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SEARCH STRATEGY FOR THE STANDARD MODEL HIGGS BOSON IN THE $H \to ZZ^{(*)} \to 4\mu$ DECAY CHANNEL USING $M(4\mu)$-DEPENDENT CUTS*

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We present a strategy for a Higgs-boson search in its four-muon decay channel $H \to ZZ^{(*)} \to 4\mu$. Cuts used in this analysis are smooth functions of a 4-muon invariant mass and a priori optimized so as to maximize statistical chances of the Higgs boson observability independently of a mass at which it might appear. The Higgs boson then manifests itself as a 4μ resonance-like peak over the continuum $M(4\mu)$ distribution and can be searched for using various statistical techniques. The most important theoretical and instrumental systematic errors as well as the fact that the search is conducted in a broad range of $M(4\mu)$ invariant masses (115–600 GeV/c^2) are taken into account.

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1. Introduction

The $H \to ZZ^{(*)} \to 4\mu$ process is one of the cleanest channels (also known as a "gold-plated" channel) for discovering the Standard Model Higgs boson at the LHC. The main background processes with four muons in final

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states are $t\bar{t}$, $Zb\bar{b}$, and ZZ (Z here stands for Z, Z^*, γ^* decaying directly to two leptons). In this paper, we outline a complete analysis strategy for discovering the Standard Model Higgs boson in the $H \to ZZ^{(*)} \to 4\mu$ channel. The explored range of Higgs masses is 115–600 GeV/c^2.

All details of the studies forming the basis for the brief summary given in this paper can be found in [1–6]. The results were obtained with the full CMS detector simulation and reconstruction software [7, 8] and included pile-up events corresponding to an instantaneous luminosity of 2×10^{33} cm^{-2} s^{-1}.

Previous studies on the search for the Standard Model Higgs boson in the $H \to ZZ^{(*)} \to 4\mu$ channel with CMS are described in [9]. Another ongoing study exploring the discovery potential with a different set of mass-independent cuts can be found elsewhere [10]. The results of the two parallel analyses using the $H \to 4e$ and $H \to 2e2\mu$ channels can be found in [11, 12].

2. Trigger and offline muon selection

We used inclusive muon triggers based on selection of a single muon with $p_{\rm T} > 19$ GeV/c or dimuons with $p_{\rm T} > 7$ GeV/c, which allows for collection of Higgs events with an efficiency of practically 100%.

In order to minimize muon reconstruction systematic uncertainties, we selected only those reconstructed muons that have a transverse momentum $p_{\rm T} > 7$ GeV/c, if they are in the central pseudorapidity region ($|\eta| < 1.1$), or with total momentum $p > 13$ GeV/c, if they are in the endcaps ($|\eta| > 1.1$). We observed a quick drop of the muon reconstruction efficiency below these thresholds. Also, we required that all four possible combinations of reconstructed dimuon masses satisfied $m(\mu^+\mu^-) > 12$ GeV/c^2 to suppress poorly simulated hadronic background contributions originating from charmonium and bottomonium dimuon decays.

3. Cut optimization and search for the signal

Given a distinct localization of the Higgs-boson signal as a resonance-like peak in the invariant mass of four muons, the cuts can be made $M(4\mu)$-dependent. We found cuts in the form of smooth functions of the four-muon invariant mass $M(4\mu)$ such that at whatever unknown a priori mass the Higgs boson might appear, the signal-to-background ratio would be already optimal to give the best chance of discovering it. This allows us to avoid *a posteriori* cut optimization.

The first half of the available Monte Carlo simulated data was used for the cut optimization based on maximizing a counting experiment significance $S_{\rm cL} = \sqrt{2(S+B)\ln((S+B)/B) - 2S}$. The cut optimization was done using GARCON package [13] for 18 Higgs boson masses from 115 to

600 GeV/c^2. It was found that, given the level of the expected dominant backgrounds ($t\bar{t}$, $Zb\bar{b}$, ZZ), there are only three critical discriminating cuts: muon isolation cut, both tracker- and calorimeter-based, on the worst isolated muon; $p_{\rm T}$ cut on the second lowest $p_{\rm T}$ muon; and $M(4\mu)$ window for the counting experiment approach. After applying these cuts, distributions of all other variables for background and signal at all simulated M_H masses looked alike.

