Recent highlights in top quark and Higgs boson physics from the LHC

Ricardo Gonçalo, on behalf of the ATLAS and CMS Collaborations
LIP, Av. Prof. Gama Pinto 2, Lisboa, 1649-003 Lisboa, Portugal
E-mail: jose.goncalo@cern.ch

Abstract. The LHC represents the current energy frontier in collider experiments. Its most notable result so far was the experimental discovery of the Higgs boson, by the ATLAS and CMS collaborations. It is also very well suited to explore the physics of the top quark, the heaviest known elementary particle, with a Yukawa coupling of order 1. The data collected by these experiments during the LHC Run II allowed the measurement of top and Higgs experimental results, which provide very stringent tests of the Standard Model expectations near the electroweak scale, and therefore likely windows into new physics. The present article discusses the most recent experimental highlights in this area.

1. Introduction
The Large Hadron Collider (LHC) [1] at CERN is the highest energy particle collider in operation. In its second physics run (Run II), which started in 2015 and will terminate at the end of 2018, it has been colliding protons at a centre of mass energy of \( \sqrt{s} = 13 \text{ TeV} \). The ATLAS [2] and CMS [3] general-purpose LHC experiments have each collected data in excess of 100 fb\(^{-1}\) at this energy, as well as around 22 fb\(^{-1}\) at \( \sqrt{s} = 8 \text{ TeV} \) and 5 fb\(^{-1}\) at \( \sqrt{s} = 7 \text{ TeV} \) during Run I. With these data, both experiments have been exploring the Standard Model of particle physics (SM) to an unprecedented degree. Two areas are of particular interest for experimental exploration at the LHC, and are the subject of this communication: measurements of the top quark and of the Higgs boson. The present article highlights some of the latest measurements published by the two collaborations in these areas.

2. The ATLAS and CMS experiments
ATLAS and CMS are multi-purpose particle detectors with cylindrical geometry and nearly 4\(\pi\) coverage in solid angle. The detectors are designed to precisely reconstruct charged leptons, photons, hadronic jets, and the imbalance of momentum transverse to the direction of the beams \( E_T^{\text{miss}} \). Both use a right-handed coordinate system with its origin at the nominal interaction point, in the centre of each detector, and the z-axis along the beam pipe. The x-axis points to the centre of the LHC ring and the y-axis points upwards. Pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln\tan(\theta/2) \) and transverse momentum is defined relative to the beamline as \( p_T = p\sin\theta \). Angular distance is measured in units of \( \Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \), where \( \phi \) is the azimuthal angle around the z-axis. The rapidity is defined as \( y = \frac{1}{2} \ln \frac{E + p_T}{E - p_T} \), where

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$p_z$ is the $z$-component of the momentum and $E$ is the energy. The reconstruction performance is challenged by the extreme environment of the LHC, particularly by the overlap of several simultaneous collisions, known as pileup, which increases with instantaneous LHC luminosity.

3. Top quark highlights

The top quark was discovered at the Tevatron in 1995 [4, 5]. With a mass of around 173 GeV [6], it is the heaviest known fundamental particle. Its extremely short lifetime ($\approx 10^{-25}$ s) inhibits the formation of bound states, providing a unique opportunity to study a quasi-free quark.

The top is abundantly produced at the LHC, with a rate dominated by the production of top-quark pairs through the strong interaction (mostly gluon fusion) with a total cross section of around 850 pb at $\sqrt{s} = 13$ TeV [7]. The production of single top quarks occurs with lower cross sections (around 250 pb at $\sqrt{s} = 13$ TeV [7]) through electroweak processes described by three leading-order (LO) diagrams known as the $t$-, $s$-, and $Wt$ channels.

The top decays almost exclusively into a $W$ boson and a $b$ quark ($t \rightarrow Wb$). Taking into account the decays of the $W$ boson, $t\bar{t}$ production results in three experimental signatures: in the “all-jets” channel, with a branching ratio (BR) of 46%, both $W$ bosons decay hadronically; in the “lepton+jets” channel (BR = 45%), one of the $W$ bosons decays to a charged lepton ($e$, $\mu$ or $\tau$) and a corresponding neutrino; finally, in the “di-lepton” channel (BR = 9%), both $W$ bosons decay leptonically to a charged lepton and a neutrino.

