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Standard Model and Higgs Physics at the HL-LHC with ATLAS and CMS

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The current LHC experimental program is scheduled to last until the end of 2023 and to result in a total data sample of about 300 fb^{-1} at a pp centre-of-mass energy close to the design value of 14 TeV. This will be followed by a high-luminosity phase in which the LHC instantaneous luminosity will be increased by a factor of up to 7.5 times the design value of $1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with the goal of accumulating a total dataset of about 3000 fb^{-1} over about a ten-year run period. This will require significant upgrades to both the accelerator infrastructure, and the detectors, which were not designed to operate under these conditions. The large anticipated data sample will allow for more precise investigations of topics already studied with the 300 fb^{-1} data sample, as well as for studies of processes that are accessible only with the much larger statistics. There will be a particular focus on investigations of the properties of the Higgs boson, which was discovered in 2012. Rates and signal strengths will be measured for a variety of production and decay modes, allowing extraction of the Higgs boson couplings. Particular final states will allow differential cross-sections to be measured for all production modes, and for studies of the Higgs width and CP properties, as well as the tensor structure of its coupling to bosons. An important part of the HL-LHC experimental program will be investigations of the Higgs self-coupling, which is accessible via studies of di-Higgs production. The program of other Standard Model measurements will also continue at the HL-LHC. Topics that have been investigated so far, for the HL-LHC, include Vector Boson Scattering as well as topics in b- and top-quark physics. Here, projections for performance at the HL-LHC will be discussed for both ATLAS and CMS.

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1. Introduction

The High-Luminosity LHC (HL-LHC) [1] is scheduled to begin operation in mid-2026, at luminosities of up to 7.5 times the LHC design luminosity of $1 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, with the goal of accumulating a dataset of 3000 fb^{-1} over a ten-year run period, following a thirty-month shutdown during which the accelerator and associated detector upgrades will be completed.

The very-high HL-LHC luminosity poses problems for some of the current detector subsystems, related to occupancy, data rates and the total dose to be integrated by the detectors over the anticipated ten-year run period. Both ATLAS [2] and CMS [3] plan to replace their inner tracking detectors, with new all-silicon trackers comprising pixel detectors close to the beam line, and strip detectors at higher radius. These will have higher granularity and a lower material budget than the existing trackers, and are likely to cover a larger range of pseudorapidity, η, with both collaborations exploring options for coverage out as far as $|\eta| \approx 4$. Both experiments also plan to upgrade their triggers to allow a much higher rate. ATLAS is considering a Level-0/Level-1 system with rates of 1 MHz and 400 kHz, respectively, while CMS is currently planning on a Level-1 system with an accept rate of $\sim$ 750 kHz. Both collaborations plan on a recording rate of about 10 kHz. Other upgrades are also planned. Details of these “Phase-II” upgrades are provided elsewhere in these proceedings [4, 5]. In some cases these build on “Phase-I” upgrades that are currently being pursued by both experiments, for installation in 2019–2020, prior to Run-3 of the LHC.

The large data sample to be collected at the HL-LHC will allow more detailed studies of physics topics already investigated during the nominal LHC experimental program, as well as sensitivity to processes that are inaccessible with the anticipated 300 fb^{-1} dataset collected prior to the HL-LHC, in particular di-Higgs production which provides information on the Higgs self-coupling.

Full simulation studies of all interesting physics channels are not feasible, so the experiments have adopted less resource-intensive methods for estimating the performance expected at the HL-LHC. The main method used by ATLAS is to parametrize the detector performance based on full simulations and apply these parametrizations (see e.g. reference [6]) to generator-level studies of the physics processes of interest. Another solution, the main one adopted by CMS [7], is to extrapolate Run-1 analyses to higher luminosity and energy, under the assumption that techniques will be developed to maintain the current level of performance for object reconstruction in the harsher conditions at the HL-LHC. CMS employs two different scenarios for the scaling of systematic uncertainties. In Scenario 1, the uncertainites are assumed to be the same as for Run-1. In Scenario 2, a slightly more optimistic approach is taken, in which the theoretical uncertainties are scaled by a factor of 1/2 and the other systematics are assumed to scale with the inverse square-root of the ratio of integrated luminosities. Most of the available studies assume $\mu = 140$, but some updates for higher pileup of $\mu = 200$ were done as part of the detector scoping exercises undertaken by the experiments in 2015 [8, 9]. Only the more recent studies have explored the improvements expected from the high-$|\eta|$ inner-tracker extensions proposed by both experiments.

