Experiments and LPC view on Run 2

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With input from many colleagues from the accelerators and the experiments
Contents

pp data taking: Many configurations
  Special runs
Heavy Ion data taking

Appendix for those who are interested:
  Remarks on operational details
  Tools available on the LPC web pages
pp – run

Many different configurations:
Experiments view
Summary of the pp run

- Large high quality data sample for all experiments
  - 160 fb\(^{-1}\) : ATLAS / CMS
  - 6.7 fb\(^{-1}\) : LHCb
  - 66 pb\(^{-1}\) : ALICE

- Continuous performance increase over the 4 years
  - 2015 : commissioning
  - 2018 : minimal amount of configuration changes

→ 32% higher lumi/hour than 2017
Multiple configurations

- During Run 2 we went through a large number of different machine configurations for various reasons
  - Constraints from the experiments
  - Work around problems
  - Prepare for Run 3 and/or HL-LHC
  - Improve performance

- Fortunately the creativity of the machine experts was matched with remarkable flexibility in the experiments
  - Experiments were able to adapt to challenging conditions compared to the original design targets:
    - Pile-up
    - Peak luminosity
Constraints from experiments (I)

- From 2016: Bunch-length leveling (blow up) when LHCb ran with positive Dipole polarity (aka “DOWN”).
  - Effective crossing angle in this polarity is maximal and leads to highest pile-up density
  - Data quality is affected when bunch length decreases below 0.9ns
  - For practical reasons (to keep the bunch length distribution under control) the bunch length was blown up when 1.0ns was reached during long fills.

- Advantage: LCHb was happy with this
- Disadvantage: Very small lumi penalty for CMS/ATLAS

\[ \sim 2\% \text{ lumi drop in IP5 after 9h} \]
Constraints from experiments (II)

- **2017: Lumi-leveling with separation in IP1 and IP5**
  - The 8b4e beams were very bright (BCS lead to very small emittances) leading to very high pile-up in the experiments at the start of the fill.
  - CMS and ATLAS were able to cope with pileup around 60.
  - Luminosity had to be limited to 1.5e34 (with 1866 colliding bunches)
Constraints from experiments (III)

- From 2016 onwards:
  Forward Physics in IP5 during pp high lumi data taking (CTPPS)
    - Acceptance depends on single pass dispersion from IP to the pots
      → Constraints on the optics

Complications in IP5:
The single path dispersion generated by the separation dipoles is partly compensated by the crossing angle bump.

- 2017: An extra TOTEM-bump was designed to mitigate this effect.
  → Huge effort in the last minute before the run.

Lessons learned: there is no such thing as an experiment transparent to operation of the LHC
Prepare the future (I)

- Need of “Full detuning” scheme for the HL-LHC era
  - Details in RF talk of Helga

- The full detuning scheme was introduced in 2017 to gain experience
  - Consequence for experiments:
    - Time of collision in IP 1 and 5 wrt LHC clock varies depending on filling scheme, beam current and RF voltage
    - In IP 2 and 8 in addition the vertex of the interaction is displaced along z.
RF Full de-tuning: Prediction and measurement

CMS: Fill 5856

ALICE: Fill 5872

25ns_2173b_2161_1872_1962_144bpi_17inj

25ns_2460b_2448_2052_2154_144bpi_19inj

Δ=97ps

Δ=1cm

Δ≈0.9cm

No issues for experiments
2017: Introduction of ATS

- ATS was tested in MDs extensively
- It was important for the machine experts to gain some experience with ATS before Run 3.
- **Forward physics:** would have preferred “standard optics” (better acceptance), however machine experts optimised ATS optics for the Forward Physics acceptance to largely mitigate the adverse effect.
  - An additional extra squeeze with Q6 going to 200A was added to the existing pre-squeeze and gained 10% of acceptance back. With this the acceptance was only 10% worse than in 2016 after the TS2 (140µrad). )
Prepare the future (III)

- \( \beta^* \) leveling or anti-leveling (See Belens talk for details)
  - Was tested in MDs during 2017
  - After discussion it was decided to use \( \beta^* \) leveling in 2018 as anti-leveling towards the end of the fill (after the crossing angle anti-leveling has finished):
    - Can be dropped in case of problems.
    - Minimises the impact on forward physics experiments