3.1. Top quark mass

The top quark mass, $m_t$, is a fundamental parameter of the Standard Model. Due to its large value, close to the electroweak symmetry breaking scale, it enters via top-induced loops in the calculation of several electroweak observables. The combination of precise measurements of the top quark mass with those of the Higgs and $W$ bosons constitutes a stringent test of the SM [8], probing both its internal consistency and the need for Beyond the Standard Model (BSM) scenarios.

Various methods have been used to measure $m_t$, which may be broadly divided into direct and indirect. In direct methods, top quarks are reconstructed by associating particular combinations of measured objects to LO partons/particles. For example a muon, a $b$-tagged jet and $E_t^{miss}$ are used to reconstruct a $\bar{t} \rightarrow bW^+ \rightarrow b\mu\nu_{\mu}$ decay chain. The value of $m_t$ is then unfolded from the measured invariant mass of the decay products. In indirect methods, an observable dependent on $m_t$, for example the $t\bar{t}$ production cross section, is used to extract the value of the top mass.

It should be noted that the definition of what is being measured is a somewhat delicate one. Beyond LO, $m_t$ can only be defined within a given renormalization scheme, where the $\overline{MS}$ and the pole mass scheme are most commonly used, but differ numerically by $O$(GeV) [9]. In the latter, $m_t^{pole}$ is constant for all orders. In addition, the unfolding procedure used in direct methods generally relies on Monte Carlo (MC) simulations, where the value of $m_t$ corresponds to a parameter of the (finite order) MC generator. For this reason, it became usual to call this $m_t^{MC}$ and to distinguish it from $m_t^{pole}$. A recent review can be found in Ref. [9].

3.2. Direct $m_t$ measurements

Both ATLAS and CMS determined $m_t$ using the $t\bar{t}$ lepton+jets events [10, 11]. ATLAS employed 20.2 fb$^{-1}$ of 2012 collision data, collected at $\sqrt{s} = 8$ TeV, whereas the CMS result includes 35.9 fb$^{-1}$ of Run II data with $\sqrt{s} = 13$ TeV. In both cases, they focused on events containing one isolated electron or muon and at least four jets, two of them $b$-tagged and, in the ATLAS case, some $E_t^{miss}$. To assess the compatibility of each event with the (LO) $t\bar{t} \rightarrow b\ell bqq^\prime$ hypothesis and improve the resolution of reconstructed quantities, a kinematic fit is used in both cases. As constraints, the fit assumes the $W$-boson mass (and width in the ATLAS case), and that the two top quarks have the same mass, and also takes into account the experimental resolutions.
ATLAS employs a simultaneous template fit to three data distributions: the reconstructed top mass, \(m_{\text{reco}}\), the reconstructed \(W\) mass, \(m_{\text{reco}}^W\), and a quantity \(R_{bj}\) sensitive to the relative \(b\)-to-light-jet energy scale. CMS uses an ideogram method \([12]\) to simultaneously determine \(m_t\) and a jet scale correction factor (JSF) for each event through a likelihood fit. Some distributions are shown in Figure 1. The measured values for the ATLAS and CMS analyses are

\[
m_{\text{ATLAS}} = 172.51 \pm 0.27 \text{ (stat)} \pm 0.42 \text{ (syst)} \text{ GeV}
\]

and

\[
m_{\text{CMS}} = 172.25 \pm 0.08 \text{ (stat + JSF)} \pm 0.62 \text{ (syst)} \text{ GeV},
\]

where statistical and systematic uncertainties are shown separately. The quoted ATLAS result includes a combination with a previous measurement at \(\sqrt{s} = 7\text{ TeV}\).

