EXPERIMENT REQUESTS AND CONSTRAINTS FOR RUN 3

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Abstract

During Long Shutdown 2, all LHC experiments will undergo upgrades to improve their performance and, in case of LHCb and ALICE, enable running at significantly higher luminosity. Preliminary requests and constraints for Run-3 running conditions, such as maximum luminosity and pile-up levels, crossing angles, etc. are presented for all experiments for both proton and heavy ion running. A first look at possible special run requests for Run 3 is presented as well.

INTRODUCTION

The second long shutdown (LS2) of the LHC is used not only to upgrade the LHC and the injector complex, but also to implement detector upgrades and consolidation programs for all LHC experiments in preparation of Run 3 and in some cases High-Luminosity LHC. The ALICE and LHCb experiments in particular are undergoing major detector upgrades [1, 2] in order to be able to efficiently take data at much higher luminosity than during Run 2. For the LHCb experiment, all of the tracker detectors, the Cerenkov light particle-identification systems and all of the readout electronics and data-acquisition systems will be replaced. This will enable the experiment to handle higher pile-up levels and read out all collisions into a software-only trigger system without any deadtime. In addition, the gas injection system, SMOG for beam profile measurements and fixed target physics [3], will be upgraded to SMOG2 [4] which can achieve a factor eight higher gas density. The ALICE experiment is also upgrading or replacing most of its detector components. In particular the gating grid will removed from the TPC and instead GEM-based readout chambers will provide continuous readout.

The upgraded detectors will provide new physics opportunities for Run 3, but will also require some beam time for commissioning and introduce some new constraints on beam operation conditions. The following presents the first iteration on experimental requests and constraints for Run 3 for both proton-proton running and runs with heavier ions. In addition, a first preliminary list of possible special runs during Run 3 is presented.

PROTON-PROTON RUNNING

Run 3 offers an opportunity to increase the collision energy as the dipole magnets will anyway need to go through a training period after LS2. The highest possible collision energy, i.e. 14 TeV, is favored by ATLAS and CMS as it significantly increases the cross-section for beyond Standard Model high-mass final states as illustrated in Fig. 1. The cross-section increases for most electro-weak and Higgs boson production channels are less significant, but still valuable for channels like top-associated Higgs production. The increases for minimum bias and b-quark production for ALICE and LHCb are almost negligible and for those experiments emphasis is on stable running conditions. If 13.5 TeV can be reached much faster than 14 TeV, this would also be of interest to ATLAS and CMS. Similarly if the maximum energy is not reached in 2021, it would be desirable to complete the magnet training at the beginning of 2022 as long as the luminosity production in 2022 and 2023 is not delayed and the same collision energy is used for both years. All experiments would like a baseline proposal for the collision energy in Run 3 to be settled in 2019 in order to start the Monte Carlo production during the second half of LS2.

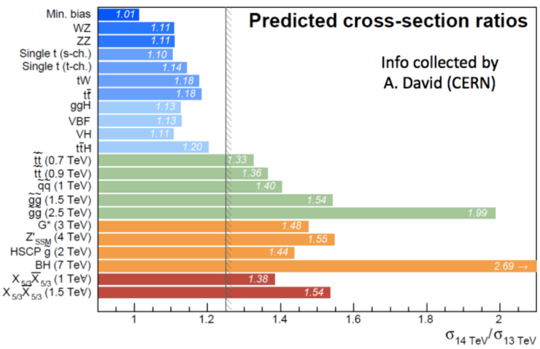

Figure 1: Ratios of cross sections at $\sqrt{s}$ = 14 TeV and $\sqrt{s}$ = 13 TeV for representative Standard Model and beyond Standard Model production processes.

All experiments would like the largest possible integrated luminosity, but they are all performance limited to a certain maximum instantaneous luminosity or pile-up. For ATLAS and CMS, the maximum limit on pile-up is expected to remain unchanged from Run 2 at about 60 pile-up events per bunch crossing on average. The expectation is that the luminosity-induced heating of the inner triplet magnets will provide a stricter limit (2×10^{34} cm^{-2}s^{-1}), unless the LHC has to run with 8b4e trains.

