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Upgrade of ATLAS and CMS for High Luminosity LHC: Detector performance and Physics potential

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Summary. — The High Luminosity Large Hadron Collider (HL-LHC) is expected to start providing proton-proton collisions by 2026. In the following 10 years it will deliver about $3000\,\mathrm{fb}^{-1}$ of integrated luminosity, more than a factor 10 of the data that will be collected by the end of Run3 at LHC in 2023. For such amount of data, an instantaneous luminosity of $\sim 7.5 \times 10^{34}\,\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ is needed. At this luminosity an unprecedented average number of pile-up collision per bunch crossing of 200 is expected. The ATLAS and CMS detectors will be upgraded to fully exploit the HL-LHC potential in this harsh environment. In this document the performances of the ATLAS and CMS upgraded detectors will be described. Their impact on crucial measurements of the Higgs boson sector, of the vector boson fusion process and on new physics searches, will be reported as well.

1. – Introduction

There are strong physics motivations to upgrade the LHC to the HL-LHC. The huge amount of data provided by HL-LHC will be crucial to improve the knowledge of the Higgs boson sector. Details can be found in [1-3]. After Run1, the Higgs couplings were measured with a precision of $\sim 20\%$ [4]. Using the expected integrated luminosity of $3000\,\mathrm{fb}^{-1}$, this precision can be improved down to $< 5\%$. Distinguishing the different Higgs boson production measurements (gluon-gluon fusion, Vector Boson Fusion (VBF), WH, ZH, $t\bar{t}H$ processes) is an important part of understanding electroweak symmetry breaking and will be not be fully realized by the end of Run3. Using $3000\,\mathrm{fb}^{-1}$ all production modes can be observed for ZZ, $\gamma\gamma$ and WW final states. Access to very rare Higgs boson decays will became possible: the decay of $H \rightarrow \mu\mu$ can be observed with a significance of $5{-}7\sigma$, while with the $300\,\mathrm{fb}^{-1}$ expected by the end of Run3, only a significance of 3σ is expected. The vector boson scattering, a key process to probe the nature of electroweak symmetry breaking, is of highest priority for the HL-LHC program. Its amplitude violates unitarity at center-of-mass energy around 1 TeV in the absence of a Standard Model (SM) Higgs boson thus providing a strong test of the Standard Model.

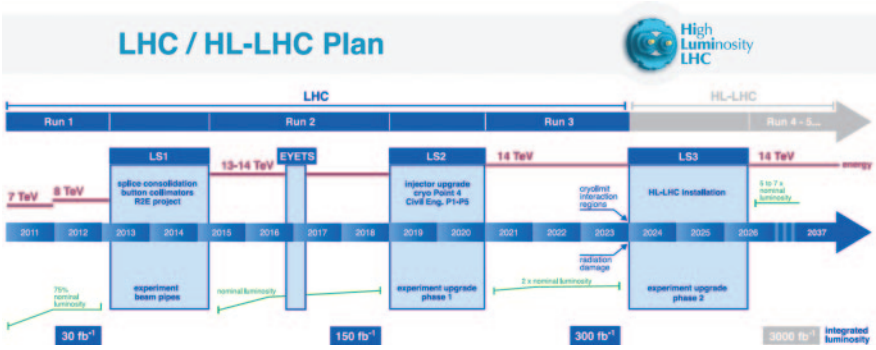

Fig. 1. – High Luminosity LHC plan beyond 2015.

However new physics processes could also contribute to stabilize the amplitude and the sensitivity to them is strong enhanced from 300 fb^{-1} to 3000 fb^{-1}. The mass reach of new particles can also be improved using higher statistics, especially for electroweak processes. In SUSY, the mass reach of the χ_1^+ and χ_2^0 neutralinos produced can be improved by 50–100% from 300 fb^{-1} to 3000 fb^{-1} [5,6].

The schedule for the upgrades to the LHC accelerator complex, leading to the HL-LHC, is shown in fig. 1. The complete accelerator and detector upgrades are expected to be progressively installed during the next two major shutdowns of the accelerator complex, defined as LS2 (currently scheduled to take place in 2019–2020 and to last for 24 months) and LS3 (currently scheduled to take place in 2024–2026 and to last for 30 months). During these periods Phase 1 and 2 experiment upgrades will be realized, respectively.

2. – Detectors performances at HL-LHC

The high luminosity needed for the large amount of data is delivered by HL-LHC at the cost of producing many additional pp pile-up interactions per bunch crossing (μ). About 200 pile-up collisions are expected at the HL-LHC, to be compared with $\sim$ 20 during Run1 and in 2015. In such harsh environment the detectors want to maintain low trigger thresholds, efficient reconstruction for hadronic objects (jets, taus) and leptons.

