LPC'S VIEW ON RUN 2

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Abstract

Run 2 is summarised from the viewpoint of the experiments. Many different machine configurations have been used during Run 2. Their motivations and consequences for the experiments will be discussed.

Particular attention will given to the special runs which require a lot of preparation from the machine experts. Their physics motivation will be briefly introduced. A short overview on the Heavy Ion programme will follow.

In the appendix tools of general interest, implemented by the LPC during Run 2, are presented.

PP DATA TAKING

Overview

The LHC has delivered a rich data sample to all experiments. The high luminosity experiments ATLAS and CMS were delivered 160fb^{-1}. LHCb collected 6.7fb^{-1} and ALICE 66pb^{-1}. The luminosity in LHCb was levelled to constant pile-up resulting in luminosities between 3×10^{32}cm^{-2}s^{-1} and 5×10^{32}cm^{-2}s^{-1} by separating the beams at the IP. ALICE was levelled between 3×10^{30}cm^{-2}s^{-1} and 4×10^{30}cm^{-1}s^{-2}. Figure 1 summarises the luminosity production for ATLAS and CMS in the various years. 2015 was considered a commissioning year. The LHC for the first time produced luminosity at 13 TeV (after the splice consolidation during LS1) and operated with a bunch spacing of 25ns.

The performance of the LHC was steadily increasing over the years. This is reflected in Fig. 2, showing the average luminosity production in IP1 and IP5 per hour of Stable Beams during the 4 years of Run 2.
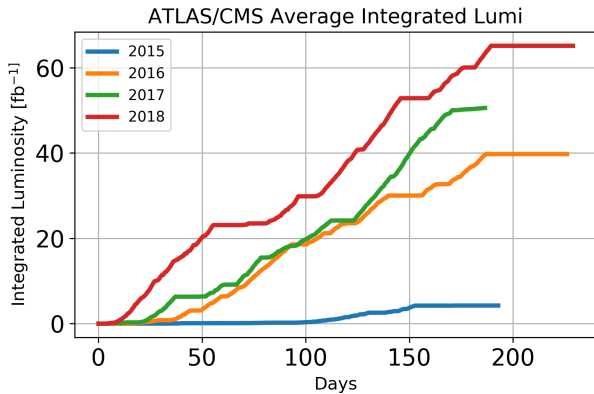

Figure 1: Average integrated luminosity taken by ATLAS and CMS in the various years of Run2. The flat luminosity production at the end of the years 2015, 2016 and 2018 correspond to the PbPb or p-Pb runs.
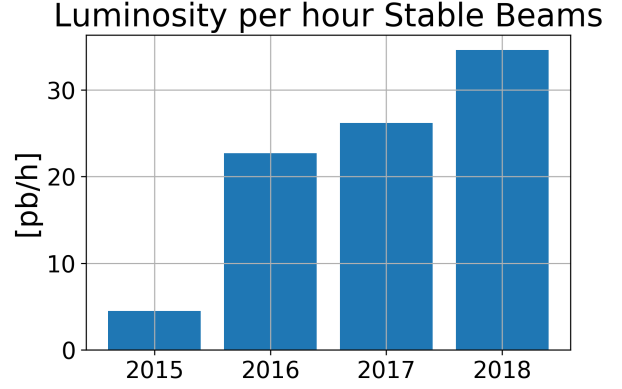

Figure 2: Average luminosity production per hour of Stable Beams in IP1 and IP5

Running Configurations

This section summarises the different LHC-configurations used in Run 2 and their implications for the experiments. According to their motivation the configurations can be grouped into four different categories. It will become clear that the combination of creativity among machine experts and flexibility in the experiments lead to a considerable higher integrated luminosity than otherwise would have been possible to collect.

Configurations Due to Experiments Constraints The maximal tolerable pile-up in CMS and ATLAS is around 60 interactions per bunch crossing. In 2017 the LHC was operated with 8b4e beams produced via BCS leading to very bright beams. If these beams had been colliding head-on in IP1 and IP5 the resulting pile-up would have been considerably beyond this limit. Therefore beams were displaced in the separation plane such that the pile-up was staying below 60 (Fig. 3). Experiments had to either re-weight or re-produce their Monte Carlo samples to cope with a different pile-up distribution than originally assumed, due to the higher fraction of events with maximal pile-up.

