Precision Higgs boson mass measurement using $H \to ZZ^* \to 4l$ decay mode

Hualin Mei on behalf of the CMS collaboration
Department of Physics, University of Florida,
Gainesville, Florida, USA

A measurement of the Higgs boson mass using $H \to ZZ^* \to 4l$ decay channel has been performed by the CMS collaboration at the LHC experiment using pp collisions at a center-of-mass energy of 13 TeV with an integrated luminosity of 35.9 fb^{-1}. This channel gives rise to a narrow four-lepton mass peak and provide means for precision Higgs boson mass measurements. The accuracy of the measurement is enhanced by using per-event four-lepton mass uncertainties, the line shape of the Z-boson closest to being on-mass-shell, and matrix element based kinematic discriminant used to separate signal and background.

1 Introduction

The $H \to ZZ^* \to 4l$ decay channel ($l = e, \mu$) has a large signal-to-background ratio and precise reconstruction of the decay products, which makes it an important channel for precise determination of Higgs boson mass. The main irreducible background for this channel comes from production of ZZ via qq annihilation or gluon fusion, is estimated from simulation. In addition, there are also reducible backgrouds (denoted as "Z+X") which are estimated using data-driven methods in dedicated control region. The reconstructed four-lepton invariant mass distribution is shown in Fig. 1 (left) for the sum of the 4e, 4μ and $2e2\mu$ subchannels, and compared with the expectations from signal and background processes.

2 Observables

To measure mass of the Higgs boson, a three-dimensional likelihood ($L(m_{4l}, D_{mass}, D^{kin}_{bkg})$) fit is performed. Fig. 1 (right) shows the three observables used in likelihood. m_{4l} is four-lepton invariant mass. $D_{mass} = \sigma_{m4l}/m_{4l}$ is per-event mass uncertainty, which is propagated from per-lepton p_T resolution. $Z \to ll$ events in simulation and data are used to calibrate per-lepton p_T resolution in different kinematic regions. Fig. 2 (left) shows comparision of meausred relative uncertainties for $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ events in data after calibration. Measured uncertainties match with prediction very well within 20% systematic uncertainty assgined to resolution. D^{kin}_{bkg} represents matrix element base kinematic discriminant, it uses kinematics information of Higgs decay product, and is sensitive to separate signal-like events from background-like events.

To improve the four lepton invariant mass resolution, a kinematic fit is performed using a mass constraint on one of the intermediate Z resonance Z_1, it is defined as l^+l^- pair with mass closer to PDG Z mass, it has a significant on-shell part, which can be seen from Fig. 2 (right). Invariant mass distribution of the other intermediate Z boson (Z_2) is much wider than detector resolution, therefore Z_2 is not used as a constraint. From Fig. 3, four lepton invariant mass resolution is improved, the improvements are 7%, 13% and 15% for 4μ, 4e and $2e2\mu$ final states