For ALICE and LHCb, the luminosity limits are significantly increased compared to Run 2 due to the LS2 detector upgrades. ALICE is expected to run leveled at about 1 MHz of proton-proton collisions, corresponding to 1.3×10^{31} cm^{-2}s^{-1} in the nominal filling scheme. The LHCb detector is expected to handle 2×10^{33} cm^{-2}s^{-1} for a full set of filled bunches (2376 bunches). This is not overly challenging for the LHC to reach as a peak luminosity. However, unlike ATLAS and CMS, LHCb has requested to be luminosity leveled throughout each fill at the same, fixed pile-up level for the majority of Run 3 in order to have the most stable beam conditions possible. If at some point during a

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fill, LHCb can no longer be leveled due to the loss of beam intensity, they expect to request the beams to be dump and refilled. The smallest possible β^* in IP8 is therefore likely needed and it should be evaluated if $2 \times 10^{33}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ for all fills is an achievable target for 2022–23. LHCb would be fine with a lower, but mostly constant, luminosity during most fills in 2021 when the experiment will anyway be recommissioned.

To maximize the luminosity for ATLAS and CMS while keeping the irradiation of the inner triplets near IP1/5 minimal, it is expected that both the β^* and crossing-angle will need to change significantly in IP1 and IP5 during most physics fills [6]. Both experiments are largely ready for this following the successful usage of β^* and crossing-angle anti-leveling in Run 2, though until now the two were not applied simultaneously. Both experiments are still concerned about the impact on their forward roman pots (PPS in CMS and AFP in ATLAS). In particular, for the IP with horizontal crossing, the acceptance of the forward detectors is affected by the leveling procedures. The use of telescopic squeeze should minimize this effect, though the actual effect still needs to be calculated once the Run-3 optics is available. The impact of a possible change in the crossing plane in order to use flat beams will also need to be evaluated for the forward detectors as both the ATLAS and CMS detectors are optimized for the existing crossing planes.

For both LHCb and ALICE, the β^* and crossing angle are expected to remain constant during each fill. ALICE has requested that for optics used during special runs with light ions (see below), the β^* in IP2 is as small as possible in order to have comparable luminosity to ATLAS and CMS. Following discussions with machine experts, it does not appear reasonable to use this as a constraint for normal proton-proton running, where a large β^* (11 m) would provide a more stable luminosity leveling. The impact of a potentially larger luminous region in IP2 due to the larger longitudinal blow-up for Run 3 is still under evaluation by ALICE.

In LHCb, a concern for Run 3 is the asymmetry in crossing angle when switching the LHCb dipole polarity. The fixed, external horizontal crossing angle and the horizontal crossing angle from the LHCb dipole, introduces a systematic difference in both the angular acceptance and luminous region size. With the improved Run-3 detector and larger data set, this could become the dominant systematic uncertainty for some precision analyses. LHCb would therefore prefer to have the same total crossing angle for both polarities. However, this would imply switching the sign of the external crossing angle with each dipole polarity flip which would require maintaining and validating two beam configurations. This would introduce significant operational overhead and instead LHCb has requested that machine experts study the possibility of having a vertical external crossing angle during stable beam running. This would result in the same magnitude of the total crossing angle for both polarities as well as the same luminous region size, though the crossing in the horizontal plane would still change sign.

Staying with BCMS beams in Run 3 is strongly preferred by all experiments as it allows to maximize the number of collisions in all IPs while keeping the e-cloud effects lower [7]. Upgrades to the SPS beam dumps and protection devices [8] will allow higher brightness and longer trains to be injected into the LHC which for example could give in 2736 colliding bunches in IP1/5, 2376 in IP8 and 2250 in IP2. However, if it becomes necessary to mix trains of BCMS and 8b4e bunches in order to mitigate e-cloud effects at higher bunch intensities, all experiments are prepared to cope with this. This should only be considered if a significant luminosity gain can be had as it would result in higher pile-up for ALICE, ATLAS and CMS and lower luminosity for LHCb. If it appears necessary from the first data in 2021, CMS has requested that a test run with this configuration be tried in 2021 even if it is not necessary for the 2021 run.

LEAD-LEAD RUNNING

Run 3 is planned to have significant running time dedicated to collisions with lead ions. The ALICE experiment, with its upgraded detector, will be able to read out more than an order of magnitude more heavy ion collisions (around 50 kHz instead of 3.5 kHz from its TPC detector). The improved granularity and rate capability of the LHCb experiment will allow more central lead-lead and proton-lead collisions to be recorded and analyzed. This increases the scope of the heavy ion physics program of LHCb which is more forward-focused than the other main LHC experiments. In addition, LHCb plans to use their new SMOG2 gas injection system to record fixed target collisions between lead ions and various injected gasses.

