Higgs boson : production and decays into bosons

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The results on the Higgs boson with decay channels into bosons from the ATLAS and CMS experiments at LHC Run 1 and early Run 2 are reviewed in the context of the Standard Model : observation of a signal, measurement of mass, width, spin, cross-sections, search for decay channels and production modes, Higgs couplings to various particles.

1 Introduction

Research on the Higgs boson discovered [1,2] in 2012 at the Large Hadron Collider (LHC) [3] by the ATLAS [4] and CMS [5] experiments, has entered the precision measurement area. The analysis of the full Run 1 exploits approximately 5 fb^{-1} of integrated luminosity accumulated by each experiment at $\sqrt{s} = 7\ TeV$ in 2011 and 20 fb^{-1} at $\sqrt{s} = 8\ TeV$ in 2012. The analysis based on early Run 2 of the year 2015 exploits 3.2 fb^{-1} and 2.6 fb^{-1} of data collected respectively by ATLAS and CMS at $\sqrt{s} = 13\ TeV$.

Taking into account the branching ratio (BR) of the Higgs boson at its mass of around 125 GeV, and the background involved, the main interesting channels are the decays $H \to \gamma\gamma$, $H \to ZZ^* \to 4l$, $H \to WW^* \to l\nu l\nu$, $H \to bb$, $H \to \tau\tau$, $H \to Z\gamma$, $H \to \mu\mu$. The main processes for the production, ordered by decreasing cross-section, are the gluon fusion from an heavy quarks loop (mainly top and bottom), the vector boson fusion (VBF) $qq \to qqH$, the associated production with a vector boson, WH, ZH, with top quarks, ttH, or with bottom quarks, bbH. An additional process, with a small rate and very sensitive to interference effects, is the production of the Higgs boson with a single top : tH.

The Higgs coupling depends on the spin nature of the particles of its decay : coupling proportional to m_V^2 for gauge bosons, to m_f for fermions. The Higgs decays to dibosons present some channels that have a good sensitivity for mass and width measurement, in particular the $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ channels, due to the intrinsic subsequent decay of the Higgs boson to particles whose energy can be measured precisely by the detector.

2 The $H \rightarrow \gamma\gamma$ channel

The $H \rightarrow \gamma\gamma$ channel takes advantage of the excellent resolution of the electromagnetic calorimeter in order to extract a narrow peak on top of a continuum of background. This background is made of the irreducible background $\gamma\gamma$, the reducible background γj and jj where respectively one and two jets are misidentified as a photon, and the high mass tail of the Drell-Yan background $Z \rightarrow ee$ where the electrons are misidentified as photons. The signal-to-background ratio is a few percent. The selection requires two high p_T photons, identified and isolated. A categorization is made in order to improve the sensitivity and probe the production modes.

A deviation from background only hypothesis is observed by the two experiments : for ATLAS, at the level of [6] $Z_{obs} = 5.2\ \sigma$, while expected at $Z_{exp} = 4.6\ \sigma$, for CMS at the level of [7] $Z_{obs} = 5.7\ \sigma$ for CMS, while expected at $Z_{exp} = 5.2\ \sigma$. The measured Higgs mass is [8] $m_H = 125.98 \pm 0.42\ (stat.) \pm 0.28\ (sys.)\ GeV$ for ATLAS and [7] $m_H = 124.70 \pm 0.31\ (stat.) \pm 0.15\ (sys.)\ GeV$ for CMS. The systematic uncertainties on the mass are dominated by the photon energy scale. The inclusive measured signal strengh is [6] $\mu = 1.17 \pm 0.27$ for ATLAS, and $\mu = 1.14\ ^{+0.26}_{-0.23}$ for CMS. The measurements of the production modes are [6] for ATLAS :

