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

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Summary. — The projection of the measurement of the Higgs boson mass in the $H \to ZZ^* \to 4\ell$ ($\ell = e, \mu$) using the CMS experiment at High-Luminosity LHC in proton-proton collisions at $\sqrt{s} = 14$ TeV using an integrated luminosity of 3000 fb^{-1} is presented here. The projection will be compared with the last published result by CMS. In addition to the increased luminosity, the analysis benefits from major upgrades in the CMS detectors as well as from enhanced analysis strategies.

1. – Physics case

In the Standard Model (SM) the mass of the elementary particles is due to the interaction between them and the Higgs field. Furthermore, many particle properties (such as the production cross section, the branching ratios and the couplings with other SM particles) depend on the Higgs boson mass (m_H). Experiments are carried out at the Large Hadron Collider (LHC) with the aim of measuring the properties of the Higgs boson, starting from its mass.

2. – The $H \to ZZ^* \to 4\ell$ channel

On 4^{th} in July 2012 the ATLAS [1] and CMS [2] Collaborations announced the observation of a new boson with mass near 125 GeV that subsequently will be identified as the SM Higgs boson [3, 4]. The decay channel $H \to ZZ^*$ with both Z decaying in a charged leptons (ℓ) pair is one of the main ones used for measuring the Higgs boson properties, due to a very high mass resolution ($\sim$ 1-2%) and a great signal to background ratio ($\sim$1.6 in a narrow mass range around the Higgs boson peak).

The last measurements performed by ATLAS and CMS experiments result in a value for the Higgs boson mass equal respectively to $m_H = 124.94 \pm 0.17(stat.) \pm 0.3(syst.)$ GeV, with a luminosity of 139 fb^{-1} [5], and $m_H = 125.26 \pm 0.20(stat.) \pm 0.08(syst.)$ GeV, with a luminosity of 35.9 fb^{-1} [6], at $\sqrt{s} = 13$ TeV. At High-Luminosity LHC (HL-LHC), the measurement can be further improved at CMS thanks to the increase in luminosity,

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the enhancements in the reconstruction due to the CMS detectors upgrade and the new analysis strategy that will be presented in the next section [7].

3. – Improved analysis strategy for HL-LHC

The goal of this analysis is the measurement of m_H at HL-LHC with the CMS experiment, by means of a two-dimensional likelihood fit defined by the likelihood function

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

where $m_{4\ell}$ is the invariant mass of the four leptons, D_{bkg}^{kin} is a kinematic discriminant defined as a likelihood ratio of the probabilities to be a $H \to ZZ^* \to 4\ell$ event (P_{sig}) and of the main background process (P_{bkg}), *i.e.*, the continuum production of ZZ. D_{bkg}^{kin} is thus defined as $P_{sig}/(P_{sig} + P_{bkg})$. The invariant mass of the 4 leptons is required to be within the mass window $105 < m_{4\ell} < 140$ GeV. In the likelihood, the signal is described by a double-sided Cristal Ball (DSCB) function convoluted with a Landau function when the Higgs boson is produced in association with W, Z, or $\mathrm{t\bar{t}}$. The main ZZ background ($gg/q\bar{q} \to ZZ$) is instead described with a third order Bernstein polynomial, while the minor contributing background, due to the production of a Z boson in association with one or two misidentified leptons, is parameterised by a Landau function.

The p_T of two leptons forming the on-shell Z boson was re-calibrated taking into account the effect of detector-related uncertainty on the estimated m_Z (Z_1 constrain).

3˙1. *Improvements in the analysis strategy.* – Four final states were considered in the analysis depending if the Z boson decays into muons (μ) or electrons (e): 4μ , $4e$, $2e2\mu$ and $2\mu 2e$. In the last two cases the first lepton pair comes from the on-shell Z-boson. In the 35.9 fb^{-1} CMS analysis, the two categories with leptons of mixed flavors were merged, even if they have different peak widths, different signal efficiencies and different relative levels of background.

To improve the $m_{4\ell}$ resolution, the four lepton tracks from Higgs boson decay are constrained looking for a common vertex that must be compatible with the beam spot (VXBS constraint). The $m_{4\ell}$ fits of the 4μ final state, for the $gg \to H$ production mode, are plotted in fig. 1, without lepton momentum improvements([1]) (1D), applying the VXBS constraint ($1\mathrm{D_{VXBS}}$) and applying also the Z_1 constrain ($1\mathrm{D'_{VXBS}}$). Since the electron p_T is mainly reconstructed with the electromagnetic calorimeter, the $4e$ final state remains unchanged applying the VXBS constraint.

