PROCEEDINGS OF SCIENCE

ATLAS: HL-LHC Upgrades and B-Physics Measurements

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The excellent performance of the Large Hadron Collider (LHC) at CERN has successfully pushed the boundaries of particle physics for over two decades. The High-Luminosity LHC is a new major upgrade that will offer a peak instantaneous luminosity of up to 7.5×10^{34} cm^{-2}s^{-1}. The upgrade will substantially increase the statistics available to the experiments for advancing the theories of particle physics. The HL-LHC is expected to start operating in 2026 and in twelve years should deliver up to 4000 fb^{-1}. The corresponding upgrades of the ATLAS detector regarding the ATLAS beauty physics program are discussed in this paper. As examples, preliminary results on the expected sensitivities for the search for CP-violation in the decay channel $B_s^0 \to J/\psi\phi$ using the parameters $\Delta\Gamma_s$ and ϕ_s are shown, among other selections.

BEAUTY2020
21-24 September 2020
Kashiwa, Japan (online)

[*] Speaker

https://pos.sissa.it/

PoS(BEAUTY2020)061

1. Introduction

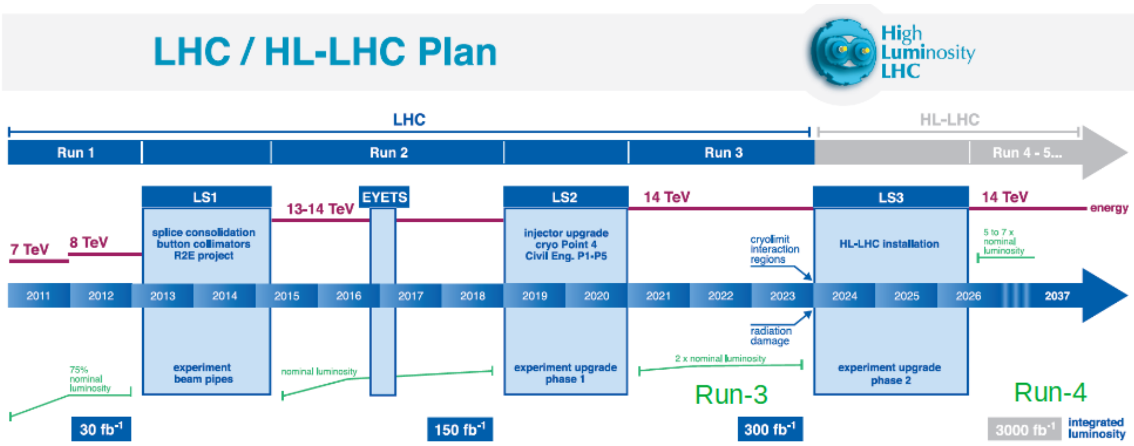

Figure 1: Upgrade program for the LHC accelerator complex [1]. The status of the past seven years and the plans for the next two decades are shown.

The Standard Model (SM) of particle physics describes a broad range of observations very well, but many open questions such as dark matter, the matter-antimatter asymmetry, neutrino masses or possible flavour anomalies are not easily described by the same framework. In order to extend the successful physics program at the LHC [2] to high precision studies and searches for new phenomena, substantially more data needs to be collected. The high-luminosity LHC (HL-LHC) aims to provide 3000 to 4000 fb^{-1} within approximately 12 years, which is more than 10 times the integrated luminosity of the LHC Runs 1-3 combined. The HL-LHC baseline parameters with a peak luminosity $\mathcal{L} \approx 5...7.5 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ and an average $\langle\mu\rangle \approx 140...200$ pp interactions every 25 ns considerably exceed the nominal LHC design parameters and present a challenge to the existing experiments.