$$
\begin{array}{lllllllllll}
\mu_{ggF} & = & 1.32 & \pm\ 0.32 & (stat.) & ^{+0.13}_{-0.09} & (sys.) & ^{+0.19}_{-0.11} & (th) & = & 1.32 \pm 0.38 \\
\mu_{VBF} & = & 0.8 & \pm\ 0.7 & (stat.) & ^{+0.2}_{-0.1} & (sys.) & ^{+0.2}_{-0.3} & (th) & = & 0.8 \pm 0.7 \\
\mu_{WH} & = & 1.0 & \pm\ 1.5 & (stat.) & ^{+0.3}_{-0.1} & (sys.) & ^{+0.2}_{-0.1} & (th) & = & 1.0 \pm 1.6 \\
\mu_{ZH} & = & 0.1 & ^{+\ 3.6}_{-\ 0.1} & (stat.) & ^{+0.7}_{-0.0} & (sys.) & ^{+0.1}_{-0.0} & (th) & = & 0.1\ ^{+\ 3.7}_{-\ 0.1} \\
\mu_{ttH} & = & 1.6 & ^{+\ 2.6}_{-\ 1.8} & (stat.) & ^{+0.6}_{-0.4} & (sys.) & ^{+0.5}_{-0.2} & (th) & = & 1.6\ ^{+\ 2.7}_{-\ 1.8}
\end{array}
$$

and for [9] CMS :

$$
\begin{array}{lllllllllll}
\mu_{ggF} & = & 1.12 & \pm\ 0.30 & (stat.) & \pm\ 0.09 & (sys.) & \pm\ 0.13 & (th) & = & 1.12\ ^{+0.37}_{-0.32} \\
\mu_{VBF} & = & 1.58 & \pm\ 0.69 & (stat.) & \pm\ 0.15 & (sys.) & \pm\ 0.20 & (th) & = & 1.58\ ^{+0.77}_{-0.68} \\
\mu_{VH} & = & -0.16 & \pm\ 0.97 & (stat.) & \pm\ 0.08 & (sys. & \& & th.) & = & -0.16\ ^{+1.16}_{-0.79} \\
\mu_{ttH} & = & 2.69 & \pm\ 2.1 & (stat.) & \pm\ 0.4 & (sys. & \& & th.) & = & 2.69\ ^{+2.51}_{-1.81}
\end{array}
$$

A dedicated analysis has searched for the ttH production with the decay $H \rightarrow \gamma\gamma$, giving in the case of ATLAS an observed limit of [10] $6.7 \times SM$ for $m_H = 125.4\ GeV$, and in the case of CMS an observed limit [11] of $6.7 \times SM$ for $m_H = 125.6\ GeV$.

The analyses with early data of 2015 of the Run 2 of the LHC at $\sqrt{s} = 13\ TeV$ have been made assuming a Higgs mass of $m_H = 125.09\ GeV$ (see section 6). ATLAS obtained a significance on the Higgs boson of [12] $1.5\ \sigma$ (exp. $1.9\ \sigma$) with an integrated luminosity of $3.2\ fb^{-1}$ and made studies on fiducial and differential cross sections (Section 10). CMS obtained a significance of [13] $1.7\ \sigma$ (exp. $2.7\ \sigma$) and a signal strength of $0.69\ ^{+0.47}_{-0.42}$ with a luminosity of $1.7\ fb^{-1}$, and probed the production modes of ggH, VBF, VH and ttH. The corresponding results are $\mu_{ggH,\ ttH} = 0.43\ ^{+0.59}_{-0.63}$, $\mu_{VBF,\ VH} = 1.98\ ^{+2.14}_{-1.98}$.

3 The $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel

The $H \rightarrow ZZ^{(*)} \rightarrow 4l$ channel has low background and a good ratio of signal over background, a low number of signal due to the low branching ratio. The background is mainly made of the irreducible $ZZ^{(*)}$ and the reducible $Z + j$ processes.