2. Higgs Physics

The current status of our understanding of the Higgs boson is summarized elsewhere in these proceedings [10, 11] for Run-1 and Run-2, respectively, and [12] in the case of BSM Higgs bosons.

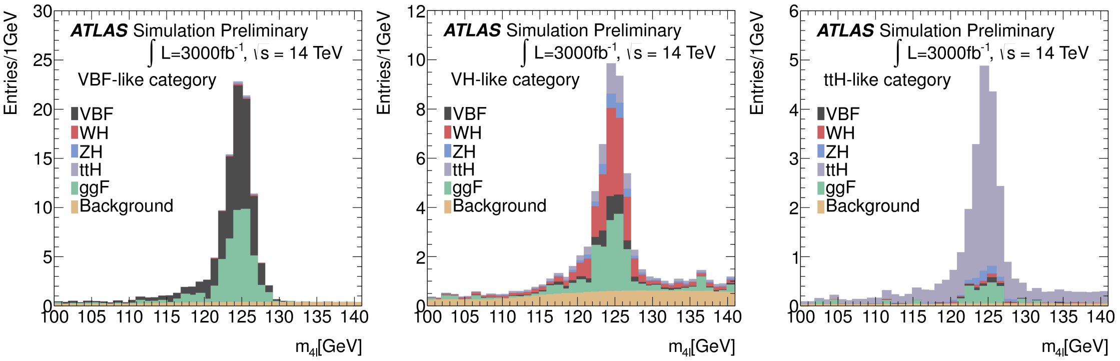

Figure 1: The expected signals in the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ final state for ATLAS, at the HL-LHC, for selections targeting the VBF, VH and $t\bar{t}H$ production modes [13]. These result do not include improvements expected due to the proposed increased η coverage of the Phase-II tracker.

In this contribution, only the SM Higgs boson will be considered. In what follows, the expected sensitivity in the various production modes is discussed, under the assumption of 3000 fb^{-1} at 14 TeV. The dominant ggF and VBF modes are already being explored using Run-1 and Run-2 data, but the lower cross section associated production modes, VH ($V = W,Z$) and $t\bar{t}H$, will require much larger data samples.

2.1 Higgs boson production and decay modes

$\boldsymbol{H \rightarrow ZZ^{(*)} \rightarrow 4\ell}$: This "golden" decay mode remains golden at the HL-LHC. It allows the reconstruction of a narrow signal over a relatively low background so is important for the Higgs mass determination. The available statistics at the HL-LHC are expected to make it possible to obtain differential cross-sections in all production modes. For ATLAS, the expected signals [13] in the lower-statistics VBF, VH and $t\bar{t}H$ production modes are shown in Figure 1. ATLAS [13] and CMS [7] each project better than 10% precision on the inclusive signal strength in this channel, based on studies assuming $\mu = 140$. ATLAS has recently updated its analysis of VBF production of this final state [8] and shown that the performance for this mode can be maintained for $\mu = 200$.

This channel provides a useful illustration of the need for detector upgrades for the HL-LHC. As stated, both ATLAS and CMS plan for full replacement of their inner tracking systems. These all-silicon trackers would have increased granularity and reduced material budget, relative to the trackers they replace. Both experiments are considering coverage out as far as $|\eta| = 4.0$, which would provide for both increased acceptance and better pileup suppression. The existing ATLAS and CMS trackers were not designed for operation at HL-LHC luminosities. This is nicely illustrated for the CMS detector in Figure 2 (left), which compares the $H \rightarrow ZZ^{(*)} \rightarrow 4\ell$ invariant mass distributions obtained with their Phase-II tracker, to what would be obtained using their Phase-I tracker after accumulation of 1000 fb^{-1} of data under HL-LHC conditions. A noticeably reduced response is visible for the degraded Phase-I tracker. The plot on the right of Figure 2 illustrates the increase in signal acceptance achievable for a number of different tracker coverages [14].

HL-LHC performance studies using this channel have also been done for analyses focussed on other Higgs boson properties. Interference between signal and background makes a comparison of on- and off-shell couplings sensitive to the Higgs boson width Γ_H. This technique has been used in Run-1 analysis by both collaborations [15, 16]. The ATLAS projections for the performance of this technique with the full HL-LHC data sample yield a sensitivity corresponding to a SM Higgs boson width measurement of $4.2^{+1.5}_{-2.1}$ MeV [17]. CP properties and investigations of the tensor structure of the Higgs coupling to vector bosons have also been explored [18].