In long runs the bunch length is shrinking due to damping effects. This can lead to an unacceptably high pile-up density in LHCb when running with positive dipole polarity where the effective crossing angle in the IP is maximal (LHCb is running at constant luminosity). In this configuration the tolerable minimal bunch length of 0.9ns is reached after ~10 hours. The RF team developed a procedure to longitudinally blow up the bunches in a controlled way before this limit was reached (see Fig. 3).

During Run 2 ATLAS and TOTEM/CMS added several Roman Pots to their detector to enhance the acceptance and efficiency of their forward physics programs. The pots were
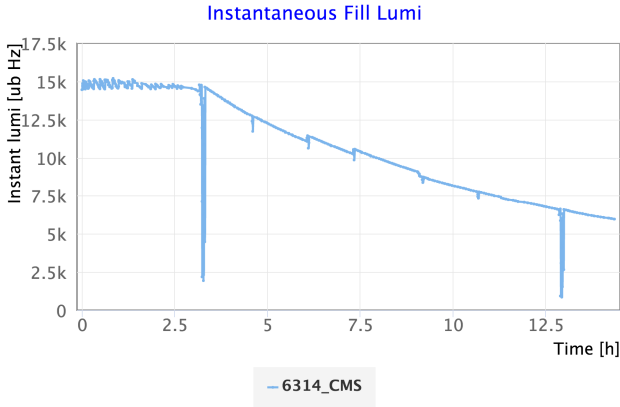
Figure 3: Instantaneous luminosity measured in CMS in Fill 6314 (2017). Clearly visible is the initial lumi levelling at $1.5 \times 10^{34} \mathrm{cm}^{-2}\mathrm{s}^{-1}$, two crossing level anti-levelling steps (around 6h and 7.3h) and a small downward step due to longitudinal blow-up after ~8h. The small luminosity dips indicate optimisation scans performed regularly throughout the fill. The larger dips at the end of levelling and towards the end of the fill are emittance scans requested by CMS.

designed to detect protons from diffractive or semi diffractive interactions close to the beam line. The acceptance of the detectors is given by its dimension, its distance to the beam and the single pass dispersion from the IP to the Roman Pot. In particular a large single pass dispersion improves the low mass acceptance. In CMS where the crossing angle is horizontal, the dispersion of the optics is partially compensated by the magnets creating the crossing angle. To improve the CT-PPS acceptance the dispersion was increased by designing a special "TOTEM bump". This showed that forward physics experiments are not transparent to pp-operation and need to be considered from the beginning when developing the machine configuration.

Configurations to Work Around Problems   In 2016 the beam intensities were limited due to the leaking SPS beam dump. This pushed machine experts to implement the BCMS production scheme for luminosity production. Due to a lower splitting factor compared to the standard production scheme (6 instead of 12) the charge effects at low energies are reduced leading to much smaller emittances. Hence the beams are resulting to be much brighter in the LHC. However, the maximal batch length in the BCMS scheme is 48 bunches instead of 72 bunches. Due to the increased brightness of the beam only 96 bunches were allowed to be injected in the LHC to avoid damage on the TDIs in case of a beam loss there. The corresponding filling schemes contain less colliding bunches in the experiments. Hence, the pileup up for the same luminosity is larger with the BCMS scheme compared to the standard scheme. The experiments ATLAS and CMS which were originally supposed to handle a pile-up of ~25, managed to cope with a pileup of up to ~60 and therefore the BCMS scheme was extremely welcome to increase the integrated luminosity. The BCMS scheme was

the preferred scheme for the rest of the Run 2 period since also in the subsequent years it lead to the highest achievable integrated luminosities.

In 2017 a problem in cell 16L2 led to fast instabilities with subsequent beam dumps. The problem was found to be related to the e-cloud in this region. To be able to continue the luminosity production, filling schemes based on sequences of 8 filled bunches and 4 empty buckets (8b4e) were used to suppress the formation of e-clouds. The beams were produced with the BCS scheme leading to small emittances at the start of Stable Beams (~$1.5 \mu m$), and hence a large luminosity per bunch. The previous section describes how the experiments managed to cope with the resulting high pile-up. In additions the new sequence of colliding bunches in the filling schemes with a lot of empty bunch slots led to a different distribution of the out-of-time pile-up in the experiments. This required substantial work to adapt the trigger algorithms.