The selection requires four high p_T isolated leptons and a boosted decision tree (BDT) to exploit the difference in the kinematics of the signal $H \rightarrow ZZ^{(*)}$ and the irreducible $ZZ^{(*)}$ background. A categorization exploits the flavour of the leptons and the sensitivity to various production modes. A deviation from background only hypothesis is observed, for ATLAS [14] at the level of $Z_{obs} = 8.1\ \sigma$, while expected at the level of $Z_{exp} = 6.2\ \sigma$, for CMS [9] at the level of $Z_{obs} = 6.8\ \sigma$, while expected at the level of $Z_{exp} = 6.7\ \sigma$. The measurement of the Higgs mass is : $m_H = 124.51 \pm 0.52\ (stat.) \pm 0.06\ (sys.)\ GeV$ for ATLAS, $m_H = 125.6 \pm 0.4\ (stat.) \pm 0.2\ (sys.)\ GeV$ for CMS. The systematic uncertainties are dominated by the energy scales. The results on production modes are $\mu_{ggF+bbH+ttH} = 1.7\ ^{+0.5}_{-0.4}$, $\mu_{WH+ZH} = 0.3\ ^{+1.6}_{-0.9}$ for ATLAS, $\mu_{ggF+ttH} = 0.80\ ^{+0.46}_{-0.36}$, $\mu_{VBF+VH} = 1.7\ ^{+2.2}_{-2.1}$ for CMS. The inclusive measured signal strengh is $\mu = 1.44\ ^{+0.40}_{-0.33}$ for ATLAS, $\mu = 0.93\ ^{+0.26}_{-0.23}\ (stat.)\ ^{+0.13}_{-0.09}\ (sys.)$ for CMS.

With the Run 2 at $\sqrt{s} = 13\ TeV$, ATLAS [15] investigated fiducial cross-section (see Section 10) using 3.2 fb^{-1} of data. With 2.8 fb^{-1} of data, CMS reports [16] a significance of 2.5 σ at $m_H = 125.09\ GeV$ and probes the production modes. The results are $\mu_{ggH+ttH} = 0.95\ ^{+0.64}_{-0.49}$, $\mu_{VBF+VH} = 0.0\ ^{+2.5}_{-0.0}$.

4 The $H \to WW^{(*)} \to l\nu l\nu$ channel

The invariant mass of the $H \to WW^{(*)} \to l\nu l\nu$ channel is not fully reconstructible due to the missing momentum from neutrinos. The main background processes are the ones with final states made of WW, $W+j$, $Z+j$ and top.

The selection requires two high p_T isolated leptons of opposite charges , and the presence of missing transverse energy. Cuts are exploited to take into account the spin correlation of the two W coming from the H decay, which tends to make collinear the leptons from W decays, in the form of $\Delta\phi_{ll}$. A categorization improves the sensitivity and probes the various production modes. A deviation from background only hypothesis is observed, for ATLAS [17] at the level of $Z_{obs} = 6.1\ \sigma$, while expected at the level of $Z_{exp} = 5.8\ \sigma$, for CMS [18] at the level of $Z_{obs} = 4.3\ \sigma$, while expected at the level of $Z_{exp} = 5.8\ \sigma$. The inclusive signal strengh measured by ATLAS is $\mu = 1.09\ ^{+0.16}_{-0.15}\ (stat.)\ ^{+0.17}_{-0.14}\ (sys.)$ for $m_H = 125.4\ GeV$, and the one by CMS is $\mu = 0.72\ ^{+0.12}_{-0.12}\ (stat.)\ ^{+0.12}_{-0.10}\ (th.\ sys.)\ ^{+0.10}_{-0.10}\ (exp.\ sys.)$ for $m_H = 125.6\ GeV$. The results on the signal strengths of the various production modes are for ATLAS : $\mu_{ggF} = 1.02 \pm 0.19\ (stat.)\ ^{+0.22}_{-0.18}\ (sys.)$, $\mu_{VBF} = 1.27^{+0.44}_{-0.40}\ (stat.)\ ^{+0.30}_{-0.21}\ (sys.)$, and for CMS in the various categories : $\mu_{2l2\nu+0/1j} = 0.74\ ^{+0.22}_{-0.20}$, $\mu_{2l2\nu\ +2j,\ VBF\ tag} = 0.60\ ^{+0.57}_{-0.46}$, $\mu_{2l2\nu\ +2j,\ VH\ tag} = 0.39\ ^{+1.97}_{-1.87}$, $\mu_{3l3\nu\ WH\ tag} = 0.56\ ^{+1.27}_{-0.95}$.