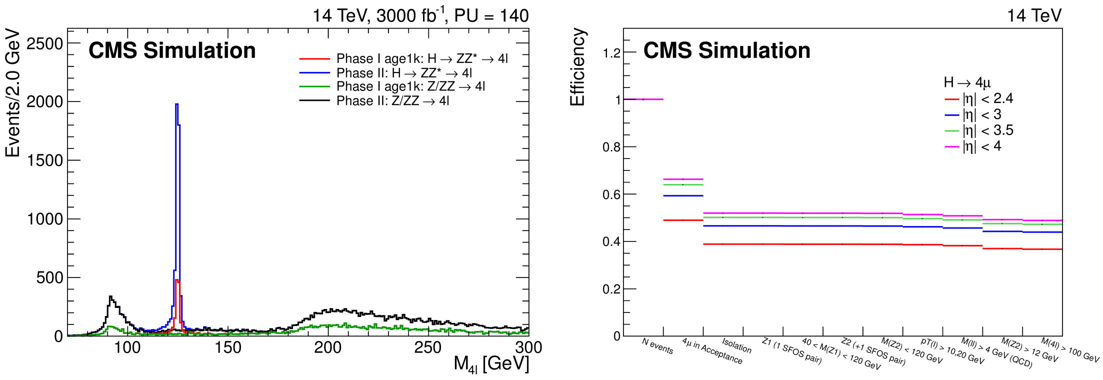

Figure 2: Left: The projected invariant mass distribution for the signal and main background in the $H \to ZZ^{(*)} \to 4\ell$ final state, for the CMS Phase-II tracker (blue) and the CMS Phase-I tracker aged by 1000 fb^{-1} of running at the HL-LHC. Right: the cutflow for the corresponding signal selection, in the 4μ final state, for various choices of the Phase-II tracker coverage, illustrating the associated acceptance gains [14].

$H \to \gamma\gamma$: This final state also provides for a narrow signal and is thus useful for studies of all production modes. ATLAS has investigated the dominant ggF and VBF production modes [13] via a selection that divides events into categories with exactly zero, one or two jets in the event, with the final category being dominated by VBF production. Investigations of the associated production modes [19] additionally classify events according to the numbers of leptons and b-tags. $\mathscr{O}(100)$ events will be obtained in these channels, with signal significance of 8.2σ for $t\bar{t}H$ and around 4σ for the VH production modes. ATLAS projects a signal strength precision about 9% inclusively and of 17–28% for non-ggF modes. Inclusively, CMS projects a precision of 4/8% in their Scenario 2/1 [7].

$H \to WW^{(*)} \to \ell\nu\ell\nu$: This is one of the benchmark channels from the Run-1 analyses, compensating for the poor mass resolution with a high branching fraction. For the HL-LHC, ATLAS has investigated the ggF and VBF production modes for $\mu = 140$ resulting in a projected signal-strength sensitivity of about 15% for both modes, and a combined sensitivity of about 10% [13]. The VBF production mode was revisited for $\mu = 200$ in 2015 [8], demonstrating that the performance achieved at $\mu = 140$ can be maintined in the higher pileup environment. CMS projects an inclusive signal-strength sensitivity of 4/7% in Scenario 2/1 [7].

$H \to b\bar{b}$: This final state can be investigated in the associated production mode, via leptonic decays of the associated vector boson, with the leptons being used for triggering and background suppression. Here, based on extrapolation of an 8 TeV analysis, ATLAS projects an 8.8σ observation, with a 14% precision on the signal strength [13]. CMS projects 5/7% precision on the signal strength, in Scenario 2/1 [7].

$H \rightarrow \tau\tau$: This final state has been investigated primarily in the VBF mode, where the forward jets can be used to tag the event. This analysis relies on good pileup suppression in the forward region and good $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution, both of which are improved in the case where the tracker coverage is extended out to $|\eta| = 4$ [14]. The expected improvements in the signal acceptance are illustrated for ATLAS and CMS in Figure 3, for different tracker upgrade scenarios. ATLAS has studied the performance for this channel for different coverages of its Phase-II tracker, and expects to measure the signal strength with a precision of 8% in the case where this extends to $|\eta| = 4.0$ [20]. CMS projects a sensitivity of 5/8% in Scenario 2/1 [7]; that study did not assume an extended tracker.