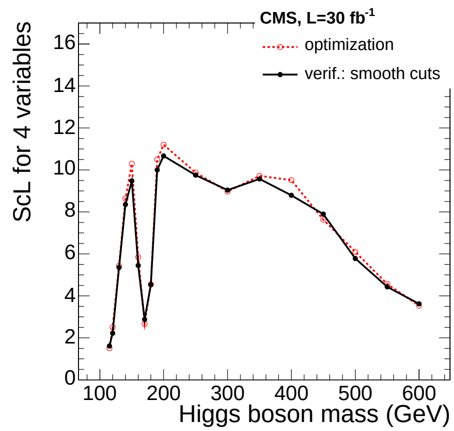

Fig. 1. Significance $S_{\rm cL}$ *vs* Higgs-boson mass: optimized cut values applied to the first half of the statistics (dashed line, empty circles) and cuts as smooth functions of 4-muon invariant mass, applied to the second half of the statistics (solid line, filled circles).

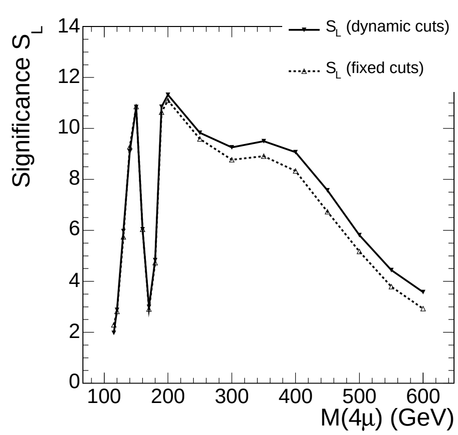

Fig. 2. Expected excess significance S_L with $L = 30$ fb^{-1} for different Higgs-boson masses for $M(4\mu)$-dependent (solid line) and independent cuts (dashed line). No systematic errors included.

In the next step, we converted 18 values for each cut into smooth function of 4-muon invariant mass. Then, we applied the three critical cuts (smooth functions of $M(4\mu)$) to the second half of the available Monte Carlo events that were not used in the cut optimization. The results are shown in figure 1.

After the cuts were applied, we searched for the 4μ resonance-like peak over the continuum background. We used the shapes of $M(4\mu)$-distributions for *background-only* and *signal+background* hypotheses to build likelihood ratio Q and a corresponding significance estimator $S_L = \sqrt{2\ln Q}$.

Figure 2 shows significance S_L of the expected excesses of events for different Higgs-boson masses at $L = 30$ fb^{-1}. To emphasize the gain in the sensitivity achievable with $M(4\mu)$-dependent cuts, the results for flat cuts, optimized for $M_H = 150$ GeV$/c^2$, are also superimposed.

4. Systematic uncertainties

Sources for the most important theoretical and instrumental systematic errors were studied. They include differences in NLO and LO dynamics, uncertainties in PDF's and QCD-scale, muon isolation cut efficiency, reconstruction efficiency, momentum measurements (scale and resolution), and luminosity.

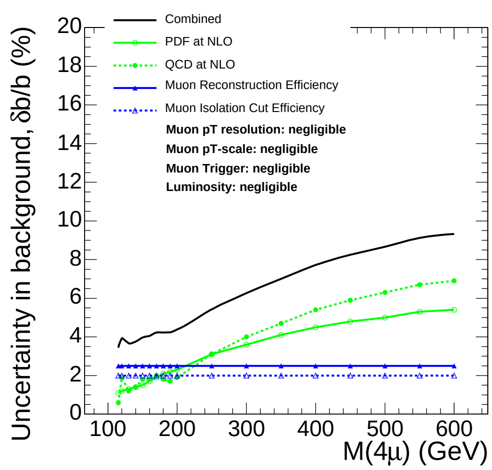

Fig. 3. Uncertainties in the number of $ZZ \to 4\mu$ background events in the signal region window at different $M(4\mu)$. The window size is $\pm 2\sigma$ of the expected experimental Higgs resonance width. The event count is referenced to the number of $Z \to 2\mu$ events. Shown are: combined uncertainty (upper solid line), PDF and QCD scale uncertainties at NLO (next two lines with circles: dashed and solid, respectively); muon reconstruction and muon cut efficiencies (two flat lines with triangles: solid and dashed, respectively).

To reduce sensitivity to uncertainties in luminosity measurements, PDF's and QCD-scale, we used the $Z \to 2\mu$ process as a control sample. To reduce sensitivity to uncertainties in the isolation cut and muon reconstruction efficiencies, we outlined methodology of measuring them directly from data. We also studied the option of evaluating background in a signal region from sidebands. This helps further reduce sensitivity to various systematic errors, but it suffers from substantial statistical penalty due to too low count of ZZ events.