As with proton-proton collisions, all experiments would prefer to record lead-lead collisions at the highest possible collision energy, i.e. 5.5 TeV per nucleon-pair, but if this is not possible, the same energy as in Run 2, i.e. 5.02 TeV per nucleon-pair, should be used. The lead-lead luminosity goal for ALICE, ATLAS and CMS for Run 3 is around 6/nb with more than 10/nb collected overall by the end of Run 4. In addition about a month of proton-lead running is requested for Run 3 to study collective effects in a smaller, but still high density environment, again at the maximum collision energy, 8.8 TeV per nucleon-pair. An additional special run with oxygen-oxygen collisions is also under consideration, see below. For all configurations, additional, low pile-up proton-proton reference data will need to be recorded at the same energy. ALICE has requested 3/pb of proton-proton data while ATLAS and CMS requested two order of magnitude more as they can record data at higher pile-up levels. The reference data can be recorded either during the first year of running (ALICE preference) or proportionally to the physics data each year to match the detector running conditions (ATLAS preference).

As part of the "Workshop on the Physics of the CERN HL-LHC" [9], held in preparation of the 2020 European Strategy update, the heavy ion community put together a proposed run plan for ion running during Run 3 and 4, see Table 1, which can fulfill these requests. This proposal, particularly the extended running time in 2022 has not been endorsed by all of the LHC experiments yet, but will be discussed as part of the overall planning for Run 3 in the future.

During the 2018 lead-lead run, LHCb successfully participated in the data taking, recording peripheral collisions at luminosities of up to $10^{27}\,\mathrm{cm^{-2}s^{-1}}$. After the upgrade in LS2, LHCb will be able record and analyze more central lead-lead collisions and have therefore requested to continue to participate in the lead-lead program for Run 3 with non-negligible luminosity. In 2018, LHCb benefited greatly from the 75 ns bunch-spacing, where they could have up to 468 colliding bunches despite the offset of their IP with respect to the three other IPs. In total about $200/\mu$b of was delivered to LHCb in just two weeks. For Run 3 it is foreseen to switch to 50 ns bunch-spacing using slip-stacking [8]. This increases the number of colliding bunches for ALICE, ATLAS and CMS by about 65%, but leaves no colliding bunches for LHCb in the otherwise optimal configuration. A luminosity sharing policy will therefore need to be developed ahead of Run 3 which provides some luminosity to LHCb without overly penalizing the other experiments. It might be possible to mix trains with 50 ns and 75 ns bunches or even apply slip-stacking to 75 ns bunch trains in the SPS, resulting in alternating bunch-spacings of 25 and 50 ns. Either option should provide luminosity for LHCb with little impact on the other experiments, but can only be considered once the slip-stacking has been commissioned. The 50 ns bunch spacing is not expected to be an issue for LHCb's fixed-target program with the SMOG2 system as only non-colliding bunches in IP8 are used for the fixed target data analysis.

SPECIAL RUN REQUESTS

Similar to Run 1 and 2, it is expected that one or more "special runs" will take place each year in Run 3. These are short periods (from one fill and up to a week) of data taking, where one or more unusual beam configurations are used and experiments are recording data in dedicated configurations. A first set of possible special runs are presented below, but none of these requests are approved yet and more requests are likely to come during LS2 and Run 3 itself.

All experiments plan to record some (very) low pile-up data early in 2021 for detector commissioning. This will likely overlap with the ramp-up phase of the LHC and therefore mostly be parasitic. It will also be important to maintain several isolated colliding bunches during early running for detector timing-in and other commissioning activities. Dedicated low pile-up data-taking for physics measurements are also likely. CMS might request a sizable data set with $\mu = 3$ for W/Z measurements as well as precision 14 TeV cross section measurements. LHCf is also planning a DAQ upgrade [10] which would allow them to significantly increase their γ, π^0 and η statistics. This will require a run with very low pile-up ($\mu = 0.01$) and well-separated bunches for a couple of fills. As LHCf needs to be installed and removed from the TAN near IP1 for this special run, the run should be scheduled right after a Technical Stop, for instance the first stop in 2021.

Multiple high-β^* runs were taken during Run 1 and Run 2 at different energies with the TOTEM and ATLAS/ALFA detectors to measure the elastic and total proton-proton cross sections as well as the ρ parameter, the ratio of the real to the imaginary part of the hadronic amplitude of the elastic scattering at momentum transfer $t = 0$. As can be seen in Fig. 2, the measurements cannot easily be described by existing models and the deviations could be a strong indication of a crossing-odd exchange, the so-called "odderon" [11]. Measurements done in 2018 at injection energy ($\sqrt{s} = 900$ GeV) should help clarify how ρ evolves with energy, but a precision measurement at $\sqrt{s} = 14$ TeV would provide further input. To match the higher energy and increase the acceptance at low t, β^* is requested to be at least 3 km though the exact values will still have to be worked out. It would also be very interesting to build on the successful experience with crystal collimation in the low energy run in 2018 [12] as this might reduce or remove the need for beam scrapings to remove beam backgrounds, thus improving the data quality and reducing the required beam time. As the ALFA roman pot performance degrades with radiation damage, ATLAS has requested for the run to take place as soon as feasible, i.e. in 2021 if the LHC runs at 14 TeV in that year.

