PROCEEDINGS OF SCIENCE

Higgs→ZZ search in Atlas and CMS

Nicola Amapane
Università di Torino and INFN, Torino, Italy
E-mail: Nicola.Amapane@cern.ch

Giacomo Artoni
Brandeis University, US
E-mail: Giacomo.Artoni@cern.ch

We present a comparison of the H→ZZ→ 4ℓ analyses performed by the ATLAS and CMS experiments at the LHC, focusing in particular on differences and analogies in the analysis techniques, and on possible future developments.

VI Italian workshop on p-p physics at the LHC,
8-10 May 2013
Acquario di Genova, Ponte Spinola, Area Porto Antico, Genova, Italy

PoS(LHCPP2013)003

1. Introduction

Among the final states accessible at the LHC, ZZ→ 4ℓ plays a very special role in the recent studies of the newly observed Higgs-like boson [1, 2]. Besides providing the best observation significance thanks to its very good signal to background ratio, the fully reconstructed four-lepton final state allows the boson mass to be measured with the best accuracy at the LHC, while the study of production and decay angles opens the possibility to probe its spin and parity.

For these reasons, the ATLAS and CMS Collaborations have developed very advanced analyses [3, 4] on the complete dataset collected at the LHC during its first three years of data taking. In the following sections, a comparison of the analysis strategies adopted by the two collaborations is presented.

1.1 Analysis strategy

The analyses search for two pairs of same-flavor, oppositely charged electrons and muons. Final states involving τ leptons are also considered by the CMS experiment, but the kinematic thresholds on reconstructed τ leptons limit their use to the search of additional resonances above $m_{4\ell} > 200$ GeV.

The lepton pair with the invariant mass closest to the nominal mass of the Z boson is considered as the primary pair. The two experiments have comparable cuts on the transverse momenta of the four leptons, as well as on the invariant mass of the two different pairs, with slightly lower momentum thresholds and more open phase-space cuts on the CMS side. To select isolated leptons, ATLAS uses both the isolation variable defined using tracker information and the one defined with calorimetric information. CMS benefits from a Particle Flow approach [5, 6], which consists of interpreting all calorimeter and tracking data in terms of a set of reconstructed charged and neutral particles, thus allowing a natural suppression of the contribution of pile-up charged particles, of the other leptons in the event, and of possible FSR photons, in a wider cone. Overall, CMS has a higher signal acceptance due to more relaxed cuts.

Final state radiation (FSR) photons are searched for and recollected by both experiments, although in a different way. In particular, ATLAS recovers the photon only on a primary muon pair, while CMS recollects FSR photons for both lepton pairs, and regardless of flavour.

ATLAS applies an invariant mass constraint on the primary lepton pair, refitting the momenta of leptons using their covariance matrices and the Z line shape. CMS does not apply such a refit, but can anyhow count on a better $m_{4\ell}$ resolution (1.2/1.7/2.0 GeV for 4μ/2e2μ/4e vs. 1.6/1.9/2.4 GeV for ATLAS, including the refit), owing to the stronger central magnetic field.

Backgrounds are treated in a very similar way by the two Collaborations. The irreducible background (Standard Model ZZ production) is modelled using the same generators (POWHEG [7] for qq → ZZ and gg2zz [8] for gg → ZZ, both interfaced to PYTHIA6 [9]) and rescaling their yields to the expected number of events predicted by MCFM [10, 11, 12]. Very similar strategies have also been adopted by ATLAS and CMS to estimate the amount of reducible backgrounds from data. These are based on specific control regions obtained by either relaxing or inverting analysis cuts on one or two of the final state leptons. Transfer factors extracted from either data or Monte Carlo are then used to extrapolate these yields to the signal region. The number of observed and expected signal and background events reported by the two Collaborations is shown in Table 1.

Table 1: Observed and expected event yields. Results of the ATLAS experiment are given in the range 100-160 GeV and correspond to 25.3 fb^{-1} of data. Results of the CMS experiment are given in the range 110-160 GeV and correspond to 24.7 fb^{-1} of data.

	4μ channel		$2e2\mu$ channel		4e channel	
	ATLAS	CMS	ATLAS	CMS	ATLAS	CMS
Signal ($m_H = 125$ GeV)	6.8 ± 0.7	6.8 ± 0.8	8.1 ± 0.9	8.9 ± 1.0	3.3 ± 0.4	3.5 ± 0.5
ZZ background	14.6 ± 0.6	13.8 ± 1.0	17.2 ± 0.9	18.1 ± 1.3	6.2 ± 0.5	6.6 ± 0.8
Reducible background	2.1 ± 0.6	1.6 ± 0.6	8.5 ± 0.2	4.0 ± 1.6	4.5 ± 0.8	2.5 ± 1.0
Total expected	23.5 ± 1.1	22.2 ± 1.4	33.8 ± 1.3	31.0 ± 2.3	14.0 ± 1.0	12.6 ± 1.4
Observed	35	23	33	32	15	16