3.3. Indirect \(m_t\) measurements

Both experiments have determined \(m_t\) from \(t\bar{t}\) production cross sections. ATLAS employed 20.2 fb\(^{-1}\) of \(\sqrt{s} = 8\text{ TeV}\) collision data and concentrated on di-leptonic \(t\bar{t}\) events. CMS used 2.2 fb\(^{-1}\) of 13 TeV data and concentrated on the lepton+jets \(t\bar{t}\) final states. In the CMS analysis \([13]\), 44 event categories are formed by requiring different numbers of jets (1, 2, 3, \(\geq 4\)), where some (0, 1, \(\geq 2\)) are \(b\)-tagged, with different categories for lepton flavour and charge. An observable that discriminates between signal and background is defined in each category, such as the minimum mass of the system formed by the charged lepton and a \(b\)-tagged jet, shown in Figure 2. The \(t\bar{t}\) production cross section is measured through a maximum-likelihood fit to the distributions found in the different categories, leading to

\[
\sigma_{t\bar{t}} = 888 \pm 2 \text{ (stat)} \pm 28 \text{ (syst)} \pm 20 \text{ (lumi)} \text{ pb},
\]

in agreement with the SM prediction at NNLO+NNLL precision. This result was re-interpreted by parametrizing the dependence of the cross section on the top pole mass, resulting in \(m_{t \text{ pole}} = 170.6 \pm 2.7\text{ GeV}\).

The ATLAS analysis \([14]\) measured differential \(t\bar{t}\) production cross sections in the di-leptonic
final state, selecting events with opposite-charge $e\mu$ pairs and at least one $b$-tagged jet. Eight differential cross sections were measured versus, respectively, the $p_T$ and (pseudo)rapidity of the lepton and the di-lepton system, the di-lepton mass, the azimuthal angle between the two leptons, and the scalar sums of the transverse momentum and energy of the two leptons: $p_T^e$, $\eta^e$, $p_T^{\mu}$, $\eta^{\mu}$, $m^{e\mu}$, $\Delta\phi^{e\mu}$, $p_T^{e+\mu}$, and $E^{e}+E^{\mu}$. These differential distributions were fitted using templates obtained from fixed-order QCD calculations, allowing to determine $m^{pole}_t$, as is shown in Figure 3. A simultaneous fit to all eight distributions (also shown in the figure) over-constrains the system, profiling various sources of theoretical uncertainty and resulting in $m^{pole}_t = 173.2^{+0.9}_{-0.8} (stat) + 0.8 (syst) + 1.2 (theory)$ GeV.

3.4. Quantum interference in single top production
Essentially all LHC results involving the top quark, either as signal or as a background process, separate $t\bar{t}$ production from the NLO single top quark production $tWb$. However, due to their identical $W^+W^-b\bar{b}$ final state diagrams (see Figure 4), these processes interfere. This becomes relevant when using NLO $t\bar{t}$ and $Wt$ MC samples. The usual treatments include diagram removal, DR, in which all doubly resonant amplitudes are removed from the $Wt$ sample. In alternative, doubly resonant contributions are canceled out by gauge-invariant subtraction terms (diagram subtraction, DS) or are only included in the interference terms (DR2).

Some recent NLO calculations of the $t\bar{t} \to \ell^+\nu\ell^-\bar{b}\bar{b}$ cross section include the correct treatment of the interference. The ATLAS collaboration has targeted a region sensitive to these effects in a measurement [15] of the di-leptonic $t\bar{t}$ differential cross section as a function of $m^{\text{minmax}}_{b\bar{b}} = \min\{\max(m_{b_1,\ell_1}, m_{b_2,\ell_2}), \max(m_{b_1,\ell_2}, m_{b_2,\ell_1})\}$, a variable sensitive to the $Wb$ invariant mass. This fiducial cross section is shown in Figure 4, where the measurement is compared to the predictions of NLO MC generators, including the DR, DS and DR2 treatments.
of the interference.

4. Higgs boson results

The discovery of the Higgs boson in ATLAS and CMS [16, 17, 18] was a groundbreaking result. It opened the field of experimental measurements in the Higgs sector, allowing an enormous body of results to build up in the last 6 years. By the end of the LHC Run I, enough data had been accumulated to achieve a Higgs mass measurement with per mille precision (0.2%) [19], establish that the total Higgs boson yield was within 10% of SM expectations [20], and determine, with minimal additional assumptions, that the overall Higgs branching fraction into BSM decays is less than 34% at 95% Confidence Level (CL).

