Physics with four-leptons at the LHC

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Abstract. Several analyses with four-leptons in the final state performed by ATLAS and CMS experiments at the LHC are summarized. These results include Standard Model measurements on $ZZ$ and Higgs boson production, as well as beyond Standard Model searches. The four-lepton signature of these processes leads to a very clean final state with low background. These features enhance the interest of these analyses, which may be performed in the context of beyond the Standard Model searches for the Run 2 period. In particular, the resonant pair production of new heavy scalars, the Madala boson, decaying to four $W$-bosons will be discussed.

1. Introduction: Four-lepton searches at the LHC

Searches relying on four leptons in the final state use a very clean signature with low background contamination. Due to these features, different four-leptons analyses are developed in ATLAS and CMS experiments for such Standard Model (SM) measurements, as $ZZ$ production and Higgs boson production as well as for exploring a wide range of new physics.‡

2. Standard Model Analyses

Inclusive $ZZ$ production cross section in proton-proton collisions at 8 TeV is measured by both CMS [1] and ATLAS [2] experiments. The former uses an integrated luminosity of 19.6 fb$^{-1}$ and the measurements are performed in the leptonic decay modes $ZZ$ to $lll'l'$, where $l = e, \mu$ and $l' = e, \mu, \tau$. The measured total cross section is
\[
\sigma(pp \rightarrow ZZ) = 7.7 \pm 0.5\,(\text{stat.})^{+0.5}_{-0.4}\,(\text{syst.}) \pm 0.4\,(\text{theo.}) \pm 0.2\,(\text{lum.}) \; \text{pb}
\]
for both $Z$ bosons produced in the mass range $60 < m_Z < 120$ GeV. For ATLAS, the total cross section for $ZZ$ events produced with both $Z$ bosons in the mass range 66 to 116 GeV is measured from the combination of the two channels to be $7.3 \pm 0.4\,(\text{stat}) \pm 0.3\,(\text{syst}) \pm 0.2\,(\text{lumi}) \; \text{pb}$. Both results are consistent with the Standard Model prediction of $6.6^{+0.7}_{-0.6} \; \text{pb}$.

‡ We don’t consider here pair production of $J/\psi$ or $\Upsilon$ states as well as such states as $\eta$, $\eta'$, $\rho$, $\omega$, $\phi$ which can also result to four-lepton final states.
2.1. Standard Model: Four-leptons Results in ATLAS

The ATLAS Collaboration measured four-lepton production cross section in the mass range from 80 to 1000 GeV [3] based on 20.3 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV. The four-lepton events are produced in the decays of resonant $Z$ and Higgs bosons and the non-resonant ZZ continuum originating from $q\bar{q}$, $gg$, and $qg$ initial states. A total of 476 signal candidate events are observed with a background expectation of 26.2 $\pm$ 3.6 events, enabling the measurement of the integrated cross section and the differential cross section as a function of the invariant mass and transverse momentum of the four-lepton system. In the mass range above on-shell $Z$-boson pair production (180 GeV) the signal strength of the gluon-fusion component relative to its leading-order prediction is determined to be $\mu_{gg} = 2.4 \pm 1.0($stat.$) \pm 0.5($syst.$) \pm 0.8($theory$)$. Figure 1 shows the four-lepton invariant-mass distribution ($m_{4\ell}$) and the measured differential cross-section as a function of $m_{4\ell}$.

![Figure 1: Four-lepton invariant-mass distribution (left) and differential cross-section as a function of $m_{4\ell}$ measured by ATLAS [3]. Bottom plots show data/MC ratio.](image)

2.2. $H \rightarrow ZZ^* \rightarrow 4\ell$ observation in the CMS and ATLAS experiments

The ATLAS Run 1 measurements of Higgs boson production rates and couplings in the decay channel $H \rightarrow ZZ^* \rightarrow 4\ell$ are described in Ref. [4]. These measurements were performed using $pp$ collision data corresponding to integrated luminosities of 4.5 and 20.3 fb$^{-1}$ at center-of-mass energies of 7 and 8 TeV, respectively. The $H \rightarrow ZZ^* \rightarrow 4\ell$ signal is observed with a significance of 8.1 standard deviations ($\sigma$), with an expectation of 6.2 $\sigma$, at $m_H = 125.36$ GeV, the combined ATLAS measurement of the Higgs boson mass from the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ channels. The production rate relative to the Standard Model expectation, the signal strength, is measured in four different production categories in the $H \rightarrow ZZ^* \rightarrow 4\ell$ channel. The measured signal strength, at this mass, and with all categories combined, is $1.44^{+0.40}_{-0.33}$.