ATLAS has an evidence for VBF production, at a level of $Z_{obs} = 3.2\ \sigma$, while expected at the level of $Z_{exp} = 2.7\ \sigma$. ATLAS has a dedicated analysis [19] on associated $W/Z\ H$ production mode. The observed significance for the combined WH and ZH production is 2.5 σ while a significance of 0.9 σ is expected. The signal strength for the combined VH production mode is $\mu_{VH} = 3.0\ ^{+1.3}_{-1.1}\ (stat.)\ ^{+1.0}_{-0.7}\ (sys.)$. This analysis is combined with the ggH and VBF production modes, giving an observed significance of 6.5 σ and an inclusive signal strength of $\mu_{ggF+VBF+VH} = 1.16\ ^{+0.16}_{-0.15}\ (stat.)\ ^{+0.18}_{-0.15}\ (sys.)$. CMS has a significance for the $VBF\ tag$ category at a level of $Z_{obs} = 1.3\ \sigma$, while expected at the level of $Z_{exp} = 2.1\ \sigma$. The corresponding significance for $VH\ tag$ are $Z_{obs} = 0.2\ \sigma$ (0.6 σ expected), the one for $WH\ tag$ are $Z_{obs} = 0.5\ \sigma$ (0.2 σ expected).

The production of Higgs from the associated production of two quarks and the Higgs has been probed by ATLAS [20] in a signature with leptons in the final states. This analysis probes, in addition to $H \to WW^*$, the $H \to \tau\tau$ channel. Due to the important tt background, leading to events with $WWWWbb$ and $\tau\tau WWbb$, the selection requires final states that cannot be produced in tt decays, such as three or more leptons, or two same-sign leptons. A deviation from background only hypothesis is observed, at a level of $Z_{obs} = 1.8\ \sigma$, while expected at the level of $Z_{exp} = 0.9\ \sigma$. The associated production tqH of the Higgs boson with a top quark and a quark is studied by CMS [21], giving a limit on the production cross-section times branching ratio of $6.7 \times SM$ at 95 % CL limit.

5 The $H \rightarrow Z\gamma$ and $H \rightarrow \gamma^*\gamma$ channels

The selection requires two high p_T isolated leptons of opposite charge and same flavour and a photon . A minimal cut on $m_{ll} > m_Z$ allows to suppress events with final state radiation from $Z \rightarrow ll\gamma$, supplemented with a minimal distance $\Delta R(l;\gamma)$, and photon conversion from $H \rightarrow \gamma\gamma$. The observed and expected limits are at the level of $10 \times SM$ at $m_H = 125$ GeV for both ATLAS [22] and CMS [23] analyses. CMS searched also for the $H \rightarrow \gamma^*\gamma \rightarrow ll\gamma$ channel. The dileptons invariant mass is restricted to be below 20 GeV in order to suppress contamination by the $H \rightarrow Z\gamma$ channel. A cut on the minimal distance $\Delta R(l,\gamma)$ suppresses contributions from FSR $Z \rightarrow ll\gamma$. The observed limits [24] are of the order of $10 \times SM$.

6 Combined mass measurement

The ATLAS-CMS combined Higgs mass measurement [25] uses the two fully reconstructed and high resolution channels : $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$. The result is $m_H = 125.09 \pm 0.21$ $(stat.)$ ± 0.11 $(sys.)$ GeV. The dominant systematic uncertainties are the electron, photon, muon energy and momentum scales, whose nominal values are obtained from analyses of large samples of J/ψ, $Y(nS)$ and Z resonances. The mass measurements obtained by the combination of the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4l$ channels are respectively of $m_H = 125.36 \pm 0.37$ $(stat.)$ ± 0.18 $(sys.)$ GeV for the ATLAS [8] experiment and $m_H = 125.02\ ^{+0.26}_{-0.27}$ $(stat.)$ $^{+0.14}_{-0.15}$ $(sys.)$ GeV for CMS [26]. The mass measurement is the first step before evaluating other quantities, such as couplings.