Configurations to Prepare for the HL-LHC   In 2017 it was decided to run the RF system in the so called "full-detuning" scheme [1] which reduces the power consumption of the RF system considerably by allowing the phase of the RF to vary as a function of the filling pattern, the beam intensity and the RF voltage. As a consequence for the experiments the time of the collisions varies with respect to the fixed LHC clock. In IP2 and IP8, in addition, the location of the interaction varies longitudinally. The effect was measured by the experiments and found to be well reproduced by the predictions and to be tolerable by all experiments (see figure 4 for an example of the shifts in IP8 with a typical filling scheme).

In 2017 the ATS (Achromatic Telescopic Squeeze) [2] scheme was introduced in order to gain experience before this scheme will be deployed in the HL-LHC era to achieve the foreseen small β^* values. For the forward experiments this optics resulted in a 10% loss of acceptance compared
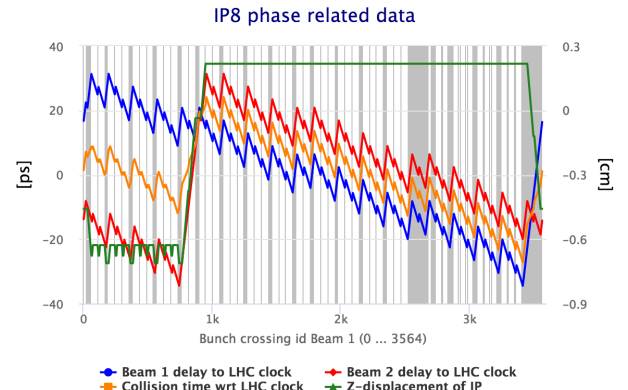

Figure 4: Phase shifts and longitudinal IP displacement in LHCb for a typical BCMS filling scheme used in Run 2. The gray vertical bars indicate positions in the orbit without colliding bunches in LHCb.

to the standard optics. This was considered acceptable. For ATLAS and CMS the introduction of this scheme was transparent.

In HL-LHC β^* levelling will be the only way to level the high lumi experiments to tolerable pile-up values. To gain first experience with β^* levelling, in 2018 it was introduced as anti-levelling at the end of long fills after crossing angle anti-levelling was completed. The β^* was reduced in two discrete steps from 30cm to 27.5cm and from 27.5cm to 25cm. The high lumi experiments observed a small increase in luminosity during these steps, however also losses went up considerably (background condition in the experiments did not become worse). During the levelling steps, which were performed in IP1 and IP5, the ALICE experiment observed luminosity transients. They could be partially mitigated with feed forward corrections however the remaining transients sometimes still exceeded 10% which was considered by ALICE to be the maximal tolerable transient. ALICE worked around the problems by pausing the data acquisition during the levelling steps without noticeable loss of luminosity.

Configurations to Improve the Performance   In 2017 the machine experts proposed to reduce the crossing angle in IP1 and IP5 during the fill to optimally exploit the available Dynamic Aperture of the machine and hence optimise the integrated luminosity for the experiments. This proposal was discussed in detail with the experiments since it meant for the first time a change of machine parameters in Stable Beams. It was concluded the anti levelling does not lead to any increased risk for the experiments and hence it was introduced in 2017 with some discrete steps (figure 3). In 2018 it was improved to a quasi continuous anti-levelling with many small steps of 1μrad from 160μrad down to 130μrad (half crossing angle). Overall $3\% - 4\%$ gain of integrated luminosity was achieved.

Over Run 2 the handling of the Abort Gap Keeper (AGK) became more flexible. In addition the gaps between batches in the SPS and between injections in the LHC were optimised by tuning the various injection kickers in different machines. This led to more efficient filling schemes allowing for more collisions in the experiments.

Major Physics Results of the Run 2 pp Run

The most important physics result of Run 1 was the discovery of the Higgs boson [3] [4]. However, with the available statistics at that time, only decay channels via Higgs interacting with bosons were observed. The part of the Standard Model Lagrangian which describes the interaction of the Higgs with Fermions, and hence the mechanism which gives the constituents of matter mass, could only be probed with the high statistics available in Run 2. ATLAS and CMS were able to detect the Higgs decaying into a b-quark pair in associated production processes where the Higgs is produced together with a W or a Z boson [6] [5]. CMS and ATLAS also were able to detect the coupling of the Higgs to top quarks [8] [7]. Since the Higgs is too light to decay into two top quarks, this coupling can only measured in production

channels where a Higgs is radiated off a top quark produced in the collision. All Higgs measurements made so far are in agreement with the Standard Model predictions.