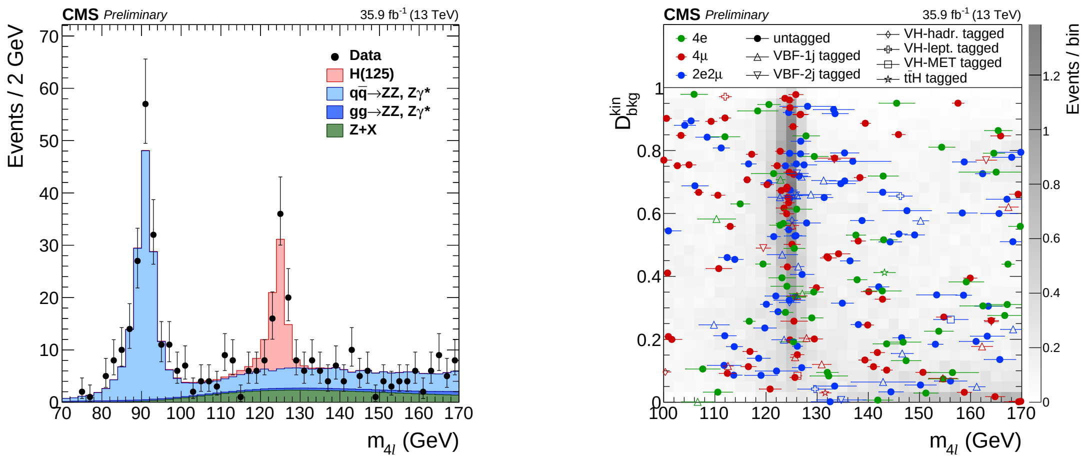

Figure 1 – Left: Distribution of the four-lepton reconstructed invariant mass m_{4l}. Points with error bars represent the data and stacked histograms represent expected distributions. The SM Higgs boson signal with $m_H = 125$ GeV, denoted as H(125), and the ZZ backgrounds are normalized to the SM expectation, the Z+X background to the estimation from data. Right: Distribution of D^{kin}_{bkg} versus m4l in the mass region $100 < m_{4l} < 170$ GeV. The gray scale represents the expected total number of ZZ background and SM Higgs boson signal events for m_H= 125 GeV. The points show the data and the horizontal bars represent D_{mass}. Different marker colors and styles are used to denote final state and the categorization of the events, respectively. [2]

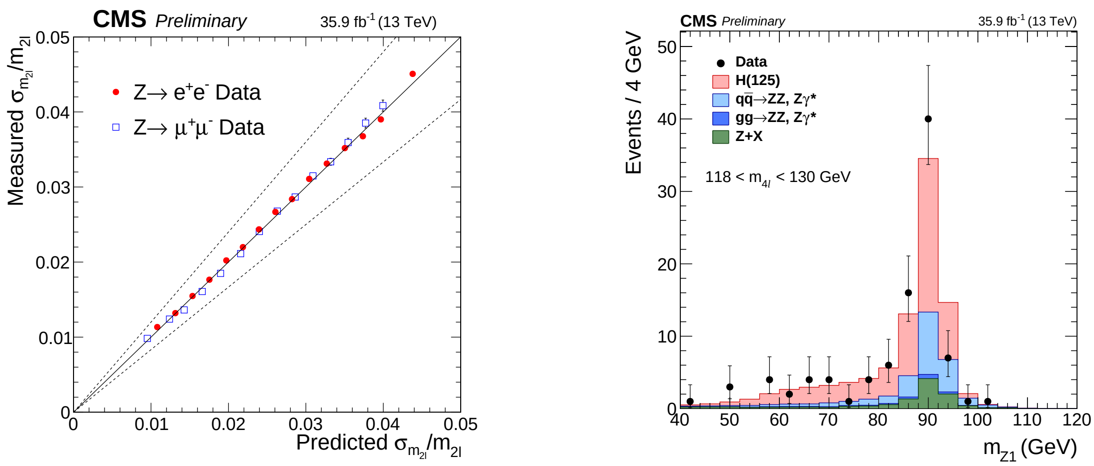

Figure 2 – Left: Measured versus predicted relative mass uncertainties for $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$ events in data. The dashed lines represent the 20% envelope, used as systematic uncertainty in the resolution. Right: Distribution of the Z_1 reconstructed invariant masses in the mass region $118 < m_{4l} < 130$ GeV. [2]

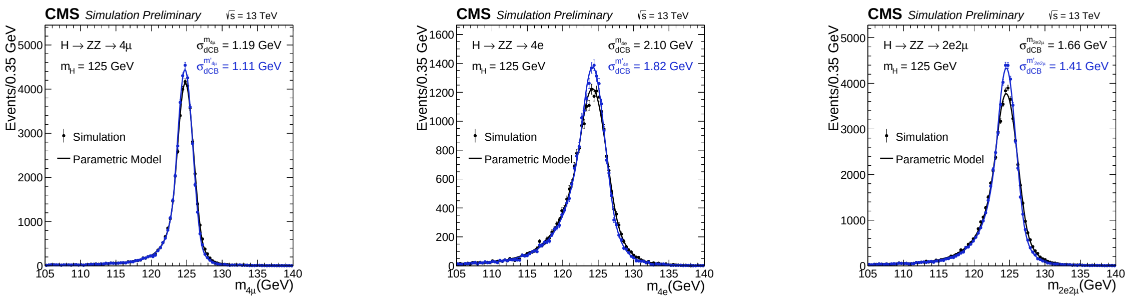

Figure 3 – The $H \to ZZ^* \to 4l$ invariant mass distribution for simulated m_H=125 GeV events in the (left) 4e, (center) $2e2\mu$, and (right) 4μ final states. The distributions are fitted with double-sided crystal ball functions and fitted values of CB width σ_{dCB} are extracted before (black curve) and after (blue curve) applying Z_1 mass constraint. [2]

respectively. From left and middle plot of Fig. 3, this technique is more effective for events with $Z_1 \to e^+e^-$.