2. ATLAS Upgrade Program

A major upgrade [3, 4] of the current ATLAS detector is planned [5] to cope with the harsher operational conditions, an outline of the timeline can be seen in figure 1. The ATLAS Inner Detector (ID) will be replaced by an all-silicon Inner Tracker (ITk). The new ITk pixel detector [6] consists of $\sim$ 13 m^2 silicon pixel modules with $\sim$ 580 million channels ($\sim$ 92 million now), organised into 5 barrel and 5 end-cap layers (with sub-rings) providing increased coverage up to $|\eta| = 4.0$ ($|\eta| = 2.5$ now). The innermost barrel layer is located at $R = 36$ mm from the beam axis and the pixel modules at the ends of the barrel layers are inclined to allow for lower incident angles of particles. The new ITk has a strip detector [7] that comprises of $\sim$ 160 m^2 of silicon strip detector modules in 4 cylindrical barrel and 6 end-cap rings, a total of $\sim$ 50 million channels as opposed to the present 6 million. Compared to the current ATLAS Inner Detector, the ITk features a reduced material budget that results in an improved tracking efficiency and better invariant mass resolution of reconstructed particles. During the phase-1 upgrade New Small Wheels (NSW) are inserted between the end-cap calorimeters and the end-cap toroid magnets in the ATLAS muon system. The NSW provide high-efficiency hits for a fast L1 trigger by Small strip Thin Gap Chambers (sTGC) and contribute to the precision measurement of muon tracks with MicroMegas (MM). Their coverage $1.3 < |\eta| < 2.7$ will reduce the rate of fake tracks in a high-radiation background region. During the phase-2 upgrade new inner barrel (BI) RPC chambers will be inserted as the innermost muon layer, increasing the L0 trigger acceptance × efficiency for reconstructed combined muons within $|\eta| < 1.05$ from 78% to 96%. Even in the "worst case" scenario with the other RPC stations running at reduced high voltage (due to aging effects) the trigger with the BI RPCs is expected to reach an acceptance × effeciency of 92% (instead of 57% to 75% without).

The phase-2 baseline design (seen in figure 2) of the ATLAS trigger and data acquisition (DAQ) system [8] consists of a L0 hardware trigger based on calorimeter and muon system information with an output rate of 1 MHz at 10 μs latency, an Event Filter combined with a Hardware Track Trigger (HTT) with software-based reconstruction on a large processor farm providing output at 10 kHz, as well as a new DAQ system based on the Front End LInk eXchange (FELIX) architecture common to all detector systems and a new storage handler. At L0, precision information from the muon system is available and a global event processor constructs refined physics objects ($e^{\pm}$, γ, τ, jet and E_T^{miss}). As an option which may also be exercised later, a dual L0/L1 trigger with hardware tracking (L1track) for additional pileup supression and with an increased L0/L1 output rate of 4 MHz at 10 μs latency is being considered.

All detector systems will upgrade their readout electronics to match the increased readout speeds.

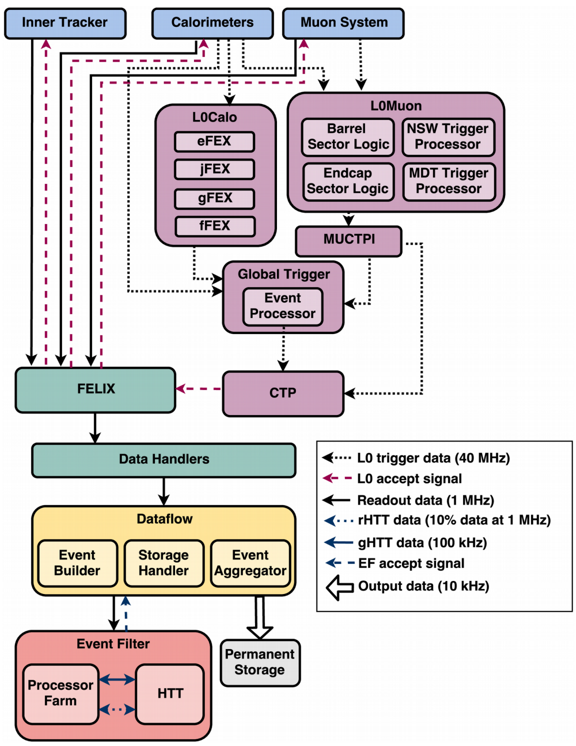

Figure 2: Diagram of the evolved TDAQ system in Phase-2 with a two-level hardware trigger [8].

