PROCEEDINGS OF SCIENCE

Higgs mass measurement in $H \to ZZ^* \to 4\ell$

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This document presents the projection of the Higgs boson mass measured in the $H \to ZZ^* \to 4\ell$ ($\ell = e, \mu$) decay channel at the CMS experiment at the High-Luminosity LHC. The analysis is based on proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 14$ TeV, with an integrated luminosity of 3000 fb^{-1}. The projected results will be compared with the latest ones published by CMS. Additionally, the analysis benefits not only from the increased luminosity but also from significant upgrades to the CMS detector and improved analysis strategies.

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1. Physics case

In the standard model (SM), the mass of the elementary particles arises from their interaction with the Higgs field. Additionally, various Higgs boson characteristics, including production cross section and branching ratios, are influenced by the Higgs boson mass (m_H). Experimental efforts at the Large Hadron Collider (LHC) are dedicated to measuring the properties of the Higgs boson.

2. The Higgs golden channel

On July 4th, 2012, both the ATLAS [1] and CMS [2] Collaborations announced the discovery of a new boson with a mass close to 125 GeV, later identified as the Standard Model Higgs boson [3–5]. The $H \to ZZ^* \to 4\ell$ decay channel (where $\ell = e, \mu$) offers high mass resolution ($\sim 1-2\%$) and an excellent signal-to-background ratio (~ 2) within a narrow mass range around the Higgs boson peak. For these reasons it has been called the "golden channel".
Recent measurements by ATLAS and CMS at $\sqrt{s} = 13$ TeV using the "golden channel" resulted in $m_H = 124.94 \pm 0.17(stat.) \pm 0.3(syst.)$ GeV (139 fb^{-1} luminosity) and $m_H = 125.26 \pm 0.20(stat.) \pm 0.08(syst.)$ GeV (35.9 fb^{-1} luminosity), respectively [6, 7]. Looking ahead to the High-Luminosity LHC (HL-LHC), CMS anticipates further improvement in the measurement due to increased luminosity, enhancements in reconstruction from CMS detector upgrades, and a new analysis strategy discussed in the upcoming section [8].

3. Improved analysis strategy for HL-LHC

The objective of this study is to measure m_H at HL-LHC using the CMS experiment. This is achieved through a two-dimensional maximum-likelihood fit, represented by the likelihood function:

$$L(m_{4\ell}, D^{kin}_{bkg} | m_H) \tag{1}$$

Here, $m_{4\ell}$ denotes the invariant mass of the four leptons, and D^{kin}_{bkg} is a kinematic discriminant calculated as $P_{sig}/(P_{sig}+P_{bkg})$ [9], where P_{sig} (P_{bkg}) is the probability of being a $H \to ZZ^* \to 4\ell$ ($gg/q\bar{q} \to ZZ$) event. $m_{4\ell}$ must fall within the mass window $105 < m_{4\ell} < 140$ GeV.
In the likelihood function, the signal is described by a double-sided Crystal Ball (DSCB) function convoluted with a Landau function when the Higgs boson is produced in association with W, Z, or $\mathrm{t\bar{t}}$. On the other hand, the main ZZ background ($gg/q\bar{q} \to ZZ$) is described using a third-order Bernstein polynomial, and the minor background, arising from the production of a Z boson in association with one or two misidentified leptons, is parameterized by a Landau function.
Additionally, the p_T of two leptons forming the on-shell Z boson was recalibrated, considering the impact of detector-related uncertainties on the estimated m_Z (Z_1 constraint).

3.1 Improvements in the analysis strategy

The analysis considers four final states based on whether the Z boson decays into muons (μ) or electrons (e): 4μ, $4e$, $2e2\mu$, and $2\mu 2e$. In the latter two cases, the first lepton pair originates from the on-shell Z-boson. In the 35.9 fb^{-1} CMS analysis, categories with leptons of mixed flavors were combined, despite having different peak widths, signal efficiencies, and background levels.

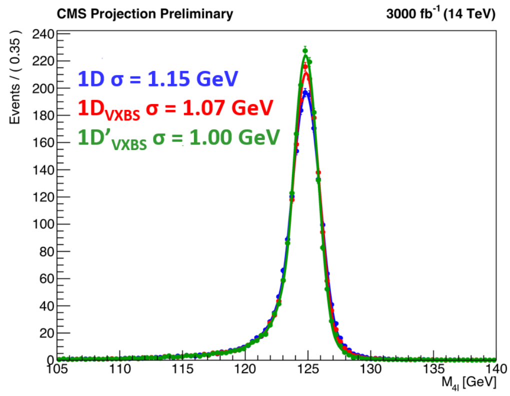

Figure 1: Fits of 4μ distribution showing the impact of the different lepton momentum improvements: blue line no improvements, red line when VXBS is included and green line when also the Z_1 constraint is applied. σ is the standard deviation of the Gaussian cores. Figure from [8].