We define the following likelihood to be maximized:

$$L(\hat{p}_T^1, \hat{p}_T^2 | p_T^1, \sigma_{p_T^1}, p_T^2, \sigma_{p_T^2}) = Gauss(p_T^1 | \hat{p}_T^1, \sigma_{p_T^1}) \cdot Gauss(p_T^2 | \hat{p}_T^2, \sigma_{p_T^2}) \cdot L(m_{12} | m_Z, m_H) \quad (1)$$

where p_T^1 and p_T^2 are the reconstructed transverse momentum of the two leptons forming the Z_1, $\sigma_{p_T^1}$ and $\sigma_{p_T^2}$ are the per lepton resolutions, these are the inputs. The outputs are $\hat{p}_T^1$ and $\hat{p}_T^2$, they are refitted transverse momentum. And m_{12} is the invariant mass calculated from the refitted four momenta. The term $L(m_{12}|m_Z, m_H)$ is the mass constraint. For a 125 GeV Higgs boson mass, the selected Z_1 is not always on-shell, so a Breit Wigner shape does not perfectly describe the Z_1 lineshape at generator level. We therefore choose $L(m_{12}|m_Z, m_H)$ to be the $m(Z_1)$ lineshape at generator level from the SM Higgs boson sample with $m_H = 125$ GeV. For each event,the likelihood is maximized and the refitted transverse momentum are used to recalculate the four-lepton mass and mass uncertainty, which are denoted as m'_{4l} and D'_{mass}. These distributions are then used to build the likelihood used to extract the Higgs boson mass.

3 Result

The nominal result for the mass measurement comes from the 3D fit with $m(Z_1)$ constraint, for which the fitted value of m_H is $125.26 \pm 0.20(stat.) \pm 0.08(sys.)$ GeV. The observed uncertainty is smaller than the expected uncertainty by approximately 49 MeV. Fig. 4 shows 1D likelihood scan vs. m_H for 1D $L(m'_{4l})$, 2D $L(m'_{4l}, D'_{mass})$ and 3D $L(m'_{4l}, D'_{mass}, D^{kin}_{bkg})$ fits including $m(Z_1)$ constraint. Signal strength and all other nuisance parameters are profiled. When estimating the systematic uncertainty, the signal strength is profiled in the likelihood scan with the systematic uncertainties removed so that its uncertainty is included in the statistical uncertainty. The systematic uncertainty is dominated by lepton momentum scale uncertainty.

Including per-event mass uncertainty in likelihood improves precision of Higgs mass measurement by 9.8%, with respect to using m_H alone in the likelihood. Matrix element based kinematic discriminat improves precision by additional 3.1%. Finally, by using $m(Z_1)$ constraint improves precision by 8.1%, comparing to CMS Run 1 style measurement, which is 3D fit without $m(Z_1)$ constraint.

References

1. CMS Collaboration, JINST 3 S08004 (2008).
2. CMS-PAS-HIG-16-041.

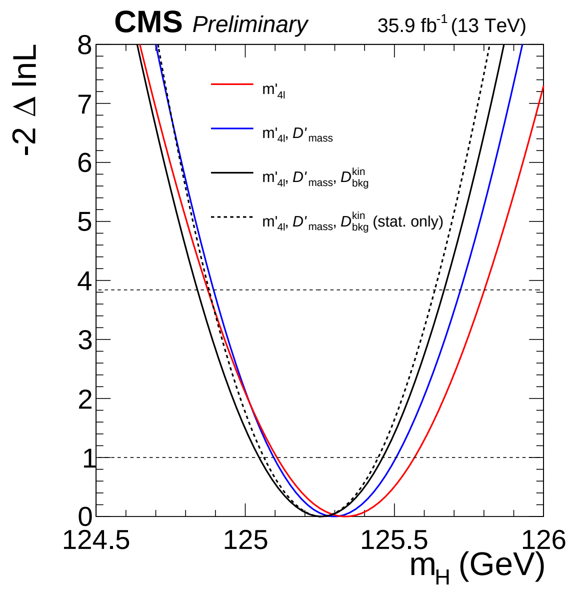

Figure 4 – 1D likelihood scan as a function of mass for the 1D, 2D, and 3D measurement. The likelihood scans are shown for the mass measurement using the refitted mass distribution with $m(Z_1)$ constraint. Solid lines represents the scan with all uncertainties included, dashed lines statistical uncertainty only. [2]