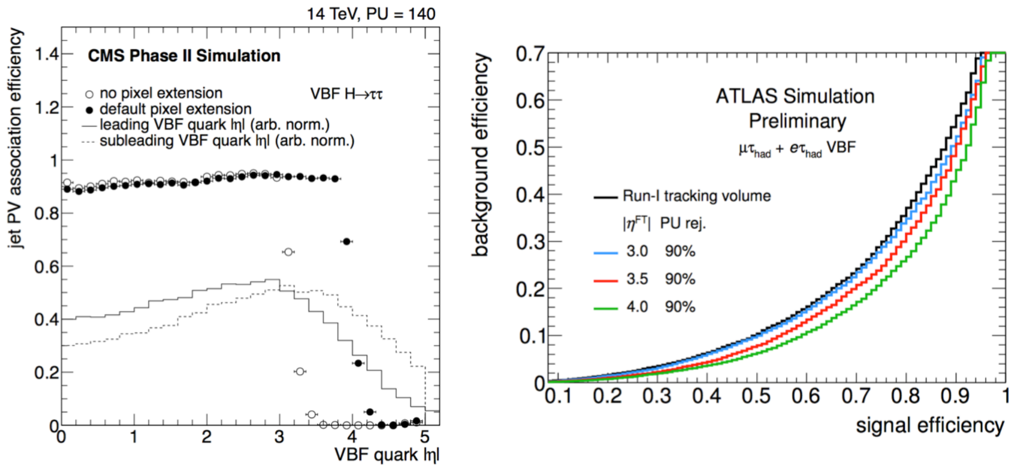

Figure 3: Left: The primary vertex association probability for VBF $H \rightarrow \tau\tau$ jets in the upgraded CMS Phase-II detector, for two different tracker coverages [14]. Right: for ATLAS, the background efficicency vs. signal efficiency for VBF $H \rightarrow \tau\tau$ events for different assumptions on the coverage of the upgraded tracker and the level of achievable pileup (PU) rejection [20].

$H \rightarrow \mu\mu$: This final state is accessible only with the very large statistics expected at the HL-LHC and allows determination of the Higgs coupling to second-generation fermions. The clean final state yields a narrow mass resolution and so will also contribute to the precision determination of the Higgs mass. For CMS, the expected mass resolution is shown on the left of Figure 4 which again illustrates the need for a tracker upgrade, by indicating the achieved resolution relative to what would be expected with the Phase-I detector for $\mu = 50$ and at the HL-LHC after 1000 fb^{-1} of data-taking. The improvements over the undegraded Phase-I detector are attributable to the higher granularity and reduced material budget. The right-hand plot shows the expected background-subtracted signal for ATLAS. Based on this, ATLAS projects a 7σ measurement of the inclusive signal and about a 20% determination of the signal strength [13]. This study does not exploit the expected improvements associated with the planned ATLAS inner tracker upgrade. From their inclusive analysis, CMS projects 5% precision on the Higgs coupling to muons [14]. ATLAS has also investigated this final state in the $t\bar{t}H$ production mode, in which a signal of 33 events is expected over a background of 22 [13].

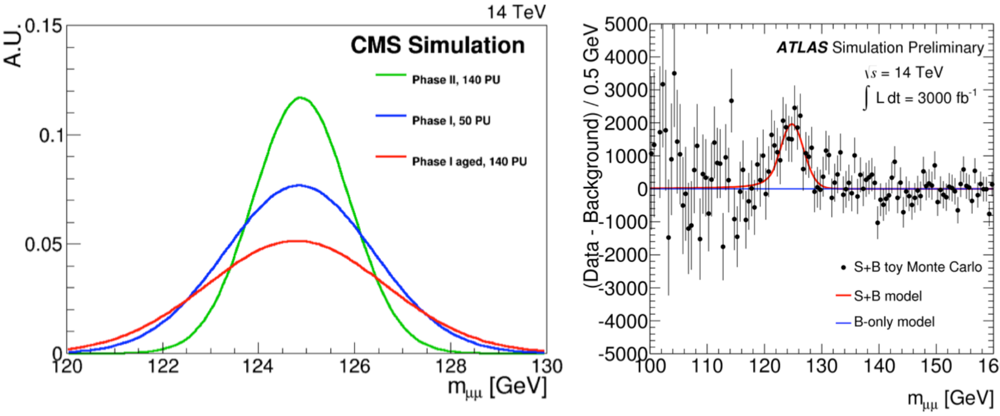

Figure 4: Left: the expected $\mu\mu$ invariant mass distributed for the CMS Phase-II tracker (green) compared that expected from the Phase-I tracker (blue) and the Phase-I tracker degraded by 1000 fb^{-1} of HL-LHC running [14]. Right: the ATLAS background-subtracted $H \to \mu\mu$ signal at the HL-LHC [13].