The CMS Collaboration also observed at 7–8 TeV [5] the new boson as a narrow resonance with a local significance of 6.8 $\sigma$, a measured mass of 125.6 $\pm$ 0.4(stat) $\pm$ 0.2(syst) GeV, and a total width less than 3.4 GeV at the 95% confidence level.
Table 1 quotes the number of events expected in the 118-129 GeV mass range and observed for the $m_H = 125$ GeV hypothesis for the four-lepton final states in ATLAS at $\sqrt{s} = 13$ TeV. Figure 2 summarizes the $H \rightarrow ZZ^* \rightarrow 4\ell$ Run-1 results for the observed local $p_0$ value obtained by ATLAS and CMS [6, 7].

| Final State | Signal | Signal $ZZ^*$ | $Z + \text{jets}, \ell\ell$ | $S/B$ | Expected | Observed |
|-------------|--------|--------------|-----------------|------|----------|----------|
| $4\mu$      | $8.8 \pm 0.6$ | $8.2 \pm 0.6$ | $3.11 \pm 0.30$ | $0.31 \pm 0.04$ | 2.4 | 11.6 $\pm$ 0.7 | 16 |
| $2e2\mu$    | $6.1 \pm 0.4$ | $5.5 \pm 0.4$ | $2.19 \pm 0.21$ | $0.30 \pm 0.04$ | 2.2 | 8.0 $\pm$ 0.4 | 12 |
| $2\mu2e$    | $4.8 \pm 0.4$ | $4.4 \pm 0.4$ | $1.39 \pm 0.16$ | $0.47 \pm 0.05$ | 2.3 | 6.2 $\pm$ 0.4 | 10 |
| $4e$        | $4.8 \pm 0.5$ | $4.2 \pm 0.4$ | $1.46 \pm 0.18$ | $0.46 \pm 0.05$ | 2.2 | 6.1 $\pm$ 0.4 | 6 |
| Total       | $24.5 \pm 1.8$ | $22.3 \pm 1.6$ | $8.2 \pm 0.8$ | $1.54 \pm 0.18$ | 2.3 | 32.0 $\pm$ 1.8 | 44 |

Table 1: Number of expected and observed candidates in the 118–129 GeV mass range for the $m_H = 125$ GeV hypothesis using four-lepton events in ATLAS [6].

Figure 2: The observed local $p_0$-value for the combination of the 2011 and 2012 data sets as a function of $m_H$ for ATLAS (left) and CMS (right) [4, 5].

2.3. $ZH \rightarrow ZWW^* \rightarrow 4\ell + 2\nu$ Results in ATLAS

A search for Higgs boson production in association with a $Z$ boson, in the $H \rightarrow WW^*$ decay channel, is performed with a data sample collected with the ATLAS detector at the LHC in proton-proton collisions at centre-of-mass energies $\sqrt{s} = 7$ TeV and 8 TeV, corresponding to integrated luminosities of 4.5 fb$^{-1}$ and 20.3 fb$^{-1}$, respectively [8].

The strategy of the analysis is to select four-lepton events with total charge zero, which are categorized according to the number of same-flavour opposite signed (SFOS) lepton pairs: 1-SFOS ($3e + 1\mu$, $1e + 3\mu$) and 2-SFOS ($4e, 4\mu, 2e + 2\mu$). The analysis exploits the kinematics of the opposite-sign lepton pair from the Higgs boson decay candidate by requiring low angular separation between the leptons in the $Z$-boosted frame. The Run-I results for the signal significance ($Z_0$) and the $H \rightarrow WW^*$ signal strength ($\mu$) evaluated at the end of the event selection are quoted in Table 2.
Table 2: The signal significance and the $H \rightarrow WW^{*}$ signal strength evaluated in the signal region, combining the 8 TeV and 7 TeV data [8].