- Impact on experiments
  - The optical functions describing the beam transport from the IP to the RP change with changing \( \beta^* \) \( \rightarrow \) CTPPS and AFP required calibration data for all \( \beta^* \) configurations used.
  - For IP 1&5 the \( \beta^* \) steps were visible in a small increase of the instantaneous luminosity
  - In IP2 luminosity transients became visible (especially during the second leveling step). These were corrected with feed forward but also after the corrections occasionally the lumi varied by more than 10% (which is the precision requirement on the leveling in ALICE)
Enhancing performance (I)

- **2016 : Introduction of the BCMS scheme**
  - Smaller emittance due to smaller splitting factor (less space charge effects at low energy in Booster)
    - The configuration change was pushed due to the intensity limitations due to SPS beam dump leaking.
  - Consequences:
    - Higher pile-up at the same luminosity (less bunches in the machine)
    - Higher total integrated luminosity due to smaller emittances.
- **2017-2018 : Crossing angle changes and quasi continuous anti-leveling**
  - To exploit optimally the dynamic aperture in the machine available during a long physics run it was decided to decrease the crossing angle in steps during physics runs.
  - The procedure was discussed in detail with the experiments since the operation is executed during Stable Beams.
  - Overall a few percent (3%-4%) in gain of integrated luminosity was measured and no disadvantage for the experiments.
    - Forward physics experiments took calibration data at different crossing angles and learned how to extrapolate for values between.
Enhancing performance (II)

- Possibility to change the AGK (see Belens talk)
  - The LHC became more flexible to allow for occasional AGK changes
  - Consequence:
    - More efficient filling schemes and hence more luminosity at constant pileup
    - This advantage largely dominated over the short extra validation time needed after an AGK change

- Reduction of Batch spacing in the SPS and Injection spacing in the LHC
  - By fine tuning the kicker timings in the accelerator chain (PS-SPS-LHC) it was possible to reduce
    - The SPS batch spacing from 250ns to 200ns
    - The LHC injection spacing from 900ns to 800ns
  - Consequence:
    - More space for colliding bunches and hence more luminosity at constant pile-up
    - No noticeable draw back for experiments
      - Occasionally blown up bunches at the edge of the batches are not noticed by experiments
Work around problems

- **2017 and 2018 : 16L2 aka Gruffalo (see Daniele’s talk)**
  - The Gruffalo’s activity is related to e-cloud activity in 16L2
  - To reduce the e-cloud dramatically while keeping high bunch currents the 8b4e scheme was introduced in 2016
    - This scheme was combined with BCS (Batch compression scheme) to reduce the splitting factor during the production and to reduce the **emittance down to ~1.5µm**.
  - The 8b4e scheme allowed machine operation with peak luminosities beyond 2 times the design luminosity.
    - **Close to 4.5/fb per week** could be acquired in spite of 16L2.
  - **8b4e needed some work to adapt in the high lumi experiments**
    - “Out-of-time” pileup changes
      - A lot of ”first” and “last” bunches due to small batches of 8 bunches.
    - After tuning of parameters in the trigger no problems were identified when running with 8b4e.
  - **8b4e saved the integrated luminosity of the year**
And why do we need all this lumi?! Examples from ATLAS/CMS

In RUN 2 ATLAS and CMS for the first time measured a fundamental part of the Standard Model Lagrangian: coupling to fermions
(bottom & top – quarks and the τ – leptons)
Challenging: $H \rightarrow b\bar{b}$

- Dominant Higgs decay channel (58%), however, large backgrounds from QCD
  - No chance in gluon fusion production

- Only measurable in collisions with associated production with $W$ or $Z$
  - $W$ or $Z$ decay can be used to “tag” the interaction
  - Many decay modes to consider and combine

- Significance Run I & 80fb$^{-1}$ of Run II: $5.4\sigma$

- Many different analysis combined
  - Different decays of associated $W/Z$ bosons

- Huge background requires large statistics to extract significant results
Challenging: $ttH$

- Only production channel
  
  - $M_H < 2 \times m_t \rightarrow$ Higgs cannot decay in top quarks

- Using 36 fb$^{-1}$ from Run II (2016 data)

- Significance $5.2\sigma$

- Combination of many decay channels for $H$ with complex event topologies
  
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow b\bar{b}$
  - $H \rightarrow WW^*, ZZ^*$
  - $H \rightarrow \tau\tau$
And why did LHCb turn into a lumi-glutton?