Additional data-taking at an intermediate β^* value (around 90m) for diffractive physics measurements might be requested by CMS/PPS, but no details for such a request is available yet.

There is an interest from the heavy ion community to have LHC collisions with light ions, such as oxygen. This would for example allow better studies of the emergence of collective effects and possible parton energy loss in small systems. This is already studied in high-multiplicity proton-proton collisions, proton-lead collisions and ultra-peripheral lead-lead collisions, but collisions of identical light ions would result in better defined initial conditions. For Run 3, a pilot run with oxygen-oxygen collisions appears to be the most realistic option as oxygen is already available in the existing ion-source as a carrier gas. The goal would be to accumulate at least a few hundred $\mu\mathrm{b}^{-1}$ in a few days. In order to achieve similar luminosity for ALICE as in ATLAS and CMS, this special run would preferably use the lead-lead optics to have the same β^* in all three IPs. However, any oxygen-oxygen run will have to take place separately from the lead-lead runs as it takes some time to switch between oxygen and lead in the source.

There is also a strong interest from the cosmic ray community in measurements of proton-oxygen collisions at the LHC energy to improve the modeling of ultra high energy cosmic ray showers. The modeling uncertainty is currently the dominant systematic uncertainty in determining the mass ($\ln A$) of incoming cosmic rays in high energy air showers. Furthermore these measurements show a discrepancy between the mass extracted from the shower maximum and from the muon density measurements as can be seen in Fig. 3. Precision LHC measurements of differential cross section

Table 1: Proposal for ion running in Run 3-4 from the heavy ion community [9].

Year	Systems, $\sqrt{s_{\mathrm{NN}}}$	Time	L_{int}
2021	Pb–Pb 5.5 TeV	3 weeks	2.3 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2022	Pb–Pb 5.5 TeV	5 weeks	3.9 nb^{-1}
	O–O, p–O	1 week	500 $\mu\mathrm{b}^{-1}$ and 200 $\mu\mathrm{b}^{-1}$
2023	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2027	Pb–Pb 5.5 TeV	5 weeks	3.8 nb^{-1}
	pp 5.5 TeV	1 week	3 pb^{-1} (ALICE), 300 pb^{-1} (ATLAS, CMS), 25 pb^{-1} (LHCb)
2028	p–Pb 8.8 TeV	3 weeks	0.6 pb^{-1} (ATLAS, CMS), 0.3 pb^{-1} (ALICE, LHCb)
	pp 8.8 TeV	few days	1.5 pb^{-1} (ALICE), 100 pb^{-1} (ATLAS, CMS, LHCb)
2029	Pb–Pb 5.5 TeV	4 weeks	3 nb^{-1}
Run-5	Intermediate AA	11 weeks	e.g. Ar–Ar 3–9 pb^{-1} (optimal species to be defined)
	pp reference	1 week	