7 Higgs width

Several methods allow to set constraints on the Higgs width Γ_H. The direct method uses a statistics test constructed with various values of the intrinsic width of the Higgs boson, convoluted with the experimental resolution. The ATLAS analysis establishes a limit at 95 % CL on the width of[8] 5.0 GeV from the $H \rightarrow \gamma\gamma$ channel and[8] of 2.6 GeV from the $H \rightarrow ZZ^* \rightarrow 4l$ channel. The CMS analysis establishes a limit of[7] 2.4 GeV from the $H \rightarrow \gamma\gamma$ channel and[9] of 3.4 GeV from the $H \rightarrow ZZ^* \rightarrow 4l$ channel. The combination of the two channels gives a limit of 1.7 GeV. The indirect method exploits the opening phase space above $2 \times m_Z$ for the $H \rightarrow ZZ^* \rightarrow 4l$ and of the ggH top-loop and the dependence of the ratio of the on- and off-shell cross-section of the Higgs production [27,28] with the Higgs width. This relationship implies that the couplings with the reconstructed mass is following the one of the gluon fusion to Higgs process. Any presence of new particles in the quark loop of the gluon fusion, or any anomalous couplings contributions to HVV, either in VBF, VH or in the decay $H \rightarrow ZZ$ would change slightly the relationship. But no experimental studies has been made on the dependence of off-shell production in presence of anomalous couplings, because there is no direct hint for new physics at the 500 GeV scale.

The ATLAS analysis establishes [29] a limit of 22.7 MeV (33.0 MeV expected) at 95 % CL, using the channels $H \rightarrow ZZ^* \rightarrow 4l$, $H \rightarrow ZZ^* \rightarrow ll\nu\nu$, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$. The CMS analysis [30], using the channels $H \rightarrow ZZ^* \rightarrow 4l$ and $H \rightarrow WW^* \rightarrow l\nu l\nu$, obtains a limit of 13 MeV (26 MeV expected) at 95 % CL, and, using the channel $H \rightarrow ZZ^* \rightarrow 4l$ [31], obtains a lower bound of $\Gamma_H > 3.5 \times 10^{-9}$ MeV at 95 % CL.

8 Spin and parity

The spin (J), parity (P) and charge conjugation (C) quantum numbers of the Higgs boson of the Standard Model correspond to the state $J^{PC} = 0^{++}$. The discovery of a resonance in the diphoton channel excludes the possibility that the observed state has a spin 1, according to Landau-Yang theorem [32,33], while favoring $C = +1$. Due to the suppression of the CP-odd scalar field at the tree order of the perturbative development order in the two-Higgs-doublet models (2HDM) models, the observation of the decay to pair of vector bosons ($WW^{(*)}$, $ZZ^{(*)}$) favors the interpretation of a CP even state, compatible with the Standard Model expectation.

The spin and parity state $J^P = 0^+$ of the particle has been tested against some alternative models, with various channels : $H \to \gamma\gamma$, $H \to 4l$, $H \to WW^* \to e\nu\mu\nu$ and combined, using angular distribution and kinematics of final state objects. All alternative models to the Standard Model that have been considered by ATLAS [34] and CMS [35] are excluded at 95 % CL. The spin-parity state of the Standard Model is favoured.

9 Combination for production modes, decays and couplings measurements

The LHC combination [36] from the ATLAS and CMS experiments on the signal and coupling strengths uses the various channels to derives constraints on the production modes, decays and couplings of the Higgs boson, using the mass of the Higgs boson of $m_H = 125.09\ GeV$, from the ATLAS and CMS combination. The signal significance and inclusive signal strength of the various decay channels are reviewed in Table 1. The three channels $H \to \gamma\gamma$, $H \to ZZ^*$, $H \to WW^* \to l\nu l\nu$ are observed individually by each experiment. The combined inclusive signal strength is $\mu = 1.09\ ^{+0.11}_{-0.10}$, with the values for ATLAS of $\mu = 1.20\ ^{+0.15}_{-0.14}$ and for CMS of $\mu = 0.98\ ^{+0.14}_{-0.13}$.

Table 1: Summary of the observed (expected) signal significance and inclusive signal strength for the various decay channels entering into the Run 1 couplings combination. The ATLAS-CMS combined significances for $H \to \gamma\gamma$, $H \to ZZ \to 4l$, $H \to WW$ decay channels are not included since they have been already clearly observed. Source : [36].