- Looking for rare decays
  - In general highly suppressed in SM
  - Therefore sensitive to new physics
  - Example $B_s^0 \rightarrow K^* \mu^+\mu^-$ “penguin”
    - FCNC only with highly suppressed loop diagrams in SM

$$\text{Br}(B_s^0 \rightarrow K^0 \mu^+\mu^-) = [2.9 \pm 1.0 \text{ (stat)} \pm 0.2 \text{ (syst)} \pm 0.3 \text{ (norm)}] \times 10^{-8}$$

- Lepton universality: broken?
  - Example:
    $$R_K = \frac{\Gamma(B^+ \rightarrow K^+\mu^+\mu^-)}{\Gamma(B^+ \rightarrow K^+e^+e^-)}$$
    - Also in $B^0$ decays

No analysis with Run2 data public yet
Special runs
VDM scans / online Lumi

- Precise knowledge of the luminosity is essential for physics
  - LHC measurements become more and more precise that this starts to be an important systematic uncertainty for cross section measurements
  - No golden physics process to measure LHC lumi
    - $e^+e^- :$ Bhabha scattering

- Principle of the measurement:
  - Need to measure the beam properties to calculate the lumi and compare to counting rates in specific lumi-detectors $\rightarrow$ absolute calibration of luminometers
    - Only possible under special conditions $\rightarrow$ VdM optics and beams
  - Then extrapolate to real physics conditions $\rightarrow$ systematic effects

- VDM scans have become (and will at least stay) more complicated during Run II
  - Justified by the increasing precision of the luminosity measurement $O(2\%)$
  - The VDM programme consists of various calibration fills around the Scanning fill itself.
    - Also “emittance scans” during physics in ATLAS and CMS to monitor long term stability
  - Needs careful planning with the experiments and the machine coordinators (and LPC).

- New since 2017: cross checks of lumi ratio ATLAS/CMS with quasi online Z-counting analysis
  - VDM calibration is only available months after the VDM scans
  - Need to have a tool to judge apparent lumi imbalances (as in 2016)
Forward physics
Or: Why do we do this to us?

“Normal” inelastic scattering

Elastic Scattering

Single Diffraction (SD)

Central Diffraction (CD)

ATLAS & CMS

TOTEM, ALFA, CTPPS, AFP
Elastic scattering

- Elastic scattering → Energy of $p$ remains unchanged, only momentum transfer $t$
  - Maximise acceptance to low $t$:
    - Measure total cross section via optical theorem (extrapolate $\sigma_{el}$ to $t=0$)
    - Measure interference of coulomb and nuclear interactions ($\rho$ – parameter) to understand underlying processes in elastic scattering

Totem (2015 2.5km run): Lower than expected can be explained by exchange of Odderon

No $\rho$ – measurement for pp in this range before 2018 run
Run II special Runs: high $\beta^*$

- **Challenging for the LHC**
  - Pots have to be driven close to the beam ($3\sigma$): large $\beta^*$, no Stable Beams
  - Large beams, background in pots depend on Halo conditions
  - The lower the energy the stronger IBS effects

- **Challenging for the LPC**
  - Conflicting requests from the experiments (TOTEM, ATLAS/ALFA) presented to LPC in an emotional environment…
    - Work by the LPC to be done here
  - Online monitoring of data quality needs improvement
    - Work by the experiments to be done here

- **2016**: Run at $E_{\text{cms}} = 13\text{TeV}$ and $\beta^* = 2.5\text{km}$

- **2018**: Run at $E_{\text{cms}} = 900\text{GeV}$ and $\beta^* \sim O(100\text{m})$ (Details: Mini workshop by H. Burkhard et al.)
  - More time invested for testing than for data taking at high $\beta^*$
  - Successful run ($>10^6$ events in ALFA and TOTEM) using 2 specifically developed collimation schemes
    - 2 stage scheme within $0.5\sigma$
    - **1st use of crystal collimation in a physics run**
Diffractive processes

- Diffractive processes: A color singlet is exchanged
  - Called “Pomeron”, in QCD this would be a colorless system of multiple gluons
  - Surviving Proton(s) looses energy ($\xi = 1 - E_p / E_{beam}$)

- Compromise of acceptance, luminosity and available time
  - **Hunt for glue balls**: need acceptance at low $\xi \rightarrow$ high $\beta^*$, pots close to beam
  - Best compromise $\beta^*$~90m (in 2018 asymmetric $\beta^*$ to optimise luminosity)