The parameters of the DSCBs describing the signal lineshapes do not depend only on $m_{4\ell}$ but also on the relative mass error $D_{m_{4\ell}} = \sigma_{m_{4\ell}}/m_{4\ell}$. The events were therefore divided in 9 $D_{m_{4\ell}}$ categories to take into account this dependence. The categorization were done independently for each final state guaranteeing an equal amount of events in each category. In each $D_{m_{4\ell}}$ category the likelihood function described in eq. (1) is built. To extract the mass value, the final measurement was obtained maximising the product of all 9 likelihoods of all final states. The $D_{m_{4\ell}}$ categorization is an improvement with respect to the 35.9 fb^{-1} CMS analysis, where the likelihood was defined as a function of $m_{4\ell}$, D_{bkg}^{kin} and $\sigma_{m_{4\ell}}$, because it allows to include the correlation between $D_{m_{4\ell}}$ and D_{bkg}^{kin} in the fit.

([1]) VXBS and Z_1 constraints.

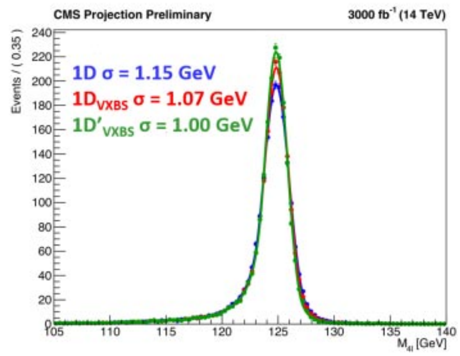

Fig. 1. – Fits of 4μ distribution showing the impact of the different lepton momentum improvements: blue line no improvements, red line when VXBS is included and green line when also the Z_1 constrain is applied. σ is the standard deviation of the Gaussian cores [7].

4. – CMS Phase-2 impact

An improvement in the measurement of m_H is expected because of the new CMS Phase-2 detectors. The improvement has been studied for $gg \to H$ production mode with the DELPHES simulation [8]. The main improvements are expected from the new tracker [9], that will improve the muon resolution and that will extend the electron acceptance from $|\eta| < 2.5$ to 3.0, and the new muon station [10], that will extend the muon acceptance from $|\eta| < 2.4$ to 2.8. As an example, the comparison between DELPHES and CMS Run 2 simulations for the 4μ invariant mass distribution is shown in fig. 2.

5. – Systematic uncertainties

The lepton momentum scale and resolution uncertainties are the dominant systematics. Scale uncertenty effect on $m_{4\ell}$ has been estimated propagating down to the $m_{4\ell}$ distribution the uncertainties on the lepton corrections. The muon (electron) scale is 0.01% (0.15%). A 10% for mass resolution is used instead.

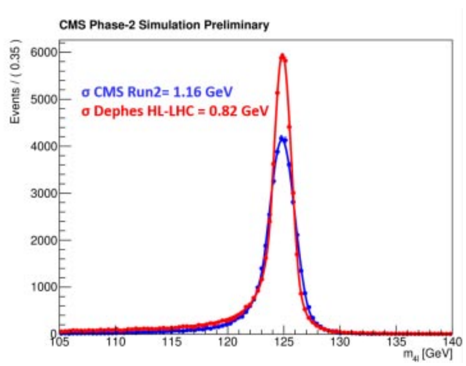

Fig. 2. – Fits of the 4μ invariant mass distribution, for the HL-LHC sample (red line) and the CMS Run 2 one (blue line). σ is the standard deviation of the Gaussian cores. There is an improvement of $\simeq 25\%$ in the mass resolution [7].

TABLE I. – *Expected Higgs boson mass measurement uncertainty, given in MeV, in the inclusive final state and for the four final states.*

Expected uncertainty	4μ	$4e$	$2e2\mu$	$2\mu2e$	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	-

6. – Results

In order to show the effects of the various improvements, the expected value of m_H was evaluated with a 1D likelihood function depending only on $m_{4\ell}$ starting from the 1D scenario, applying in succession the lepton momentum improvements, the $D_{m_{4\ell}}$ categorization (N-1D'_{VXBS}) and including the kinematic discriminant D^{kin}_{bkg} in the N-2D likelihood (N-2D'_{VXBS}). Finally, all systematic uncertainties are considered. Uncertainties are summarised (splitted by final states) in table I. The expected result, at the HL-LHC, for mass measurement, is $m_H = 125.38 \pm 0.03[0.022(stat) \pm 0.020(syst)]$ GeV. The expected error is reduced to 1/9th of the one in [6]. After the IFAE 2023 conference, CMS updated m_H using the full Run2 statistics and the same improved analysis strategy as described above [11].

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