LHCb made use of the large statistics of Run 2 to look for rare decays of B mesons. An example is the decay $B_s^0 \rightarrow K^*\mu^+\mu^-$ which in the Standard Model can only occur via a highly suppressed Penguin diagram involving a loop with a W and top quark (probing the V_{td} element of the Cabbibo Kobayashi Maskawa Matrix) [9]. These measurements are very sensitive to new physics. If a new heavy particle exists it might contribute to the decay amplitude via a loop diagram which interferes with the Standard Model diagram. Since the latter is extremely small, the branching ratio is sensitive to very small changes of the decay amplitude.

SPECIAL RUNS

Most of the special runs performed in Run 2 were dedicated to physics involving the Roman Pots installed in the forward regions of the experiments ATLAS and CMS. The two main physics programs measure either elastic pp scattering processes or single diffractive or central diffractive scattering processes.

Elastic pp Scattering

In elastic scattering processes the energy of the participating protons is unchanged, however the protons change their momentum and hence they leave the interaction with a small angle with regards to to the original beam direction.

The main physics interests are the measurement of the total pp cross section via the optical theorem[1] and the investigation of the region where elastic coulomb and nuclear scattering processes interfere (measurement of the ρ-parameter[2]).

Experimentally both measurements are challenging since they require acceptance for very low t in the Roman Pots. This is achieved by deploying a special optics (large β^*) so that the beams at the pots are small and the pots can be moved as close as possible to the beam. In general the measurements are not performed in Stable Beams and with low intensity beams ("safe beam limits").

In 2016 TOTEM and ATLAS/ALFA performed a special run at 13 TeV with a specifically developed optics at β^*=2.5km. TOTEM published the result of the ρ-measurement [10] which was found to be significantly smaller than most popular models predicted (figure 5). Since the ρ-parameter has not been measured at any energy between ~600 GeV and 8 TeV (for pp scattering) there was a strong interest to have an intermediate measurement at injection energy of the LHC (900 GeV). This run was performed in 2018. Some first attempts in 2017 and in 2018 had been unsuccessful due to intolerable high backgrounds in ALFA. However,

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[1] The optical theorem states that the total pp cross section can be calculated from the elastic cross section extrapolated to $t = 0$ there t is the Mandelstam variable describing the momentum transfer during the scattering process.

[2] The ρ-parameter is the ratio of the real and the imaginary part of the the elastic scattering amplitude extrapolated to t=0.
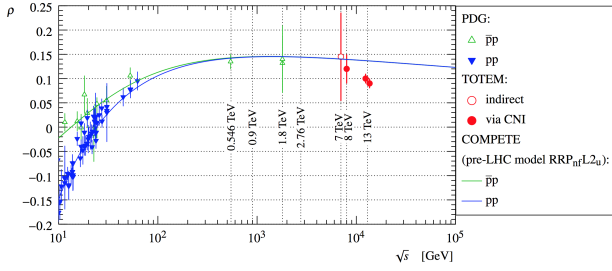
Figure 5: The TOTEM ρ-measurements of the 2.5km special run in 2016 are indicated in red. The two points at 13 TeV correspond to two different fit methods. Model predictions are indicated as blue (pp) and green ($p\bar{p}$) lines.

after the development of two new collimation schemes, one involving crystals as primary collimators, both experiments were able to take high quality data for this measurement. Data taken with the crystal collimation scheme were cleaner and conditions more stable than with the traditional 2-stage collimation scheme. Possibly due to some small drifts, the latter resulted in bad background conditions for TOTEM towards the end of the physics run. For ALFA both collimation schemes delivered high quality data, however, during the run they preferred the 2 stage collimation scheme since they were not able to assess the data quality of the crystal collimation scheme sufficiently well at the time of running. The running time towards the end of the run was shared between both collimation schemes such that both experiments were able to take the requested sample of 10^6 events in good conditions. This run was the first physics run using crystal collimation.