- First run in 2015: modest luminosity since pile-up had to be very small

- Second run in 2018 with new timing detectors in TOTEM and ATLAS/ALFA participating
  - Higher pile-up could be tolerated due to the presence of timing detectors
  - Machine successfully delivered 50ns beams
  - Much higher statistics (Factor 8-10)

- During high lumi pp running (CTPPS, ATLAS/AFP):
  - Potential to discover new heavy particles which have been missed by ATLAS/CMS.
  - Needed lowering of pot impedance: Successful collaboration with MPP and Impedance team

- 2015: LHCf pp run at 19m: ~32h of data taking
  - Valuable resource for astronomic air-shower model-builders
Ion programme 2015-2018
(see talk of John Jowett)

- 2015 and 2018: PbPb runs
  - 2015: 433µb ALICE; ~585µb CMS and ATLAS, 6.3µb LHCb
  - 2018: 905µb ALICE and 1.8nb⁻¹ CMS and ATLAS, 235µb LHCb
    - Peak lumi in ATLAS and CMS reached 6x10³⁷.
  - Official Goal of first 10 years exceeded (1nb⁻¹ in 2 experiments)
    - **Experiments very pleased**

- 2016: Pb-p run
  - Due to conflicting requests, ran with 2 configs:
    - 5.02 TeV (optimised for ALICE)
    - 8 TeV optimised for IP1 & 5
    - LHCf run for 9.5 hours
  - **All experiments requirements were satisfied**

- 2017: Reference data taking (pp) at 5.02 and 8 TeV

- Xe Xe pilot run
  - ALICE: 4 publications
  - CMS: 3 preliminary results, ATLAS 2 conference notes
  - LHCb: first results shown at conference
  - **Extremely good “value for beam-time”**
Example why lumi is important in HI

- ALICE : Nuclear modification factor and anisotropic distribution of charm in PbPb events

Charm: constraining the QGP transport properties

\[ R_{AA} = \left( \frac{dN}{dp_T} \right)_{AA} / \left( \frac{dN}{dp_T} \right)_{pp} \]

- powerful constraint from combination of \( R_{AA} \) and \( v_2 \)
Paper on LHC Energy

- Energy paper (Joerg Wenninger and Ezio Todesco)
  - This paper allows experiments to cite consistently a value for the error on the energy
  - In some cross section measurements this becomes an important systematic error
  - This work is highly appreciated by the physics community
The experiments warmly thank the accelerator communities for the enormous effort which made Run II so successful.

The LPC thank the accelerator experts and the experiments for all the productive collaboration and patience with us.

It was a great pleasure to work with you.

Brian will now steer the LPC towards Run III.
Appendix

Operational details suggested by experiments

LPC tools on LPC website
Suggestions for Operation

- Commissioning spread sheet introduced in run 2 was highly appreciated by experiments
- Early release of MD schedules with requests to experiments is very useful for planning of work in experiments
- Page-1 comments could be updated more frequently
- More realistic estimations of down times would be useful to plan work
  - Understood that experiments must stay in the shadow of the work to remove a problem
- ALICE would appreciate a systematically early declaration of SB
- LHCb would like to have the most realistic lumi target possible in order to plan efficient use of computing resources
  - If possible, last minute schedule changes should be avoided.
LPC tools

- Minutes of meetings
  - Minutes can be searched

- Lumi calculator (with basic plotting)

- Fill length estimator and “Ion Sharer”
  - Mini simulations based on lumi formula considering crossing angle anti leveling and $\beta^*$ anti leveling (Thanks to M. Hohstettler!!!)
  - Calculates integrated lumi and lumi per time

- Re-introduction of Massi files
  - Versioning of Massi files introduced
    - Comments for users to judge the contents

- A set of performance plots
  - Luminosity
  - Measured optimal lumi (turn around time as a parameter)
    - Measured for fills which went beyond the optimum
  - Lumi ratio IP1/5 $\rightarrow$ geometrical factor

- Lumi comparison IP1&5 based on Z counting
  - Very valuable cross check of online luminosities
LPC tools

- **Filling scheme editor** and Filling scheme viewer
  - Allows to download json file with filled bunches
  - Easy transfer to LHC filling scheme editor
  - Calculates predictions of the full detuning phase shifts
  - Can calculate a Fourier transform for any filling scheme

- **Fill association table**

- **Annotated fill table**
  - For all fills reaching stable beams (or being used for physics)
  - This table does not contain many of the changes of the settings of the LHC but more remarks relevant for the experiments. It is filled out by the LPC (mainly during the morning meetings)