3. ATLAS B-Physics Prospects at the High-Luminosity LHC

The ATLAS B-physics program at the HL-LHC encompasses precision measurements of $B_s^0 \to J/\psi\phi$ or $\Lambda_b^0 \to J/\psi\Lambda^0$ and rare processes like $B_s^0 \to \mu^+\mu^-$ to search for beyond-SM effects, the search for lepton flavor violation and test lepton flavor universality e.g. in $\tau \to 3\mu$, $B_s^0 \to e\mu$ or $B^0 \to K^{*0}e^+e^-/B^0 \to K^{*0}\mu^+\mu^-$, as well as heavy flavor production to test QCD predictions to study double parton scattering and to search for new or exotic states or decay modes.

The angular distributions in the decay $B_s^0 \to J/\psi\phi$ with $J/\psi \to \mu^+\mu^-$ and $\phi \to K^+K^-$ are sensitive to the CP-violating phase ϕ_s. The latest ATLAS result $\phi_s = -0.087 \pm 0.036$ (stat.) ± 0.021 (syst.) rad., based on 99.7 fb^{-1} of Run 2 and Run 1 data [9], agrees well with the SM and measurements by other experiments while there is still room for New Physics in CP-violation. The sensitivity to ϕ_s as well as to the B_s^0 decay width difference $\Delta\Gamma_s$ is improved considerably by the detector upgrades. As shown in figure 3 the addition of the Insertable B-Layer (IBL) [10] in Run 2 improved the proper decay time resolution σ_t by $\sim$ 30%.

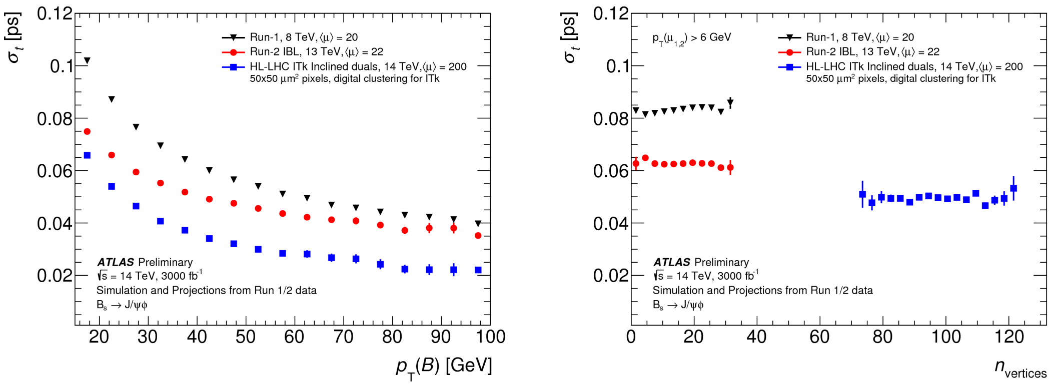

Figure 3: The average B_s^0 proper decay time resolution as a function of the transverse momentum p_T of the B_s^0-meson (*left*) and stability of the average B_s^0 proper decay time resolution against the number of reconstructed primary vertices (*right*) of simulated $B_s^0 \to J/\psi\phi$ decays, shown for ITk (blue), the Run 1 detector (black) and the Run 2 detector including the IBL (red), for their respective pile-up conditions [10].

A dedicated study [10] with dedicated MC signal samples with $\langle\mu\rangle = 200$ pile-up events and $\mathcal{L} = 7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ for an ITk layout with $50 \times 50\ \mu\text{m}^2$ pixels and the innermost pixel layers at $R = 39$ mm and 80 mm from the beamline shows further improvement, especially at higher $p_T\,(B_s^0)$. figure 3 *right* demonstrates the very good stability of proper decay time uncertainty (σ_t) as a function of the number of reconstructed vertices. The additional gain expected from the use of analogue instead of digital pixel clustering is not yet included. An earlier study [11] for ECFA 2013 with simulated signal MC events and fits to pseudo-experiments based on the Run 1 analysis strategy showed the statisical reach for an integrated luminositry of 3 000 fb^{-1} resulting in $\sigma(\phi_s) \sim 0.022$ rad. A later study indicates a further potential improvement of a factor 3 by the use of topological muon triggers which will allow for lower $p_T\,(\mu)$ trigger thresholds. The systematic uncertainties of various aspects of the analysis are expected to improve with increased statistics as well.