Central Diffractive Processes

Central diffractive processes can be measured in ATLAS and TOTEM/CMS by identifying 2 protons in the Roman Pots and some activity in the central detector. The energy loss of the protons can be measured with the knowledge of the optics transporting the protons from the IP to the Roman Pots. Measuring both protons on both sides of the IP allows reconstruction of the complete kinematics of the event. To have acceptance for low masses of the exchanged color singlet (Pomeron) the pots should be driven as close to the beam as possible. On the other hand high statistics is needed for the physics analysis and the operation of the central detectors in ATLAS and CMS requires Stable Beams to be declared. The optimal compromise for these requirements resulted in an optics with β^*=90m. A first run in 2015 has been performed at low luminosity since the Roman Pots were not able to tolerate any pile-up. The addition of new timing detectors and the reduction of the impedance of the pots in collaboration with the machine experts, however, allowed to repeat this run in 2018 with much higher luminosity. TOTEM was able to take approximately eight times the statistics of 2015 during this run. The data sample will be used to search for glue-balls which are popular candidates for the exchange of colour-singlets in these processes.

Table 1: Overview of Heavy Ion runs in Run 2 and the integrated luminosities collected in the various experiments.

Year	Part.	E [TeV]	Integ. Lumi
2015	Pb - Pb	5.02	IP2: $433\mu b^{-1}$ IP1 & IP5: $584\mu b^{-1}$ IP8: $6.3\mu b^{-1}$
2016	Pb-p	5.02	IP2: 780×10^6 events IP1 & IP5: $> 0.4nb^{-1}$ IP8: Smog data
2016	Pb-p	8.0	IP2: $39nb^{-1}$ IP1 & IP5: $190nb^{-1}$ IP8: $32nb^{-1}$ LHCf: 9.5 hours
2017	p-p	5.02	IP2: 170 hours IP1 & IP5: $280/350nb^{-1}$ IP8: $120pb^{-1}$
2017	Xe - Xe	5.44	One pilot run with 16 bunches.
2018	Pb - Pb	5.02	IP2: $905\mu b^{-1}$ IP1 & IP5: $1.8nb^{-1}$ IP8: $235\mu b^{-1}$

THE HEAVY ION PROGRAMME

Table 1 shows and overview of the Heavy Ion runs performed during Run 2.

The official goal for the integrated luminosity ($1nb^{-1}$ for two experiments in the first 10 years of LHC operation) has been largely exceeded. In Run 2 all the four large LHC experiments participated in the Heavy Ion programme.

The way to optimise the integrated luminosities in the various experiments for the PbPb runs differ significantly. For technical reasons the luminosity in ALICE had to be levelled at $10^{27}cm^{-2}s^{-1}$. Therefore ALICE preferred long fills at this luminosity with the other experiments being levelled to maximise the length of the fill. ATLAS and CMS were able to sustain any achievable peak luminosity and hence preferred to run at the highest possible peak luminosity in short fills. Although LHCb only recorded peripheral collisions they were able to sustain any peak luminosity and hence were interested in a high number of collisions at high peak luminosity.

In 2015 the bunch spacing of the lead beams was 100ns. Due to the location of the LHCb IP for every collisions in LHCb one of the participating bunches does not collide in any other experiment, hence reducing the number of collisions there. Therefore the integrated luminosity for LHCb in 2015 was small. However, in 2018 a large fraction of the run was performed with beams of 75ns bunch spacing. This configuration naturally leads to a large number of collisions in LHCb and the integrated luminosity was a factor of 37 higher than in 2017.