Figures 4 and 5 show how inclusion of systematic uncertainties changes sensitivity in the Higgs boson search in terms of the significance as well as required luminosities for 5σ-discovery, 3σ-evidence, and 95% C.L. exclusion limit for the Standard Model Higgs boson.

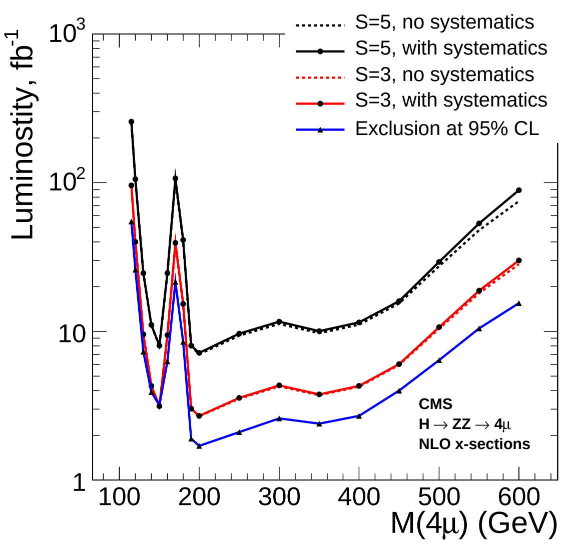

Fig. 4. Integrated luminosity needed for 95% C.L. exclusion (triangles, lower line), 3σ (circles, two middle lines), and 5σ (circles, two upper lines) discovery *versus* Higgs boson mass. Dashed curves are for the case if we did not have systematic errors. Solid lines are for the case of systematic errors estimated from the measured number of $Z \to 2\mu$ events.

Finally, we verified by how much the local excess significance should be effectively degraded due to the fact that we would look for a narrow resonance in a broad range of $M(4\mu)$ invariant masses. We performed 10^8 pseudo-experiments for *background-only* hypothesis looking for a *signal-like* event excess. Figure 6 shows one of the results of this study: the significance renormalization function to account for the true probability to find such an excess with a given value of $S_{\rm cL}$ significance. Note that this plain statistical effect is larger than the effect of including systematic errors (Fig. 5).

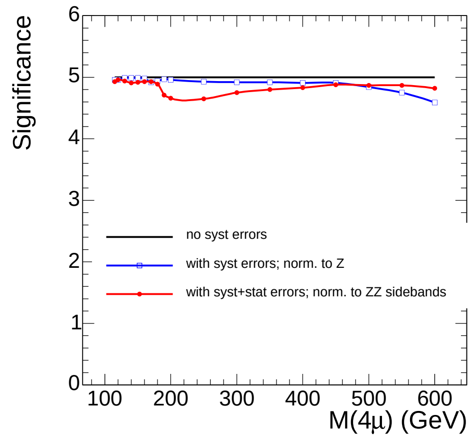

Fig. 5. Degrading of statistical significance due to including systematic errors in the analysis at the time when event excess in a Higgs peak would be close to a 5σ-significance in absence of systematic errors.

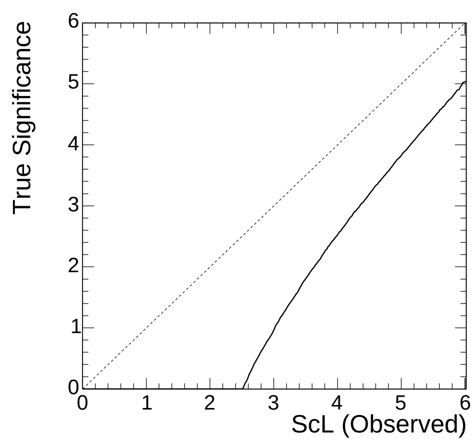

Fig. 6. Local significance renormalization. Significance de-rating is required due to the fact that the search is performed in a broad range of masses.

5. Summary

Discovery of the Standard Model Higgs boson in the "gold-plated" decay mode $H \to ZZ^{(*)} \to 4\mu$ was analyzed in the context of the CMS Detector, including a complete analysis of the dominant systematic errors. The explored range of Higgs-boson masses was 115–600 GeV/c^2.

It was shown that the discoveries at the level of "5σ" significance could be already possible at ~ 10 fb^{-1} for M_H in the range 140–150 and 190–400 GeV/c^2. By the time we reach ~ 30 fb^{-1}, the discovery range would open up to 130–160 and 180–500 GeV/c^2. An observation of the Higgs boson with the mass $M_H \sim 170$ GeV/c^2 or ~ 600 GeV/c^2 in the $H \to ZZ^{(*)} \to 4\mu$ decay channel would require an integrated luminosity of the order of 100 fb^{-1}.

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