2.2 Rare Higgs Decays

Other rarer decay modes are expected to be investigated with the larger event samples available at the HL-LHC. In particular, both ATLAS [13] and CMS [7] have investigated the process $H \to Z\gamma$ which proceeds via loops, so may be sensitive to the existence of new heavy states. ATLAS projects about a 30% determination of the signal strength in this final state, while CMS expects 20%/24% in Scenario 2/1.

ATLAS has also investigated the $H \to J/\Psi\gamma$ decay, which would give access to the coupling to second-generation quarks. However, only limits are currently anticipated in this final state [21].

2.3 Higgs Couplings

The set of signal strength measurements made in the various production and decay modes can be used to extract information on the Higgs boson couplings, or alternatively on the ratios of these couplings; the latter require no assumptions on the Higgs total width, and allow for the cancellation of some experimental and theoretical systematic uncertainties. Both ATLAS and CMS employ fits following the recommedations of the LHC Higgs Cross Section working group as described in reference [22]. Projected sensitivities for both experiments are illustrated in Figure 5. For CMS, the Run-1 results for the couplings to bosons and fermions are compared to those projected for the HL-LHC, in each case as a function of the boson or fermion mass [14]. The expected improvements at the HL-LHC are evident. The plot on the right shows the ATLAS projections [13] for the precision on the ratios of couplings, $\Delta\lambda_{XY}$ which are defined in terms of the coupling strength modifiers (which scale the SM couplings in the fit) for the two decays in the ratio. These are shown for both the 300 fb^{-1} dataset expected following LHC Run-3 (light band), and the 3000 fb^{-1} sample expected at the HL-LHC (dark band). In each case the hashed areas indicate the increase of the estimated error due to theoretical uncertainties. The ratios shown in the plot are with respect to the coupling to the Z boson, and vary in the range of 3–14%.

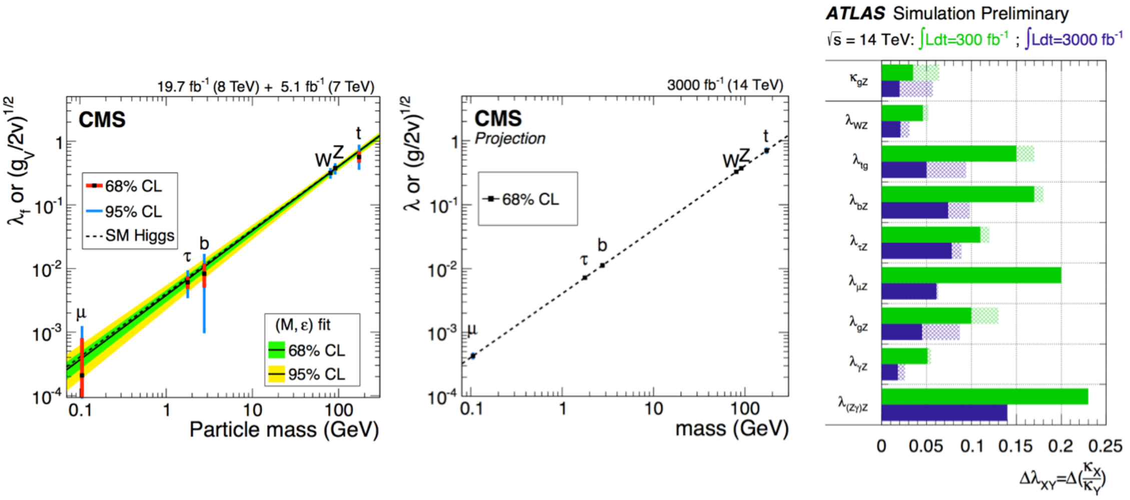

Figure 5: Left: CMS results [14] for Run-1 Higgs coupling measurements and corresponding projections at the HL-LHC. Right: ATLAS projections [13] for the ratios of coupling strengths.