To find a fair way to share the available luminosity in 2018 a tool was developed which allowed to quantify the luminosity sharing in different running scenarios. The tool
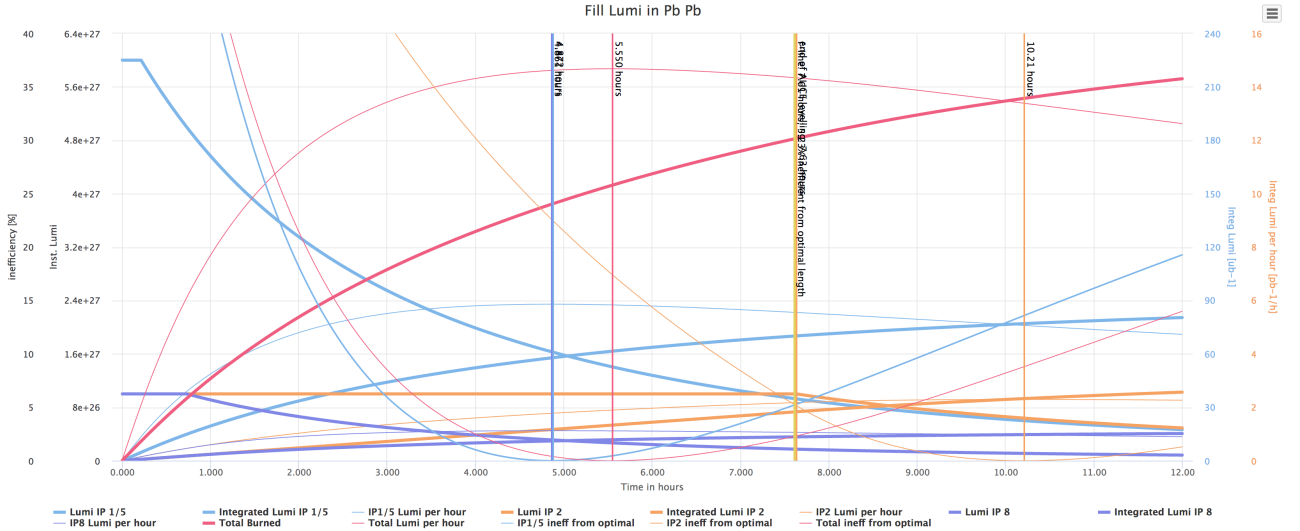
Figure 6: The output of the tool used to establish a fair luminosity sharing for the Pb – Pb run. For all experiments the integrated luminosity and the luminosity per hour (assuming 5h turn-around time) are shown. To indicate the overall efficiency of of the LHC, in red the sum of all integrated luminosities and all luminosities-per-time are shown. The vertical lines indicate the maxima of the luminosity-per-time curves. The yellow vertical line indicates the position where ATLAS/CMS and ALICE are equally far away from their optimal running scenario. For typical running scenarios in 2018 this point corresponds to the time where ALICE levelling stops.

simulates the intensity decay of every bunch due to burn-off. To account for all other effects which can lead to a luminosity decay during a run a constant emittance growth per time can be fed into this naive simulation. This tool was checked against more complete simulations of the machine experts and against observations during the 2018 physics fills and it was found to be consistent with these within a few percent, largely enough for the purpose of finding a fair sharing policy. For 2018 it was agreed with all experiments that the best running policy would be:

1. To keep fills at least as long as ALICE can be levelled.

2. To not level any other experiment for the reason of sharing the luminosity (in practice the luminosity at the start of the run in ATLAS and CMS was increased in steps in order not to risk a quench due to Bound Free Pair Production (BFPP) and collision debris impinging on cold magnets. For the same reason the peak luminosity in LHCb was limited to $1 \times 10^{27} \mathrm{cm}^{-2}\mathrm{s}^{-1}$.)

The policy was adopted also because it allowed to run the LHC at an overall lead burning efficiency reasonable close to the optimum. The policy was considered fair since ALICE ATLAS and CMS all would be equally far away from their optimal running scenario. This is illustrated in Fig. 6 which shows the result of the simulation for typical beam parameters in 2018.

APPENDIX: LPC TOOLS

This section gives an overview of the tools developed during Run 2 on the LPC website. Emphasis is given to those which might be of interest to a wider community. All tools are implemented on the LPC web-site [11]

Minutes of LPC meetings

The minutes of all LPC meetings are kept on the LPC website. They can be searched for keywords and expressions.

Filling Schemes

The LPC are responsible to create the filling schemes for physics runs. A variety of tools have been created for this purpose.

Overview Table This table lists all filling schemes of a year used in Stable Beams. Links to the so called "csv-files" of the schemes are provided. The number of non colliding bunches is listed since this number is not encoded in the filling scheme name.

Fill - Scheme association A table which associates each Physics fill with the filling scheme used. The filling schemes are linked to their csv-files. Start time and duration in Stable Beams are listed. A restful API has been implemented to allow the retrieval of the filling scheme for any given physics fill in a programmatic way. Schemes can be downloaded as csv-file or in json-format.