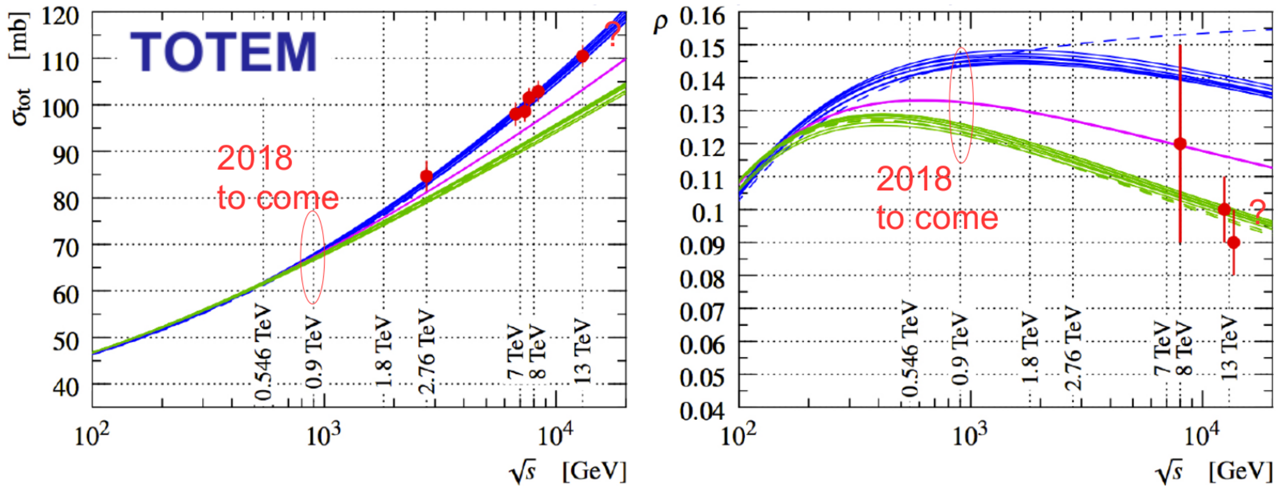

Figure 2: Predictions of COMPETE models [13] for proton-proton interactions compared to TOTEM measurements [14]. The left figure shows the total proton-proton cross-section, while the right figure shows the ρ parameter.

for charged and neutral particles in proton-oxygen collisions over a large rapidity range could help resolve this discrepancy and reduce the modeling uncertainty. This would require at least a few hundred million minimum bias events which could be recorded in a couple of fills assuming sufficient luminosity, $O(5 \times 10^{27}\mathrm{cm}^{-2}\mathrm{s}^{-1})$, could be achieved. Such a run would ideally be taken in combination with an oxygen-oxygen special run to minimize the overall setup time. LHCb and LHCf have expressed the strongest interest in a proton-oxygen run, while ALICE, ATLAS and CMS are mostly interested in the oxygen-oxygen run.

Finally LHCb has expressed interest in taking fixed target data at injection energy, injecting helium, hydrogen and deuterium gas into the proton beam using their SMOG2 system. The purpose is to improve the understanding of anti-proton production in spallation of cosmic rays in the interstellar medium (hydrogen and helium) as higher than expected anti-proton rates have been measured by AMS-02 [15]. Measurements were already carried out by LHCb with proton-helium with 6.5 Tev proton beam ($\sqrt{s_{NN}}$ = 110 GeV) [16], and adding measurements at injection energy would increase the acceptance for forward production and better cover the full $\sqrt{s_{NN}}$ relevant for AMS-02. To take useful data, the VELO detector would need to be closed and regular stable beam proton-proton collisions provided. Further investigations will be needed to understand if this is feasible with the upgraded LHCb VELO.

SUMMARY

The first experimental requests and constraints for Run 3 have been presented. These are very preliminary and likely to evolve during LS2.

For ATLAS and CMS, the requests and constraints are largely unchanged from Run 2 for regular proton-proton running. The maximum possible energy and luminosity remain highly desired, though the pile-up level should be

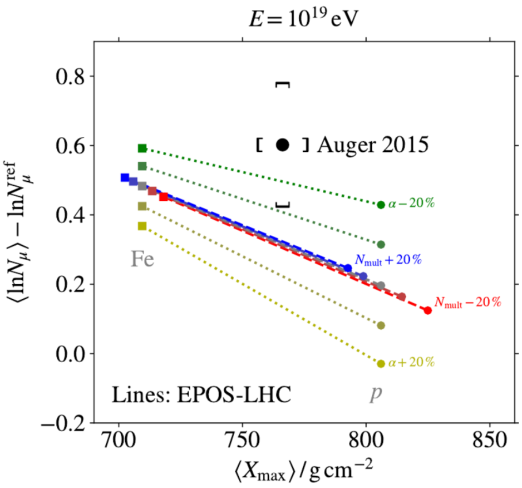

Figure 3: Impact of changes of the hadron multiplicity N_{mult} (dashed lines) and the energy fraction α (dotted lines) which goes into neutral pions in collisions at the LHC energy scale on EPOS-LHC predictions for X_{max} and ln N_μ in 10^{19} eV air showers, compared to Auger data [9].

kept below about 60. Any optics changes should consider the impact on the forward detectors.

LHCb and ALICE will carry out major detector upgrades during LS2 which will enable them to run at significantly higher instantaneous luminosity. LHCb requests to run at 2×10^{33}cm^{-2}s^{-1} (at constant pile-up) and that the possibility of using a vertical external crossing angle in LHCb be investigated in order to minimize the systematics from different acceptance and beam conditions with different magnet polarity.

Lead-lead collisions are planned through-out Run 3 and it is hoped that slip-stacking can be quickly and successfully deployed in order to deliver high integrated luminosity to ALICE, ATLAS and CMS. If successful, a fair-sharing policy with LHCb will need to be agreed upon.

Multiple special runs are already under consideration for Run 3, and more are likely to come during LS2 and Run 3. Prioritization and a possible schedule will need to be worked out during LS2 in consultation with experiments, accelerator, LHCC etc.

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