3. Higgs pair production

Higgs pair production is a very important part of the HL-LHC experimental program, as this final state allows for investigations of the Higgs self-coupling, λ_{HHH}, which is related to the form of the Higgs potential. The production is dominantly via ggF; two diagrams contribute at lowest order, only one of which involves λ_{HHH}, and these interfere destructively to reduce the cross-section to about 41 fb assuming the SM value for λ_{HHH}. For a data sample of 3000 fb^{-1}, the expected yields in the available final states range from 1 in the case of $\gamma\gamma\gamma\gamma$ to about 41,000 for $b\bar{b}b\bar{b}$. Experimentally, the two most promising modes are $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau\tau$ with expected yields of 330 and 9000 events, respectively. These final states have been investigated by both ATLAS and CMS. For $b\bar{b}\gamma\gamma$ the $m_{\gamma\gamma}$ distribution is narrow, while that for $m_{b\bar{b}}$ is broad. For its projections, ATLAS [23] uses a cut-and-count analysis, while CMS [14] employs a 2D fit to ($m_{\gamma\gamma}$, $m_{b\bar{b}}$). Figure 6 shows the $m_{\gamma\gamma}$ distribution from the ATLAS analysis on the left, and the projection of the CMS fit onto the $m_{\gamma\gamma}$ axis on the right. The projected signal significances are 1.3σ for ATLAS and 1.6σ for CMS. For $b\bar{b}\tau\tau$, ATLAS has studied the $\tau_h\tau_h$, $\tau_h\tau_\ell$, and $\tau_\ell\tau_\ell$ final states ($\ell = e, \mu$) while CMS focuses on $\tau_h\tau_h$ and $\tau_h\tau_\mu$. Both experiments project significances that are somewhat lower than those achieved in the $b\bar{b}\gamma\gamma$ final state: 0.6σ for ATLAS [24] and 0.9σ for CMS [14].

4. Vector Boson Scattering

Investigations of vector boson scattering (VBS) play an important part in tests of the Higgs sector of the Standard Model, since the Higgs boson is responsible for regularizing the cross-section for longitudinal vector boson scattering $\sigma(V_LV_L \to V_LV_L)$. There are both strong and electroweak contributions to this process, and the same-sign channel is normally used since in this case the strong component does not dominate. Both ATLAS [25] and CMS [26] have searched for same-sign WW scattering in Run-1 data, in final states with two same-sign leptons (e,μ), two forward jets, and moderate missing transverse energy. The ATLAS results provided evidence for the EW process

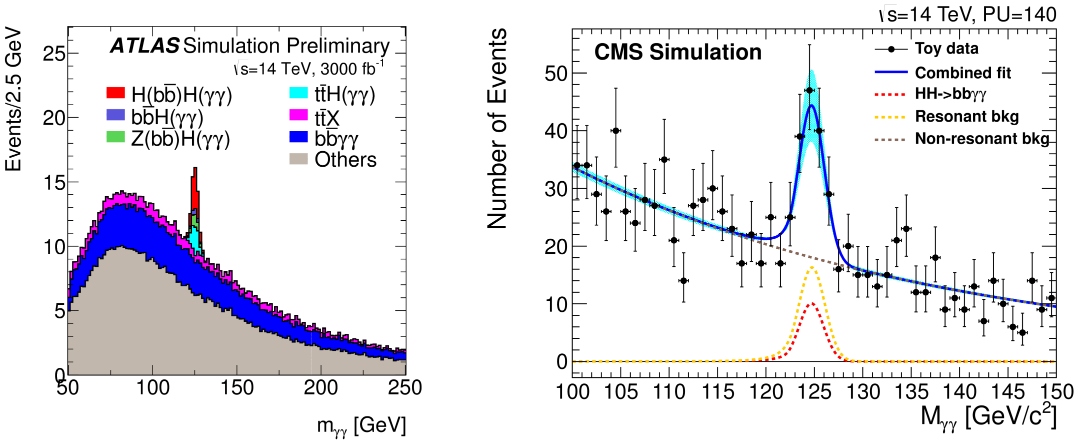

Figure 6: The plot on the left shows the ATLAS $m_{\gamma\gamma}$ distribution from the $b\bar{b}\gamma\gamma$ final state for di-Higgs production [23]. The plot on the right shows the projection of the CMS 2D fit (for the same final state) onto the $m_{\gamma\gamma}$ axis [14].