Filling Scheme Viewer The filling scheme viewer visualises filling schemes in two different ways. The distribution of the bunches in the LHC rings is shown and a linear representation as used in the filling scheme editors is given. An animation moves the beams around the LHC. A plot showing the phase shifts due to the full-detuning scheme

can be generated for every filling scheme (e.g. Fig. 4). The data of these plots can be downloaded in JSON format for further processing.

Filling Scheme Editor The LPC use this tool to generate the filling scheme for physics fills. Being available on the LPC webpage, every interested person can use this tool. After creation of a user account any possible filling scheme can be created. Filling schemes can be saved for later retrievals in the user account. Filling schemes are composed of LHC-injections which in turn consist of SPS-batches. For exotic configurations custom injections and batches can be edited in an Injection and Batch editor (e.g. for the 8b4e schemes). Predefined algorithms ease the creation of filling schemes for standard physics scenarios (pp runs or PbPb runs). To optimise schemes, injections can be moved with a graphical tool. All available information on the scheme are updated in real time. Schemes are presented in two graphical representations. The first shows the location of the batches in the scheme and indicates for IP2 and IP8 where these batches would collide with batches of the other beam. A second graphical representation indicates via colour coding for every bunch in which IP it collides.

Further the phase shifts due to the full-detuning scheme can be generated as well as a Fourier Spectrum of the filling scheme.

Additional information is provided in form of tables. The number of long range interactions in the various IPs, the number of collisions in the IPs and the number of available bunch slots in the region from the AGK to the Abort Gap are calculated. The editor generates strings which can be used to paste into the LHC filling scheme editor to quickly enter the schemes into the LHC database.

The filling scheme, the associated phase-shift information and the Fourier-Spectrum for each scheme can be downloaded in form of a JSON file.

Some online help to use the editor is provided.

Performance plots

Most of the performance plots are based on data provided by the experiments in form of the so called "Massi"-files. These contain luminosity data and information on the size of the luminous region. Most of the plots are available for the pp period of each year and for the Heavy Ion period. However any arbitrary time interval can be chosen. All plots can be downloaded as png-files.

Of particular interest is the plot which measures the optimal fill length in ATLAS or CMS for a given turn-around time. The measurement is done for fills which were kept longer than the optimal fill length and hence a maximum in the curve "Lumi per time" can be identified. Together with the histogram of the turn around times this helps to identify the optimal fill length for LHC fills.

A plot to compare the luminosity ratio of ATLAS and CMS based on the experiments online luminosity values and the same ratio based on a quasi online Z-counting analysis

performed by the experiments is provided. Since both measurements are subject to different systematic effects this plot helps to judge apparent differences in online luminosities of ATLAS and CMS.

The contents of the Massi Files can be plotted for every physics fill. An interesting plot shows the ratio of the length (in z) of the luminous region of ATLAS and CMS. This ratio is equivalent to the ratio of the geometric factor in the luminosity formula. Hence, plotting it over the length of the fill can reveal interesting information on the evolution of the beam parameters (especially the vertical and horizontal emittances) during the fill.

Annotated fill table

The LPC maintain a table of all physics fills with basic information on details of the fills. This table is useful to consult in case some unusual effects are observed in a specific fill. The table is maintained by the LPC based on information provided in various LHC meetings. It is not a complete record of all activities or actions during each fill.

Luminosity Calculators

A simple luminosity calculator implements the luminosity formula and allows to plot some parameter dependencies. A second calculator estimates the luminosity evolution and the integrated luminosity over a fill. It allows to consider effects like crossing angle anti-levelling and β^*-levelling[3].

"Massi" file versioning overview

A versioning system of the Massi files has been introduced in Run 2 to provide users of the Massi files with information on the contents of the files (these files are updated by the experiments whenever better quality data becomes available, e.g. due to improved calibrations). The version information is provided in form of automatically created tables.

LHC Scheduling tool

A tool to draw or modify the LHC schedule counts the number of days in the various schedule categories (e.g. physics days, special runs, MDs, ...)

Ion Sharer

To establish a fair policy to share the luminosity in Pb-Pb runs this tool calculates the burn-off of the bunches in Heavy Ion runs considering the optics and the levelling in the various IPs. And example of the output of this tool is shown in figure 6 and details have been discussed in section

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[3] These features have been added by Michi Hostettler.

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