Channel	Observed (expected) significance [σ]			Signal strength μ		
	ATLAS	CMS	ATLAS-CMS	ATLAS	CMS	ATLAS-CMS
$H \to \gamma\gamma$	5.0 (4.6)	5.6 (5.1)	-	$1.15^{+0.27}_{-0.25}$	$1.12^{+0.25}_{-0.23}$	$1.16^{+0.20}_{-0.18}$
$H \to ZZ \to 4l$	6.6 (5.5)	7.0 (6.8)	-	$1.51^{+0.39}_{-0.34}$	$1.05^{+0.32}_{-0.27}$	$1.31^{+0.27}_{-0.24}$
$H \to WW$	6.8 (5.8)	4.8 (5.6)	-	$1.23^{+0.23}_{-0.21}$	$0.91^{+0.24}_{-0.21}$	$1.11^{+0.18}_{-0.17}$
$H \to \tau\tau$	4.4 (3.3)	3.4 (3.7)	5.5 (5.0)	$1.41^{+0.40}_{-0.35}$	$0.89^{+0.31}_{-0.28}$	$1.12^{+0.25}_{-0.23}$
$H \to bb$	1.7 (2.7)	2.0 (2.5)	2.6 (3.7)	$0.62^{+0.37}_{-0.36}$	$0.81^{+0.45}_{-0.42}$	$0.69^{+0.29}_{-0.27}$
$H \to \mu\mu$	-	-	-	-0.7 ± 3.6	0.8 ± 3.5	-

The signal significance and signal strength of the various production modes for the analyses of the combination are reviewed in Table 2. The VBF process is observed with a significance of 5.4 σ. There is evidence for both VH and ttH, respectively with a significance of 3.5 σ and 4.4 σ.

No deviations from the Standard Model are observed in the various tested scenarios.

10 Fiducial, integrated and differential cross-section

The measurements of total and fiducial cross-sections allow to probe the theoretical modeling (pertubative QCD, pdfs), the relative contribution of production modes, and possible physics

Table 2: Summary of the observed (expected) signal significance and signal strength for the various production modes entering into the Run 1 couplings combination. The significance for ggH production mode is not included since it has been already clearly observed. Source : [36].

Production process	Observed (expected) significance [σ]	signal strength μ		
	ATLAS+CMS	ATLAS	CMS	ATLAS+CMS
ggH	-	$1.25^{+0.24}_{-0.21}$	$0.84^{+0.19}_{-0.16}$	$1.03^{+0.17}_{-0.15}$
VBF	5.4 (4.7)	$1.21^{+0.33}_{-0.30}$	$1.13^{+0.37}_{-0.34}$	$1.18^{+0.25}_{-0.23}$
WH	2.4 (2.7)	$1.25^{+0.56}_{-0.52}$	$0.46^{+0.57}_{-0.54}$	$0.88^{+0.40}_{-0.38}$
ZH	2.3 (2.9)	$0.30^{+0.51}_{-0.46}$	$1.35^{+0.58}_{-0.54}$	$0.80^{+0.39}_{-0.36}$
VH	3.5 (4.2)	-	-	-
ttH	4.4 (2.0)	$1.9^{+0.8}_{-0.7}$	$2.9^{+1.0}_{-0.9}$	$2.3^{+0.7}_{-0.6}$

beyond Standard Model. The fiducial and integrated cross-sections have been computed by ATLAS and CMS at different energies in the center of mass, with various dibosons channels : $H \to \gamma\gamma$ [12,37], $H \to ZZ^* \to 4l$ [15,38,16], $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ combined [39], $H \to WW^* \to l\nu l\nu$ [17], $H \to WW^* \to e\nu\mu\nu$ [40,41]. The differential cross-sections are explored for various observables (multiplicity, transverse momentum and energy, angles, etc.) of various objects (photon, lepton, jet, MET) and from topology of several objects, including the reconstructed Higgs from its decay products, for various decay channels ($H \to \gamma\gamma$, $H \to ZZ \to 4l$, $H \to WW \to l\nu l\nu$) [42,43,44,40,37,38,41]. No significative deviation is observed with respect to the prediction from the Standard Model.

11 Conclusion

The Higgs to bosons channels provide an important legacy from the ATLAS and CMS experiments at Run 1 for the measurement of properties : mass, width, production modes and couplings, cross-section, either integrated or differential. The early measurements with Run 2 of 2015 don't have enough sensitivity to compete with Run 1. Data-taking of Run 2 may bring answers and surprises.

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