The branching fraction measurement [12] of the very rare decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$ that are sensitive to New Physics in the decays via loop diagrams will benefit from the increased statistics and the improved invariant mass resolution at the HL-LHC. The ATLAS Run 1 result is compatible with the SM at $\sim 2\sigma$ level and the $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ values are lower than the CMS-LHCb combined result. A study of the B_s^0 mass resolution with simulated $B_s^0 \to \mu^+\mu^-$ MC events for Run 2 conditions as in 2015 and for the HL-LHC with $\langle\mu\rangle = 200$ pileup events and $\mathcal{L} = 7 \times 10^{34}\text{cm}^{-2}\text{s}^{-1}$ for an ITk layout with $50 \times 50\mu\text{m}^2$ pixels covering $|\eta| < 4.0$ and applying an analysis strategy similar to the Run 1 analysis shows a considerable improvement. The separation of the B_s^0 and B_d^0 mass peaks increases by a factor of 1.65 (1.5) to 2.3σ (1.3σ) in the barrel (end-cap) region when compared to Run 1 [13].

The projection of the ATLAS detector performance can be seen in figure 4. This shows $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ with the expected datasets during the full LHC Run 2 (130 fb^{-1}) and at the HL-LHC (3 000 fb^{-1}) using pseudo-MC experiments that are based on the Run 1 analysis. Scale factors are applied for the integrated luminosity based on the signal estimates from Run-2 increasing the cross section due to the higher center-of-mass energy of 13 or 14 TeV. A selection of topological trigger scenerios are applied ($p_T(\mu_{1,2}) > 6$ GeV) or ($p_T(\mu_1) > 6$ GeV, $p_T(\mu_2) > 4$ GeV) resulting in 7 times the number of signal events in Run 1.

For the HL-LHC case three potential trigger scenarios are considered: two muons with $p_T > 10$ GeV ("conservative"), one muon $p_T > 10$ GeV and $p_T > 6$ GeV ("intermediate") as well as two muons with $p_T > 6$ GeV ("high yield") providing 15, 60 and 70 times the Run 1 statistics, respectively. The profile likelihood contours of pseudo- experiments based again on the likelihood of the Run 1 analysis demonstrate the increased sensitivity of the ATLAS detector for $\mathcal{B}(B_s^0 \to \mu^+\mu^-)$ and $\mathcal{B}(B^0 \to \mu^+\mu^-)$ at the HL-LHC (figure 4).

A study in the search for lepton flavour violation in the charged sector by searching for $\tau \to 3\mu$ decays at the HL-LHC is published as [14]. This study is based on the results of the $W \to \tau(\to 3\mu)\nu$ search performed on the data collected during Run 1 of LHC, and takes into account several aspects of the extrapolation such as trigger selections and efficiencies, detector performance effects, luminoisty and collision energy conditions, which has been validated using Run 2 simulations. Systematic uncertainties are extrapolated from the Run 1 analysis. Extrapolations to the statistics ATLAS expects to collect at the HL-LHC are performed and upper limits on the $\tau \to 3\mu$ branching fraction are obtained for the different levels of background and $\mathcal{A} \times \epsilon$. These can be seen in figure 5.

4. Summary

To profit from the HL-LHC with ~ 5 times the LHC's peak instantaneous luminosity, many components of the ATLAS detector will be upgraded. The ATLAS B physics program will continue during the LHC Run 3 and at the HL-LHC with a similar focus as during LHC run 1 and Run 2. It will exploit the upgrades, especially the new Inner Tracker and the muon system, which provide an improved secondary vertex reconstruction and a better invariant mass resolution. The development of topological L0/L1 triggers to keep low lepton p_T thresholds will be important. The increased data statistics will be used for precision measurements and searches, some of which were presented.