In addition, CMS introduces a kinematic discriminant (K_D):

$$K_D(\theta^*, \Phi_1, \theta_1, \theta_2, \Phi, M_{Z_1}, M_{Z_2} | m_{4\ell}) = \mathcal{P}_{\text{sig}} / (\mathcal{P}_{\text{sig}} + \mathcal{P}_{\text{bkg}}) \tag{1.1}$$

where $\mathcal{P}$ is defined using matrix element techniques, using `JHUGen` [13] for the signal and `MCFM` for the ZZ background. Other matrix elements, as well as machine trained techniques, were used as a crosscheck. This additional variable is used in the statistical analysis of all reported measurements to build signal and background models together with the invariant mass of the four-lepton system ($m_{4\ell}$) and a third variable specific for each measurement. This third variable is: the event-by-event estimated uncertainty on $m_{4\ell}$ for the mass measurement; a vector boson fusion (VBF)-sensitive variable for the determination of signal strength, significance, and for the measurement of couplings; and an additional kinematic discriminant for testing spin-parity hypotheses alternative to the Standard Model (SM), i.e. $J^P = 0^+$. Inclusion of K_D in the signal and background models for the statistical analysis allows the extraction of maximal information from the available data by weighting events according to how signal-like they appear to be.

1.1.1 Significance and Mass Measurement

The significance of the signal excess relative to the background expectation is obtained by ATLAS with an inclusive fit to $m_{4\ell}$ and yields an observed number of standard deviations of 6.6, with 4.4σ expected for a SM Higgs boson. CMS presents results with an inclusive fit to $m_{4\ell}$, with a 2D fit to $m_{4\ell}$ and K_D, and with a 3D fit using in addition the VBF-sensitive variables for the two separate categories described in Sec 1.1.3. In the first case CMS observes 4.7σ (5.6 expected) while the addition of the kinematic discriminant in the full model gives 7.2σ (6.7 expected).

For the measurement of the boson mass, ATLAS performs an inclusive fit to $m_{4\ell}$ and obtains $m_{\text{H}} = 124.3^{+0.6}_{-0.5}{}^{+0.5}_{-0.3}$ GeV, while CMS performs a 3D fit to $m_{4\ell}$, the kinematic discriminant and the event-by-event $m_{4\ell}$ estimated uncertainty to get $m_{\text{H}} = 125.8 \pm 0.5 \pm 0.2$ GeV. It can be noted that the mass measurement in this channel is still dominated by the statistical uncertainty. A significant effort has been put by the two Collaborations into calibrating the lepton momentum scales and constraining their uncertainty, in particular using resonances (Z, J/Ψ, Υ). The Z$\rightarrow 4\ell$ peak [14] is also used to validate the lepton momentum scale, as it provides a clean reference with signal-like kinematics.

PoS(LHCPP2013)003

1.1.2 Spin/parity measurements

As already pointed out, this channel provides the perfect environment for a measurement of the properties of the newly found particle. For this purpose, ATLAS has developed two different approaches, one based on a boosted decision tree trained on fully simulated Monte Carlo samples and another one based on a matrix element built using the theoretical decay rates corrected for detector acceptance and analysis selection effects.

CMS defines a kinematic discriminant similar to K_D, but using the probability ratio for two signal hypotheses instead of the signal-to-background probability ratio. This is used in conjunction with a second discriminant built from $m_{4\ell}$ and K_D to provide discrimination versus the background. Six alternative spin-parity hypotheses are tested.

For all tests, the Standard Model hypothesis ($J^P = 0^+$) is found to be consistent with data by both experiments. Other hypotheses are disfavoured by the data; e.g. the pure pseudoscalar hypothesis 0^- is disfavoured with CL_s values of 0.4% and 0.16% in the case of ATLAS (ME approach) and CMS, respectively.

In addition to simple hypothesis testing, CMS performs a fit for a continuous parameter f_{a3} defined as the fraction of the CP-violating term in the decay amplitude for a spin-0 boson. This is a first attempt at investigating the presence of different contributions in the decay amplitude, besides testing pure J^P states. The measured value is found to be consistent with the SM expectation.

1.1.3 Couplings

The couplings of the newly found boson to vector bosons and fermions are also investigated. The strategy used by ATLAS is to divide the data sample in three different categories. A candidate is associated to the vector boson fusion category if at least two jets are found in the event and the two highest-p_T jets satisfy cuts on their separation in pseudo-rapidity and on their invariant mass. Otherwise, if an additional lepton is found in the event, the candidate is assigned to a category corresponding to associated production with a vector boson. If none of the above conditions are met, the candidate belongs to the gluon fusion category. From a fit of the yields in these categories, ATLAS extracts the signal strength for the coupling to fermions and vector bosons, obtaining respectively $\mu_F = 1.8^{+0.8}_{-0.5}$ and $\mu_V = 1.2^{+3.8}_{-1.4}$.