To face these requirements in a high pile-up environment, the main upgrades of the ATLAS and CMS detectors are:

- track trigger at the trigger Level 1 (L1)
- new forward calorimetry to face a factor 10 more radiation, with higher granularity
- new tracker to face a factor 10 more radiation, with higher angular coverage up to $|\eta| <4$.

More details can be found in [7,8].

With tracks available at L1, vertices can be reconstructed. Through the association of tracks to the primary vertex at L1, powerful pile-up suppression can be obtained for muons, electrons, jets, tau and Missing Transverse Energy (MET). In fig. 2, left, the trigger rate as a function of the VBF $H \to \tau\tau$ signal efficiency for a single τ selection is

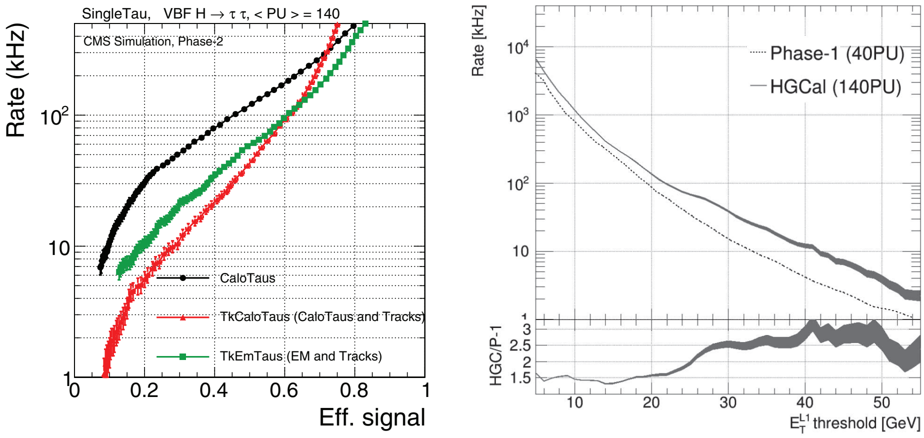

Fig. 2. – Left: the trigger rate *vs.* VBF $H \to \tau\tau$ signal efficiency for a single τ selection. Right: comparison of rates between the Phase 1 electromagnetic object trigger with 40 pile-up interactions per bunch crossing, and the HGC with a mean of 140 pile-up interactions per crossing.

shown. The use of tracks (red and green curves) clearly shows a strong rate reduction at the same signal efficiency.

Forward calorimetry will be upgraded as well. In CMS a new High Granularity sampling calorimeter (HGC) with high transverse and longitudinal granularity in the region $1.5 < |\eta| < 3$ is expected to allow separation of signal and pile-up particles. Therefore a better reconstruction of electron, photon, jets can be achieved. In fig. 2, right, the Level 1 single electromagnetic trigger rate is only 1.5 times higher for thresholds up to 20 GeV, and 2.5 times higher for thresholds up to 30 GeV, despite the increase in the instantaneous luminosity by a factor of 3.5. In ATLAS a new Forward Calorimeter in the region $3.1 < |\eta| < 4.9$ has been proposed to prevent over-heating (even local boiling) in the liquid argon due to large energy deposits expected in the detector because of the very high instantaneous luminosity. The new forward calorimeter will have a factor 4 higher granularity to improve pile-up suppression and jet-substructure visibility. Timing capabilities for the calorimeters upgrades are being considered at ATLAS and CMS to provide both pile-up suppression at Level 0 trigger where tracking is not available and pile-up suppression of neutral particles at the higher level trigger.

The replacement of the tracker will be a major upgrade both for ATLAS and CMS detectors. The availability of tracks in the forward region enables powerful pile-up suppression techniques based on the association of tracks to the primary vertex. This is specially crucial for measurement of forward jets and MET, whose reconstruction is strongly deteriorated at high pile-up conditions. In fig. 3, left, the number of pile-up jets is shown to be strongly reduced using track-based pile-up suppression techniques in the current $|\eta| < 2.5$ tracker acceptance (red line). If this latter is extended up to $|\eta| < 3.2$ and $|\eta| < 4.0$ (blue and black lines) forward jets can be efficiently suppressed as well. The suppression of pile-up jets using track information can be exploited in the MET reconstruction. In fig. 3, right, the MET resolution as a function of the total energy in the event is shown for simulated $t\bar{t}$ events. A clear gain is observed extending the tracker acceptance up to $|\eta| < 4$.