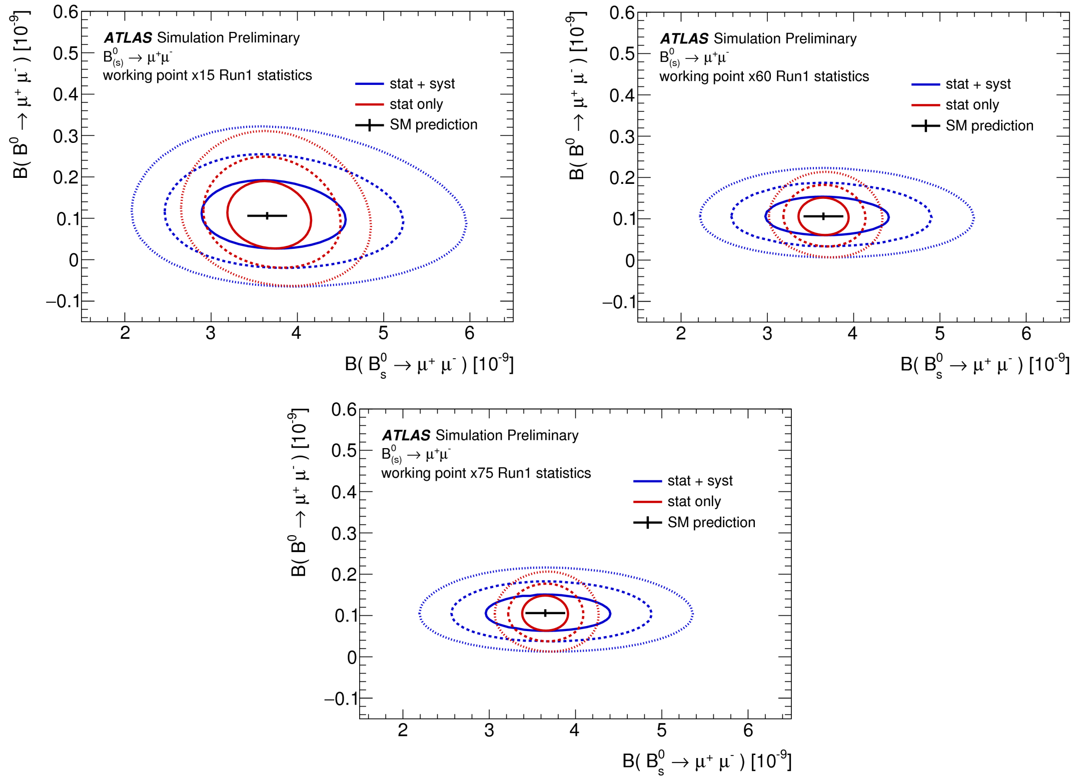

Figure 4: Comparison of confidence level profiled likelihood ratio contours for the conservative, intermediate and the high-yield HL-LHC extrapolation with ×15, ×60, and ×75 the Run 1 statistics for the (10 GeV, 10 GeV), the (6 GeV, 10 GeV) and the (6 GeV, 6 GeV) dimuon trigger scenarios respectively [12].

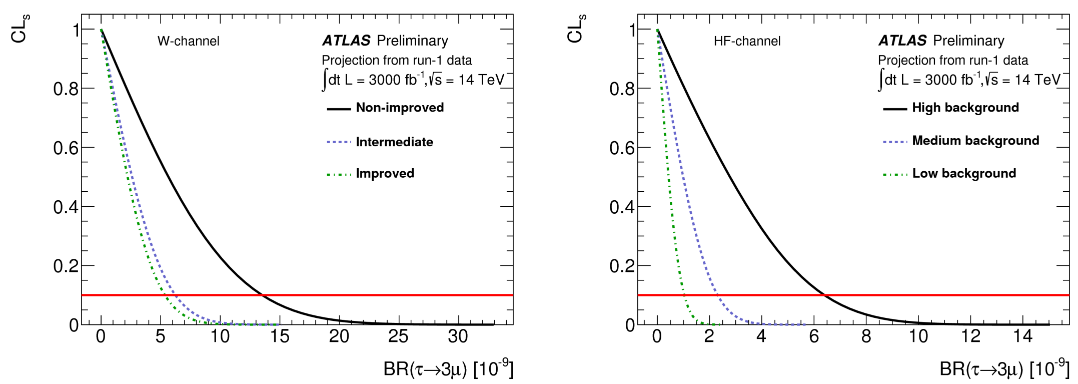

Figure 5: CL_s versus the $\tau \to 3\mu$ branching fraction BR($\tau \to 3\mu$), for each of the discussed scenarios in the W-channel and HF-channel.

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PoS(BEAUTY2020)061