2.4. $t\bar{t}H$ results with four-leptons in ATLAS

The Yukawa coupling of the Higgs boson to the top quark is a key parameter of the Standard Model, and can be constrained using the associated production process $pp \rightarrow t\bar{t}H + X$. A search for this process using final states with multiple leptons has been performed in ATLAS using Run 1 and Run 2 data samples [9, 10]. The analysis of the four-lepton final state is statistically limited and only one event is observed with Run 1 data. This leads to a measured signal strength of $1.8^{+6.9}_{-2.0}$ (tot.) $^{+6.8}_{-2.0}$ (stat.).

3. Beyond Standard Model Searches

3.1. High Mass $S \rightarrow ZZ^{*} \rightarrow 4\ell$ with Run 2 data

A search for scalar resonances decaying into the four-lepton final state is performed in ATLAS [6] and CMS [11] using Run 2 data at 13 TeV. Related $S \rightarrow ZZ$ analyses closely follow the SM Higgs strategy but extending the search to the higher mass range 200–800 GeV to cover different $S$ mass hypotheses. Figure 3 shows the distribution of the four-lepton reconstructed invariant mass in the high-mass range for both ATLAS and CMS experiments and the ATLAS 95% confidence level limits on the $S$ boson production of the additional heavy Higgs-like boson assuming the Narrow Width Approximation (NWA) [12] for different mass hypotheses in the range 200 – 1000 GeV.

Figure 3: Invariant mass of the four-lepton system for high mass $S \rightarrow ZZ^{*} \rightarrow 4\ell$ searches at ATLAS (left) and CMS (middle) [6, 11]. The 95% confidence limits as function of $m_S$ for an additional narrow heavy scalar in ATLAS (right).
3.2. The Madala Boson Hypothesis

Higgs boson searches at the LHC can be extended assuming the validity of the so-called Madala boson model [13–16]. This model introduces an additional doublet of two hypothetical scalars $H$ and $S$ with $2m_h < m_H < 2m_t$ and $m_h < m_S < m_H$, where $m_h$ and $m_t$ represent the masses of the Higgs boson and top-quark, respectively. In addition, the introduction of new $HSS$ vertex leads to the $H \rightarrow SS$ decay with $S$ being a portal to dark matter (DM) through its interaction with $\chi$, a DM candidate.

This feature motivates a search in ATLAS for the $H \rightarrow SS \rightarrow 4W$ decay. Specially the presence of four leptons in the final state leads to a unique final state with a very clean signature due to low expected background contribution. The strategy of the search relies on the kinematics of the four-lepton system as well as on the kinematics of the lepton pairs. Figure 4 compares different kinematic quantities from simulation of $H \rightarrow SS$, $Sh$ process with four-lepton final states.

![Figure 4: The invariant mass of the four lepton system (left) and the minimum distance of leptons (right) for the signal \(pp \rightarrow H \rightarrow SS, Sh\) processes from MC simulation for \(m_H = 275(300)\) GeV in blue(red) assuming \(\text{BR}(S \rightarrow \chi\chi) = 0.5\) [14].](image)

4. Conclusions

Results of some four-lepton analyses performed by the ATLAS and CMS experiments at the LHC are presented. They include $Z^*Z^* \rightarrow 4\ell$ and $H \rightarrow ZZ^* \rightarrow 4\ell$ SM production cross sections as well as rates of associated $ZH$ and $ttH$-production with four-lepton final states. Apart of the SM analyses, new physics can be also explored using events with four leptons. Upper limits on the high mass $S \rightarrow ZZ$ production cross section in the NWA model are quoted and for new massive scalar searches, as the Madala boson, are discussed. The 2017 Run 2 data would become crucial to verify the obtained results so far, to measure other Higgs production mechanisms ($ZH$ and $ttH$) and to provide enough statistics to obtain for the first time results on new physics as the Madala boson.
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