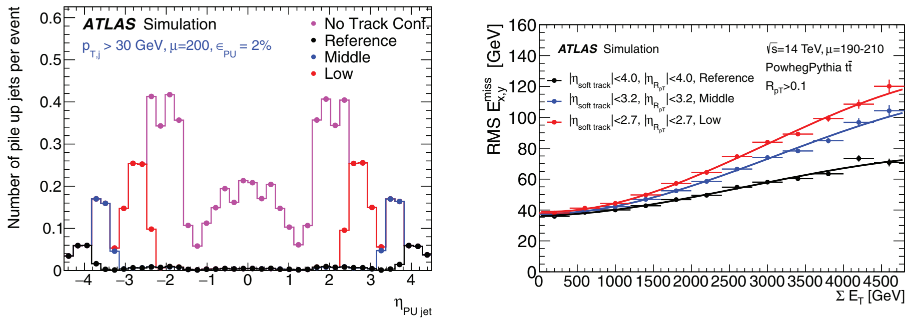

Fig. 3. – Left: Distribution of the number of pile-up jets per event with no tracking confirmation (TC), and applying the TC algorithm tuned to give 2% pile-up jet acceptance, for three different tracker acceptances. Right: The resolutions of the x and y components of MET in $t\bar{t}$ events with $\mu = 200$ as a function of the scalar sum of total energy in the event, for three different tracker acceptances

3. – Physics potential of HL-LHC

Studies on the physics performances with the HL-LHC detectors have been performed in different simulation scenarios. For the CMS upgrades studies [7], these scenarios are considered:

1. Phase 1 detector with $\mu = 50$ with new pixel layer for Run 2.
2. Phase 1 detector aged at $\mu = 140$ with modeling for the radiation damage after exposure to $1000\,\text{fb}^{-1}$ for outer tracker and the hadronic and electromagnetic calorimeters.
3. Phase 2 detector at $\mu = 140$.

For the ATLAS upgrades studies [8] these scenarios are considered:

1. Reference Scenario: tracker up to $|\eta| < 4$, muon tagger at high $|\eta|$.
2. Middle Scenario: tracker up to $|\eta| < 3.2$ with less disks.
3. Low Scenario: tracker up to $|\eta| < 2.4$ with less disks/pixels.

The $W^{\pm}W^{\pm}$-electroweak scattering process with two same charge leptons in the final states has been studied. In ATLAS a factor ~ 2 of improvement in the sensitivity has been gained from the Low to the Reference scenario. The gain is driven by the larger coverage for 3rd lepton veto and the reduction of events with pile-up jets from 27% to 17% with extended coverage of tracker up to $|\eta| < 4$. In CMS the High-granularity forward calorimeter and the tracker extension are essential to tag efficiency the forward jets in the final state in the high pile-up environment. Figure 4, left, shows that the upgraded detector is expected to recover the performances of the phase 1 detector.

VBF production of the Higgs boson is a clear benchmark for the upgraded detectors performance. In ATLAS an improvement of ~ 2 on the measurement of the VBF $H \to WW^{(*)} \to l\nu l\nu$ cross section is obtained from the Low to the Reference scenario due to the better pile-up rejection and b-tagging. In CMS the VBF $H \to \tau\tau$ channel has been considered. Using the track-based L1 trigger, the acceptance is improved by a

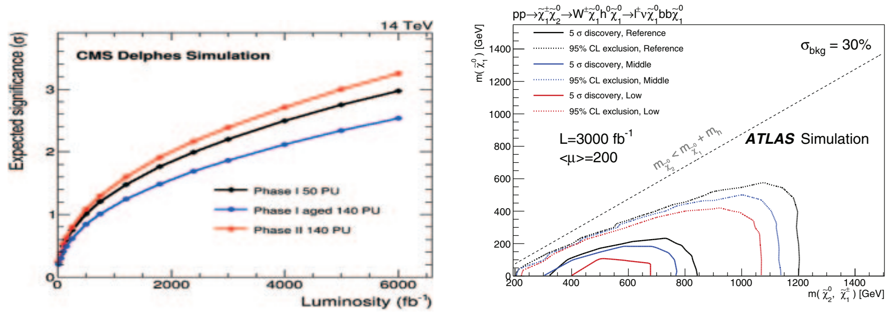

Fig. 4. – Left: the expected significance for the discovery of the longitudinal same-sign WW scattering after $3000\,\mathrm{fb}^{-1}$ of integrated luminosity as a function of the integrated luminosity. Right: Discovery contour and exclusion limits for the $3000\,\mathrm{fb}^{-1}$ data-set in the χ_2^0, $\chi_1^\pm$ and χ_1^0 mass plane.

factor ~ 5. The measurement of the inclusive $H \to ZZ^{(*)} \to 4l$ cross section has been also considered. The uncertainty is expected to be reduced by $\sim 20\%$, both at ATLAS and CMS, thanks to the extended acceptance of the tracker and muon system, as well as to the improved mass resolution, from the reduction of material and better spatial resolution of the tracker. Performance of the upgraded detectors for the discovery of new physics has also been addressed. In ATLAS, the electroweak production of a wino-like χ_1^+ and wino-like χ_2^0 with a subsequent decay into a W and a SM-like Higgs boson has been considered. Thanks to the better resolution for MET with the forward tracker up to $|\eta| < 4$, the mass reach is expected to increase from 675 to 850 GeV from the Low to the Reference Scenario (fig. 4, right).

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