CMS divides its sample in a di-jet category and an untagged category. Both categories include a contribution of VBF events; a VBF-sensitive variable is defined as the p_T of the four-lepton system divided by $m_{4\ell}$ in the untagged category, and as a linear discriminant built from the invariant mass and difference in pseudo-rapidity of the two leading jets in the di-jet category. These variables are used in a 2D fit together with $m_{4\ell}$, separately for the two categories, to extract the signal strengths for the vector boson and fermion couplings: $\mu_F = 0.9^{+0.5}_{-0.4}$, $\mu_V = 1.0^{+2.4}_{-2.3}$.

2. Discussion

The H→ZZ channel played a major role in the recent discovery of the Higgs-like boson at the LHC, and is already providing a wealth of information on its properties: mass, spin/parity, couplings to fermions and bosons. The results presented so far are consistent between the two Collaborations, and with the Standard Model predictions.

PoS(LHCPP2013)003

A lot of effort has been put by the two Collaborations in the corresponding analyses, which at the time of writing this report appear to be complete and very mature. Substantial improvements are not expected between current preliminary results and the final publications on 7 and 8 TeV data. Also, all results presented are still dominated by the statistical uncertainty. For the boson mass measurement, simple scaling arguments suggest that this may continue to be the case even after the first year of data taking after shutdown, in an hypothetical scenario of 20-30 fb^{-1} collected at 13 TeV; providing that the Collaborations manage to maintain the same performances in the harsher expected pile-up environment. This is definitely the main future challenge for these analyses.

For what regards theoretical uncertainties, improvements in the knowledge of the boson p_T spectrum and in the $gg \to$H+2 jets signal cross section would be particularly relevant for the measurement of couplings, and were discussed extensively in this Workshop [15].

Besides improving the accuracy of the present measurements, additional data will allow further studies on this final state, in particular to set a limit on the width of the boson, to extend spin/parity studies to generic mixtures of different CP states, and eventually to study the associated production separately from the gluon fusion and VBF mechanisms. In addition, by also making use of the $2\ell 2\tau$, $2\ell 2\nu$, $2\ell 2$q final states, additional data could be used to improve the search for additional resonances, as those predicted in some beyond-SM models that were discussed in this Workshop [16, 17].

References

[1] The ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012) 1–29.

[2] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B **716** (2012) 30–61.

[3] The ATLAS Collaboration, *Measurements of the properties of the Higgs-like boson in the four lepton decay channel with the ATLAS detector using 25 fb^{-1} of proton-proton collision data*, ATLAS-CONF-2013-013 (2013).

[4] CMS Collaboration, *Properties of the Higgs-like boson in the decay H to ZZ to 4l in pp collisions at sqrt s =7 and 8 TeV*, CMS-PAS-HIG-13-002 (2013).

[5] CMS Collaboration, *Particle–Flow Event Reconstruction in CMS and Performance for Jets, Taus, and MET*, CMS Physics Analysis Summary CMS-PAS-PFT-09-001 (2009).

[6] CMS Collaboration, *Commissioning of the Particle–Flow reconstruction in Minimum–Bias and Jet Events from pp Collisions at 7 TeV*, CMS Physics Analysis Summary CMS-PAS-PFT-10-002 (2010).

[7] S. Frixione, P. Nason, and C. Oleari, *Matching NLO QCD computations with Parton Shower simulations: the POWHEG method*, JHEP **11** (2007) 070.

[8] T. Binoth, N. Kauer, and P. Mertsch, *Gluon-induced QCD corrections to $pp \to ZZ \to \ell\bar{\ell}\ell'\bar{\ell}'$*, in *Proceedings of the XVI Int. Workshop on Deep-Inelastic Scattering and Related Topics (DIS'07)*, 2008.

[9] T. Sjöstrand, S. Mrenna, and P. Z. Skands, *PYTHIA 6.4 Physics and Manual*, JHEP **05** (2006) 026.

[10] J. M. Campbell and R. K. Ellis, *MCFM for the Tevatron and the LHC*, Nucl. Phys. Proc.Suppl. **205** (2010) 10.

[11] J. M. Campbell and R. K. Ellis, *An update on vector boson pair production at hadron colliders*, Phys. Rev. D **60** (1999) 113006.

[12] J. M. Campbell, R. Ellis, and C. Williams, *Vector boson pair production at the LHC*, JHEP **07** (2011) 018, doi:10.1007/JHEP07(2011)018.

[13] Y. Gao et al., *Spin determination of single-produced resonances at hadron colliders*, Phys. Rev. D **81** (2010) 075022.

[14] CMS Collaboration, *Observation of Z decays to four leptons with the CMS detector at the LHC*, JHEP **1212** (2012) 034.

[15] M. Grazzini, *Incertezze nella produzione del bosone di Higgs*, these proceedings.

[16] R. Contino, *Interpretazione teorica dei risultati sperimentali sul bosone di Higgs*, these proceedings.

[17] S. Diglio, S. Lacaprara, *Ricerche di Higgs esotici*, these proceedings.