To enhance the resolution of $m_{4\ell}$, the four lepton tracks from the Higgs boson decay were constrained by enforcing a common vertex compatible with the beam spot (VXBS constraint). The $m_{4\ell}$ fits for the 4μ final state in the $gg \to H$ production mode are presented in Fig.1, without lepton momentum enhancements[1] (1D), applying the VXBS constraint (1D$_{\mathrm{VXBS}}$), and also applying the Z_1 constraint (1D'$_{\mathrm{VXBS}}$). Given that the electron p_T is mainly reconstructed with the electromagnetic calorimeter, the $4e$ final state remained unchanged with the application of the VXBS constraint.
The parameters of DSCB functions describing the signal shapes depended not only on $m_{4\ell}$ but also on the relative mass error $D_{m_{4\ell}} = \sigma_{m_{4\ell}}/m_{4\ell}$. Events were divided into nine $D_{m_{4\ell}}$ categories to account for this dependence. The categorization was performed independently for each final state, ensuring an equal number of events in each category. The likelihood function described in eq. (1) was constructed for each $D_{m_{4\ell}}$ category. The final measurement was obtained by maximizing the product of all nine likelihoods for all final states. This categorization represents an improvement over the 35.9 fb^{-1} CMS analysis, where the likelihood was defined as a function of $m_{4\ell}$, D_{bkg}^{kin}, and $\sigma_{m_{4\ell}}$, as it allows for the inclusion of the correlation between $D_{m_{4\ell}}$ and D_{bkg}^{kin} in the fit.

4. CMS HL-LHC upgrade impact

The m_H measurement enhancement, due to the upgraded CMS detector for the HL-LHC, has been explored specifically for the $gg \to H$ production mode using DELPHES simulation [10]. Key improvements are foreseen with the new tracker [11], which will enhance muon resolution and extend electron acceptance from $|\eta| < 2.5$ to 3.0. Additionally, the new muon station is expected to broaden muon acceptance from $|\eta| < 2.4$ to 2.8 [12]. For instance, a comparison between DELPHES and CMS Run 2 simulations for the 4μ invariant mass distribution is illustrated in Fig. 2.

[1]VXBS and Z_1 constraints

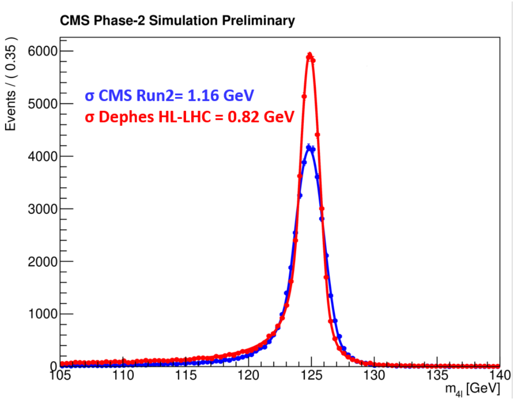

Figure 2: Fits of the 4μ distribution, for the HL-LHC sample (red line) and the CMS Run 2 one (blue line). σ is the standard deviation of the Gaussian cores. Mass resolution improved of $\simeq 25\%$. Figure from [8].

5. Systematic uncertainties

The primary sources of systematic uncertainties lie in the lepton momentum scale and resolution. To assess the impact of scale uncertainties on $m_{4\ell}$, the uncertainties in lepton corrections are propagated down to the $m_{4\ell}$ distribution. The scale uncertainties for muons and electrons are 0.01% and 0.15%, respectively. A 10% uncertainty is applied for the mass resolution.

6. Results

Expected uncertainty	4μ	$4e$	$2e2\mu$	$2\mu 2e$	inclusive	relative improvement
Total	32	206	107	112	30	-
Systematic impact	15	189	94	95	20	-
Statistical uncertainty only						
N-2D'_{VXBS}	28	83	51	59	22	-4%
N-1D'_{VXBS}	30	88	53	61	23	-8%
1D'_{VXBS}	32	103	61	68	25	-7%
1D_{VXBS}	34	115	78	71	27	-7%
1D	37	115	78	74	29	-

Table 1: Expected Higgs boson mass measurement uncertainty, given in MeV, in the inclusive final state and for the four final states

To showcase the impact of various enhancements, the m_H evaluation began with the 1D scenario (1D likelihood function solely dependent on $m_{4\ell}$) and successively incorporated improvements such as lepton momentum enhancements, $D_{m_{4\ell}}$ categorization (N-1D'_{VXBS}), and the inclusion of D^{kin}_{bkg} in the N-2D likelihood (N-2D'_{VXBS}). Subsequently, all systematic uncertainties were taken into account. The summarized uncertainties (segmented by final states) are presented in Table 1. The expected measured mass at the HL-LHC is $m_H = 125.38 \pm 0.03[0.022(stat) \pm 0.020(syst)]$ GeV. This expected error is reduced to 1/9th of the one reported in [7]. After the LHCP 2023 conference, CMS updated the measurement of m_H in the Higgs golden channel using the full Run 2 data, and using the same refined analysis strategy as detailed above [13].

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