the lepton flavour violating channel $H \rightarrow \tau\mu$. The search has been repeated with the 2015 data and, oppositely to the Run 1 result, a background underfluctuation has been reported. Figure 65 shows the distribution of the invariant mass $m_{\mu\tau}$ for the analysis performed in Run 1. The upper limit obtained in each category is shown in Fig. 66. The observed (expected) combined upper limit is $\mu < 1.20\%(1.62\%)$, and it does not exclude the Run 1 excess ($\mu = 0.80 \pm 0.37\%$).
6. Conclusions and outlook

In Run 2, the Higgs boson has been observed at 13 TeV and the sensitivity of many analysis is already close to the Run 1. All properties confirm the SM expectation and no hint of new...
Physics have been found. In 2016, LHC delivered more than 40 fb\(^{-1}\) of proton-proton collisions, as shown in Fig. 67, and LHC is expected to deliver more than 100 fb\(^{-1}\) by the end of Run 2. Many important CMS Higgs physics results are expected to come soon.

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