with about 3σ significance. The expected performance at the HL-LHC is sensitive to performance improvements from the increased tracker acceptance, due to both an increased acceptance for the leptons and improved pileup suppression. HL-LHC projections from ATLAS and CMS studies are shown in Figure 7. The plot on the left shows an ATLAS projection for the "reference" Phase-II upgrade detector described in the ATLAS Phase-II Scoping Document [8], for $\mu = 200$. The reference detector includes an upgraded tracker with coverage over the region $|\eta| < 4.0$. The plot shows the η distribution of the leading jet, and illustrates both the signal and background contributions. The other two plots show results from a CMS study [14] for $\mu = 140$, for a Phase-II detector with tracker coverage out to $|\eta| = 4.0$ and a new high-granularity forward calorimeter. The middle plot shows the $\Delta\eta_{jj}$ distribution from that analysis, prior to a selection cut applied to that quantity, while the one on the right shows the distribution of the invariant mass of the dilepton system, after the full selection, for the SM and for a scenario with enhanced anomalous couplings, i.e. in which the Higgs is not solely responsible for unitarization of $\sigma(V_L V_L \to V_L V_L)$, illustrating the expected sensitivity to such models.

5. B-physics

In the SM, the process $B_s^0 \to \mu\mu$ is highly suppressed, with a braching ratio of order 10^{-9}, while the process $B^0 \to \mu\mu$ is predicted to have a branching ratio 30 times smaller. The CMS experiment has measured the B_s^0 branching ratio with Run-1 data [27] and has also published a combined result [28] with the LHCb experiment (see Figure 8), resulting in measurements of $BR(B_s^0 \to \mu\mu) = 2.8^{+0.7}_{-0.8} \times 10^{-9}$, which is consistent with the SM prediction and $BR(B^0 \to \mu\mu) = 3.9^{+1.6}_{-1.4} \times 10^{-10}$ which is higher than predicted but has large uncertainties. The latter measurement corresponds to a 3.2σ observation of this decay. Somewhat lower results for both branching ratios have been reported by ATLAS [29]. With the data sample anticipated from the HL-LHC, both of these braching ratios will be well measured, with the significance of the CMS $B^0 \to \mu\mu$ signal pro-

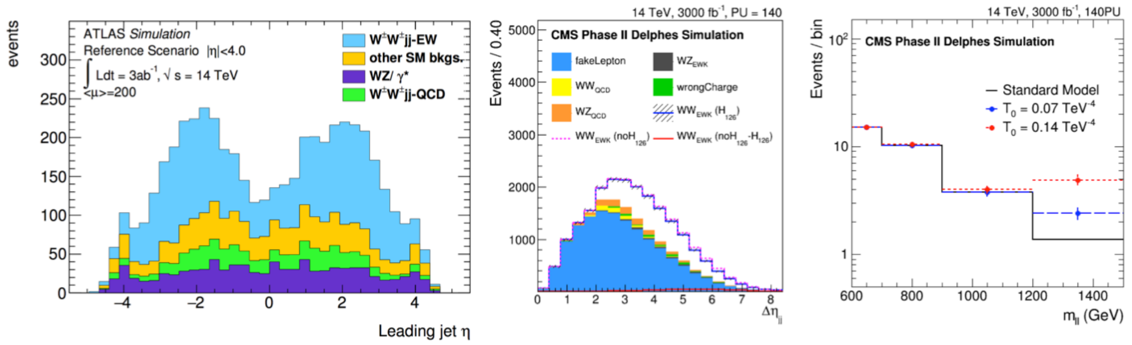

Figure 7: ATLAS [8] and CMS [14] projections for $W^{\pm}W^{\pm}$ VBS analyses at the HL-LHC.