The Higgs boson is produced at the LHC with cross sections spanning some three orders of magnitude (see Figure 5), dominated by the gluon fusion process (ggF: \( pp \rightarrow H \)), followed by vector boson fusion (VBF: \( pp \rightarrow q\bar{q}H \)), and associated production with a vector boson (VH: \( pp \rightarrow W^\pm H, ZH \)), a pair of top quarks (\( ttH: pp \rightarrow ttH \)), or other final states currently
beyond our experimental reach. It decays to gauge bosons and fundamental fermions with couplings dependent on their masses [21]. Run I achievements [20] included the $5\sigma$ observation of the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ$ and $H \rightarrow W^+W^-$ independently by ATLAS and CMS, and the $5\sigma$ observation of VBF production and $H \rightarrow \tau^+\tau^-$ by a combination of ATLAS and CMS results. Some evidence for VH and $ttH$ production was found, as well as for $H \rightarrow b\bar{b}$ decays, but no clear observation was possible with the available data.

![Graph](image1.png)

**Figure 6.** Left: summary of the $m_H$ measurements from [22] compared with the combined Run I measurement [19]. Right: likelihood scan for a CMS 3D mass fit to $m_H$, mass uncertainty, and a kinematic discriminant [23]. (Figures coloured online)

### 4.1. Higgs boson mass

As mentioned in Section 3.1, measurements of the Higgs boson mass are fundamental to probe the limits of the SM description of particle physics. Using 36 $fb^{-1}$ of LHC Run II data collected in 2015 and 2016, ATLAS [22] and CMS [23] have used the high mass resolution $H \rightarrow ZZ \rightarrow 4\ell$ and $H \rightarrow \gamma\gamma$ channels to obtain exquisite measurements of $m_H$. In the $H \rightarrow ZZ \rightarrow 4\ell$ final state, CMS obtained $m_H = 125.26 \pm 0.21$ GeV whereas ATLAS obtained $m_H = 124.86 \pm 0.27$ GeV from combining both channels. ATLAS further combined this result with Run I data, obtaining $m_H = 124.97 \pm 0.24$ GeV (see Figure 6).

![Graph](image2.png)

**Figure 7.** CMS measurement of the $H \rightarrow \gamma\gamma$ cross section following the STXS scheme [26].
4.2. Higgs boson cross sections

With the enlargement of the accumulated LHC data, the measurement of Higgs production cross sections has entered a new precision era, evolving from the measurement of a signal strength parameter, \( \mu = \frac{(s.BR)_{\text{obs}}}{(s.BR)_{\text{SM}}} \), which quantifies the agreement between the observed event yield and SM expectations. A noteworthy development has been the establishment of the Simplified Template Cross Section (STXS) scheme [24]. This scheme corresponds to the establishment of a set of fiducial regions to be used for measurements, optimizing the balance between experimental sensitivity and theoretical uncertainties. Both ATLAS [25] and CMS [23, 26] have published \( H \to \gamma \gamma \) and \( H \to ZZ \) cross section measurements using the STXS scheme (see e.g. Figure 7). Within the available precision, all measurements show agreement with SM expectations.

Complementary to the fiducial cross section measurements, both collaborations have produced several measurements of differential Higgs cross sections, illustrated by Figure 8. These are sensitive probes to the detailed physics of this sector: the cross section with respect to the number of jets is sensitive to the production mode and to the modelling of additional QCD radiation, whereas distributions of Higgs \( p_T \) and rapidity are sensitive to physics beyond the SM.

In their latest publications, ATLAS and CMS have, respectively, used 79.8 fb\(^{-1}\) and 35.9 fb\(^{-1}\) of Run II data to measure various cross sections in the \( H \to ZZ \to 4\ell \) [27] and \( H \to \gamma \gamma \) [28] channels.