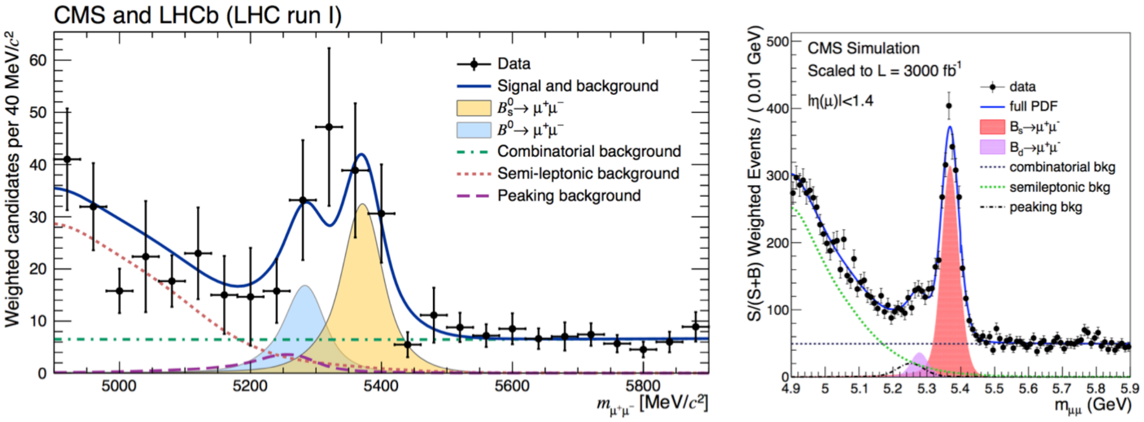

Figure 8: Left: the combined CMS+LHCb measurement of the processes $B_s^0/B^0 \to \mu\mu$, based on Run-1 data [28]. Right: the projected $\mu\mu$ invariant mass distribution from CMS, for 3000 fb^{-1} of HL-LHC data [9].

jected to reach about 7σ [9]. The anticipated invariant mass distribution from CMS is also shown in Figure 8.

6. Top quark physics

CMS has investigated a number of topics in top-quark physics at the HL-LHC, including searches for flavour changing neutral currents (FCNC) and the expected precision on the top-quark mass. Both topics are described briefly below.

FCNC decays of top quarks have been searched for in the mode $t\bar{t} \to (Wb)(Zq)$. In the SM, the $t \to Zq$ branching ratio is expected to be of order 10^{-14} [30]. However, in some BSM models [31, 32, 33] it can reach values up to about 10^{-4}. Both CMS [34] and ATLAS [35] have searched for this in Run-1 data, with the best limit of 5×10^{-4} (for 9×10^{-4} expected) coming from CMS. CMS has investigated the expected sensitivity to this process at the HL-LHC and projects a 95% CL limit of about 10^{-4} [36].

For future investigations of the top quark mass, CMS has studied the systematic uncertainties associated with a number of different methods for extracting this from the data, including conventional techniques involving kinematic reconstruction, endpoint methods, the J/Ψ method and the L_{xy} method, in each case to determine the precision achievable with specific projected data samples. The results of these studies are displayed in Figure 9 [37]. For the anticipated HL-LHC dataset, using standard techniques, this precision is expected to reach about 200 MeV.

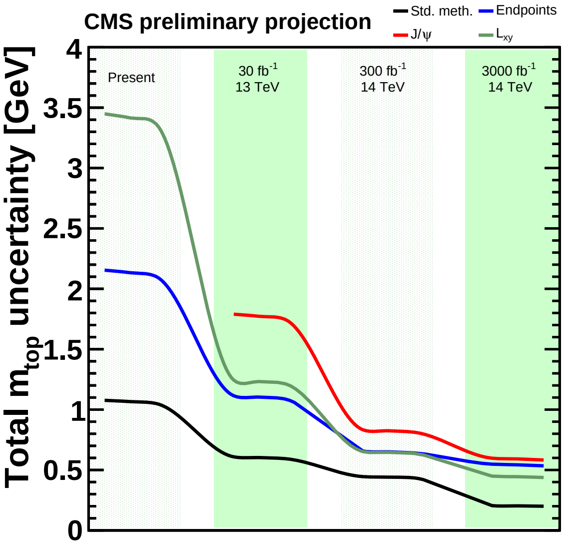

Figure 9: The precision on the top-quark mass determination expected from CMS, using a variety of analysis techniques, for datasets corresponding to integrated luminosities of 30, 300 and 3000 fb^{-1} [37].

7. Summary

Studies of the physics performance that can be expected from ATLAS and CMS at the HL-LHC began in earnest as part of the European Strategy discussions in 2012, that ultimately identified the full exploitation of the LHC, including the high-luminosity phase, as the highest-priority of European particle physics for the coming two decades. These performance studies have continued, and been refined, through the 2013 Snowmass process, the EFCA HL-LHC workshops in 2013 and 2014, and then the detector scoping exercises undertaken by both experiments in 2015. Initial studies were mainly done for an instantaneous luminosity of $5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ corresponding to $\mu = 140$. For the Phase-II detector scoping exercises the experiments were asked to assume a maximum instantanous luminosity of $7.5 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ corresponding to $\mu = 200$. Some selected analyses have been re-investigated for these higher pileup conditions, and additional studies are being pursued in advance of the ECFA 2016 workshop in the fall of 2016. Further studies will be undertaken once ATLAS and CMS have fully defined their Phase-II detector configurations.

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