![Figure 8.](image)

**Figure 8.** Examples of differential cross sections of \( H \to ZZ \to 4\ell \) [27] and \( H \to \gamma \gamma \) [28] by ATLAS and CMS. Good agreement is found with SM expectations. (Figures coloured online)

4.3. Observation of \( H \to \tau^+\tau^- \)

Both ATLAS [29] and CMS [30] have made independent observations of \( H \to \tau^+\tau^- \) decays. In these analyses, around 36 fb\(^{-1}\) of Run II data was employed by each experiment to identify events consistent with the decays of \( \tau \) lepton pairs with the Higgs boson invariant mass. All combinations of hadronic (\( \tau_h \)) and leptonic (\( \tau_l \)) decays were used. To enhance the sensitivity, data samples were furthermore divided into the 0-jet, VBF, and boosted categories. Figure 9 shows an example distribution of the \( \tau \tau \) invariant mass. The \( \sqrt{s} = 13 \text{ TeV} \) data were combined with Run I data at 7 and 8 TeV, leading to observed significances of 6.4\( \sigma \) and 5.9\( \sigma \) for ATLAS and CMS, respectively, where 5.4\( \sigma \) and 5.9\( \sigma \) were expected.
4.4. Observation of $H \rightarrow b \bar{b}$

Both collaborations have obtained compelling evidence of $H \rightarrow b \bar{b}$ [31, 32] (see Figure 10). The experimental sensitivity is driven by the associated Higgs production with a vector boson, VH. These analyses make use of the $Z \rightarrow \ell^+\ell^-$, $Z \rightarrow \nu\bar{\nu}$, and $W \rightarrow \ell\nu$ decays to suppress the overwhelming QCD $b \bar{b}$ background. Using 36.1 fb$^{-1}$ of Run II data, ATLAS and CMS have
obtained observed significances of $3.5\sigma$ (3.0\sigma expected) and $3.3\sigma$ (2.8\sigma expected), respectively. After combining with Run I data, CMS increased this significance to $3.8\sigma$ (2.8\sigma expected). At the time of writing, the above evidence was confirmed by independent ($\geq 5\sigma$) observations of these channels.

4.5. Observation of $t\bar{t}H$ production

Perhaps the most significant Higgs topic highlighted in this communication was the recent observation of $t\bar{t}H$ production, independently by ATLAS [33] and CMS [34]. This channel, combining the top and Higgs areas, is sensitive to the largest Yukawa coupling in the SM at tree level, unlike the more complicated loop diagrams present in ggF. This is a very challenging analysis, and several final states were combined to achieve the necessary experimental sensitivity: the multilepton channel is sensitive to $H \to ZZ / W^+W^- / \tau^+\tau^-$ decays, and experimental signatures include searching for events containing two (same-sign), three, or four charged leptons; the $t\bar{t}H(\to b\bar{b})$ channel profits from the higher $H \to b\bar{b}$ branching ratio but is beset by large irreducible backgrounds, especially $t\bar{t}+$heavy flavour jets; finally, the $H \to \gamma\gamma$ channel has very good purity but is suppressed by a low $H \to \gamma\gamma$ branching ratio. Figure 11 shows the $H \to \gamma\gamma$ invariant mass and the measured signal strengths in each experiment. Using $36 \text{ fb}^{-1}$ of Run II data combined with Run I data, CMS obtained an observation significance of $5.2\sigma$ (4.2\sigma expected), whereas ATLAS obtained $6.3\sigma$ (5.1\sigma expected) from up to $79.8 \text{ fb}^{-1}$ Run II data combined with Run I data. The signal strength and $t\bar{t}H$ cross section are shown in Figure 12.
5. Conclusions
This paper highlights some of the most significant recent results from the ATLAS and CMS experiments in the areas of top-quark and Higgs physics. It should be clear from the above, that both experiments cover these important subjects in great depth, using the fantastic exploration machine which is the LHC. With the above results, both collaborations probe the electroweak sector of the SM, searching for the BSM physics that we know must exist in Nature. So far, the SM has been showing consistent agreement with experimental data, indicating perhaps the need to search in subtle effects for signs of this new physics, after mapping the landscape with direct measurements such as the ones described here. An important part of this landscape is becoming very clear: like in top physics in the past, we have now reached a precision era in the Higgs sector, with the Yukawa couplings to third-generation fermions firmly established. And much more will soon be within our reach: the collision data from the planned High-Luminosity upgrade of the LHC, and the continuous improvements to the ATLAS and CMS detectors, will allow us to explore beyond the current boundaries of particle physics.

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